

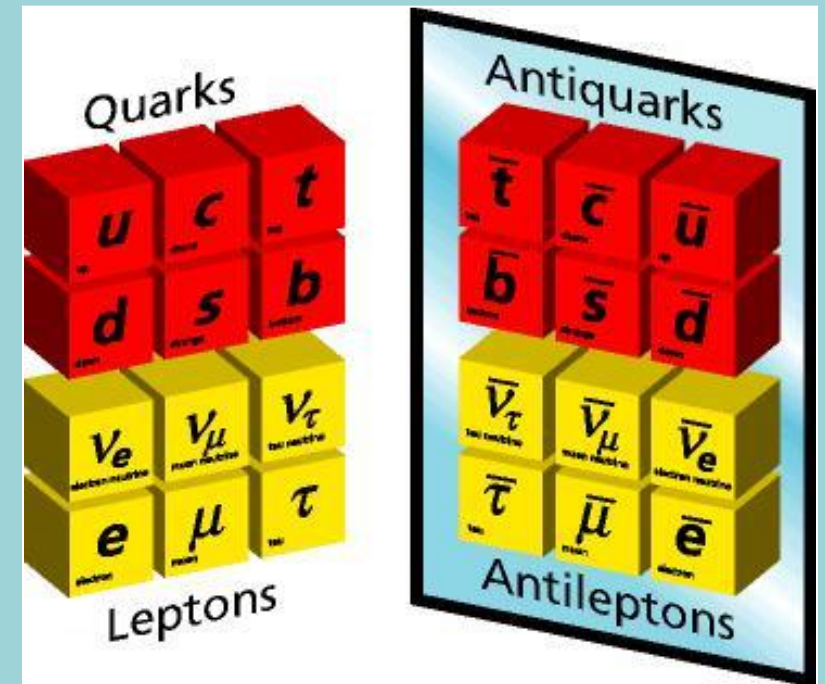
# Antimatter Gravitation and Dark Matter searches at the CERN Antiproton Decelerator



Marco Giammarchi

*Istituto Nazionale di Fisica Nucleare – Sezione di Milano*

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



# Antimatter: the Cosmic Mystery

## Fundamental (2023) Physics and the Universe

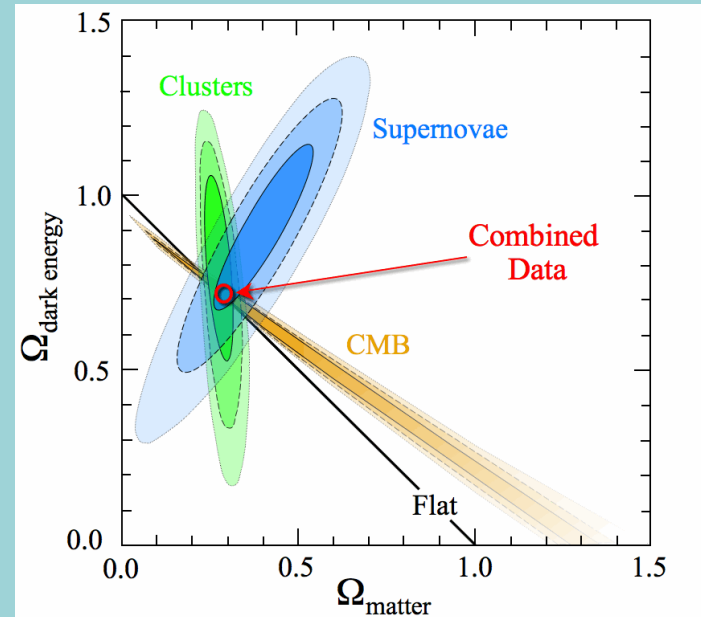
Known fundamental particles  
(and their interactions)

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	$H$ Higgs boson
	$d$ down	$s$ strange	$b$ bottom	$\gamma$ photon	
	$e$ electron	$\mu$ muon	$\tau$ tau	$Z^0$ Z boson	
LEPTONS	$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	$\nu_\tau$ tau neutrino	$W^\pm$ W boson	

