XLI. Arbeitstreffen “Kernphysik“, Schleching, 18.-25. Februar 2010

Review: FLAIR and Antiprotons

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FLAIR and antiprotons — Topics at Schleching

Th	18-02-2010	E. Widmann (1)	Low-energy antiproton sources
		D. Gotta	X-ray spectroscopy of antiprotonic atoms
		F. Maas	The new Helmholtz Institute Mainz
Fr	19-02-2010	E. Widmann (2)	Antiprotonic helium; Tests of CPT
Sa	20-02-2010	W. Oelert	$p\overline{p} \to \Lambda\overline{\Lambda}$, $S = -2$, ATRAP
Mo	22-02-2010	~~Th. Stöhlker~~	~~FLAIR and ions in storage rings~~
		W. Quint	FLAIR and ions in traps — HITRAP
Tu	23-02-2010	E. Widmann (3)	Antihydrogen; Experiments at FLAIR
We	24-02-2010	M. Doser	Antimatter gravity – the AEgIS experiment
		K. Blaum	New approach to antihydrogen experiments
		O. Hartmann	Nuclear physics with antiprotons
		S. Ulmer	Magnetic moment of the (Anti-)Proton

FLAIR and antiprotons — Topics not discussed at Schleching

- Polarized antiprotons (PAX, spin-polarized Helium, . . .)
- collisions physics / reaction microscope
- antiprotons and rare isotopes
- antideuteron breeding
- ultracold Rydberg plasmas
- Lyman-alpha generation and laser cooling
- Sympathetic cooling with laser-cooled Os^-

