Testing Special Relativity at the ESR

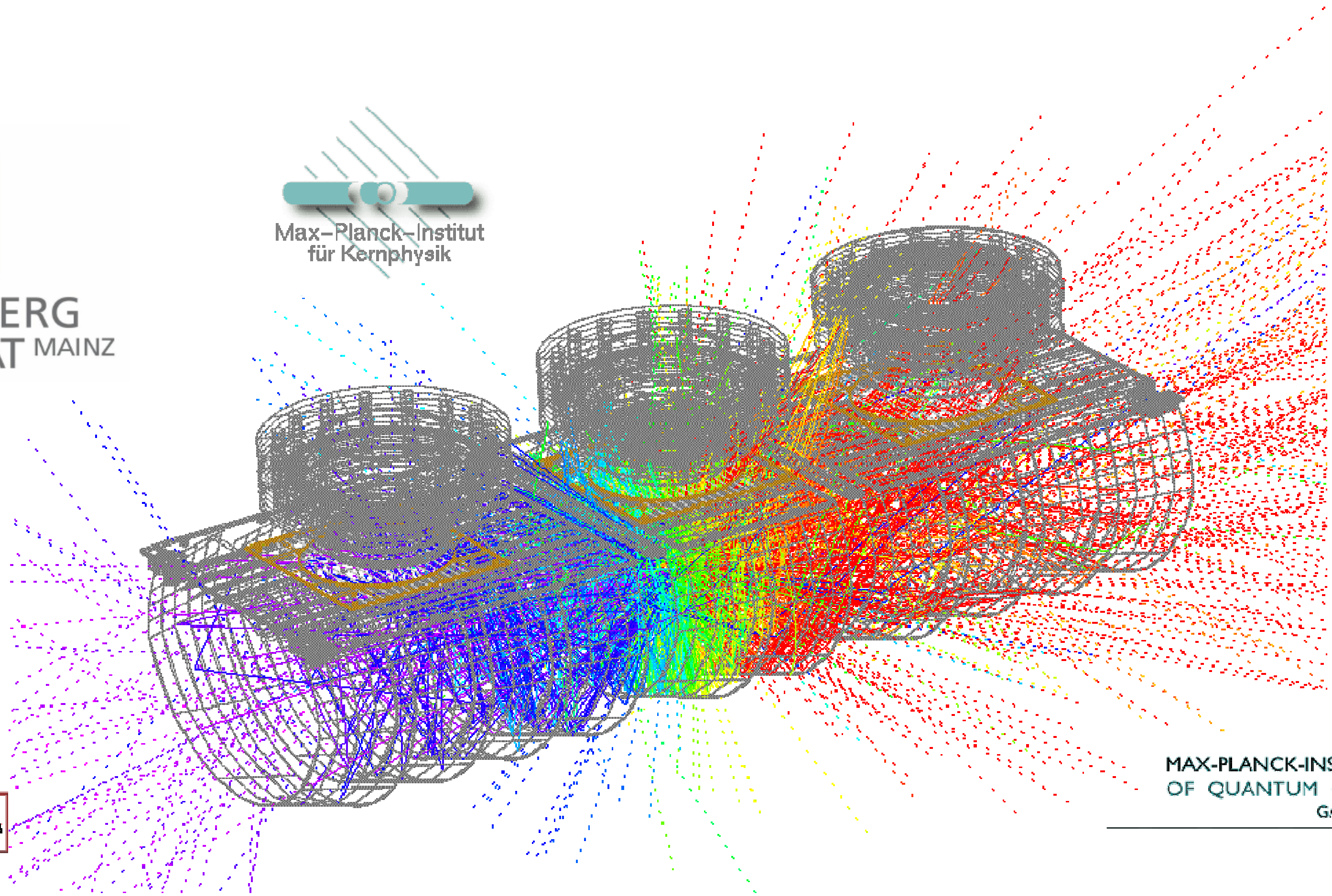
Johannes Gutenberg Universität Mainz

Max-Planck-Institut für Kernphysik

University of Manitoba

GSI

Max-Planck-Institute of Quantum Optics Garching



11.02.2010

Outline

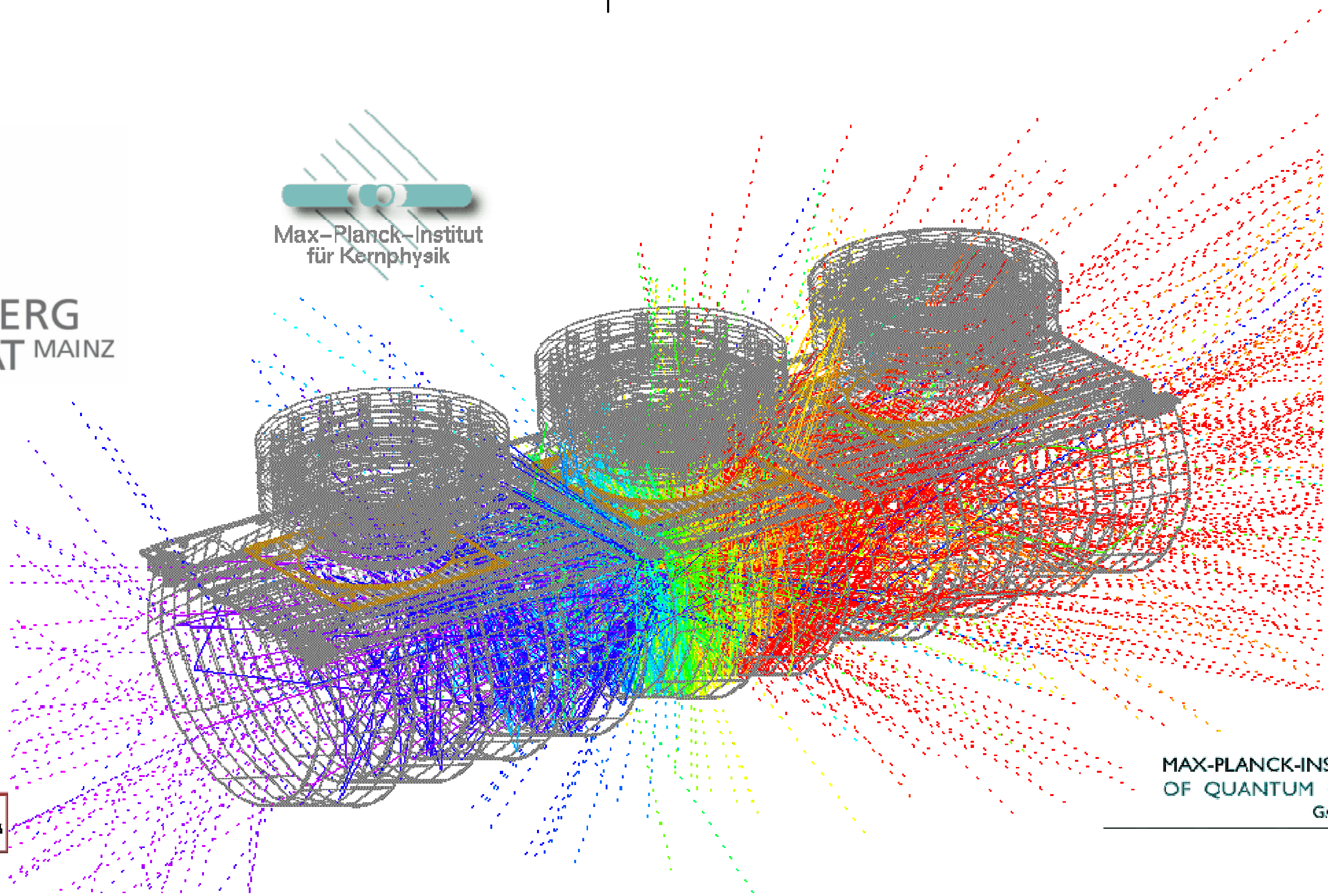
- Motivation
- Principle of time dilation tests
- The experiment techniques
- Results

Johannes Gutenberg Universität Mainz

Max-Planck-Institut für Kernphysik

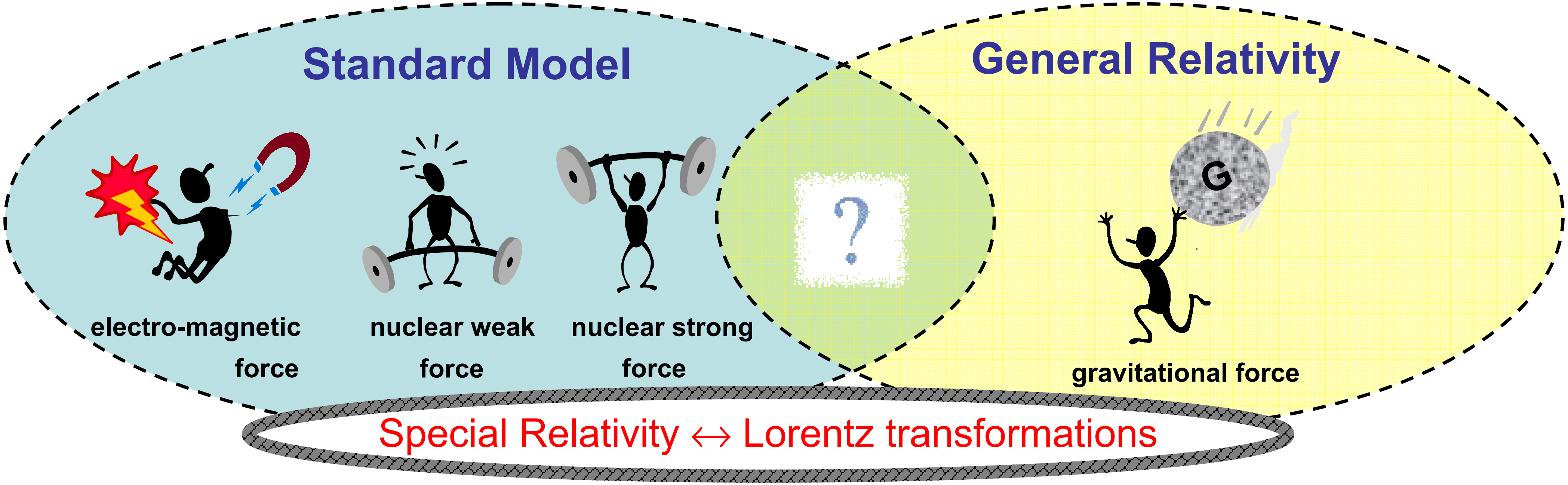
University of Manitoba

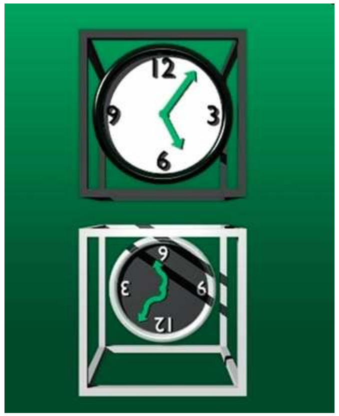
GSI

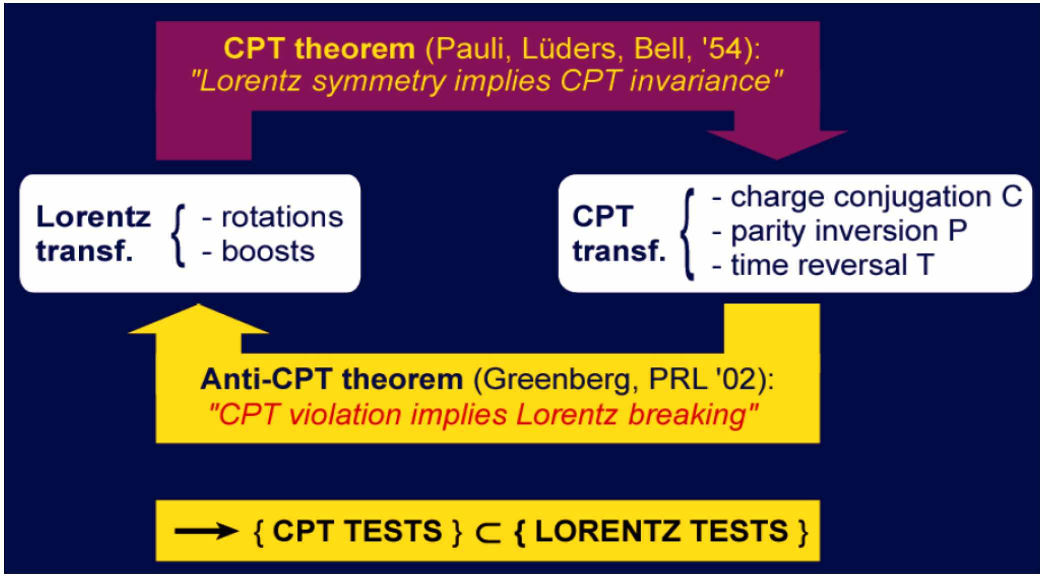


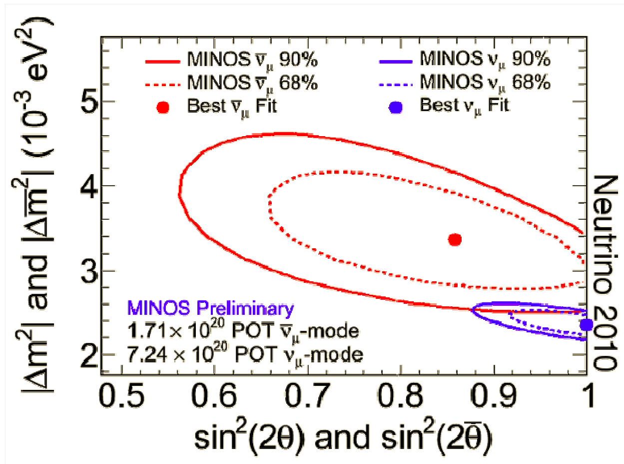
Max-Planck-Institute of Quantum Optics Garching

Why Testing Lorentz Invariance ?









Ralf Lehnert (2007)

Einstein's Postulates for SRT

Principle of Relativity:

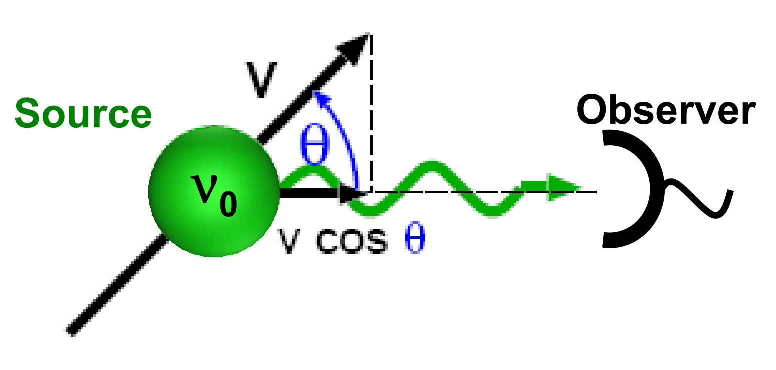
The laws of physics are the same for all inertial frames.

Principle of Constancy of the Speed of Light:

Any ray of light moves in the "stationary" system of coordinates with determined velocity c, whether the ray be emitted by a stationary or by a moving body.

The Relativistic Doppler Effect

Relativistic Doppler effect



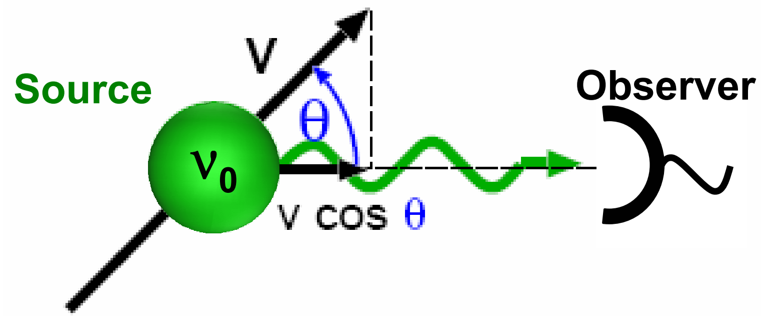
$$\nu = \nu_0 \frac{1}{\gamma\,(1 - \beta \cos \theta)}$$

$$\beta = v/c_0$$

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}}$$

The First Ives-Stilwell Experiment

Relativistic Doppler effect

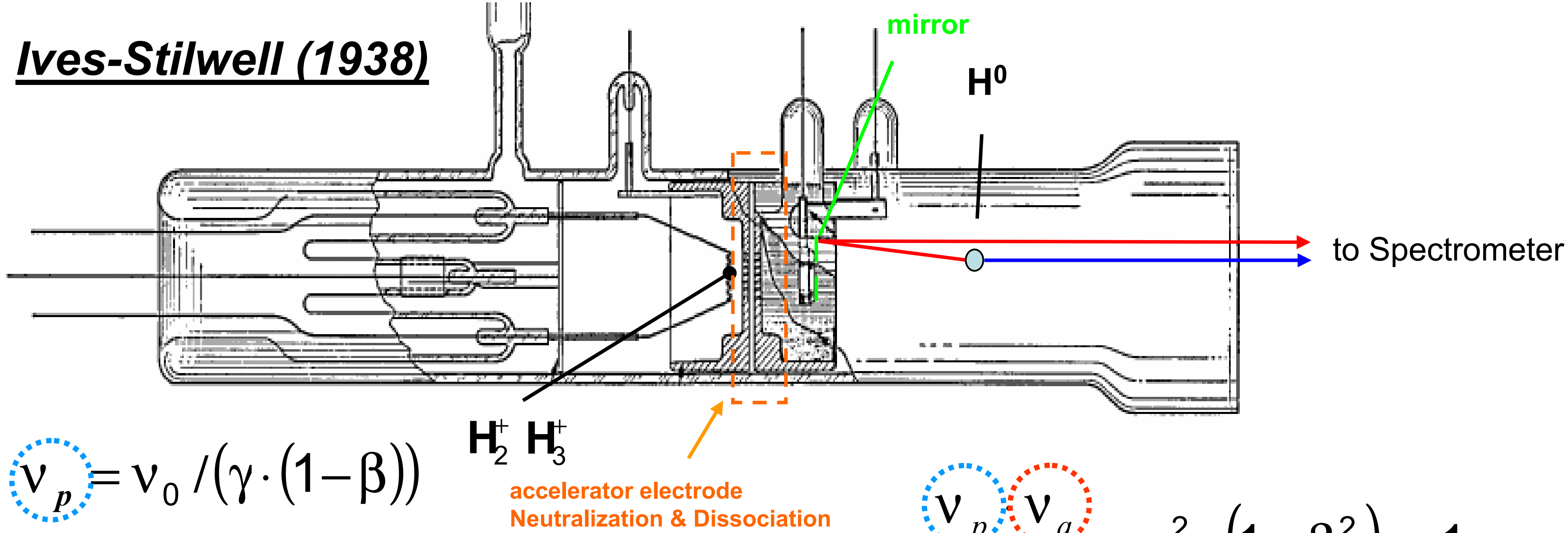


$$\nu = \nu_0 \frac{1}{\gamma\,(1 - \beta \cos \theta)}$$

$$\beta = {}^{v}\!/\!_{c_0}$$

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}}$$

Ives-Stilwell (1938)



$$\nu_p = \nu_0 / (\gamma \cdot (1 - \beta))$$

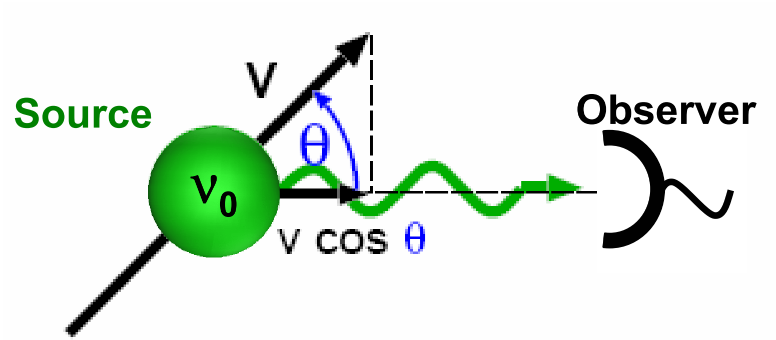
$$\nu_a = \nu_0 / (\gamma \cdot (1 + \beta))$$

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

[J. Opt. Soc. Am. **28** (1938) *215*]

The First Ives-Stilwell Experiment

Relativistic Doppler effect

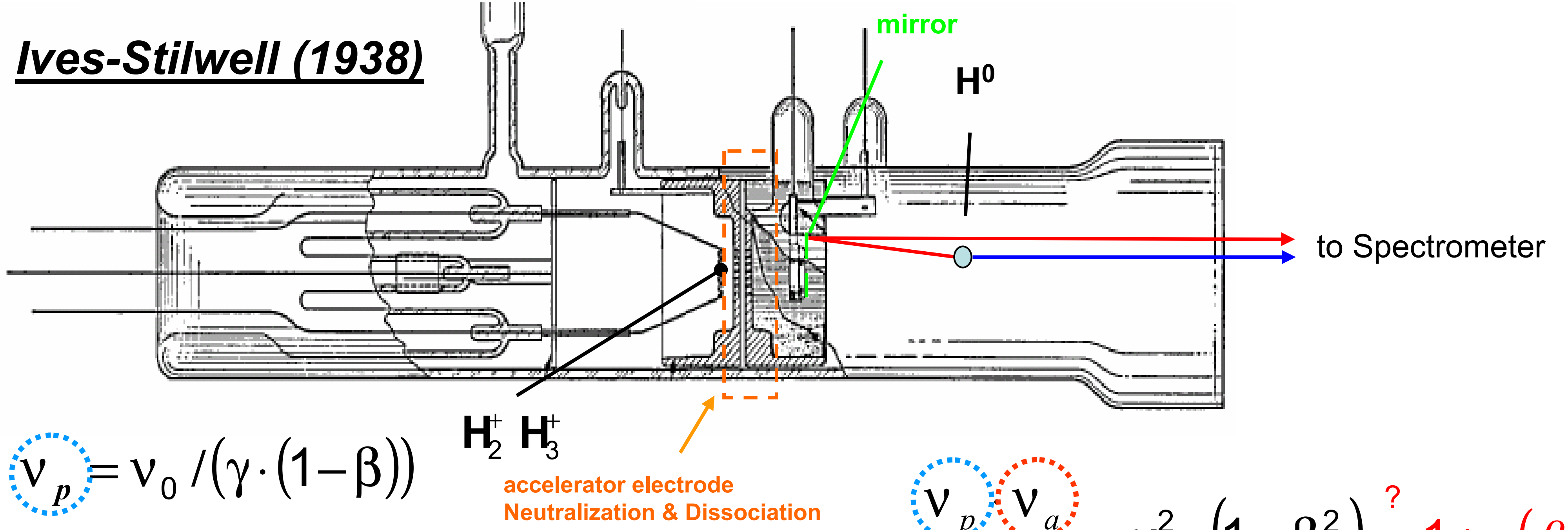


$$\nu = \nu_0 \frac{1}{\gamma\,(1 - \beta \cos\theta)}$$

$$\beta = {}^{v}\!/_{c_0}$$

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}}$$

Ives-Stilwell (1938)



$$\nu_p = \nu_0 / (\gamma \cdot (1 - \beta))$$

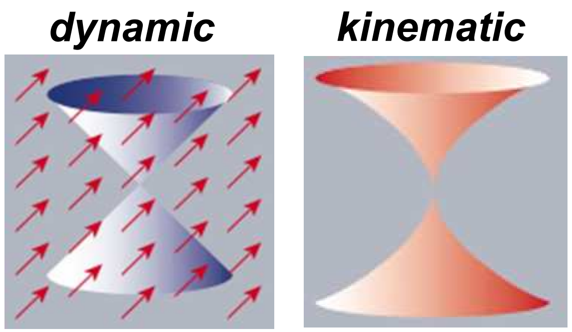
$$\nu_a = \nu_0 / (\gamma \cdot (1 + \beta))$$

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

[J. Opt. Soc. Am. **28** (1938) *215*]

