Antimatter Gravitation and Dark Matter searches at the CERN Antiproton Decelerator

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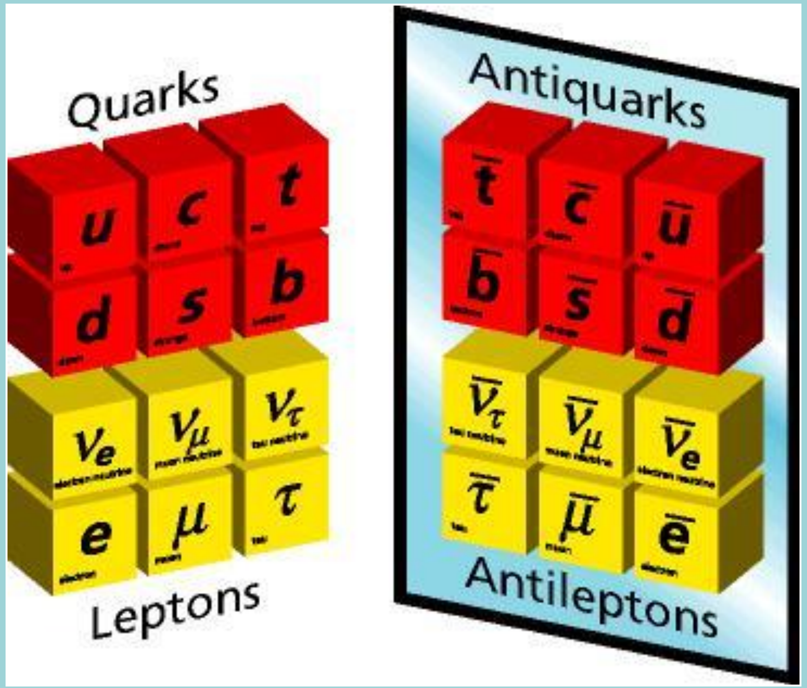
- Antimatter: the Cosmic Mistery
- Fundamental Laws and Antimatter
- Sexaquark as Dark Matter Candidate

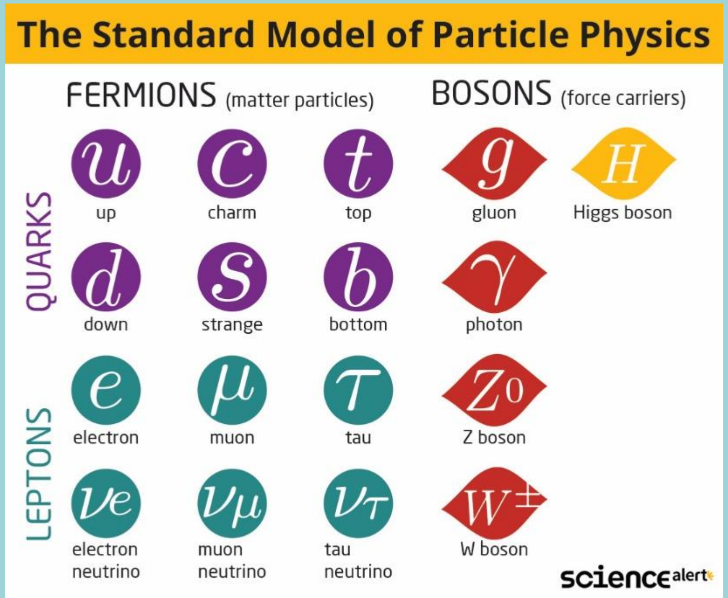


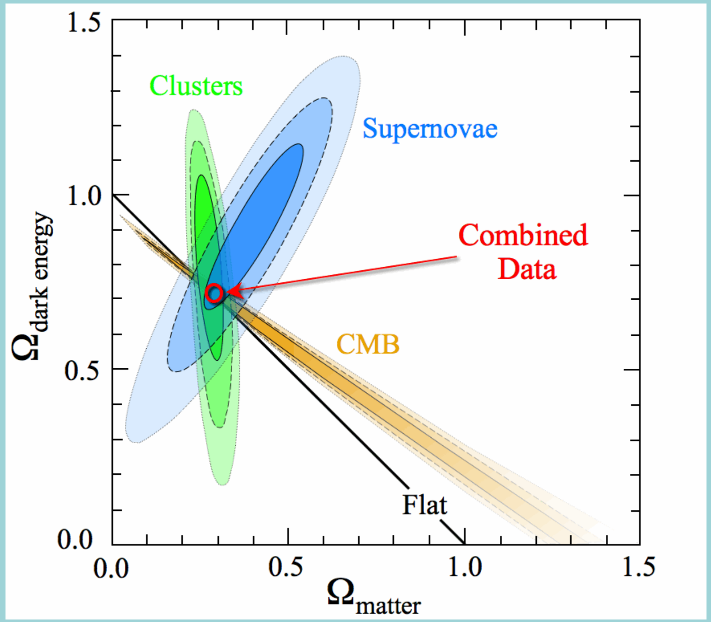
Antimatter: the Cosmic Mistery

Fundamental (2023) Physics and the Universe

Known fundamental particles
(and their interactions)

