FLAIR

Facility for Low-energy Antiproton and Ion Research

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Johannes Gutenberg University

International Conference on Science and Technology for FAIR in Europe 2014, Worms

HELMHOLTZ
Institut Mainz

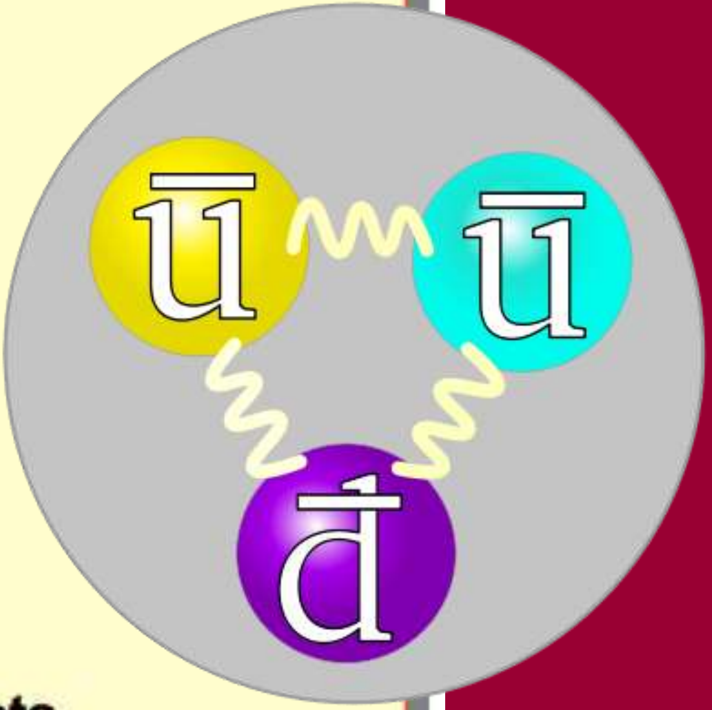
Why FLAIR ?

- High-brightness high-intensity low-energy antiproton ($\bar{p}$) beams

Why low-energy $\bar{p}$?

EXPERIMENTS WITH ANTIPROTONS AT EXTREMELY LOW ENERGIES

- **fundamental interactions**
  - CPT (antihydrogen, HFS, magnetic moment)
  - gravitation of antimatter
- **atomic collision studies**
  - ionization
  - energy loss
  - matter-antimatter collisions
- **antiprotonic atoms**
  - formation
  - strong interaction and surface effects



What about ions?

- Accelerator and facilities can be used for both p̄ and ions

- HCI = Highly Charged Ions

- Synergy → FLAIR ←→

- Stored Particles Atomic

  Research Collaboration Wilfried

Green Paper

The Modularized Start Version

The FLAIR Collaboration

Low-energy antiprotons will be available at FAIR with Module 4. The currently running experiments at the Antiproton Decelerator (AD) of CERN will be able to continue operation for the next few years as decided recently by the CERN management. A delay in the construction of FLAIR at FAIR will be temporarily bridged by the ELENA project at CERN. It can however not replace FLAIR in antiproton intensity and in providing slow extraction, and also lacks the synergies with highly charged ions and unstable nuclei available only at FAIR.

October 2009

Glossary

- SIS: SchereIonenSynchrotron (the main thing @ FAIR)
- ESR: Experimental Storage Ring

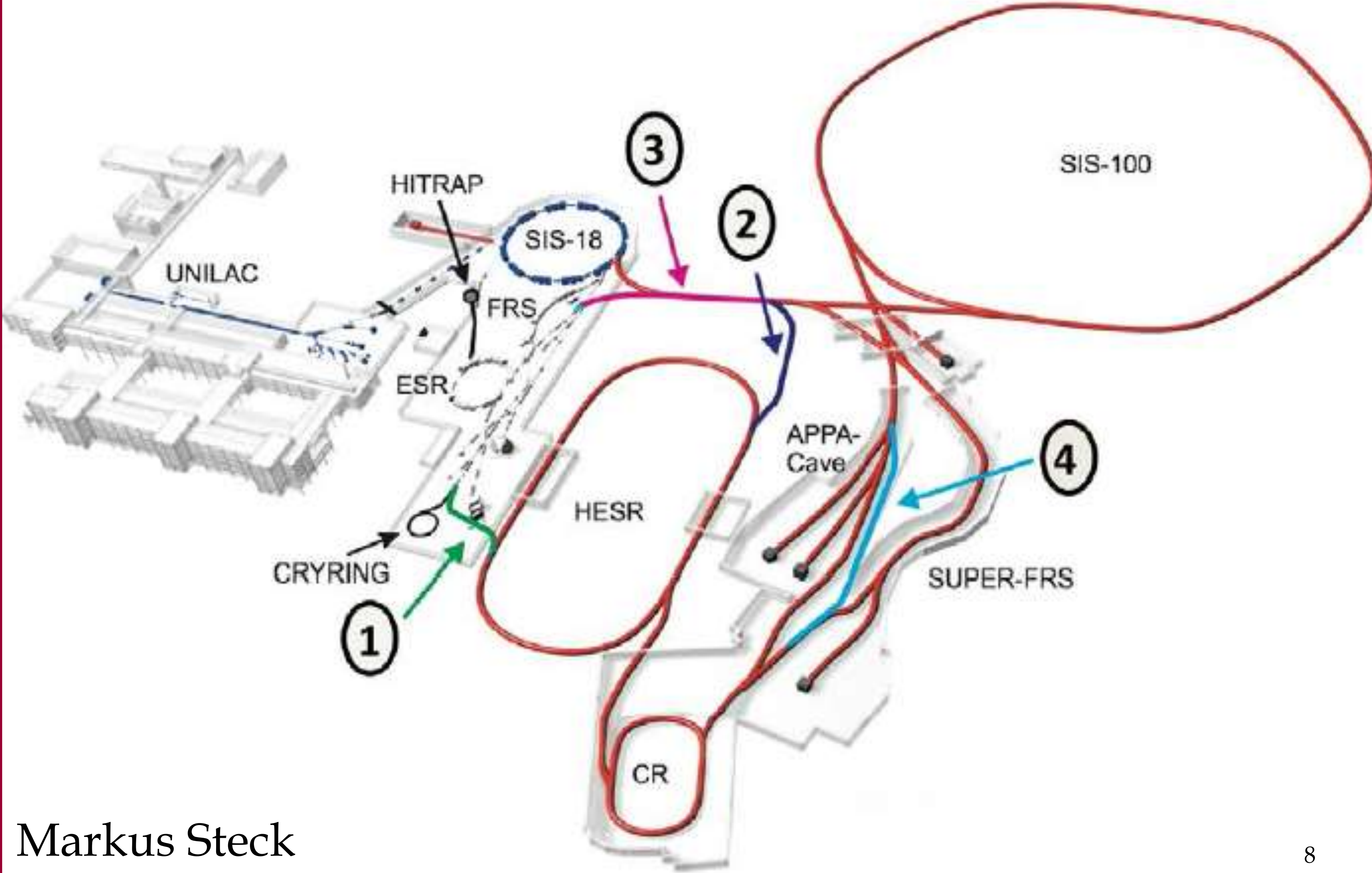
- LSR: Low-energy Storage Ring (magnetic)
  E = 300 keV – 30 MeV (e-cooled)
- CRYRING: atomic-physics ring from Sweden → LSR

- HITRAP: Penning trap after LSR (or USR)

- CR: Collector Ring

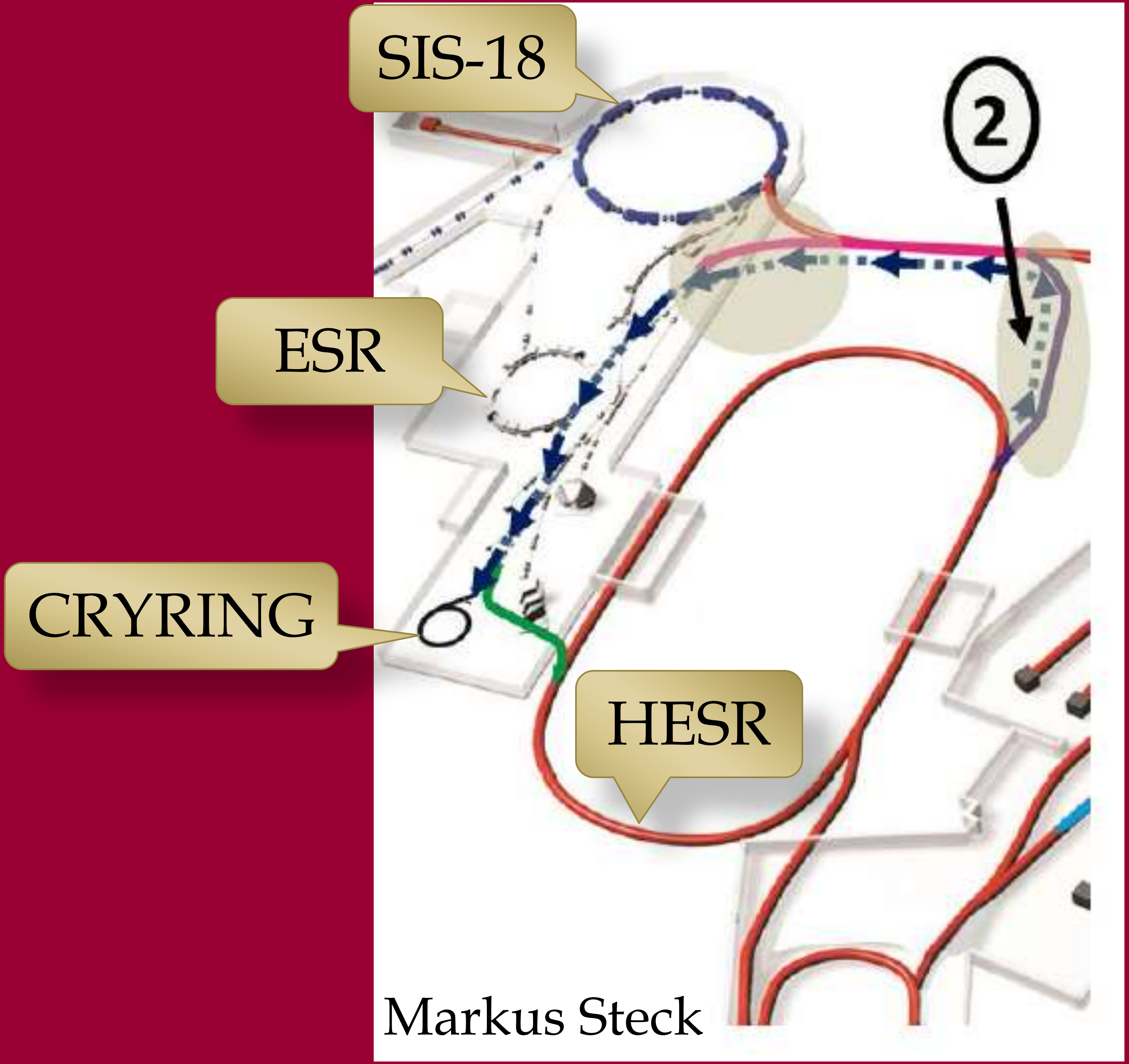
- ELENA: antiproton decelerator @ CERN
  (5 MeV-100 keV); expected in 2017

