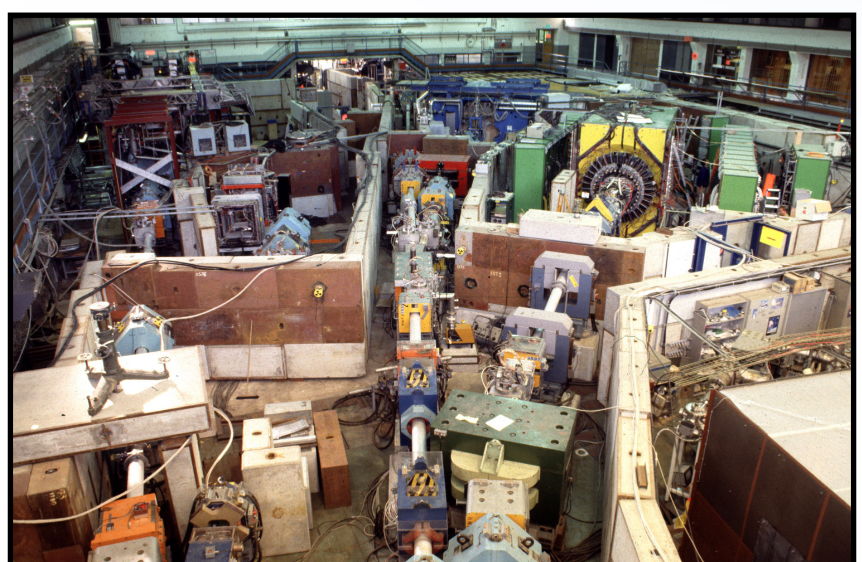
RECAP' ON ANTIMATTER PHYSICS

Chloé Malbrunot
CERN



AVA School on Precision Physics 23-27 March 2020

Content

- Antimatter & fundamental questions of physics
- Discrete symmetries
- The ingredients for $\bar{H}$ production : $\bar{p}$ and e^+ production
- Insights in $\bar{H}$ new results and planned measurements
- Primordial antimatter search

What is antimatter?

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

Quarks	u up	c charm	t top
	d down	s strange	b bottom
Leptons	ν_e e neutrino	ν_μ μ neutrino	ν_τ τ neutrino
	e electron	μ muon	τ tau

+ force carriers

What is antimatter?

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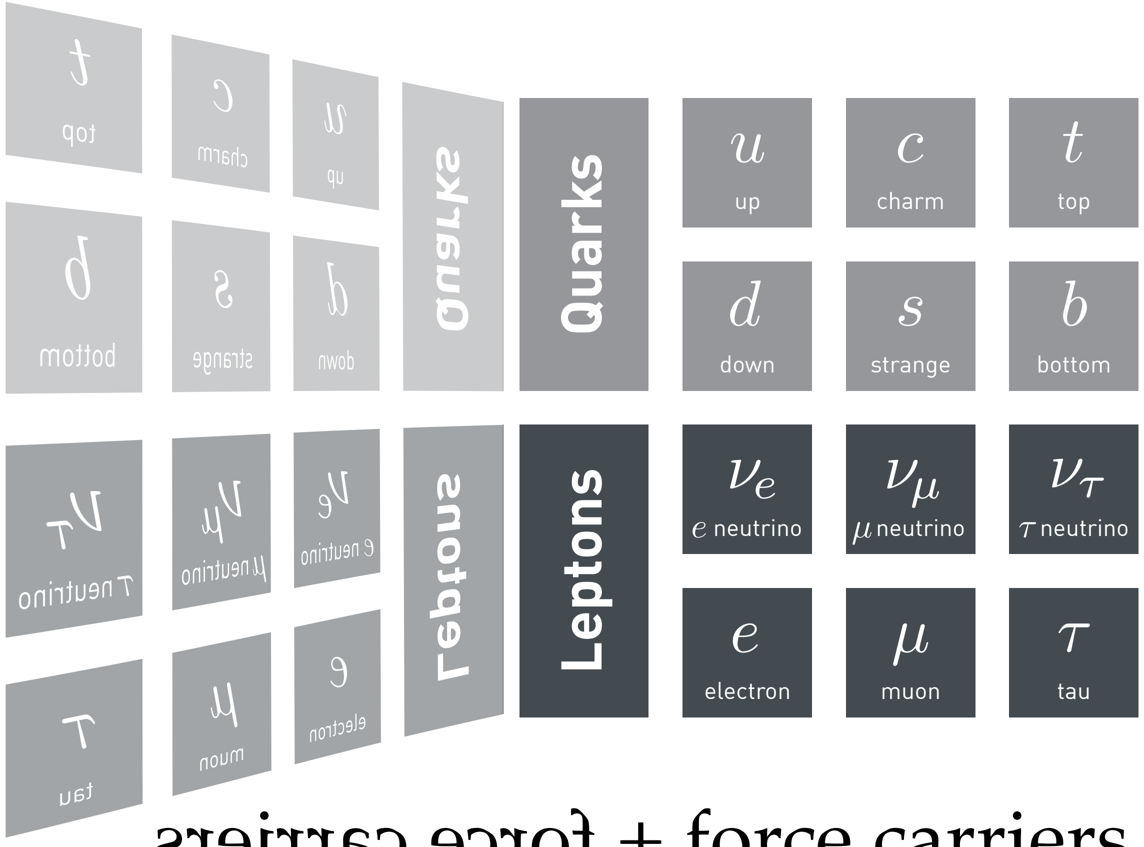

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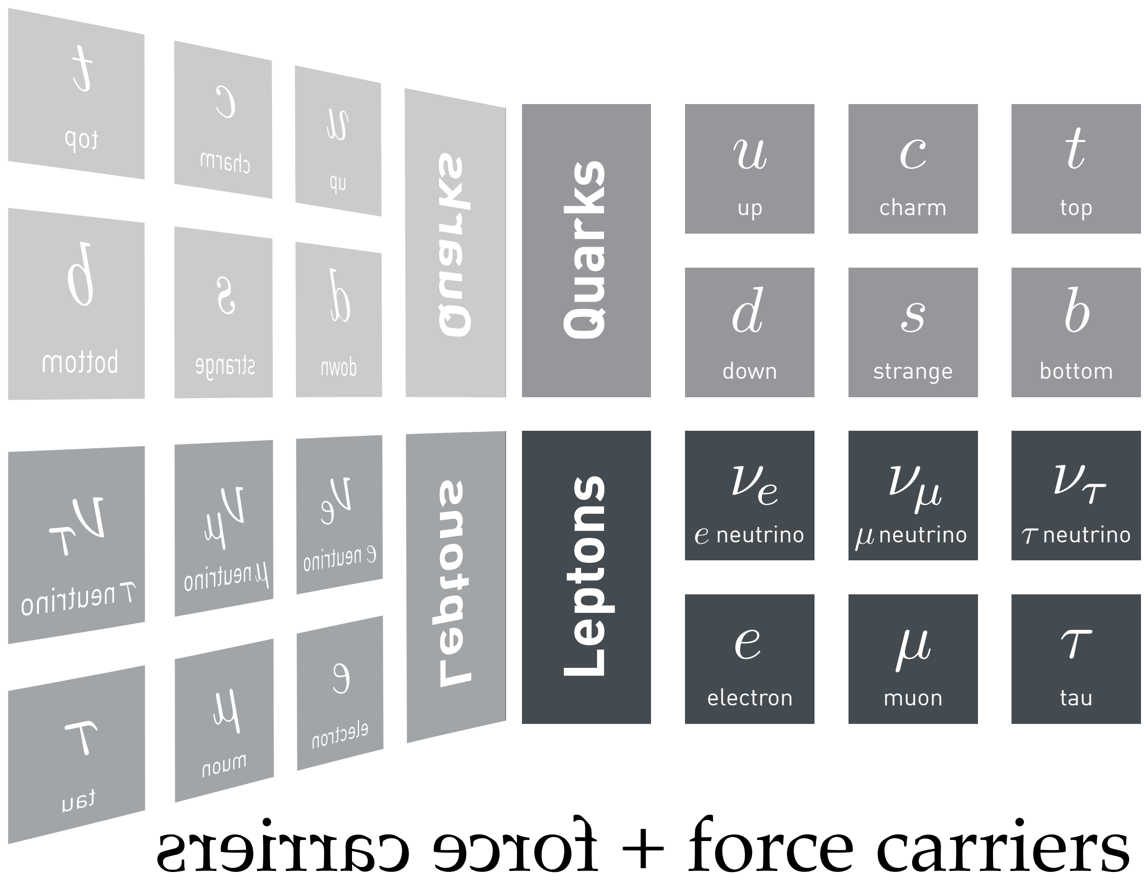
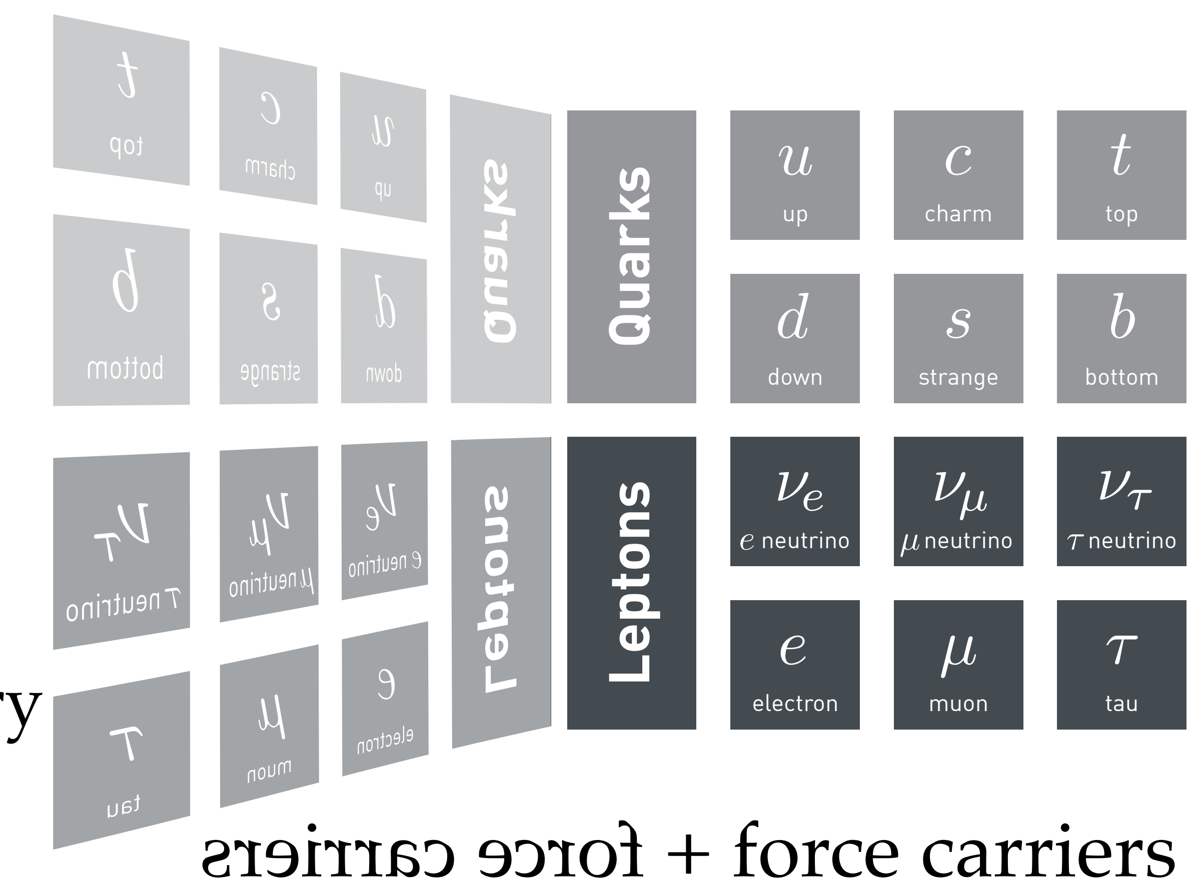


- Why a copy?
- Why is the primordial antimatter gone?

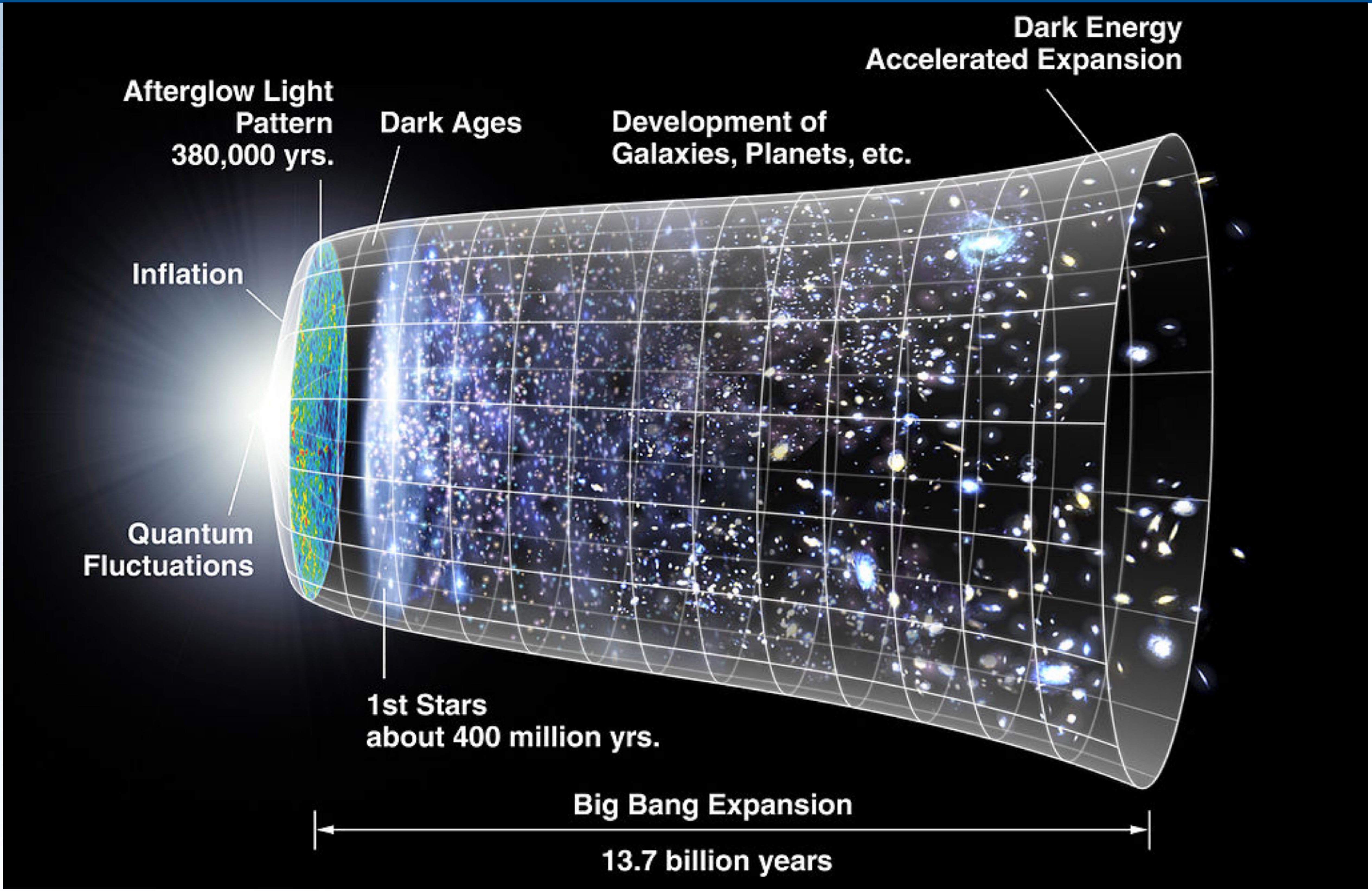
What is antimatter?

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



- Why a copy?
  - QFT+Lorentz invariance+locality+unitary imply CPT conservation
- Why is the primordial antimatter gone?
  - mechanism to create an asymmetry between matter and antimatter: CP violation?

Matter - Antimatter asymmetry



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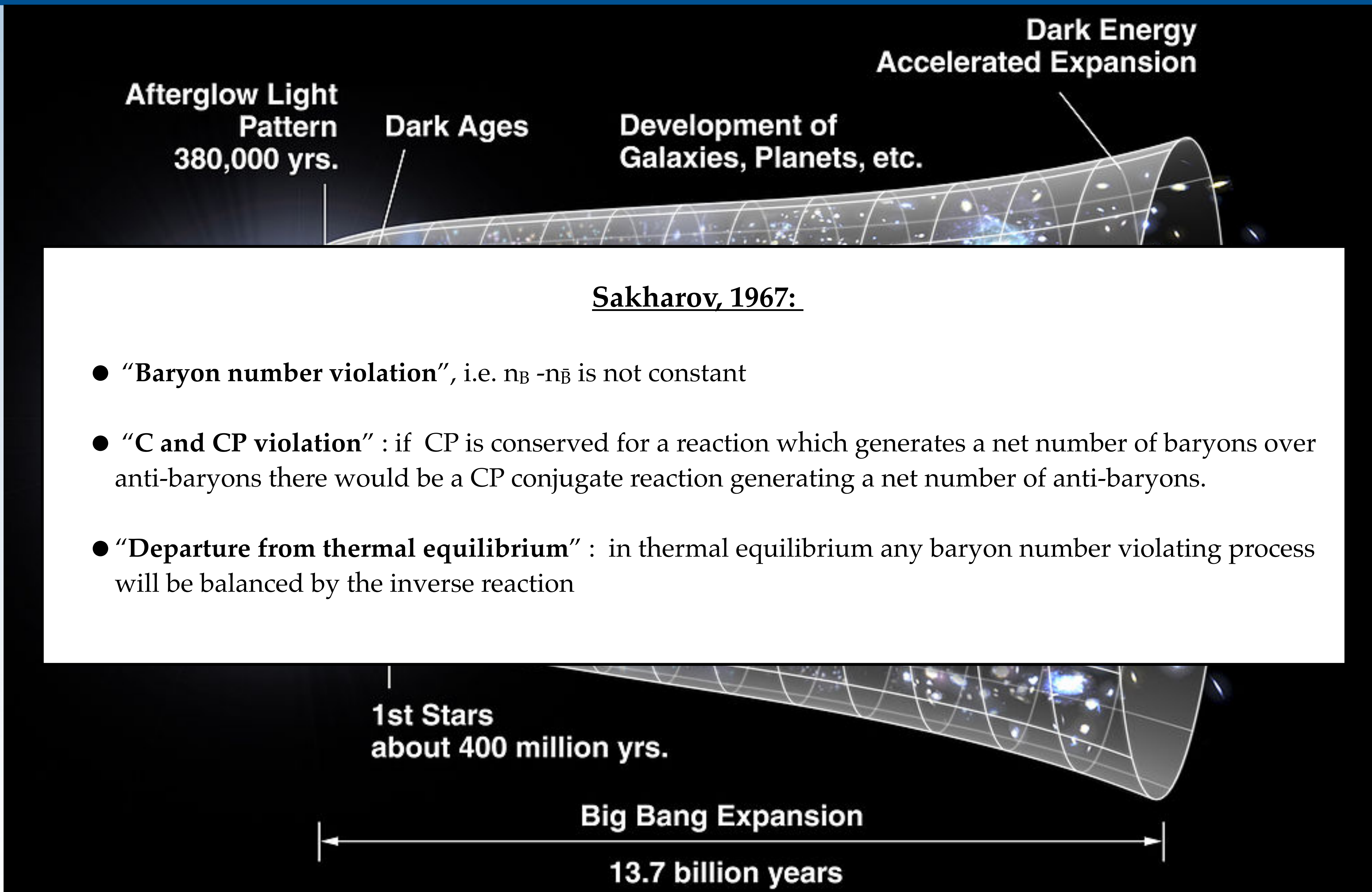


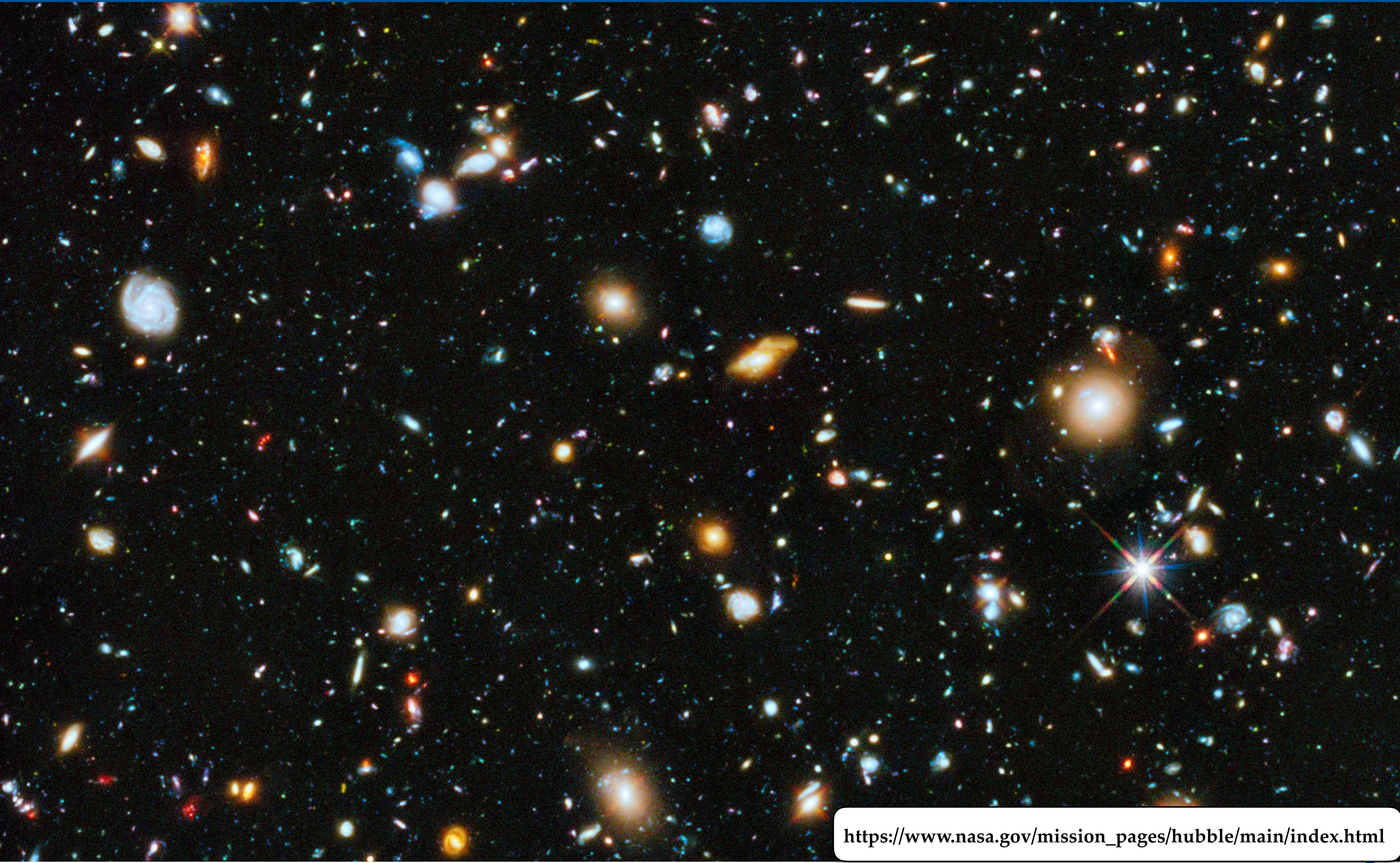
<u>Sakharov, 1967:</u>

- "**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.

