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

www.flairatfair.eu

Eberhard Widmann

ECT* Trento

17 Jun 2019

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*** *Operation from 2021*
Availability of pbar and RI	FAIR

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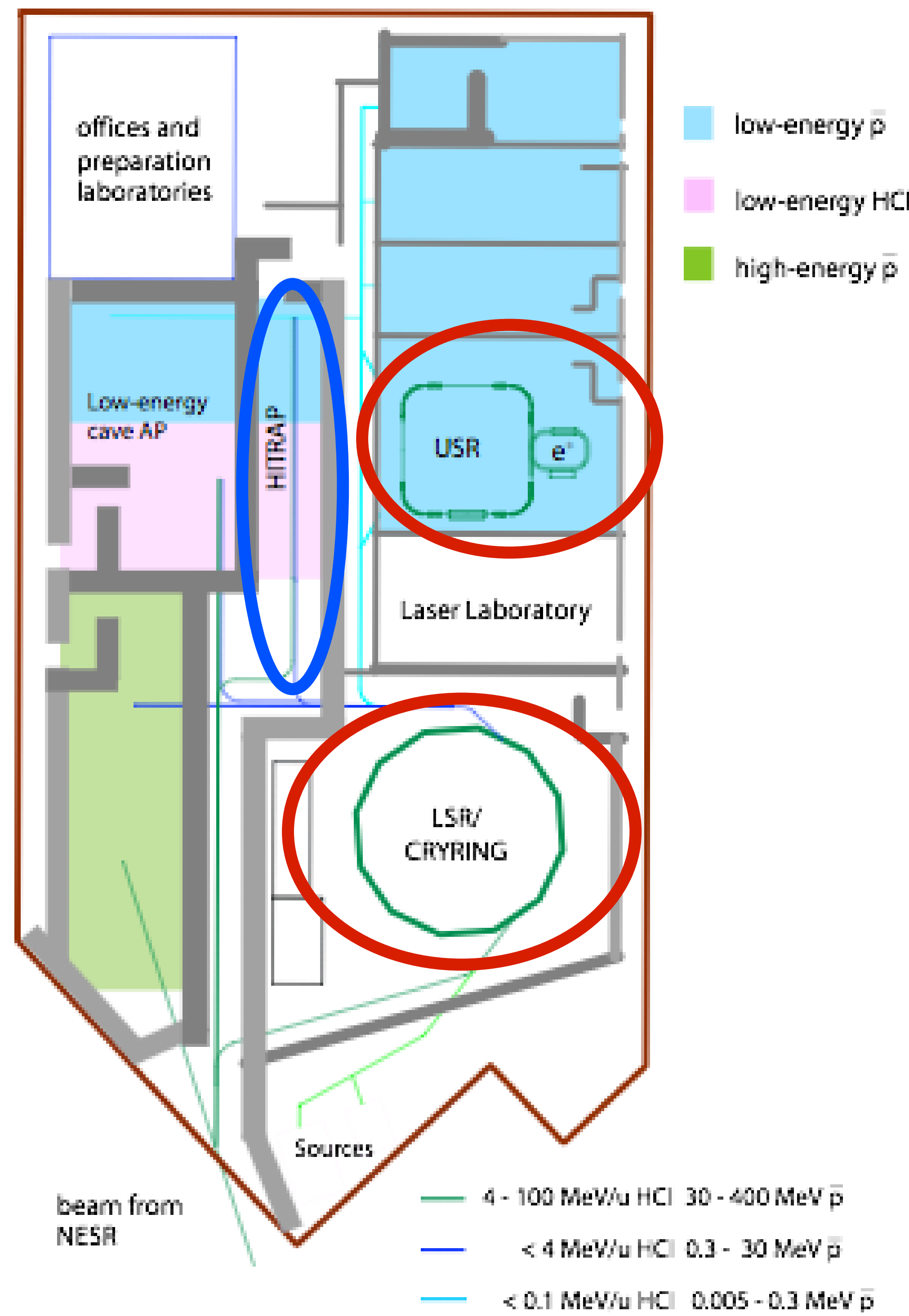
FLAIR@ FAIR - Baseline Technical Report 2005

- 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
- Slow and fast extraction
- Ion traps
  - 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

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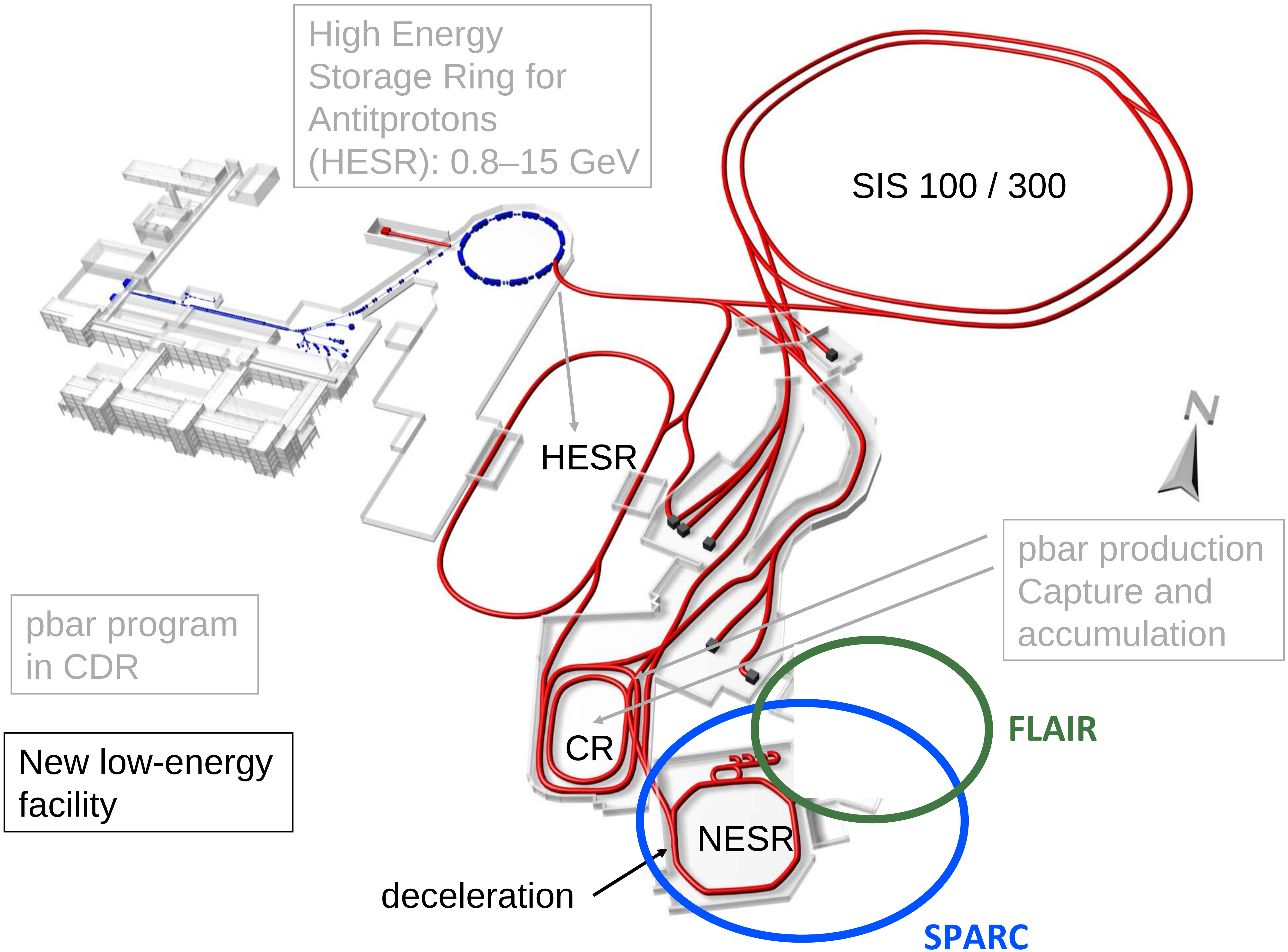
Antiprotons at FAIR



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; module 3: orange.

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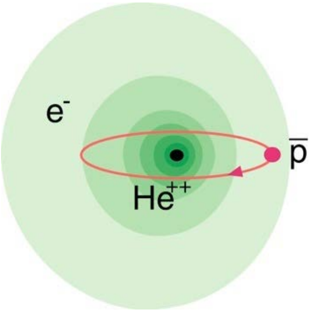
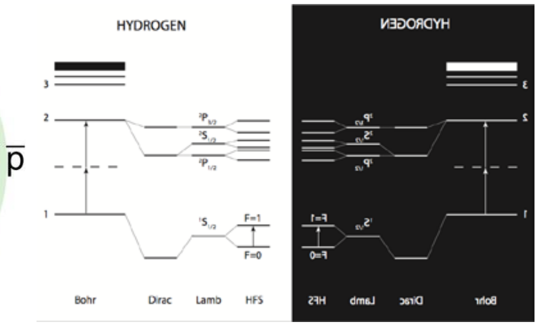
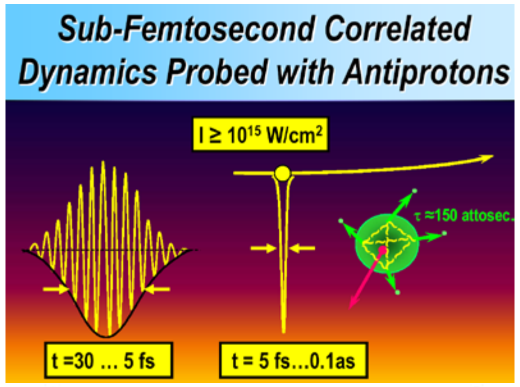
Low Energy Antiproton Physics @ FLAIR

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

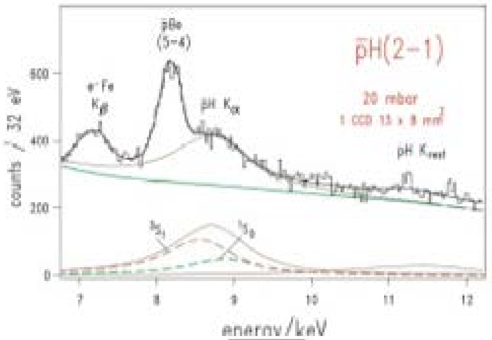


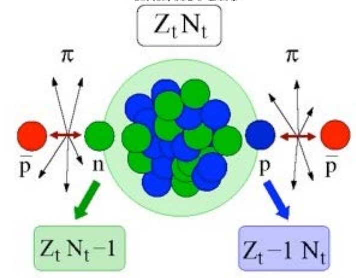


- Atomic collisions
  - Sub-femtosecond correlated dynamics: ionization, energy loss, antimatter-matter collisions

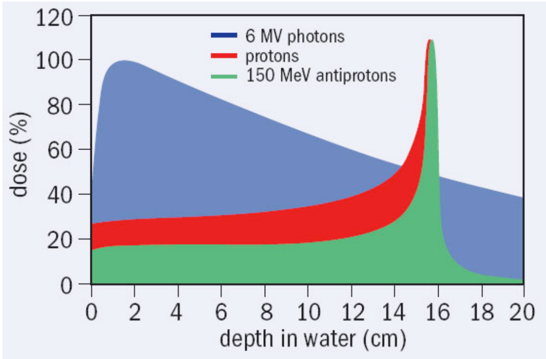


- Antiprotons as hadronic probes
  - X-rays of light antiprotonic atoms: low-energy QCD
  - X-rays of neutron-rich nuclei: nuclear structure (halo)
  - Antineutron interaction
  - Strangeness –2 production



