

# Scaling laser cooling of ion beams toward high beam energies

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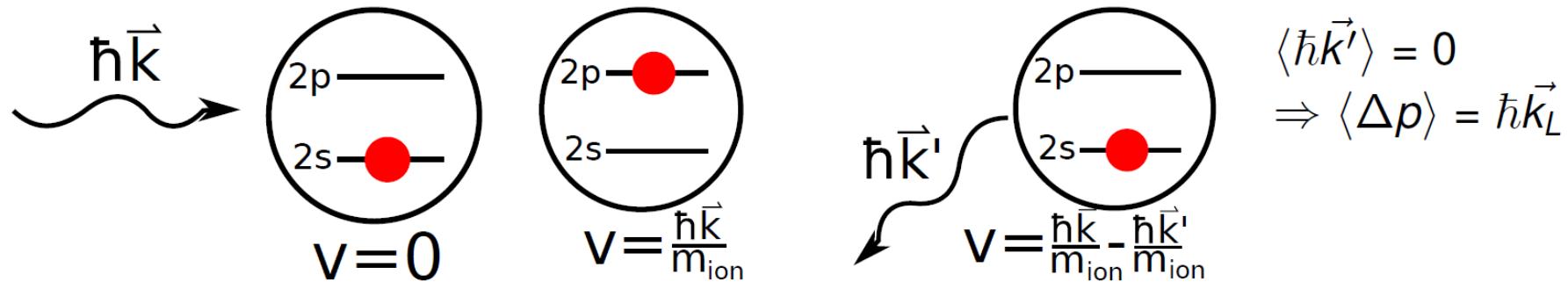
<sup>6</sup> Technische Universität Dresden

<sup>7</sup> Universität Münster



# Laser Cooling in a Nutshell

# Using fast atomic transitions in ions for laser cooling

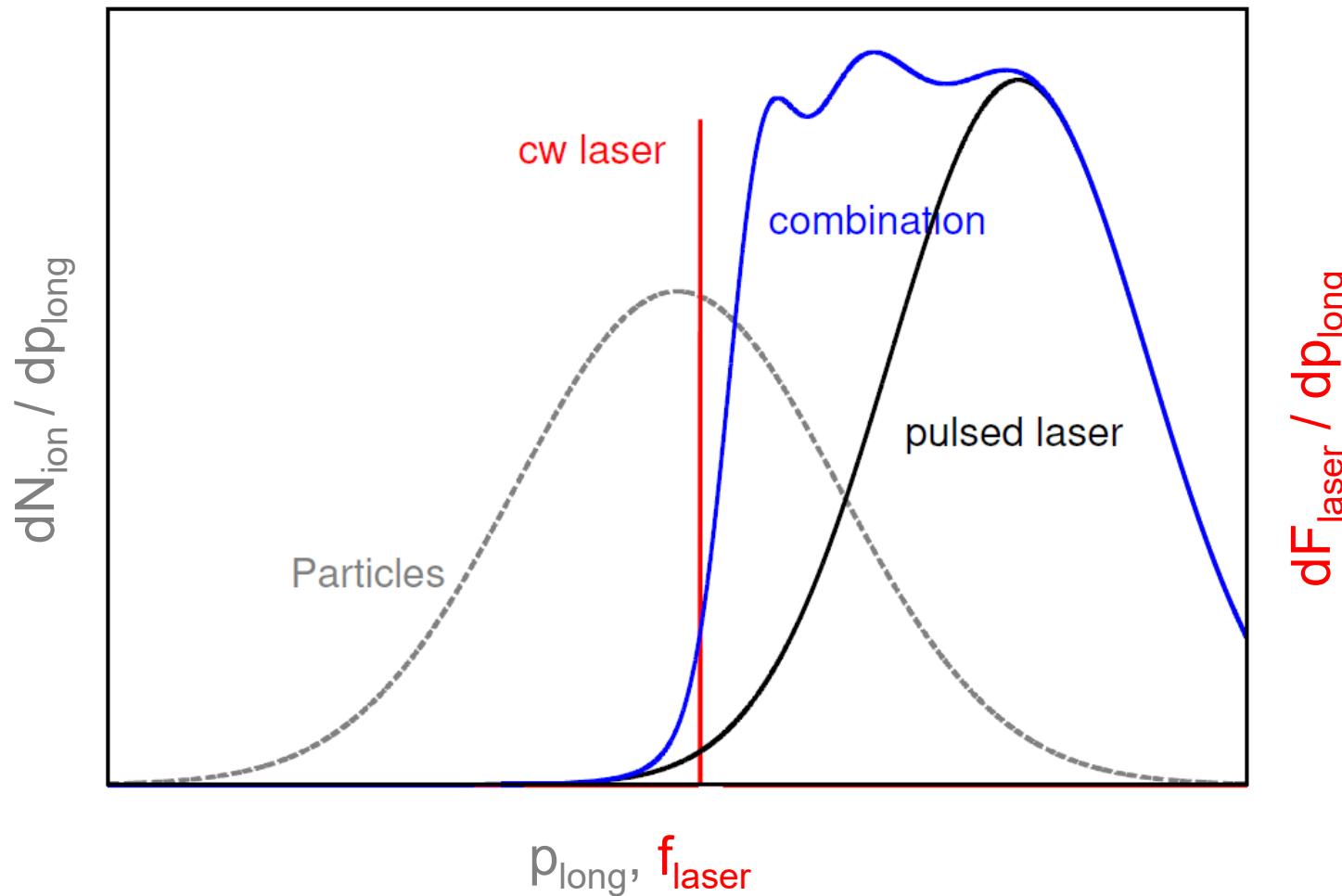


$$\vec{F}(\vec{v}_{ion}) = \pi \hbar \vec{k}_{laser} \times L(\omega) / \tau_{trans}$$

Annotations explain the components of the force:

- Photon Momentum:** Points to the term  $\pi \hbar \vec{k}_{laser}$ .
- Scattering Rate:** Points to the term  $L(\omega) / \tau_{trans}$ .

# Laser force momentum acceptance range is small for cw-lasers



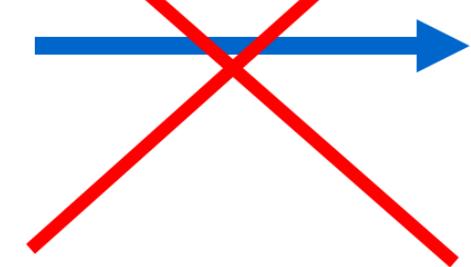
... but can be large for pulsed lasers

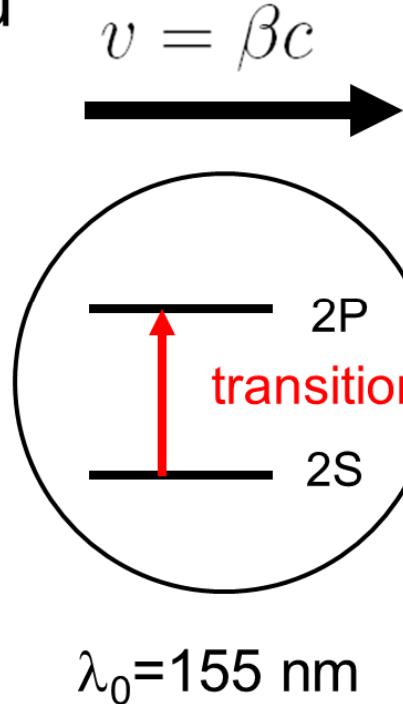
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# The relativistic Doppler shift of the laser wavelength is HUGE

ESR example:

$\text{C}^{3+}$  ion energy  $\approx 122 \text{ MeV/u}$   
 $(\beta \approx 0.47, \gamma \approx 1.13)$

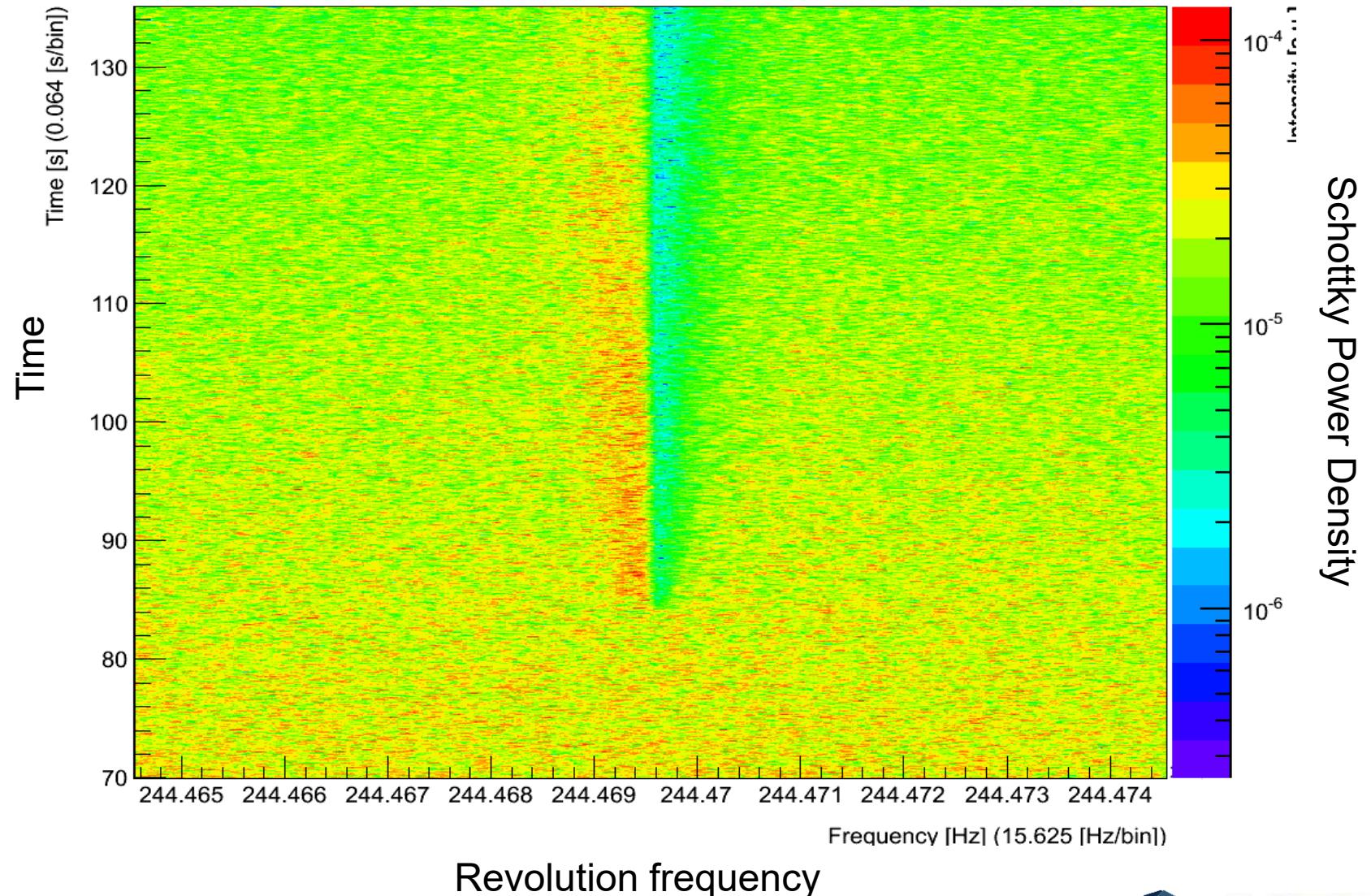
$$\cancel{\lambda_p = \frac{\lambda_0}{\gamma(1 + \beta)}}$$

$$\lambda_p = 93 \text{ nm}$$



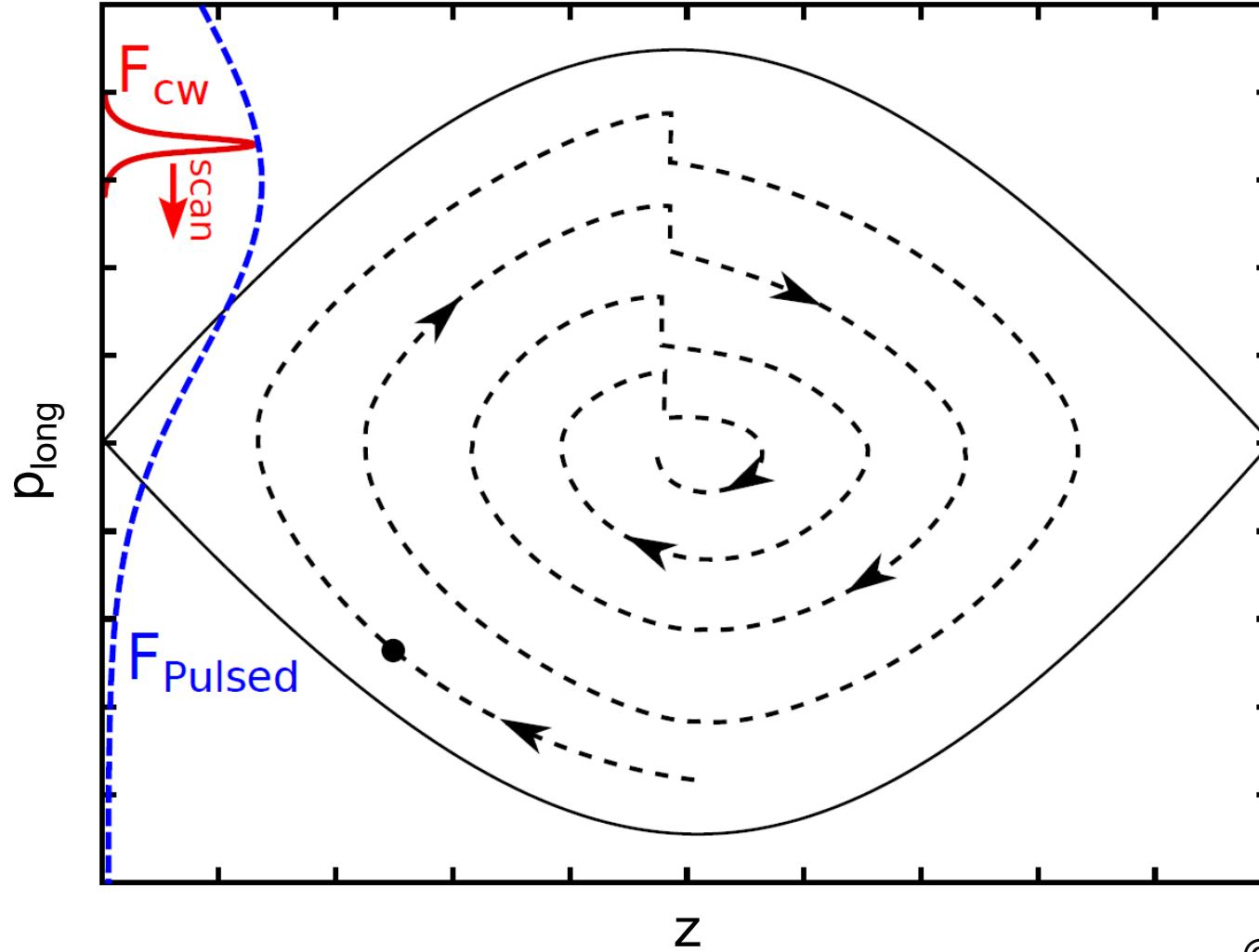
$$\lambda_a = \frac{\lambda_0}{\gamma(1 - \beta)}$$

