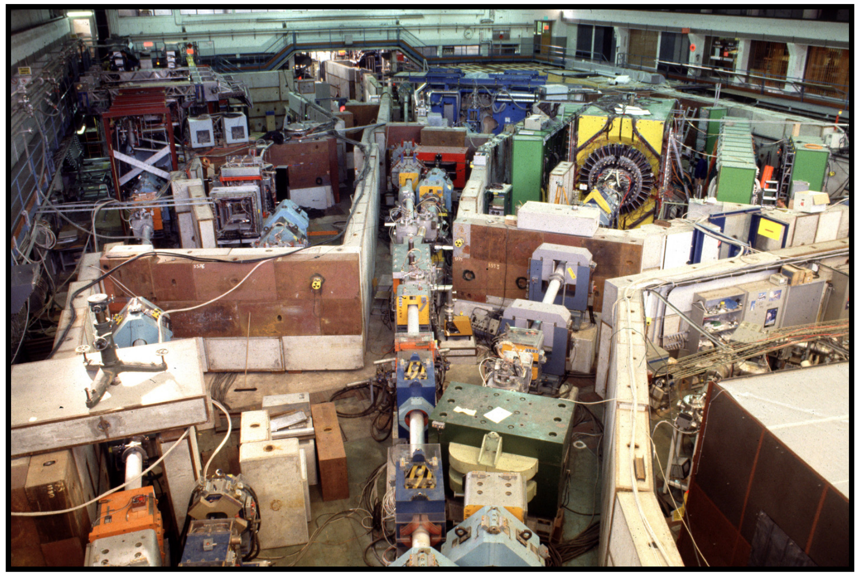
ANTIMATTER IN THE LAB

Chloé Malbrunot
CERN



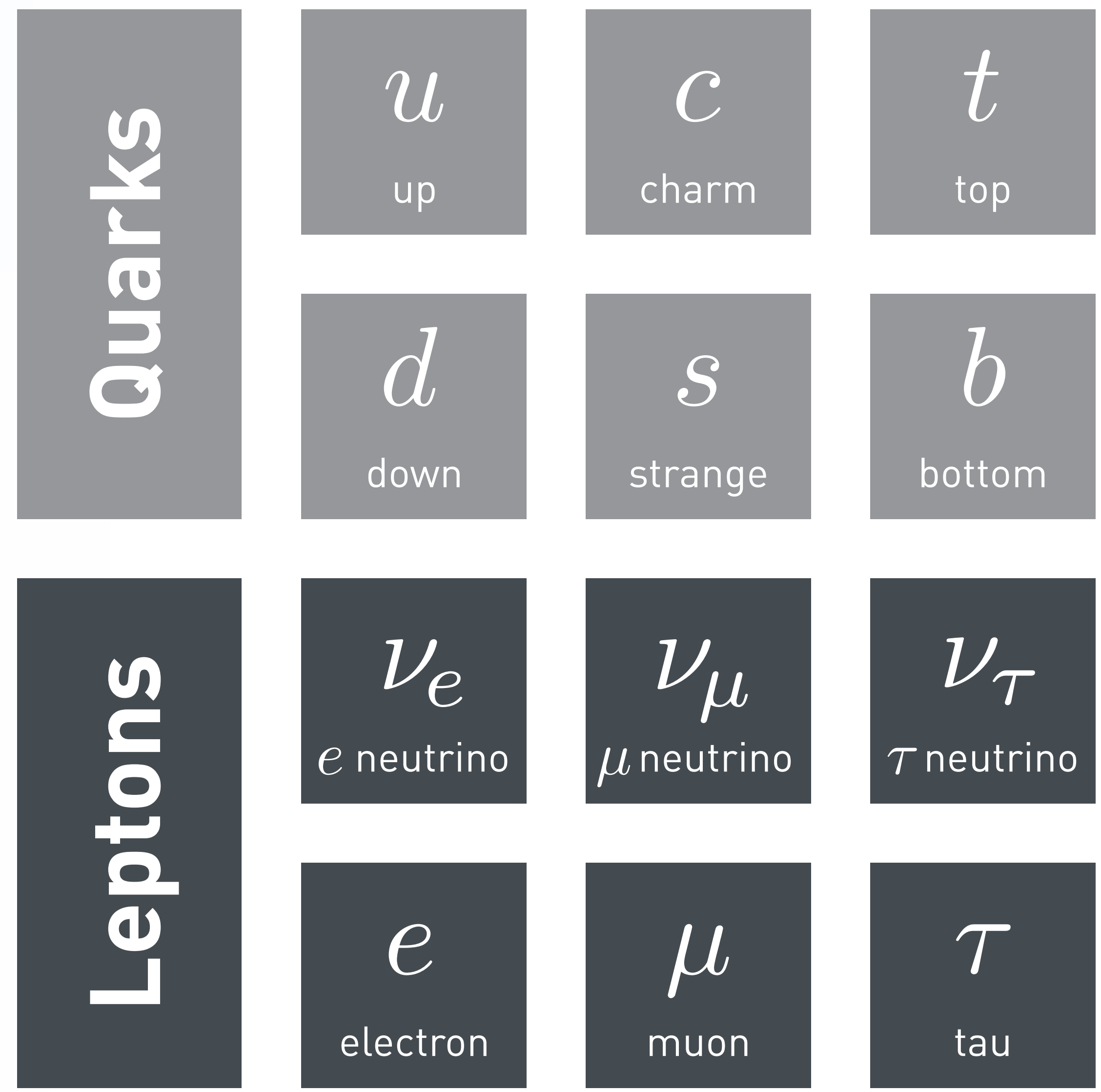
CERN Summer student lecture 2019

Content

LECTURE # 1 (This lecture)
- What is antimatter?
- Some historical reminders
- Discrete symmetries
- Primordial antimatter search

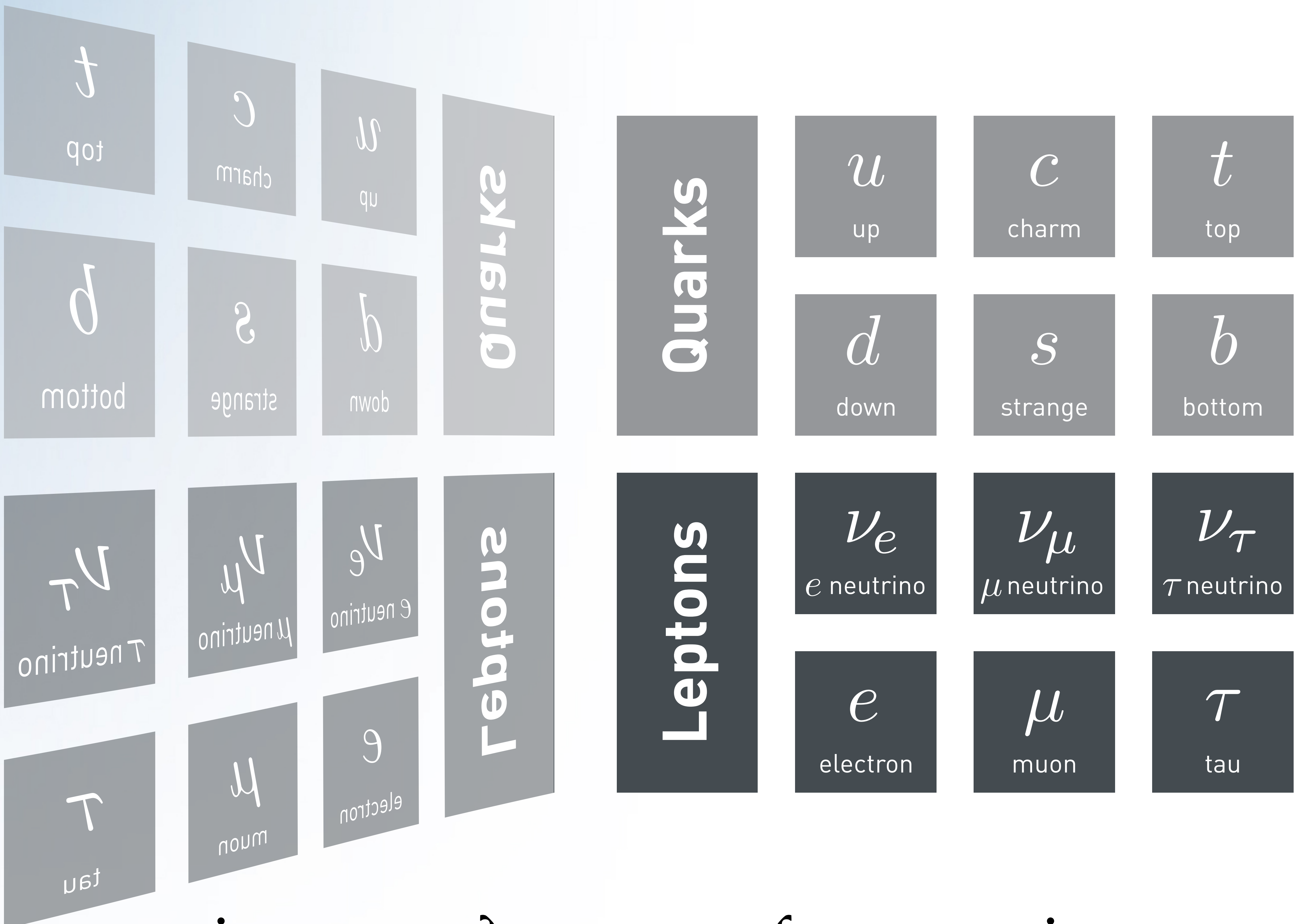
LECTURE # 2
- Antiprotons at low energies : cooling and trapping
- Experiments at the AD : exotic atoms made of antimatter
- Antihydrogen : a tool to study matter-antimatter asymmetry
- Everyday's application of antimatter

What is antimatter?



+ force carriers

What is antimatter?



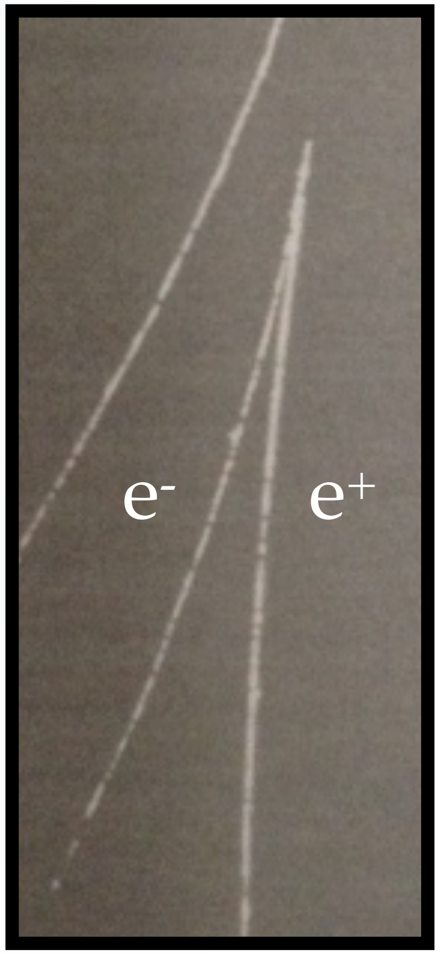
+ force carriers

What is antimatter?

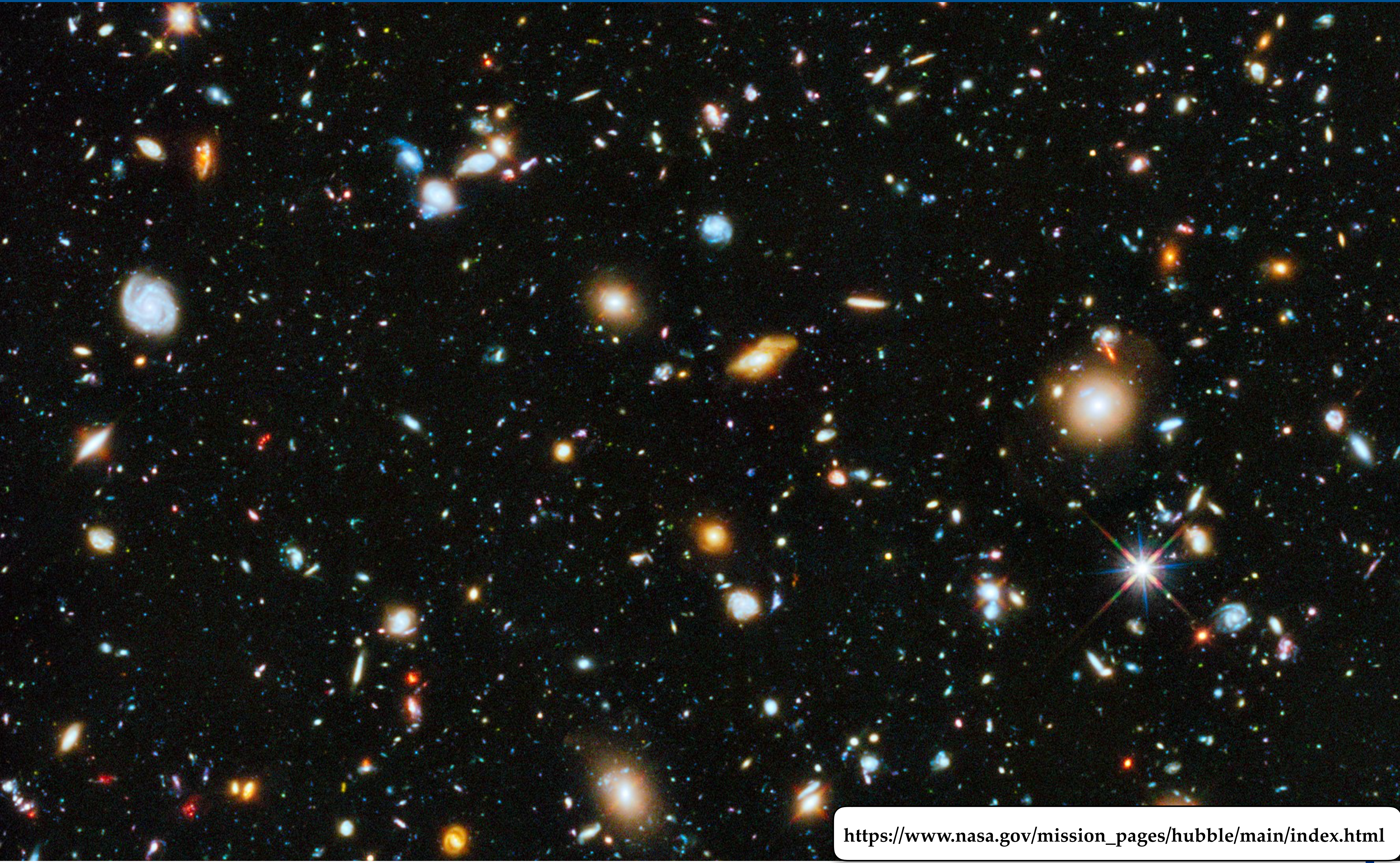
$$E = mc^2$$

What is antimatter?