New Beamlines



Markus Steck

HESR→ESR→CRYRING



FLAIR vs. AD (ELENA)

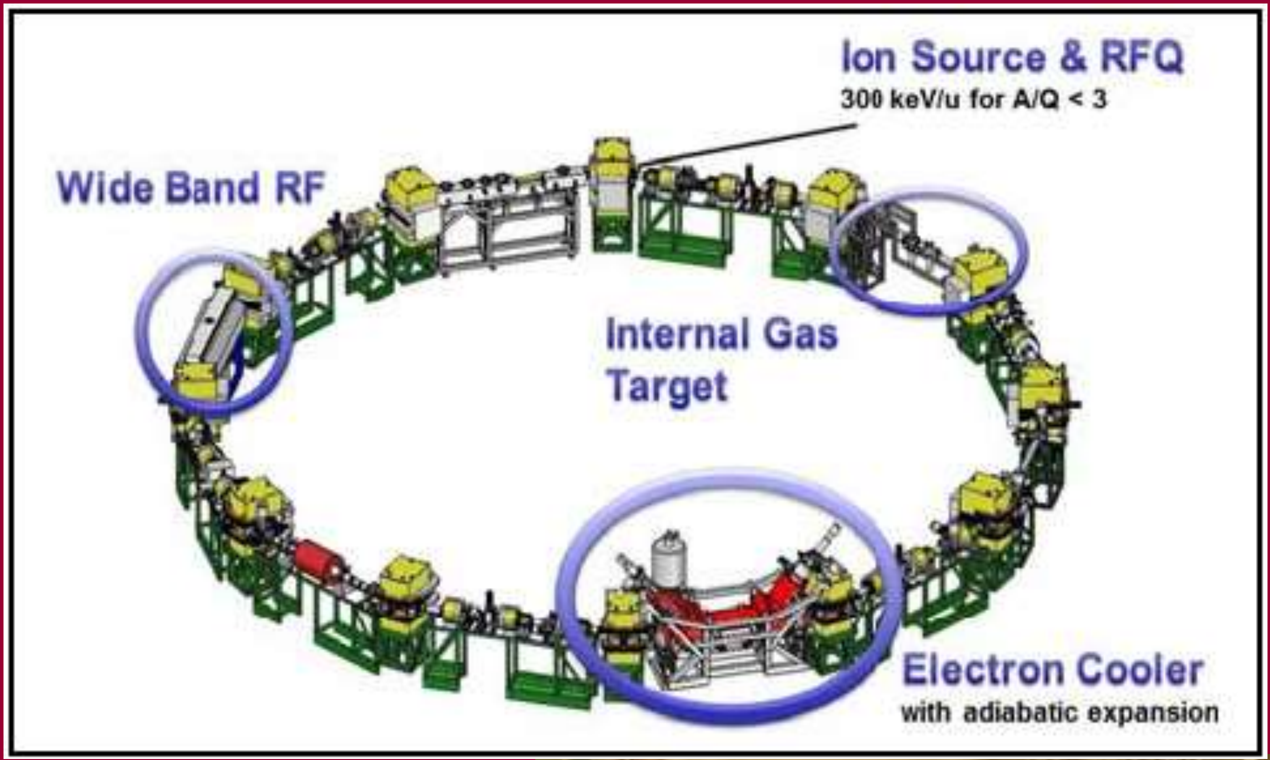
- Production: 10^8 / 4 s
- Deceleration time ~ 20 s
- Limits from space charge in rings:
  - 300 keV: 3 x 10^6 / s
  - 20 keV: 5 x 10^5 / s
    for 10 π mm mrad
  - HITRAP:
    0 keV: 1 x 10^6 / s
- In-ring experiments
- Effective rates: 10^{10}– 10^{12} /s
- Pulsed and slow (continuous) extraction

- All-in-one machine:
  - Antiproton capture
  - deceleration & cooling
  - AD: 100 MeV/c (5.3 MeV)
  - ELENA: 100 keV

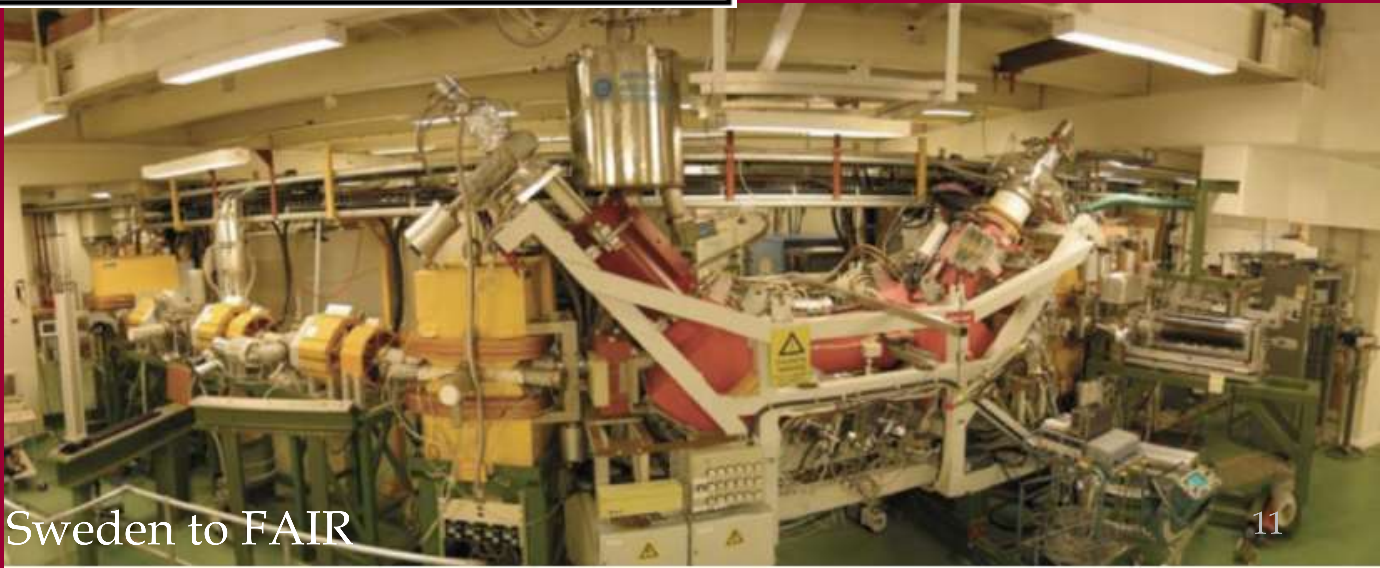
- Pulsed extraction
- 2-4 x 10^7 antiprotons per pulse of 100 ns length
- 1 pulse / 85–120 seconds

See Eberhard Widmann's talk Wednesday

CRYRING→LSR



- Circumference: 52 m
- Rigidity:
  < 1.44 Tm (96 MeV $\bar{p}$)
  > 0.052 Tm (130 keV $\bar{p}$)
- 300+ keV $\bar{p}$ in practice



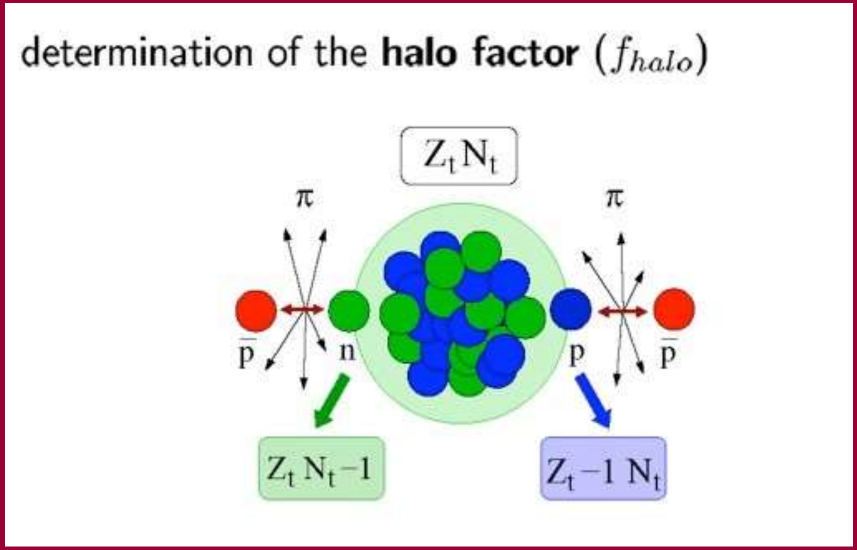
* In kind contribution of Sweden to FAIR