Cosmological ingredients
Dark Matter, Dark Energy

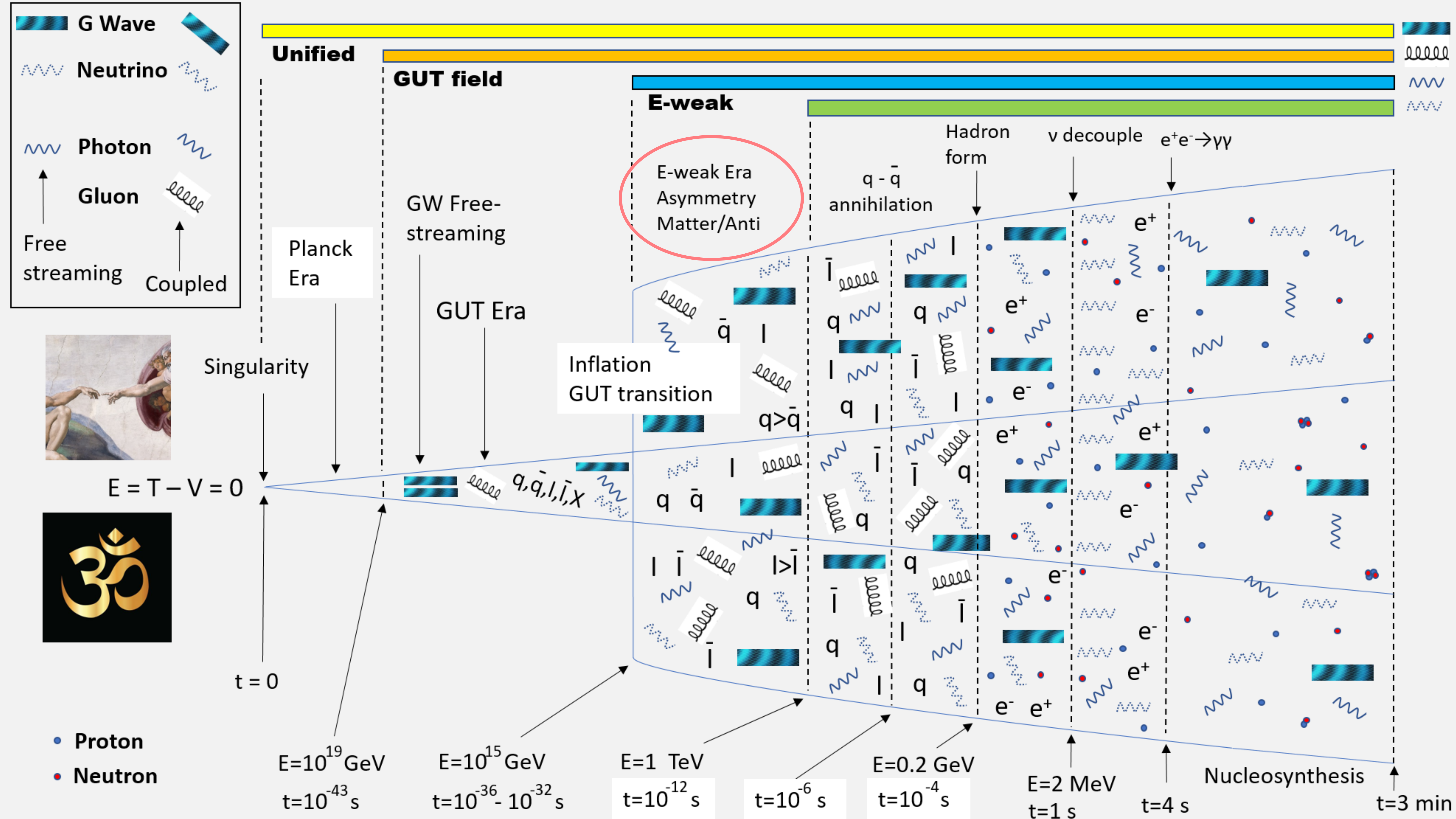




Not fully confirmed **Λ-CDM Model**

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

•Inflation (new Physics)



G Wave
Neutrino
Photon
Gluon
Free streaming
Coupled
Unified
GUT field
E-weak
Planck Era
GW Free-streaming
GUT Era
Singularity
Inflation GUT transition
E-weak Era Asymmetry Matter/Anti
q - q̄ annihilation
Hadron form
ν decouple
e⁺e⁻→γγ
q>q̄
l>l̄
q,q̄,l,l̄,X
E = T – V = 0
t = 0
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