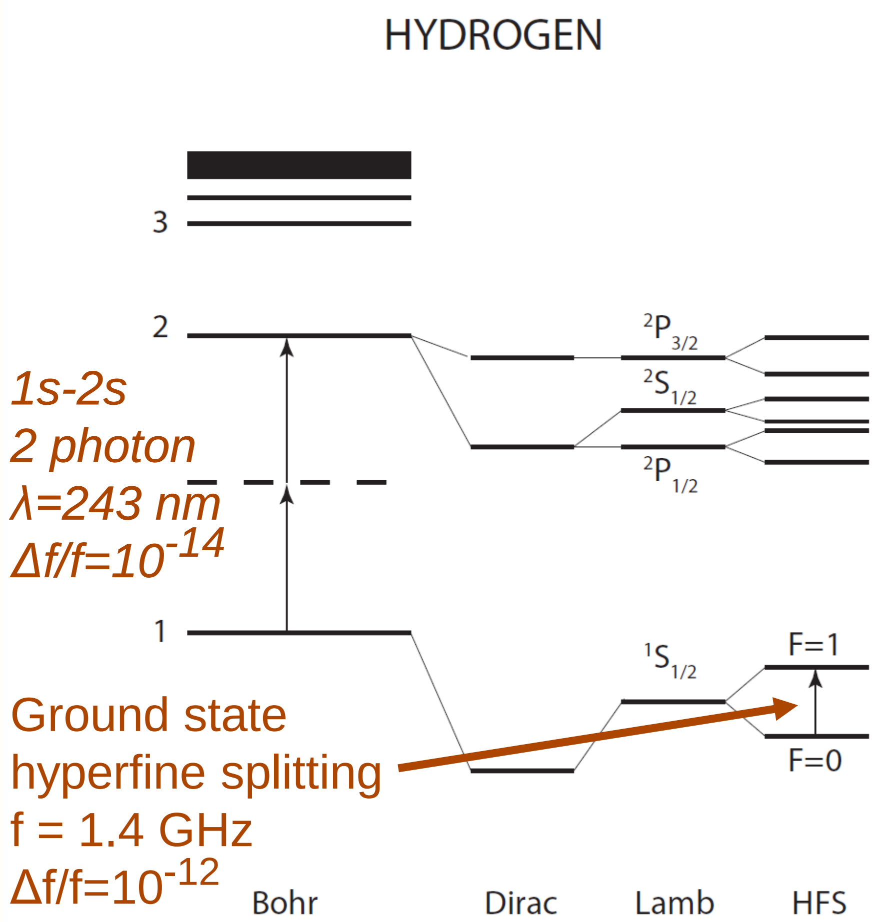


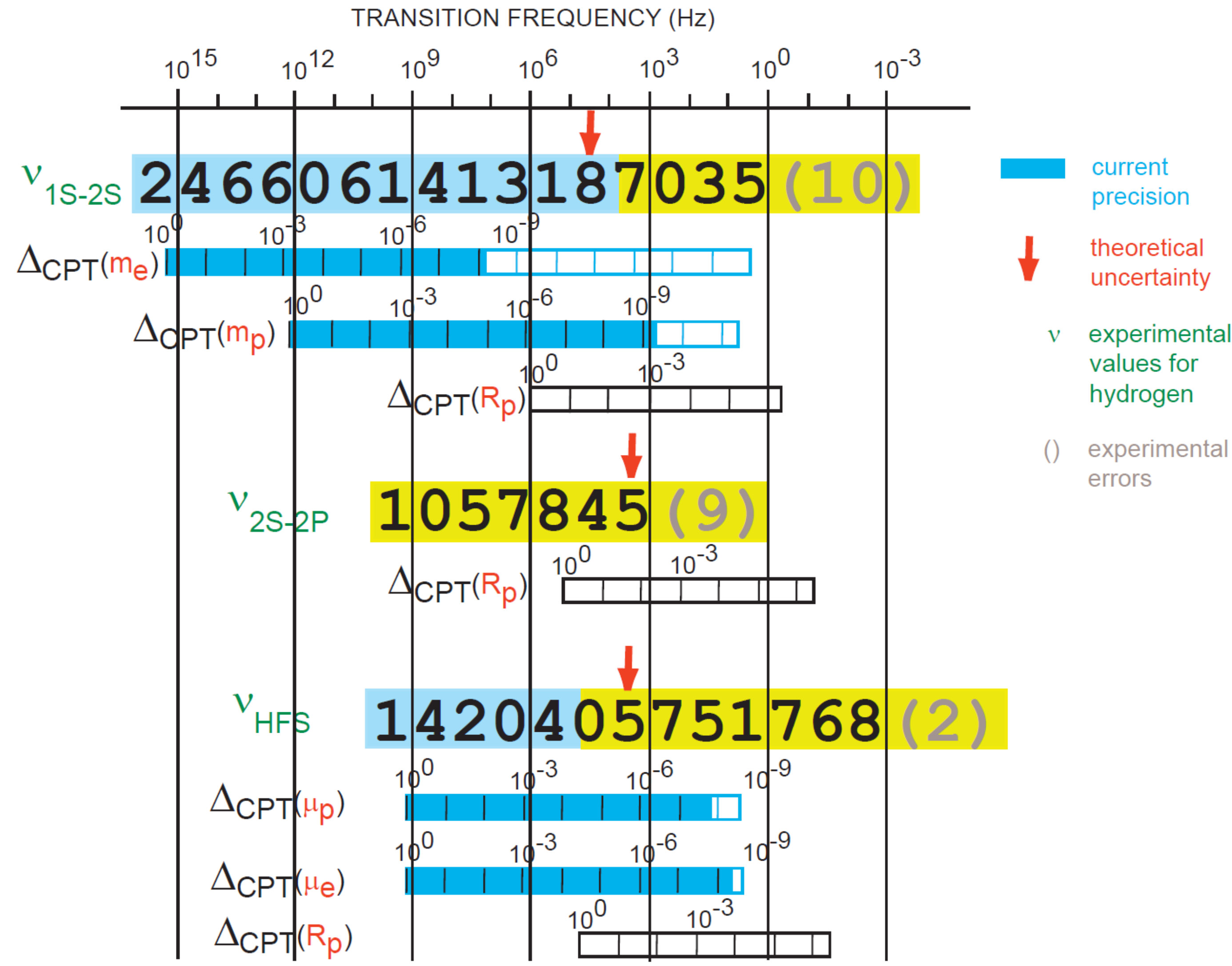
- Medical applications: tumor therapy



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

Sensitivity of $\overline{\mathrm{H}}$ spectroscopy





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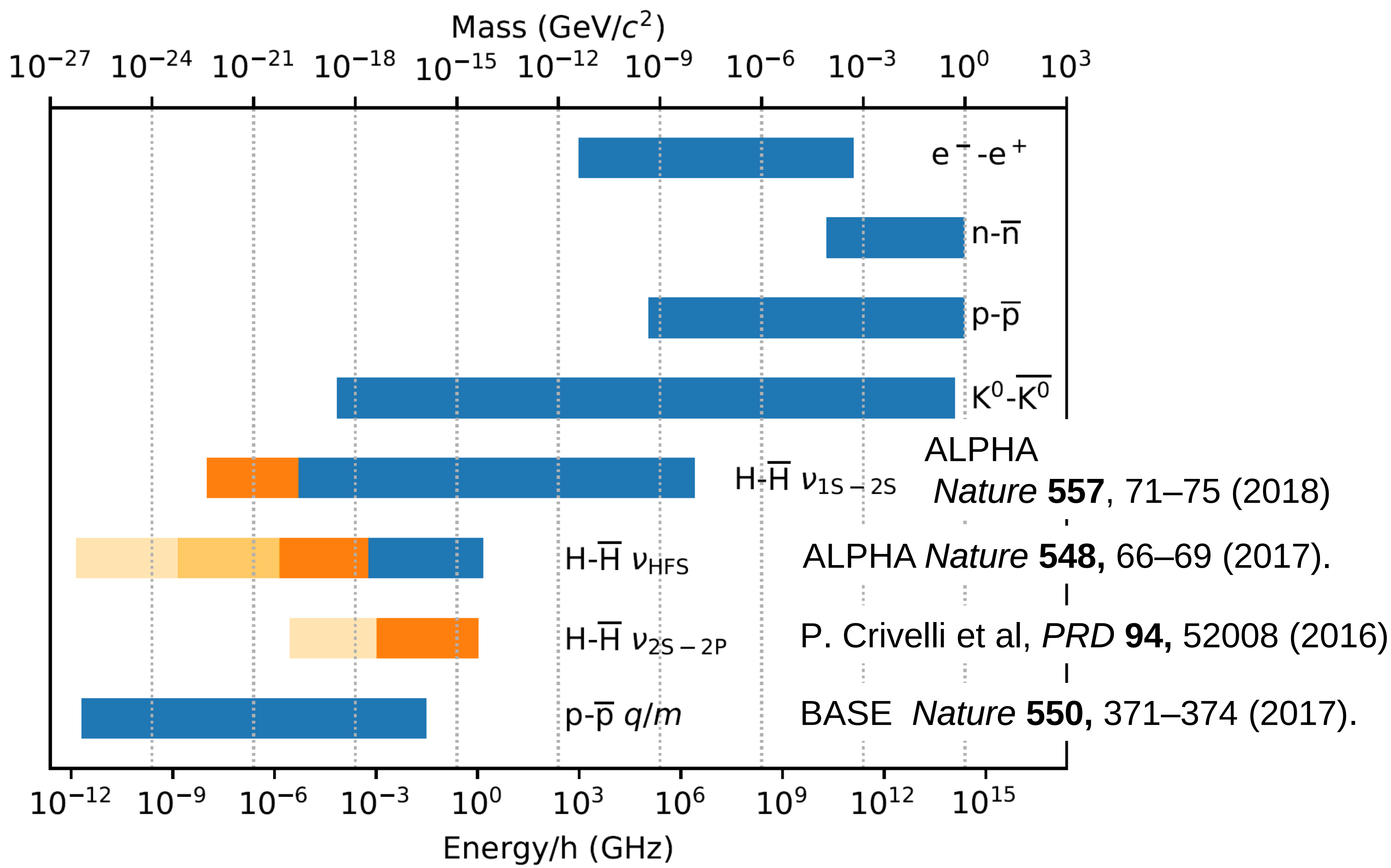
Status of antimatter CPT tests



Right edge: value
Bar length: relative precision
Left edge: absolute sensitivity

Source: PDG
Blue: measured
Orange: planned
Yellow: potentially reachable

Widmann, E. et al. *Hyperfine Interact. 240:5 (2019)*
https://doi.org/10.1007/s10751-018-1536-9.

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Comparison of CPT tests: SME

- Standard Model Extension SME

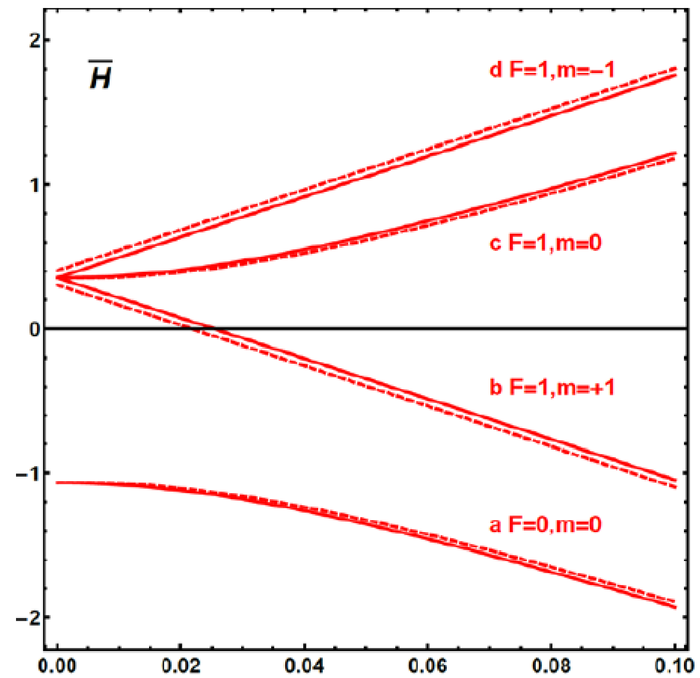
CPT & LORENTZ VIOLATION

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

LORENTZ VIOLATION

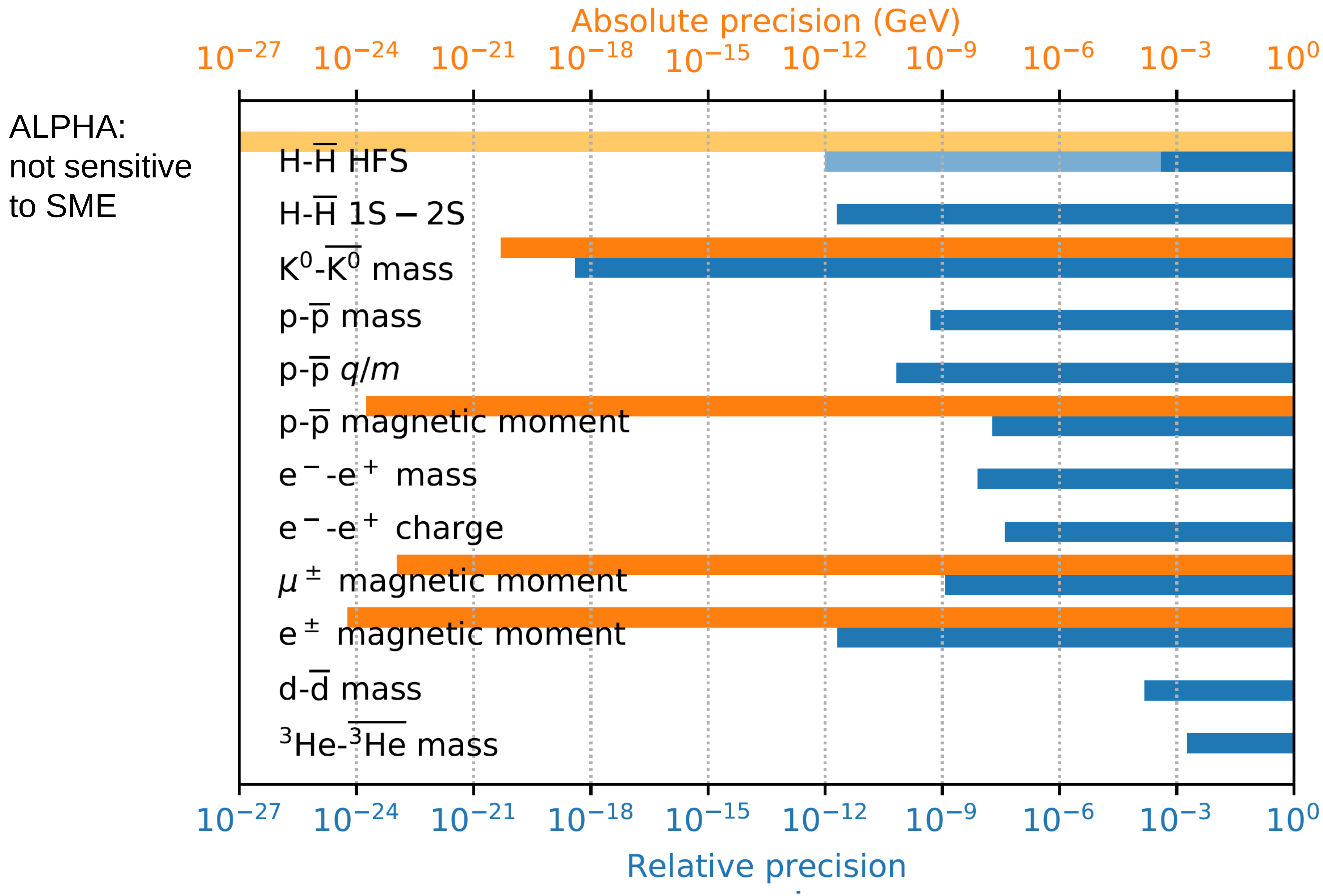
D. Colladay and V.A. Kostelecky, PRD 55, 6760 (1997)

- Minimal SME: only HFS
- Non-minimal SME: also 1S-2S shows CPTV



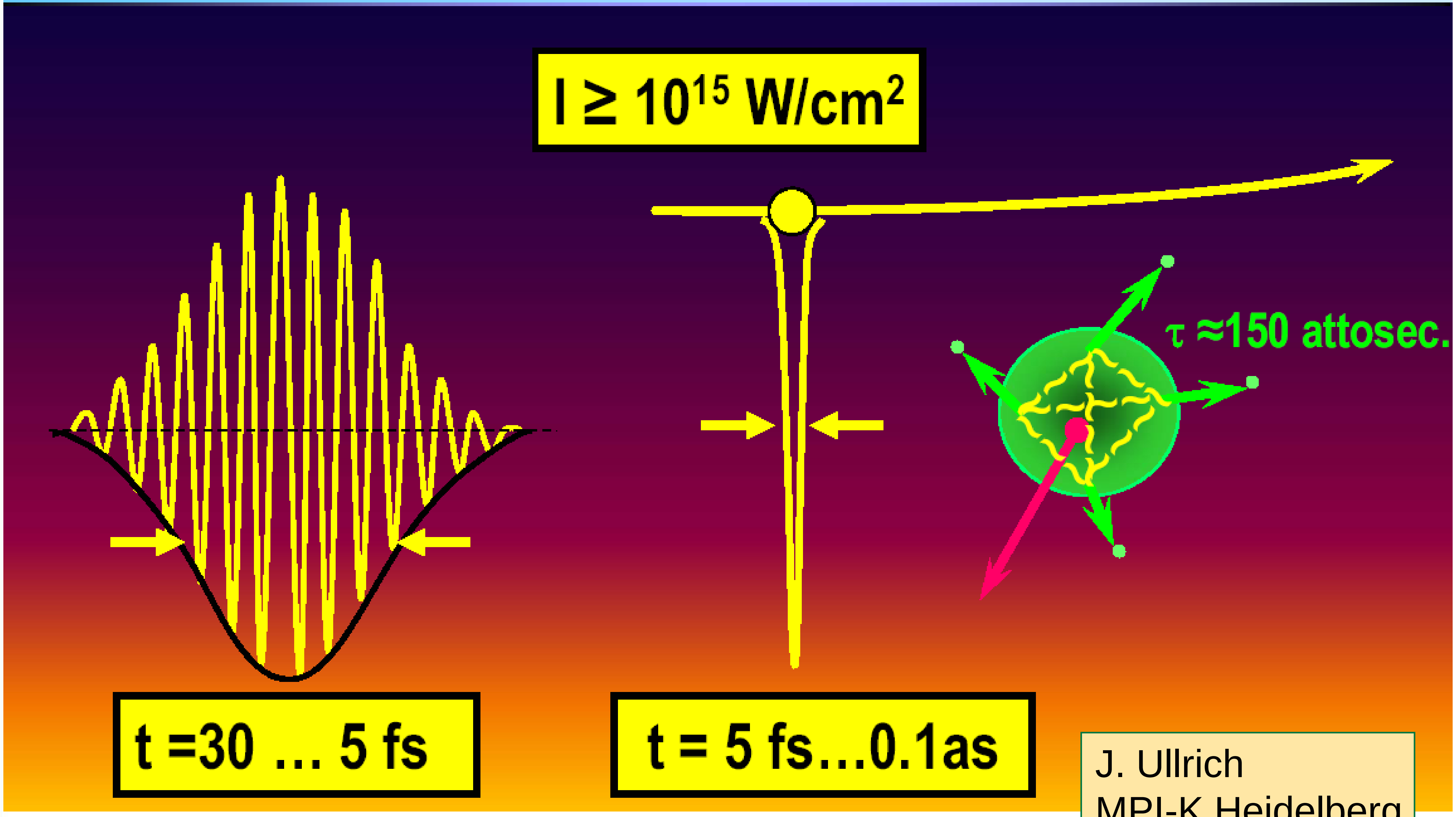
Bluhm, R., Kostelecky, V., & Russell, N., PRL *82*, 2254–2257 (1999).