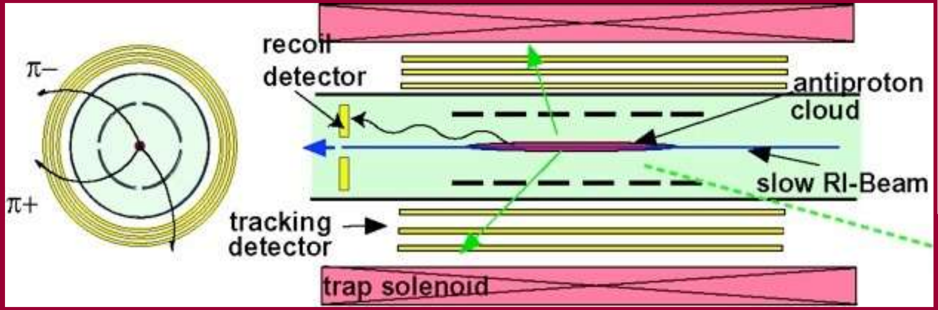
FLAIR day-1 experiments

unique at FLAIR: slow p̄ extraction → hadron physics

p̄ as probe of nuclear structure

- halo structure of RI
- nested Penning trap

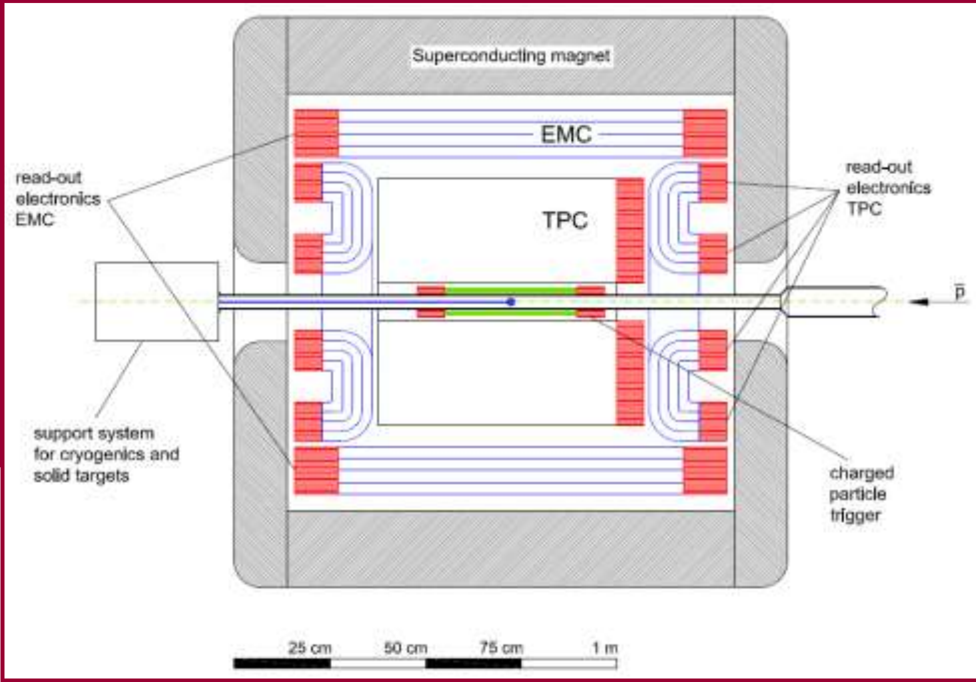




M. Wada, Y. Yamazaki NIM B214 (2004)

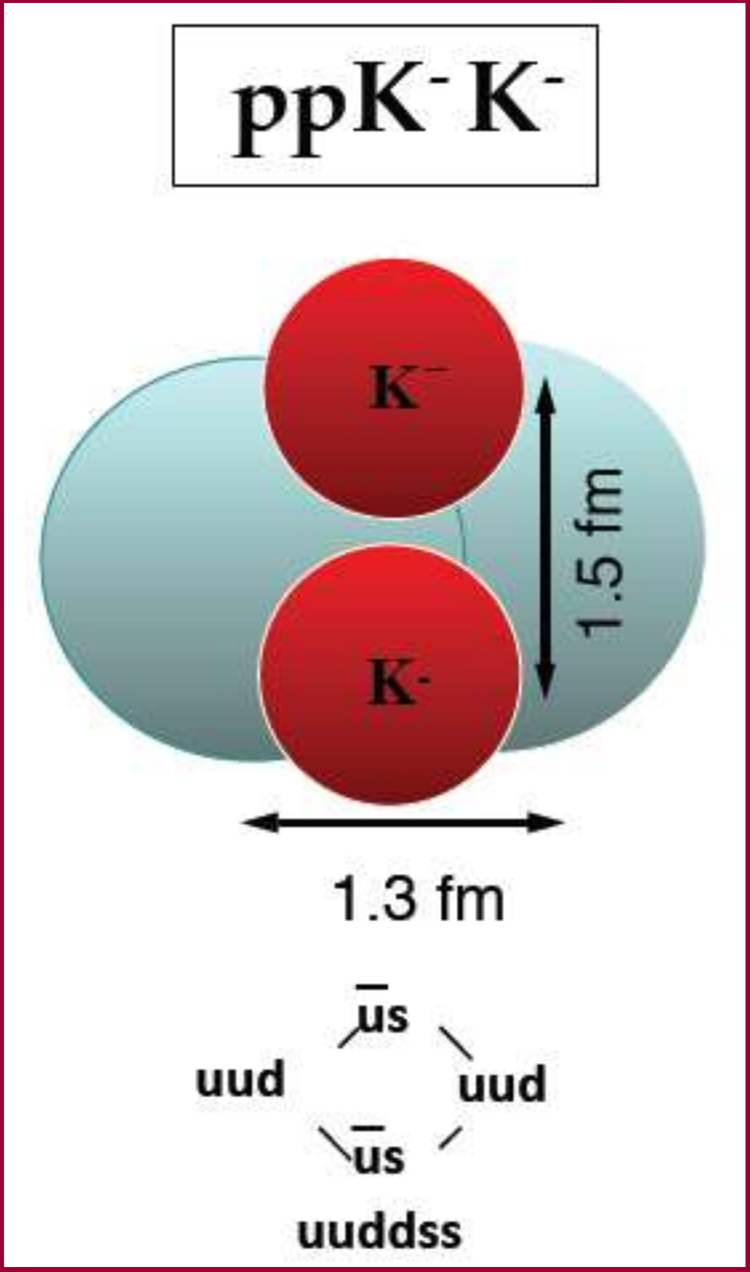
hadron physics with stopped p̄

- search for (deeply) bound baryonic matter with strangeness −1 and −2
- needs 4π detector



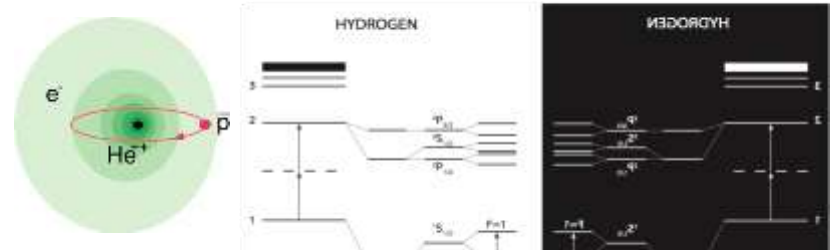
J. Zmeskal et al. Hyperfine Interact 194,
249-254 (2009)

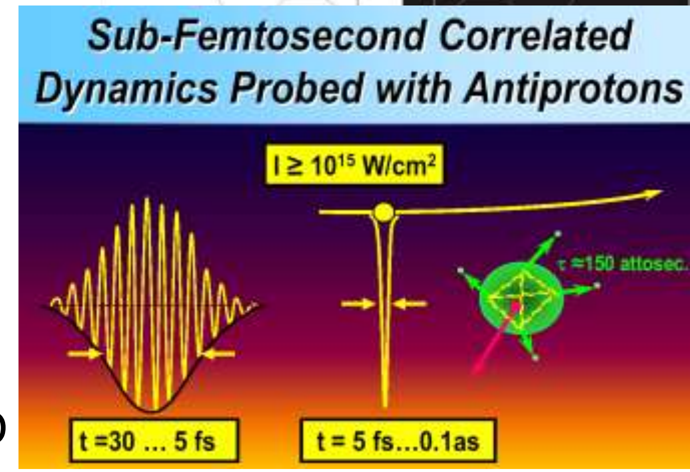
Jaffe di-baryon

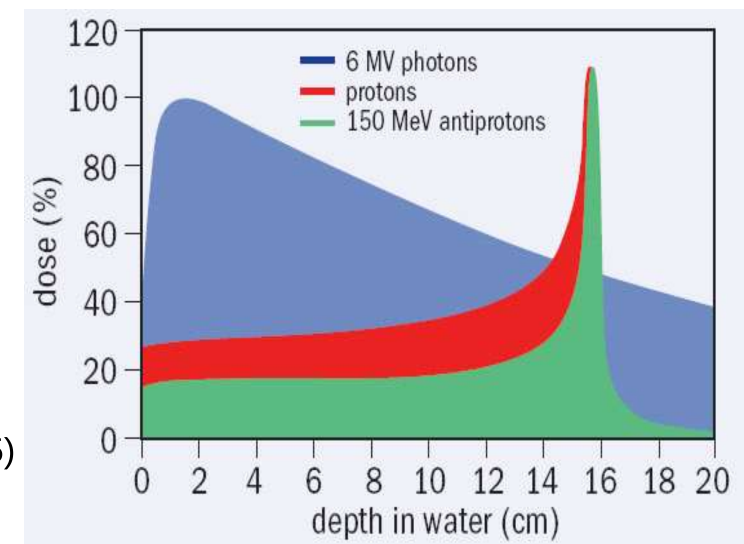


More Low-Energy $\bar{p}$ Physics @ FLAIR

- Spectroscopy for tests of CPT and QED
  - Antiprotonic atoms (pbar-He, pbar-p), antihydrogen
- Atomic collisions
  - Sub-femtosecond correlated dynamics: ionization, energy loss, antimatter-matter collisions
- Antiprotons as hadronic probes
  - X-rays of light antiprotonic atoms: low-energy QCD
  - X-rays of neutron-rich nuclei: nuclear structure (halo)
  - Antineutron interaction
- Medical applications: tumor therapy