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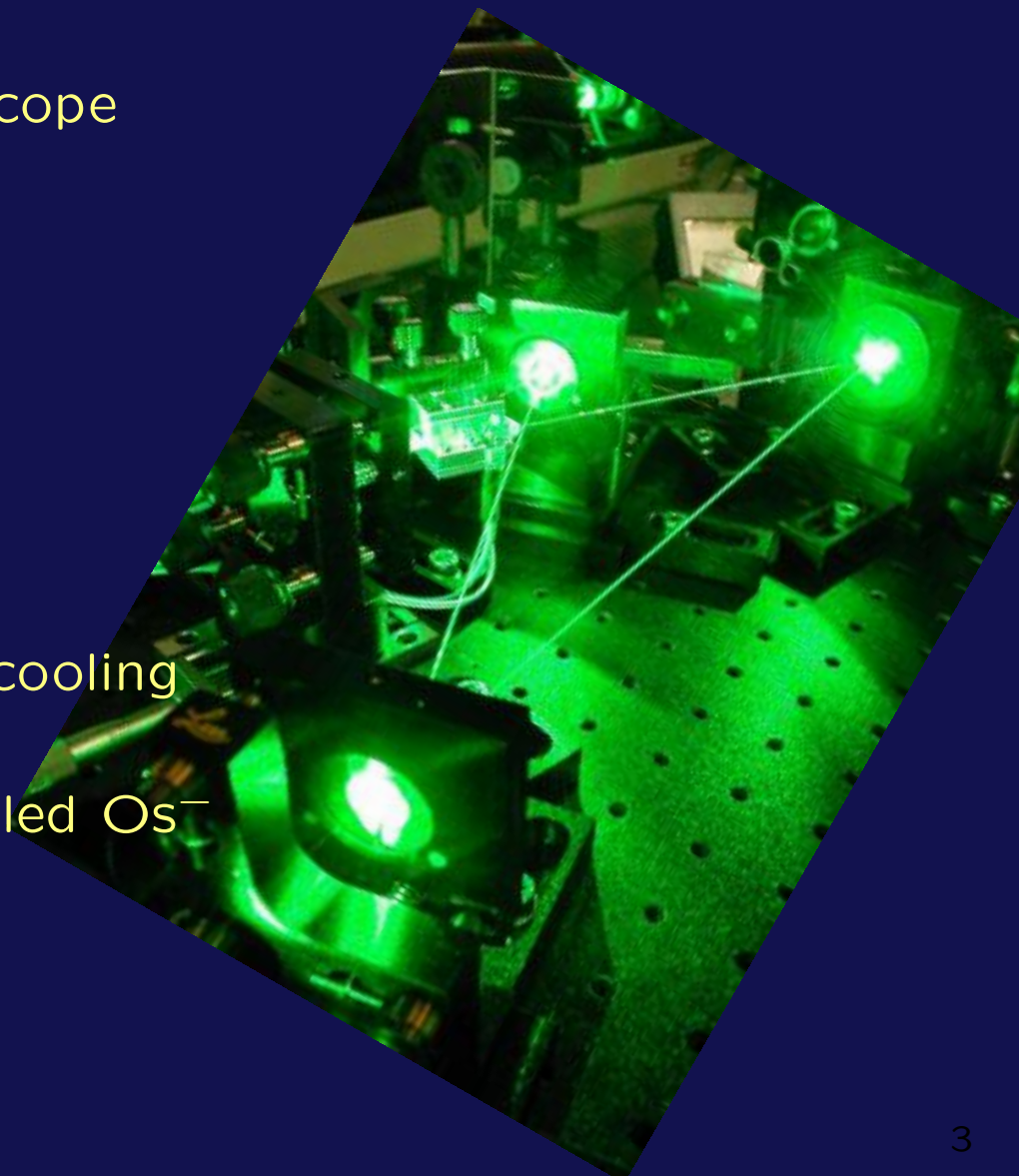
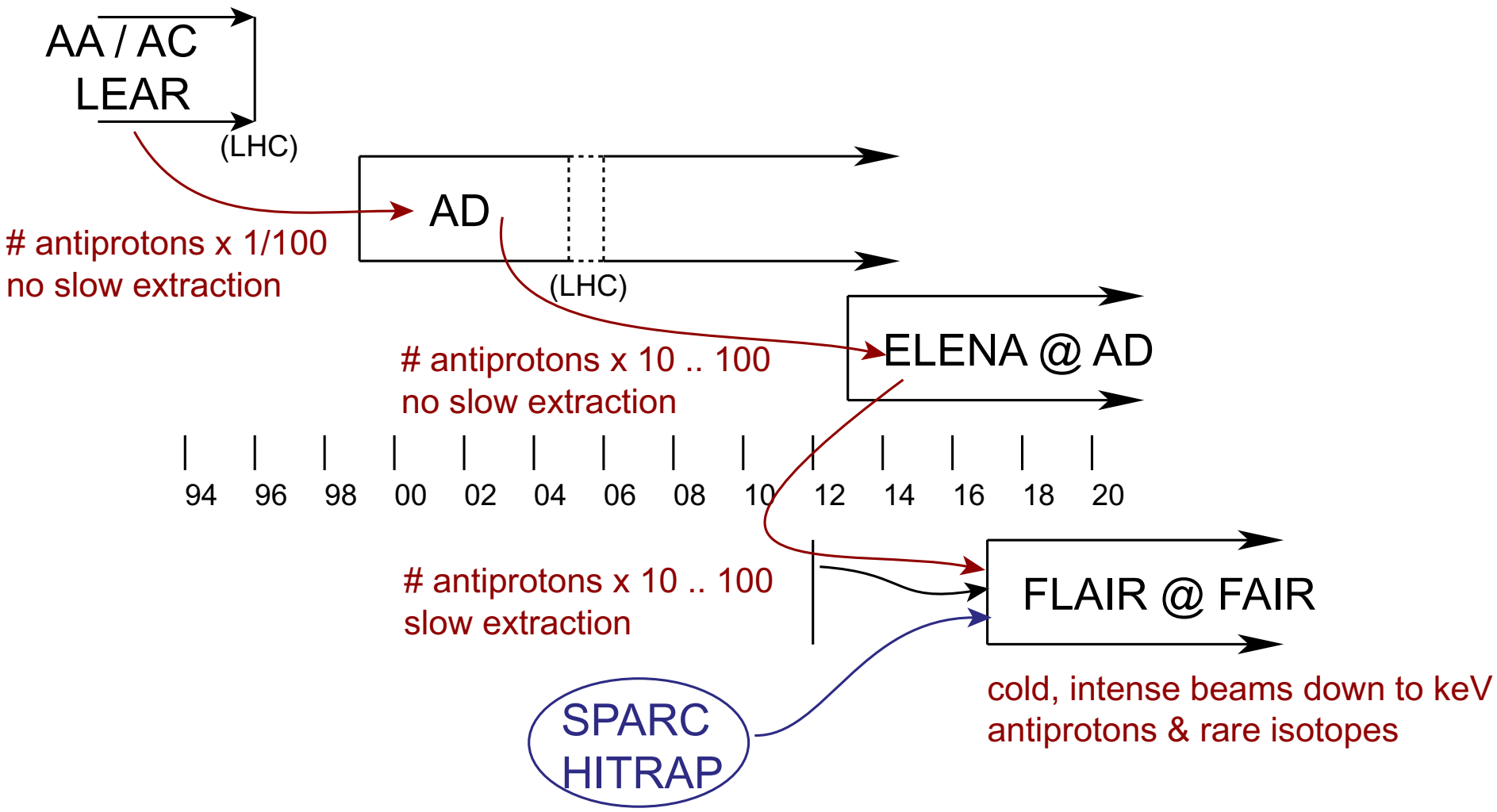


