Status of FLAIR – Facility for Low-energy Antiproton and Ion Research @ FAIR

www.flairatfair.eu

Eberhard Widmann

LEAP2018

Paris, 12 Mar 2018

Stefan Meyer Institute for Subatomic Physics, Vienna

Next-generation Low-energy Antiproton Facility (2004)

Feature	Solution
Higher intensity	Accumulation scheme
Fast and slow extraction	Coincidence experiments (nuclear physics)
Cooled beams down to < 500 keV	Storage rings: ***ELENA***
Availability of pbar and RI	FAIR

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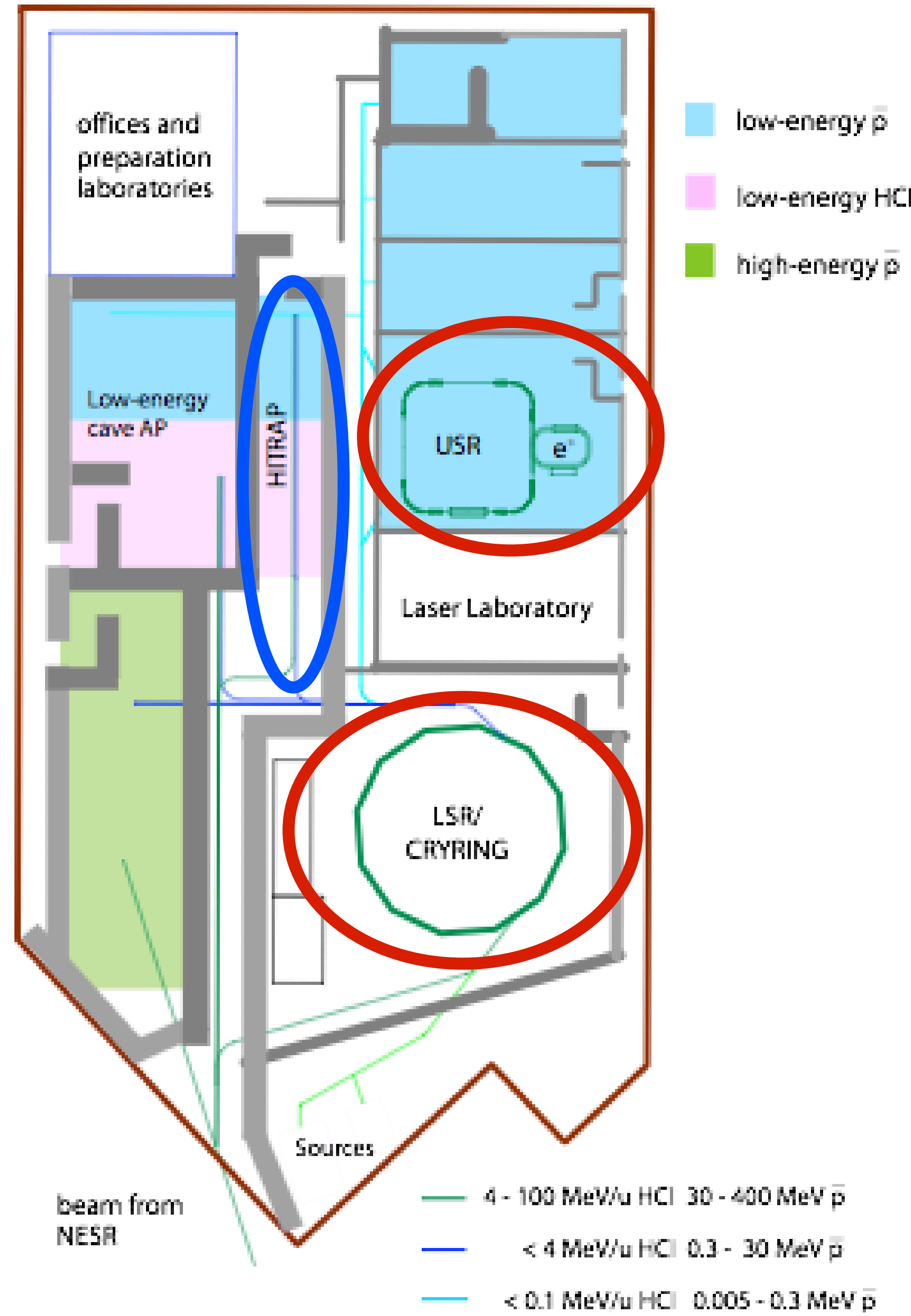
FLAIR@ FAIR - Baseline Technical Report 2005

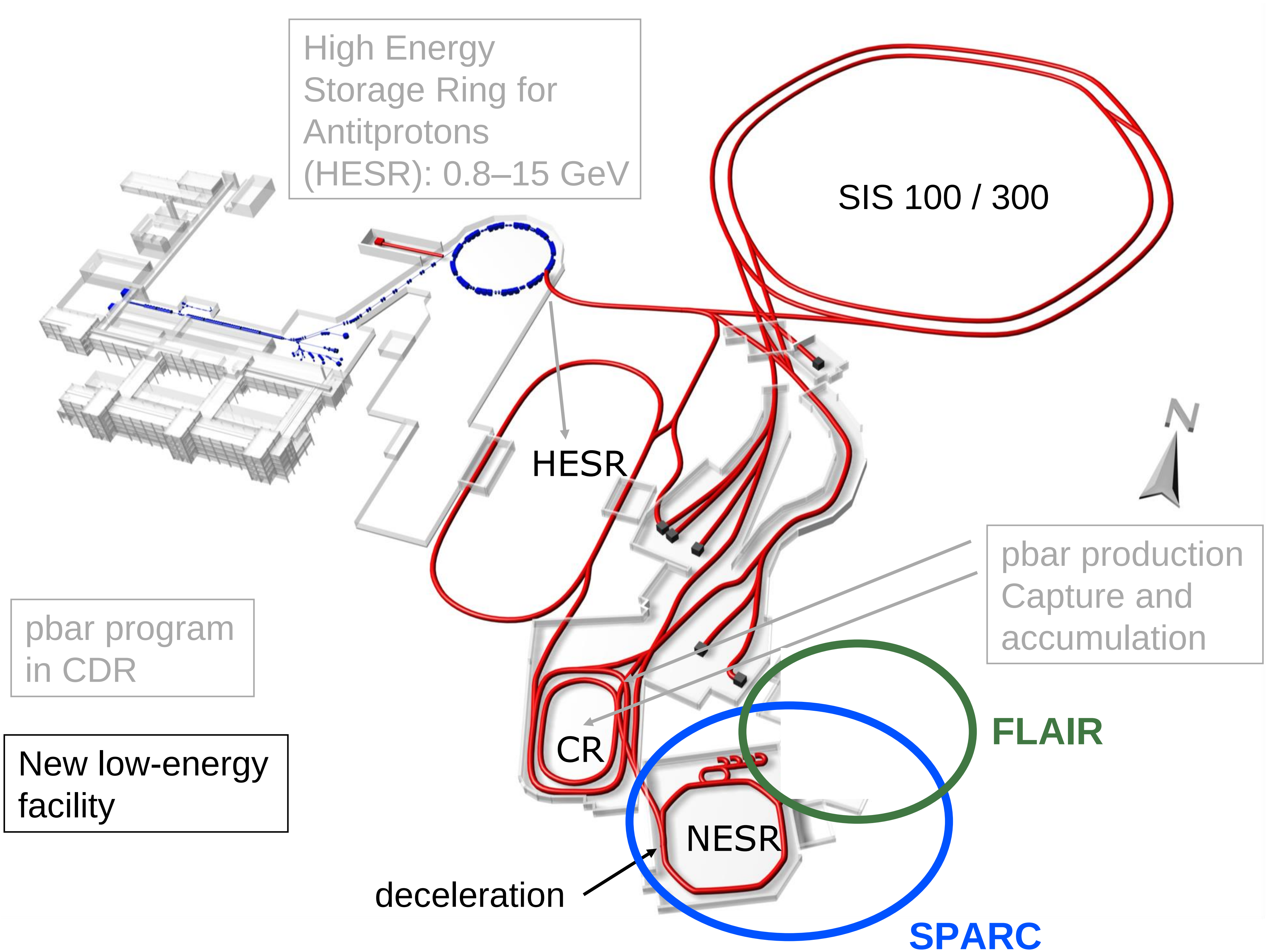
- High brightness low energy beams
  - two storage rings with 300 keV (LSR) and 20 keV (USR)
  - electron cooling
    - $\varepsilon \sim 1\ \pi$ mm mrad
    - $\Delta p/p \sim 10^{-4}$
- Storage rings with internal targets for collision studies
- Ion traps
- Slow and fast extraction
  - HITRAP facility for HCI & pbar
- Many new experiments possible
- same facilities can be used for HCI

Factor 100 more pbar trapped or stopped in gas targets than CERN-AD



FLAIR BTR www.flairatfair.eu

Antiprotons at FAIR



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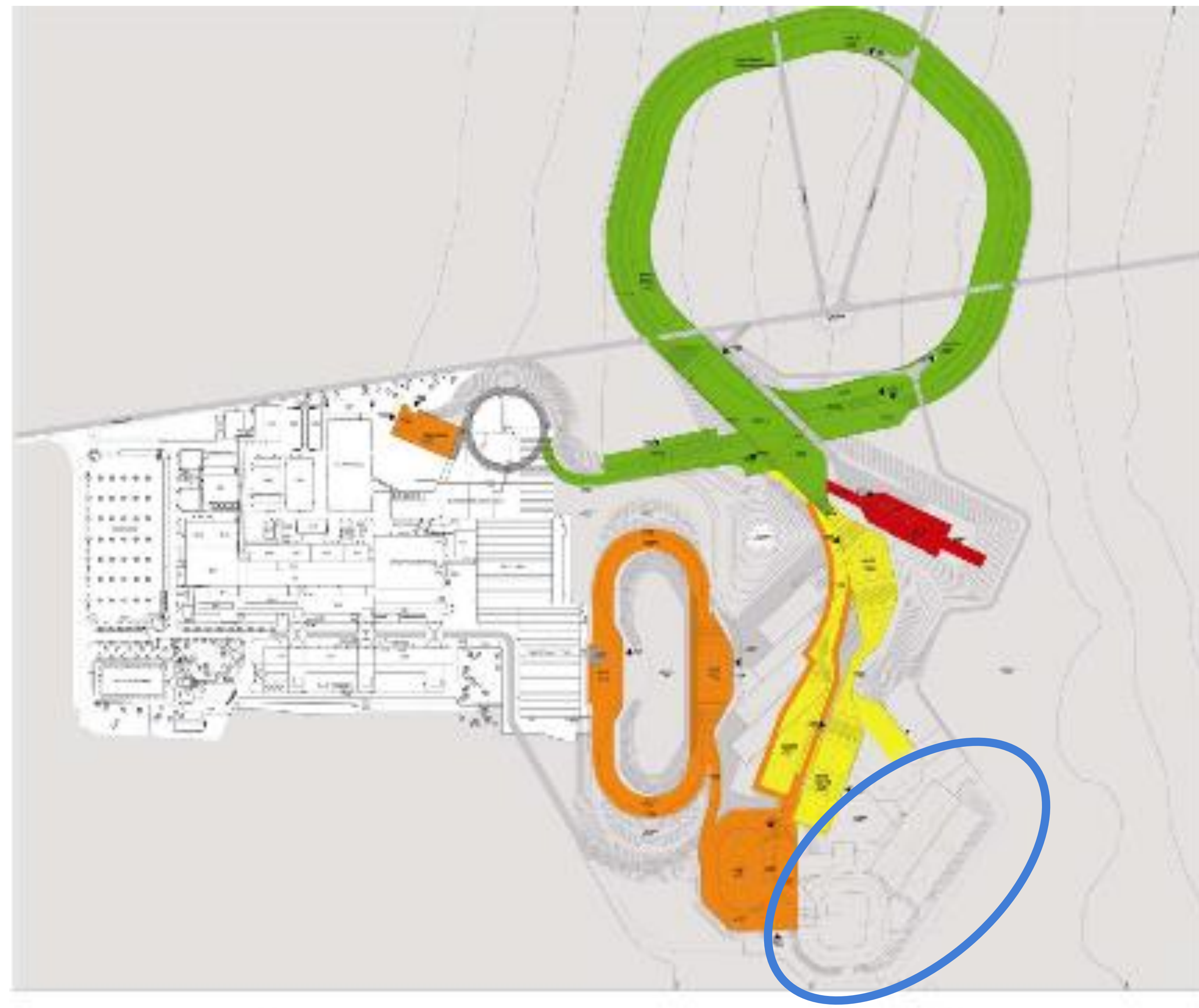
Modularized start version of FAIR

- Modularized start version 0-3
  - founded Oct. 2010
  - construction started
- FLAIR: Module 4 with NESR, SFRS-LEB
  - additional funding of ~100 M€ needed
    - *in 2005 prizes*
- Storage rings are a core feature of FAIR



Modules 0 to 3 of FAIR. Module 0: green; module 1: red; module 2: yellow;

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Low Energy Antiproton Physics @ FLAIR

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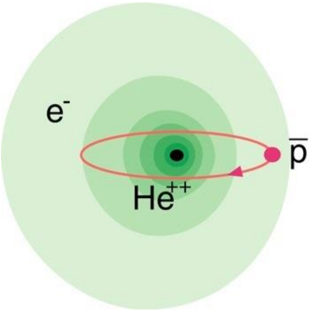
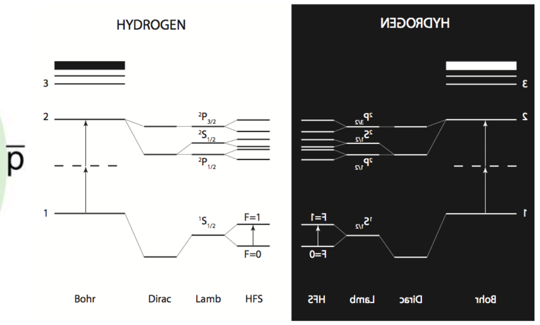
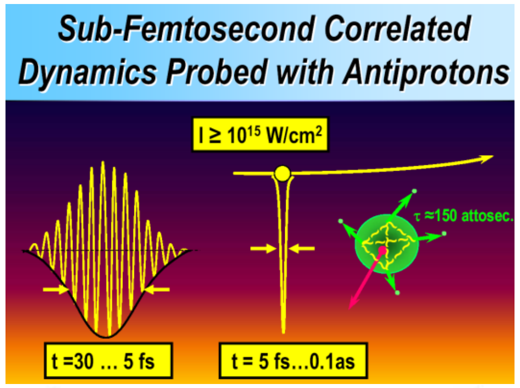
- Spectroscopy for tests of CPT and QED
  - Antiprotonic atoms (pbar-He, pbar-p), antihydrogen

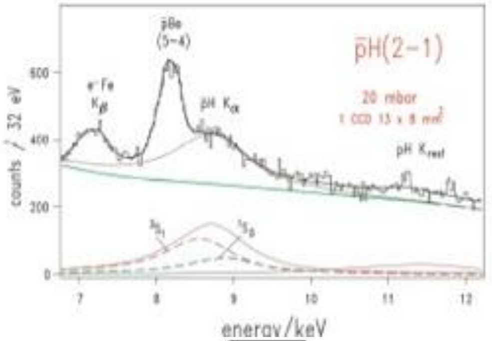


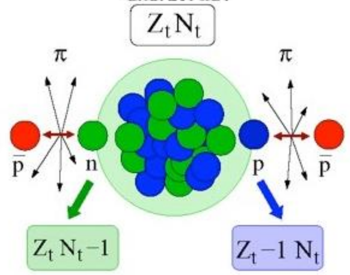


- Atomic collisions
  - Sub-femtosecond correlated dynamics: ionization, energy loss, antimatter-matter collisions

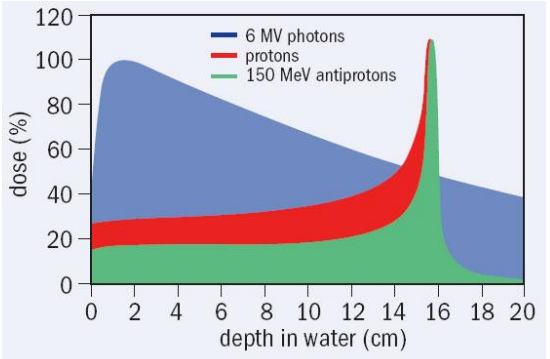


- Antiprotons as hadronic probes
  - X-rays of light antiprotonic atoms: low-energy QCD
  - X-rays of neutron-rich nuclei: nuclear structure (halo)
  - Antineutron interaction
  - Strangeness –2 production



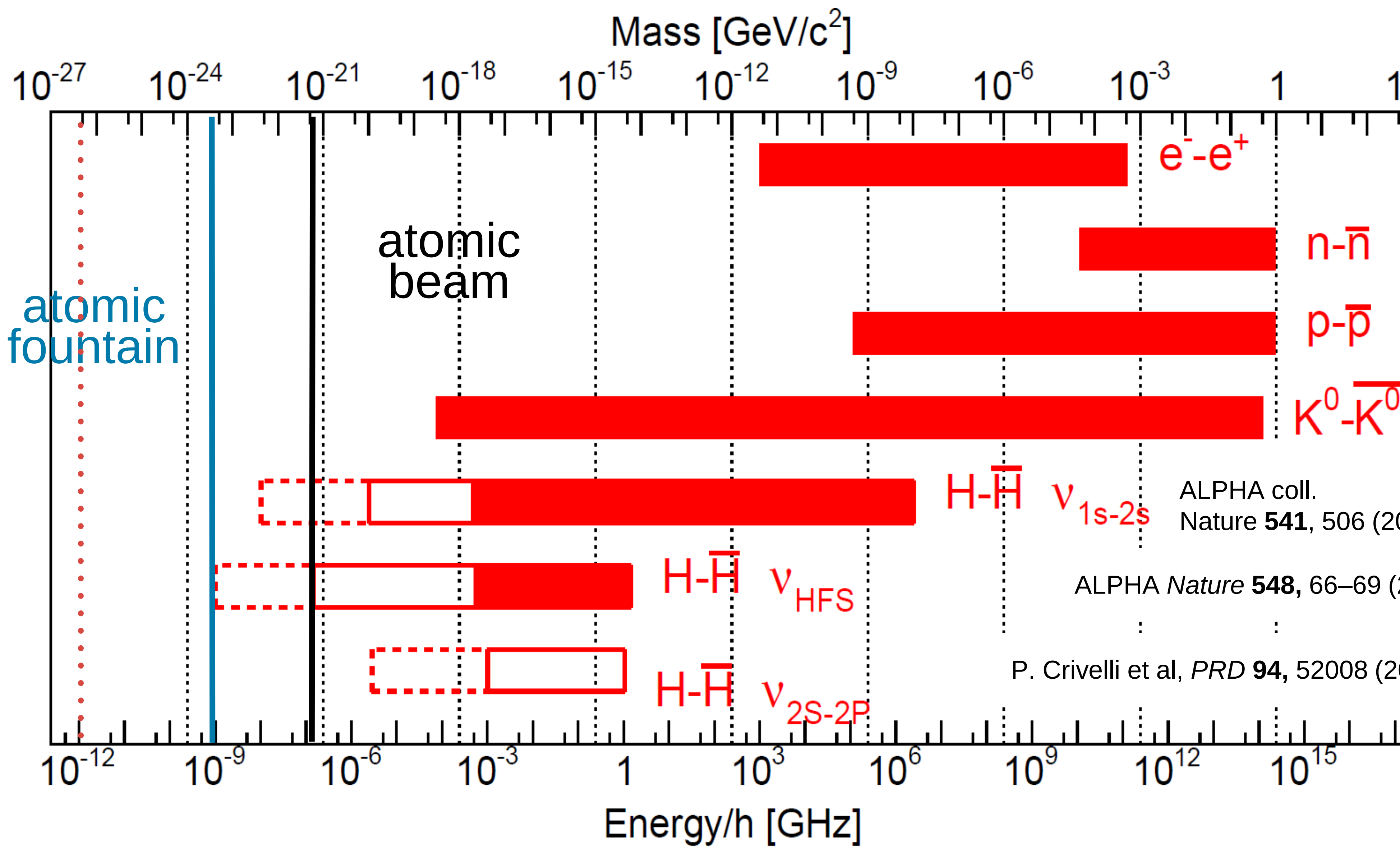


- Medical applications: tumor therapy



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

Status of antimatter CPT tests



ALPHA coll. Nature **541**, 506 (2017)

ALPHA *Nature* **548,** 66–69 (2017).

P. Crivelli et al, *PRD* **94,** 52008 (2016).

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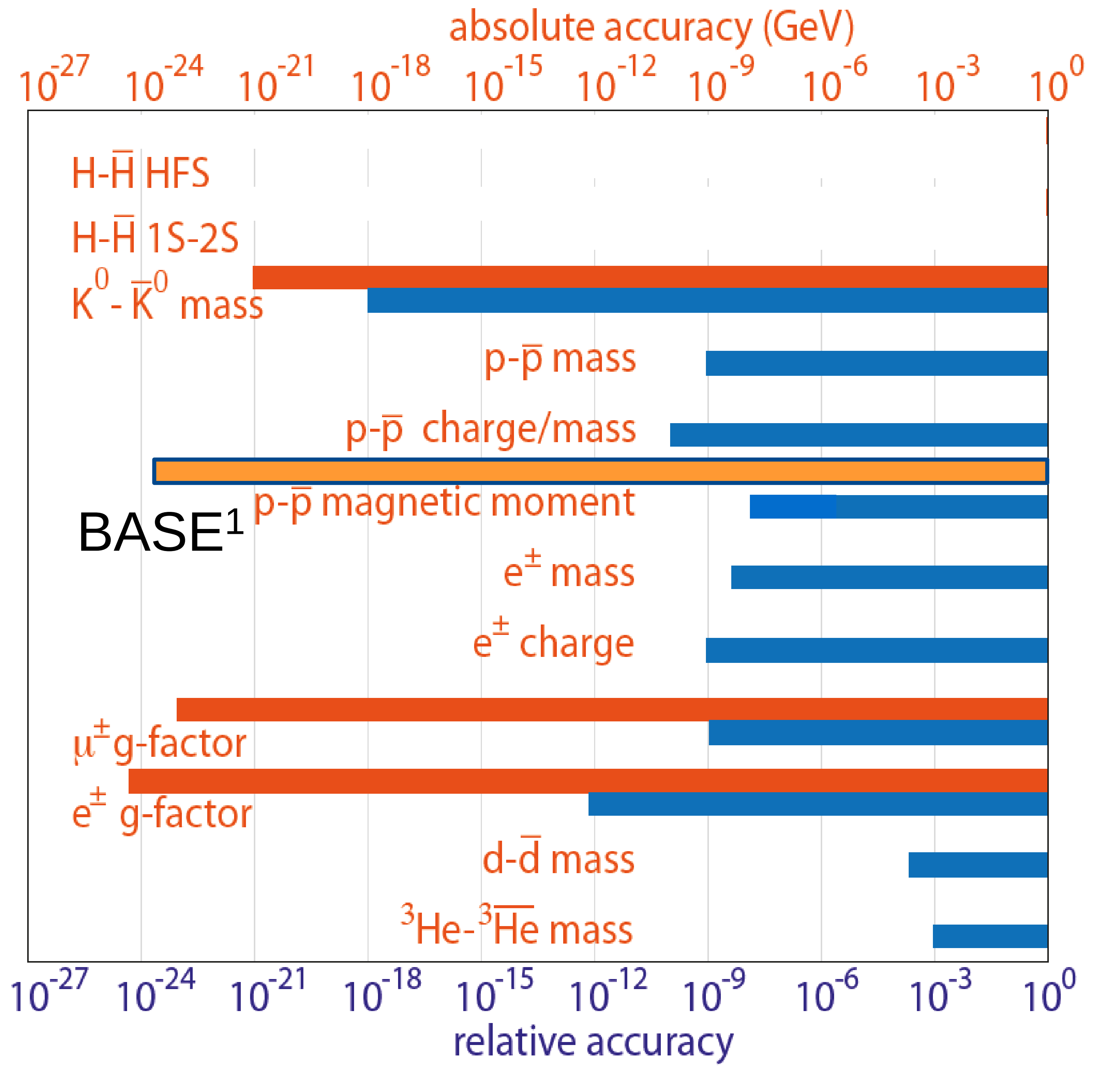
CPT tests and SME

- 1S-2S not sensitive in mSME
- Combination of HFS transitions measured by ALPHA[2] not sensitive to SME
  - See talk by A. Vargas earlier today



From: NuPECC Long Range Plan 2017 (M. Doser) + EW
Based on Kostelecky & Bluhm arXiv:0801.0287

[1] Smorra, C. *et al. Nature* **550,** 371–374 (2017).
[2] Ahmadi, M. *et al. Nature* **548,** 66–69 (2017).

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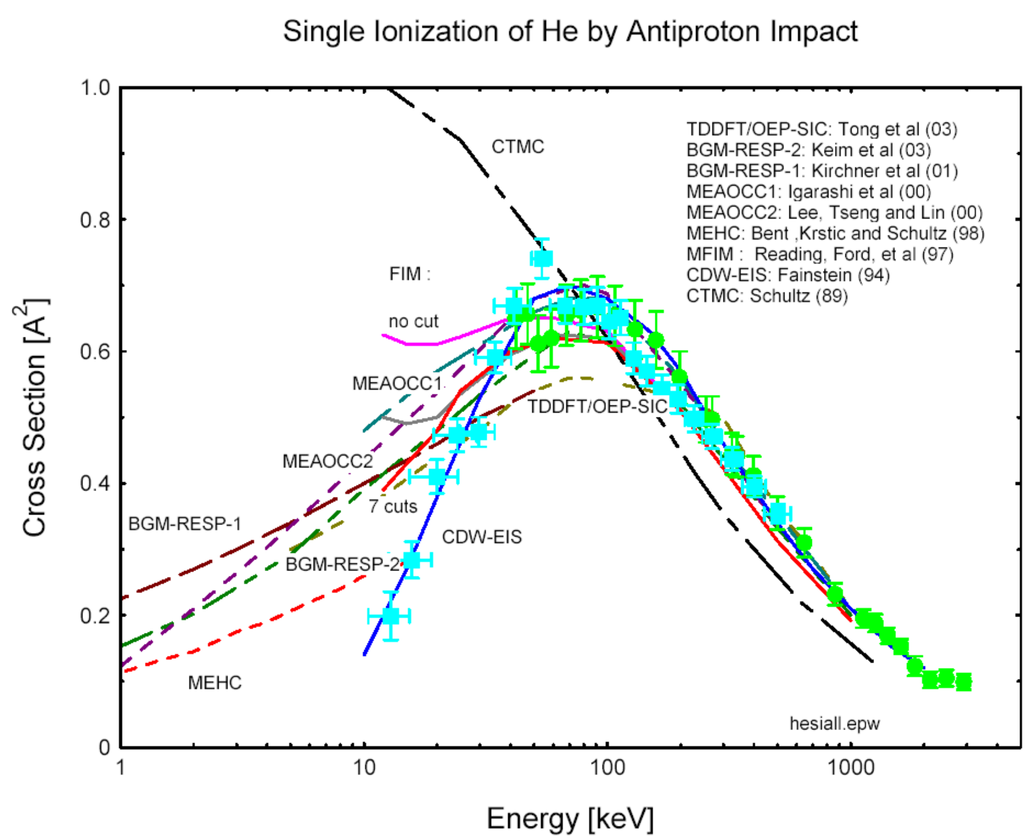
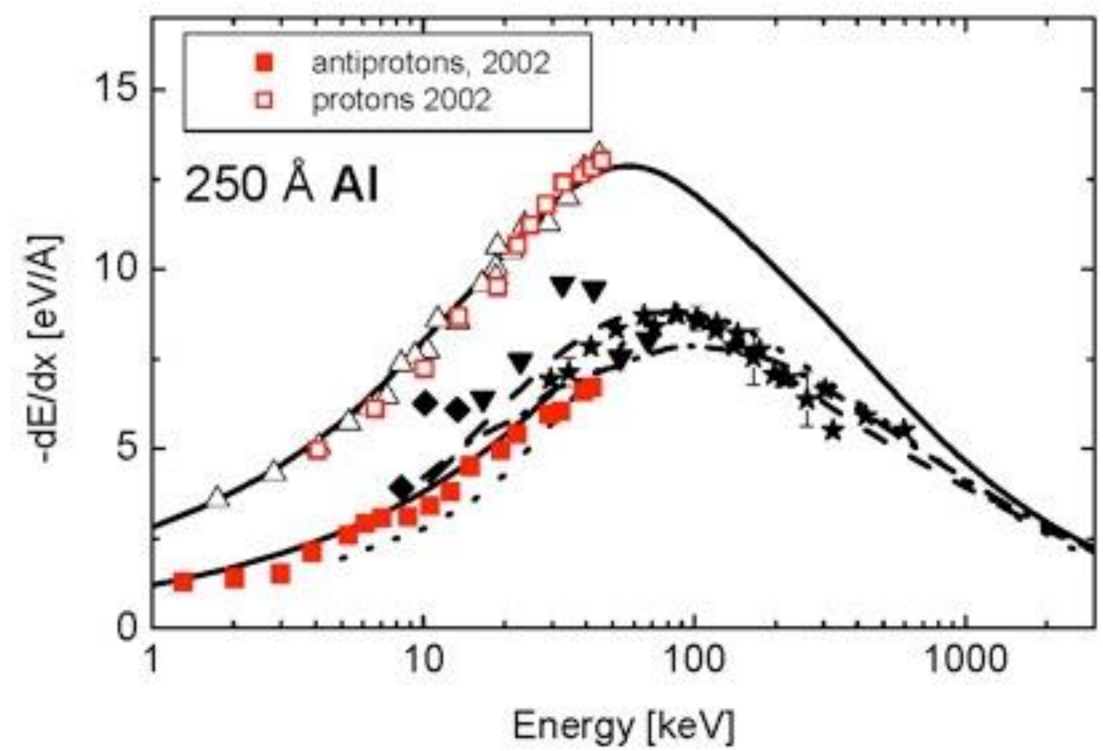
Atomic Collision Physics with USR

