Antimatter Gravitation and positronium

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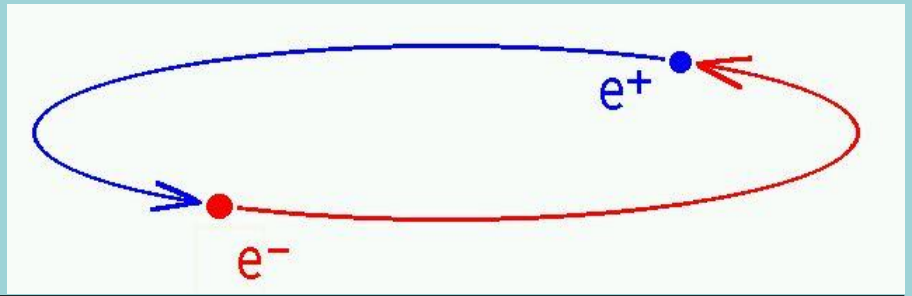
- Antimatter: the Cosmic Mistery
- Fundamental Laws and Antimatter
- Gravitational Measurements and positronium

0
Ps
0.0011



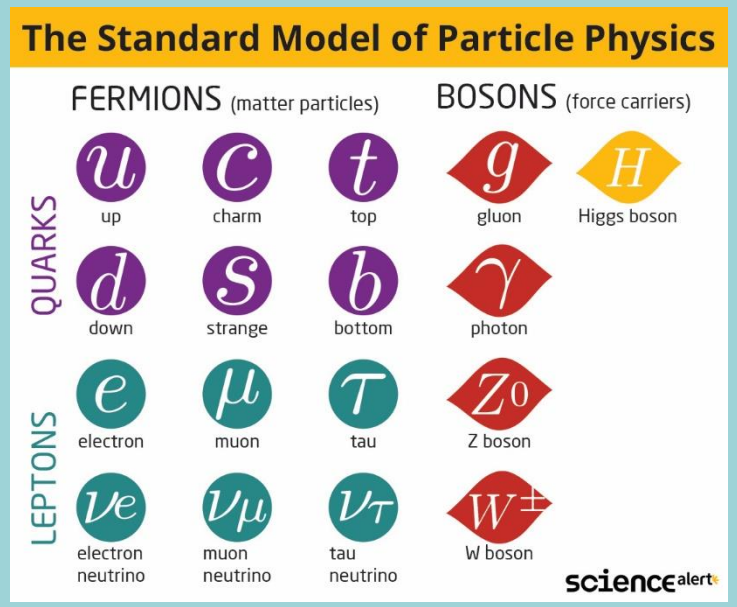
Ortho-Ps (parallel spin states) 142 ns lifetime
Para-Ps (antiparallel spin) 125 ps

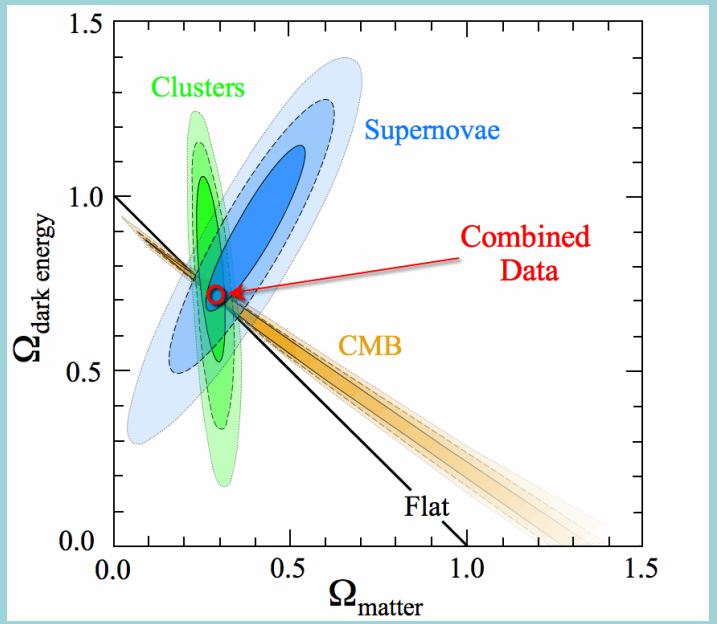
Antimatter: the Cosmic Mistery

Fundamental (2024) Physics and the Universe

Known fundamental particles
(and their interactions)

Cosmological ingredients
Dark Matter, Dark Energy





Not fully confirmed **Λ-CDM Model**

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

- Inflation (new Physics)