Framework for interpretation

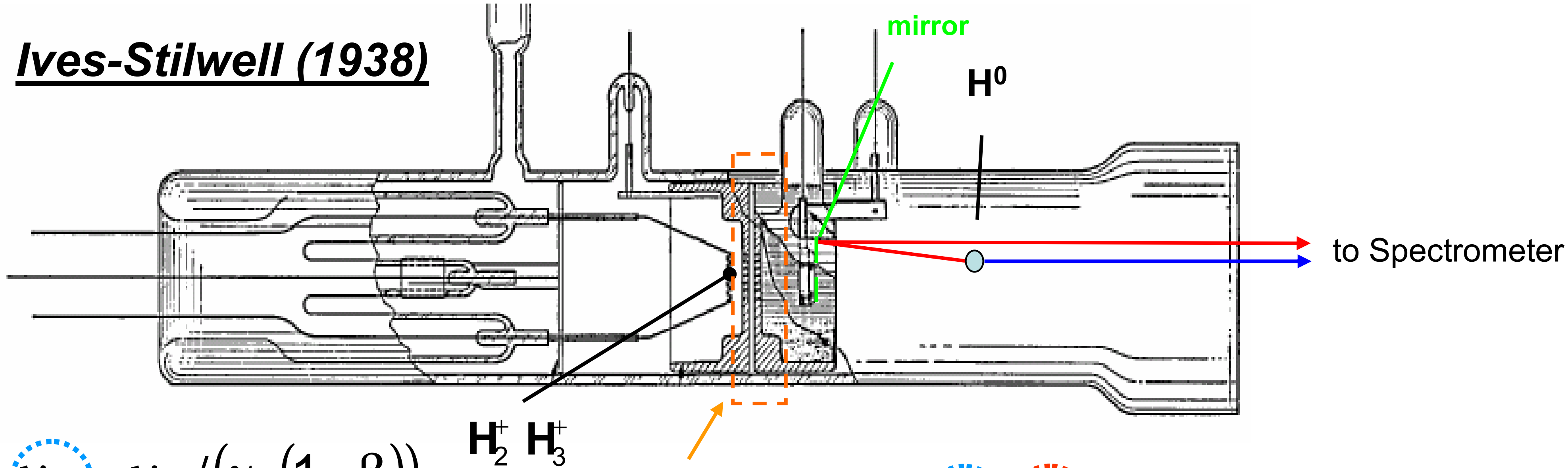
Test theories:



e.g.:
Standard Model Extension
Mansouri-Sexl Expansion

$$e.g.: \quad \varepsilon(\beta) = 2 \cdot \delta\alpha \cdot \beta^2$$

Ives-Stilwell (1938)



$$\nu_p = \nu_0 / (\gamma \cdot (1-\beta))$$

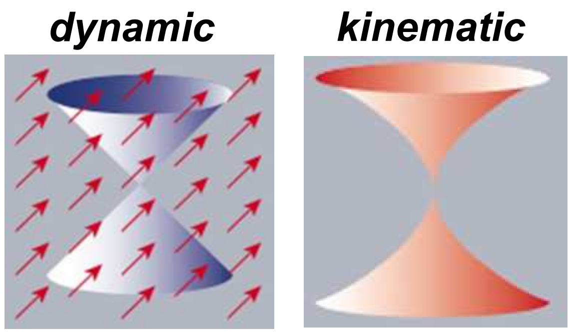
$$\nu_a = \nu_0 / (\gamma \cdot (1+\beta))$$

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

[J. Opt. Soc. Am. **28** (1938) *215*]

Framework for Interpretation

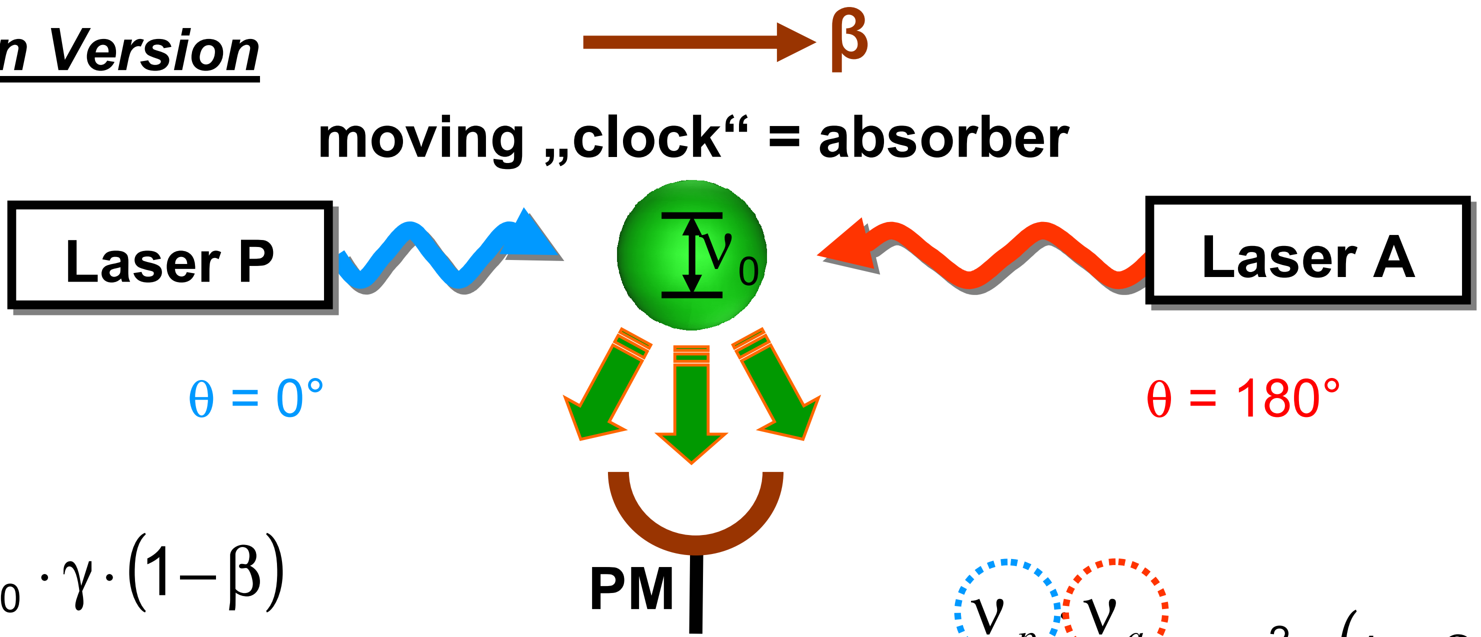
Test theories:



e.g.:
Standard Model Extension
Mansouri-Sexl Expansion

$$e.g.: \quad \varepsilon(\beta) = 2 \cdot \delta\alpha \cdot \beta^2$$

modern Version



$$\nu_p = \nu_0 \cdot \gamma \cdot (1-\beta)$$

$$\nu_a = \nu_0 \cdot \gamma \cdot (1+\beta)$$

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

Modern Ives-Stilwell Experiment

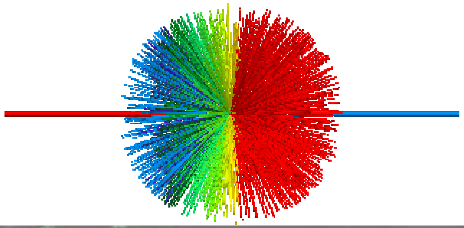
$\Delta\nu/\nu \sim 10^{-10}$

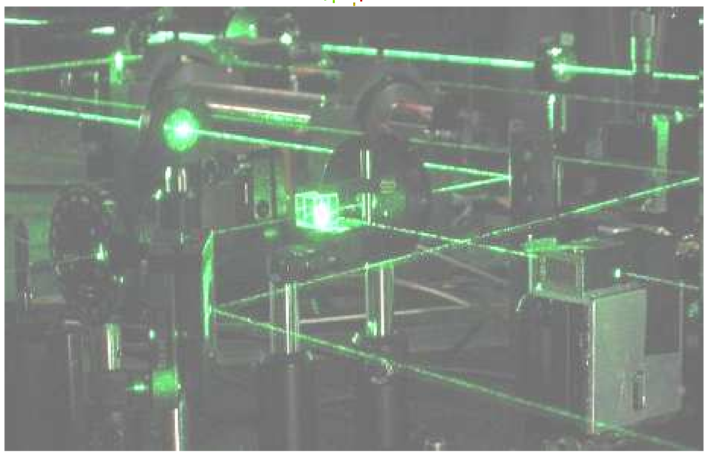
frequencies has to been known very accurate

$\varepsilon(\beta) \sim \beta^2$

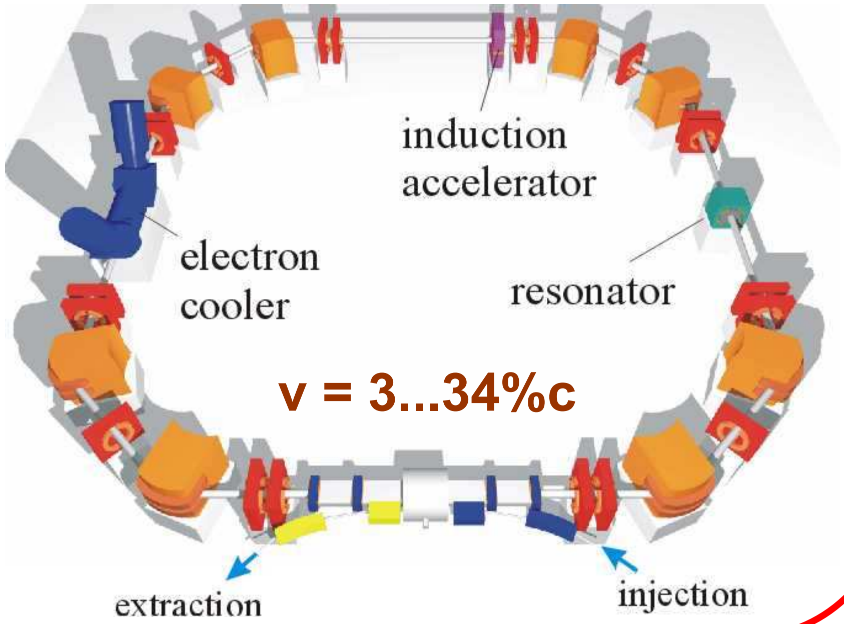
the higher the clock velocity, the higher the sensitivity

Precision Laser Spectroscopy

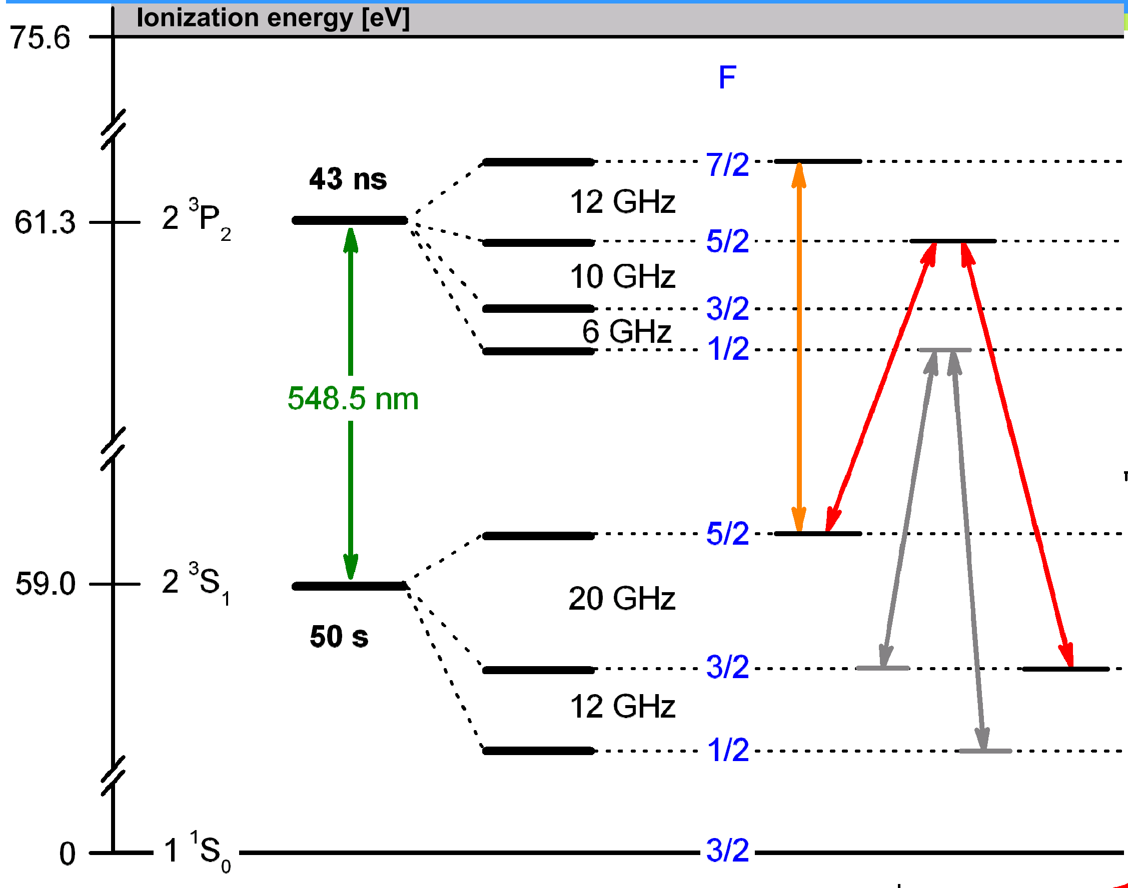




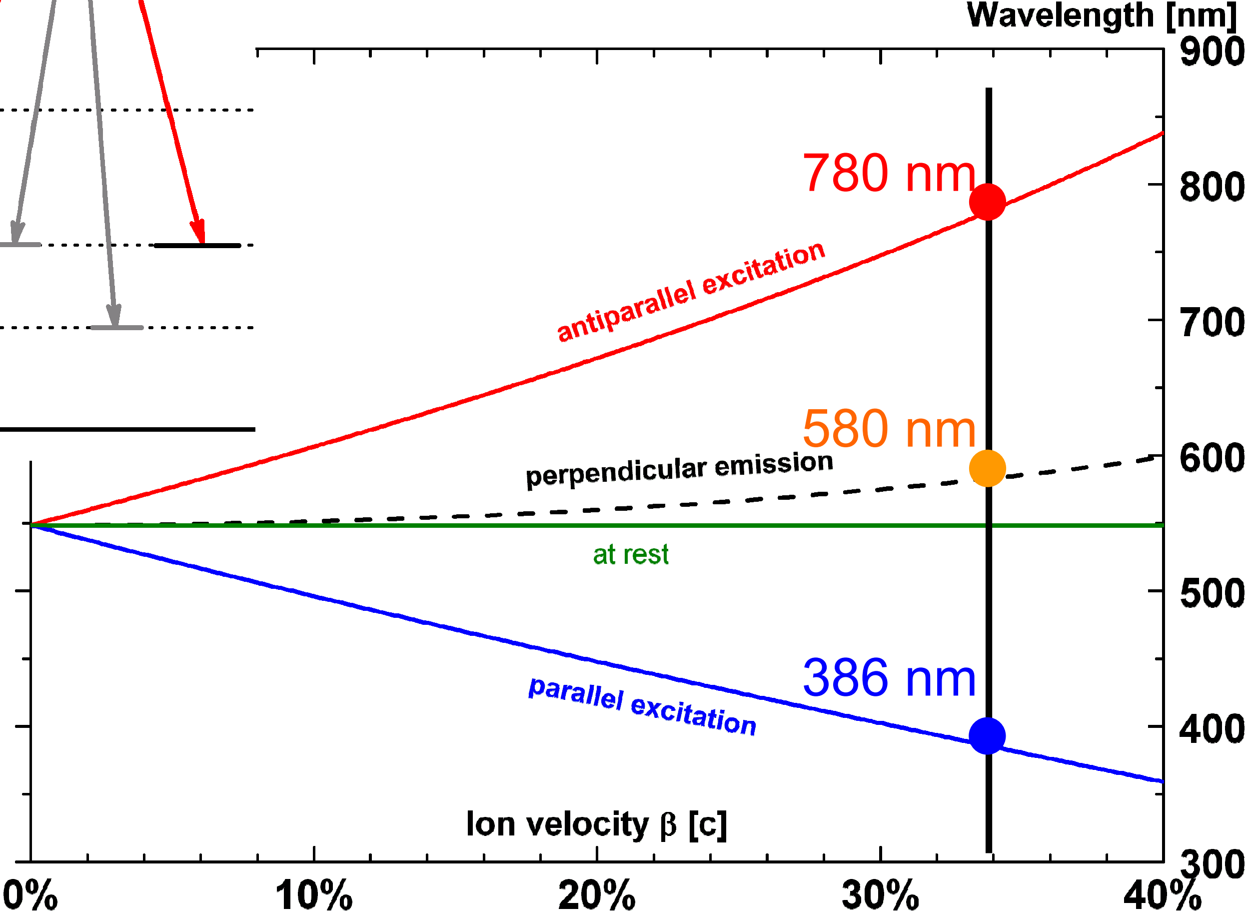
Storage Ring



The Clock: Metastable $^{7}Li^{+}$



$^{7}Li^{+}$ as absorber

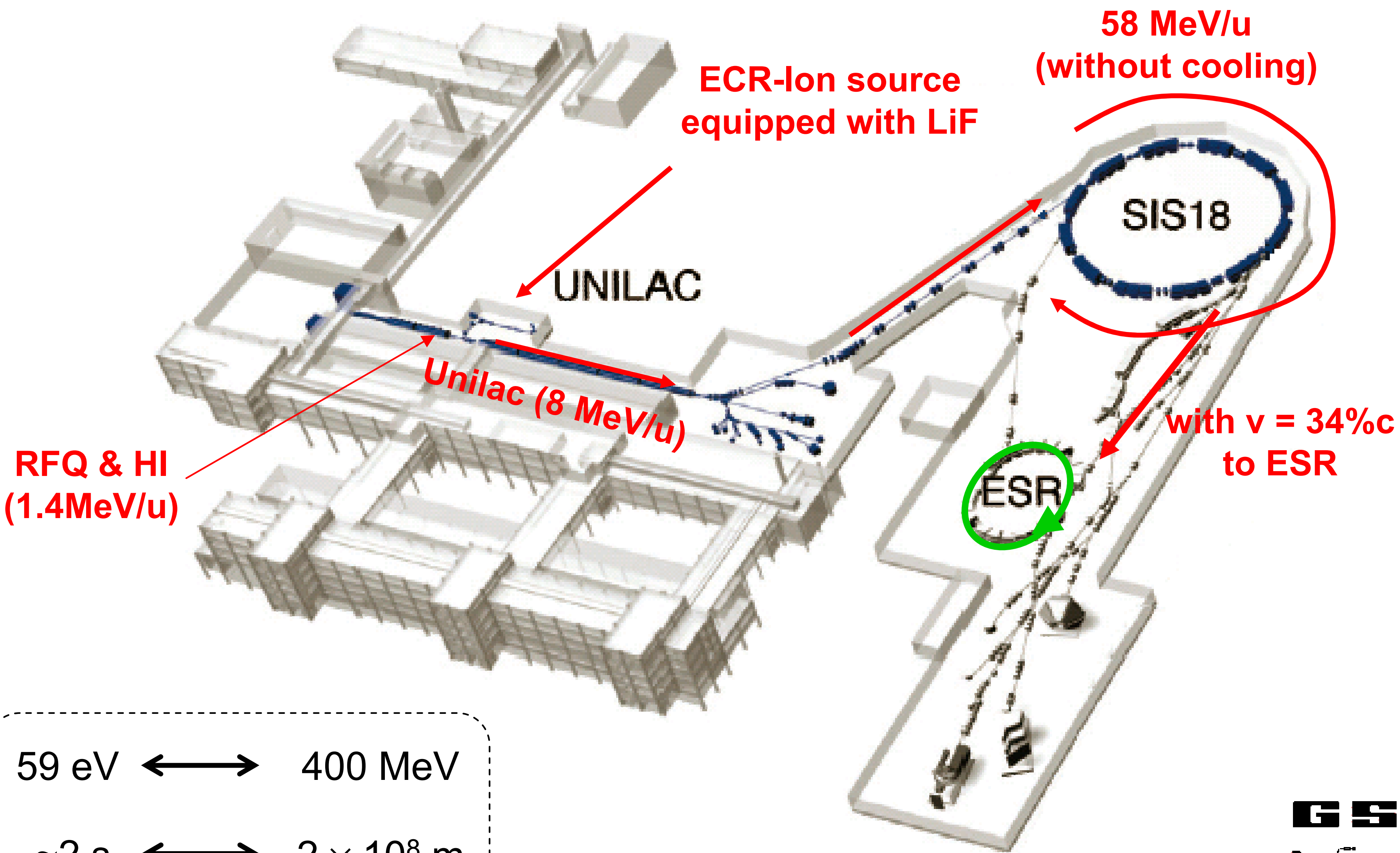


natural line width

3.7 MHz

can be *accelerated* to and *stored* at high velocities with *superb beam qualities*

