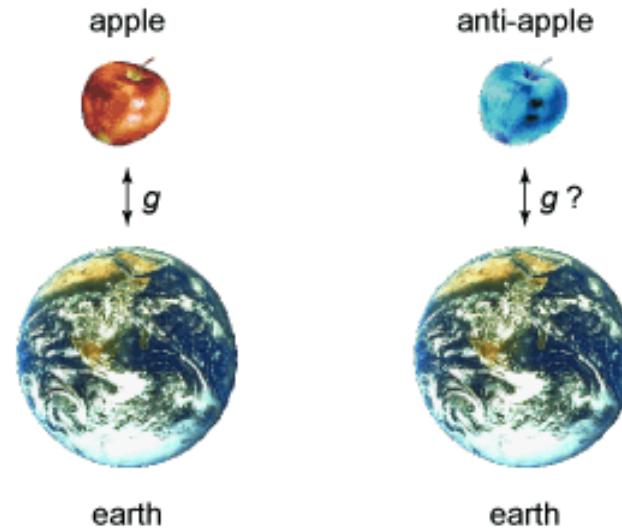




# ANTIMATTER and GRAVITATION



- Motivation & Theory
- Experiments : past and next
- The GBAR experiment

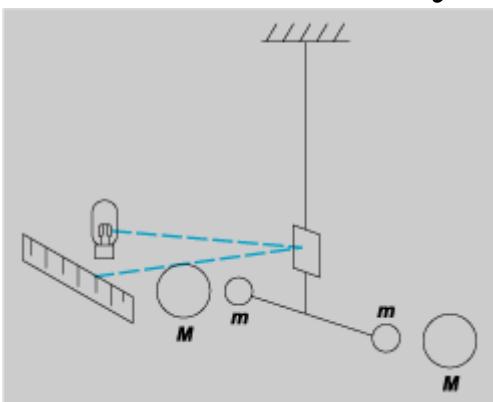
# Motivation

A direct test of the Equivalence Principle with antimatter

The acceleration imparted to a body by a gravitational field is independent of the nature of the body :

$$\text{Inertial mass} = \text{gravitational mass}$$

Tested to a very high precision with many materials



Weak Equivalence Principle (torsion pendulum)

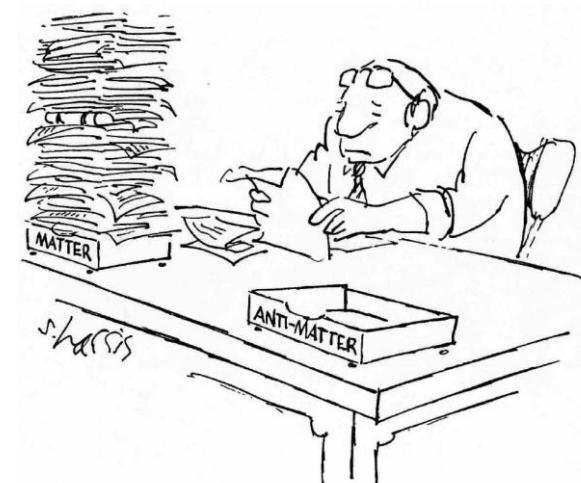
$$(\Delta a / a)_{Be/Ti} = (0.3 \pm 1.8) \times 10^{-13}$$

S.Schlamminger et al, Phys Rev Lett 100 (2008) 041101

Strong Equivalence Principle (Lunar Laser Ranging)

$$(\Delta a / a)_{Earth/Moon} = (-1.0 \pm 1.4) \times 10^{-13}$$

J.G.Williams et al, Phys Rev Lett 93 (2004) 261101



# Theory (1)

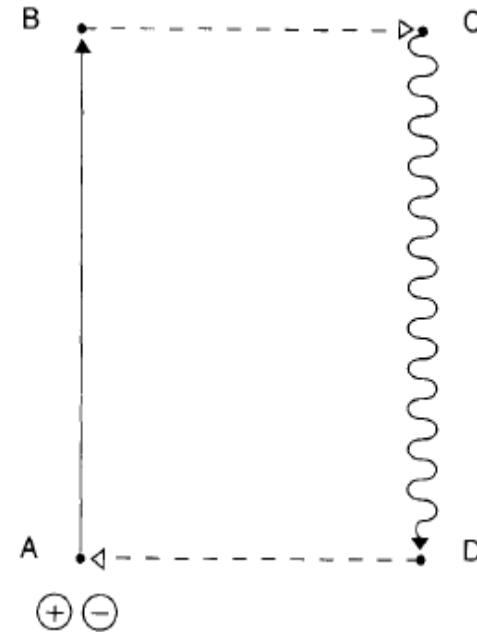
Morrison argument (1958) :  
antigravity in General Relativity  
→ violation of energy conservation

if  $m_G(+)= -m_G(-)$ :

$$E_A = E_B = 2m_I c^2 = h\nu_C$$

$$h\Delta\nu_{CD} = h\nu_C(gL/c^2) = 2m_I gL$$

$$E_D = E_A + 2m_I gL$$



# Theory (2)

- new gravi-vector and gravi-scalar fields coupled to baryon number
  - distinguish  $m_G$  and  $\bar{m}_G$
- (*J. Scherk, Phys. Lett. B (1979) 265*)

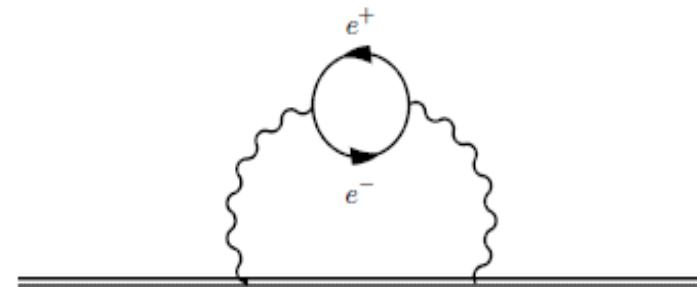
$$V = -G \frac{mm'}{r} \underbrace{(1 \mp a \exp(-r/v) + b \exp(-r/s))}_{\text{supergravity : one repulsive contribution}}$$

Tests with matter give only limits on  $\sim |b-a|$

But exact cancellation scalar/vector impossible  
(*D.S.M. Alves et al SU-ITP-09/36*)

# Theory (3)

Anti matter content of ordinary matter  
(Schiff argument)



$$\left| \frac{g - \bar{g}}{g} \right| \sim \left| \frac{g - g_{\Delta E \text{rad}}}{g} \right| \Rightarrow$$

**FIG. 2:** Loop contribution to the electrostatic self-energy of the nucleus

Scenario	Argument	Bound on $ g_H - g_{\bar{H}} /g_H$
Modification of GR	Lamb shift	$\lesssim 10^{-2}$
	Electrostatic self-energies of nuclei	$\lesssim 10^{-7}$
	Antiquarks in nucleons	$\lesssim 10^{-9}$
Scalar-vector	Radiative damping of binary systems	$\lesssim 10^{-4}$
	Scalar charges are not vector charges	$\lesssim 10^{-8}$
	Velocity dependence	$\lesssim 10^{-7}$

(D.S.M. Alves et al SU-ITP-09/36)

# Theory (4)

## Standard Model Extension (*Kostelecky et al*)

based models for analysis of CPT&LI tests escape these arguments

*J.D. Tasson Int. J. Mod. Phys. Conf. Ser. 30, 1460273 (2014) (WAG2013)*

But are sensitive to other tests (atomic interferometry and best :  
bound kinetic energy of nuclei :  $(\bar{g}-g)/g < 10^{-6} - 10^{-8}$   
but model dependant limit)

*M. Hoensee et al, Phys.Rev.Lett. 111, 151102 (2013)*

*Autres modèles → voir références WAG 2015*

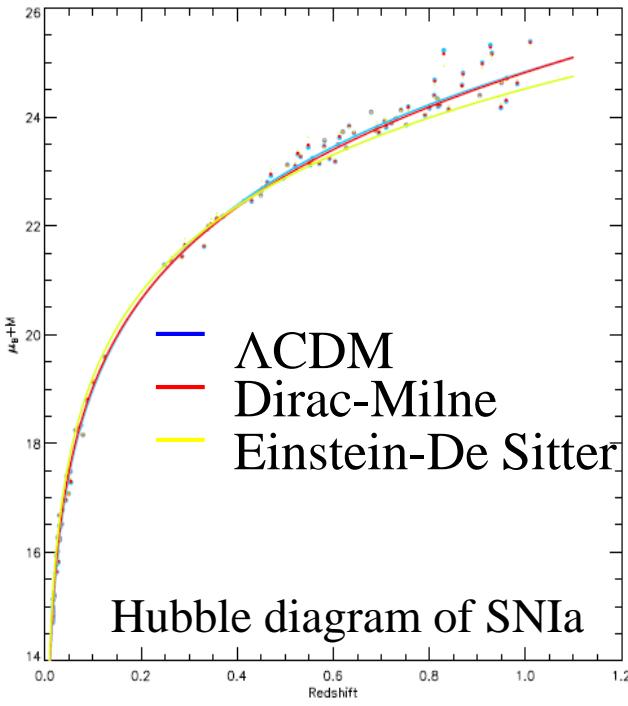
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*“In conclusion whether or not one now accepts the existence of non-Newtonian gravitational forces, the possibility of new non-inverse-square and/or composition-dependent components of gravity must be thoroughly studied”*

Nieto – Goldman *Phys. Rep. (Review Section of Physics Letters) 205, No. 5(1991)*

# Cosmology

- Matter-antimatter asymmetry in the Universe ???
- RG OK but with dark energy, dark matter and inflation: pb with gravitation?
- Could there be a matter-antimatter repulsive force?