Matter-Antimatter Asymmetry Generation

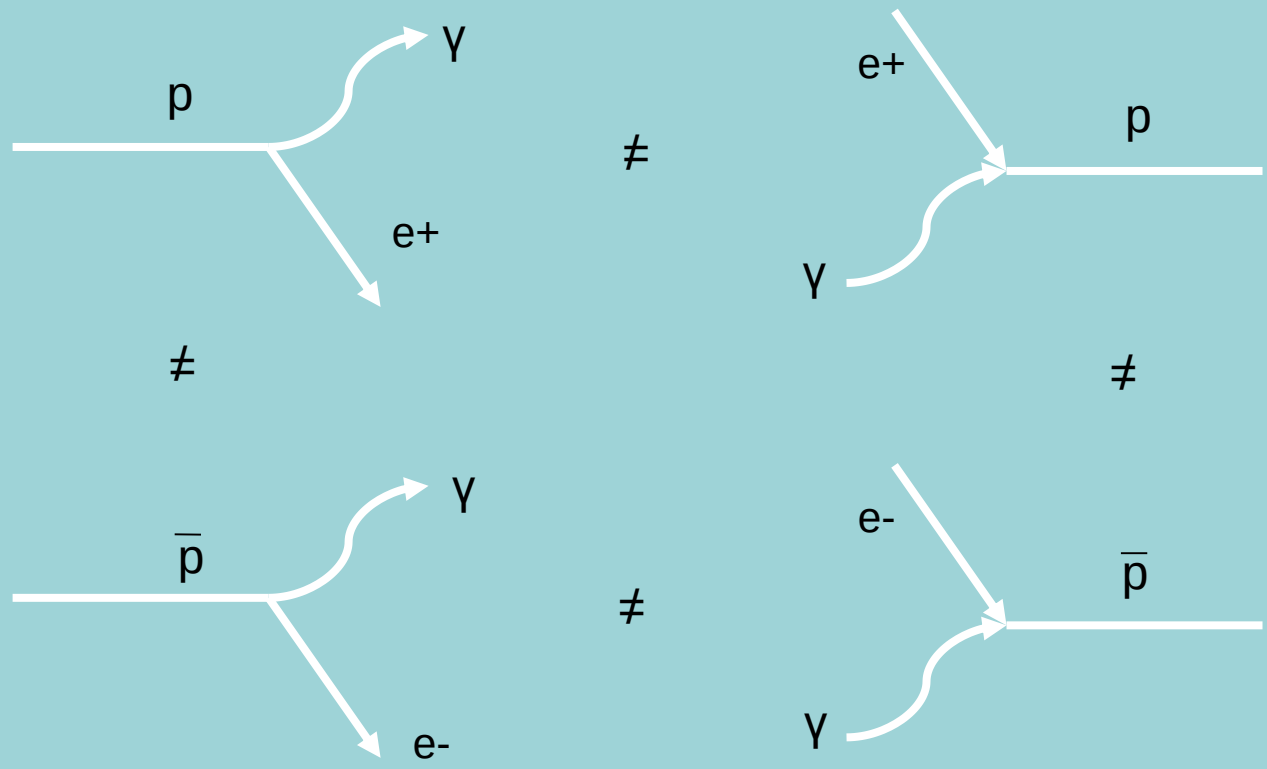
CP Violation in the Standard Model

- Baryogenesis
- Leptogenesis

Generally accepted Baryogenesis scheme

- Baryon Number Violation
- CP Violation
- Out of Equilibrium

Sakharov conditions



Fundamental Laws and Antimatter

Laws relating Particles (Matter) to Antiparticles (Antimatter)

Einstein Equivalence Principle (EEP)

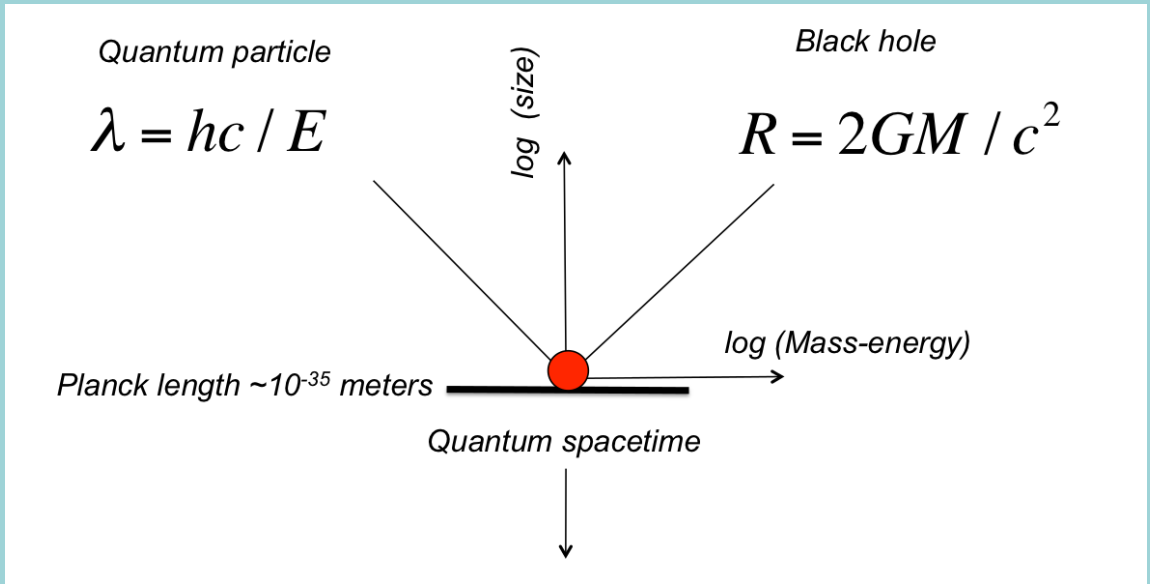
- Weak Equivalence Principle
- Local Position Invariance
- Strong Equivalence Principle