The GSI Facility

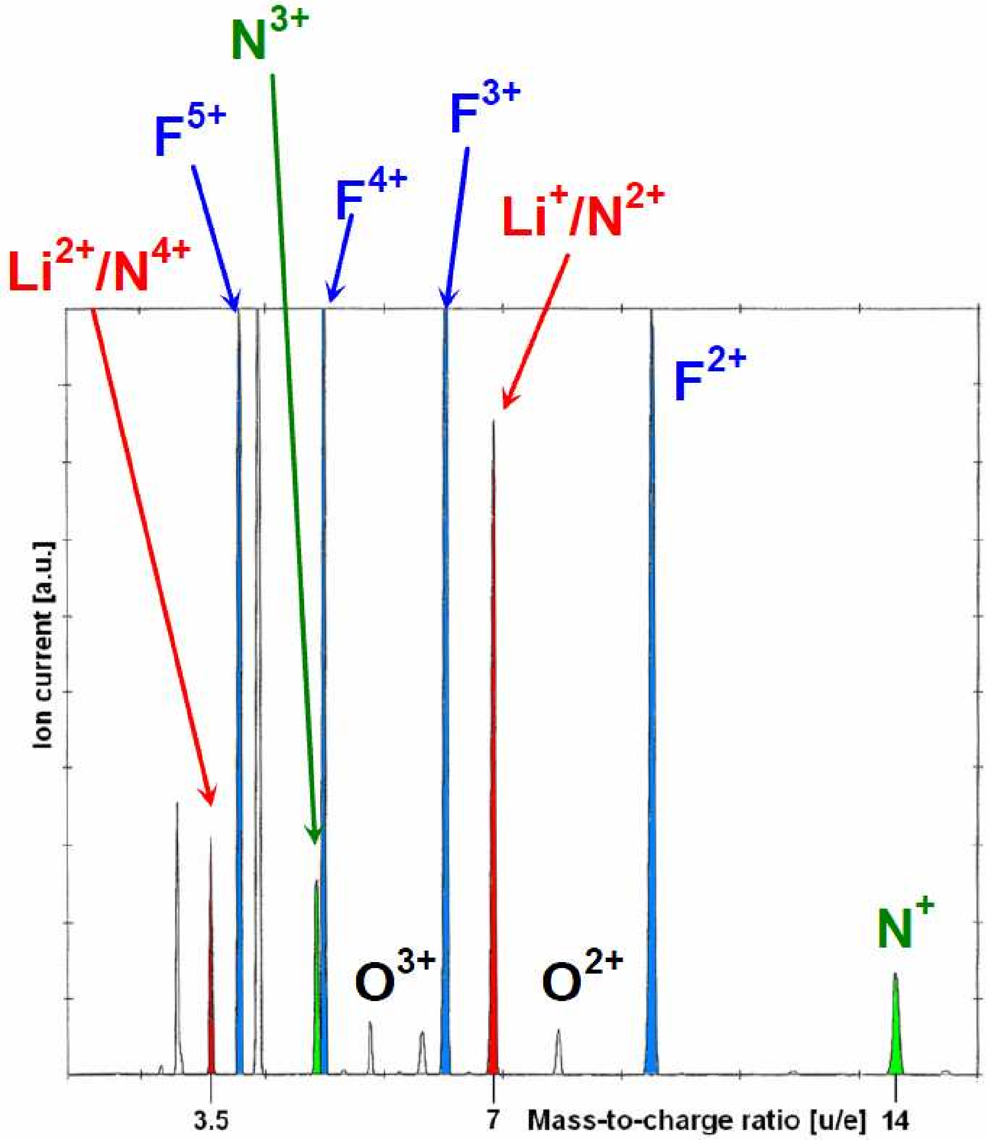


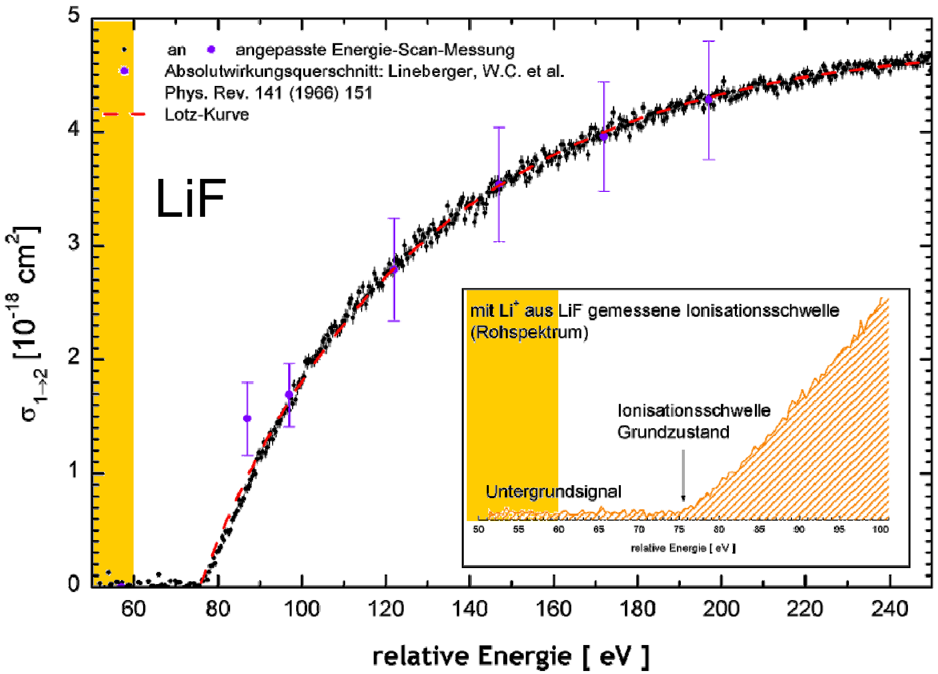
59 eV ⟷ 400 MeV

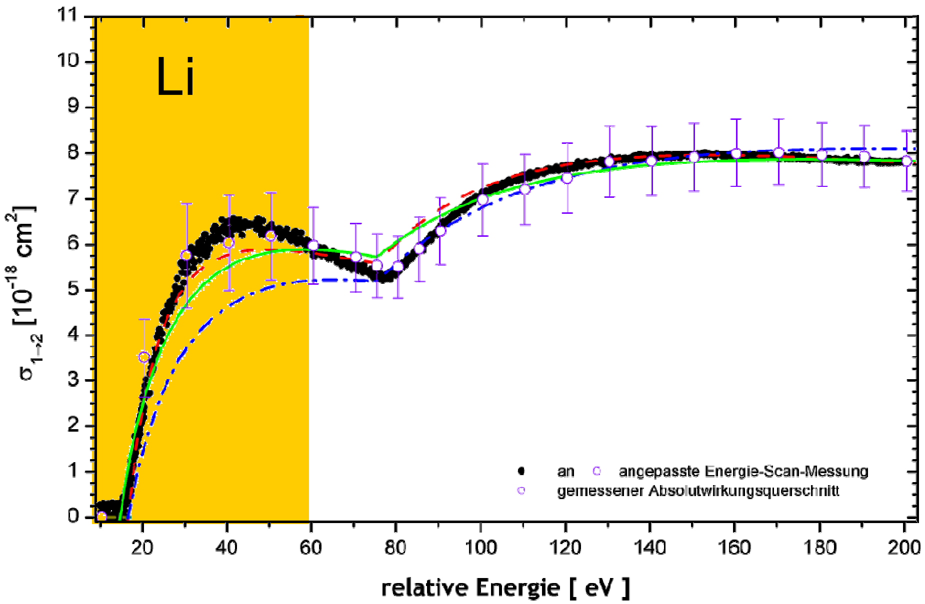
~2 s ⟷ 2×10^8 m

The ECR Ion Source

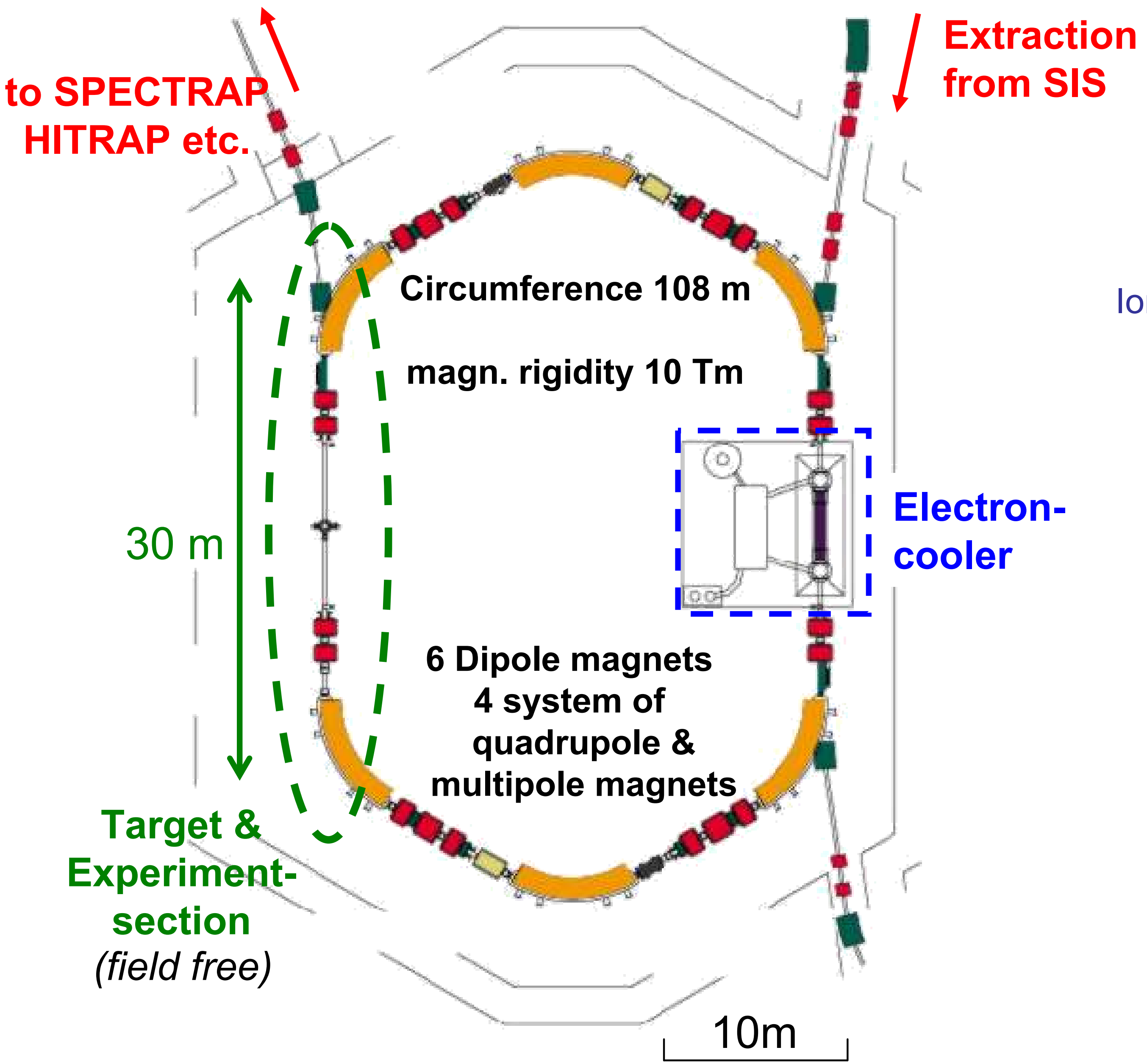
Amount of metastable $^{7}Li^{+}$: < 0.1 ‰







The Experimental Storage Ring ESR

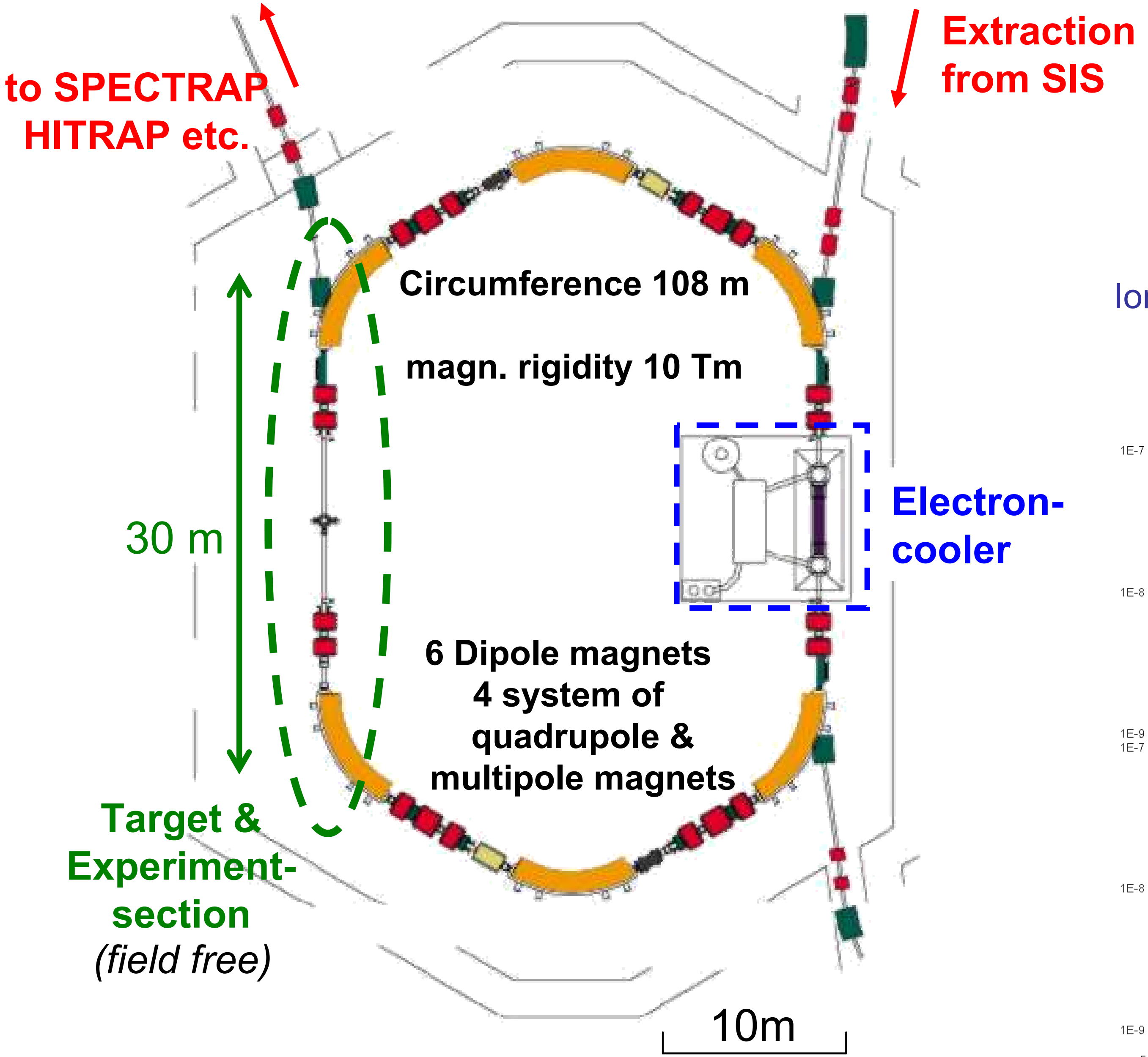


Ion current **~25 µA** **2×10^8 Ions**

Ion beam storage time **τ = 20 s…3 min**

Momentum spread **$\Delta p/p \sim 8 \times 10^{-6}$**

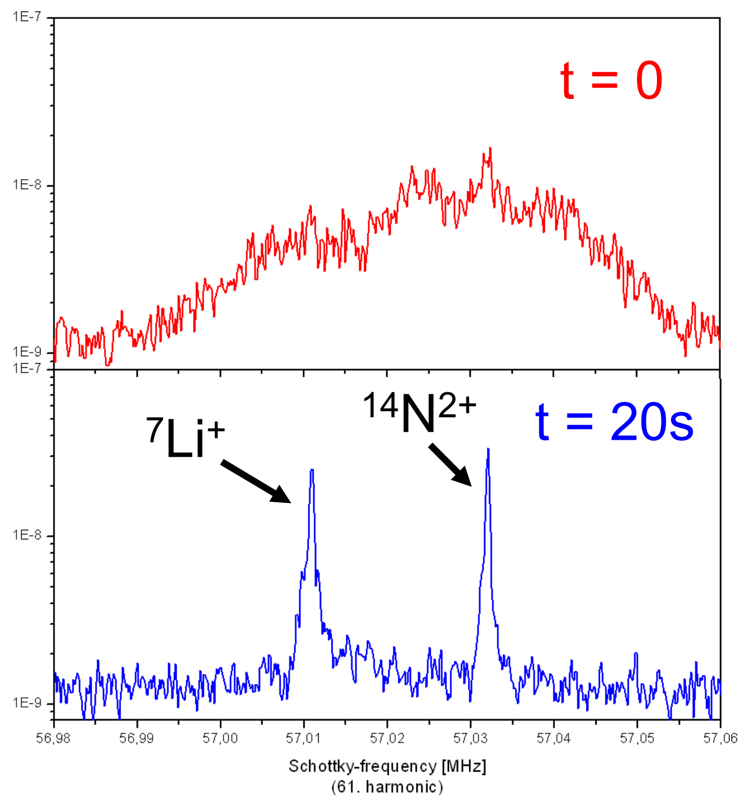
The Experimental Storage Ring ESR



Ion current ~25 µA 2×10^8 Ions

Ion beam storage time τ = 20 s…3 min

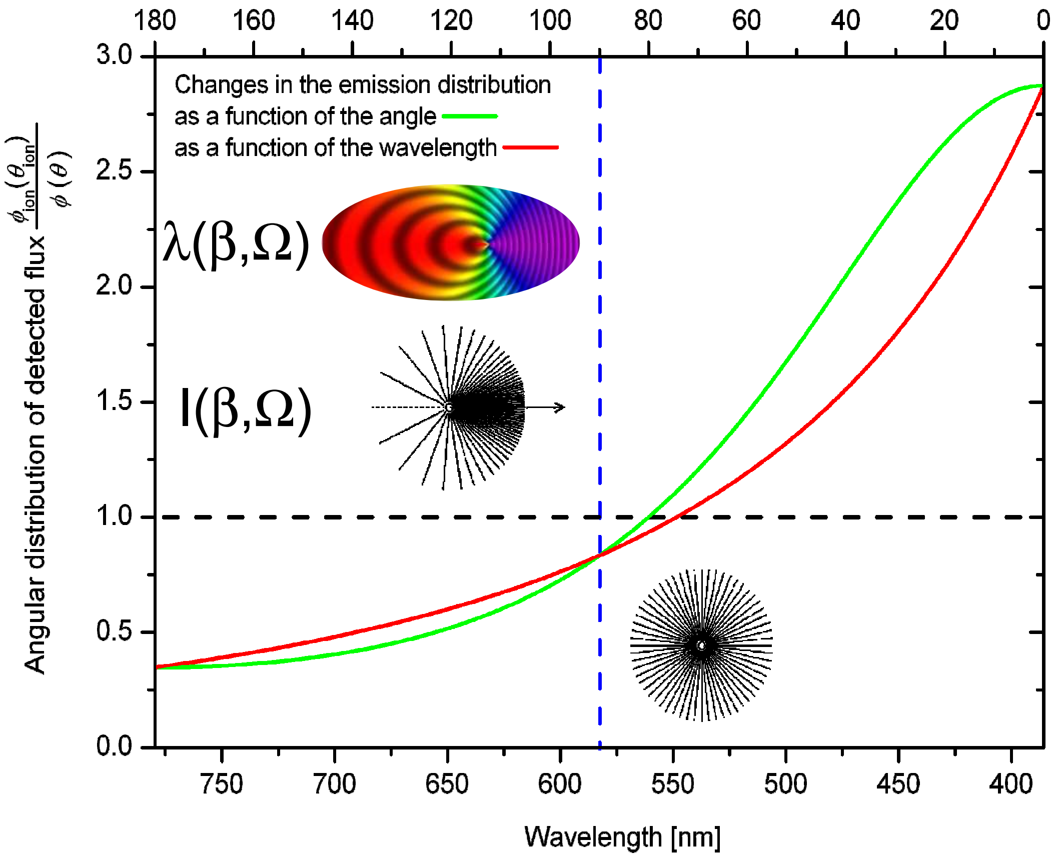
Momentum spread $\Delta p/p \sim 8 \times 10^{-6}$

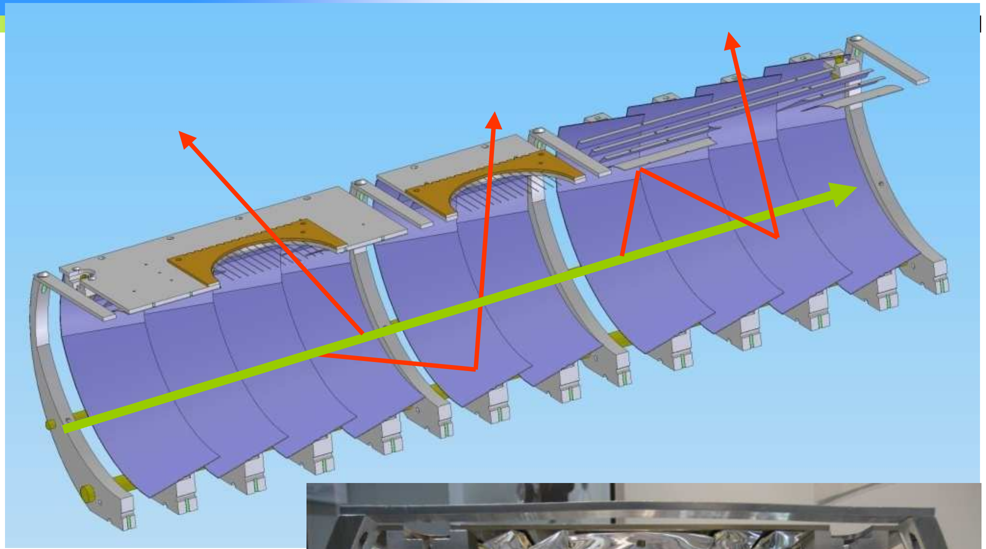


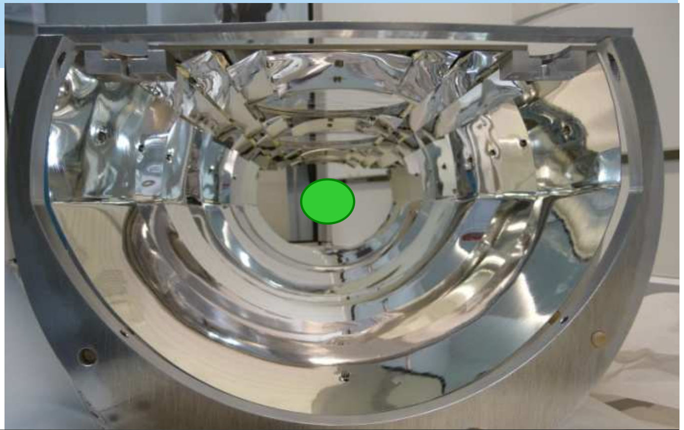
The $^7Li^+$ Ion as an Emitter @ 34 % c

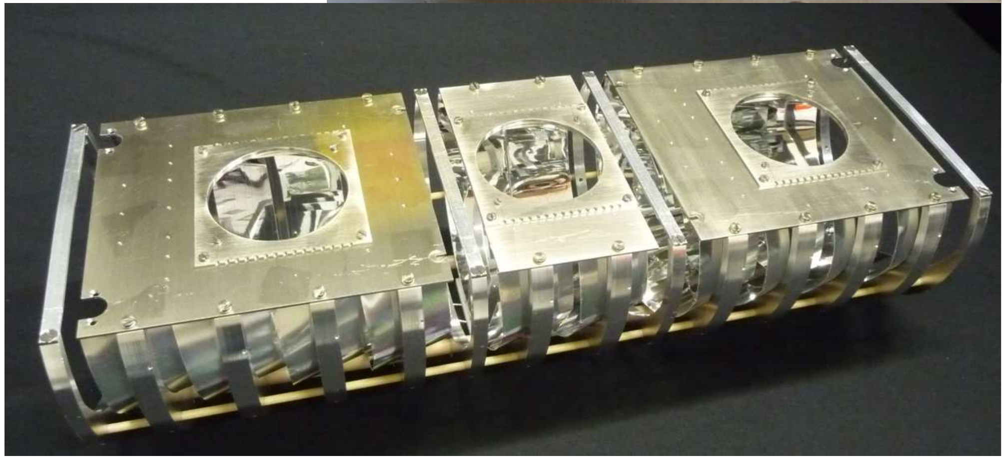
Wavelength & Intensity boost

$$\frac{\phi_{ion}(\theta_{ion})}{\phi(\theta)} = \frac{\left(\sqrt{1-\beta^2}\right)^3}{(1-\beta\cdot\cos\theta)^3}$$