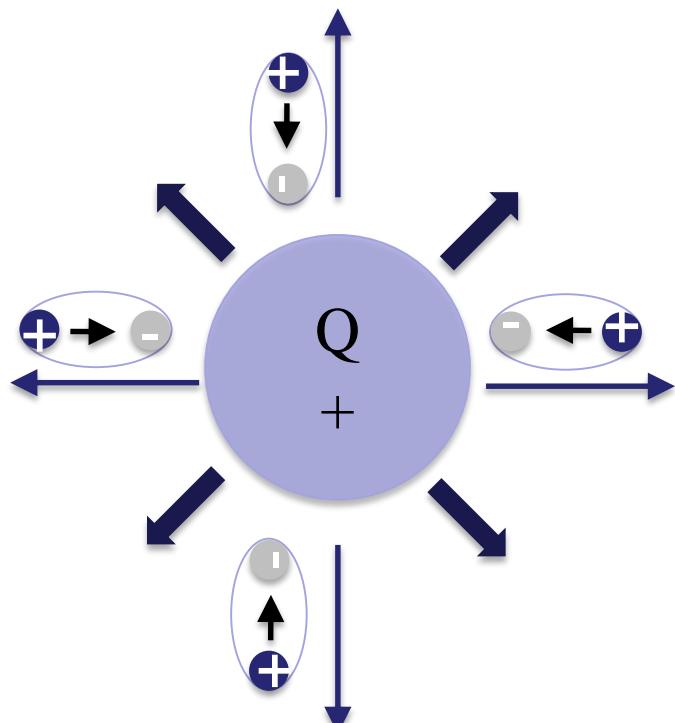
- Dirac Milne Universe: Attempt to build a cosmology with:
  - Matter-antimatter symmetry
  - Mechanism to separate matter from antimatter

*PhD Thesis Paris XI ,A. Benoît-Lévy – dir G. Chardin (2009)*  
*Benoit-Lévy & G. Chardin, A&A 537, A78 (2012)*
- MOND phenomenology with gravitational polarization

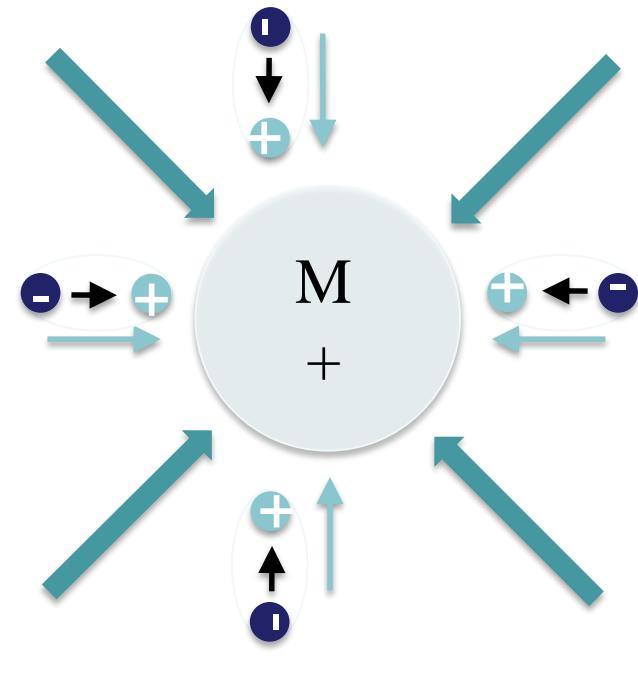
*L. Blanchet, Class. Quantum Grav. 24 (2007) 3529 ; CQG 24 (2007) 3541*  
*L. Blanchet & A. Tieck, Phys.Rev. D 78, 024031 (2008); D 80, 023524 (2009)*

# Polarisation effect

Electric field  
*With polarized dipoles*



Gravitational field  
*With polarized dipoles*



# **Experiments : past and next**

# Experiment (1)

-  $\eta^\pm$  et  $\Phi^\pm$  as a function of time: CPLEAR

$K^0$ - $\bar{K}^0$  oscillations depend on  $\delta m_{\text{eff}} = M_{K^0} (g - \bar{g}) \frac{U}{c^2} \exp(-r/r_I) f(I)$

A. Apostolakis *et al.*, Phys Lett B 452 (1999) 425

Summary of limits on  $|g - \bar{g}|$  for spin 0, 1 and 2 interactions

Source	Spin 0	Spin 1	Spin 2
Potential variation with time	$6.4 \times 10^{-5}$	$4.1 \times 10^{-5}$	$1.7 \times 10^{-5}$
	$1.8 \times 10^{-4}$	$7.4 \times 10^{-5}$	$4.8 \times 10^{-5}$
	$6.5 \times 10^{-9}$	$4.3 \times 10^{-9}$	$1.8 \times 10^{-9}$
Need an absolute potential $\rightarrow$	$1.4 \times 10^{-12}$	$9.1 \times 10^{-13}$	$3.8 \times 10^{-13}$
	$7.0 \times 10^{-14}$	$4.6 \times 10^{-14}$	$1.9 \times 10^{-14}$

# Experiment (2)

Cyclotron frequency of p (or H<sup>-</sup>) and  $\bar{p}$  in the same magnetic field

*R. Hughes and M. Holzscheiter, Phys Rev Lett 66 (1991) 854*

*G. Gabrielse et al. Phys Rev Lett 82 (1999) 3198*

$$\omega = qB / 2\pi m + \alpha U / c^2 \quad |\omega - \bar{\omega}| / \omega = (9 \pm 9) \times 10^{-11} \rightarrow |g - \bar{g}| / g \leq 10^{-6}$$

Arrival time of 1 (?) : 90 % CL neutrino and 18 antineutrinos from SN1987A in Kamiokande&IMB

*(S. Paksava et al. Phys Rev D 39 (1989) 1761)*

$$\text{gravitational delay : } \delta t = MG \left[ -R / \sqrt{R^2 + b^2} + \left( 1 + \boxed{\gamma} \right) \ln \left| R + \sqrt{R^2 + b^2} / b \right| \right]$$

$$|\delta t(v_e) - \delta t(\bar{v}_e)| / \delta t(\bar{v}_e) < 10^{-6} \rightarrow |\gamma(v_e) - \gamma(\bar{v}_e)| / \gamma(\bar{v}_e) < 10^{-6}$$

ALL those estimations are by-products of experiments  
NOT done for this study.

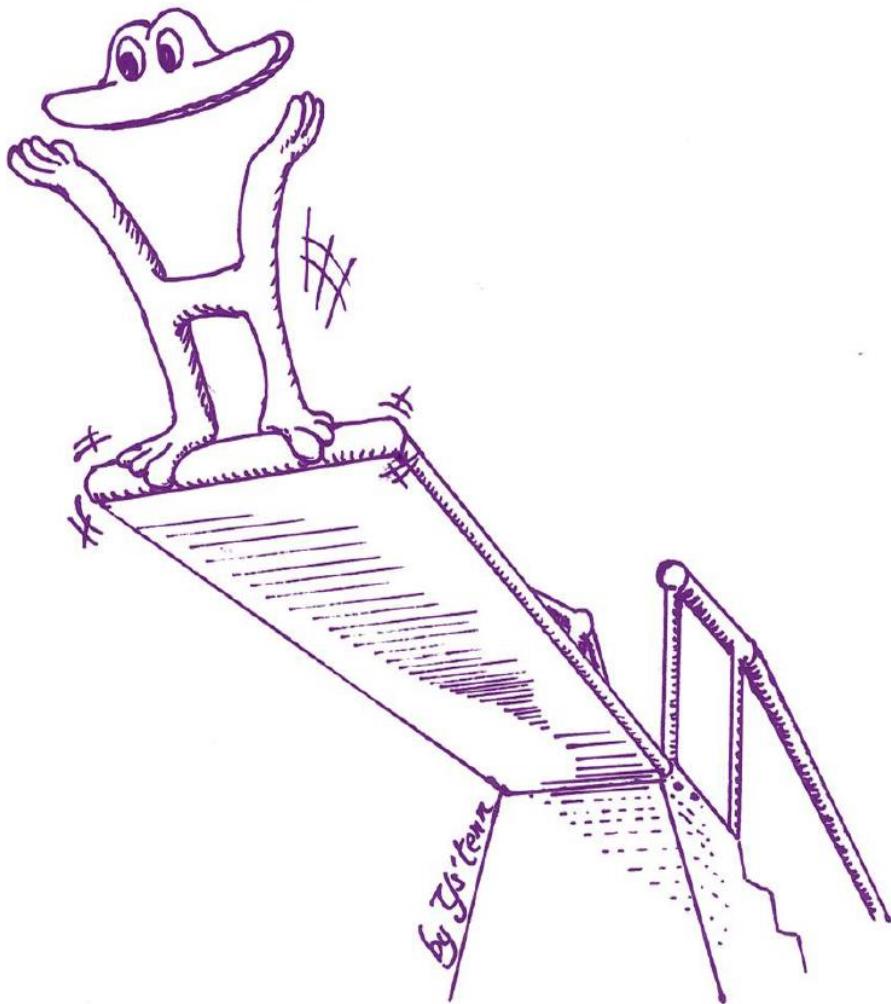
# Past attempts and proposals

- **positrons** : *F. Witteborn and W. Fairbank, Phys Rev Lett 19 (1967) 1049*
- *Very difficult* :  $m_e g / e = 5.6 \times 10^{-11} V / m$  (one elementary charge at 5 m)
- **antiprotons** : *PS200 Proposal Los Alamos Report LA-UR 86-260*
- **antineutrons** : difficult to slow down  
*T. Brando et al, Nuc. Instr. Methods 180 (1981) 461*
- **positronium** : short life time (142 ns for orthopositronium) if  $n = 1$   
Maybe possible if excited  $n \gg 1$  ( $\tau \sim (n/25)^{5.236} \times 2.25 \text{ ms}$ )  
Pb : cooling, polarizability, ionisation from thermal radiation...  
*A.P. Mills, M. Leventhal, Nuc. Instr. Meth. in Phys. Research. B192 (2002) 102*  
*Project by D. Cassidy at Cambridge UK*  
*(described in G. Dufour et al, Adv. In High Energy Physics 2015/ID379642)*