sciencealert



### Not fully confirmed $\Lambda$ -CDM Model

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



# Matter-Antimatter Asymmetry Generation

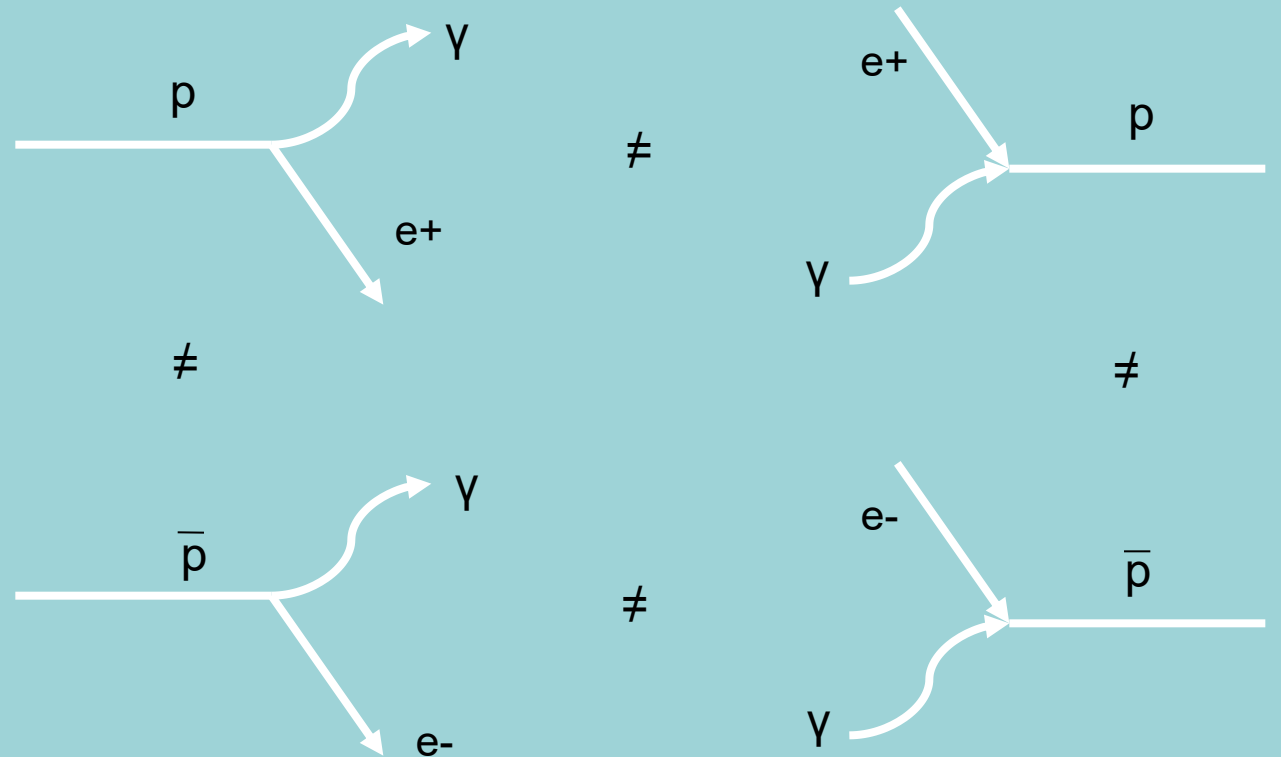
Generally accepted Baryogenesis scheme

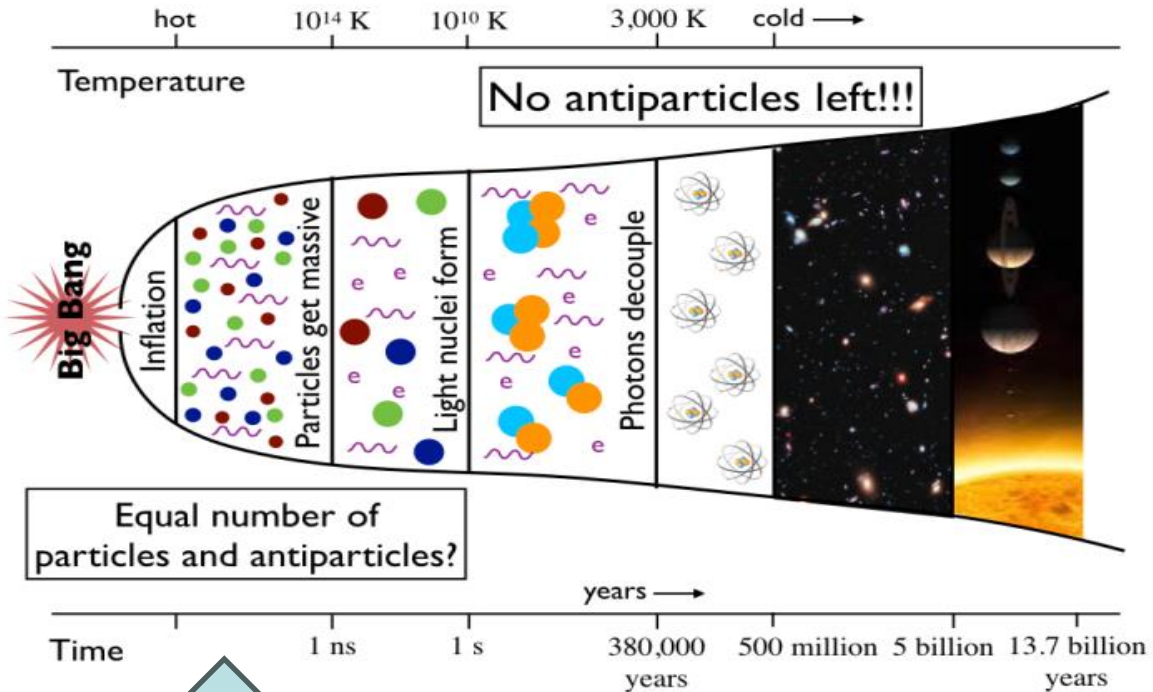
- Baryon Number Violation
- CP Violation
- Out of Equilibrium