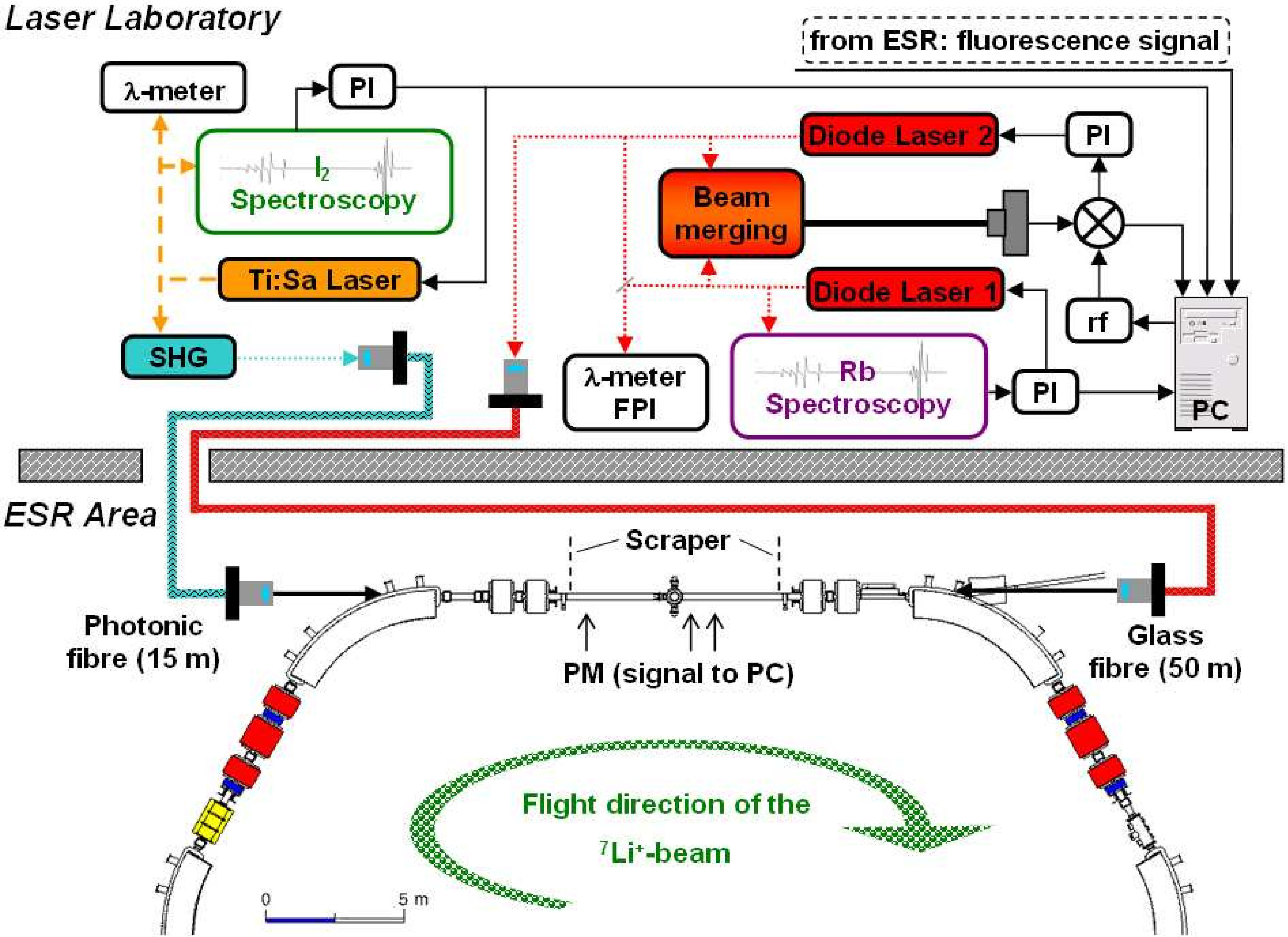




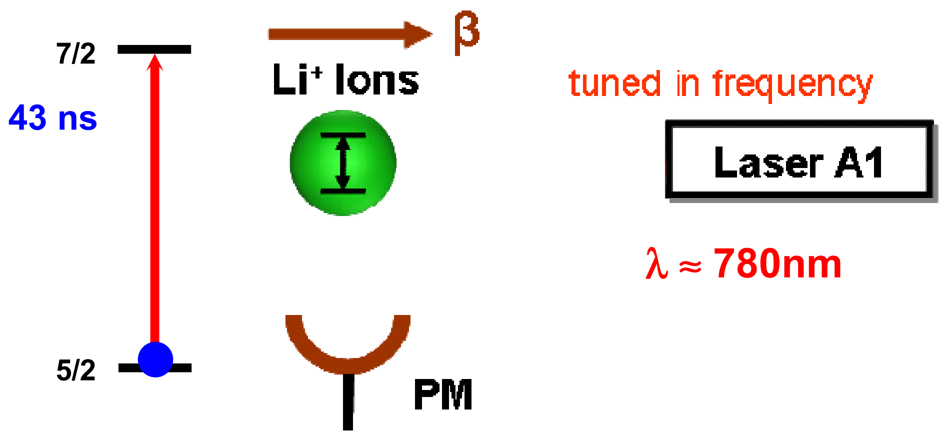


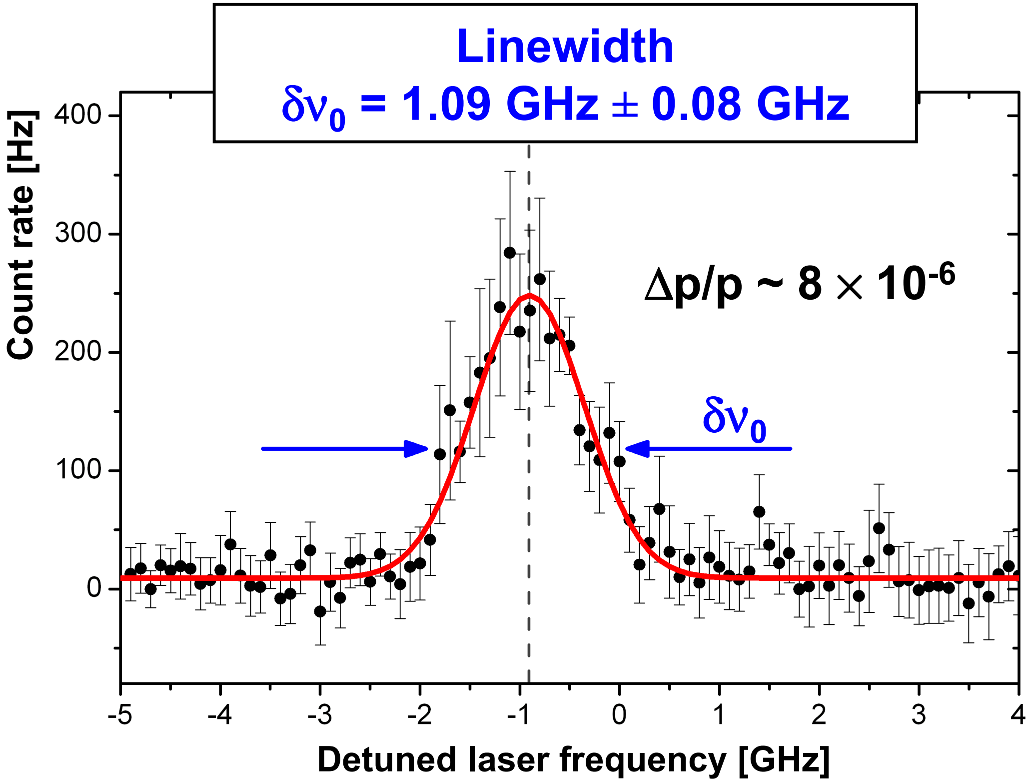


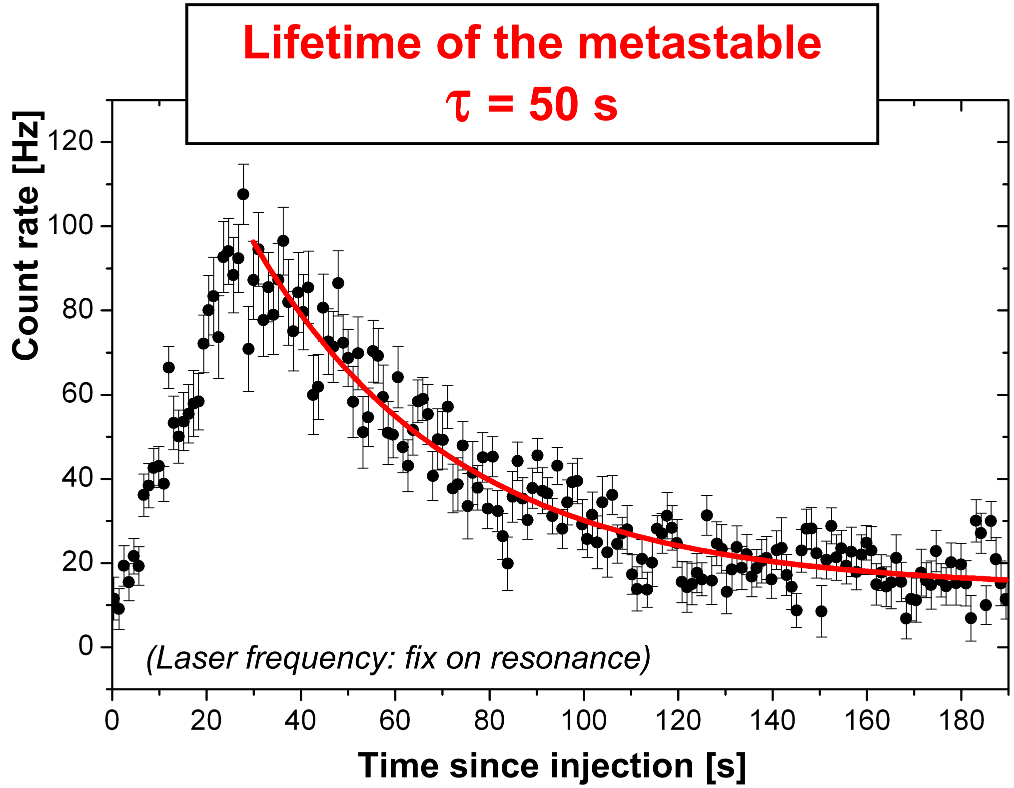
Experimental Setup



Characteristics of the metastable $^7Li^+$





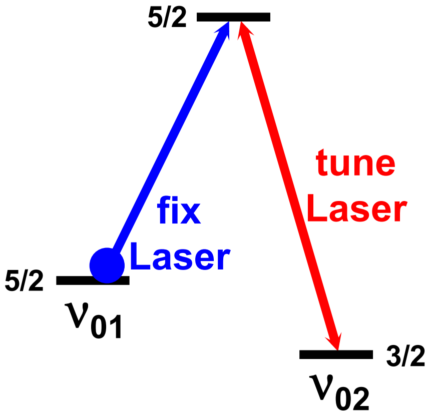


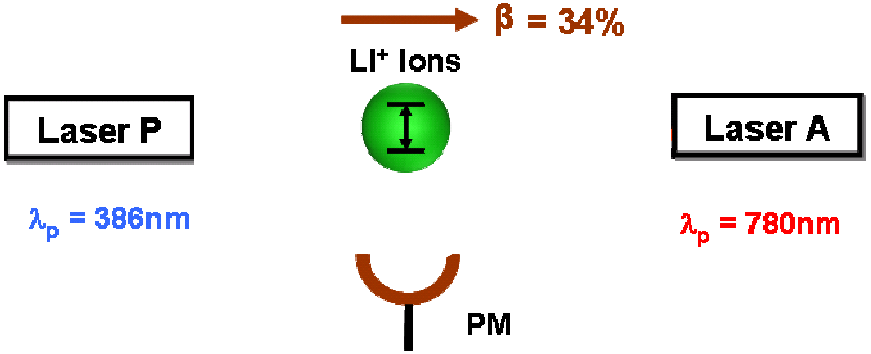
- 0.01 % in the metastable state
- calibration of the electron cooler (100 times more precise than with "on board means")

[Hyperfine Interact. **171** (2006) *57*]

[Can. J. Phys. **87** (2009) *749*]

Test of time dilation



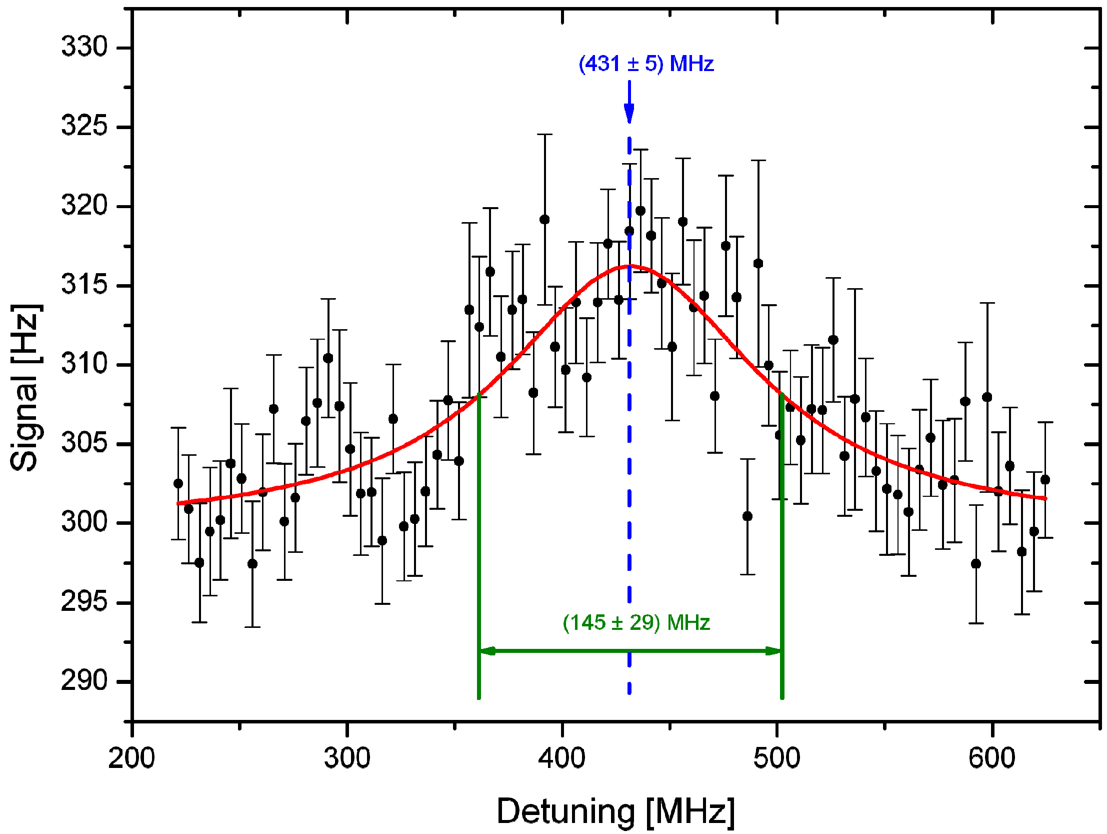


Linewidth

$\delta\nu = (145 \pm 29)$ MHz

Peak position

$\Delta\nu = \pm 5$ MHz



$\nu_a = (384\,225\,614 \pm 6)$ MHz

$\nu_p = (777\,210\,167 \pm 1)$ MHz

$\nu_{01} = (546\,455\,144.8 \pm 0.3)$ MHz

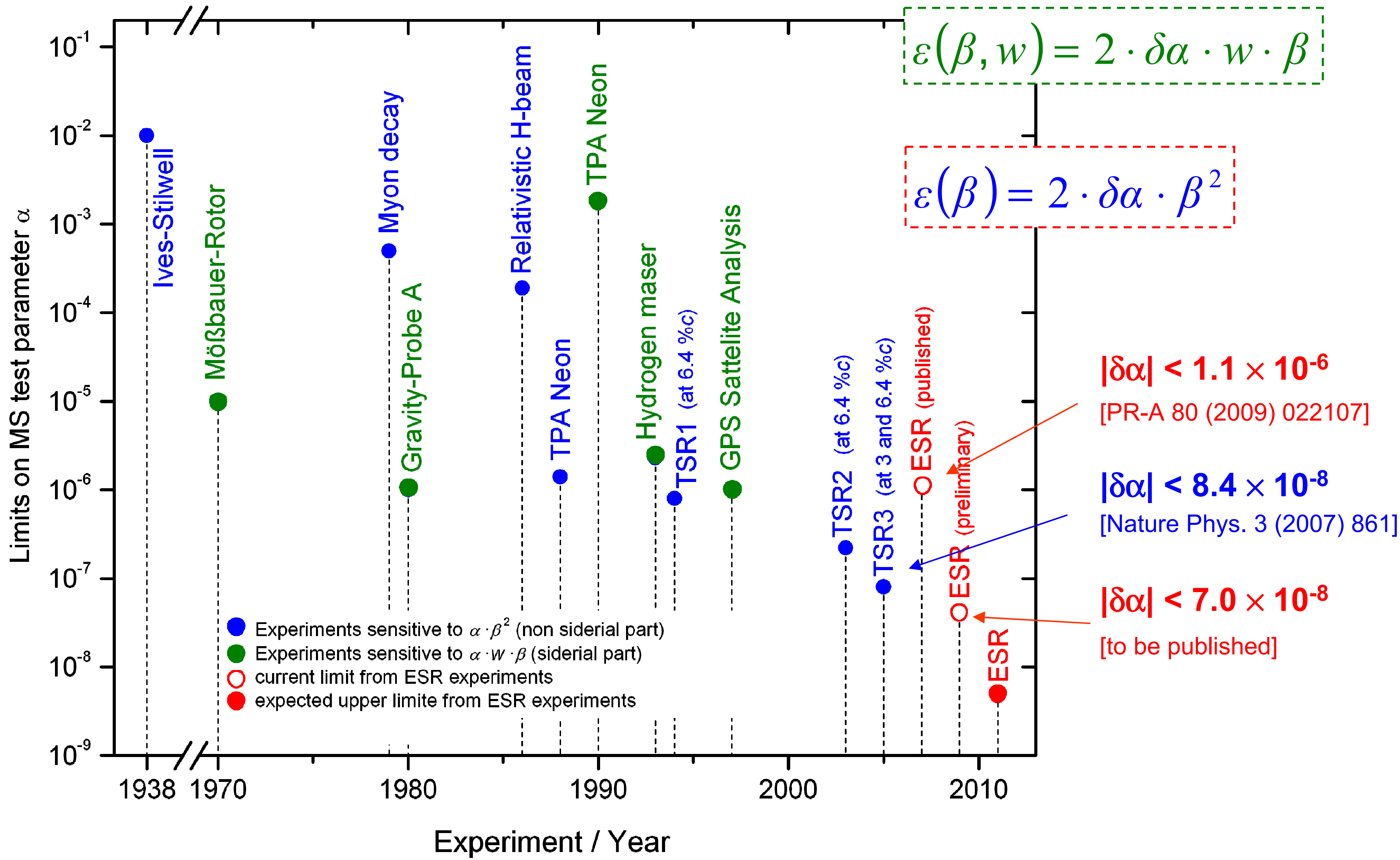
$\nu_{02} = (546\,474\,962.7 \pm 0.3)$ MHz

$$\frac{\nu_p \cdot \nu_a}{\nu_{01} \cdot \nu_{02}} = 1 + \varepsilon(\beta)$$

$\varepsilon(\beta) = (0.3 \pm 1.6) \times 10^{-8}$

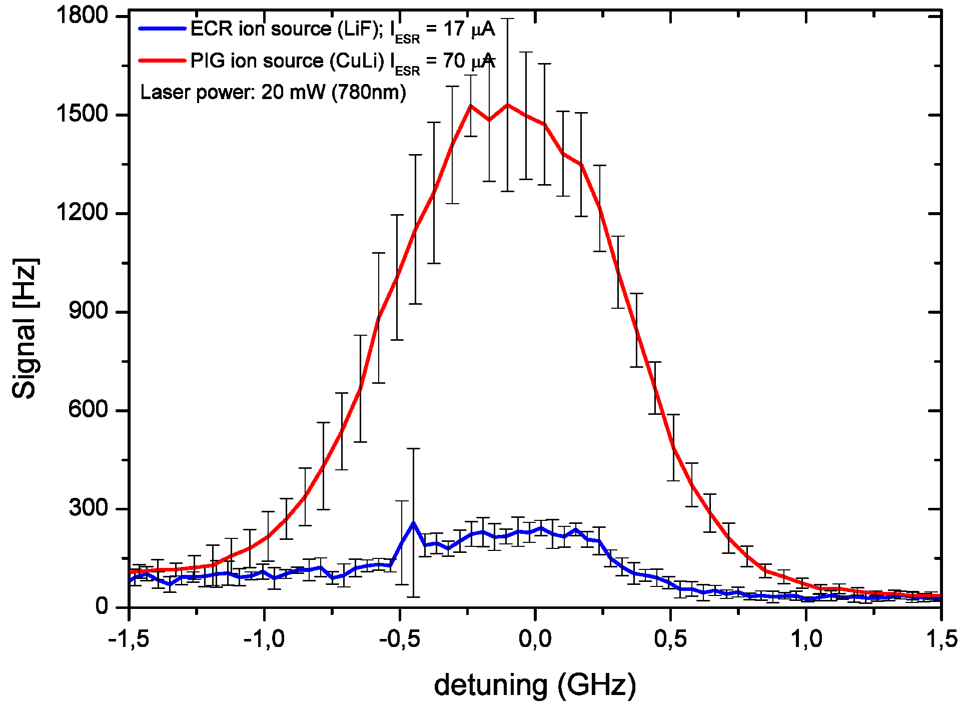
[PR-A 80 (2009) *022107*]

Limits for Hypothetical Deviations

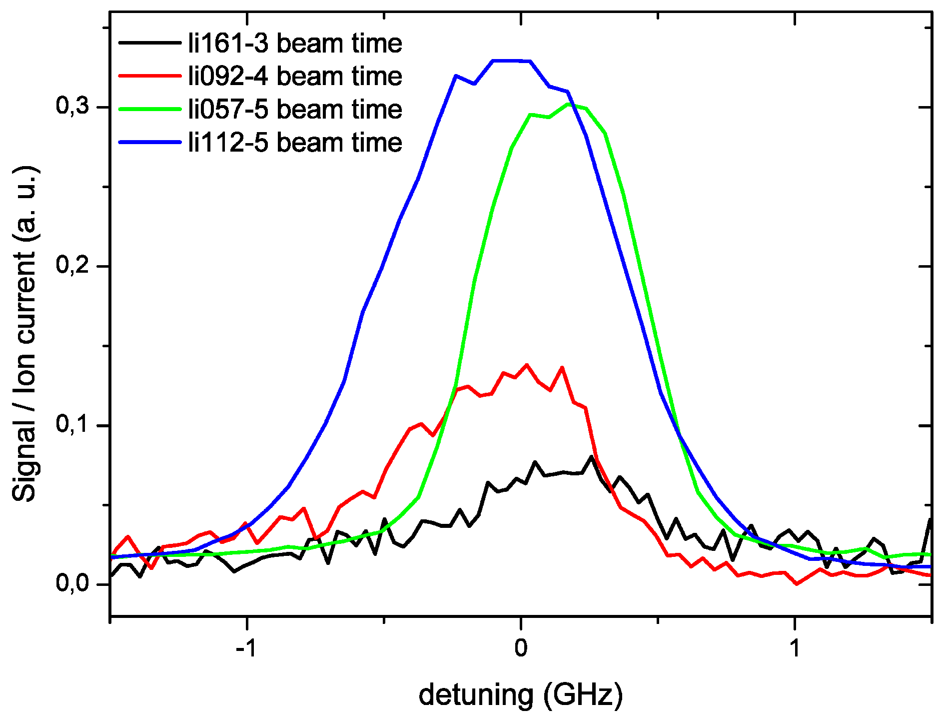


Improvement of Metastable Production

Absolut Signal



normalized to DC-Trafo



	EZR (LiF)*	PIG (CuLi)
Ion current :	10...30 µA	60...100 µA
Count rate (peak) :	300 Hz	1500 Hz
Number of Ions :	~1 ×10^8	< 6 ×10^8
Fraction of metastable Ions :	2...3 ×10^{-4}	6...8 ×10^{-4}

*** Not qauntified Fraction of N^{2+}**

Conclusions SRT

- ✓ **one can test LI via measurement of three frequencies**
- ✓ **first Doppler-free spectroscopy on high relativistic particles**
- ✓ **on the same level as the leading experiment (10^{-8})**
- ✓ ***waiting for beamtime !!***

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

GSI

3

MAX-PLANCK-INSTITUTE OF QUANTUM OPTICS GARCHING MPQ

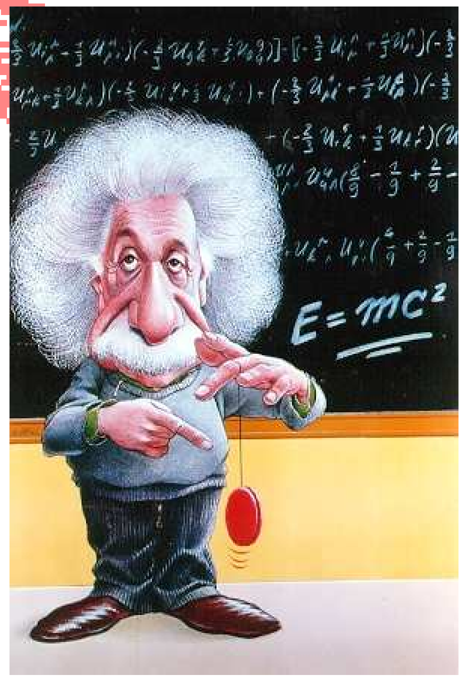
4

5

UNIVERSITY OF MANITOBA

Max-Planck-Institut für Kernphysik

2



SRT: The team

D. Bing[2], B. Botermann[1], G. Ewald[3], C. Geppert[2], G. Gwinner[5], T. W. Hänsch[4], R. Holzwarth[4], G. Huber[1], H.-J. Kluge[3], T. Kühl[1,3], W. Nörtershäuser[1,3], D. Schwalm[2], T. Stöhlker[3], T. Udem[4], A. Wolf[2]