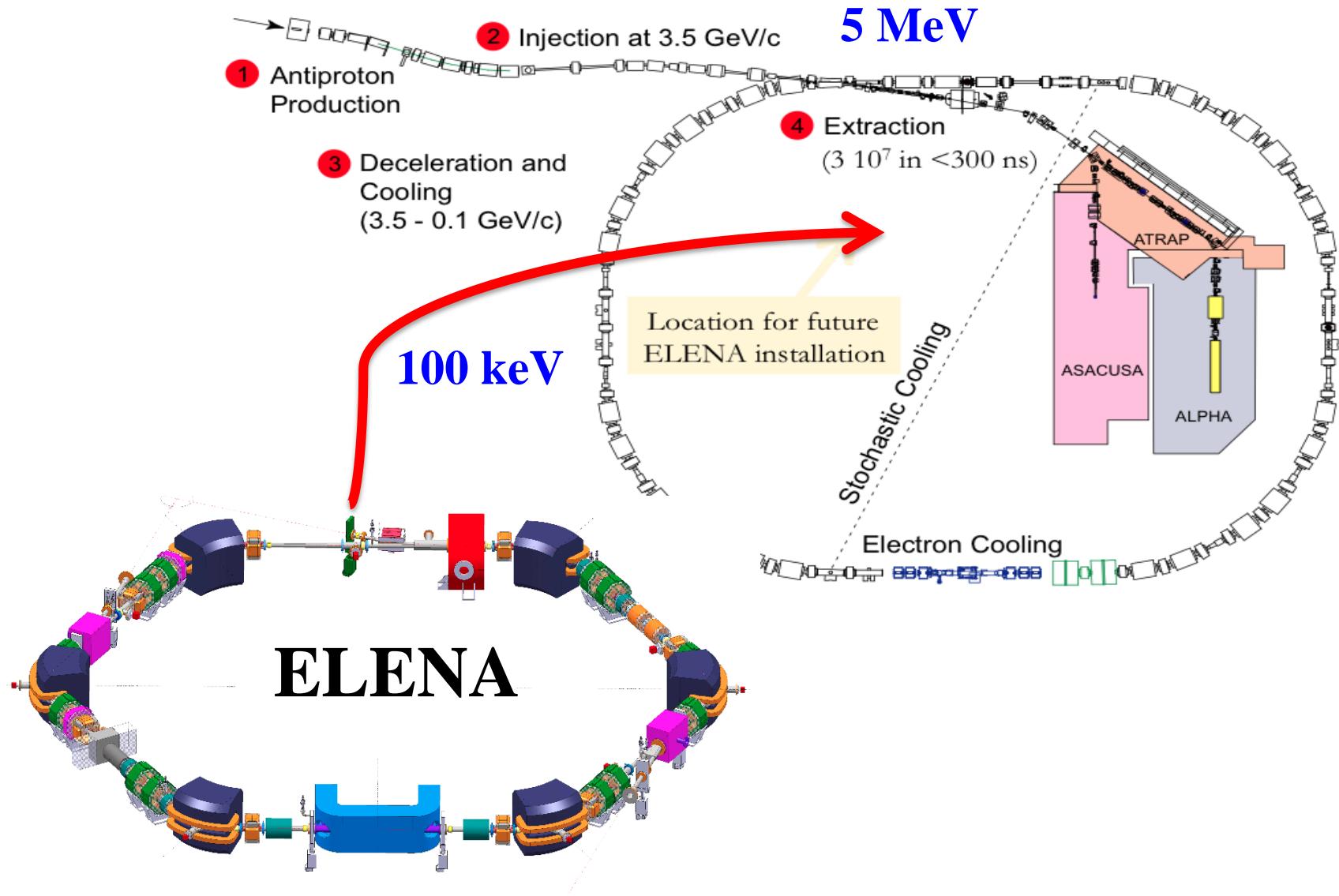
Remaining best tool: **ANTIHYDROGEN**

# Antihydrogen

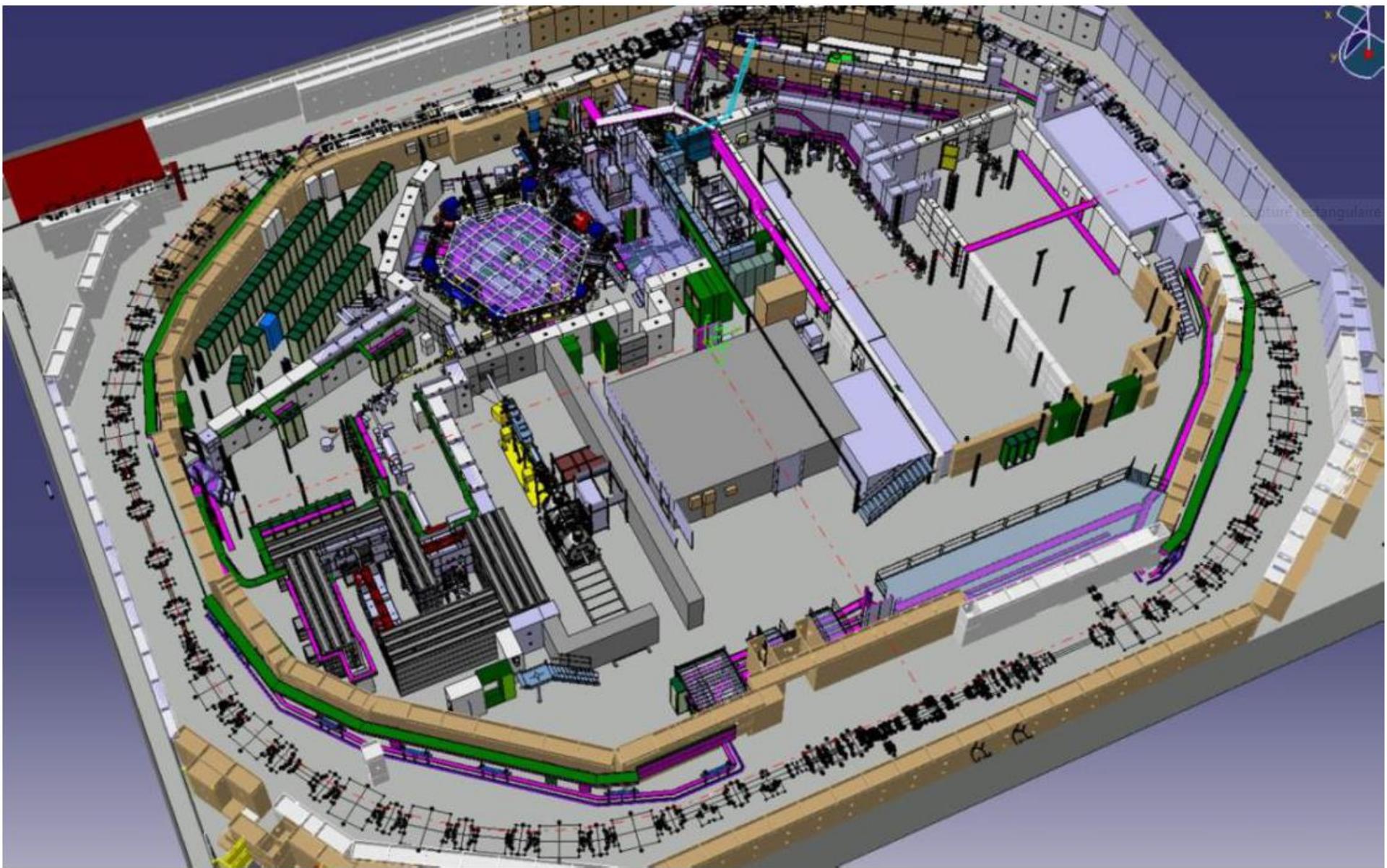
Production  
Trapping  
experimentation



# Antiprotons: CERN AD / ELENA

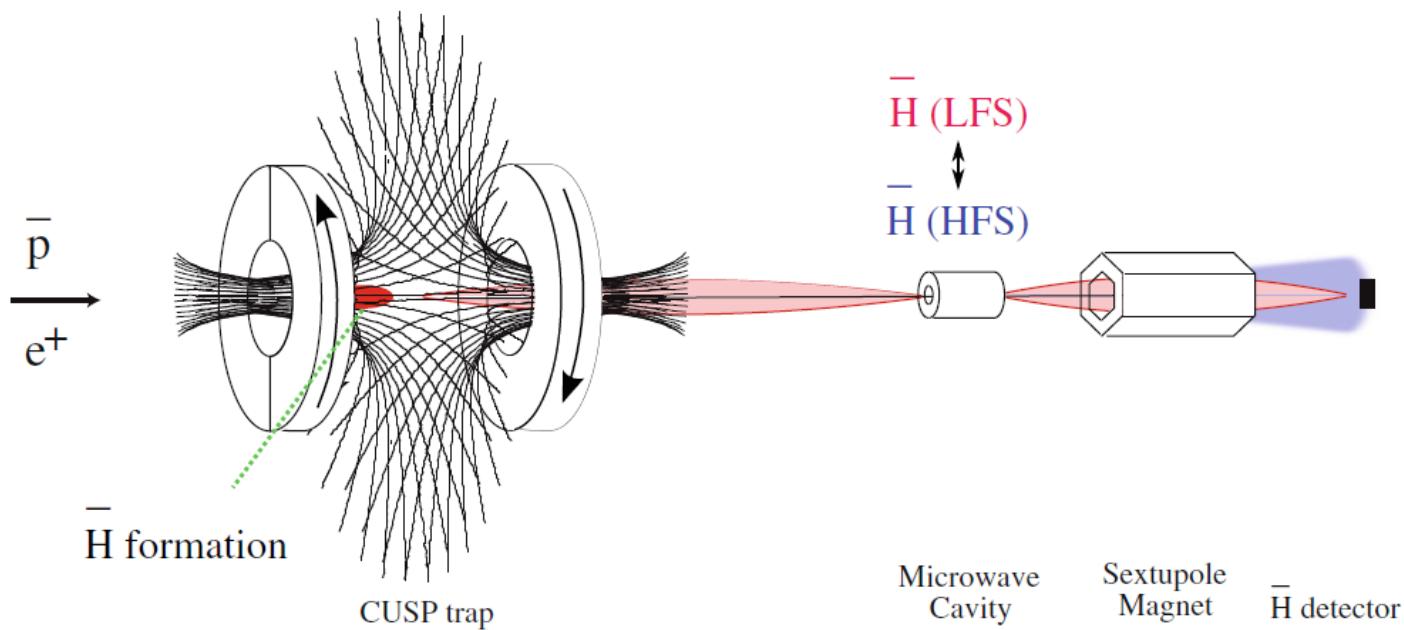


# Antiprotons: CERN AD / ELENA



# How to produce Antihydrogen (1)

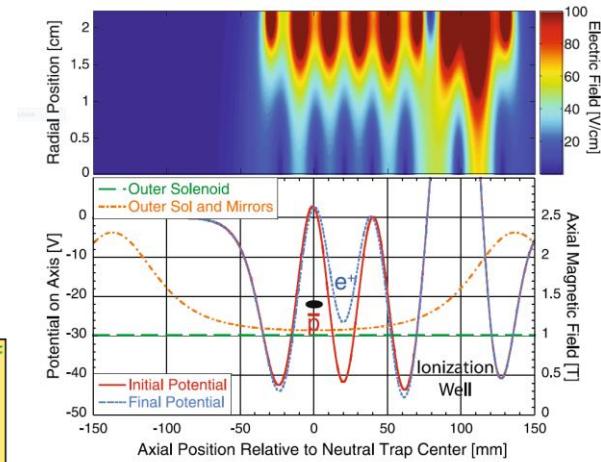
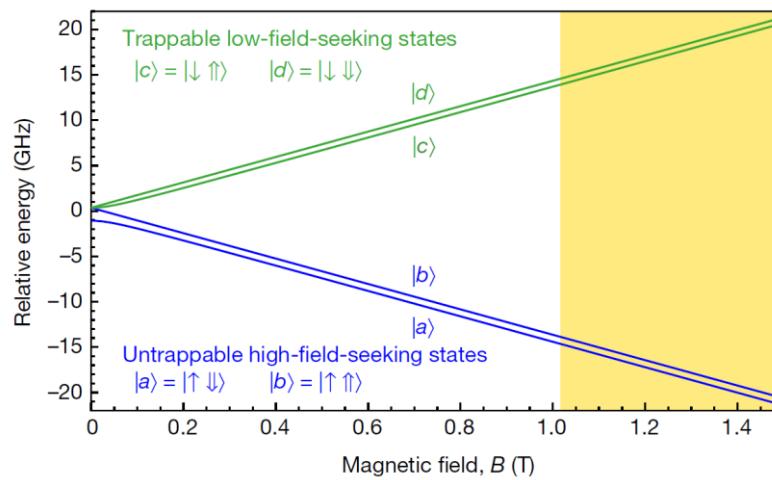
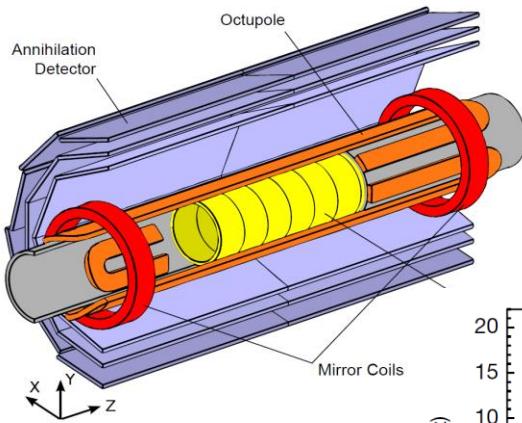
- Historically (LEAR 1995): 1.93 GeV/c  $\bar{p}$  on Xe gas jet → detection in flight
- AD: with a cusp trap (ASACUSA):
  - Multiring trap in a high B field done by anti-Helmholtz coils: mixing of  $\bar{p}$  and  $e^+$ , low efficiency
  - Produce  $\bar{H}$  beam, not trapped



# How to produce Antihydrogen (2)

- AD: with a multiring Penning trap (ALPHA, ATRAP):

- High uniform B field + Electric potential wells : Standard  $\bar{H}$  production via 3-body process :  $\bar{p} + e^+ + e^+ \rightarrow \bar{H}^* + e^+$
- mixing of  $\bar{p}$  and  $e^+$ , low efficiency
- + Octupolar B field: trapping  $\bar{H}$  by magnetic momentum:  $\sim 0.5\text{K}$  max E

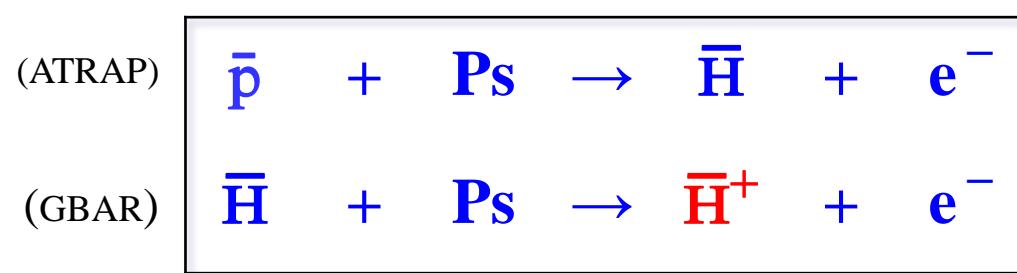
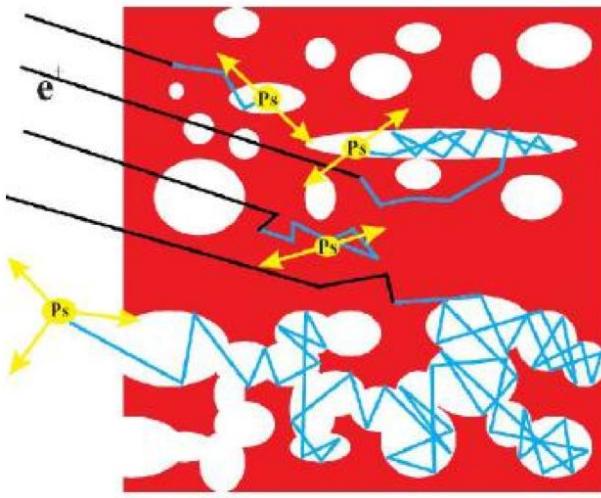


$$(E_{\text{mag}} = -\vec{\mu} \cdot \vec{B})$$

# How to produce Antihydrogen (3)

## - AD: Using positronium (AEgIS, GBAR):

- Produce ortho-positronium ( $oP_s$ ) sending  $e^+$  on mesoporous silicate;