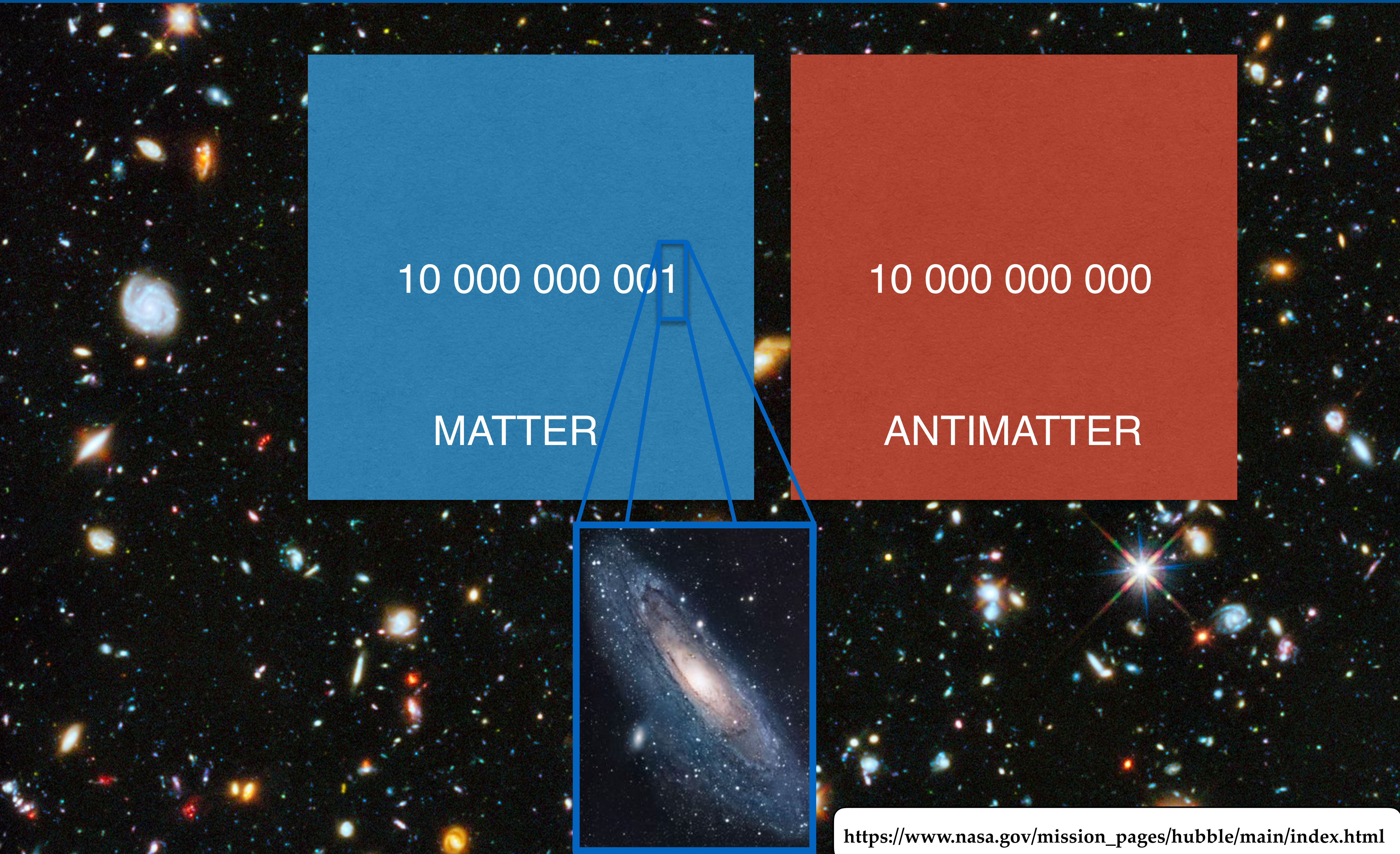
- "**Departure from thermal equilibrium**" : in thermal equilibrium any baryon number violating process will be balanced by the inverse reaction

Matter - Antimatter asymmetry



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

Matter - Antimatter asymmetry



The "BIG" questions

<u>Excerpt of the list containing the open questions in particle physics:</u>

- 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 ?
- …

Discrete Symmetries

Discrete Symmetries

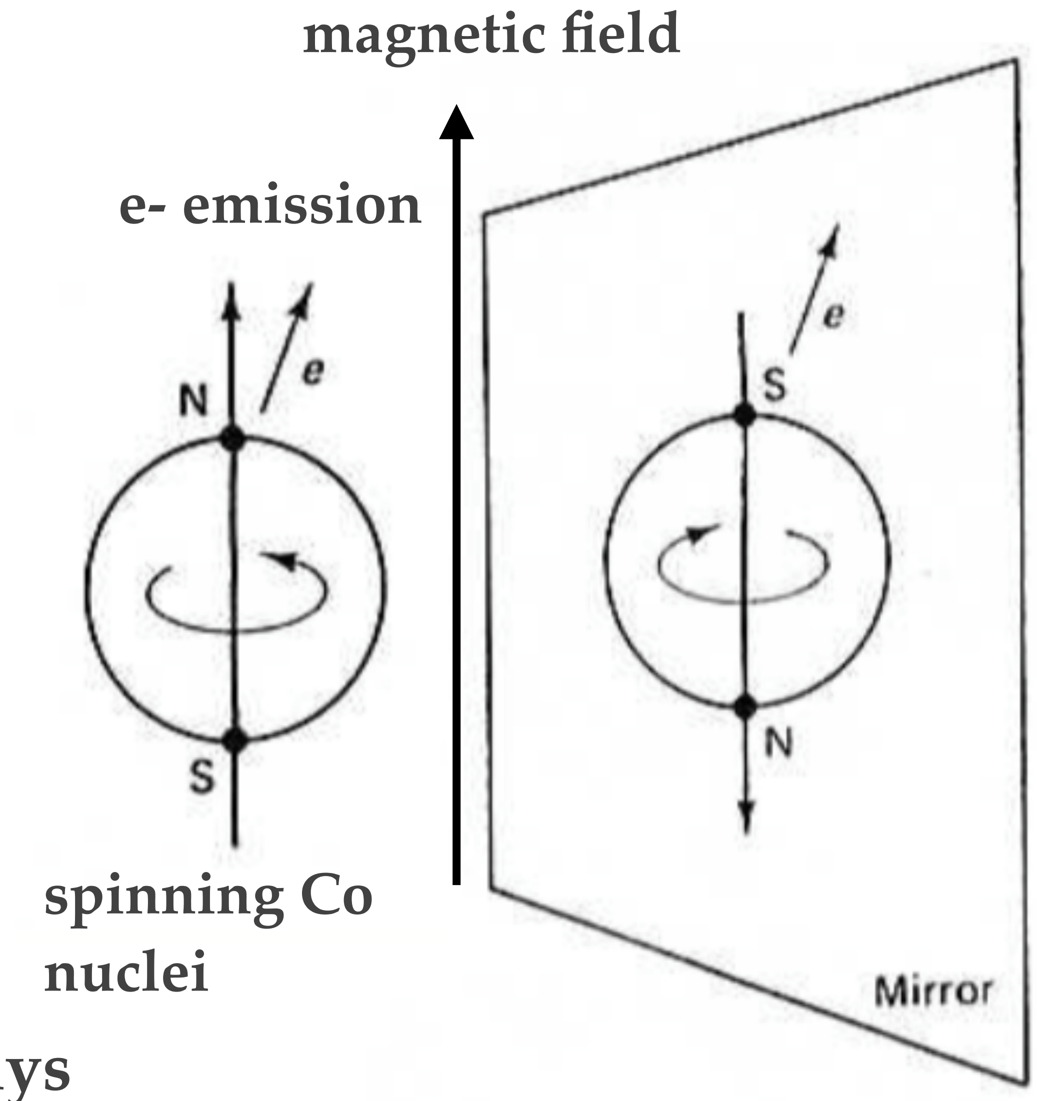
P : Parity transformation. Invert every spatial coordinates

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

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

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

Limited use because few particles are C-eigenstates

C is conserved in strong and EM interactions

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

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

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

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

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

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

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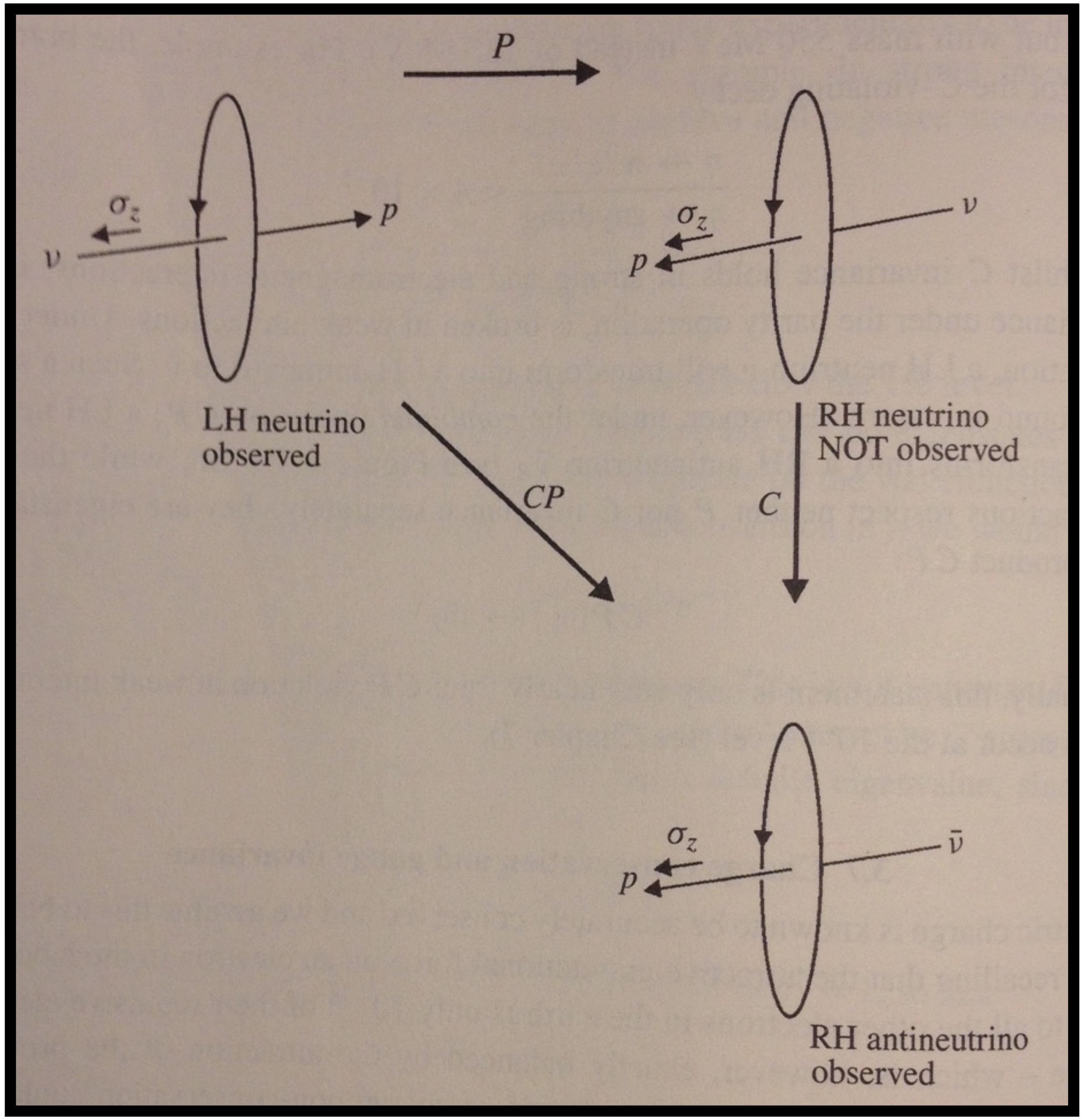

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Discrete Symmetries

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 K^0 beam

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

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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

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Interferences : observed in modulation of the 2 pion signal

Leptonic mode :

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

Discrimination criteria between matter and antimatter :

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

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

CP Violation

CP violation in the quark sector (weak interaction)

CKM matrix :

$$\begin{bmatrix} c_1 & -s_1 c_3 & -s_1 s_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta} \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & c_1 s_2 s_3 - c_2 c_3 e^{i\delta} \end{bmatrix}$$

CP-violating phase

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CP-violating phase

CP violation in the strong sector: $\theta_{QCD} \neq 0$?

CP Violation

CP violation in the quark sector (weak interaction)

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CP-violating phase

CP violation in the strong sector: $\theta_{QCD} \neq 0$?

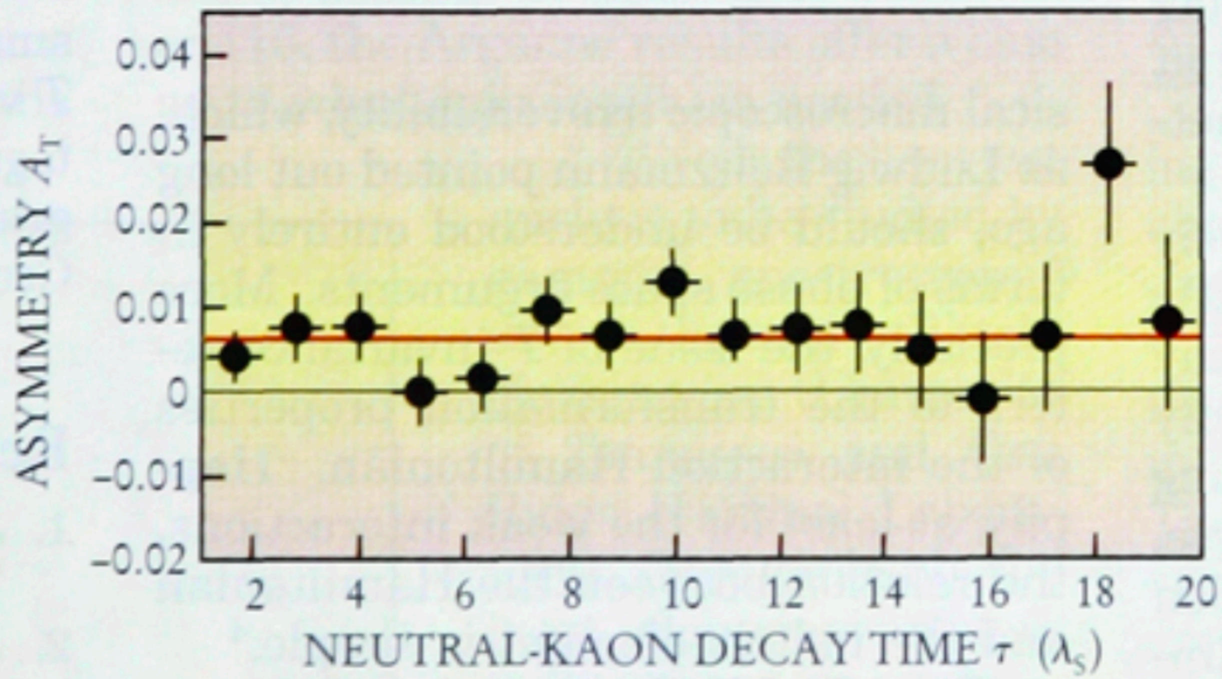
CP violation in the lepton sector : PMNS matrix → Leptogenesis

$$\begin{bmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta_{CP}} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta_{CP}} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta_{CP}} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta_{CP}} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta_{CP}} & c_{23} c_{13} \end{bmatrix}$$

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

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

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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 :

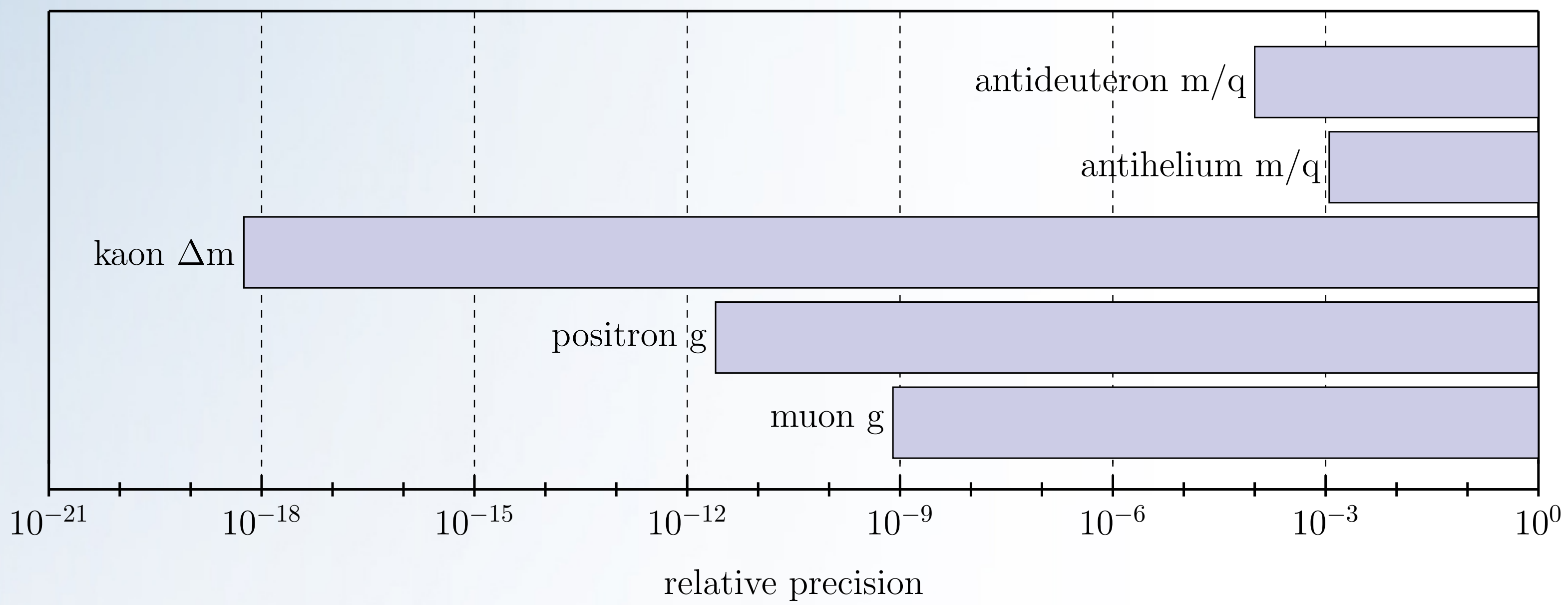
A local, Lorenz invariant theory with canonical spin-statistics relation must be invariant with respect to CPT-transformation

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

Non-exhaustive list of **C**harge - **P**arity - **T**ime symmetry test



Tests of CPT Symmetry

Comparison of fundamental properties of simple baryonic and anti-baryonic systems at **low energy** and with **high precision**

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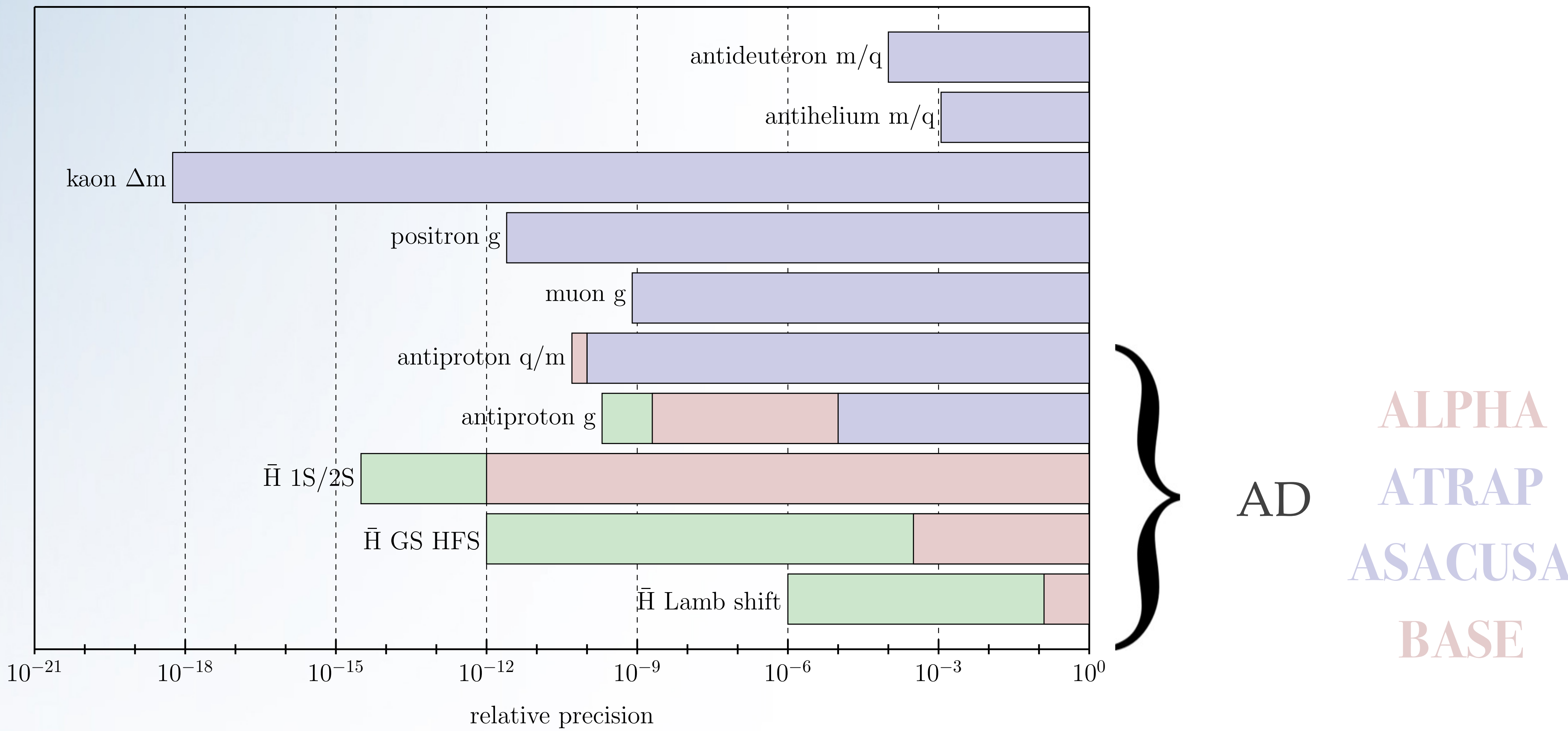

Precision reached on **hydrogen** and **proton**
Experimental knowledge prior 2015
Measurements (2015-2020)

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Comparison of fundamental properties of simple baryonic and anti-baryonic systems at **low energy** and with **high precision**