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

Fundamental (2024) Physics

$$\mathscr{L} = \mathscr{L}_{EH} + \mathscr{L}_{SM}$$

General Relativity | Standard Model

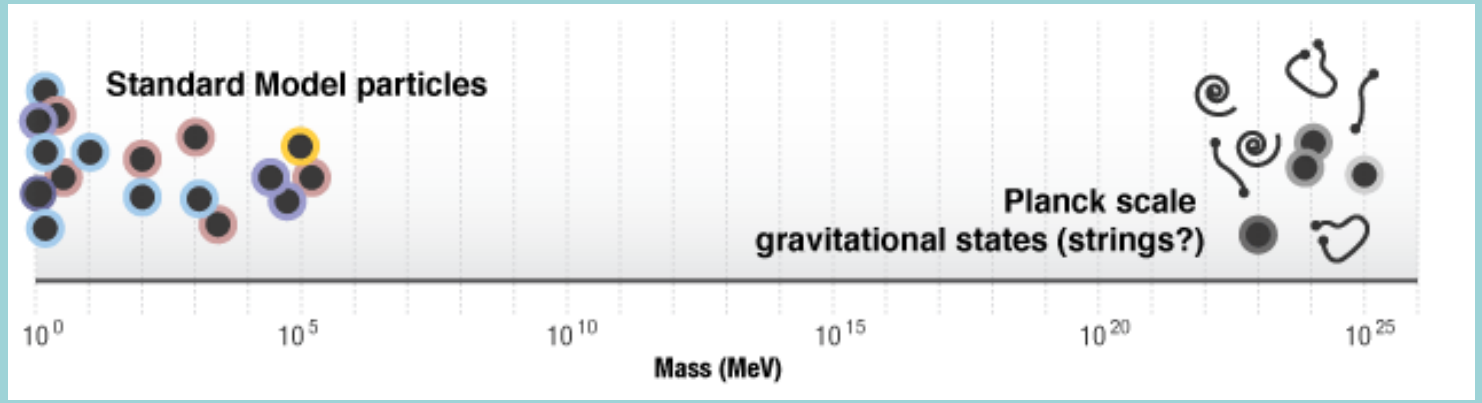
Curvature scalar R
Metrics g(x)
(Classical Matter Fields)

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

Hierarchy Problem

Cosmological Constant Problem

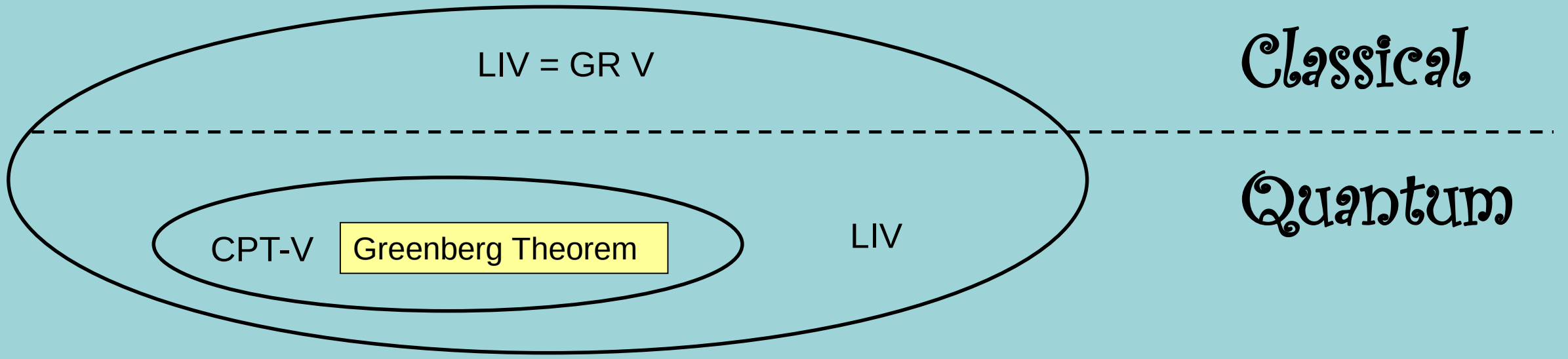
Lack of SUSY (DM?) Particles



Standard Model Extension

$$\mathscr{L} = \mathscr{L}_{EH} + \mathscr{L}_{SM} + \mathscr{L}_{LIV}$$

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



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

Einstein Equivalence Principle

(old equivalence principle, Galileo)

•But this [view of Aristotle] is completely erroneous, and our view may be completely corroborated by actual observation more effectively than by any sort of verbal argument. For if you let fall from the same height two weights, one many times heavier than the other you will see that the ratio of the times required for the motion does not depend [solely] on the weights, but that the difference in time is very small. ... (Wikipedia)

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John Philoponus (c. 490 – c. 570), also known as **John the Grammarian** or **John of Alexandria**.

He was a Byzantine Greek philologist from Alexandria, Aristotelian commentator, Christian theologian and an author of a considerable number of philosophical treatises and theological works.

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

$$\mathscr{L} = \mathscr{L}_{EH} + \mathscr{L}_{SM} + \mathscr{L}_{LIV}$$

LIV terms up to some mass dimension
If d<5 → mSME

A fermion in the (flat spacetime) SME :

CPT & LORENTZ VIOLATION

$$(i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu - \tfrac{1}{2} H^e_{\mu\nu} \sigma^{\mu\nu} + i c^e_{\mu\nu} \gamma^\mu D^\nu + i d^e_{\mu\nu} \gamma_5 \gamma^\mu D^\nu)\psi = 0 .$$

LORENTZ VIOLATION

Standard Model + LIV, no gravity, a fermion

LIV coefficients depend on the specific particle!

