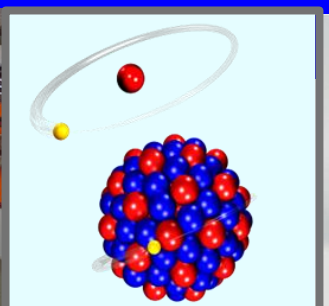
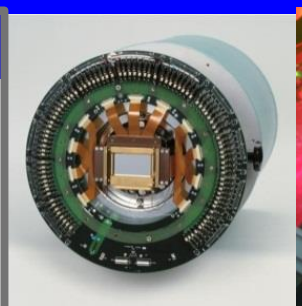
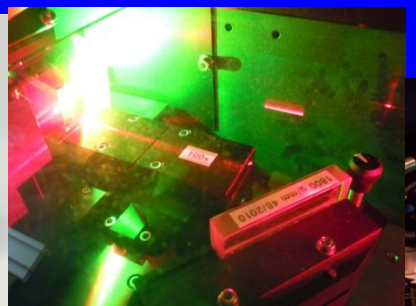
SPARC at FAIR: Prospects for Atomic Spectroscopy

Wilfried Nörtershäuser

Institut für Kernphysik
Technische Universität Darmstadt

FAIR Conference, 2014, Worms


The SPARC collaboration

AUSTRIA
Vienna University of Technolgy
CANADA
University of Manitoba
York University
CHINA
China Institute of Atomic Energy, Beijing
Institute of Applied Physics and Computational Mathematics, Beijing
Institute of Modern Physics, Fudan University, Shanghai
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou
Institute of Atomic and Molecular Physics, Jilin University, Jilin
Lanzhou University, Lanzhou
University of Science and Technology of China, Hefei
Wuhan Institute of Physics and Mathematics
Physics Department, Tsinghua University
Department of Physics and Astronomy, University of Aarhus
DENMARK
Department of Physics and Astronomy, University of Aarhus
EGYPT
Physics Department, Beni-Suef Faculty of Science
FRANCE
CIRIL Ganil
Ecole Normale Superieure – Lyon
Institut de Physique Nucléaire de Lyon

>300 participants from over 20 countries

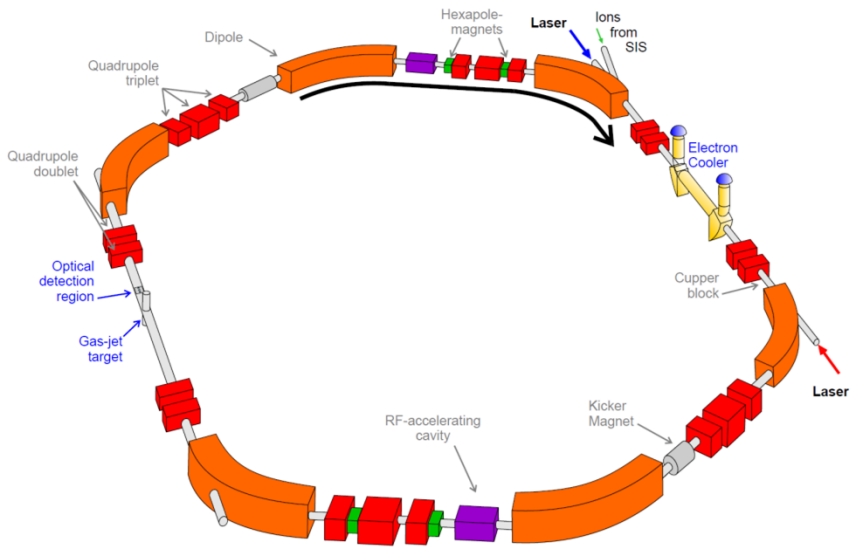
Vaish College, Rohtak
Nuclear Science Centre, New Delhi
Bhabha Atomic Research Centre
ITALY
Inst. Naz. Fisica Nucleare, Dip. di Fisica, Catania
JAPAN
University of Tokyo & Atomic Physics Laboratory RIKEN, Wako
JORDAN
Hashemite University
POLAND
Institute of Physics, Swietokrzyska Academy
Institute of Physics, Jagiellonian University
Institute of Theoretical Physics, Warsaw University
Institute of Nuclear Physics of Polish Academy of Sciences
The Soltan Institute For Nuclear Studies
ROMANIA
NIPNE National Institute for Physics and Nuclear Engineering
RUSSIA
Lebedev Physical Institute, Moscow
Institute of Physics, St. Petersburg State University
Institute of Metrology for Time and Space at VNIIFTRI
Institute of Spectroscopy of the RAS
V.G.Khlopin Radium Institute, St.Petersburg
SERBIA AND MONTENEGRO
Institute of Physics, Belgrade

Much more than I can show !!
Personally biased selection of a few examples !

Max-Planck-Institut für Kernphysik, Heidelberg
Institut für Theoretische Physik, TU Dresden
Tübingen University
IKF, J.W.v.Goethe Universität Frankfurt am Main
Institut für Physik, Universität Mainz
Institut für Physik, Universität Kassel
Institut für Theoretische Physik, TU Clausthal
Kirchhoff-Institut für Physik, Universität Heidelberg
TU Darmstadt
Physikalisch-technische Bundesanstalt
Mathematics Institute, University of Munich, 80333 Munich
HUNGARY
Inst. of Nuclear Research (ATOMKI), Debrecen
INDIA
Tata Institute of Fundamental Research

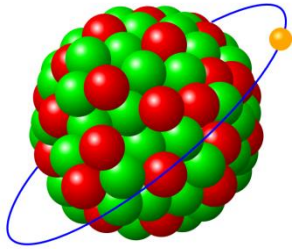
Institut für Physik, Universität Basel
UNITED KINGDOM
Department of Physics, The University of Durham
Queen's University, Belfast
UNITED STATES
Lawrence Berkeley National Laboratory
Georgia State University
University of Missouri Rolla
Oak Ridge National Laboratory
Western Michigan University
Harvard-Smithsonian Center for Astrophysics
Brown University, Physics Department
Univeristy of Texas at Austin
Kansas State University
Columbia Astrophysics Laboratory, Columbia University

Uniqueness of FAIR for Atomic Physics



STORAGE RINGS

+



HEAVY HIGHLY
CHARGED IONS

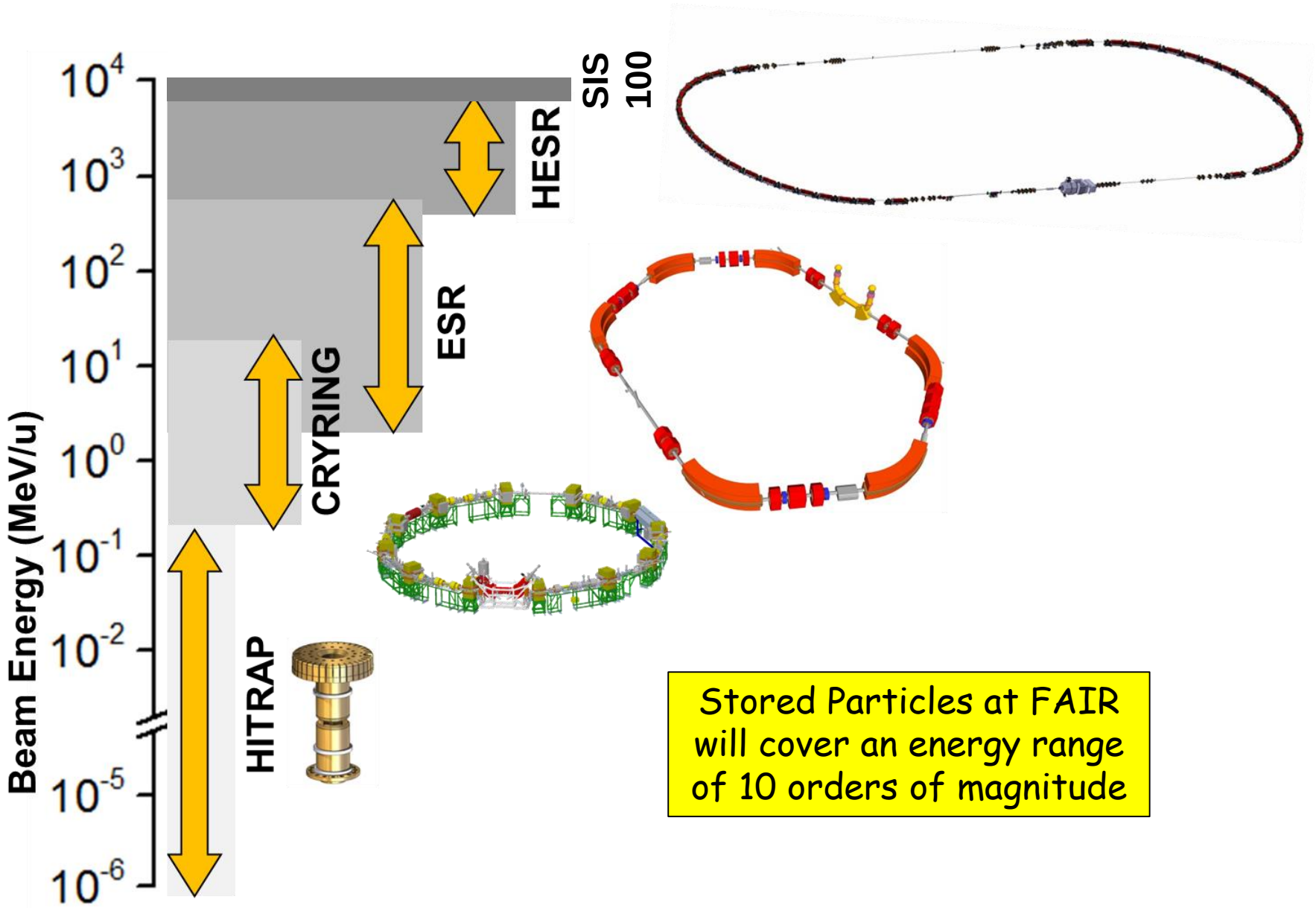
Investigation by „Collisions" with

Atoms
Ions
Electrons
Photons

Study **Structure** and
Dynamics of and with
Highly Charged Ions

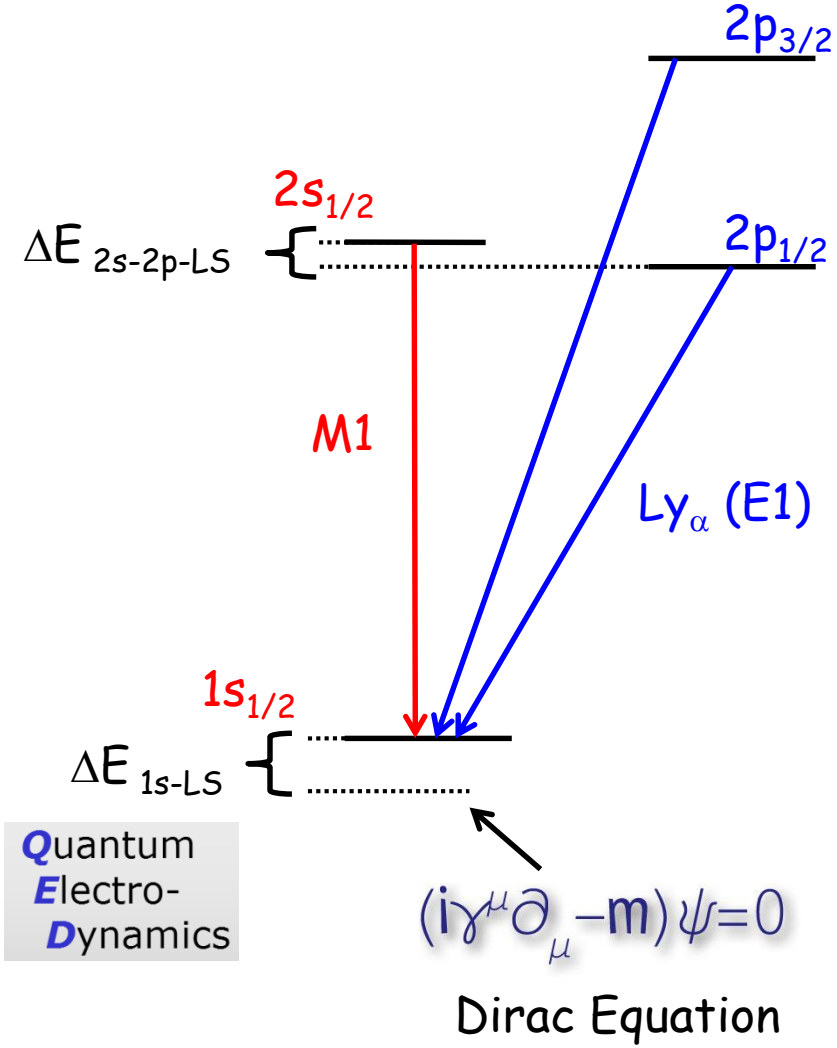
Ion Storage at FAIR (MSV)