Matter-Antimatter Asymmetry Generation

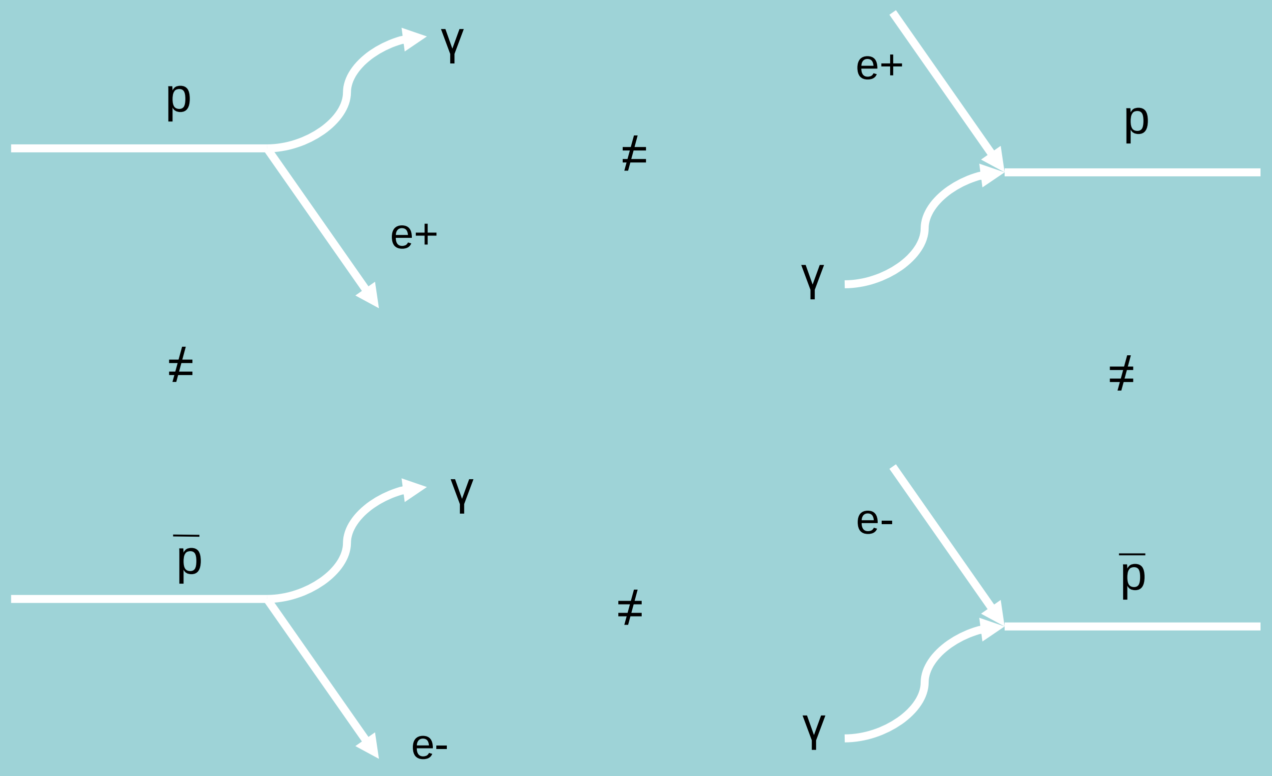
CP Violation in the Standard Model

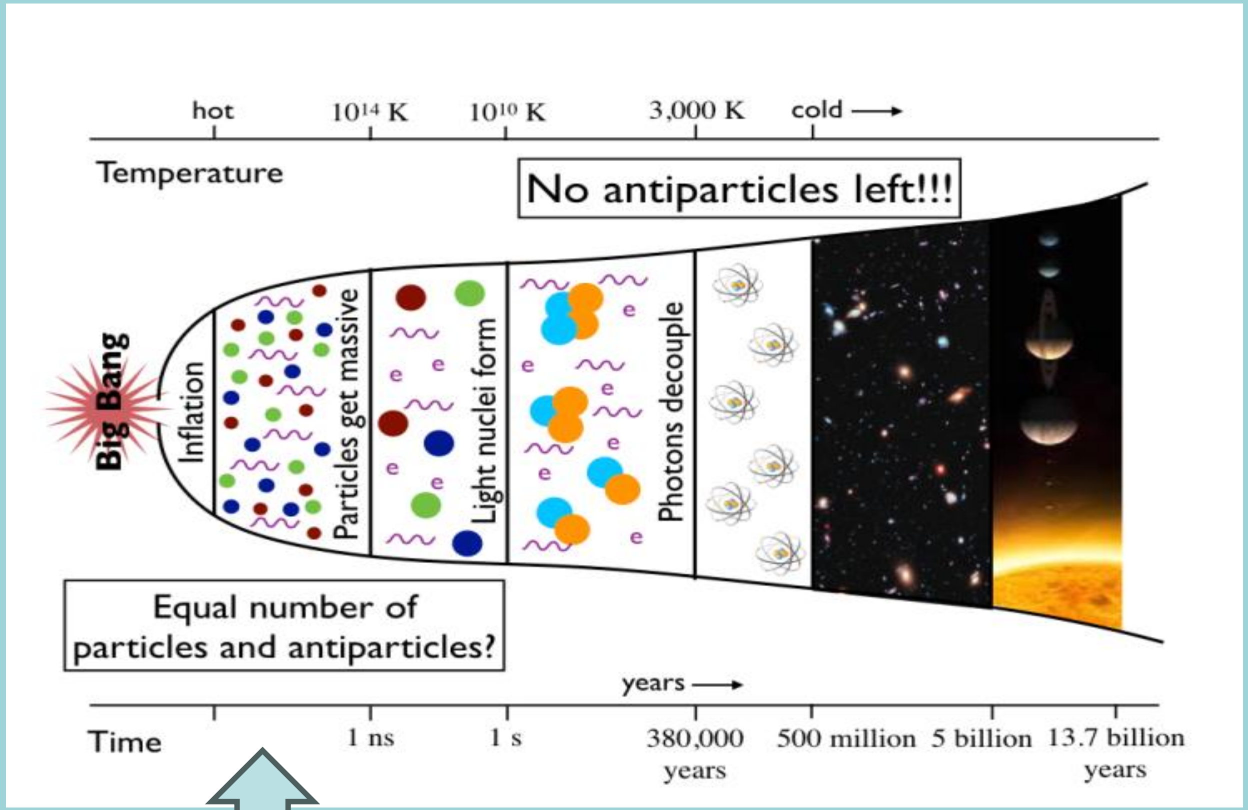
- Baryogenesis
- Leptogenesis

Generally accepted Baryogenesis scheme

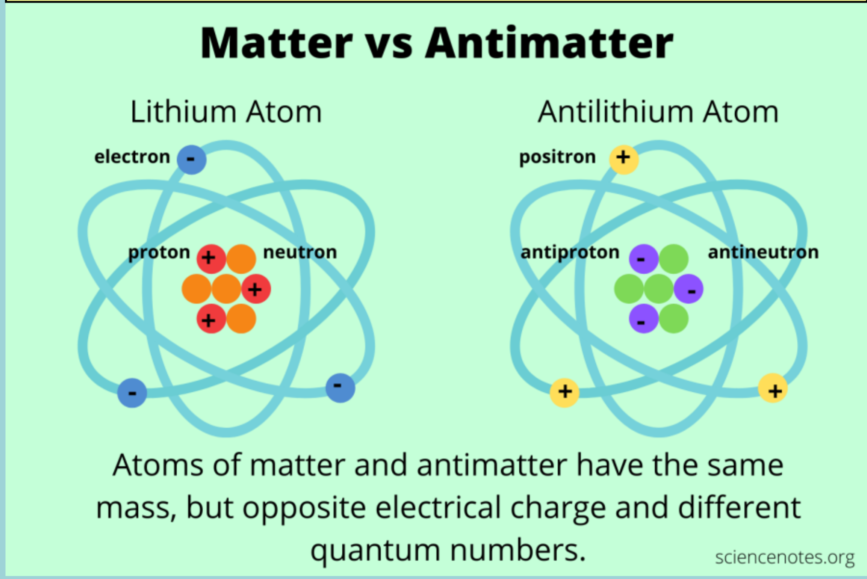
- Baryon Number Violation
- CP Violation
- Out of Equilibrium

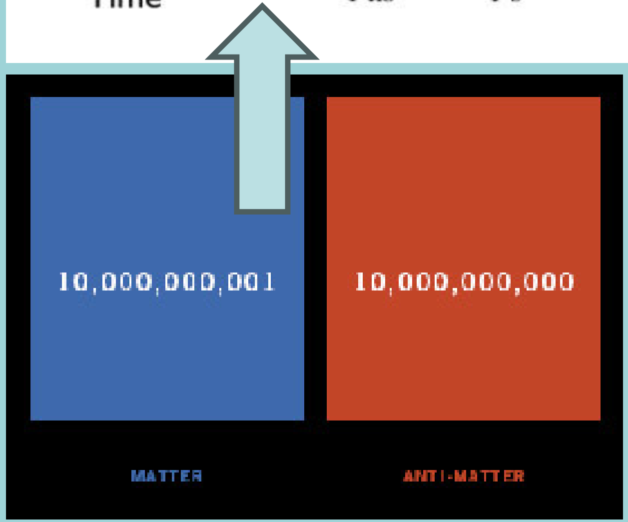
Sakharov conditions





Cosmological Nucleosynthesis
Just 3 minutes to synthetize light nuclei
(with whatever baryon is present)

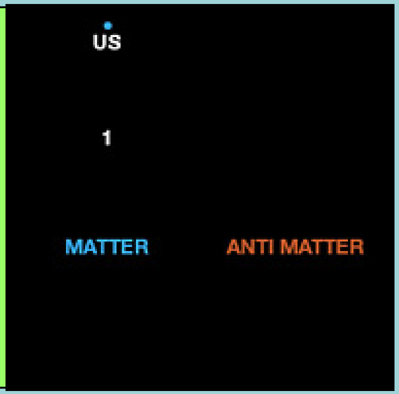




The unbalance was created withing the first 10^{-12} s of Universal Time

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)