1 JOHANNES GUTENBERG UNIVERSITÄT MAINZ

2 Max-Planck-Institut für Kernphysik

3 GSI

4 MAX-PLANCK-INSTITUTE OF QUANTUM OPTICS GARCHING MPQ

5 UNIVERSITY OF MANITOBA

The E083 Collaboration (LIBELLE)

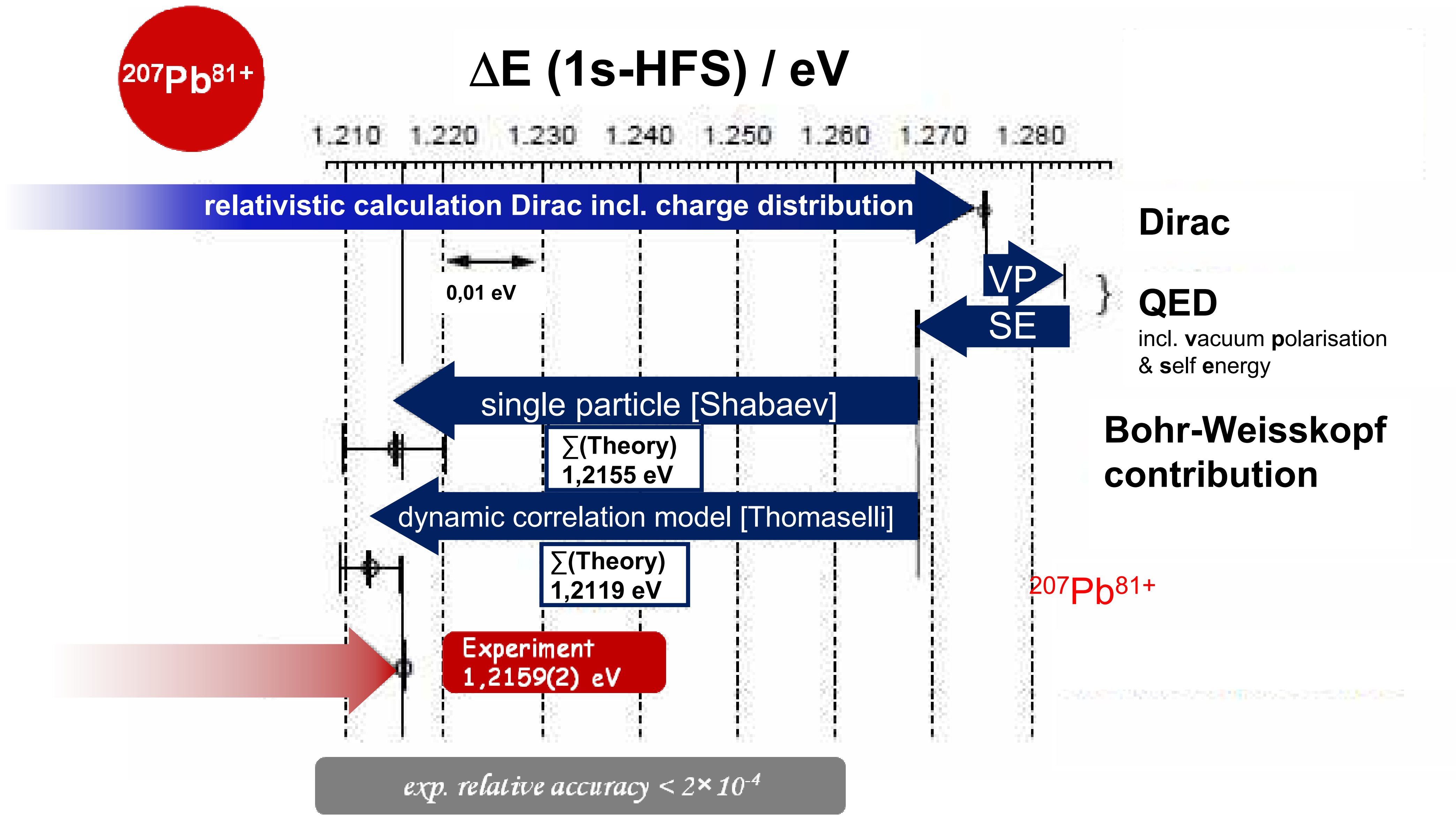
M. Lochmann[1,3], D. Anielski[4], C. Brandau[3], D. Church[5], A. Dax[9], Ch. Geppert[1,3], V. Hannen[4], G. Huber[2], Th. Kühl[3], Ch. Novotny[2], R. Sánchez[1,3], D. Schneider[6], V. Shabaev[7], Th. Stöhlker[3,10], R. C. Thompson[8], A. Volotka[11,7], Ch. Weinheimer[4], D.F.A. Winters[10], W. Nörtershäuser[1,3]

[1]*Institut für Kernchemie, Johannes Gutenberg-Universität Mainz* — [2]*Institut für Physik, Johannes Gutenberg-Universität Mainz* — [3]*GSI Helmholtzzentrum für Schwerionenforschung GmbH* — [4]*Institut für Kernphysik, Westfälische Wilhelms-Universität Münster* — [5]*Department of Physics, Texas A&M University* — [6]*Ernest Orlando Lawrence Berkeley National Laboratory (LBNL)* — [7]*Department of Physics, St. Petersburg State University* — [8]*Department of Physics, Imperial College London* — [9]*Department of Physics, University of Tokyo* — [10]*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg* — [11]*Institut für Theoretische Physik, TU Dresden*

LIBELLE (Dragonfly)

Lithium-like Bismuth Excitation with Laser Light at the ESR

QED Tests with M1-Transitions in Hydrogenlike Ions



P. Seelig et al., PRL 81 (1998)
P. Seelig, PhD thesis Mainz/GSI 1999

Disentangling QED and nuclear structure

H-like:

$$\Delta E^{(1s)} = \Delta E^{(1s)}_{\mathrm{Dirac}}(1 - \varepsilon^{(1s)}) + \Delta E^{(1s)}_{\mathrm{QED}} ,$$

Li-like:

$$\Delta E^{(2s)} = \Delta E^{(2s)}_{\mathrm{Dirac}}(1 - \varepsilon^{(2s)}) + \Delta E_{\mathrm{int}}(1 - \varepsilon^{(\mathrm{int})}) + \Delta E^{(2s)}_{\mathrm{QED}} + \Delta E_{\mathrm{int\text{-}QED}} .$$

It can be shown that the ratios

$$\frac{\varepsilon^{(2s)}}{\varepsilon^{(1s)}} = f(\alpha Z)$$

and

$$\frac{\varepsilon^{(\mathrm{int})}}{\varepsilon^{(2s)}} = f_{\mathrm{int}}(\alpha Z) .$$

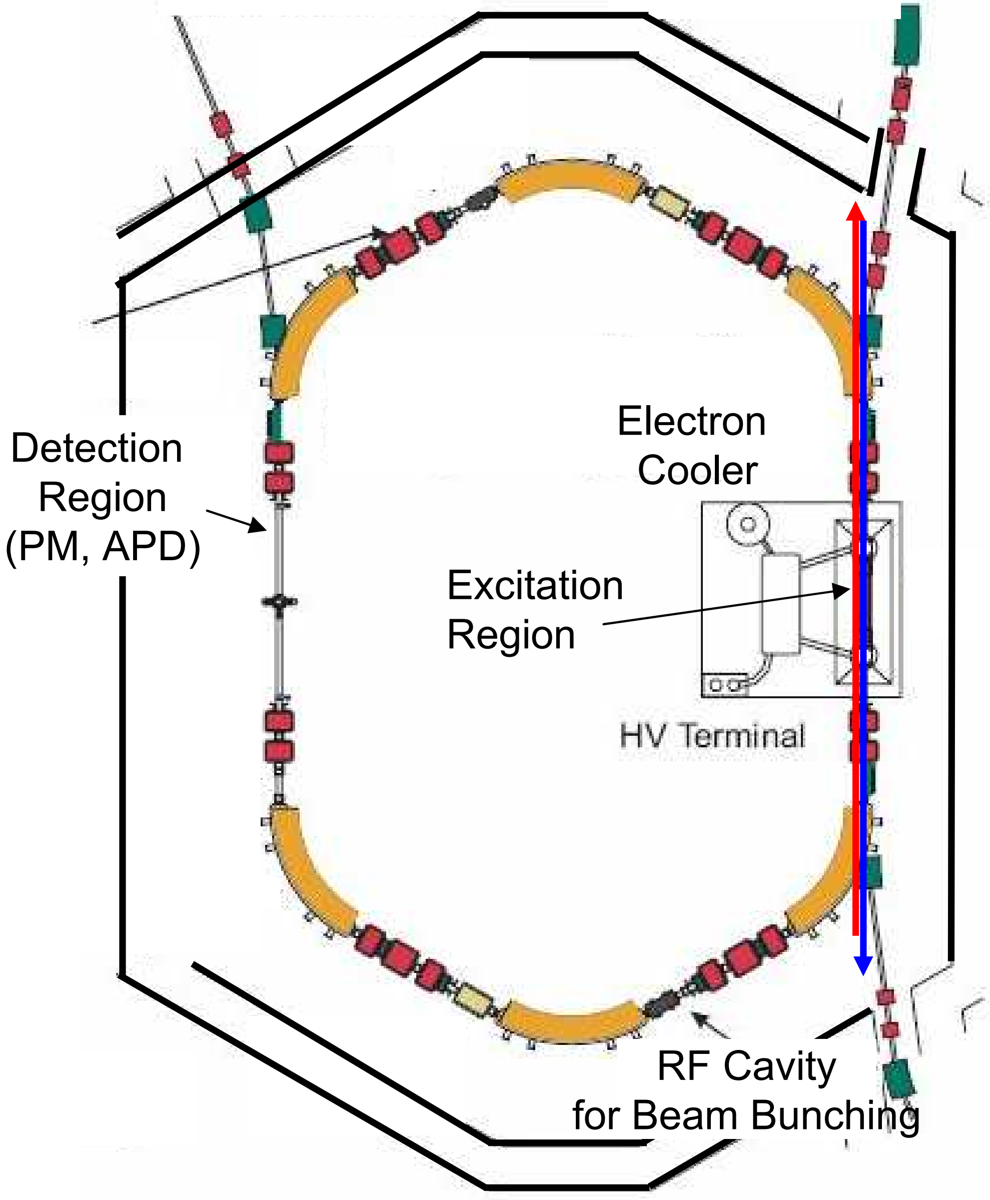
can be calculated to rather high accuracy and is almost independent of the nuclear structure ⇒ Bohr-Weisskopf effect cancels !

Knowing the hyperfine splitting in the H-like ion, the HFS in the Li-like ion can be predicted with high accuracy!

Shabaev *et al.*, PRL **86** 3959 (2001)

ESR: Doppler-Assisted Laser Spectroscopy

Principle:



Doppler Shift:

$$\lambda_{\mathrm{Lab}}^{\uparrow\downarrow} = \lambda_0 \frac{1}{\gamma\,(1+\beta)}$$

$$\lambda_{\mathrm{Lab}}^{\uparrow\uparrow} = \lambda_0 \frac{1}{\gamma\,(1-\beta)}$$

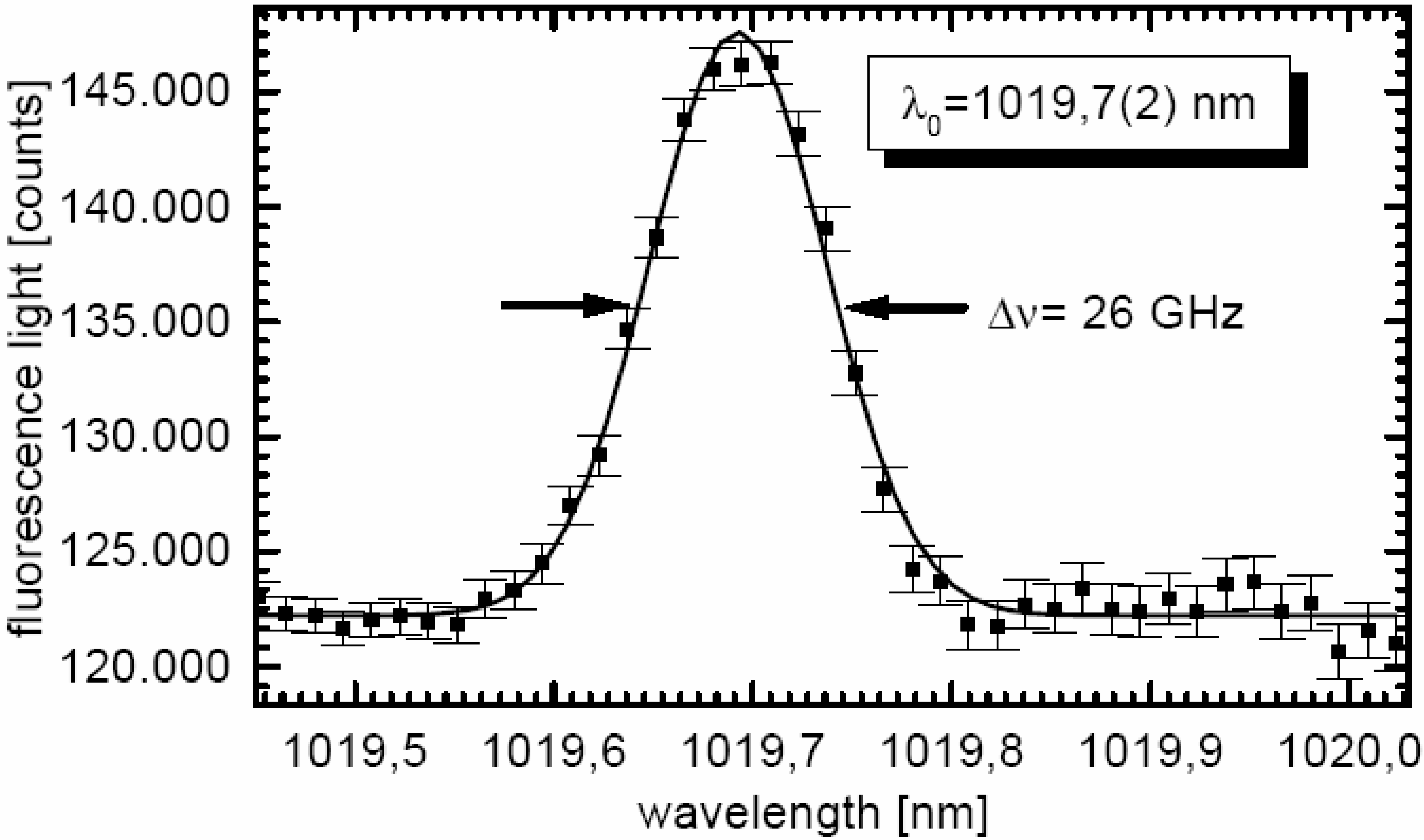
Examples:

$^{207}Pb^{80+}$: λ_0 = 1020 nm
β = 0.57 (211 MeV/u)
λ_{Lab} = 532 nm

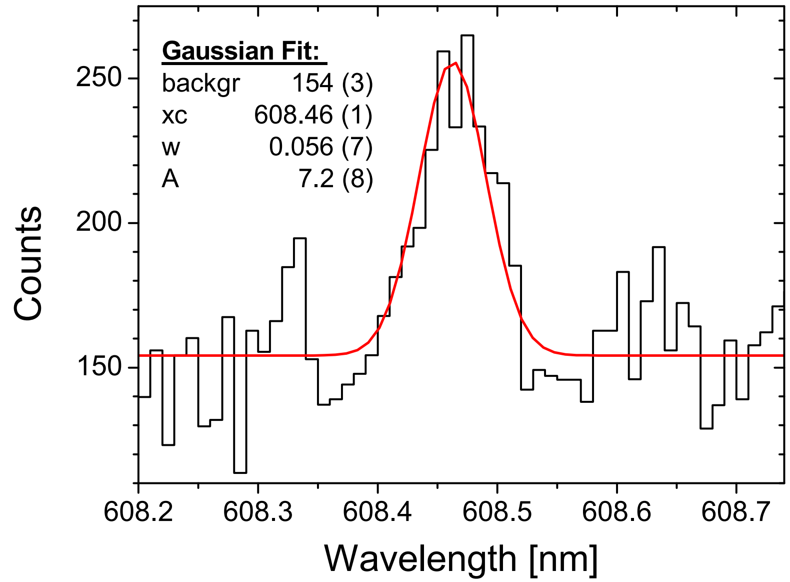
$^{209}Bi^{82+}$: λ_0 = 250 nm
β = 0.59 (218 MeV/u)
λ_{Lab} = 489 nm

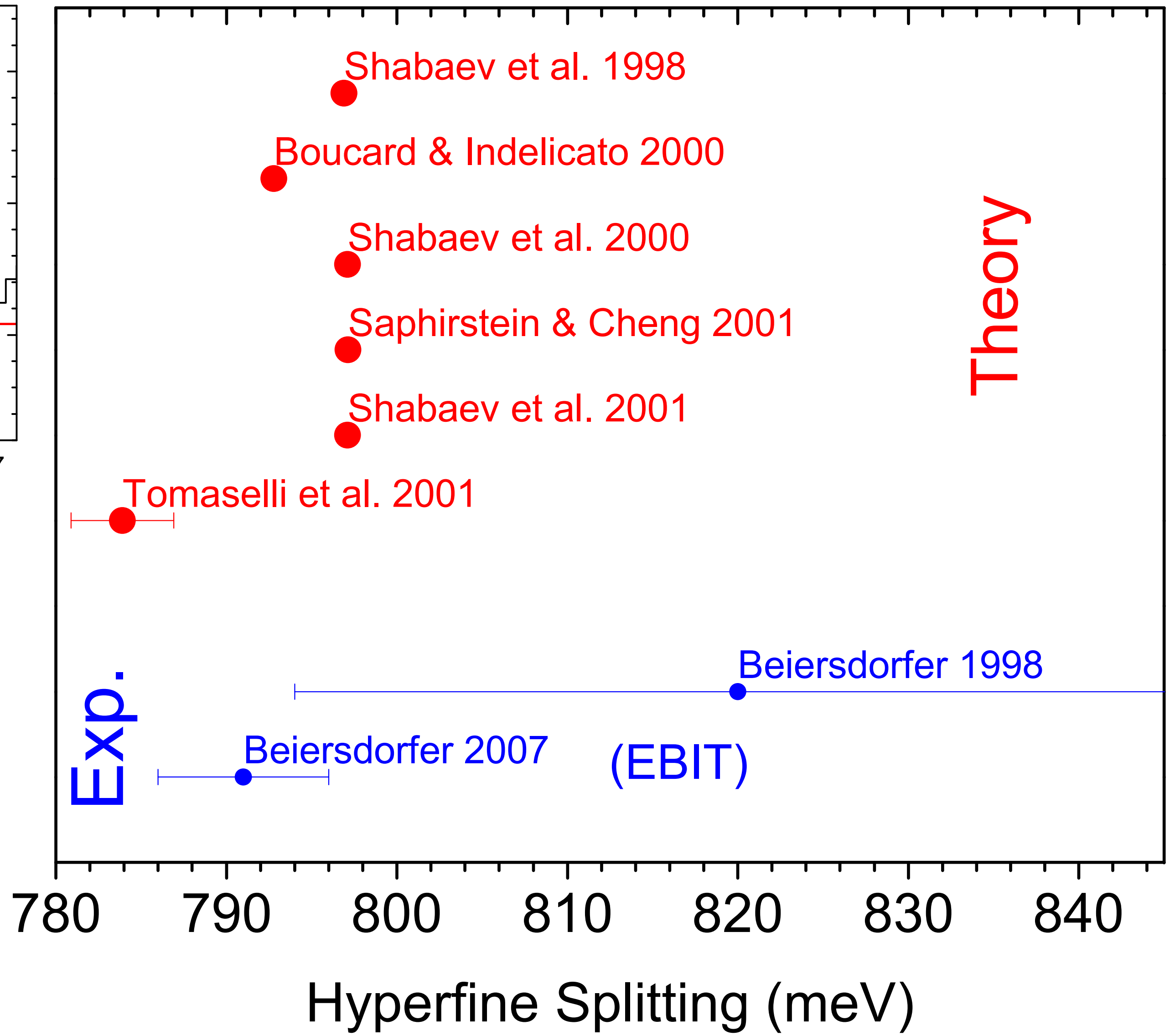
Hyperfine Splitting in Hydrogen-Like Pb^{81+}

ΔE_{HFS} = 1.2159(2) eV



Status for Li-Like $^{209}Bi^{82+}$

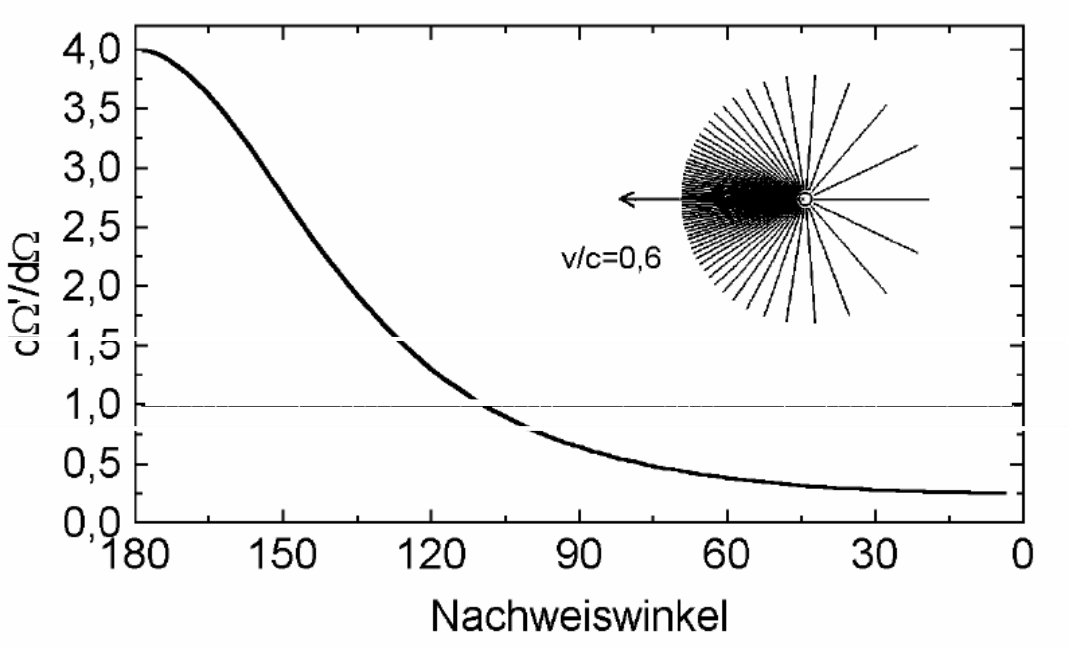


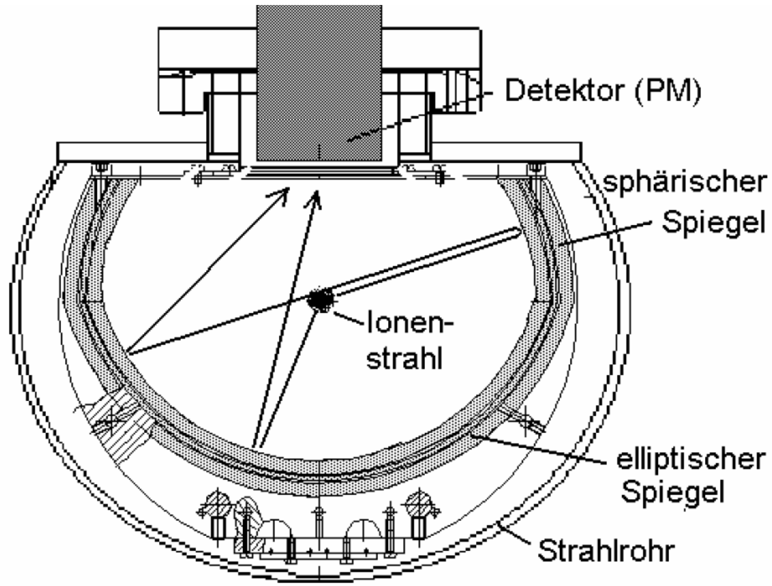


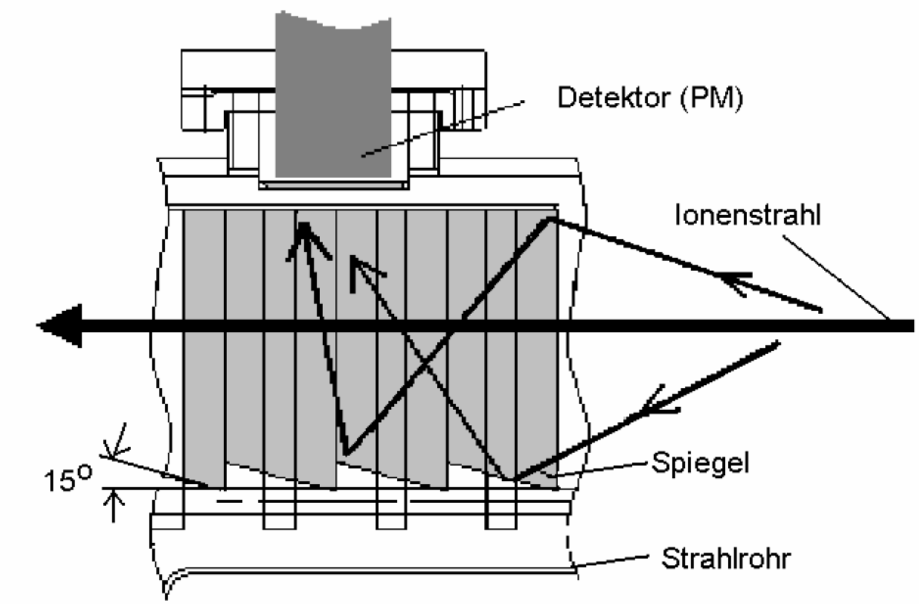
Hyperfine Transition in Li-like Bismuth $^{209}Bi^{80+}$ not found yet. (3 Trials at the ESR)

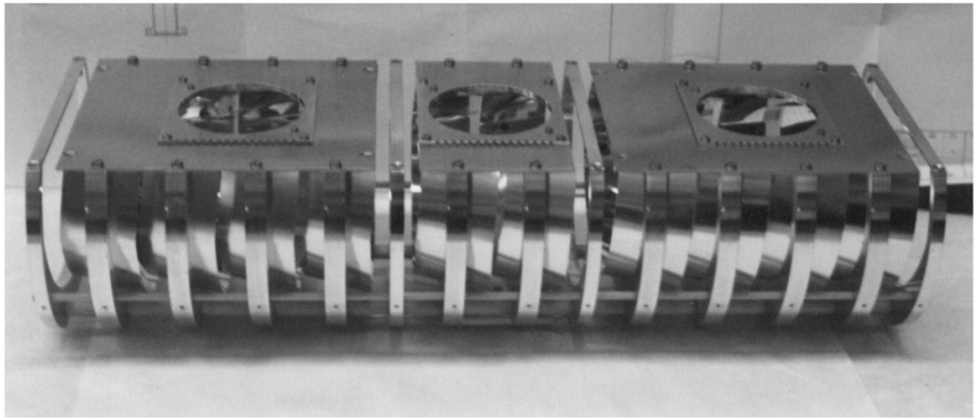
P. Beiersdorfers Result (Beiersdorfer 2007) still not published.