- Ionization in single collision by slow antiprotons
- Energy loss

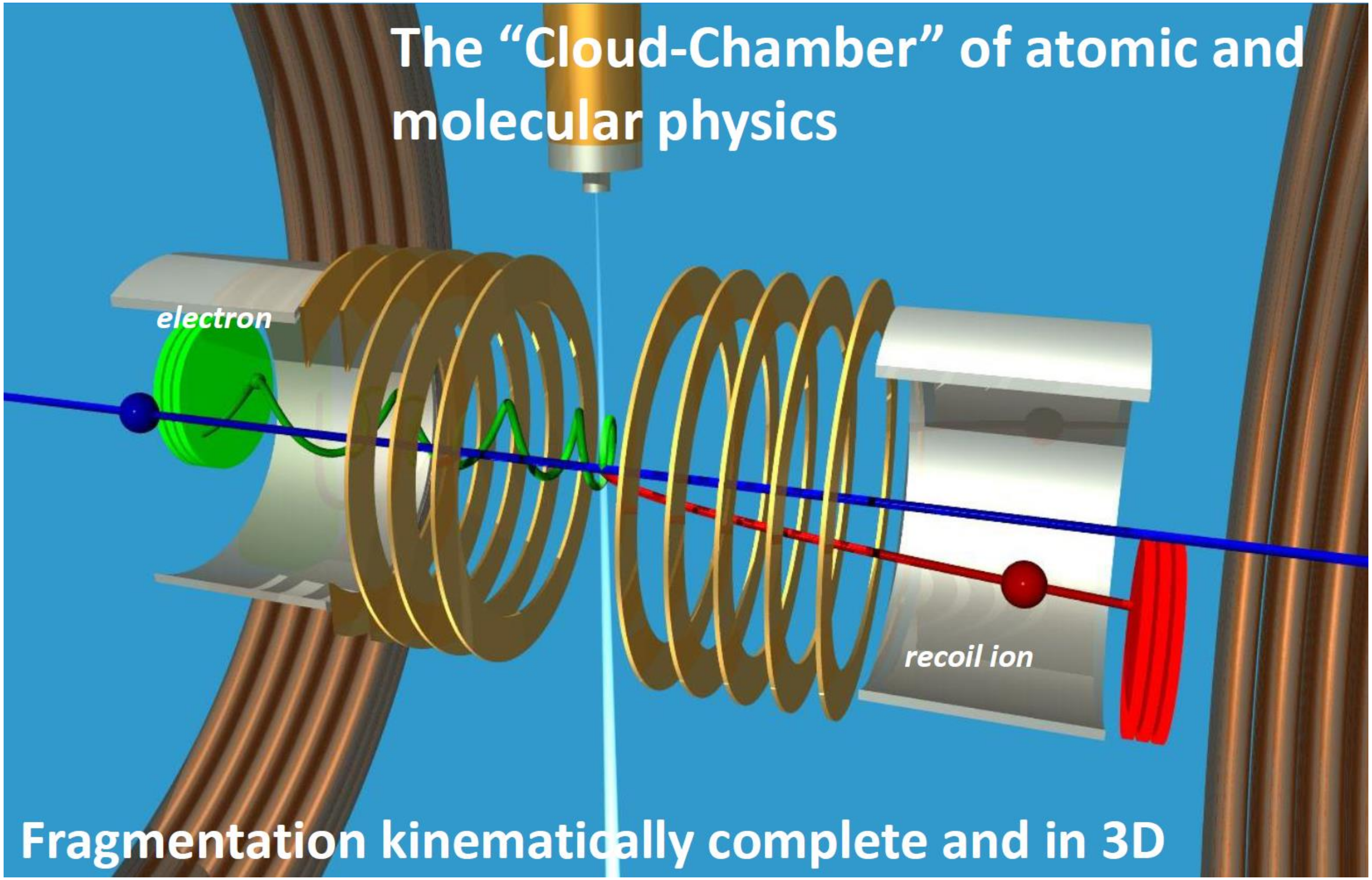




- Benchmark system for theory
- Antiproton does not suffer from charge screening
- Kinematically complete measurements possible with an internal target in a storage ring

see talks by Nordlund and Bondarev We morning

Reaction microscope



D. Fischer, FLAIR workshop Heidelberg 2014
https://indico.gsi.de/event/2495/

p̄-RI in Traps for Nuclear Structure Study

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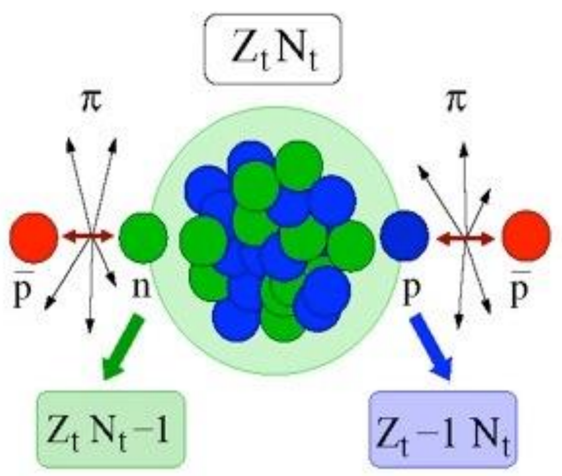
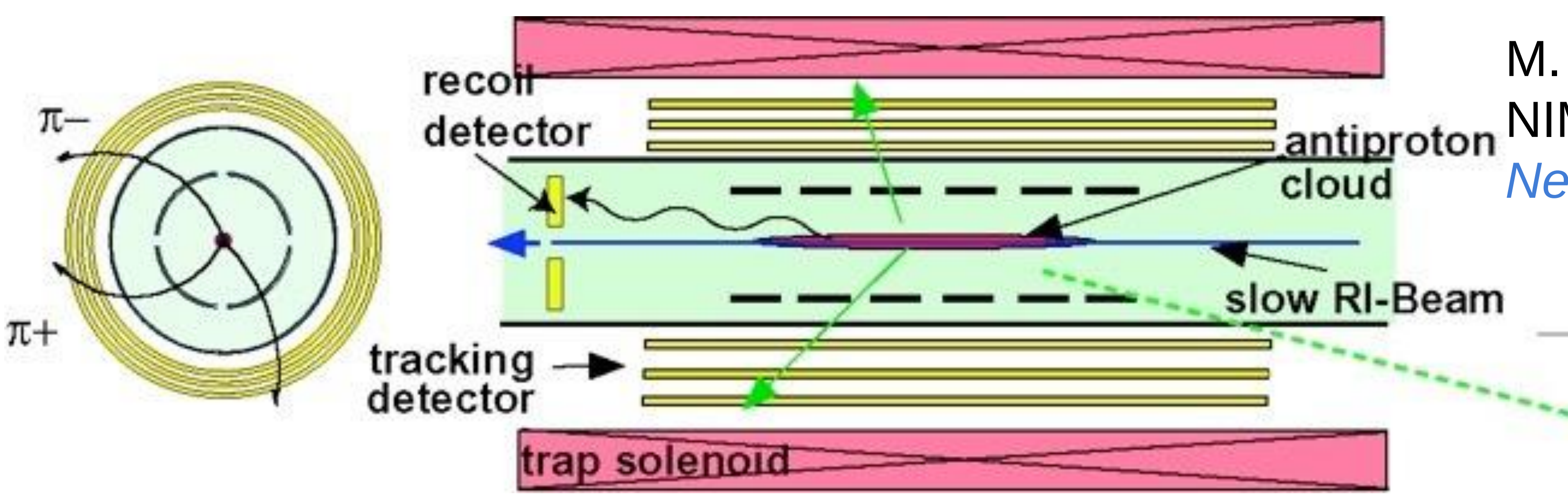
PS209@LEAR

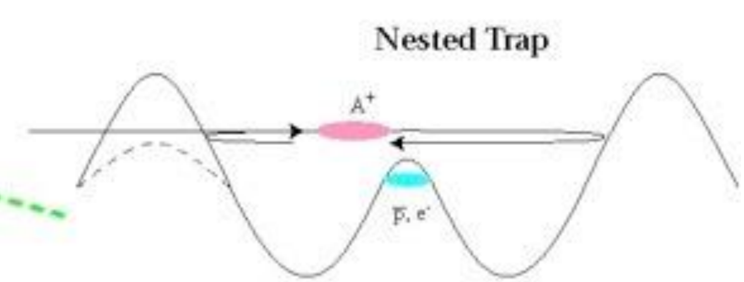
determination of the **halo factor** (f_{halo})



- Momentum distribution of recoil nuclei
  - Wave function of outer-most nucleon
- Charged pion multiplicity
  - Distinguish annihilation on p and n
  - Halo factors
  - Less model dependent than X-rays
- Antiprotons from FLAIR
- RI from LEB-SFRS gas catcher



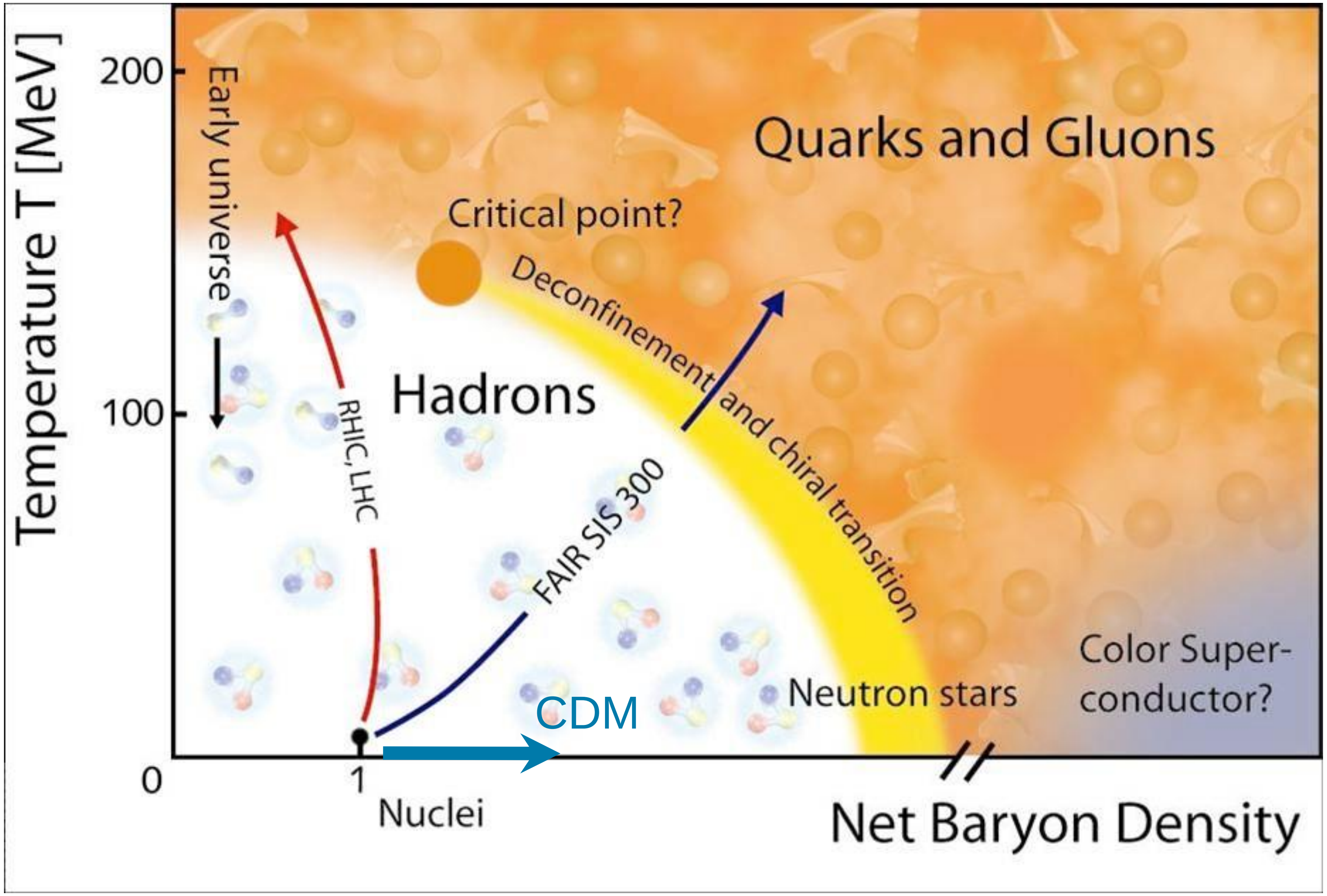
M. Wada, Y. Yamazaki (Tokyo)
NIM B214 (2004) 196
Nested Penning trap



Exo+pbar

New idea: PUMA, talk A. Obertelli Tu 9:00

Cold dense nuclear matter



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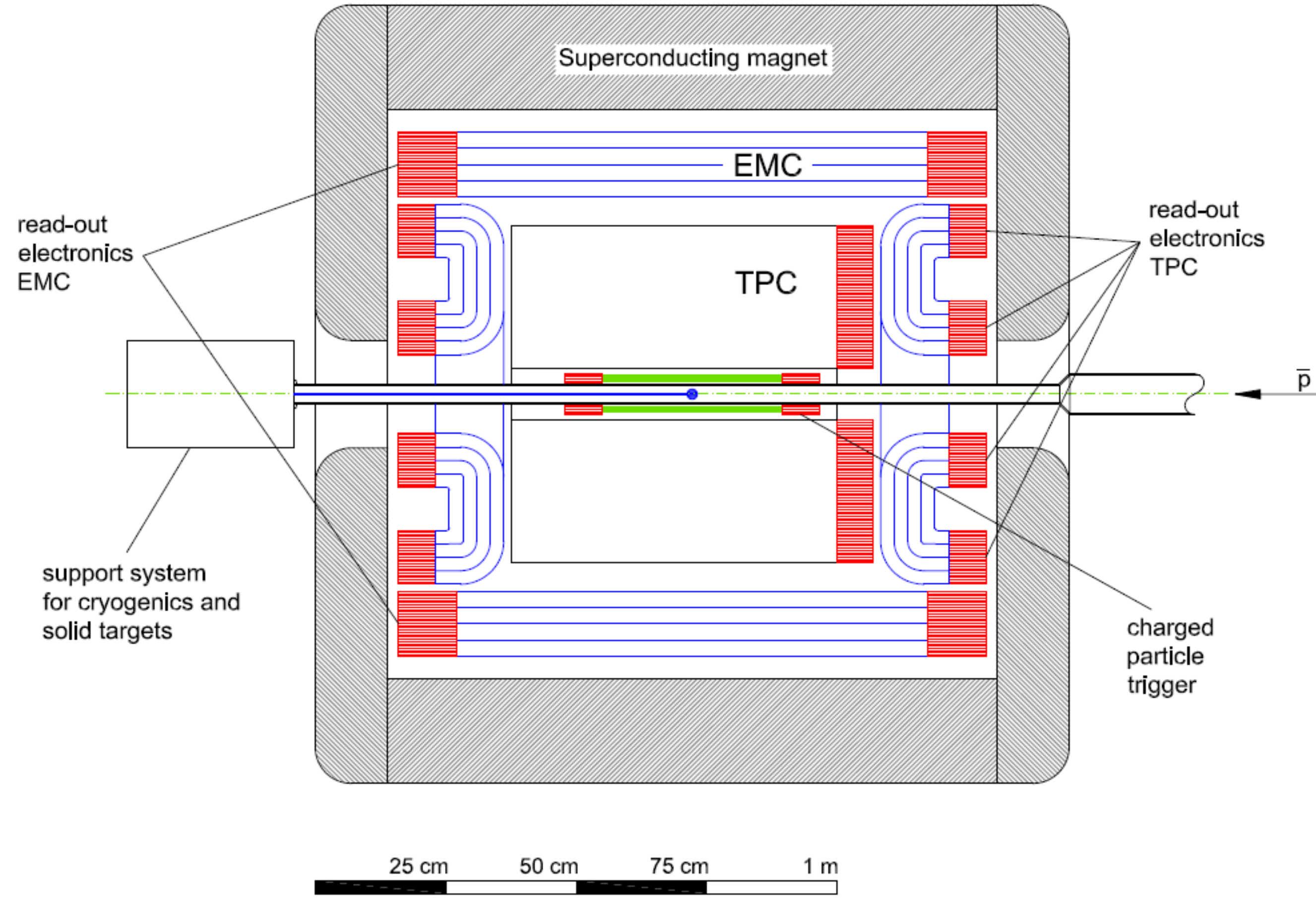
Cold, dense hadronic matter by antiproton annihilation in nuclei at rest

- Strong attraction in antikaon-nucleon interaction below threshold
  - Bound states of single and double kaons exist?
- Large cross section for production of 2 K^+ in proton-antiproton annihilation at LEAR
- re-measurement with stopped antiprotons
- 4π detector needed: *FOPI*
  - also useful for meson spectroscopy with stopped

J. Zmeskal et al. Hyperfine Interact 194, 249-254 (200



$$\bar{p} + p \longrightarrow K^+ + K^+ + K^- + K^- - 0.098\,\text{GeV}$$

$$\bar{p} + {}^4He \longrightarrow K^+ + K^+ + [pnnK^-K^-]$$

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New developments

USR: electrostatic storage ring

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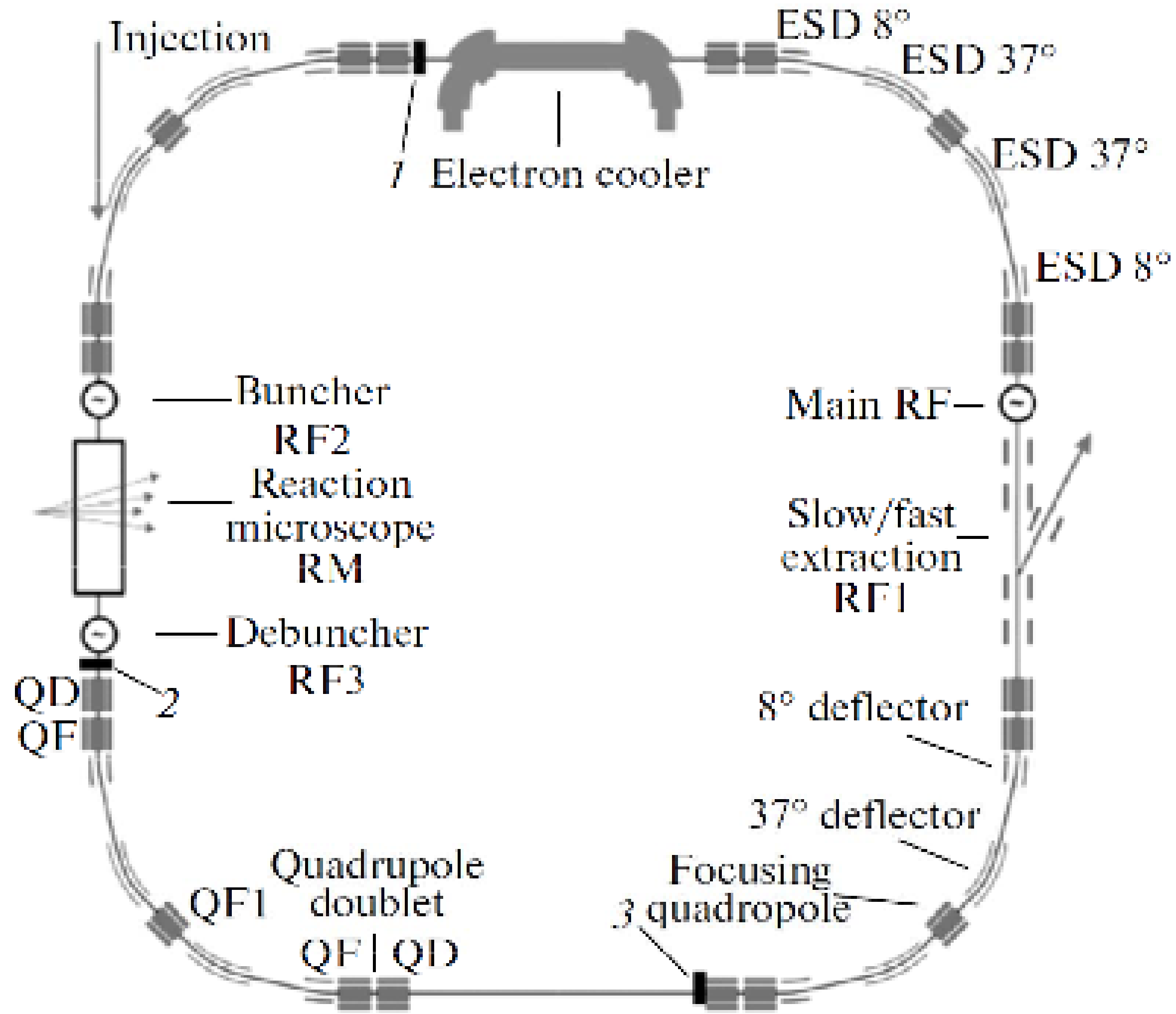
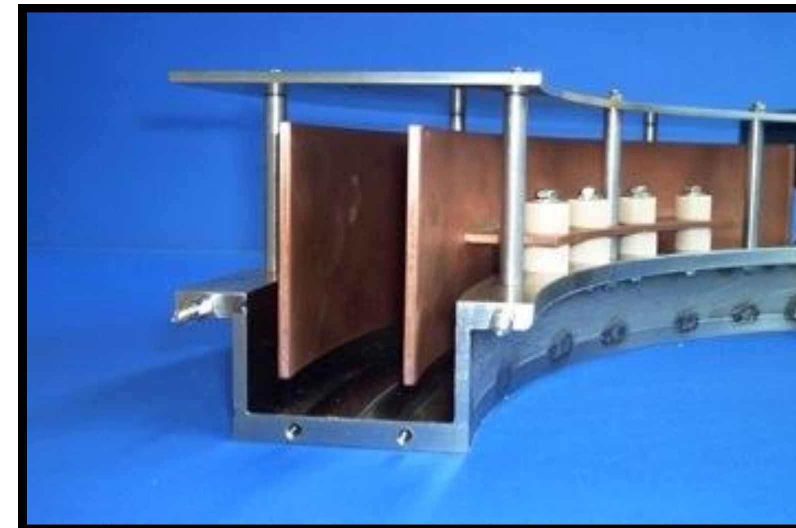
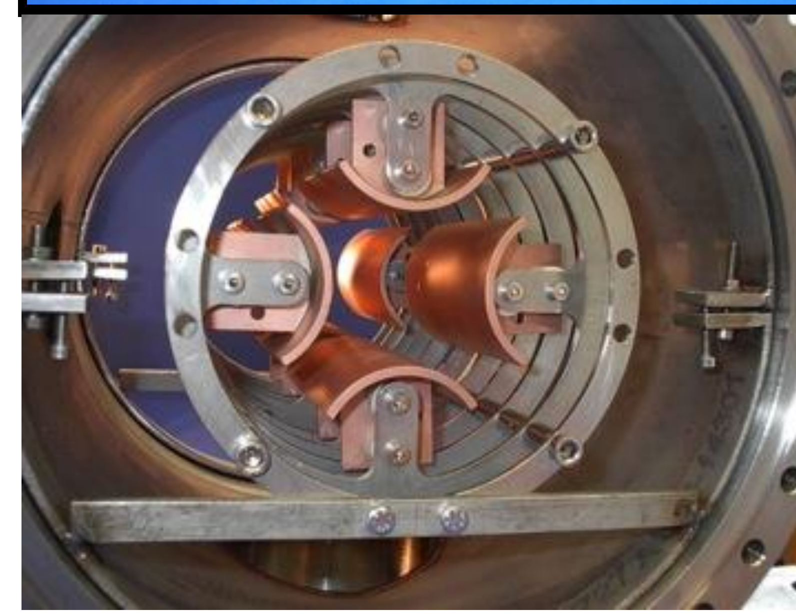


Part Phys. Nucl. Letters 8 (2011)





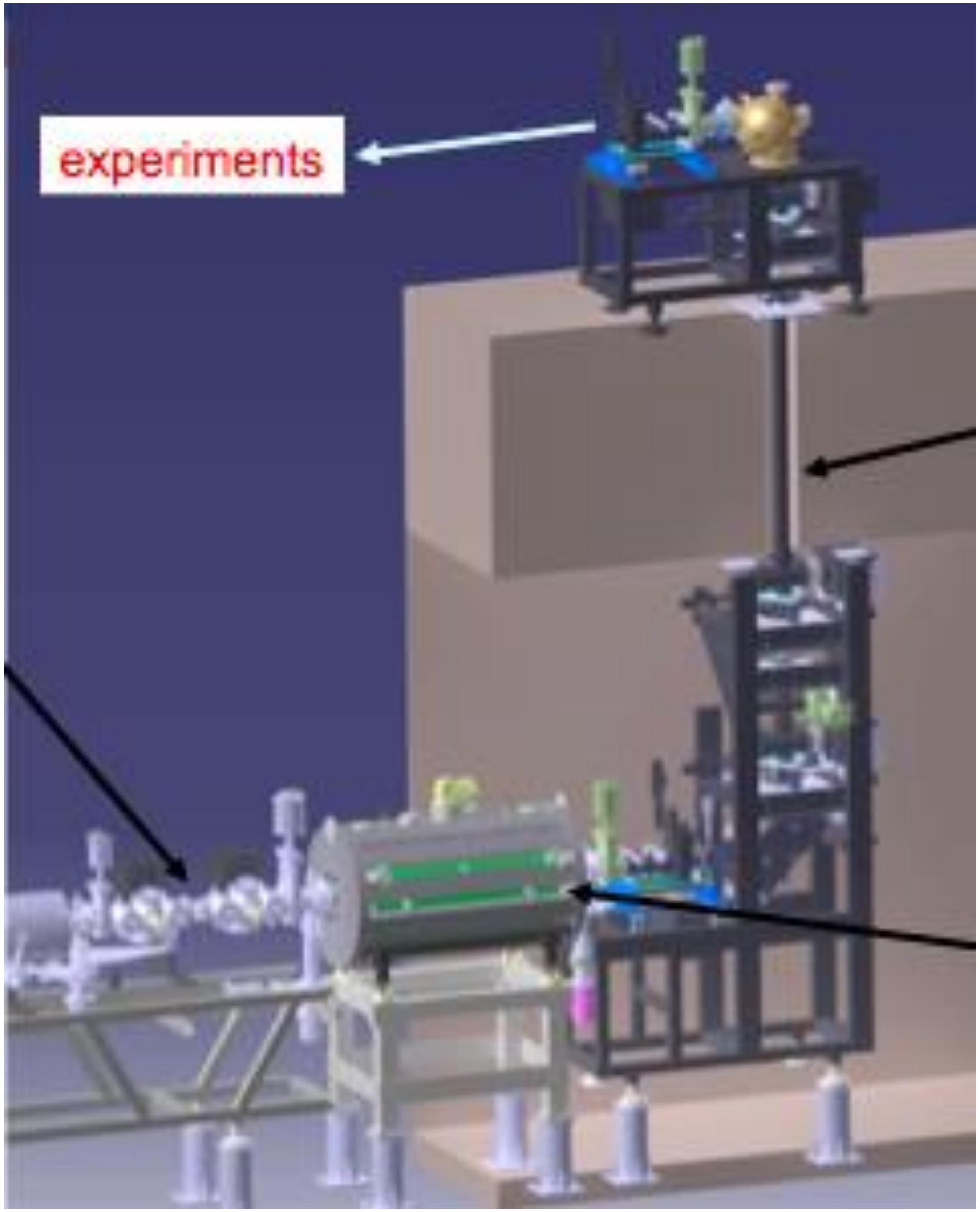
E_{min} / E_{max}	20 / 300 keV
Voltages	< ± 20 kV
number of pbars at 20 keV	$1 \cdot 10^7$

TDR exists

CSR@MPI-K Heidelberg; USR: C. Welsch Cockcroft Institute

HITRAP

- LINAC + RFQD + Penning trap for HCI and pbar
- extraction of eV beams
- precision mass measurements, reaction microscopes for collision studies, etc.
- **being commissioned for ESR@GSI**