CPT tests and SME



PDG, Kostelecky & Bluhm arXiv:0801.0287

Sub-Femtosecond Correlated Dynamics Probed with Antiprotons



J. Ullrich
MPI-K Heidelberg

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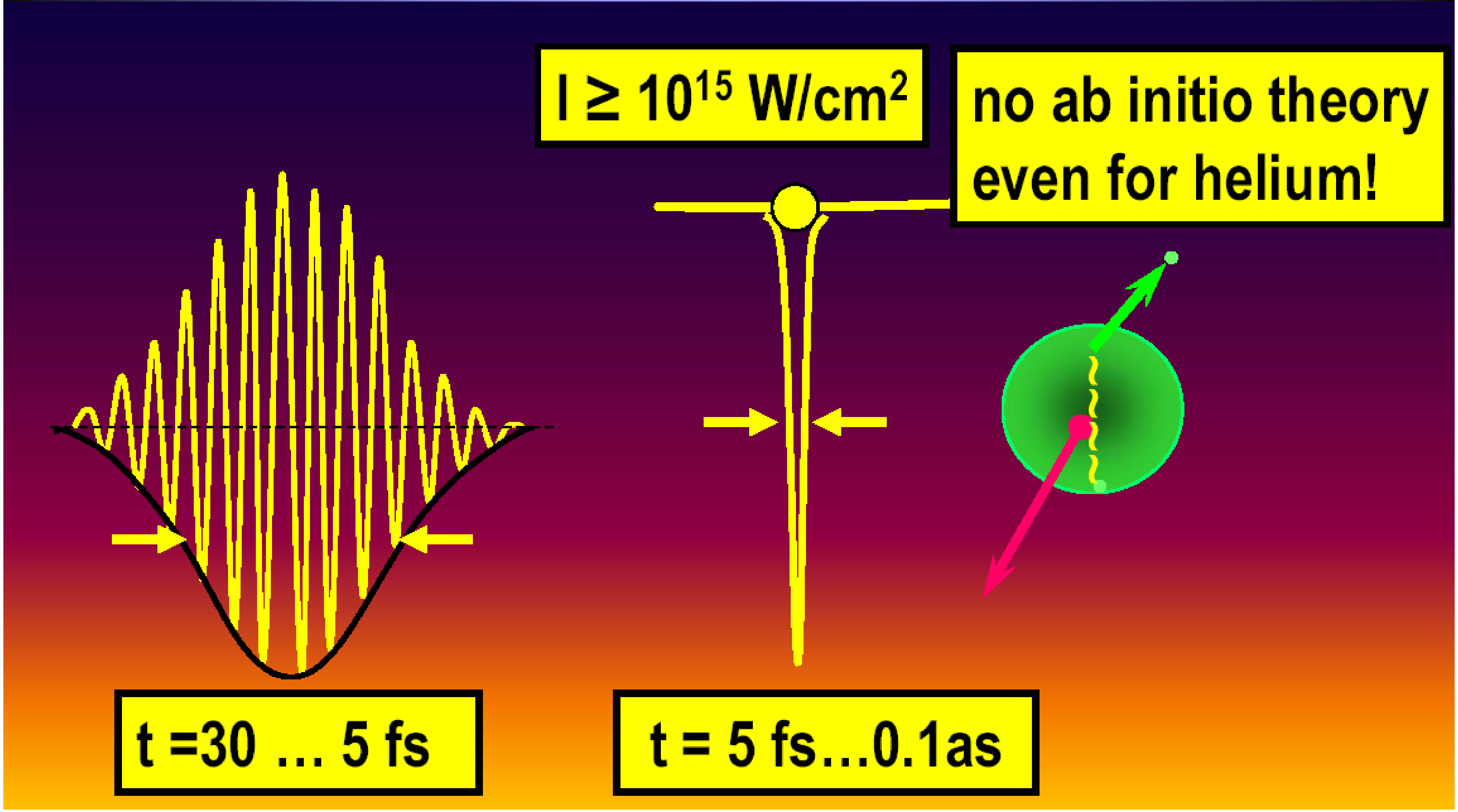
Sub-Femtosecond Correlated Dynamics Probed with Antiprotons



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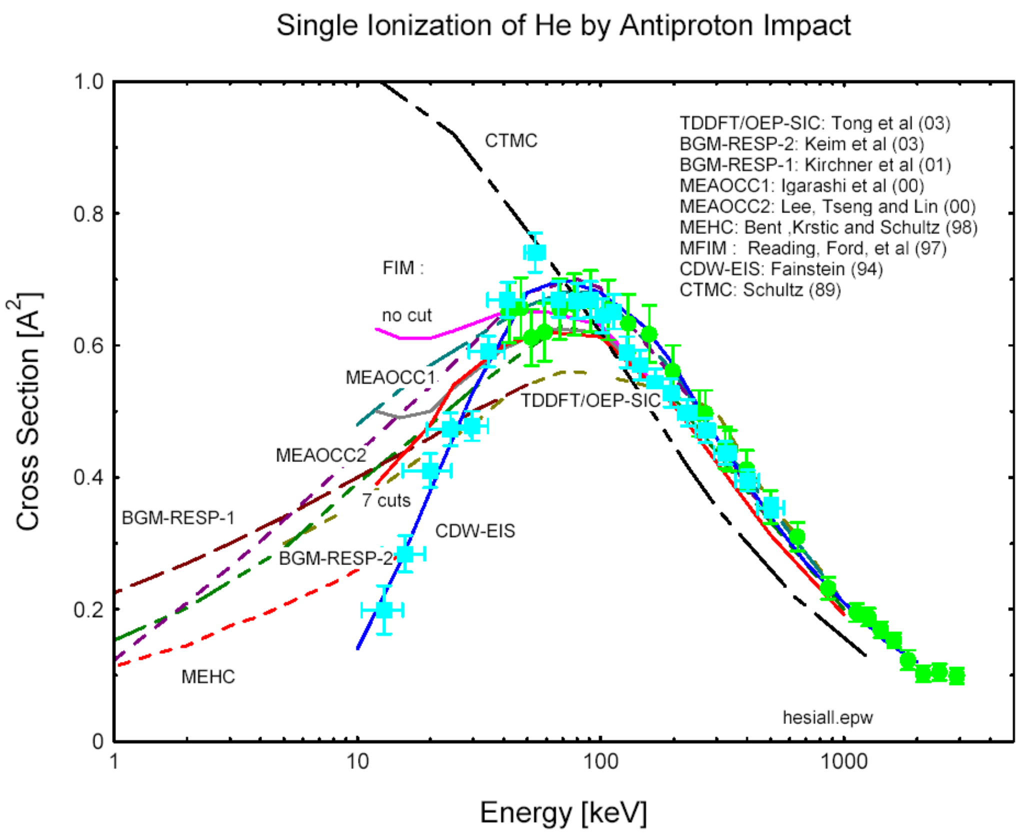
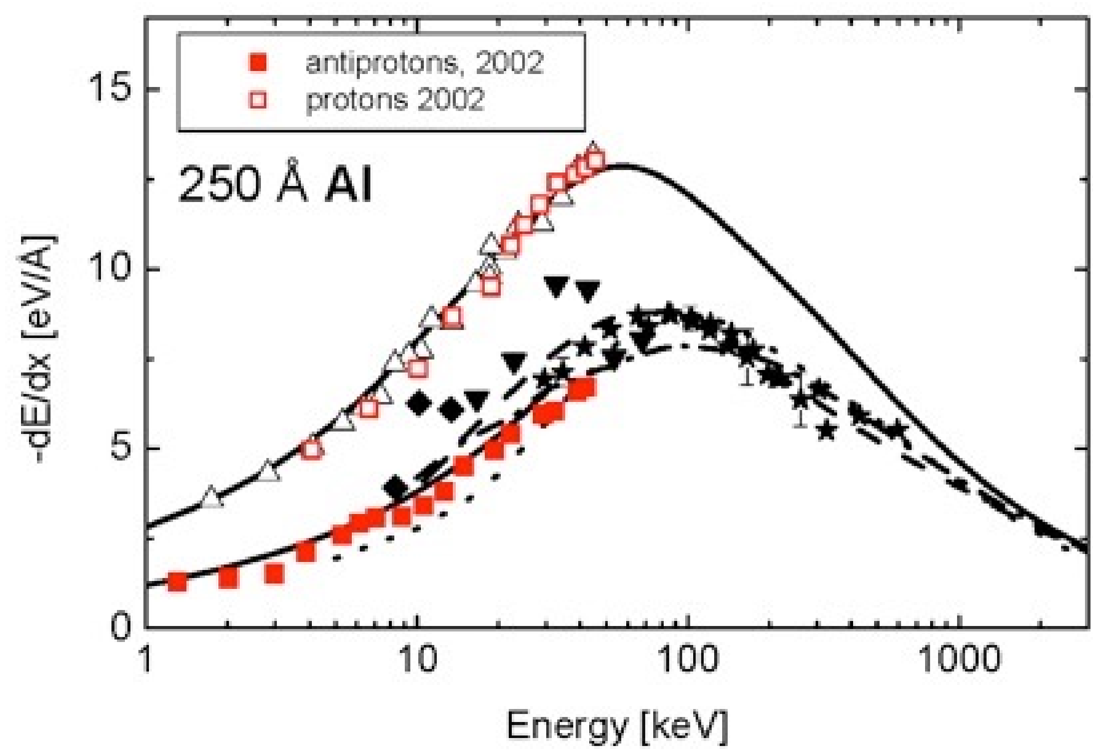
Atomic Collision Physics with USR

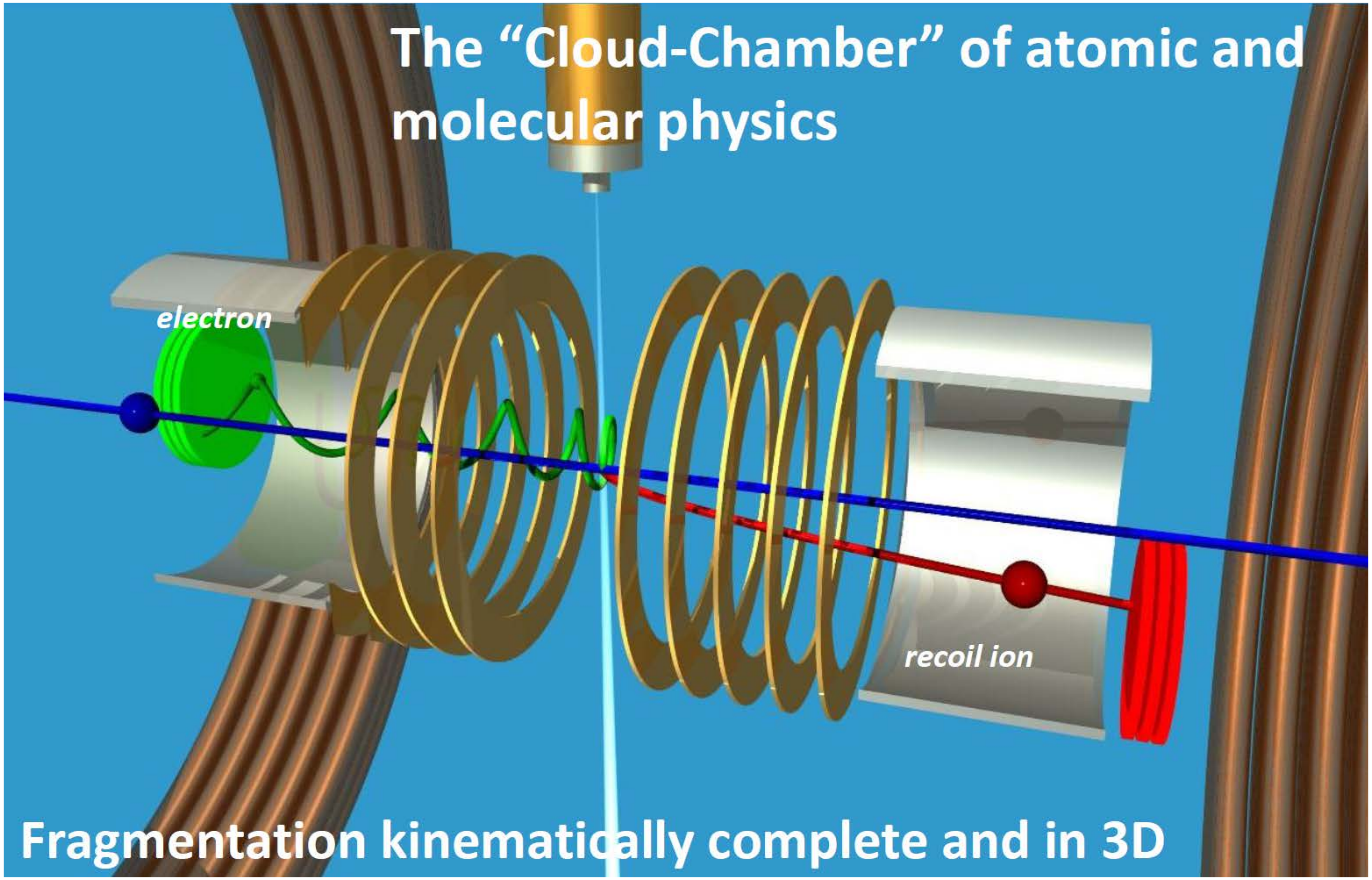
- Ionization in single collision by slow antiprotons
- Energy loss





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

Reaction microscope



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

Fully differential cross sections for ions

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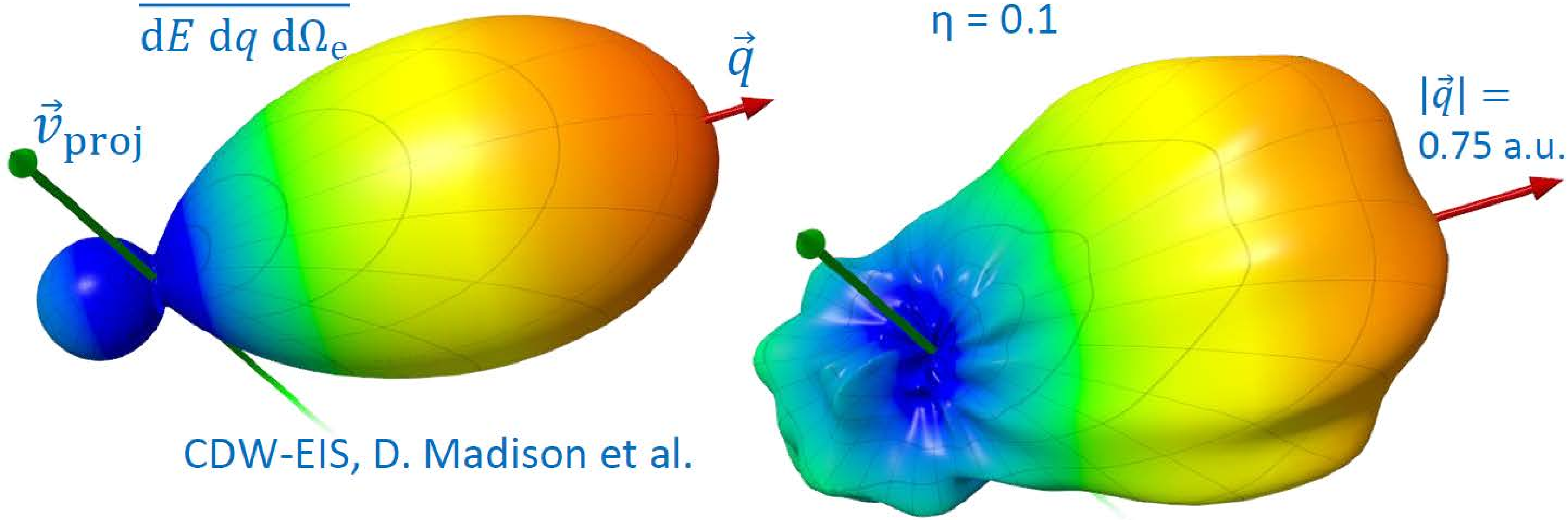
Fully differential cross section

$$\frac{d^3\sigma}{dE\ dq\ d\Omega_e}$$



1.2 GeV C^{6+} + He
η = 0.1

CDW-EIS, D. Madison et al.