- Then send antiprotons on Ps :  $\bar{p} + P_s \rightarrow \bar{H} + e^-$
- Simple charge exchange reaction, better efficiency if Ps excited
- demonstrated by ATRAP (2004)
- **Idea for GBAR:** 2<sup>nd</sup> charge exchange reaction  $\Rightarrow$  Antihydrogen ion; more easily trappable



P. Pérez & A. Rosowsky, NIM A 532, 523-532 (2004)

Binding energy of  $\bar{H}^+ = 0.75$  eV = energy level of  $Ps(n=3)$

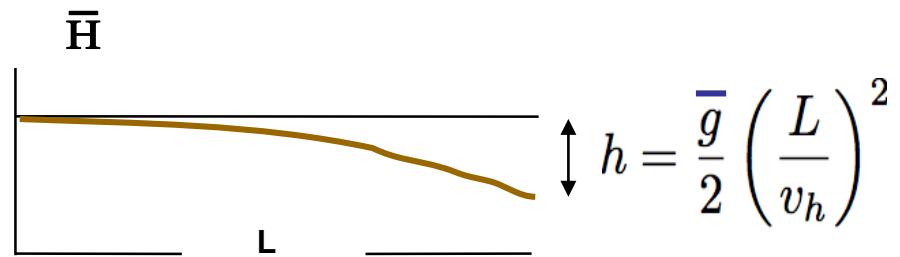
Expect cross-section enhancement if Ps excited to n=3

# Gravitation measurement: a race to slowness...

Principle :

**Parabolic flight of  $\bar{H}$**

Measured by deflectometer or  
free fall time



- $L = 2 \text{ cm}$  and  $v_h \sim 100 \text{ m/s}$  ( $T(\bar{H}) \lesssim 500 \text{ mK} \sim 65 \text{ meV}$ )  
→ *ALPHA* : - atoms  $\bar{H}$  (neutral)
- $L = 1 \text{ m}$  and  $v_h \sim 50 \text{ m/s}$  →  $h = 20 \mu\text{m}$  ( $T(\bar{H}) \sim 100 \text{ mK} \sim 10 \mu\text{eV}$ )  
→ *AEGIS* : - atoms  $\bar{H}$  (neutral)
- $L = 0.1 \text{ m}$  and  $v_h = 0.5 \text{ m/s}$  →  $h = 20 \text{ cm}$  ( $T(\bar{H}) \sim 10 \mu\text{K} \sim 1 \text{ neV}$ )  
→ *GBAR*: - *create and cool  $\bar{H}^+$*

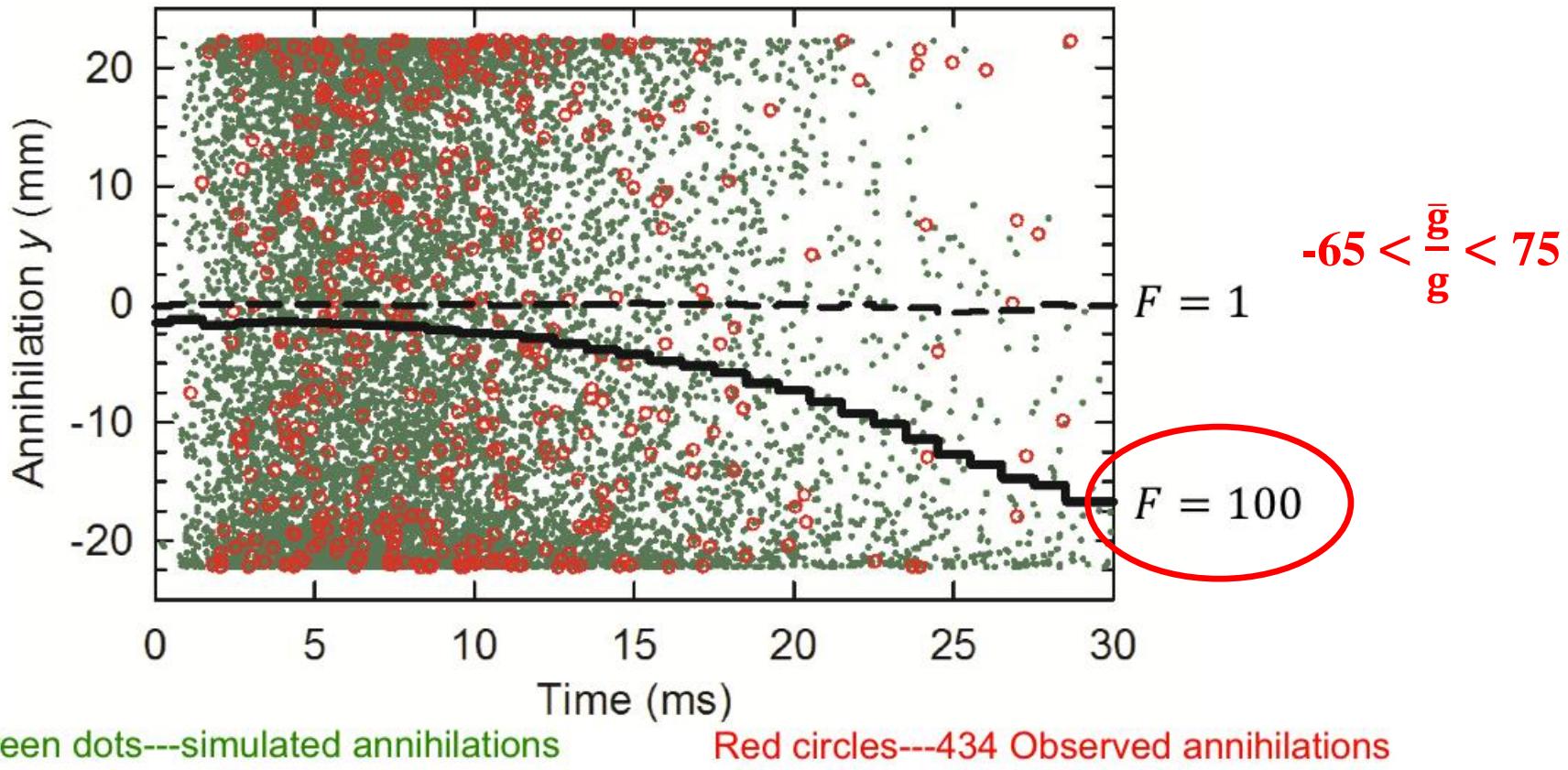
P. Pérez et al, *Proposal CERN - SPSC- 029 (2011)*