Next talk M. Vogel

CRYRING: a perfect match for LSR

- LSR is central “work horse” of FLAIR
  - Beam delivery for HITRAP, USR, experiments
- Choice of CRYRING (MSL, Stockholm)
  - Fitting energy range, electron cooling, fast ramping, internal target, low-energy injection from ion source for commissioning
  - Expertise: MSL staff has designed & built CRYRING
  - CRYRING will be contributed by Sweden as in-kind contribution to FAIR

has been

being set up @GSI

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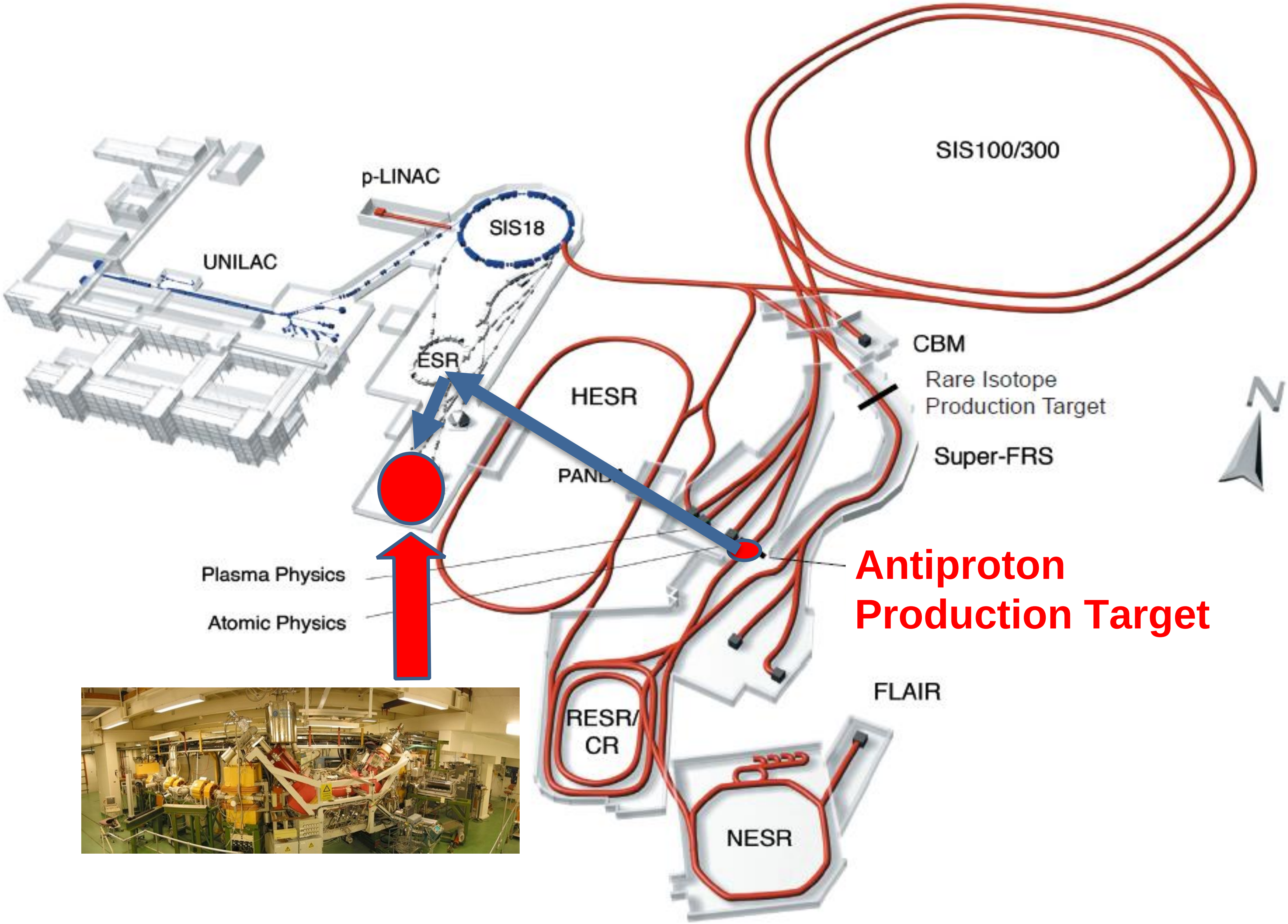
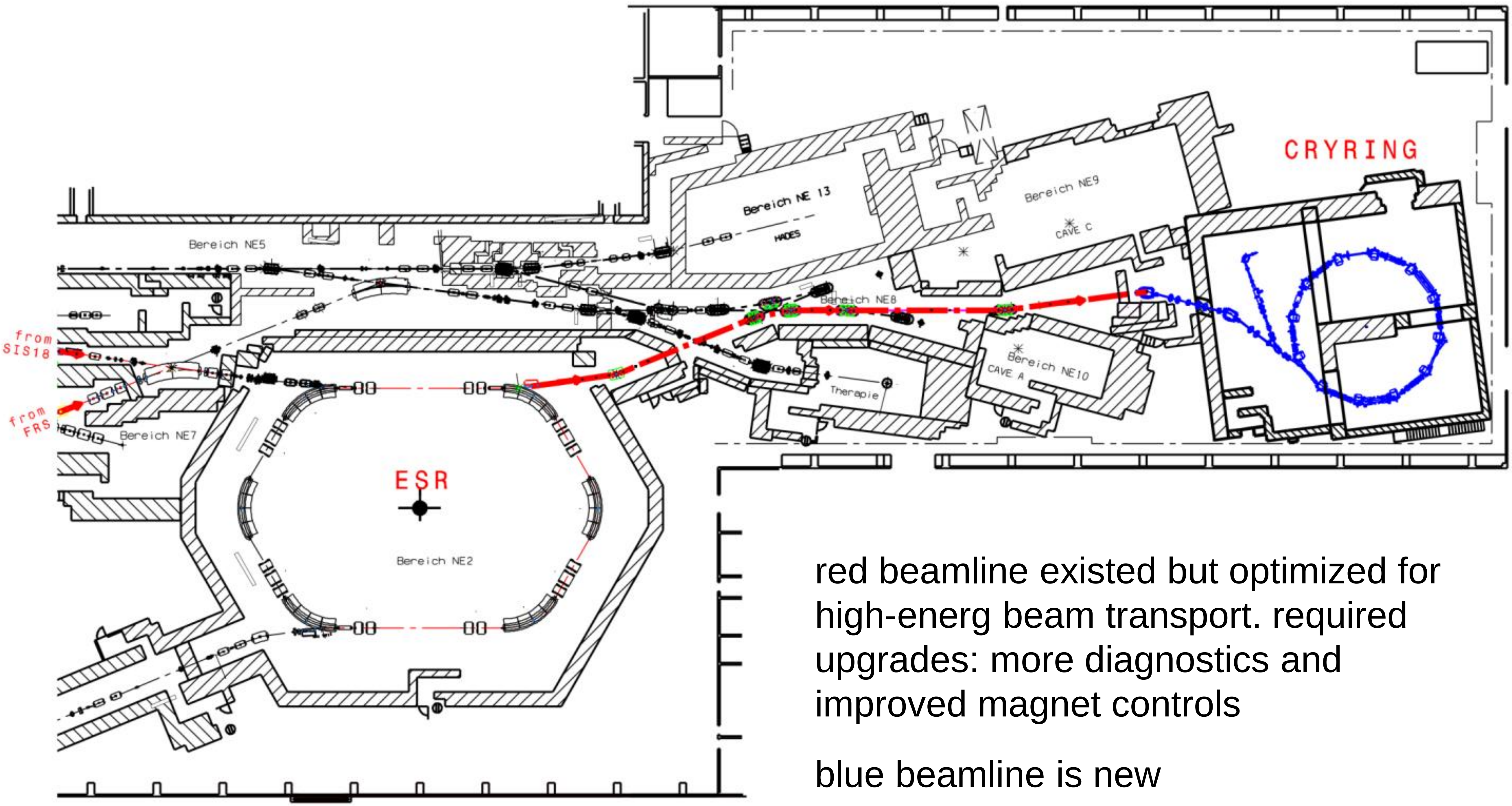
CRYRING@ESR –
a Swedisch in-kind contribution



GSI/FAIR beamline topology with CRYRING@ESR

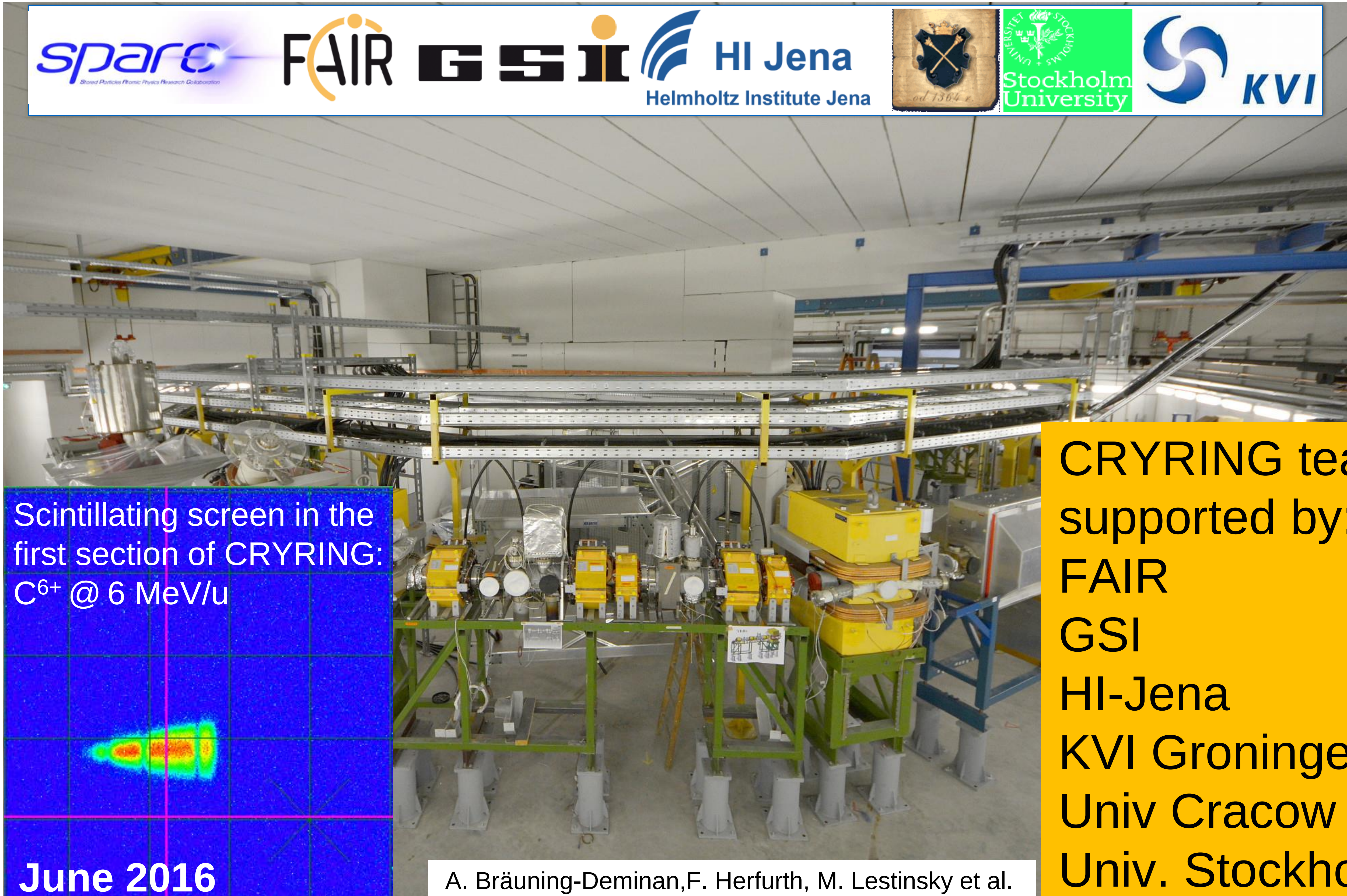


red beamline existed but optimized for high-energ beam transport. required upgrades: more diagnostics and improved magnet controls

blue beamline is new

ESR fast extraction towards CRYRING

CRYRING: First transfer of ions from ESR to CYRING



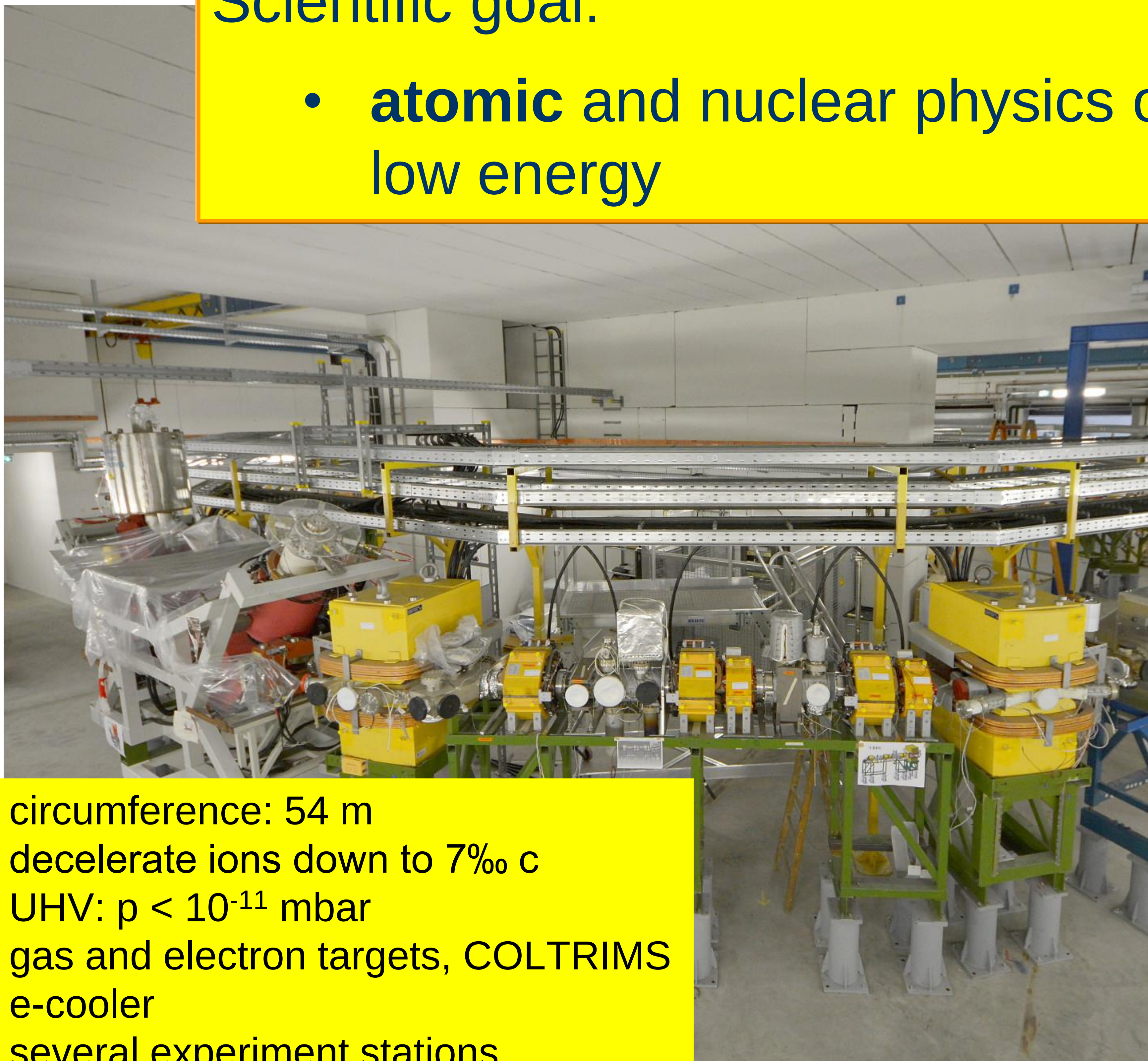
CRYRING team supported by:
FAIR
GSI
HI-Jena
KVI Groningen
Univ Cracow
Univ. Stockholm

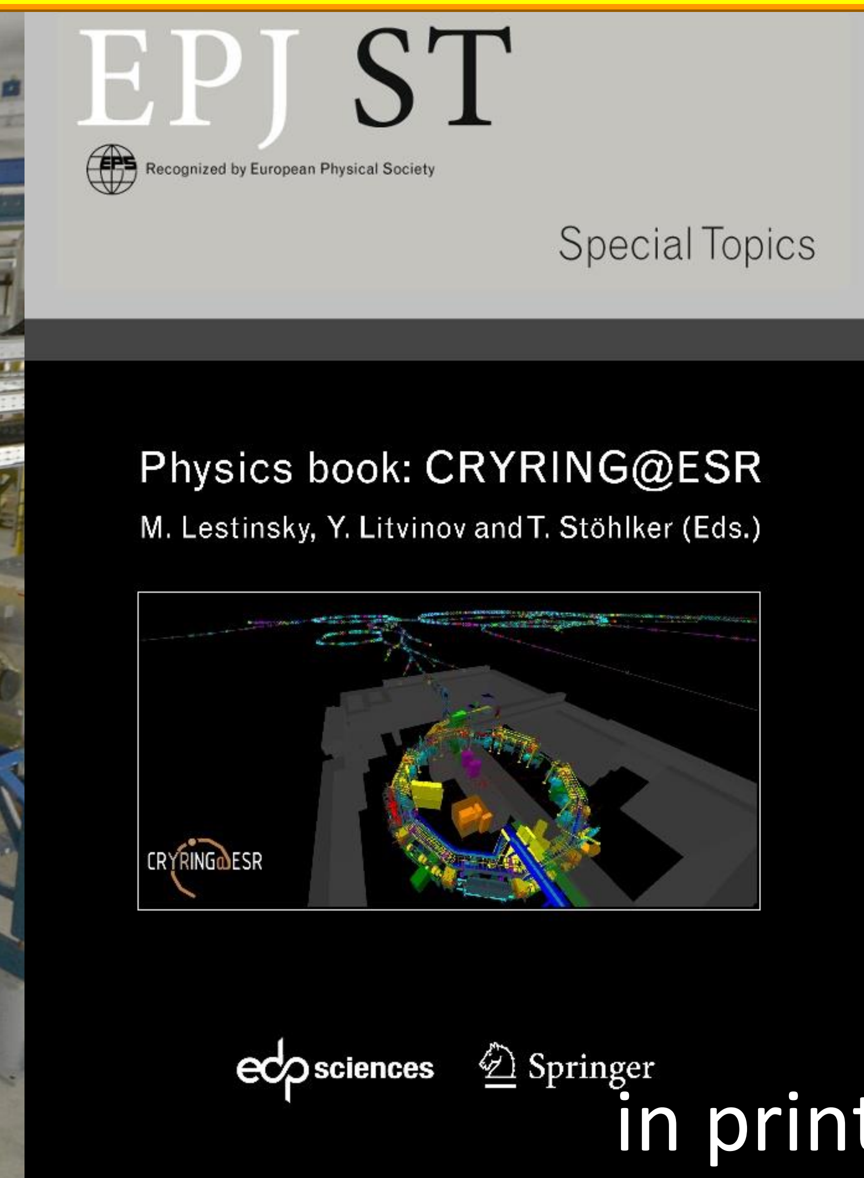
From Th. Stöhlker

CRYRING / FAIR

Scientific goal:

- **atomic** and nuclear physics of exotic systems at low energy





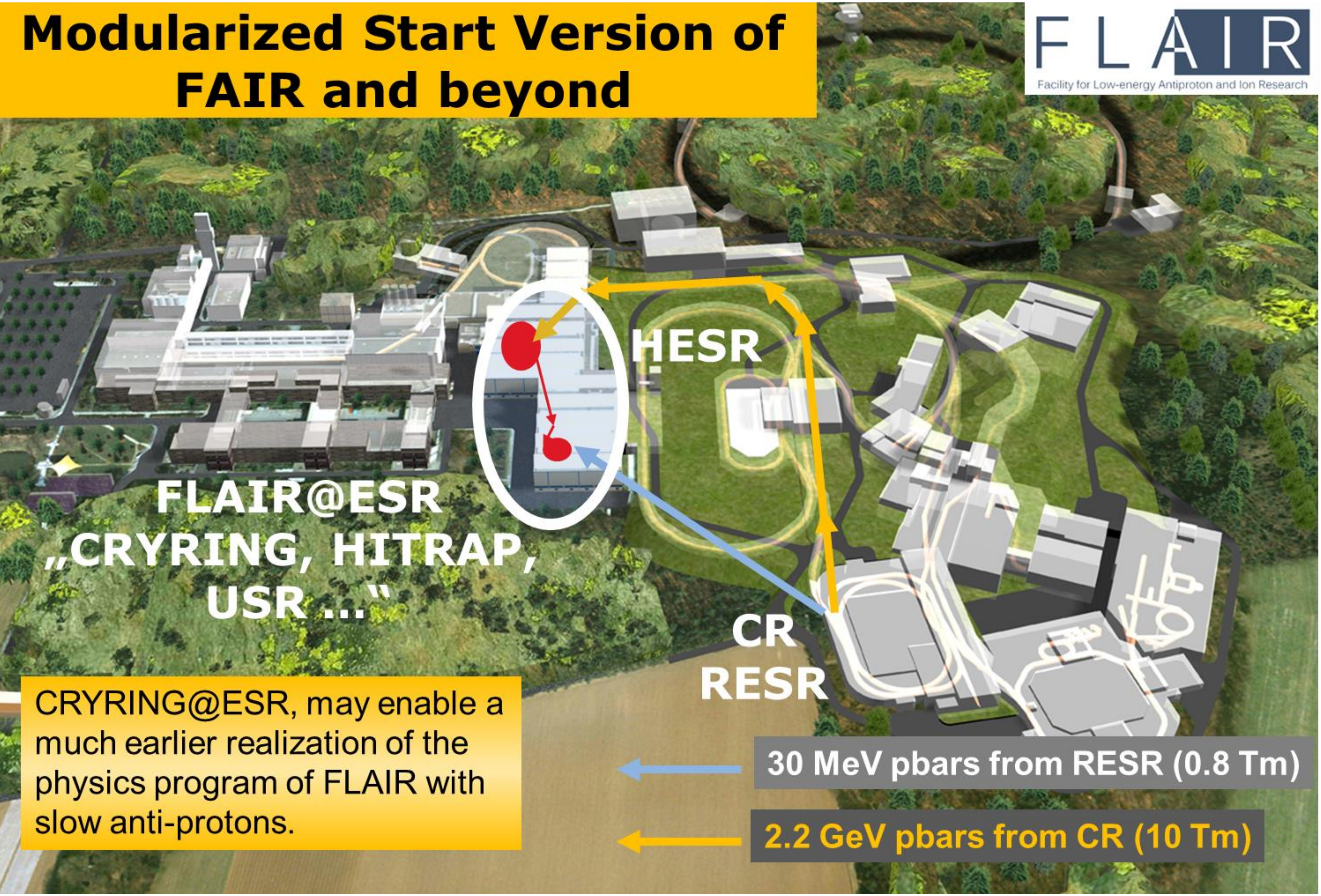
in print

- circumference: 54 m
- decelerate ions down to 7‰ c
- UHV: $p < 10^{-11}$ mbar
- gas and electron targets, COLTRIMS
- e-cooler
- several experiment stations

CRYRING in the SIS18 target hall @ GSI/FAIR

From Th. Stöhlker

Modularized Start Version of FAIR and beyond



CRYRING@ESR, may enable a much earlier realization of the physics program of FLAIR with slow anti-protons.

From Th. Stöhlker

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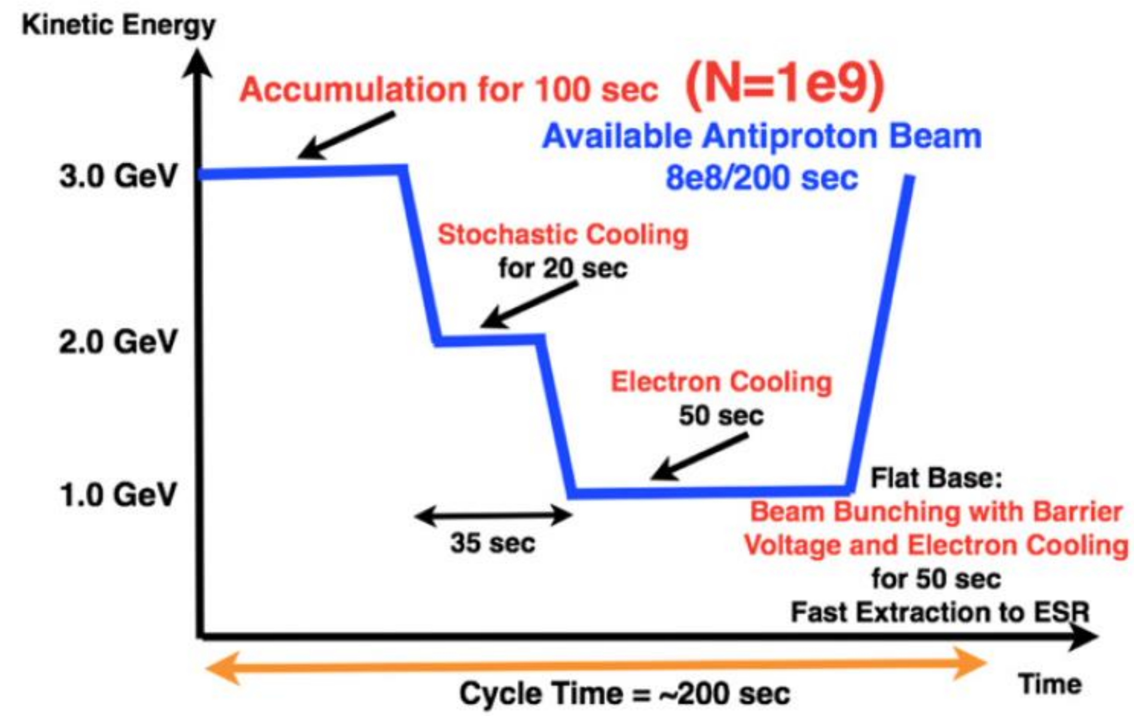
Scenarios: p̄ rates in MSV from HESR

- Leftover from PANDA
  - few 10^9 per 60 min
  - decelerate & transfer to ESR
    - T. Katayama: 100s, 80% eff.
  - average 5×10^5/s
  - 5×10^7/s every 100 s
    - *similar to AD-ELENA*
  - fast or *slow* extraction



T. Katayama et al., Phys. Scr. T166 (2015) 014073

- Low-energy p̄ production: full use of HESR
  - CR 13 Tm
  - ESR 10 Tm, but above transition energy
  - deceleration needed to avoid loss: HESR
  - T. Katayama:
    - start with10^9 p̄ (stacking for 100 s)
    - deceleration to 30 MeV in HESR&ESR: 8×10^8 p̄ /100 s: *10xELENA*
    - max. 10^{10} p̄ (stacking for 1000 s): similar average rate

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Summary and Outlook

- Low energy antiprotons offer exciting possibilities for a variety of fields
  - Fundamental symmetries, nuclear & atomic physics
- CERN-AD and ELENA: Antihydrogen
  - essential for continuation of current program
  - Antihydrogen spectroscopy and gravity
- FLAIR: offers further opportunities
  - continuous $\bar{p}$ beams available from CRYRING
    - nuclear and particle physics type experiments (not possible at AD)
  - Availability of radioactive ion beams (RIB) offers new synergies
    - requires independent beam line from (S)FRS
  - Cooled antiprotons down to 20 keV (with USR)
  - higher rates (phase 2, with RESR)
  - Time line: beyond 2025
- Major components of FLAIR are ready or will be soon
  - CRYRING can play a major role in future experiments with

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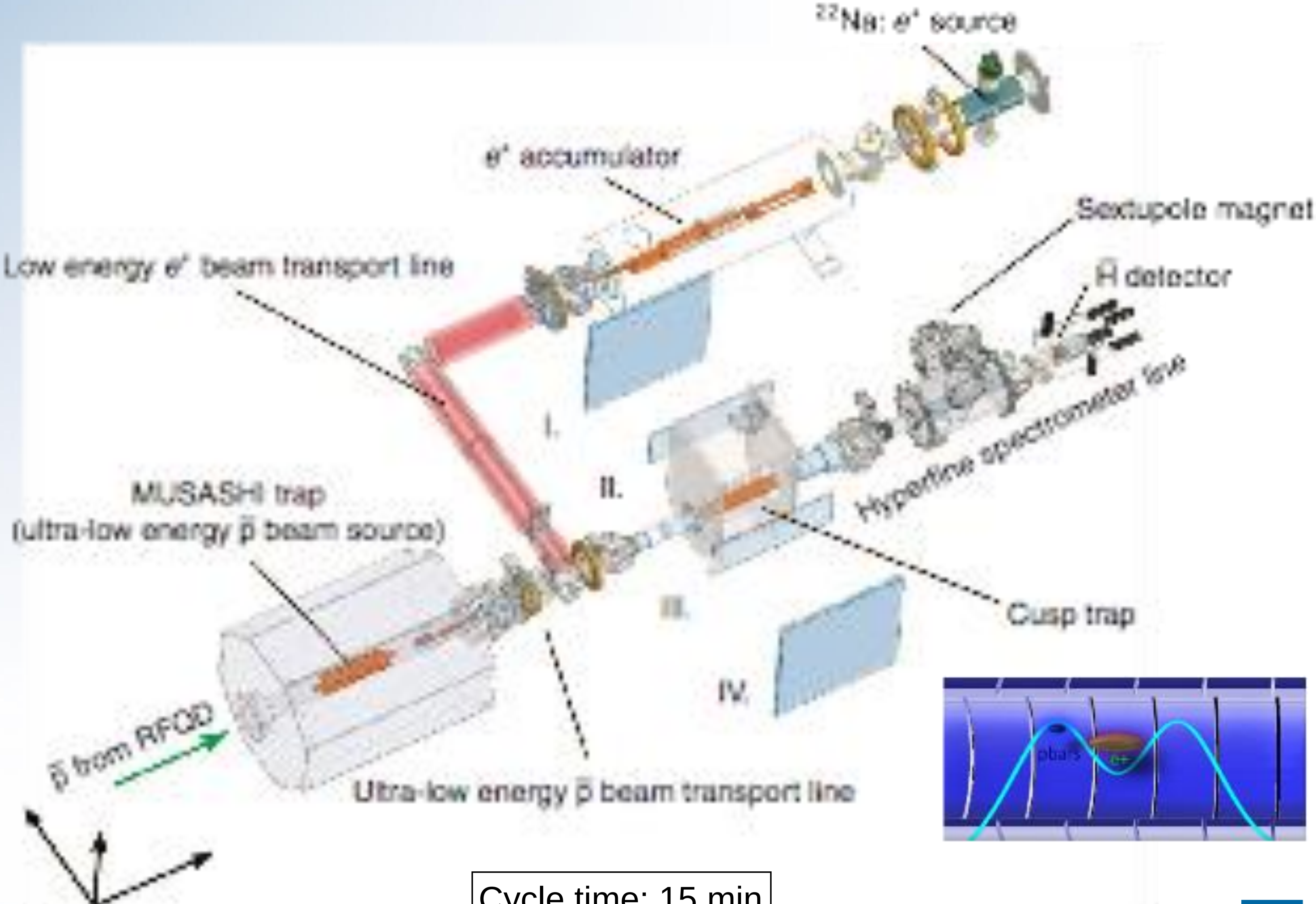
Thank you

SUMMARY

- AEḡIS aims at first ever direct measurement of deflection of antihydrogen beam by the Earth's gravitational field
  - Test of WEP with antimatter
- Experiment is ready for beam this year
  - 2014 goal: $\bar{H}$ production at T=7 K (current min. temperature)
    - later stage → 100 mK
  - $\bar{H}$ beam production
  - Gravity measurement
  - $\bar{H}$-HFS spectroscopy
    - ASACUSA & AEḡIS