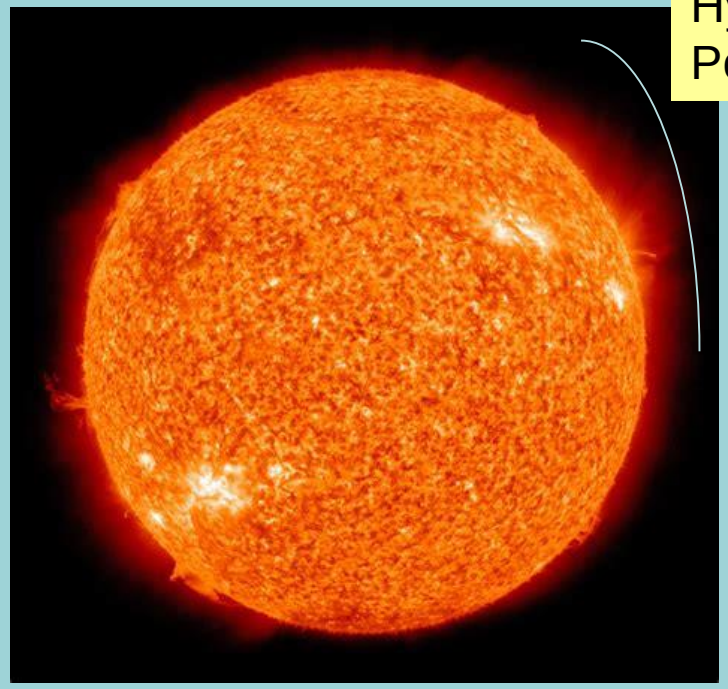
D. Colladay and V.A. Kostelecky, PRD 55, 6760 (1997)

Gravitating Matter/Antimatter Systems in the Standard Model Extension

$$L_{IPM} = \frac{1}{2} m_i^T + \frac{G}{r} m_g^T m_g^S$$

T test particle S Sun

In the Isotropic Parachute Model of the SME (Sun coordinates)



Hydrogen, Positronium

This model overcomes several «objections» to theories with different gravitational couplings between matter and antimatter

B=T,S w: different particles

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

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

a^w CPT-odd

c^w CPT-even

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

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

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

$$m_i = m_g \quad (matter)$$

Anti-Hydrogen

Positronium

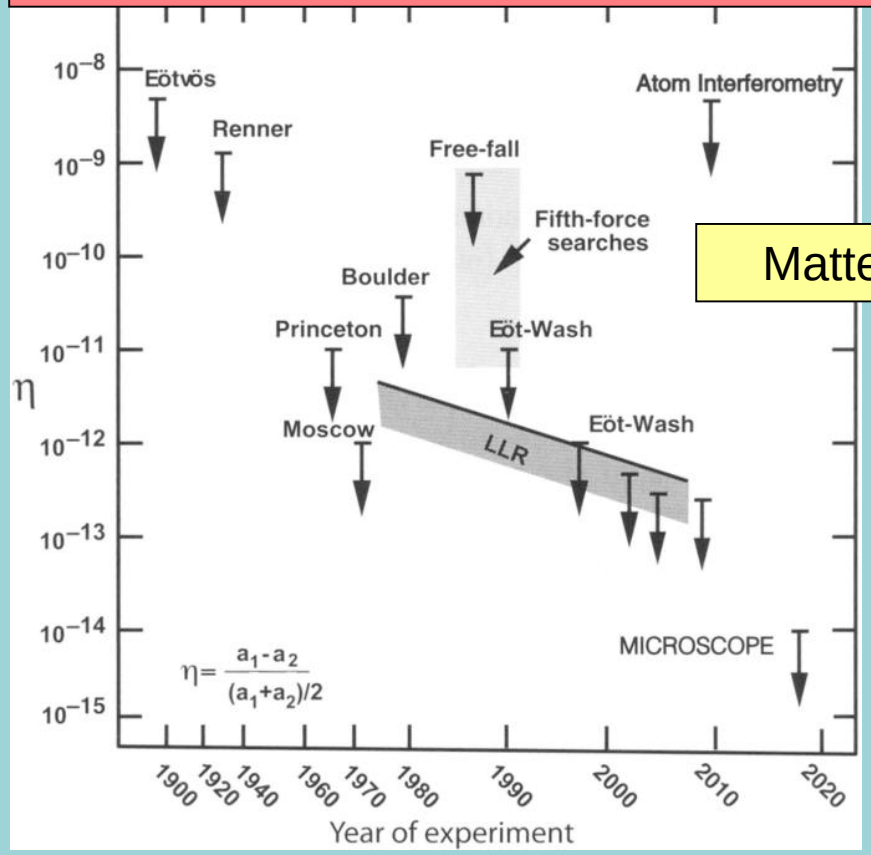
$$\frac{\delta g}{g} = \frac{2}{m} \sum_w \left(\alpha\, a^w + \frac{1}{3} m^w c^w \right)$$

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

The proton (antiproton) system is mostly made up of color field, so the parameters do not directly address constituent masses

Gravitational Measurements

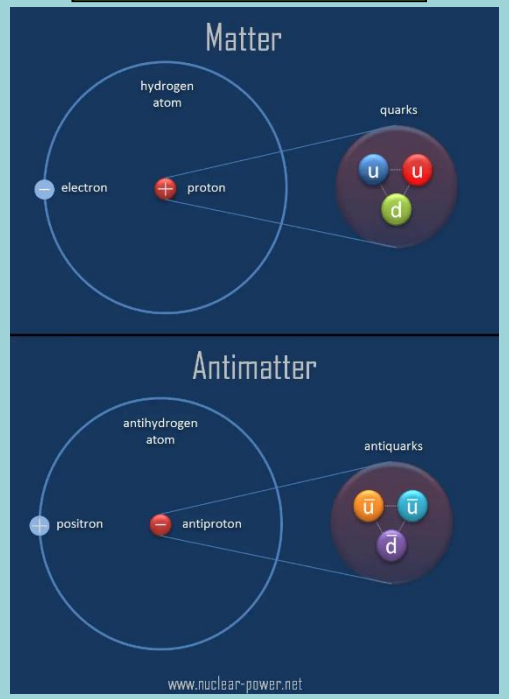
Tests of the Weak Equivalence Principle



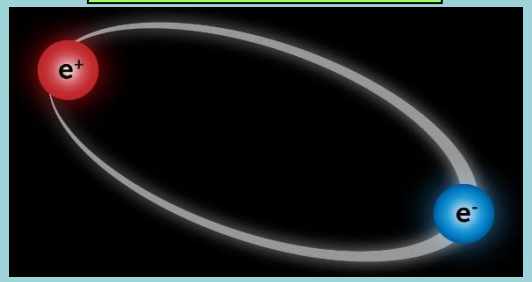
Matter

Antimatter ?