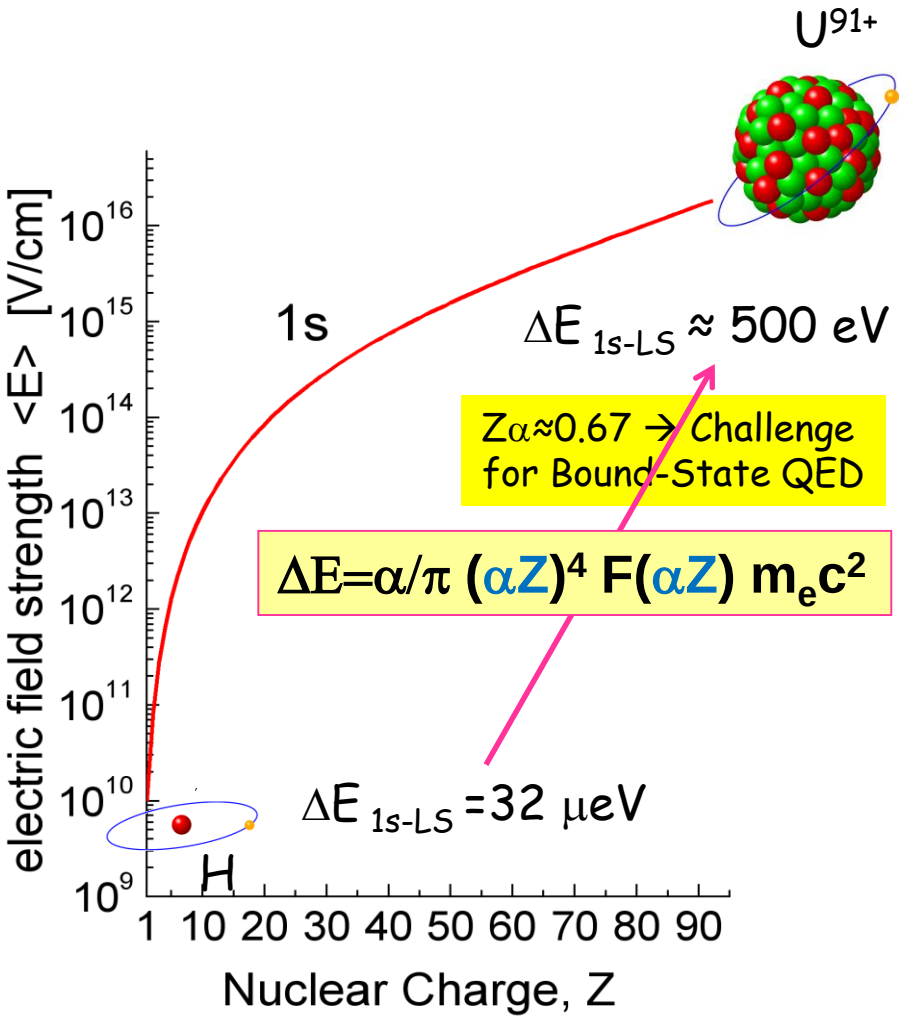
Energy Spectrum



Stored Particles at FAIR will cover an energy range of 10 orders of magnitude

Structure of Heavy H-Like Ions

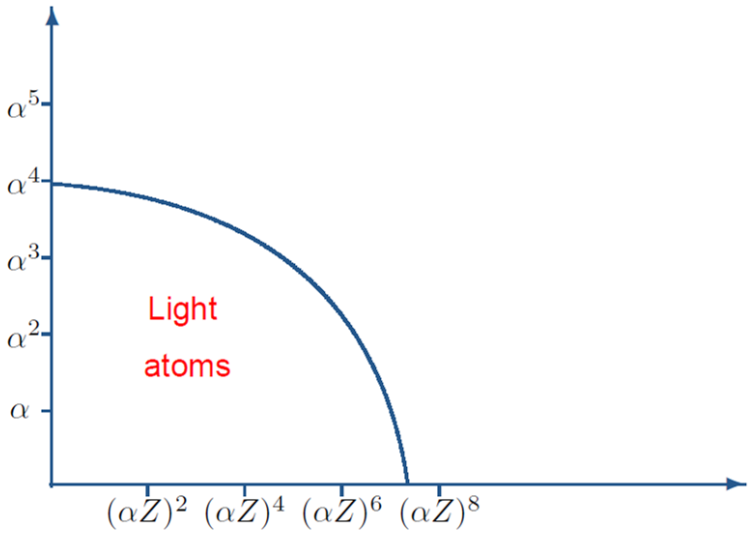




Strong-Field Bound-State QED

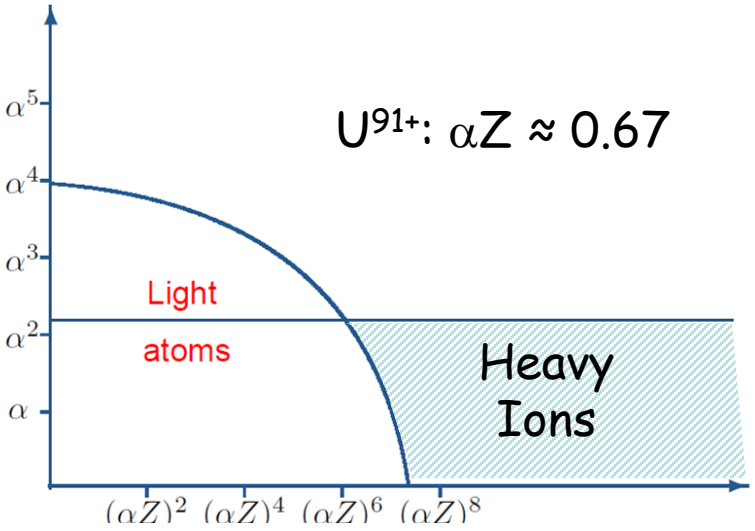
light ions
(singly charged, free electrons …)

Tests of QED to lowest orders in $\alpha \approx \frac{1}{137}$ and in $\alpha Z \ll 1$
(Z is the nuclear charge number)



heavy ions
(highly charged)

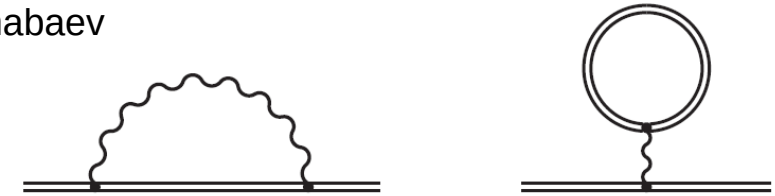
Tests of QED to lowest orders in α and to all orders in αZ



U^{91+}: $\alpha Z \approx 0.67$

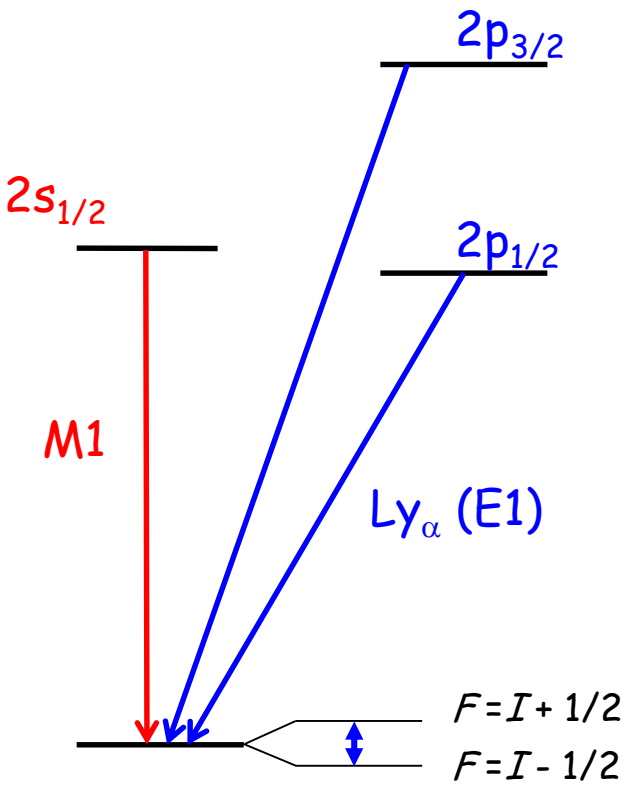
Courtesy of V. Shabaev

Bound state QED:
g-factor (Penning Traps)
Helium fine structure
→ Tests on < ppb level



$$[-i\boldsymbol{\alpha}\cdot\boldsymbol{\nabla}+\beta+V(\mathbf{r})]\,\psi(\mathbf{r})=E\psi(\mathbf{r})$$