Fluorescence Detection at Relativistic Velocities

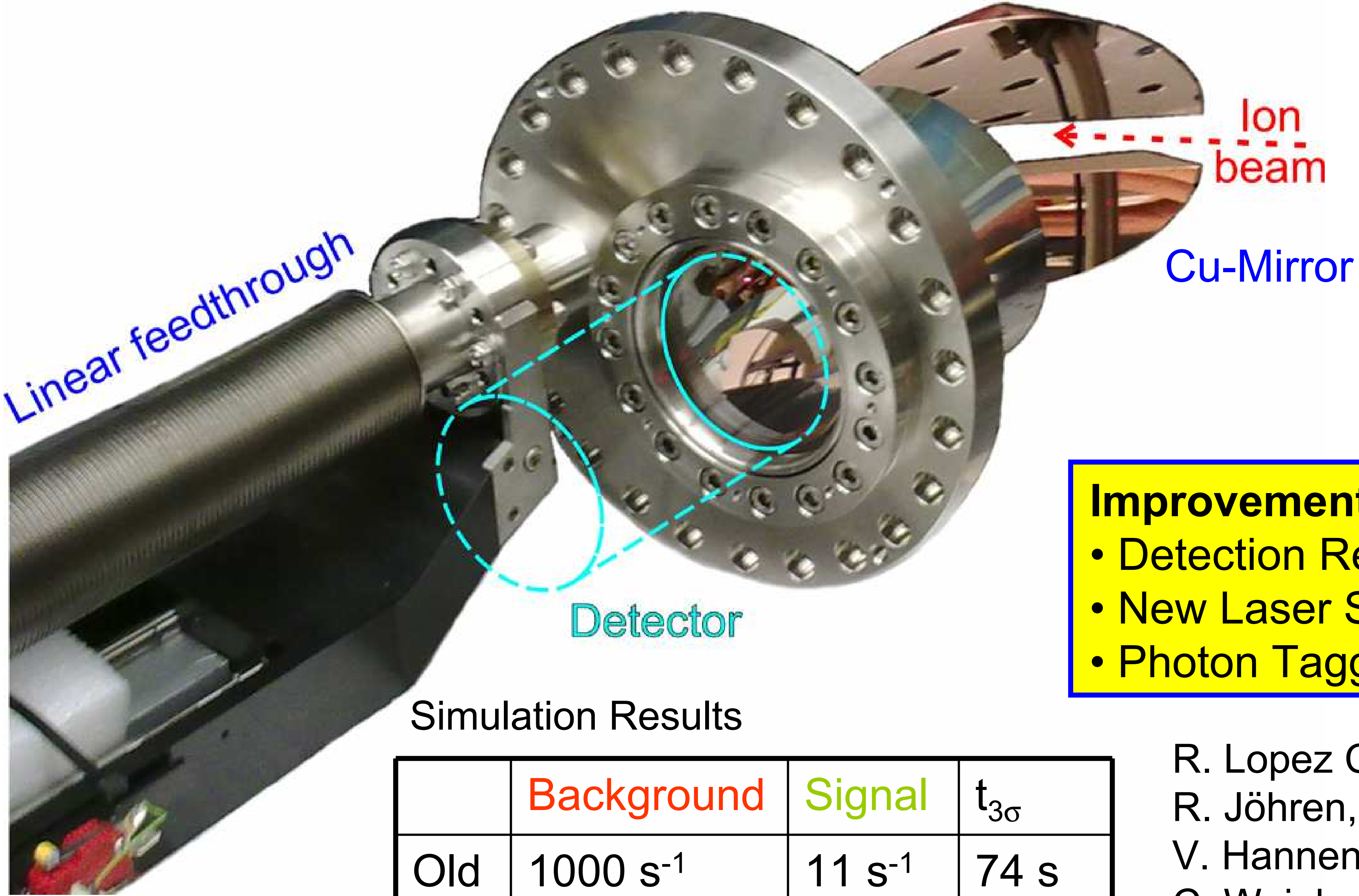








New Detection Device for ESR Spectroscopy



Improvements
- Detection Region
- New Laser System
- Photon Tagging

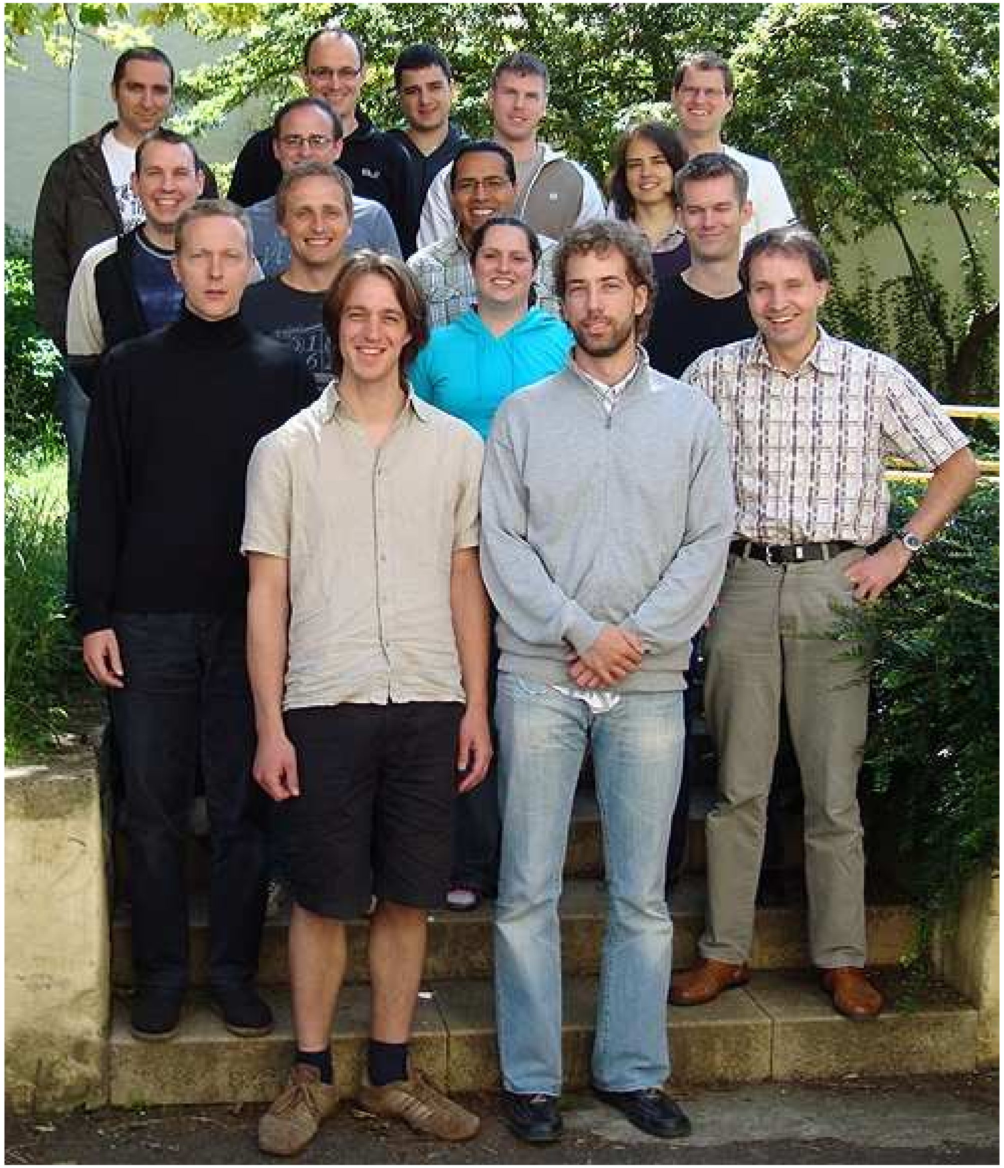
Simulation Results

	Background	Signal	$t_{3\sigma}$
Old	1000 s^{-1}	11 s^{-1}	74 s
new	160 s^{-1}	45 s^{-1}	0,7 s

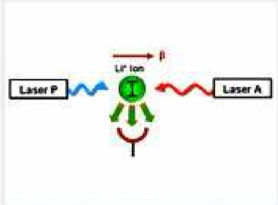
R. Lopez Coto,
R. Jöhren,
V. Hannen,
C. Weinheimer
Universität Münster

LaserSpHERe

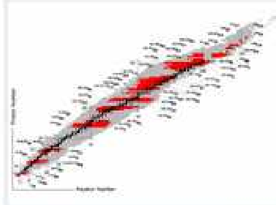
Laser SpHERe



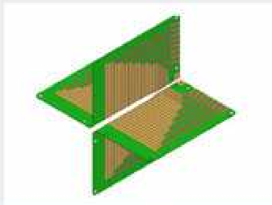
ToPLIS



Test der SRT am ESR



Laserspektroskopie on-line

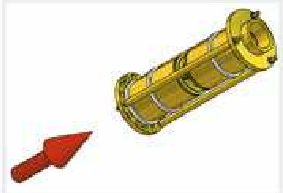


BeTINa

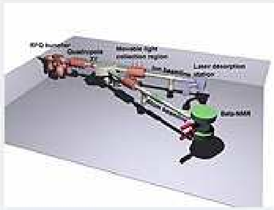
Laser Spektroskopie an

Laser SpHERe

hochgeladenen Ionen und **e**xotischen **r**adioaktiven Nukliden

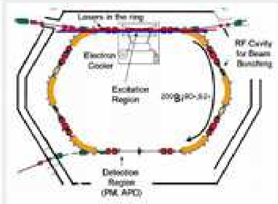


SpecTrap



LaSpec

TRIGA-LASER



Lithiumähnliches Bismut

http://www.uni-mainz.de/FB/Chemie/AK-Noertershaeuser/

Funding :

HELMHOLTZ GEMEINSCHAFT

Bundesministerium für Bildung und Forschung

Deutsche Forschungsgemeinschaft DFG

HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

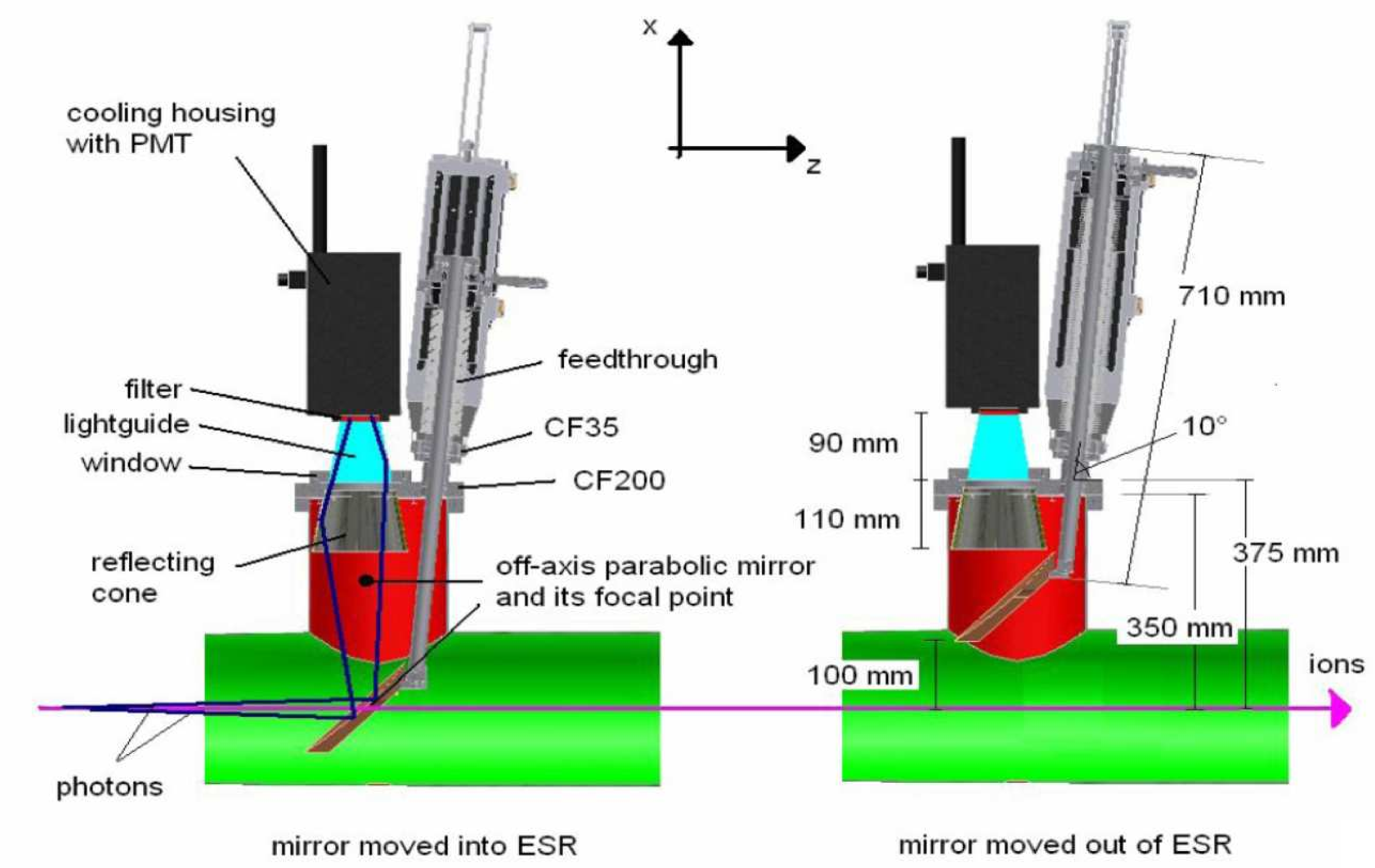
HELMHOLTZ Institut Mainz

emg

Stiftung Rheinland-Pfalz für Innovation

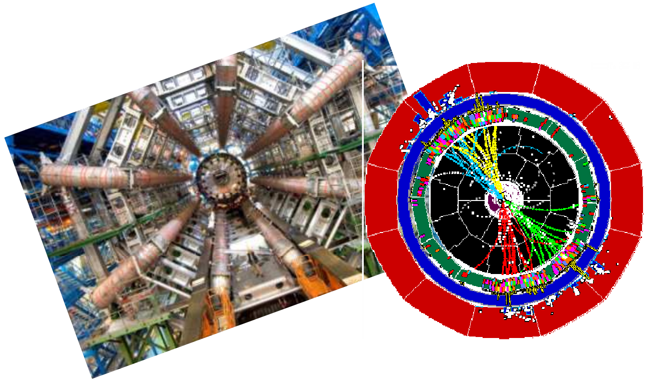
Carl Zeiss Stiftung

New Detection Device for ESR Spectroscopy



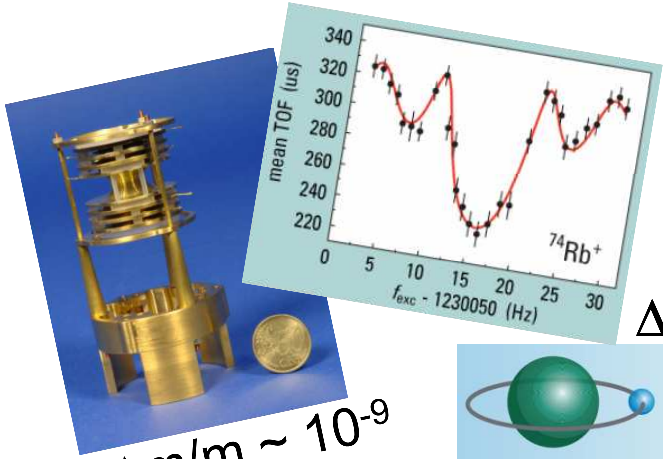
Fundamental Tests

Highest Energies



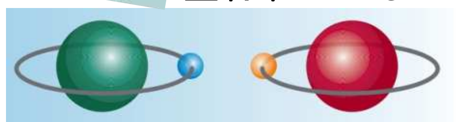
E_{kin} ~ 14 TeV

Highest precision experiments on “cold particles”



$\Delta m/m \sim 10^{-9}$

$\Delta\nu/\nu \sim 10^{-14}$



H $\bar{H}$

Time Dilation / Doppler Effect

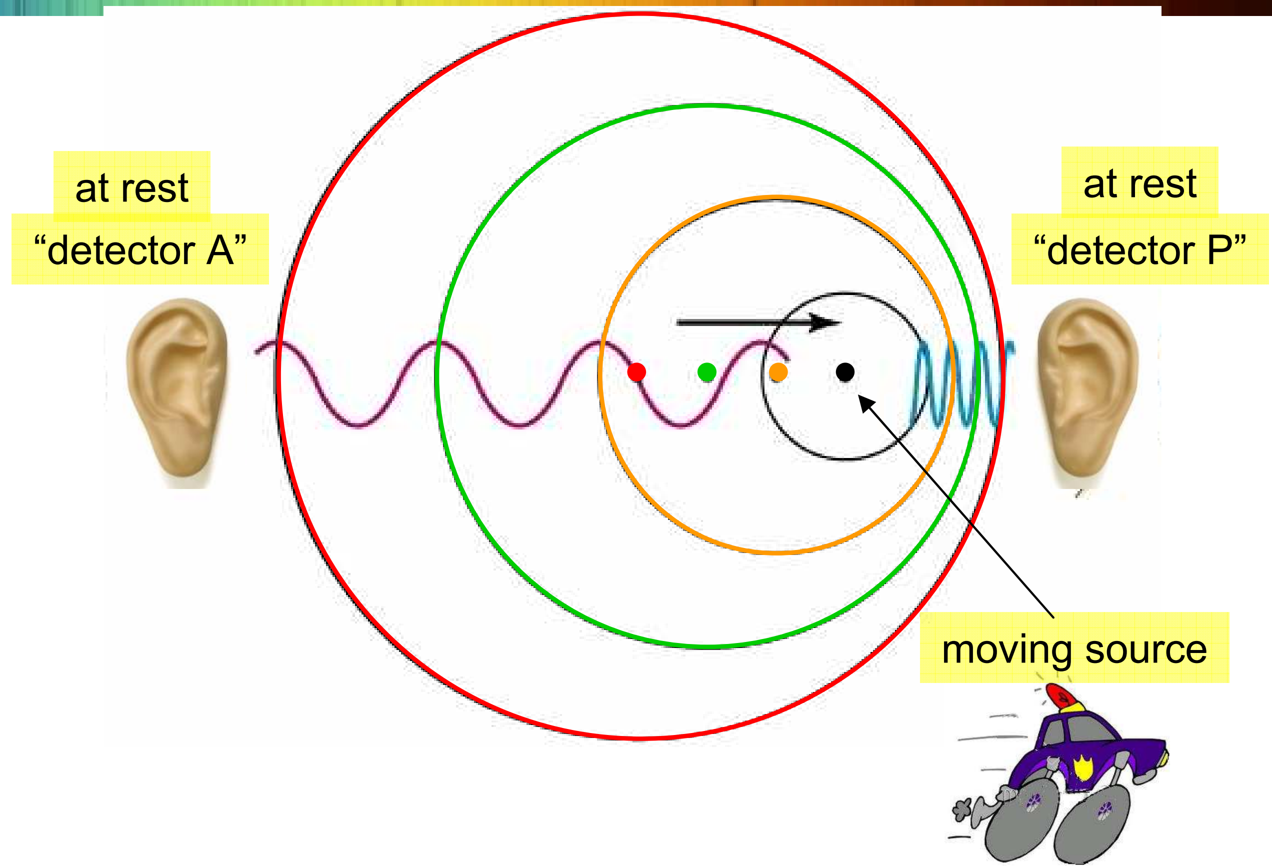
classical (acoustic)