Low Energy Antiproton Sources

K. Jungmann: "Precision experiments need Time, Care, and Particles."



Why antihydrogen spectroscopy?

The Planck Scale
at 10^{19} Gev / 10^{-35} m:
quantum gravity,
grand unified theories,
superstrings . . .

CPT symmetry

charge conjugation
parity inversion
time reversal

Pauli, Lüders, Bell 1954

Greenberg '02

Lorentz symmetry
(rotations, boosts)

mysteries:
no antimatter in the universe,
dark matter / dark energy,
quantum theory of gravity

The Standard Model:
"perfect symmetry."

hydrogen frequencies:

$\nu_{1S-2S} = 2\,466\,061\,102\,474\,851\,(34)$ Hz

$\nu_{HF} = 1\,420\,405\,751.768\,(1)$ Hz

Experimental tests of CPT symmetry

$\left\lvert m_{K^0} - m_{\bar{K}^0} \right\rvert / m_{\text{average}}$	< 8	$\times 10^{-19}$
$\left(g_{e+} - g_{e-}\right) / g_{\text{average}}$	(-0.5 ± 2.1)	$\times 10^{-12}$
$\left(\left\lvert \frac{q_{\bar{p}}}{m_{\bar{p}}} \right\rvert - \frac{q_p}{m_p}\right) / \frac{q_p}{m_p}$	(-9 ± 9)	$\times 10^{-11}$
$(m_p - m_{\bar{p}}) / m_p$	< 2	$\times 10^{-9}$
$\left(g_{\mu+} - g_{\mu-}\right) / g_{\text{average}}$	(-0.11 ± 0.12)	$\times 10^{-8}$

→ pdg.lbl.gov

The Standard Model Extension

Indiana group, Kostelecký et al., since 1997

modified Dirac equation for an electron in the proton Coulomb potential:

$$(\underbrace{i\gamma^\mu \partial_\mu - q\gamma^\mu A_\mu - m_e}_{\text{standard Dirac equation}} \underbrace{- a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu}_{\text{CPT violating}} \underbrace{- \frac{1}{2} H^e_{\mu\nu} \sigma^{\mu\nu} + i c^e_{\mu\nu} \gamma^\mu D^\nu + i d^e_{\mu\nu} \gamma_5 \gamma^\mu D^\nu}_{\text{CPT preserving terms}}) \Psi = 0$$

CPT-violating terms a and b have energy dimensions

$\Rightarrow$ dimensionless comparison not meaningful

$$\Delta^{H-\bar{H}} \nu_{1S\text{–}2S} \approx -(b^e_3 - b^p_3)/\pi$$
$$\Delta^{H-\bar{H}} \nu_{\text{HFS}} \approx -2 b^p_3/\pi$$