Sakharov conditions

## CP Violation in the Standard Model

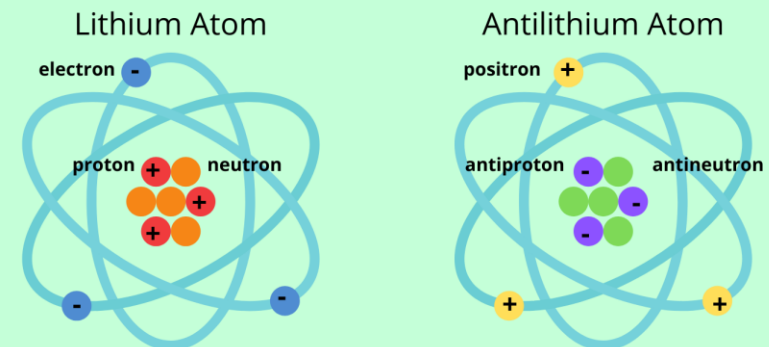
- Baryogenesis
- Leptogenesis





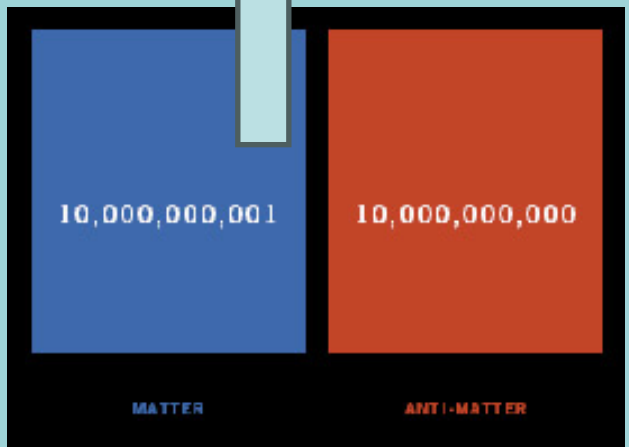
Cosmological Nucleosynthesis  
 Just 3 minutes to synthesize light nuclei  
 (with whatever baryon is present)

### Matter vs Antimatter

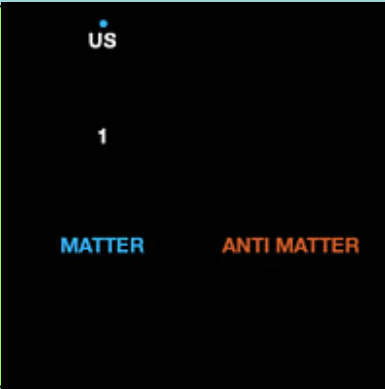


Atoms of matter and antimatter have the same mass, but opposite electrical charge and different quantum numbers.

sciencenotes.org



The unbalance was 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)

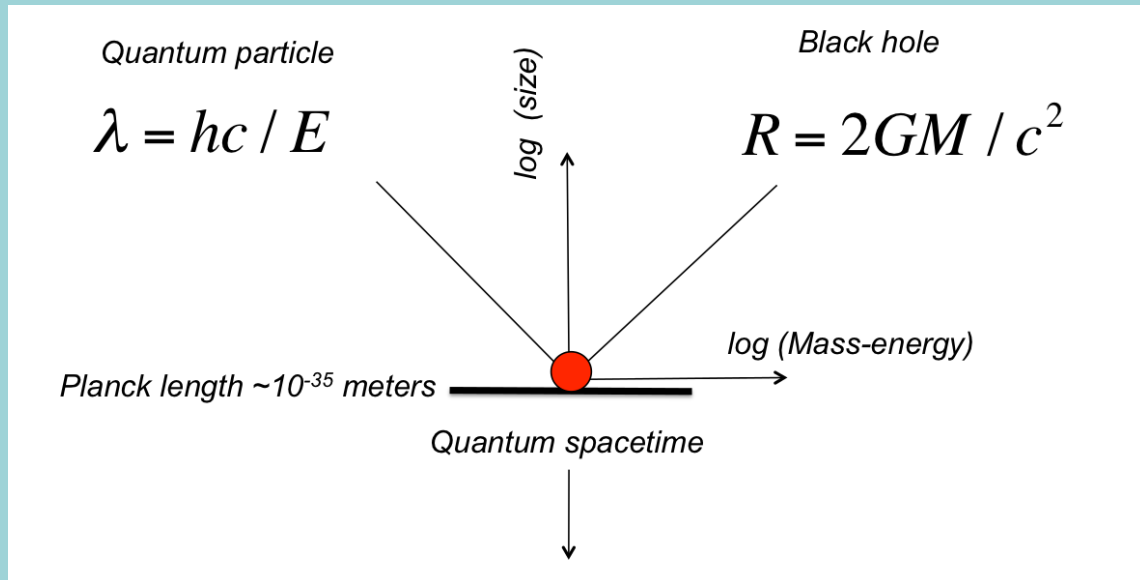
- Weak Equivalence Principle
- Local Position Invariance
- Strong Equivalence Principle

In a classical theory of Gravitation

CPT Theorem

- Lorentz-invariant QFT
- Flat spacetime

Only a Quantum meaning



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

# Fundamental (2023) Physics

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

General Relativity

Standard Model

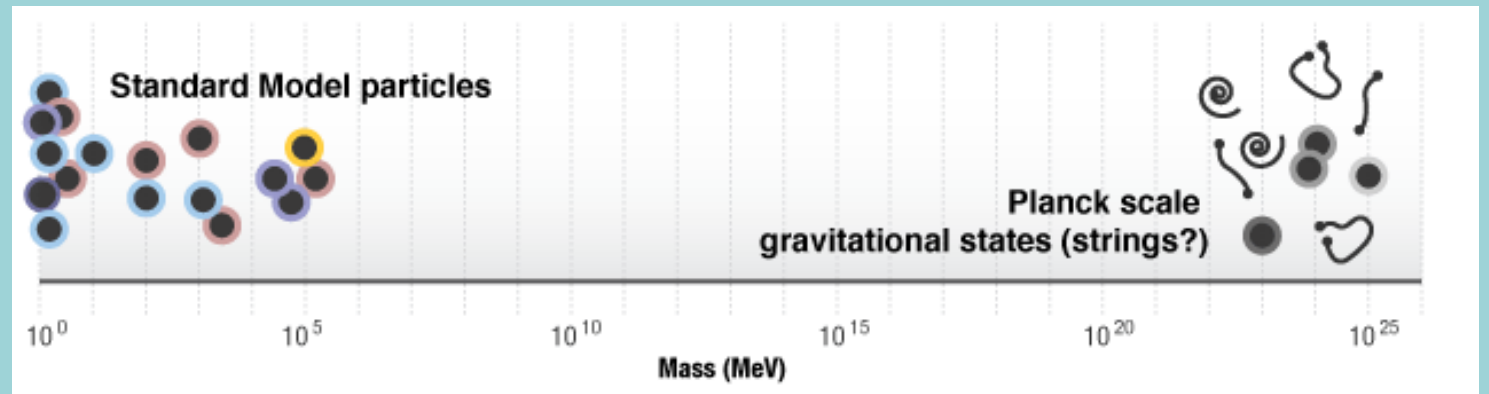
Curvature scalar  $R$   
Metrics  $g(x)$   
(Classical Matter Fields)

