Spectroscopy of lithium ions at 34% of the speed of light with sub-Doppler linewidth

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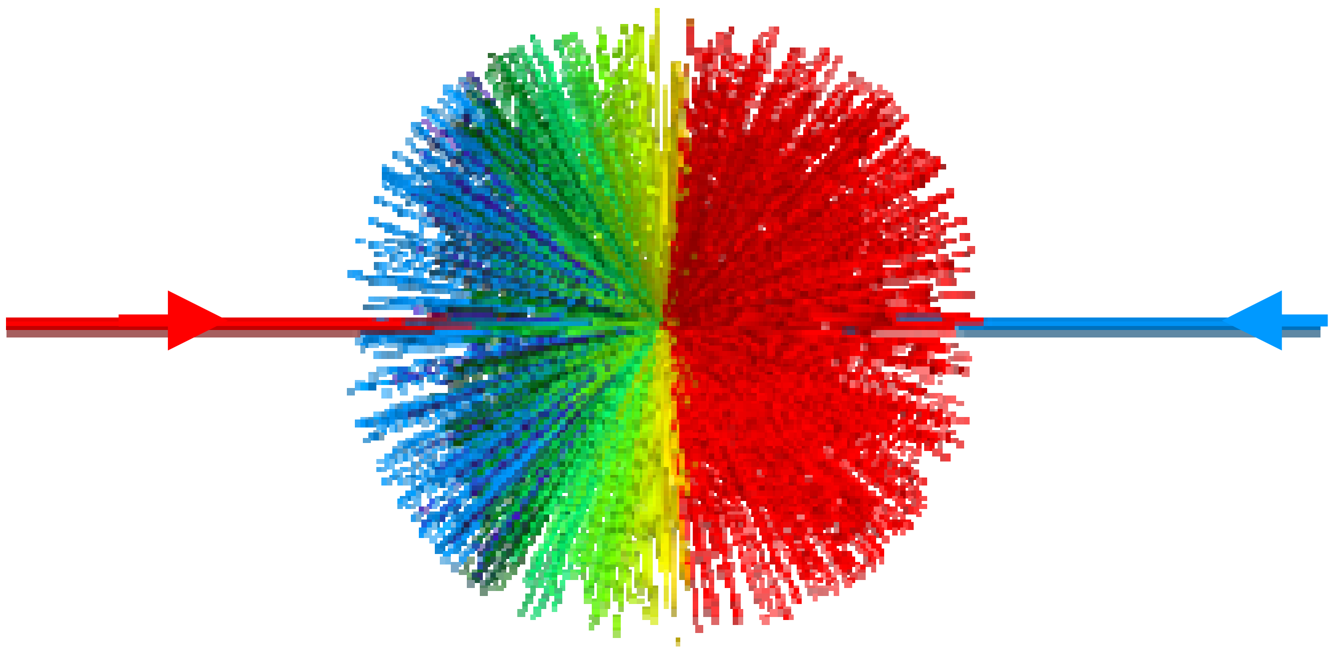
Outline



Introduction: test theories for SRT

Tools for modern test of time dilation

Status of the experiment at GSI and first signals

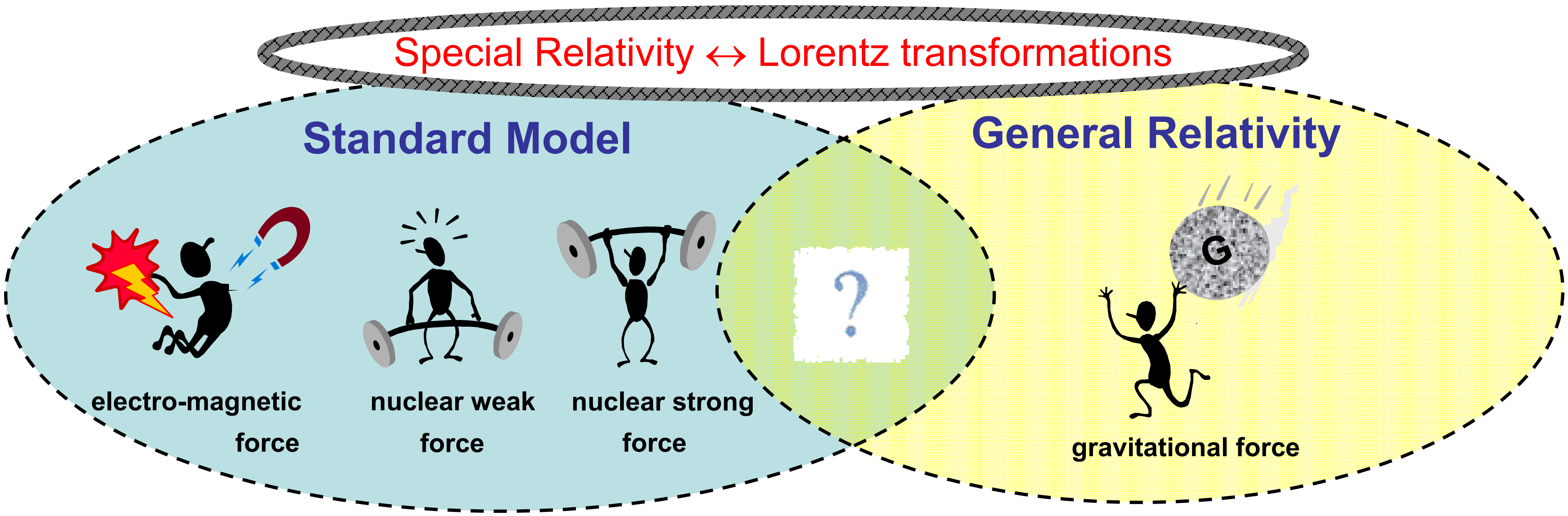
Results & Outlook

Why testing time dilation?

Lorentz invariance is a **fundamental constituent**

in the *standard model* of particle physics as well as

in the *theory of general relativity*



In some models hypothetical Lorentz violations are included

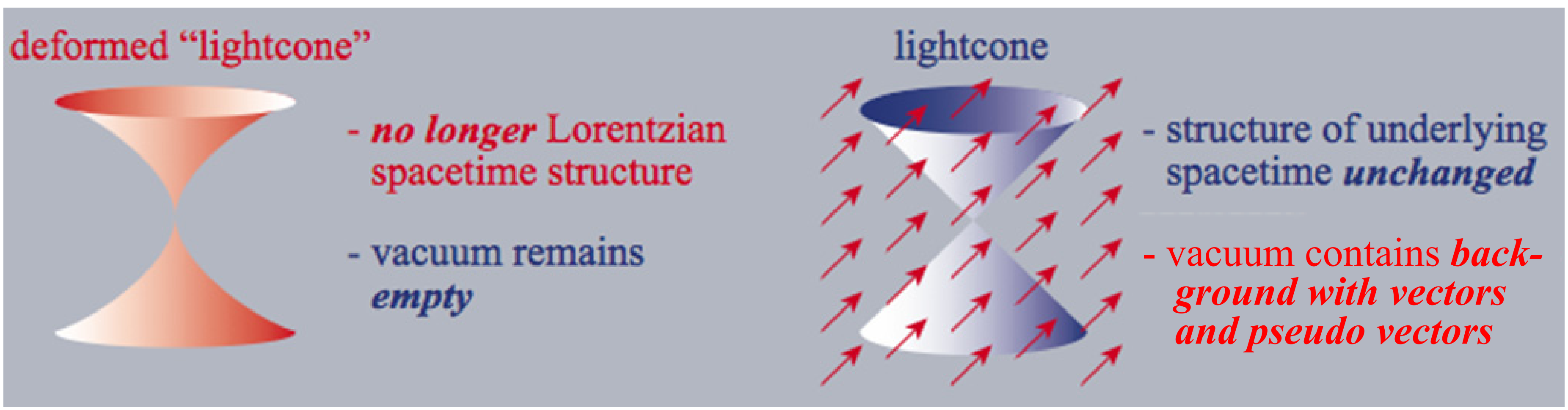
Lorentz violation could be a **revealed by experiment** as a *signature* of *new physics*

Hypothetical deviations can be included as quantitative parameters in test theories

Dynamical / kinematical test theory

<u>*Any test theory gives:*</u> a base to **compare different experiments** and **parameterize possible violations**

<u>*Kinematical test theory*</u>	<u>*Dynamical test theory*</u>
(e.g. Robertson, Mansouri & Sexl)	(e.g. Standard Model Extension) (Kostelecký et al.)
generalized Lorentz transformation	*small extension of the SM Lagrangian*
preferred frame assumed only a few parameters are needed	can describe particle couplings several hundreds of parameters



Dynamical / kinematical test theory

Any test theory gives: a base to **compare different experiments** and **parameterize possible violations**

Kinematical test theory

(e.g. Robertson, Mansouri & Sexl)

generalized Lorentz transformatio…

preferred frame as…
only a few…

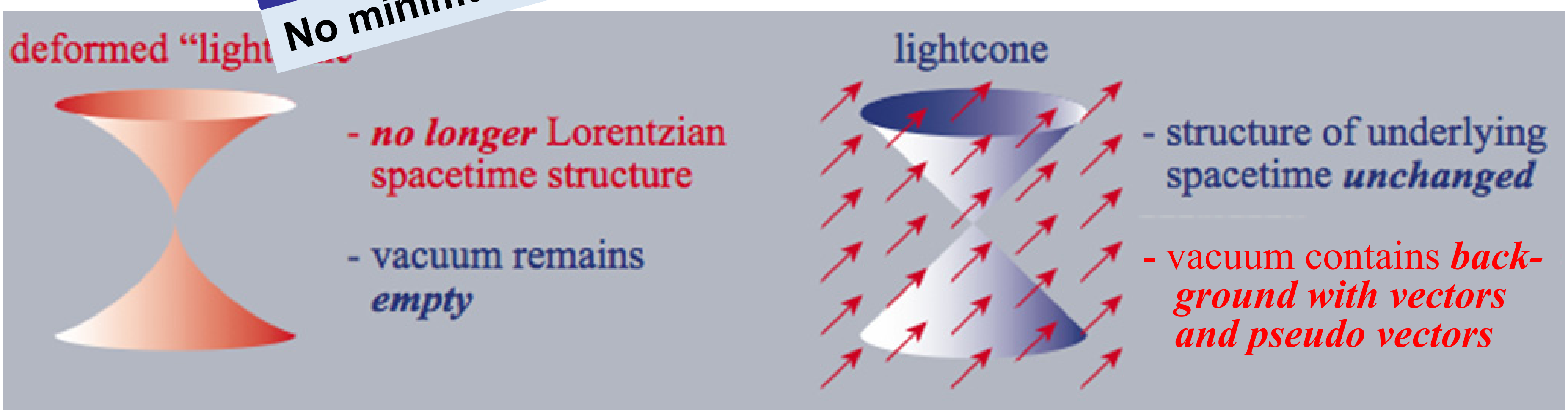
Dynamical test theor…

(e.g. Stand…

…sion of the SM Lagrangian

can describe particle couplings
several hundreds of parameters

BUT!
No minimum limit for Lorentz violation is stated by (test) theories!