FLAIR TDR - E. Widmann CAMOP - Physica Scripta 72, C51-C56 (2005)

E. Widmann

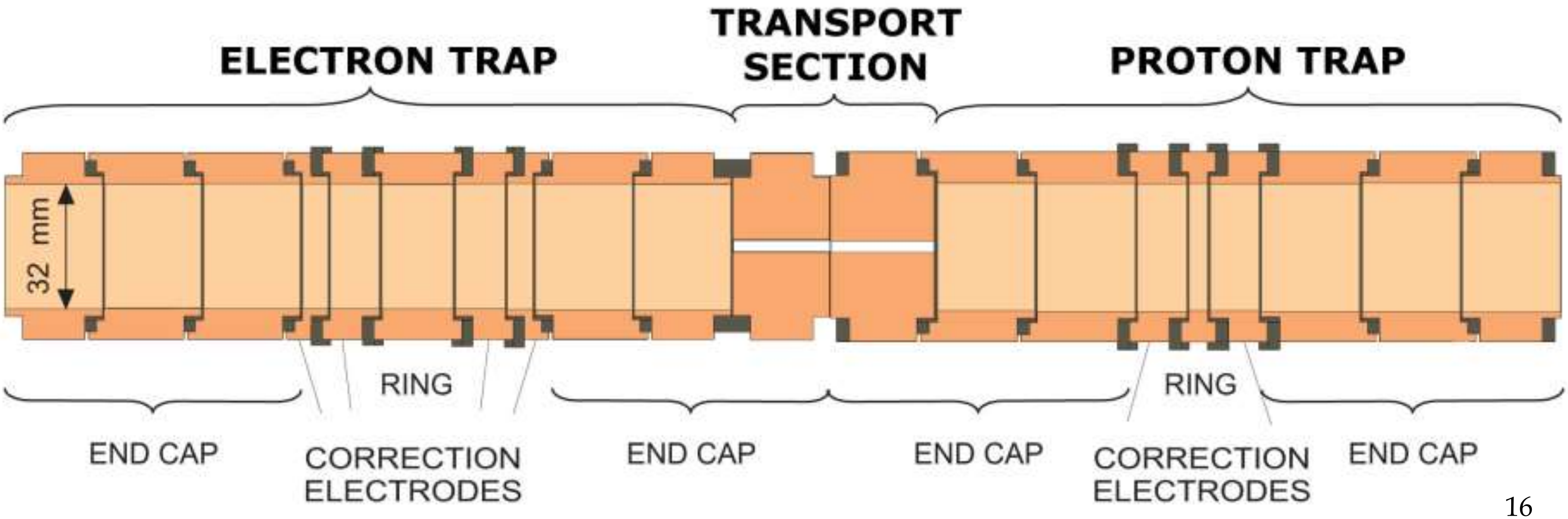
An experimental test of the weak equivalence principle for $\bar{H}^+$ at the future FLAIR facility

Klaus Blaum, Mark G. Raizen, and Wolfgang Quint

An experimental test of the weak equivalence principle for $\bar{H}$ at the future FLAIR facility

Klaus Blaum, Mark G. Raizen, and Wolfgang Quint

- Goal: a ***beam*** of antihydrogen that may be cooled and stopped
- Start with “mirror experiment” with H
- Sympathetic laser cooling of positive particles---protons (Be+ ; Mg+)
- Sympathetic evaporative cooling for antiprotons



An Alternative to Laser Cooling

"Comprehensive Control of Atomic Motion"
M. G. Raizen, Science 324, 1403 (2009)

Predicted Performance

Up to 10^{15} ultra-cold atoms per second (in beam or stopped)

Phase space density: up to 10^{-3}

~100 photons per atom

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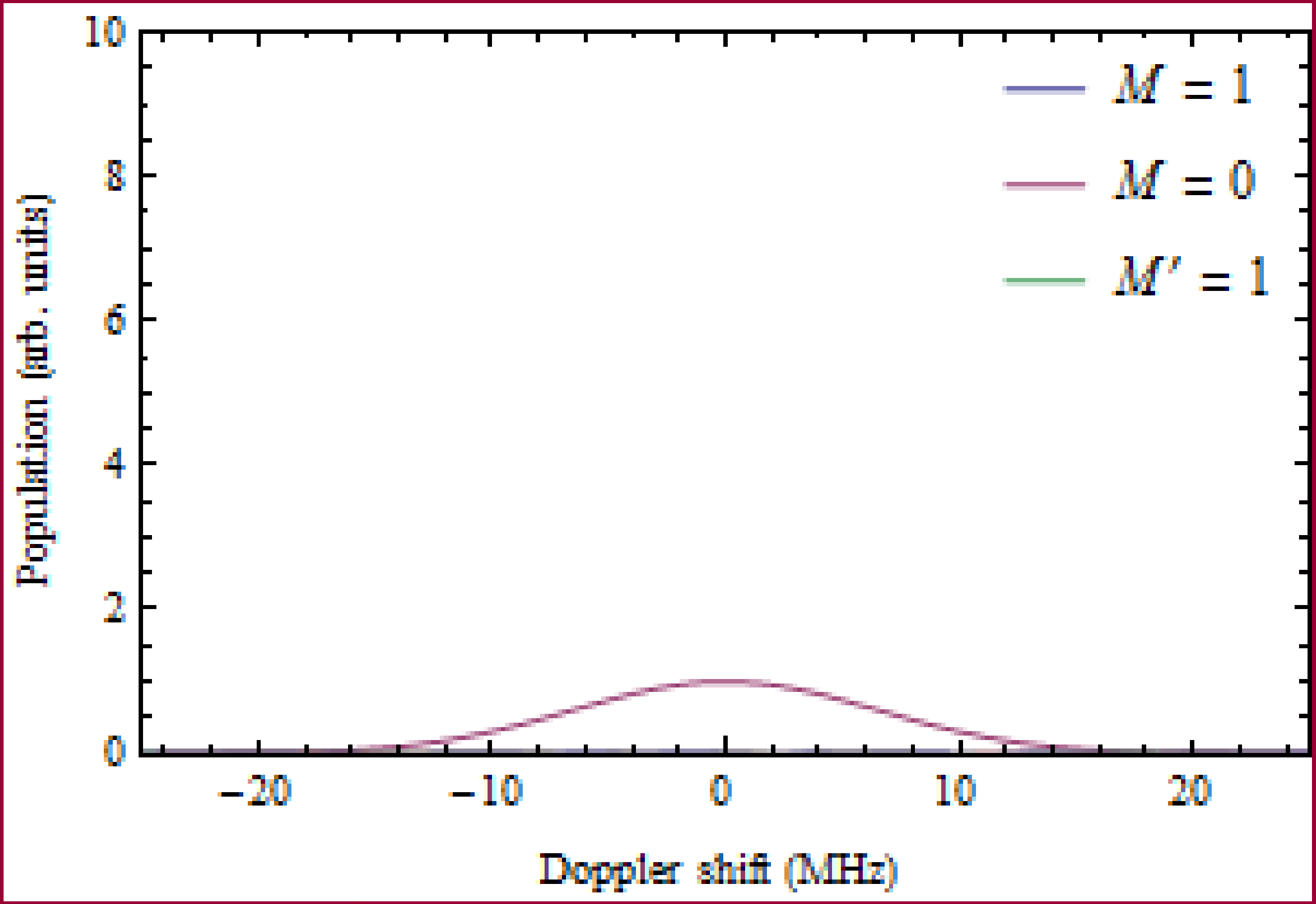
Magneto-optical cooling of atoms

Mark G. Raizen,[1,*] Dmitry Budker,[2,3] Simon M. Rochester,[3] Julia Narevicius,[4] and Edvardas Narevicius[4]
[1]Department of Physics, University of Texas at Austin, Austin, Texas 78712, USA
[2]Department of Physics, University of California at Berkeley, Berkeley, California 94720, USA
[3]Rochester Scientific, El Cerrito, California 94530, USA
[4]Department of Chemical Physics, Weizmann Institute of Science, Rehovot, Israel