M. Schulz, ..., DF et al.
Nature 422, 48 (2003)

Cross section (Born series):

$$d\sigma = 8\pi\frac{\eta^2}{q^3}\left|\langle\psi^f_{cont}\middle|e^{-i\vec{q}\cdot\vec{r}}\middle|\psi^i_{atom}\rangle\right|^2 dq + \sigma(\eta^3)$$

Perturbation parameter: $\eta = \frac{Z_P}{v_P}$

E. Widmann

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

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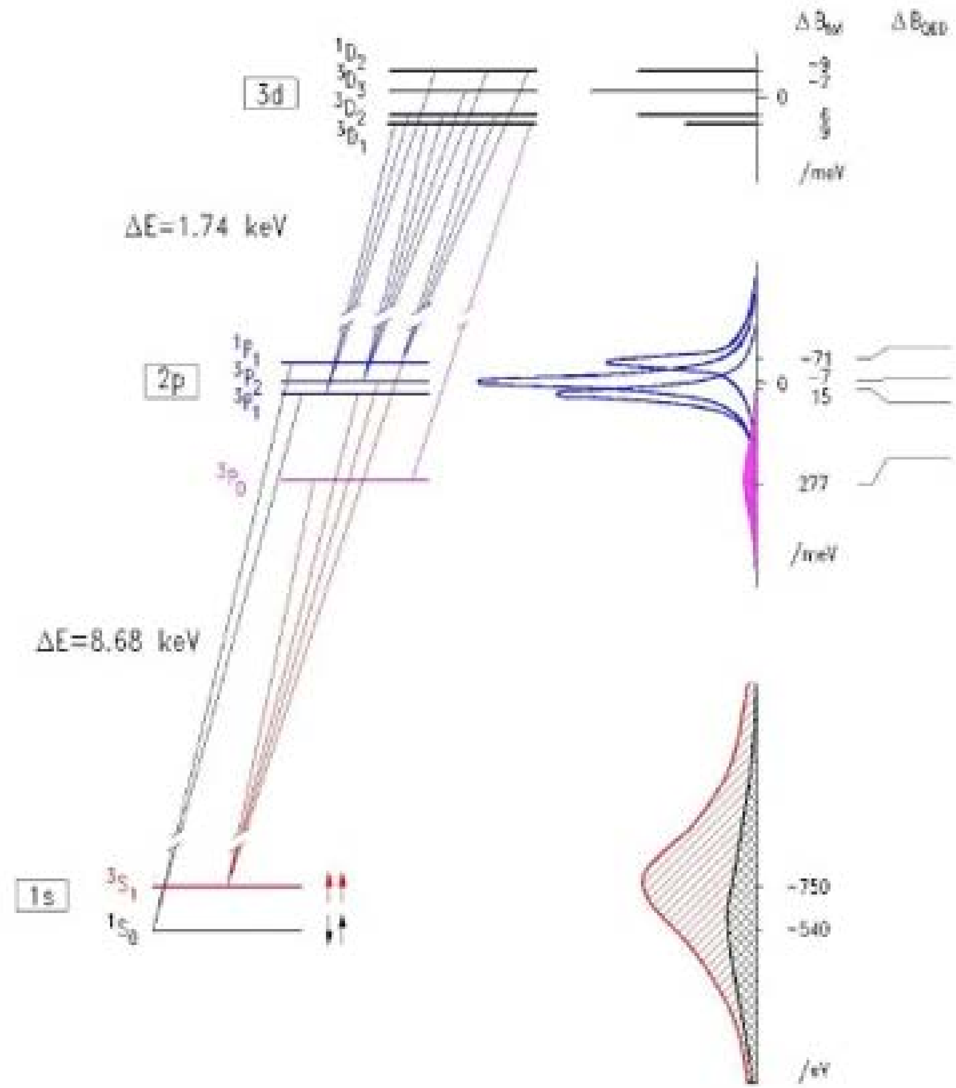
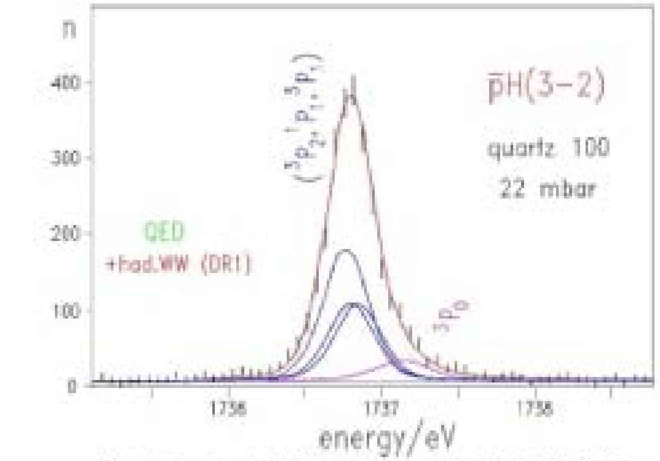
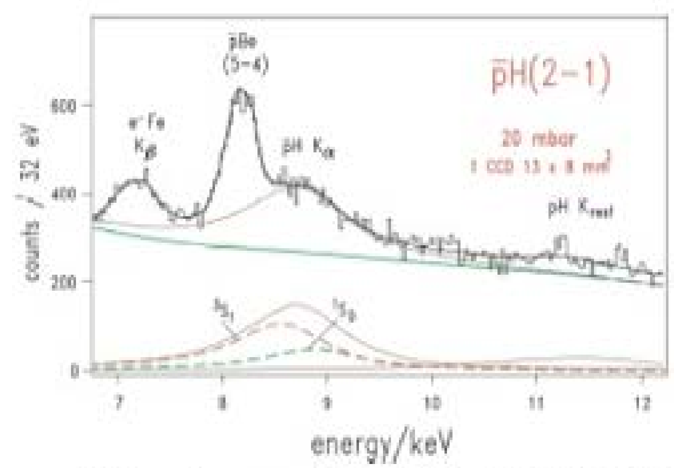
X-rays of light antiprotonic atoms





D. Gotta et al., Nucl. Phys. A 660 (1999) 283



M. Augsburger et al., Nucl. Phys. A 658 (1999) 149

Ground-state
HFS could not
be resolved @ LEAR

Talk D. Gotta Fr 10:00

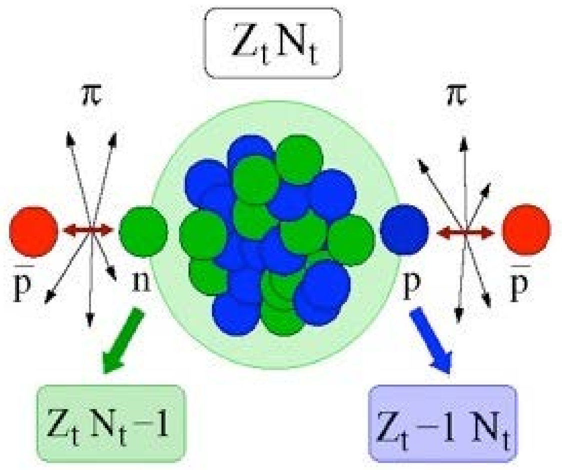
- Continuous pbar beam needed:
- Low-energy nucleon-antinucleon interaction
- spin dependencies
- Isotope effects: relative strength of annihilation p,n: halo effects

p̄-RI in Traps for Nuclear Structure Study

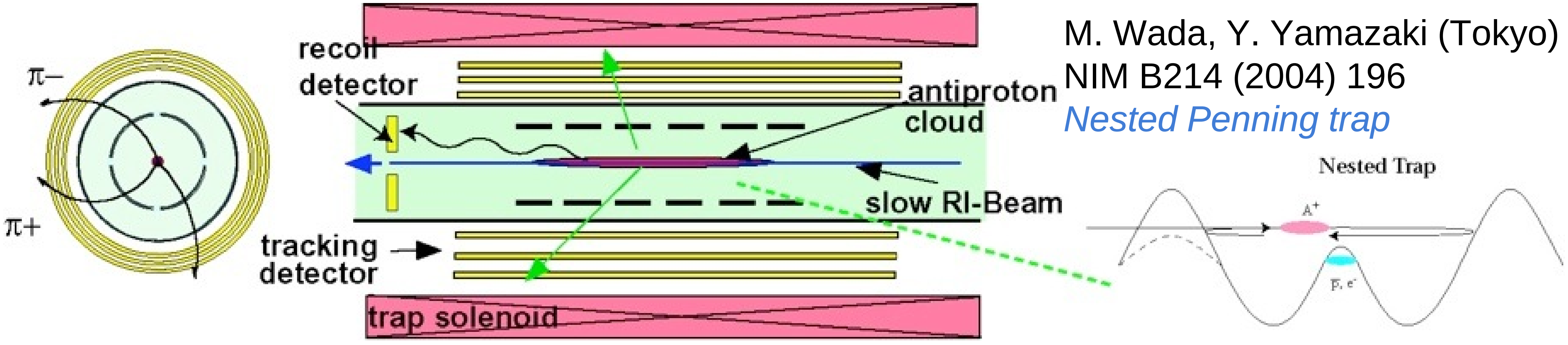
Talk A. Trzinksa Tu 11:00

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

Talk M. Wada Tu 14:45
New idea: PUMA, talk Nagatsuka Tu 15:45

Exo+pbar

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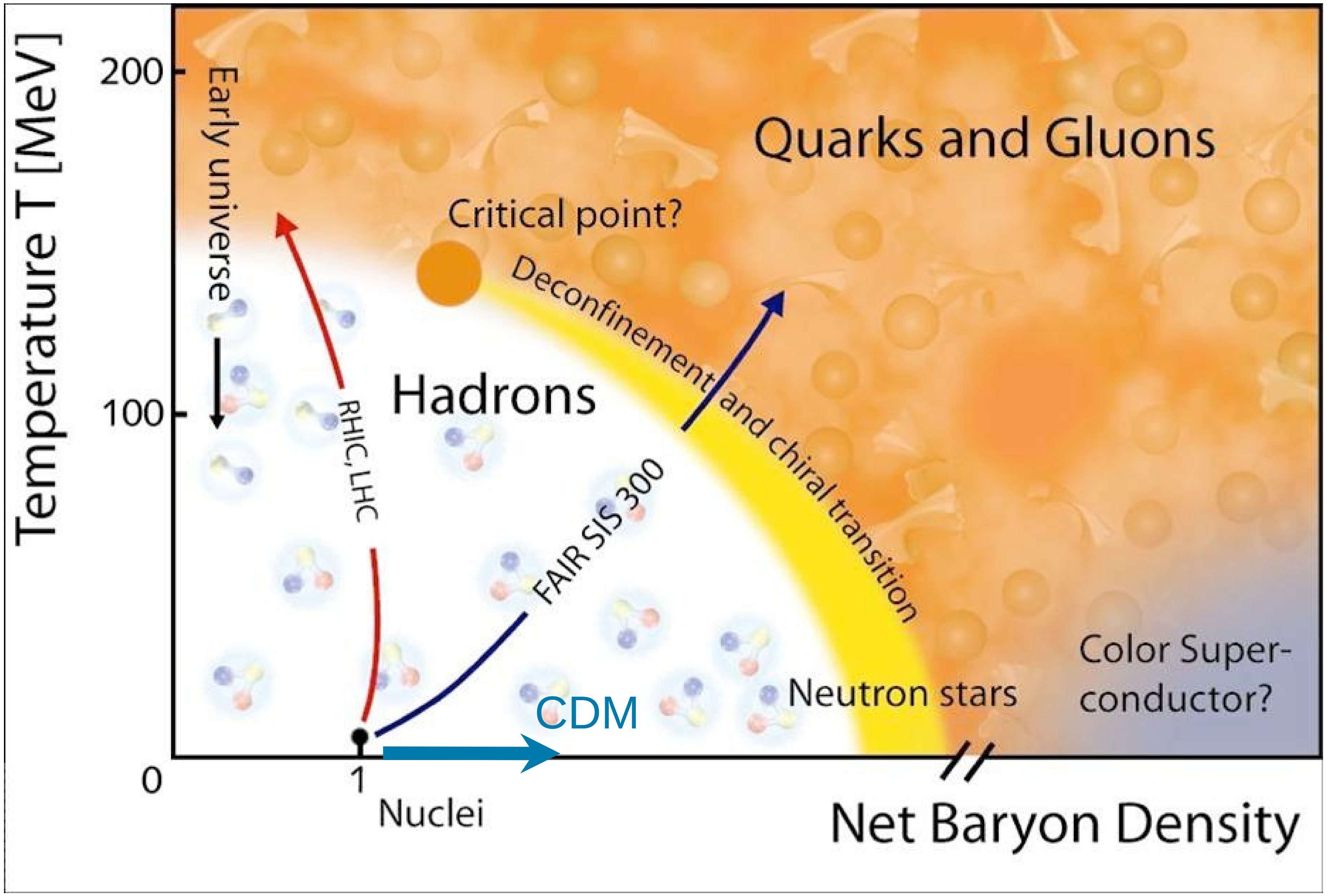
Cold dense nuclear matter



Signal of bound states ?