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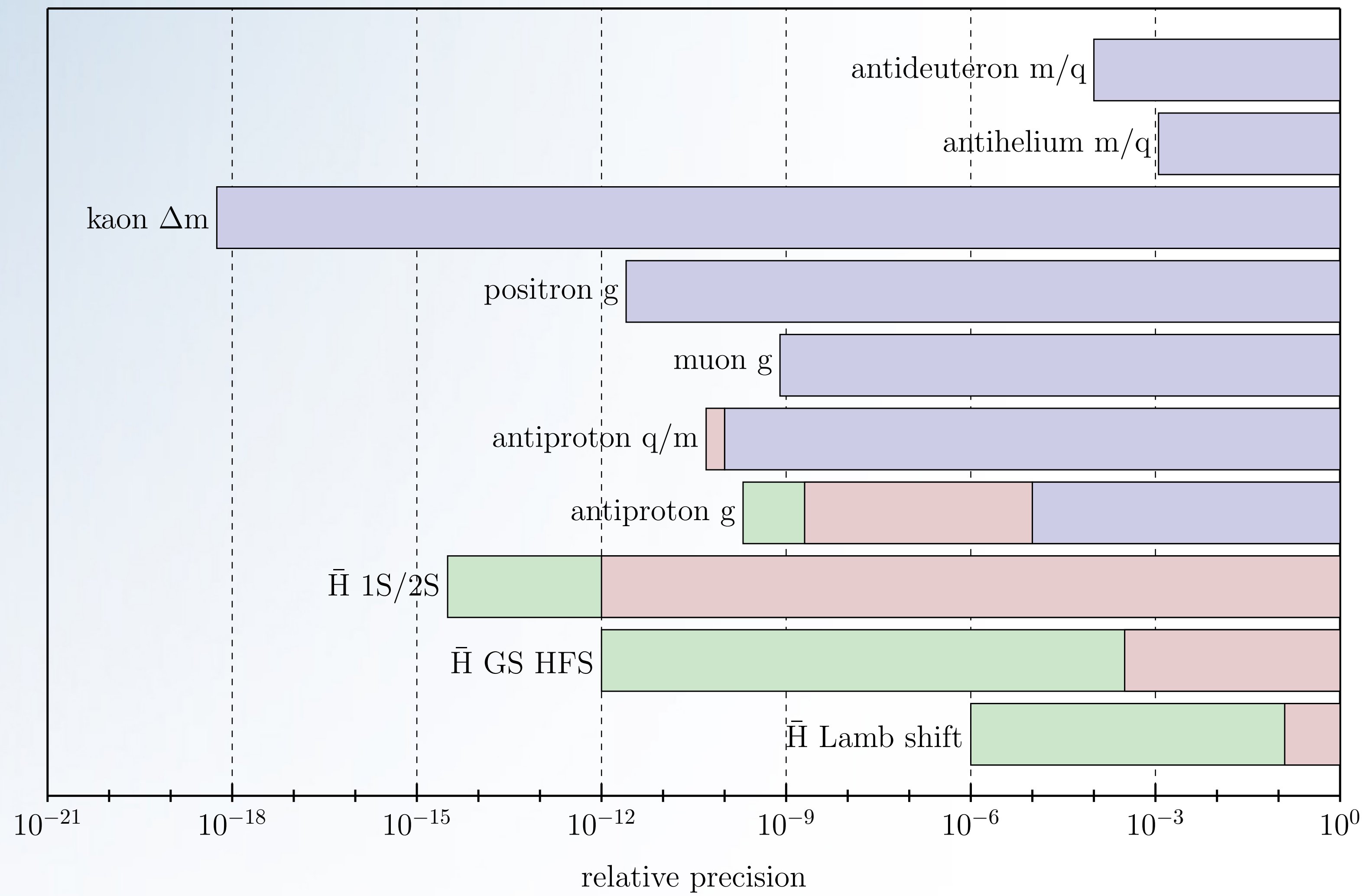


	relative precision	energy resolution [ev]
Kaon	~10[-18]	~10[-9]
p̄ Q/M	~10[-10]	~10[-18]
H̄ 1S-2S	~10[-12]	~10[-11]
H̄ GS-HFS	~10[-4]	~10[-10]

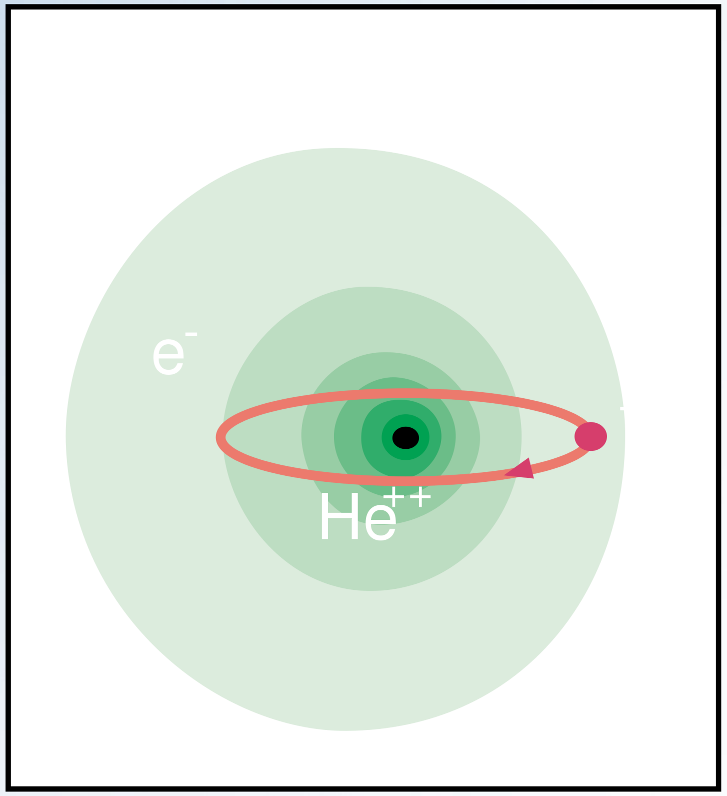
AD: ALPHA, ATRAP, ASACUSA, BASE

Precision reached on **hydrogen** and **proton**
Experimental knowledge prior 2015
Measurements (2015-2020)

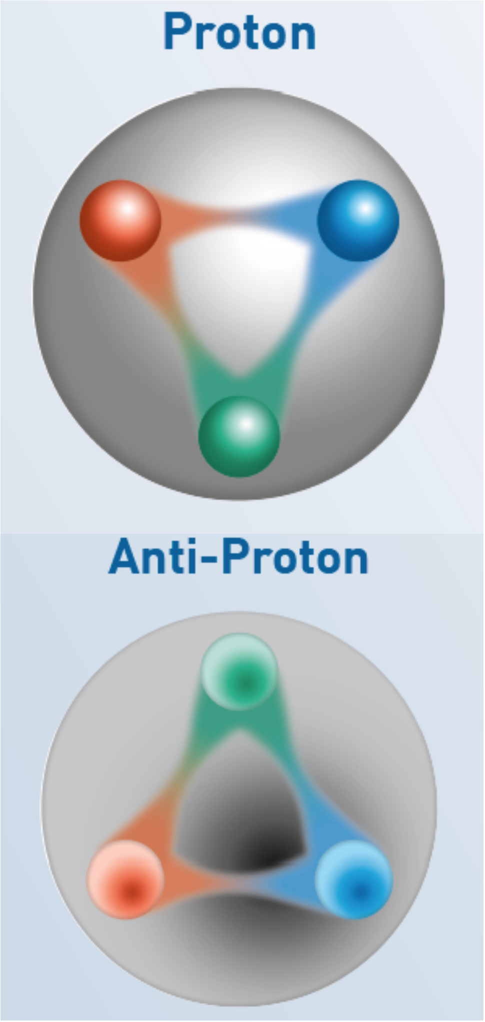
Standard Model Extension

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

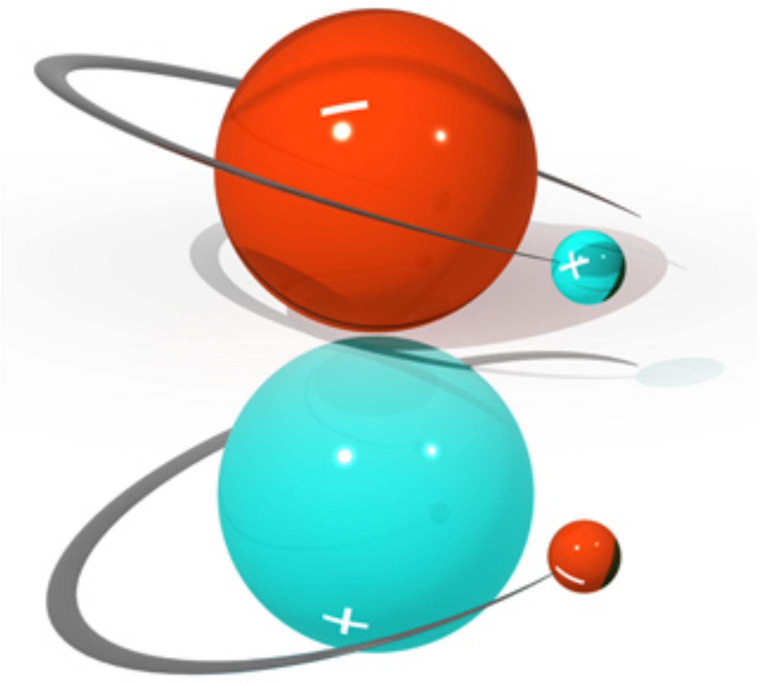
Antimatter experiments at the AD



ASACUSA



BASE
ASACUSA
(ATRAP)



ALPHA
(ATRAP)
ASACUSA
AEGIS
GBAR

Production of antimatter

The case of antiprotons

$$p + p \rightarrow \boxed{\bar{p} + p} + p + p$$

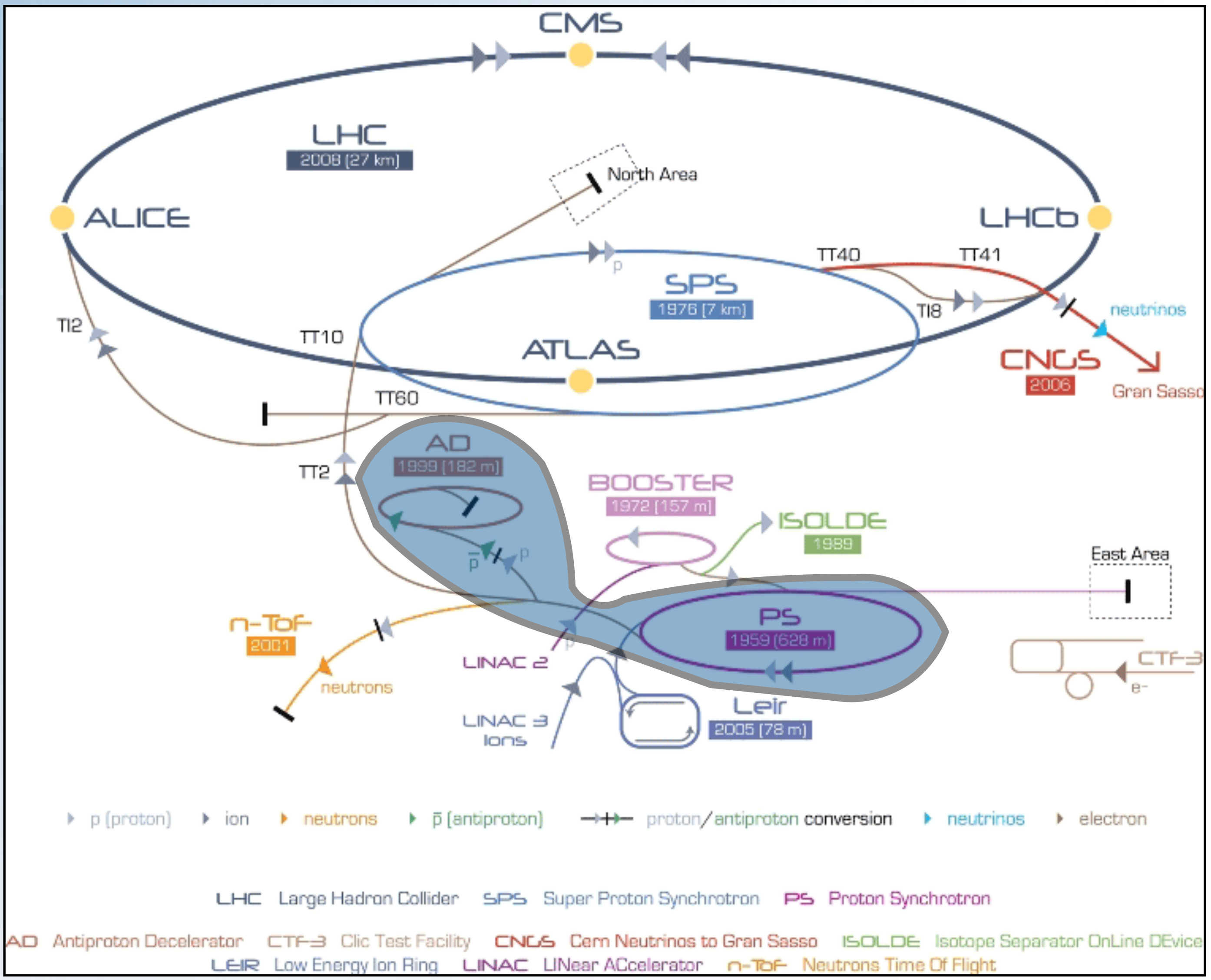
$$\boxed{\sqrt{s} = \sqrt{2m_p^2 + 2E_p m_p}}$$

Pair production : Threshold energy at 5.6 GeV

Bevatron was right at threshold when producing the first antiprotons !

Need higher proton energies to produce more antiprotons

Production of antiprotons



Production at 26 GeV/c

Maximum production at 3.7 GeV/c
(~ collection momentum)
Sharp fall-off around the peak

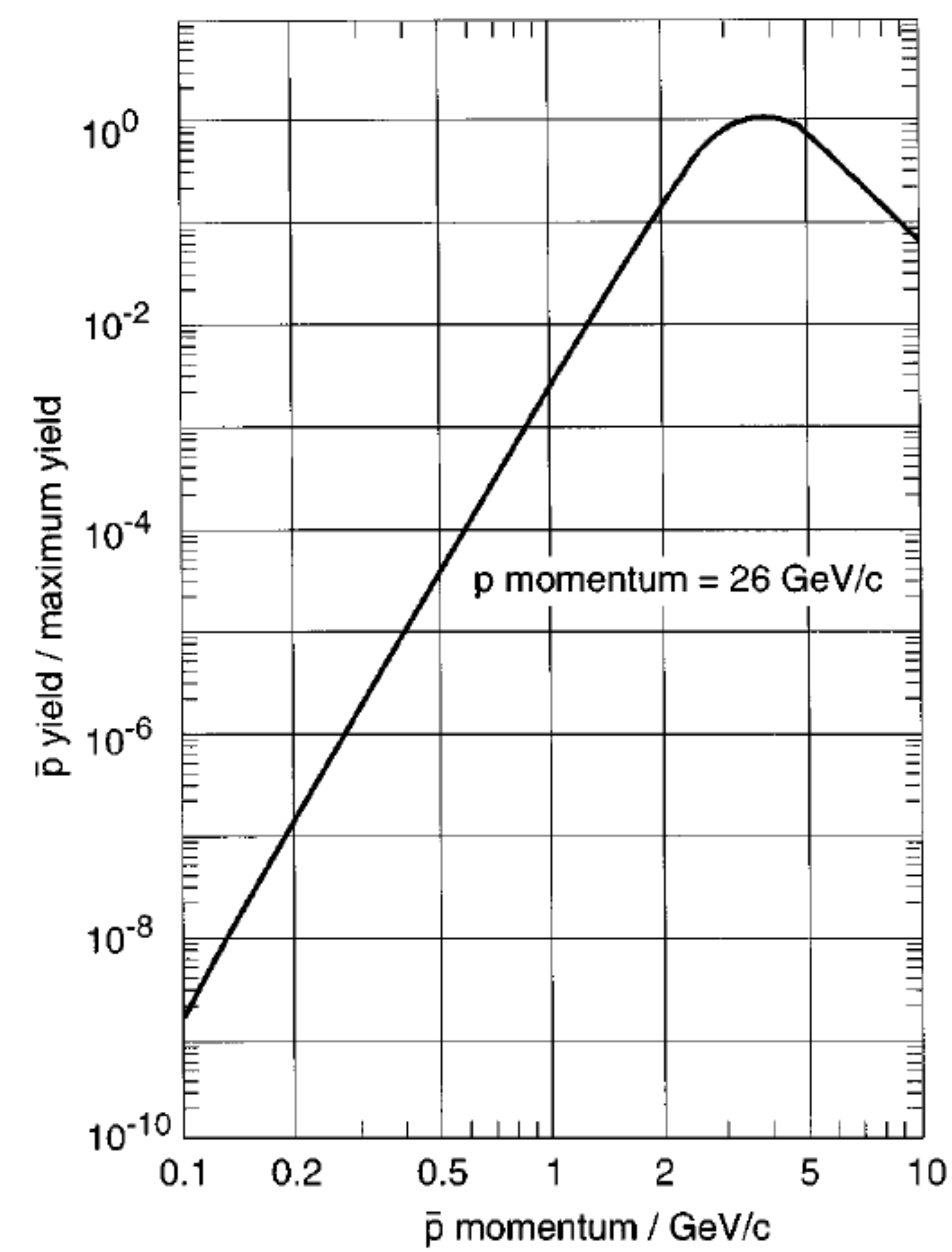


FIG. 1. Normalized antiproton yield (antiprotons per proton) at 26 GeV/c proton-beam momentum. The normalization is chosen so that the yield is one at the maximum.

Antiproton cooling

$(E_k)_{\bar{p}}$ **~3 GeV** must be reduced by ~10^6 before $\bar{p}$ can be caught in Penning traps

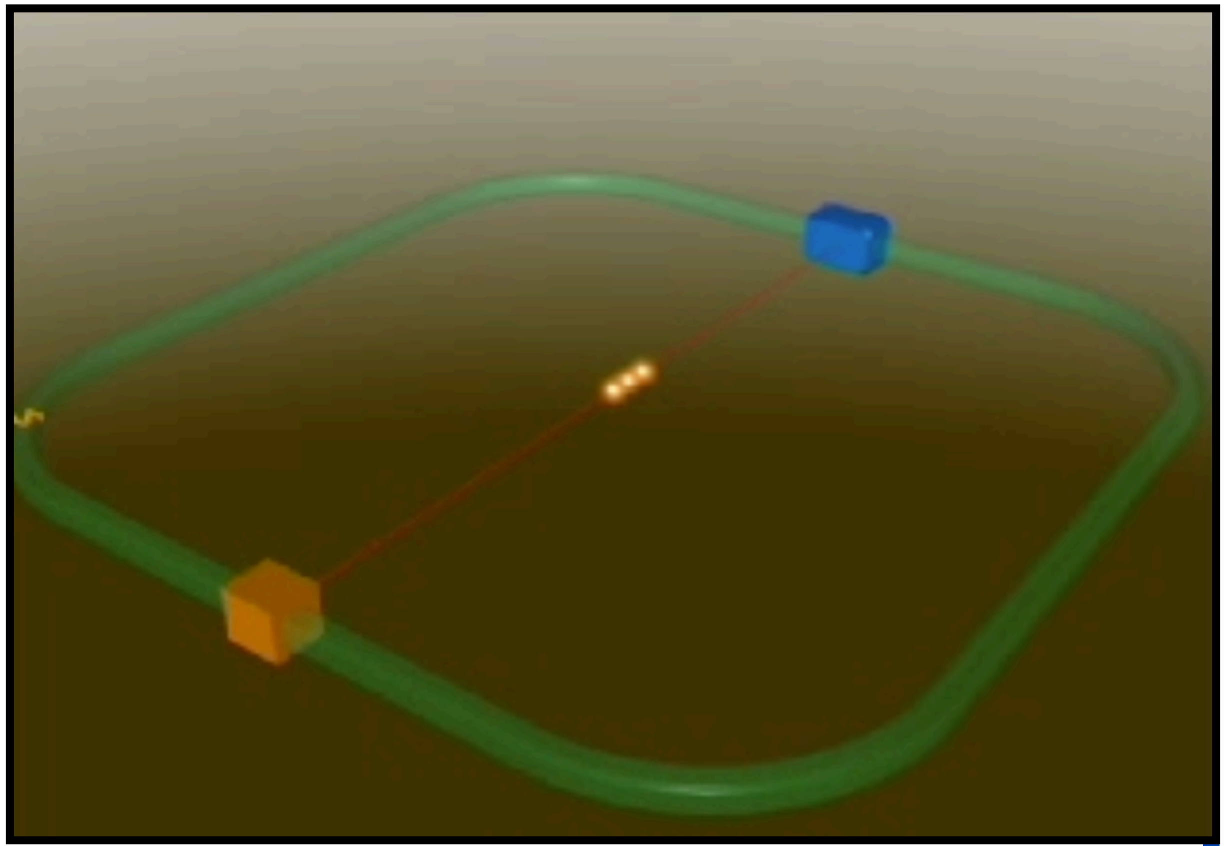
AD : RF cavity deceleration, stochastic and electron cooling

3.5 GeV/c -> 100 MeV/c ($(E_k)_{\bar{p}}$ =5.3 MeV)

Cooling : reduce phase space and increase phase-space density

$$D = \frac{N}{\sqrt{E_h E_v L \frac{\Delta p}{p}}}$$

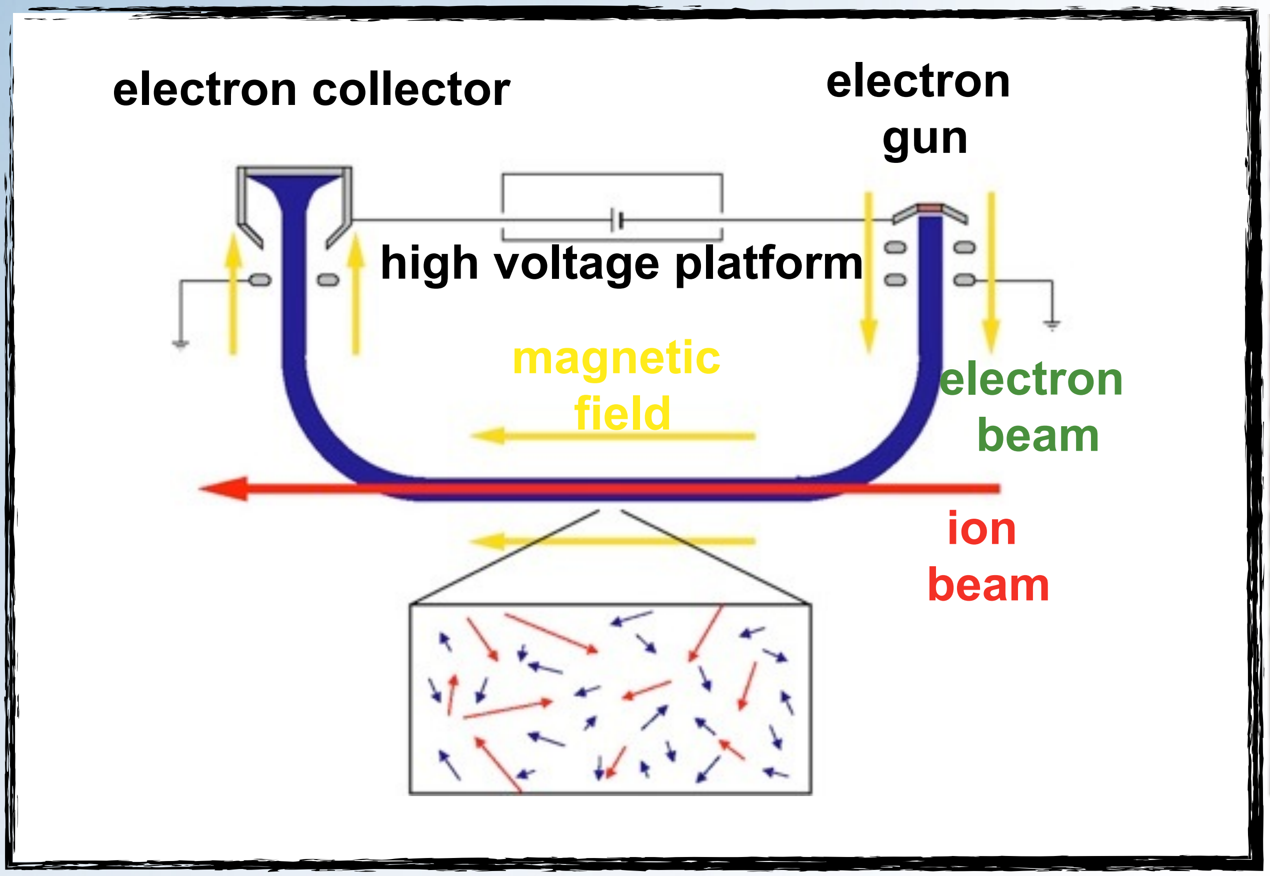
E_h, E_v: horizontal, vertical emittances
L: longitudinal spread
N: number of particles
$\Delta p/p$: momentum spread