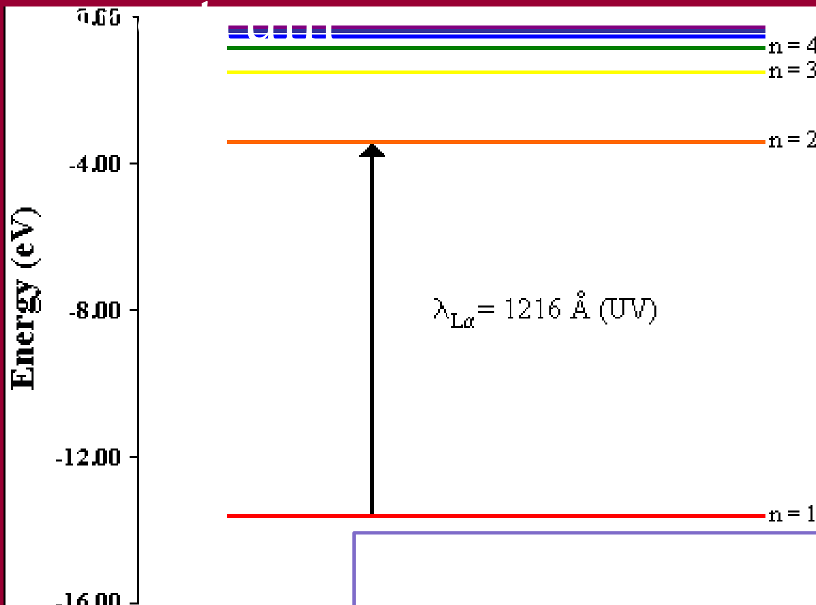
"MOP" cooling

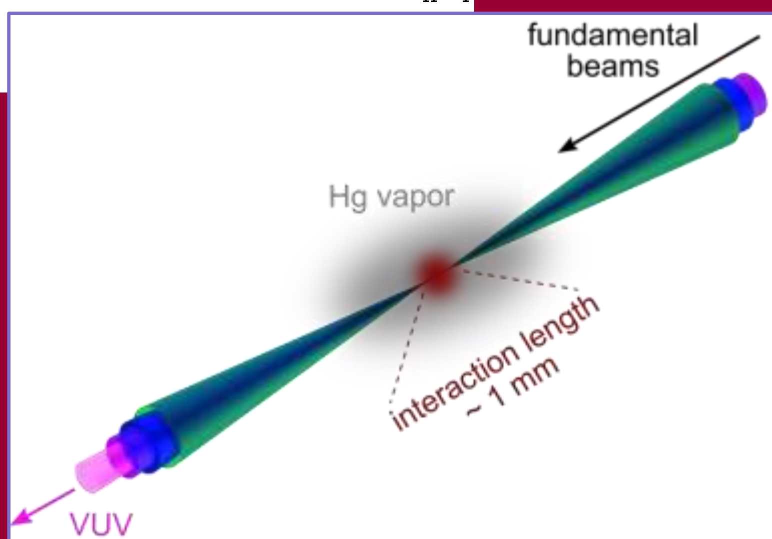


10
8
6
4
2
0
Population (arb. units)
−20
−10
0
10
20
Doppler shift (MHz)
M = 1
M = 0
M′ = 1

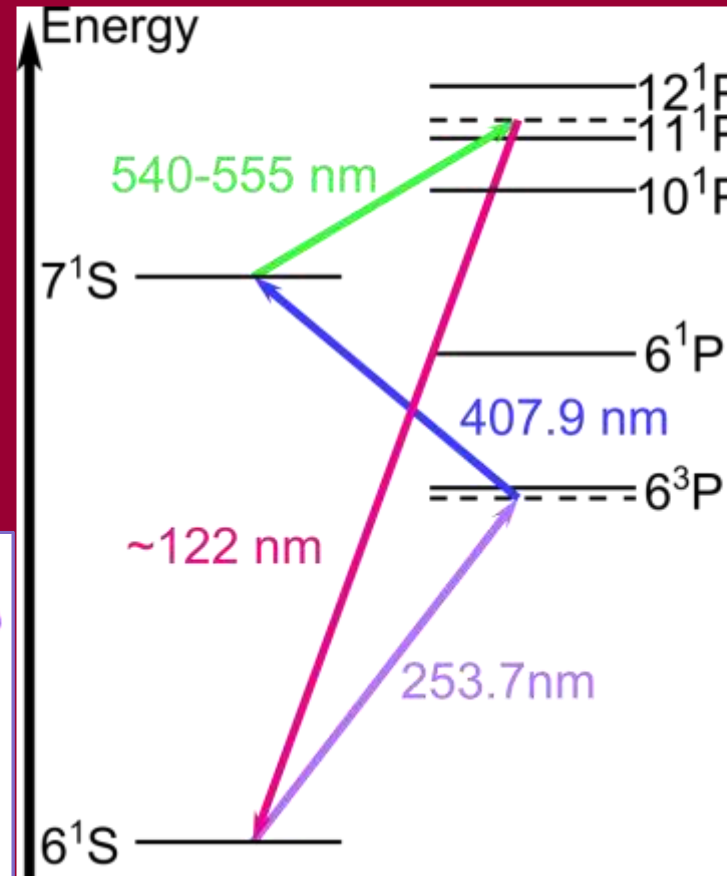
Lyman-α source
for laser cooling of antihydrogen

(Anti)hydrogen



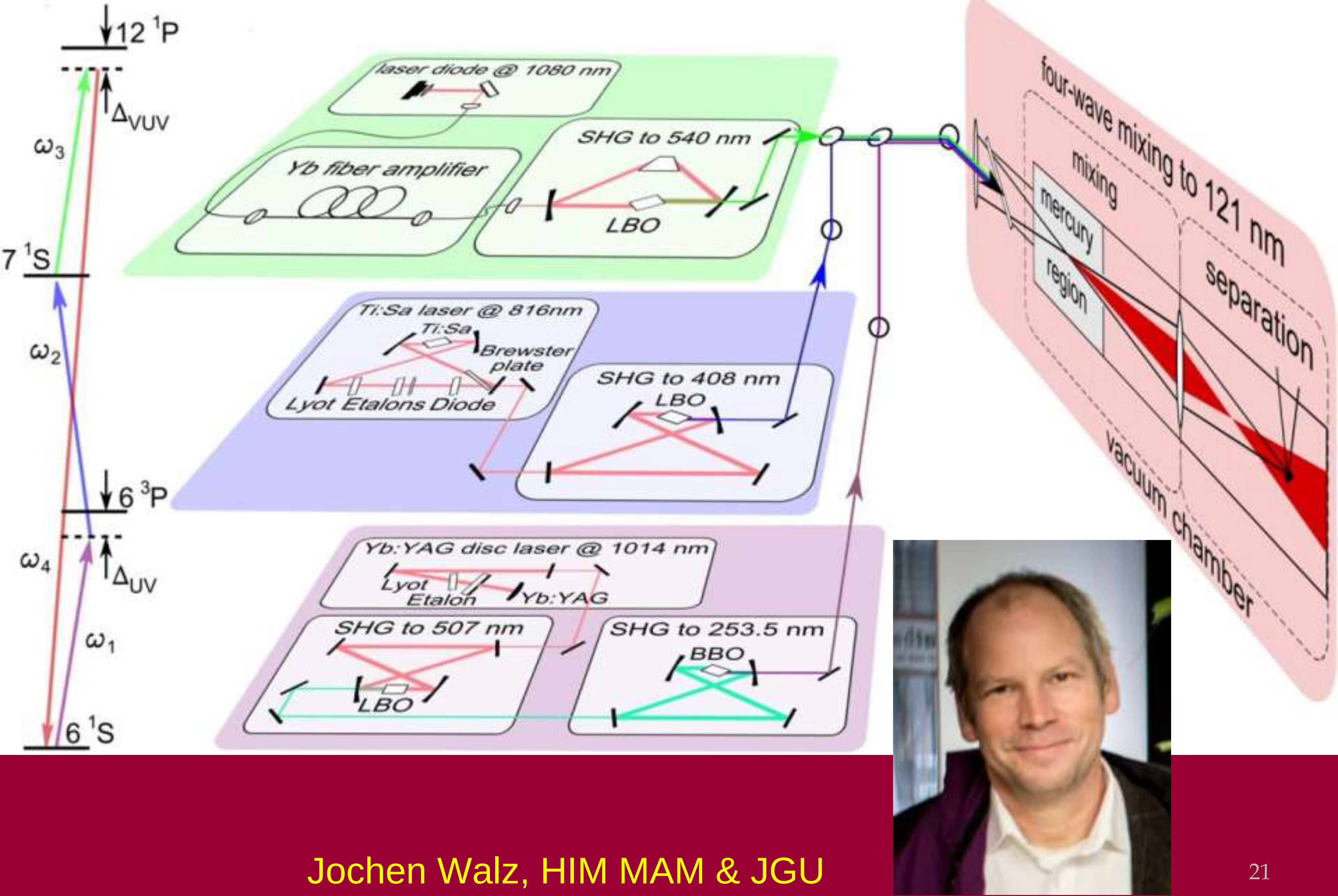


Wavemixing in mercury



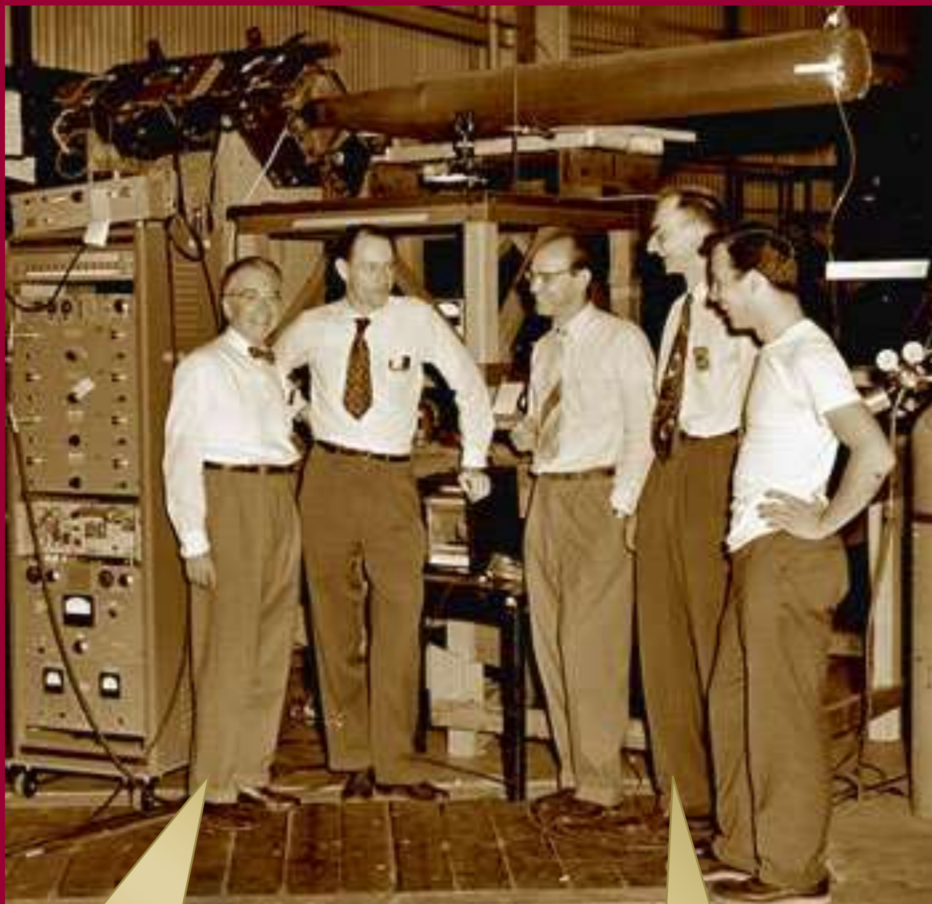
Jochen Walz,
HIM MAM & JGU

cw Lyman-α source



Jochen Walz, HIM MAM & JGU

Discovery of the $\bar{p}$ @ Berkeley



Emilo Segrè

Owen Chamberlain

Gerson Goldhaber

Conclusions

- FLAIR may be running in ~ 1 year !