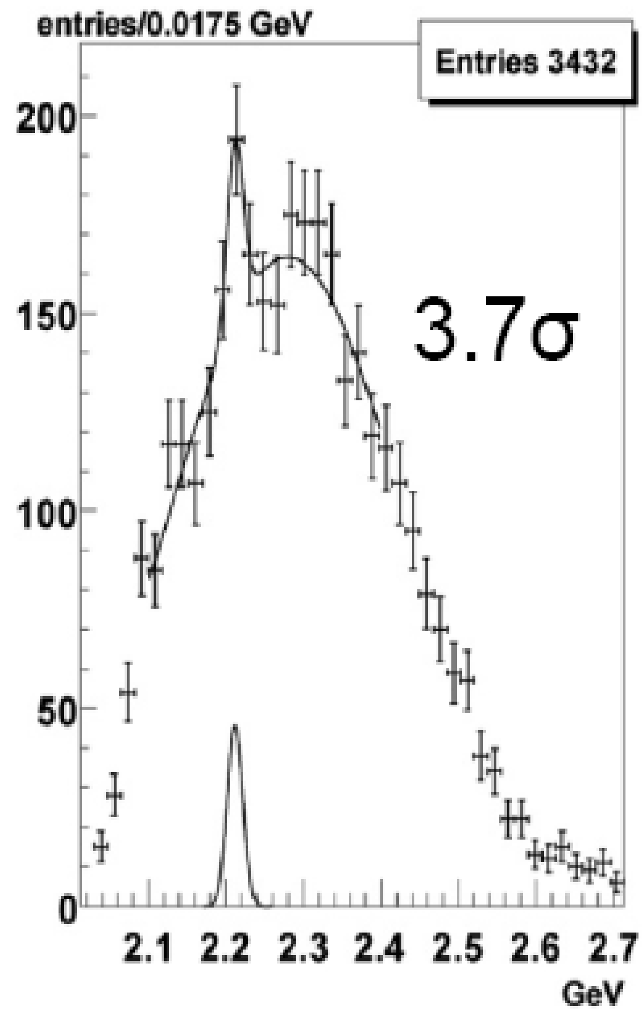
Antiproton annihilation

OBELIX data

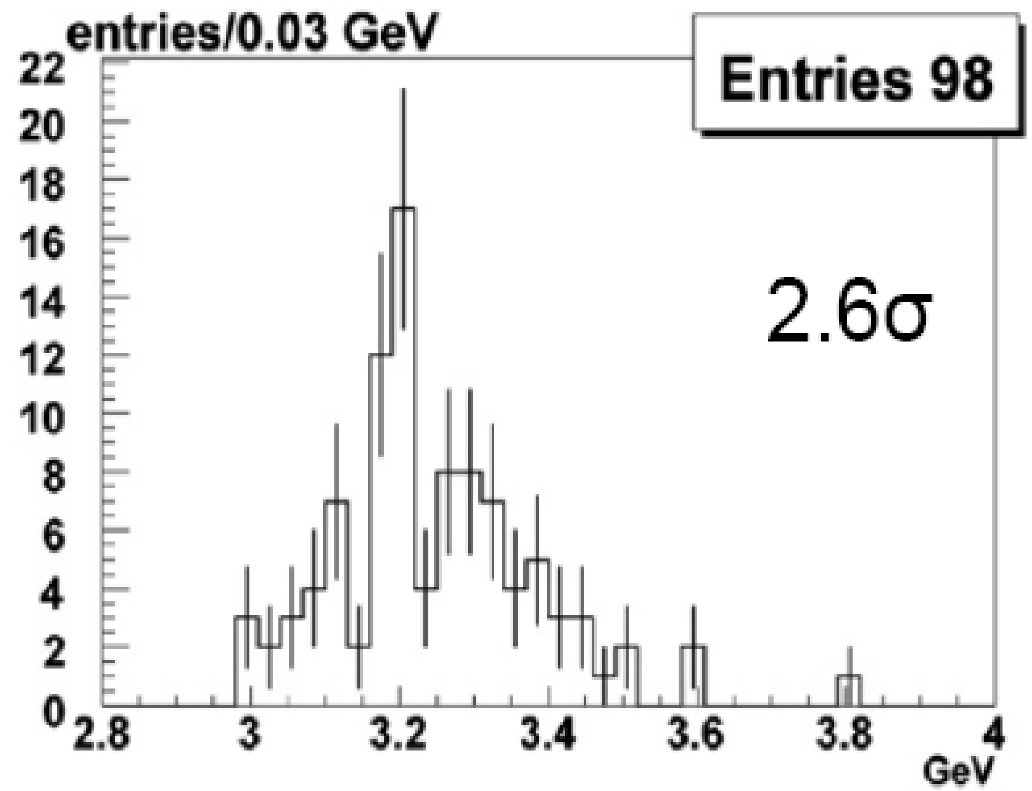
$$\bar{p} + {}^4He \rightarrow ppnK^- + K^0$$

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

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

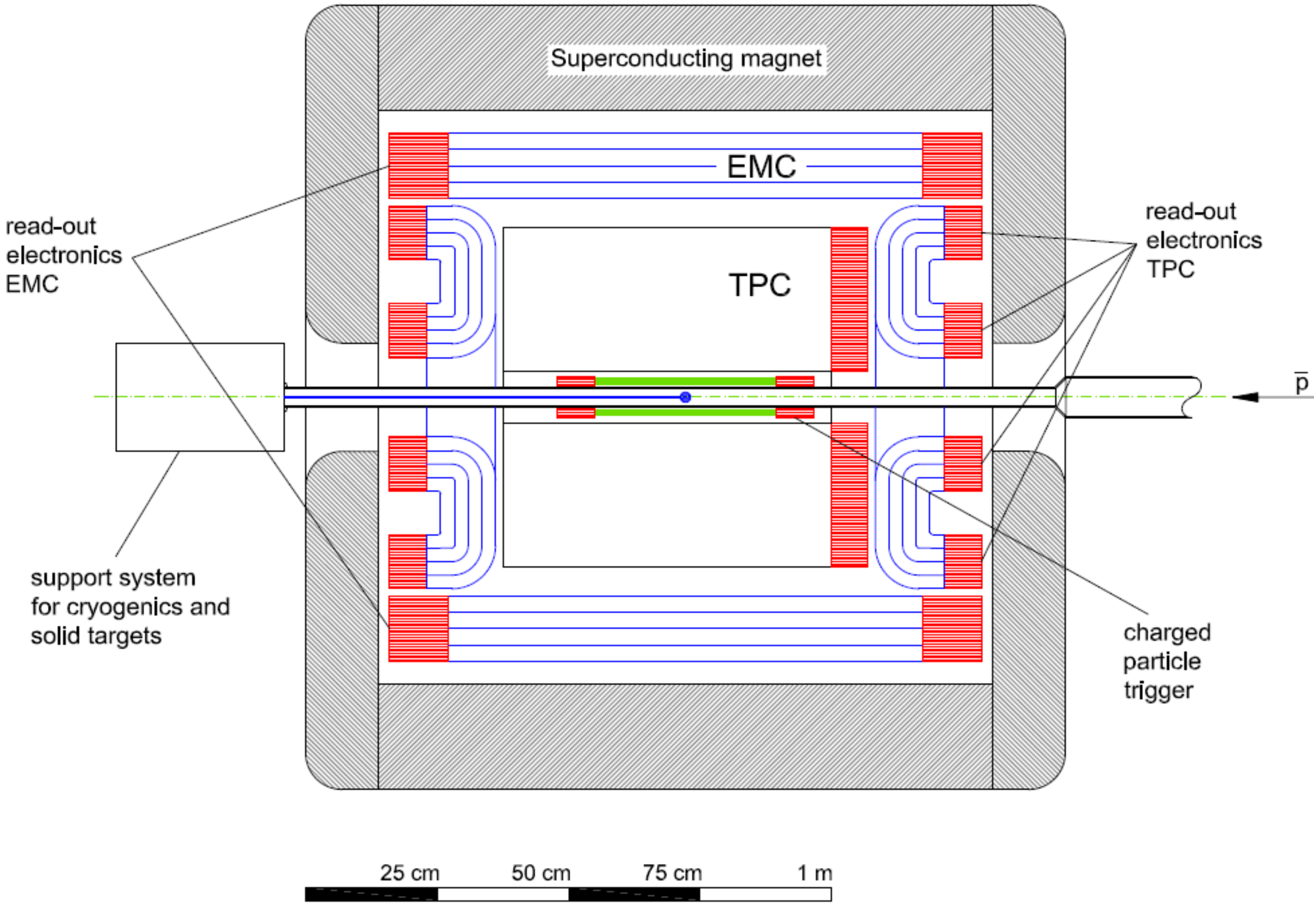
B.E. = −(121±15) MeV

Γ < 60 MeV $0.4 \cdot 10^{-4}$

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 antiprotons

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



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

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

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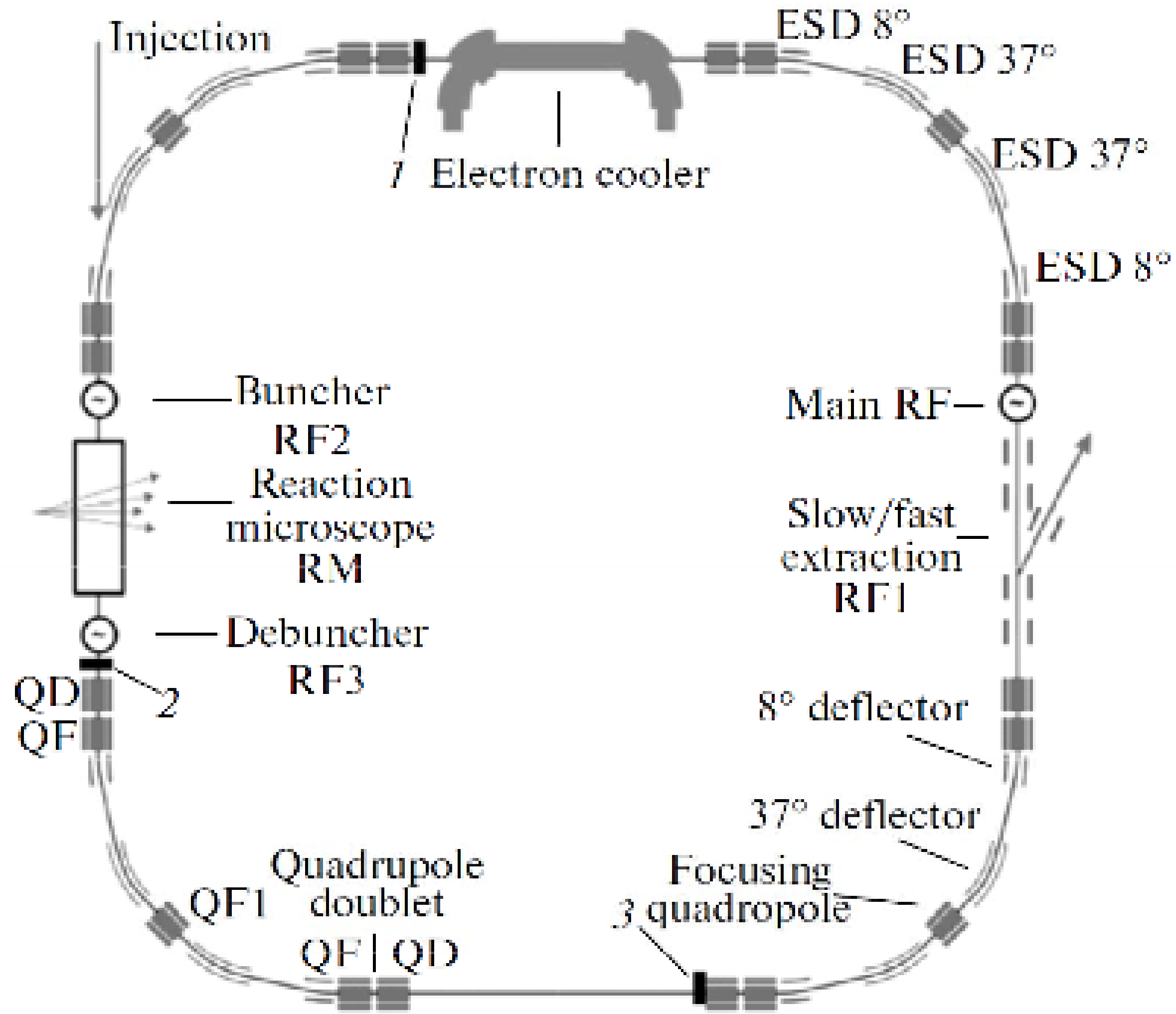
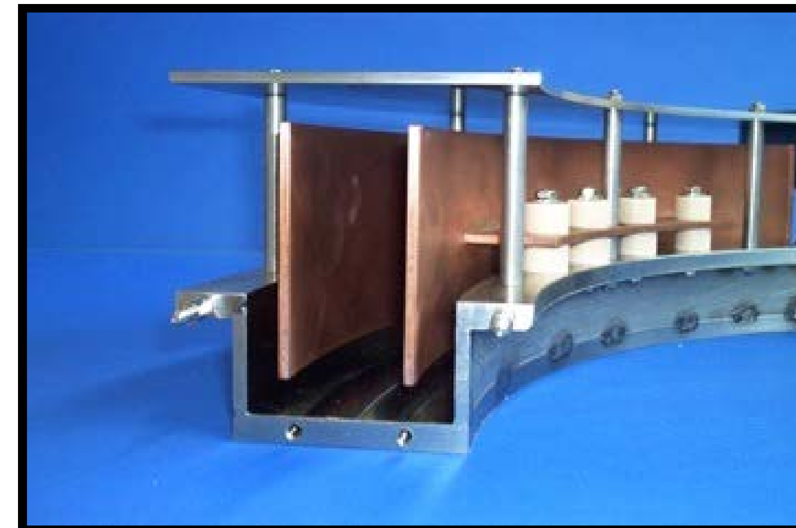
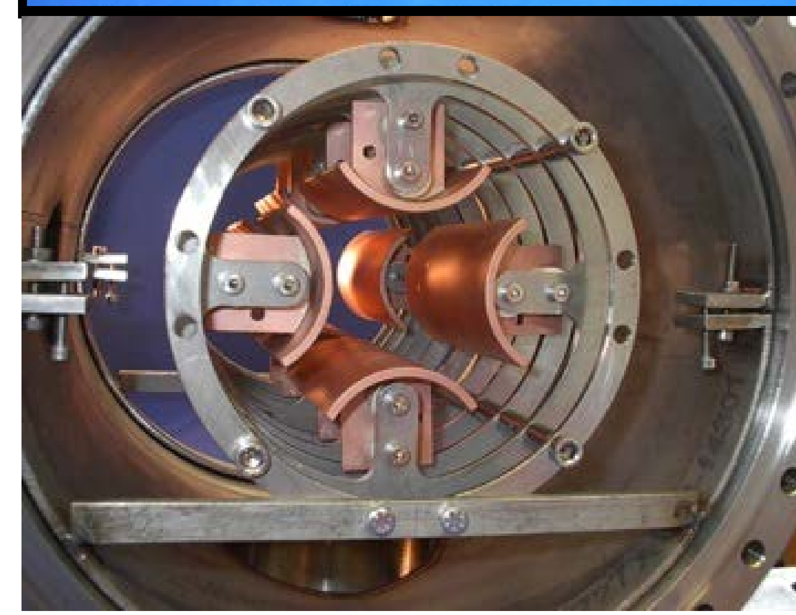
New developments

USR: electrostatic storage ring



Part Phys. Nucl. Letters 8 (2011)





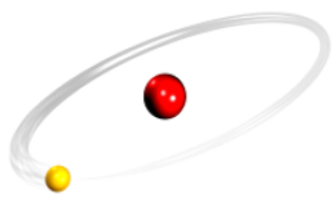
E_{min} / E_{max}	*20 / 300 keV*
Voltages	*< ± 20 kV*
number of pbars at 20 keV	*$1 \cdot 10^7$*