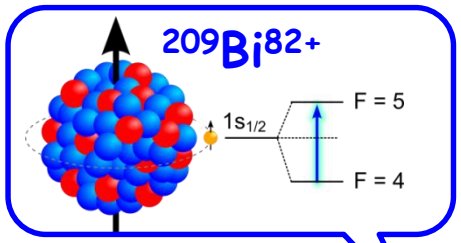
Transitions in H-like Systems



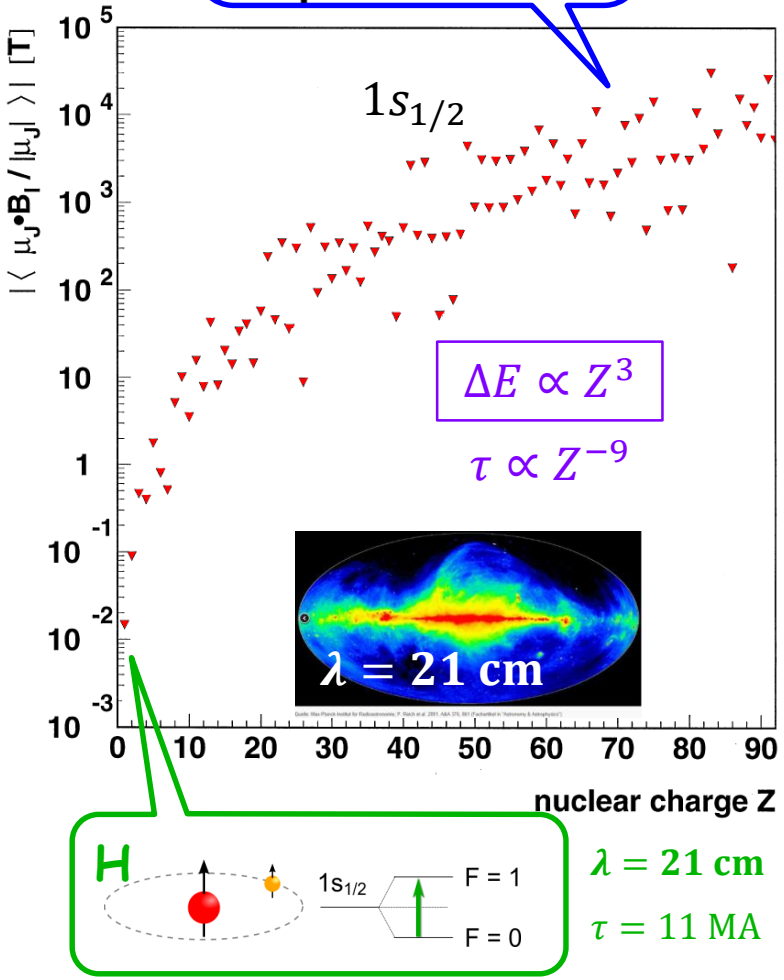
HFS:
Probing magnetic field regime

$\lambda = 243$ nm

$\tau = 400\ \mu s$



Nuclear Surface: B ≈ 10^9 – 10^{10} T

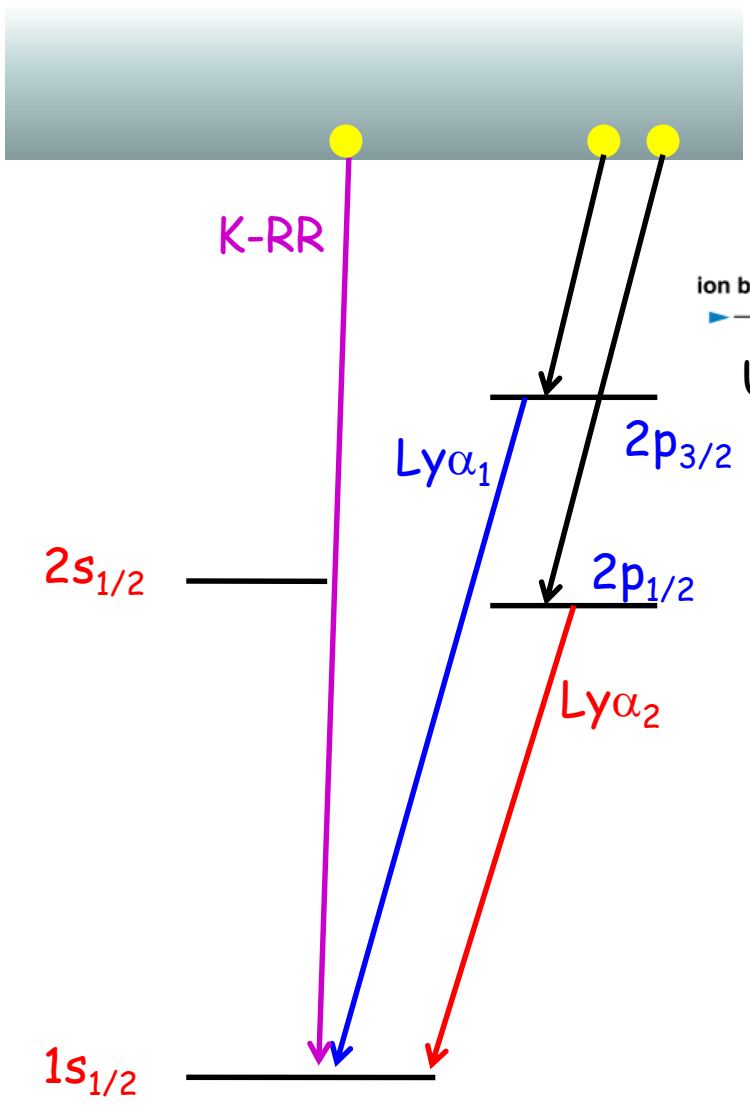


$\lambda = 21$ cm

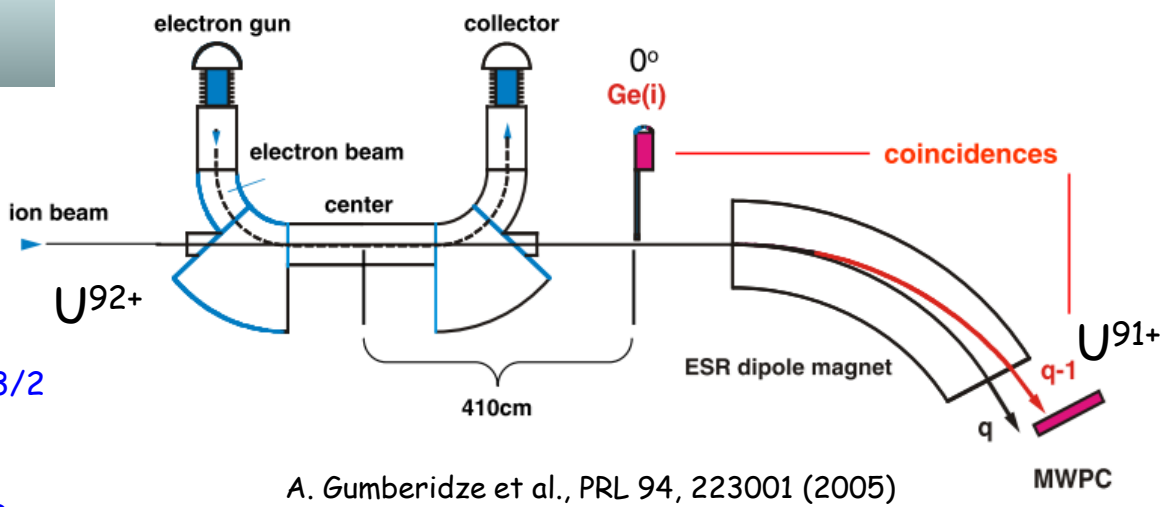
$\tau = 11$ MA

Hyperfine Structure probes extremely strong magnetic fields very close to the nuclear surface.
But there is no conclusive test of QED in the magentic domain yet !

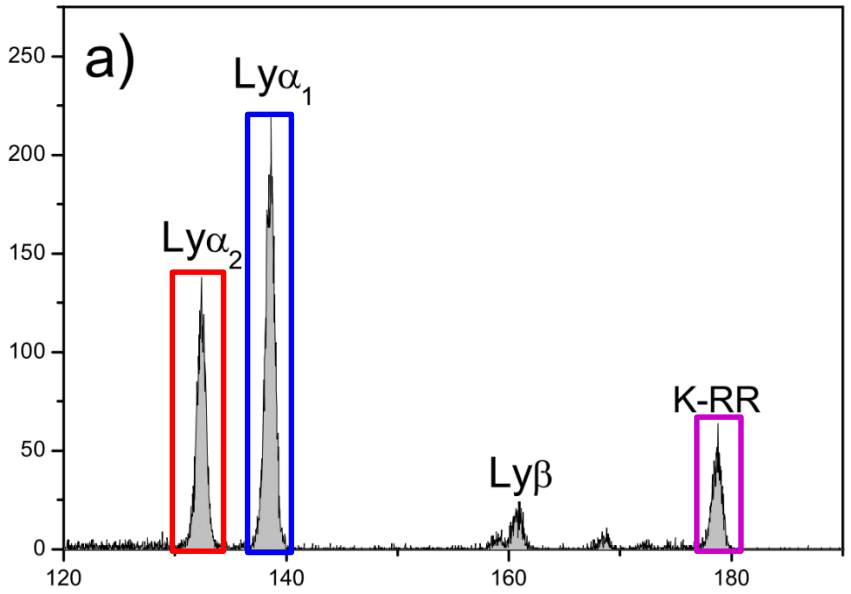
Classical Spectroscopy: X-Ray Emission after Electron Capture



Electron capture



A. Gumberidze et al., PRL 94, 223001 (2005)



Test of QED (1s Lambshift): Status today

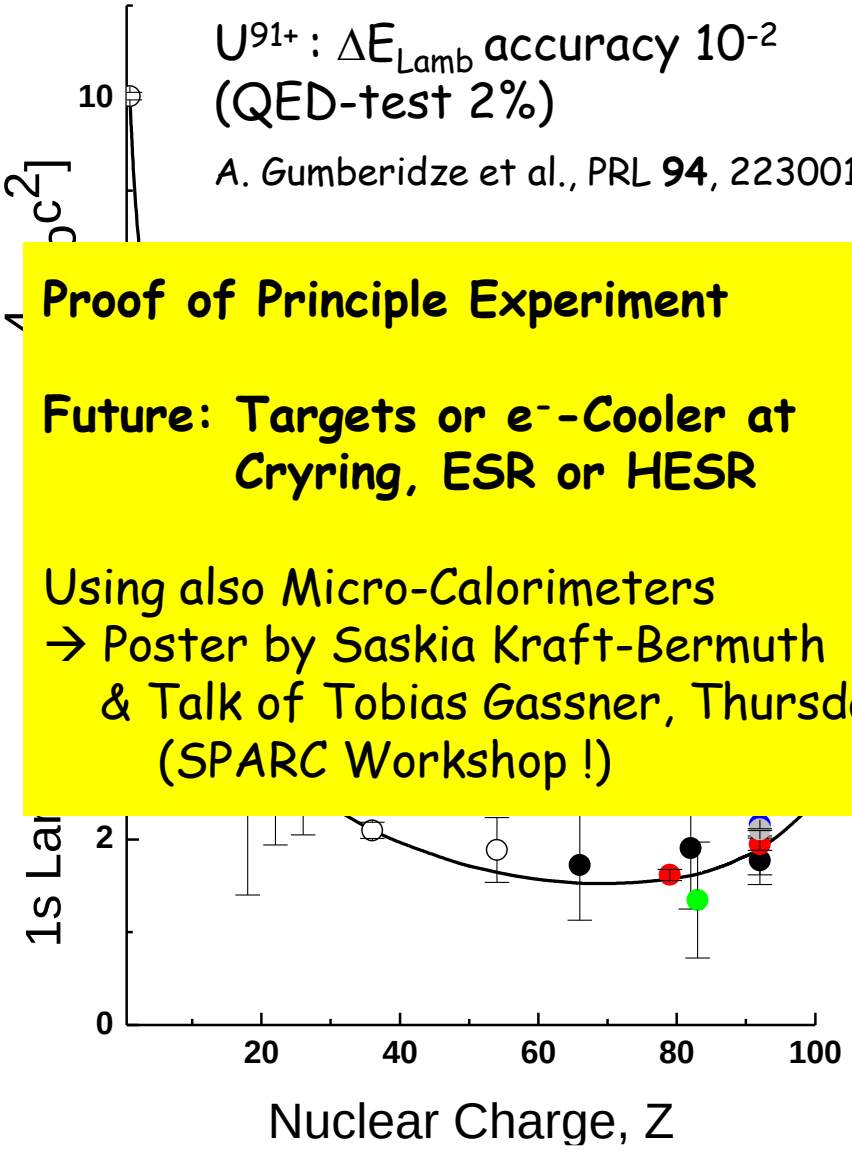
U^{91+} : ΔE_{Lamb} accuracy 10^{-2}
(QED-test 2%)

A. Gumberidze et al., PRL **94**, 223001 (2005)

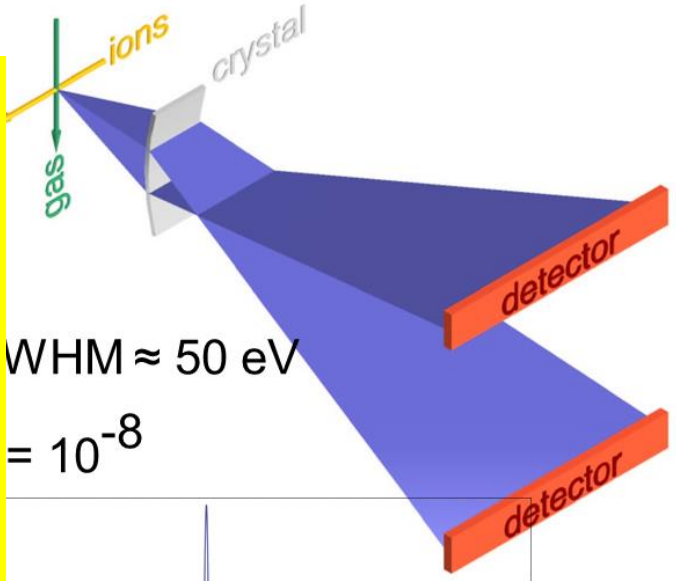
Proof of Principle Experiment

Future: Targets or e^--Cooler at Cryring, ESR or HESR

Using also Micro-Calorimeters
→ Poster by Saskia Kraft-Bermuth
& Talk of Tobias Gassner, Thursday 18:00
(SPARC Workshop !)

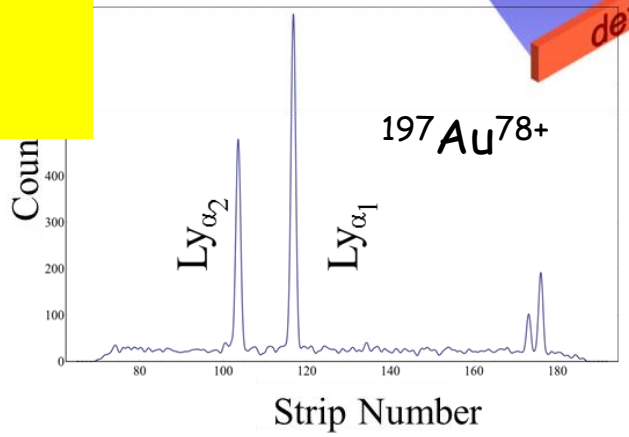


Status 2012 FOCAL
Transmission crystal spectrometer



WHM ≈ 50 eV

= 10^{-8}

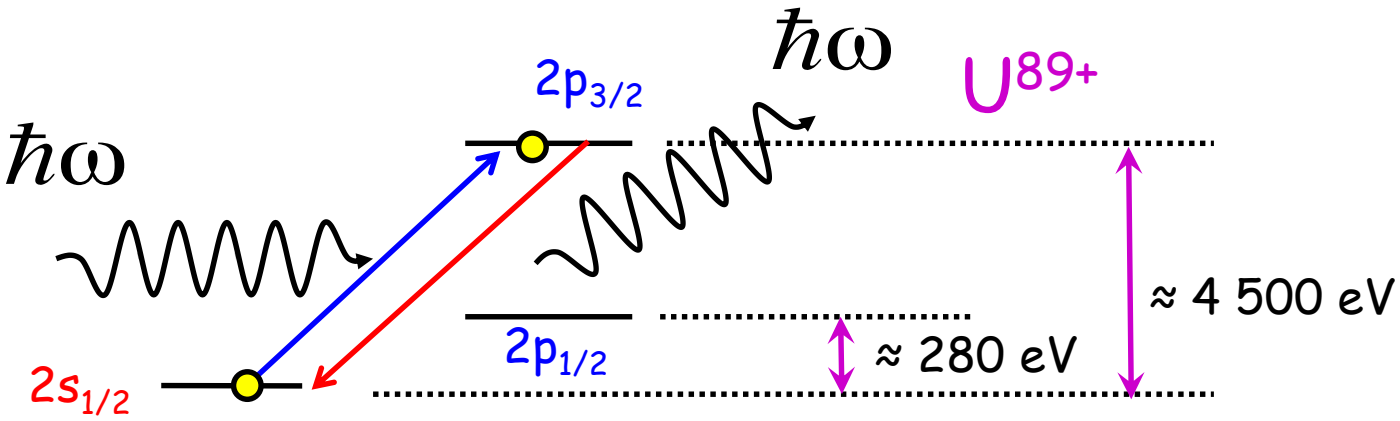


H.F. Beyer et al., to be published

Resonance Fluorescence Spectroscopy

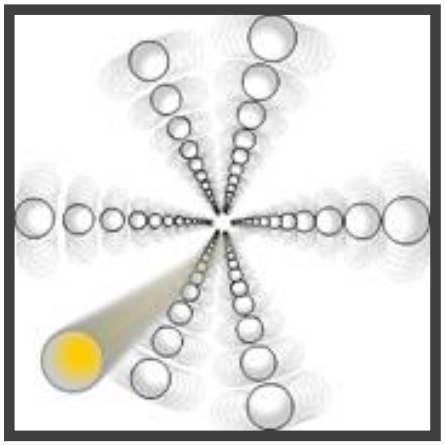
Lithium-Like Ions

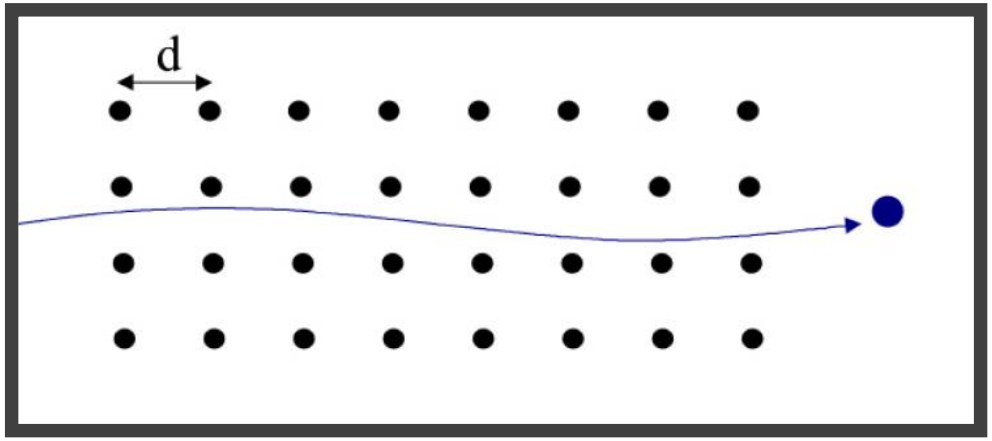
Interest also in electron-electron interaction and correlation dynamics