$$\lambda_a = 257 \text{ nm}$$

# Cooling a coasting beam with a cw laser

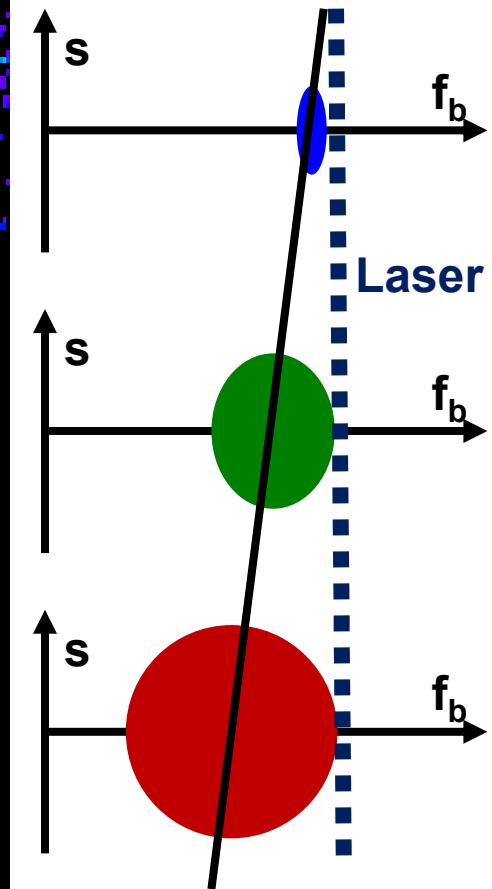
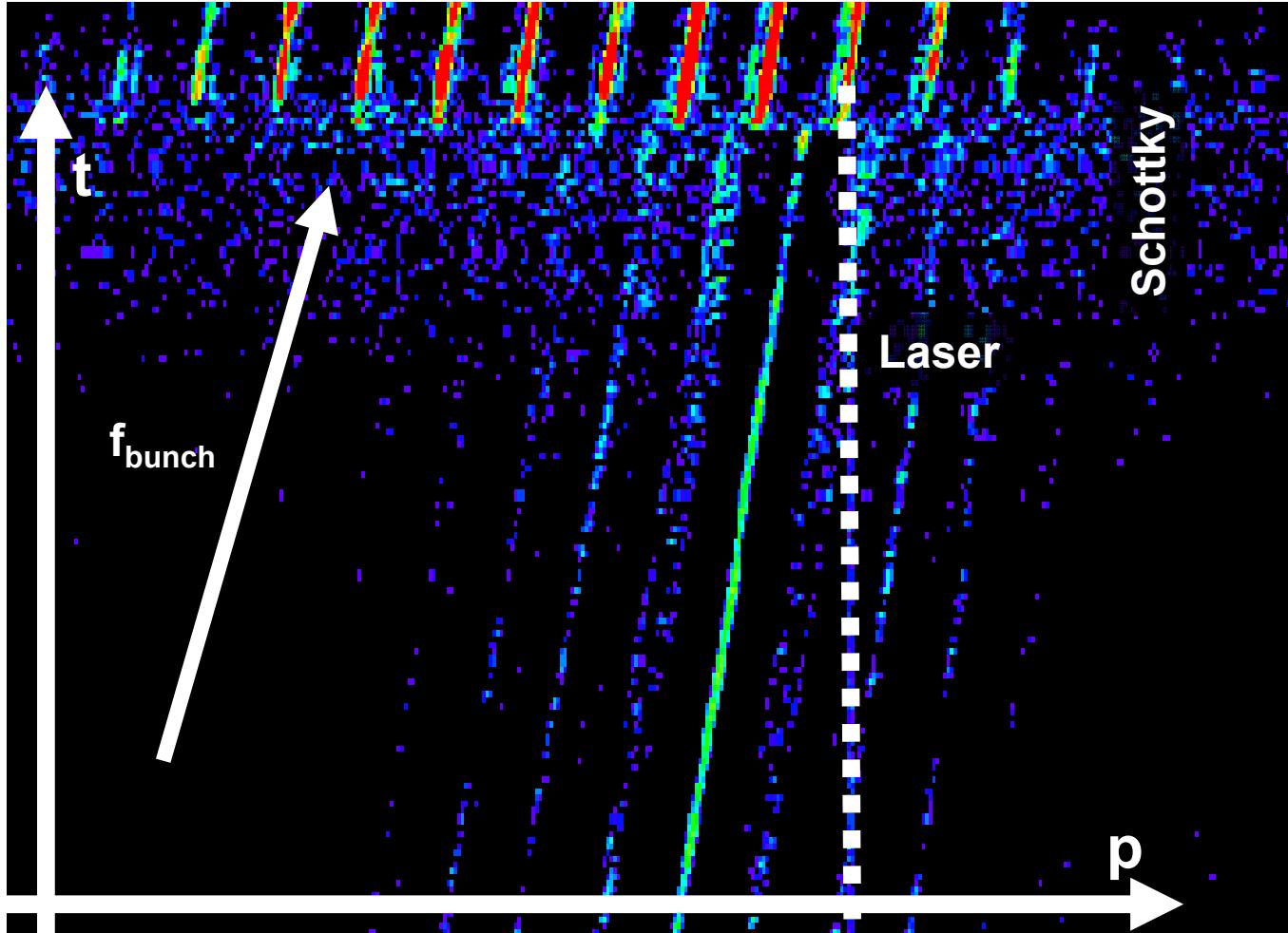


We need to bunch relativistic beams to have a stable cooling point



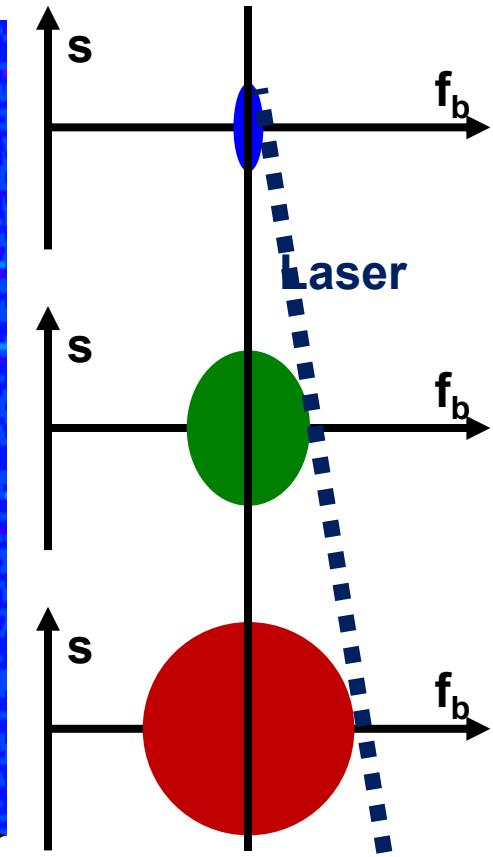
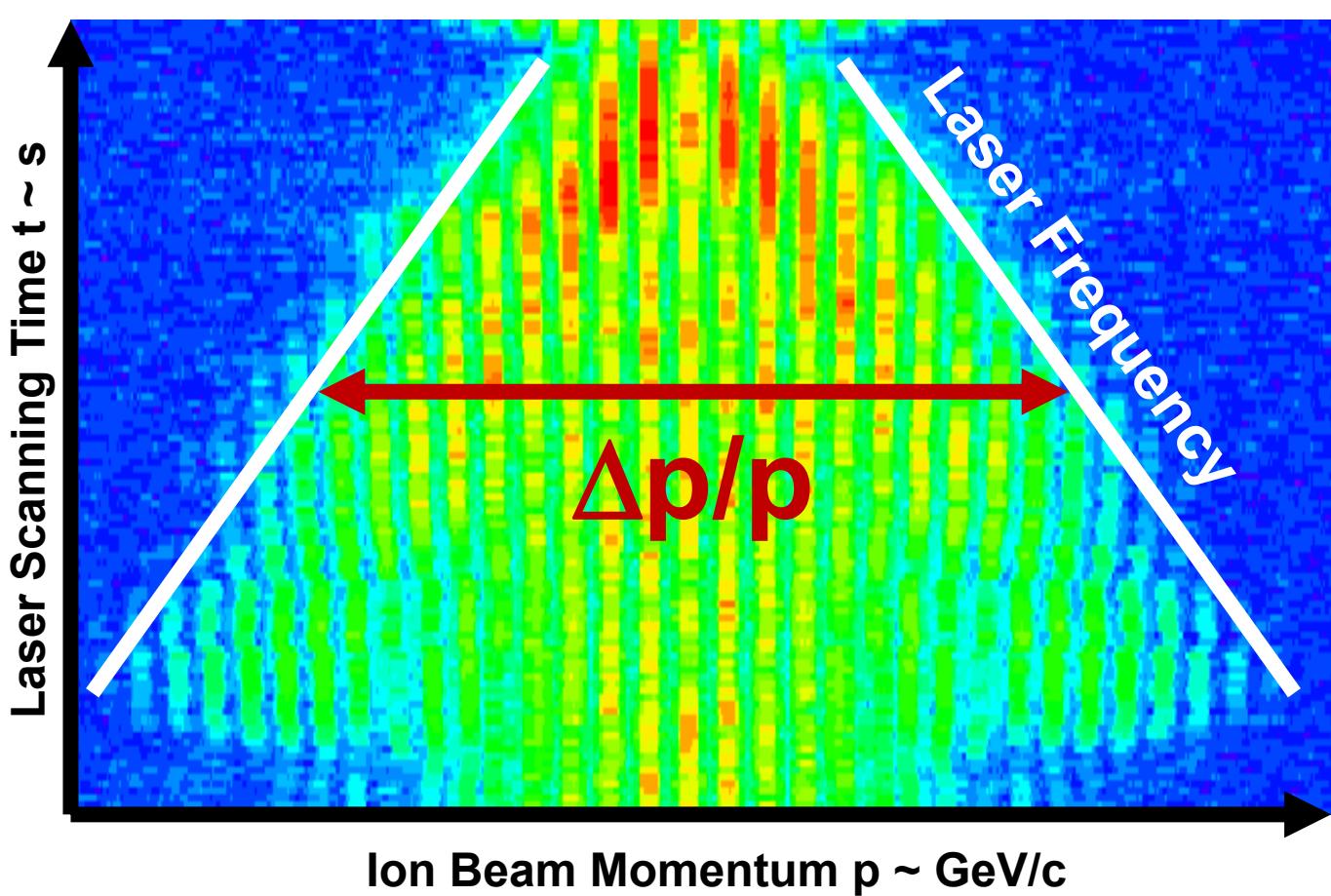
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# Technique 1: Scanning the bunching frequency

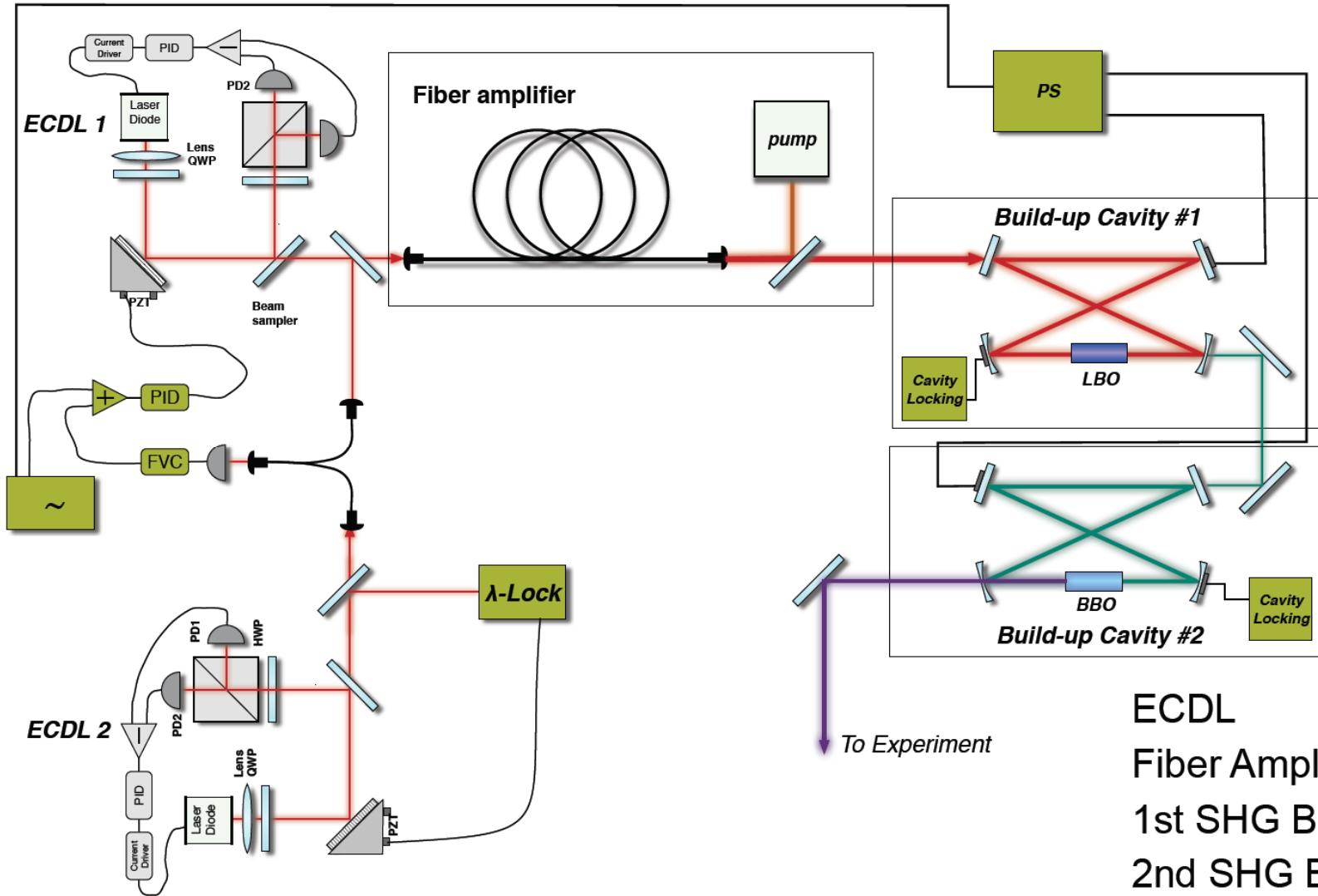


$$f_{\text{bunch}} = 20 \times 1.295 \text{ MHz} — \Delta f_{\text{bunch}}/\Delta t = 20 \text{ Hz} / 5 \text{ s} — f_{\text{sync}} \sim 170 \text{ Hz} — \Delta p/p_{\text{accept}} \approx 10^{-5}$$