TDR exists

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

Cooled Heavy Ions at GSI/FAIR

hydrogen

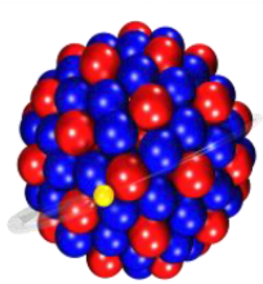


Z=1

E_b = 13.6 eV

$Z \cdot \alpha \ll 1$

uranium ion



Z=92

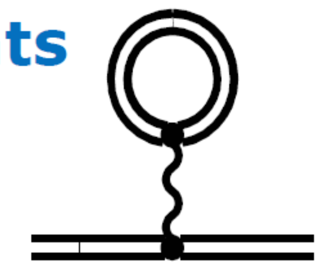
E_b = 132 keV

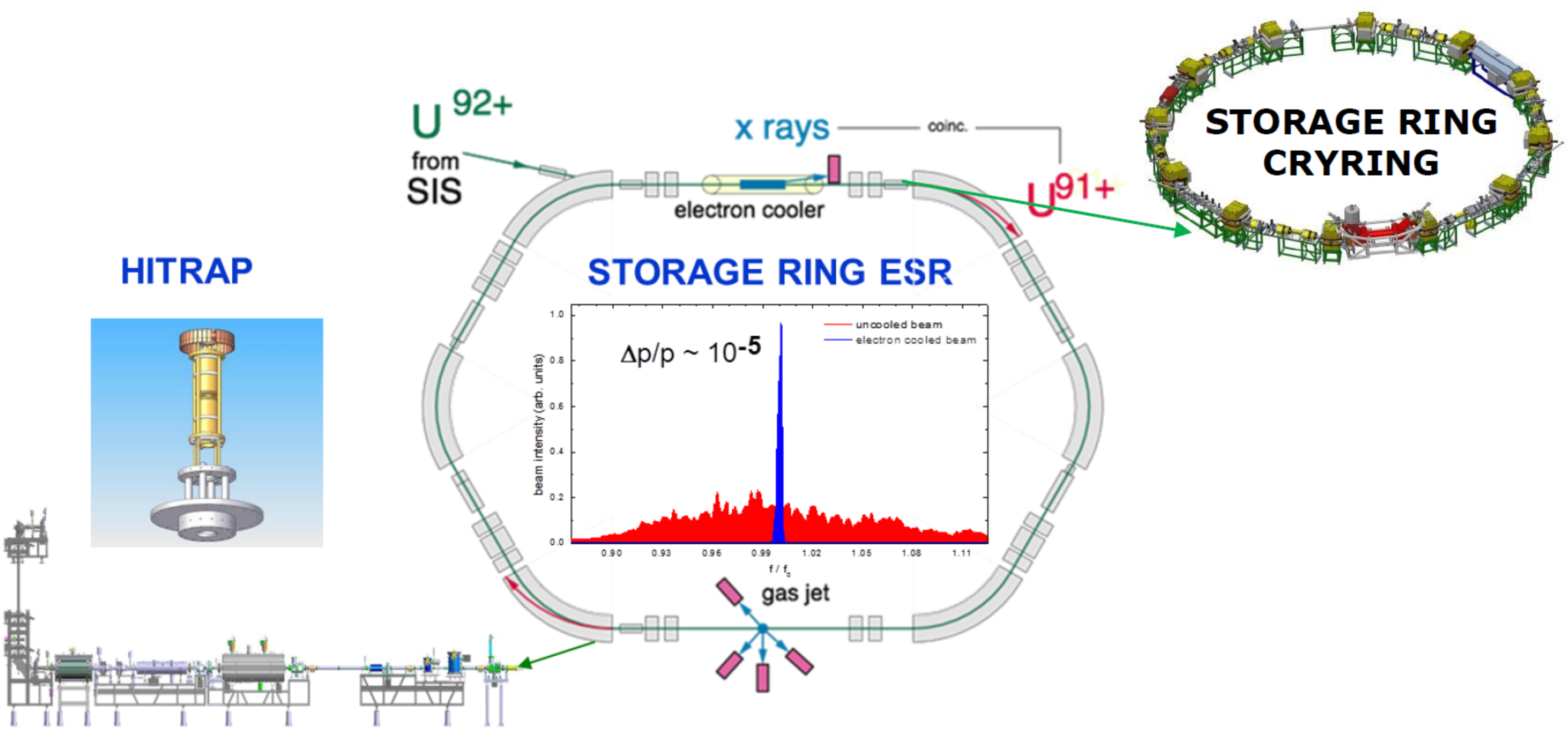
$Z \cdot \alpha \approx 1$

Strong Field QED/ Fundamental Constants

Atomic Collisions in Extreme Fields

Border to Nuclear Physics



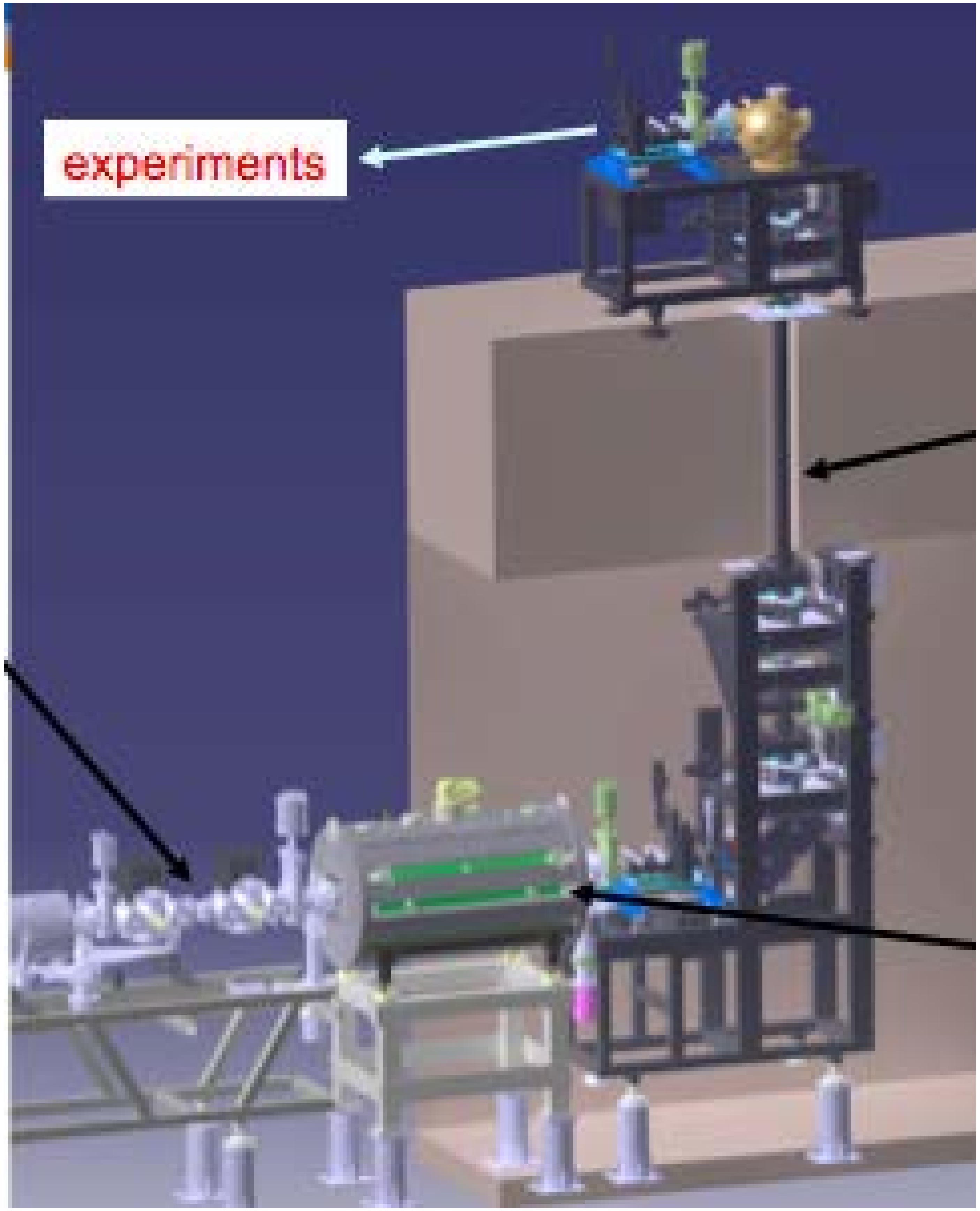


ions at rest in the laboratory

CRYRING: Swedish in-kind contribution to FAIR

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**



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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

Ready for beam@GSI

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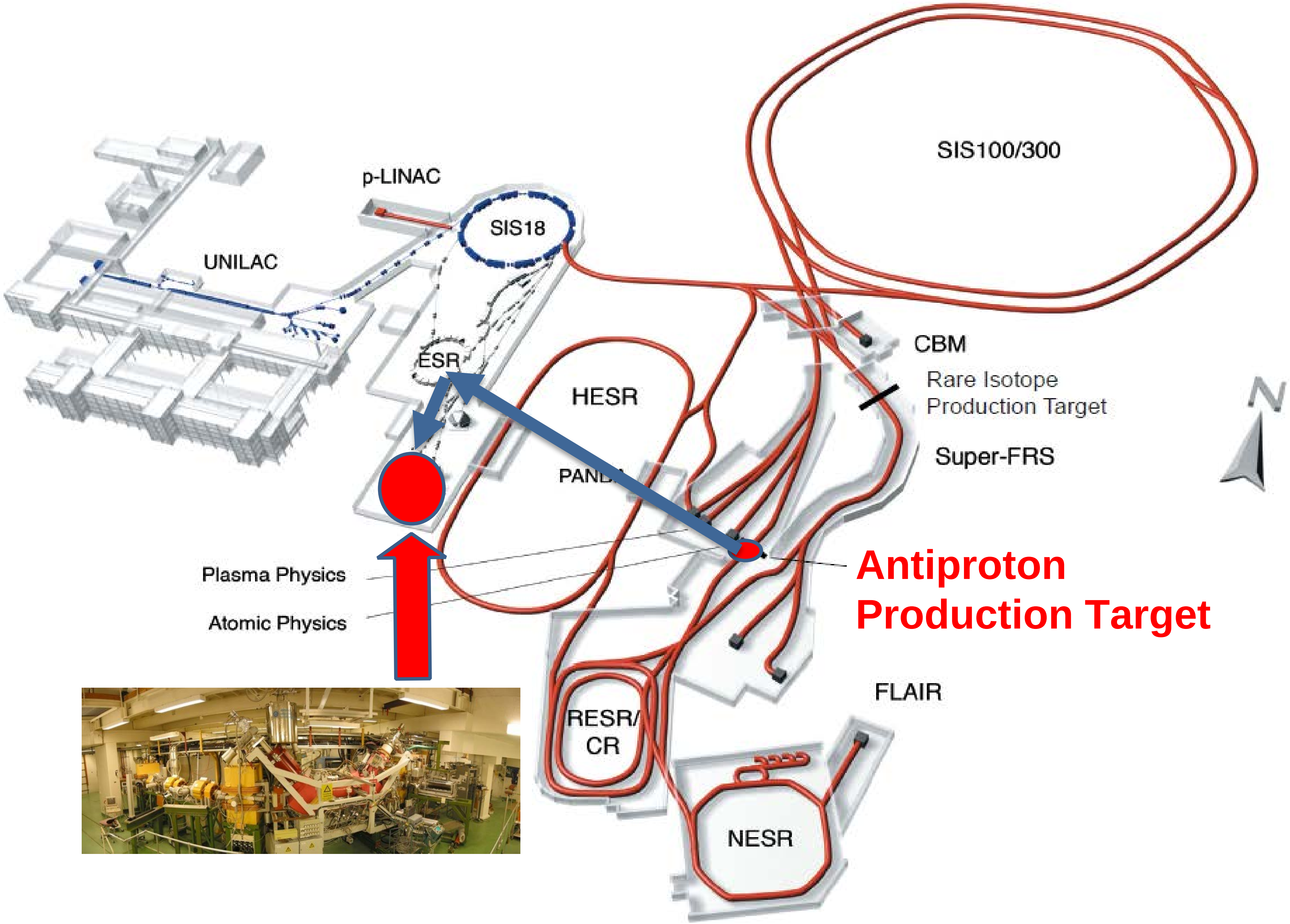
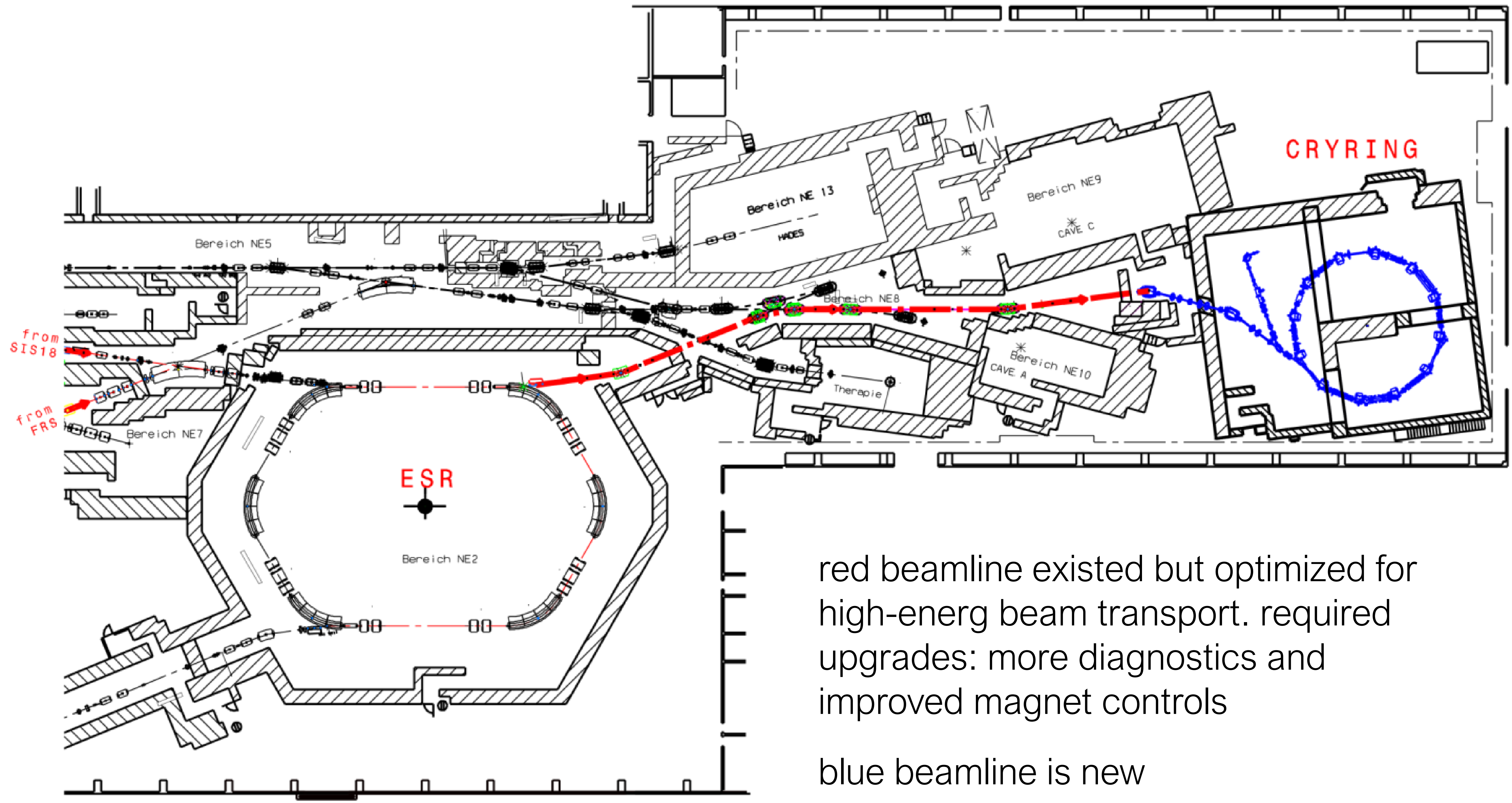
CRYRING@ESR – a Swedisch in-kind contribution