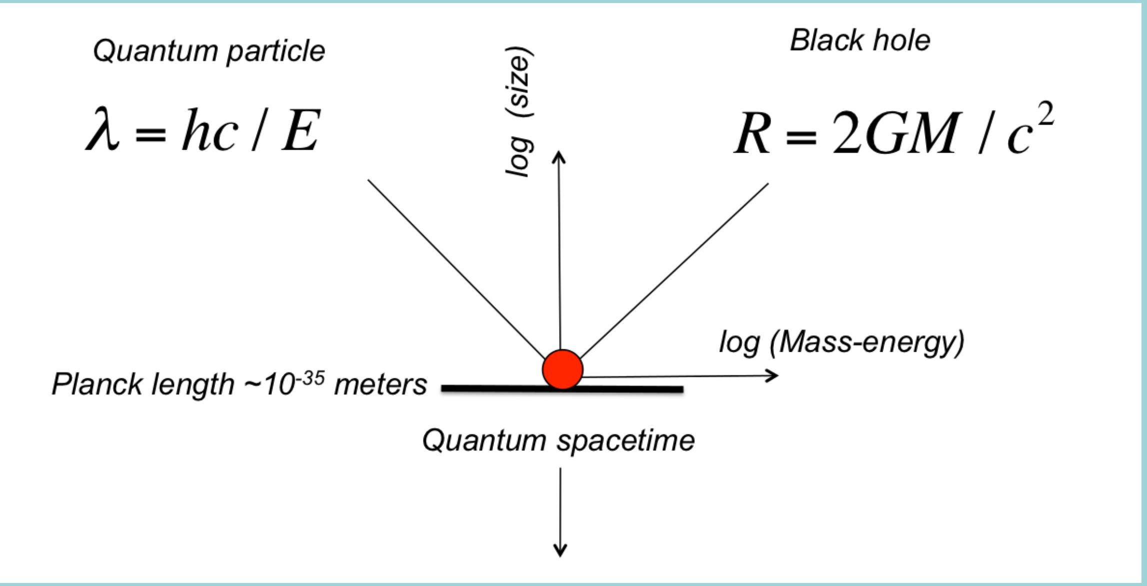
- Weak Equivalence Principle
- Local Position Invariance
- Strong Equivalence Principle

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

Fundamental (2023) Physics

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

General Relativity

Standard Model

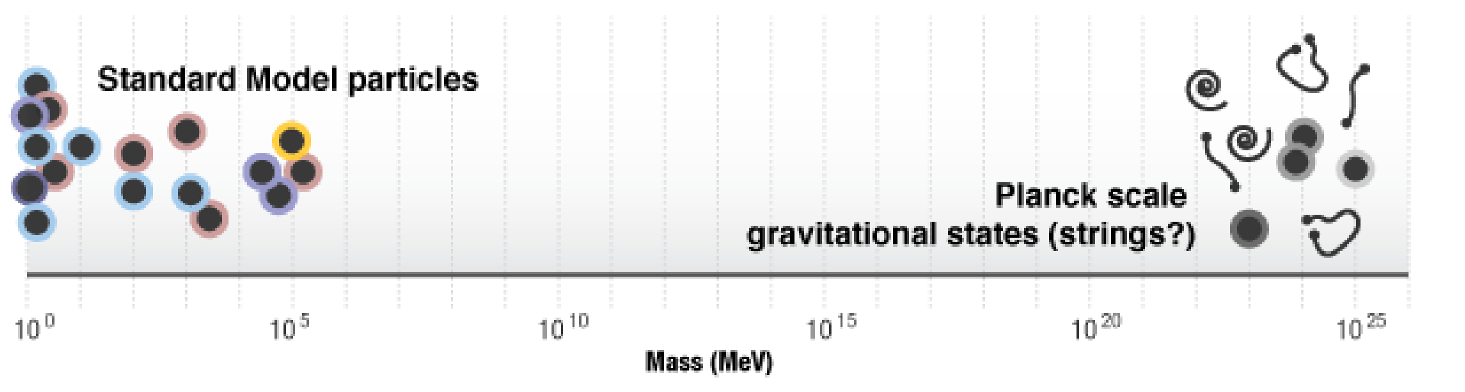
Curvature scalar R
Metrics g(x)
(Classical Matter Fields)

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

Hierarchy Problem

Cosmological Constant Problem

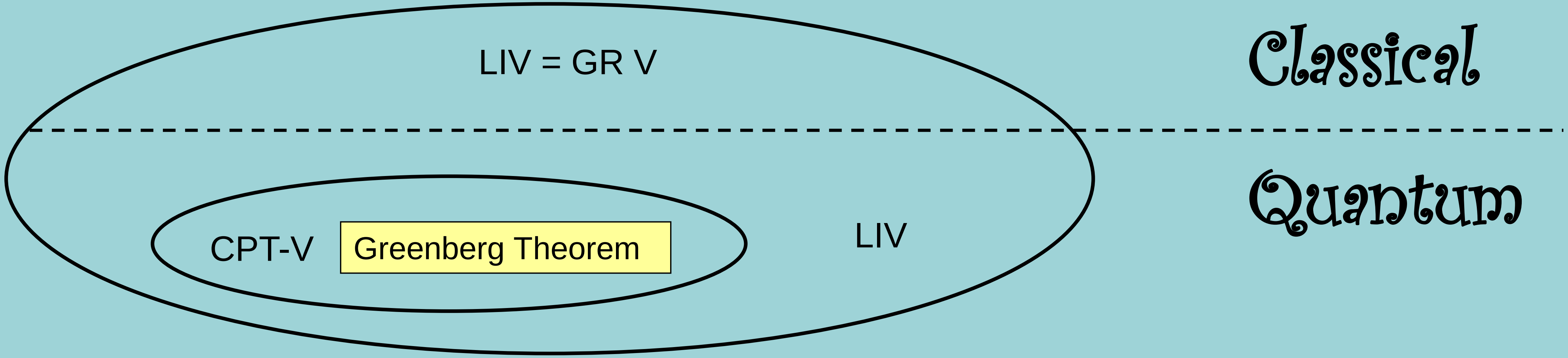
Lack of SUSY (DM?) Particles



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

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

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

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

A fermion in the (flat spacetime) SME :