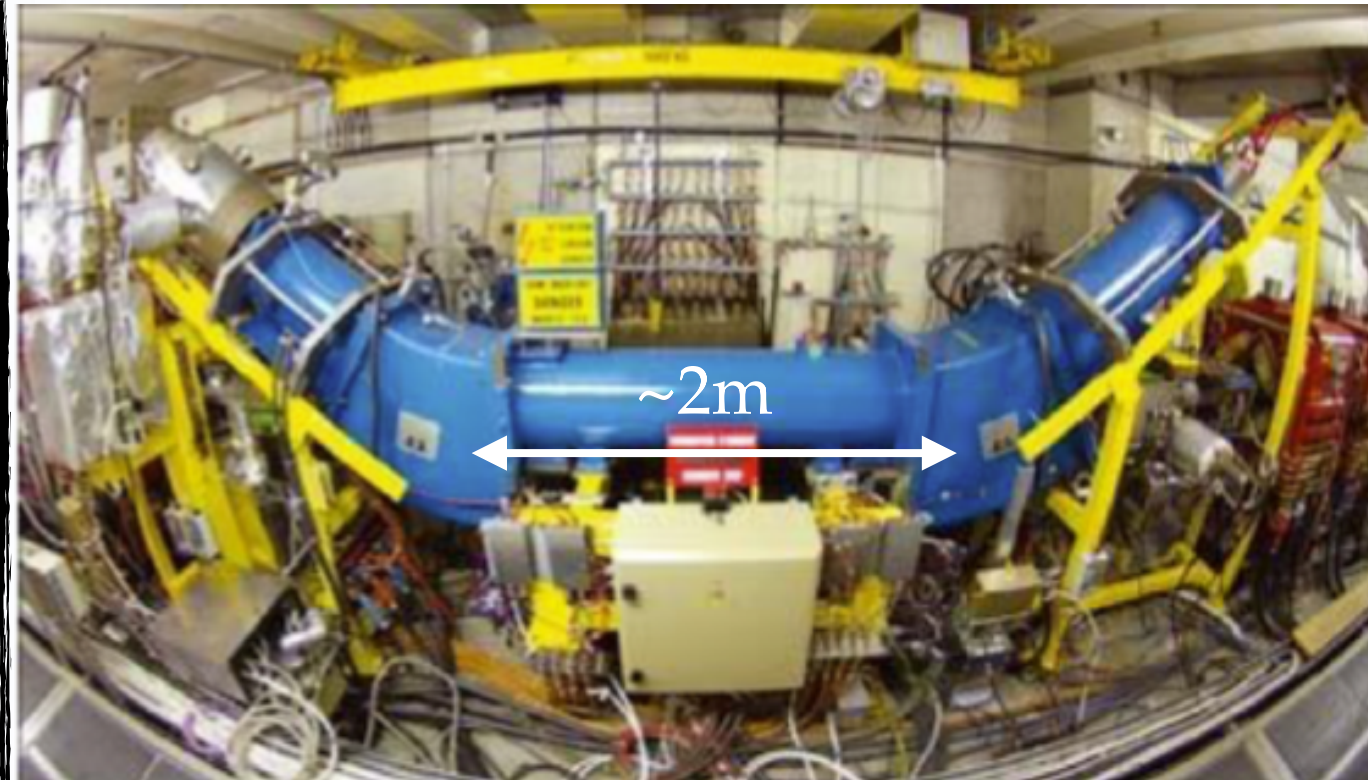


Cooling methods :

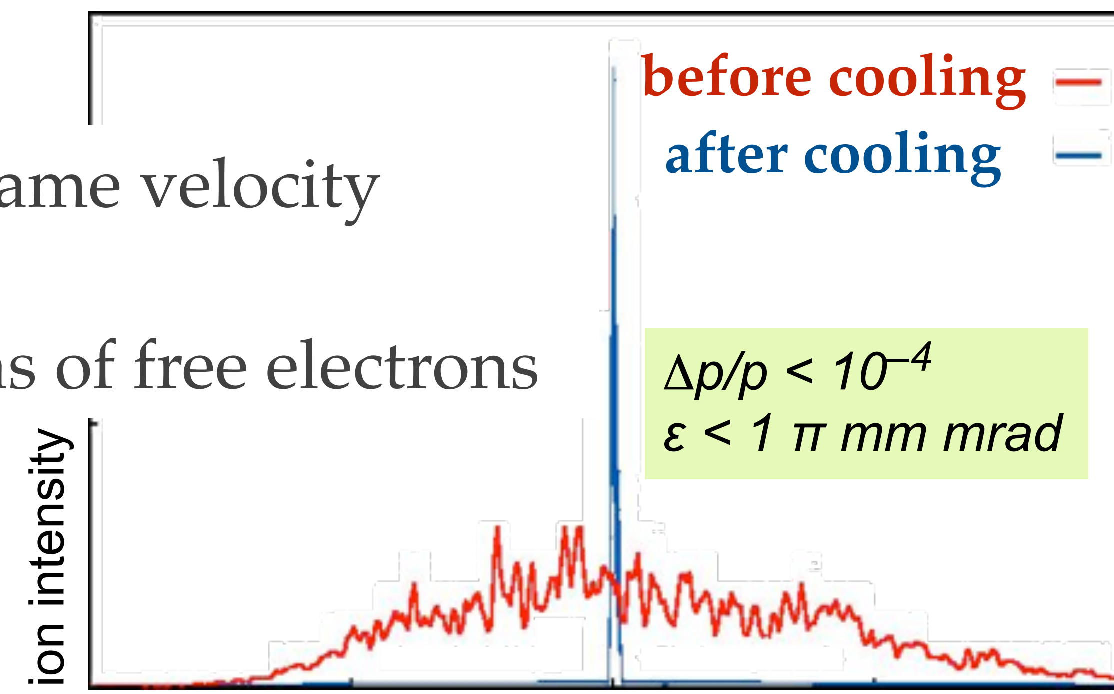
- **Stochastic cooling**
- **Electron cooling**

Electron cooling





- Superposition of cold intense e- beam with p̄ at same velocity
- Momentum transfer by Coulomb collisions
- Cooling results from energy loss in co-moving gas of free electrons



At the AD for the 300 MeV/c plateau, a 25mm radius e⁻ beam of ~3A merge with the p̄

Stochastic cooling

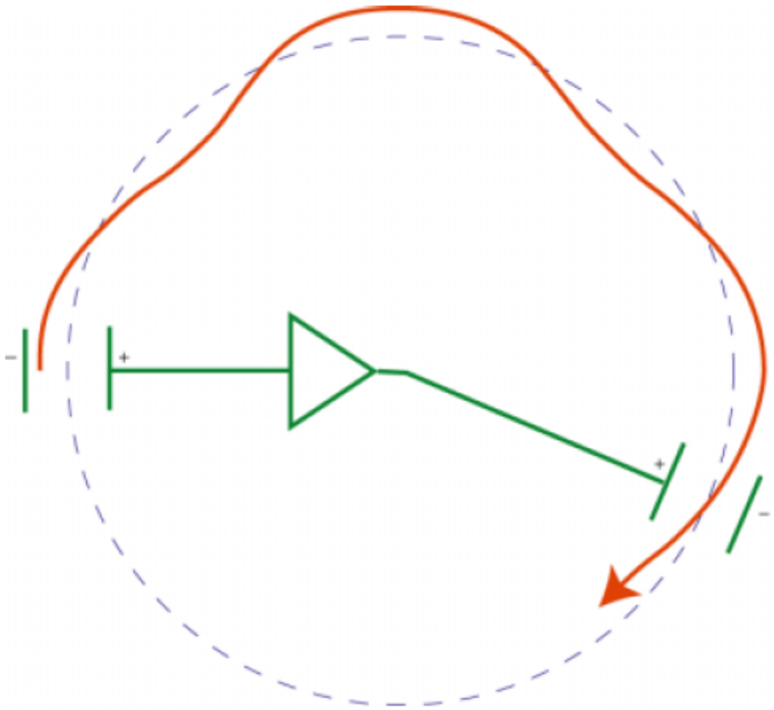
Measure beam center by pick-ups
Correction signal to opposite kicker

Pioneered at CERN for discovery
W,Z bosons

Nobel Prize S. van der Meer

Cooling power decreases with
decreasing energy

Cooling time ~ number of particles

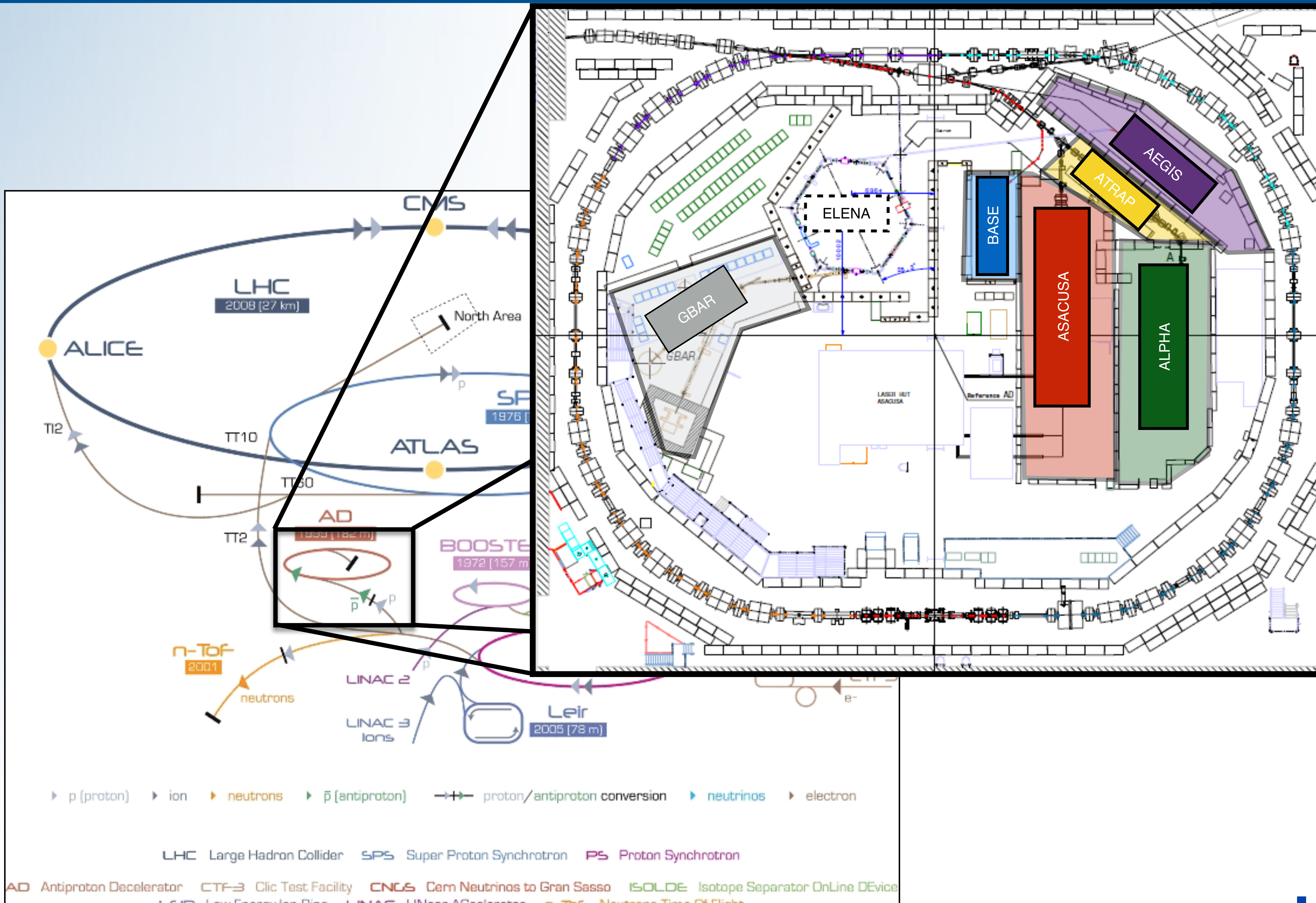


Repeated steps:

$\Delta p/p$ ~0.07% from initially ~1.5%
Emittance ~3 πmm.mrad from initially ~ 200 πmm.mrad

LEAR

The AD facility

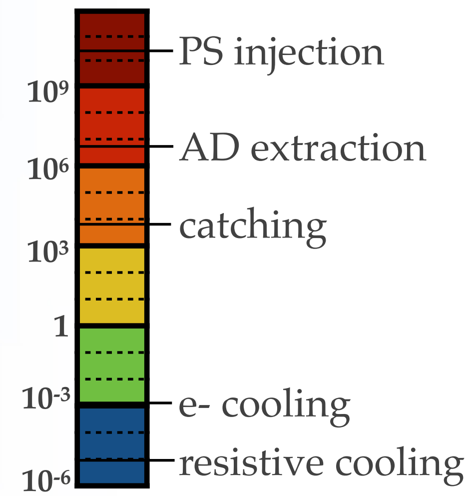


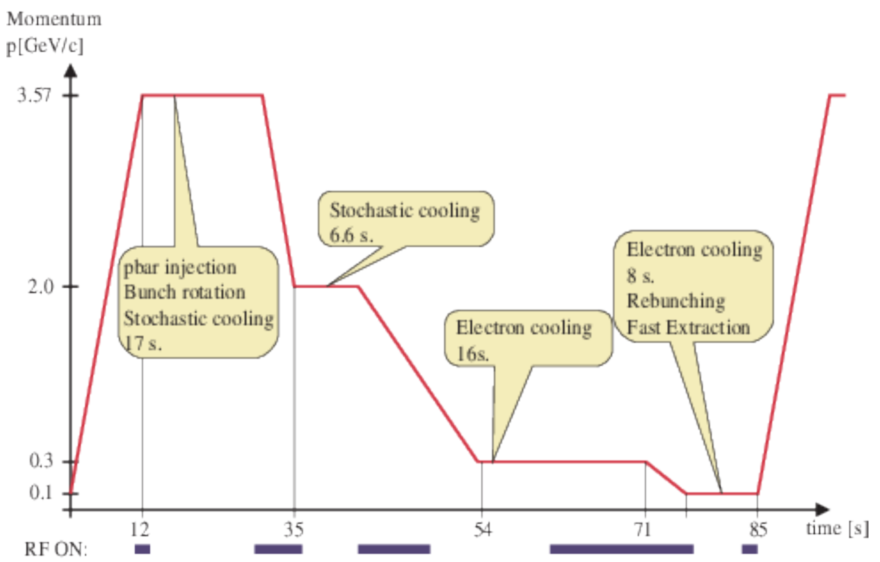
The AD facility

AD

PS : 26 GeV/c proton on target
3x10⁷ p̄ at 5.3 MeV (100 MeV/c) ~120s cycle

p̄ caught in Penning traps: 99.9% are lost





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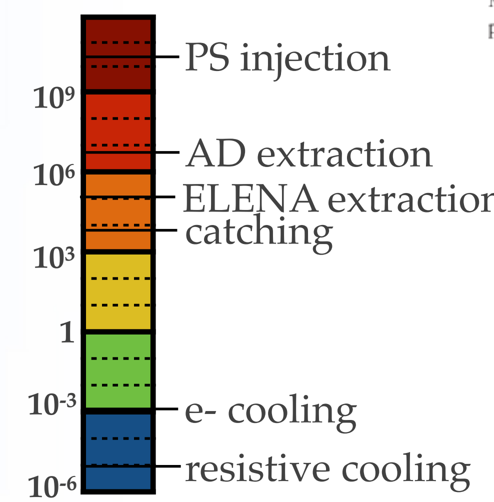
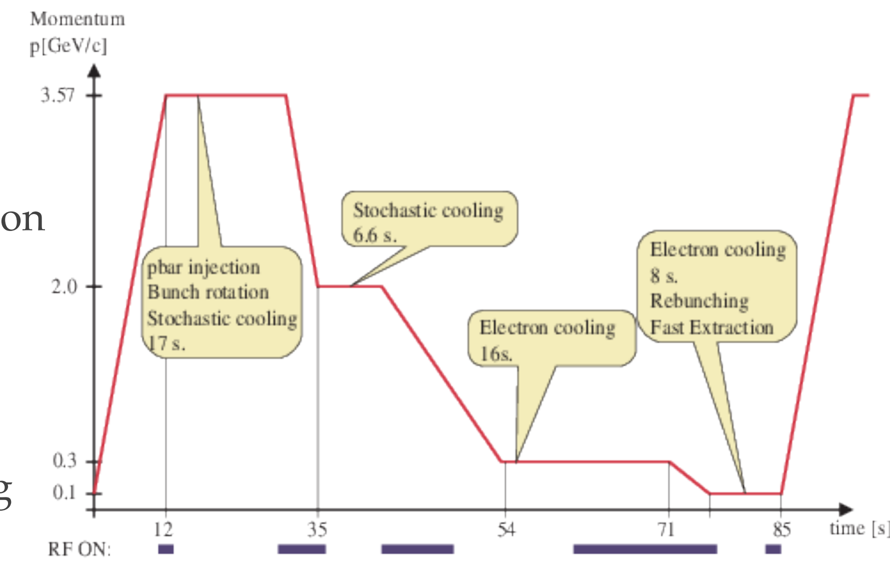




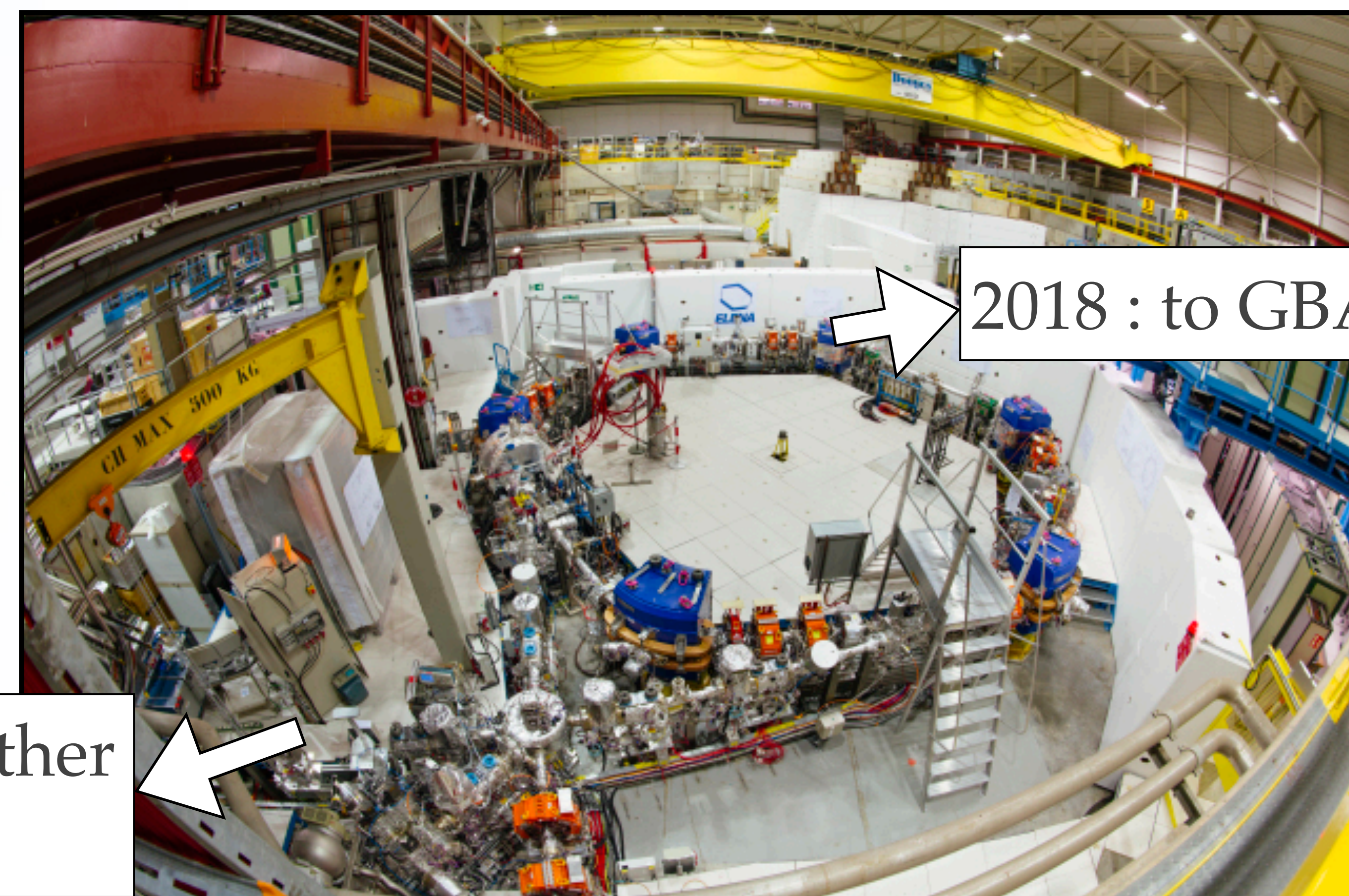
ELENA

$\bar{p}$ at 100 keV at improved beam emittance

all experiments gain a factor 10-100 in trapping efficiency

"simultaneous" delivery to almost all experiments

additional experimental zone



2018 : to GBAR

2021: to all other experiments

Production of antimatter

The case of positron

Two ways to get positrons at the AD:

- $\beta+$ emitter
  $^{22}Na \rightarrow ^{22}Ne^* + e^+ + \nu_e$
  $^{22}Ne^* \rightarrow ^{22}Ne + \gamma$ (1.274 MeV)

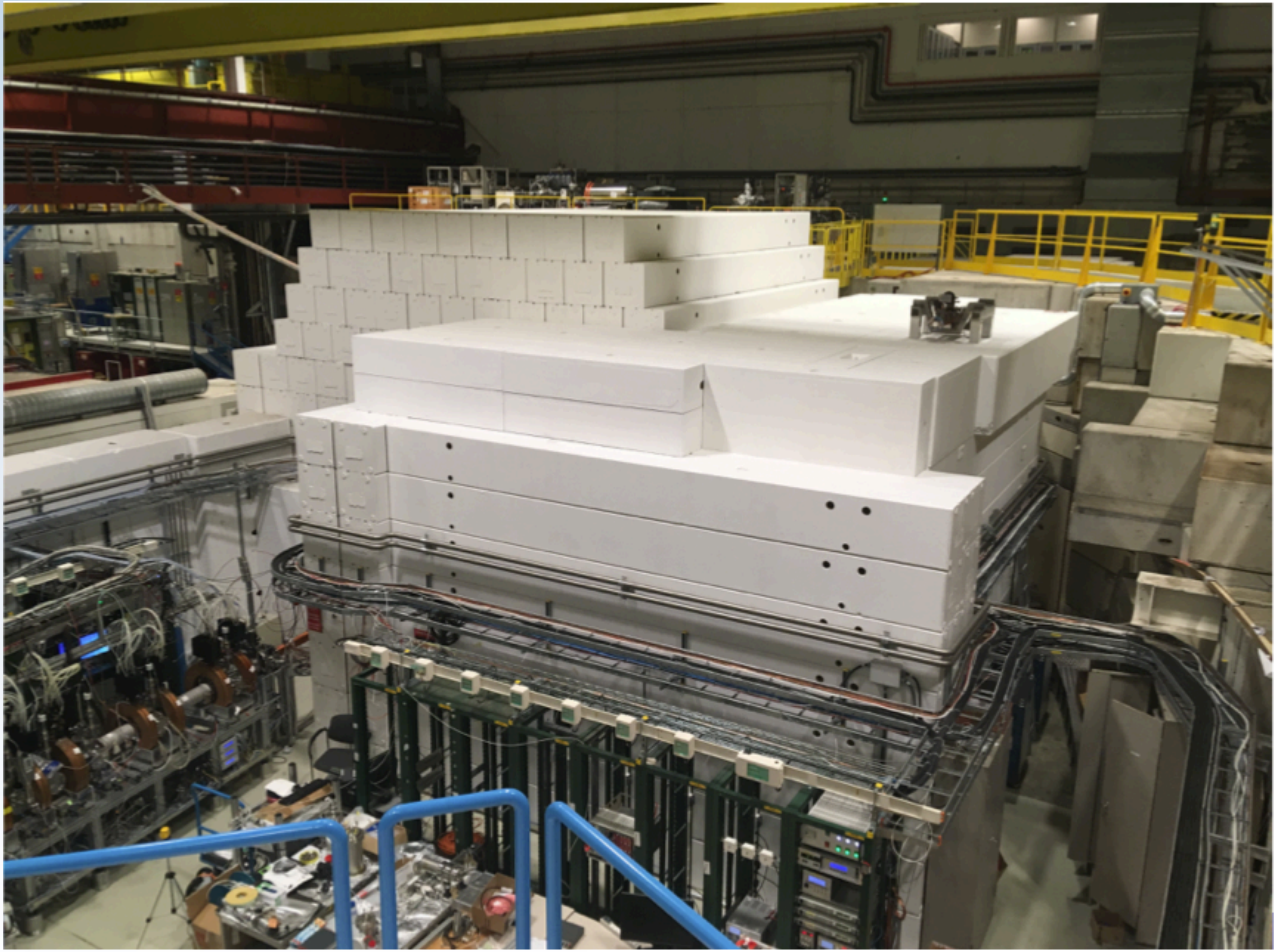
Strong $\beta+$ source (~GBq~27mCi) combined with efficient moderator (solid Ne; efficiency ~5×10^{-3})
Beam of a ~10^6 e^+/s