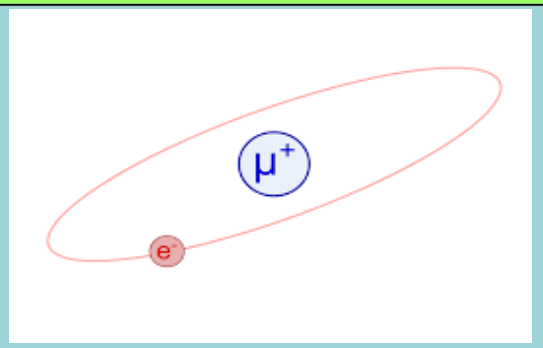
Anti-Hydrogen



Positronium



Muonium (Mu-atom, please)

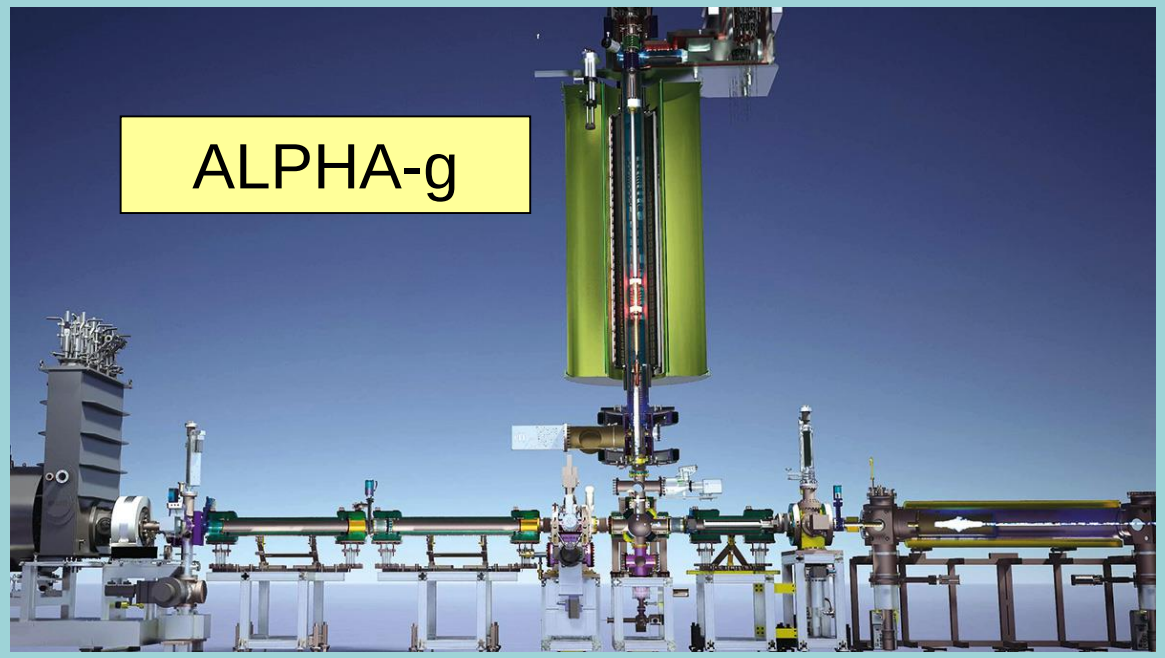


First anti-g measurement

Talk by G. Bonomi

Observation of the effect of gravity on the motion of antimatter

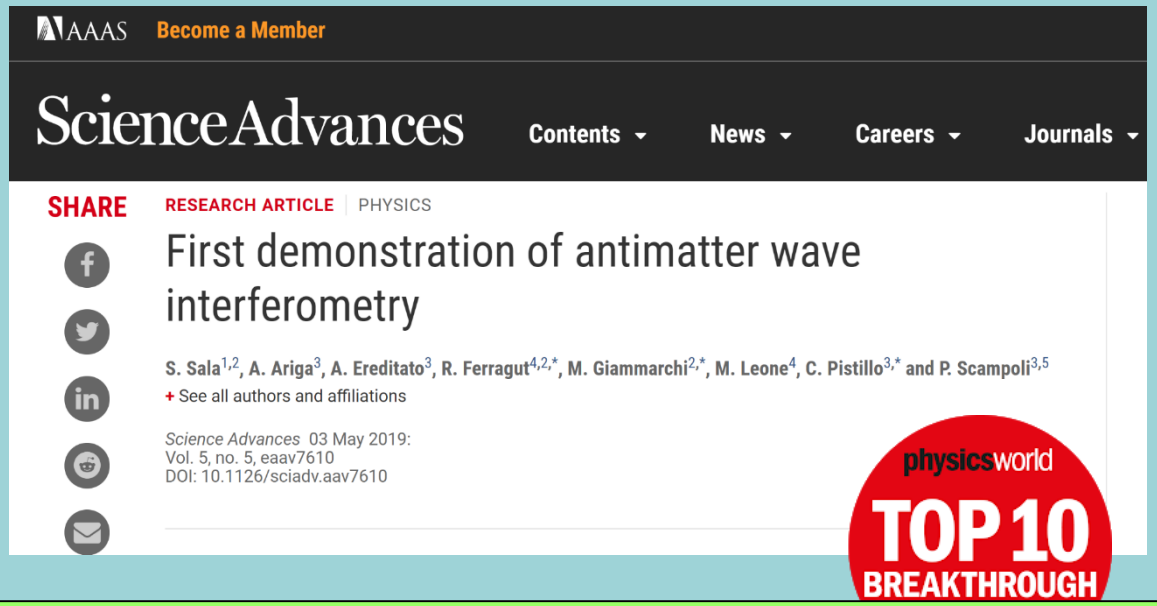
Nature **621**, pages 716–722 (2023)