1s1/2

Resonant Coherent Excitation (RCE)





Frequencies of virtual field oscillations

$$E_{trans} = h\nu = h\gamma\langle g.v\rangle$$

reciprocal lattice vector $\mathbf{g}_{k,l,m} = k\mathbf{A}^* + l\mathbf{B}^* + m\mathbf{C}^*,$

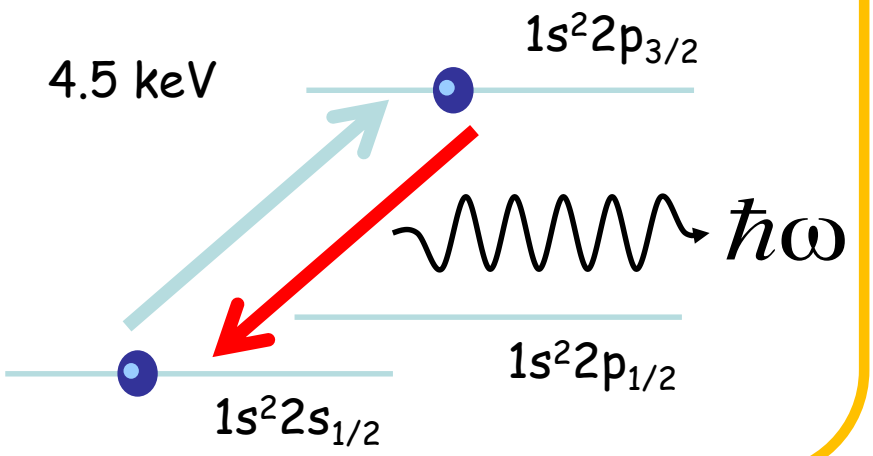
$$\begin{aligned}\nu_{k,l,m}(\theta,\phi) &= \gamma\mathbf{g}_{k,l,m}\cdot\mathbf{v} \\ &= \frac{\gamma v}{\mathrm{d}}\{(\sqrt{2}k\cos\phi + \sqrt{2}m\sin\phi)\cos\theta + l\sin\theta\},\end{aligned}$$

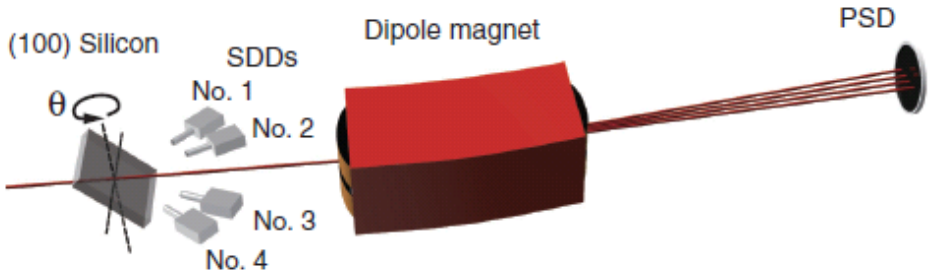
Crystal lattice: d≈10^{-10} m, Velocity v ≈ 3×10^8 m/s, Frequency: $\nu = \gamma\, v / d = 10^{18}$ Hz

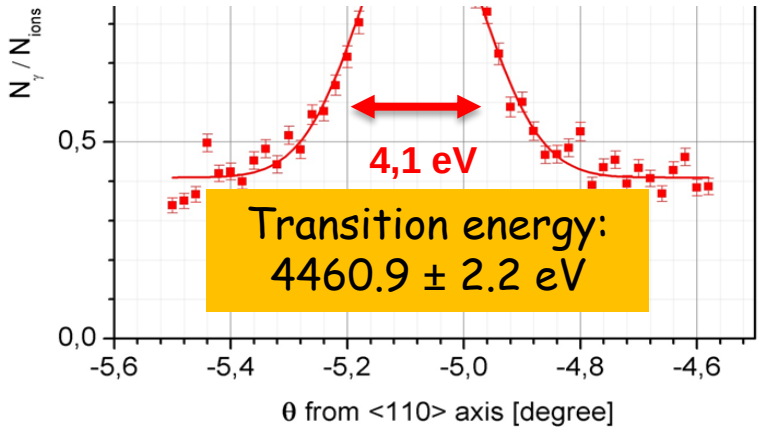
Resonant Coherent Excitation of Relatvistic Highly Charged Ions

$2p_{3/2} \rightarrow 2s_{1/2}$ transition in Li-like uranium
Experiment at SIS with U^{89+} @ 192 MeV/u

Li-like uranium





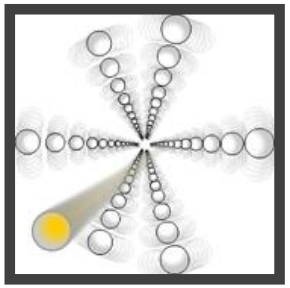


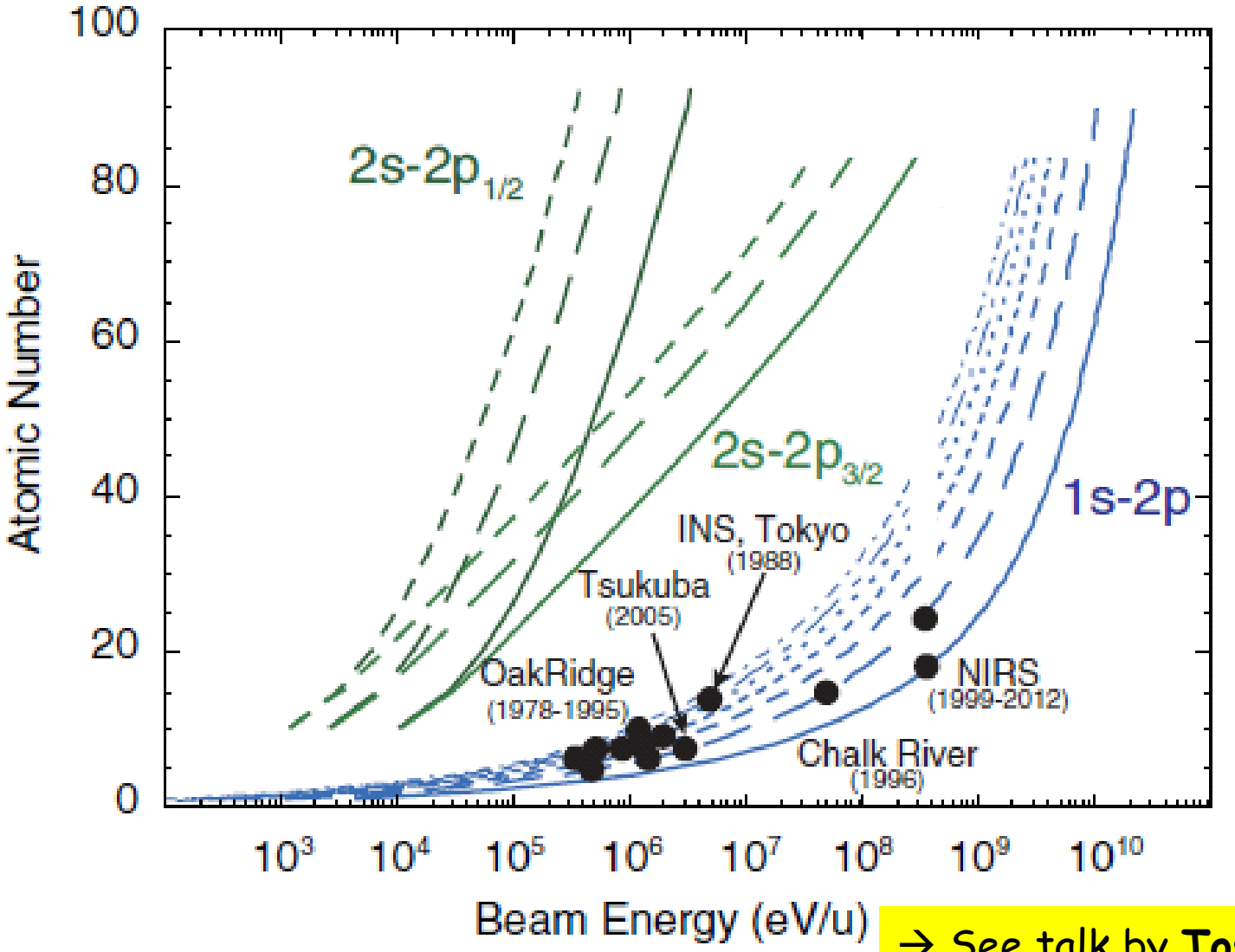
Largest contribution to the width of 4.1 eV: $\Delta p/p \approx 10^{-3}$ of the SIS beam

=> use cooled ion beams from/in ion storage rings $\Delta p/p < 10^{-4}$

Y. Nakano et al., PRA 86, 060501 (R) (2013)

Resonant Coherent Excitation (RCE) at FAIR





→ See talk by **Toshiyuki AZUMA**
Wednesday at **4:30 PM**

Y. Nakano et al., PRA 86, 060501 (R) (2013)

Ion channeling at relativistic energies

APPA-Cave
Receiving SIS-100 beams

Y. Yamazaki et al.

FAIR SIS100: excitation of 1s-2p in U^{91+} possible for the first time

RCE perspectives at FAIR

The ion energy range at SIS100 will permit state-selective RCE of **atomic** and **nuclear** levels

… **but** beams with low emittance/small divergence required !!
Challenge: ion cooling at relativistic energies

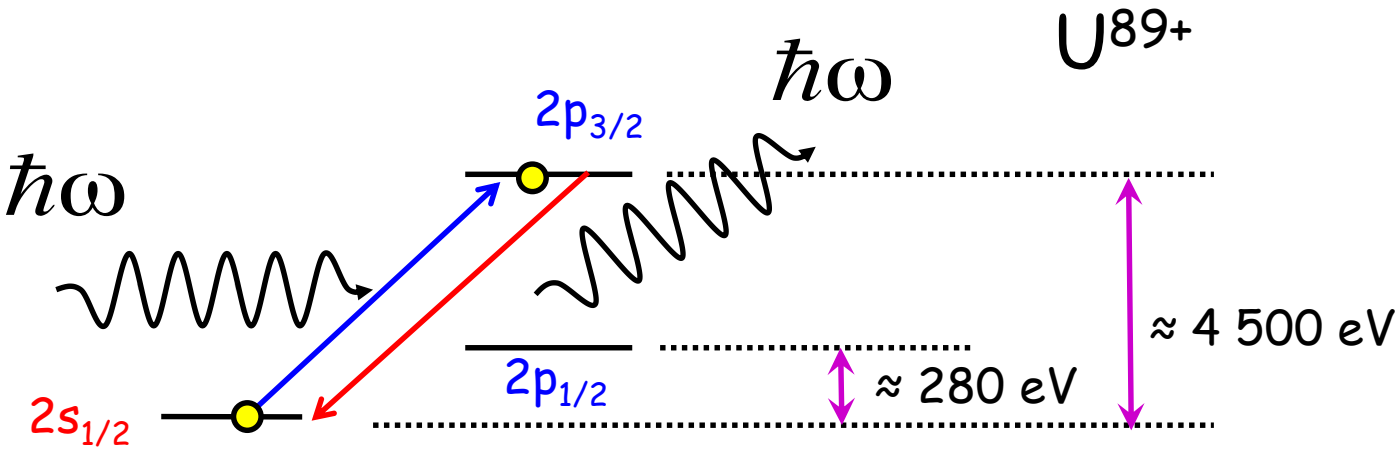
Laser Cooling @ ESR, SIS
→ **D.WINTERS, Wed at 2:35 PM (Parallel Tier 1)**
Michael BUSSMANN (Tuesday, Poster Session)

Electron Cooling @ HESR
→ atomic transitions with extracted beams,
nuclear transitions in ring !!

Applications: Absolute determination of ion velocity
Determination of beam quality ($\Delta p/p$)

Laser Spectroscopy in Li-Like Ions ?

Lithium-Like Ions



Is Laser Spectroscopy possible at such transitions ?