$$(t)^{-1} = \nu = \frac{\nu_0}{\left(1 \pm \frac{\upsilon}{c}\right)}$$

emitted source frequency (at rest) : ν_0

in flight direction : $\nu_p > \nu_0$

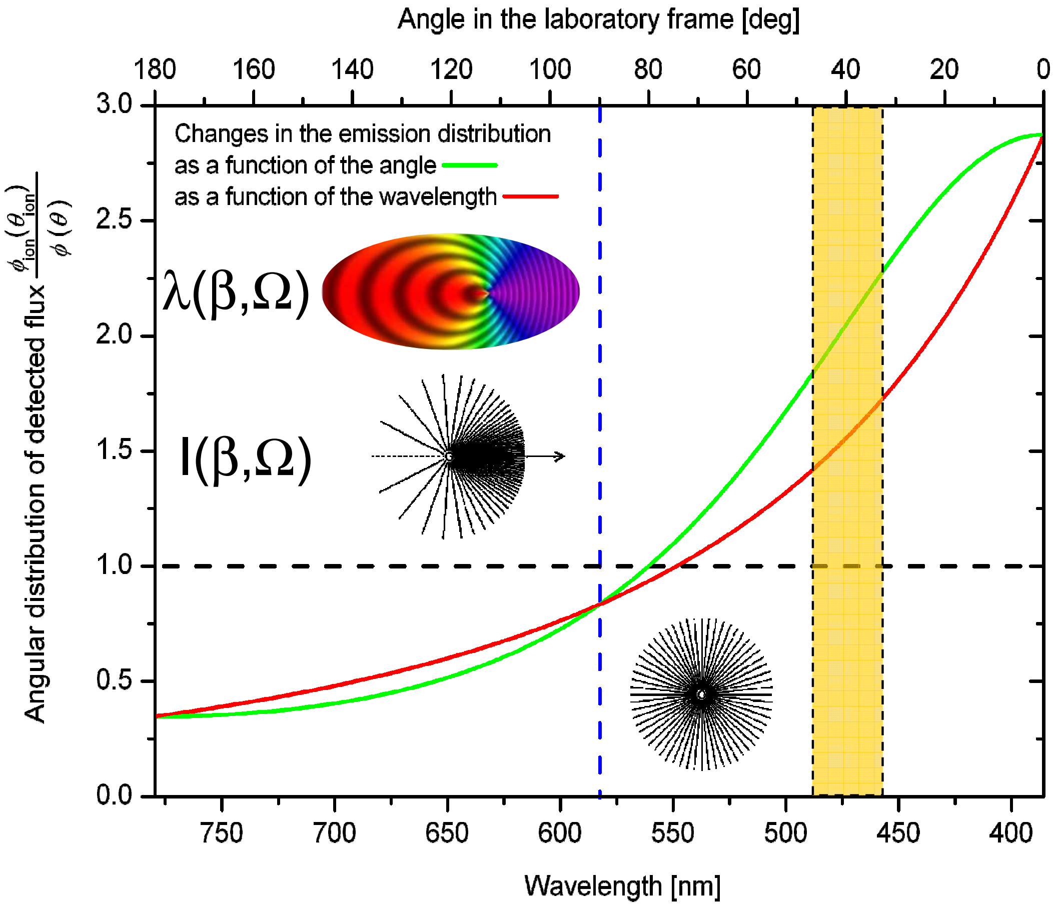
against direction : $\nu_a < \nu_0$

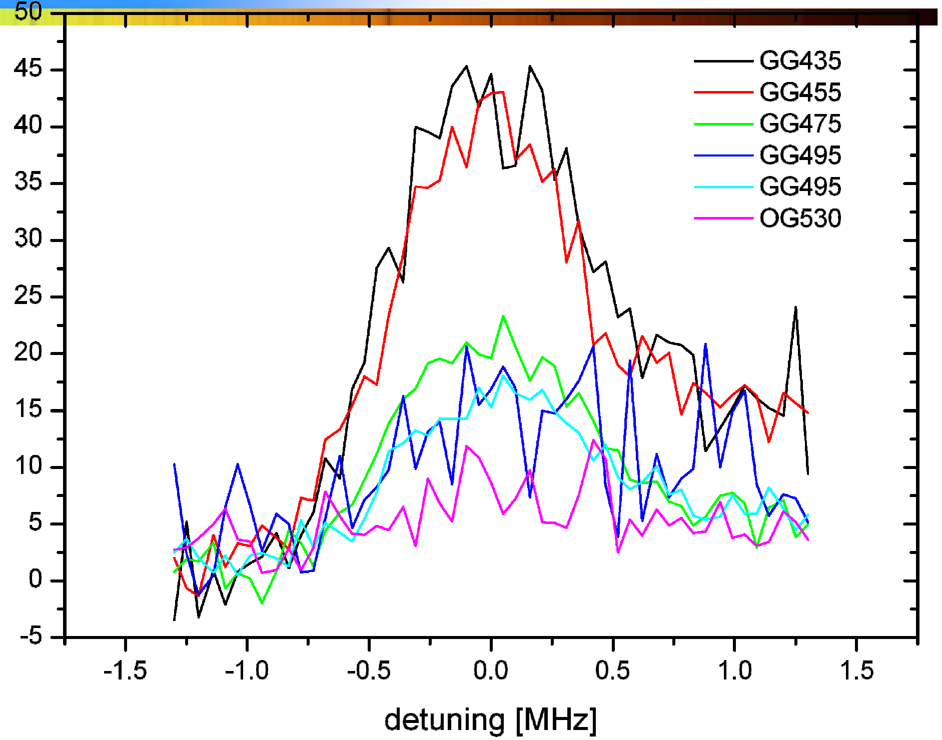


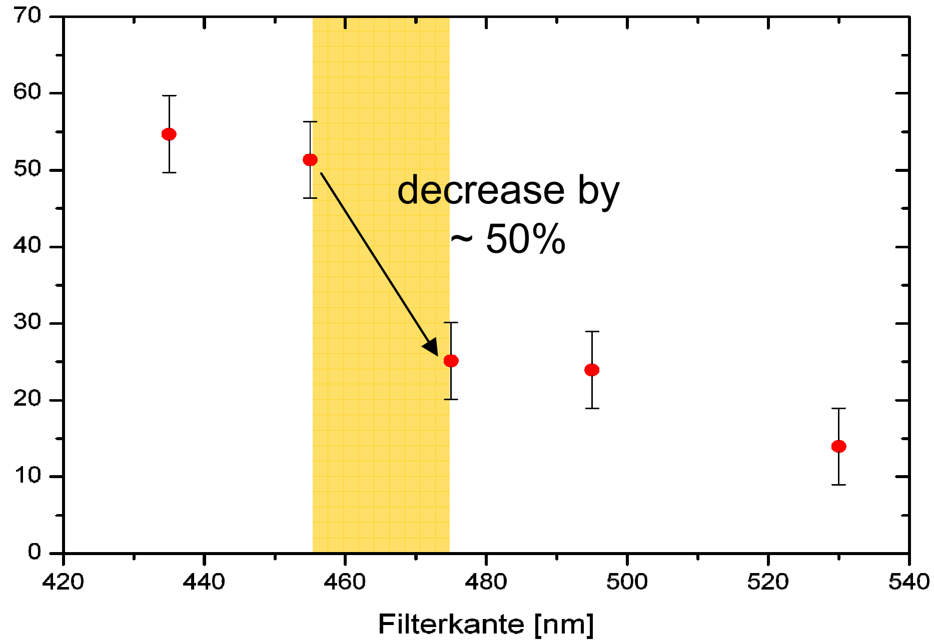
The $^7Li^+$ Ion as an Emitter @ 34 % c

Wavelength & Intensity boost

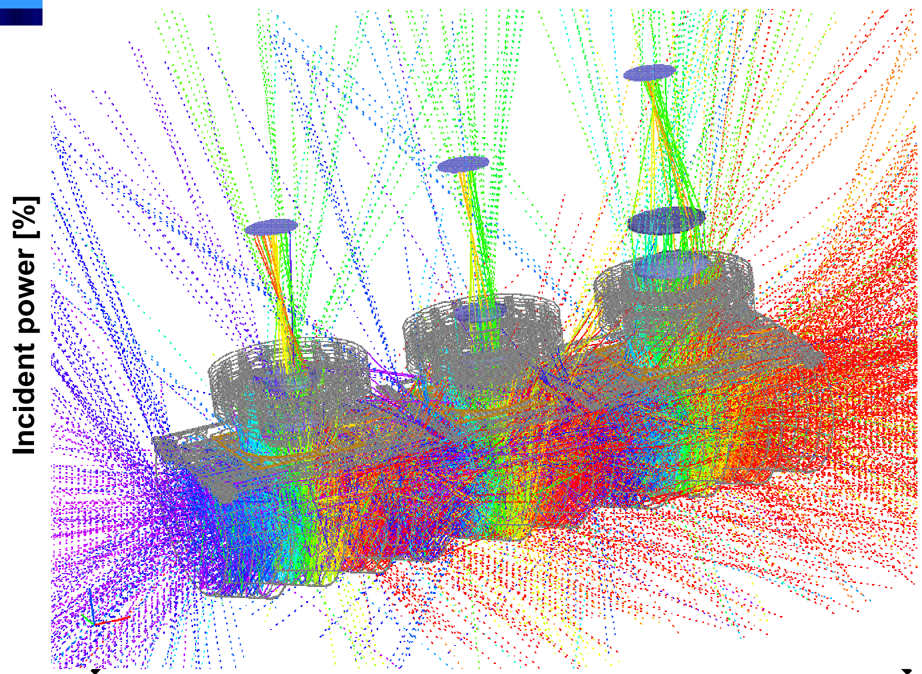
$$\frac{\phi_{ion}(\theta_{ion})}{\phi(\theta)} = \frac{\left(\sqrt{1-\beta^2}\right)^3}{(1-\beta\cdot\cos\theta)^3}$$







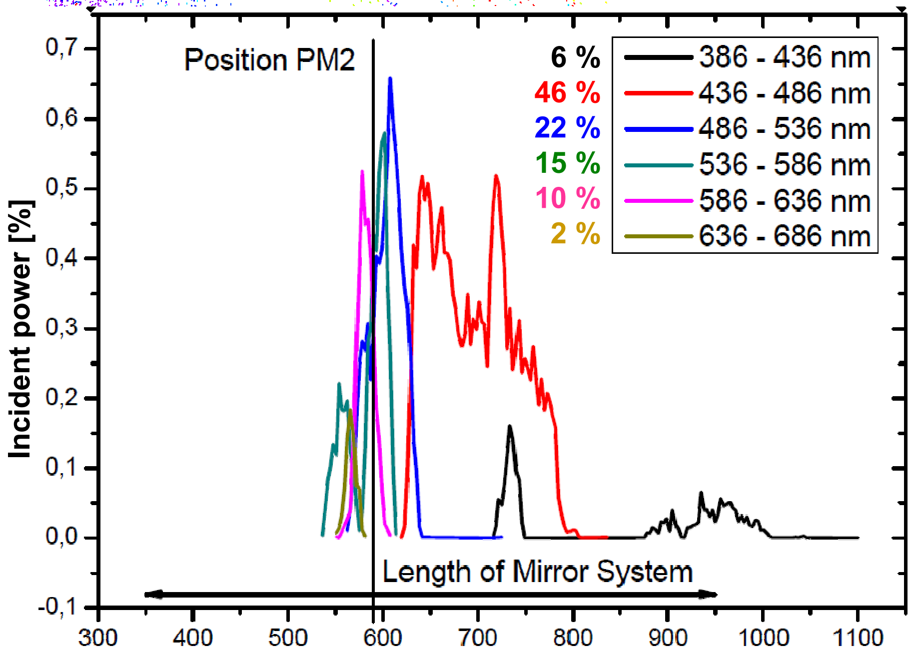
„Color code“ of the Signal



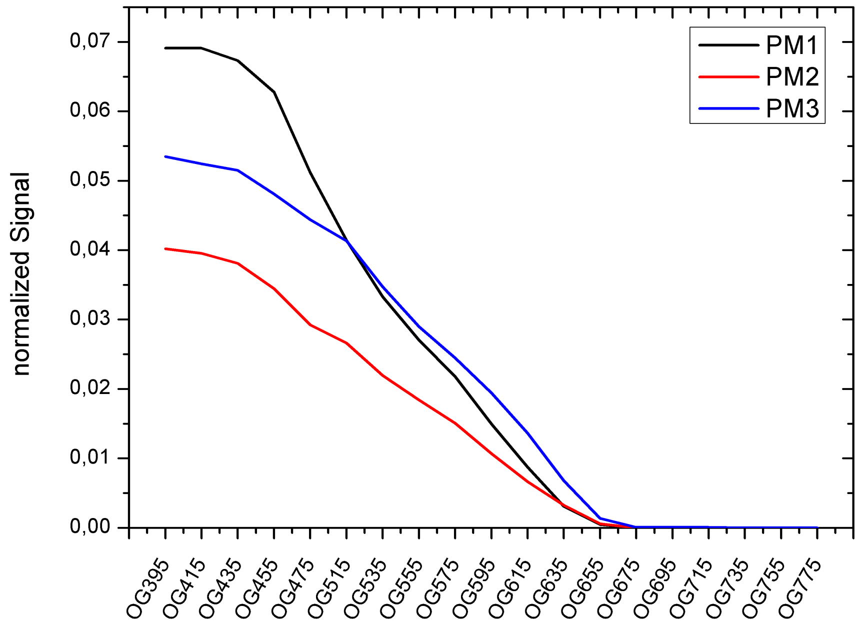
PM1

PM2

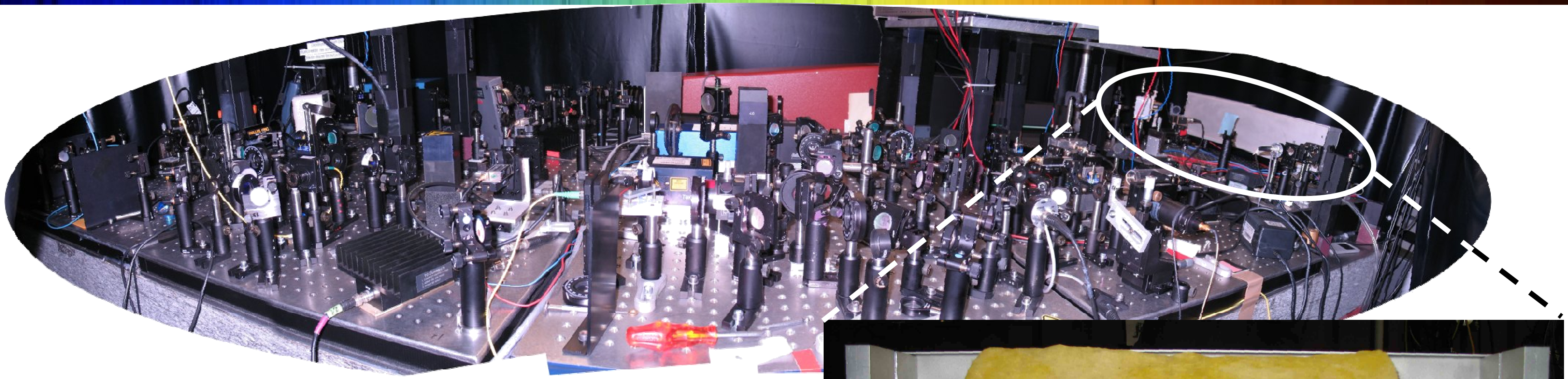
PM3

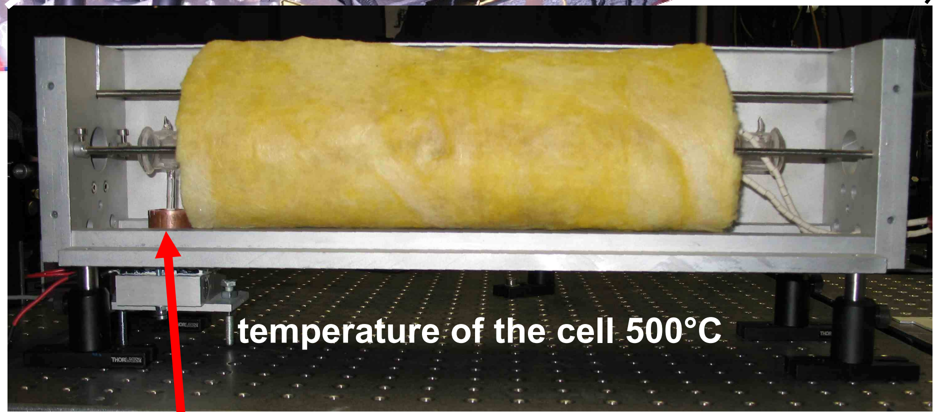


most detected photons emerge at an angle of 30°… 50°



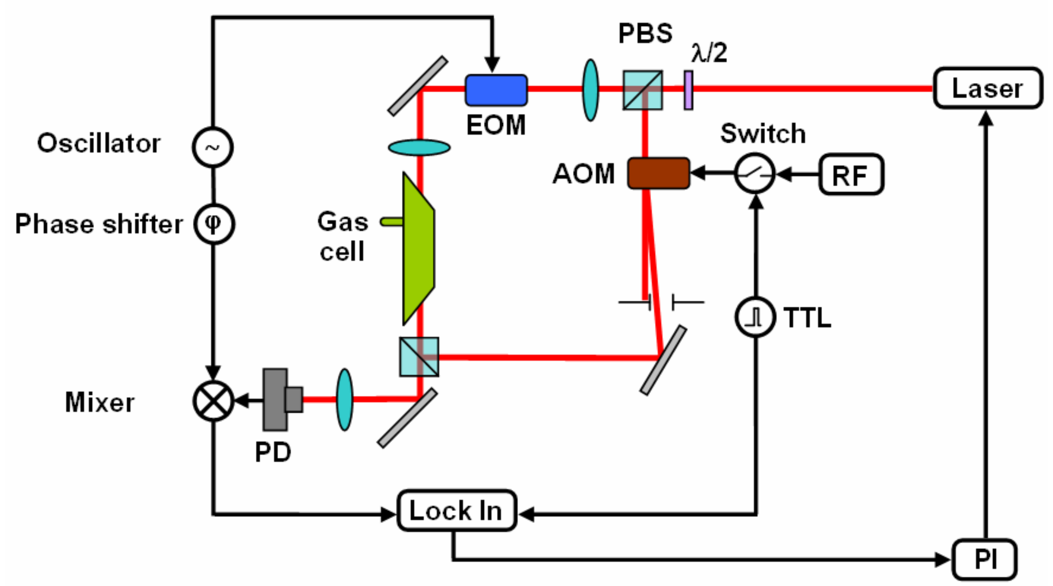
Experiment setup (a few details)

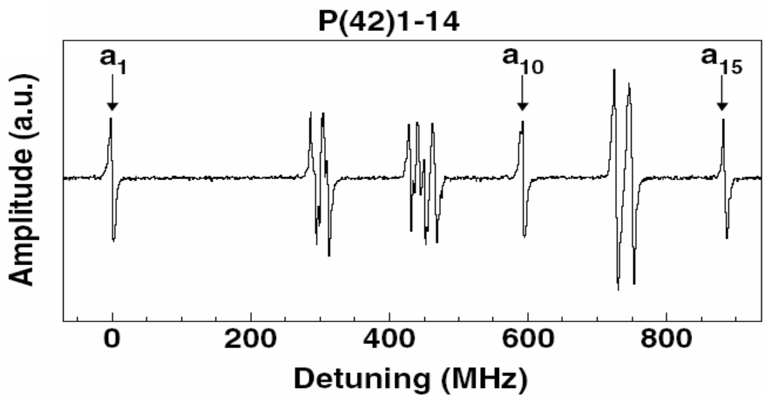




temperature of the cold finger 30°C

FM-saturation Spectroscopy on I_2



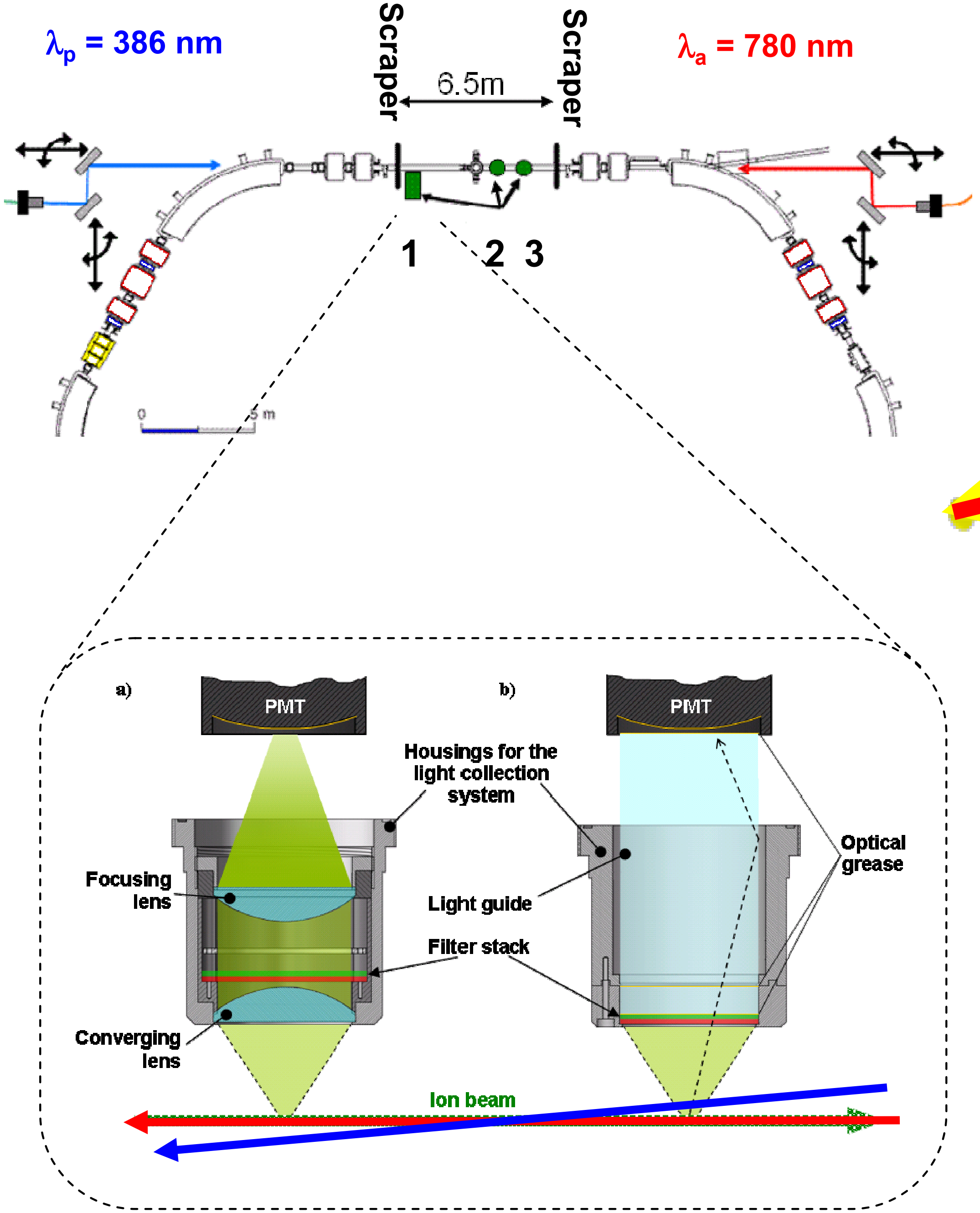


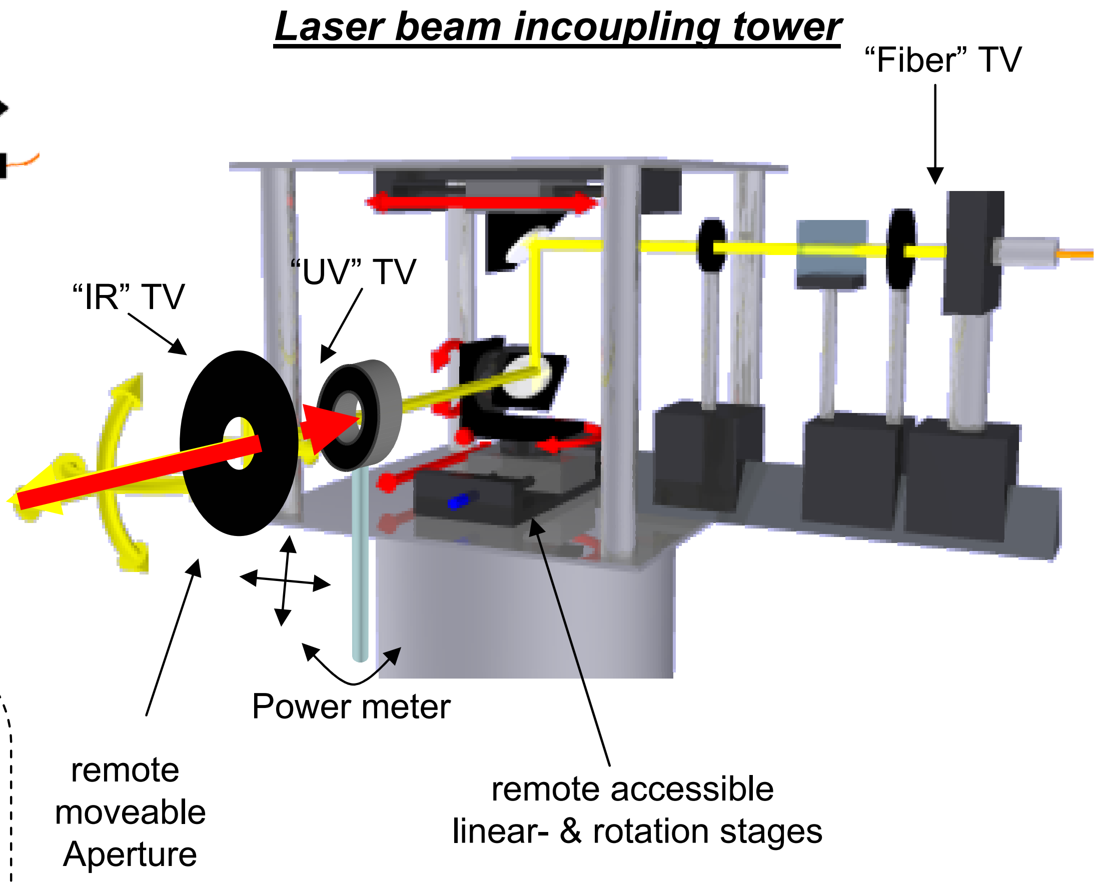
calibrated transition for the SRT experiment: P(42) 1-14 (772nm)

a_1: (388 605 083.71 ± 0.30) MHz

[Opt. Com. **274** *(2007)* 354]