- compact electron linac: pair production
  $\gamma + \text{nucleus} \rightarrow e^+ + e^- + \text{nucleus}$

  The γ originate from electrons giving of Bremsstrahlung in a tungsten target

Beam of a ~10^8 e^+/s

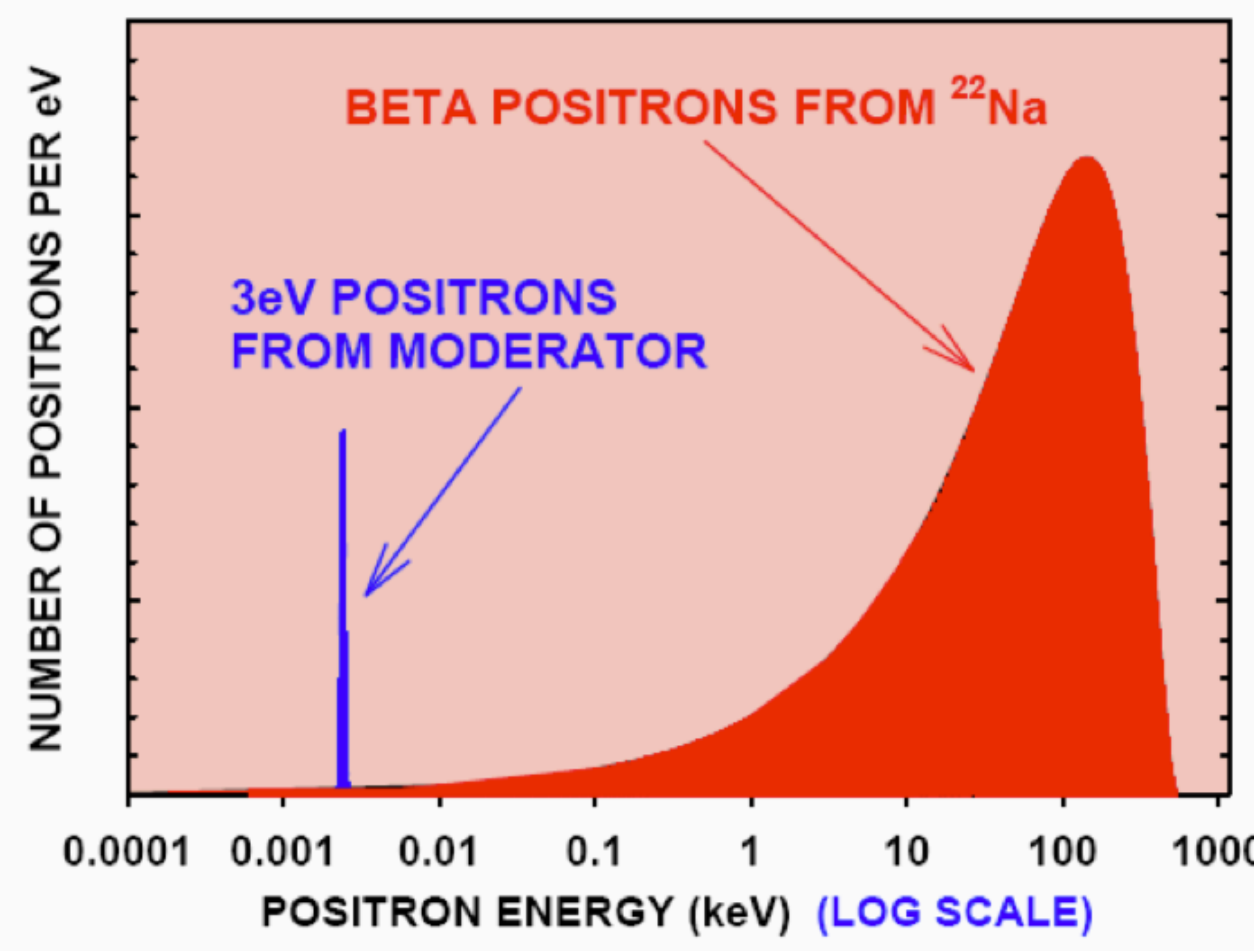
Production of positrons



Positron moderation

- Solid rare gas: e.g. Neon
  - Positrons are thermalized by electron-hole excitation until their energy is lower then the bandgap. Thereafter they can only loose energy via the production of acoustic phonons (slow process).
  - Rare gases have positive work functions for positrons
  - The moderated energy distribution ~ 2 eV.
  - Max efficiency ~ 10^{-2}

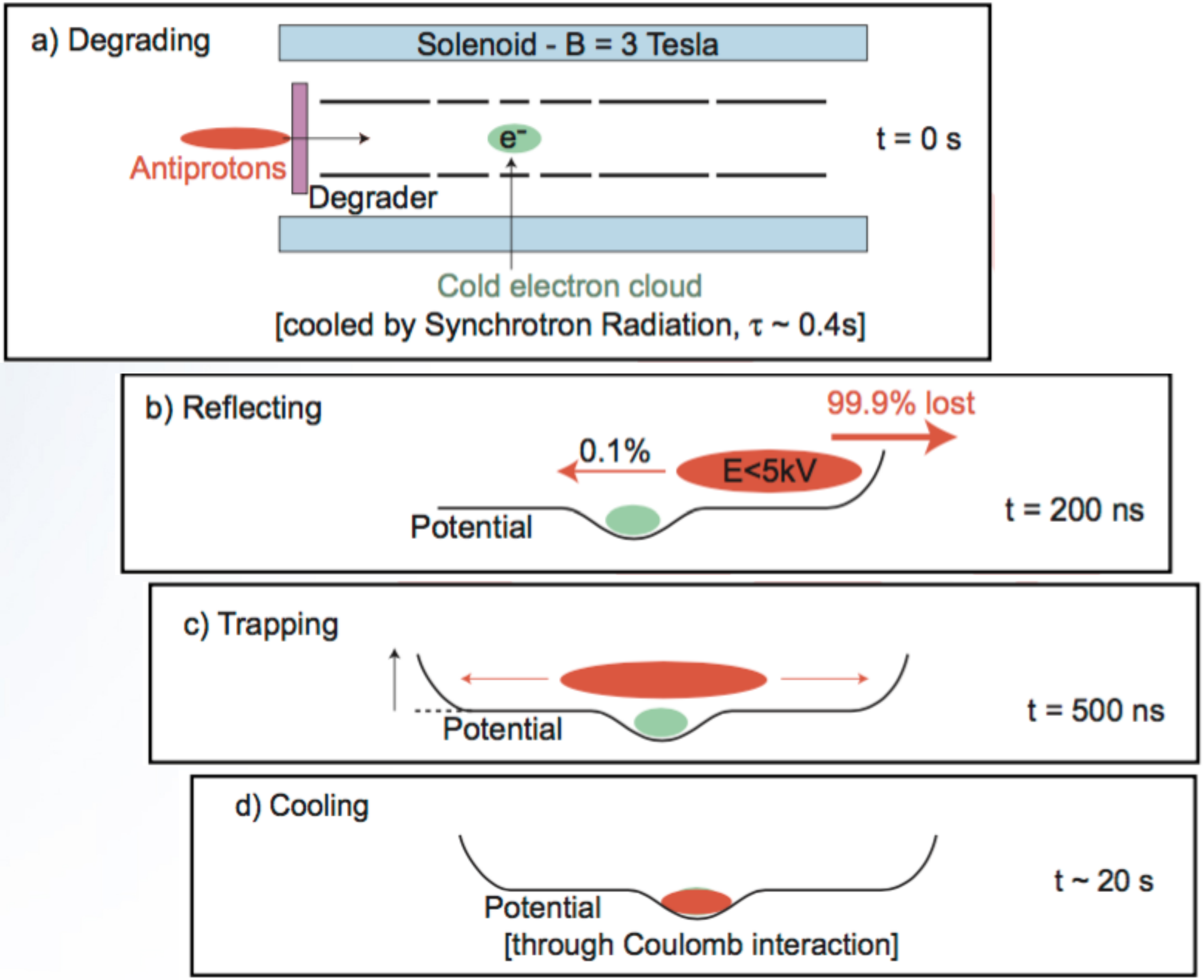
- Metal: e.g.Tungsten
  - Positrons are thermalized by inelastic collisions with electrons and then diffuse to the surface.
  - Subsequently they are ejected due to the negative work function of the positron in tungsten.
  - The moderated positrons have a narrow energy distribution.
  - Max efficiency ~ 10^{-3}



Moderation followed by buffer-gas accumulation, stacking (with RW)

Penning traps

Long trapping times require
good vacuum!

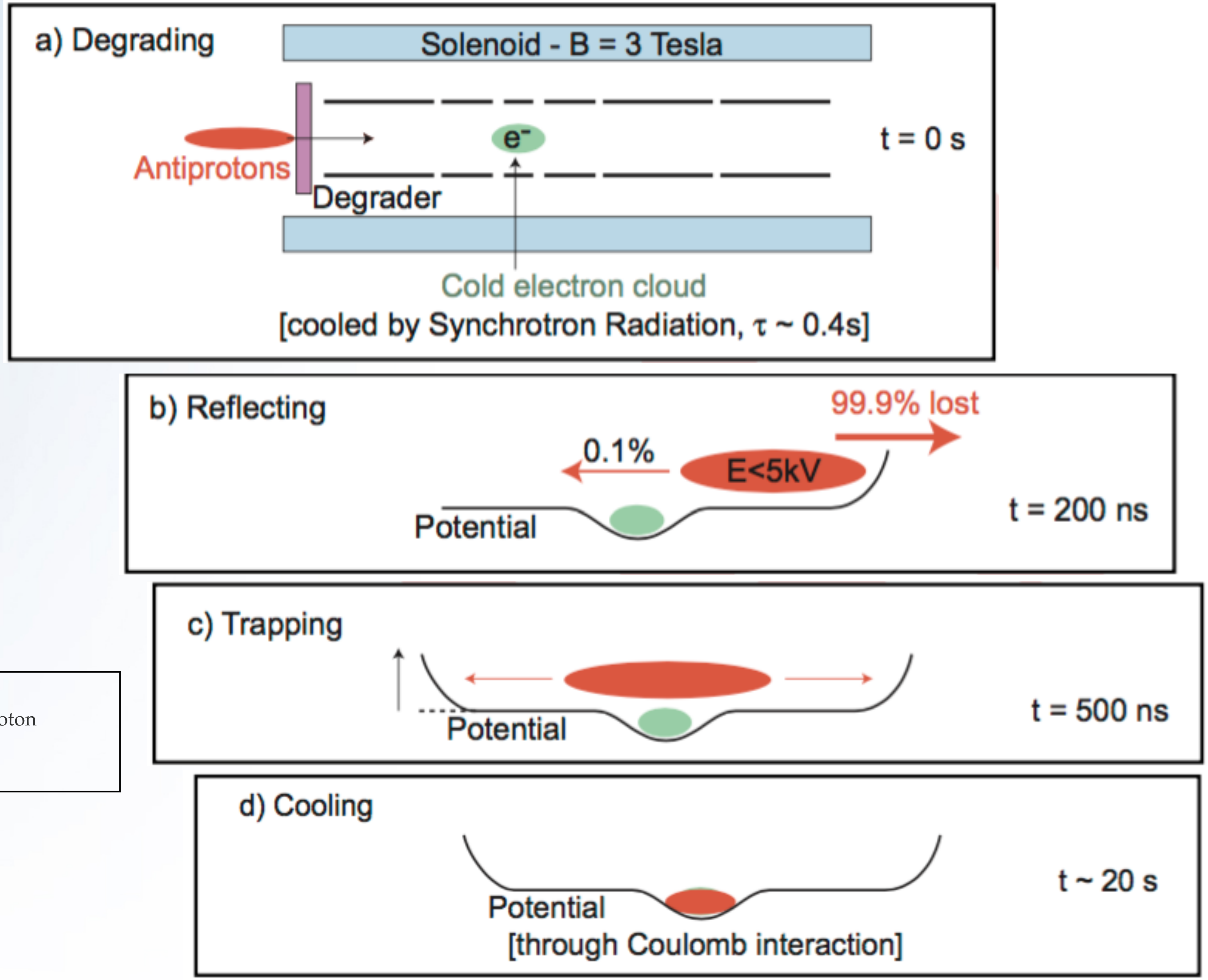


Penning traps

Long trapping times require
good vacuum!

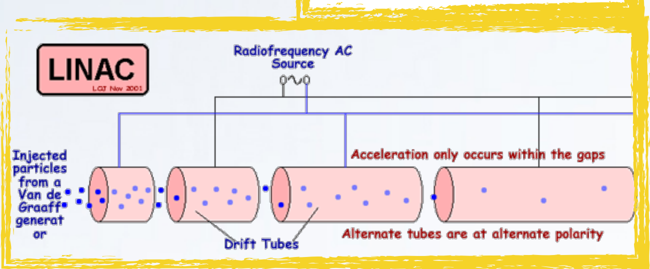
BASE : **P < 2. 10^{-18} mbar**
$\boldsymbol{\tau(\bar{p})}$ **> 10.2 years** (68% confidence level)

Stefan Sellner et al.
"Improved limit on the directly measured antiproton lifetime"
New Journal of Physics, 19, (2017)



Antihydrogen formation

$\bar{p}$



e^+

Antihydrogen formation

$\bar{p}$

$$\bar{p} + e^+ \rightarrow \bar{H} + \gamma$$

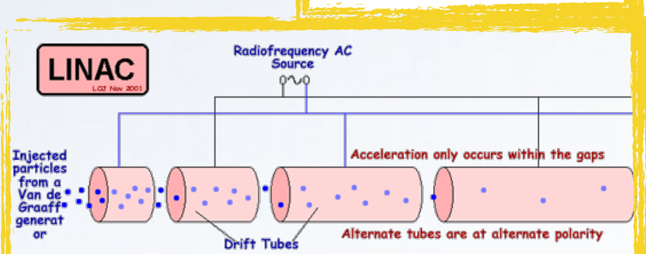
$$\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$$

ASACUSA

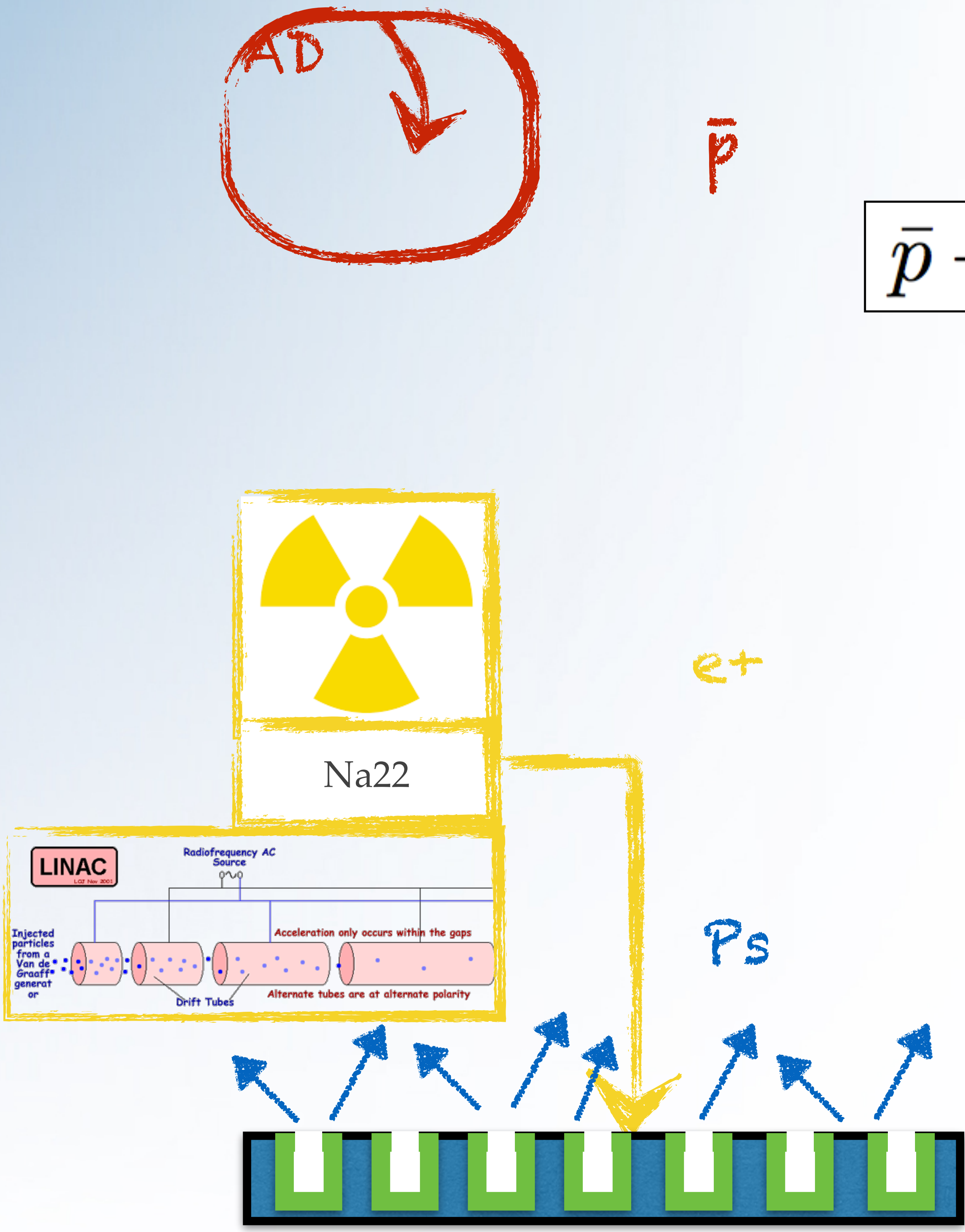
ALPHA

ATRAP

e^+



Antihydrogen formation



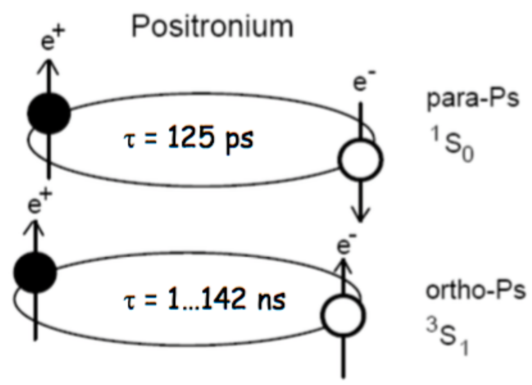
$$\bar{p} + e^+ \rightarrow \bar{H} + \gamma$$

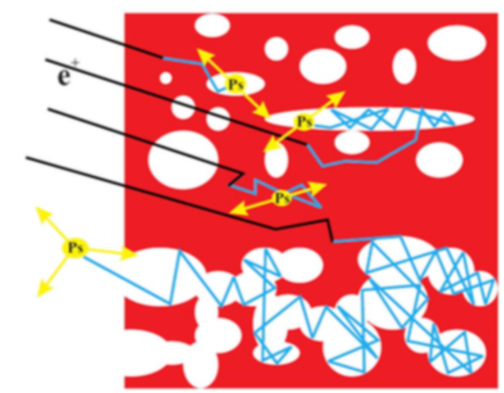
$$\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$$