GSI/FAIR beamline topology with CRYRING@ESR

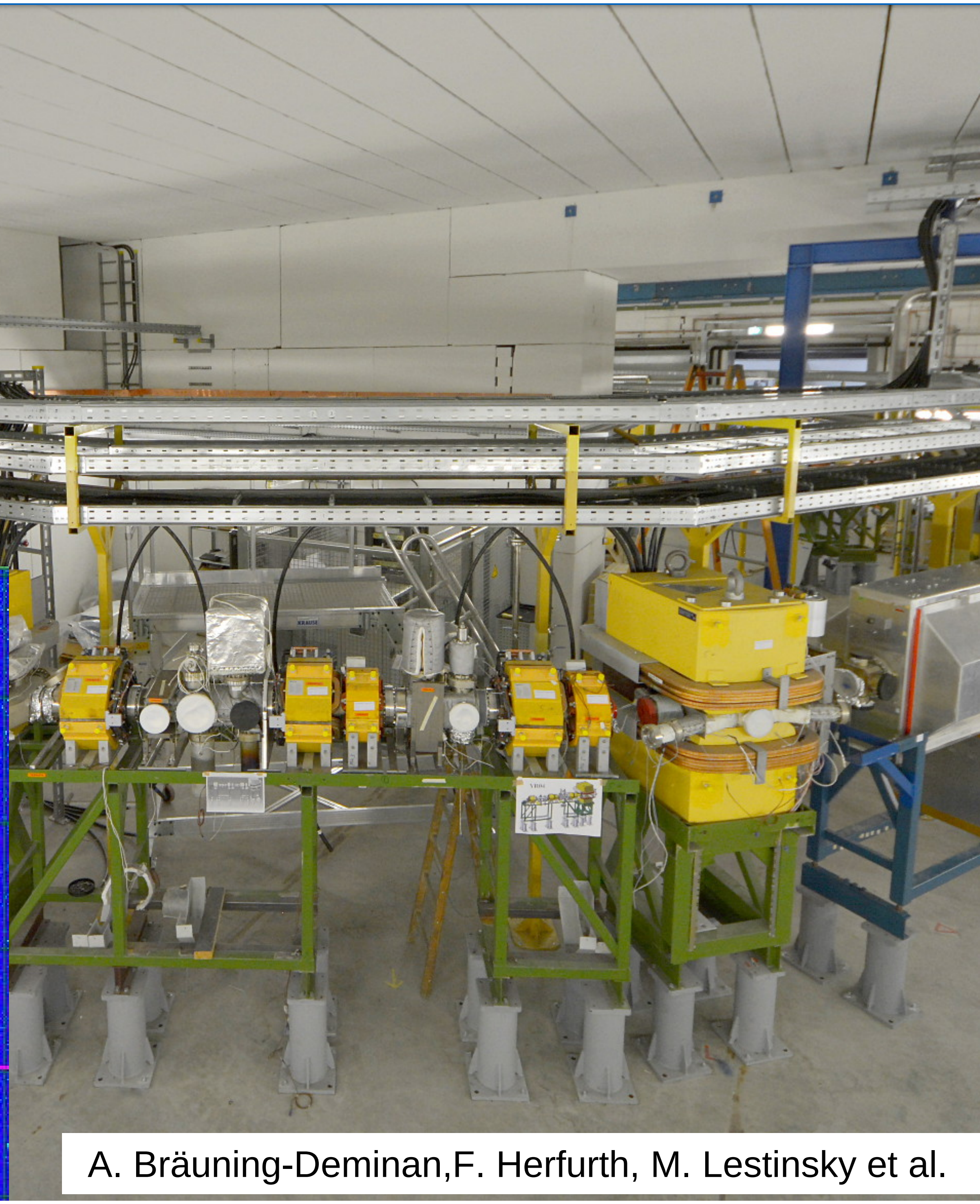


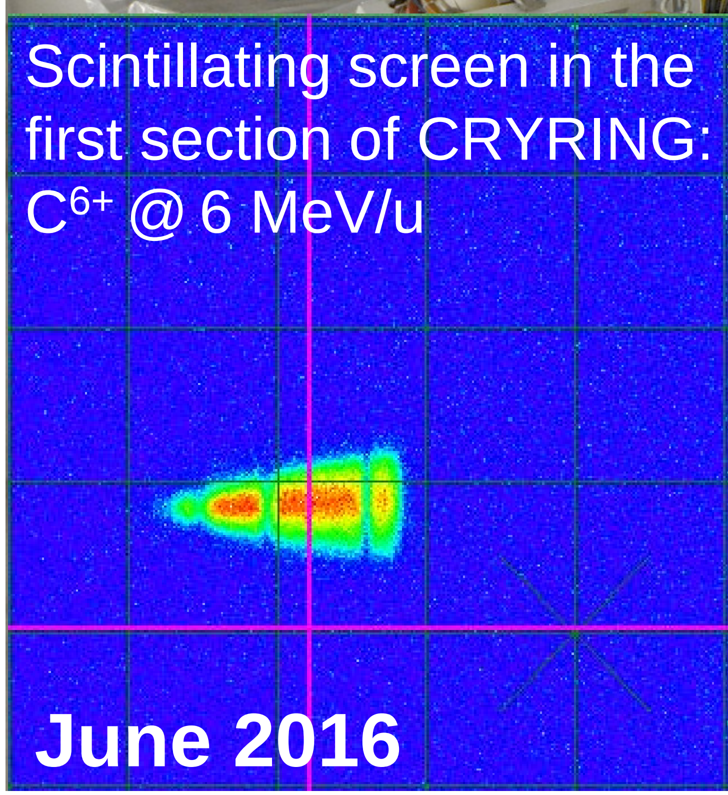
red beamline existed but optimized for high-energ beam transport. required upgrades: more diagnostics and improved magnet controls

blue beamline is new

ESR fast extraction towards CRYRING

CRYRING: First transfer of ions from ESR to CYRING





A. Bräuning-Deminan,F. Herfurth, M. Lestinsky et al.

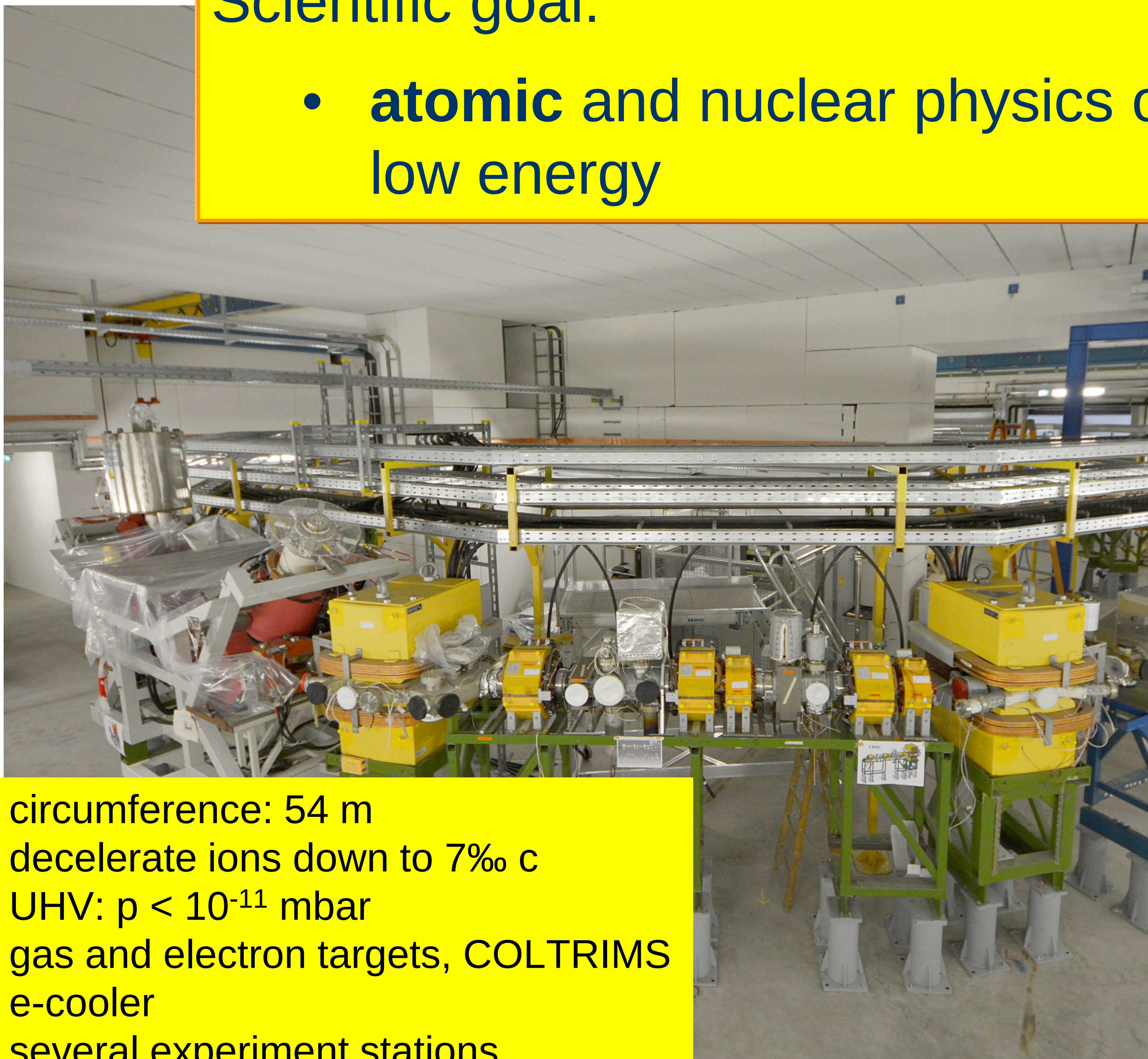
CRYRING team supported by:
FAIR
GSI
HI-Jena
KVI Groningen
Univ Cracow
Univ. Stockholm