  (need a transfer line)

- Exciting, diverse p̄ (ion) physics opportunities

- Competition

FLAIR

Facility for Low-energy Antiproton and Ion Research

Back-up Slides

Glossary

- SIS: SchereIonenSynchrotron (the main thing @ FAIR)
- LSR: Low-energy Storage Ring (magnetic)
  E = 300 keV – 30 MeV (e-cooled)
- USR: Ultralow-energy Storage Ring (Electrostatic)
  E_{min} =300 keV – 20 keV
- HITRAP: Penning trap after LSR (or USR)
- CRYRING: atomic-physics ring from Sweden → LSR
- ESR: Experimental Storage Ring
- CR: Collector Ring
- CSR: Cryogenic (2 K) ring @ Heidelberg; prototype for USR
- ELENA: antiproton decelerator @ CERN
  (5 MeV-100 keV); expected in 2017

Concept for Antiprotons in the MSV

Proton acceleration in Proton Linac, SIS18, and SIS 100 to 29 GeV

Single short bunch (50 ns) of 2×10^{13} protons is directed to the antiproton production target

Theoretical production rate (2×10^{-5} pbar /p) in useful phase space volume (acceptance of separator and Collector Ring CR) should reliably give 1×10^{8} antiprotons per pulse every 10 s (limited by cooling time in CR)

After bunch rotation and stochastic cooling the cooled antiprotons will be transferred to the HESR

Beam accumulation by combination of barrier buckets and stochastic cooling in the HESR will allow accumulation of stacks of 1×10^{10} pbar

Acceleration/deceleration to energies 0.8 – 14 GeV in the HESR

Stored antiprotons in the HESR:
Internal target and cooling (stochastic and electron) of antiprotons

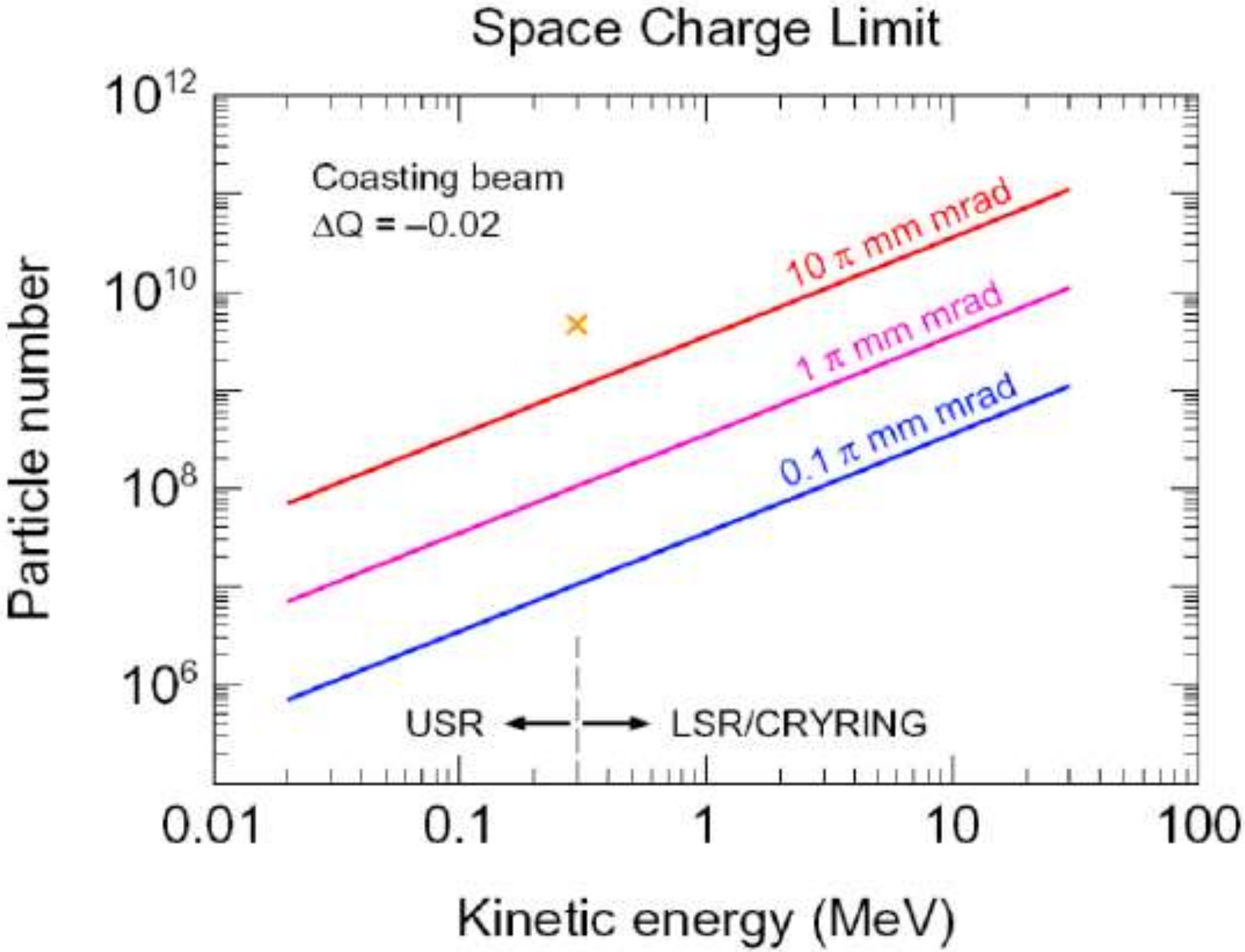
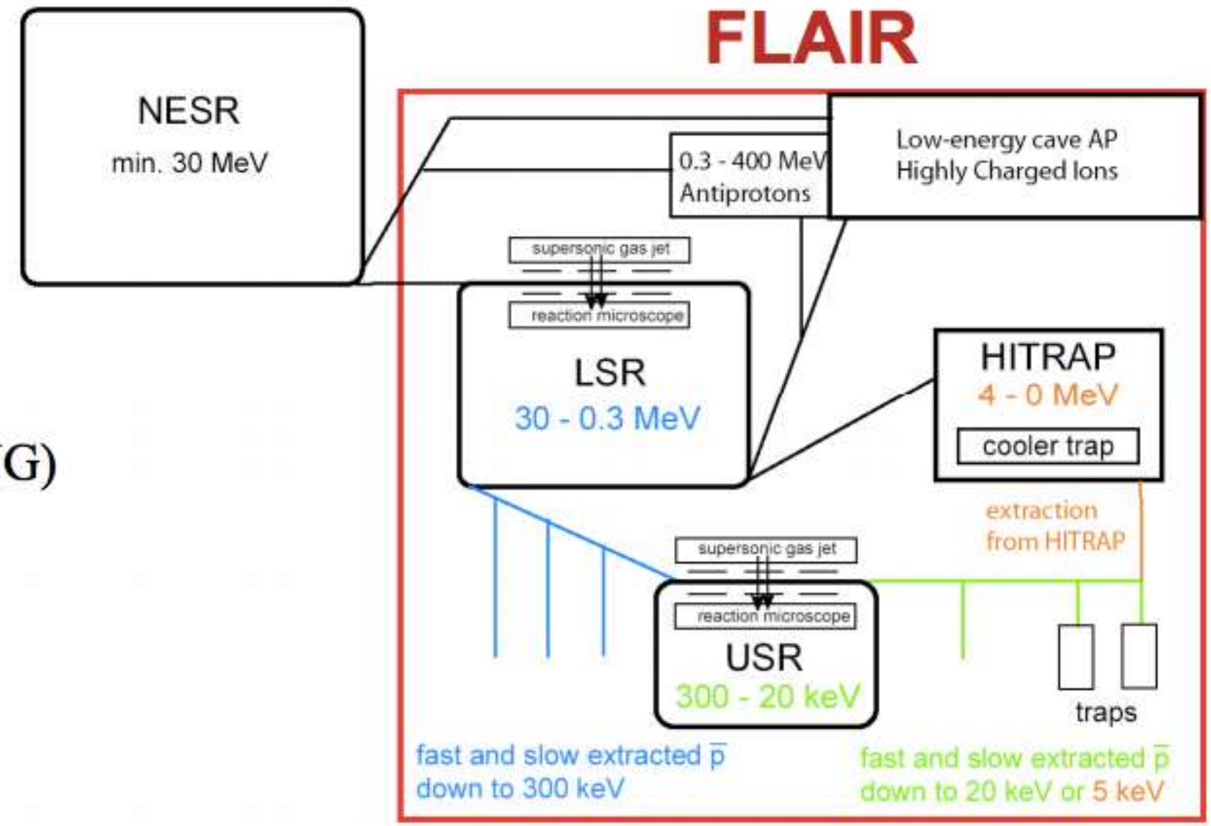


Fig. 2: Space charge limits in storage rings for different emittances. The orange cross corresponds to a recent measurement in CRYRING