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

Hierarchy Problem

Cosmological Constant Problem

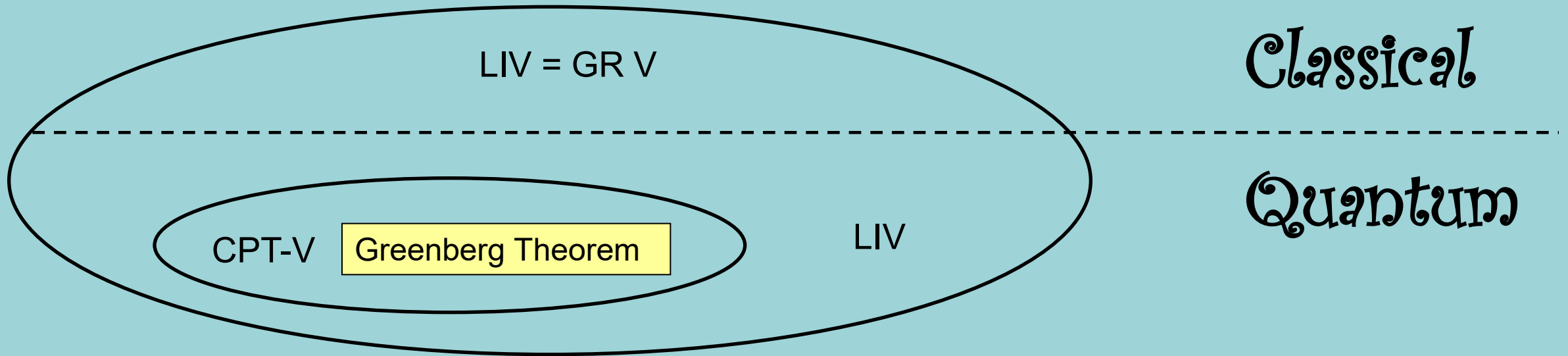
Lack of SUSY (DM?) Particles



Standard Model Extension

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

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

LORENTZ VIOLATION

Standard Model + LIV, no gravity, a fermion

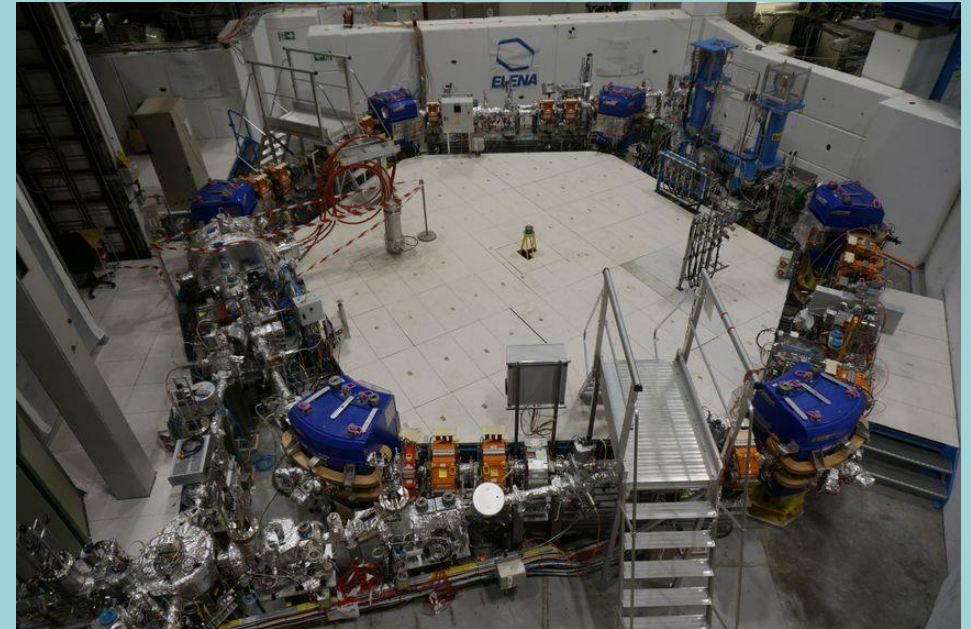
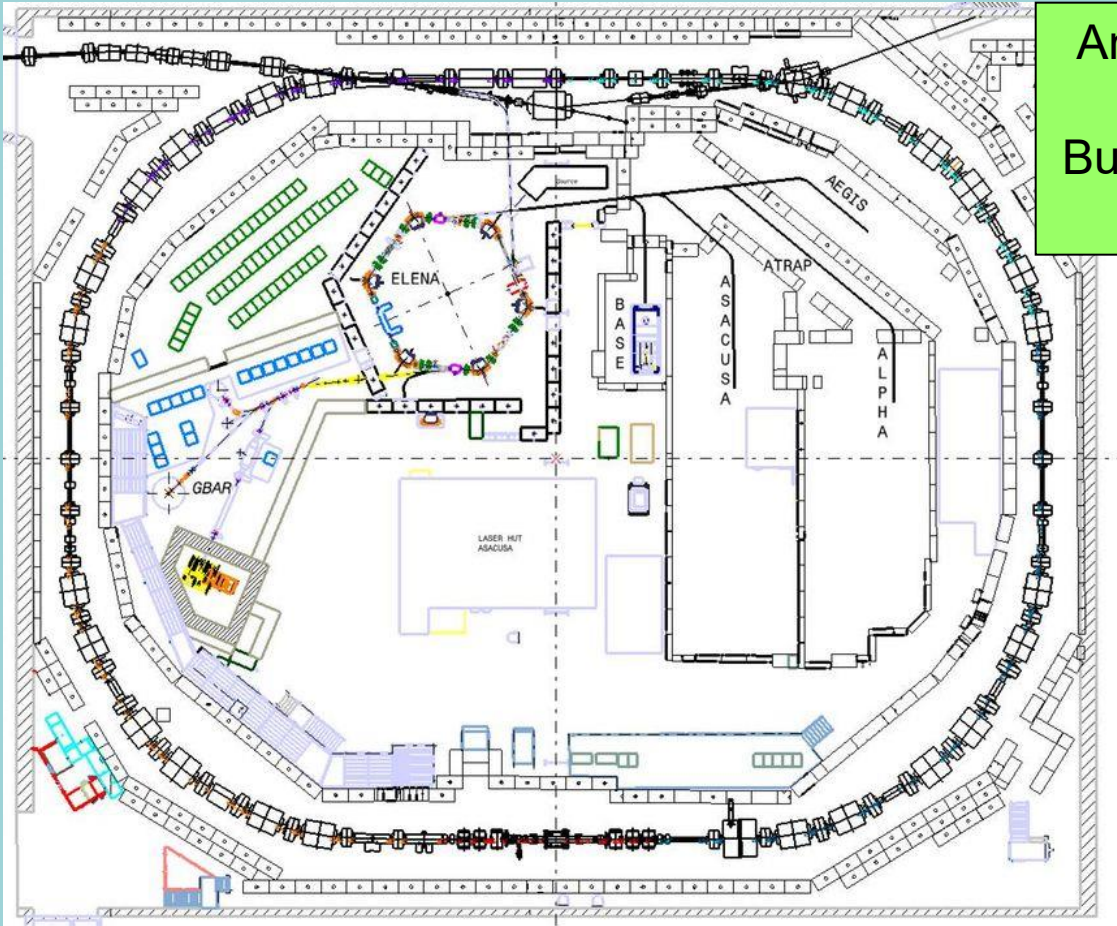
LIV coefficients depend on the specific particle!