ASACUSA

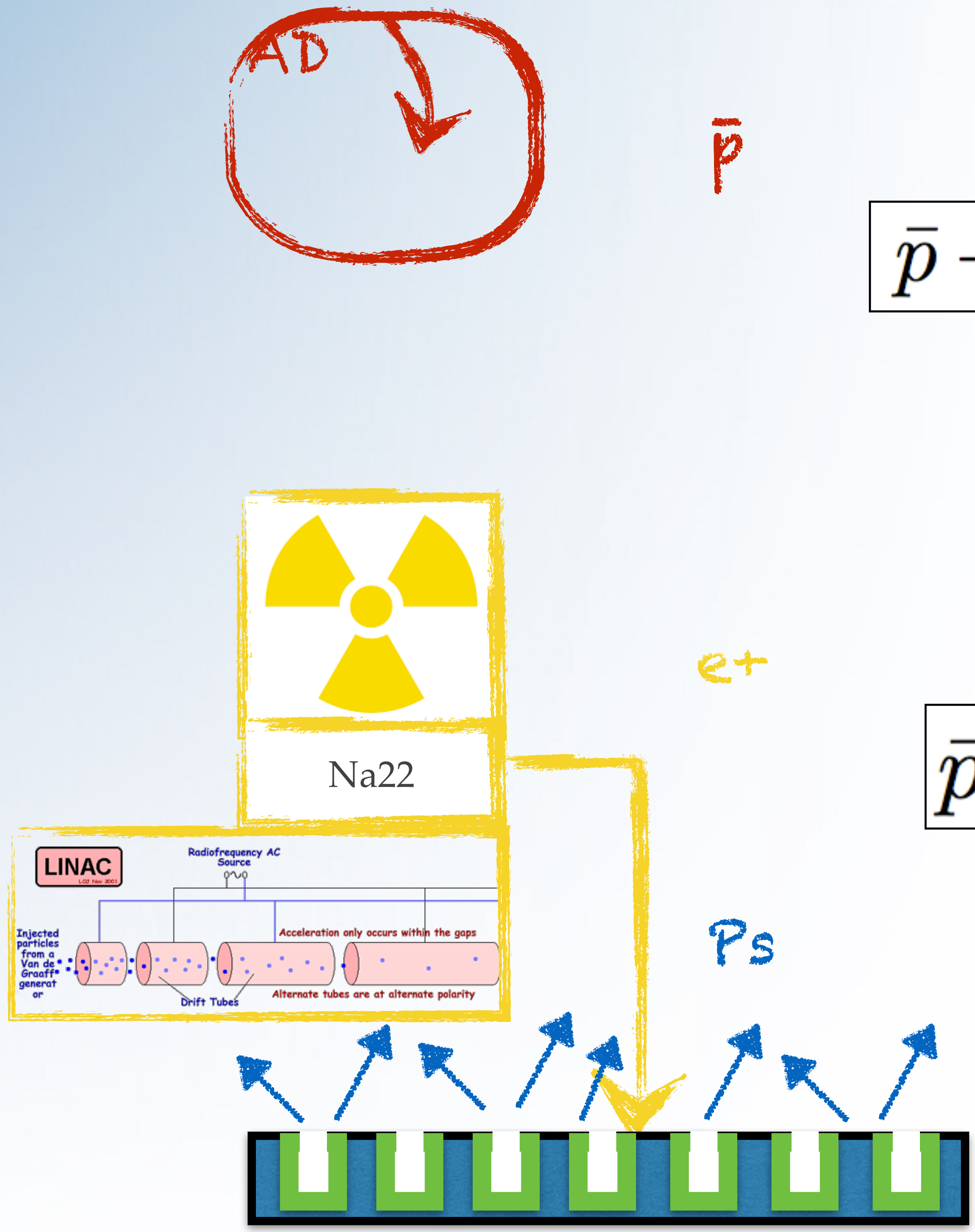
ALPHA

ATRAP





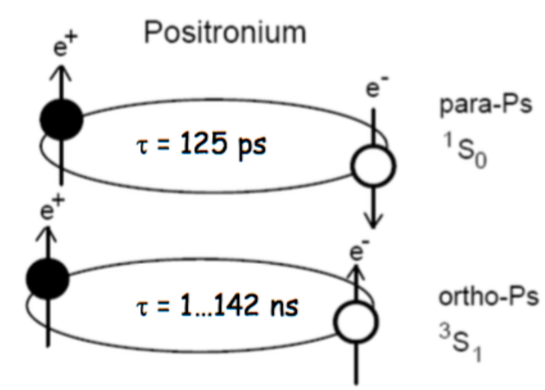
Antihydrogen formation

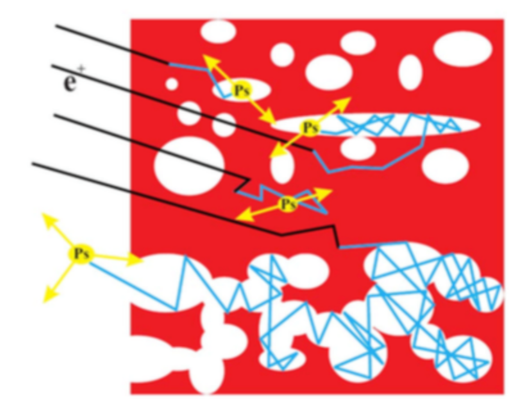


$$\bar{p} + e^+ \rightarrow \bar{H} + \gamma$$

$$\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$$

ASACUSA
ALPHA
ATRAP

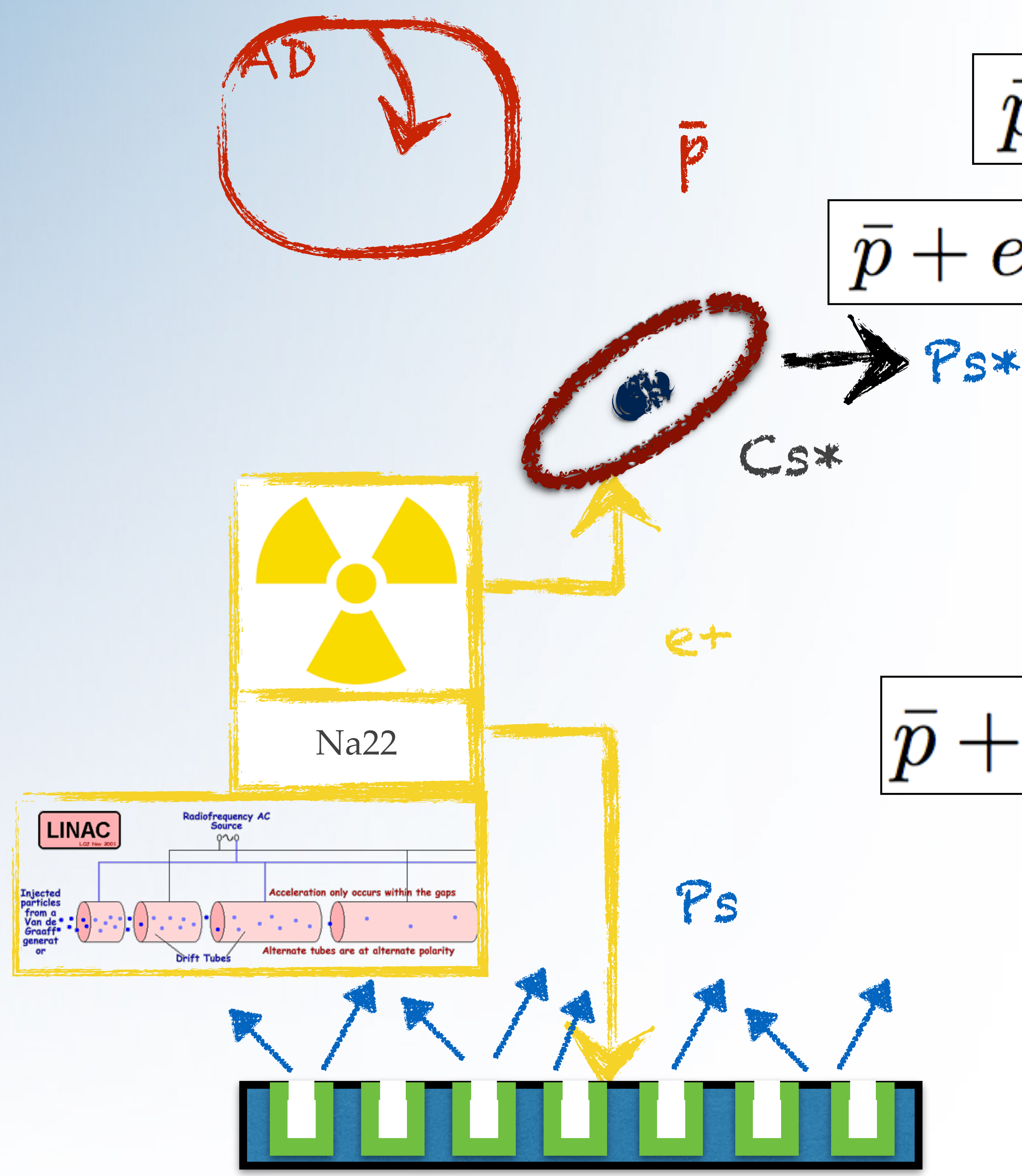




$$\bar{p} + Ps^\star \rightarrow \bar{H}^\star + e^-$$

AEGIS
ATRAP

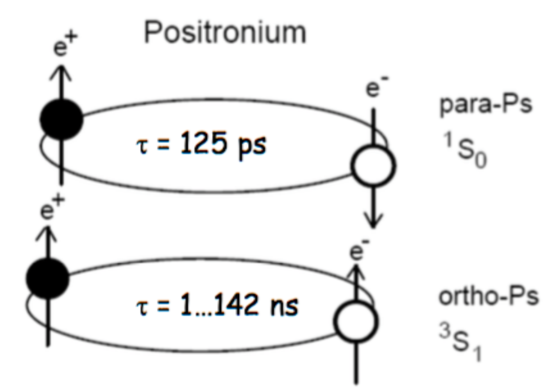
Antihydrogen formation

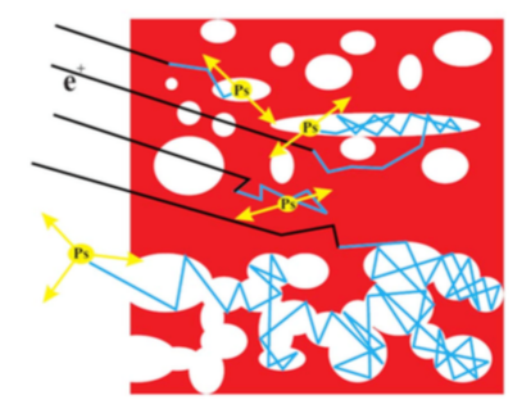


$$\bar{p} + e^+ \rightarrow \bar{H} + \gamma$$

$$\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$$

ASACUSA
ALPHA
ATRAP

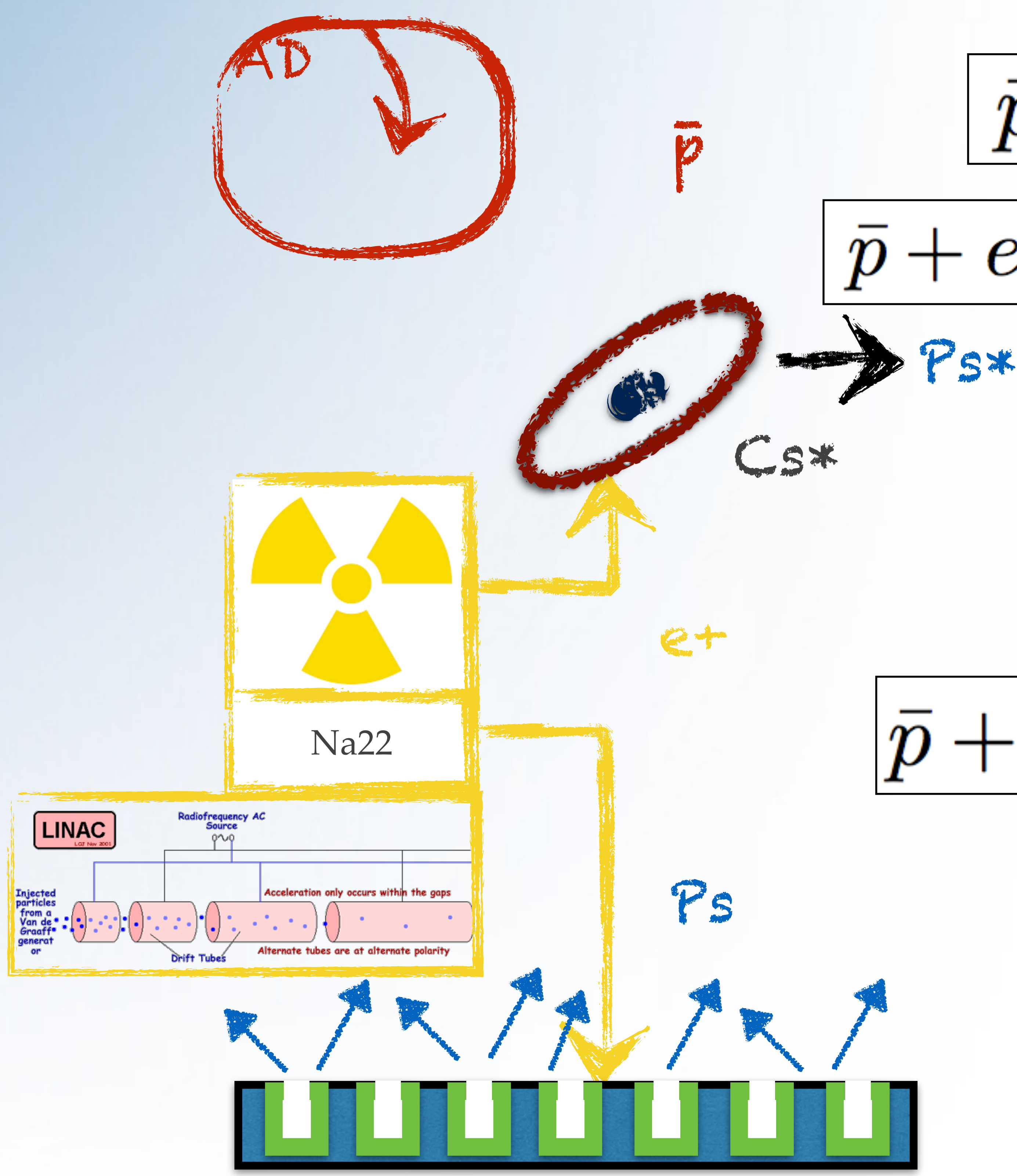




$$\bar{p} + Ps^\star \rightarrow \bar{H}^\star + e^-$$

AEGIS
ATRAP

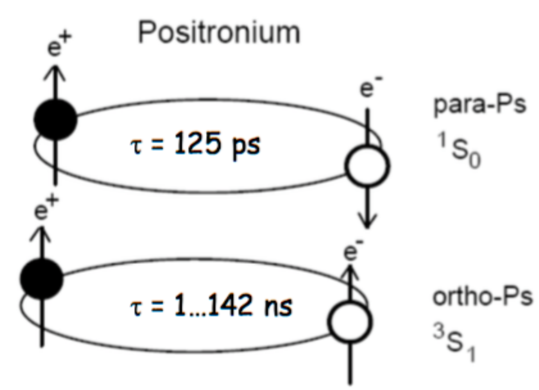
Antihydrogen formation

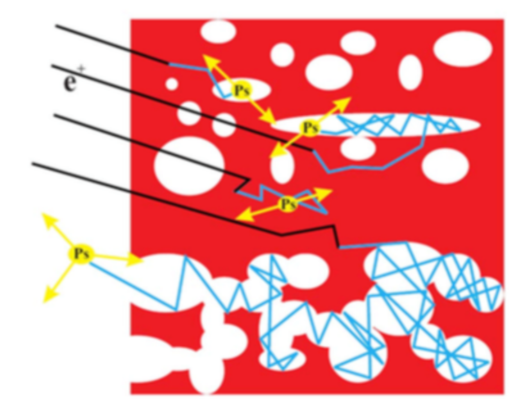


$$\bar{p} + e^+ \rightarrow \bar{H} + \gamma$$

$$\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$$

ASACUSA
ALPHA
ATRAP





$$\bar{p} + Ps^\star \rightarrow \bar{H}^\star + e^-$$

AEGIS
ATRAP

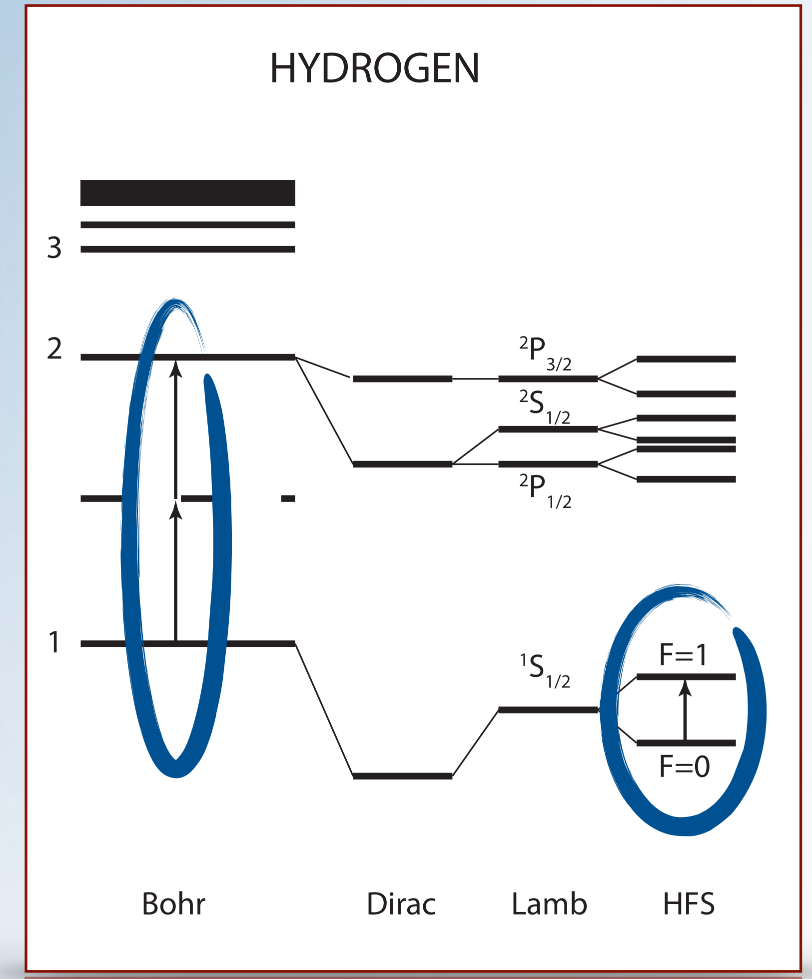
Antihydrogen ION !

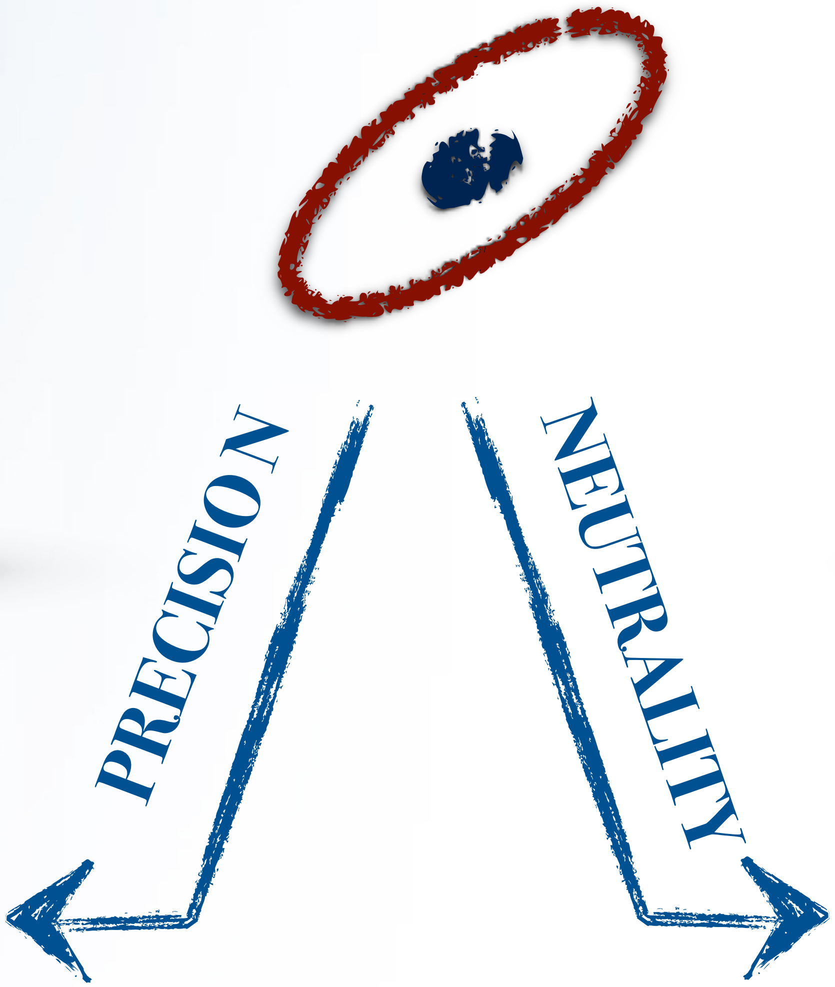
$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$

GBAR

$$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$$

Antihydrogen experiments





ASACUSA

ALPHA

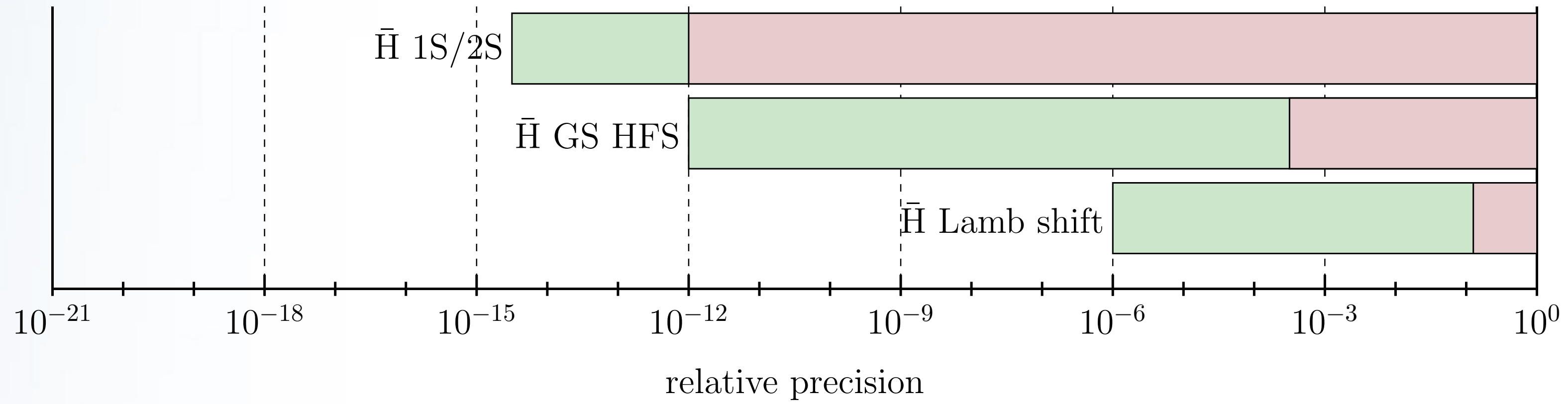
ATRAP

AEGIS

GBAR

ALPHA-G

FUTURE SPECTROSCOPY GOALS



Comparison to H in the same apparatus

<u>For enhanced precision:</u>

- More $\bar{H}$
- Control the QS in beams: deexcitation techniques (collisional or light-stimulated)
- Colder $\bar{H}$:
  - Laser cooling (sympathetic cooling of particles/ions) Be^{+}, La^{-},C_2^{-} …
  - Lyman-alpha cooling of $\bar{H}$

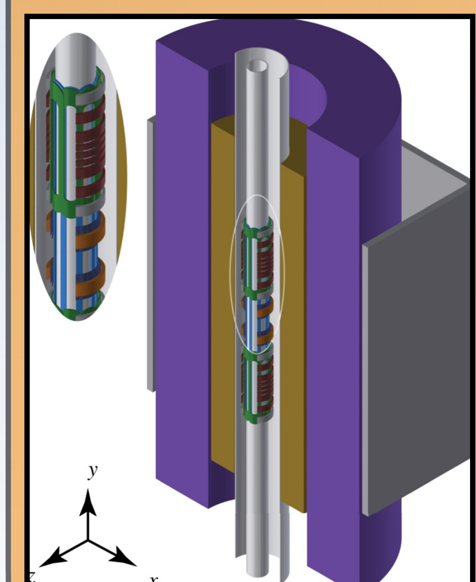
FUTURE GRAVITY GOALS

Plurality of approaches

VERTICAL TRAP

- increase up/down sensitivity (up to 1.3m trapping range)
- much improved field control

<u>Sign measurement</u> planned soon
1% targeted $\bar{H}$ cooling to ~20 mK and advanced magnetometry



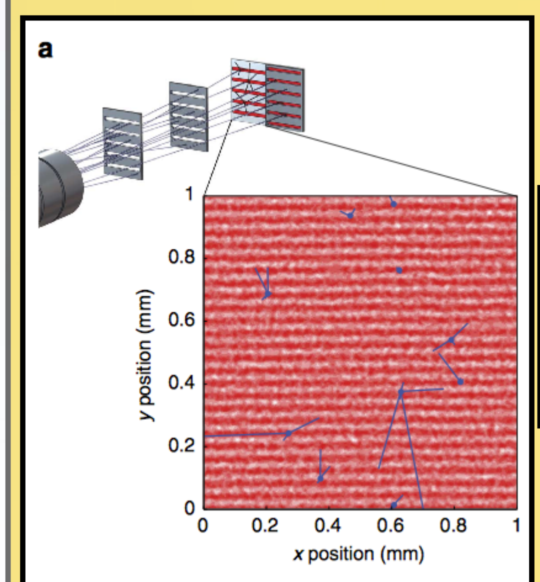
W. A. Bertsche Phil. Trans. R. Soc. A 2018 376 20170265; DOI: 10.1098/rsta.2017.0265. (2018)

ALPHA-G

$\bar{H}$ BEAM

- Sensitivity to ~10 µm deflection needed
- cold antiproton translates in cold $\bar{H}$ thanks to CE mechanism

<u>Sign measurement</u> targeted



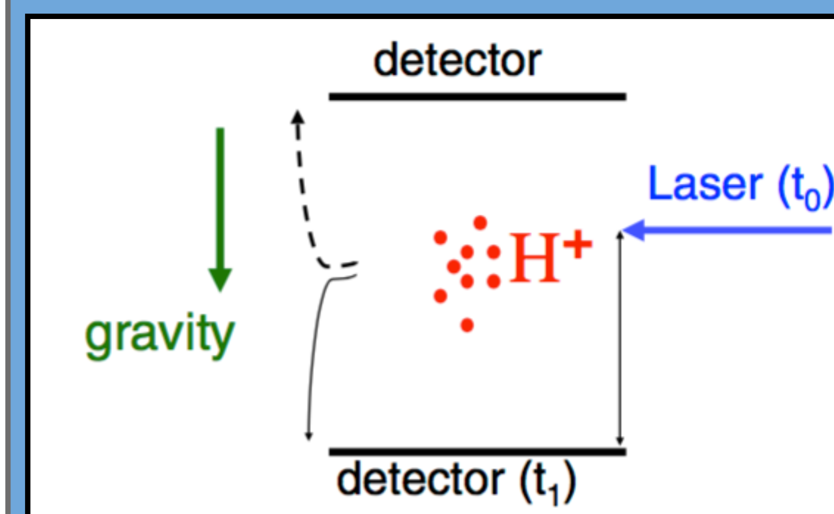
S. Aghion et al. Nature Communications 5 (2014) 4538