## Technique 2: Scanning the laser frequency

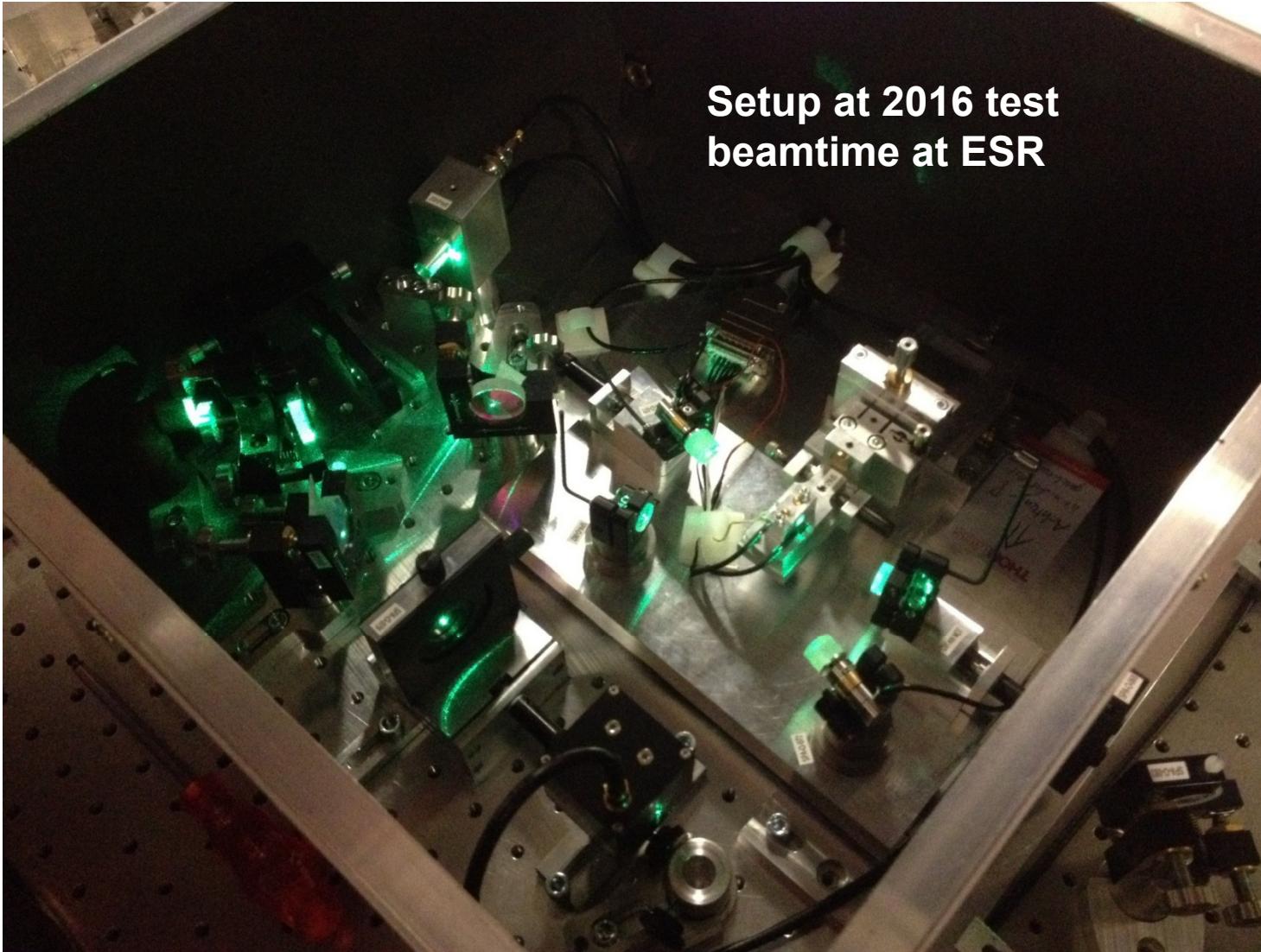


# Broad-scanning cw laser system (T. Walther, TU Darmstadt)



ECDL  
Fiber Amplifier  
1st SHG Built-up Cavity  
2nd SHG Built-up Cavity

# Broad-scanning cw laser system @ ESR, GSI, Darmstadt



# Laser cooling in a nutshell

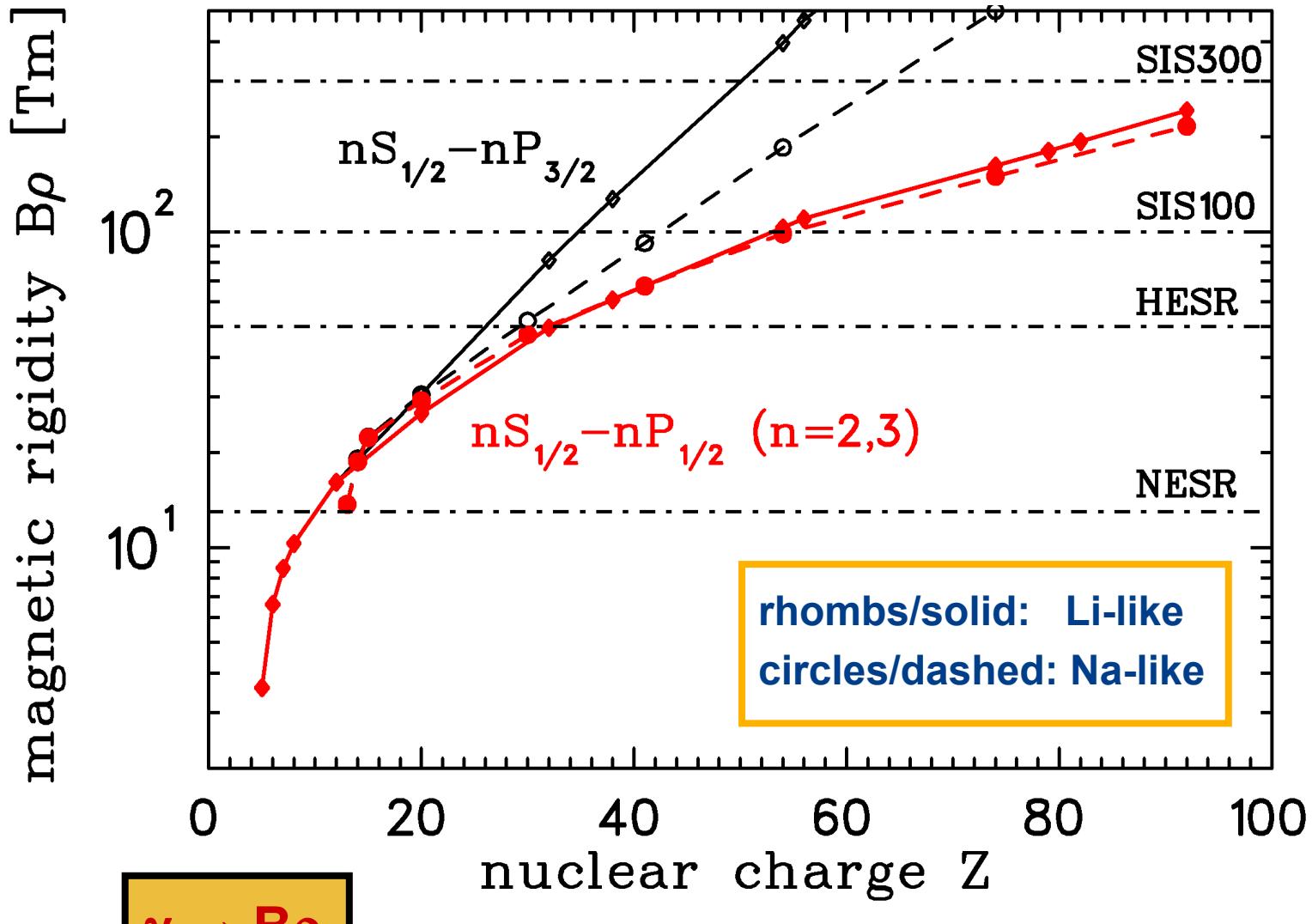
- A cw laser has small momentum acceptance ( $<10^{-7}$  dp/p)
- Scanning laser or bunching frequency can cool a large dp/p
- Pulsed lasers can cool large dp/p beams „in parallel“
- The relativistic Doppler shift affect transition wavelengths ...
- ... and lifetimes
- Typically, one needs bunching to have stable cooling

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# Towards high Energies

# Addressing many ion species with a single laser system

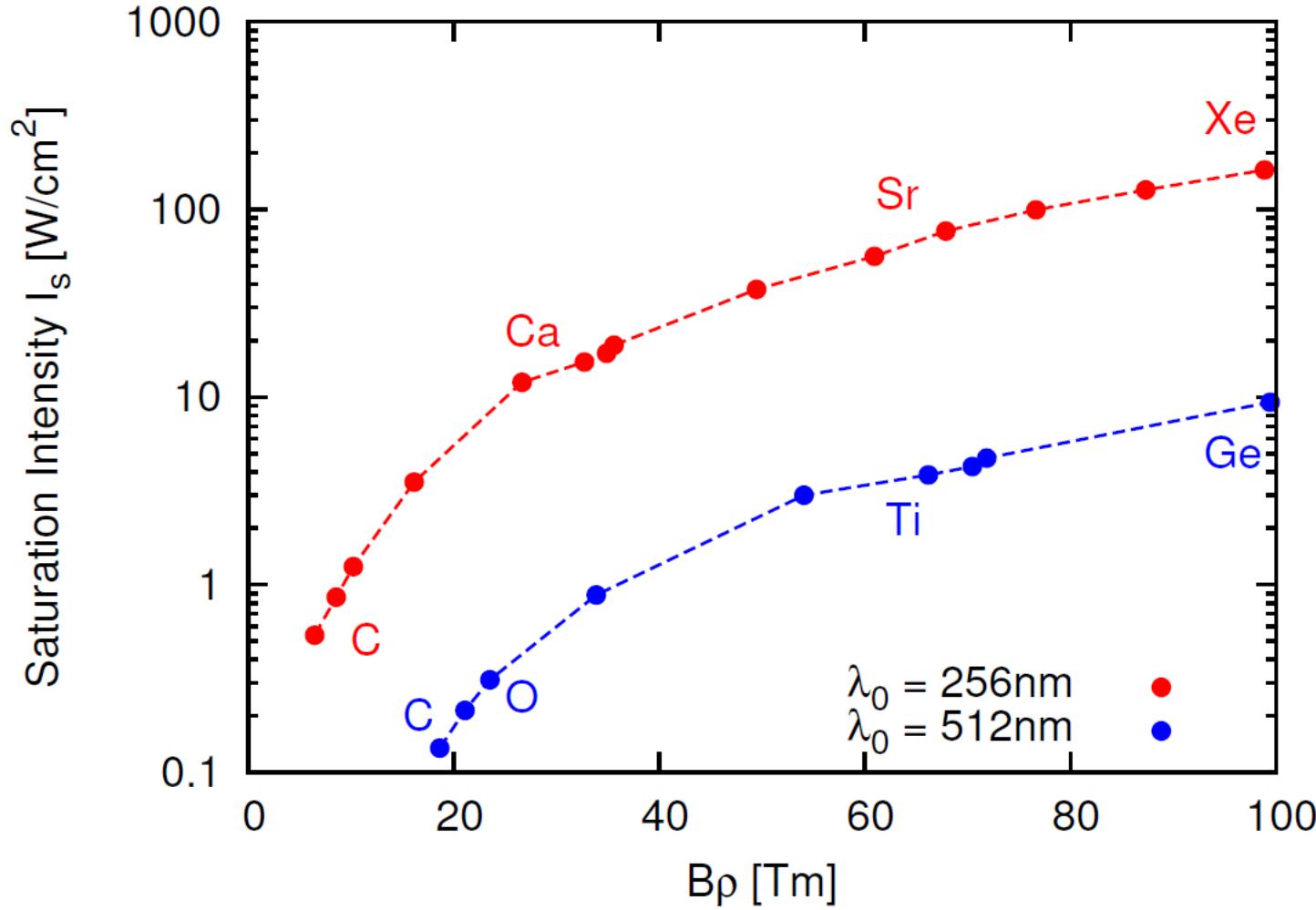


## Example: CSRe at IMP, Lanzhou

$$\gamma = \sqrt{((B\rho Qe)/(m_0c)) + 1}$$

A	Q	$2P_{1/2}$ $2S_{1/2}$ rest	$2P_{1/2}$ $2S_{1/2}$ rest	$\gamma$	$\beta$	$2P_{1/2}$ $2S_{1/2}$ lab	$2P_{1/2}$ $2S_{1/2}$ lab
9	1	313.2	315.2	1.06	0.32	<b>435.7</b>	<b>438.5</b>
11	2	206.8	206.6	1.14	0.48	<b>349.8</b>	<b>349.5</b>
12	3	155.1	154.8	1.25	0.60	<b>311.7</b>	<b>311.2</b>
14	4	124.3	123.9	1.32	0.65	<b>271.7</b>	<b>270.8</b>
16	5	103.8	103.2	1.38	0.69	<b>240.9</b>	<b>239.6</b>

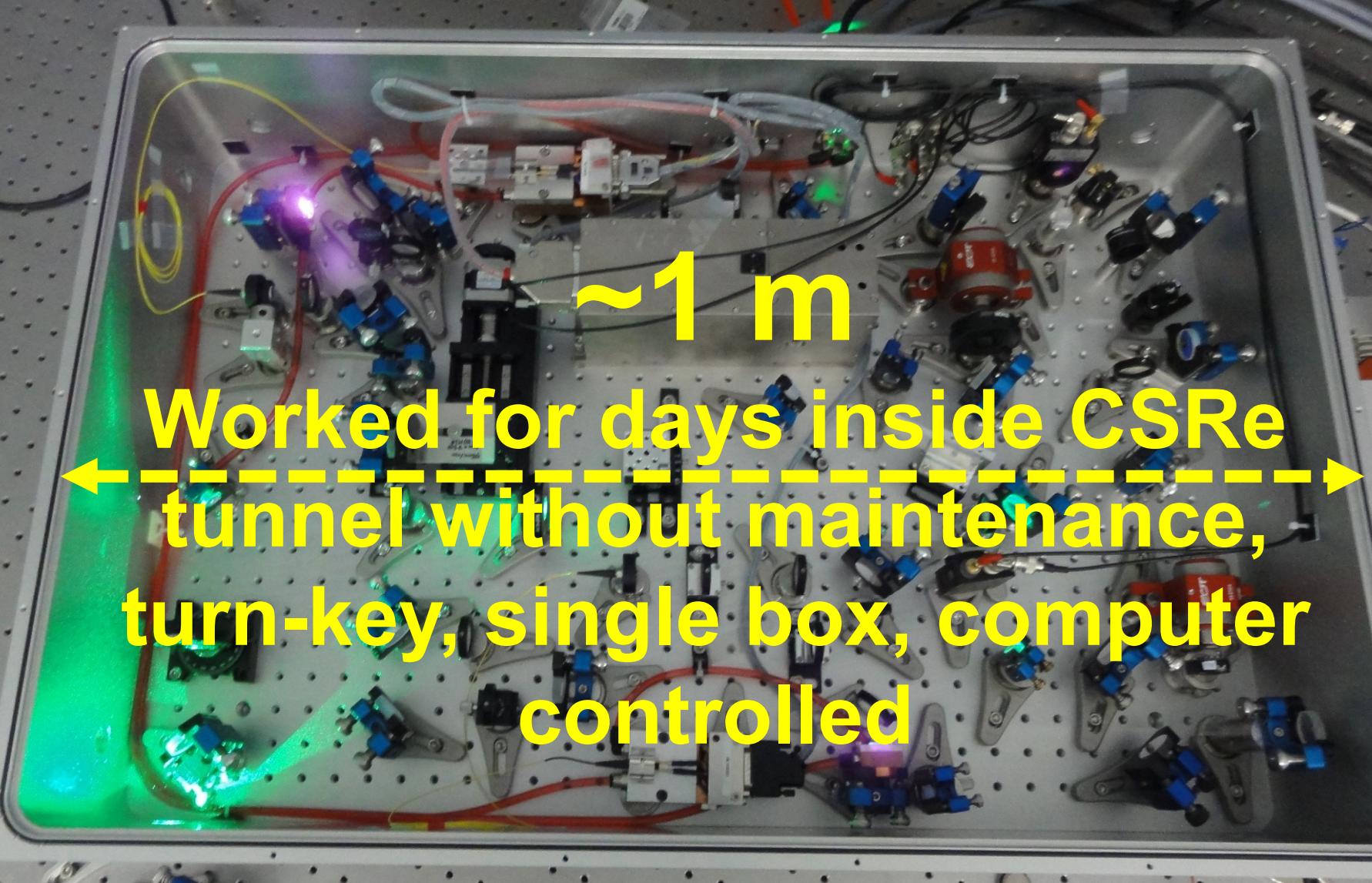
# We need LOTS of laser power to saturate cooling transitions



e.g. Ø10 mm @ SIS 100 relates to 100 W @ 257 nm

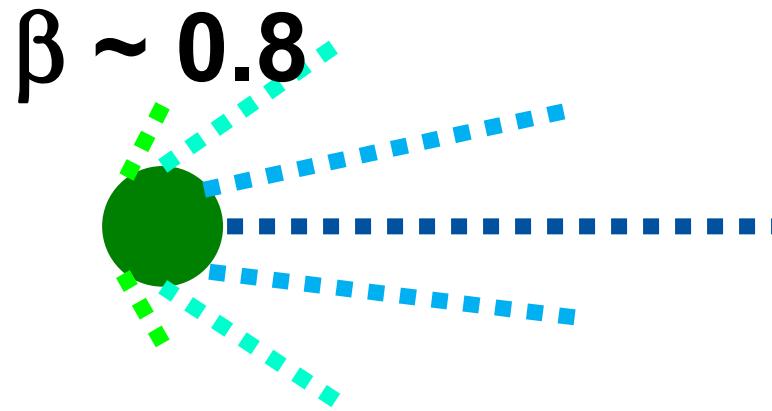
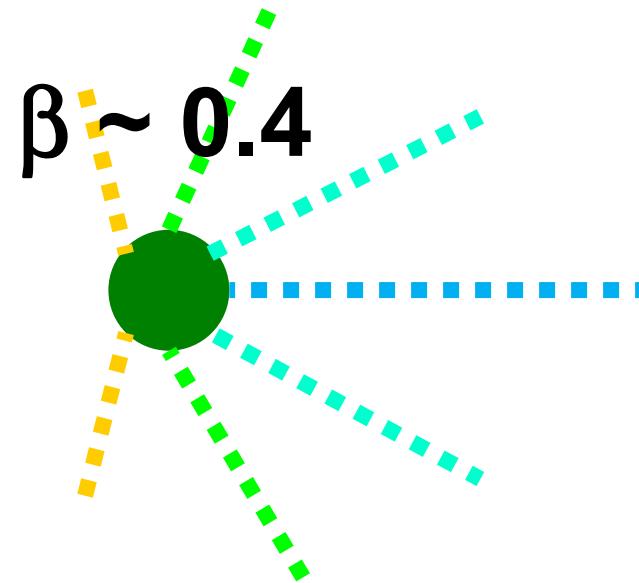
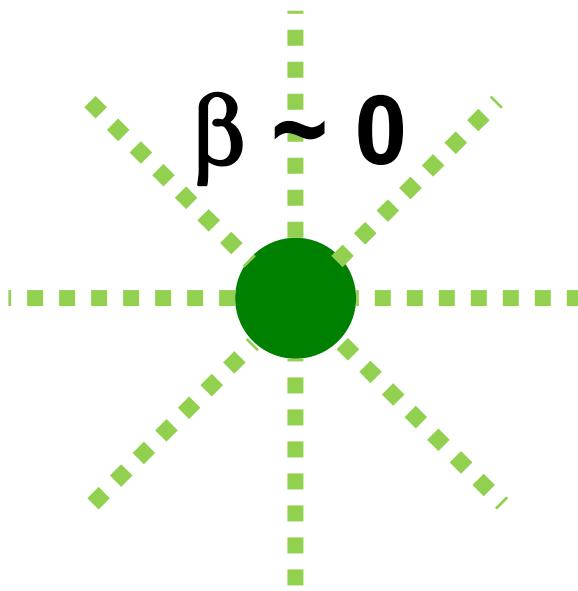
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Turn-key pulsed laser system ( $\Delta p/p$  acc.  $\sim 10^{-4}$ , MHz repetition rate)