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

# 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

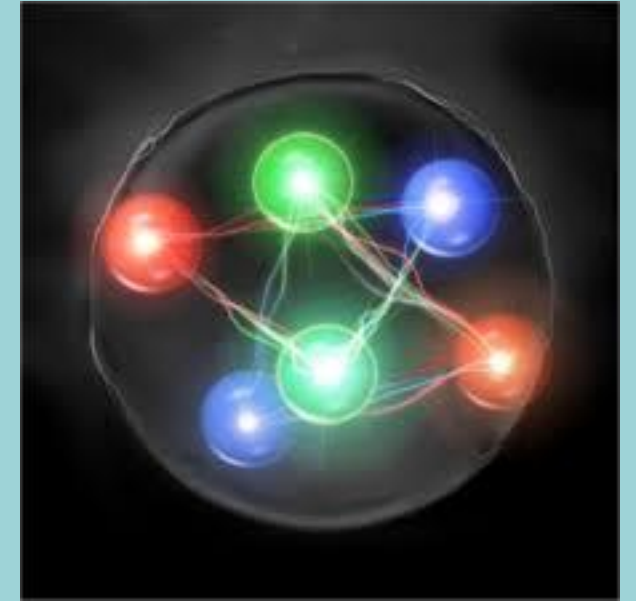
Neutral and flavor-singlet

Likely to exist (QCD lattice calculations)

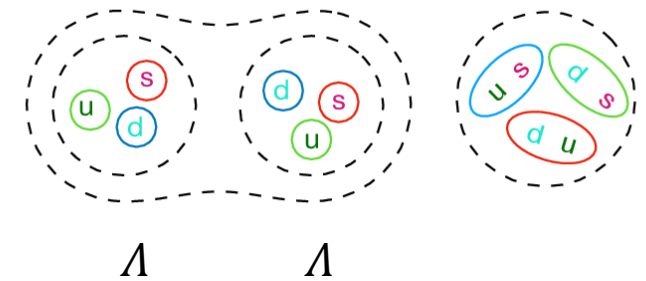
If  $m(S) < m(\Lambda) + m(p) = 2 \text{ GeV}$