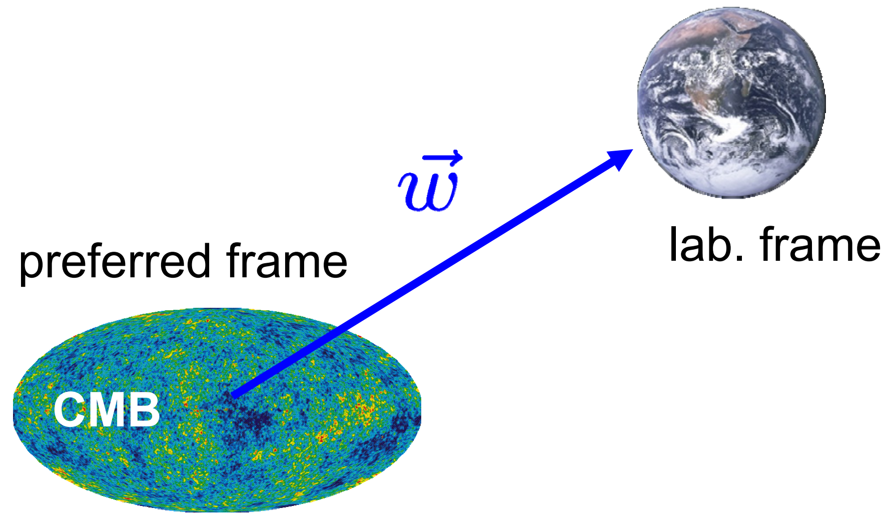
Mansouri-Sexl (MS) test theory

Generalized Lorentz transformations

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

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

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



for special relativity

$$a = b^{-1} = \underbrace{\sqrt{1 - w^2}}_{\gamma^{-1}}$$

$$d = 1$$

Assumptions:

- preferred "ether" frame Σ (CMB ?)
- only in Σ the light speed is isotropic
- lab. frame is moving with along the x-axis

expansion in velocity terms

$$a(w^2) = (1 - w^2)^{1/2}(1 + \delta\alpha \cdot w^2 + \ldots)$$

$$b(w^2) = (1 - w^2)^{-1/2}(1 + \delta\widehat{\beta} \cdot w^2 + \ldots)$$

$$d(w^2) = (1 + \widehat{\delta} \cdot w^2 + \ldots)$$

a → time dilation (Ives-Stilwell)

b, d → isotropy of space (Michelson-Morley & Kennedy-Thorndike)

Time dilation in the MS-framework

Generalized Lorentz transformations

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

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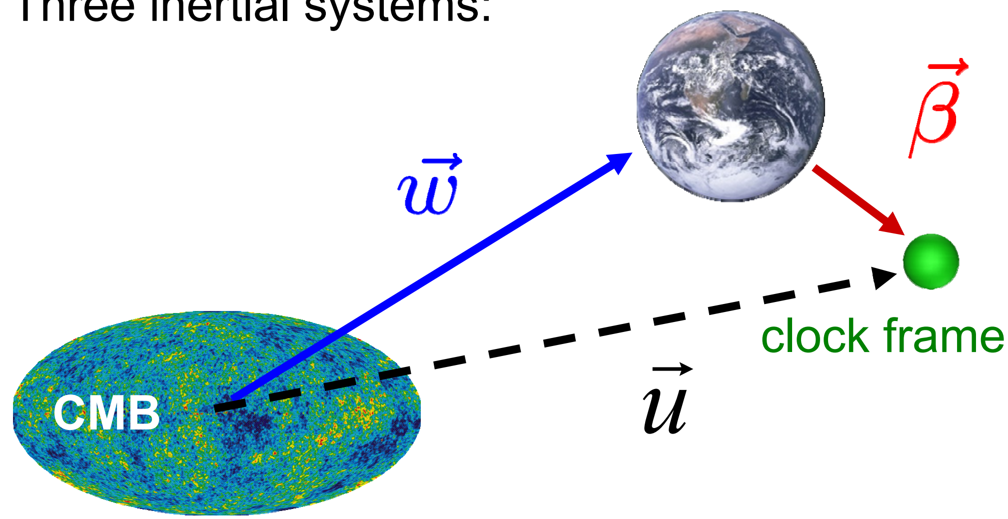
Three inertial systems:



lead to a modified Lorentz factor:

$$\gamma_{MS} = \gamma \cdot \left[1 + \delta\alpha \cdot \left(\beta^2 + 2 \cdot \vec{\beta} \cdot \vec{w}\right) + \ldots\right]$$

Test parameter

is a function of

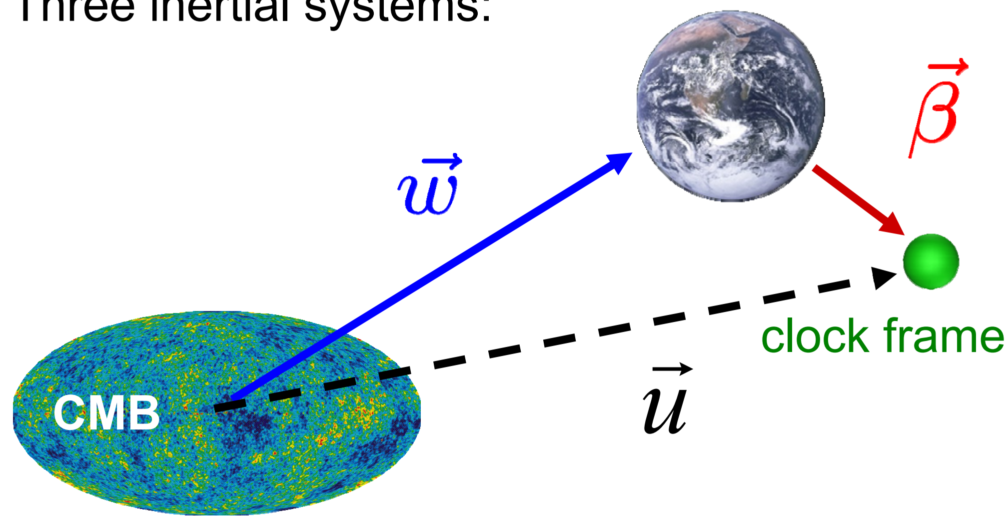
$\vec{w}$ = 350 km/s

Time dilation in the MS-framework

Generalized Lorentz transformations

$$
\begin{aligned}
T &= \frac{1}{a}\left(t + \frac{wx}{c_0}\right) \\
X &= \frac{x}{b} + \frac{wc_0}{a}\left(t + \frac{wx}{c_0}\right) \\
Y &= \frac{y}{d}, \qquad Z = \frac{z}{d}
\end{aligned}
$$

Three inertial systems:



lead to a modified Lorentz factor:

$$\gamma_{MS} = \gamma \cdot \left[1 + \delta\alpha \cdot \left(\beta^2 + 2 \cdot \vec{\beta} \cdot \vec{w}\right) + \ldots\right]$$

Test parameter

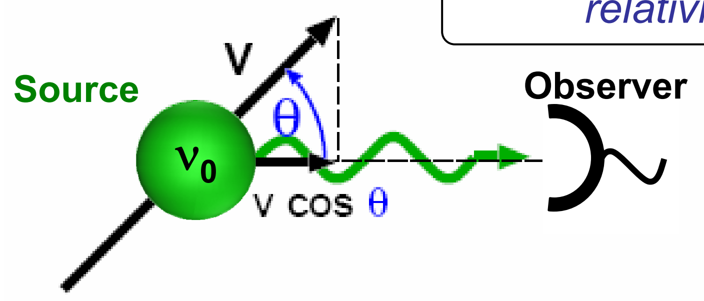
is a function of β^2

we neglect sidereal term

$\vec{w}$ = 350 km/s << $\vec{\beta}$ ~ 10 000 km/s

Test of time dilation

relativistic Doppler effect



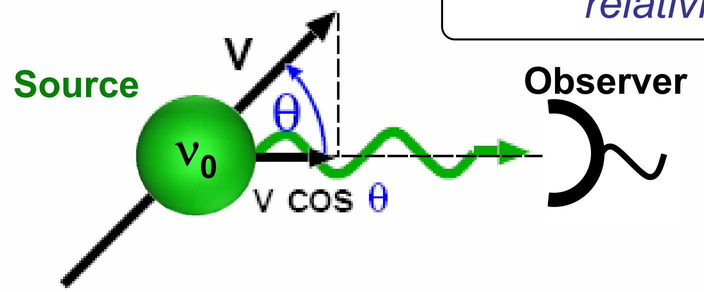
$$\nu = \nu_0 \frac{1}{\gamma\,(1 - \beta \cos\theta)}$$

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

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

Test of time dilation

relativistic Doppler effect



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

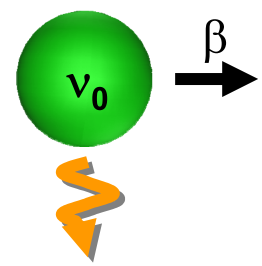
$$\beta = {}^{v}\!/_{c}$$

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

Einstein proposed 1907:

$$\theta = 90°$$

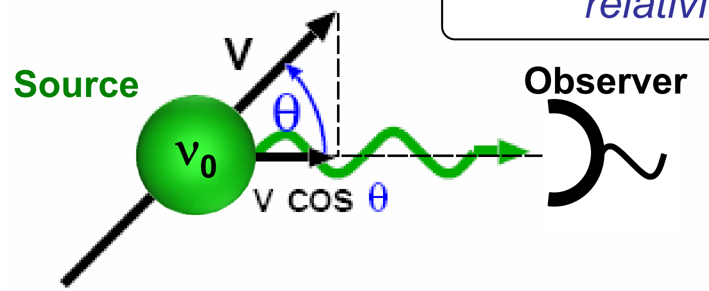
$$\frac{\nu_0}{\nu} = \gamma$$



➔ Experimentally impossible to measure light emitted only at 90°

Test of time dilation

relativistic Doppler effect



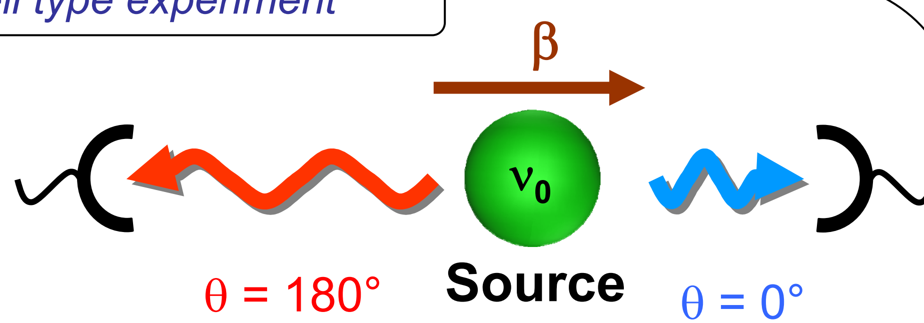
$$\nu = \nu_0 \frac{1}{\gamma\,(1 - \beta \cos\theta)}$$

$$\beta = v/c$$

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

Ives-Stilwell type experiment

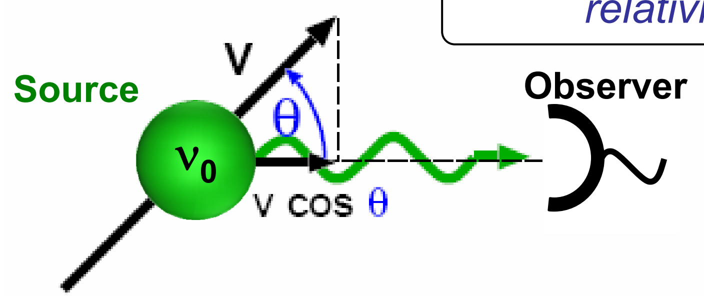
$$\nu_p = \frac{\nu_0}{\gamma \cdot (1-\beta)} \qquad \nu_a = \frac{\nu_0}{\gamma \cdot (1+\beta)}$$



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

Test of time dilation

relativistic Doppler effect



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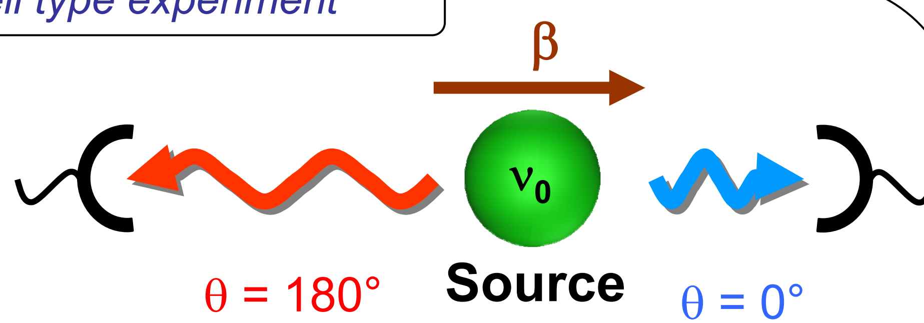