# A first estimate...



Antihydrogen

$$F = M_G/M$$



Vertical position of annihilation vertex during release of trapping field

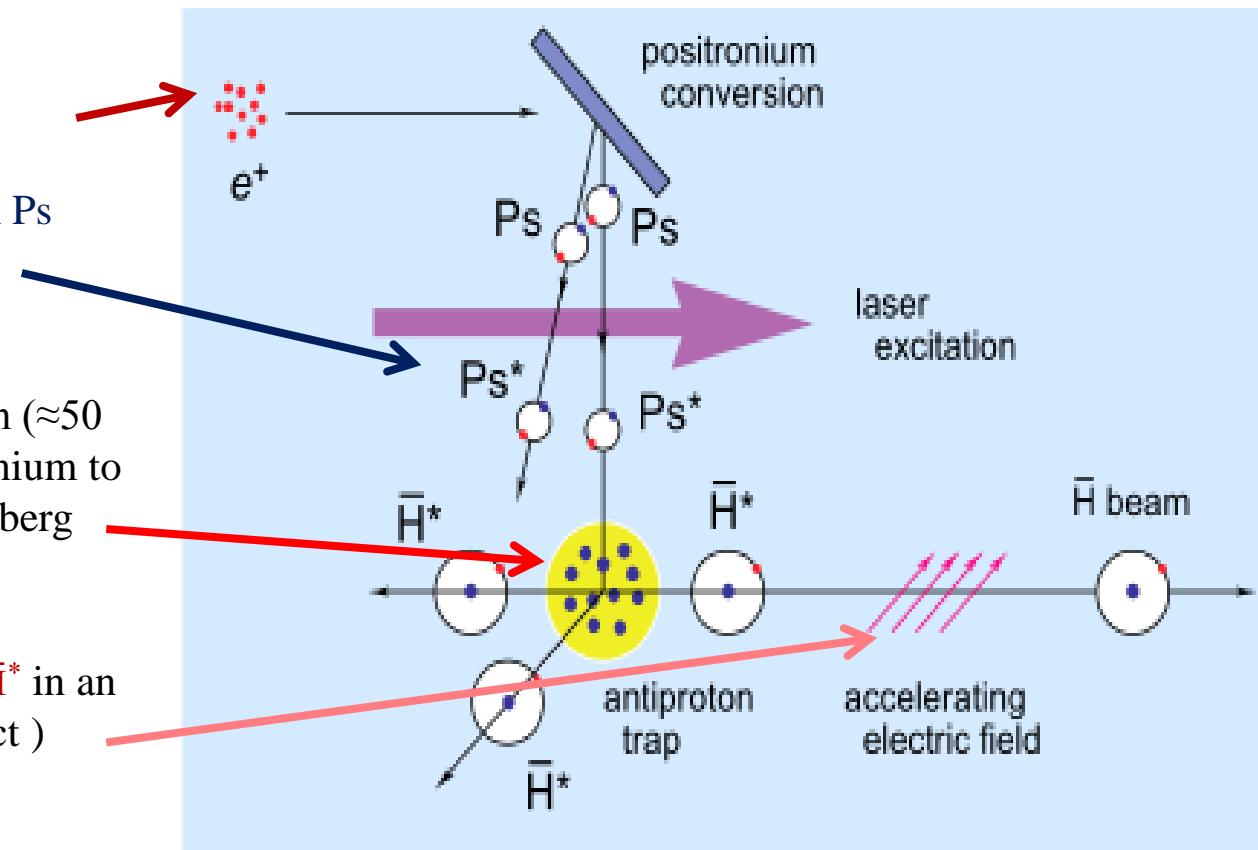
The ALPHA collaboration

Nature comms 2013 (4:1785 / DOI: 10.1038/ncomms2787)

# Experiment to come: AEgIS

*Principle: Measure of a very small gravitational deflection of antihydrogen atom trajectories using Moiré detector*

- Accumulation of **positrons** in a trap
- Creation of excited positronium Ps (atom  $e^+e^-$ ),
- Antiprotons cooling at 0,1 kelvin ( $\approx 50$  m/s), interacting with the positronium to form slow antihydrogen  $\bar{H}^*$  (Rydberg state)
- Controlled acceleration of the  $\bar{H}^*$  in an electric field gradient (Stark effect )
- Passage through a Moiré deflectometer : detection of shifts of the order of micrometers.



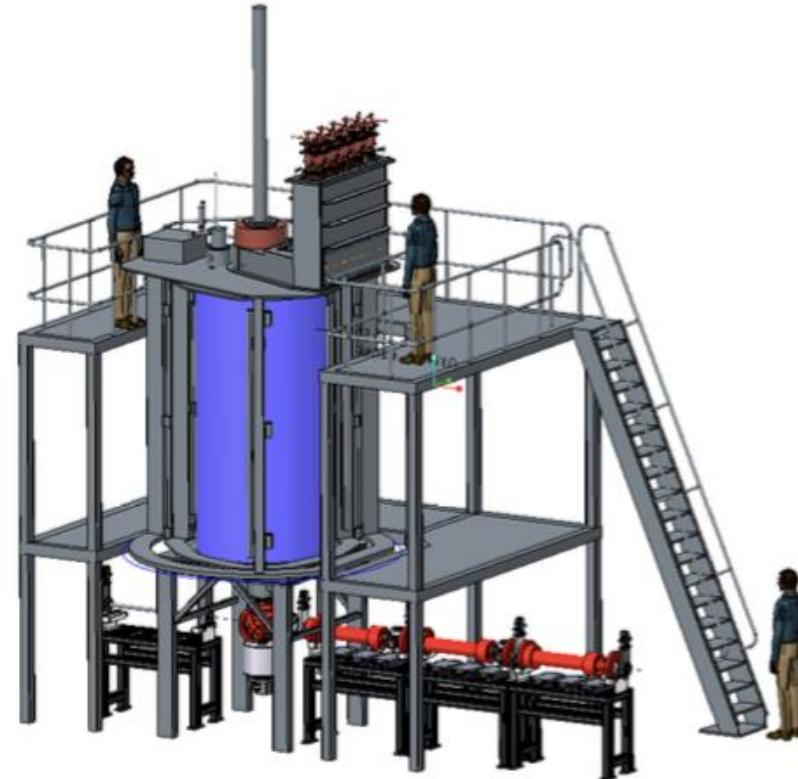
# Experiment to come: Alpha-g

## Principle:

*Trap antihydrogen atoms in an octupolar magnetic field in a vertical trap.  
Reduce the field: antihydrogen are more energetic at the trap bottom.*

CERN-SPSC-2016-031 / SPSC-P-325-ADD-1

- Formation of antihydrogen atoms in a trap, as in the present ALPHA apparatus.
  - Only the coolest ones (<500 mK) are trapped by the magnetic field gradient created by the octupolar field (low field seeking antiatoms).
  - From top to bottom, an antihydrogen gains 1.2 mK in energy by the gravitational field.
  - Gradient for trapping 1.2 mK  $\bar{H}$  : 15 G/m
  - Reduces octupolar field slowly (15 G/m in one bounce of 5 ms)
- Observe and measure the  $\bar{H}$  annihilating at the bottom → Sign of  $\bar{g}$   
➤ Vary gradient to make up-down measurement →  $\bar{g}$  at 1 %



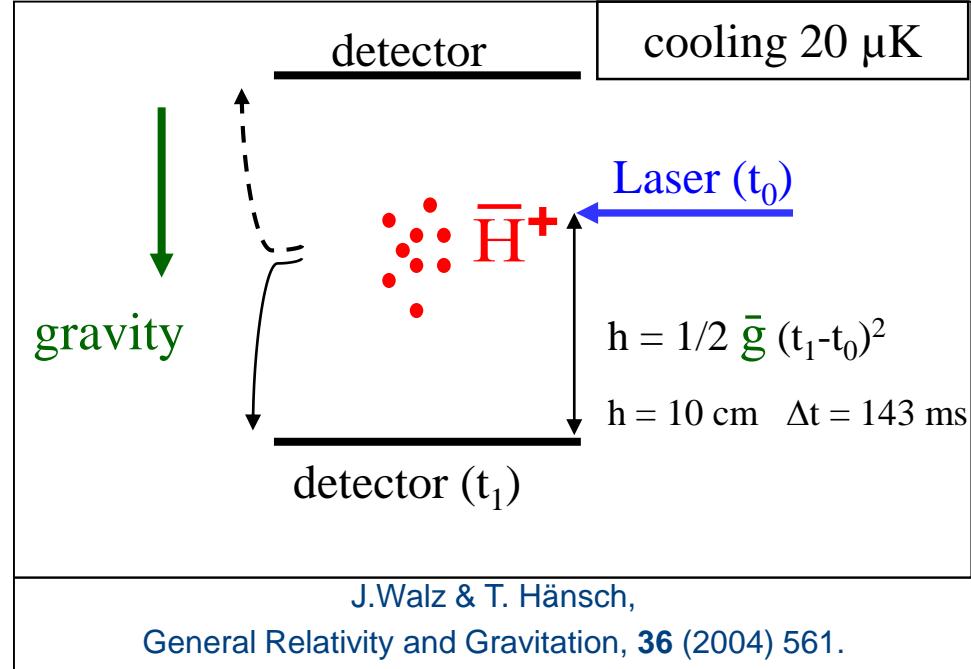
# Experiment to come: GBAR



*(Gravitational Behaviour of Antihydrogen at Rest)*

# Gbar : use $\bar{H}^+$ to get $\bar{H}$ atoms

- Produce ion  $\bar{H}^+$
- Capture ion  $H^+$
- Sympathetic cooling 20  $\mu K$
- Photodetachment of  $e^+$
- Free fall time of flight measurement



Relative precision on  $\bar{g}$

$\bar{H}^+$ in ion trap	$\Delta g/g$
$5 \cdot 10^5$	0.001
$10^4$	0.006
$10^3$	0.02