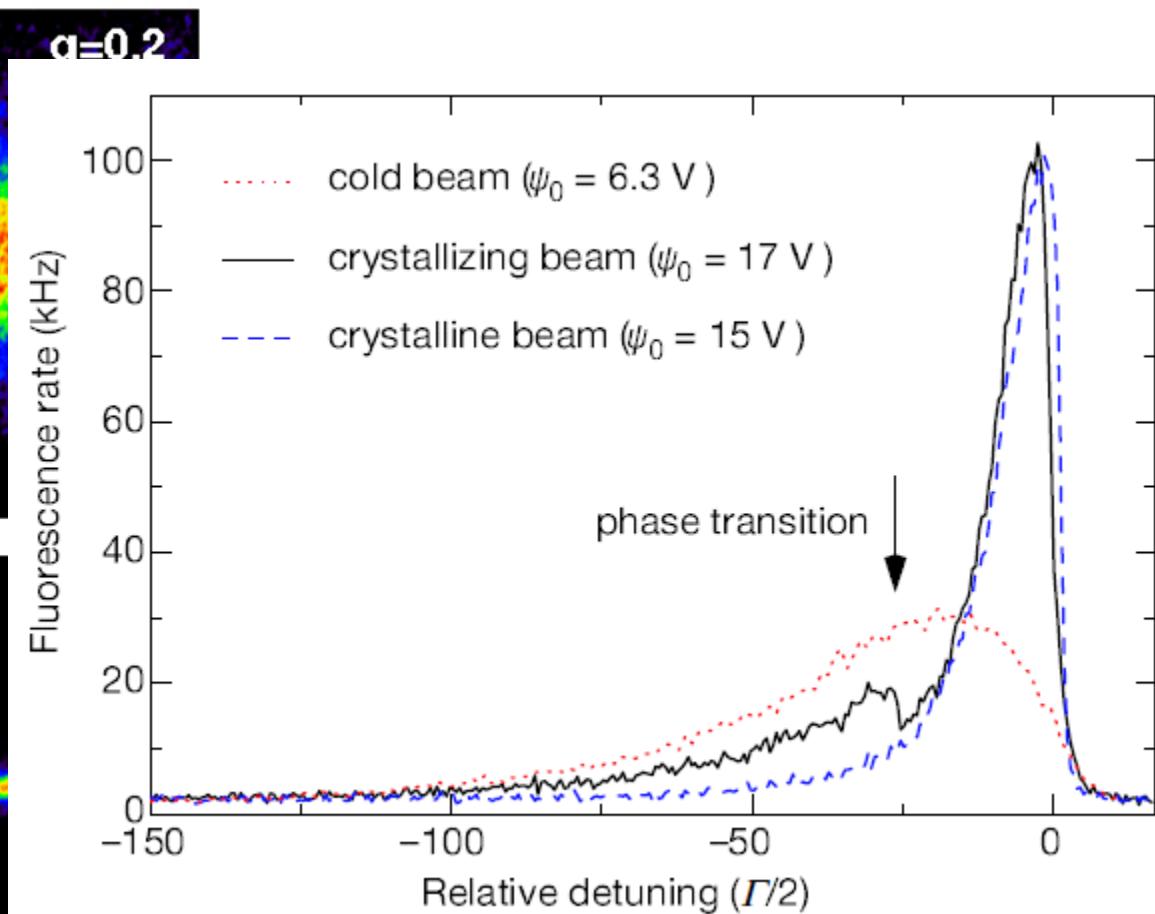
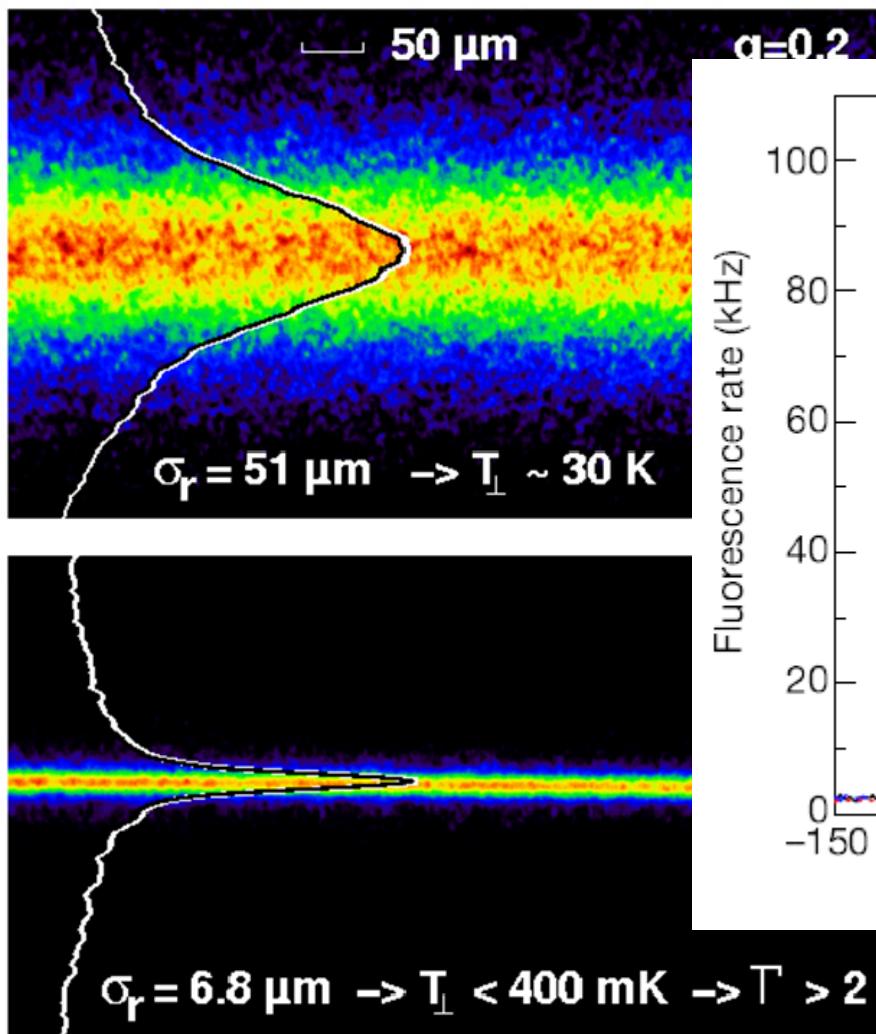


$\sim 1 \text{ m}$   
Worked for days inside CSRe  
tunnel without maintenance,  
turn-key, single box, computer  
controlled

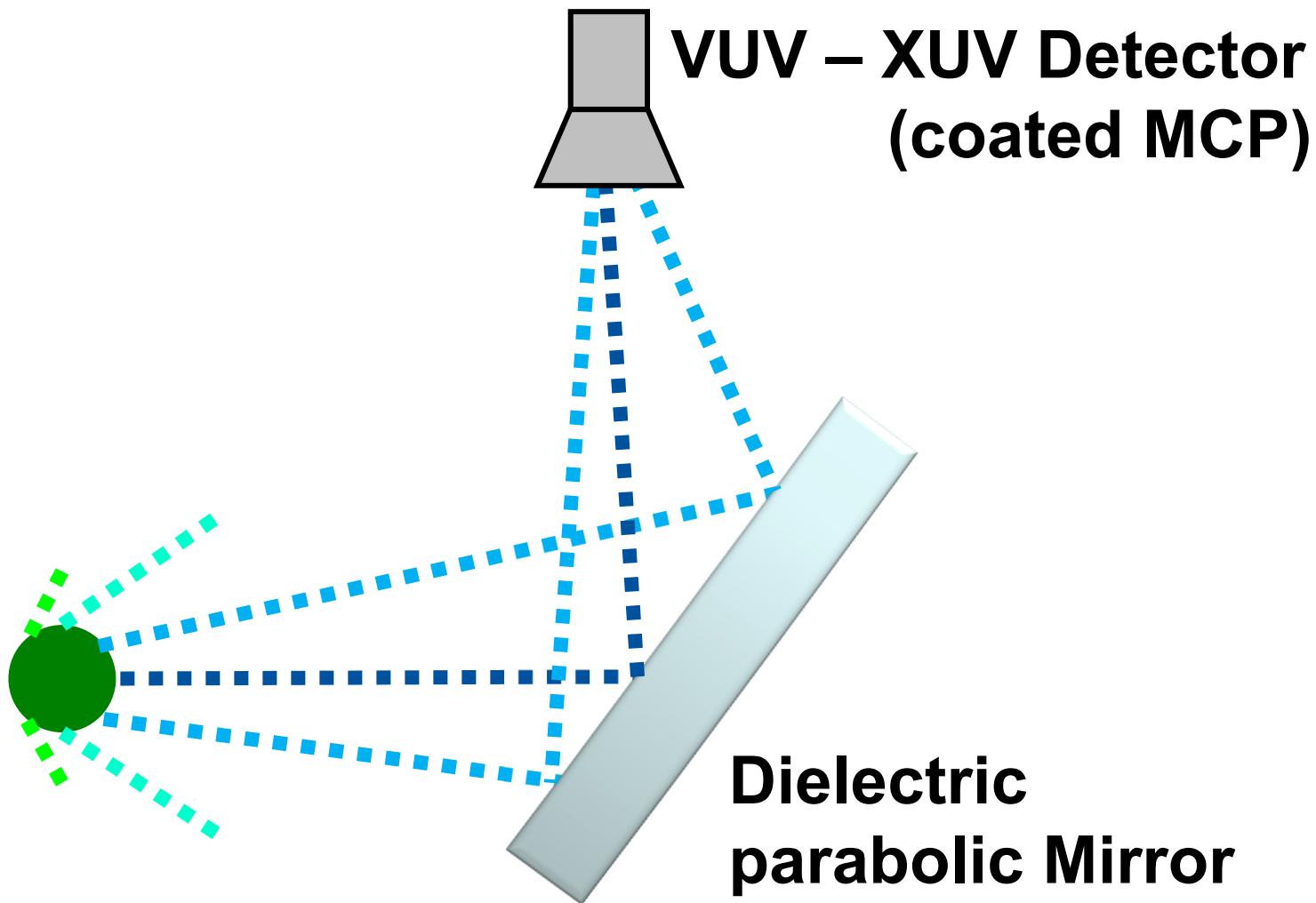
# Lorentz-boosted fluorescence as diagnostic



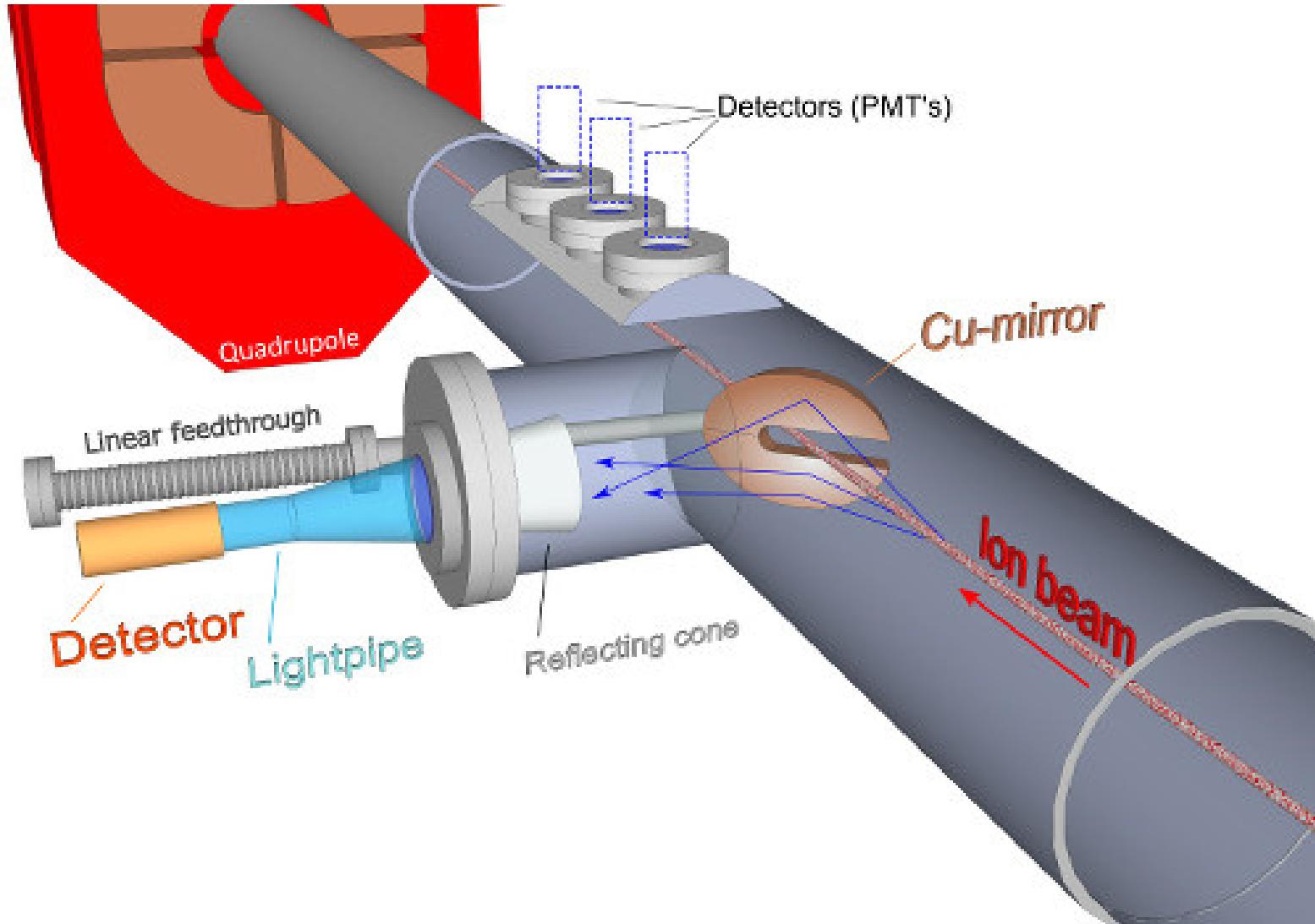
# Using fluorescence intensity as a diagnostic (@ PALLAS)