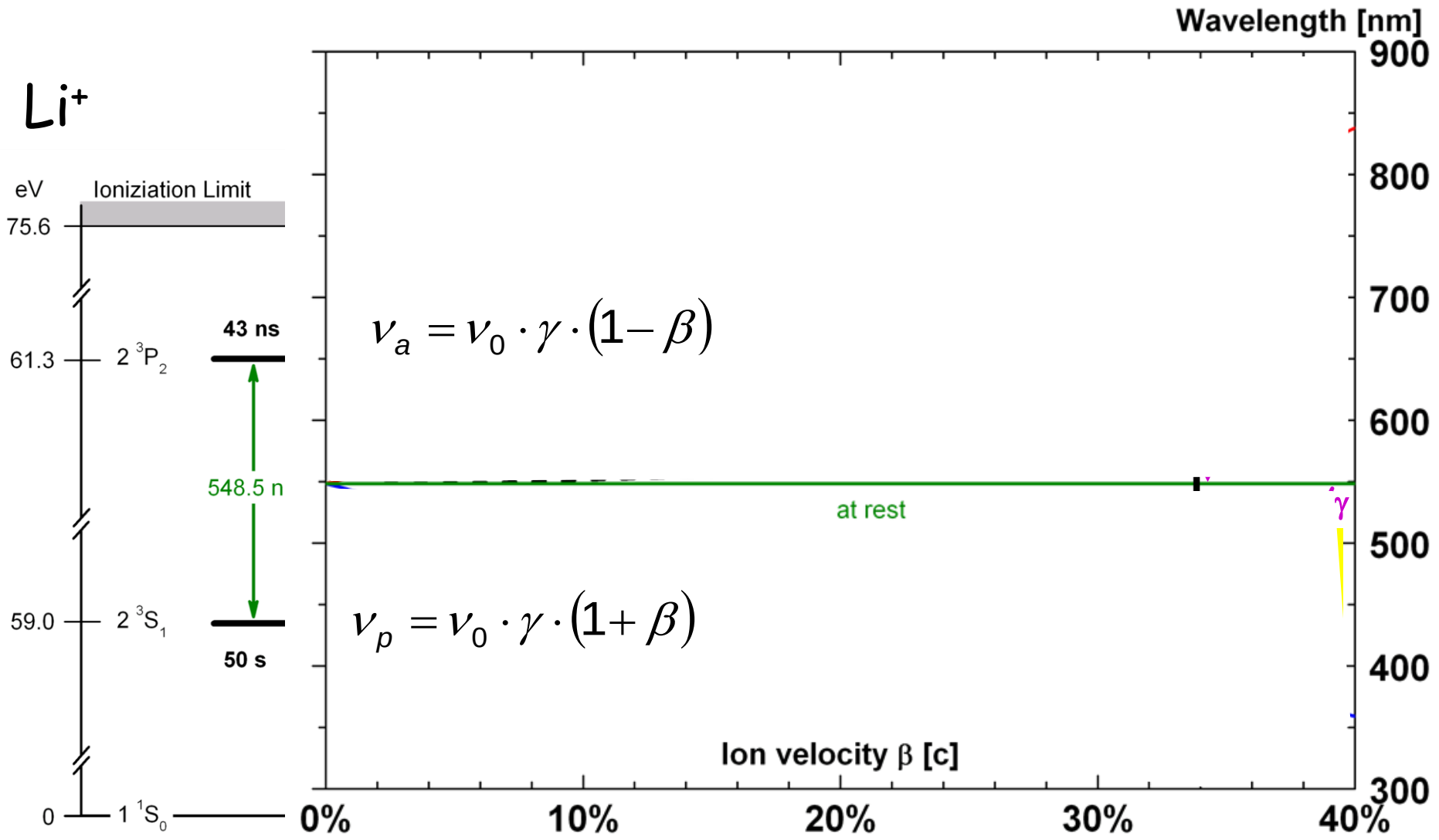
$1s_{1/2}$

The Optical Doppler Effect

… for Dummies !

The lights of the cars approaching you are bluish, while the lights of the ones moving away from you are red

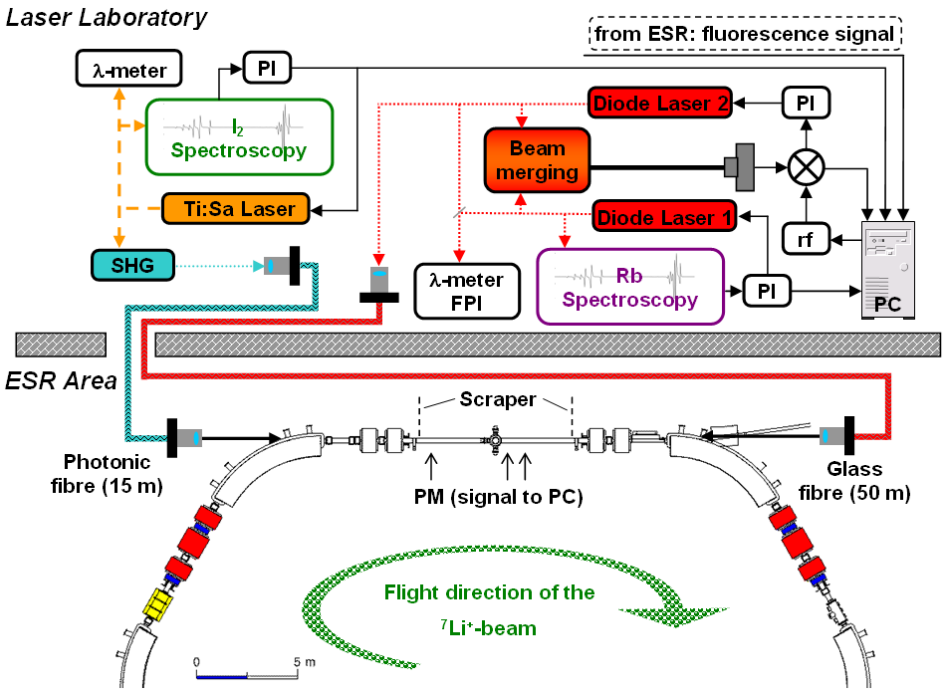
The Optical Doppler Effect: An Example

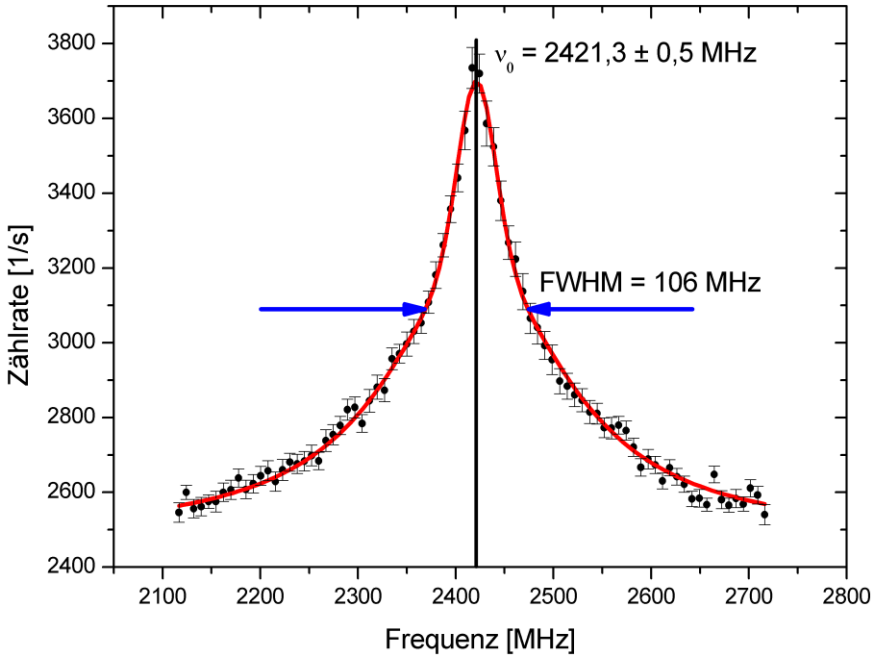


Test of Time Dilation at High Velocities

Ives & Stilwell, JOSA 28, 215 (1938)

$$\frac{\nu_p \cdot \nu_a}{\nu_0^2} = \gamma^2 \cdot \left(1-\beta^2\right) \overset{?}{\equiv} 1+\varepsilon\left(\beta^2\right)$$





ν_a = 384 225 534.98 ± 1.60 MHz
ν_p = 777 210 326.98 ± 1.25 MHz

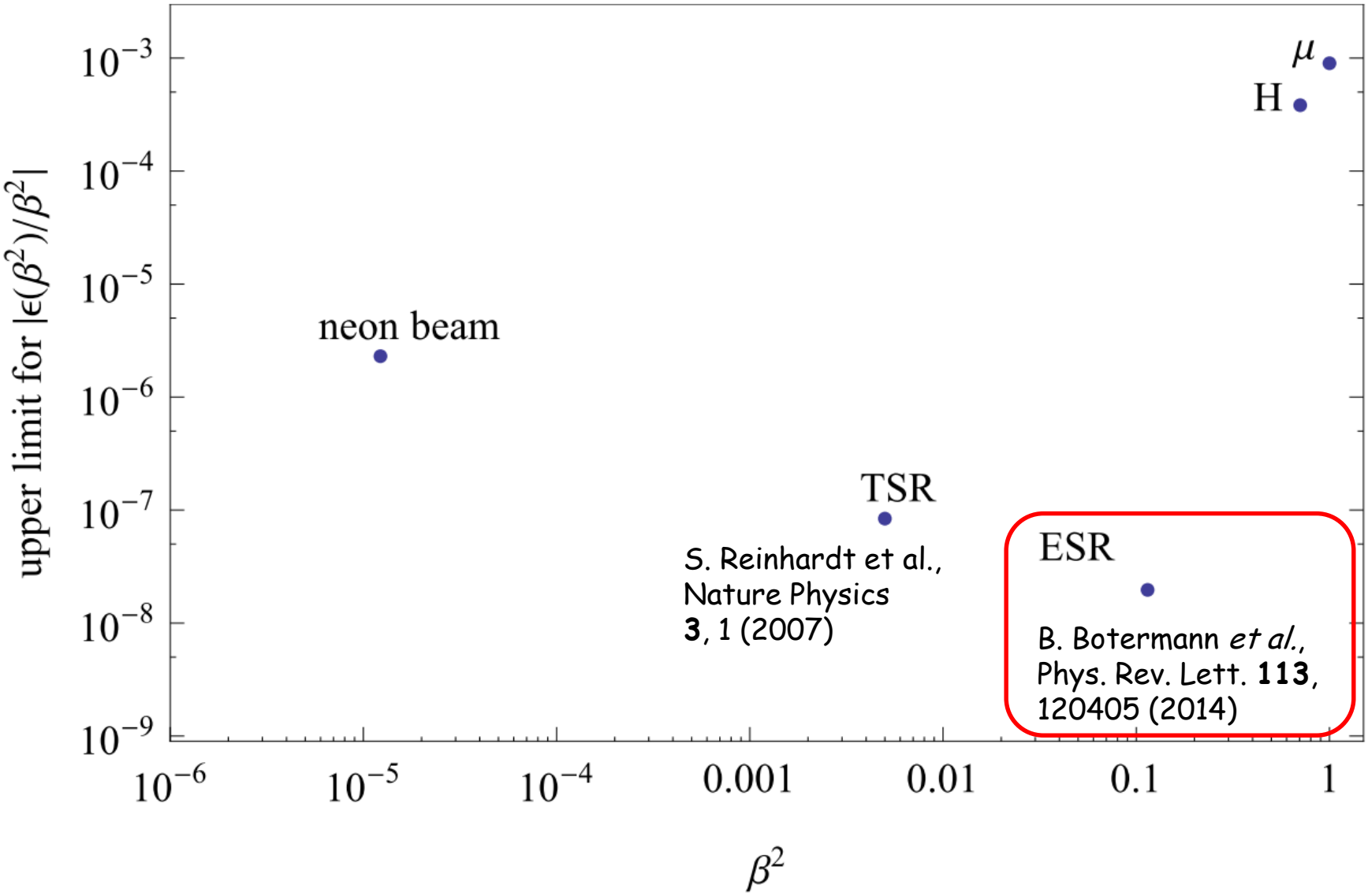
$$\varepsilon = \frac{\nu_p \cdot \nu_a}{\nu_0^2} - 1$$

$$\varepsilon = (1{,}5 \pm 2{,}3) \times 10^{-9}$$

$$\alpha = \frac{\varepsilon}{\beta^2} \leq 2.0 \times 10^{-8}$$

B. Botermann et al.,
PRL **113**, 120405
Published 16 September 2014

Test of Time Dilation at High Velocities



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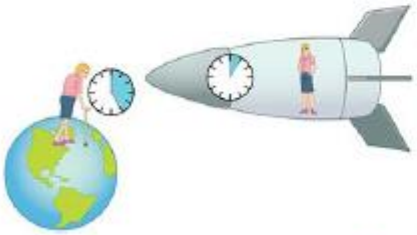
Synopsis: Relativity is Right on Time, Aga



Test of Time Dilation Using Stored Li^+ Ions as

Benjamin Botermann, Dennis Bing, Christophe
Theodor W. Hänsch, Gerhard Huber, Sergei K
Thomas Kühl, Wilfried Nörtershäuser, Christian
Rodolfo Sánchez, Dirk Schwalm, Thomas Stöh
Saathoff

Phys. Rev. Lett. **113**, 120405 (2014)

Published September 16, 2014

http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.113.120405

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NEWS & COMMENT

Nature Special: Diversity

Embracing diversity – in all its forms – is key to good science. In this special, *Nature* and its sister publication *Scientific American* explore the experiences of gay, lesbian, bisexual and transgendered scientists in the lab, and how neglecting to include participants from all ethnicities in clinical trials can endanger populations. We also cover how confronting economic inequalities within collaborations can strengthen global research, and how a more ethnically diverse team can have a positive impact on citation rate. Read more >

Martin Poole/Getty

Special relativity aces time trial

'Time dilation' predicted by Einstein confirmed by lithium ion experiment.