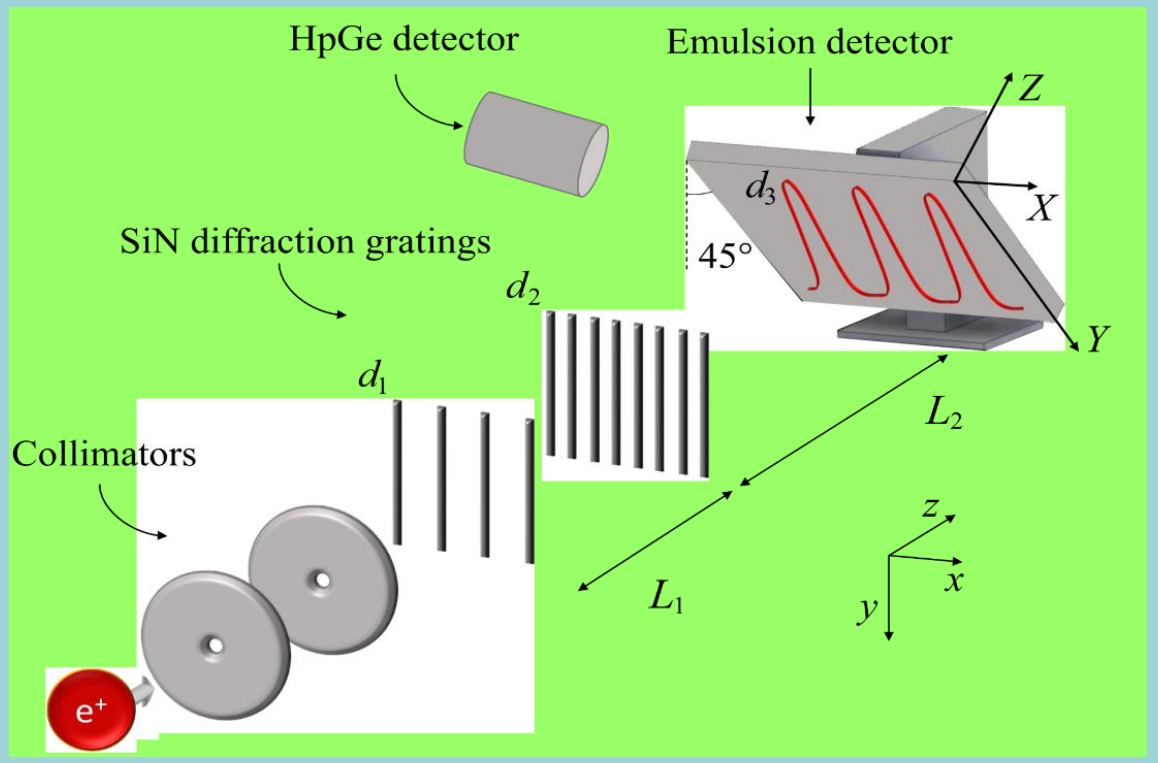


Antihydrogen gravitational coupling (0.75 ± 0.13 (statistical + systematic) ± 0.16 (simulation)) *g*

Most likely excludes the hypotesis of ANTIGRAVITY

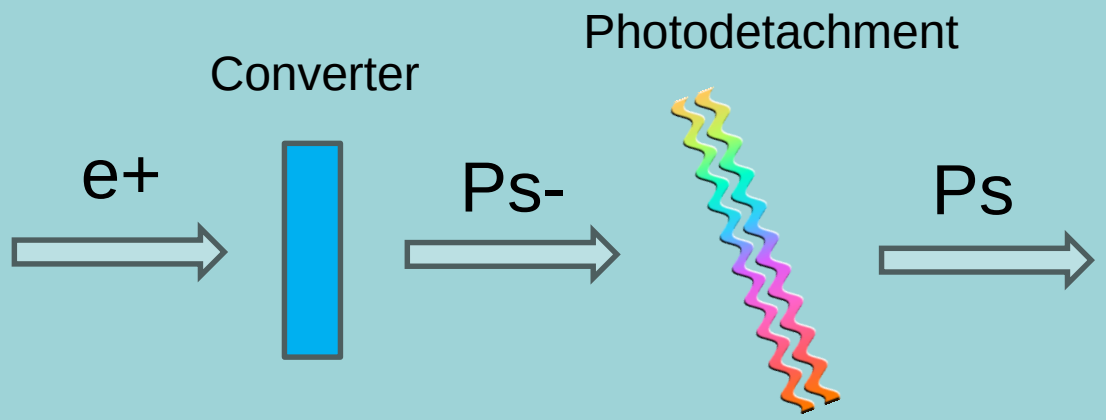
QUPLAS : Positron Interferometry and Positronium Gravitation