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

$S = uuddss$

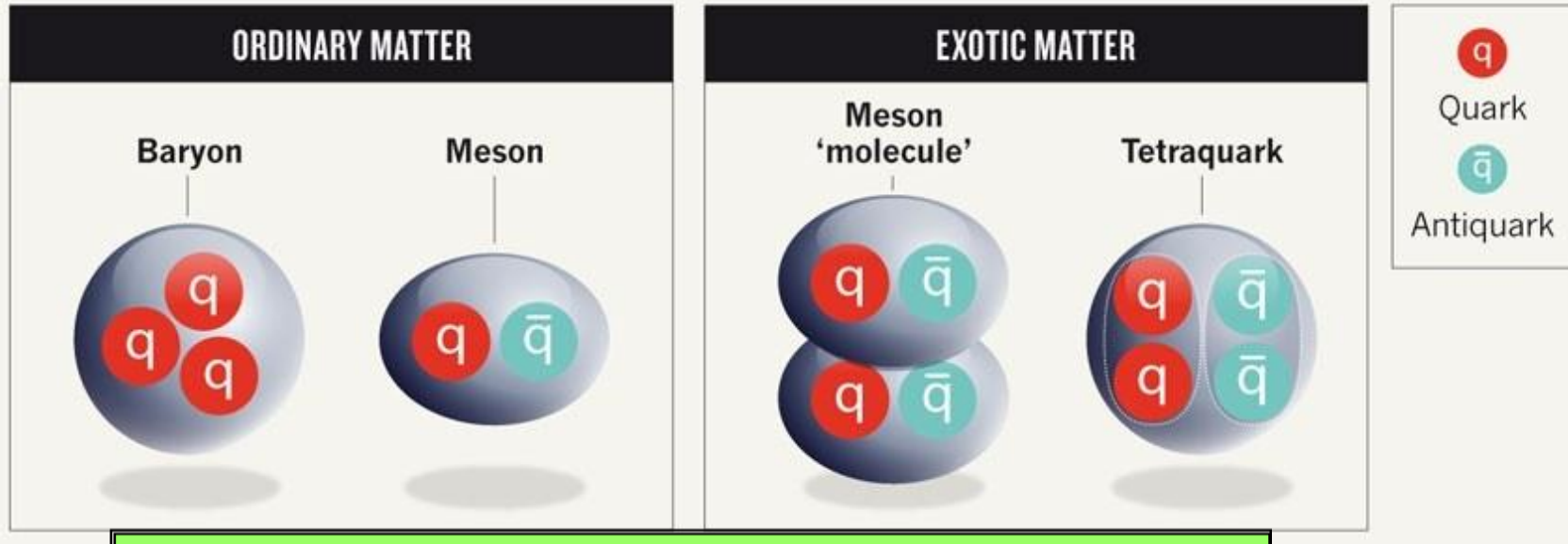


Two different realizations of a color singlet



# QUARK SOUP

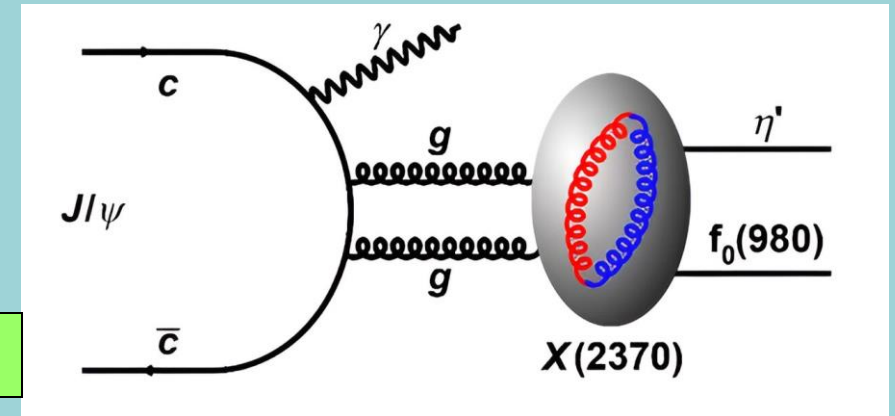
Exotic matter made of quarks allows for an interesting DM candidate



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)

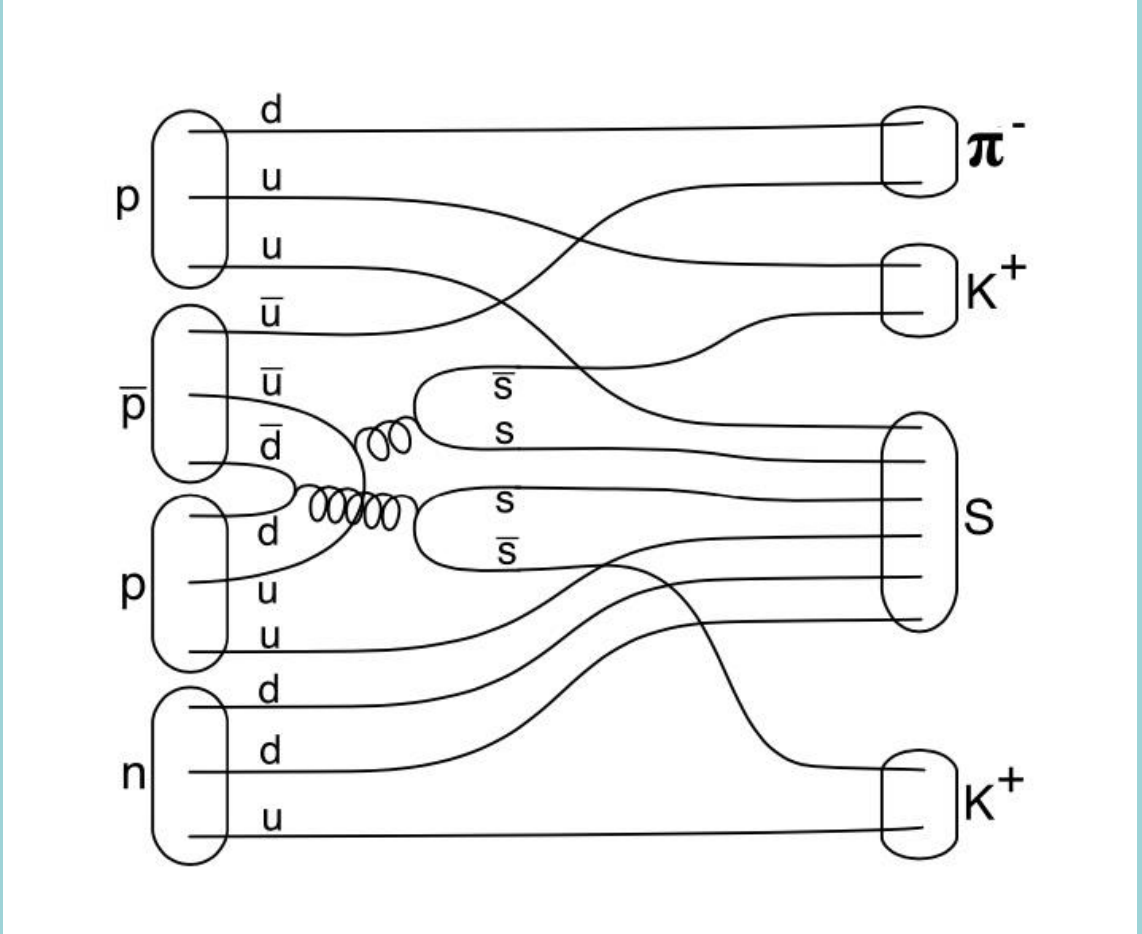


Formation reaction in a low antiproton environment regime (and a He jet target)