Fluorescence Detection Section

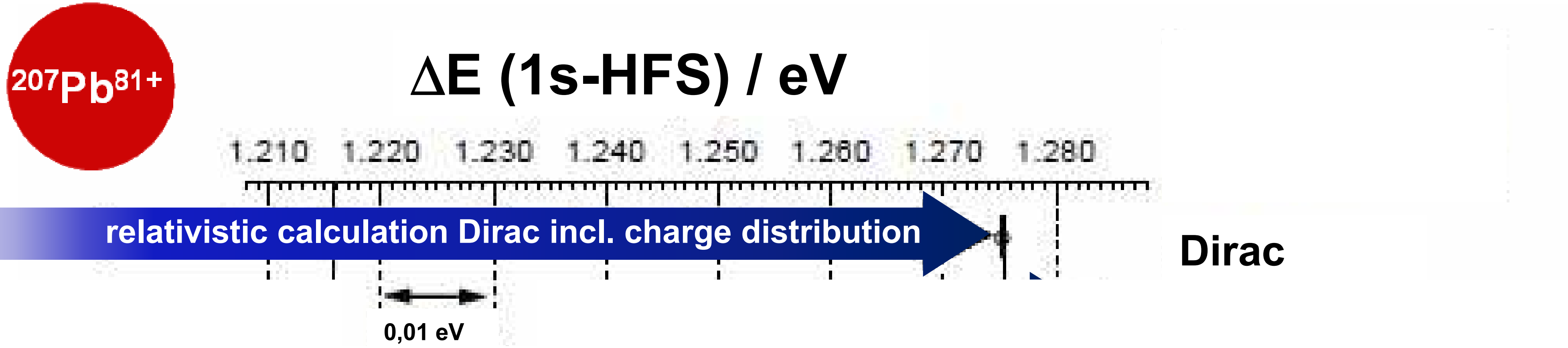




Geometric uncertainties

Laser beam / ion beam overlap	Laser beam / Laser beam overlap
$\Delta\nu < \pm 0.6$ MHz	**$\Delta\nu < \pm 0.05$ MHz**

QED Tests with M1-Transitions in Hydrogenlike Ions

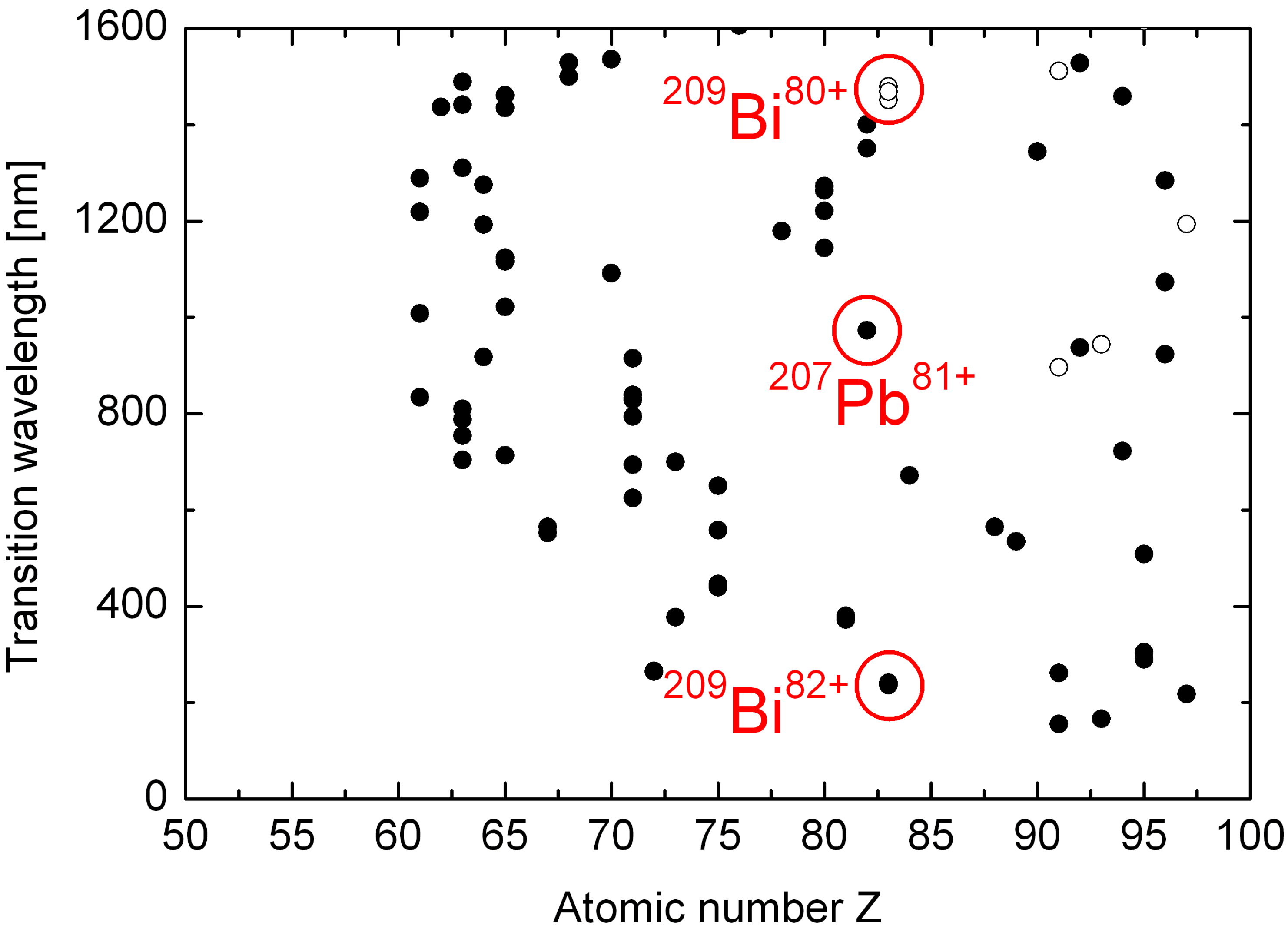


$^{207}Pb^{81+}$

exp. relative accuracy < 2× 10⁻⁴

P. Seelig et al., PRL 81 (1998)
P. Seelig, PhD thesis Mainz/GSI 1999

Candidates for Spectroscopy

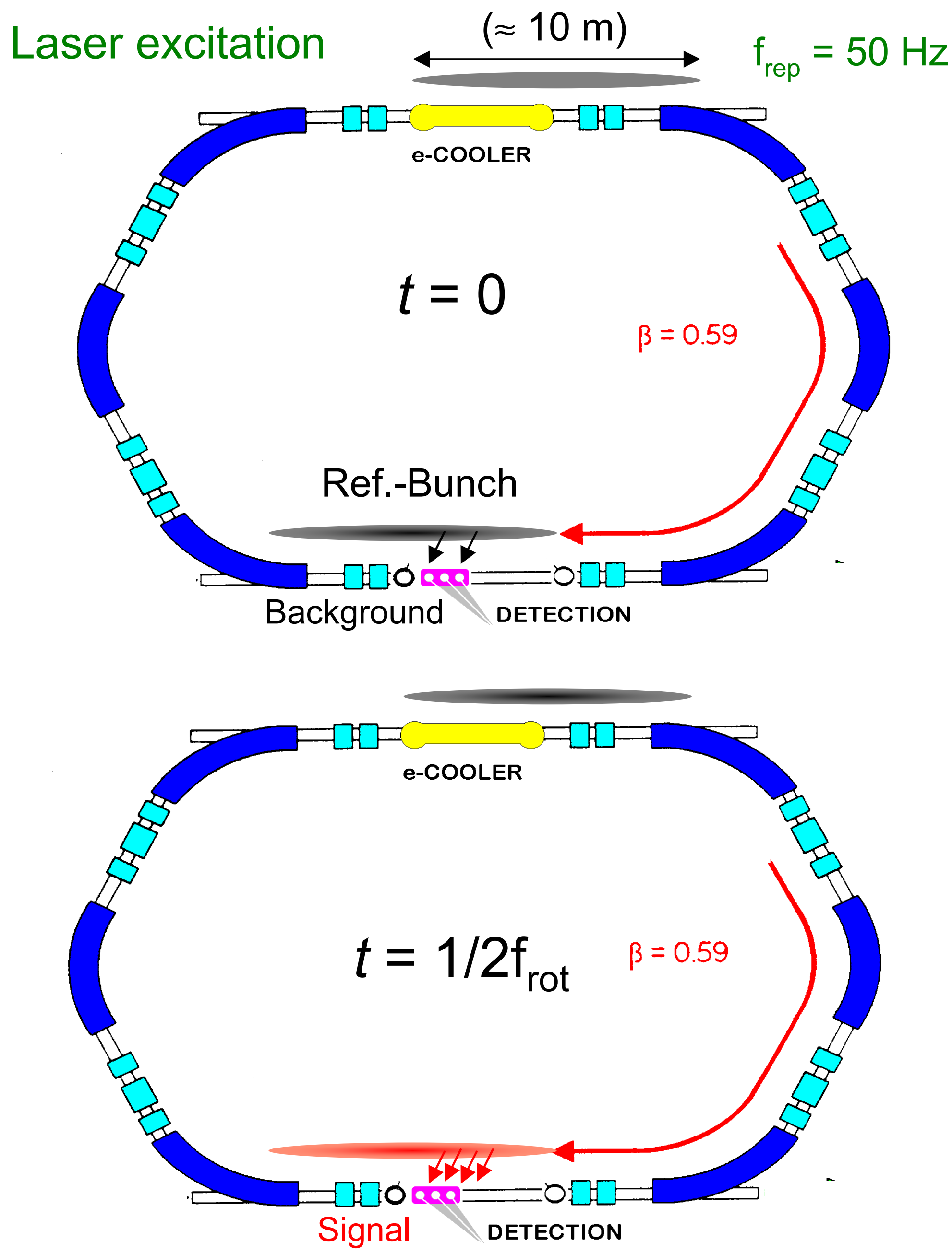


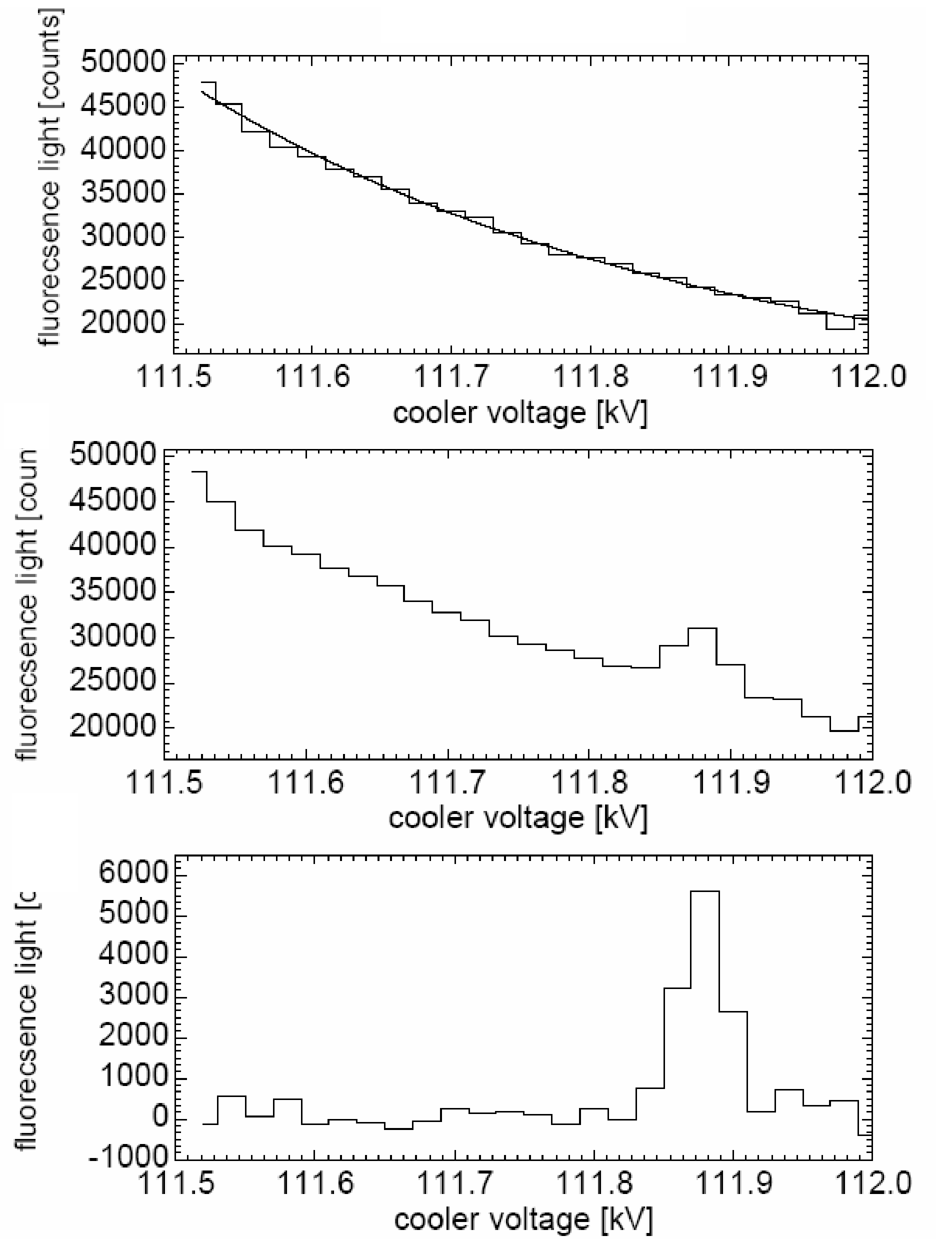
Approaches:

E083:
Relativistic Ions at the ESR

SPECTRAP @ HITRAP:
Laser Spectroscopy on Trapped Ions inside a Penning Trap

Laser Spectroscopy Technique





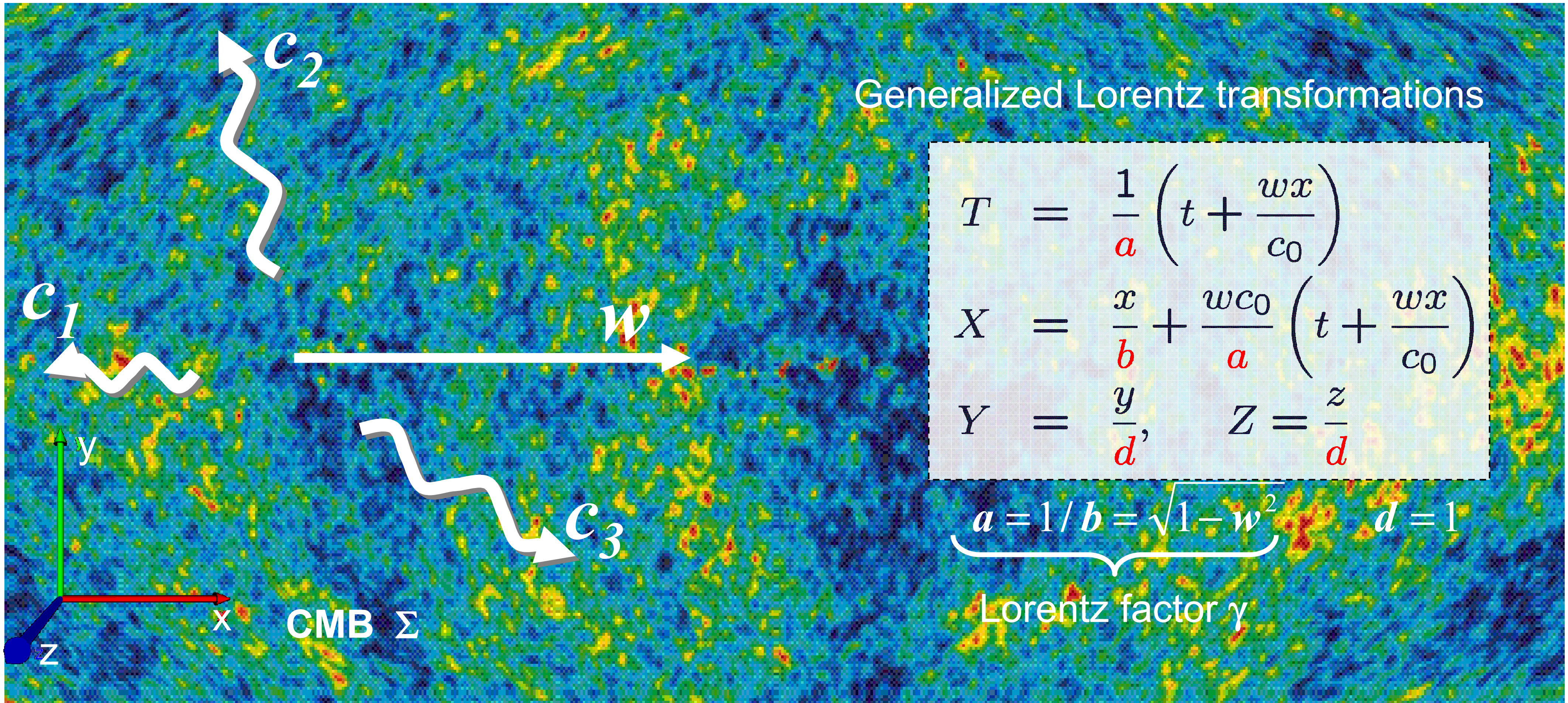
Einstein's Postulates for SRT

<u>*Principle of Relativity:*</u>

The laws of physics are the same for all inertial frames.

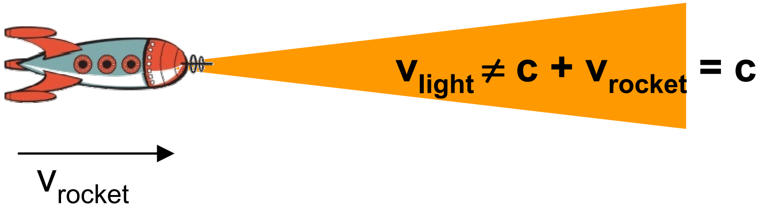
<u>*Principle of Constancy of the Speed of Light:*</u>

Any ray of light moves in the "stationary" system of coordinates with determined velocity c, whether the ray be emitted by a stationary or by a moving body.

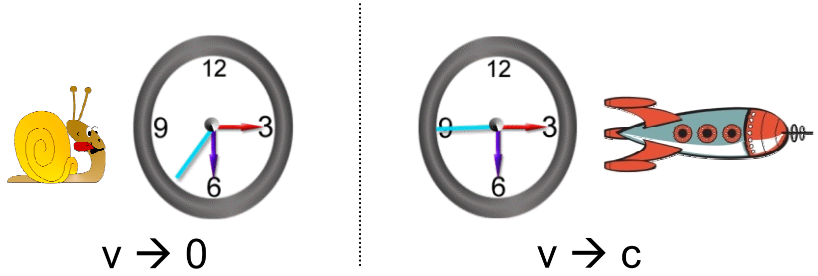


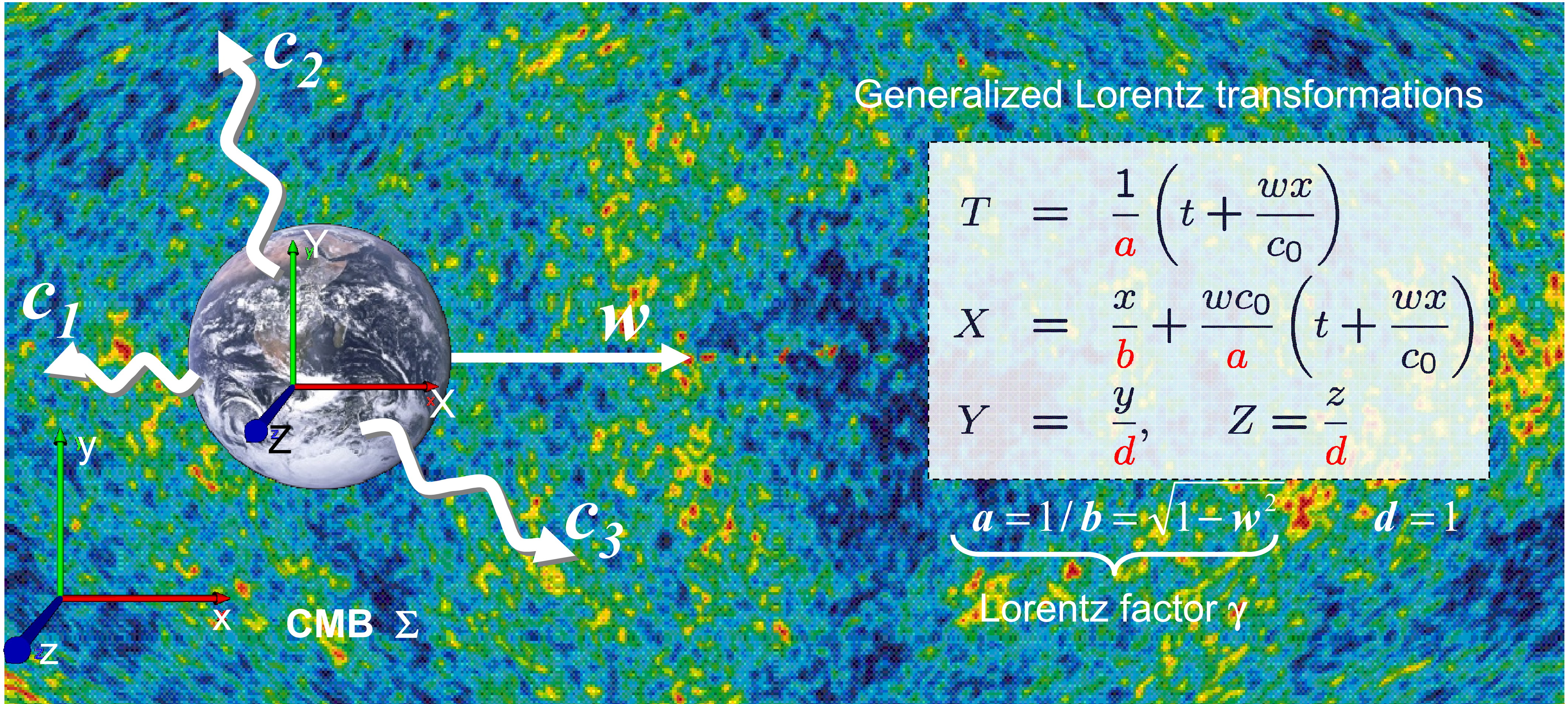
Consequences of the postulates

independence of the light speed of the speed of the laboratory



Time dilation





$$T = \frac{1}{a}\left(t + \frac{wx}{c_0}\right)$$

$$X = \frac{x}{b} + \frac{wc_0}{a}\left(t + \frac{wx}{c_0}\right)$$

$$Y = \frac{y}{d}, \qquad Z = \frac{z}{d}$$

$$\underbrace{a = 1/b = \sqrt{1-w^2}}_{\text{Lorentz factor } \gamma} \qquad d = 1$$