CPT & LORENTZ VIOLATION

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

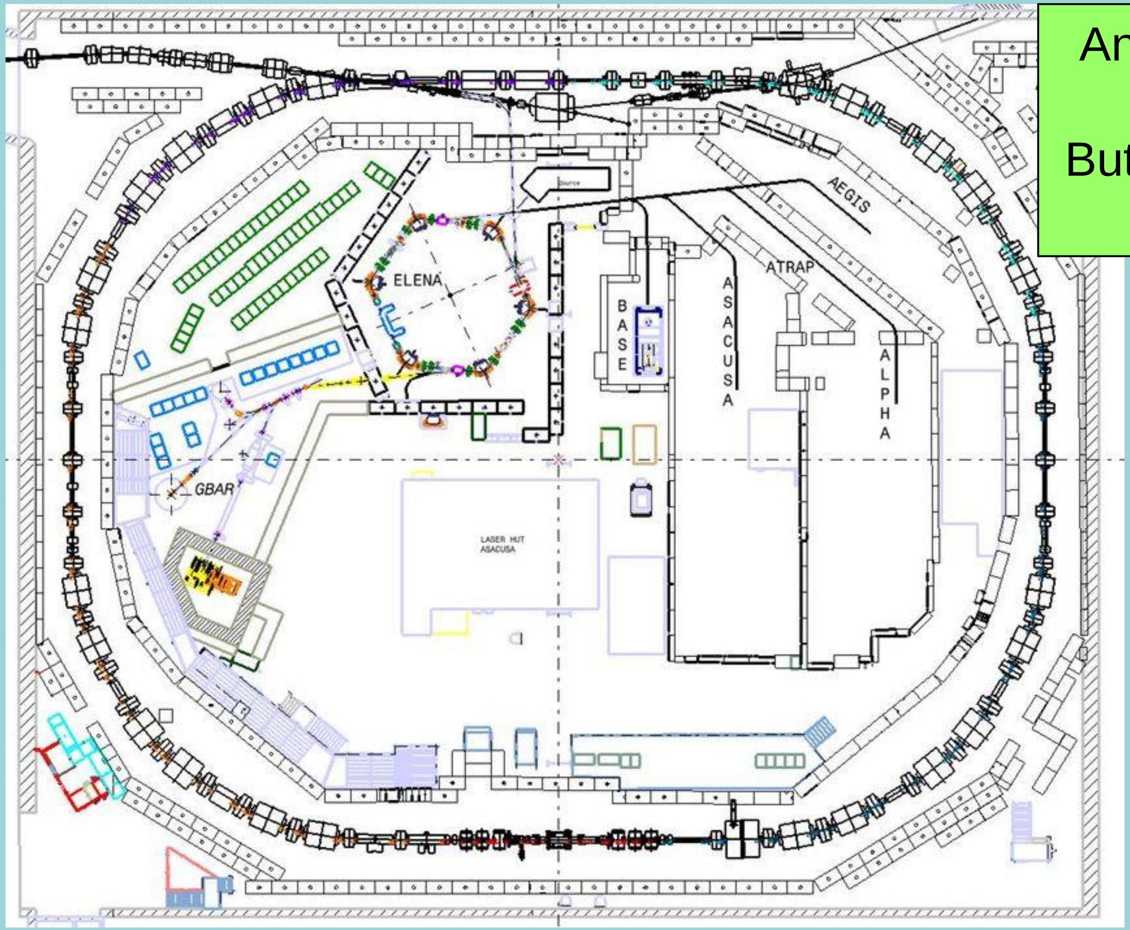
LORENTZ VIOLATION

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

Standard Model + LIV, no gravity, a fermion

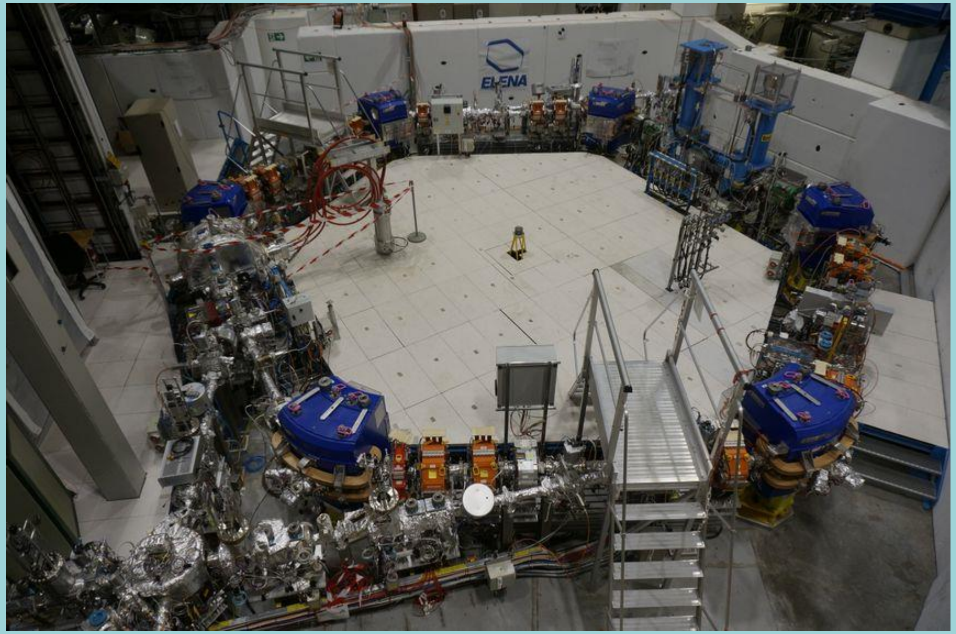
LIV coefficients depend on the specific particle!

The CERN Antiproton Decelerator: an Antimatter Factory



Antiprotons in AD 5.3 MeV

But down to 200 keV kinetic energy in ELENA



The Sexaquark as a Dark Matter candidate

A compact, deeply bound state of *uuddss* quarks

Deeply bound, 0^+ long lived B = 2,   S = - 2,   Q = 0

Similar to the H di-baryon, but a lot more compact and stable

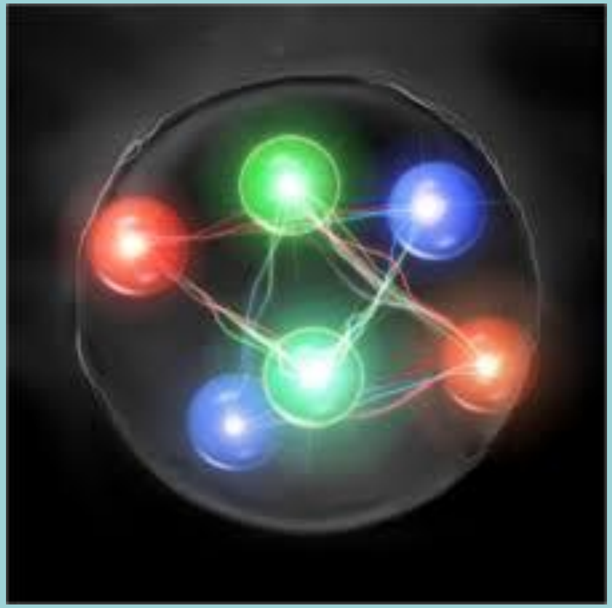
Neutral and flavor-singlet

Likely to exist (QCD lattice calculations)

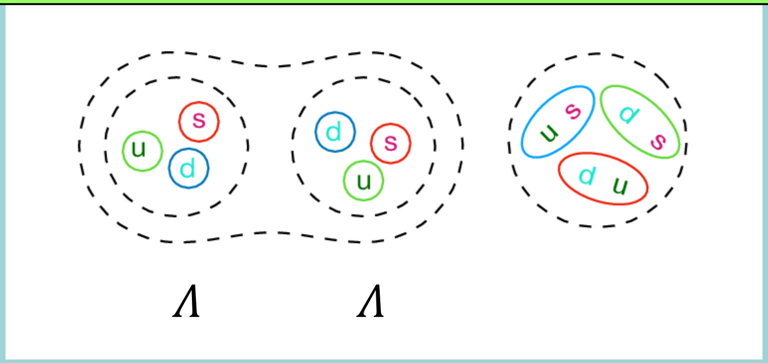
If $m(S) < m(\Lambda) + m(p) = 2$ GeV

lifetime probably longer than age of the Universe (decay must be doubly-weak)