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

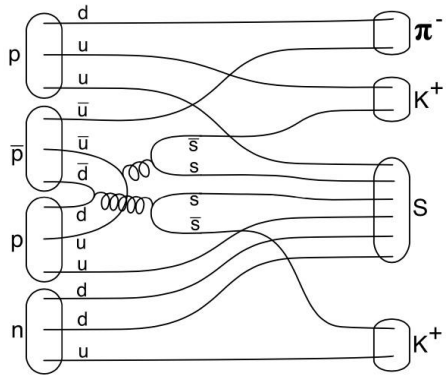


$S = +2$   $Q = +1$  final state  
 Very low energy process  
 Annihilation at rest  
 Kinematic reconstruction



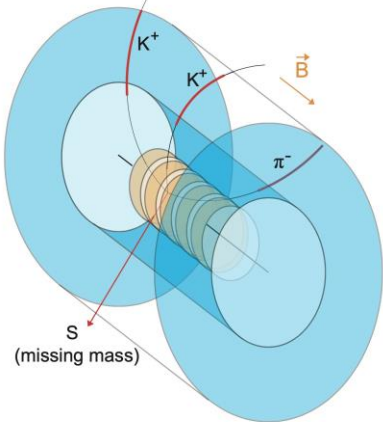
Experimental studies of multi-nucleon annihilation and final states K production (OBELIX)

«Easy channel» (up to 2 GeV mass S)



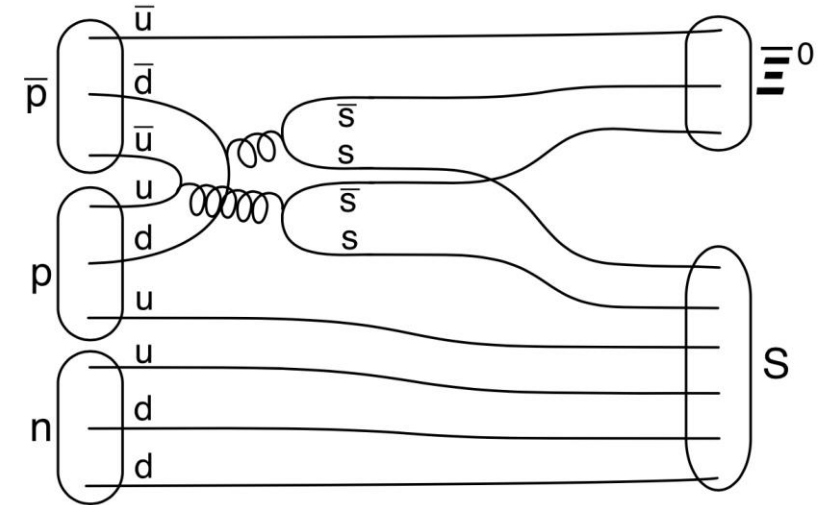
4 nucleons involved

A TPC in a magfield

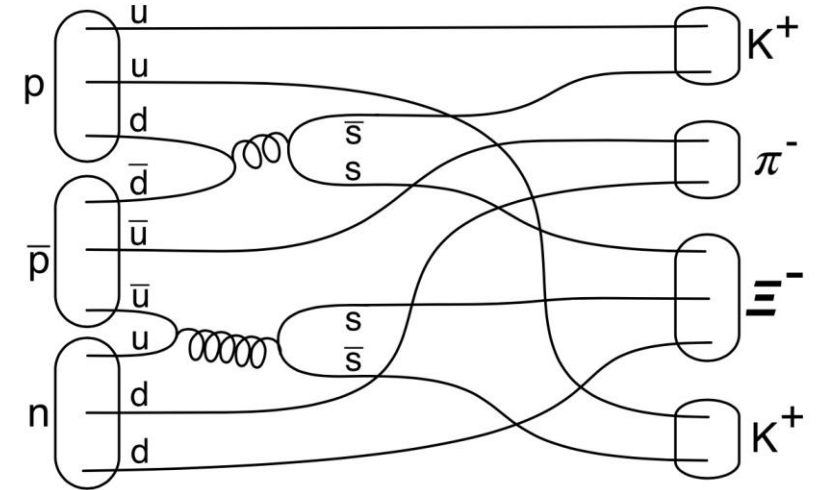


More difficult possibilities (for lower mass S)