$$E = mc^2$$

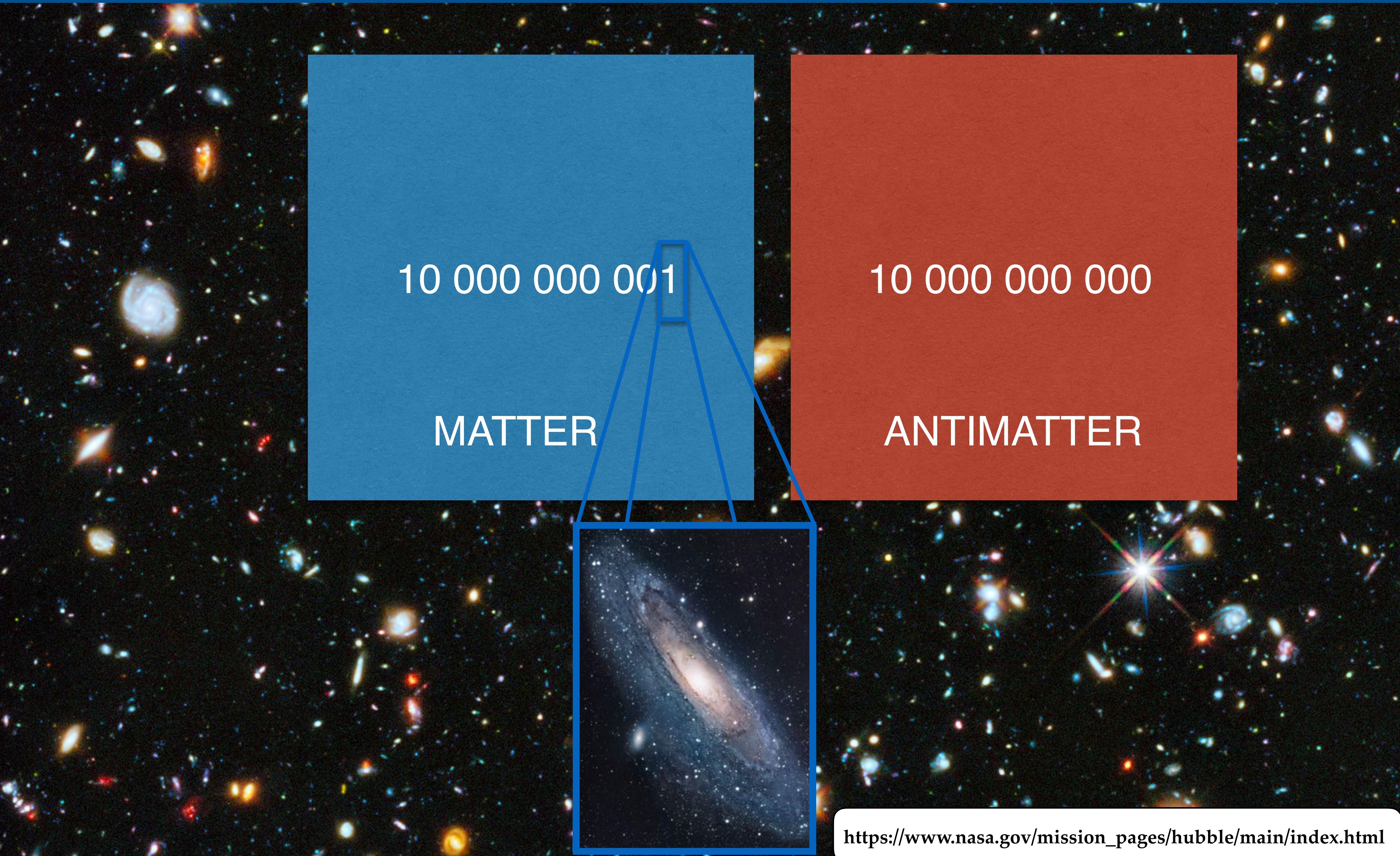


Matter - Antimatter asymmetry

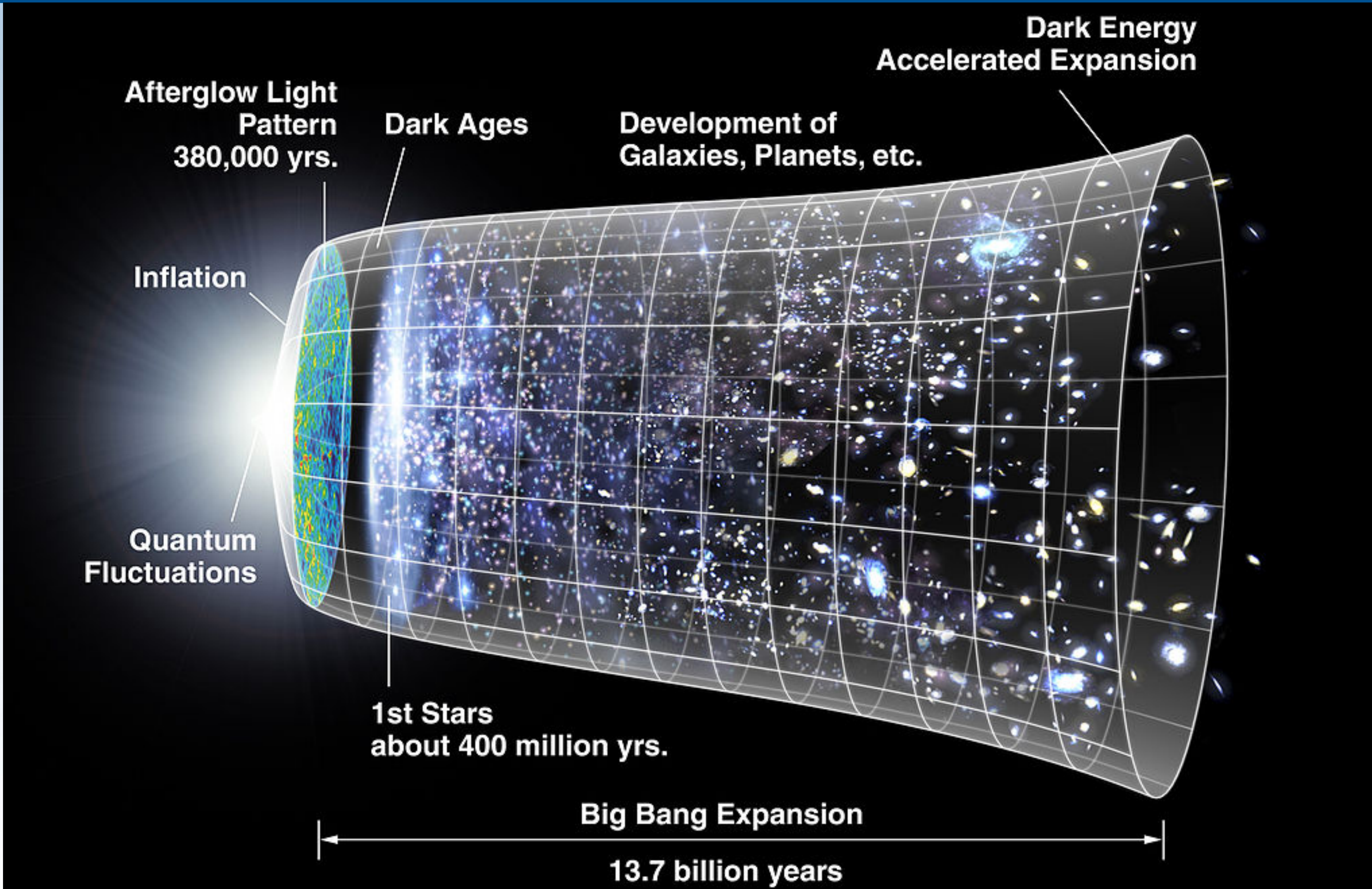


https://www.nasa.gov/mission_pages/hubble/main/index.html

Matter - Antimatter asymmetry



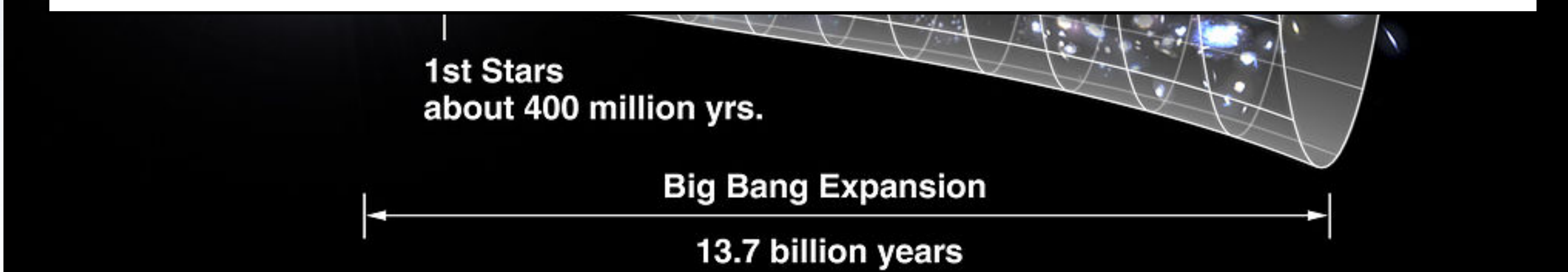
Matter - Antimatter asymmetry



Matter - Antimatter asymmetry

Sakharov, 1967:

- "**Baryon number violation**", i.e. $n_B - n_{\bar{B}}$ is not constant
- "**C and CP violation**" : if CP is conserved for a reaction which generates a net number of baryons over anti-baryons there would be a CP conjugate reaction generating a net number of anti-baryons.
- "**Departure from thermal equilibrium**" : in thermal equilibrium any baryon number violating process will be balanced by the inverse reaction

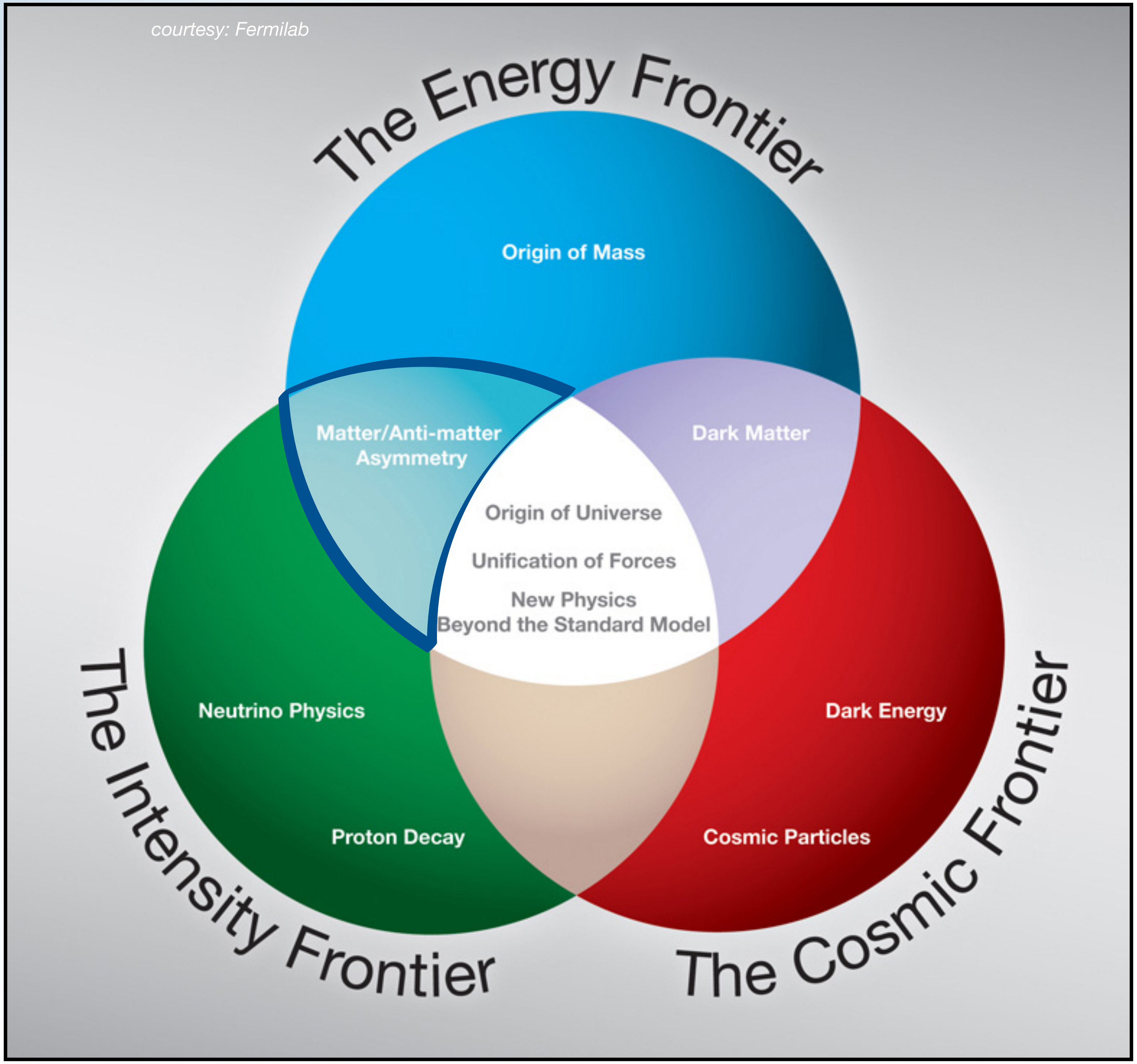


The “BIG” questions

Excerpt of the list containing the open questions in particle physics:

- Why is the Higgs boson so light (so-called “naturalness” or “hierarchy” problem) ?
- What is the origin of the matter-antimatter asymmetry in the Universe ?
- Why 3 fermion families ? Why do neutral leptons, charged leptons and quarks behave differently ?
- What is the origin of neutrino masses and oscillations ?
- What is the composition of dark matter (23% of the Universe) ?
- What is the cause of the Universe’s accelerated expansion (today: dark energy ? primordial: inflation ?)
- Why is Gravity so weak ?
- …

Frontiers of Particle Physics

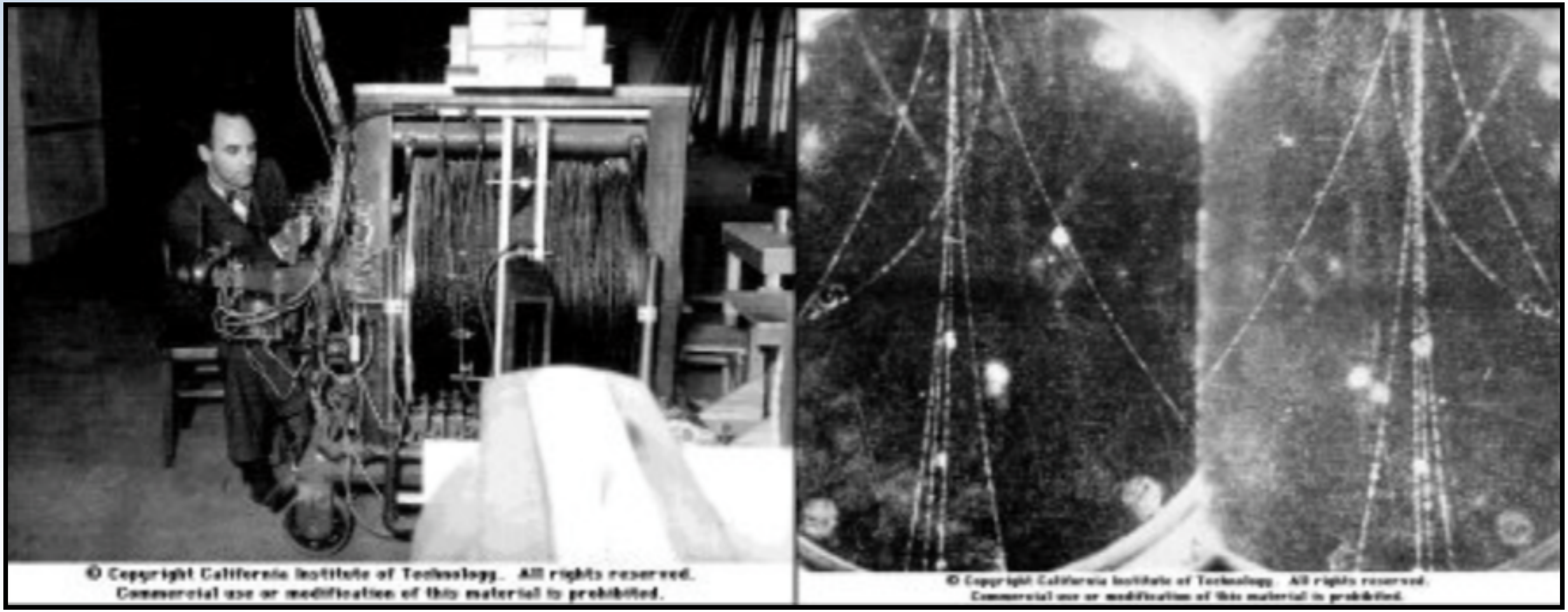


The first antimatter discovery

1932 : Discovery of the positron (Nobel Prize shared with V. Hess in 1936)

C. Anderson

In Cosmic Rays using a Cloud Chamber



Some Bits of History : the Dirac eq.

<u>1928 : The Dirac equation (Nobel Prize in 1933)</u>

$$E = \frac{p^2}{2m} \rightarrow \quad i\hbar\frac{\partial}{\partial t}\psi = -\frac{\hbar^2}{2m}\nabla^2\psi$$

$$E \rightarrow i\hbar\frac{\partial}{\partial t}$$

$$p \rightarrow -i\hbar\nabla$$

$$H\psi = (\alpha \cdot \mathbf{P} + \beta m)\psi$$

$$E^2 = p^2 + m^2 \rightarrow \quad -\hbar^2\frac{\partial^2}{\partial t^2}\psi = -\hbar^2\nabla^2\psi + m^2\psi$$

Some Bits of History : the Dirac eq.

1928 : The Dirac equation (Nobel Prize in 1933)

$$E = \frac{p^2}{2m} \rightarrow \quad i\hbar \frac{\partial}{\partial t}\psi = -\frac{\hbar^2}{2m} \nabla^2 \psi$$

$E \rightarrow i\hbar \frac{\partial}{\partial t}$

$p \rightarrow -i\hbar \nabla$

$$H\psi = (\alpha \cdot \mathbf{P} + \beta m)\psi$$

$$E^2 = p^2 + m^2 \rightarrow \quad -\hbar^2 \frac{\partial^2}{\partial t^2}\psi = -\hbar^2 \nabla^2 \psi + m^2 \psi$$

$$H^2\psi = (\alpha_i P_i + \beta m)(\alpha_j P_j + \beta m)\psi$$

$$= (\alpha_i^2 P_i^2 + (\alpha_i \alpha_j + \alpha_j \alpha_i) P_i P_j + (\alpha_i \beta + \beta \alpha_i) P_i m + \beta^2 m^2)\psi$$

α_i^2 =1, $(\alpha_i \alpha_j + \alpha_j \alpha_i)$ =0, $(\alpha_i \beta + \beta \alpha_i)$ =0, β^2 =1

$$H^2\psi = (\mathbf{P^2} + m^2)\psi$$

Some Bits of History : the Dirac eq.

1928 : The Dirac equation (Nobel Prize in 1933)

$$E = \frac{p^2}{2m} \rightarrow \quad i\hbar\frac{\partial}{\partial t}\psi = -\frac{\hbar^2}{2m}\nabla^2\psi$$

$E \rightarrow i\hbar\frac{\partial}{\partial t}$

$p \rightarrow -i\hbar\nabla$

$$H\psi = (\alpha \cdot \mathbf{P} + \beta m)\psi$$

$$E^2 = p^2 + m^2 \rightarrow \quad -\hbar^2\frac{\partial^2}{\partial t^2}\psi = -\hbar^2\nabla^2\psi + m^2\psi$$

$$H^2\psi = (\alpha_i P_i + \beta m)(\alpha_j P_j + \beta m)\psi$$

$$= (\alpha_i^2 P_i^2 + (\alpha_i\alpha_j + \alpha_j\alpha_i)P_iP_j + (\alpha_i\beta + \beta\alpha_i)P_i m + \beta^2 m^2)\psi$$

=1 =0 =0 =1

$$H^2\psi = (\mathbf{P^2} + m^2)\psi$$

$$(i\gamma^\mu\partial_\mu - m)\psi = 0$$

$$\gamma^0 = \begin{pmatrix} I_2 & 0 \\ 0 & -I_2 \end{pmatrix}, \gamma^1 = \begin{pmatrix} 0 & \sigma_x \\ -\sigma_x & 0 \end{pmatrix},$$

$$\gamma^2 = \begin{pmatrix} 0 & \sigma_y \\ -\sigma_y & 0 \end{pmatrix}, \gamma^3 = \begin{pmatrix} 0 & \sigma_z \\ -\sigma_z & 0 \end{pmatrix}.$$

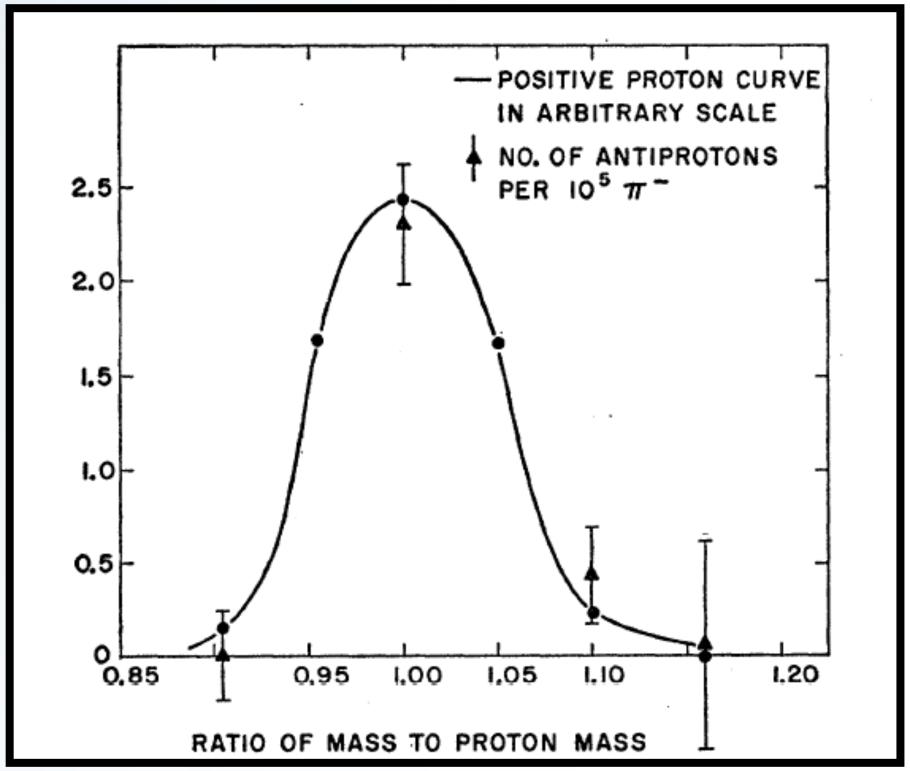
Some Bits of History

1955 : Discovery of the antiproton (Nobel Prize to Chamberlain & Segré in 1959)

Discovery at the Bevatron

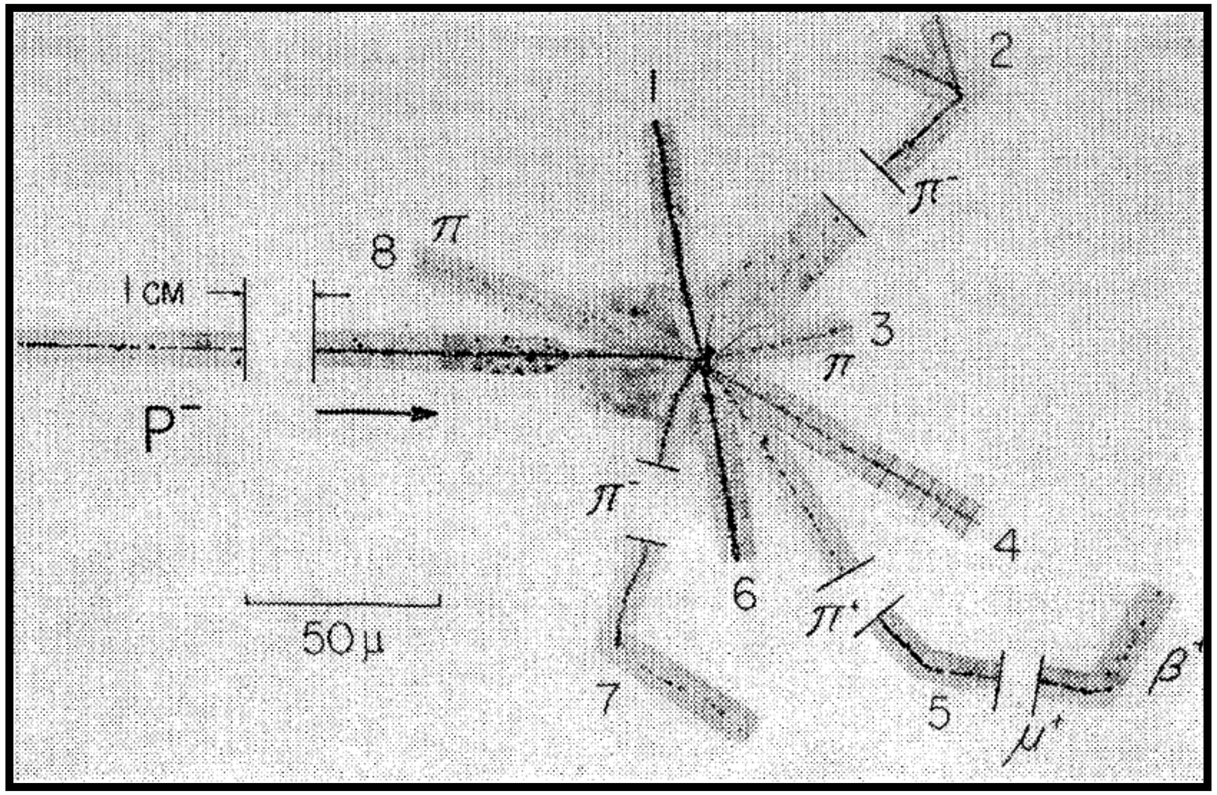
Identified 60 events

Delta m/m ~ 5%



Discrimination against other negatively charged particles via momentum & velocity selection