S = *uuddss*

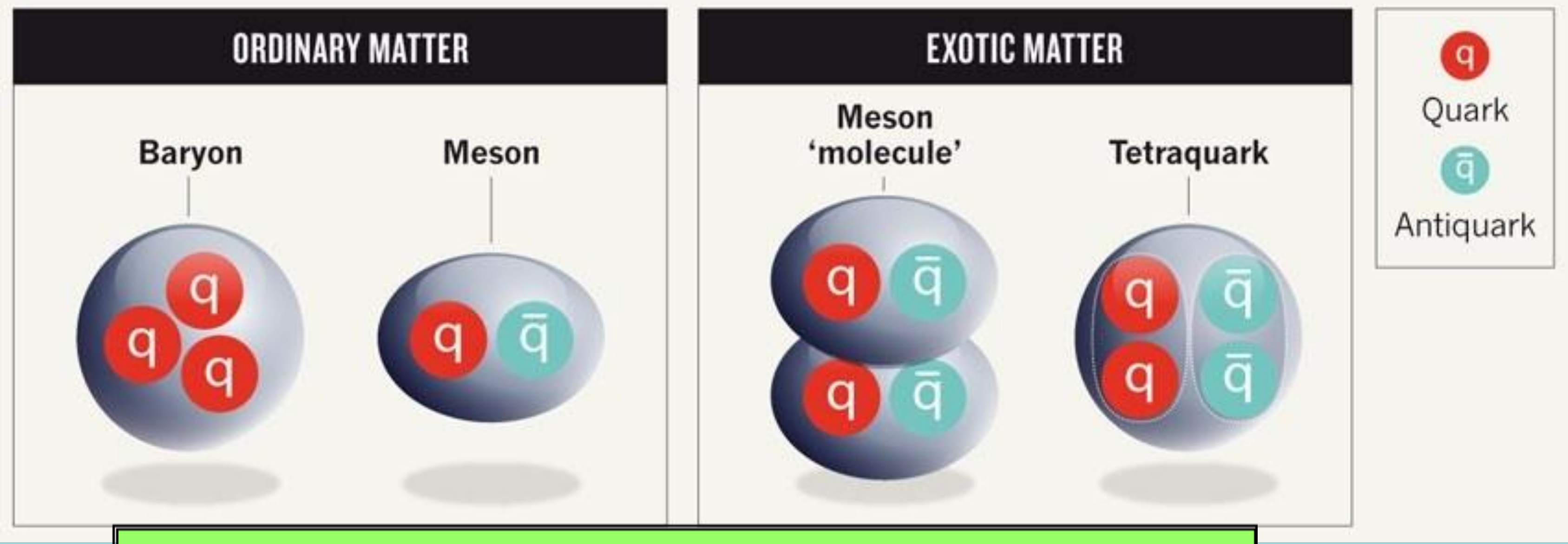


Two different realizazions of a color singlet



QUARK SOUP

Exotic matter made of quarks allows for an interesting DM candidate

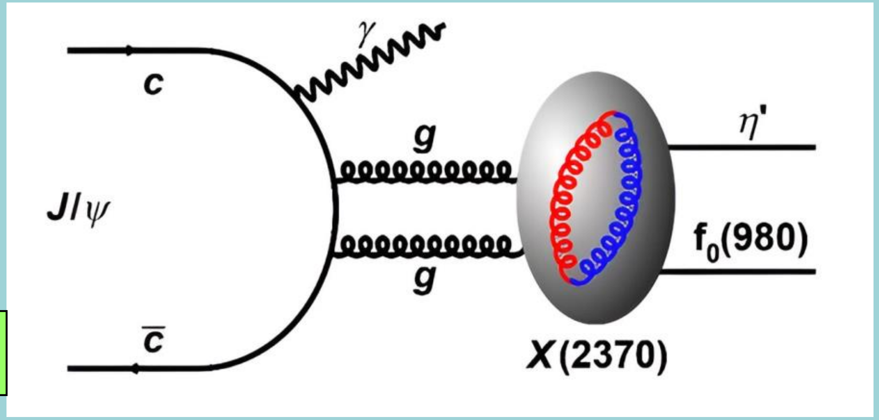


QCD: all the freedom of a colorful theory

Tetraquarks (2003 Belle discovery of the X(3872) $c\bar{c}u\bar{u}$)

Pentaquark states observed

Bound quark states or QCD «molecules»?



Discovery of a glueball particle at BES (2024)

Formation reaction in a low antiproton environment regime (and a He jet target)

Sexaquark (*uuddss*) formation in the presence of an antiproton

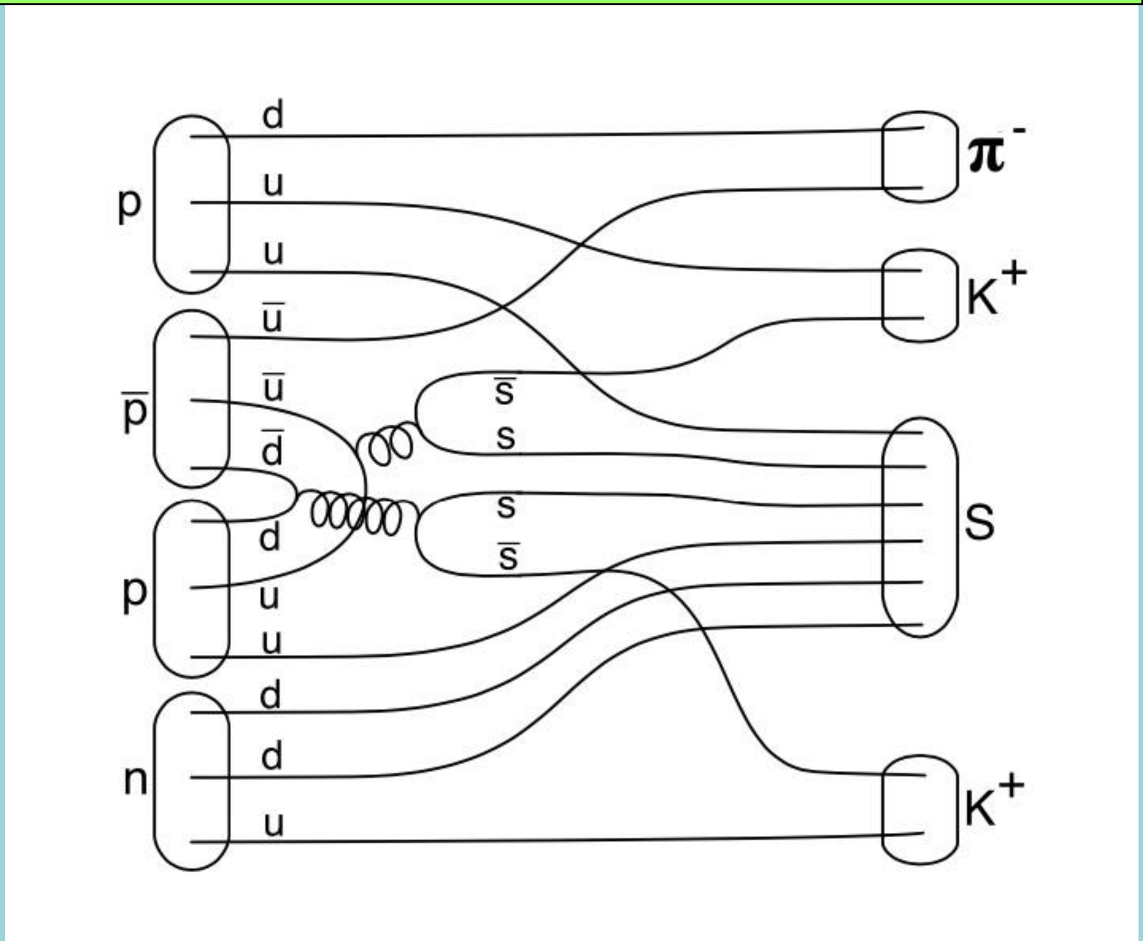
$$\bar{p} + {}^{3}_{2}He \rightarrow \; S + \; K^{+} + K^{+} + \pi^{-}$$