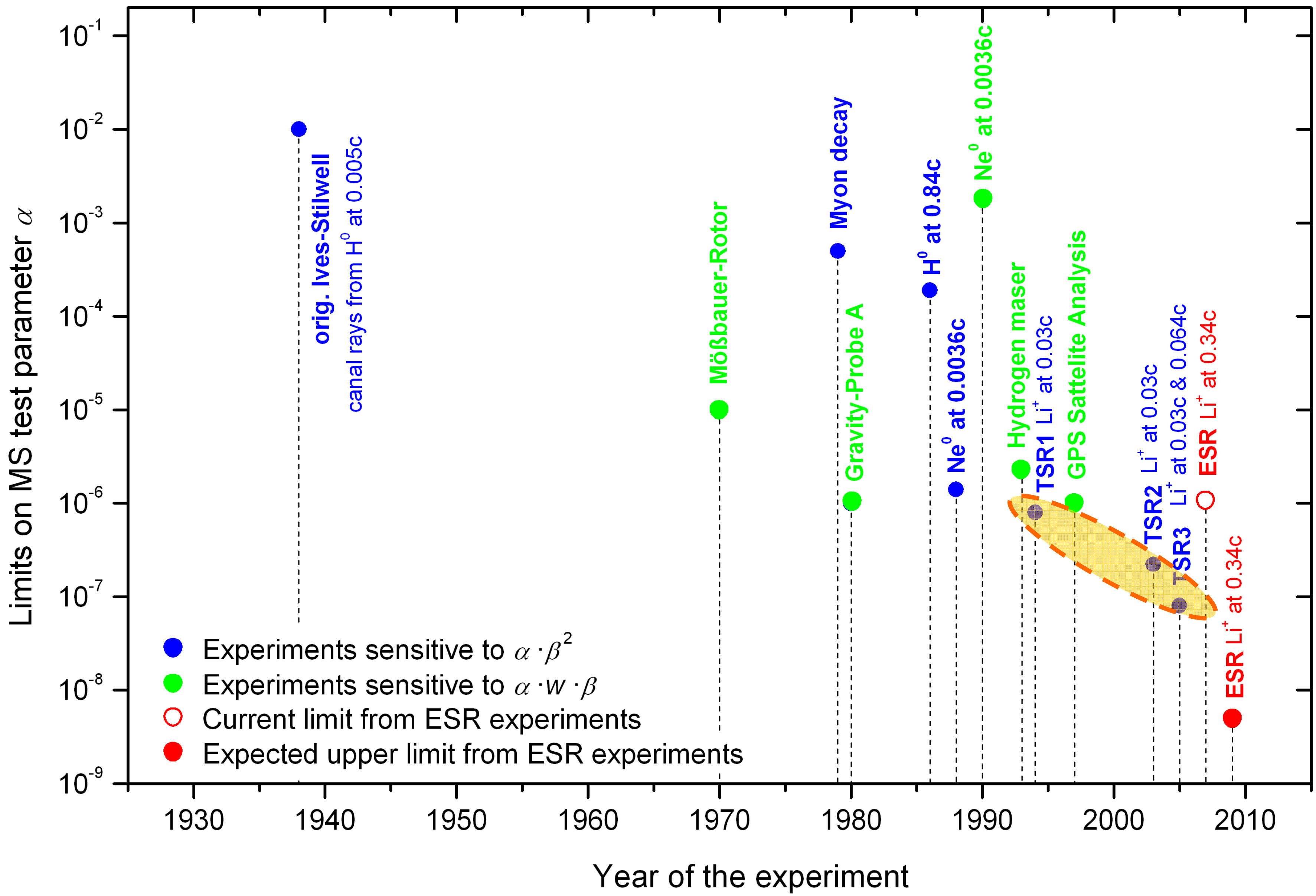
$$\frac{\nu_a \cdot \nu_p}{\nu_0^2} = \gamma^2 \cdot (1-\beta^2) \overset{?}{\equiv} 1+\varepsilon$$

$$\gamma \xrightarrow{\varepsilon \neq 0} \gamma_{MS}$$

$$= \gamma_{MS}^2 \cdot (1-\beta^2) = 1 + 2 \cdot \delta\alpha \cdot \beta^2 + (\delta\alpha + 2 \cdot \delta\alpha_2) \cdot \beta^4 + \ldots$$

Time Dilation can be tested via comparing **three optical frequencies**

Evolution of time dilation tests



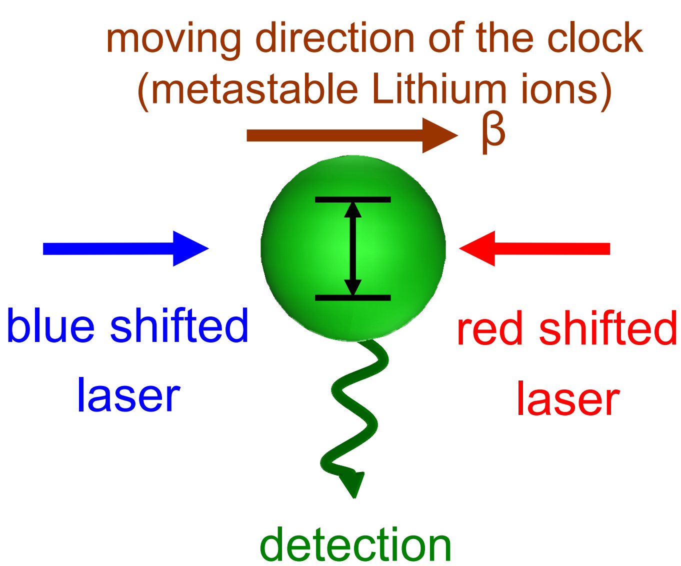
Modern Ives-Stilwell experiment

$$\frac{\nu_a \cdot \nu_p}{\nu_0^2} = 1 + 2 \cdot \delta\alpha \cdot \beta^2$$

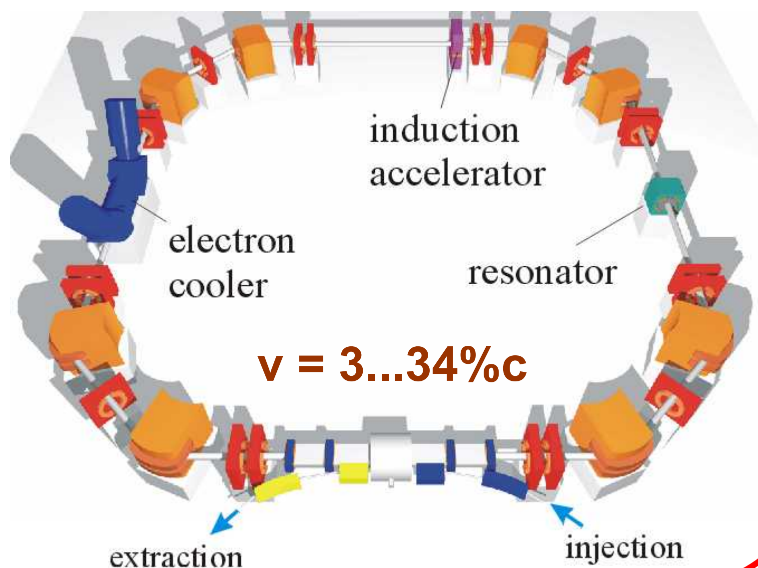
frequencies has to been known very accurate

the higher the clock velocity, the higher the sensitivity to $\delta\alpha$

Precision Spectroscopy

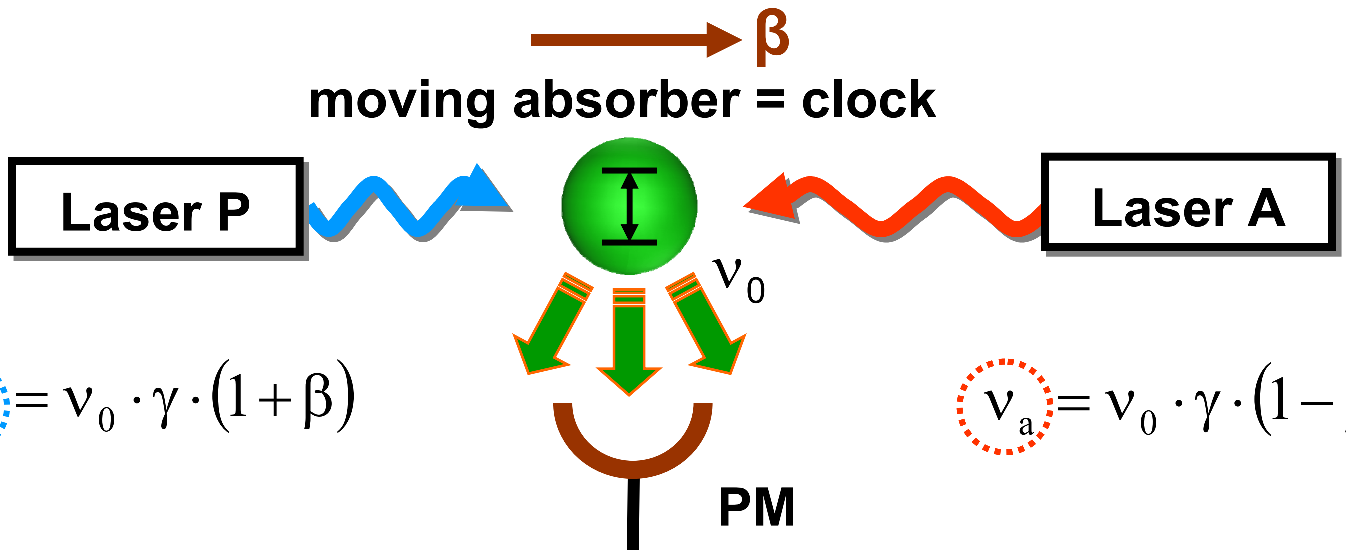


Storage Ring



Modern Ives-Stilwell experiment

Testing Lorentz transformation via measuring of the optical frequencies



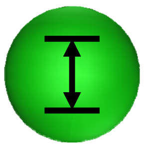
$$\nu_p = \nu_0 \cdot \gamma \cdot (1+\beta)$$

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

Testing time dilation via three optical frequencies

$$\frac{\nu_a \cdot \nu_p}{\nu_0^2} = \gamma^2 \cdot (1-\beta^2) \stackrel{?}{\equiv} 1 \longrightarrow \frac{\nu_a \cdot \nu_p}{\nu_0^2} = 1 + 2 \cdot \delta\alpha \cdot \beta^2$$