Annihilation of an antiproton detected in a emulsion a year later :
first p̄-N annihilation observed
35 events
—> proof of antimatter character



more antimatter …

1932 Discovery of positron

1948 Discovery of positronium

1955 Discovery of antiproton

1956 Discovery of antineutron

1965 Discovery of antideuteron

1970 Discovery of anti- ^{3}He

1978 Discovery of anti-tritium

1996 First creation of relativistic antihydrogen atoms

more antimatter …

1932 Discovery of positron

1948 Discovery of positronium

1955 Discovery of antiproton
1956 Discovery of antineutron

1964 First measurement of a difference between matter & antimatter

1965 Discovery of antideuteron

1970 Discovery of anti- ^{3}He

1978 Discovery of anti-tritium

1996 First creation of relativistic antihydrogen atoms

Discrete Symmetries

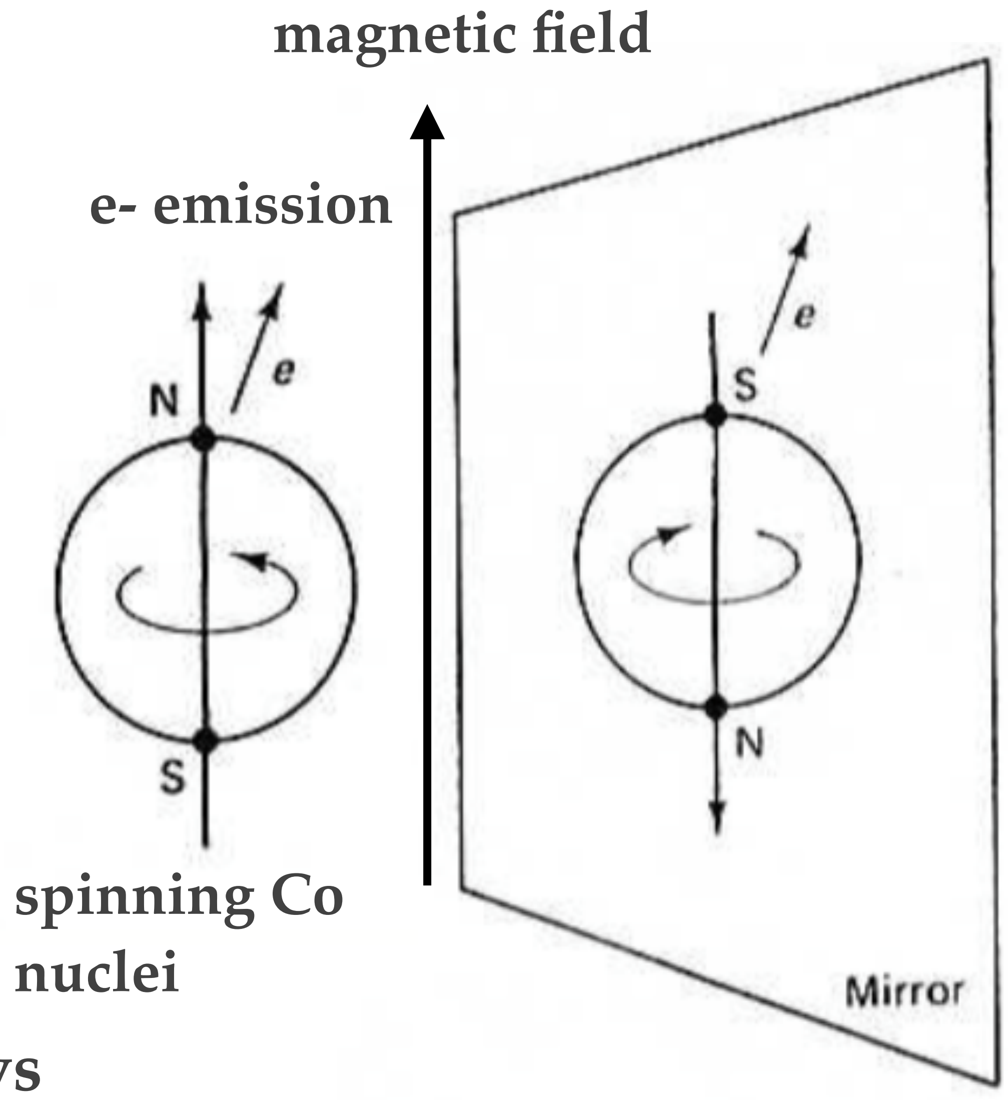
P : Parity transformation. Invert every spatial coordinates

$$P(t, r) = P(t, -r)$$

fermions and anti-fermions have opposite parity

1956 : Yang and Lee realized that parity invariance had never been tested experimentally for weak interactions

Wu's experiment: recorded the direction of the emitted electron from a ^{60}Co β-decay when the nuclear spin was aligned up and down



P symmetry is MAXIMALLY violated in weak decays

Discrete Symmetries

C : Charge Conjugaison. C reverses every internal additive quantum number (e.g. charge, baryon/lepton number, strangeness, etc.). Exchange of particle and antiparticle

$C \mid p> = \mid \bar{p}>$

few particles are C-eigenstates

C is conserved in strong and EM interactions

$$C|n\gamma\rangle = (-1)^n |\gamma\rangle$$

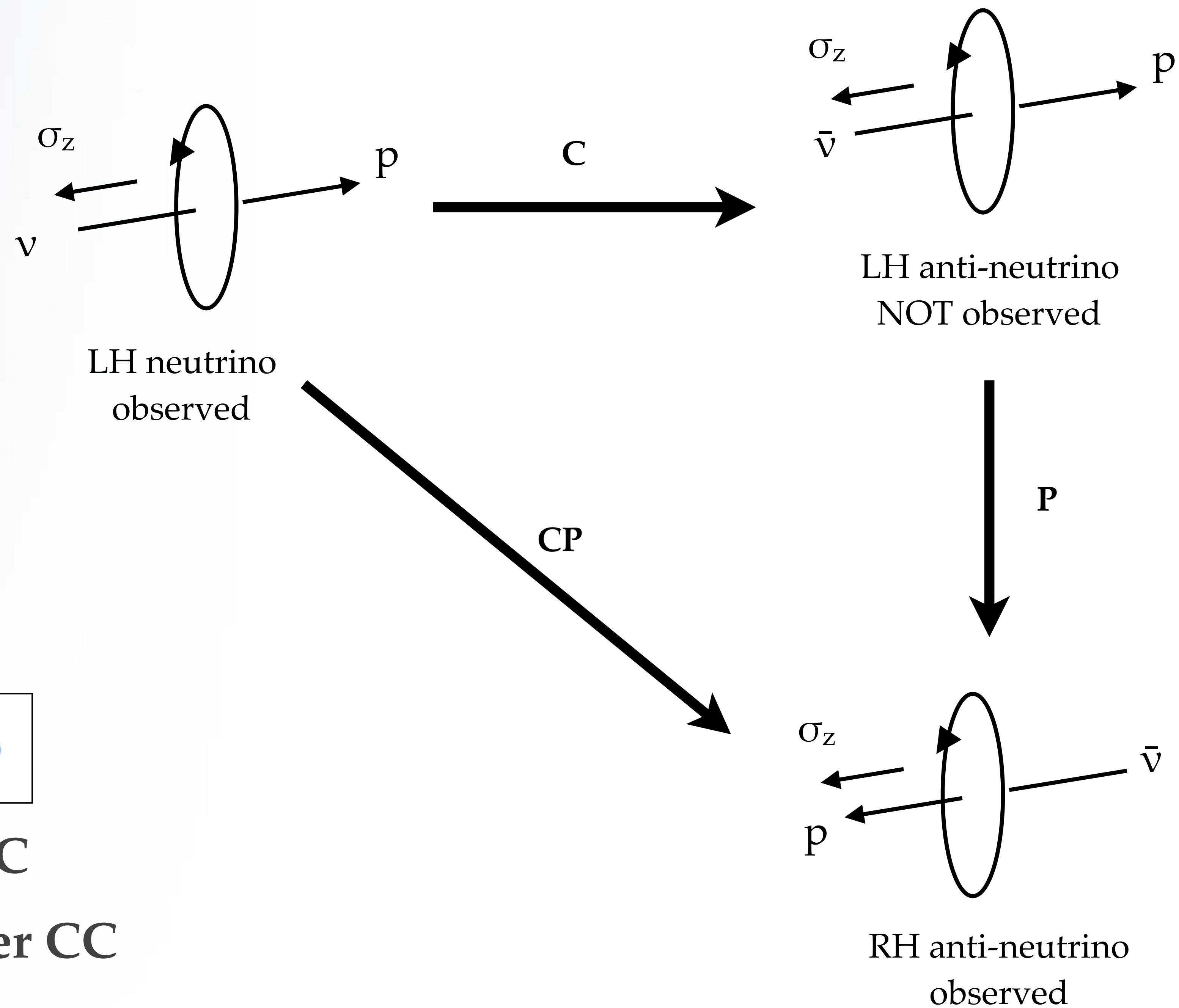
$$C=(-1)^{l+s}$$

$$C|\pi^0\rangle = |\pi^0\rangle$$

$\pi^0 \rightarrow 2\gamma$ is allowed under CC

$\pi^0 \rightarrow 3\gamma$ is not allowed under CC

$< 3.1 \times 10^{-8}$



Discrete Symmetries

CP Violation in Neutral Kaons:

$$K^0 : \quad (d\bar{s}) \quad S = +1$$
$$\bar{K^0} : \quad (s\bar{d}) \quad S = -1$$

Production through $\Delta S=0$
Decay through $\Delta S=+/-1$

Start with a pure K^0 beam

$$|K(t)\rangle = \alpha(t)\left|K^0\right\rangle + \beta(t)\left|\bar{K^0}\right\rangle$$

Discrete Symmetries

CP Violation in Neutral Kaons:

$$K^0 : \quad (d\bar{s}) \quad S = +1$$
$$\bar{K^0} : \quad (s\bar{d}) \quad S = -1$$

Production through ΔS=0
Decay through ΔS=+/- 1

Start with a pure K⁰ beam

$$|K(t)\rangle = \alpha(t)\,|K^0\rangle + \beta(t)\,|\bar{K^0}\rangle$$

CP Eigenstates :

$$|K_S\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K^0}\rangle) \quad CP = +1$$
$$|K_L\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K^0}\rangle) \quad CP = -1$$

$$|K_S\rangle \to 2\pi, \quad CP = +1, \quad \tau \sim 0.9 \times 10^{-10}\,\mathrm{s}$$
$$|K_L\rangle \to 3\pi, \quad CP = -1, \quad \tau \sim 0.5 \times 10^{-7}\,\mathrm{s}$$

Discrete Symmetries

Measured quantity :

$$|\eta_{+-}| = \frac{\text{amplitude}(K_L \to \pi^+\pi^-)}{\text{amplitude}(K_S \to \pi^+\pi^-)} \sim 2.3 \times 10^{-3}$$

Interferences : observed in modulation of the 2 pion signal

Discrete Symmetries

Measured quantity :

$$|\eta_{+-}| = \frac{\text{amplitude}(K_L \to \pi^+\pi^-)}{\text{amplitude}(K_S \to \pi^+\pi^-)} \sim 2.3 \times 10^{-3}$$

Interferences : observed in modulation of the 2 pion signal

Semi-leptonic mode :

$$K_L \to e^+ + \nu_e + \pi^-$$
$$K_L \to e^- + \bar{\nu}_e + \pi^+$$

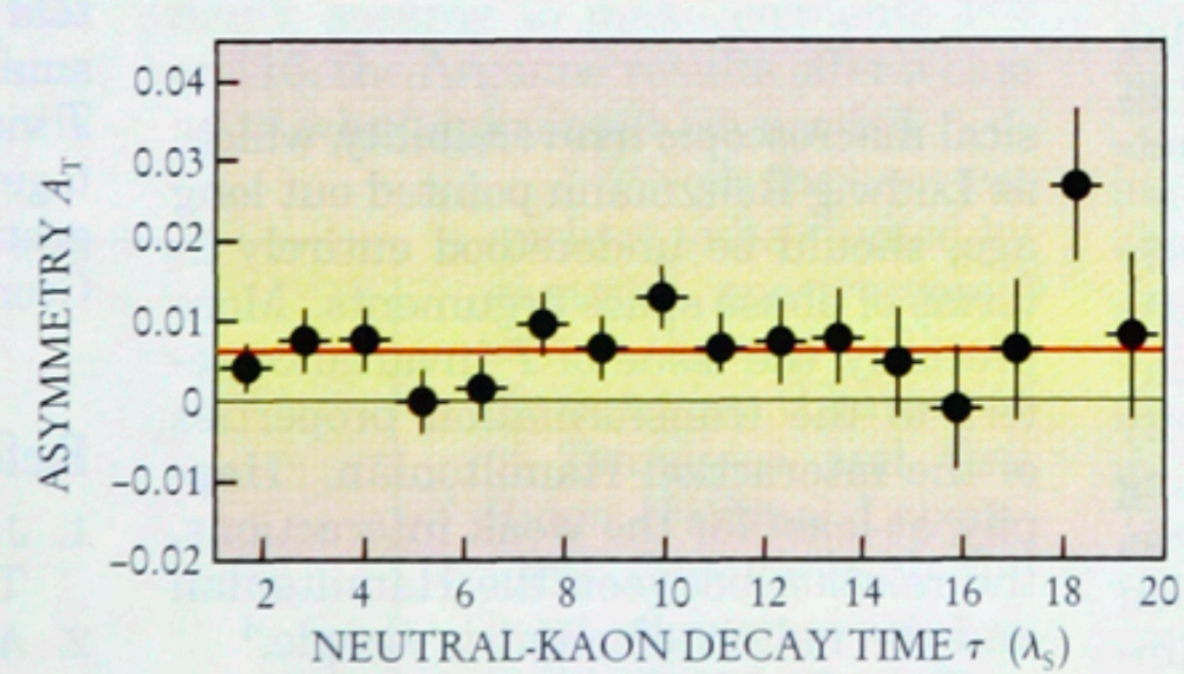
Discrimination criteria between matter and antimatter :

$$\Delta = \frac{\text{rate}(K_L \to e^+ + \nu_e + \pi^-) - \text{rate}(K_L \to e^- + \bar{\nu}_e + \pi^+)}{\text{rate}(K_L \to e^+ + \nu_e + \pi^-) + \text{rate}(K_L \to e^- + \bar{\nu}_e + \pi^+)}$$