S = + 2   Q = + 1 final state

Very low energy process

Annihilation at rest

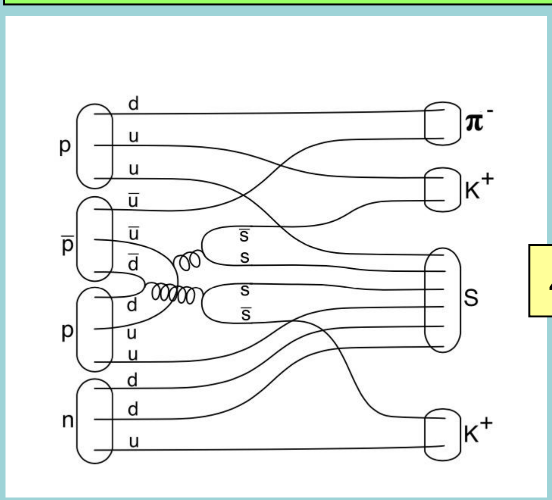
Kinematic reconstruction



Experimental studies of multi-nucleon annihilation and final states K production (OBELIX)

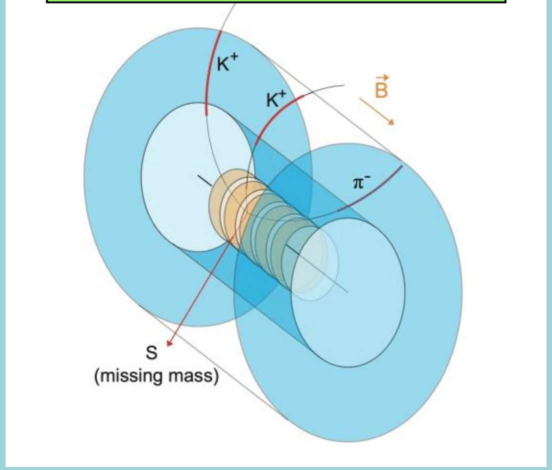
«Easy channel» (up to 2 GeV mass S)

More difficult possibilities (for lower mass S)