Helium-like lithium ion in the metastable triplet state



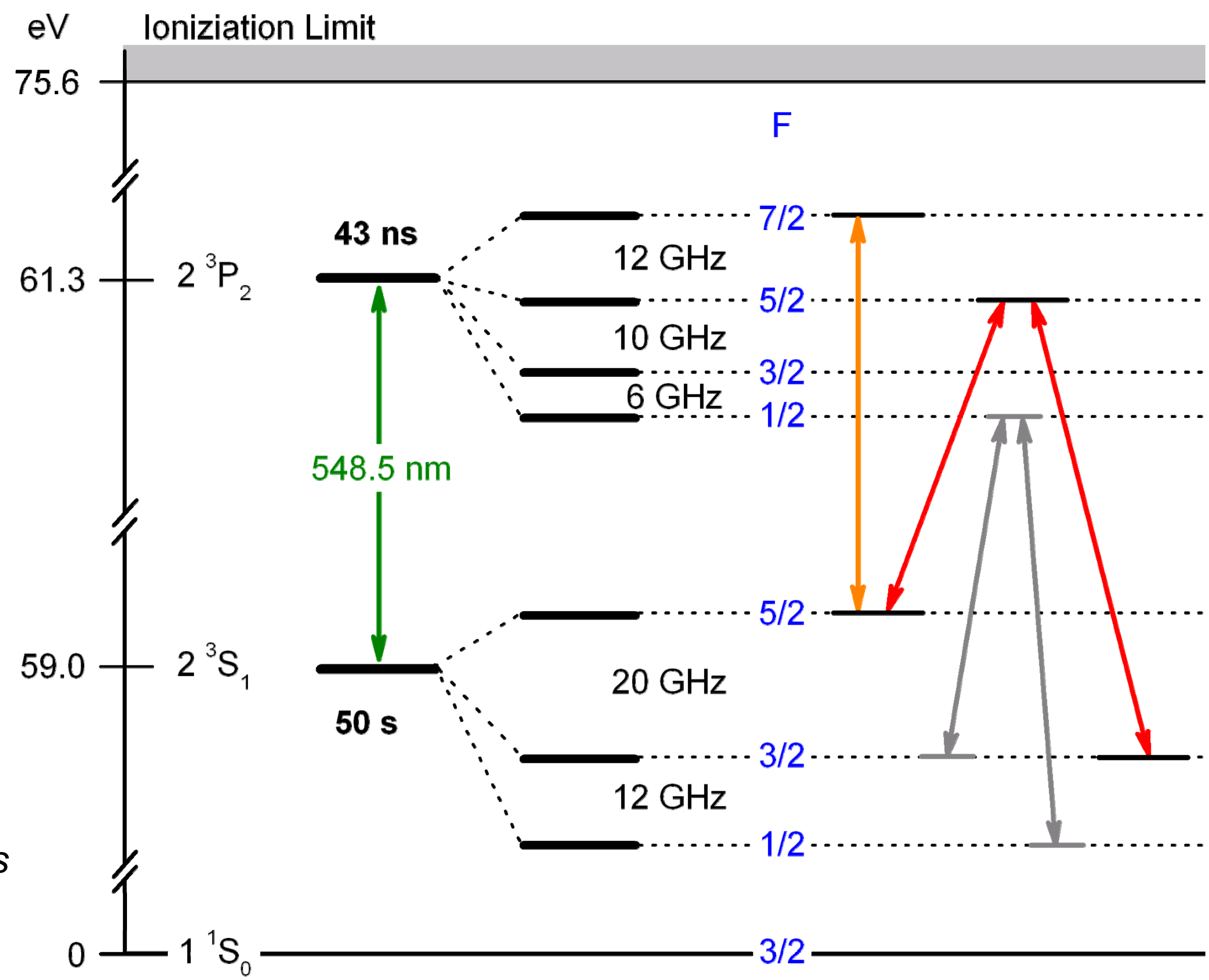
closed two level system

$2s^3S_1 \longrightarrow 2p^3P_2$

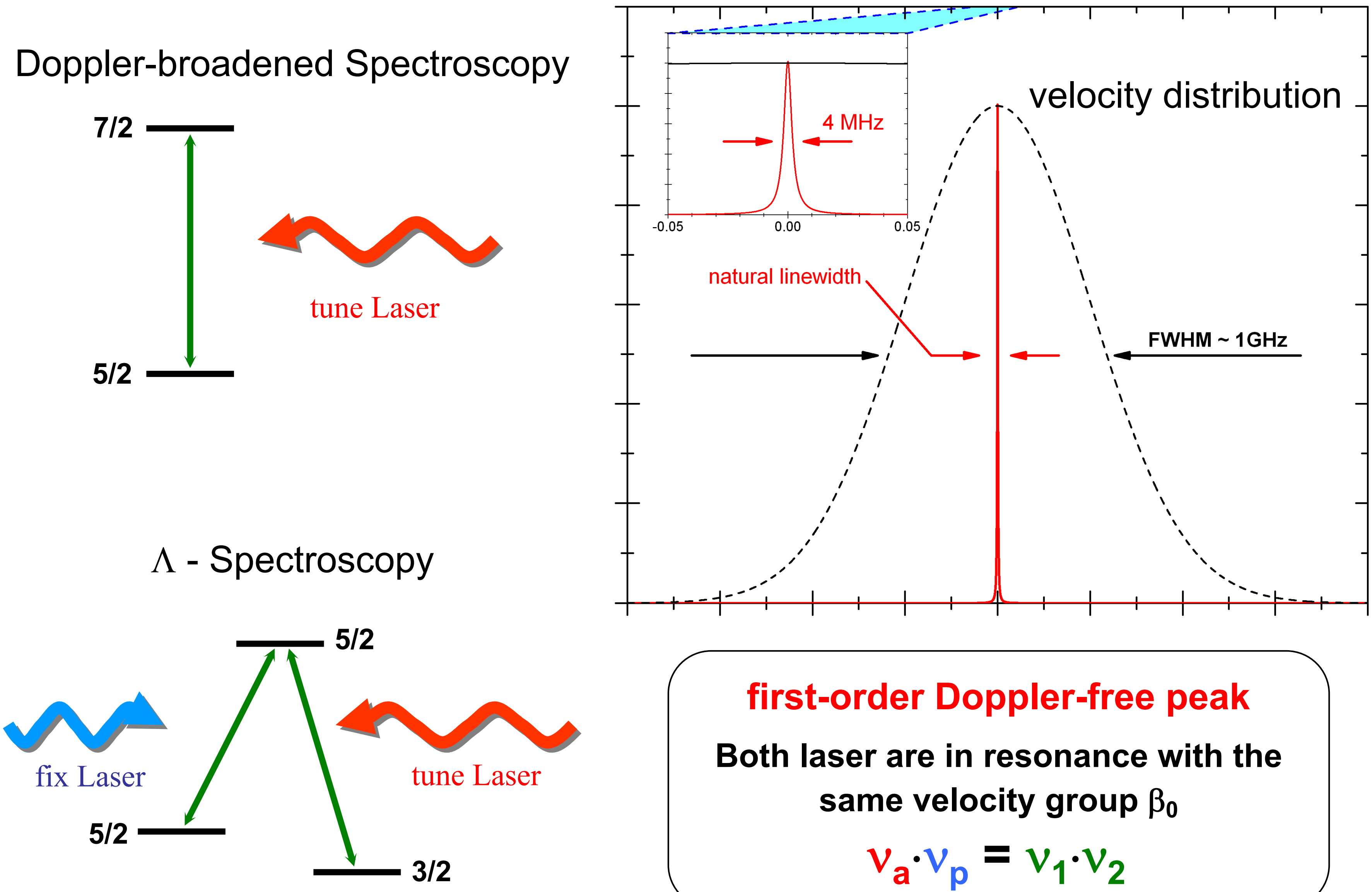
natural line width

3.7 MHz

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



Spectroscopy in a storage ring

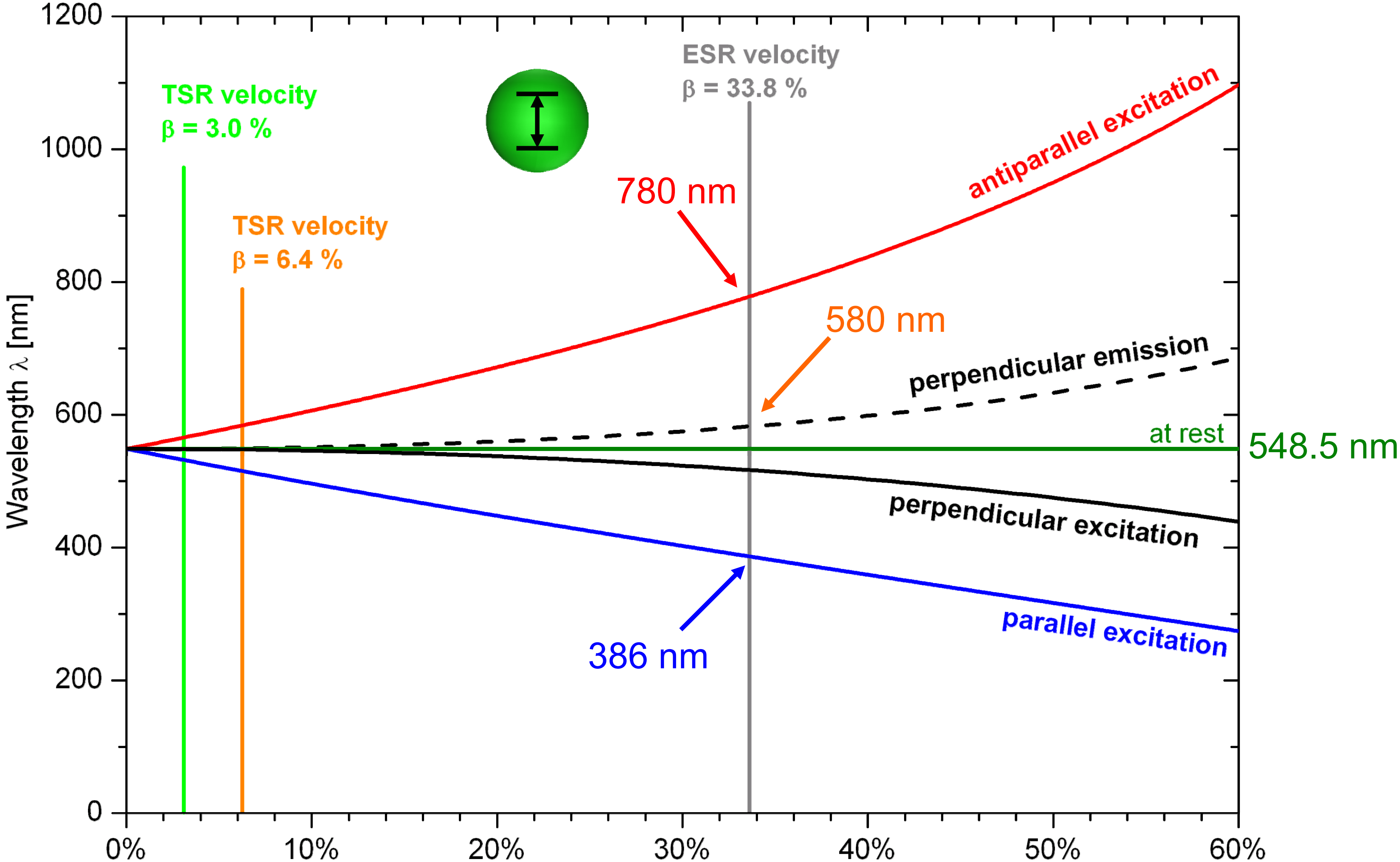


first-order Doppler-free peak

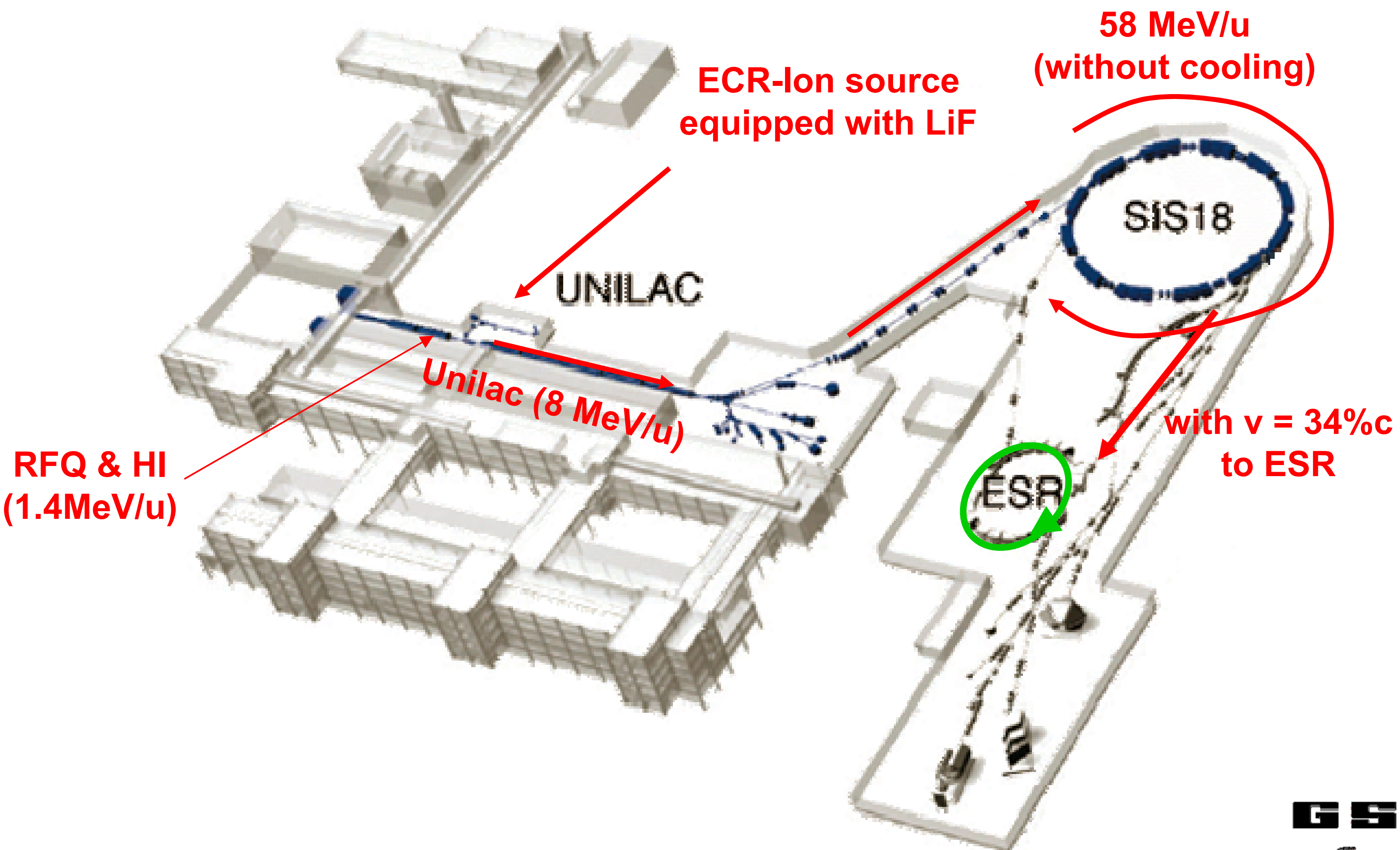
Both laser are in resonance with the same velocity group β_0