ERC Advanced Grant
291242
HbarHFS
www.antimatter.at
PI EW

ASACUSA H̄ PRODUCTION

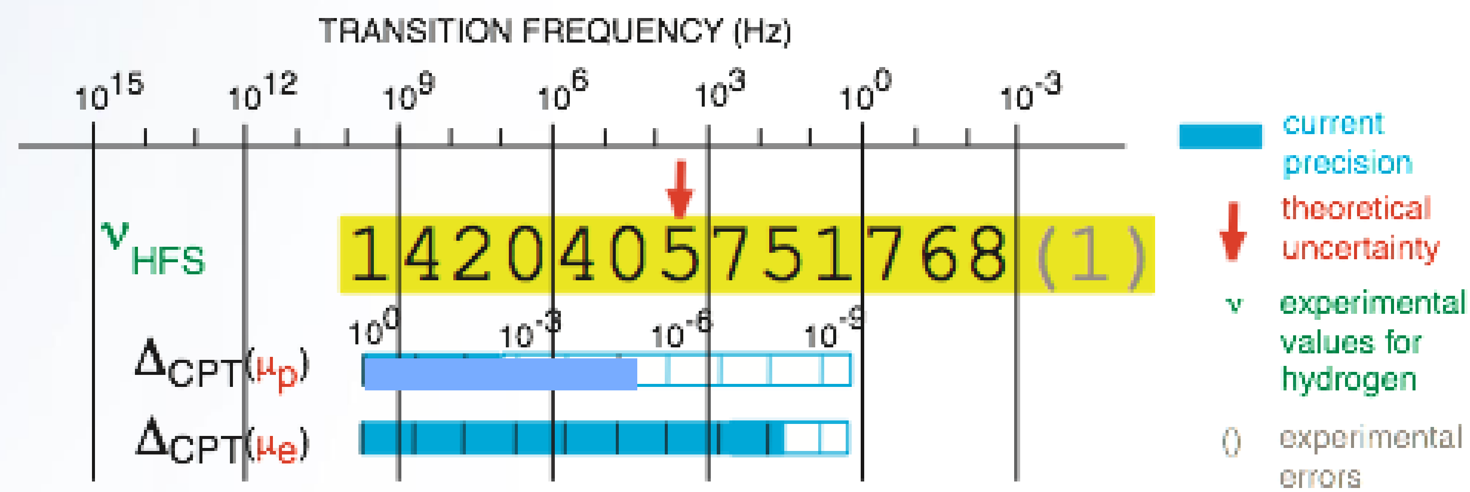


Cycle time: 15 min
Mixing time: 100 sec

GROUND-STATE HYPERFINE SPLITTING OF H/H̄

- spin-spin interaction positron - antiproton
- Leading: Fermi contact term

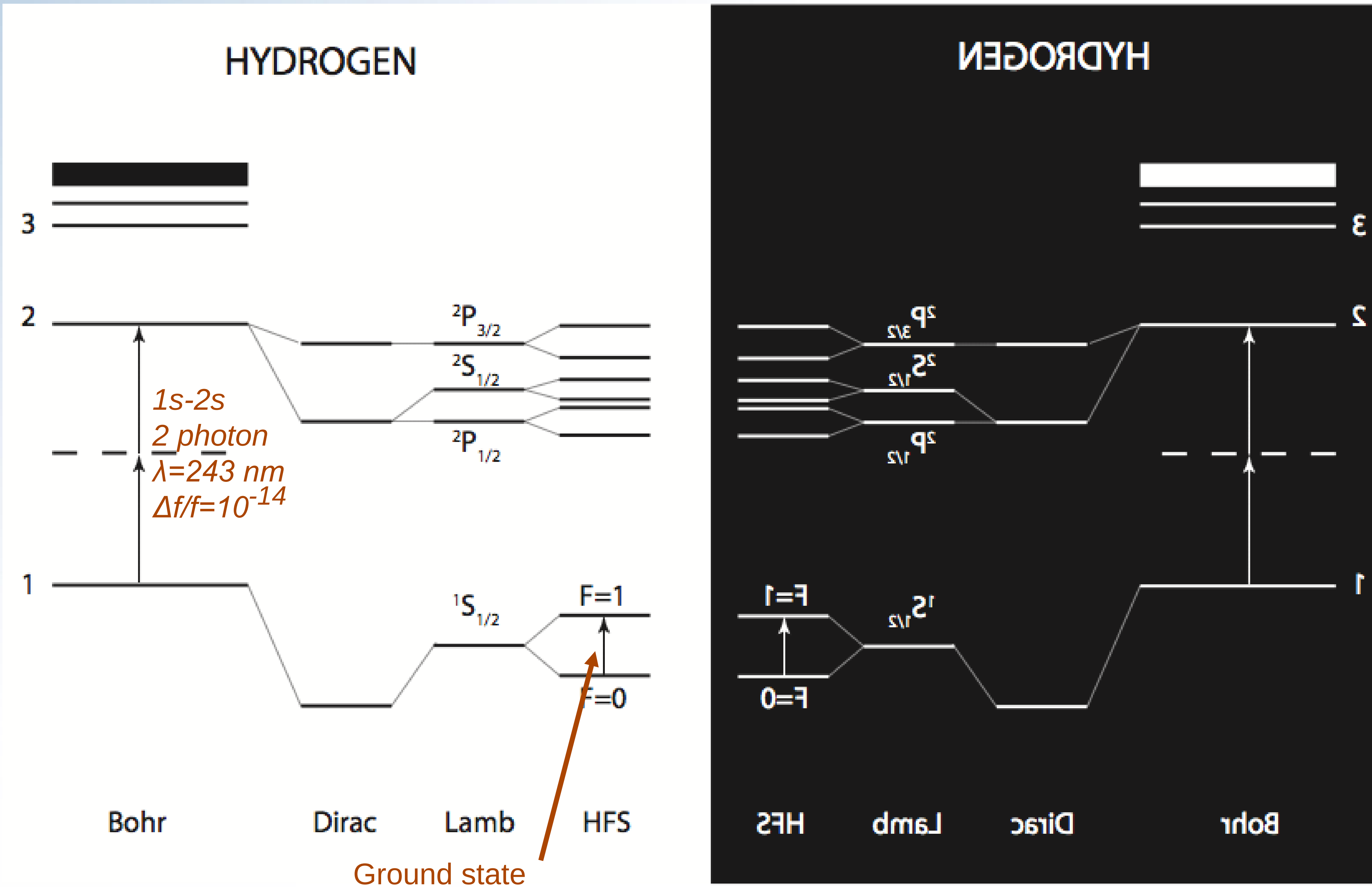
$$\nu_F = \frac{16}{3}\left(\frac{M_p}{M_p + m_e}\right)^3 \frac{m_e}{M_p}\frac{\mu_p}{\mu_N}\alpha^2 c\, Ry,$$



- magnetic moment of p̄
  - previously known to 0.3%, 2012 Gabrielse Penning trap 5 ppm PRL 110,130801 (2013)
- H: deviation from Fermi contact term: −32.77±0.01 ppm
  - finite electric & magnetic radius (Zemach corrections): −41.43±0.44 ppm
  - polarizability of p/p̄ (g_1, g_2 PRA 78, 022517 (2008)): 1.88±0.64 ppm
  - remaining deviation th-exp: 0.86±0.78 ppm

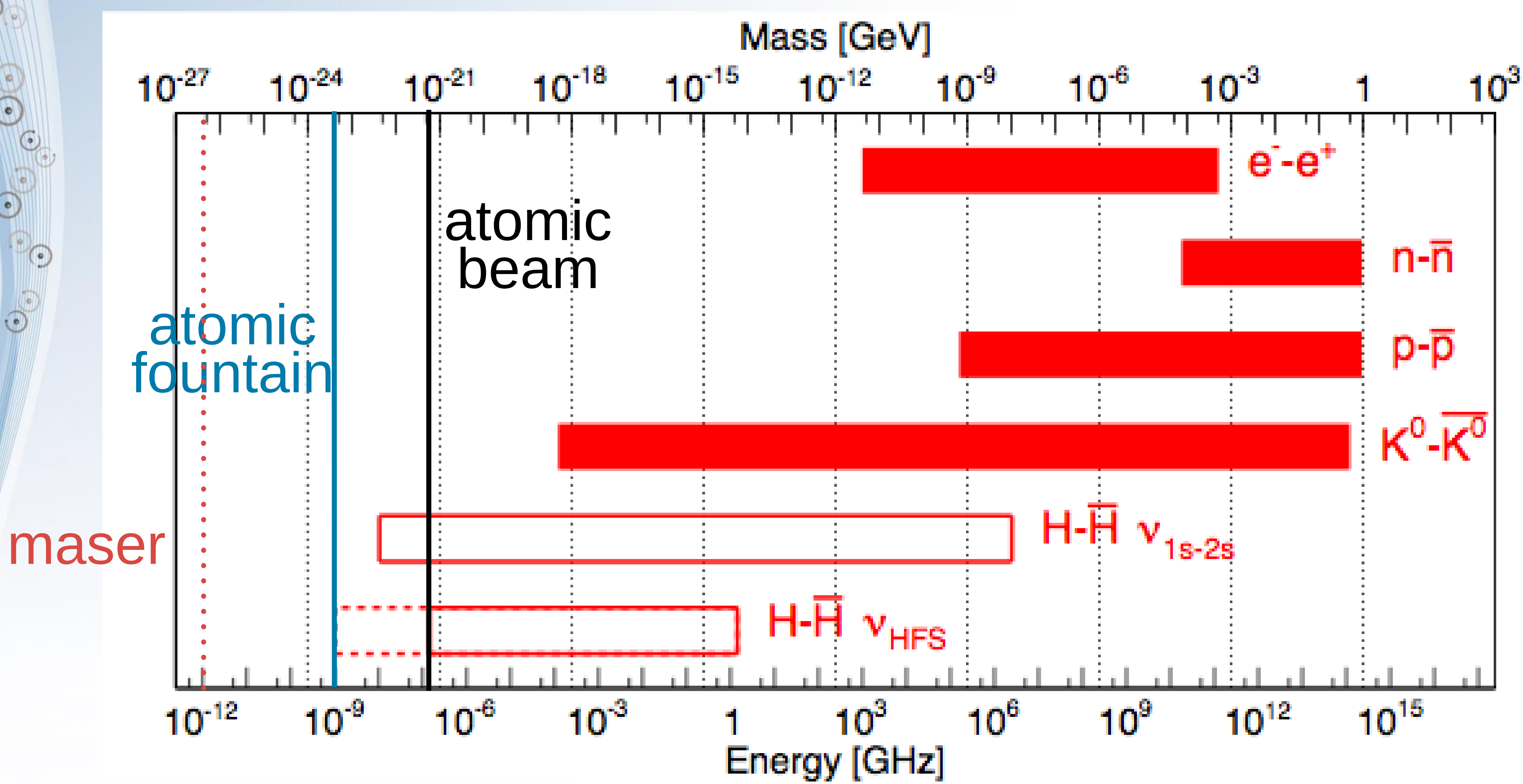
$$\Delta\nu(\text{Zemach}) = \nu_F \frac{2Z\alpha m_e}{\pi^2}\int \frac{d^3p}{p^4}\left[\frac{G_E(p^2)G_M(p^2)}{1+\kappa} - 1\right]$$

HYDROGEN AND ANTIHYDROGEN



Ground state
hyperfine splitting
f = 1.4 GHz
$\Delta f/f=10^{-12}$

CPT TESTS - RELATIVE & ABSOLUTE PRECISION



Atomic physics experiments, especially antihydrogen offer the most sensitive experimental verifications of CPT

ASACUSA CUSP COLLABORATION

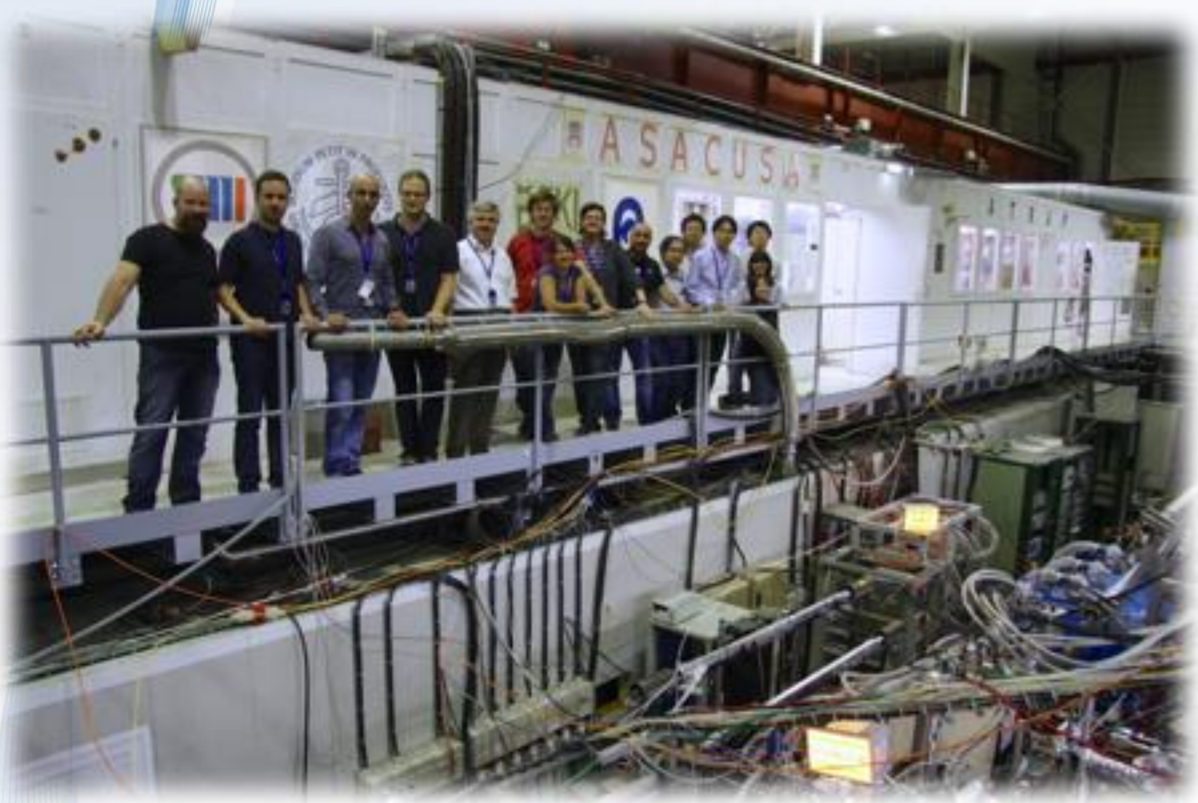
A tomic
S pectroscopy
A nd
C ollisions
U sing
S low
A ntiprotons

ASACUSA Scientific project

(1) Spectroscopy of $\bar{p}$He

(2) $\bar{p}$ annihilation cross-section

(3) $\bar{H}$ production and spectroscopy



The $\bar{H}$ team

University of Tokyo, Komaba: K. Fujii, N. Kuroda, Y. Matsuda, M. Ohtsuka, S. Takaki, K. Tanaka, H.A. Torii

RIKEN: Y. Kanai, A. Mohri, D. Murtagh, Y. Nagata, B. Radics, S. Ulmer, S. Van Gorp, Y. Yamazaki

Tokyo University of Science: K. Michishio, Y. Nagashima

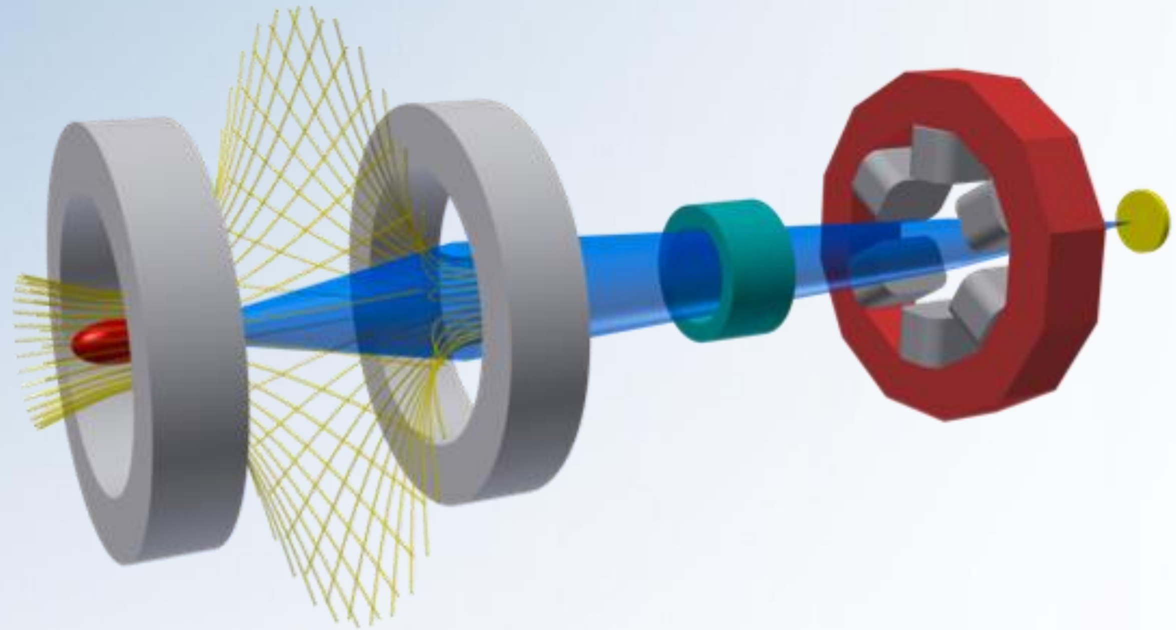
Hiroshima University: H. Higaki, S. Sakurai

Univerita di Brescia: M. Leali, E. Lodi-Rizzini, V. Mascagna, L. Venturelli, N. Zurlo

Stefan Meyer Institut für Subatomare Physik: P. Caradonna, M. Diermaier, S. Friedreich, C. Malbrunot, O. Massiczek, C. Sauerzopf, K. Suzuki, E. Widmann, M. Wolf, J. Zmeskal

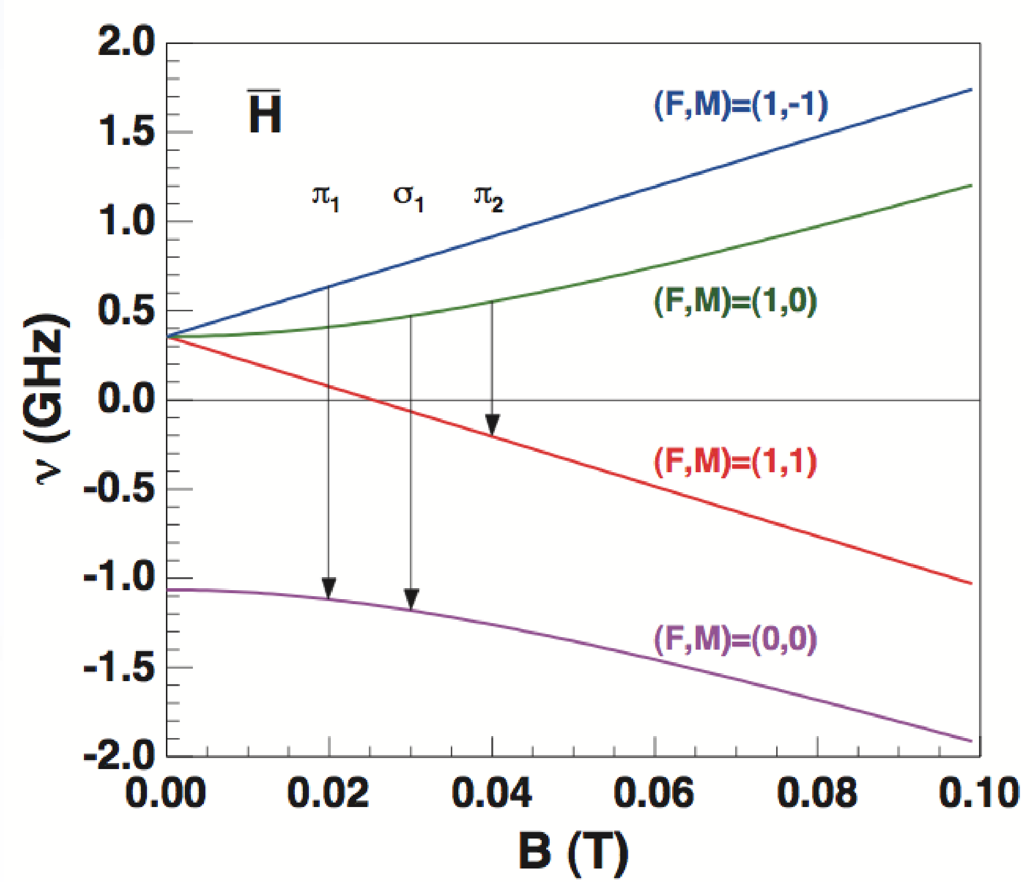
H·HFS

HFS MEASUREMENT IN AN ATOMIC BEAM



- atoms evaporate - no trapping needed
- cusp trap provides polarized beam
- spin-flip by microwave
- spin analysis by sextupole magnet
- low-background high-efficiency detection of antihydrogen

E.W. et al. ASACUSA proposal addendum CERN-SPSC 2005-002



achievable resolution

- better 10^{-6} for T ≤ 100 K
- > 100 H̄/s in 1S state into 4π needed
- event rate 1 / minute: background from cosmics, annihilations uptsreams

Recent results: $\bar{\text{H}}$ beam

- $\bar{\text{H}}$ beam observed with 5σ
  - n≲43 (field ionization)
  - 6 events / 15 min
- significant fraction in lower n
  - n≲29: 3σ
  - 4 events / 15 min
  - τ ~ few ms

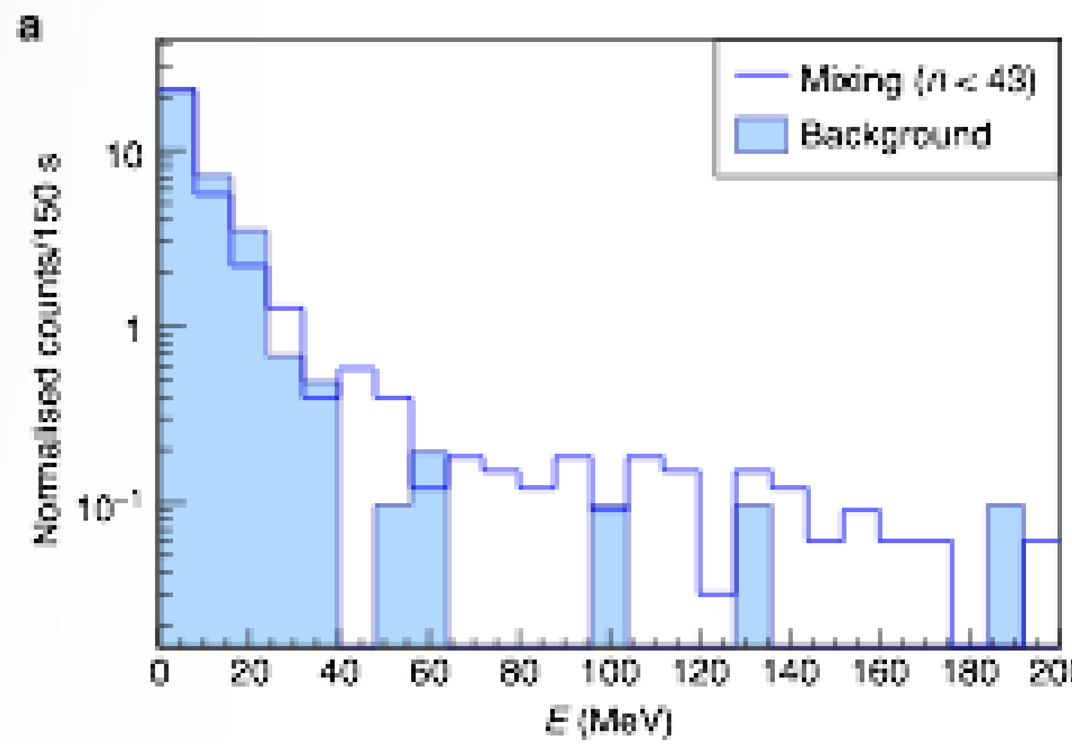


Table 1 | Summary of antihydrogen events detected by the antihydrogen detector.

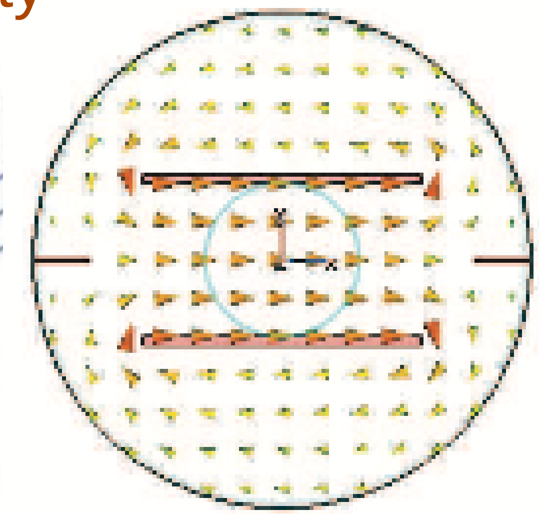
	Scheme 1	Scheme 2	Background
Measurement time (s)	4,950	2,100	1,550
Double coincidence events, N_t	1,149	487	352
Events above the threshold (40 MeV), $N_{>40}$	99	29	6
Z-value (profile likelihood ratio) (σ)	5.0	3.2	—
Z-value (ratio of Poisson means) (σ)	4.8	3.0	—
	$n \lesssim 43$	$n \lesssim 29$	

N. Kuroda[1], S. Ulmer[2], D.J. Murtagh[3], S. Van Gorp[3], Y. Nagata[3], M. Diermaier[4], S. Federmann[5], M. Leali[6,7], C. Malbrunot[4,1], V. Mascagna[6,7], O. Massiczek[4], K. Michishio[8], T. Mizutani[1], A. Mohri[3], H. Nagahama[1], M. Ohtsuka[1], B. Radics[3], S. Sakurai[9], C. Sauerzopf[4], K. Suzuki[4], M. Tajima[1], H.A. Torii[1], L. Venturelli[6,7], B. Wünschek[4], J. Zmeskal[4], N. Zurlo[6], H. Higaki[9], Y. Kanai[3], E. Lodi Rizzini[6,7], Y. Nagashima[8], Y. Matsuda[1], E. Widmann[4] & Y. Yamazaki[1,3]

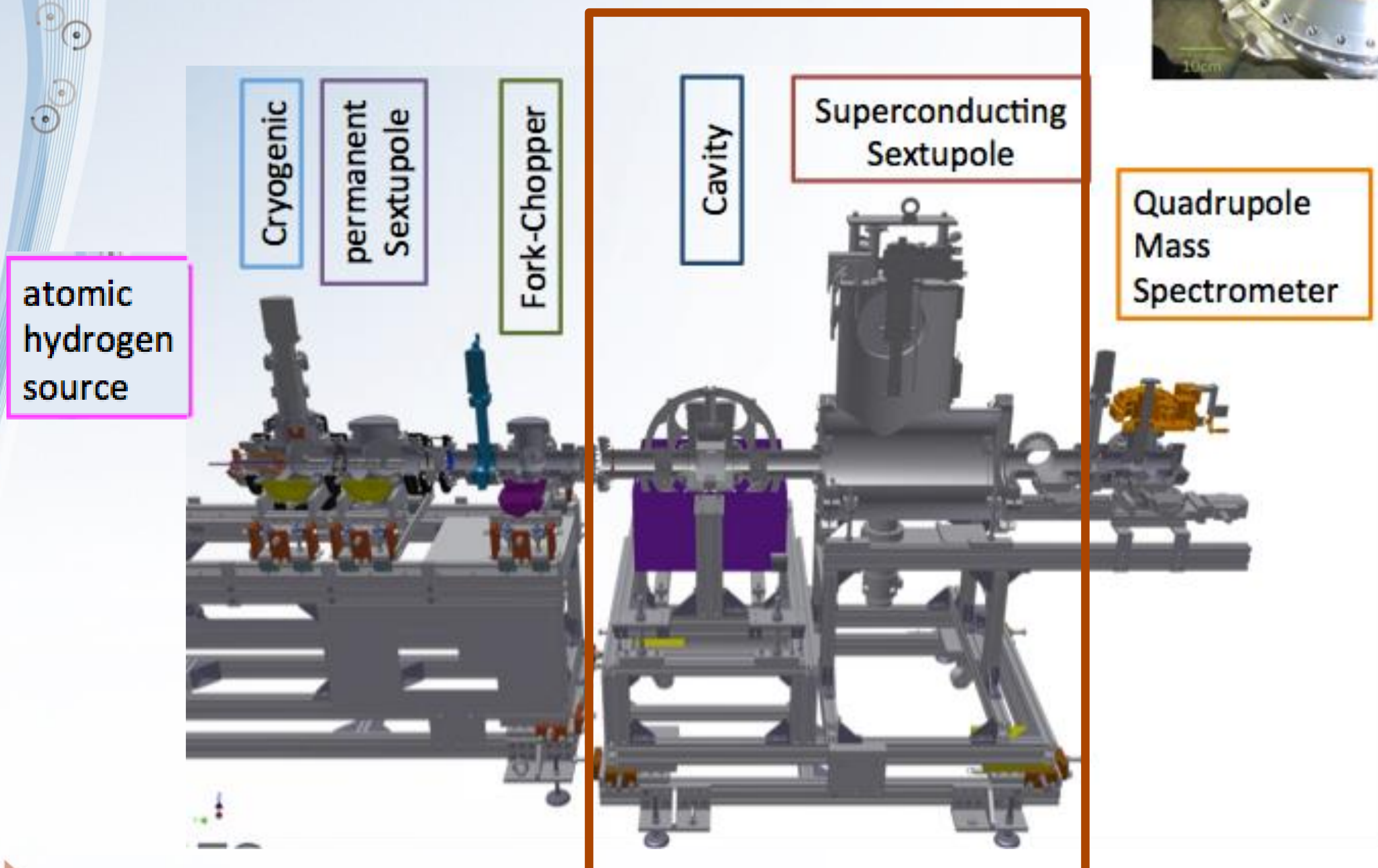
NATURE COMMUNICATIONS | 5:3089 | DOI: 10.1038/ncomms4089 | www.nature.com/naturecommunications