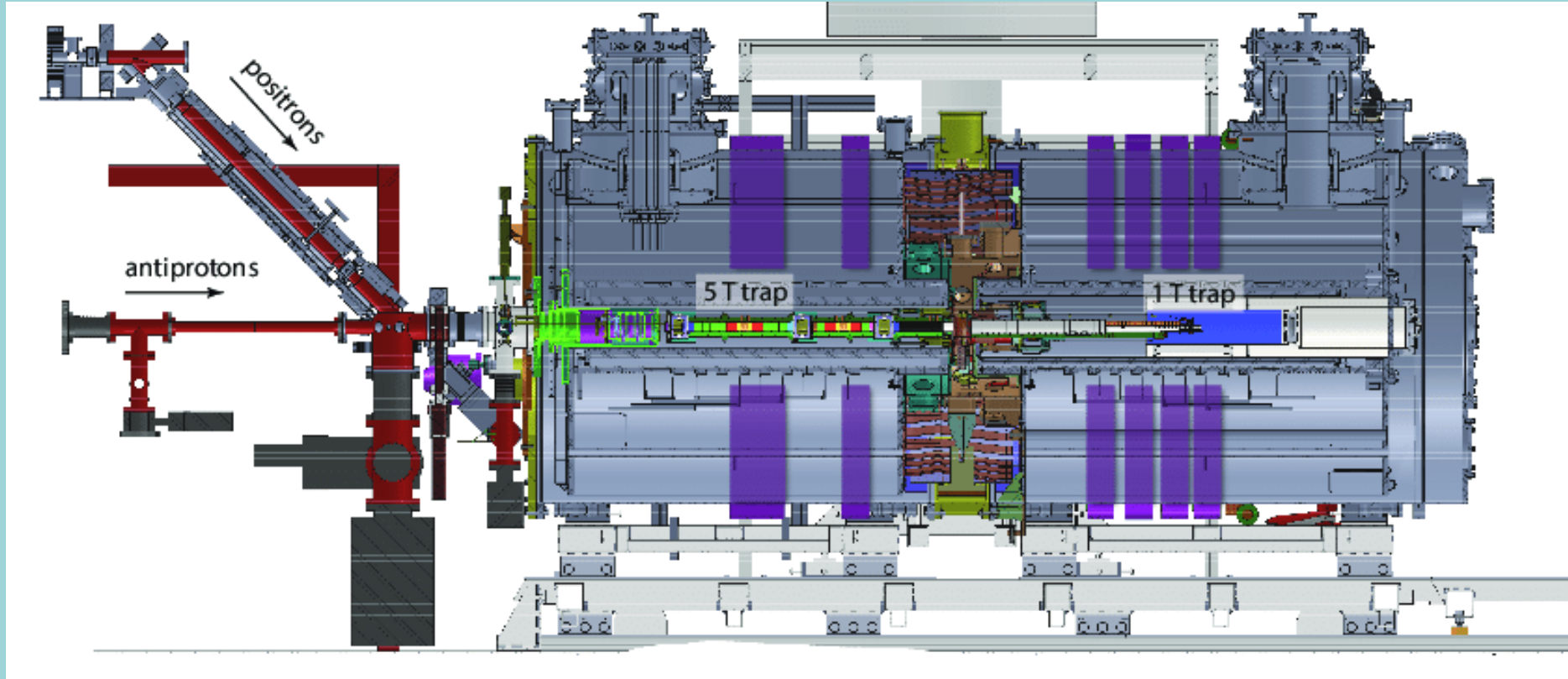
3 nucleons involved with a spectator p



3 nucleons involved with a spectator p

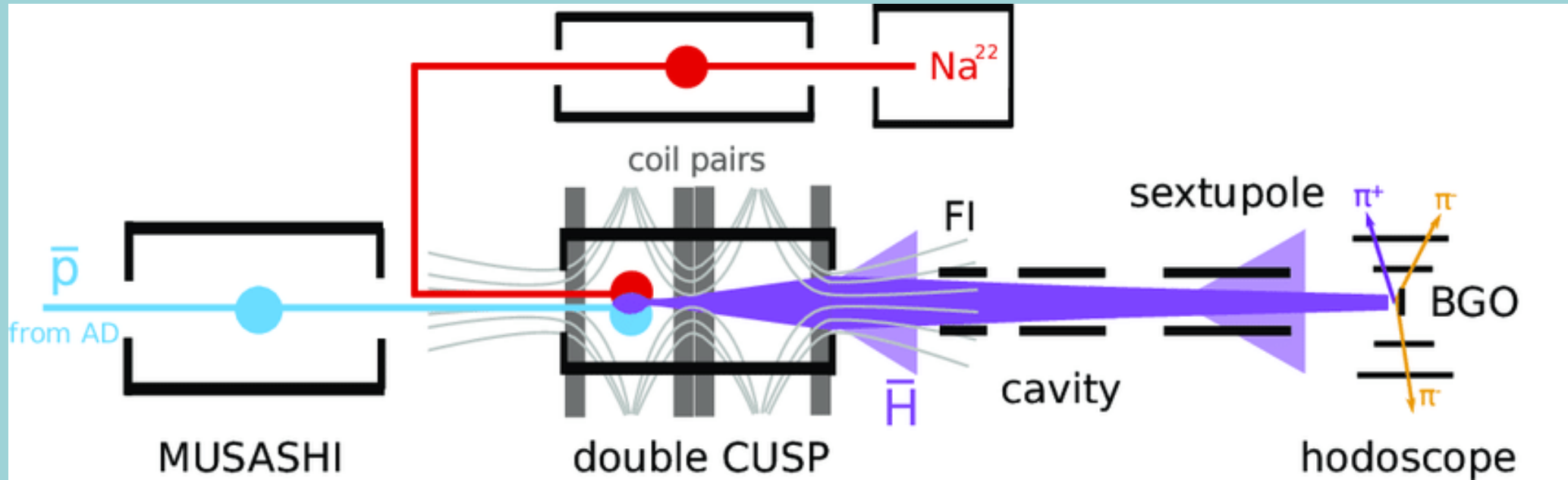


# The typical trapping scheme for antiproton treatment (AEGIS)



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

Thank you for your attention