$$\nu_a \cdot \nu_p = \nu_1 \cdot \nu_2$$

(High) relativistic $^7Li^+$

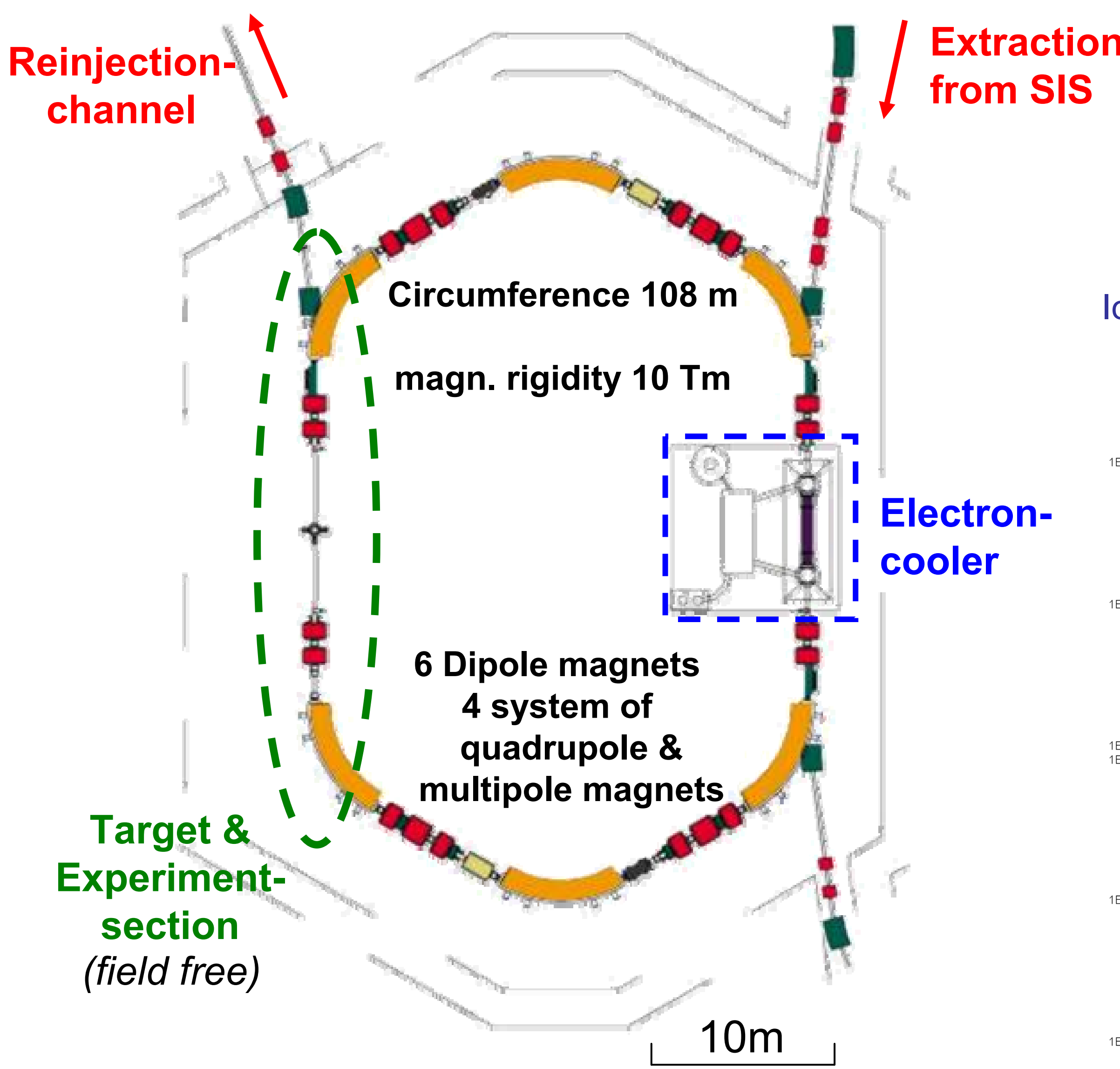


The GSI facility



The experimental storage ring ESR

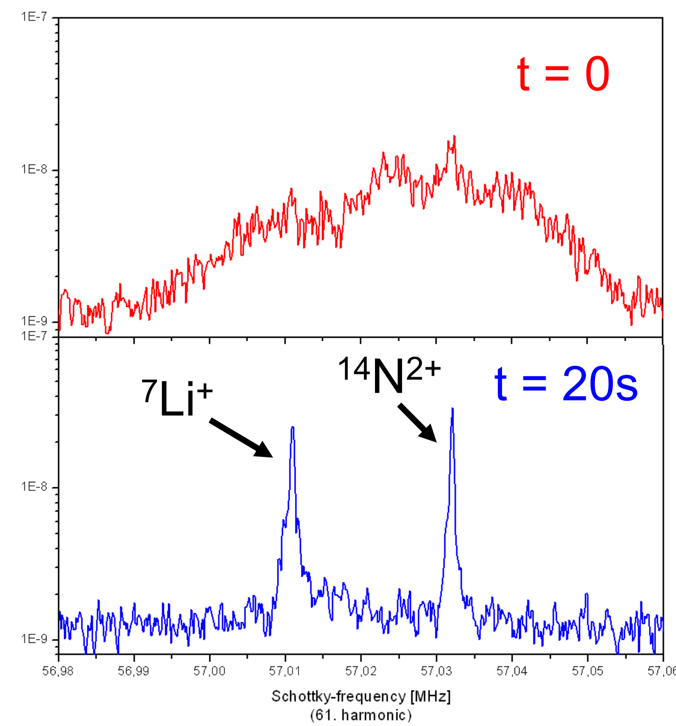
GSI



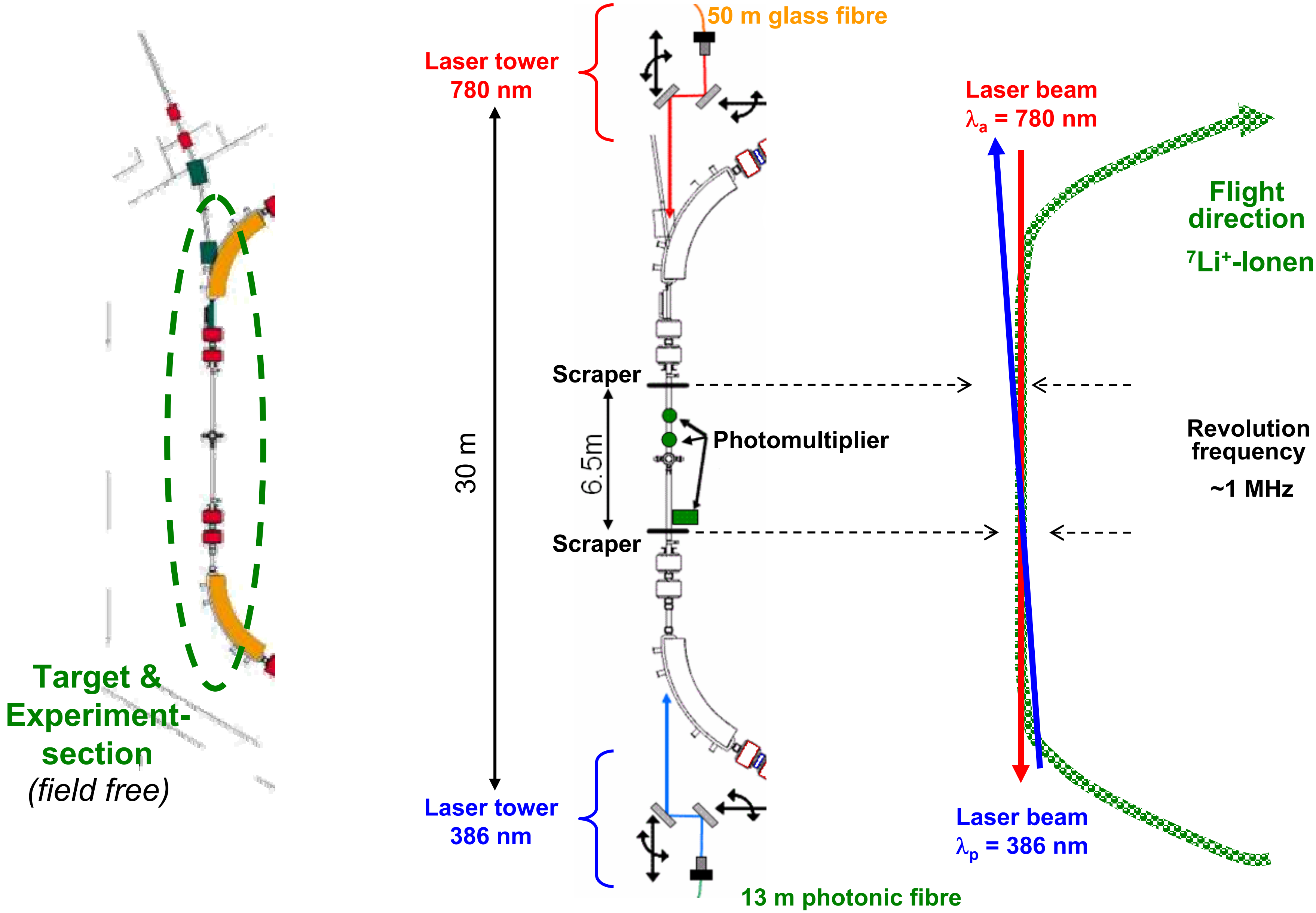
Ion current **~25 μA** **2 × 10^8 Ions**

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

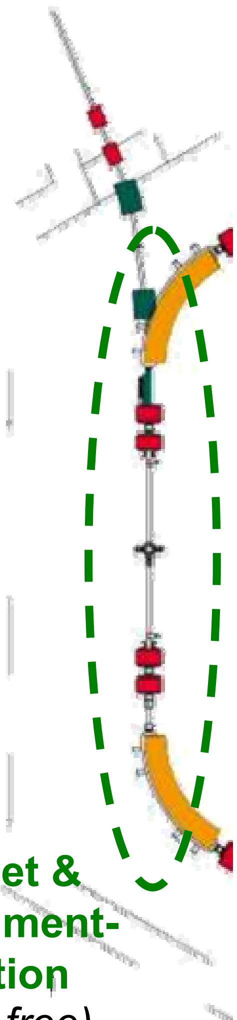
Momentum spread **$\Delta p/p \sim 10^{-6}$**