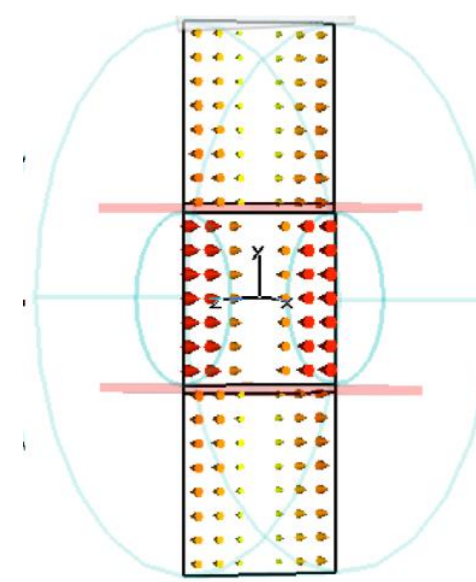
HYDROGEN BEAM MEASUREMENTS

RF cavity



$\bar{H}$ HFS spectrometer

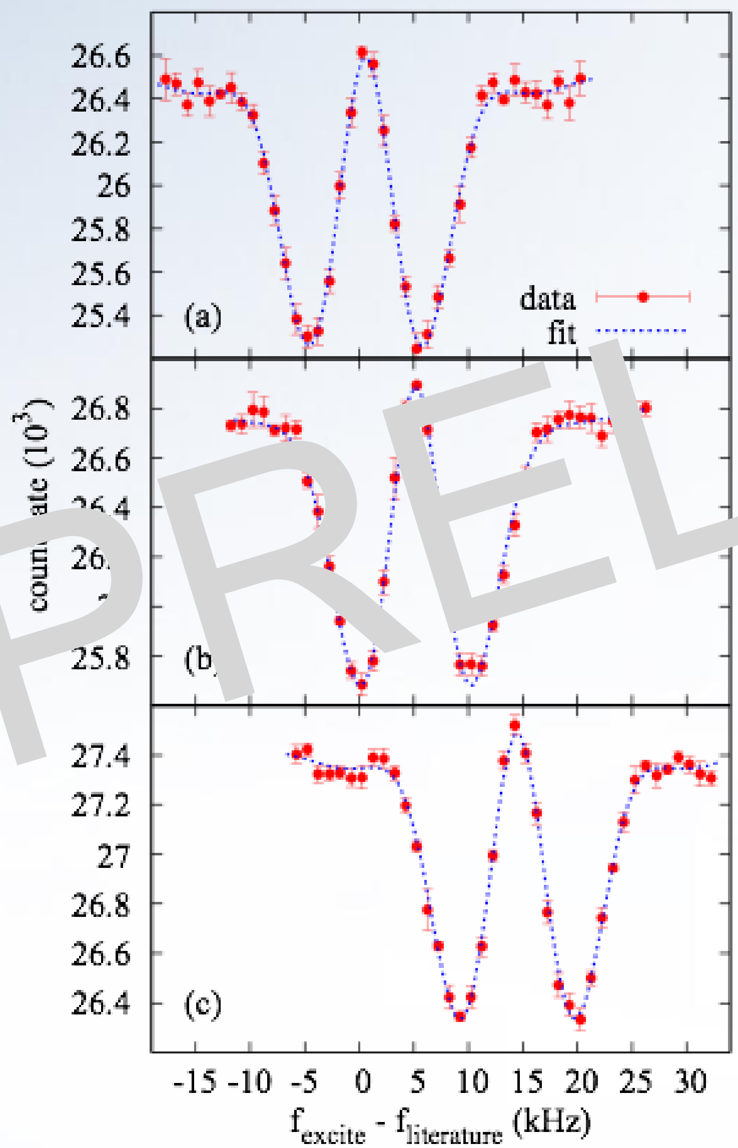




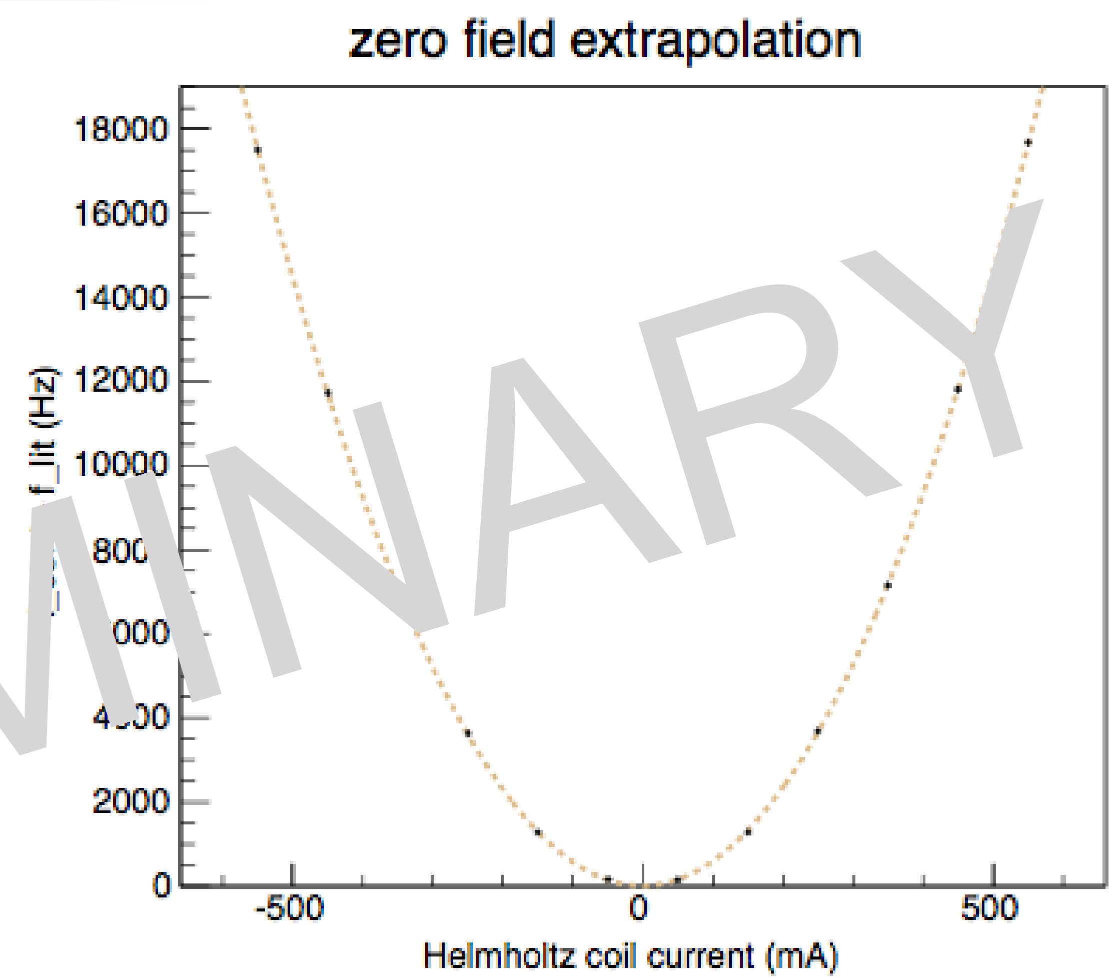
RF field

H BEAM HFS RESULT

- σ_1 transitions
- Fit the data with numerical simulated Bloch equations data



shift of resonances in magn. field
(a) 100 mA (b) 300 mA (c) 500 mA



$$\nu = 1420.405757(9)\,\mathrm{MHz}$$

$$\frac{\Delta\nu}{\nu} = 6.5 \times 10^{-9}$$

$$\nu_{hyp} - \nu_{lit} = 6.06 \pm 9.26\,\mathrm{Hz}$$

H·HFS

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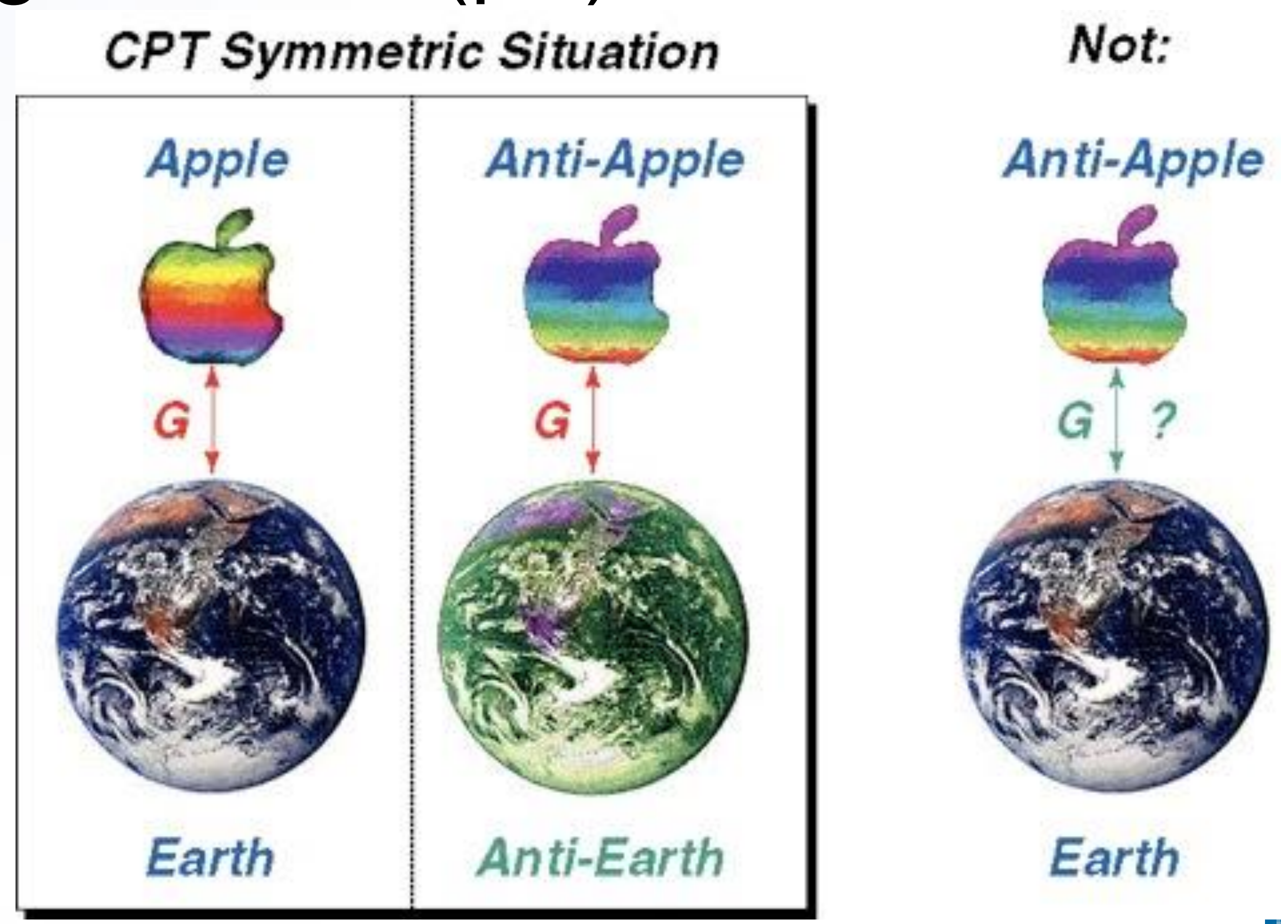
Gravitational Acceleration of Antimatter

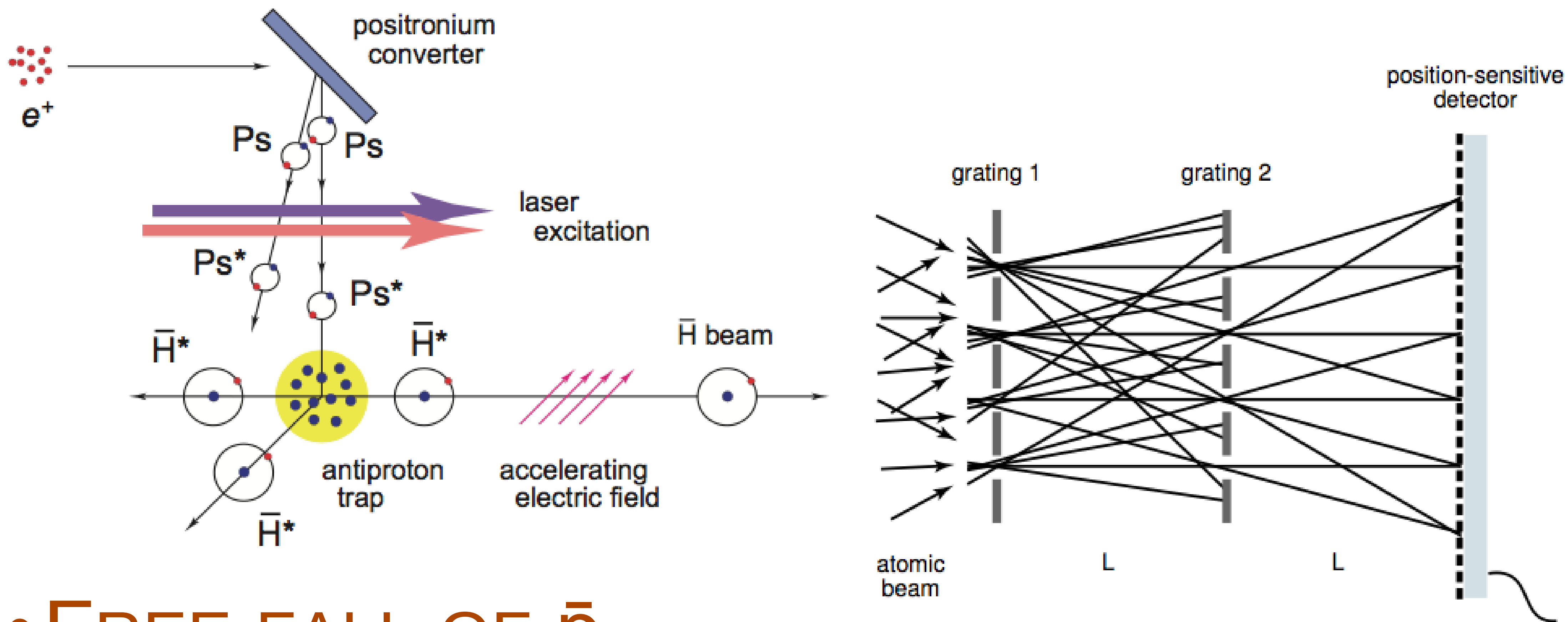
- No direct test of CPT
  - Weak equivalence principle
- no experimental test done ever
- Highest precision reachable with neutral antimatter
- Ultra-cold antihydrogen atoms (μK) from neutral atom traps
  - GBAR (P. Perez)
- low-energy beam
  - AEgIS (M. Doser)



AEḡIS COLLABORATION

- ÖAW Stefan Meyer Institute
- CERN
- Czech Technical University
- ETH Zurich
- University of Genova
- University of Milano
- University of Padova
- University of Pavia
- Institute of Nuclear Research of the Russian Academy of Science
- Max-Planck Institute Heidelbert
- Politecnico di Milano
- University College London
- University of Bergen
- University of Bern
- University of Brescia
- Heidelberg University
- Université de Lyon — University of Lyon 1
- University of Oslo
- Université Paris Sud — University of Paris Sud
- University of Trento
- INFN sections of: Genova, Milano, Padova, Pavia, Trento

AEGIS - Antimatter Experiment: Gravity, Interferometry, Spectroscopy



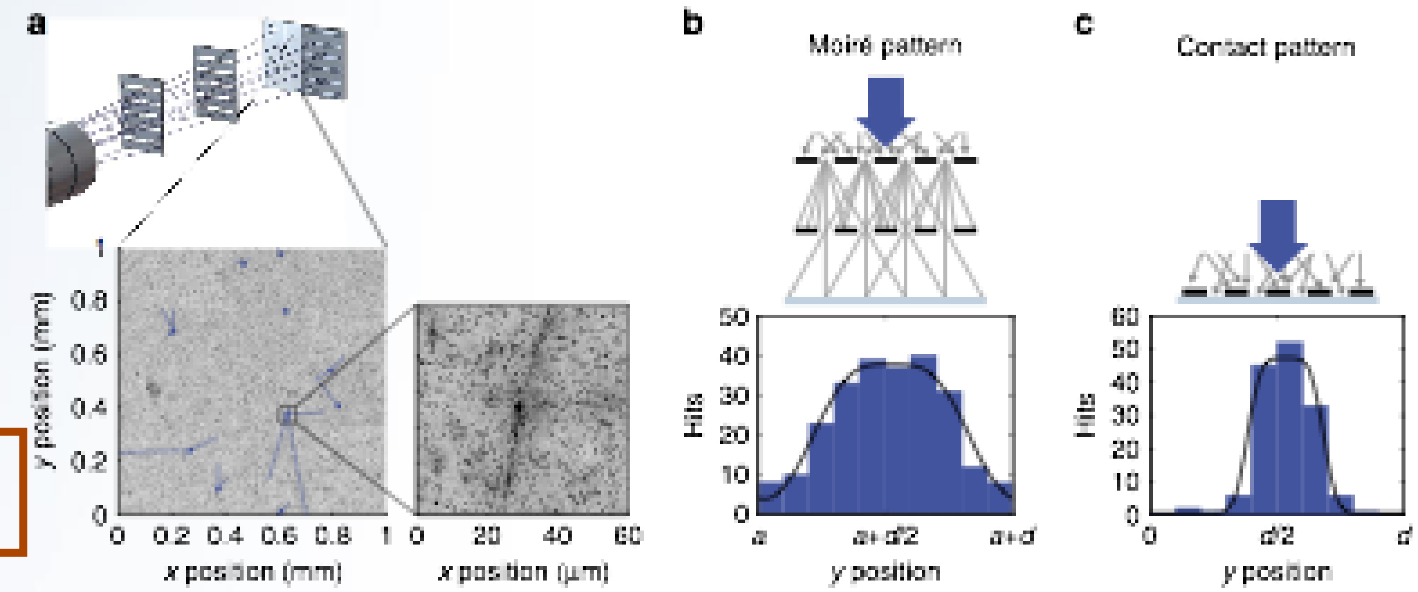
- FREE FALL OF $\bar{p}$
  - $\bar{H}$ production at 100 mK
  - resonant charge exchange with excited positronium
  - acceleration of Rydberg $\bar{H}$ by Starck effect
  - pulsed production, measure TOF & position

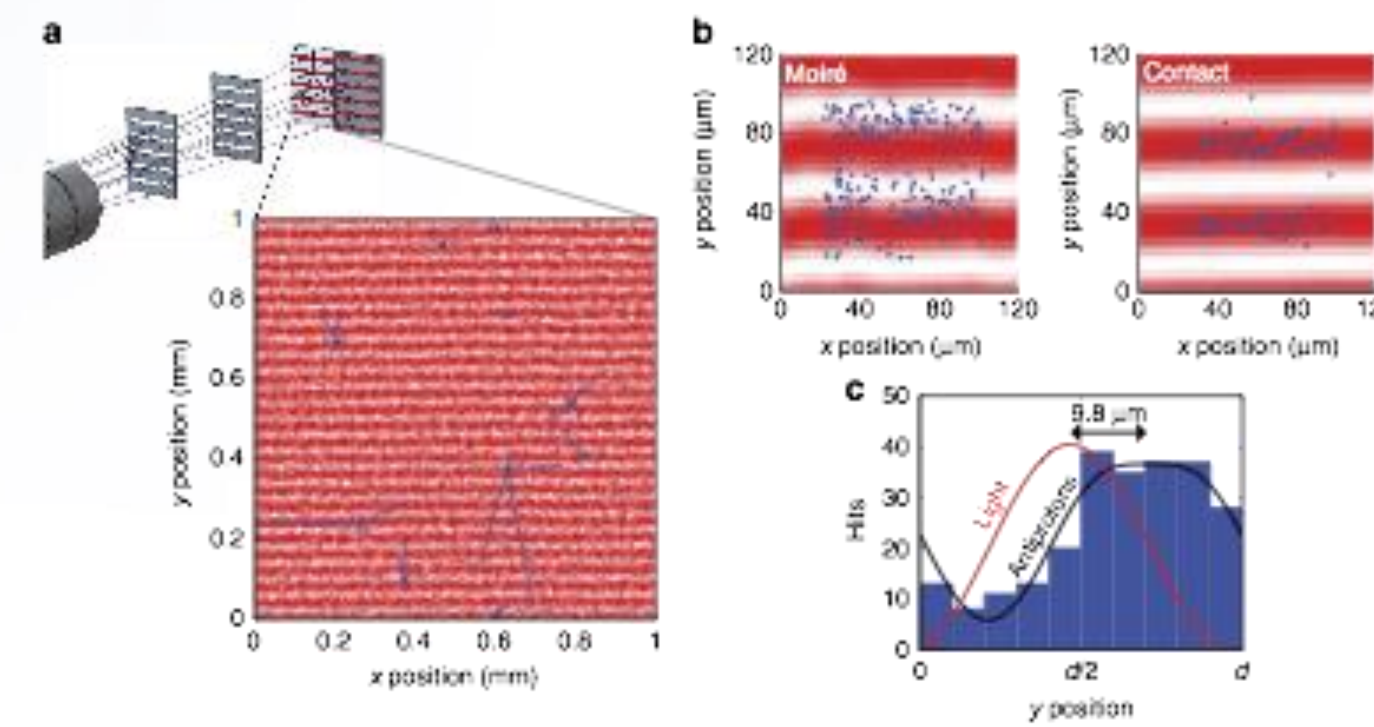
$\bar{p}$ DEFLECTOMETER RESULT

- Pattern observed
  - Shift between $\bar{p}$ and light observed

$\Delta y = 9.8 \pm 0.9(\text{stat}) \pm 6.4(\text{syst})$ μm

  - consistent with residual B, E fields
  - sensitivity of μm reached
  - $\bar{H}$ beam case
    - velocity $*10^{-4}$
    - distance * 40
    - Force 10^{-10}





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

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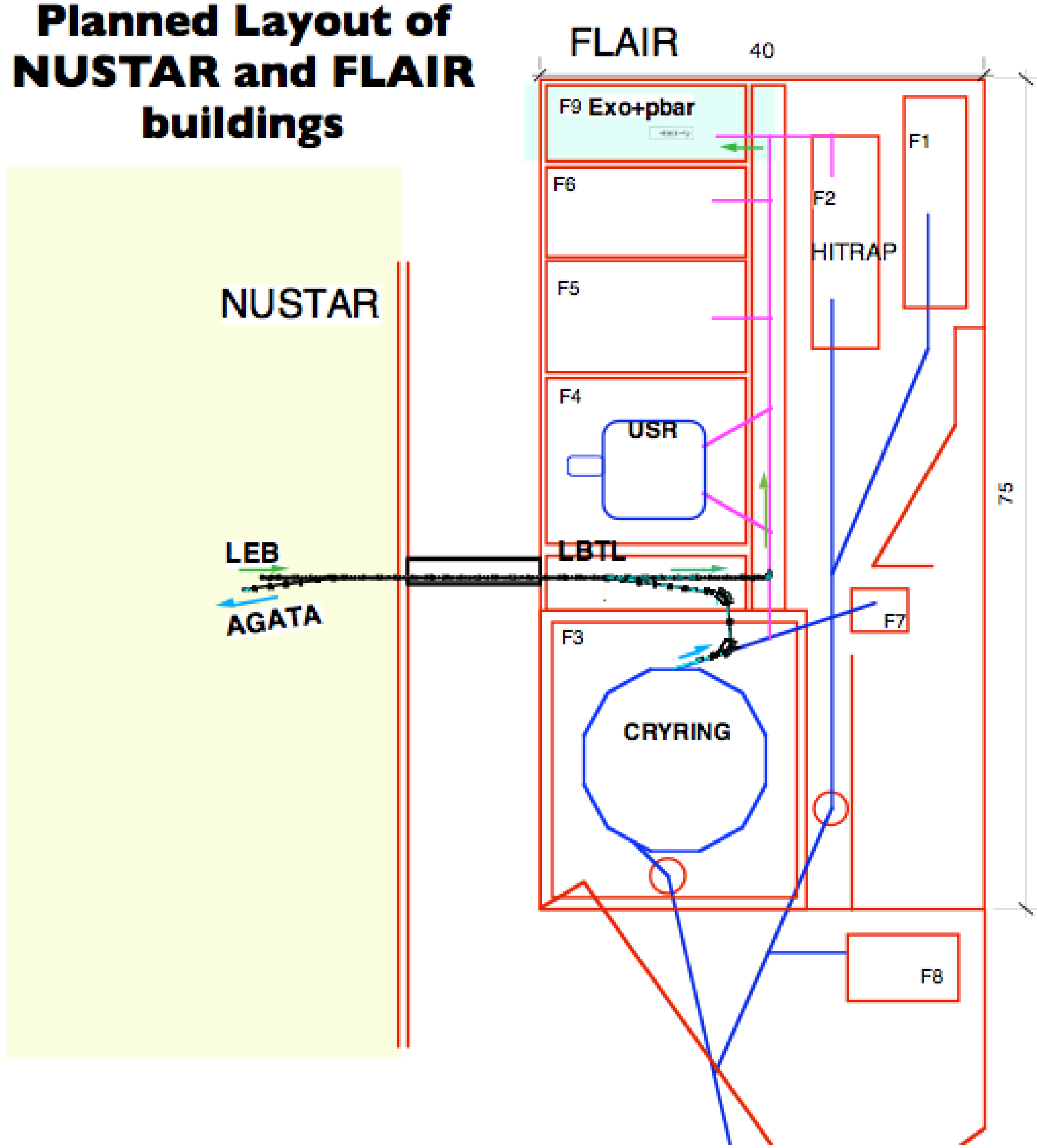
Original layout

Planned Layout of NUSTAR and FLAIR buildings



M. Wada 2005

Slow RIB:

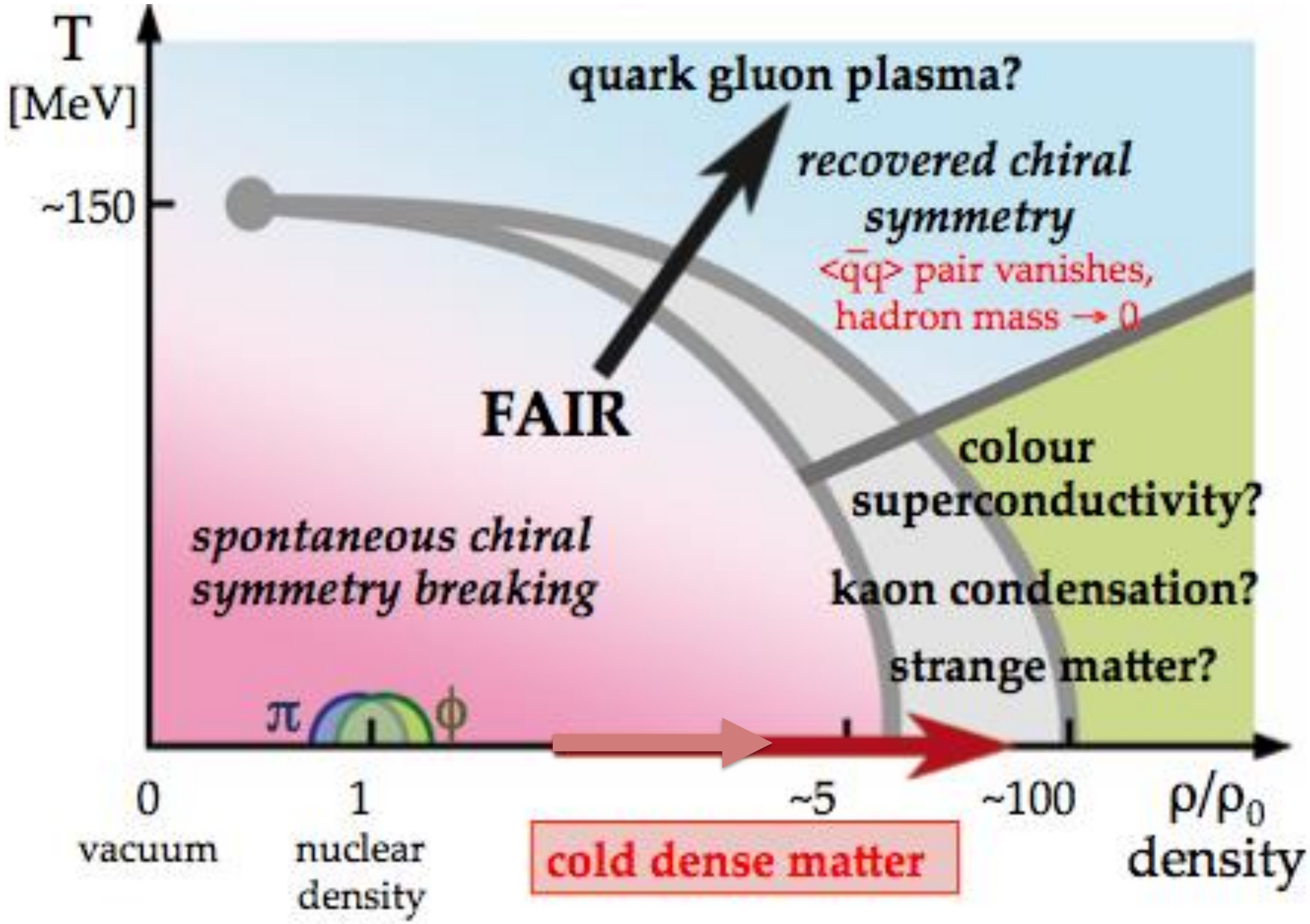
SuperFRS -
LEB (gas catcher) -
LBTL -
FLAIR common BTL -
Exo+pbar

Antiproton:

NESR -
CRYRING (LSR) -
USR -
FLAIR common BTL -
Exo+pbar

Highly charged 6MeV/u RIB,
300 keV antiprotons,
can be transported from
FLAIR to NUSTAR

Search for strange baryonic matter



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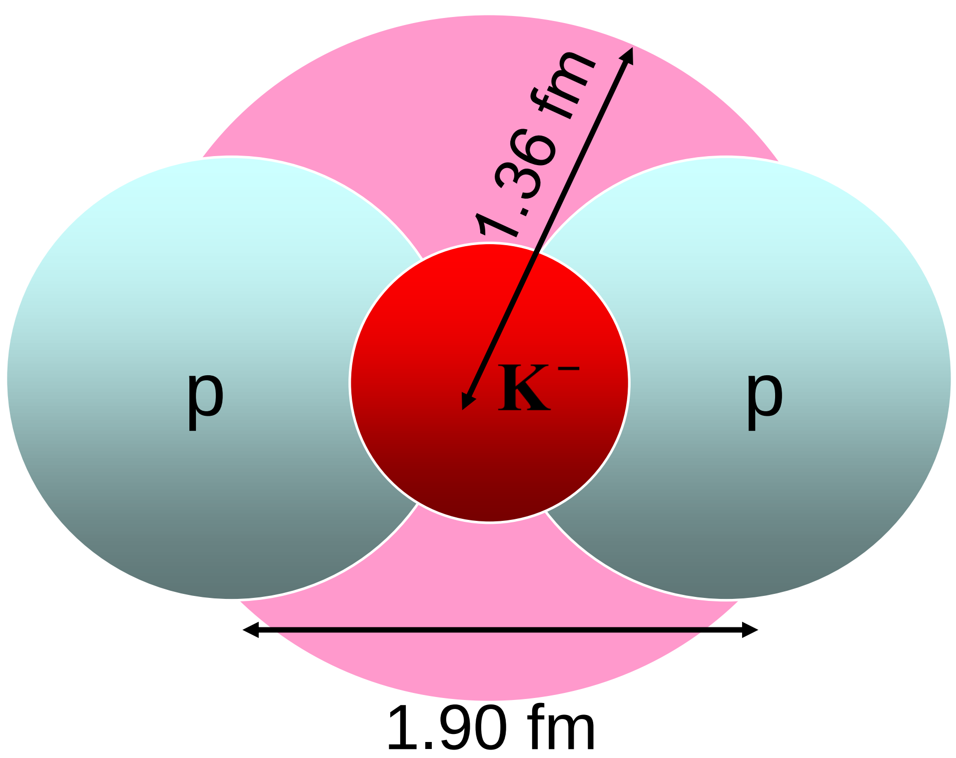
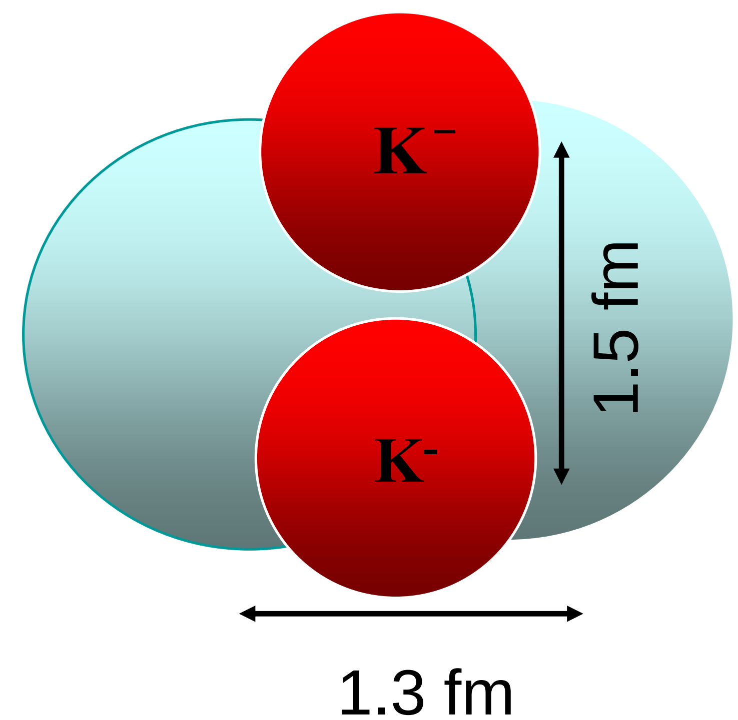
Search for dense baryonic matter with double strangeness

ppK^-



Strange deuteron?