*Uncertainty dominated by temperature of  $\bar{H}^+$*

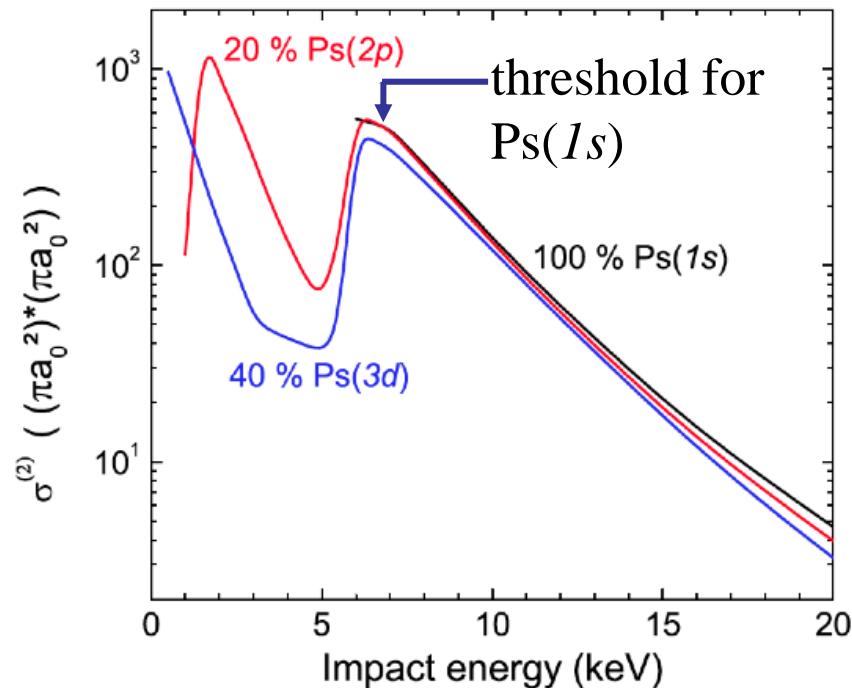
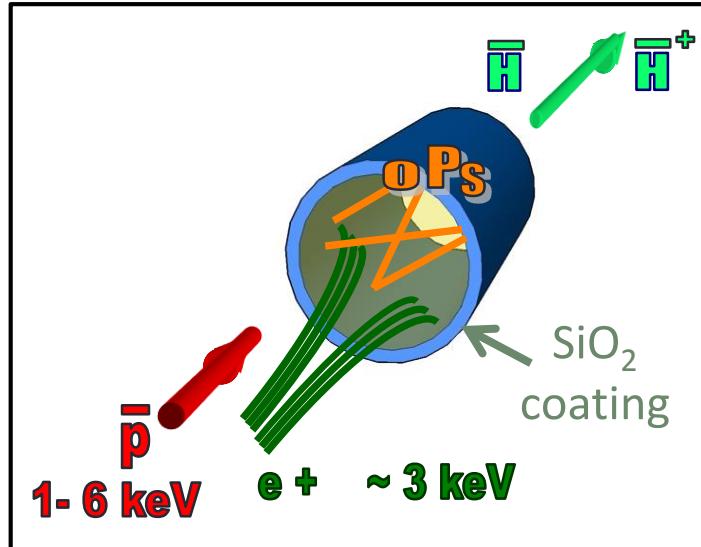
# $\bar{H}^+$ production yield

CERN provides per bunch  
every 110 s

dump  $3 \times 10^{10}$   $e^+$   
On a  $\text{SiO}_2$  porous surface



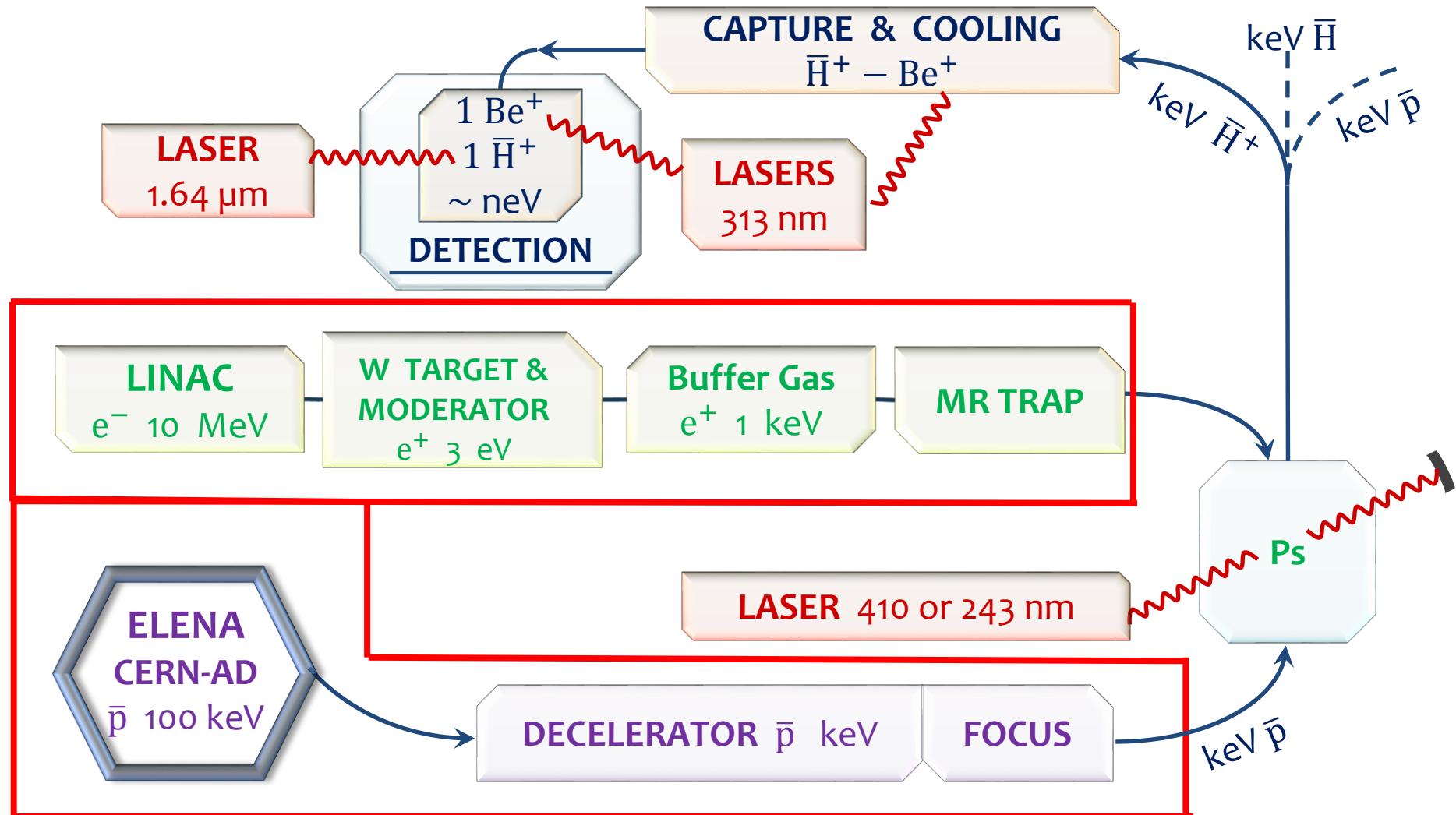
$$\begin{array}{c} \sim 0.5 \cdot 10^7 \bar{p} \\ 10^{12} \text{ P}_S / \text{cm}^2 \end{array} \quad \left. \right\} \rightarrow \begin{array}{l} 10^4 \bar{H} \\ 1 \bar{H}^+ \end{array}$$



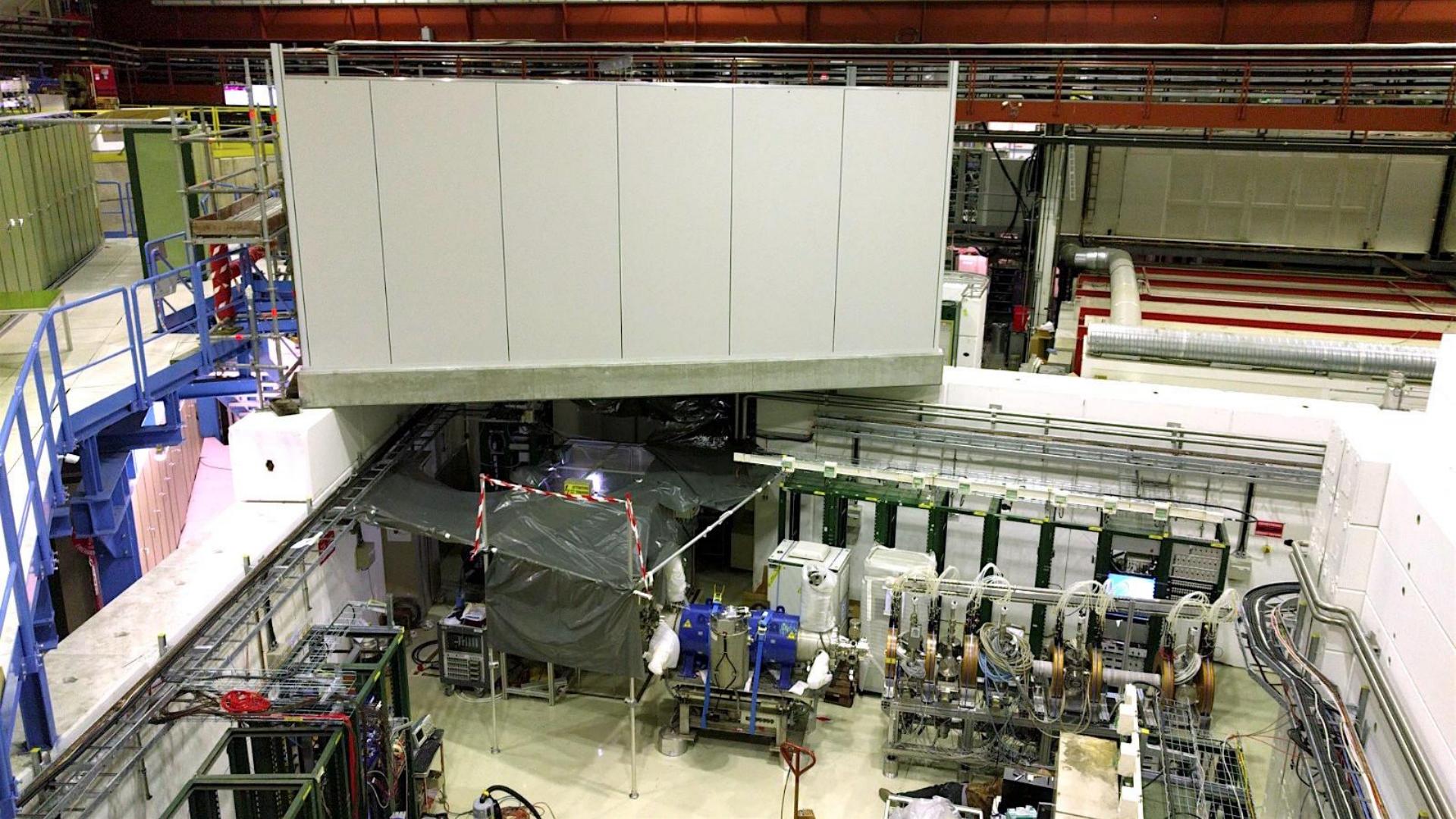
P. Comini and P-A. Hervieux, J. Phys.: Conf. Ser. **443**, 012007 (2013)