$$\Delta \sim 0.3 \times 10^{-2}$$

Discrete Symmetries

T : Time Reversal **@ CPLEAR**

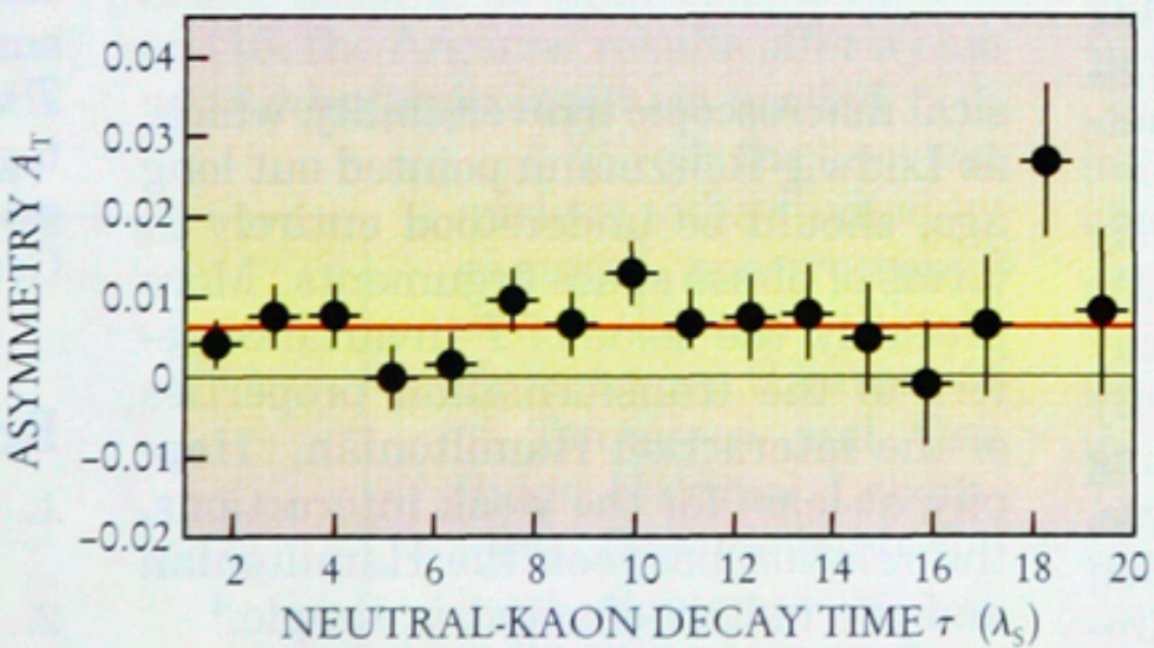


TIME-REVERSAL ASYMMETRY A_T, the observed difference between the rates for $\overline{K}^0 \to K^0$ and $K^0 \to \overline{K}^0$, divided by their sum, is plotted here as a function of the proper time interval τ between the creation of the neutral kaon in the CPLEAR facility at CERN and its subsequent decay from a state of opposite strangeness. The time is given in units of $\lambda_S = 89.3$ ps, the shorter of the two neutral-kaon lifetimes. The red line is the fitted average measured asymmetry, $(6.6 \pm 1.6) \times 10^{-3}$, in good agreement with the theoretical expectation. (Adapted from ref. 2.)

$$\Delta = \frac{\text{rate}(\bar{K}_0 \to K_0) - \text{rate}(K_0 \to \bar{K}_0)}{\text{rate}(\bar{K}_0 \to K_0) + \text{rate}(K_0 \to \bar{K}_0)}$$

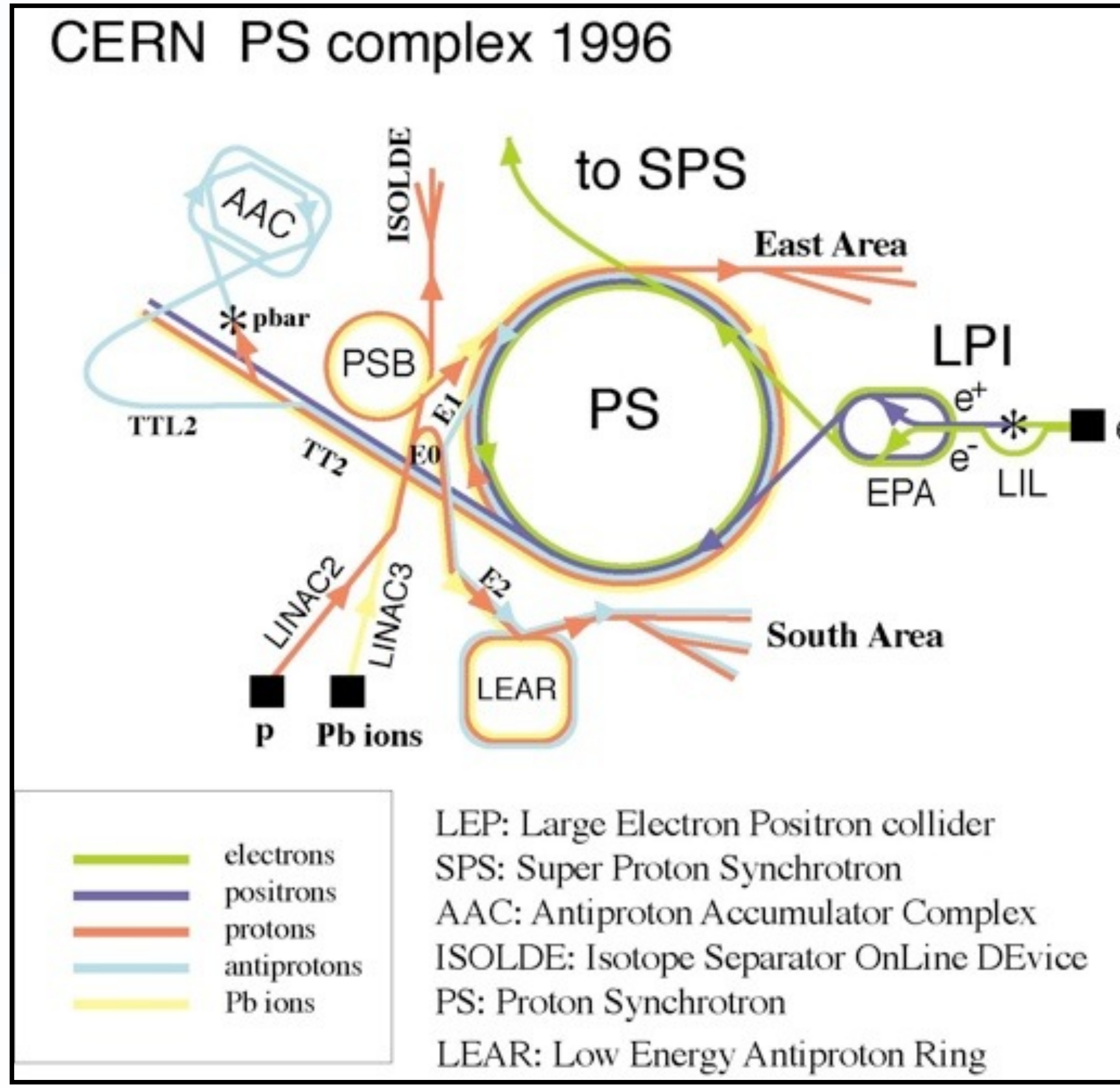
Discrete Symmetries

T : Time Reversal **@ CPLEAR**



TIME-REVERSAL ASYMMETRY A_T, the observed difference between the rates for $\overline{K}^0 \to K^0$ and $K^0 \to \overline{K}^0$, divided by their sum, is plotted here as a function of the proper time interval τ between the creation of the neutral kaon in the CPLEAR facility at CERN and its subsequent decay from a state of opposite strangeness. The time is given in units of λ_S = 89.3 ps, the shorter of the two neutral-kaon lifetimes. The red line is the fitted average measured asymmetry, $(6.6 \pm 1.6) \times 10^{-3}$, in good agreement with the theoretical expectation. (Adapted from ref. 2.)

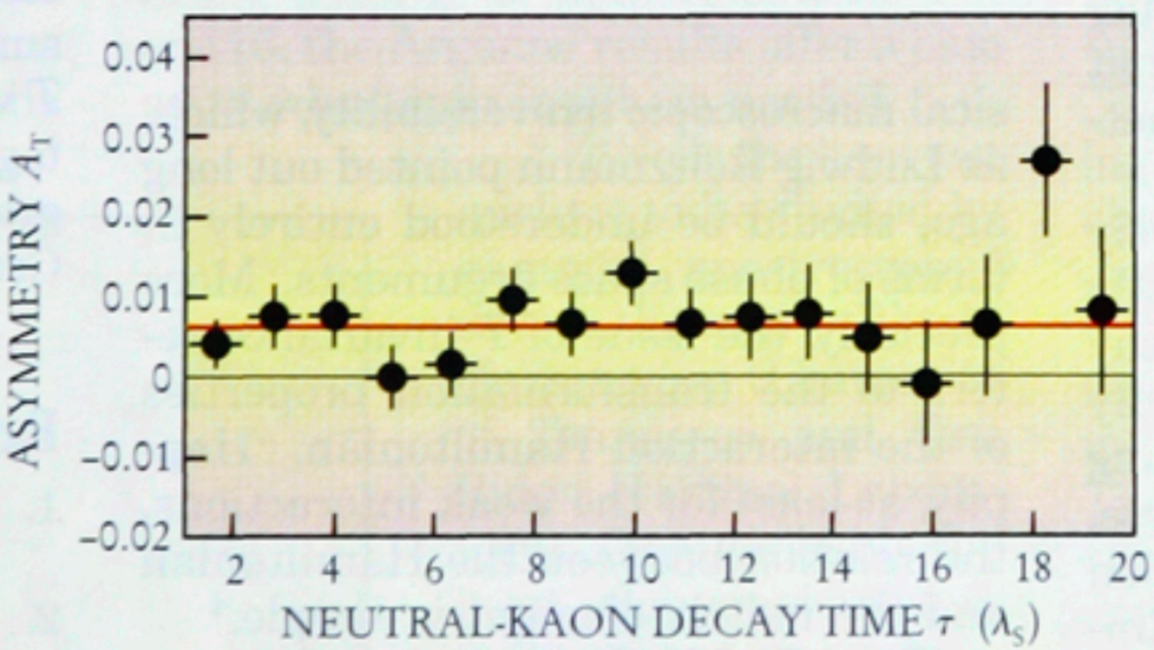
$$\Delta = \frac{\text{rate}(\bar{K}_0 \to K_0) - \text{rate}(K_0 \to \bar{K}_0)}{\text{rate}(\bar{K}_0 \to K_0) + \text{rate}(K_0 \to \bar{K}_0)}$$



1982-1996 : AAC
3 separate rings
AC, AA, LEAR

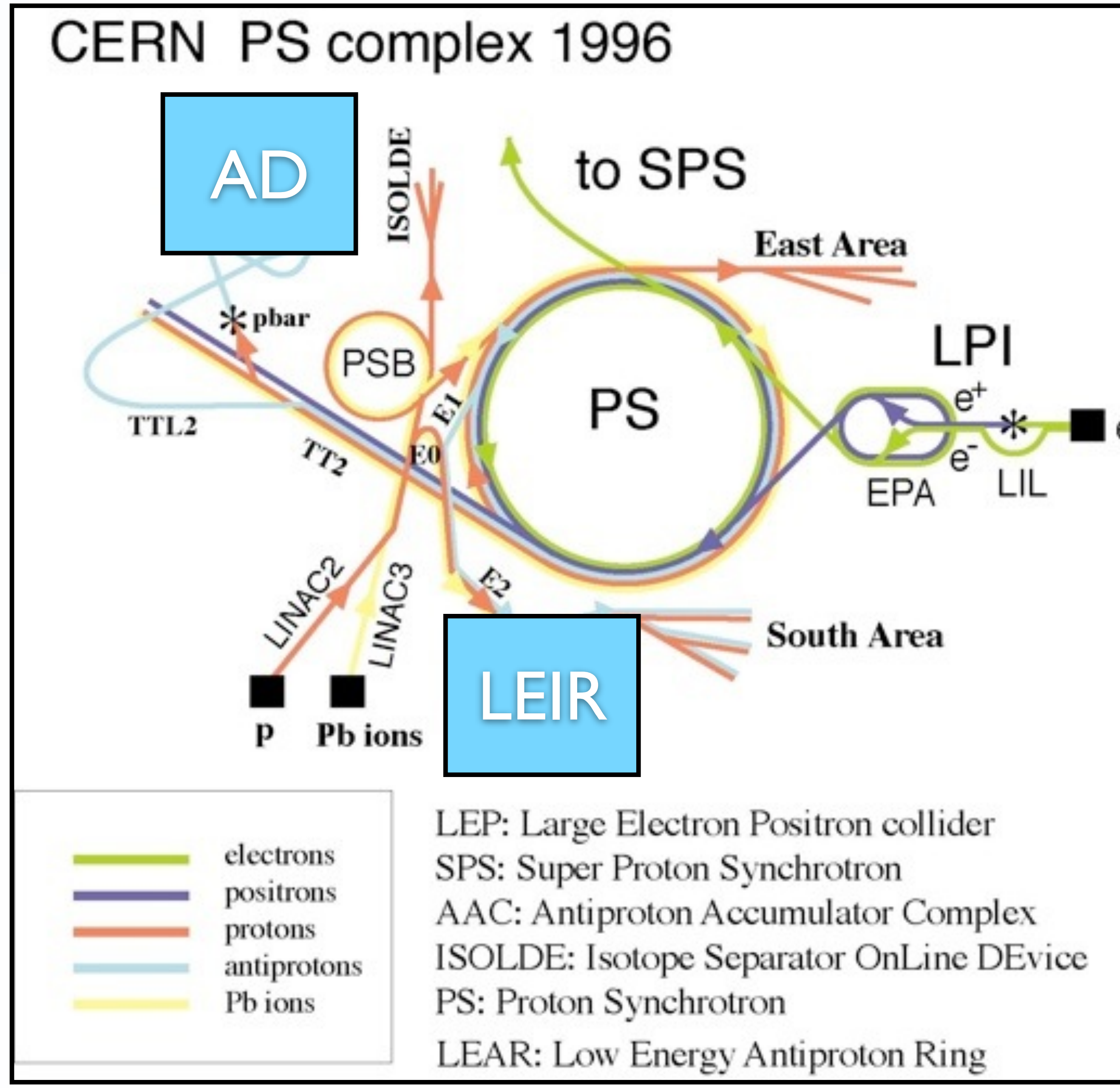
Discrete Symmetries

T : Time Reversal @ CPLEAR



TIME-REVERSAL ASYMMETRY A_T, the observed difference between the rates for $\overline{K}^0 \to K^0$ and $K^0 \to \overline{K}^0$, divided by their sum, is plotted here as a function of the proper time interval τ between the creation of the neutral kaon in the CPLEAR facility at CERN and its subsequent decay from a state of opposite strangeness. The time is given in units of $\lambda_S = 89.3$ ps, the shorter of the two neutral-kaon lifetimes. The red line is the fitted average measured asymmetry, $(6.6 \pm 1.6) \times 10^{-3}$, in good agreement with the theoretical expectation. (Adapted from ref. 2.)