$ppK^- K^-$



$\bar{u}s$

uud **uud**

$\bar{u}s$

uuddss

Jaffe’s H* di-baryon?

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FLAIR Community

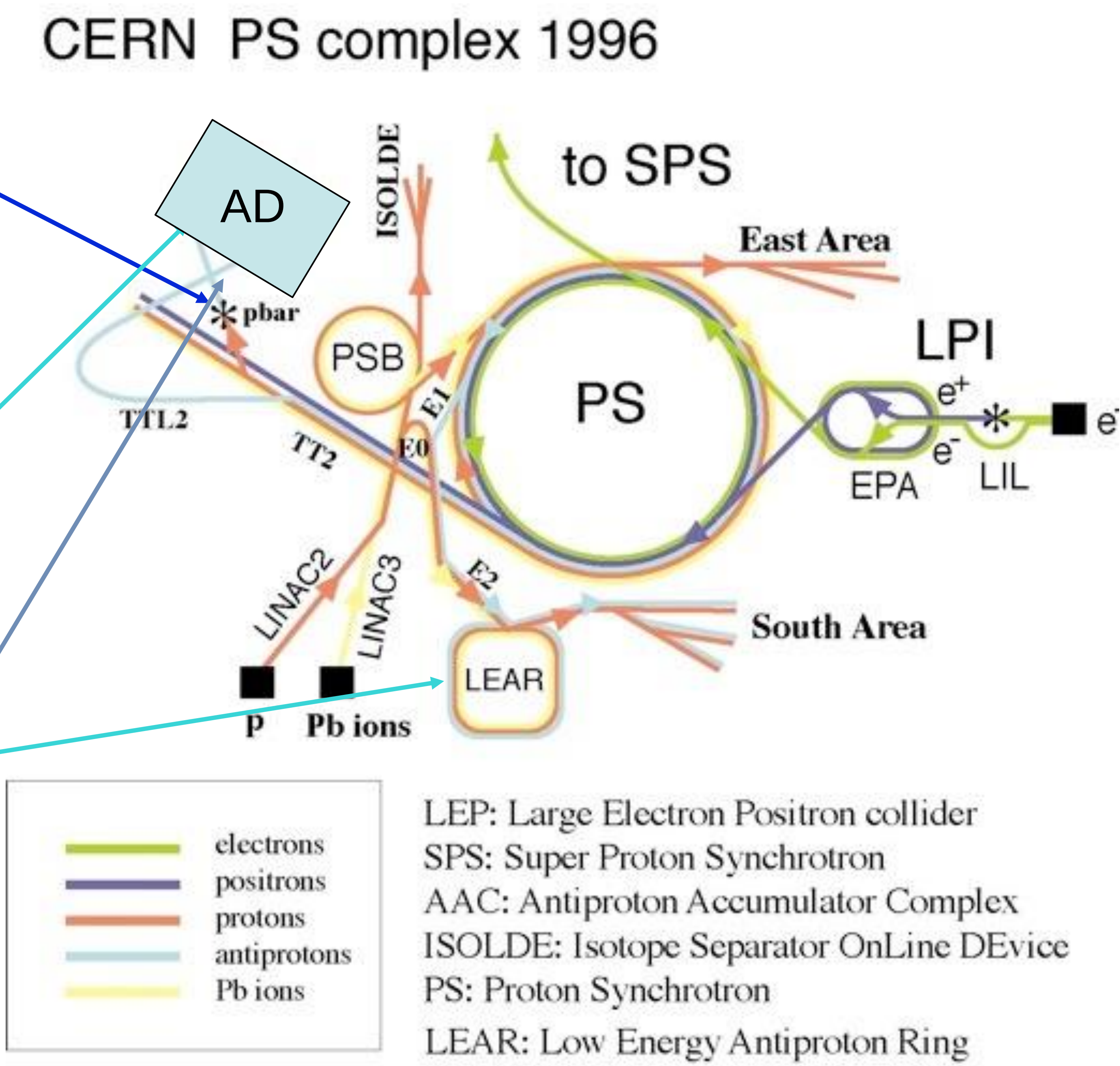
- Austria (SMI Vienna, TU)
- Canada (TRIUMF, York)
- Denmark (Aarhus U)
- France (P. & M. Curie, Paris)
- Germany (Berlin, GSI, Frankfurt, LMU München, Giessen, MPI Heidelberg, U Heidelberg, Jülich, U Mainz)
- Hungary (Budapest, Debrecen U, ATOMKI)
- India (Kolkata)
- Italy (Brescia, Firenze, Genova)
- Japan (Tokyo, Saitama (RIKEN))
- Netherlands (Amsterdam U)
- Poland (Warsaw U, Soltan Inst., Cracow)
- Russia (Moscow, St. Petersburg, Troitsk)
- Sweden (Stockholm U, Manne Siegbahn Laboratory, Uppsala, ESSS Lund)
- United Kingdom (Belfast, London, Liverpool, Swansea)
- USA (Albuquerque, Harvard, Texas A&M, Tallahassee, Rolla)

Spokesperson E.W.
2012 -> K. Blaum (MPI-K HD)

BTR 2005: 49 institutions, 144 scientists, 15 countries,
needs redefinition: currently 45 institutions, 93 scientists. 15 countries

Antiproton production @ CERN

- Threshold 6 mp (5.6 GeV)
- PS: 26 GeV
- Antiprotons of 3.7 GeV/c
- Low-energy beam
  - Accumulation
  - Deceleration
  - Cooling (stochastic, electron)
- 1982 – 1996 : AAC
  - 3 separate rings AC, AA, LEAR
- Since 2000
  - All-in-one machine: AD



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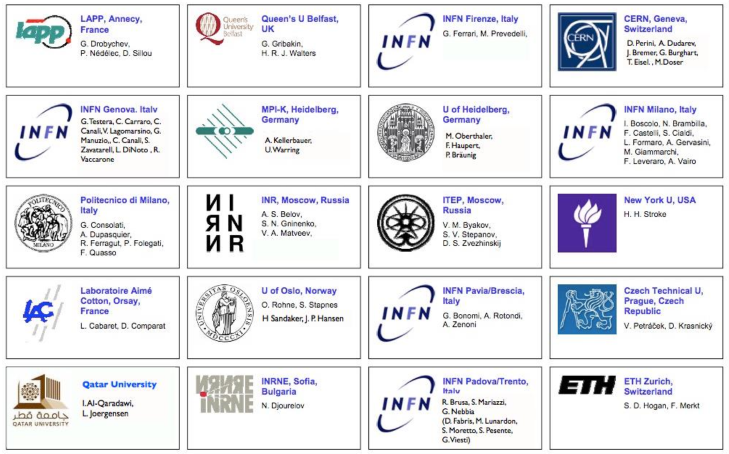
AD EXPERIMENTS

- ATRAP - G. Gabrielse, Harvard
- ALPHA - J. S. Hangst, Aarhus
  - Antihydrogen trapping and 1S-2S spectroscopy
- ASACUSA* - R.S. Hayano, Tokyo
  - Antiprotonic atoms, collisions, antihydrogen hyperfine structure
- AEgIS* - M. Doser, CERN
  - Antimatter gravity
- GBAR - P. Perez, Saclay
  - Antimatter gravity
- BASE - S. Ulmer, RIKEN
  - p̄ magnetic moment
- ACE - M. Holzscheiter, Heidelberg
  - biological effects of p̄ annihilations

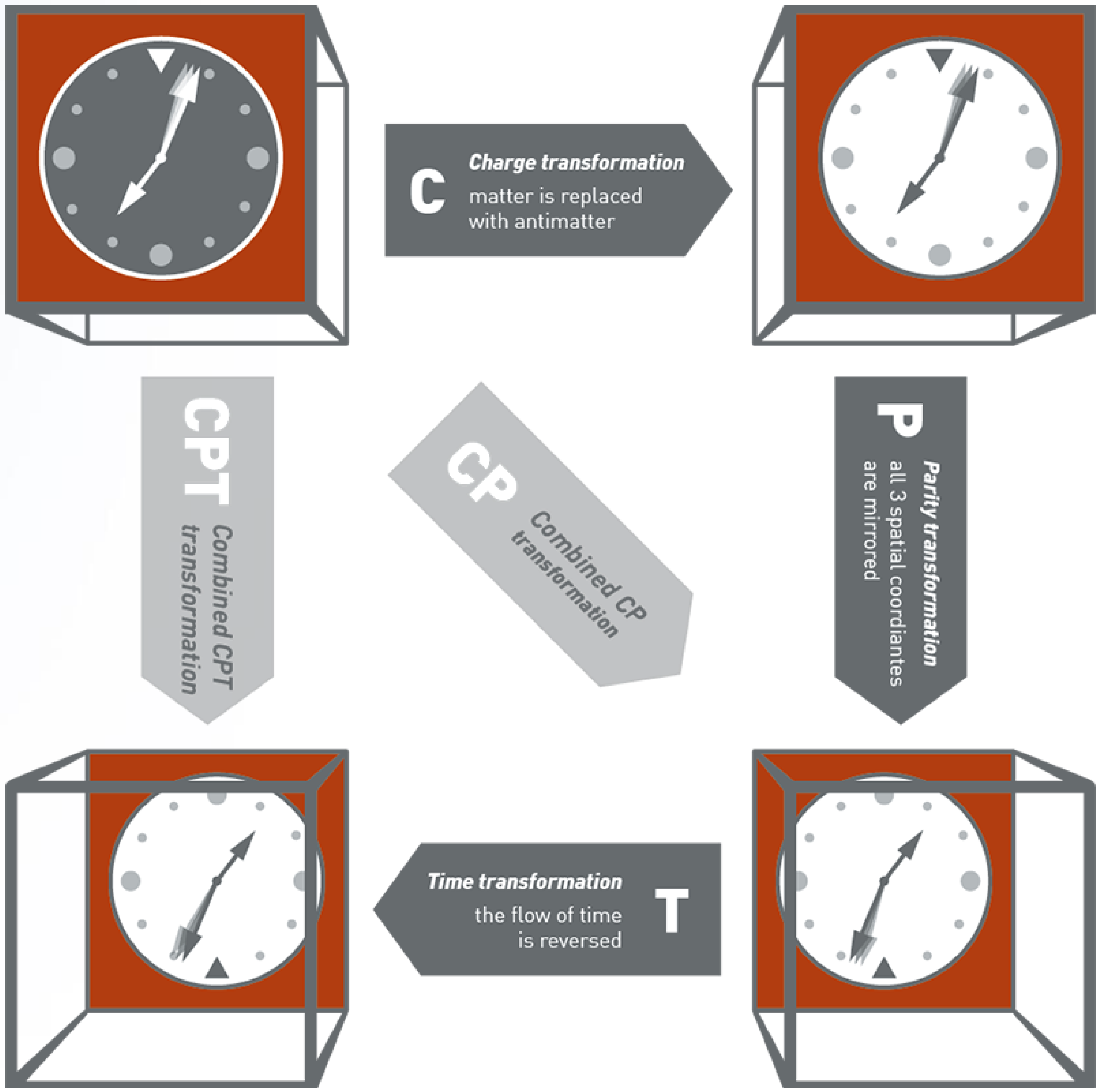
AEGIS



*E.W.

FUNDAMENTAL SYMMETRIES C,P,T

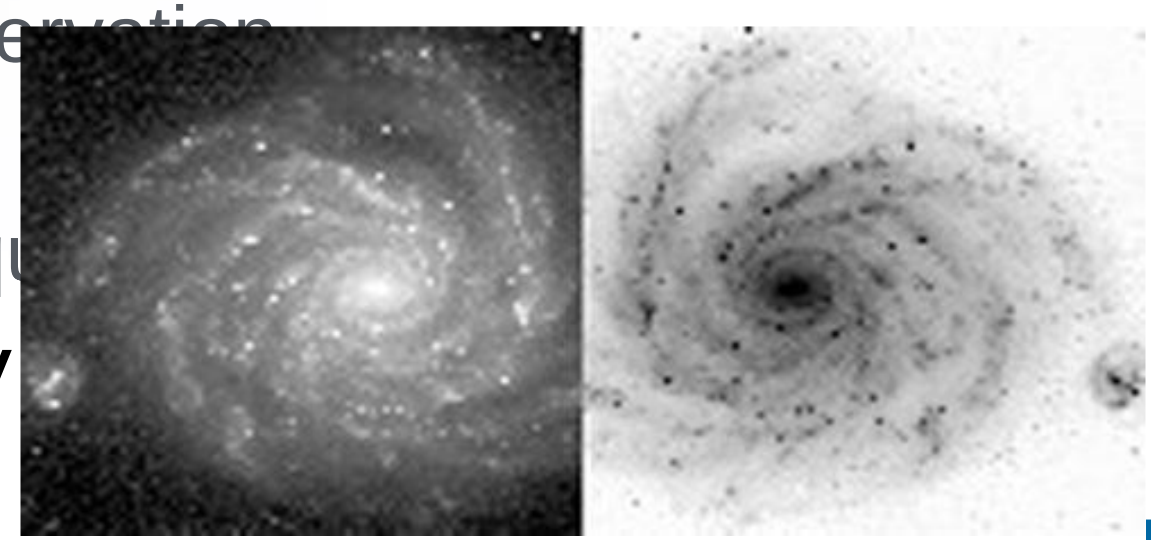
- C: CHARGE CONJUGATION
  PARTICLE ↔ ANTIPARTICLE
- P: PARITY: SPATIAL MIRROR
- T: TIME REVERSAL
- CPT THEOREM:
  CONSEQUENCE OF
  - Lorentz-invariance
  - local interactions
  - unitarity
    - *Lüders, Pauli, Bell, Jost 1955*
- ALL QFT OF SM OBEY CPT
- NOT NECESSARILY TRUE FOR STRING THEORY



CPT → particle/antiparticle: same masses, lifetimes, g-factors, |charge|,...

CPT SYMMETRY & COSMOLOGY

- MATHEMATICAL THEOREM, NOT VALID E.G. IN STRING THEORY, QUANTUM GRAVITY
- POSSIBLE HINT: ANTIMATTER ABSENCE IN THE UNIVERSE
  - Big Bang -> if CPT holds: equal amounts matter/antimatter
  - Standard scenario for Baryogenesis (Sakharov 1967)
    - Baryon-number non-conse
    - C and CP violation
    - Deviation from thermal equ
- CURRENTLY KNOWN CPV
  NOT LARGE ENOUGH
  - Other source of baryon asymmetry?



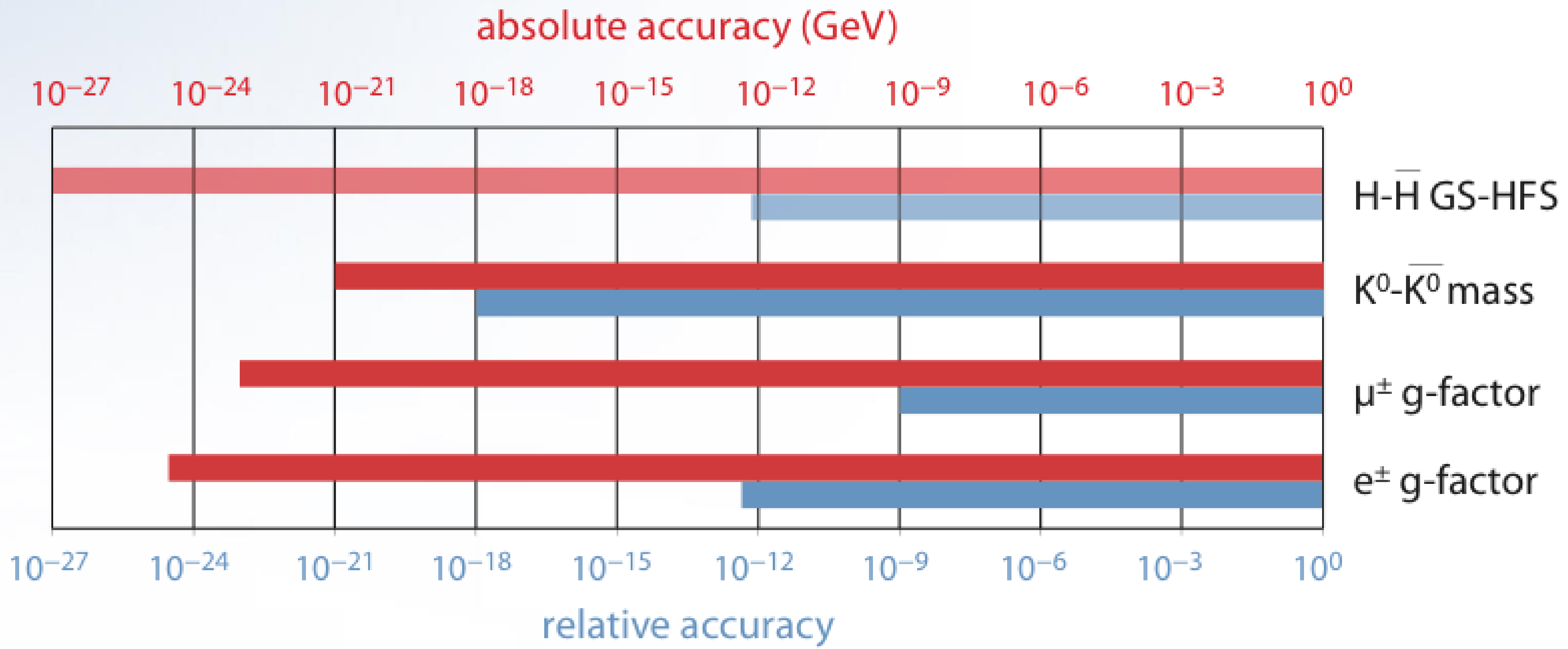
HFS and Standard Model Extension

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

CPT & Lorentz violation ($a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu$)

Lorentz violation ($\tfrac{1}{2} H^e_{\mu\nu}\sigma^{\mu\nu} + ic^e_{\mu\nu}\gamma^\mu D^\nu + id^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu$)

D. Colladay and V. A. Kostelecky, PRD 55 (1997) 6760.



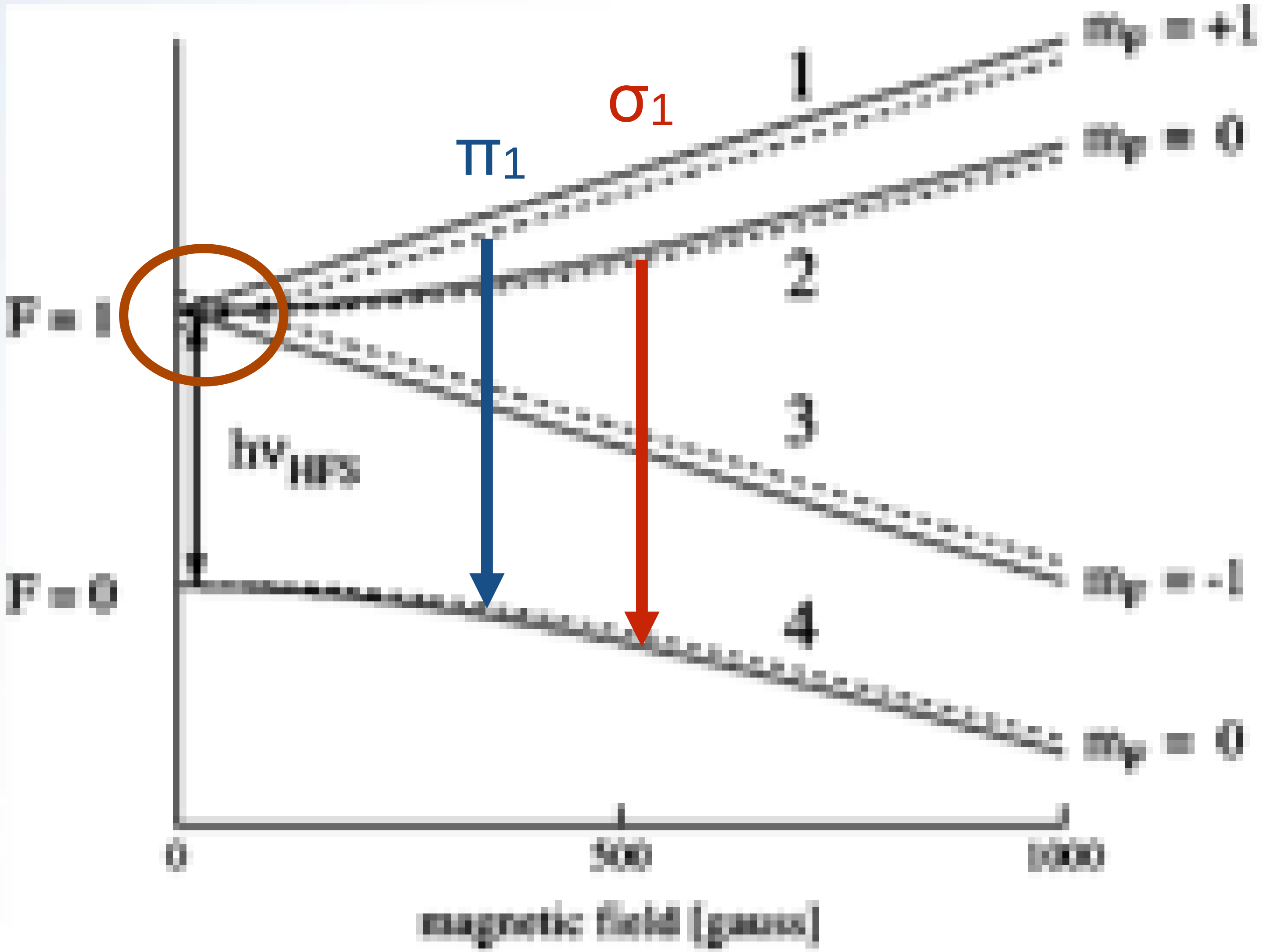
no CPT effect on 1S-2S transition

allows to compare different quantities in different sectors

H vs. H̄ HFS in SME

Breit-Rabi diagram

- Splitting of triplet substates in zero field
  - F=1,−1 cross!
- no effect in 0 field σ_1 transition
- need to measure also π_1
  - siderial and seasonal variations



Humphrey, M., Phillips, D., Mattison, E., Vessot, R., Stoner, R., & Walsworth, R. Testing CPT and Lorentz symmetry with hydrogen masers. Physical Review A, 68(6), 63807 (2003)

ANTIMATTER AND GRAVITY

- ANTIGRAVITY: $g_{matter} = -g_{antimatter}$
  - separation of matter and antimatter in Universe
- QUANTUMGRAVITY
  - Graviton (S=2)→adds Gravivector (S=1), Graviscalar (S=0)
  - simplest case: static potential

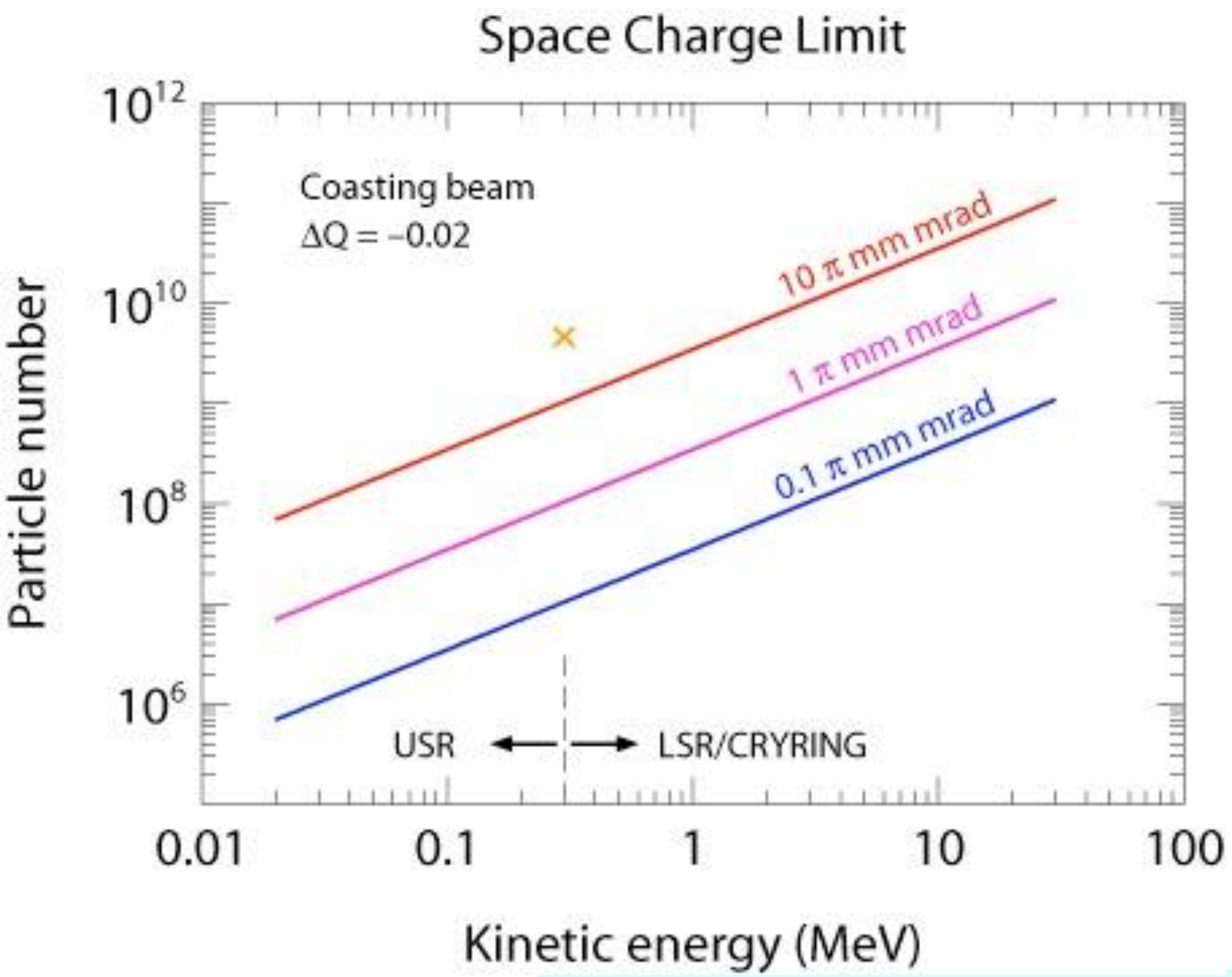
$$V = -\frac{G m_1 m_2}{r}(1 \mp a\, e^{-r/v} + b\, e^{-r/s})$$

  - a: Gravivector, b: Graviscalar
  - − attractive (matter-matter), +: repulsive: matter-antimatter
  - matter experiments: |a−b|
  - antimatter: a+b

FLAIR: Expected Antiproton Rates

Stefan Meyer Institute

- 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
- Phase space density much higher than AD
  - AD production rate 5x10^7 / 100 s