P. Comini, P-A. Hervieux and F. Biraben, LEAP 2013

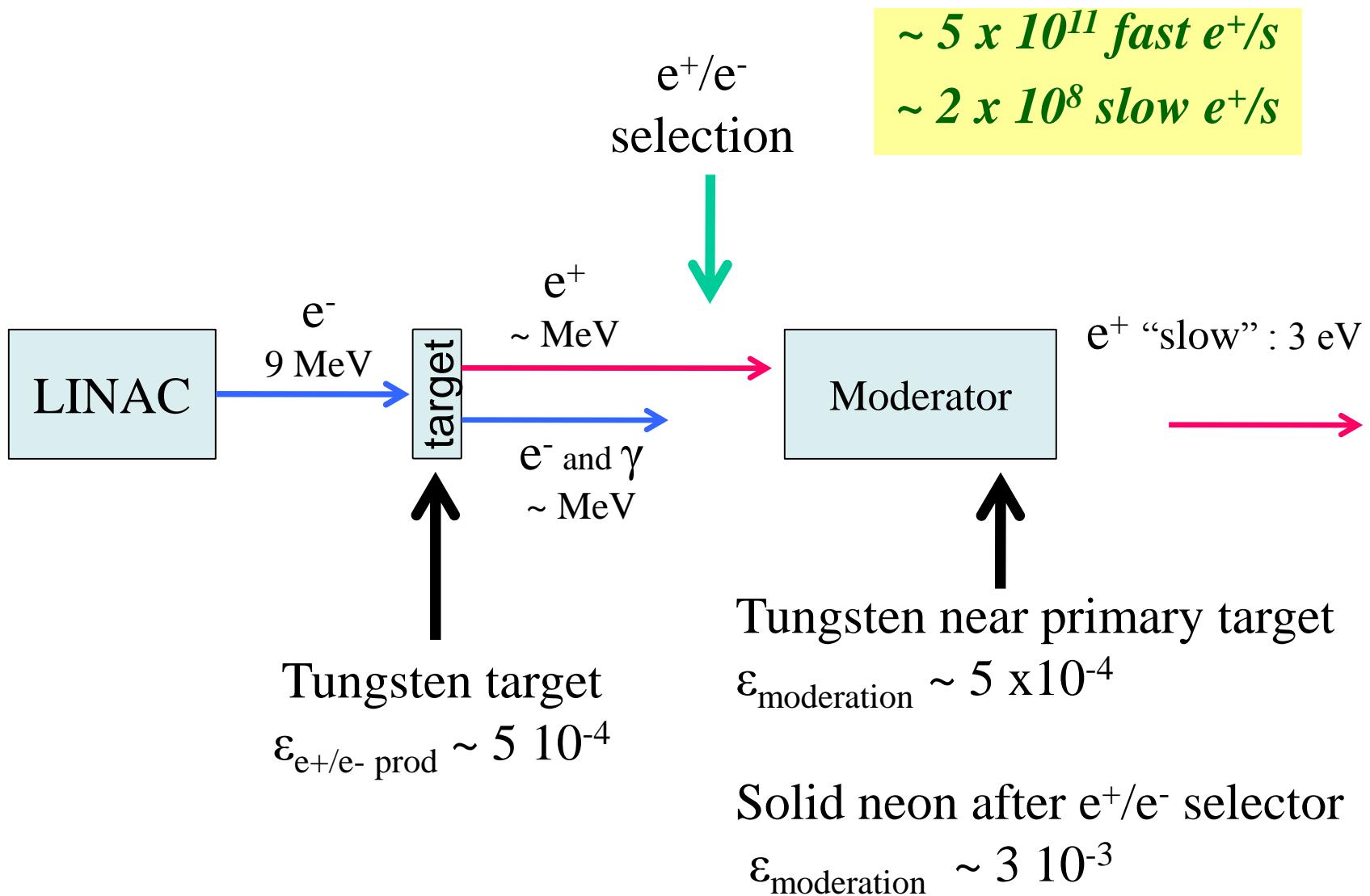
# GBAR experimental scheme



# CERN GBAR Zone (Nov. 2017)



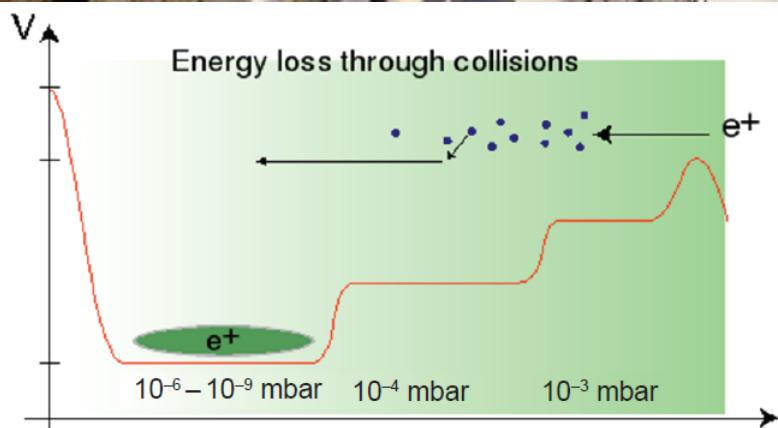
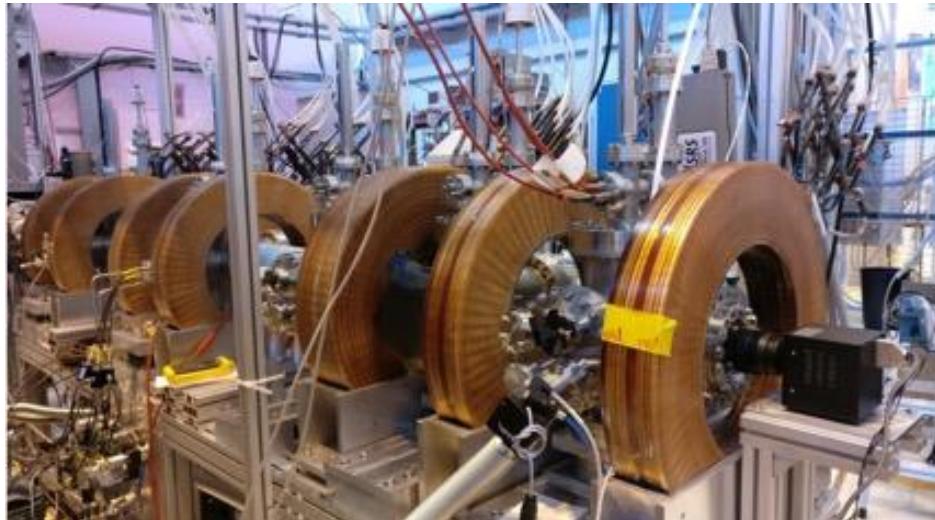
# High intensity slow positrons source



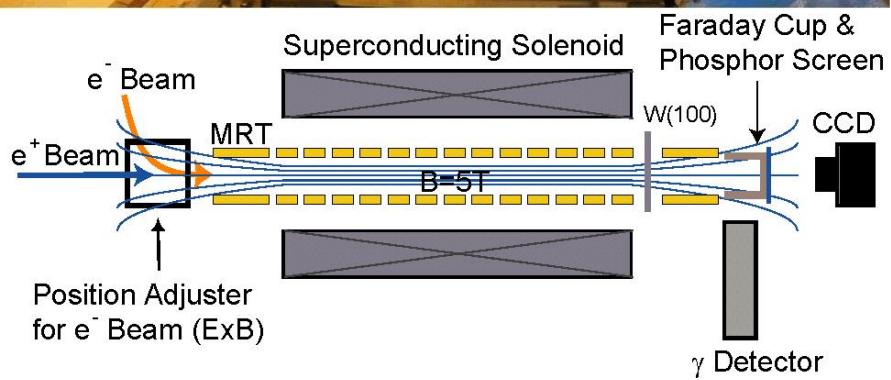
# Positron trapping

A two stage accumulation being realized at Saclay:

1. buffer gas trap to cool positrons with nitrogen

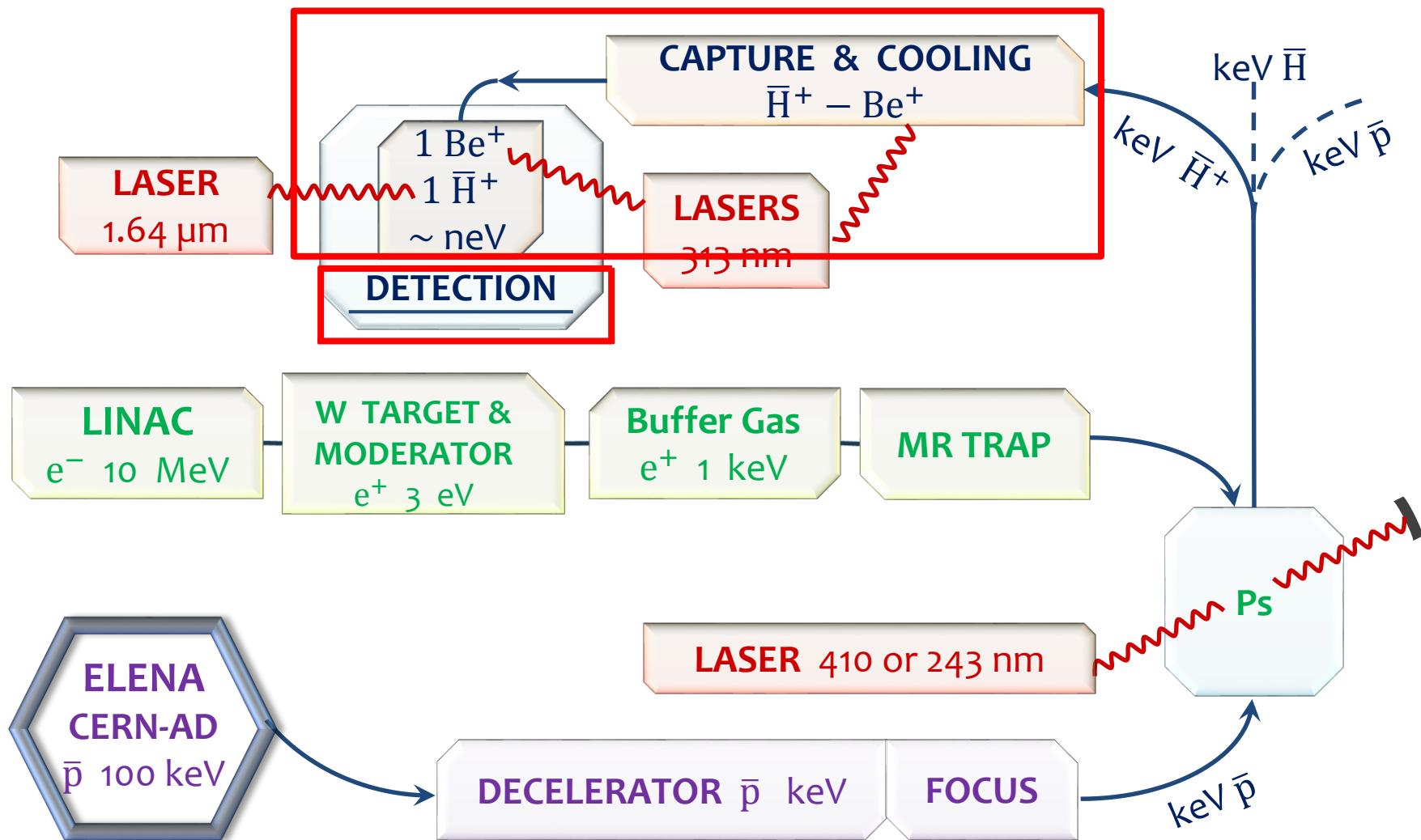


2. Multi Ring Trap accumulator



Must accumulate  $3 \cdot 10^{10} e^+$  in 110 s

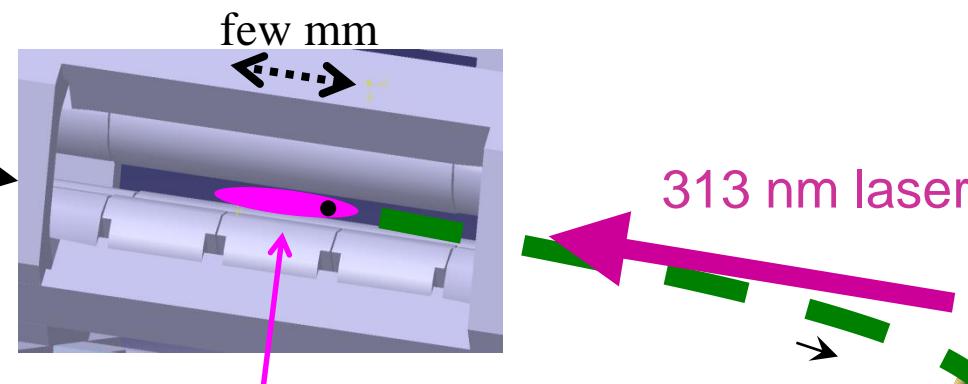
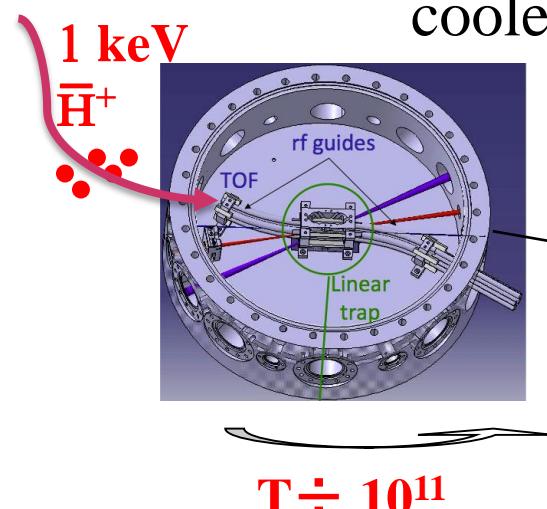
# Experimental Scheme



# $\bar{H}^+$ with $v < 1$ m/s: from 700000 K to 20 $\mu$ K !!!

Done in 2 steps

First step Capture and sympathetic cooling by Doppler laser cooled  $Be^+$  ions in the linear **capture trap**

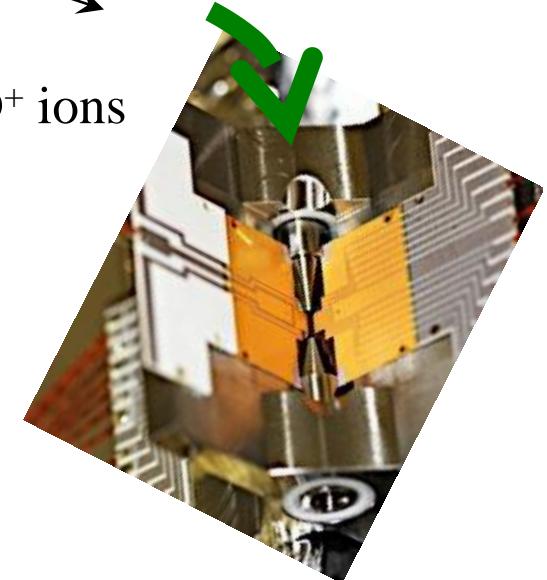


> 10 000 laser cooled  $Be^+/HD^+$  ions  
100 neV,  $T \sim mK$

Second step

Transfer and ground state cooling  
of a  $Be^+/H^+$  ion pair in the **precision trap**

tests with  $H_2^+ / H^+$  REMPI source



# Free Fall

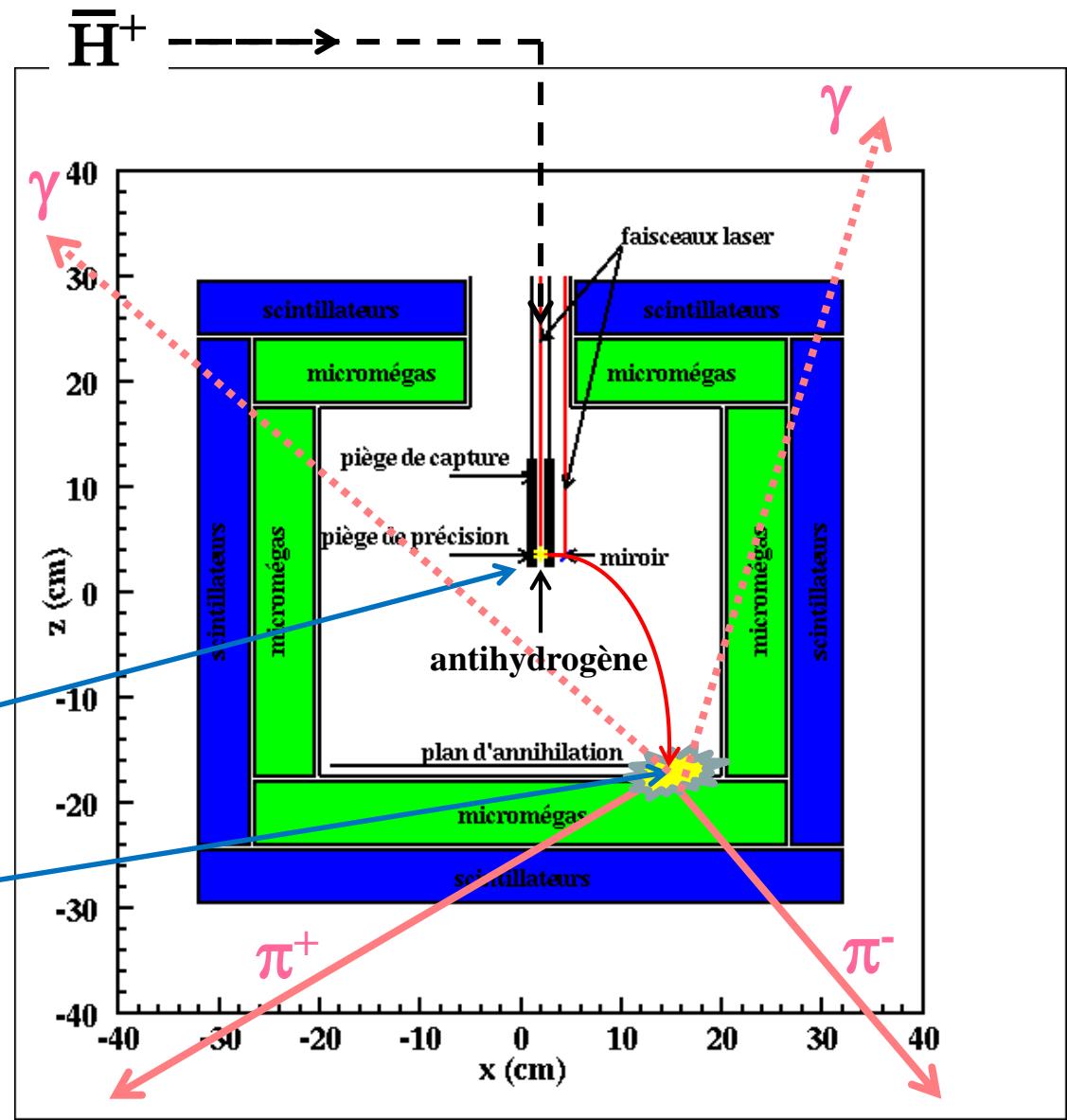
**Aim :**  
**measure  $\bar{g}$  to 1 %**  
 (phase 1)  
 ~ 1500 events

Detection	Requirement
TOF	150 $\mu$ s
Annihilation vertex	2 mm
Background rejection	event topology

Laser shot  
 $t_0$   
 annihilation  
 $t_1$

Free fall height  $h = 20$  cm

$$h = \frac{1}{2} \bar{g} (t_1 - t_0)^2 + v_{z0}(t_1 - t_0)$$





# GBAR Collaboration



P.N. Lebedev Physical  
Institute of the Russian  
Academy of Science



JOHANNES GUTENBERG  
UNIVERSITÄT MAINZ



Swansea University  
Prifysgol Abertawe



서울대학교  
SEOUL NATIONAL UNIVERSITY



KOREA  
UNIVERSITY

# SUMMARY

Motivation is high

Theory is low

Experiments are on the track

Bets are open!