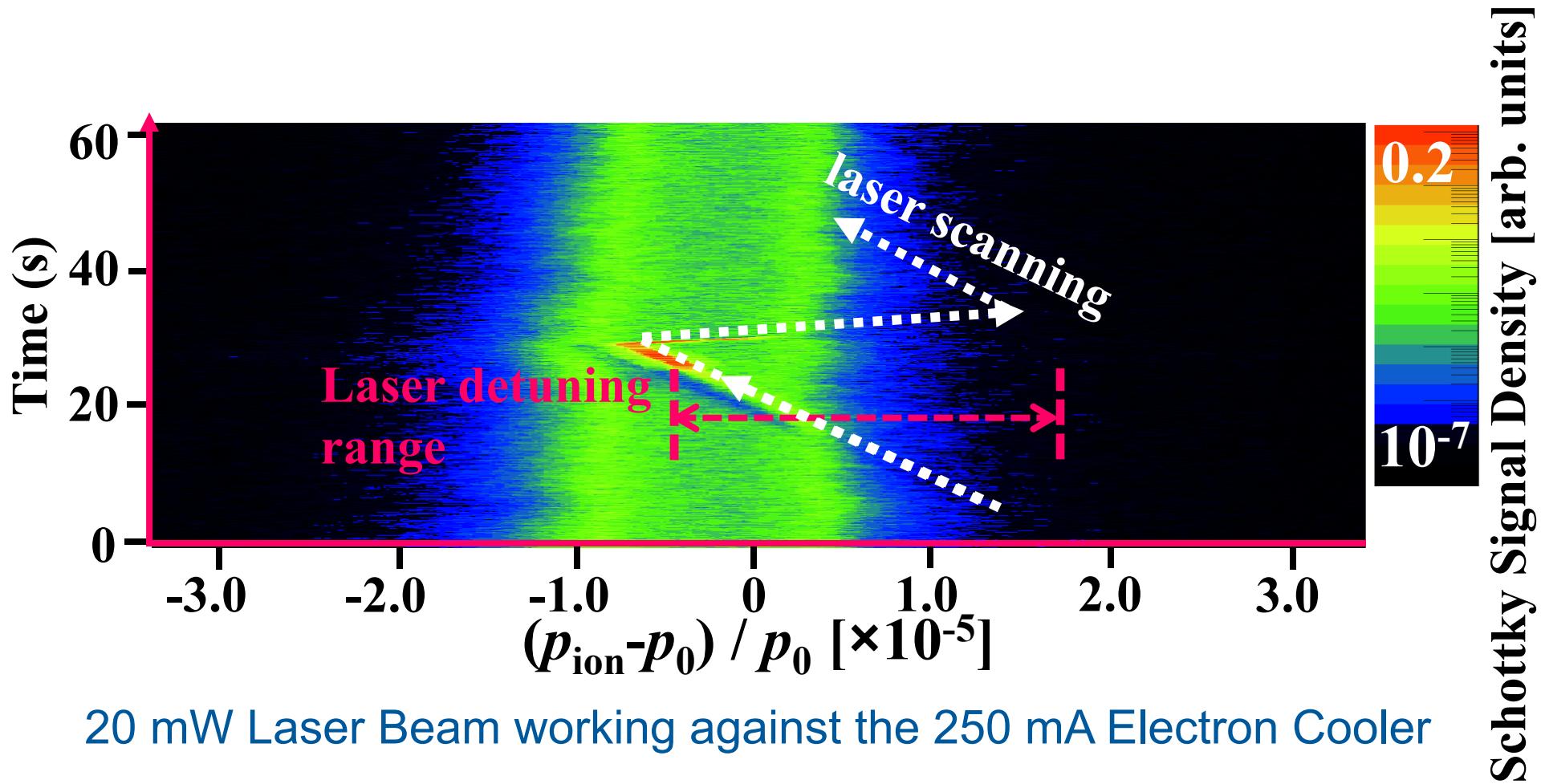
# The in-beam mirror concept



# In-beam mirror design (updated in 2016, M. Lochmann, V. Hannen)



# Laser cooling force increases with beam energy

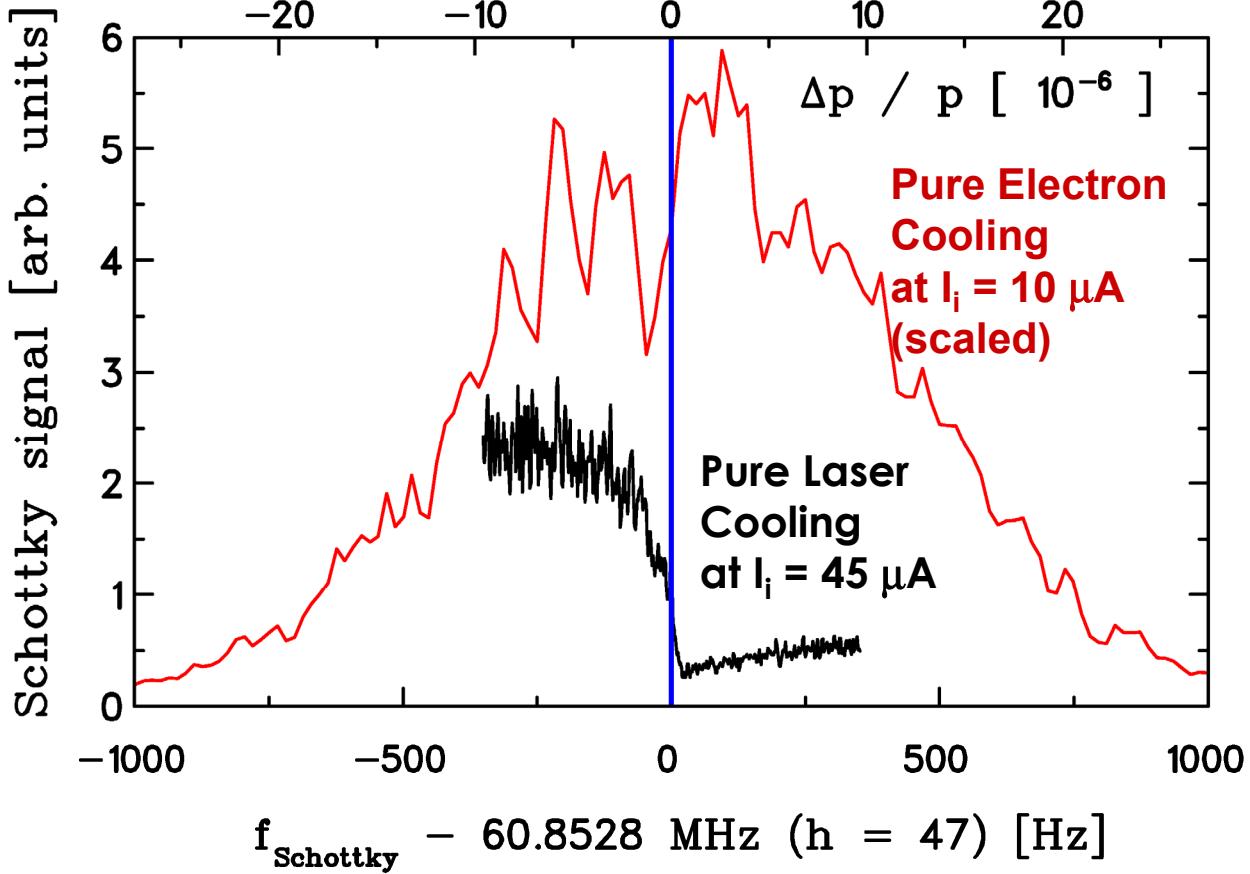


# Towards high energies

- The relativistic Doppler effect „shifts“ the transition wavelength
- We use this to cool many ion species with a single laser system
- With increasing energies the laser force becomes stronger
- With increasing energies and ion charge we need more power
- Pulsed lasers can deliver enough power in a compact form
- Fluorescence detection is complimentary to standard techniques

# Spectroscopy

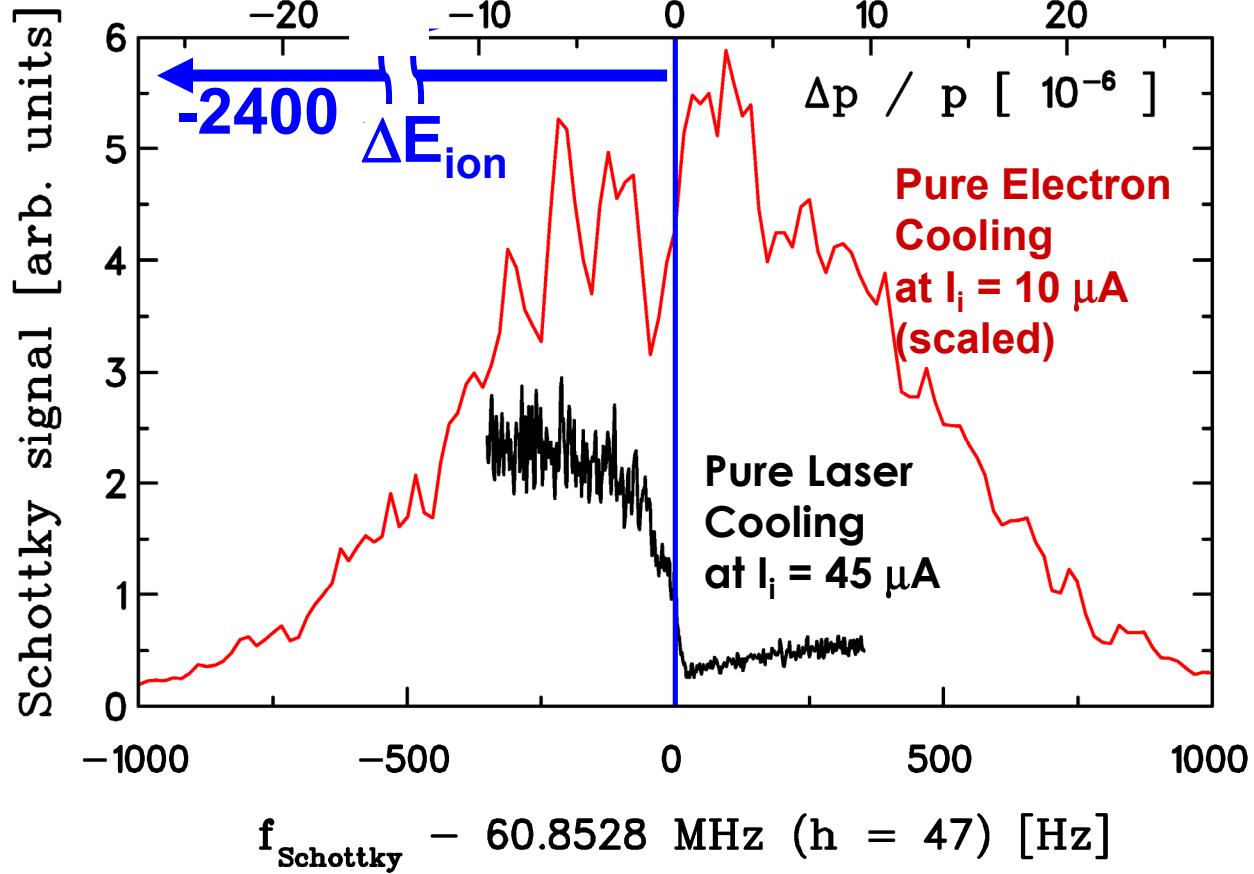
# $C^{3+}$ spectroscopy in the old days



- Mark Doppler-shifted transition in Schottky spectrum (coasting)
- Adjust electron cooled distribution to the same revolution frequency
- Extrapolate to zero ion current to eliminate space charge effects

	$\lambda (2S_{1/2} \rightarrow 2P_{1/2}) [\text{nm}]$	$\lambda (2S_{1/2} \rightarrow 2P_{3/2}) [\text{nm}]$
ESR C3+ experiment	155.0705 (39) (3)	154.8127 (39) (2)
Theory (I. Tupitsyn, V. Shabaev)	155.0739 (26)	154.8173 (53)

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- Mark Doppler-shifted transition in Schottky spectrum (coasting)
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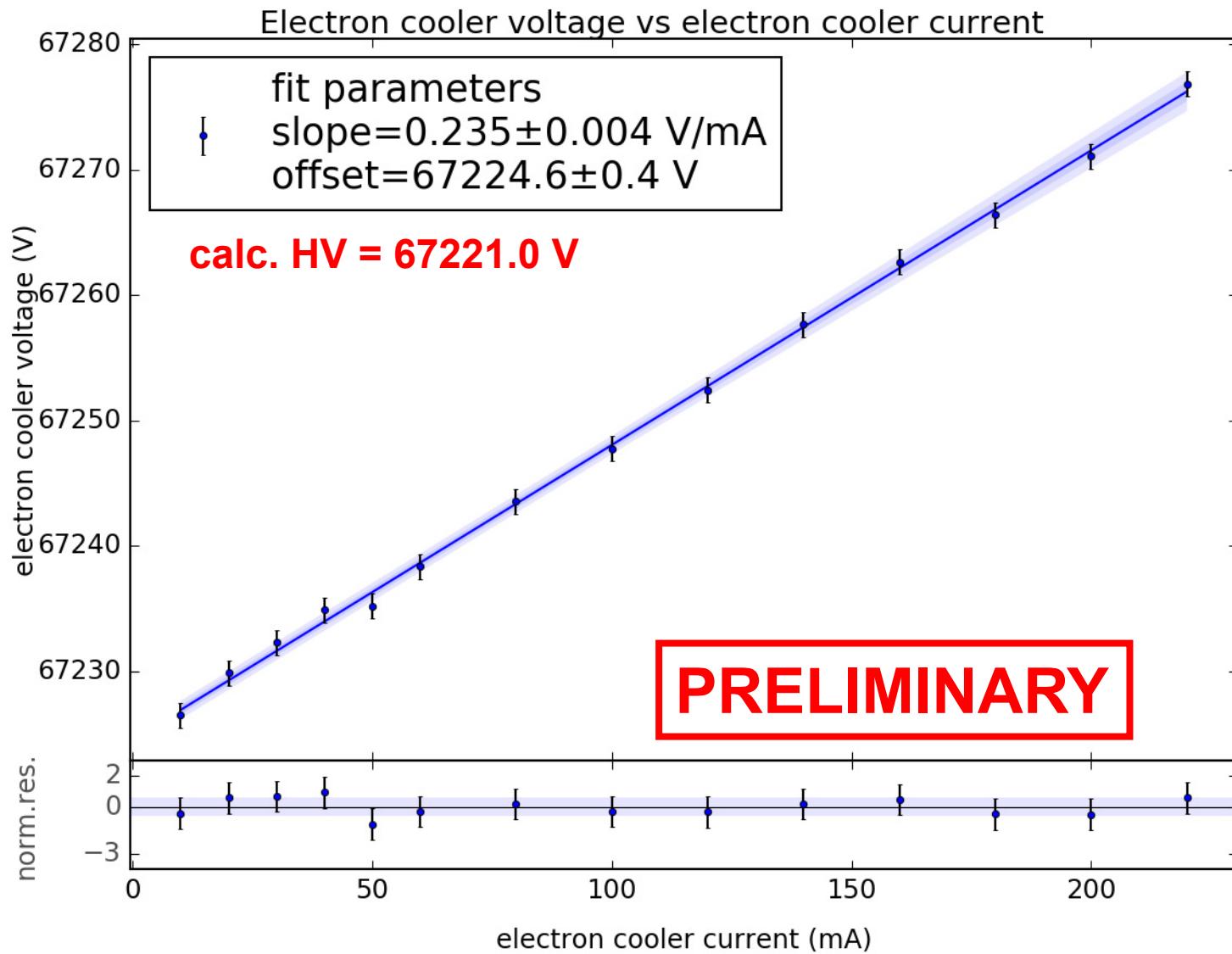
Uncertainty in absolute ion energy

	$\lambda (2S_{1/2} \rightarrow 2P_{1/2}) [\text{nm}]$	$\lambda (2S_{1/2} \rightarrow 2P_{3/2}) [\text{nm}]$
ESR $C^{3+}$ experiment	155.0705 (39) (3)	154.8127 (39) (2)
Theory (I. Tupitsyn, V. Shabaev)	155.0739 (26)	154.8173 (53)