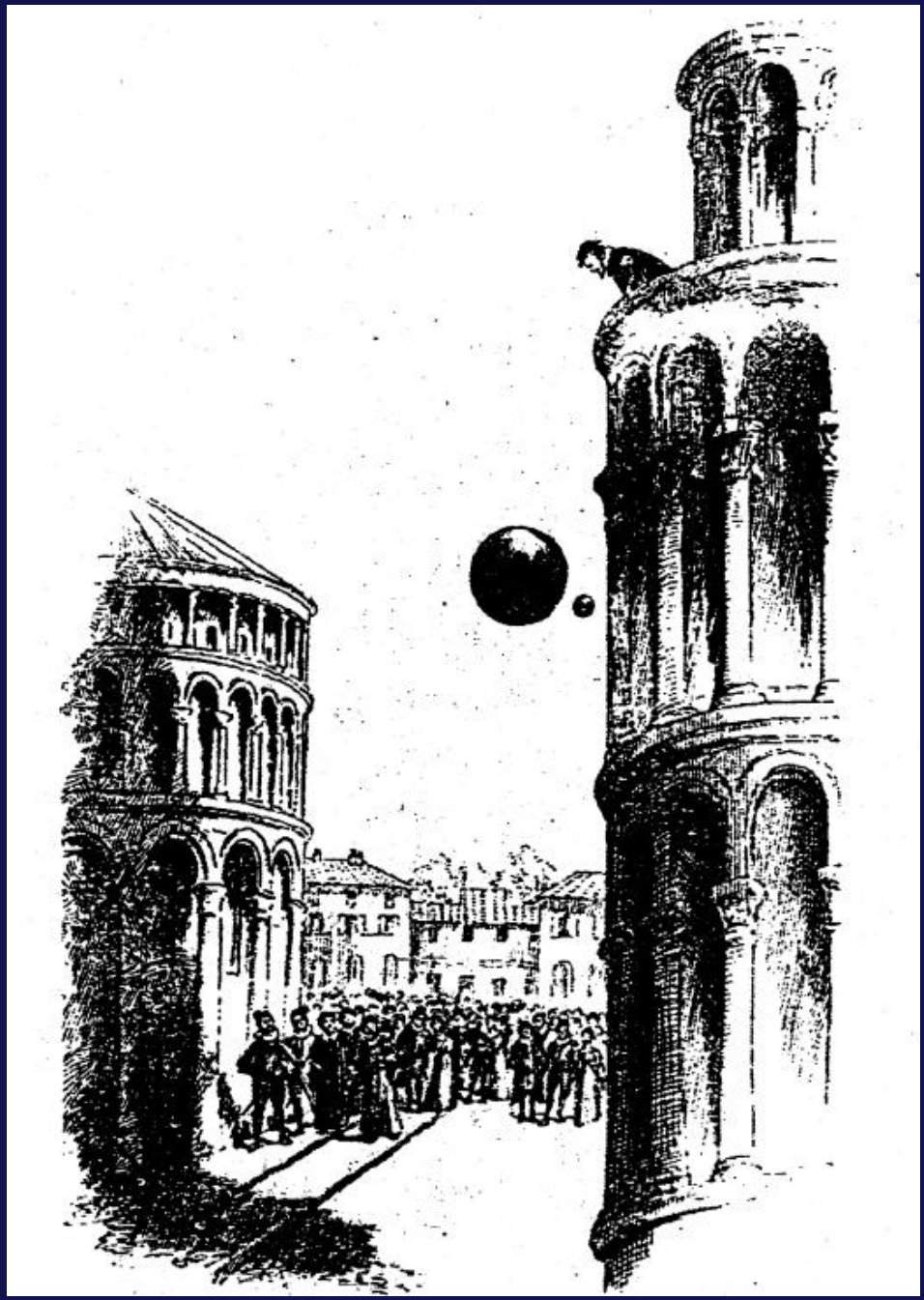
$\nu_{1\,S\text{–}2\,S} = 2\,466\,061\,102\,474\,851\,(34)$ Hz

$\nu_{\text{HF}} = 1\,420\,405\,751.768\,(1)$ Hz

$(\delta m/m)_{K^0/\bar{K}^0} \sim 10^{-18}$ ↑ ↑ benchmark: $\frac{m_e^2}{M_{\text{Planck}}} = 2.1 \times 10^{-17}$ eV

Gravitational acceleration of antimatter

- Never been measured directly.
- Stable antimatter used to be available as charged particles, only.
- Charged particles are extremely sensitive to stray electric fields.
- New situation: cold antihydrogen atoms are available.



Antimatter gravity

Equivalence Principle valid for antimatter?

$$m_{\text{inertial}} \stackrel{?}{=} m_{\text{gravitational}}$$

m_{inertial}: well-known

$m_{\text{gravitational}}$: unknown for antimatter

J. S. Bell (1986) "exchangeable energy does not antigravitate"

Supersymmetry / Quantum Gravity:

graviphotons (spin-1) and graviscalars (spin-0) ?