FLAIR - Facility for Low-Energy Antiproton and Ion Research

- NESR
  - Pbars and ions
  - 30 – 400 MeV
- LSR
  - Magnetic ring
  - Min. 300 keV (former CRYRING)
- USR
  - Electrostatic ring
  - Min. 20 keV
- HITRAP
  - Pbars and ions
  - Stopped & extracted @ 5 keV

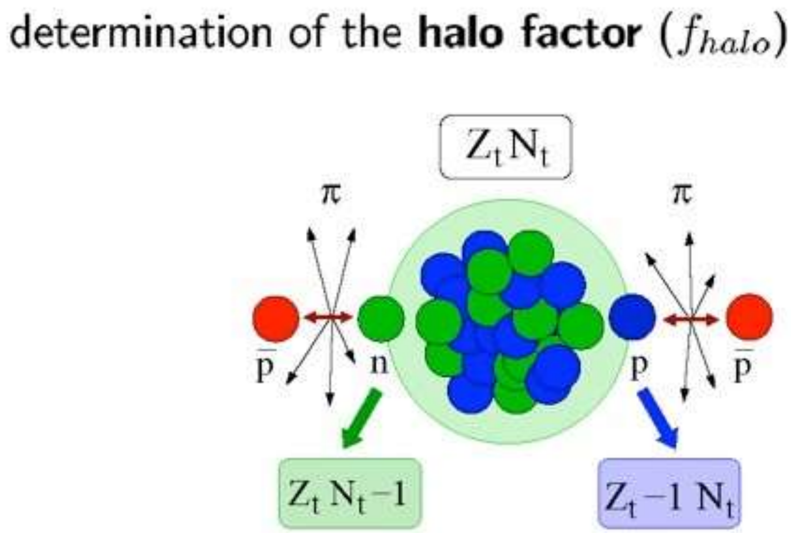


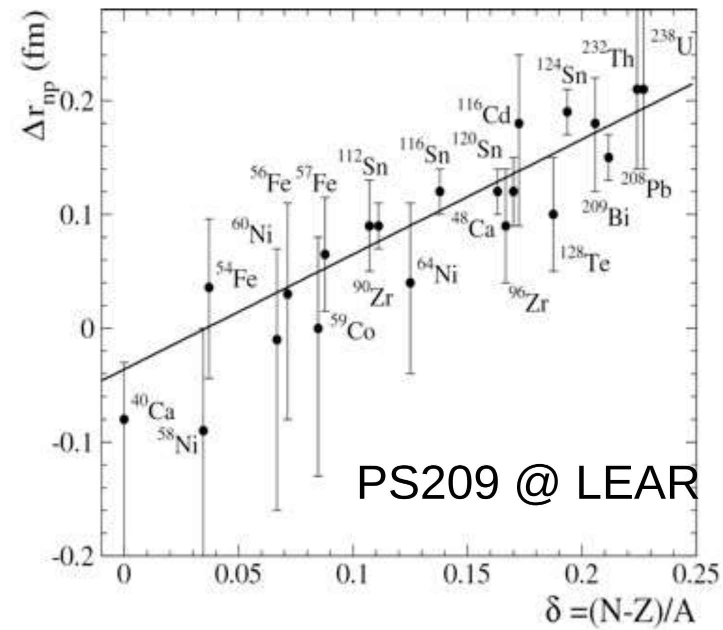
energy range: 400 MeV – 1 meV

ÖAW
Austrian Academy of Sciences

Stefan Meyer Institute

Nuclear Periphery with antiprotonic Atoms





- Exotic atom formation -> cascade ->
  - Annihilation with outermost nucleons (<r>+ 2 fm)
- Measurement of neutron halo parameters
  - Radiochemical method, X-rays + model calculations
- Neutron diffuseness increases with neutron excess
- Extension to unstable nuclei interesting

A. Trzcinska,
J. Jastrzebski et al.
PRL 87 (082501)
2001

"MOP" cooling

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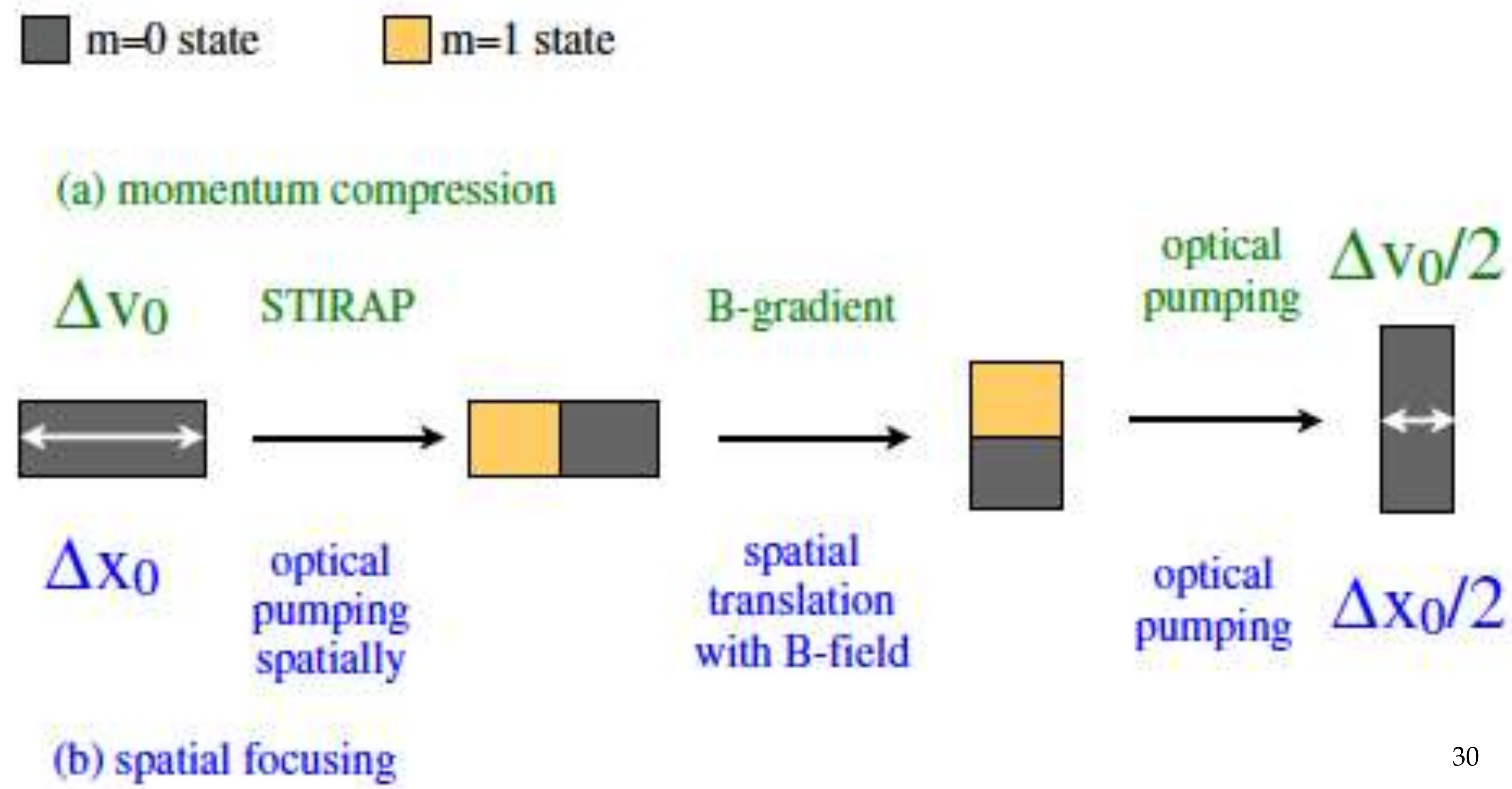