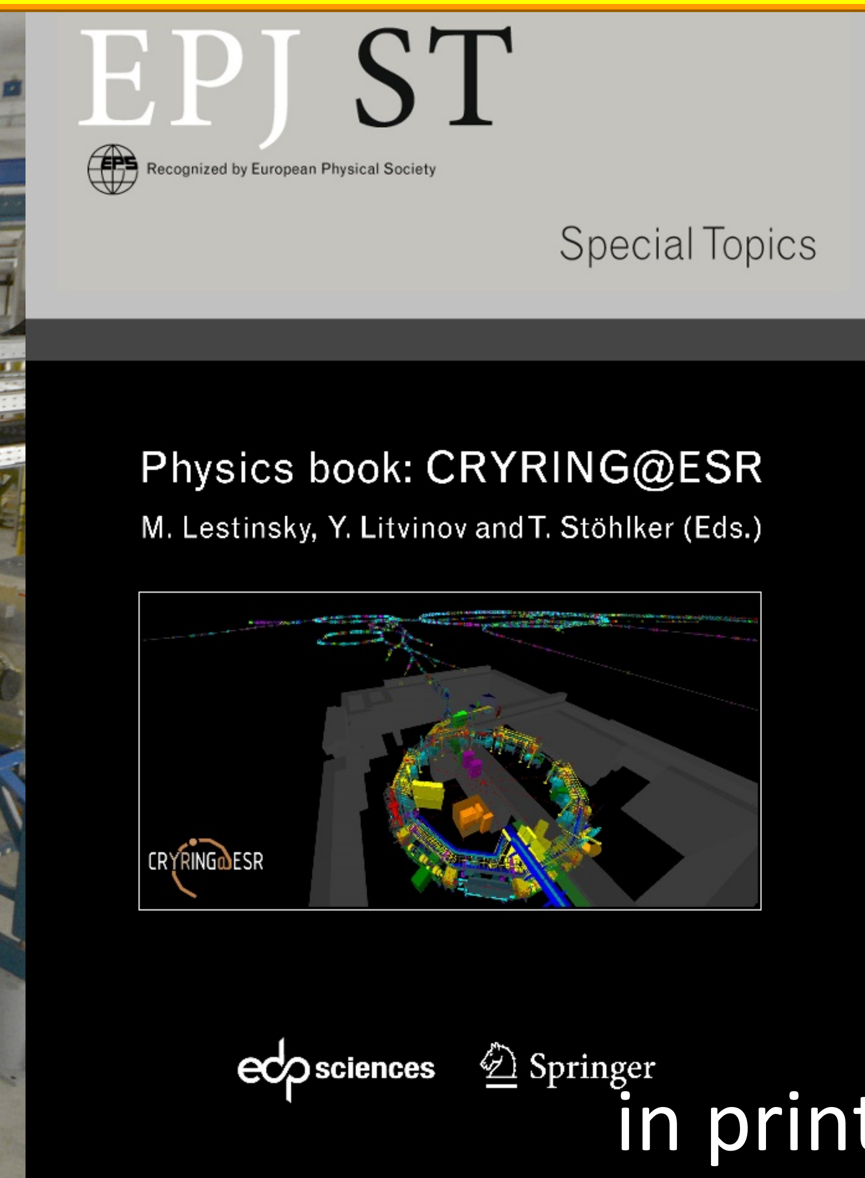
From Th. Stöhlker

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

CRYRING@ESR: Highly-Charged Ions at Low Energies

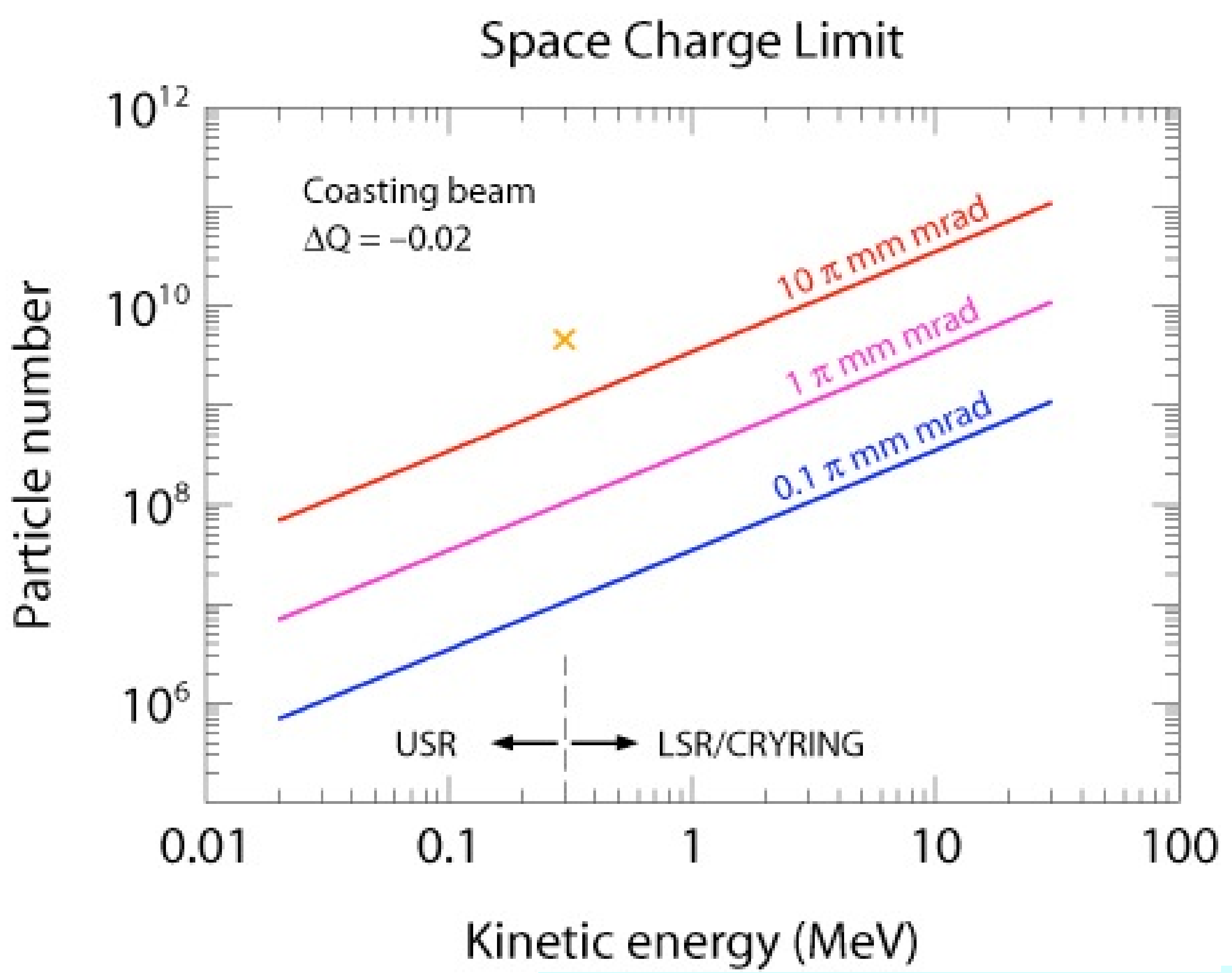
- **Spectroscopy for tests of QED**
  - High-precision x-ray spectroscopy
    - 1s-Lamb-Shift
    - Two-Electron-QED
  - Recoil ion momentum spectroscopy
    - Highly-excited stated
  - Laser spectroscopy
  - Recombination spectroscopy with high resolution
- **Atomic collisions**
  - Sub-femtosecond correlated dynamics
  - Unexplored regime: strong perturbation Q/v
- **Nuclear Physics at low-energies**
  - exotic nuclear decay modes
  - astrophysical reactions

Features@Cryring

- Low-energy and electron cooled beams
- Electron cooling with adiabatic expansion
- High-luminosity for in-ring experiments
- Very fast deceleration 7 T/s
- Internal jet and electron target
- Slow extraction

FLAIR: Expected Antiproton Rates

- 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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ELENA @ CERN

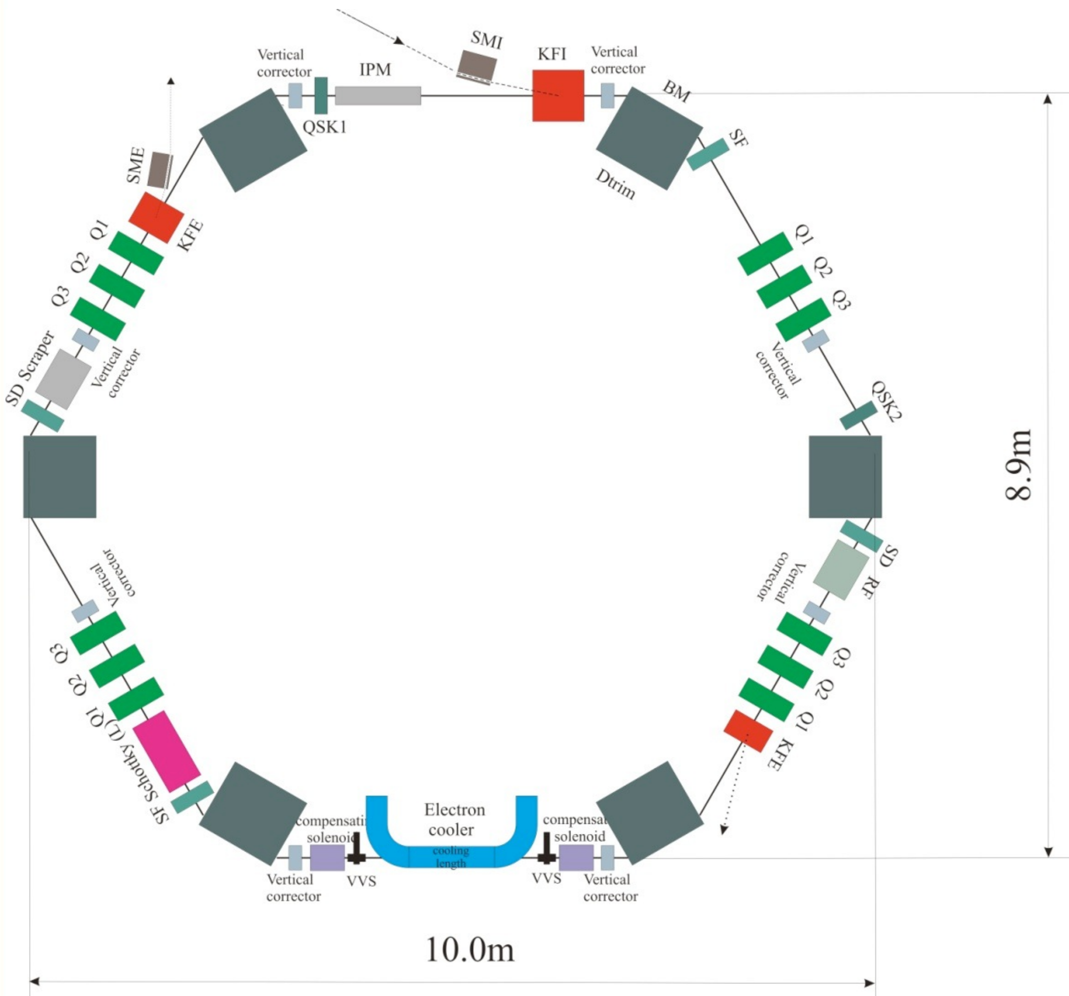


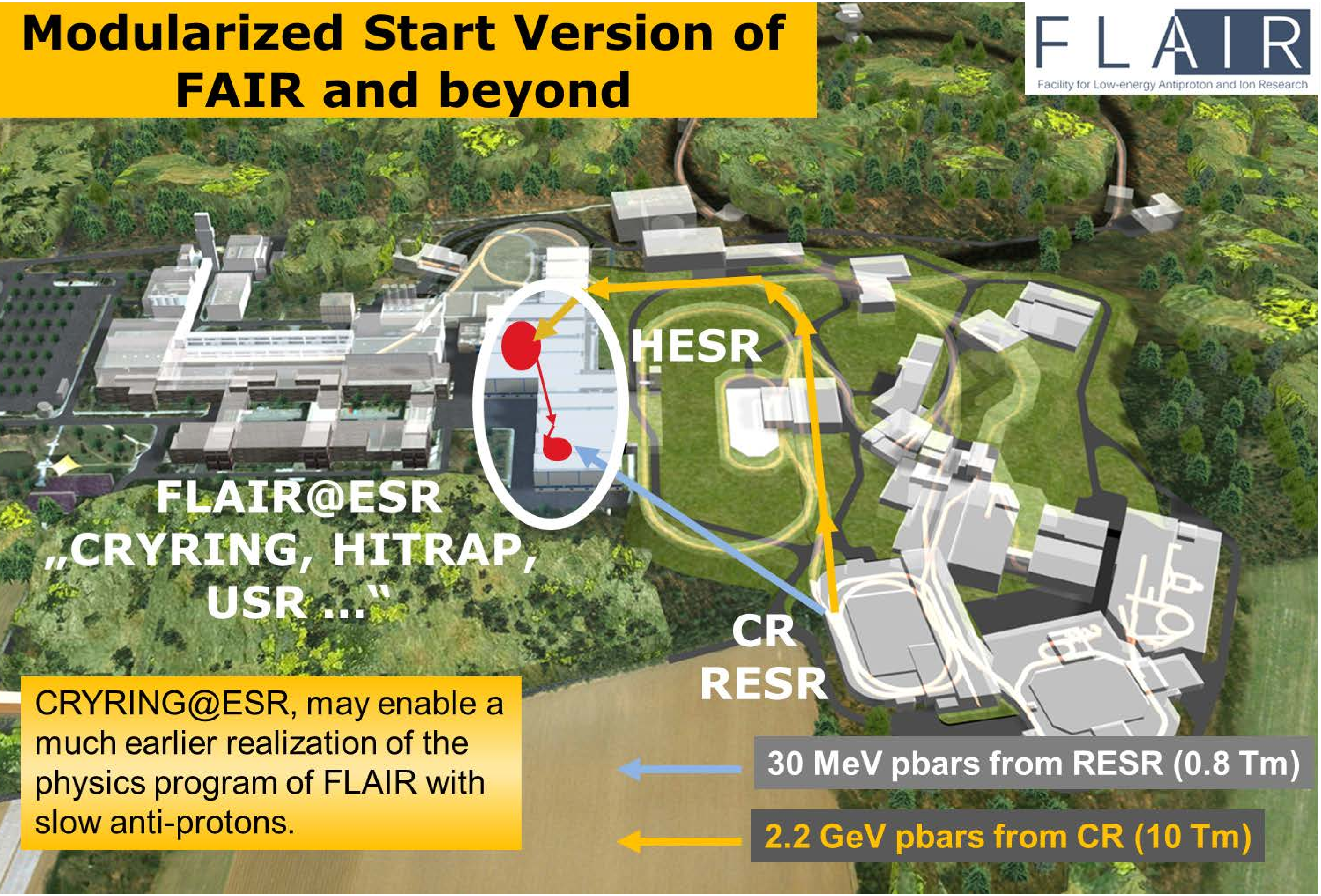
Table 1. ELENA machine and beam parameters.	
momentum range, MeV c^{-1}	100–13.7
kinetic energy range, MeV	5.3–0.1
machine tunes h/v[a]	2.46/1.46
circumference, m	30.4
repetition rate, s[b]	≈100
injected beam intensity	3×10^7
ejected beam population (total of all bunches)	1.8×10^7
number of extracted bunches	4[c]
$\Delta p/p$ of extracted bunches, (95%)[d]	2.5×10^{-3}
bunch length at extraction, (95%), m/ns[d]	1.3/300
emittance (h/v) at extraction, π µm, (95%)[d]	6/4
nominal (dynamic) vacuum pressure, Torr	3×10^{-12}

[a]With sufficient tuning range, e.g. to avoid resonances.
[b]Limited by the AD repetition rate; the expected ELENA cycle length is ≈25 s.
[c] Less extracted bunches is an option leading to slightly larger emittances and momentum sp
[d]Present best guesses based on simulations.

Cite this article: Bartmann W, Belochitskii P, Breuker H, Butin F, Carli C, Eriksson T, Oelert W, Ostojic R, Pasinelli S, Tranquille G on behalf of the ELENA and AD teams. 2018 The ELENA facility. *Phil. Trans. R. Soc. A* **376**: 20170266. http://dx.doi.org/10.1098/rsta.2017.0266

Fast extraction only

Approved in 2011, start 2021



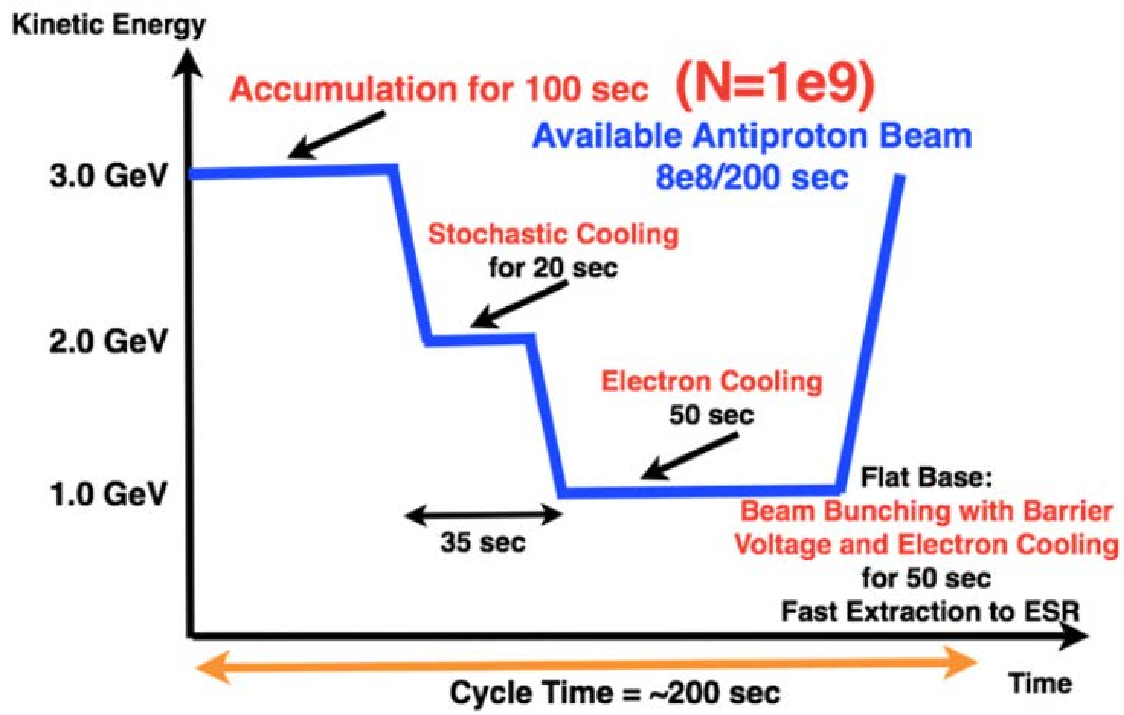
From Th. Stöhlker

Scenarios: p̄ rates in MSV from HESR

Austrian Academy of Sciences

Stefan Meyer Institute

- Leftover from PANDA
  - few 10^9 per 60 min
  - decelerate & transfer to ESR
    - T. Katayama: 100s, 80% eff.
  - average $5x10^5$/s
  - $5x10^7$/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: $8x10^8$ p̄ /100 s: *10xELENA*
    - max. 10^{10} p̄ (stacking for 1000 s): similar average rate

ÖAW Austrian Academy of Sciences

Stefan Meyer Institute

Latest FAIR news 2019

- Very positive scientific report
- Cost increase 850 M€
  - Due to booming construction industry

Report

of the

FAIR Progress and Cost Review Board:

Detailed Review of Progress and Financial Status of the FAIR Project

April 2019

29 April 2019

RevBoardReport_20190429_Public 1/17

Stefan Meyer Institute

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 (continuous) beams of slow antiprotons