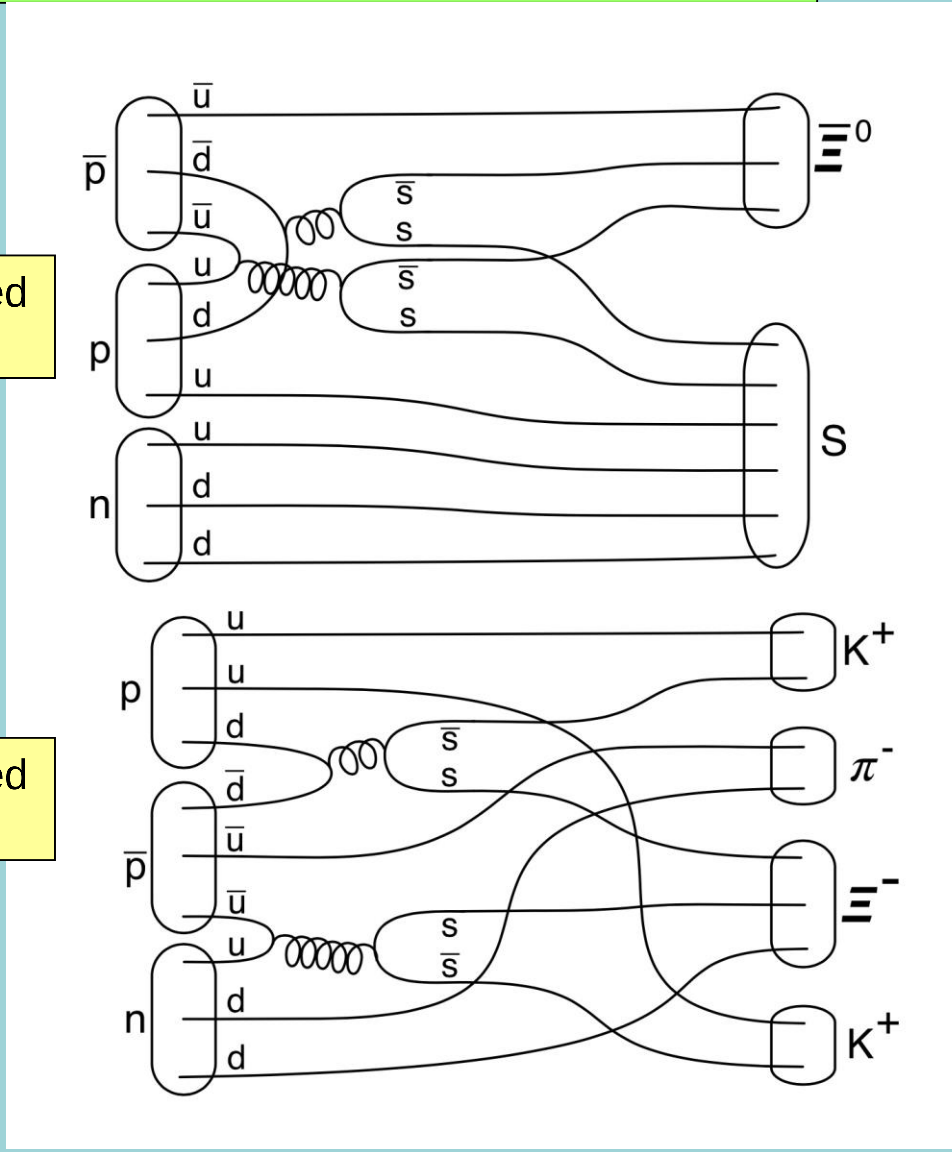
4 nucleons involved

A TPC in a magfield

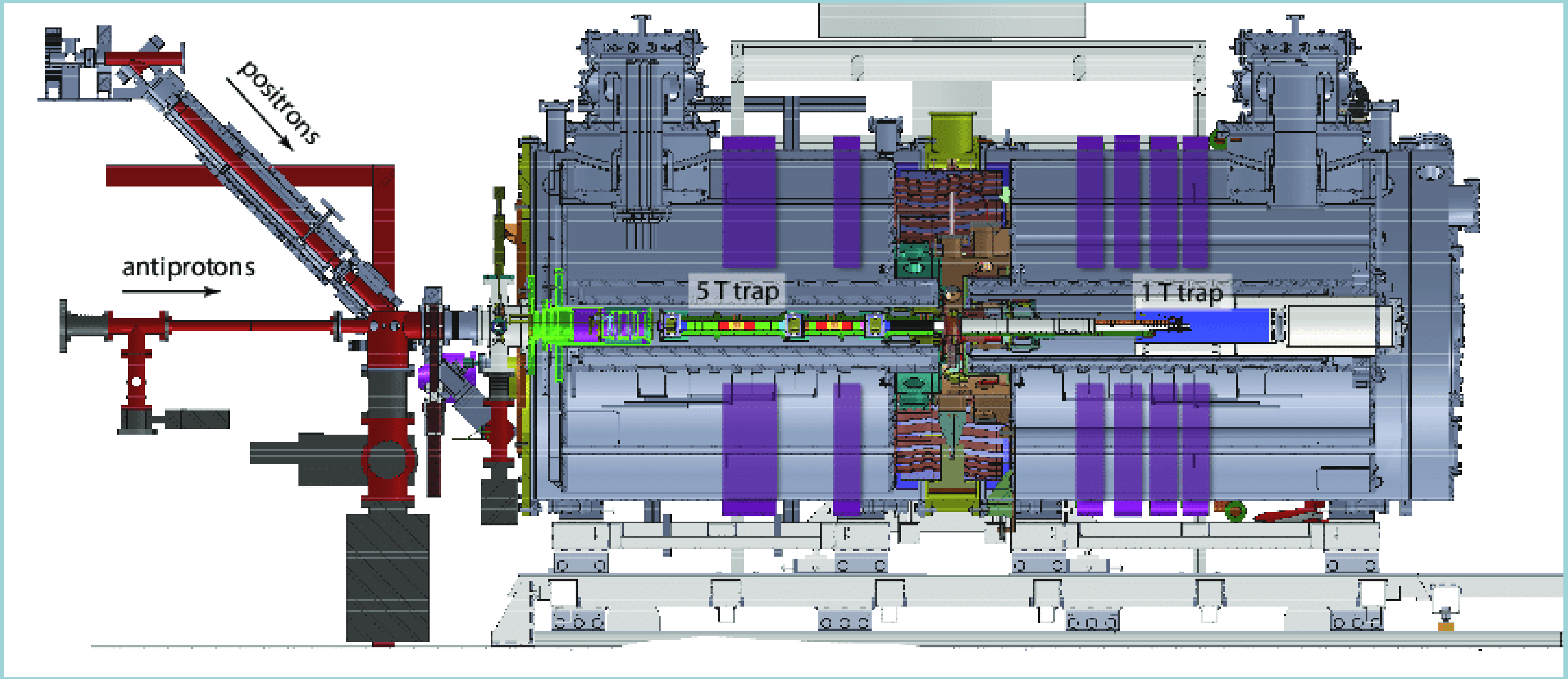


3 nucleons involved with a spectator p

3 nucleons involved with a spectator p

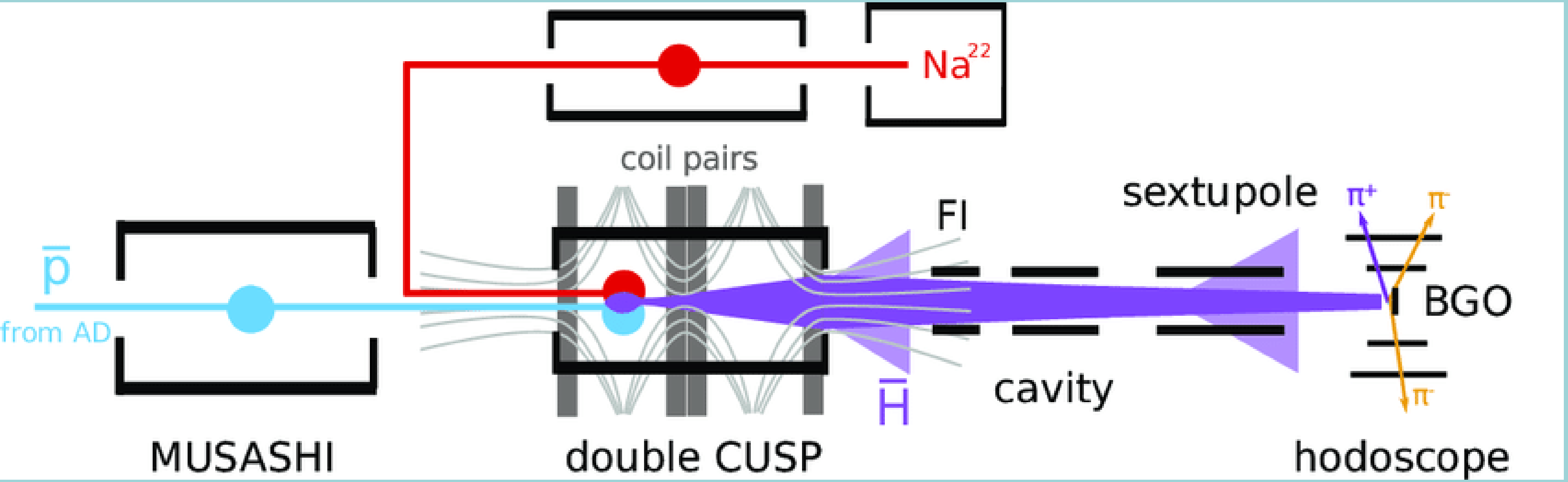


The typical trapping scheme for antiproton treatment (AEGIS)



Magnetic system for anti-proton trapping in AEGIS (millions of antiprotons!)

The typical trapping scheme for antiproton treatment (ASACUSA)



These experiments are intended to produce a BEAM of anti-protons to different goals

(can be used for sexaquark searches)

Antimatter search at the CERN Antiproton Decelerator deals with fundamental physics

Antimatter experiments are intended to produce beams of anti-protons to achieve various goals

These experiments are intended to produce a BEAM of anti-protons to different goals

- Anti-hydrogen gravitation (Equivalence Principle for Antimatter)
- Ground State Hyperfine Splitting of Anti-hydrogen (CPT test)

Can be used also to Dark Matter searcher at low energies

G. Farrar – A Stable Sexaquark: Overview and Discovery Strategies - https://arxiv.org/abs/2201.01334

M. Doser, G. Farrar, G. Kornakov - Searching for a dark matter particle with antiprotonic atoms –
Eur. Phys.J.C 83 (2023) 12, 1149

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Thank you for your attention