New estimates & test results
H. Danared, TP p. 159

Assumptions: 10% of accumulated p̄

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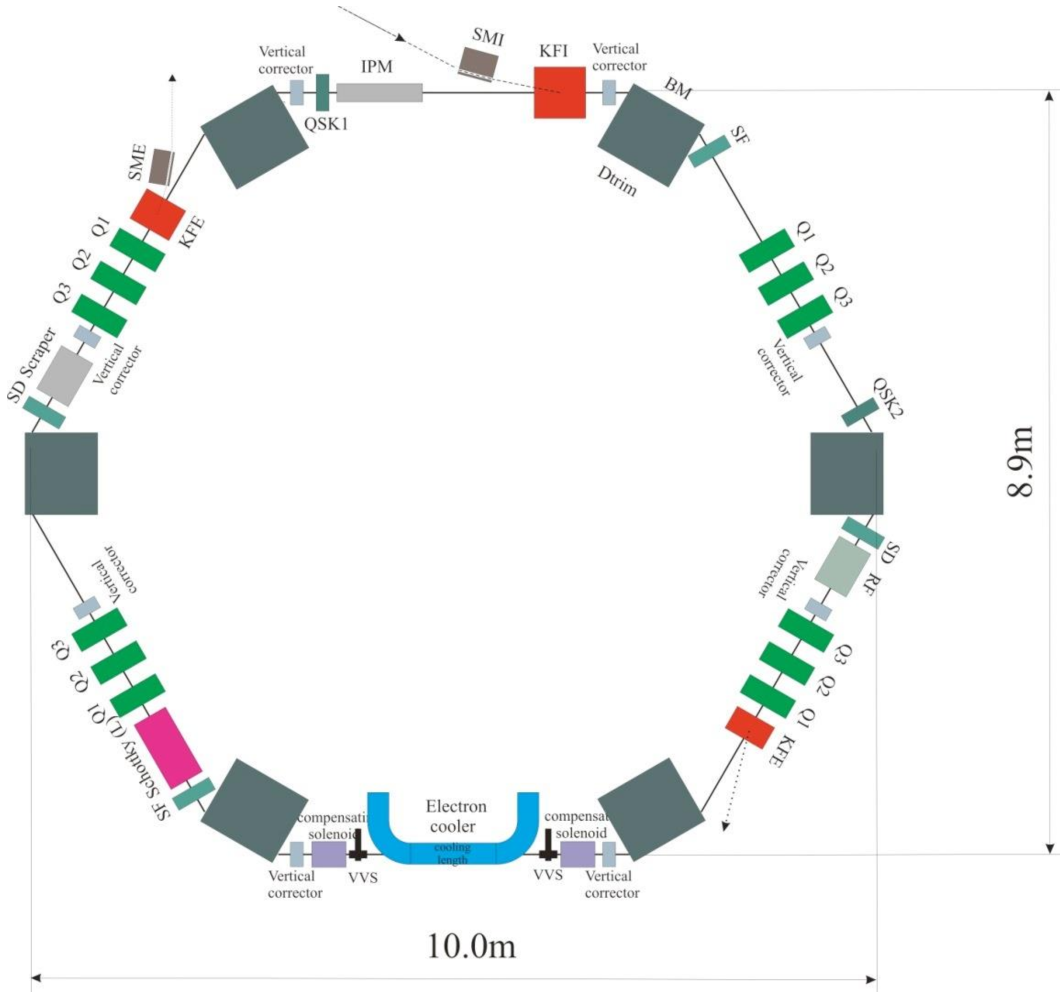
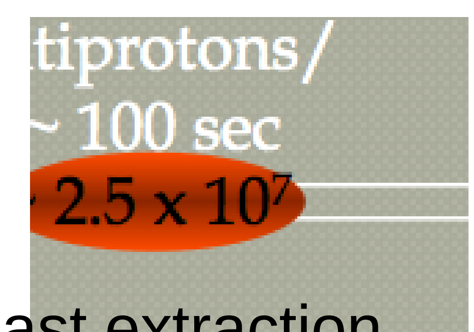
New Development I: ELENA @



Momentum range, MeV/c	100 - 13.7
Energy range, MeV	5.3 - 0.1
Circumference, m	30.4
Intensity of injected beam	3×10^7
Intensity of ejected beam	2.5×10^7
Number of extracted bunches	4
Emittances (h/v) at 100 KeV, π·mm·mrad, [95%]	4 / 4
Δp/p after cooling, [95%]	10^{-4}
Bunch length at 100 keV, m / ns	1.3 / 300
Required (dynamic) vacuum, Torr	3×10^{-12}



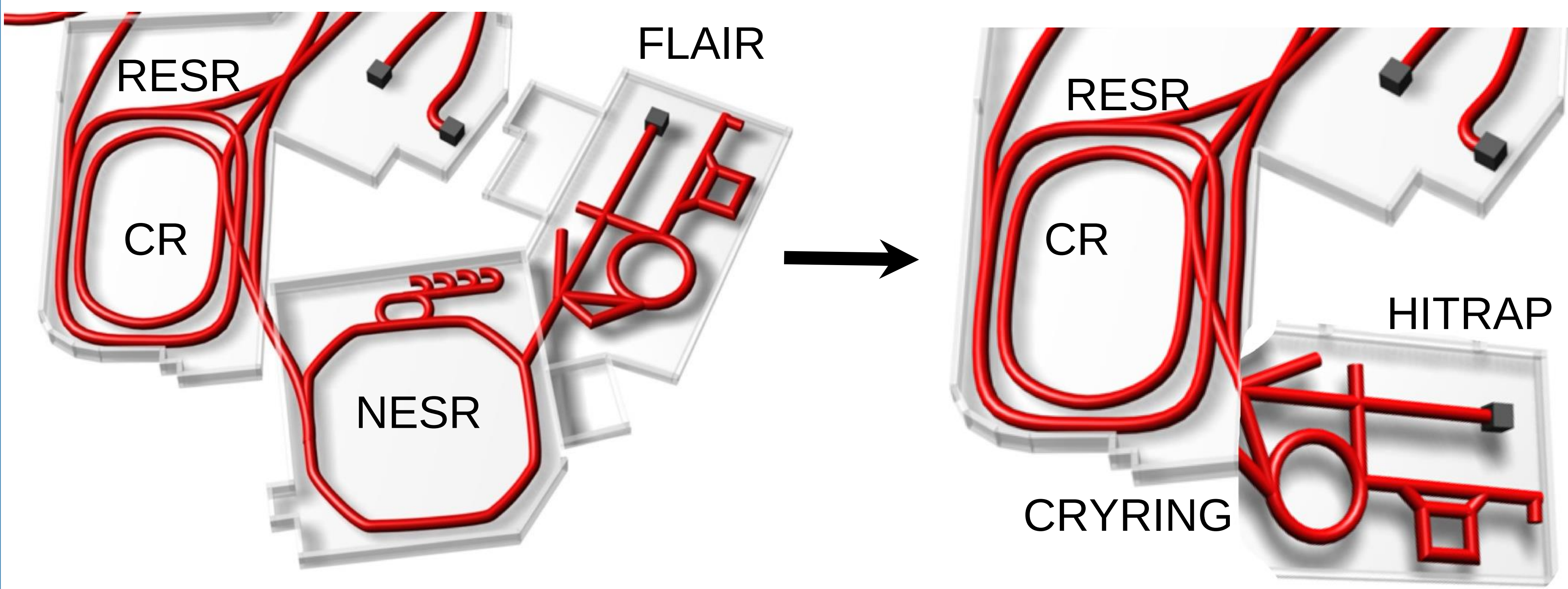
Fast extraction only

Penning trap

Approved in 2011, start foreseen 2016

New Development II: RESR

- RESR in module 5, but cheap (19 M€ + small modification)
- no stacking, but decelerate in RESR
  - foreseen for AIC, needs electron cooler
  - production rate: $1x10^7$ /s
  - cycle time 50-100 s
  - rates like ELENA, but ***fast extraction***



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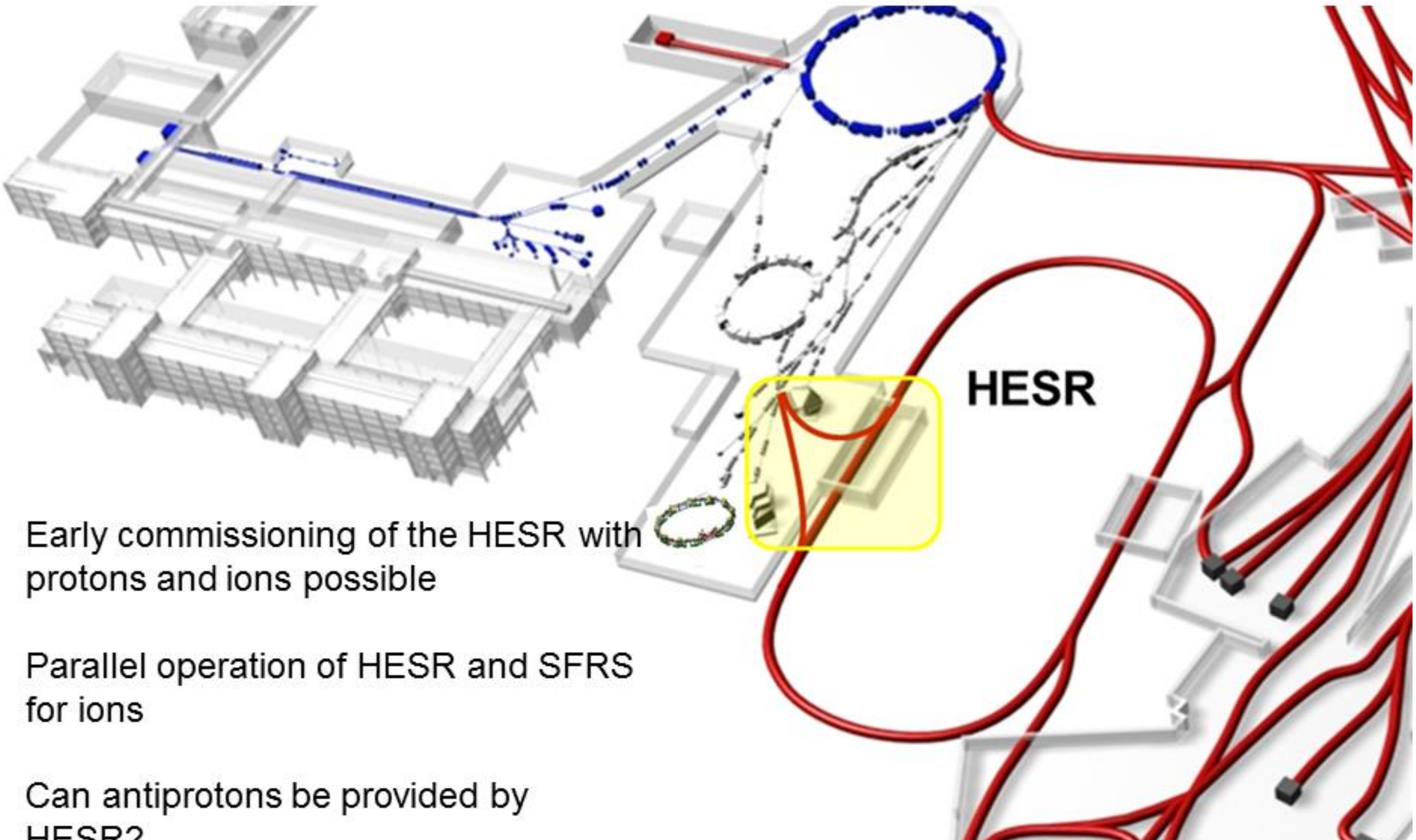
Many new ideas:
Separate injection beam line for HESR



- Early commissioning of the HESR with protons and ions possible
- Parallel operation of HESR and SFRS for ions
- Can antiprotons be provided by HESR?

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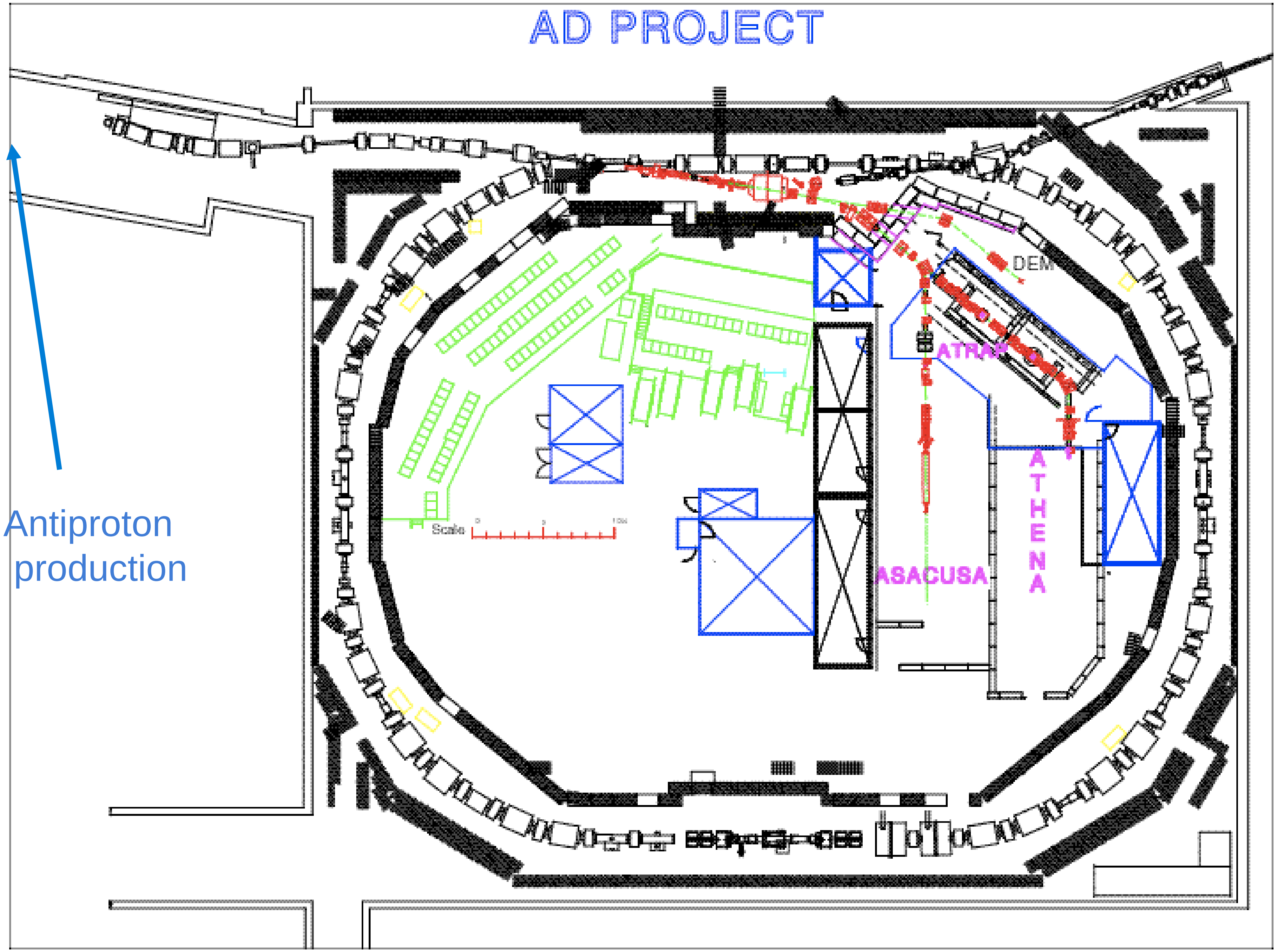
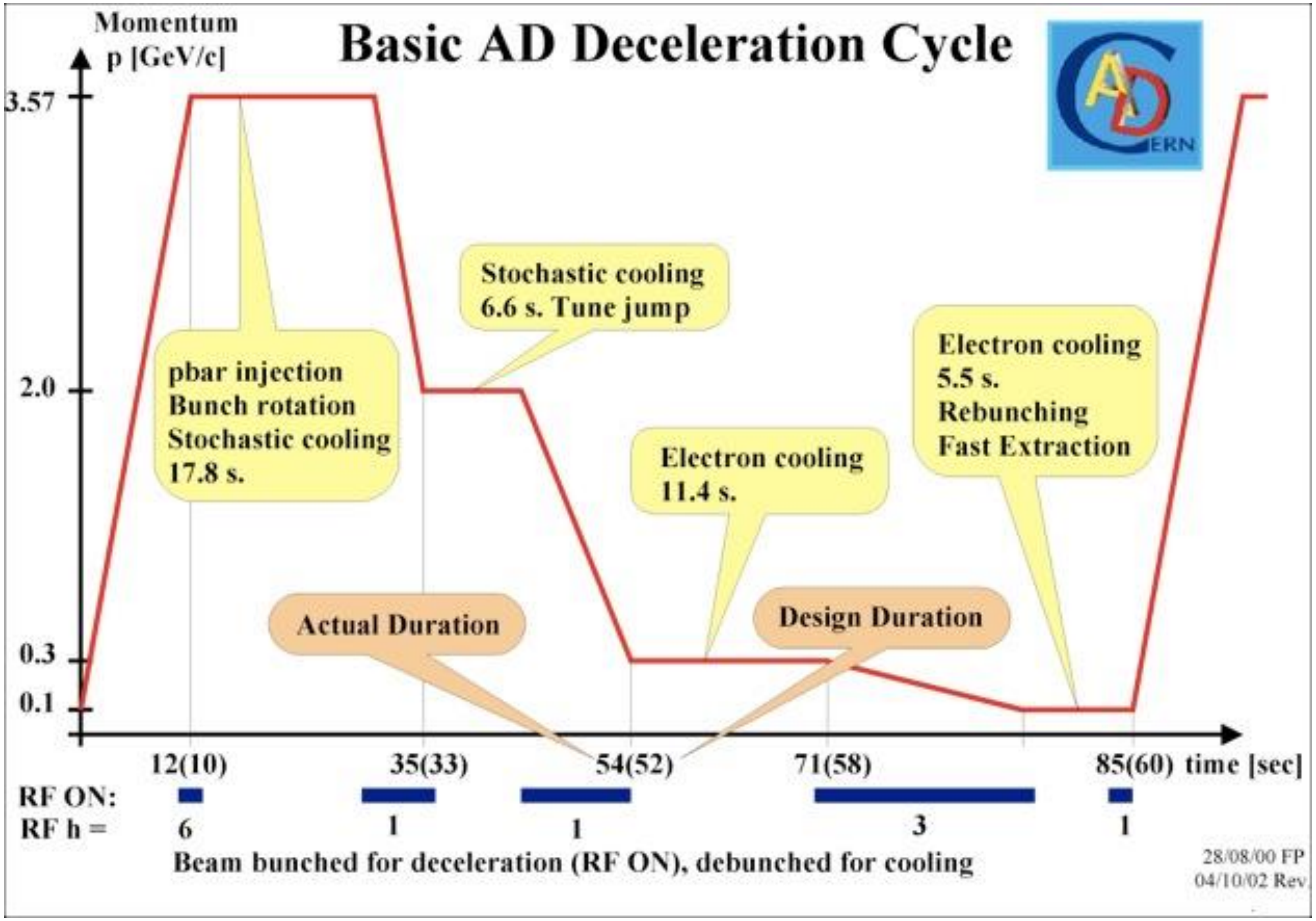
Current source: AD @ CERN

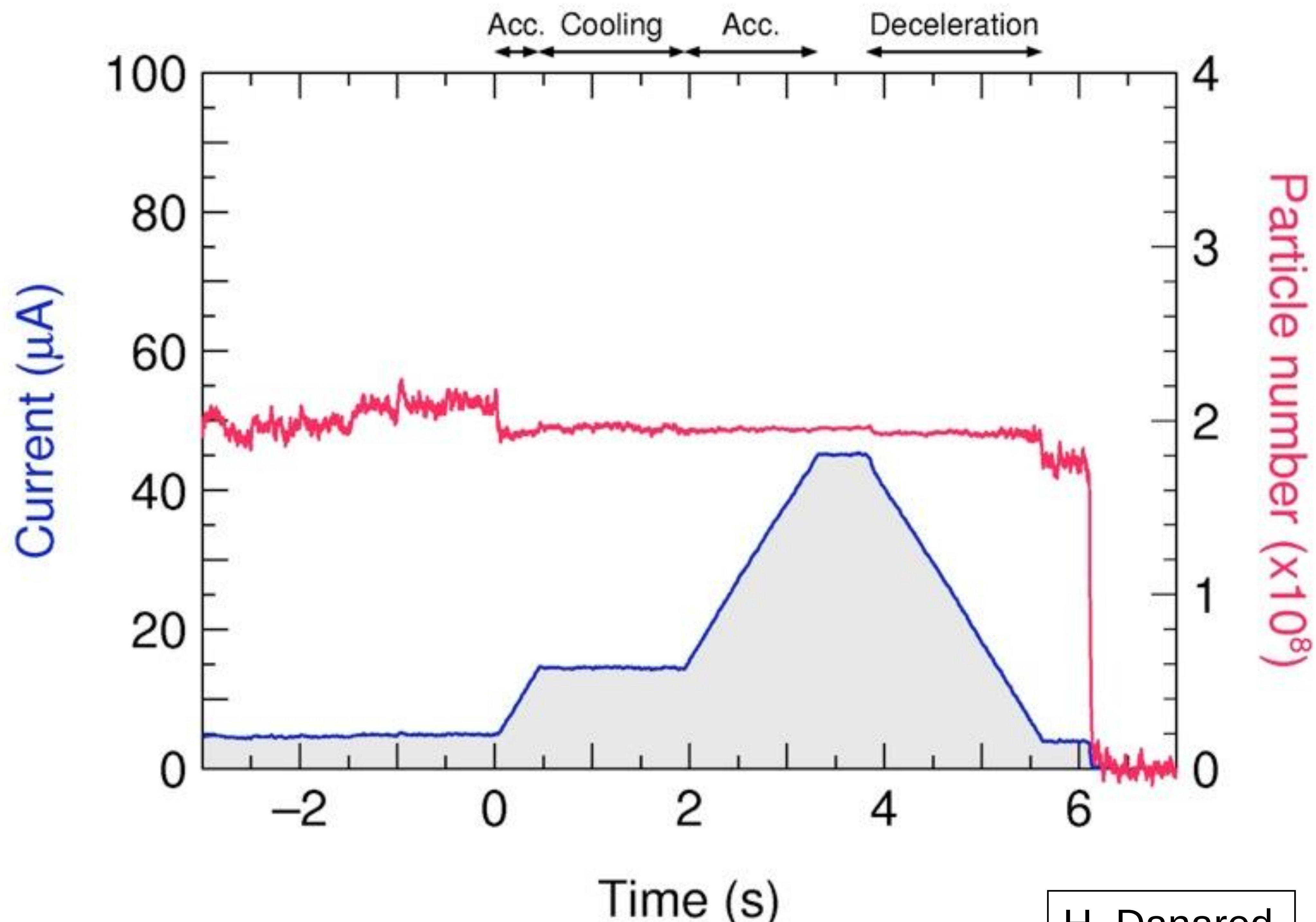


AD @ CERN: start 2000



- All-in-one machine:
  - Antiproton capture
  - deceleration & cooling
  - 100 MeV/c (5.3 MeV)
- Pulsed extraction
  - 2-4 x 10^7 antiprotons per pulse of 100 ns length
  - 1 pulse / 85−120 seconds

p̄ deceleration in CRYRING



H. Danared
MSL

Antiproton annihilation

OBELIX ('86~'96) [Nucl. Phys., **A797**, 109 (2007).]

- $\bar{p}$-^{4}He annihilation
- stopped $\bar{p}$ @ CERN/LEAR
- gas target (^{4}He@NTP, H_2@3atm)
- **cylindrical spectrometer**
- spiral projection chamber, scintillator barrels, jet-drift chambers
- 2.4x10^5/4.7x10^4 events of 4/5-prong in ^{4}He
- **p_{min} = 100/150/300MeV/c for □/K/p**

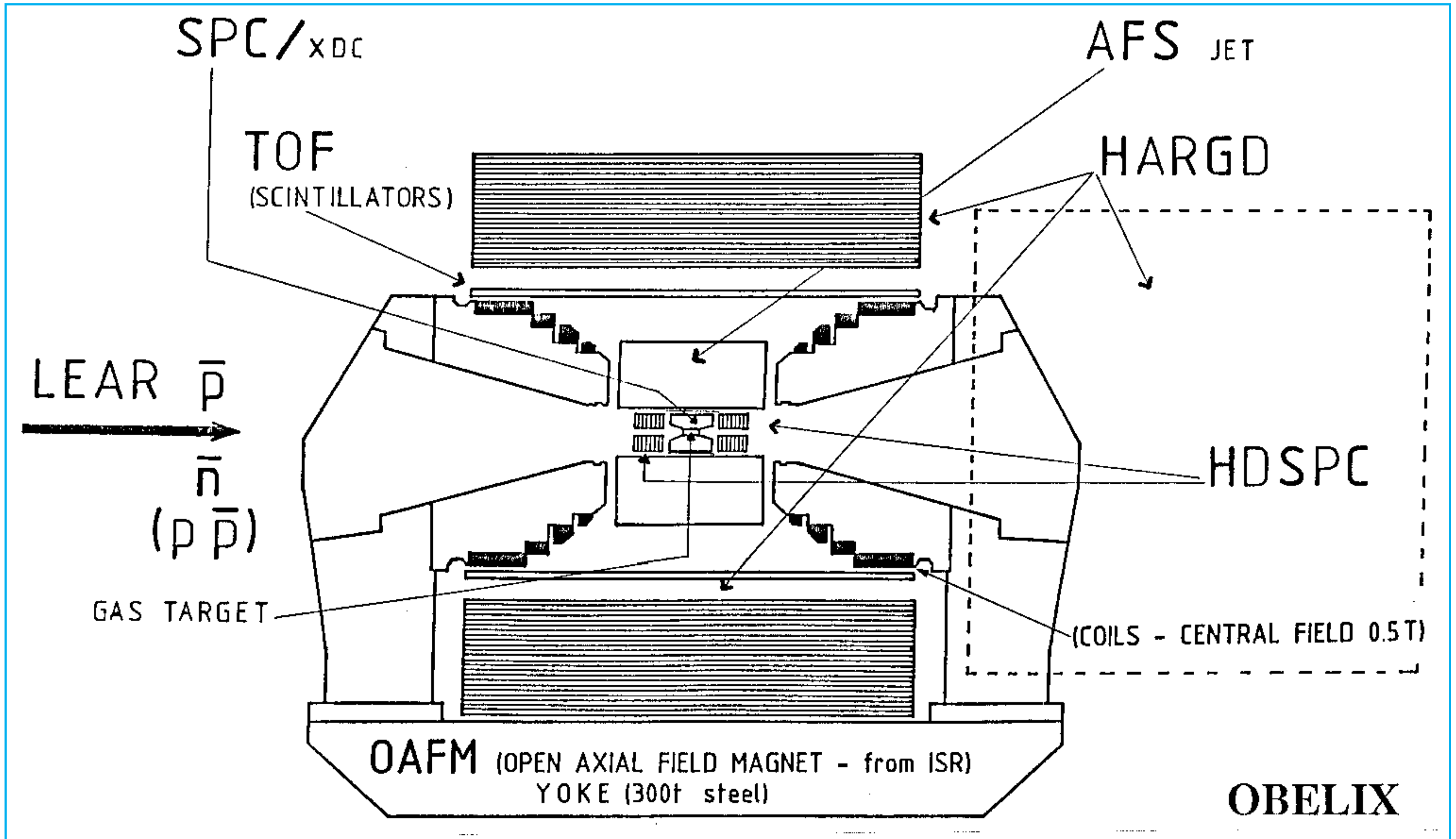


Fig. 1.1 OBELIX detector: schematic view

ÖAW Österreichische Akademie der Wissenschaften

Signal of bound states ?

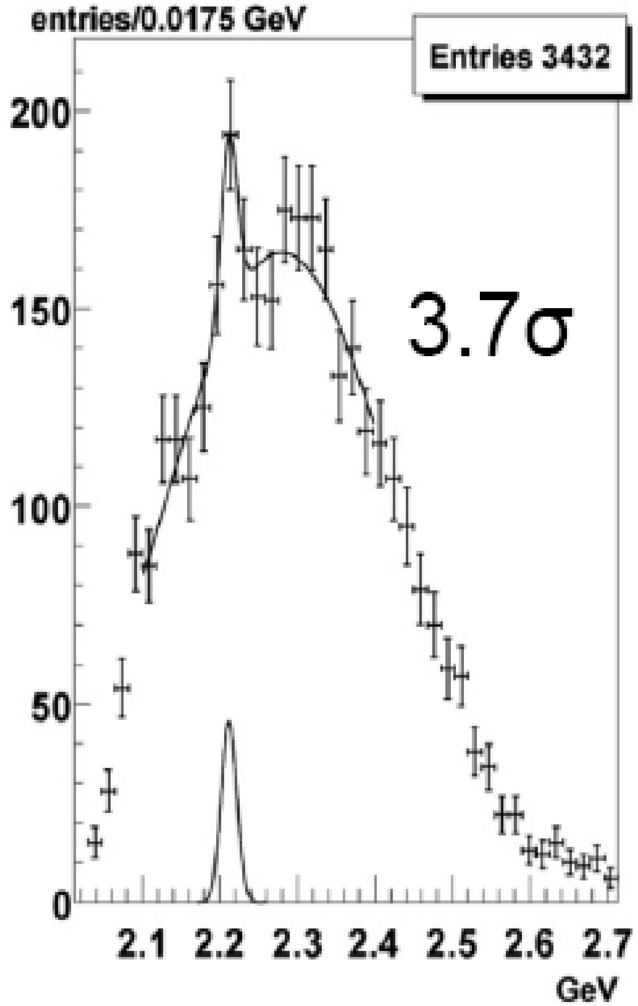
Antiproton annihilation

OBELIX data

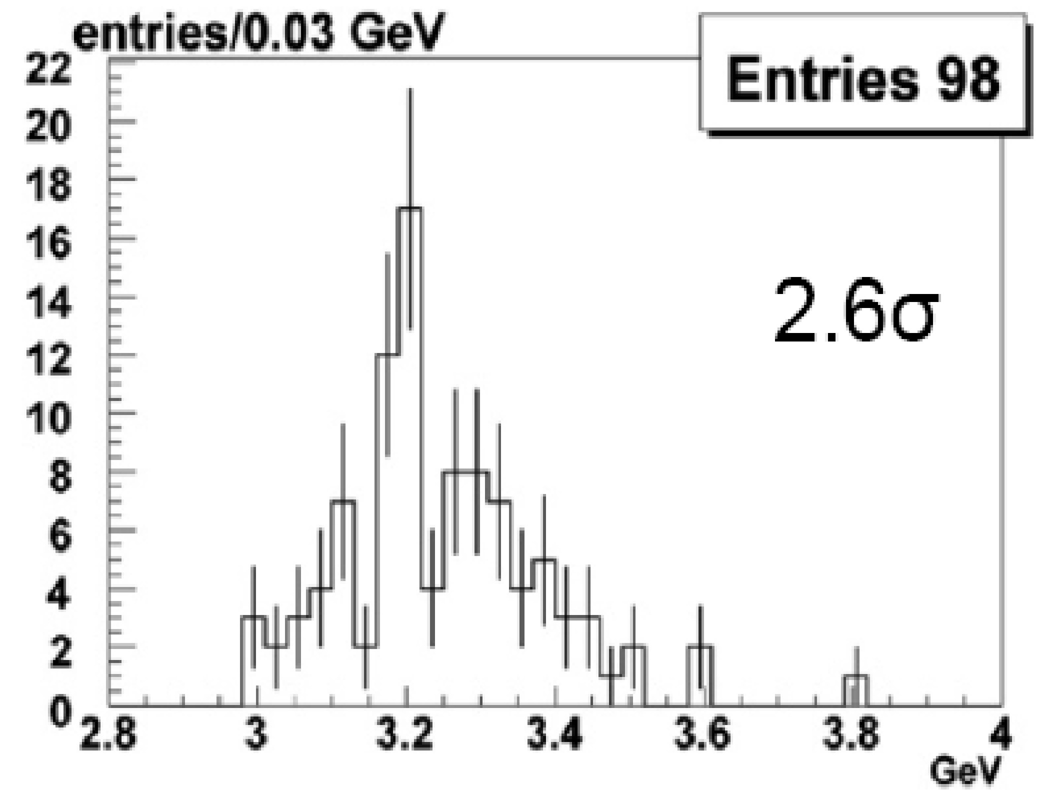
$$\bar{p} + {}^4He \rightarrow ppnK^- + K^0$$

$$ppnK^- + K^0 \rightarrow \Lambda^0 + d + K^0$$

Λp invariant mass



Λd invariant mass



G. Bendiscioli, et al., Nuclear Phys. A 789 (2007) 222

m = (2212.1±4.9) MeV
B.E. = −(160.9±4.9) MeV
Γ < (24.4±8.0) MeV $1.5 \cdot 10^{-4}$

m = (3190±15) MeV
B.E. = −(121±15) MeV
Γ < 60 MeV $0.4 \cdot 10^{-4}$

OBELIX (CERN/LEAR) data for double strangeness production

S=–2 strangeness production in $\bar{p}\,{}^4He$ annihilations at rest

G. Bendiscioli, T. Bressani, *L. Lavezzi, A. Panzarasa and P. Salvini*

channel	events	yield (10^{-4})
$K^+K^+\Sigma^-\Sigma^-p_s$	34+/–8	0.17+/–0.04
$K^+K^+\Sigma^-\Sigma^+n\pi^-$	36+/–6	2.71+/–0.47
$K^+K^+\Sigma^-\Lambda n$	16+/–4	1.21+/–0.29
$K^+K^+K^-\Lambda nn$	4+/–2	0.28+/–0.14

Antiproton annihilation

14 October 1999

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 464 (1999) 323–330

Double strangeness production in $\bar{p}Xe$ annihilation at low energy

DIANA Collaboration

V.V. Barmin [a], V.G. Barylov [a], V.S. Borisov [a], G.V. Davidenko [a], A.G. Dolgolenko [a], C. Guaraldo [b], V.A. Matveev [a], G.S. Mirosidi [a], K. Myklebost [c], M. Olsen [c], C. Petrascu [b,1], V.A. Shebanov [a], N.N. Shishov [a], A.A. Sibirtsev [d], L.I. Sokolov [a], B.S. Volkov [a], N.K. Zombkovskaya [a]

[a] Institute of Theoretical and Experimental Physics, 117218 Moscow, Russia
[b] Laboratori Nazionali di Frascati dell' INFN, C.P. 13, I-00044 Frascati, Italy
[c] Physics Department, University of Bergen, N-5007 Bergen, Norway
[d] Institut für Theoretische Physik, Universität Giessen, D-35392 Giessen, Germany

→ 33 double kaon events were found
yield ~ 10^{-4}

Strangeness S=−2 production

Antiproton annihilation

We propose to use the antiproton annihilation reaction on light nuclei to produce and study double-strange nuclei in reactions such as:

$$\bar{p} + p \rightarrow K^- + K^- + K^+ + K^+$$

energetically forbidden at rest (−98 MeV)

$$\bar{p} + A \rightarrow K^+ + K^+ + [K^- K^- pp(A-3)]$$

bound state formation E_B ~ 100 MeV

2 K^+ indicate a strong binding of the K^- pair in the nucleus

ÖAW Österreichische Akademie der Wissenschaften

Search for antikaon bound systems

performing an “exclusive” measurement

formation process:

$$\bar{p} + {}^4He \rightarrow K^+ + K^0 + X \equiv [ppnK^-K^-]$$

$$\rightarrow K^+ / \pi^+ / \pi^-$$

decay processes:

$$[ppnK^-K^-] \rightarrow n + \Lambda + \Lambda$$

$$\rightarrow n + (p + \pi^-) + (p + \pi^-)$$

$$[ppnK^-K^-] \rightarrow p + \Lambda + \Sigma^-$$

$$\rightarrow n + (p + \pi^-) + (n + \pi^-)$$

$$\rightarrow p / \pi^+ / \pi^- / n$$

How to Measure?