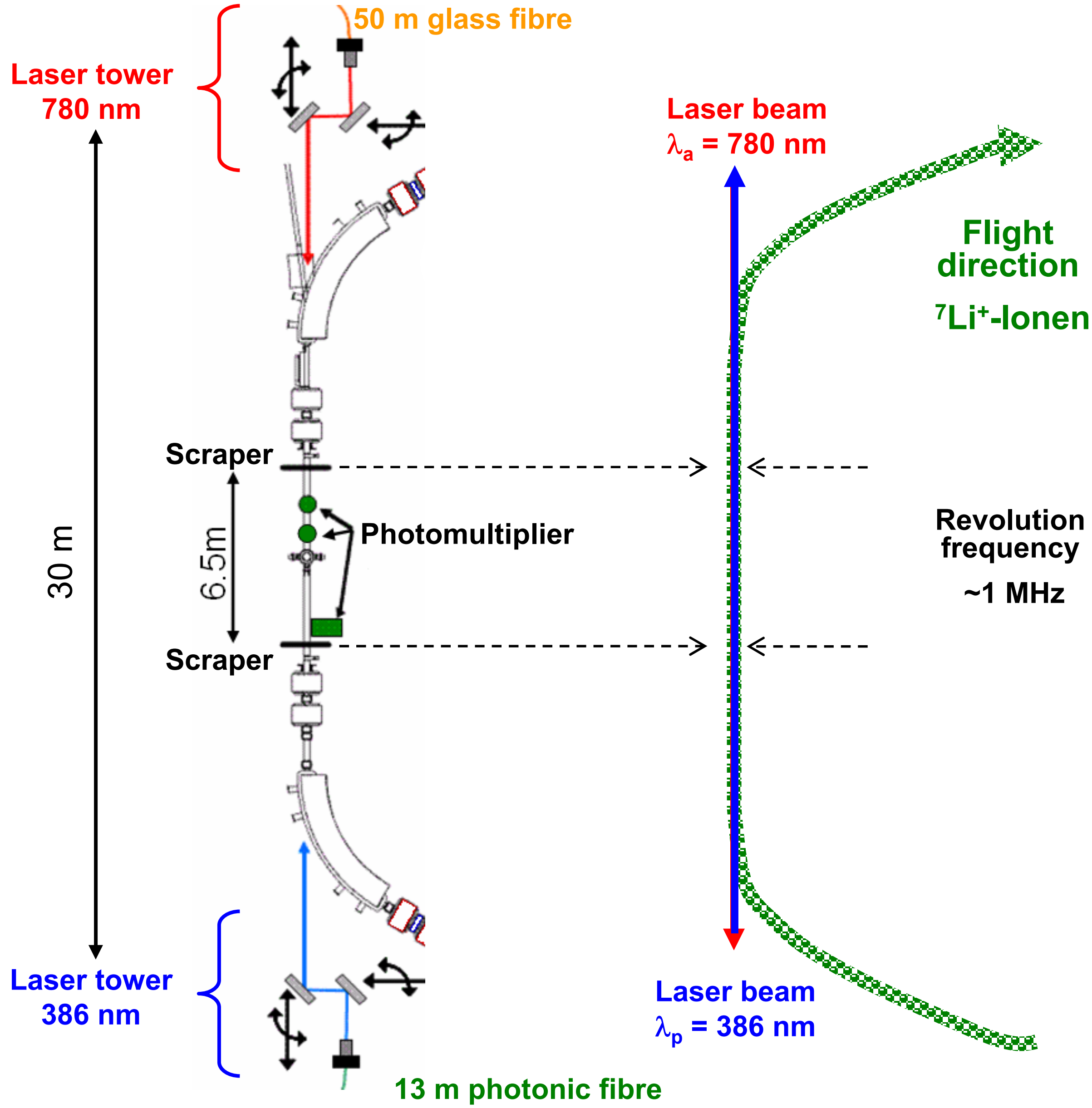


Experimental section



Experimental section





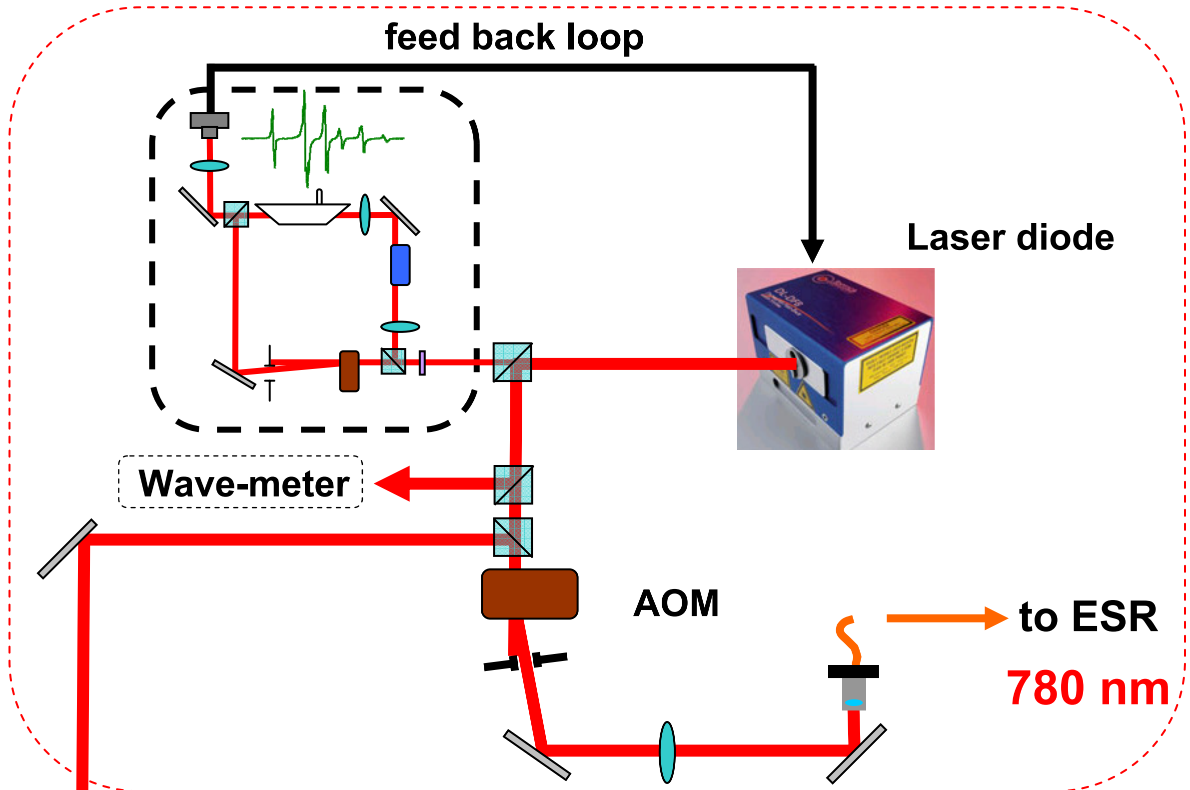
Laser system (simplified)

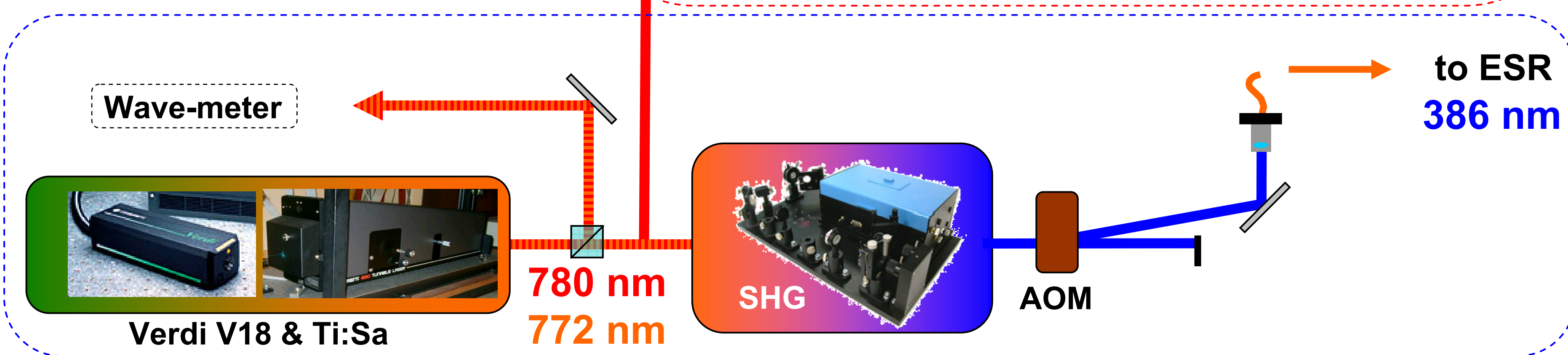
antiparallel excitation

frequency reference
on **rubidium** via
fm-saturation spectroscopy
(< 1 MHz)

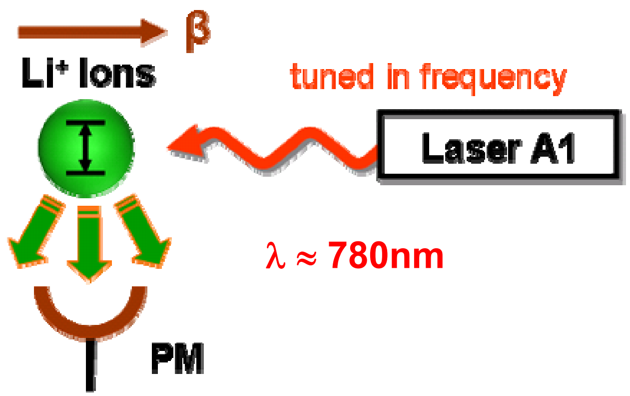
parallel excitation

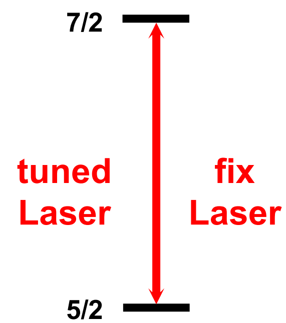
frequency reference
wave meter (~100 MHz)
(*more accurate reference tested but not applied in beam time yet*)

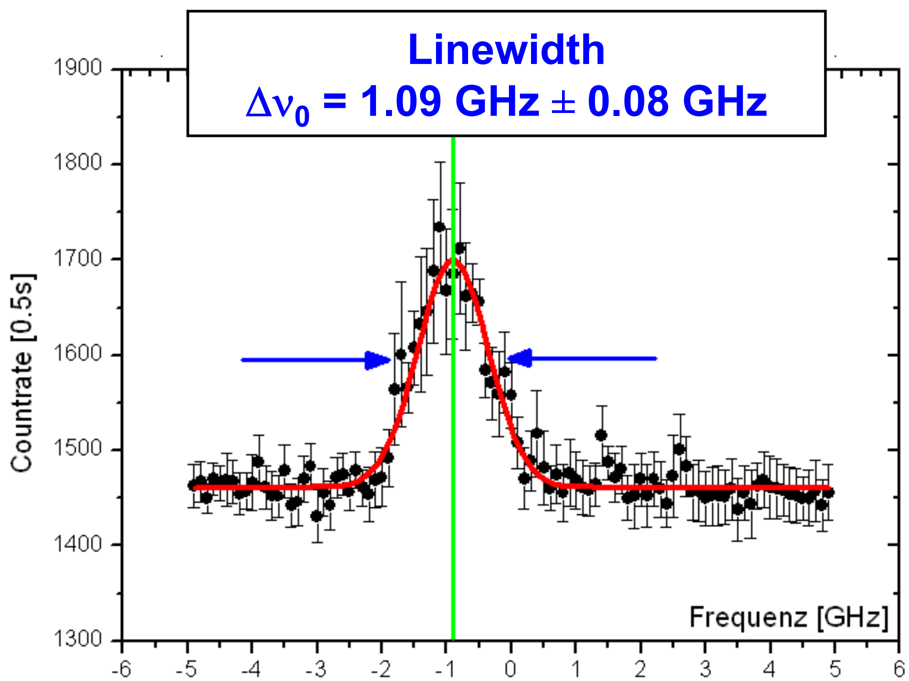




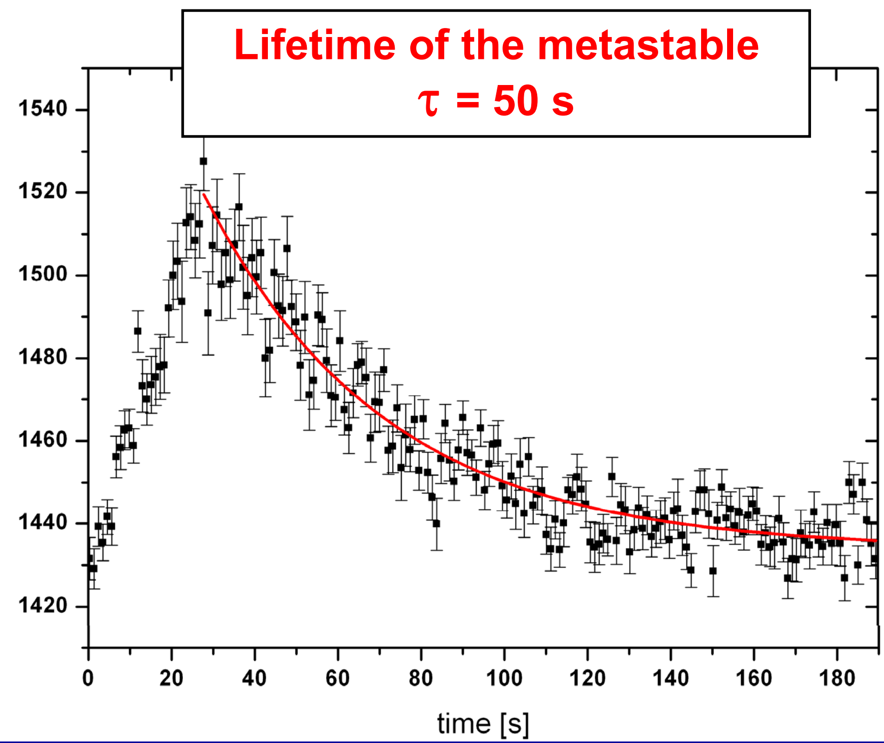
Characteristics of the metastable $^7Li^+$