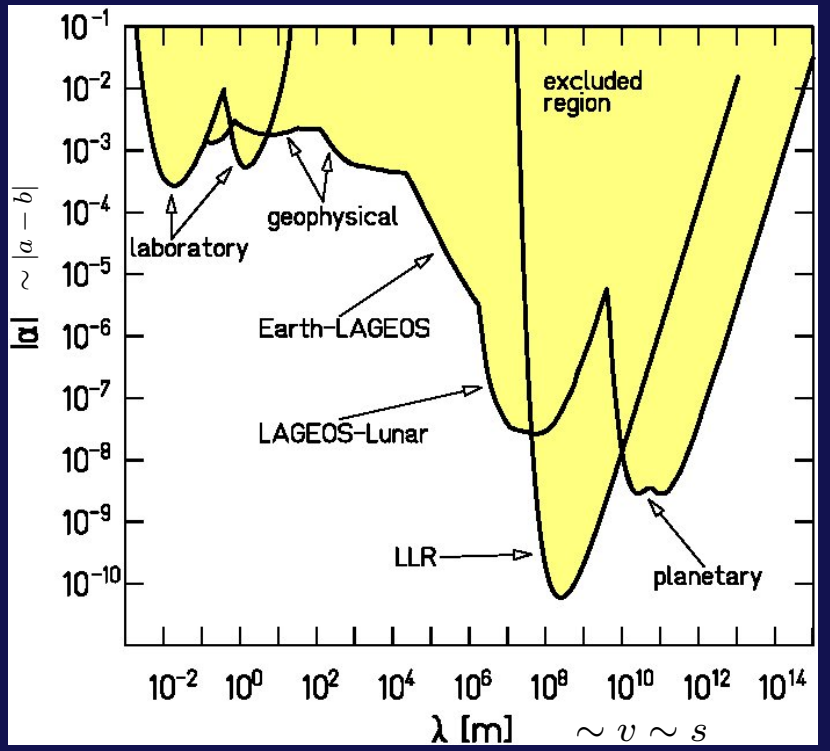
range v, charge a range s, charge b

$\Rightarrow$ non-Newtonian gravity

$$V(r) = \frac{-G\,m_1\,m_2}{r}\left(1 \pm a\; e^{-r/v} + b\; e^{-r/s}\right)$$

experiments with

matter are	sensitive to	$\lvert a-b\rvert$
antimatter	...	$\lvert a+b\rvert$



Experiments with charged particles (positrons / antiprotons) never got to the end.

Antihydrogen is electrically neutral and stable $\Rightarrow$ ideal for experiments in antimatter gravity.

Antihydrogen experiments – an overview

ATHENA
1 S–2 S 1999–2005

ALPHA
1 S–2 S 2005–

AEgIS
antimatter gravity 2007–

ATRAP
1 S–2 S 1999–

ASACUSA
antihydrogen experiments 2003–
- hyperfine splitting
- cusp trap
- two-tone Paul trap w/ laser-stim. recombination

Saclay (P. Perez)
antimatter gravity, $\bar{H}^+$ 2008 (LoI)