Sakuma et al. *Hyp. Int. 213*, 51 (2011).

we focus the reaction:

$$\bar{p} + {}^{3}He \rightarrow K^{+} + K^{0} + X \quad (X = K^{-}K^{-}pp)$$

(although $K^{-}K^{-}pp$ decay modes are not known at all,)

we assume the most energetic favored decay mode:

$$K^{-}K^{-}pp \rightarrow \Lambda + \Lambda$$

final state = $K^{+}K^{0}$⊄⊄

We can measure the $K^{-}K^{-}pp$ signal **exclusively**
by detection of all particles, $K^{+}K^{0}$⊄⊄,
using $K^{0}\rightarrow$□$^{+}$□$^{-}$ mode

wide-acceptance detector is important

Expected Kinematics

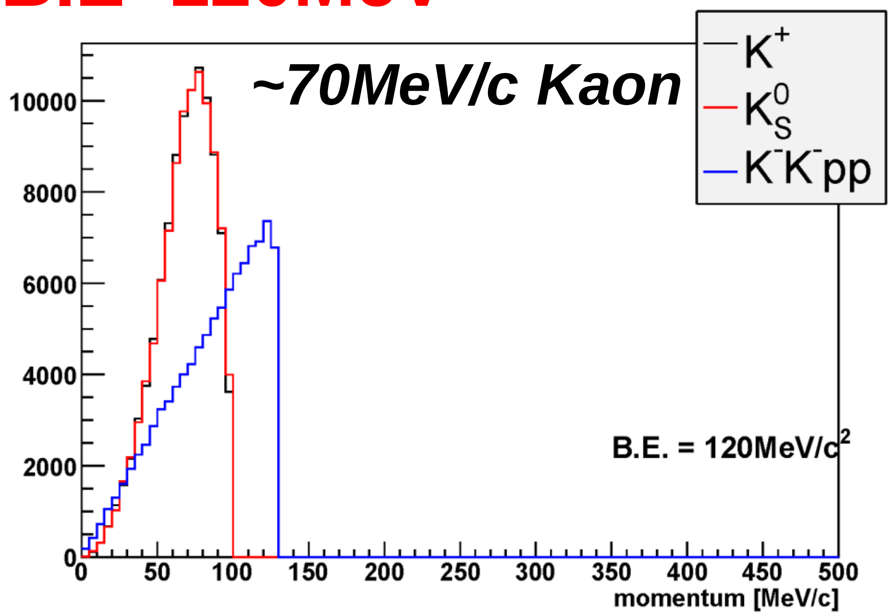
Sakuma et al. *Hyp. Int. 213*, 51 (2011).

K^+K^0X momentum spectra

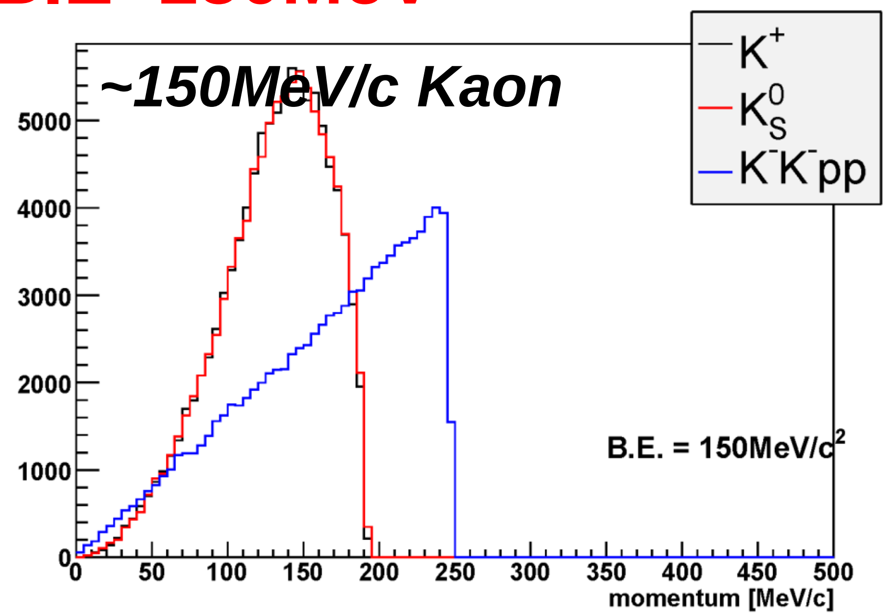
$$\bar{p} + {}^3He \rightarrow K^+ + K^0_S + K^-K^-pp$$

assumptions:
- widths of K^-K^-pp = 0
- isotropic decay

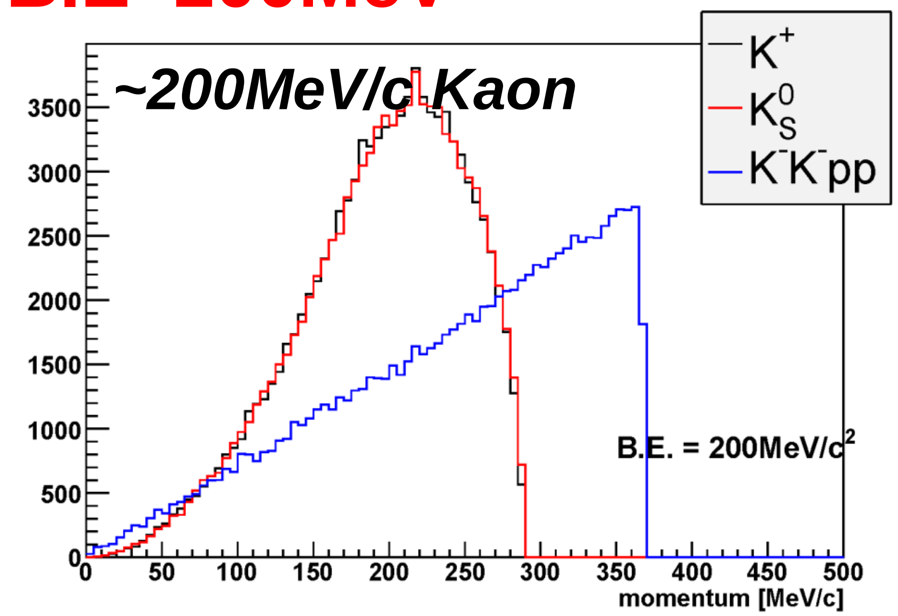
B.E=120MeV



B.E=150MeV



B.E=200MeV

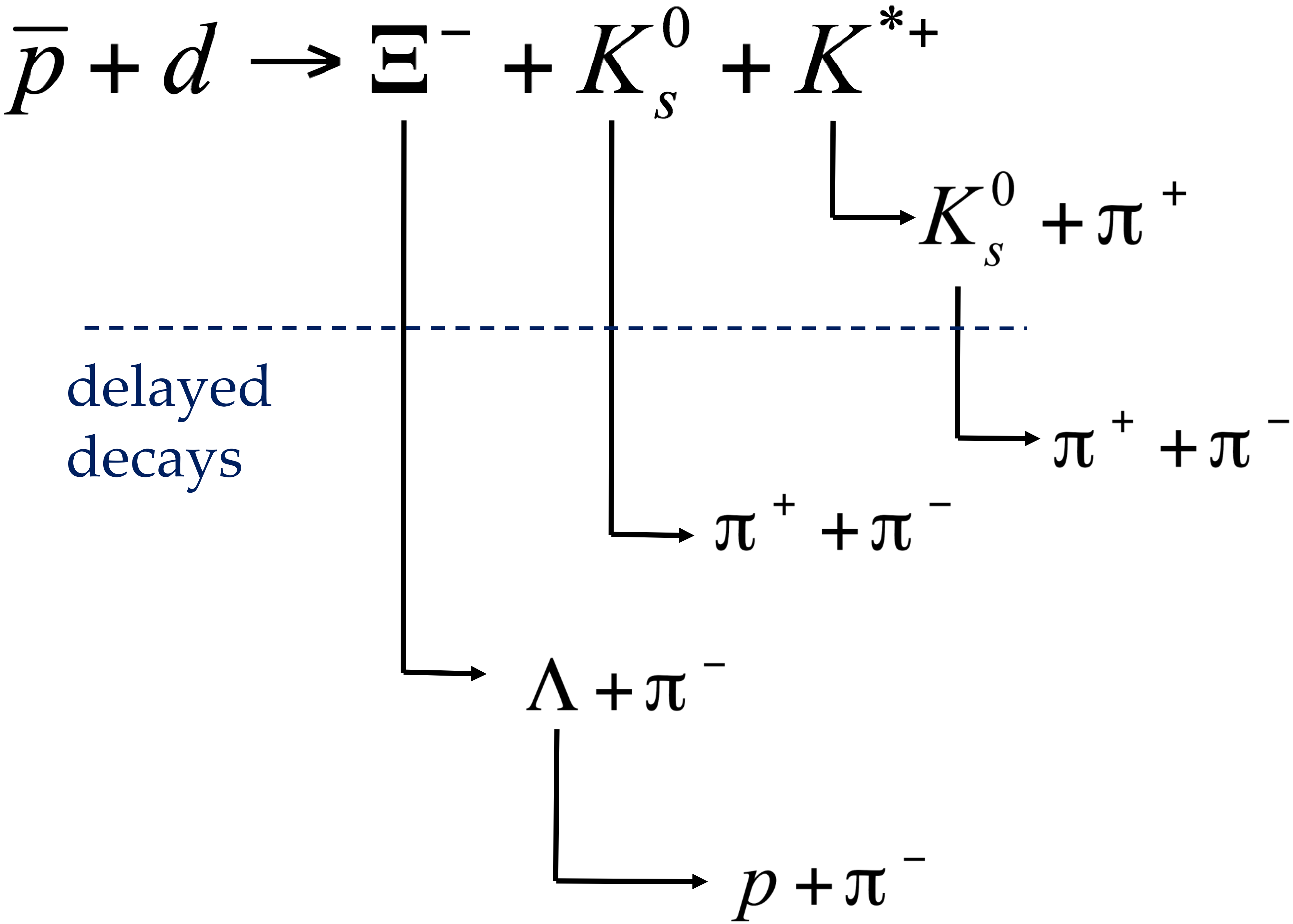


In the K^-K^-pp production channel, the kaons have very small momentum of up to 300MeV/c, even if B.E.= MeV.

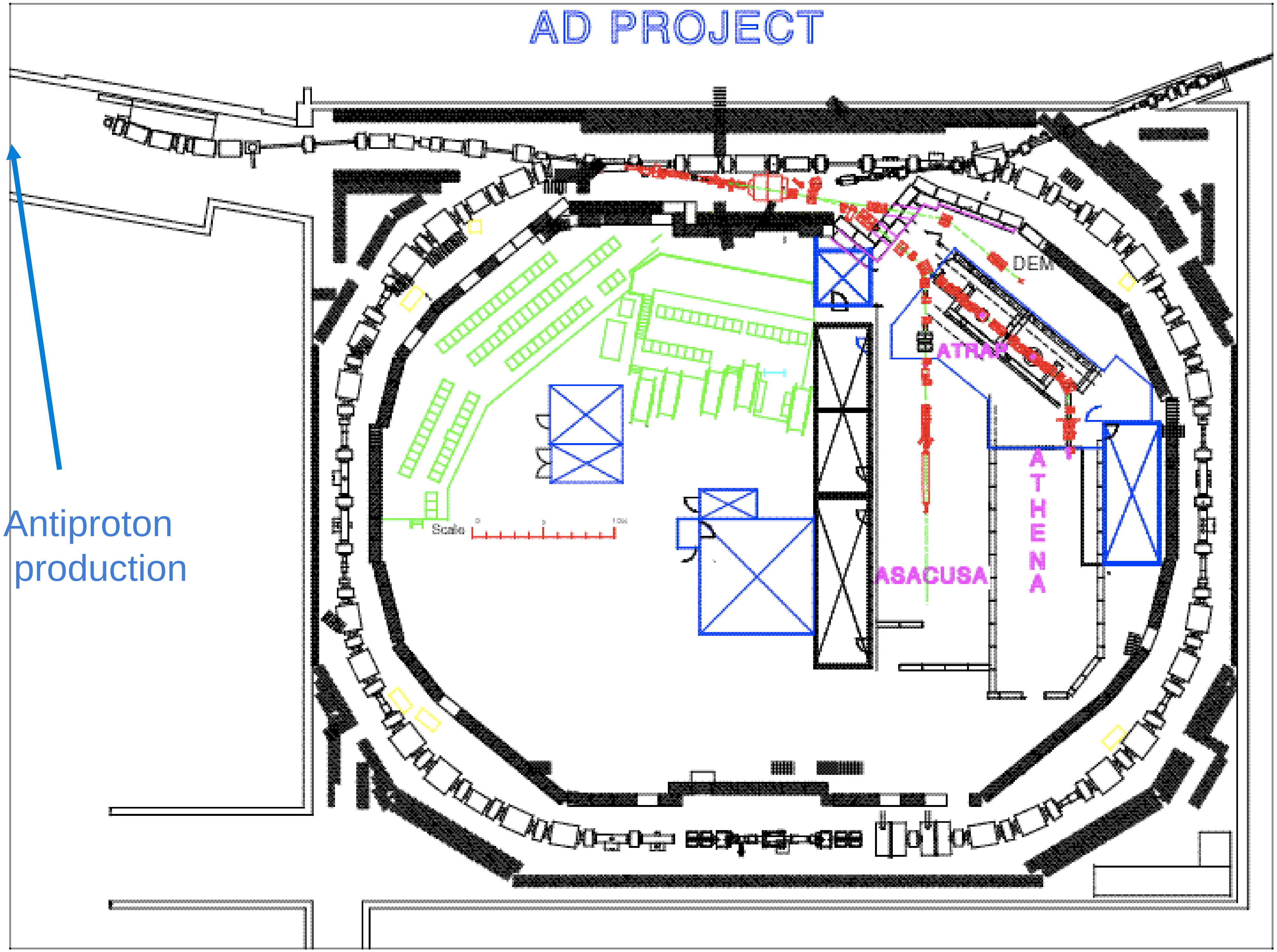
low mass detectors

~200MeV/c π from K^0_S, ~700MeV/c p from Λ, ~150MeV/c π^- from Λ

Production of S=−2: $\in^-$

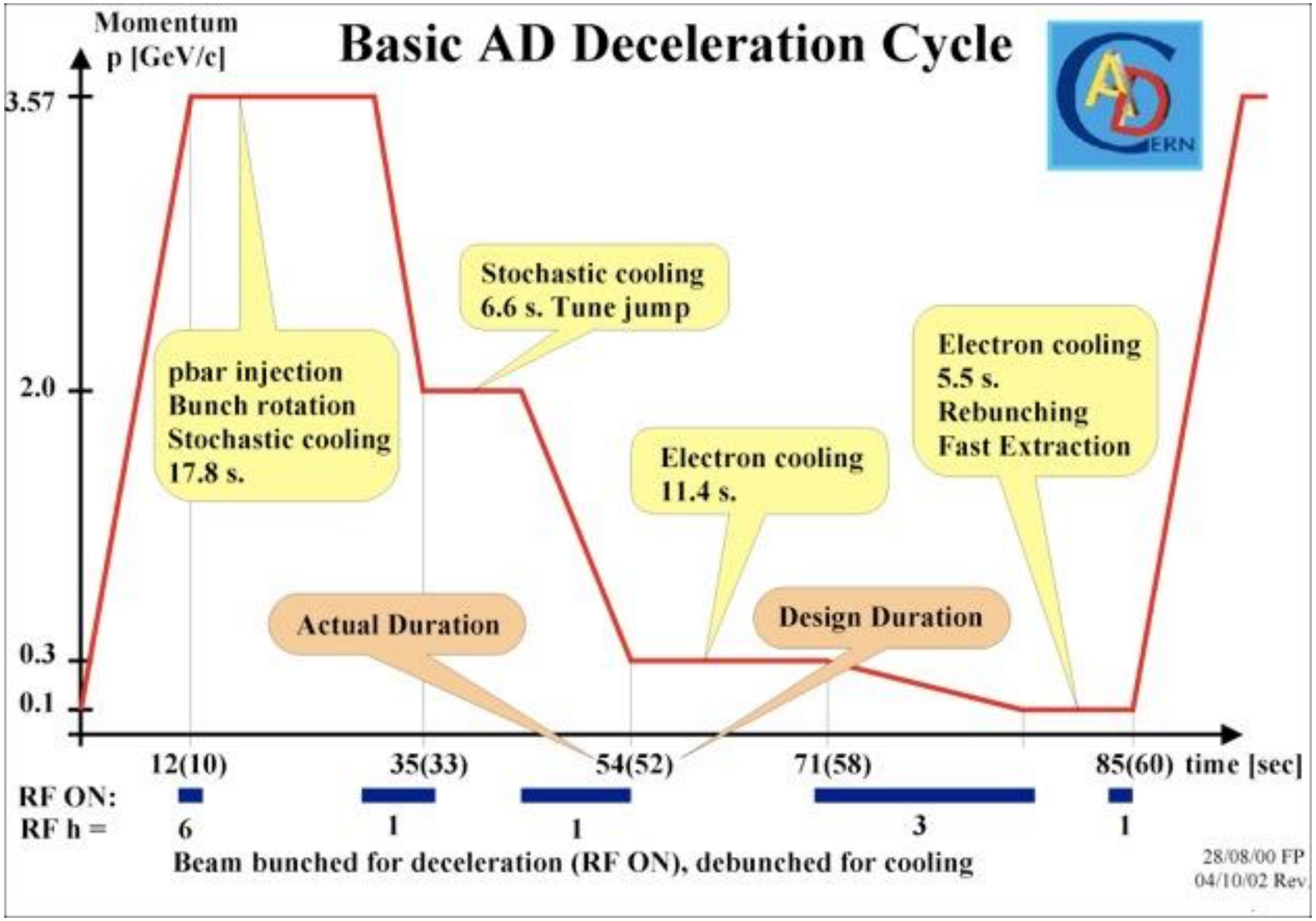


Current source: AD @ CERN



Antiproton production

AD @ CERN: start 2000



- All-in-one machine:
  - Antiproton capture
  - deceleration & cooling
  - 100 MeV/c (5.3 MeV)
- Pulsed extraction
  - 2-4 x 10^7 antiprotons per pulse of 100 ns length
  - 1 pulse / 85−120 seconds

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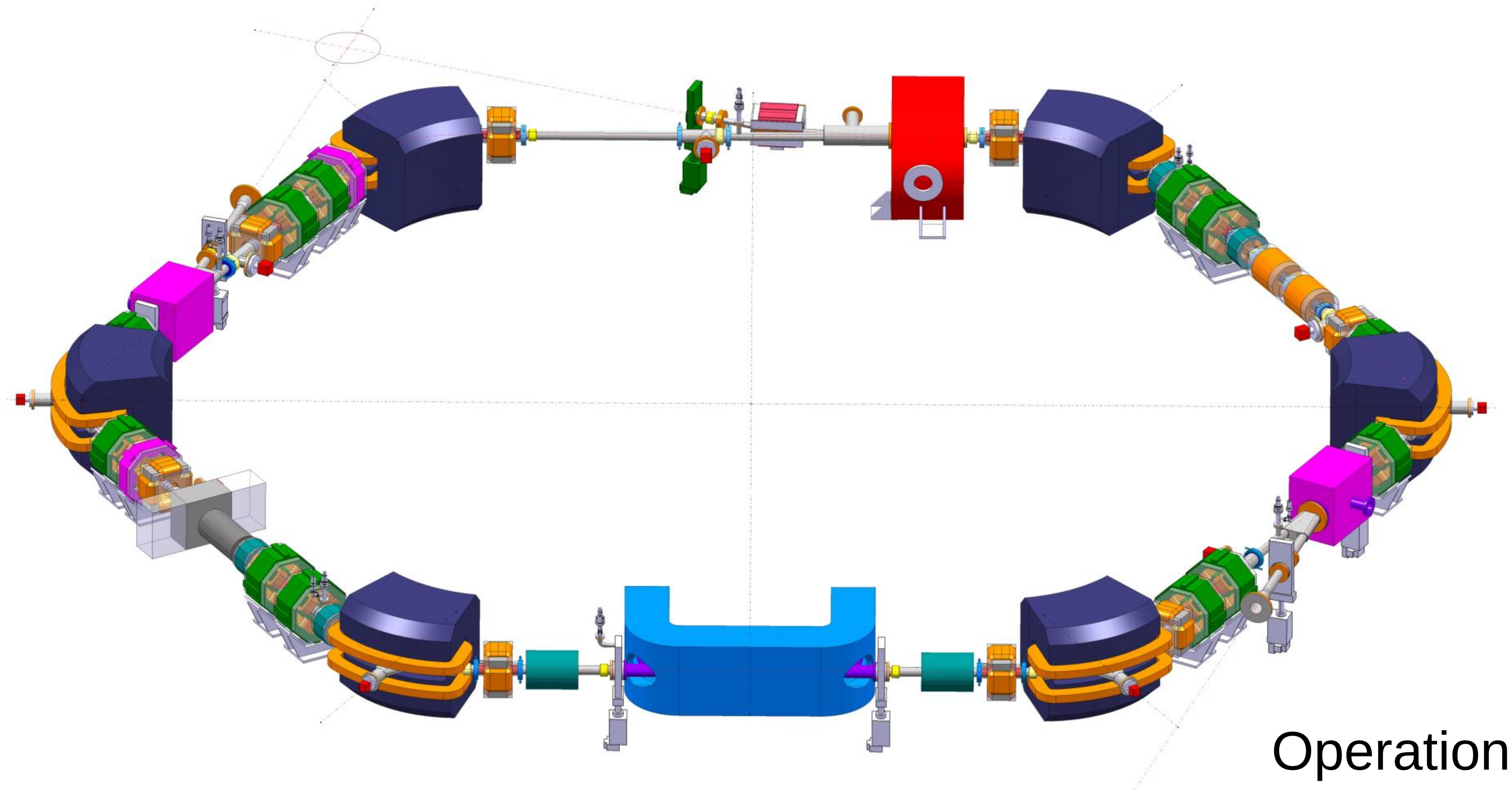
New development: ELENA @ CERN-AD

- Decelerator after AD 5 MeV → 100 keV

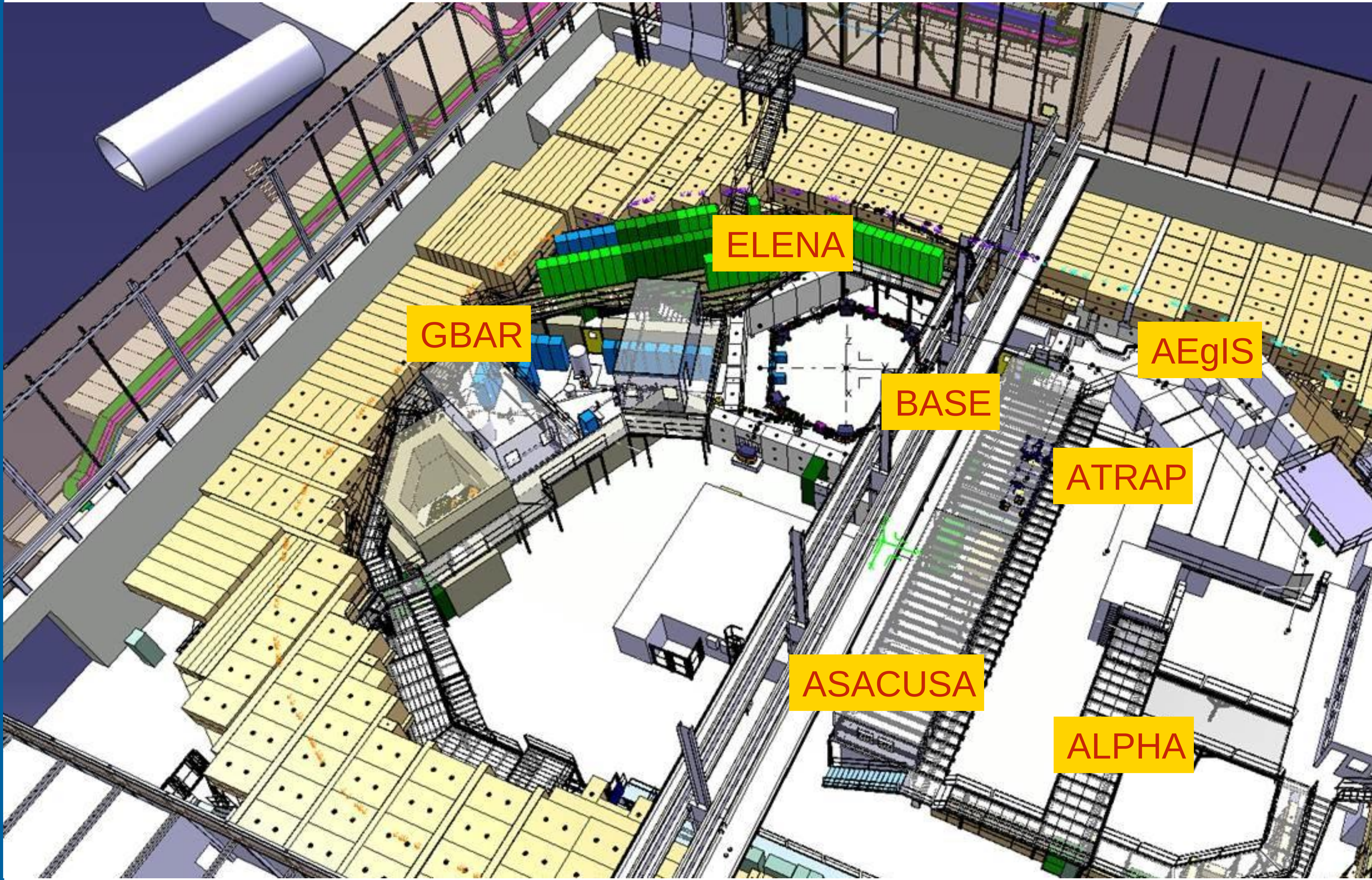


Operation from 2017
for > 10 years

Energy range, MeV	5.3 - 0.1
Intensity of ejected beam	1.8×10^7
$\varepsilon_{x,y}$ of extracted beam, π·mm·mrad, [95%], standard	4 / 4
$\Delta p/p$ of extracted beam, [95%], standard	$8 \cdot 10^{-3}$

100 keV
1 pulse every ~100 s:
average $10^5 \bar{p}$/s

AD & ELENA area and experiments



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