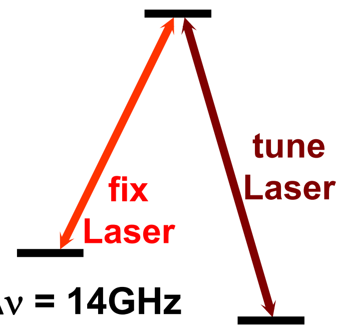




[C. Novotny et al., Hyperfine Interact. **171** *(2006)* 57]



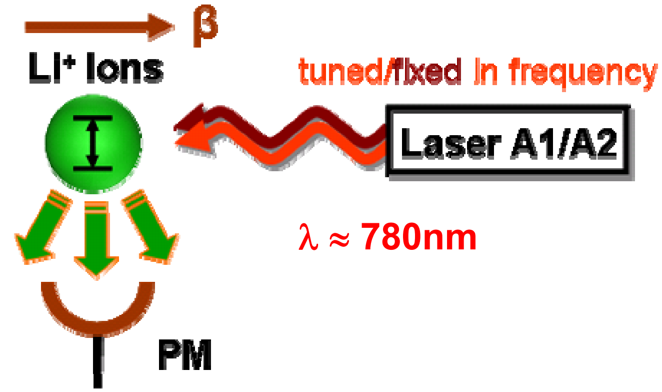
Parallel lambda spectroscopy



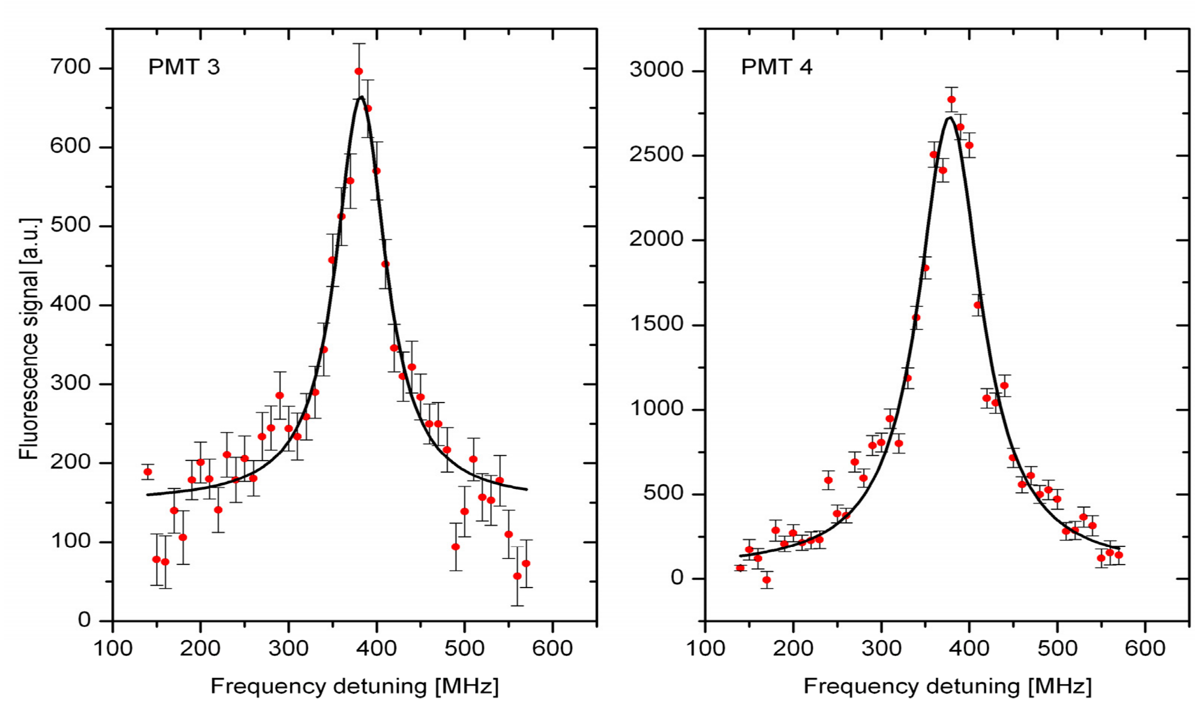
Δν = 14GHz
difference of the two lasers

→ **two "red" lasers :**

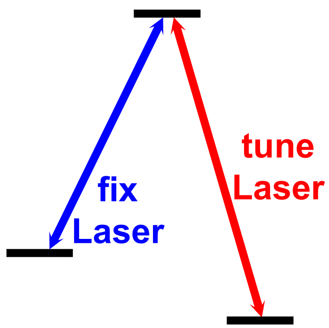
***first-order Doppler-free spectroscopy*:**
linewidth: (70…126) MHz
(10 times wider than the natural one)



- **both lasers from one site**
  (through one fiber)
- **no uncertainty in**
  laser-laser alignment
- **less background**
- **higher signal (less filters)**



Antiparallel lambda spectroscopy

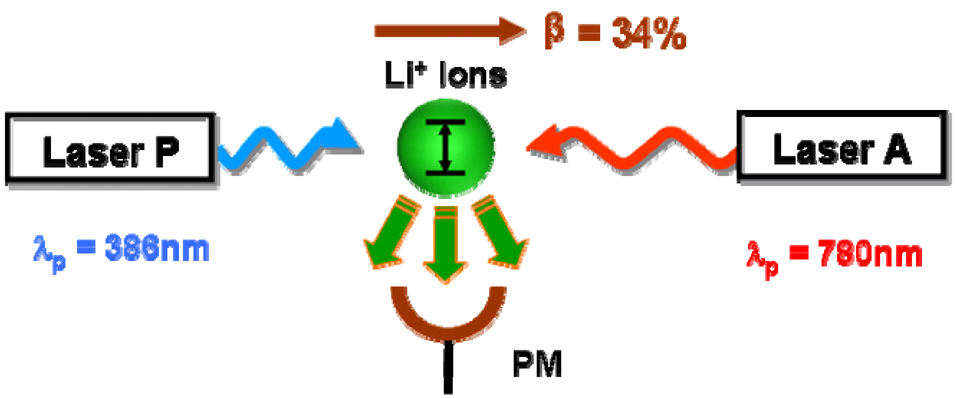


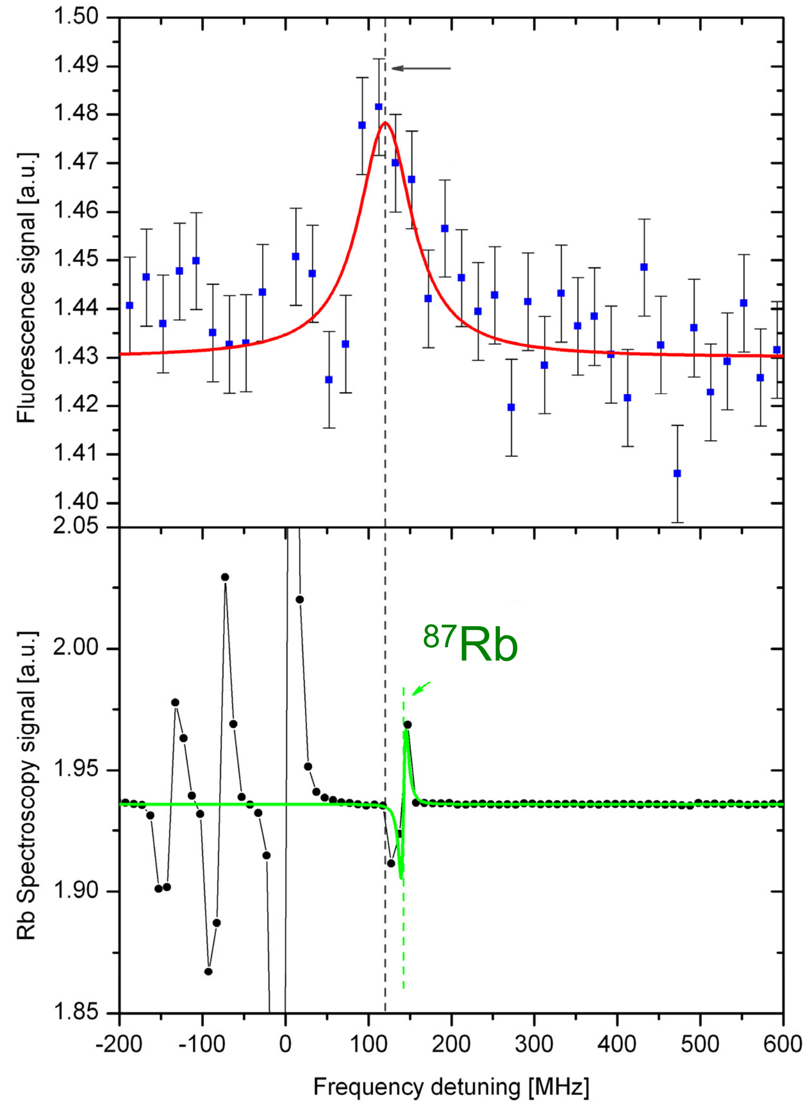
→ "red" & "blue" laser

$\Delta\nu$ = 79 ± 25 MHz (laboratory frame)

$\Delta\nu$ = 109 ± 32 MHz (ion frame)

Peak position: ± 10 MHz





Impact on the test parameter

Using TSR to fix $\delta\alpha$ and ESR for second order terms

$$\left|2\cdot\delta\alpha\cdot\beta^2+(\delta\alpha+2\cdot\delta\alpha_2)\cdot\beta^4\right|<\left(\frac{\nu_p\cdot\nu_a}{\nu_1\cdot\nu_2}-1\right)=3\times10^{-7}$$

$\delta\alpha_{TSR} < 8.4\times10^{-8}$

[S. Reinhardt, et al. Nature Physics *3 (2007)* 861]

Δ_{ESR}

$$\longrightarrow \quad \left|\delta\alpha_2\right|<9\times10^{-6}$$

Improvement by factor of **28** compared to former upper limit measured on H^0 @ 84%c