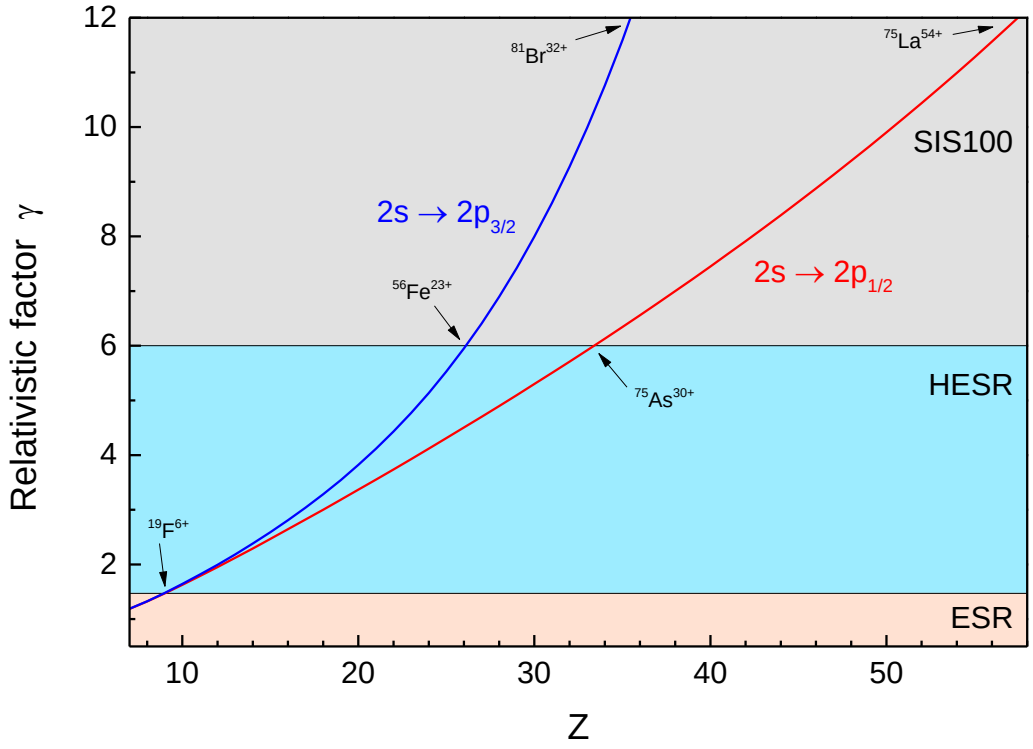
Fine Structure Spectroscopy in Li-Like Ions

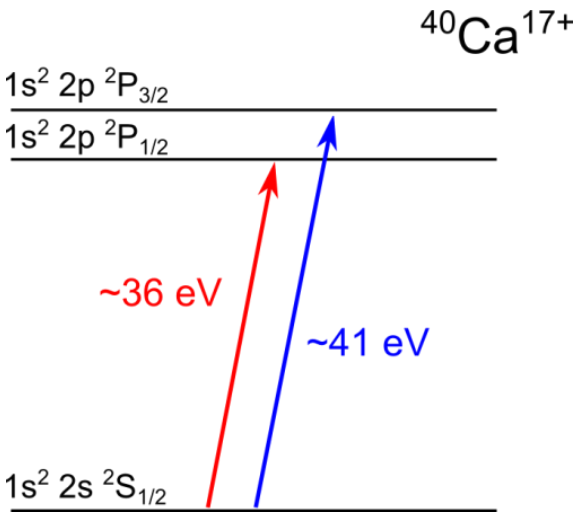
$$\omega_{\mathrm{Ion}} = \omega_{\mathrm{Lab}} \cdot \gamma \cdot (1+\beta)$$

$$\omega_{\mathrm{Ion}} = 2 \cdot \gamma\omega_{\mathrm{lab}}$$

HESR:
$\gamma \approx 6$, $\beta \approx 0{,}98$

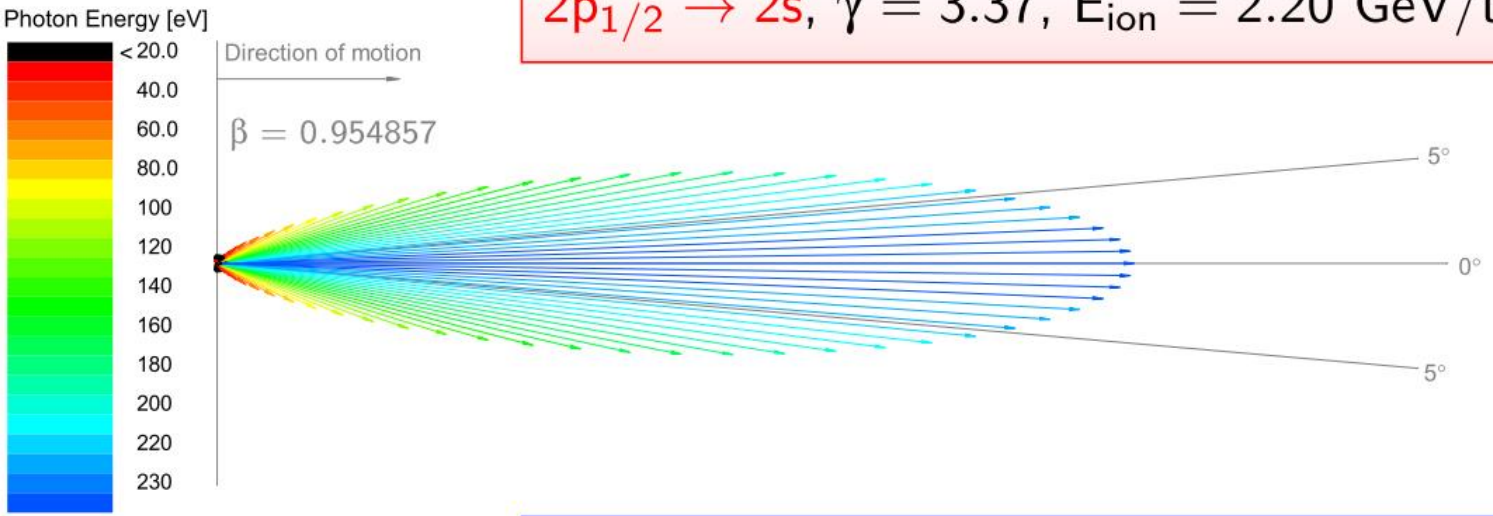
Laser wavelength fix at $\lambda_{\mathrm{lab}} = \mathbf{226.87}$ nm, $E_{\mathrm{photon}} = \mathbf{5.465}$ eV



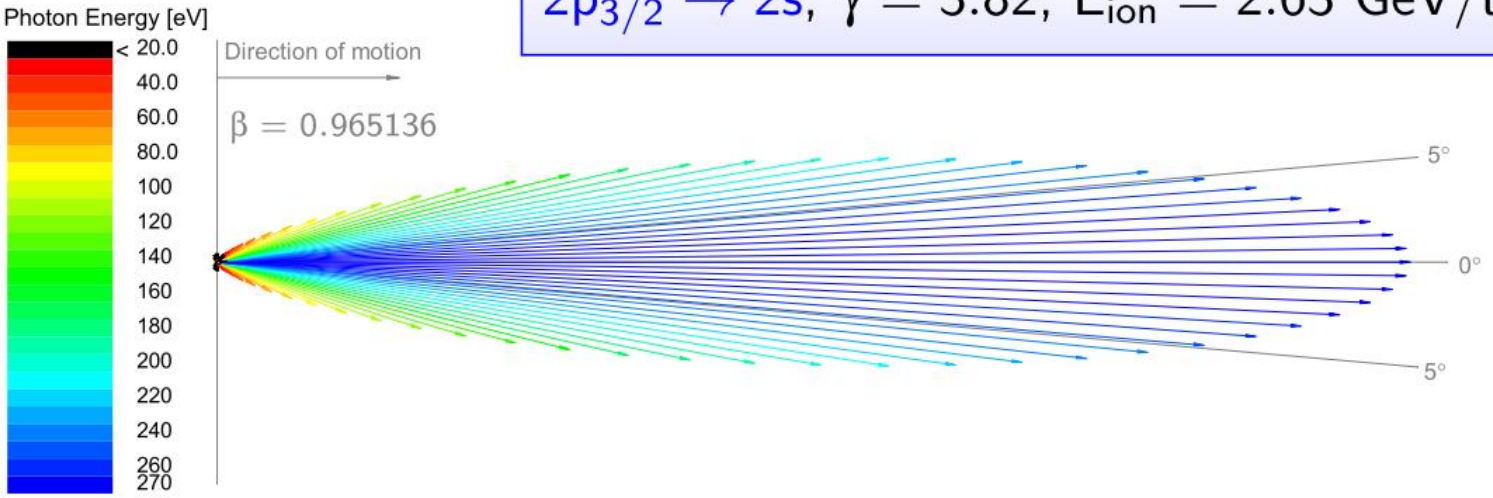


Challenge for Laser Spectroscopy at the HESR

$2p_{1/2} \rightarrow 2s$, $\gamma = 3.37$, $E_{ion} = 2.20$ GeV/u

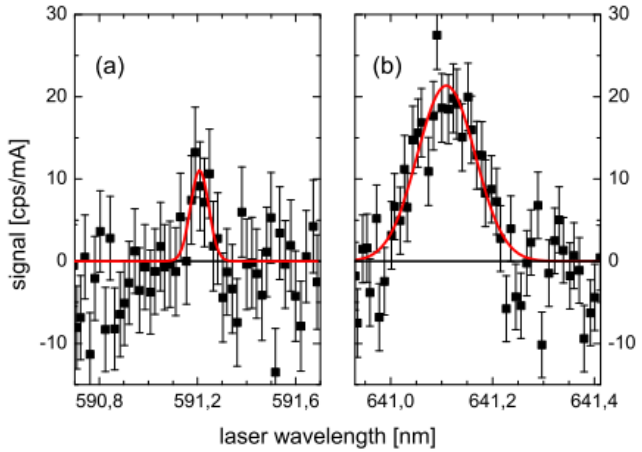


$2p_{3/2} \rightarrow 2s$, $\gamma = 3.82$, $E_{ion} = 2.63$ GeV/u

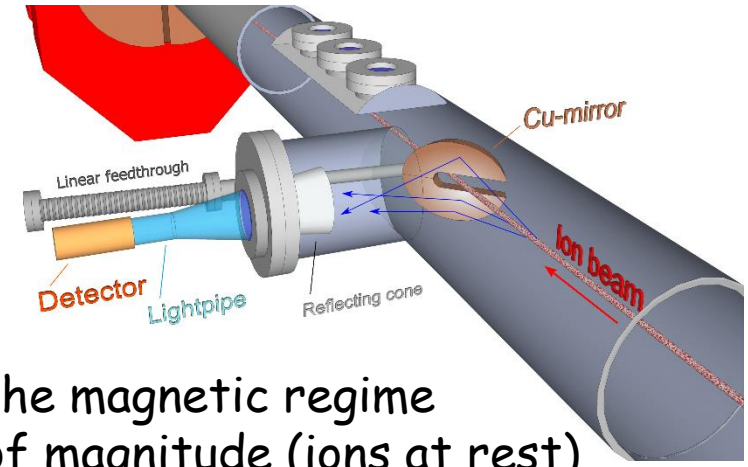


Detection of Forward-Emitted Photons

VISIBLE



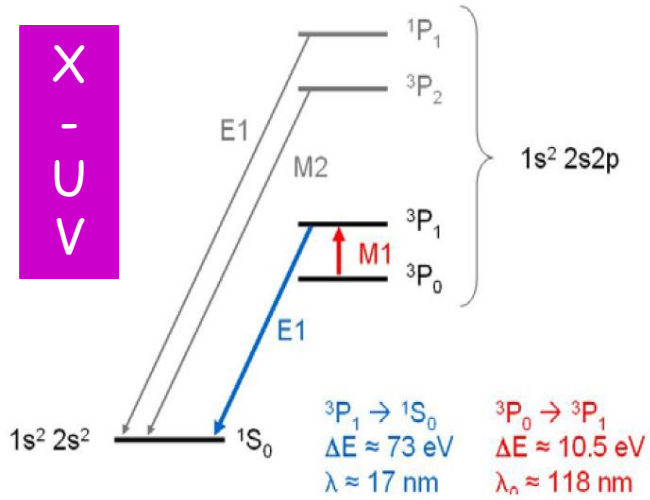
Developed at University of Münster
V. Hannen *et al.* J. Instr. 8, P09018 (2013)