# Nörtershäuser group effort for increasing voltage accuracy



# Preliminary results with PTB-calibrated electron cooler voltage

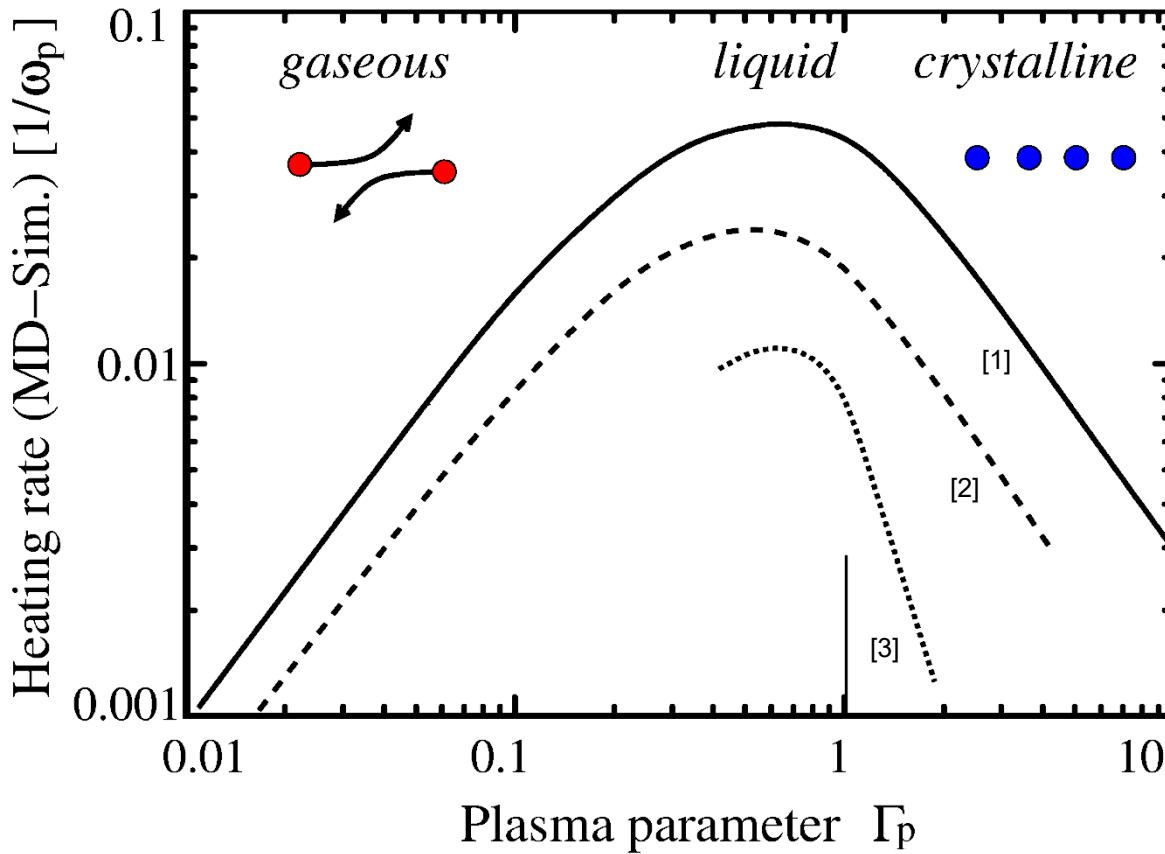


# Spectroscopy

- Precision spectroscopy „for free“
- QED effects at higher energies and ion charge
- Fluorescence detection mandatory
- At ultra-relativistic energies precise beam energy measurement

# Ultracold Ion Beams

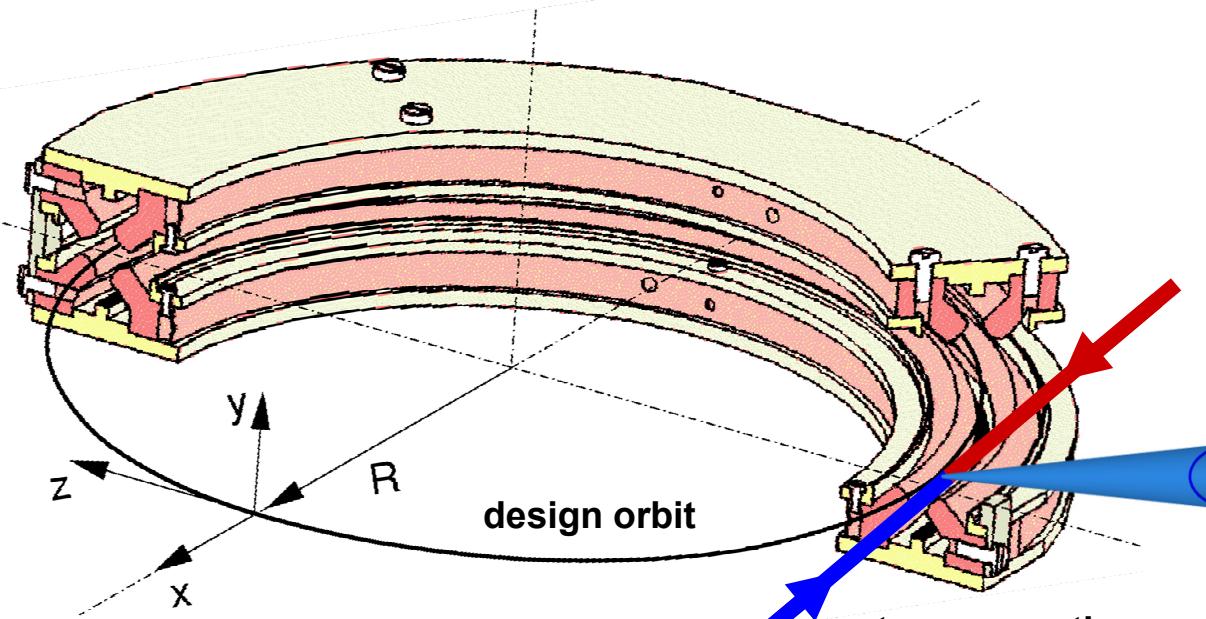
# With increasing coupling, IBS increases (but not forever!)



$$\Gamma_P = \frac{E_{\text{Coulomb}}}{E_{\text{thermal}}} = \frac{Z_{ion}^2 e^2}{4\pi\epsilon_0 a_{WS} \cdot k_B T_{ion}}, \quad a_{WS} = \left( \frac{4}{3} \pi n_{ion} \right)^{-\frac{1}{3}}$$

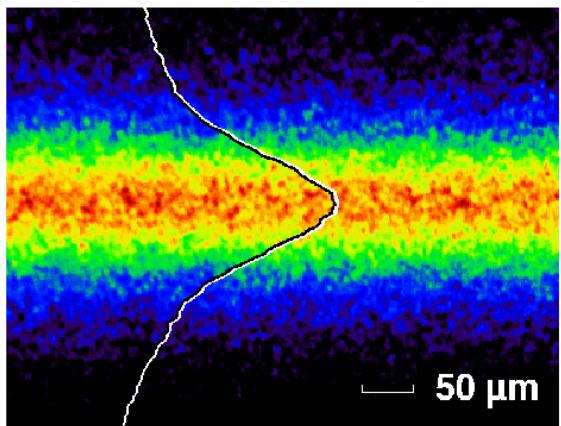


# „Crystalline“ ion beams at the eV RFQ storage ring PALLAS

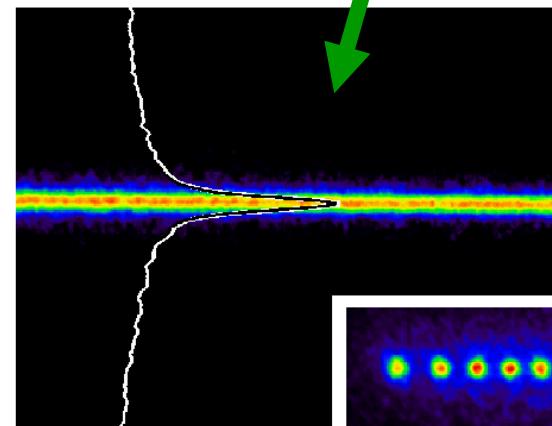
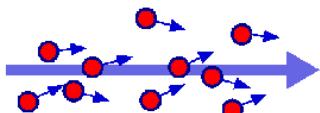


## PALLAS

- Beam energy  $\sim$ eV
- Radius 57 mm
- Tune 50
- Periodicity 800



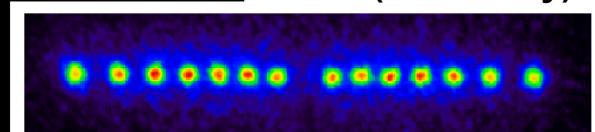
‘gaseous’ beam  
IBS-dominated



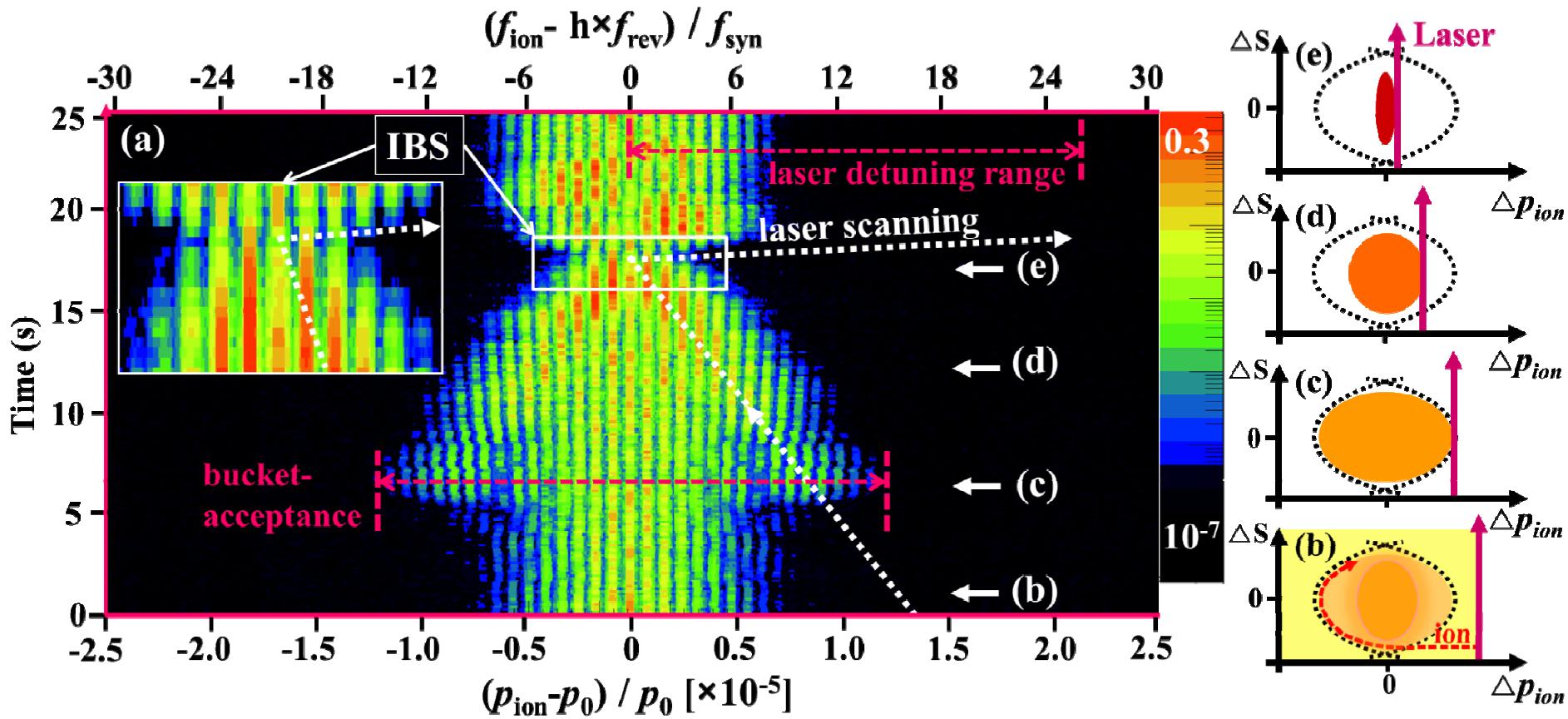
crystalline beam  
long-range order



(stationary)