$$\Delta = \frac{\text{rate}(\bar{K}_0 \to K_0) - \text{rate}(K_0 \to \bar{K}_0)}{\text{rate}(\bar{K}_0 \to K_0) + \text{rate}(K_0 \to \bar{K}_0)}$$



1982-1996 : AAC
3 separate rings
AC, AA, LEAR

Since 2000 :
all-in-one machine : AD

Discrete Symmetries

Summary:

	Interactions		
	Strong	EM	Weak
P	yes	yes	no
C	yes	yes	no
CP (or T)	yes	yes	~10^-3 1964 : K0 decay 1999 (2012) : Direct T Violation 2001: B decay (BELLE, BaBar) 2013 : strange B decay (LHCb)
CPT			

Discrete Symmetries

Summary:

	Interactions		
	Strong	EM	Weak
P	yes	yes	no
C	yes	yes	no
CP (or T)	yes	yes	~10^-3 1964 : K0 decay 1999 (2012) : Direct T Violation 2001: B decay (BELLE, BaBar) 2013 : strange B decay (LHCb)
CPT	yes	yes	yes

Discrete Symmetries

Observation of C, P, T, CP violation, what about CPT?
In the SM, CPT is conserved. So, if T is violated, CP is violated & vice-versa

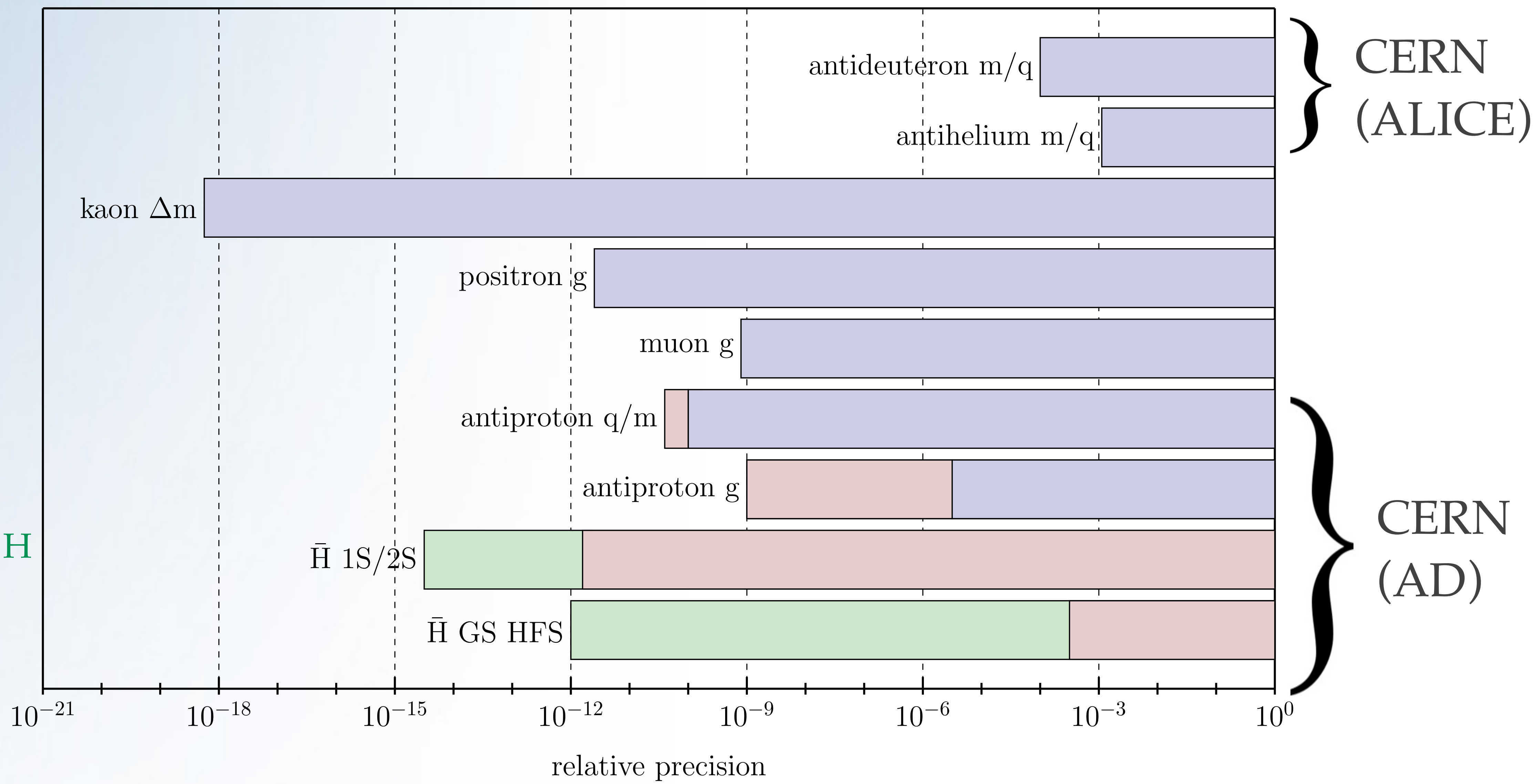
CPT Theorem :

A local, Lorenz invariant theory with canonical spin-statistics relation must be invariant with respect to CPT-transformation

J. Schwinger, Phys. Rev.82, 914 (1951);
G. Lüders, Kgl. Danske Vidensk. Selskab. Mat.-Fys. Medd.28, 5 (1954);
G. Lüders, Ann. Phys.2, 1 (1957);
W. Pauli, Nuovo Cimento,6, 204 (1957);
R. Jost, Helv. Phys. Acta30, 409 (1957);
F.J. Dyson, Phys. Rev.110, 579 (1958).

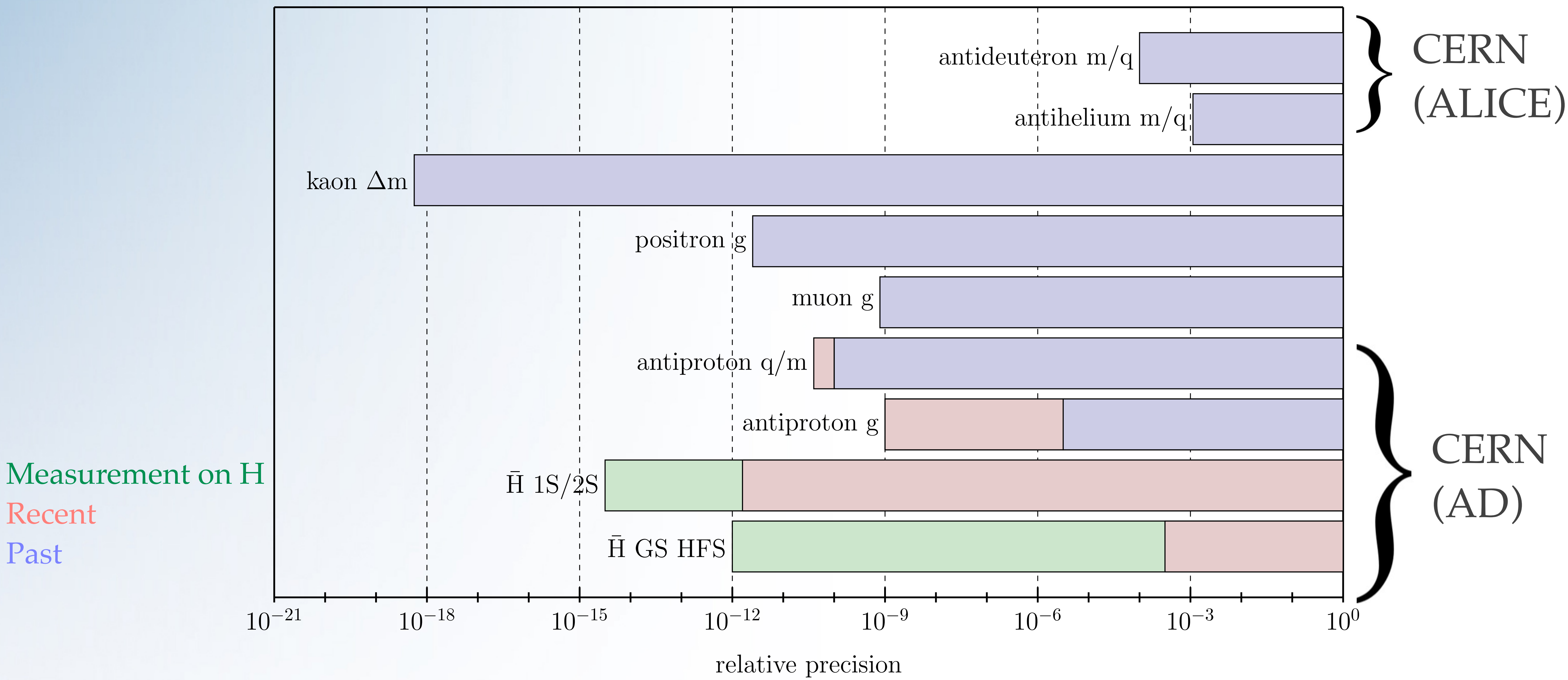
Implication : properties of matter & antimatter particles should be the same

Tests of CPT Symmetry



Measurement on H
Recent
Past

Tests of CPT Symmetry



Standard Model Extension

$$(i\gamma^\mu D_\mu - m_e - a^e_\mu\gamma^\mu - b^e_\mu\gamma_5\gamma^\mu$$
$$-\frac{1}{2}H^e_{\mu\nu}\sigma^{\mu\nu} + ic^e_{\mu\nu}\gamma^\mu D^\nu + id^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0$$

Search for Primordial Antimatter

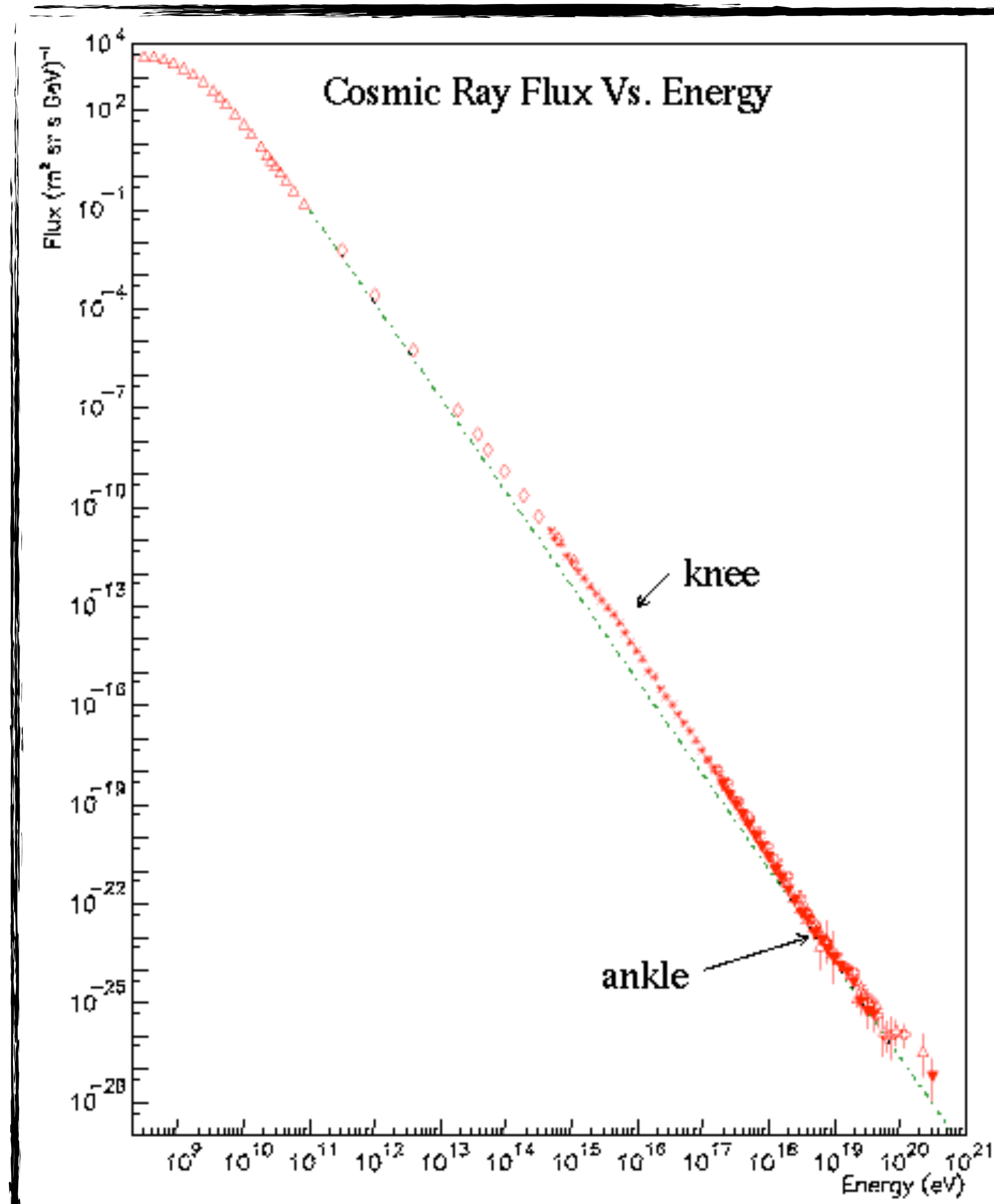
IS THERE ANTIMATTER LEFT IN THE UNIVERSE?