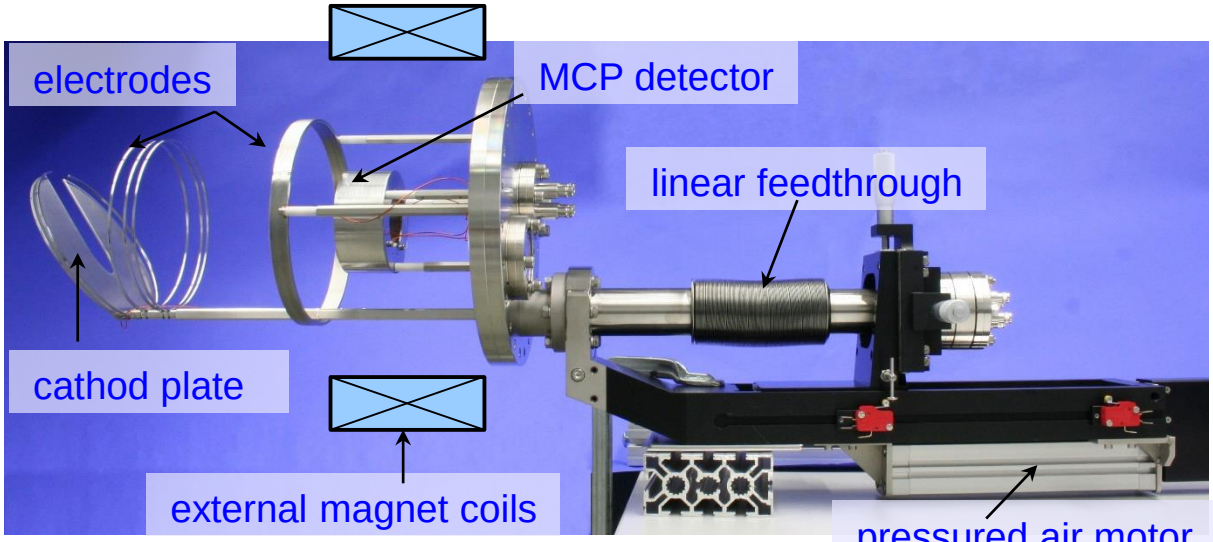


→ M. Lochmann *et al.*, PRA 90,030501 (2014) S-QED in the magnetic regime

→ to be improved at **HITRAP** by 3 orders of magnitude (ions at rest)

X - UV

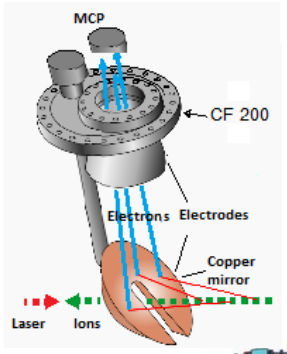




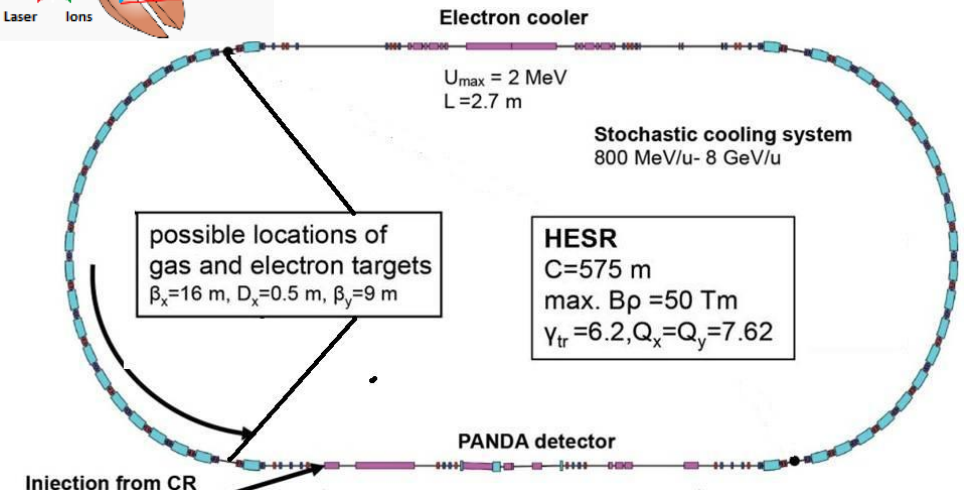
Development: Münster → Test HI Jena
→ Commissionning ESR → Application HESR

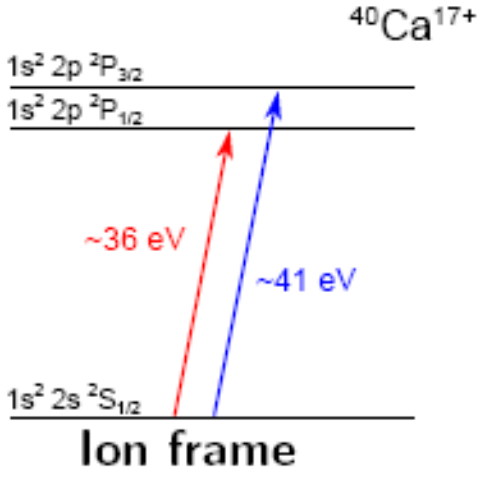
Bundesministerium für Bildung und Forschung
supported by BMBF
05P12PMFAE (Münster)
05P12RDFA4 (TU Darmstadt)

Laser Spectroscopy of Li-Like HCI



By using existing laser equipment and detection scheme, fine structure spectroscopy up to Z=20 is possible, exploiting a frequency shift of up to a factor of 10 !!!





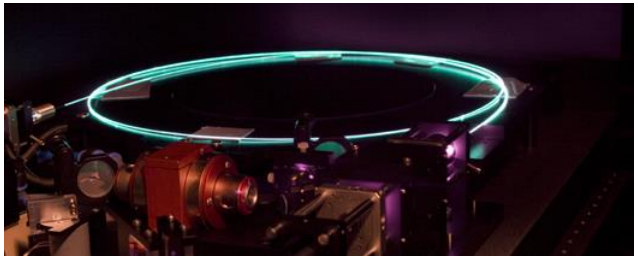
- Novel tests of atomic structure theory (correlation, relativity and QED)
- Model-independent determination of nuclear parameters
- Laser cooling

$$\omega = 2 \cdot \gamma \omega_L$$

Collaboration: HI-Jena, GSI, Paris-Sud, LOA, Lisbon, Bucuresti, Lanzhou

New Light Sources for Spectroscopy at Heavy Ion Storage Rings

High harmonic generation - a table-top source of coherent XUV radiation

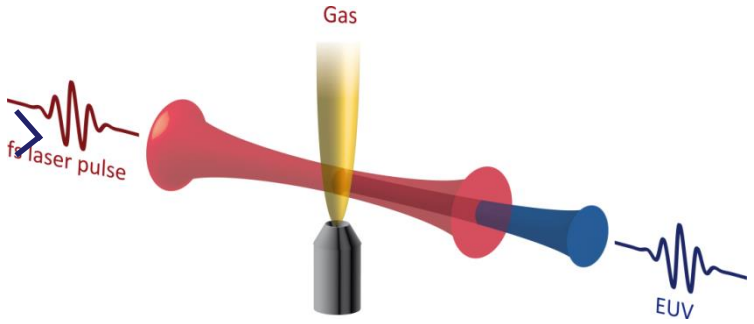


Femtosecond fiber lasers

high average power (up to 1 kW)

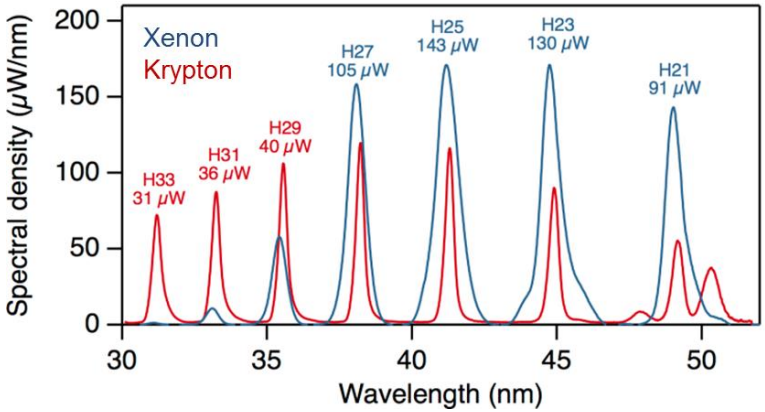
flexible repetition rate (up to 1 MHz)

+



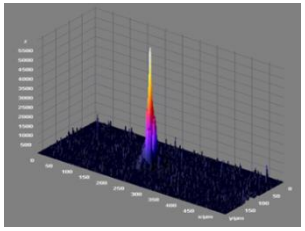
$\eta=10^{-6}$

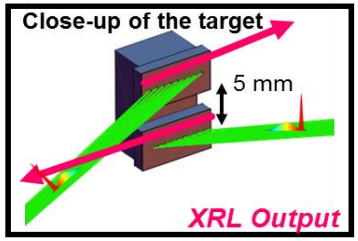
table-top source of high photon flux fs and attosecond pulses



X-Ray laser:

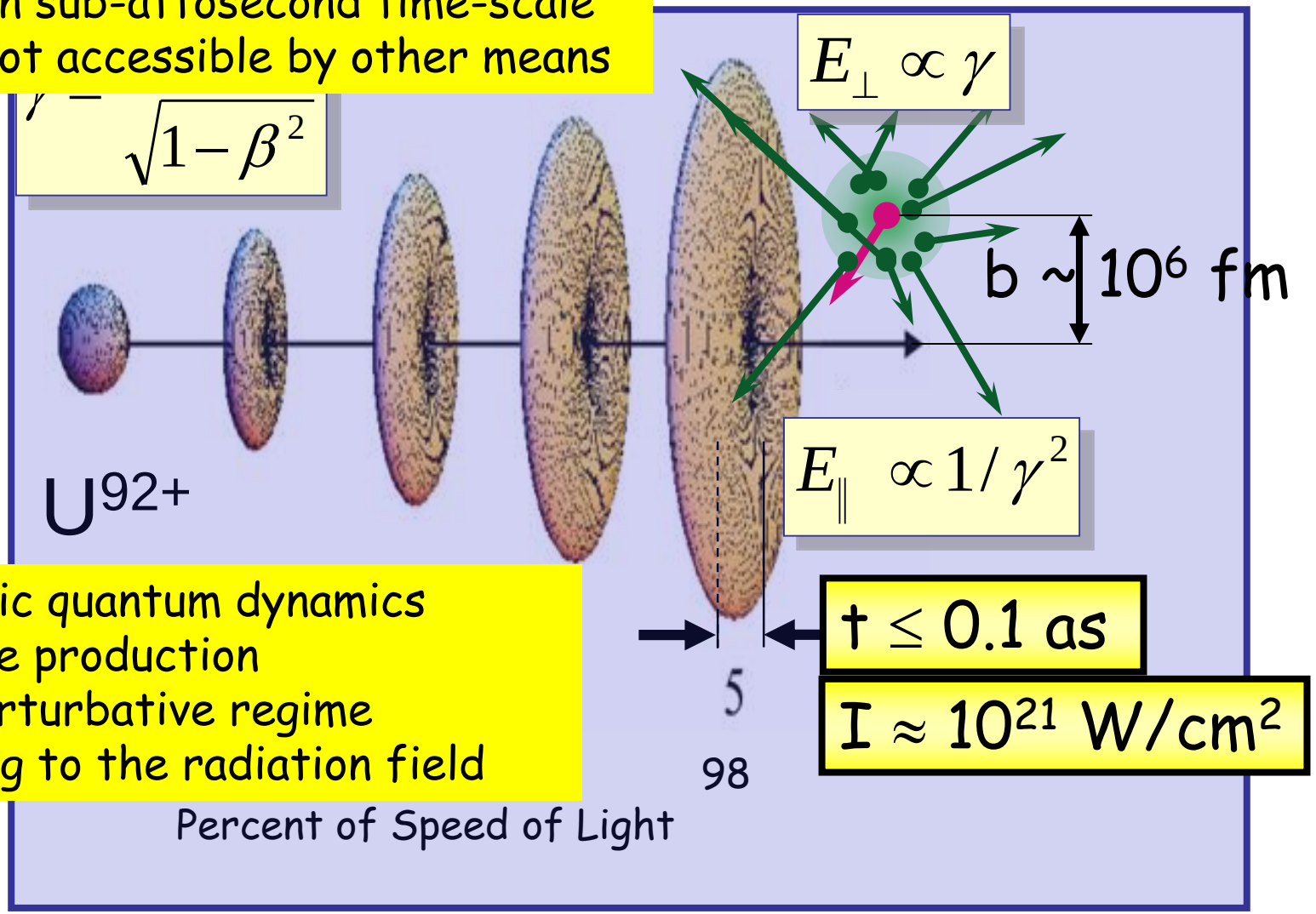
GSI, HIJ (Spielmann), Paris-Sud, LOA, Lisbon, Bucuresti, Lanzhou





Extreme Dynamic Fields

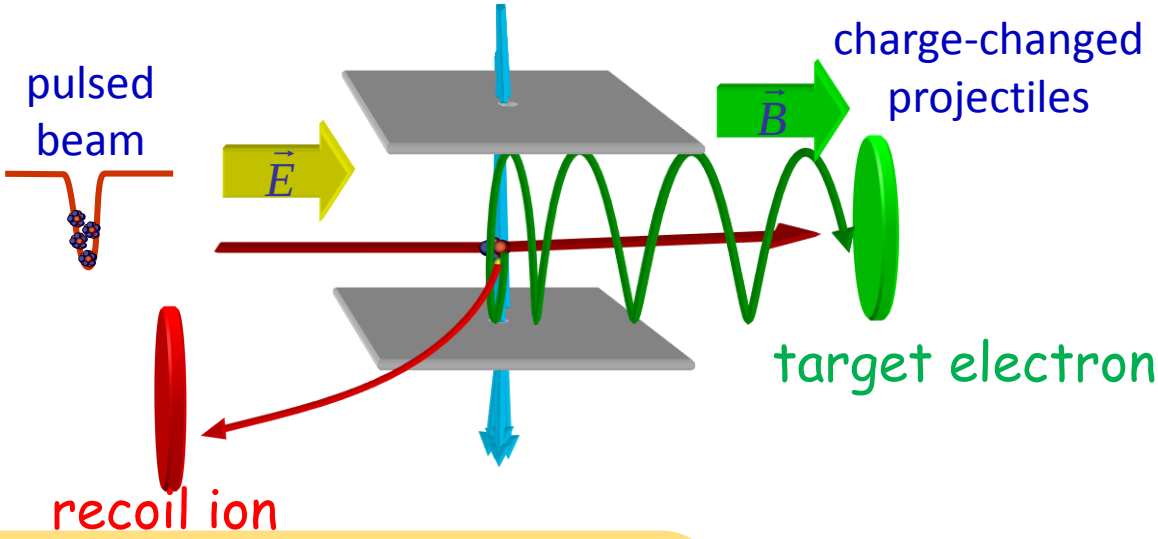
Explore correlated electron dynamics
- on sub-attosecond time-scale
- not accessible by other means