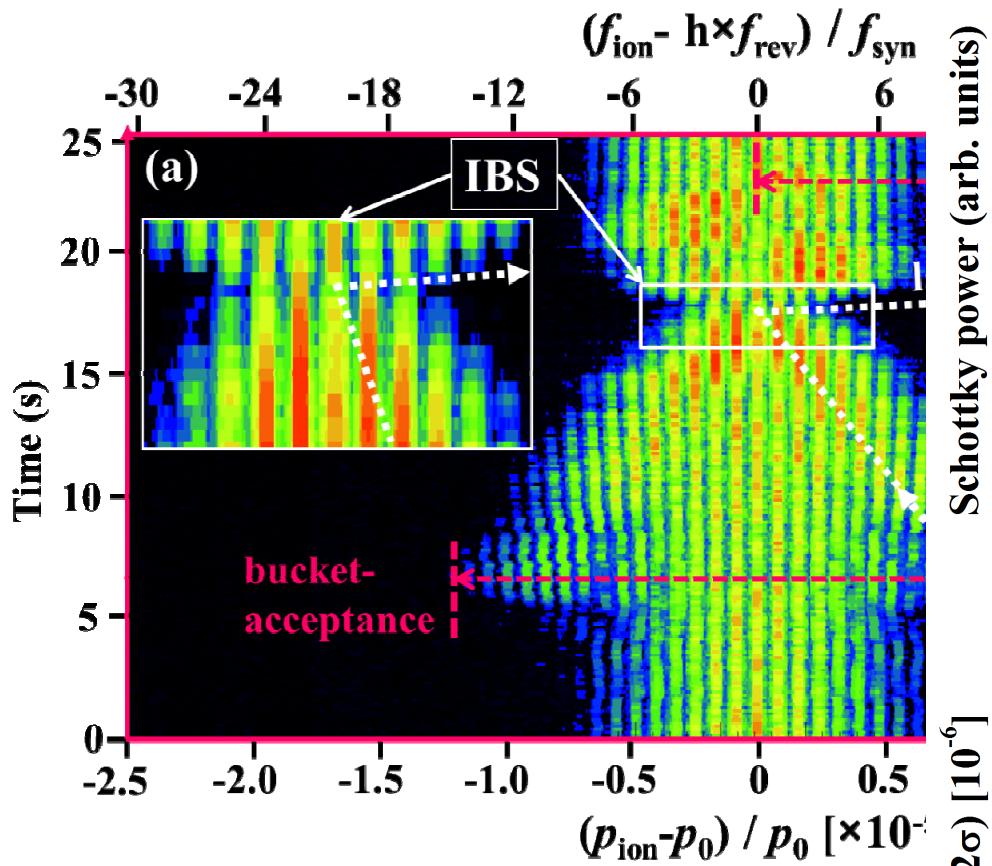


# Schottky measurements of bunched laser cooled $\text{C}^{3+}$ beams

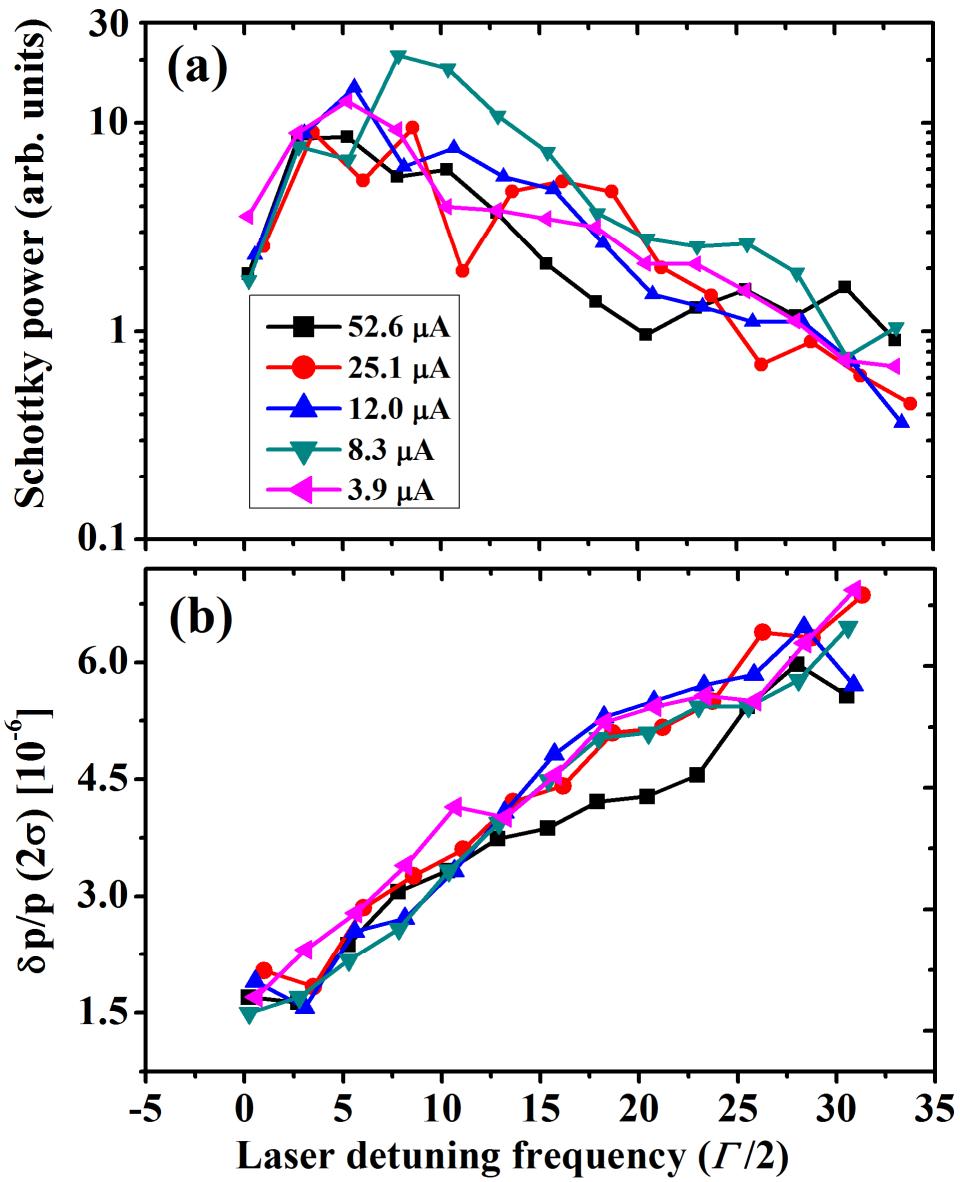


**PRELIMINARY**

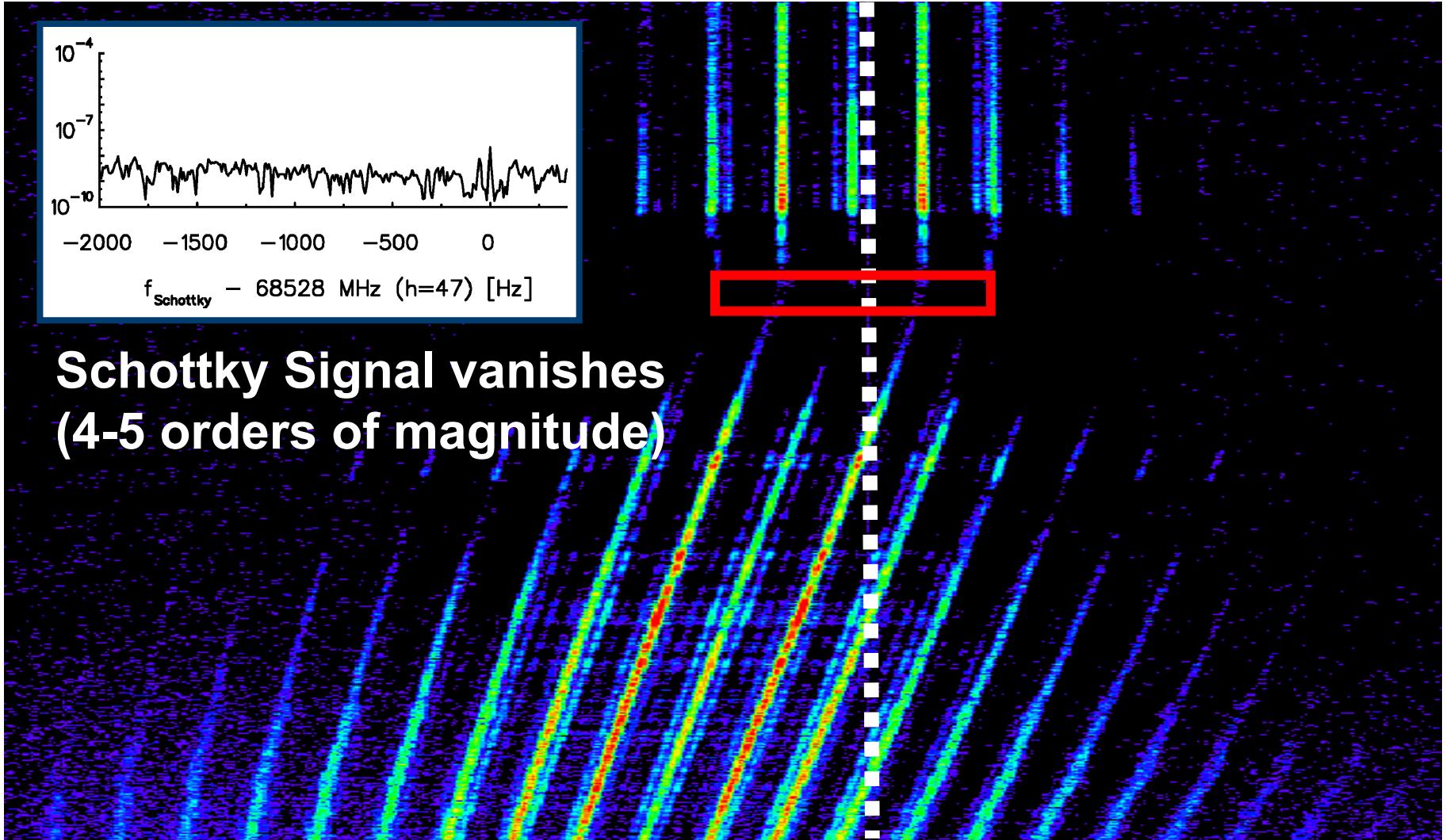
# Schottky measurements of bunched laser cooled $\text{C}^{3+}$ beams



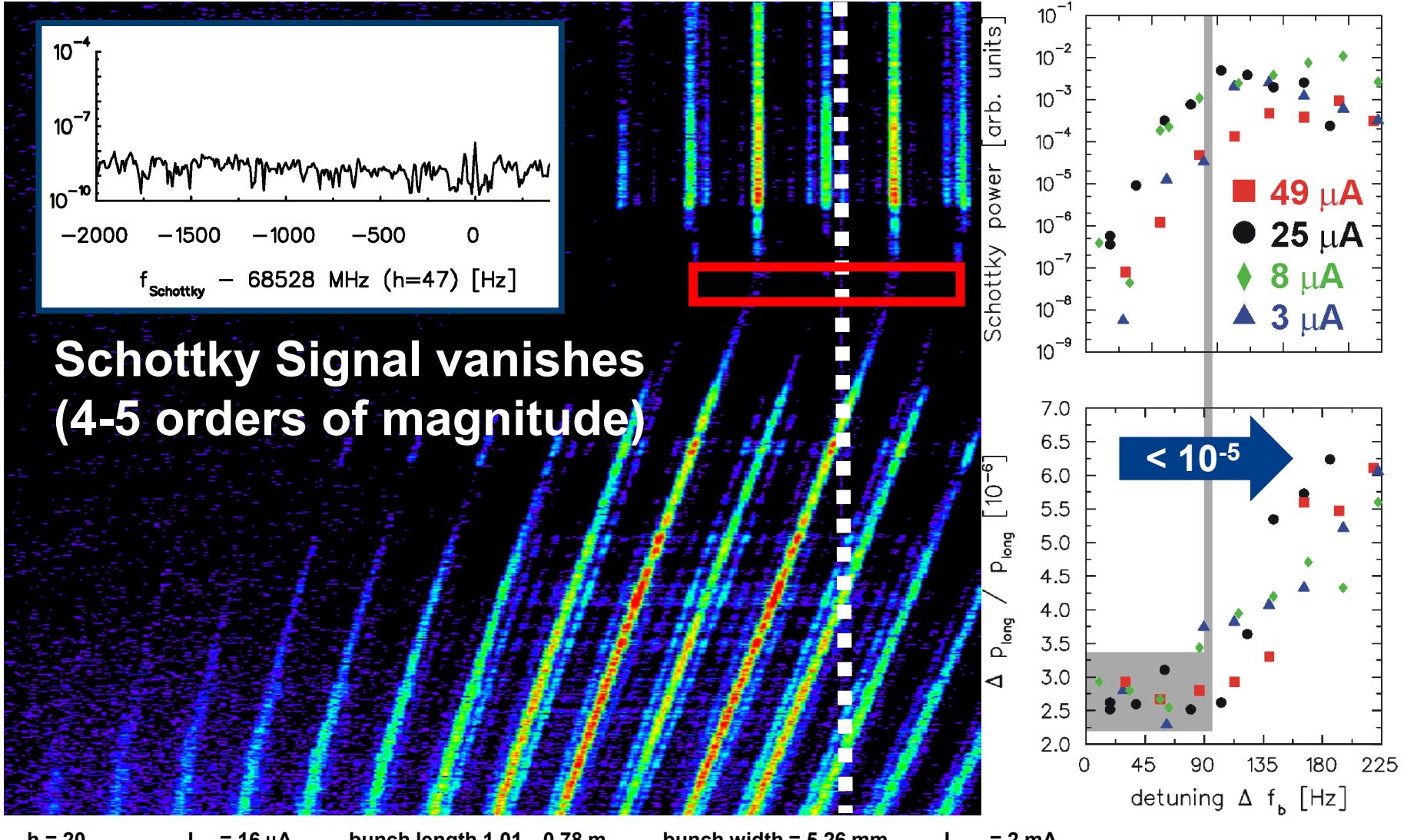
PRELIMINARY



# Zero Schottky signal @ 16 $\mu$ A (much better vacuum in 2006)

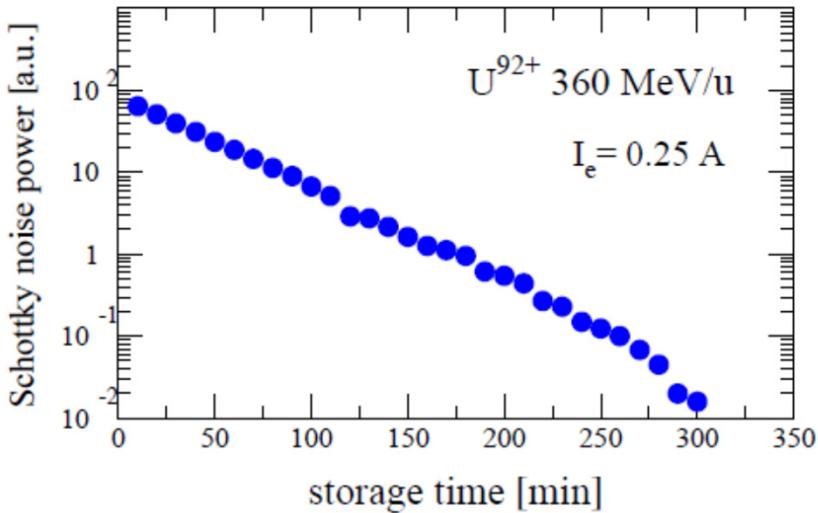


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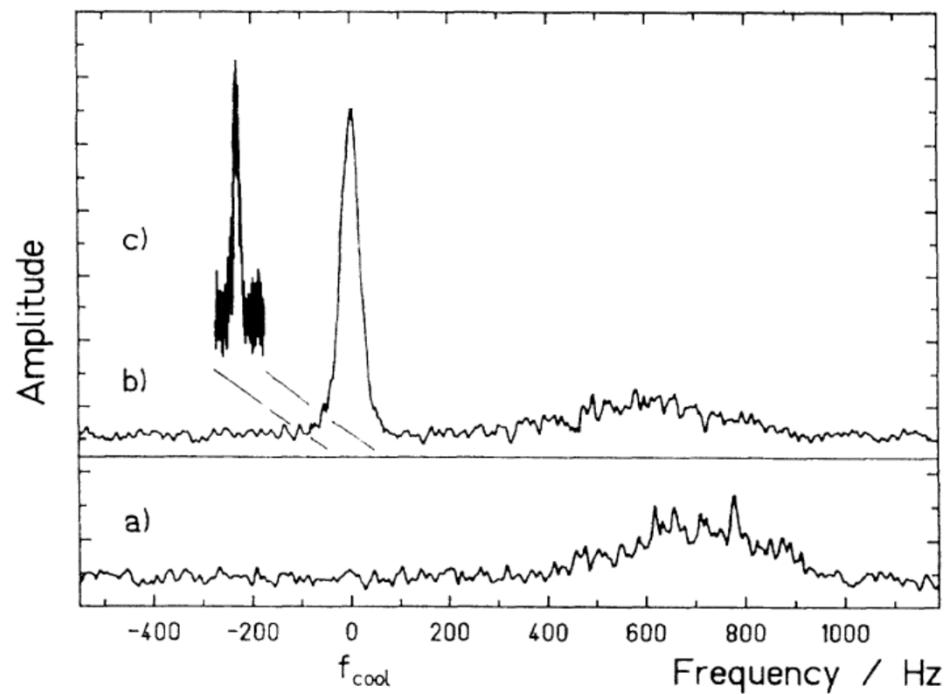


# What does zero Schottky signal even mean?

ESR, electron cooled, coasting beam  
(2001)



TSR, laser cooled, coasting beam  
(1990)

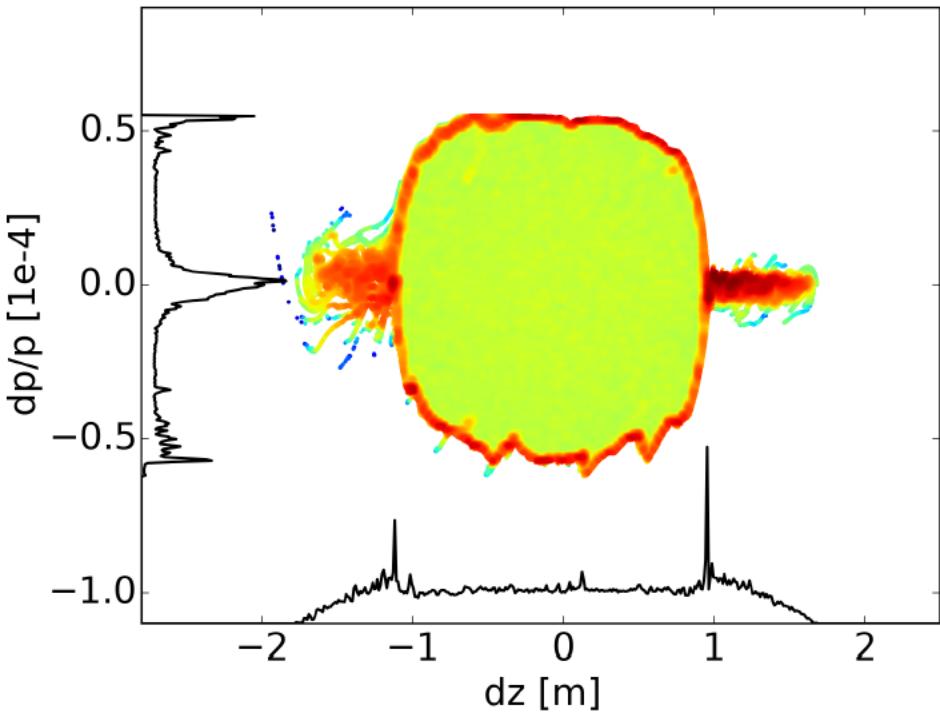


# Ultracold ion beams

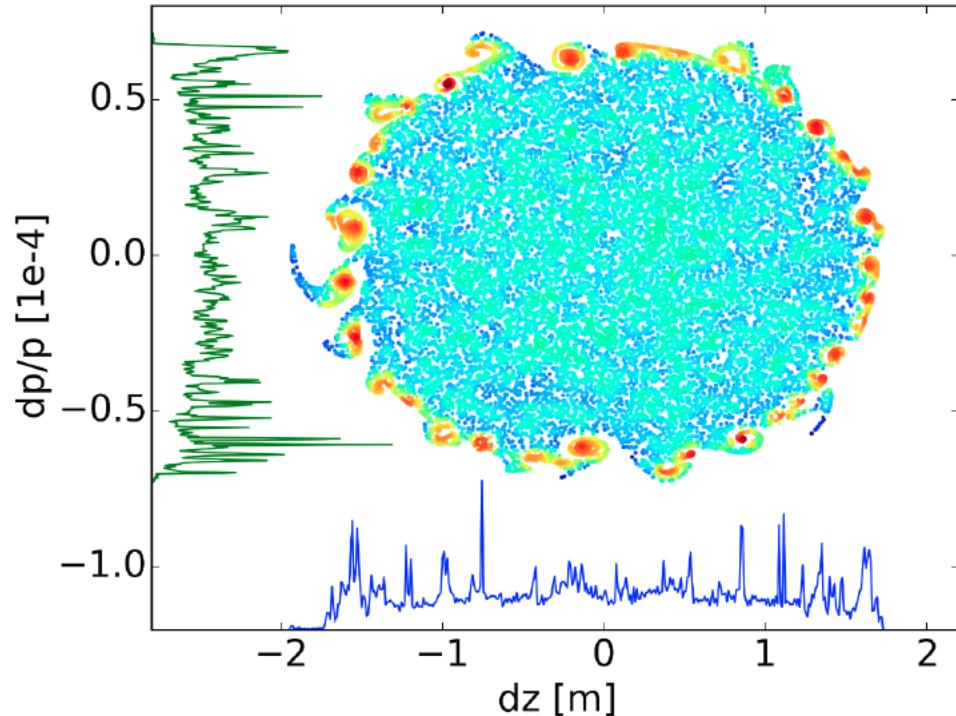
- Unlikely to see crystallization...
- ... but who knows?
- Coupling to transverse degree of freedom needed
- Zero Schottky signal for bunched beams not understood
- Fluorescence detection might give clues