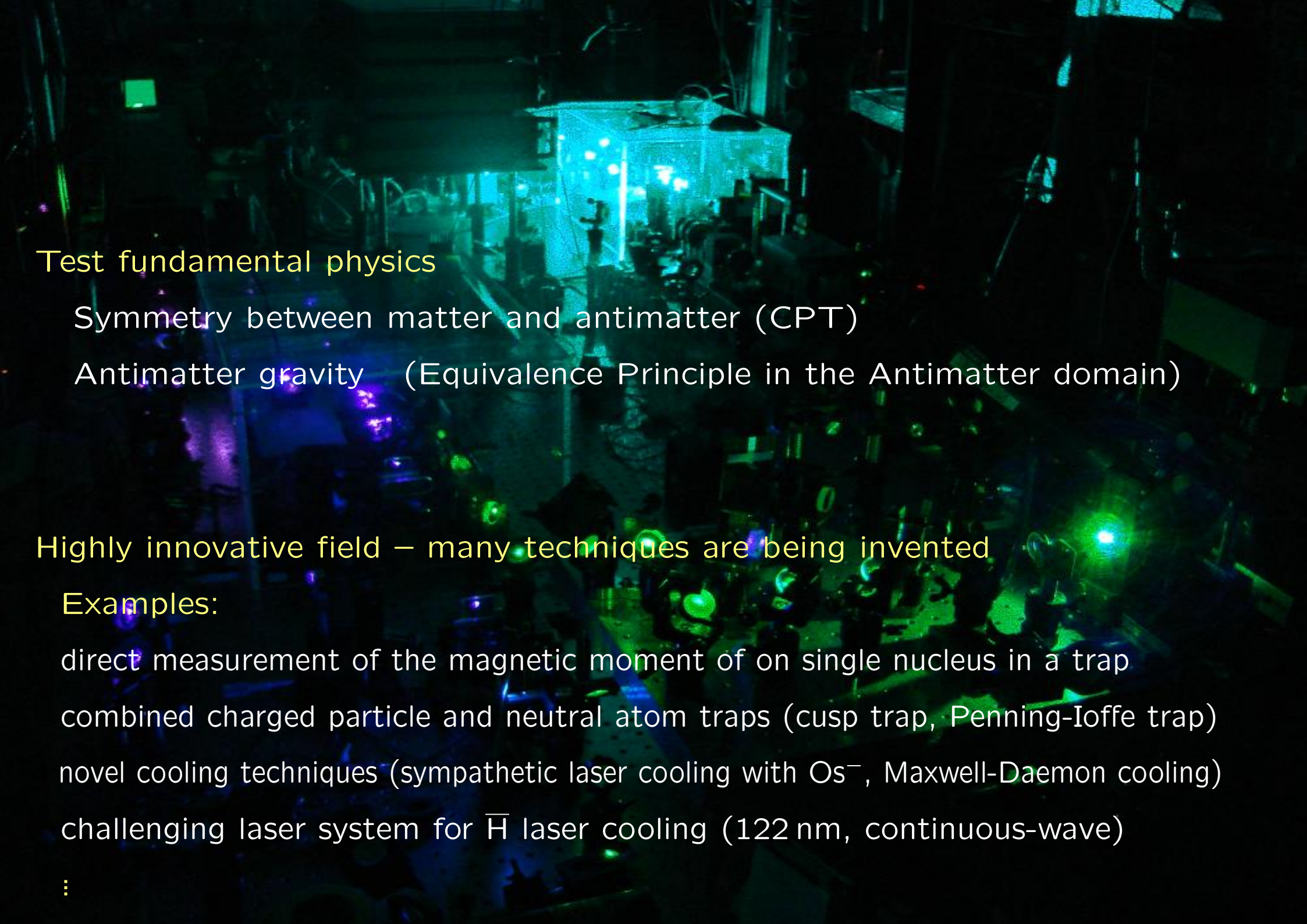
Blaum / Merkt / Raizen
new approach 2009 (white paper for FLAIR)

in 1999 (AD startup):
two $\overline{H}$ experiments
now:
3 × more!

Antihydrogen Physics – Progress ATRAP, only

1995	in-beam production of fast antihydrogen antiproton Penning-trap mass measurement ultrahigh-resolution hydrogen laser-spectroscopy	
1999	CERN's Antiproton Decelerator starts	
2002	cold antihydrogen production in three-body collisions by mixing cold positron and antiproton plasmas	PRL **89** (2002) 213401 PRL **89** (2002) 233401
2003	measurement of antihydrogen Rydberg states, recombination rates, velocities	PRL **93** (2004) 073401
2004	laser-controlled antihydrogen production	PRL **93** (2004) 263401
2005	CERN: no beam	
2006	antiproton and positron plasmas are stable in the combined charged-particle & neutral atom trap	PRL **98** (2007) 113002
2007	antihydrogen production in the combined charged-particle & neutral atom trap	PRL **100** (2008) 113001
next:	magnetic trapping $\longrightarrow$ spectroscopy	

The other collaborations (ATHENA, ALPHA, . . .) have made similar, or even more impressive progress.



Test fundamental physics

Symmetry between matter and antimatter (CPT)

Antimatter gravity (Equivalence Principle in the Antimatter domain)

Highly innovative field – many techniques are being invented

Examples:

direct measurement of the magnetic moment of on single nucleus in a trap

combined charged particle and neutral atom traps (cusp trap, Penning-Ioffe trap)

novel cooling techniques (sympathetic laser cooling with Os^-, Maxwell-Daemon cooling)

challenging laser system for $\overline{H}$ laser cooling (122 nm, continuous-wave)

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