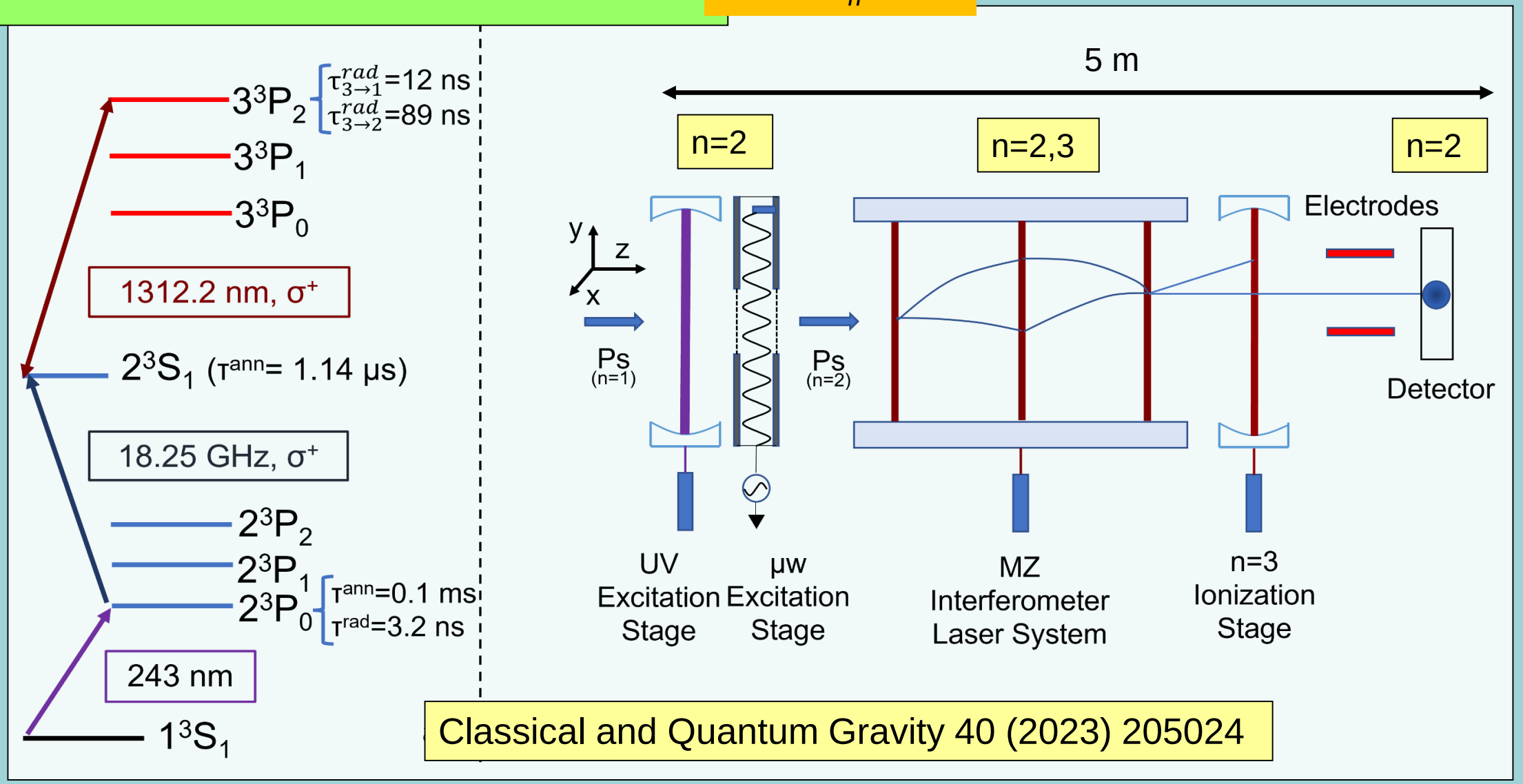
Detection of micrometric interferometric patter by emulsions (talks by V. Tioukov, A. Alexandrov)

Development of a new concept of Ps beams, by making intermediate use of the Ps- ion system. arXiv:2307.12894



QUPLAS LMT – Mach Zehnder Interferometer

$$\Delta\phi = k_{eff}\, g\, T^2$$



Classical and Quantum Gravity 40 (2023) 205024

A conclusion

Research on Antimatter at Low Energy :

- Deals with Fundamental Laws
- Has several aspects which I could not cover (CPT tests)
- Studies the interplay between Quantum Physics and Gravitation
- Could (help to) solve a Cosmic Mistery…and…