# Intense Ion Beams

# Space charge effects when using a scanning cw laser (Simulation!)



Space charge „flattens out“ bucket,  
ions do no longer perform  
synchrotron oscillations



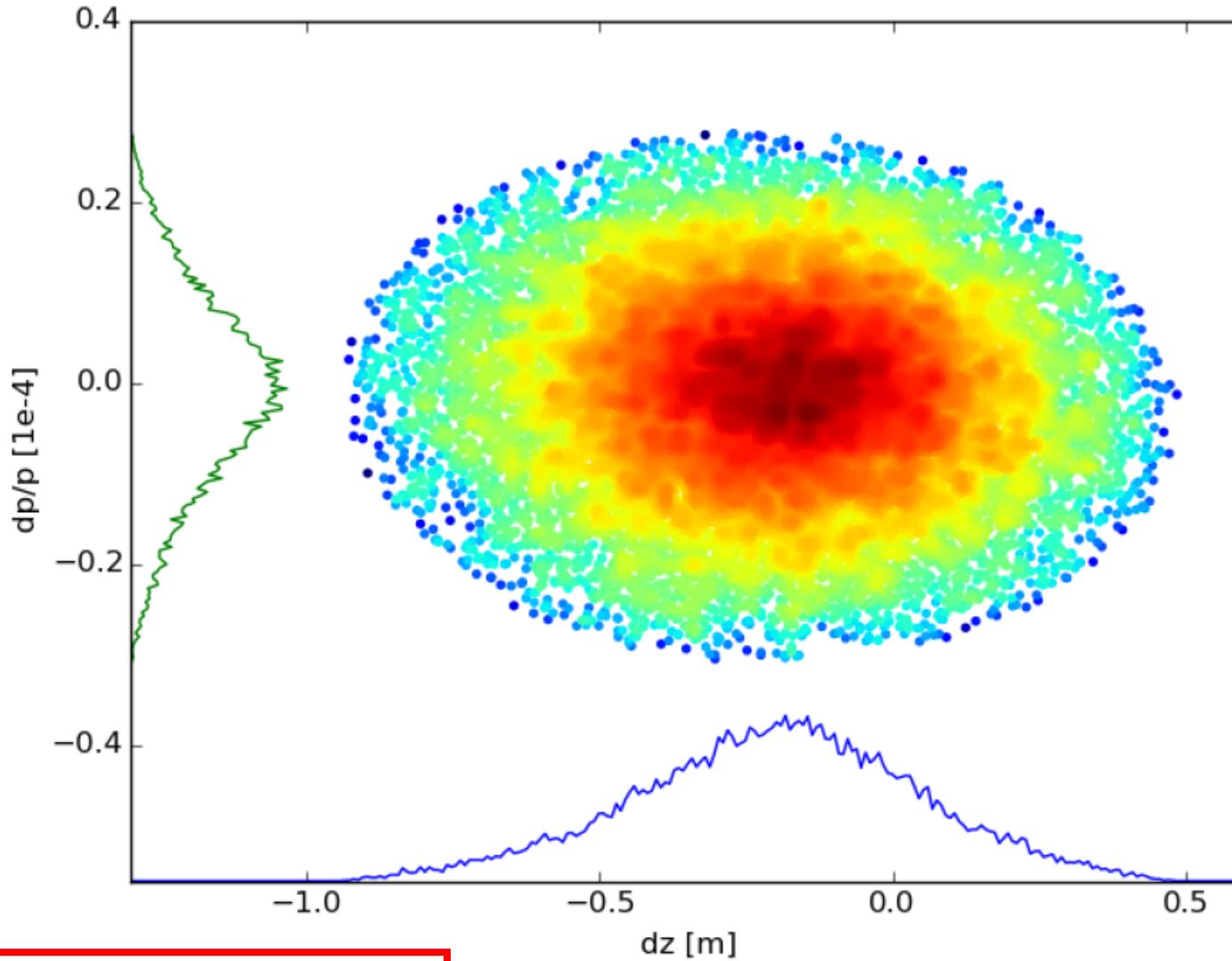
Strong instabilities ( $\sim$  negative mass)  
due to high density at the border of  
the phase space to where the cw  
laser pushes ions with higher  
momenta

**PRELIMINARY**

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# Both effects suppressed when using pulsed lasers (Simulation!)



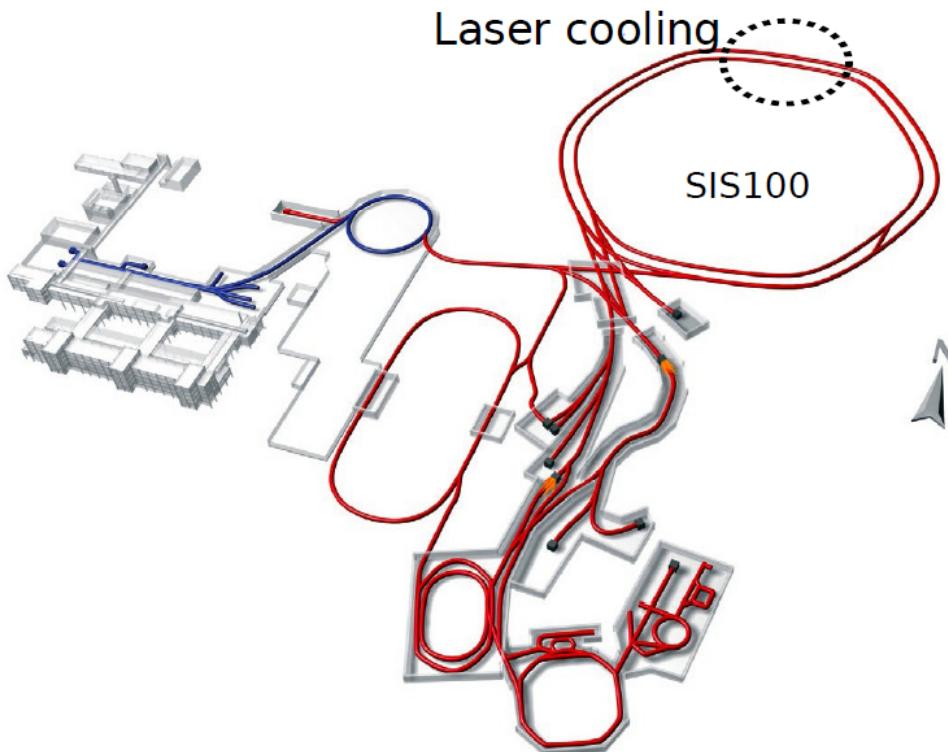
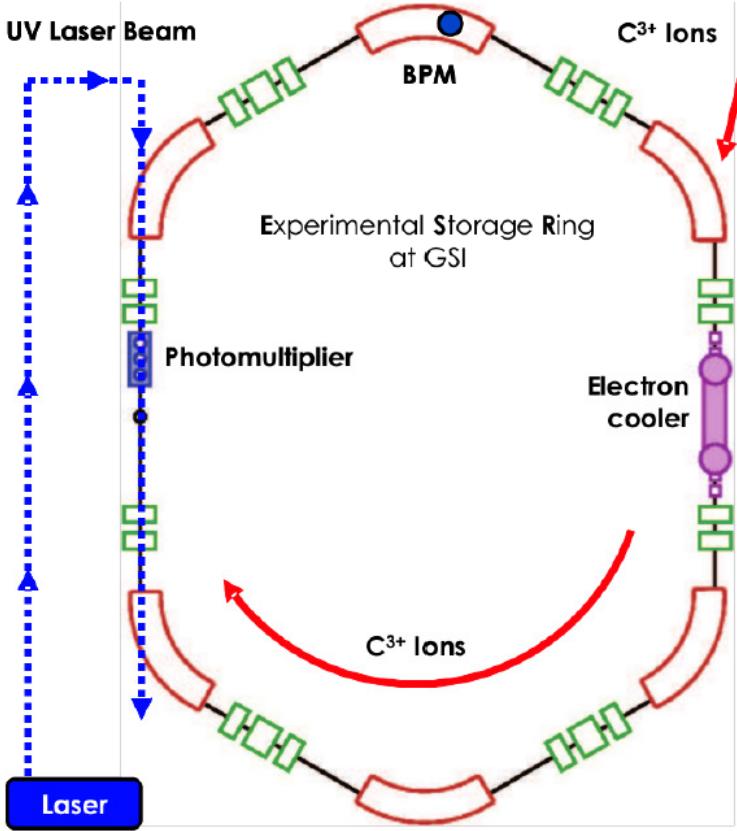
**PRELIMINARY**

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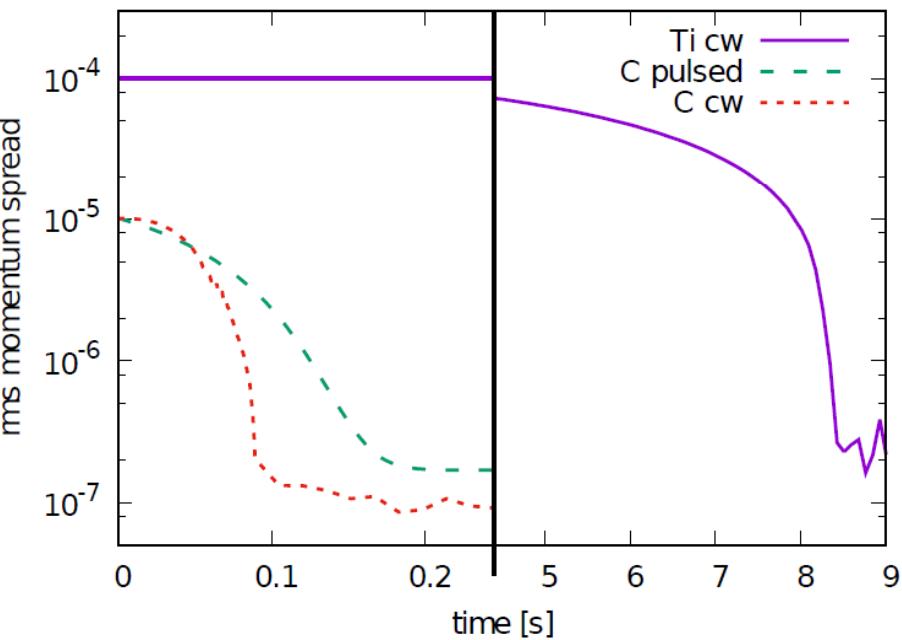
# Preliminary cooling times estimates comparing ESR to SIS100

	Ion	$T_{rev}$	$L_{interact}$	$\delta_{rms\ 0}$	$d_{beam}$	$\gamma$	$L_{bunch}$
ESR	$^{12}\text{C}^{3+}$	0.8 ms	25 m	$10^{-5}$	3 mm	1.13	4 m
SIS100	$^{48}\text{Ti}^{19+}$	3.6 ms	26 m	$10^{-4}$	10 mm	8.50	100 m



# Preliminary cooling times estimates comparing ESR to SIS100

	$\lambda_L$	$P_L$	$n_{scat}$	$\Delta\delta^{LF}$	$\Delta_{fwhm}$	$\rho_{excit}^{pulsed}$
$^{12}\text{C}^{3+}$	256 nm	20 mW	7.5	$1.5 \cdot 10^{-9}$	$5.8 \cdot 10^{-8}$	0.278
$^{48}\text{Ti}^{19+}$	512 nm	5 W	4.7	$9.3 \cdot 10^{-10}$	$3.9 \cdot 10^{-8}$	$8 \cdot 10^{-5}$

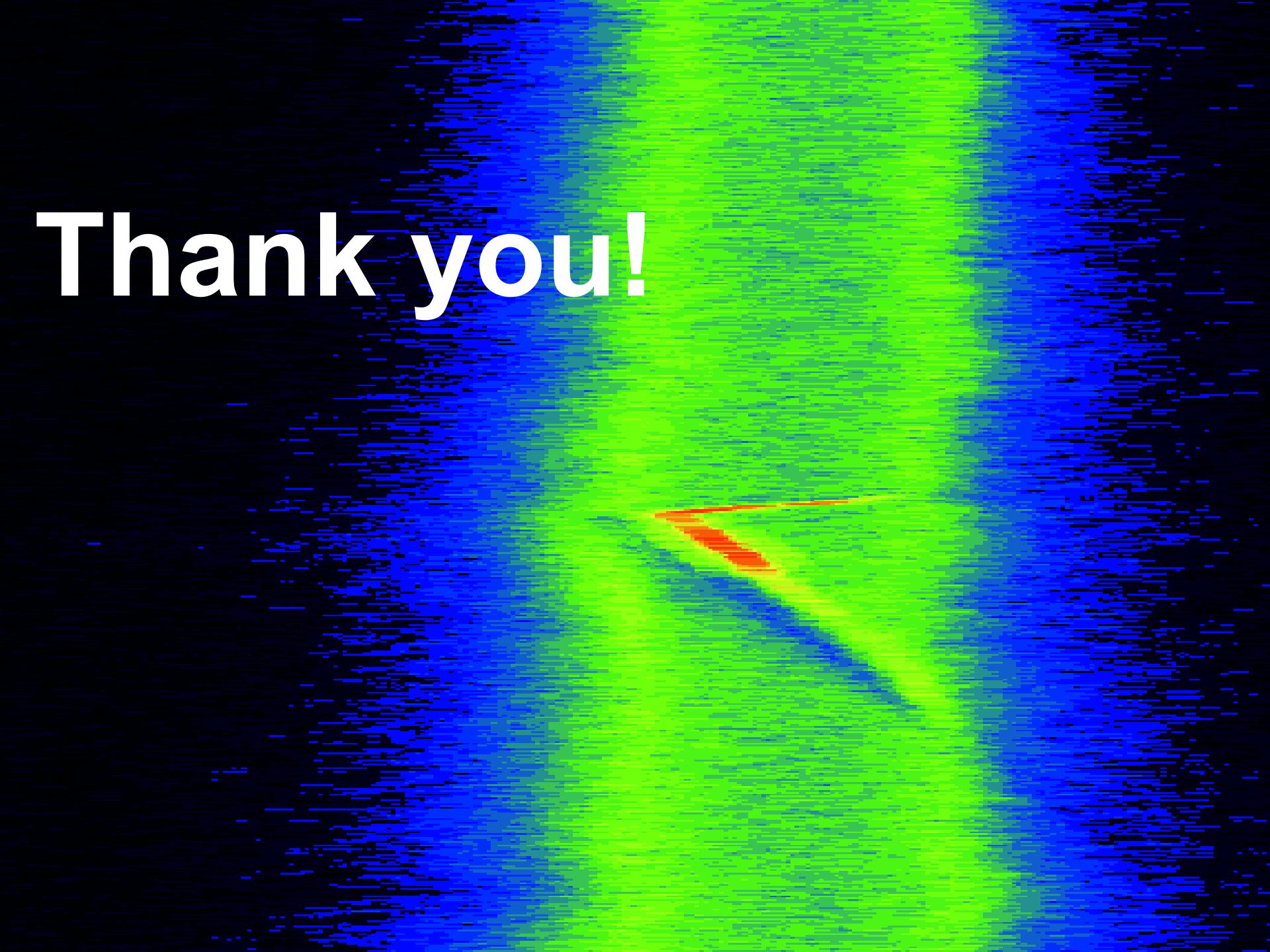


	$^{12}\text{C}^{3+}$	$^{48}\text{Ti}^{19+}$
$d_{scan}^{max}$ analytic	$2 \cdot 10^{-10}$	$2 \cdot 10^{-11}$
$d_{scan}$ sim	$2 \cdot 10^{-10}$	$1 \cdot 10^{-10}$
$N_p^{max}$ analytic	$6.7 \cdot 10^6$	$6.8 \cdot 10^7$
$N_p$ sim	$1.5 \cdot 10^6$	$10^7$
$L_{equ}$ sim	1.4 m	3.6 m

**PRELIMINARY**

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A grayscale heatmap of a brain scan is displayed against a black background. A prominent red arrow points from the top right towards the center-left, highlighting the amygdala region.

Thank you!