AEGIS

$\bar{H}^+$ BEAM

- Cooling below 1 m/s : Sympathetic cooling of $\bar{H}^+$
- opens new horizons

<u>1% measurement</u> targeted

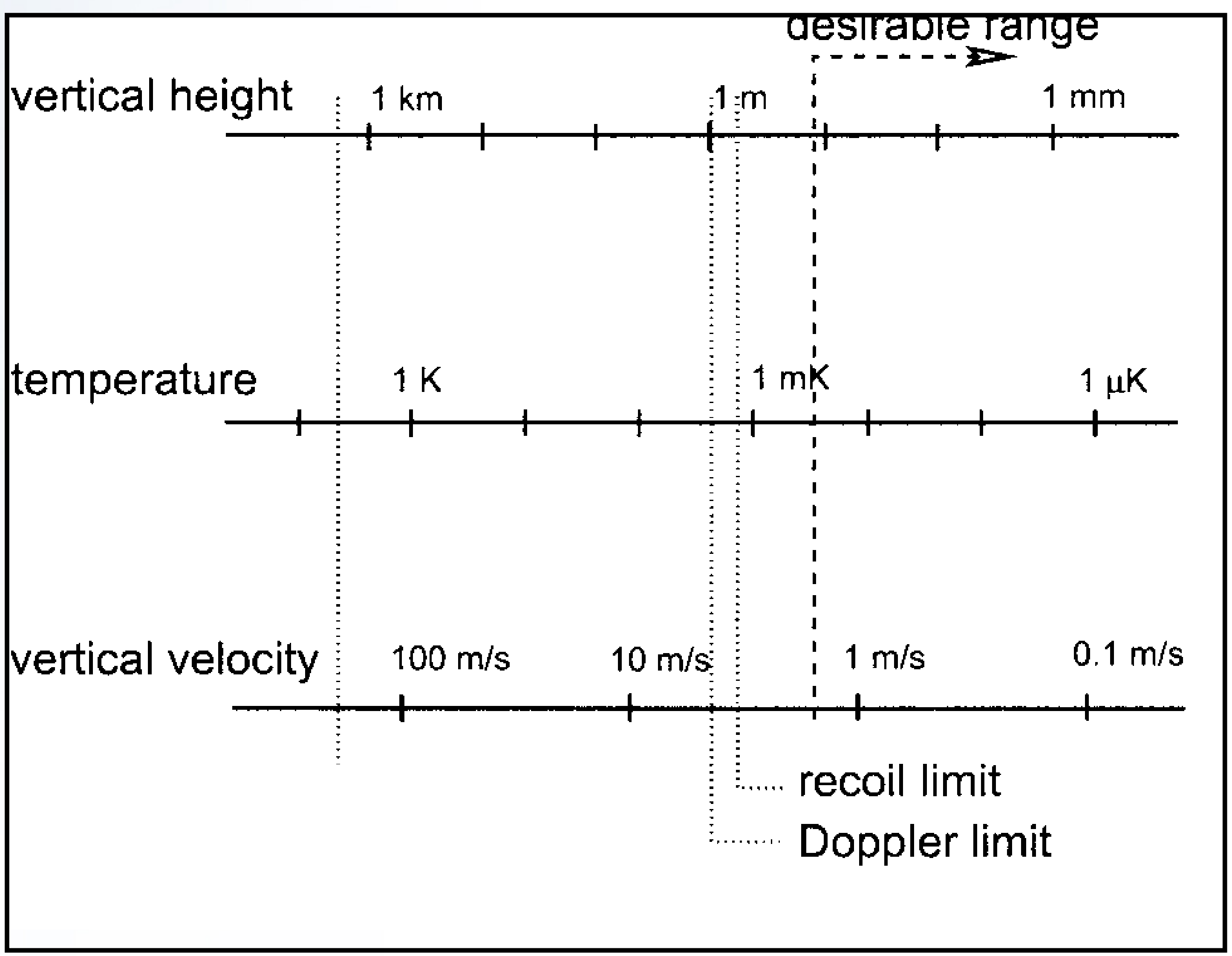


e.g.: The GBAR antimatter gravity experiment
P. Pérez et al., Hyperfine Interactions 233, 21-27 (2015)

GBAR

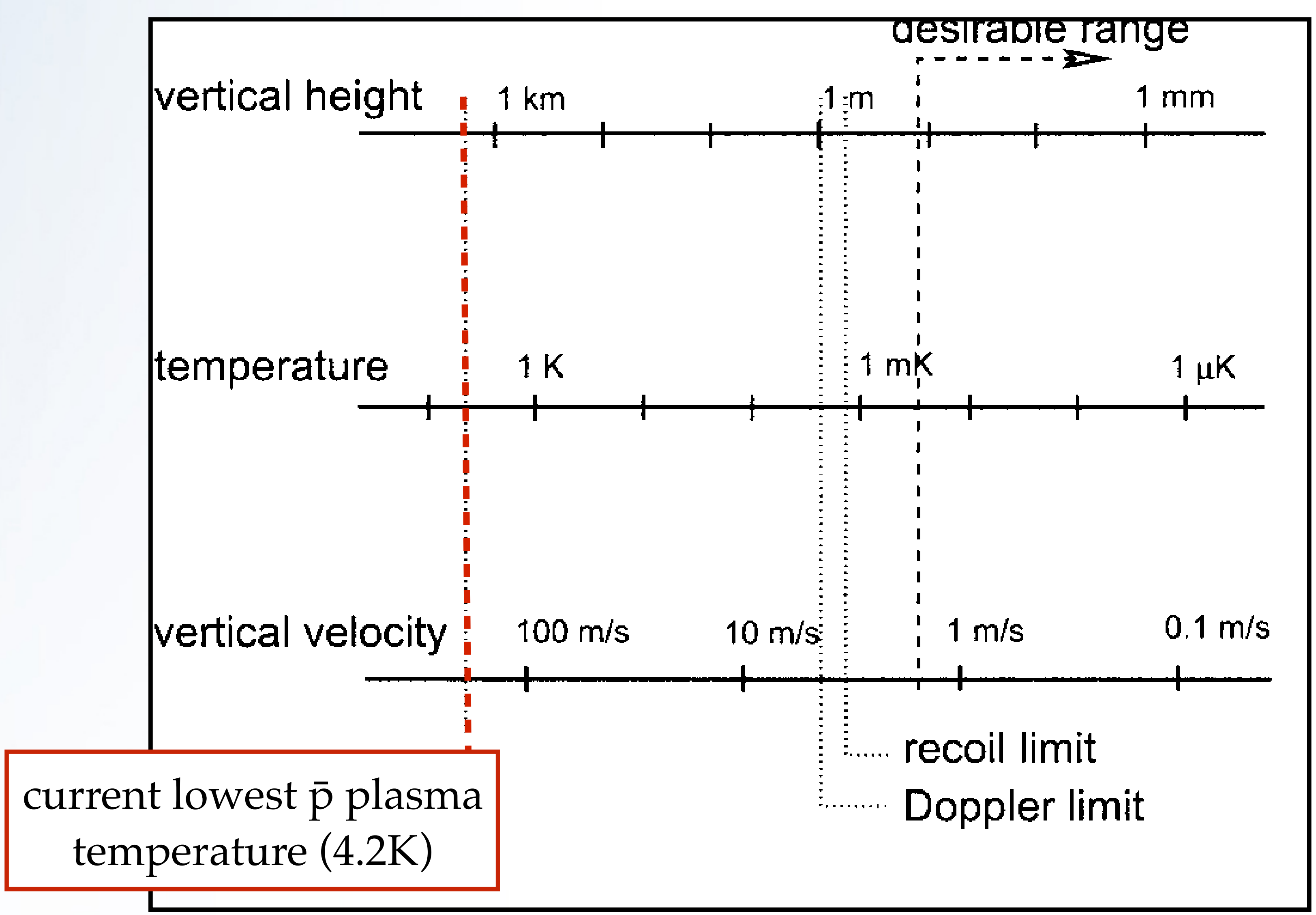
FUTURE GOALS

Some numbers to set the scale



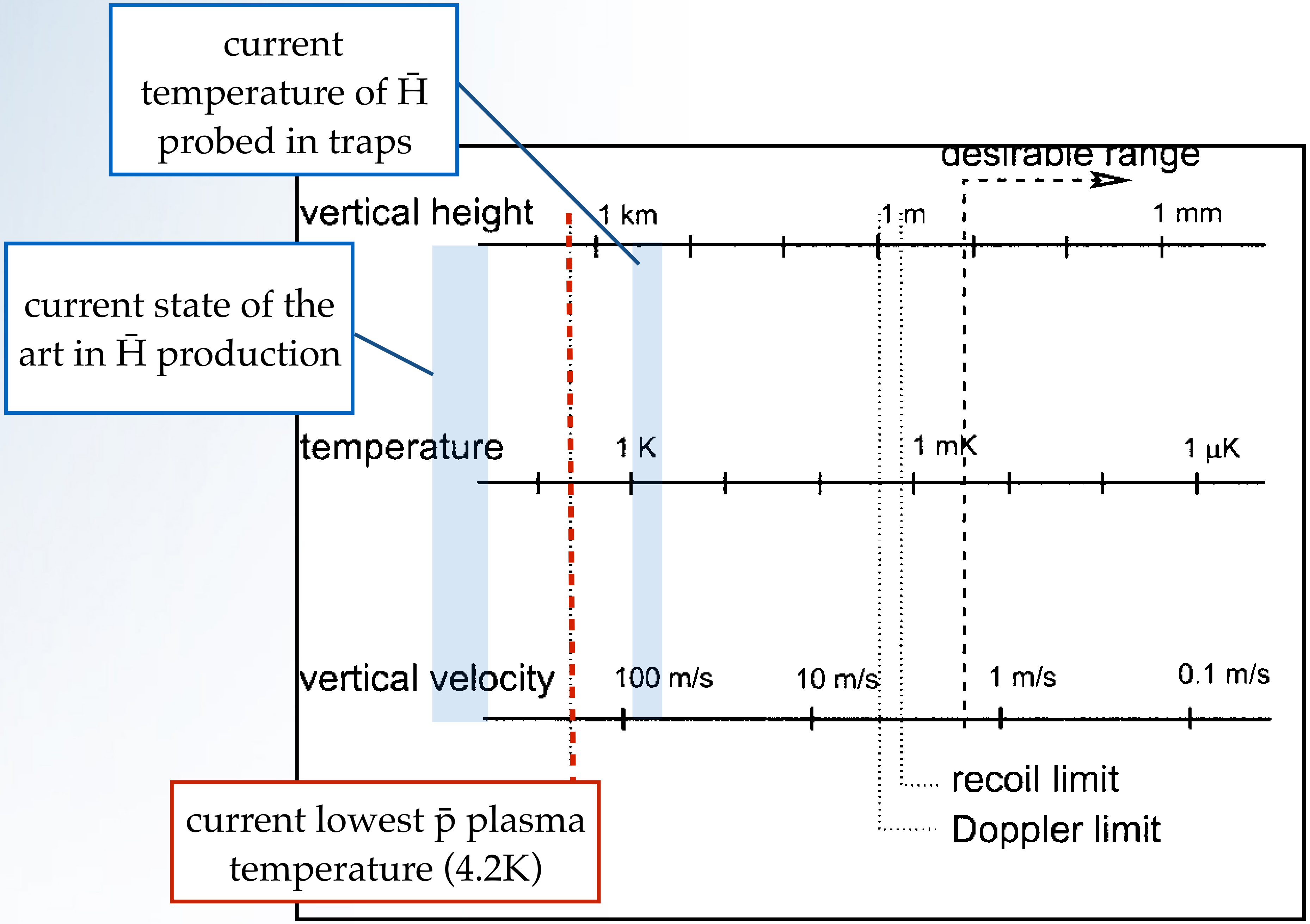
FUTURE GOALS

Some numbers to set the scale



FUTURE GOALS

Some numbers to set the scale



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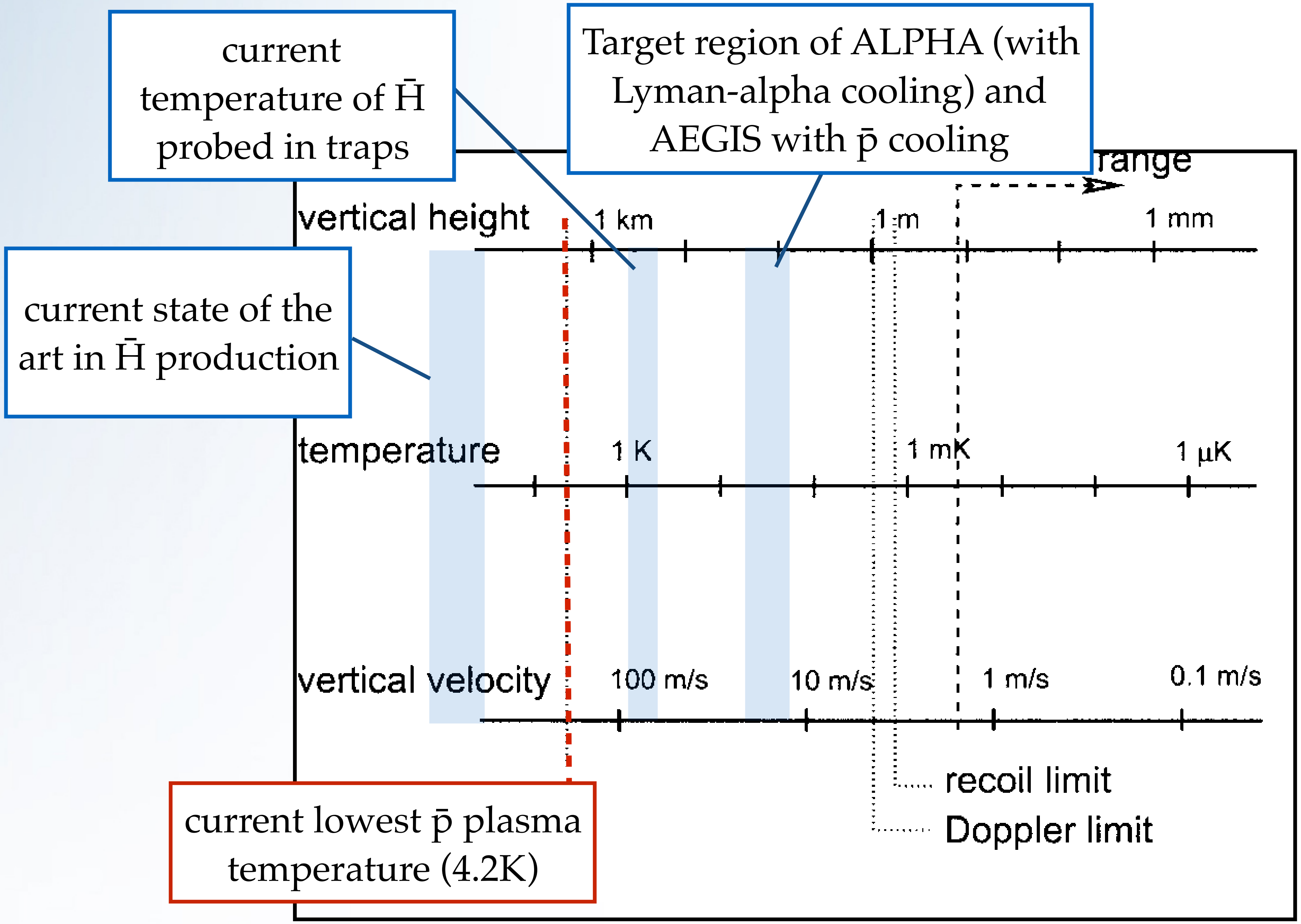
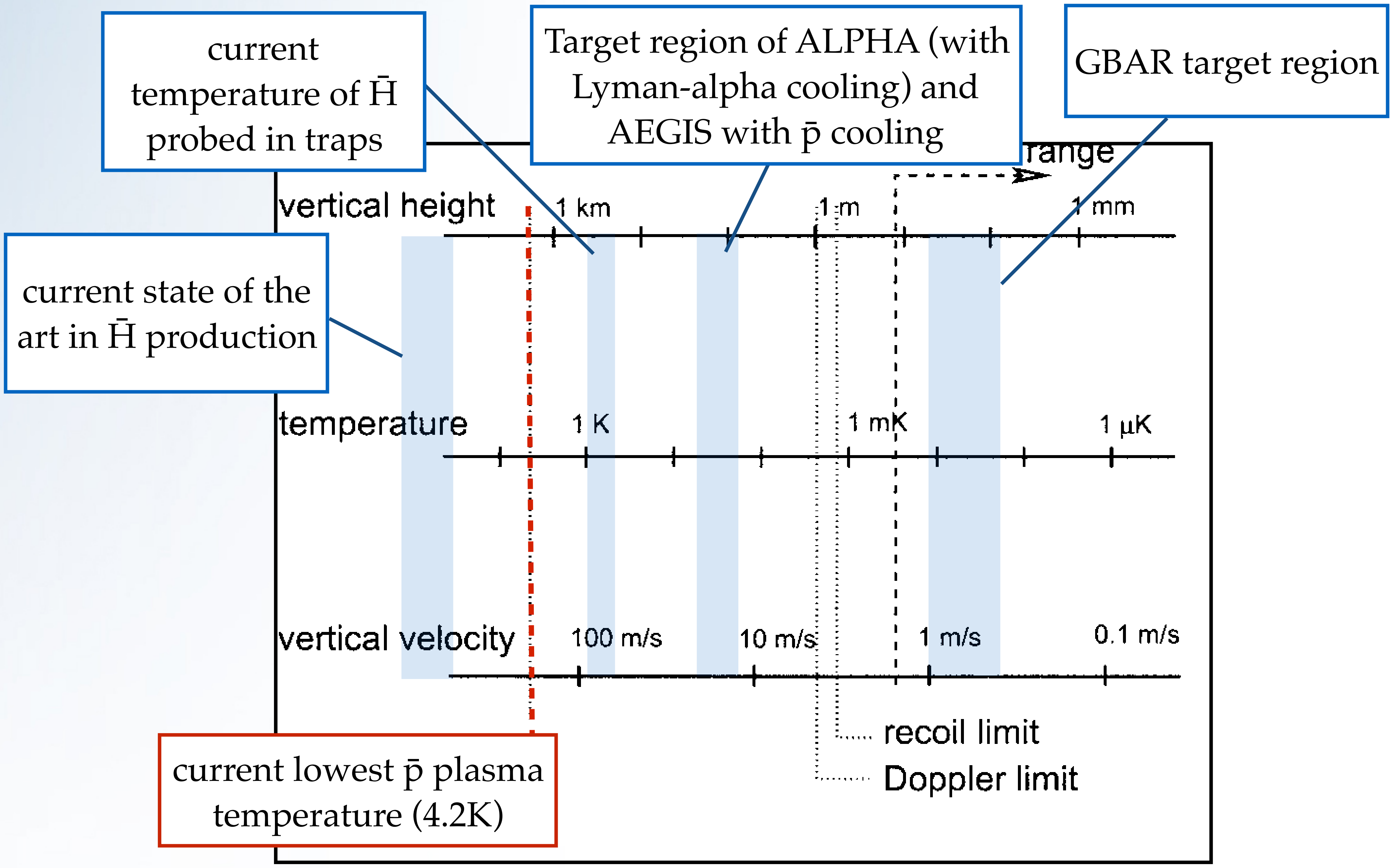
Some numbers to set the scale



FUTURE GOALS

Some numbers to set the scale



Search for Primordial Antimatter

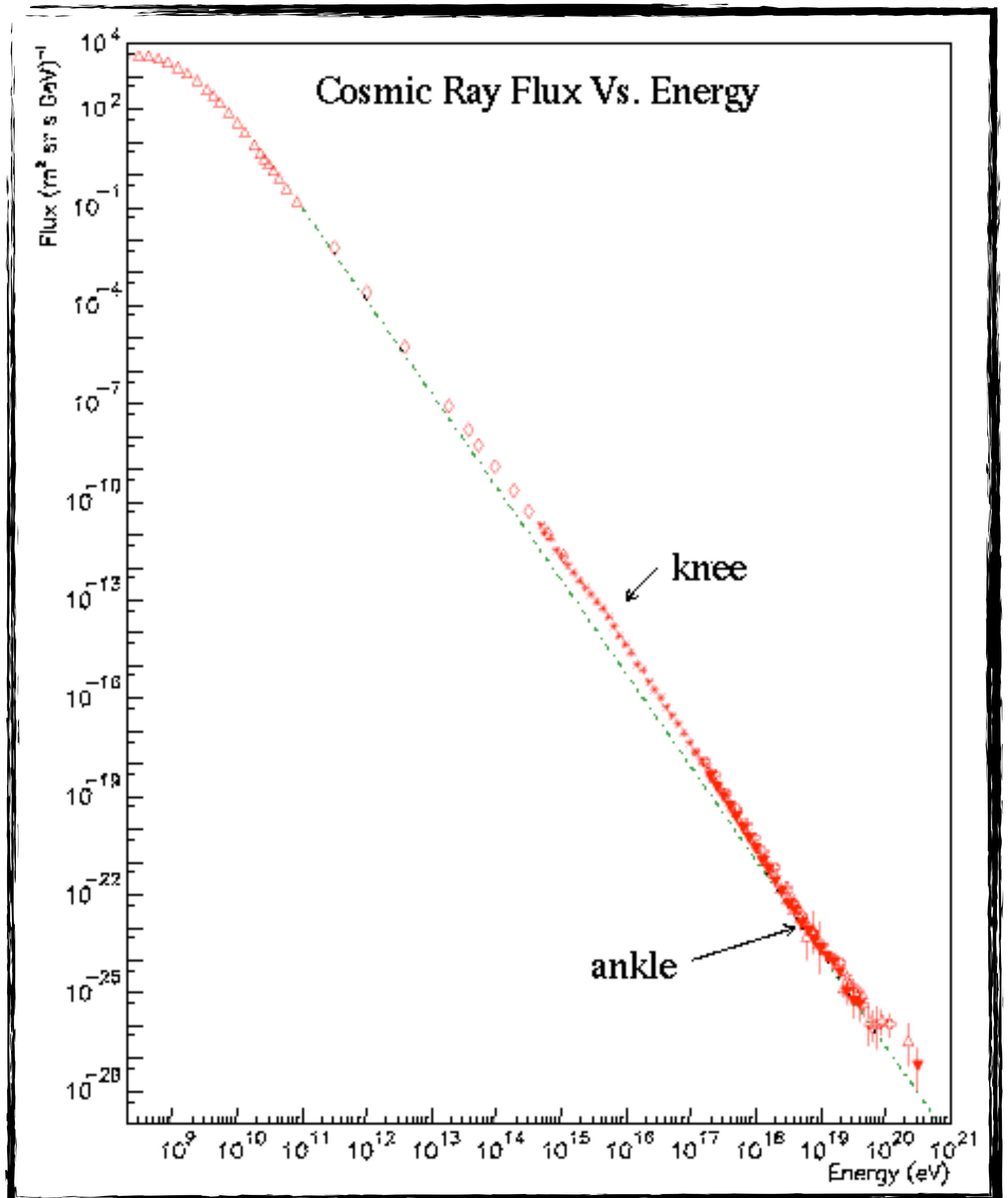
IS THERE ANTIMATTER LEFT IN THE UNIVERSE?