[D.W. MacArthur et al., PRL **56** *(1986)* 282]

consequences for $\delta\alpha$

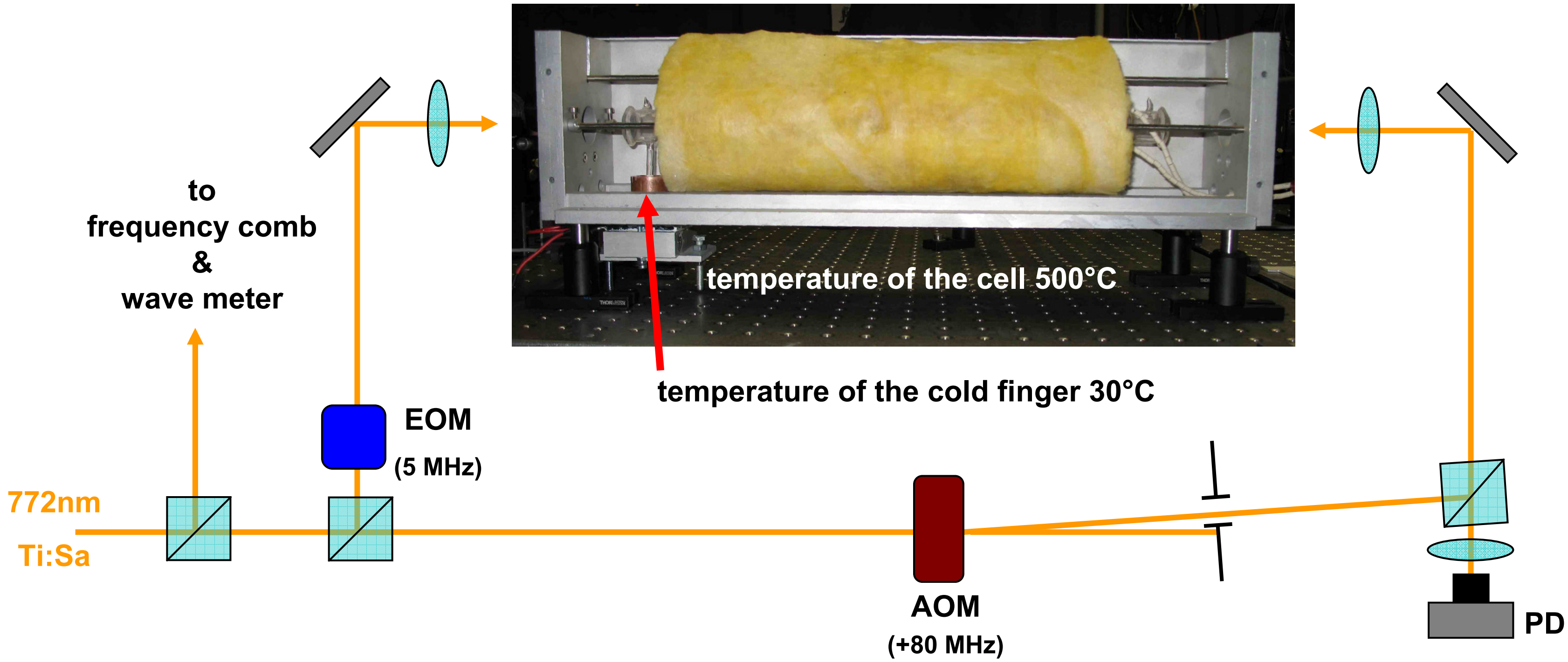
$$\frac{\nu_p\cdot\nu_a}{\nu_1\cdot\nu_2}-1=2\cdot\delta\alpha\cdot\beta^2$$

$\delta\alpha_{ESR}$ **= (7 ± 11) × 10^{-7}**

$\delta\alpha_{TSR}$ **= (4.8 ± 8.4) × 10^{-8}**

$$\frac{ESR}{TSR}\approx 13$$

Iodine reference @ 772 nm



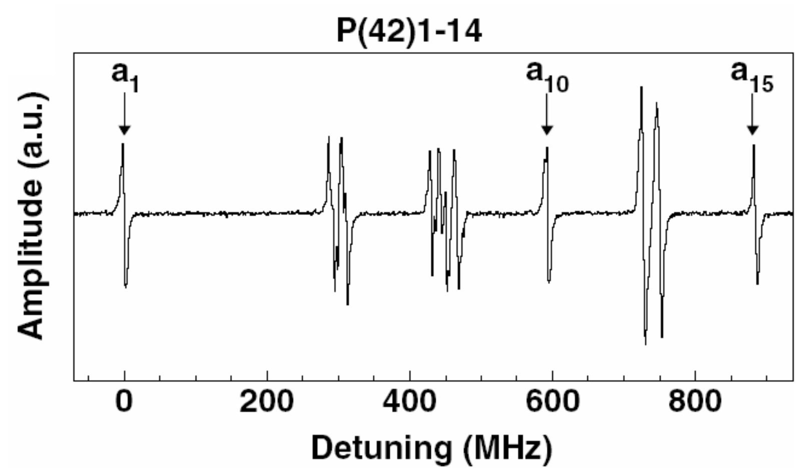
calibrated transition for the SRT experiment

P(42) 1-14 (772nm)

a_1: (388 605 083.71 ± 0.30) MHz

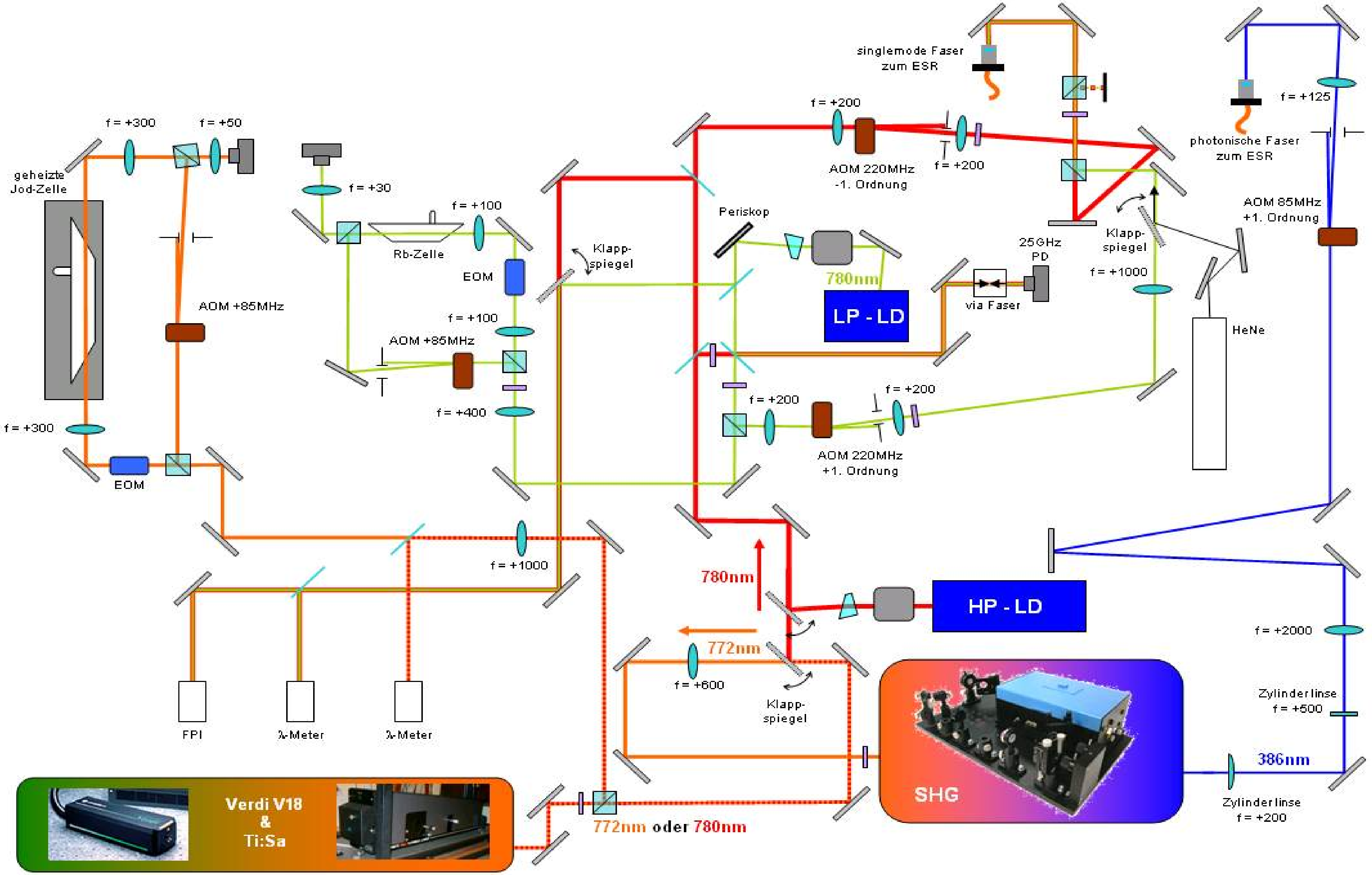
$|a_1-a_{10}|$: (587 187 ± 42) kHz

$|a_1-a_{15}|$: (881 362 ± 42) kHz



[S. Reinhardt et al., Opt. Com. **274** *(2007)* 354]

"Extended" laser system



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Summary

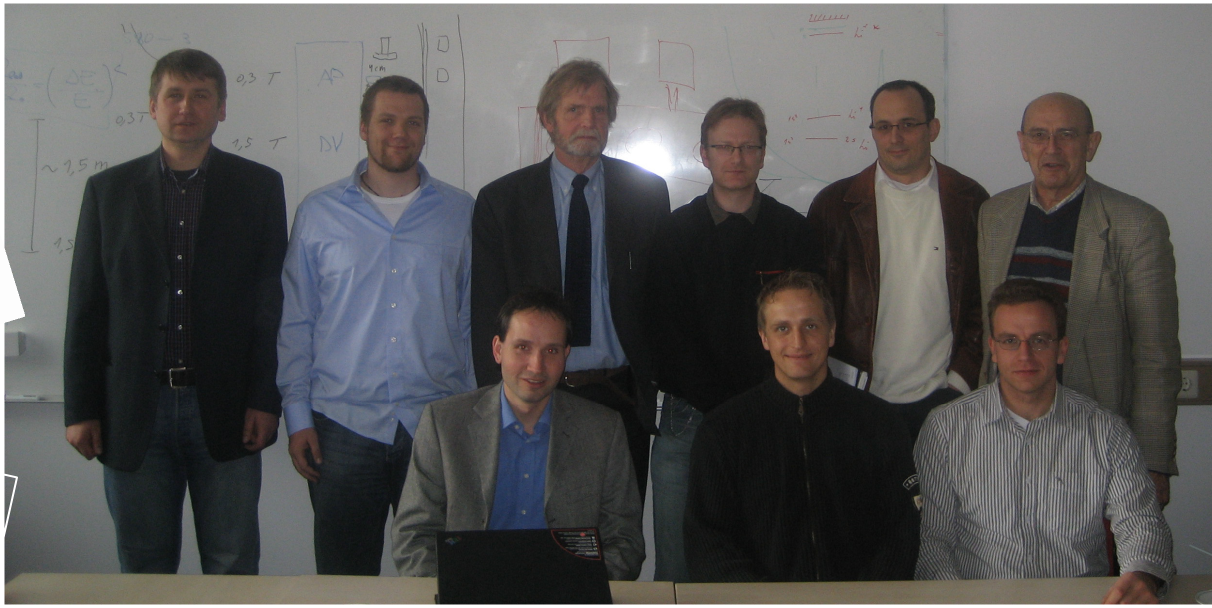
Presented :

- ✓ upper bound on test parameter α **< 8 × 10^{-8}** (at TSR)
- ✓ the **possibility** of **precision spectroscopy** in high **relativistic ion beams**
- ✓ **improved upper limit** for second-order deviations by a **factor 28** (at ESR)
- ✓ the **feasibility** for a **new first-order upper limit**
- ✓ **calibration** of **iodine transitions** at 772 nm

Next steps :

- ☒ beam time with full frequency resolution ($\Delta\nu < 1$ MHz)
- ☒ systematic investigations (switching schemes, geometrical uncertainties, etc…)
- ☒ applying saturation spectroscopy

The SRT-Collaboration



C. Novotny[1], S. Reinhardt[2,4], S. Karpuk[1],
B. Bernhardt[4], D. Bing[2], 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], G. Saathoff[2,4],
D. Schwalm[2], T. Stöhlker[3], T. Udem[4], A. Wolf[2]

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