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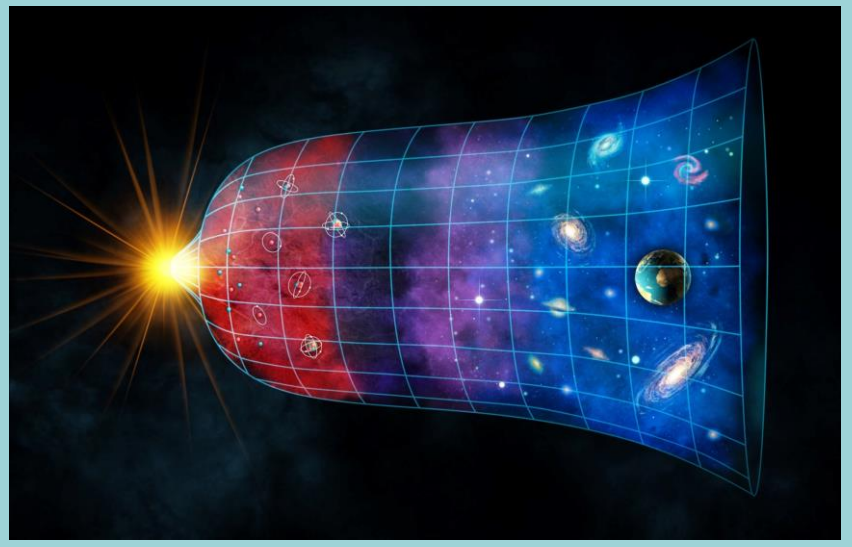
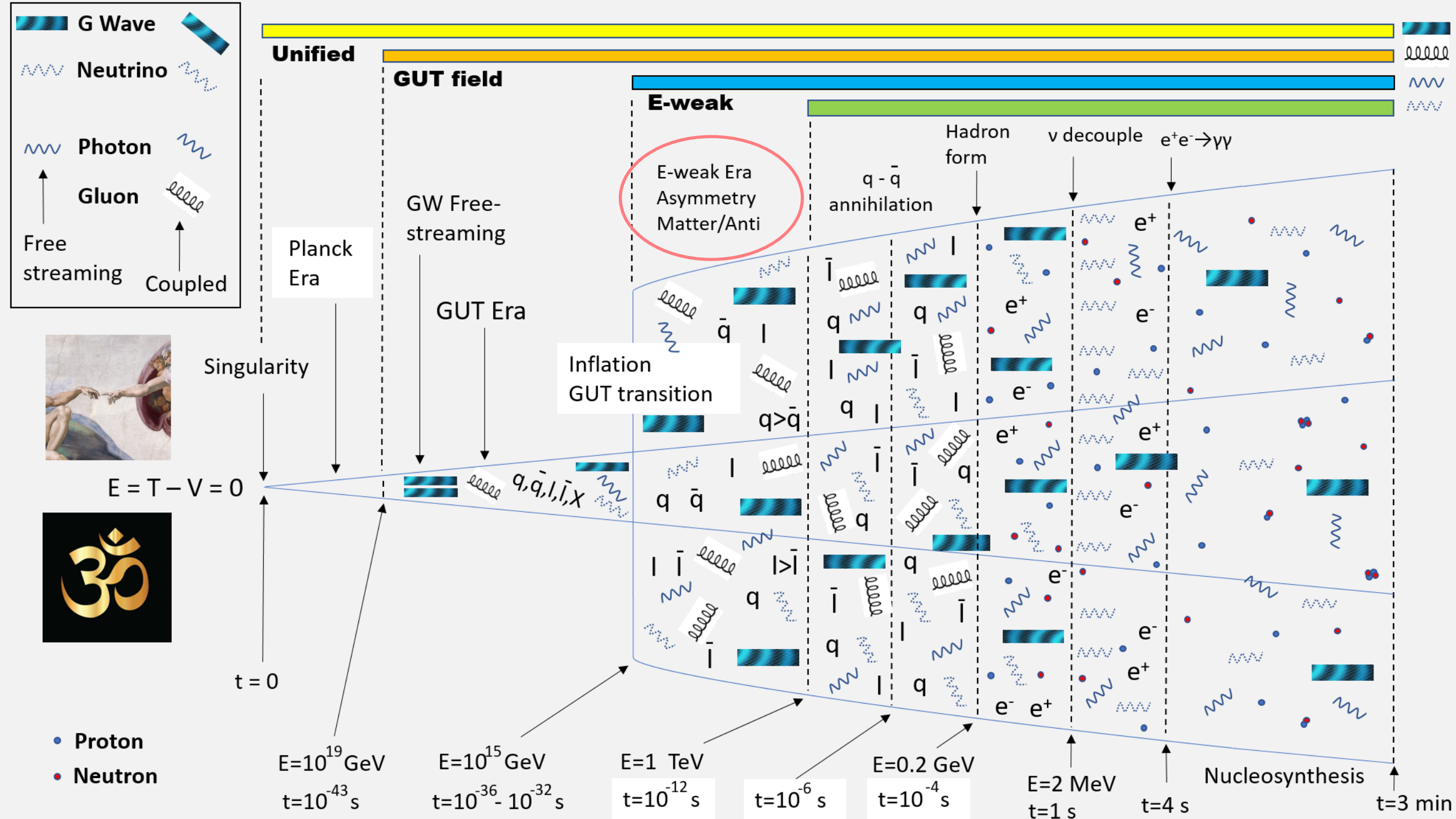
Two things fill the soul with ever new and growing admiration and veneration, the more often and steadily one reflects about them:

cosmology above me, and **quantum physics** within me.

(M. Giammarchi – but not totally original!)




G Wave
Neutrino
Photon
Gluon
Free streaming
Coupled
Unified
GUT field
E-weak
E-weak Era Asymmetry Matter/Anti
q - q̄ annihilation
Hadron form
ν decouple
e⁺e⁻→γγ
Planck Era
GW Free-streaming
GUT Era
Singularity
Inflation GUT transition
E = T – V = 0
t = 0
q,q̄,l,l̄,X
q>q̄
l>l̄
Proton
Neutron
E=10^19 GeV
t=10^-43 s
E=10^15 GeV
t=10^-36 - 10^-32 s
E=1 TeV
t=10^-12 s
t=10^-6 s
E=0.2 GeV
t=10^-4 s
E=2 MeV
t=1 s
t=4 s
Nucleosynthesis
t=3 min