Search for Primordial Antimatter

- **DIRECT SEARCHES IN COSMIC RAYS**

  Creation of Secondaries in IGM : Test source and propagation models for cosmic rays

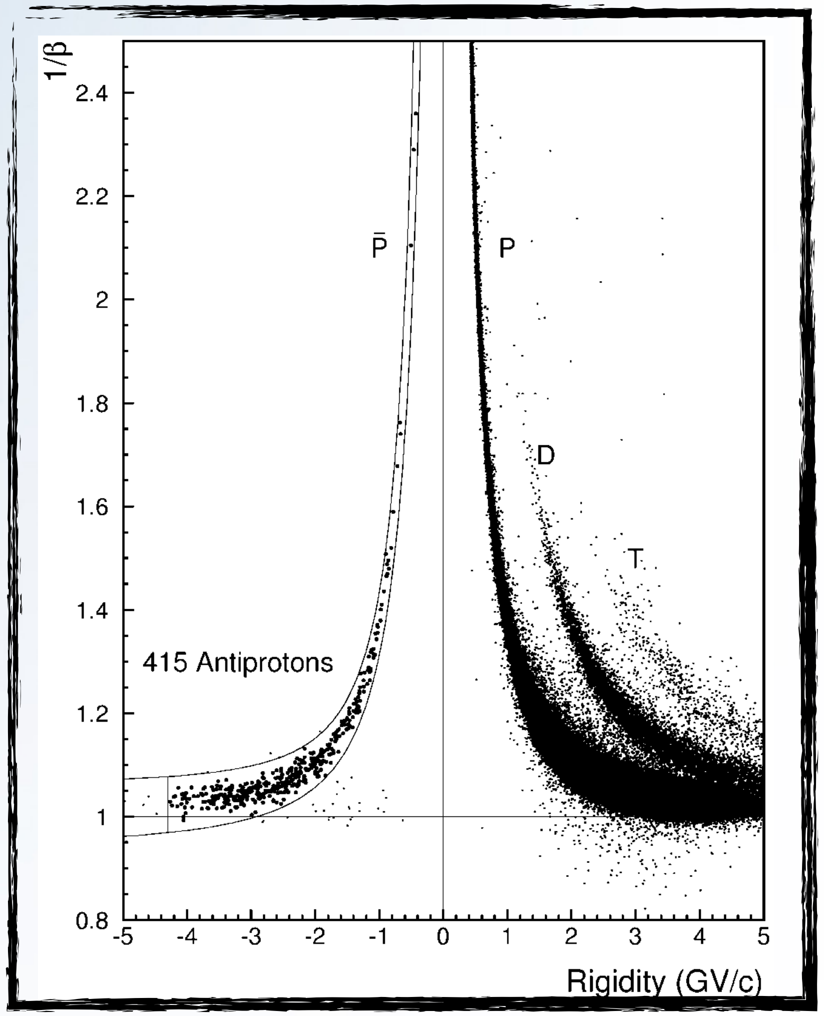
A large part of positrons and antiprotons impinging on Earth are produced in high-energy interactions between cosmic rays nuclei with the interstellar medium. Their spectra can provide an insight on the origin, production and propagation of cosmic rays in our galaxy. Any observed flux larger than that predicted by the Leaky Box Model (LBM), the "standard" model of cosmic ray propagation, could indicate exotic sources of antimatter. The predictions of the propagation models are different above 10 GeV where more refined measurements are needed.

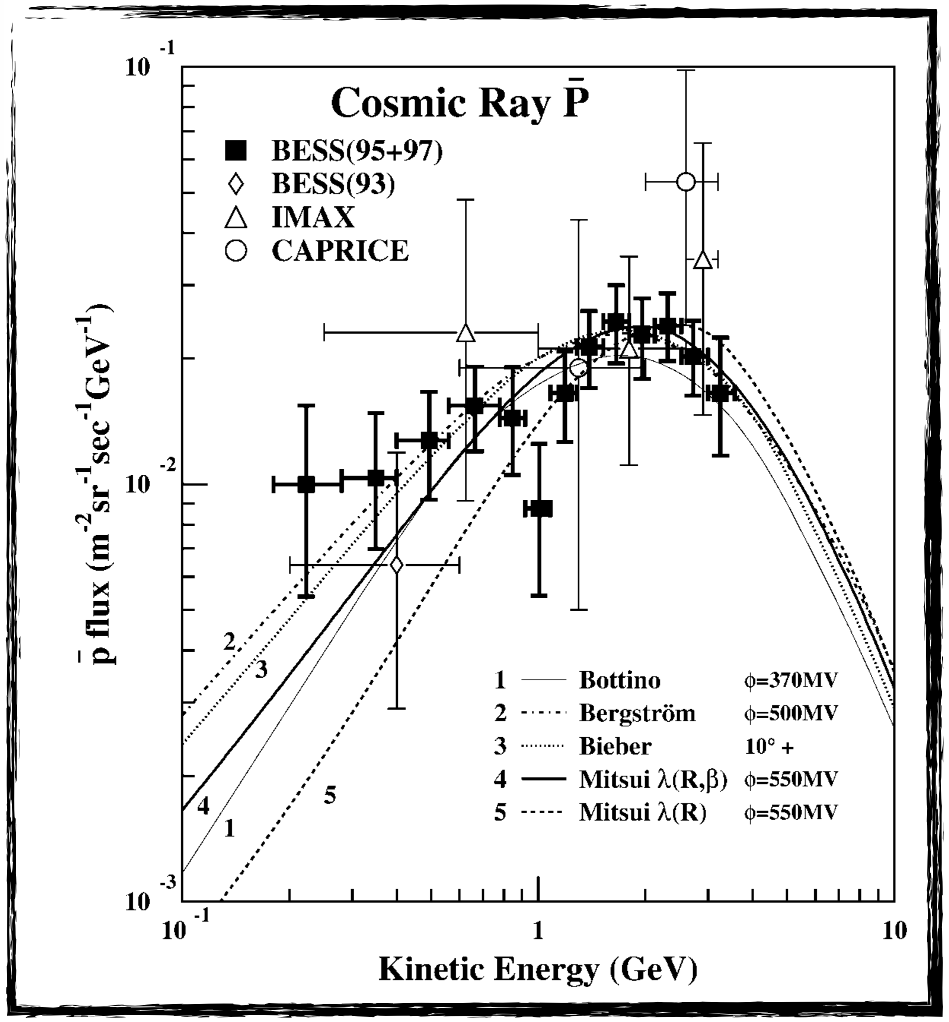


Balloon experiments

Results from CAPRICE/BESS

height of flight = 38 km (top of atmosphere)





PRL 84 (2000) 1078

http://prl.aps.org/pdf/PRL/v84/i6/p1078_1

http://arxiv.org/abs/astro-ph/9809101

subsidiary result (data+propagation model) = **τ**(p̄) > 1.7 Myr

Space experiments

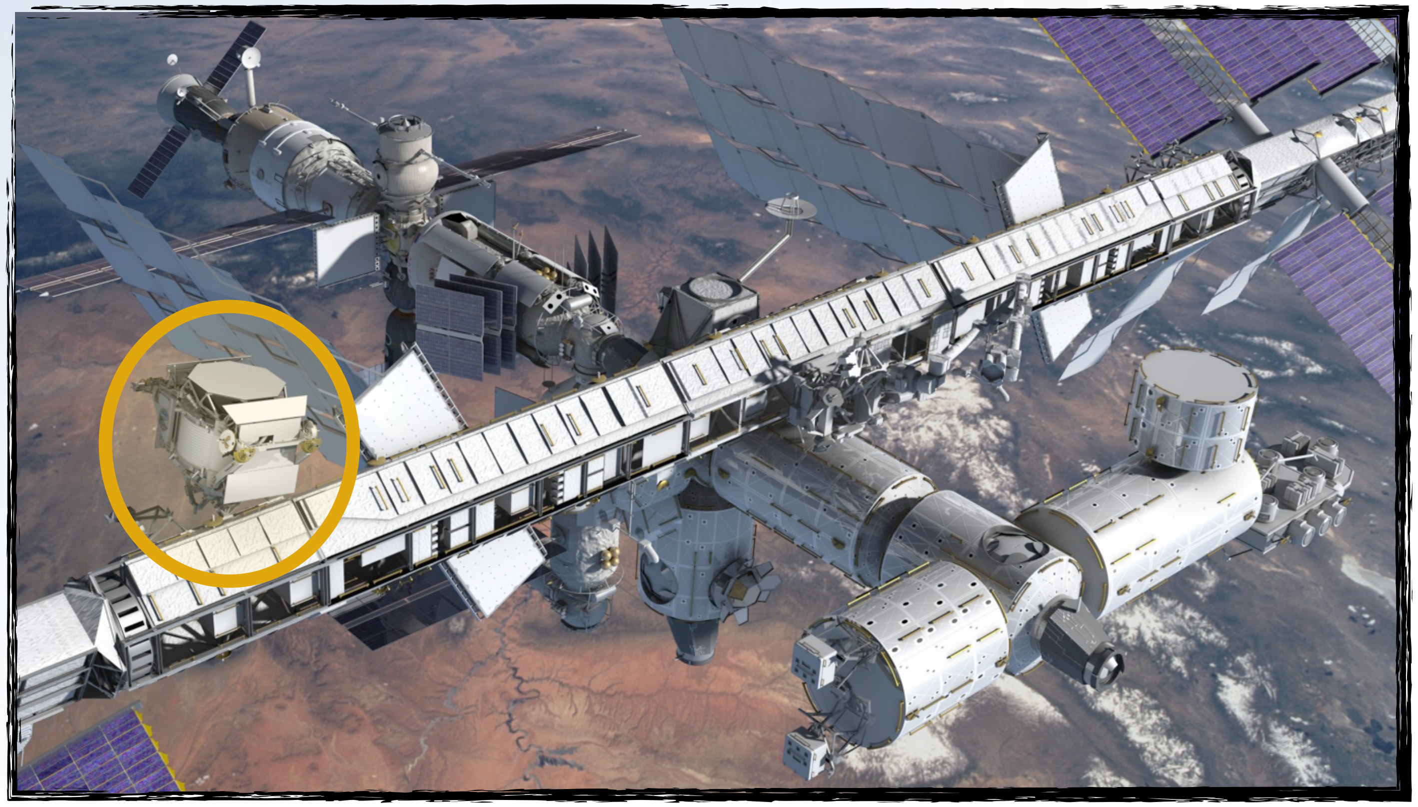
PAMELA (satellite), AMS (space station)

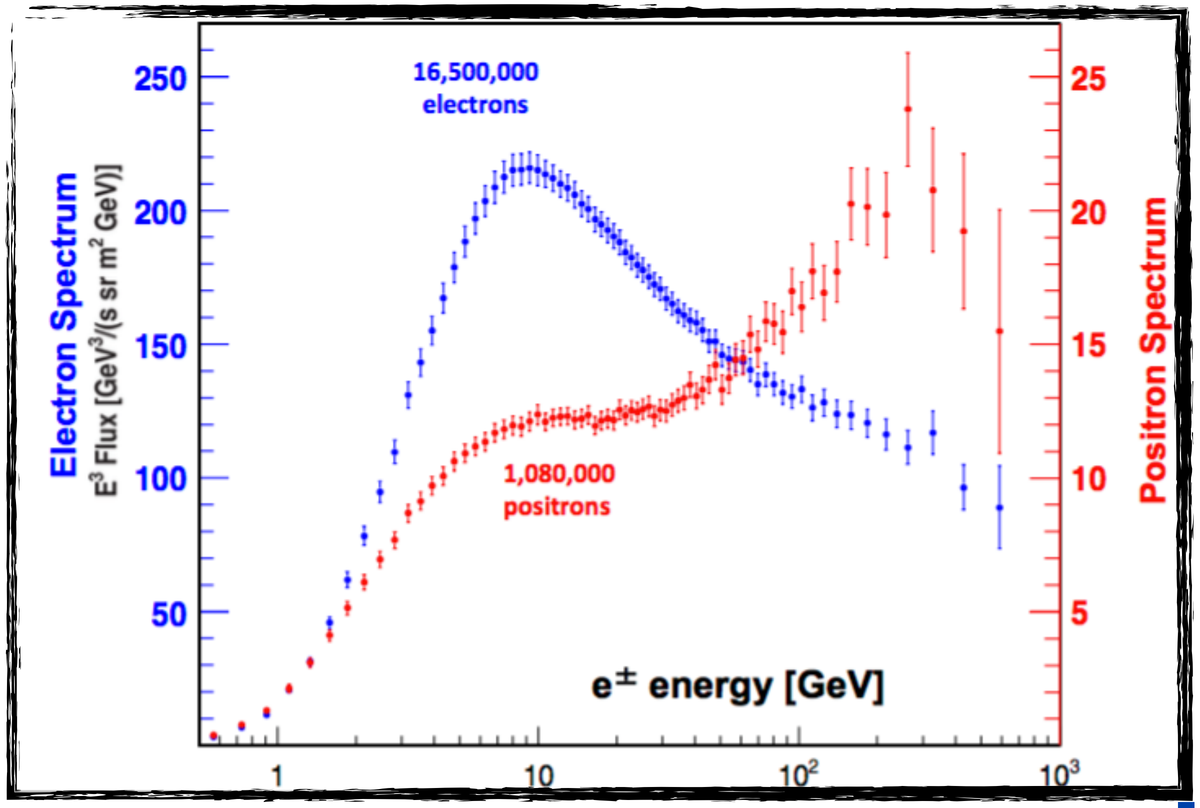
- SEARCH FOR PRIMARY ANTIMATTER

e+, p̄, anti-alpha

Note : positrons are difficult to measure/interpret:

- radiative losses close to sources
- possibility of primary positron cosmic rays





Space experiments

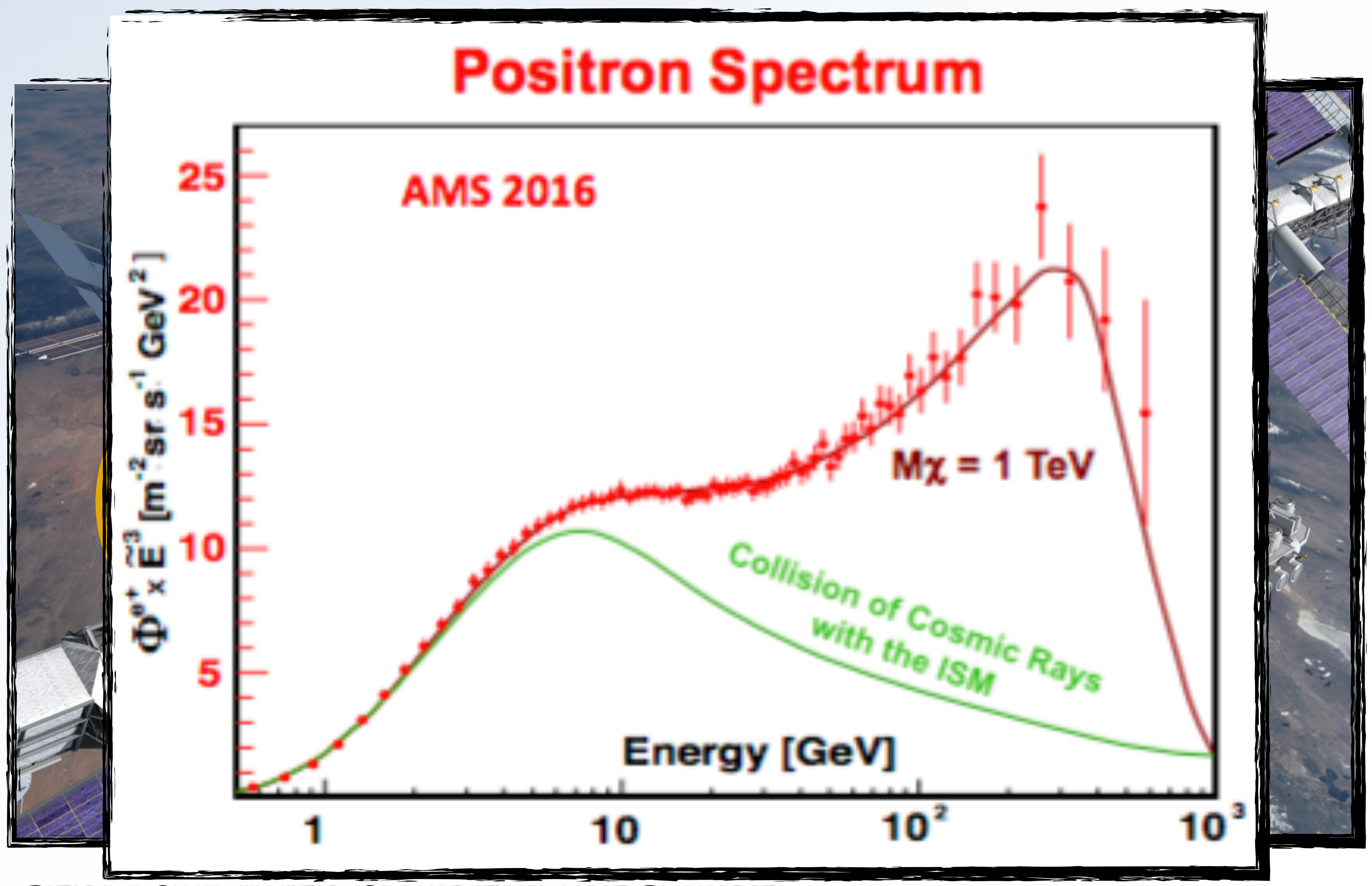
PAMELA (satellite), AMS (space station)

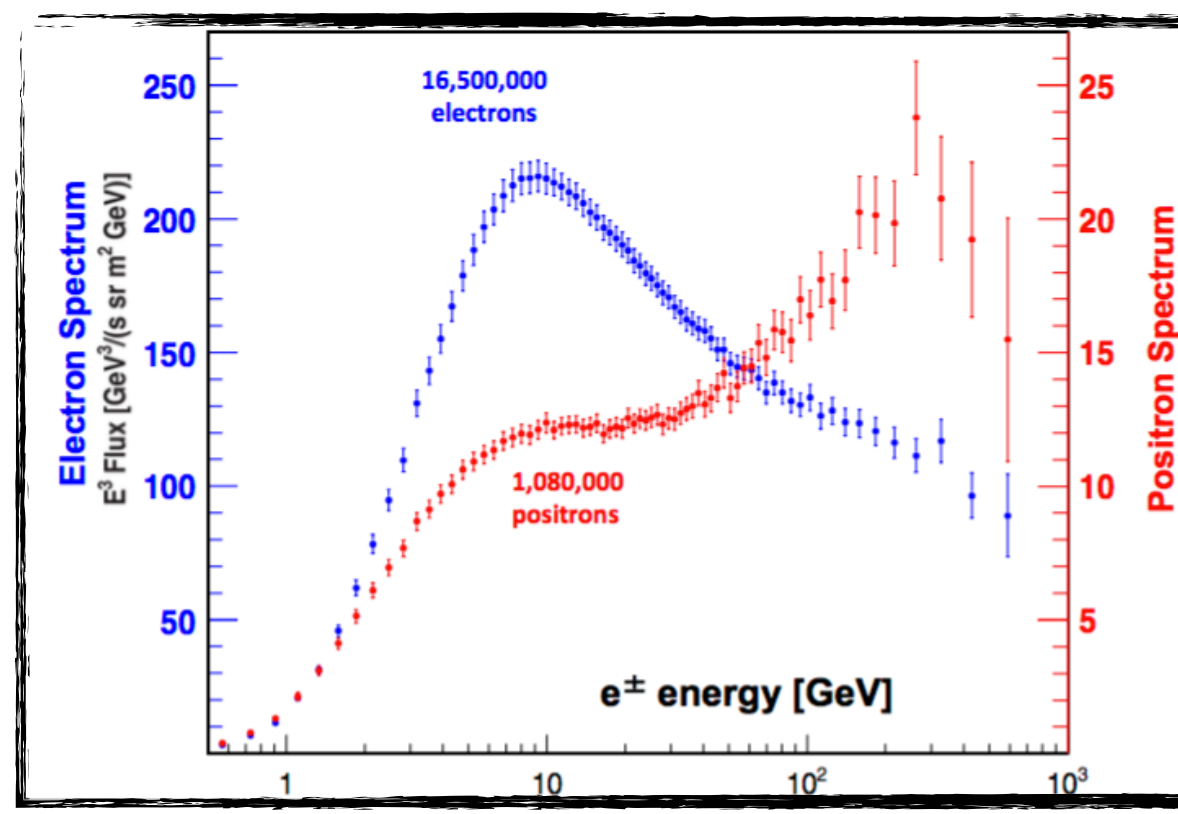
- SEARCH FOR PRIMARY ANTIMATTER

e+, p̄, anti-alpha

Note : positrons are difficult to measure/interpret:

- radiative losses close to sources
- possibility of primary positron cosmic rays

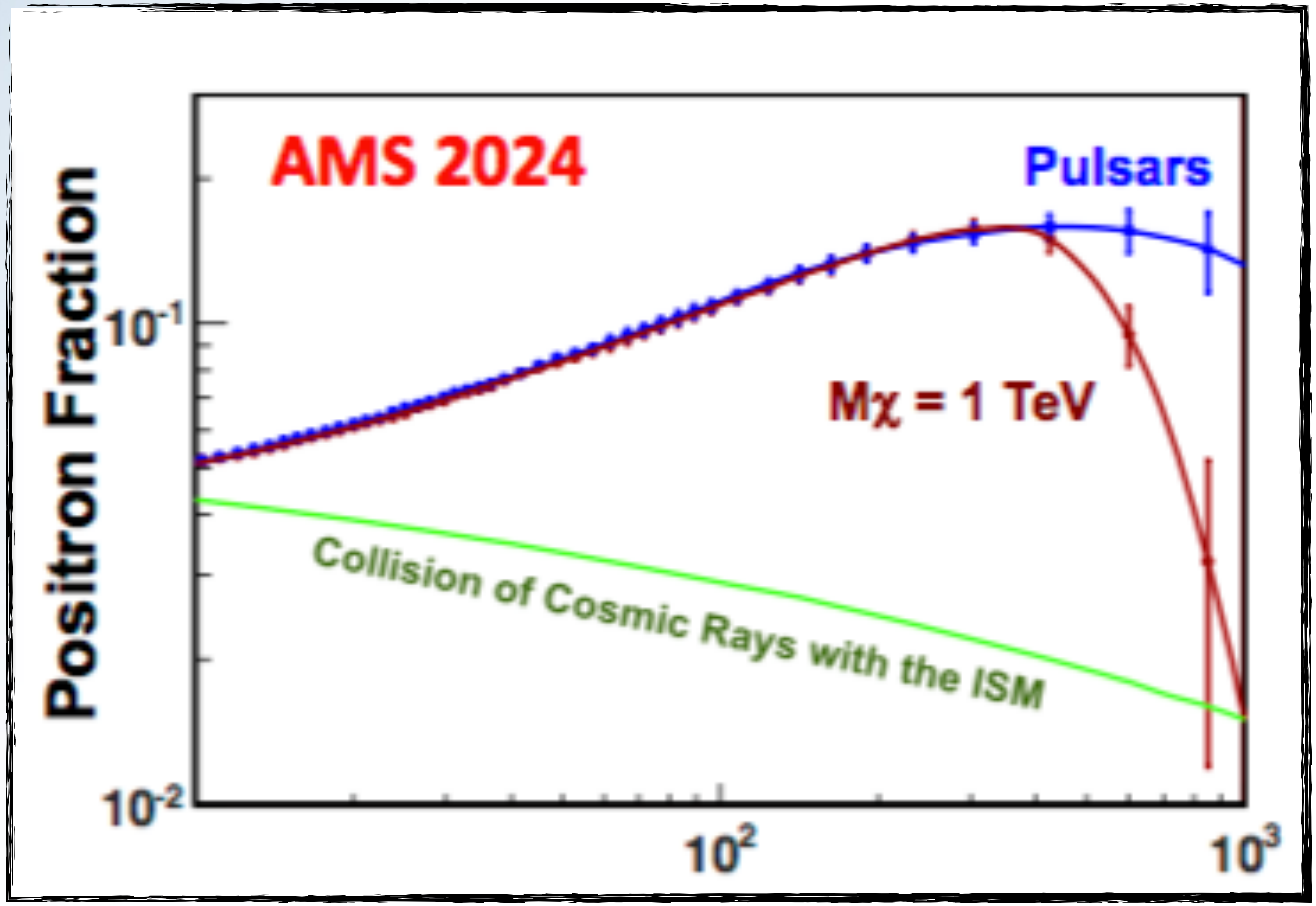




Space experiments

Other sources :

- Modified Propagation of Cosmic Rays, Supernova Remnants, Pulsars



Cosmological Models

<u>Distortions in the CMB:</u>

- CMB would have been affected by late annihilations (if antimatter would have survived longer than expected) & photons from the annihilation would contribute to the diffuse gamma rays

> If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.

Dirac Nobel lecture 1933

- B=0 universe is mostly excluded by standard cosmology scenarios based on CMB observation (annihilation at boundaries, at least for domains which are smaller than the size of the visible universe)

Cosmological Models

Big Bang Nucleosynthesis

Existence of antimatter during nucleosynthesis would have affected the formation of nuclei (annihilation, formation of pp̄ etc.., annihilation gamma rays would photodesintegrate etc)

Estimate the baryon density from SBBN and CMB

Photons are final products of annihilation processes

$$\eta = \left(\frac{N_B}{N_\gamma}\right)_{T=3\,\mathrm{K}} \quad \eta = \left(\frac{N_B - N_{\bar{B}}}{N_\gamma}\right)_{T=3\,\mathrm{K}}$$

$$\eta_{SBBN} = (5.80 \pm 0.27) \times 10^{-10}$$
$$\eta_{CMB} = 6.160^{+0.153}_{-0.156} \times 10^{-10}$$

Summary

INITIAL POSTULATION OF ANTIMATTER THROUGH THE DIRAC EQUATION

EXPERIMENTAL CONFIRMATION IN COSMIC RAYS

PUZZLE OF MATTER -ANTIMATTER ASYMMETRY IN THE UNIVERSE

TRIGGERS PRECISE COMPARISON OF MATTER & ANTIMATTER PROPERTIES

THROUGH TEST OF DISCRETE SYMMETRIES IN THE LAB

AND SEARCH OF PRIMORDIAL ANTIMATTER IN OUTER SPACE

Summary

INITIAL POSTULATION OF ANTIMATTER THROUGH THE DIRAC EQUATION

EXPERIMENTAL CONFIRMATION IN COSMIC RAYS

PUZZLE OF MATTER -ANTIMATTER ASYMMETRY IN THE UNIVERSE

TRIGGERS PRECISE COMPARISON OF MATTER & ANTIMATTER PROPERTIES

THROUGH TEST OF DISCRETE SYMMETRIES IN THE LAB

AND SEARCH OF PRIMORDIAL ANTIMATTER IN OUTER SPACE

LECTURE # 2 : EXPERIMENTS AND APPLICATIONS OF LOW ENERGY ANTIMATTER