Search for Primordial Antimatter

- **DIRECT SEARCHES IN COSMIC RAYS**

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

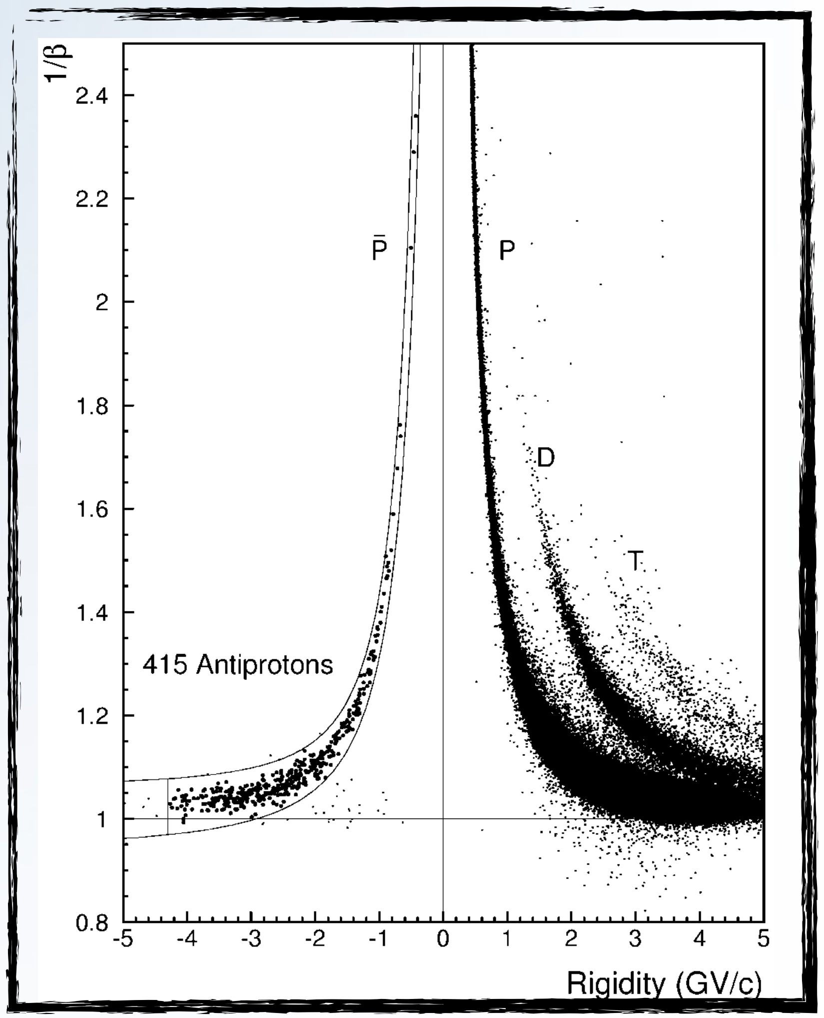
A large part of positrons and antiprotons impinging on Earth are produced in high-energy interactions between cosmic rays nuclei with the interstellar medium. Their spectra can provide an insight on the origin, production and propagation of cosmic rays in our galaxy. Any observed flux larger than that 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.

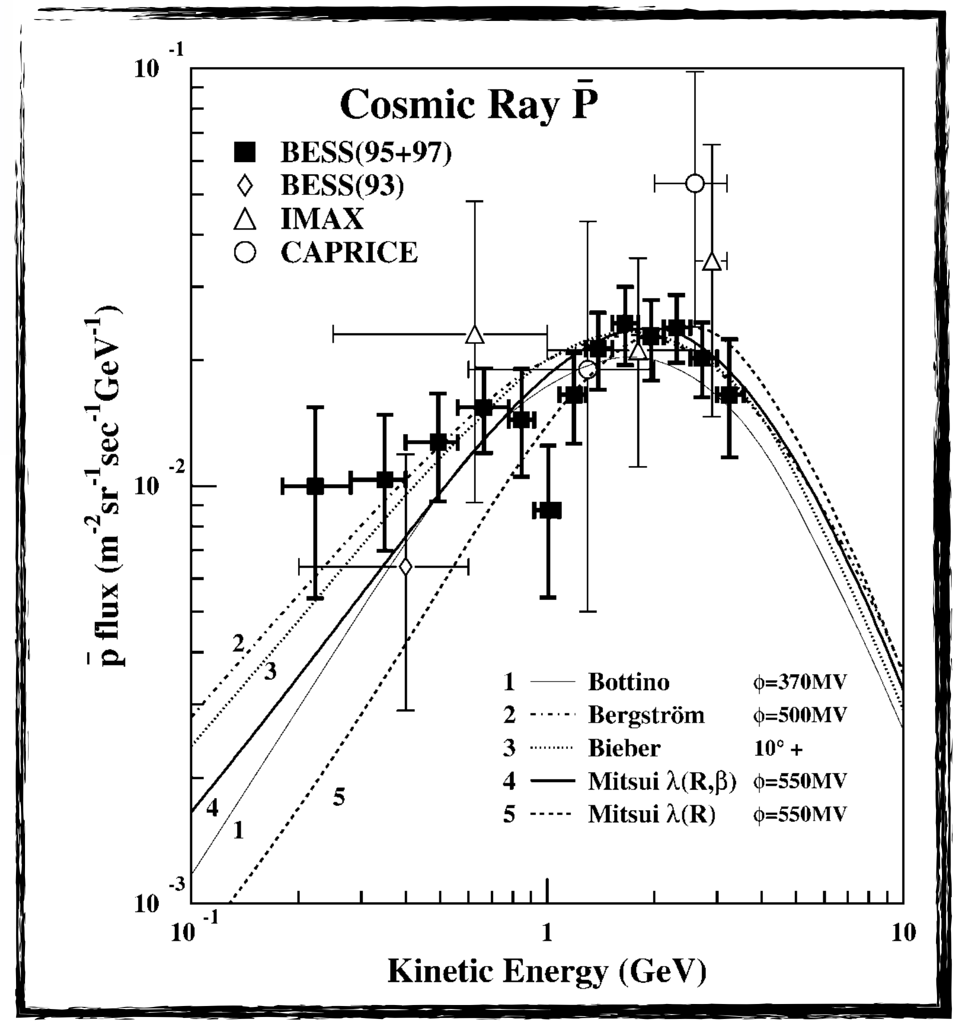


Balloon experiments

Results from CAPRICE / BESS

height of flight = 38 km (top of atmosphere)





PRL 84 (2000) 1078

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

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

subsidiary result (data+propagation model) = $\boldsymbol{\tau}(\bar{p}) > 1.7$ Myr

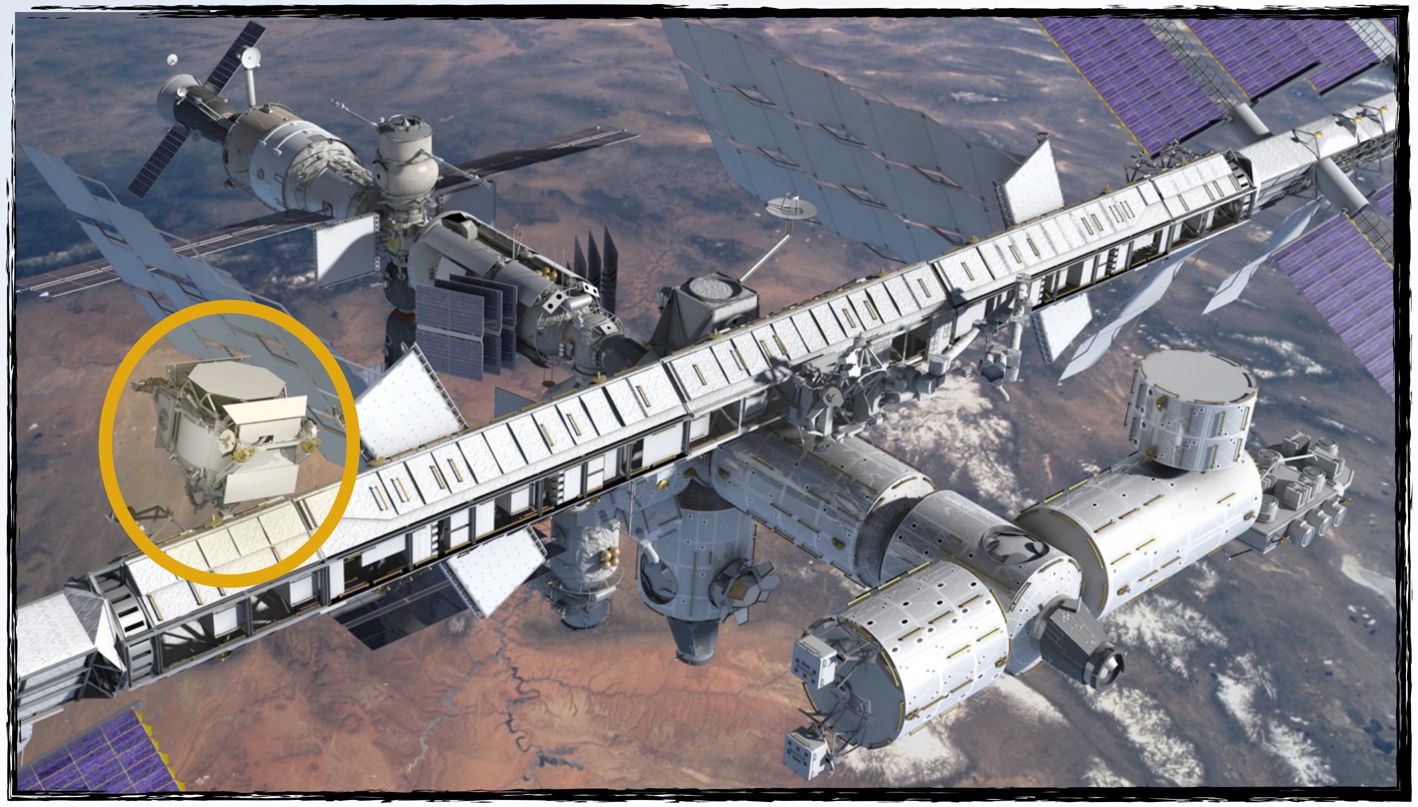
PAMELA (satellite), AMS (space station)

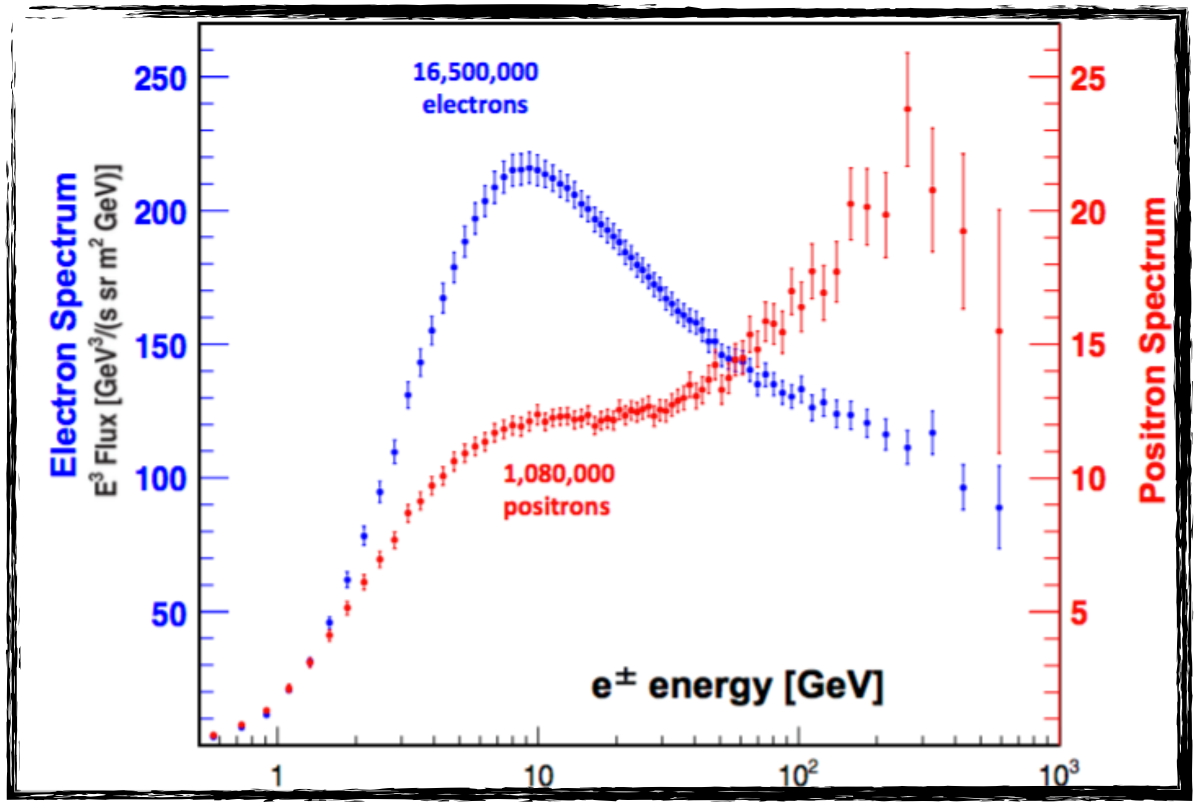
- SEARCH FOR PRIMARY ANTIMATTER

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)

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e+, p̄, anti-alpha

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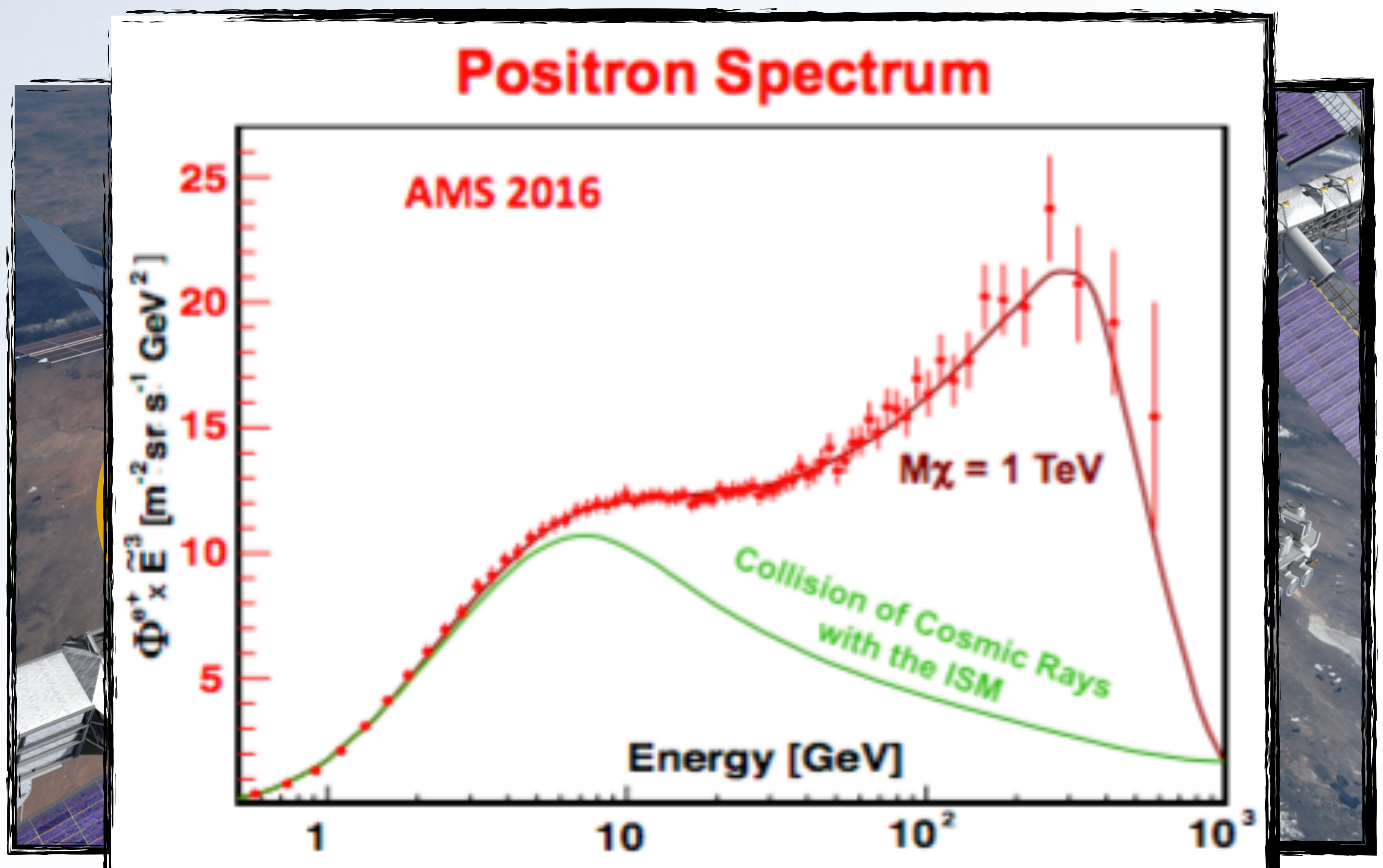
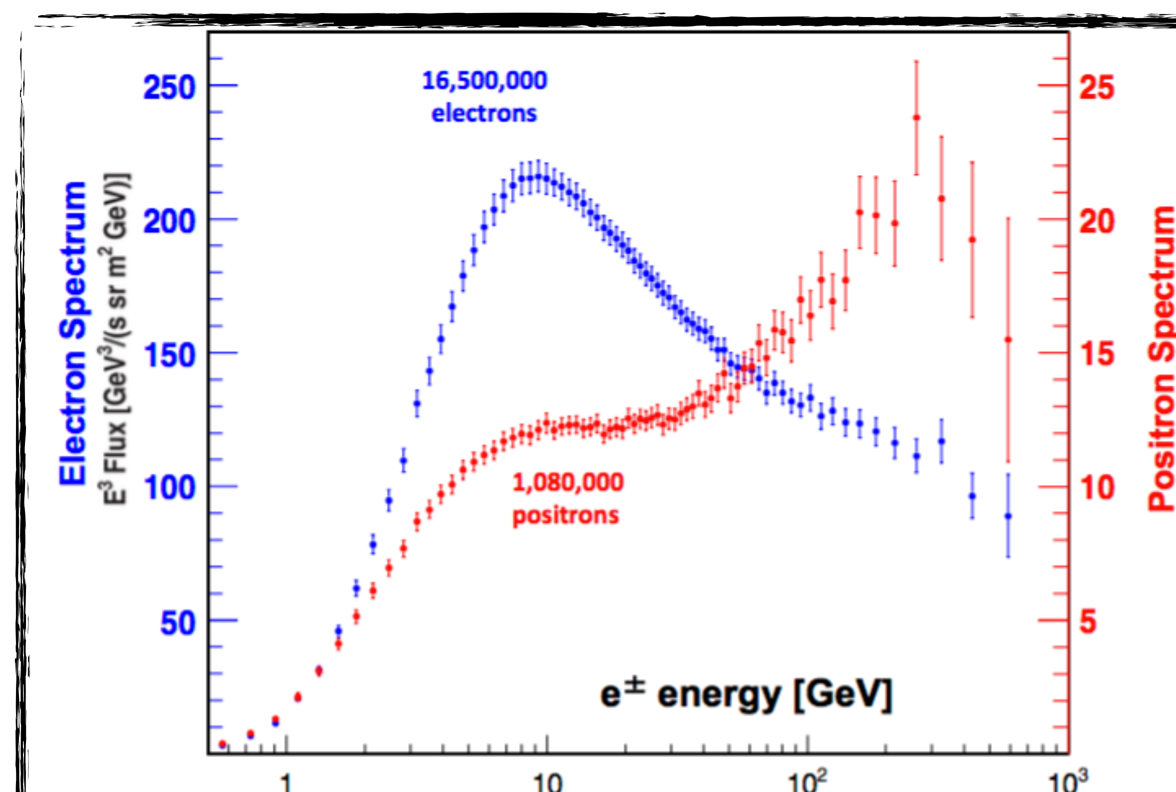
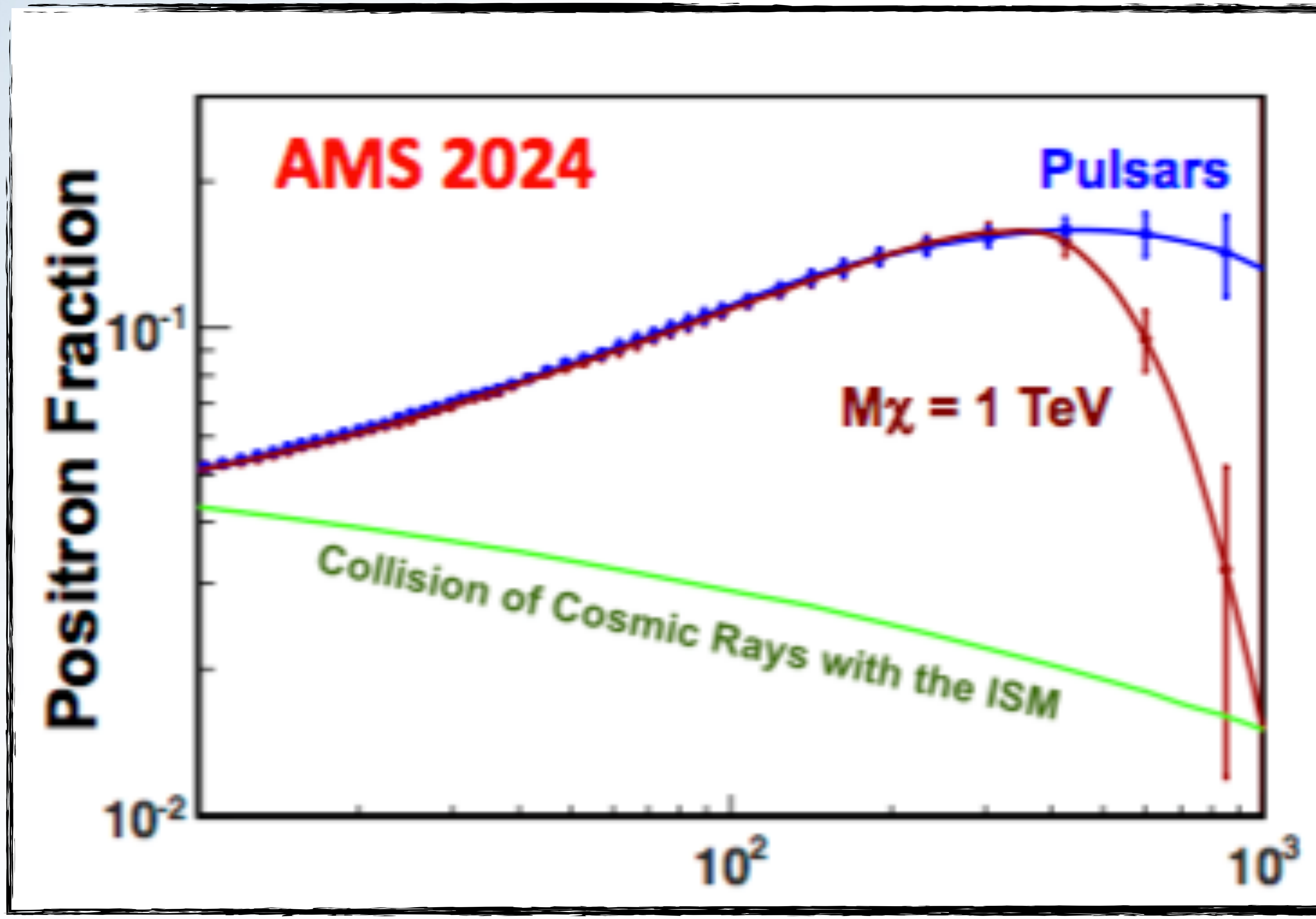




Space experiments

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 $p\bar{p}$ 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 SEARCHES FOR PRIMORDIAL ANTIMATTER IN OUTER SPACE

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ENJOY THE REST OF THE WEEK!