Relativistic quantum dynamics
- particle production
- non-perturbative regime
- coupling to the radiation field

COLTRIMS Combined with Ion Storage Rings

- kinematically complete (i.e. full momentum and energy information)
- 4π acceptance

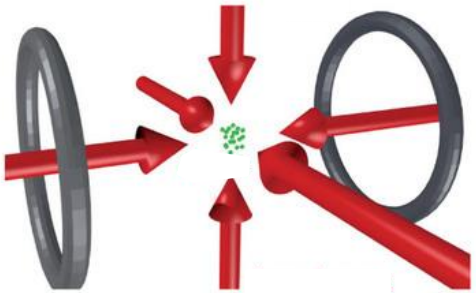


Probing many-electron dynamics

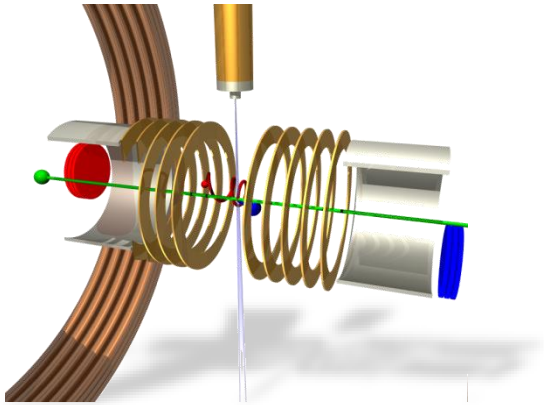
from the times-of-flight and hitting positions:

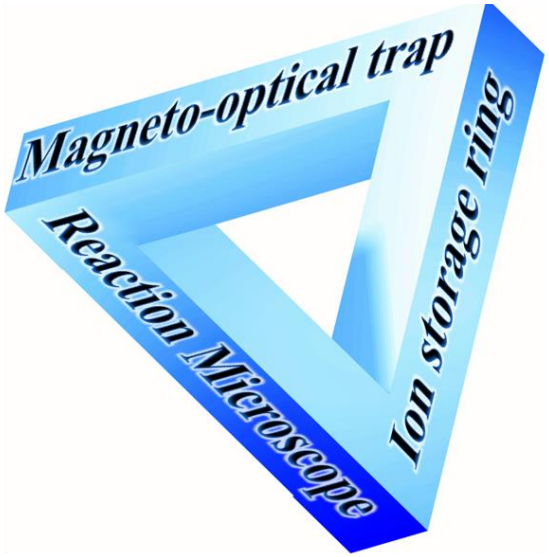
- on an **subattosecond** time scale
- in extremely **intense fields**
- vector momenta of electrons: ΔE_e ~ meV
- vector momenta of ions: ΔE_R < μeV
- no postcollision interaction

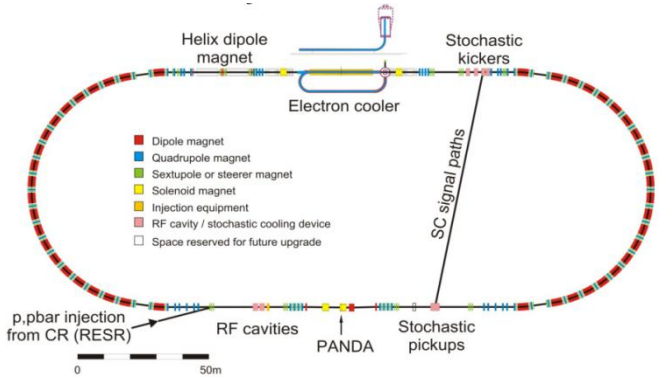
The In-Ring MOTReMi



D. Fischer et al.



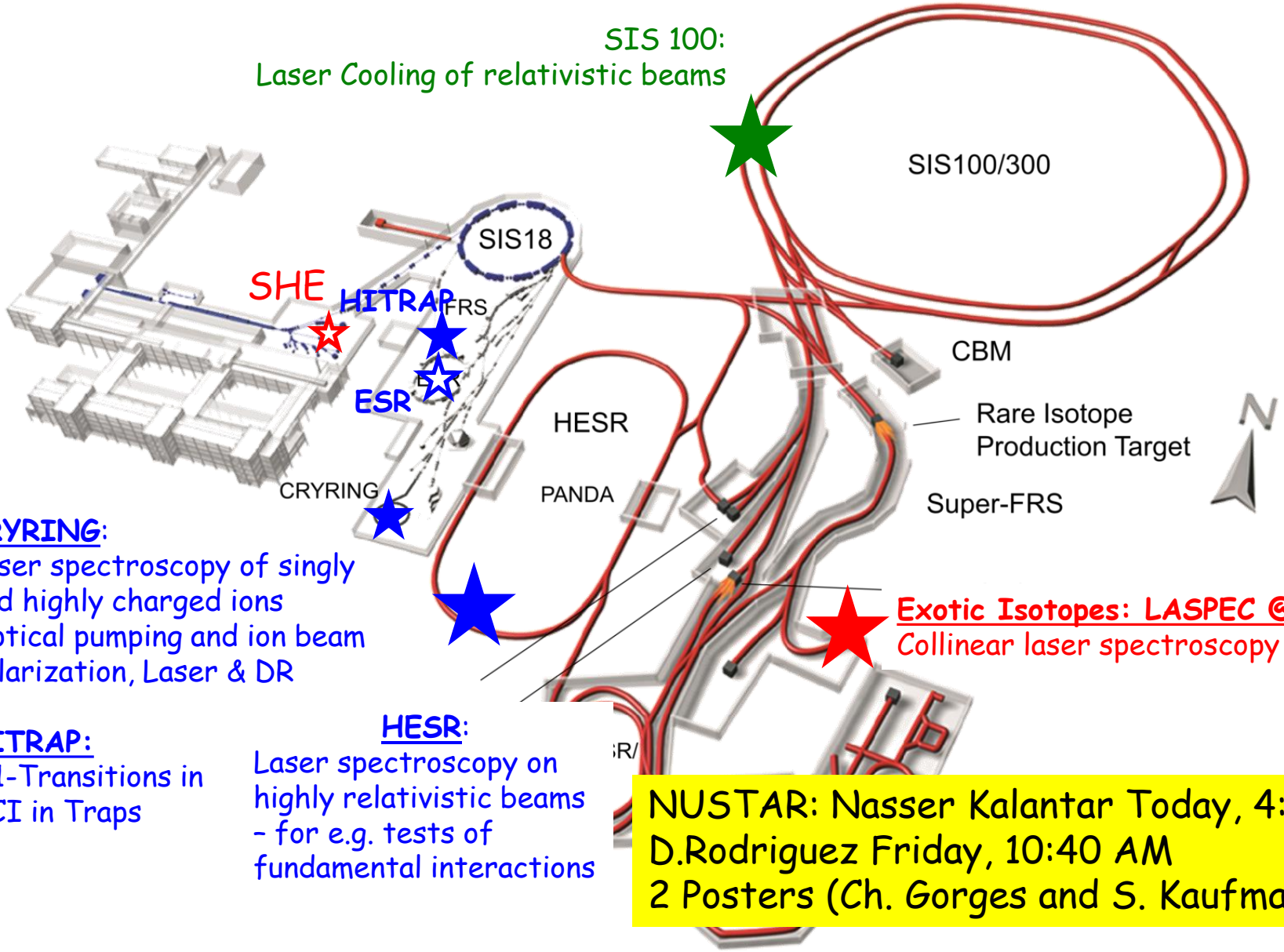




- uUtracold target (T ~ 0.5 mK)
  (conventional gas-jet: T > 50 mK)
- State preparation and polarized targets

Laser Spectroscopy at GSI: Future

SIS 100:
Laser Cooling of relativistic beams



CRYRING:
Laser spectroscopy of singly and highly charged ions
Optical pumping and ion beam polarization, Laser & DR

HITRAP:
M1-Transitions in HCI in Traps

HESR:
Laser spectroscopy on highly relativistic beams – for e.g. tests of fundamental interactions

Exotic Isotopes: LASPEC @ LEB
Collinear laser spectroscopy

NUSTAR: Nasser Kalantar Today, 4:30 PM
D.Rodriguez Friday, 10:40 AM
2 Posters (Ch. Gorges and S. Kaufmann)

Quantum Dynamics in Extreme Fields: The Program of the SPARC Collaboration

Scientific Goal:

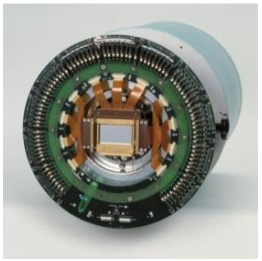
Precision Studies of the Quantum Dynamics of Atomic Systems in Critical and Super-Critical Fields

Observables: photons, electrons, positrons, ions (projectiles, recoils)

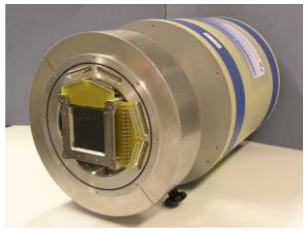
Discovery Potential:

- New concepts for QED in extreme fields
- Insight into the correlated many-body dynamics via ultrashort and super intense field pulses ($<10^{-18}$ s)
- Precision determination of fundamental constantes (α, m_e)
- Proof of fundamental symmetries
- Discovery and understanding of new decay modes of nuclei
- Determination of fundamental nuclear properties via atomic data

More Details / Not Covered At All

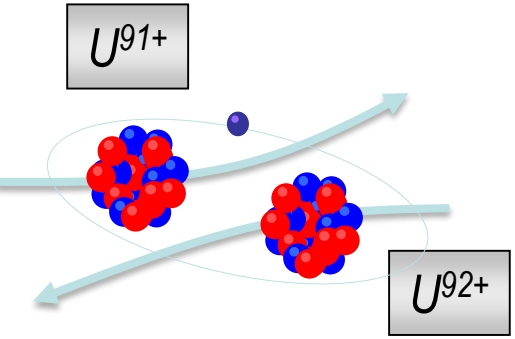


SPARC-Instrumentation:
Uwe Spillmann Tuesday, 2:00 PM

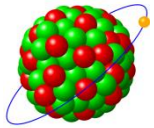


Testing Quantum Electrodynamics at critical background electromagnetic fields, Antonino Di Piazza, Wednesday, 9:45 AM:

Ring Activities : Yuri Litvinov Friday, 10:20 AM



Low-energy heavy-ion collisions, supercritical fields:
Ilia Maltsev,
Darya Mironova



Structure Of HCI (Theory)

Aleksei Malyshev	(Be-like Ions)
Oleg Andreev	(HFS, Li-like Bi)
Vladimir Shabaev	(IS g-factor, Li-like)
Arseniy Shchepetnov	(g-factor, B-like)
Natalia Zubova	(IS, Li-like)
Valentina Akishina	(IS, Li-like)

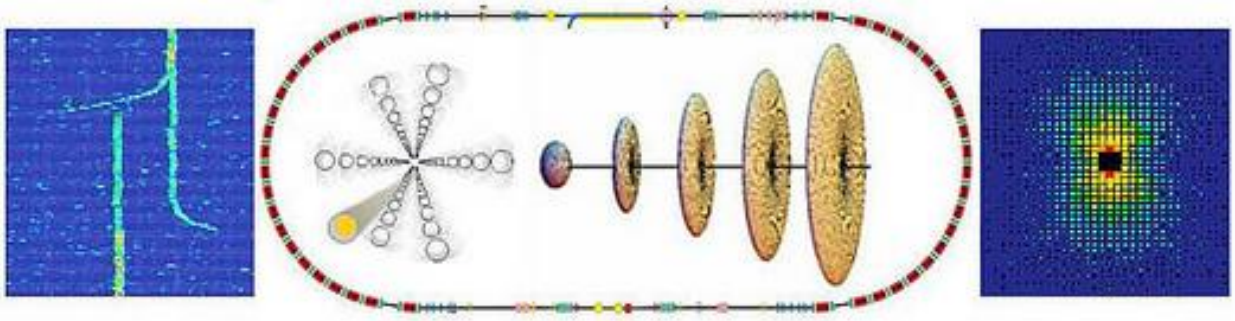
Polarimetrie: Stanislav Tashenov
PNC: Vladimir Zaytsev
Strong Laser Fields: Irina Ivanova
Radiative Recombination: Anna Maiorova

11th SPARC Workshop

Special Thanks to Thomas Stöhlker, Alex. Gumberidze, Rodolfo Sanchez, Reinhold Schuch, Volker Hannen

for providing Material,

and all colleagues who might have spotted their migrating slides.



HIC for FAIR
Helmholtz International Center

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Bundesministerium
für Bildung
und Forschung

- Großer Liebfrauensaal -