LETTER

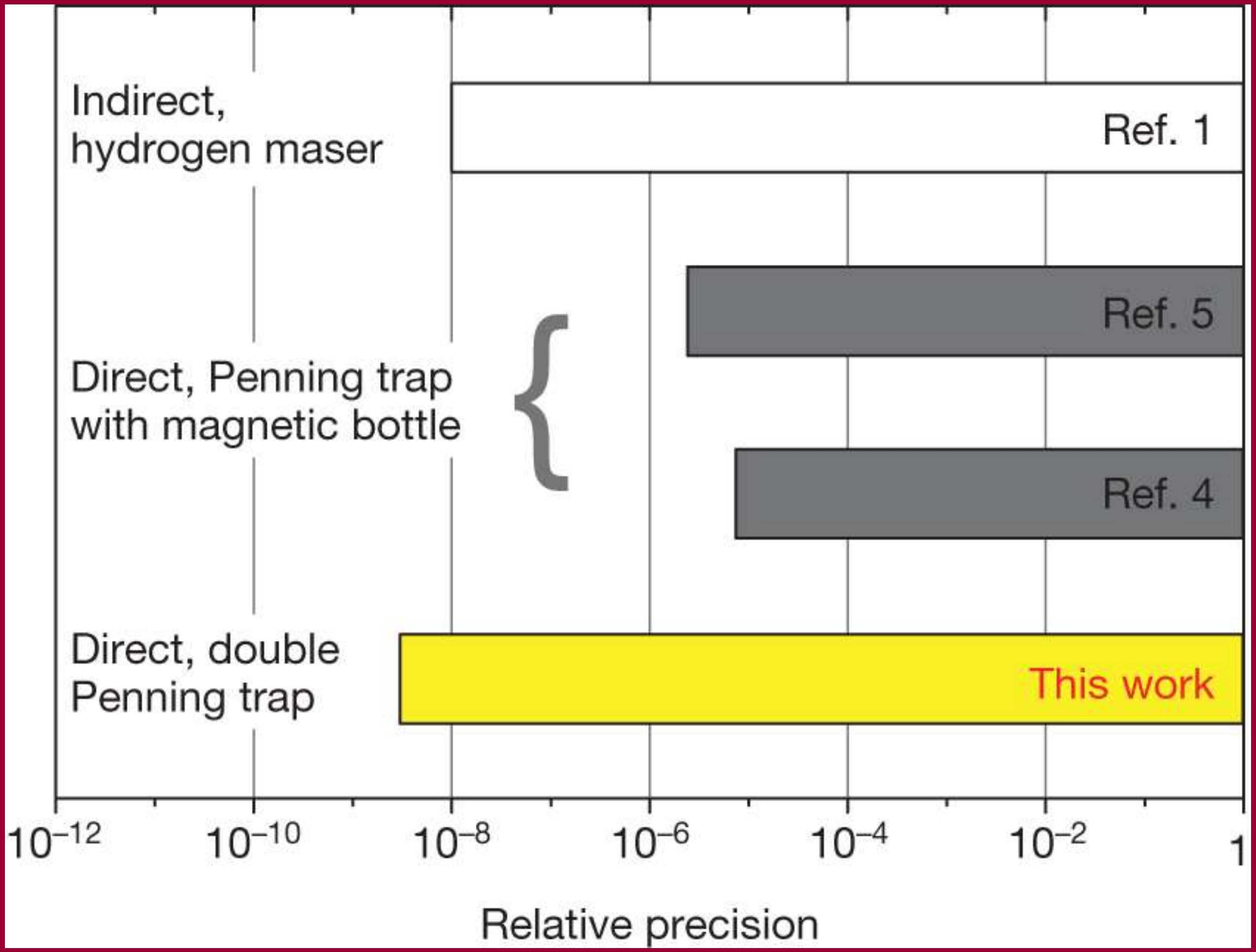
nature

doi:10.1038/nature13388

Direct high-precision measurement of the magnetic moment of the proton

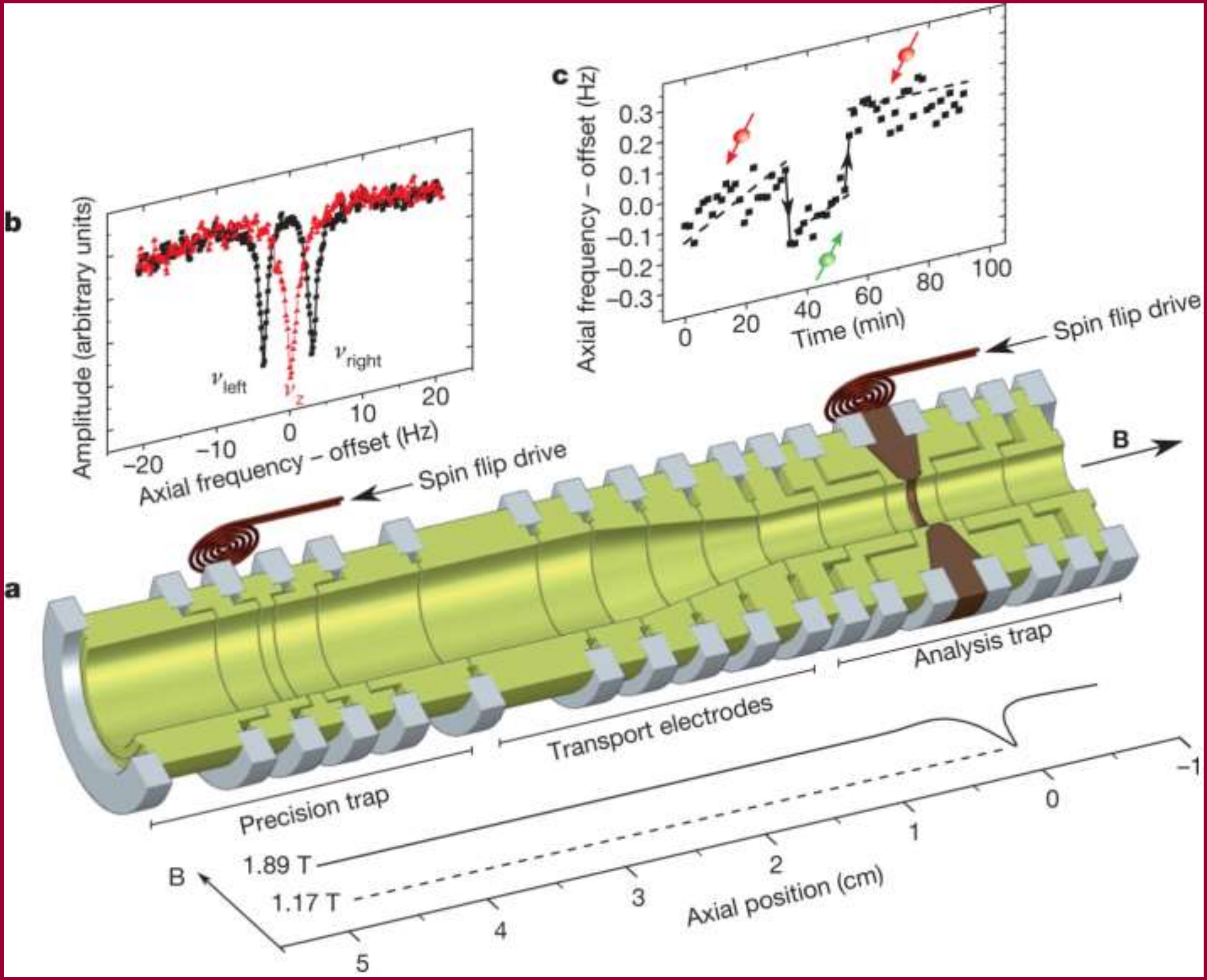
A. Mooser[1,2]†, S. Ulmer[3], K. Blaum[4], K. Franke[3,4], H. Kracke[1,2], C. Leiteritz[1], W. Quint[5,6], C. C. Rodegheri[1,4], C. Smorra[3] & J. Walz[1,2]

Relative precision achieved in measurements of the Proton magnetic moment



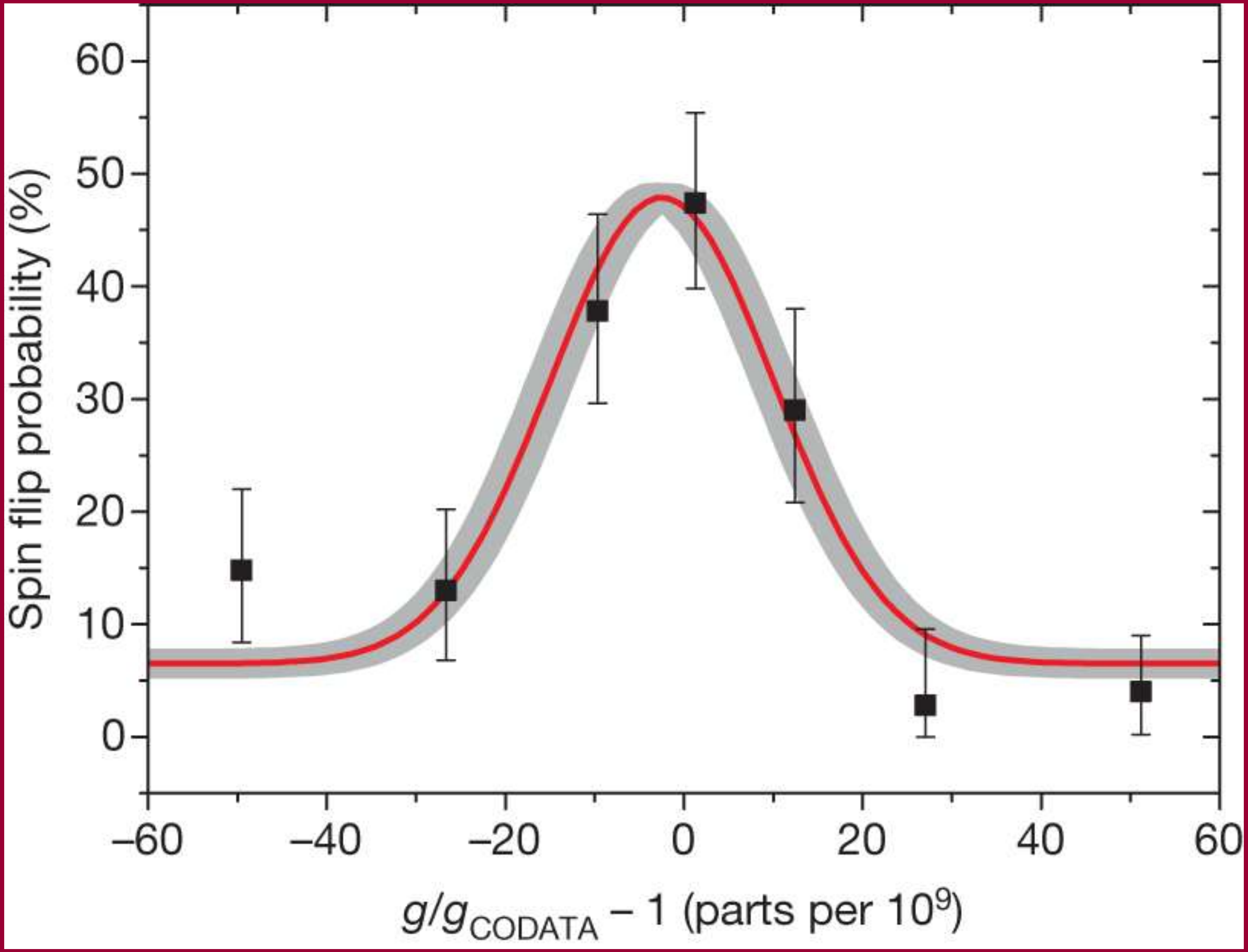
A Mooser *et al. Nature* **509**, 596-599 (2014) doi:10.1038/nature13388

Experimental setup and measurement procedures



A Mooser *et al.* *Nature* **509**, 596-599 (2014) doi:10.1038/nature13388

Measured g-factor resonance



A Mooser *et al. Nature* **509**, 596-599 (2014) doi:10.1038/nature13388

nature