Laser cooling of relativistic heavy ion beams

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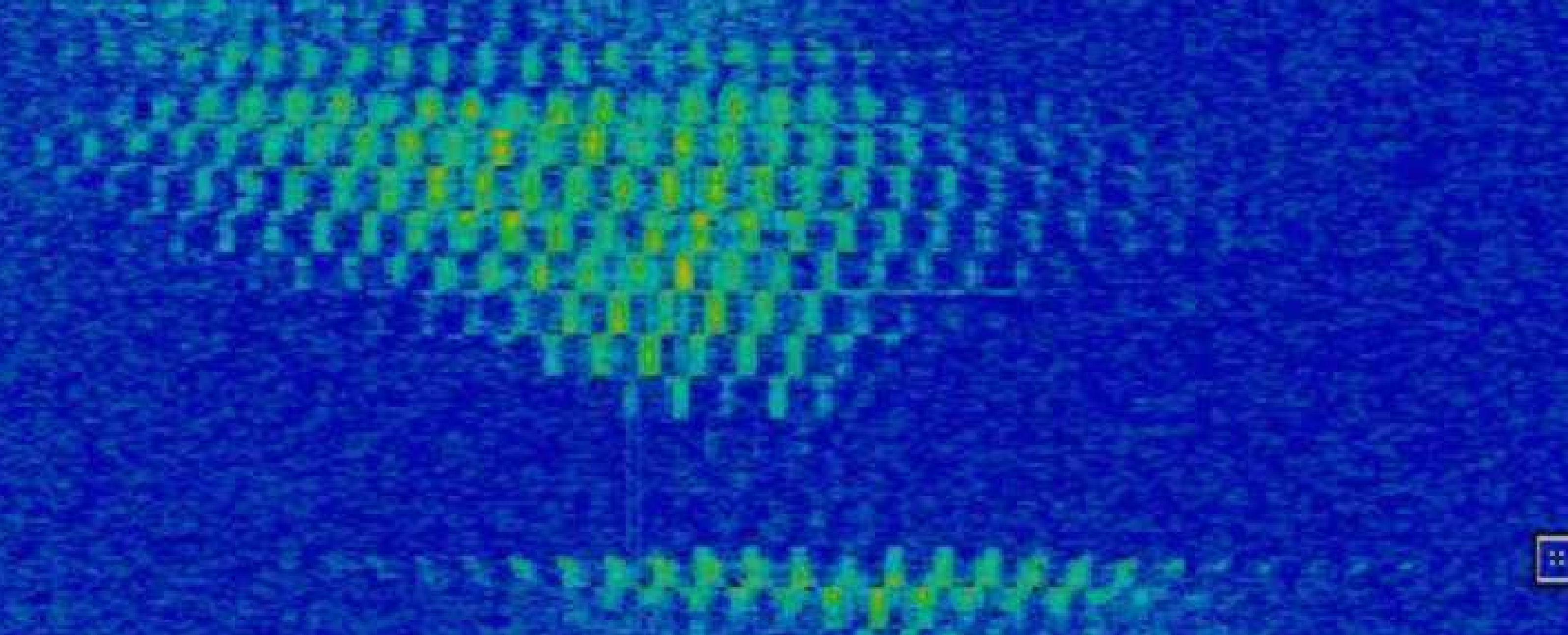
COOL05, Galena, Il, USA, Sept. 2005

Why laser cooling under such ‘extreme’ conditions at SIS300?



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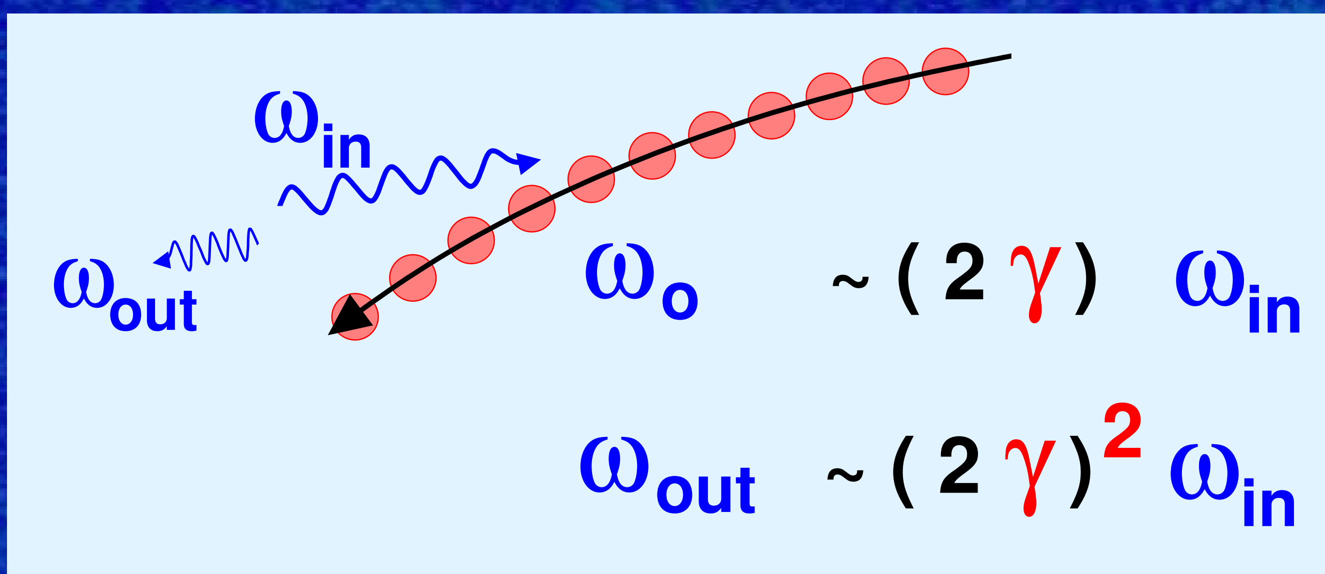
Laser cooling of relativistic heavy ion beams

Why laser experiments under such 'extreme' conditions ?



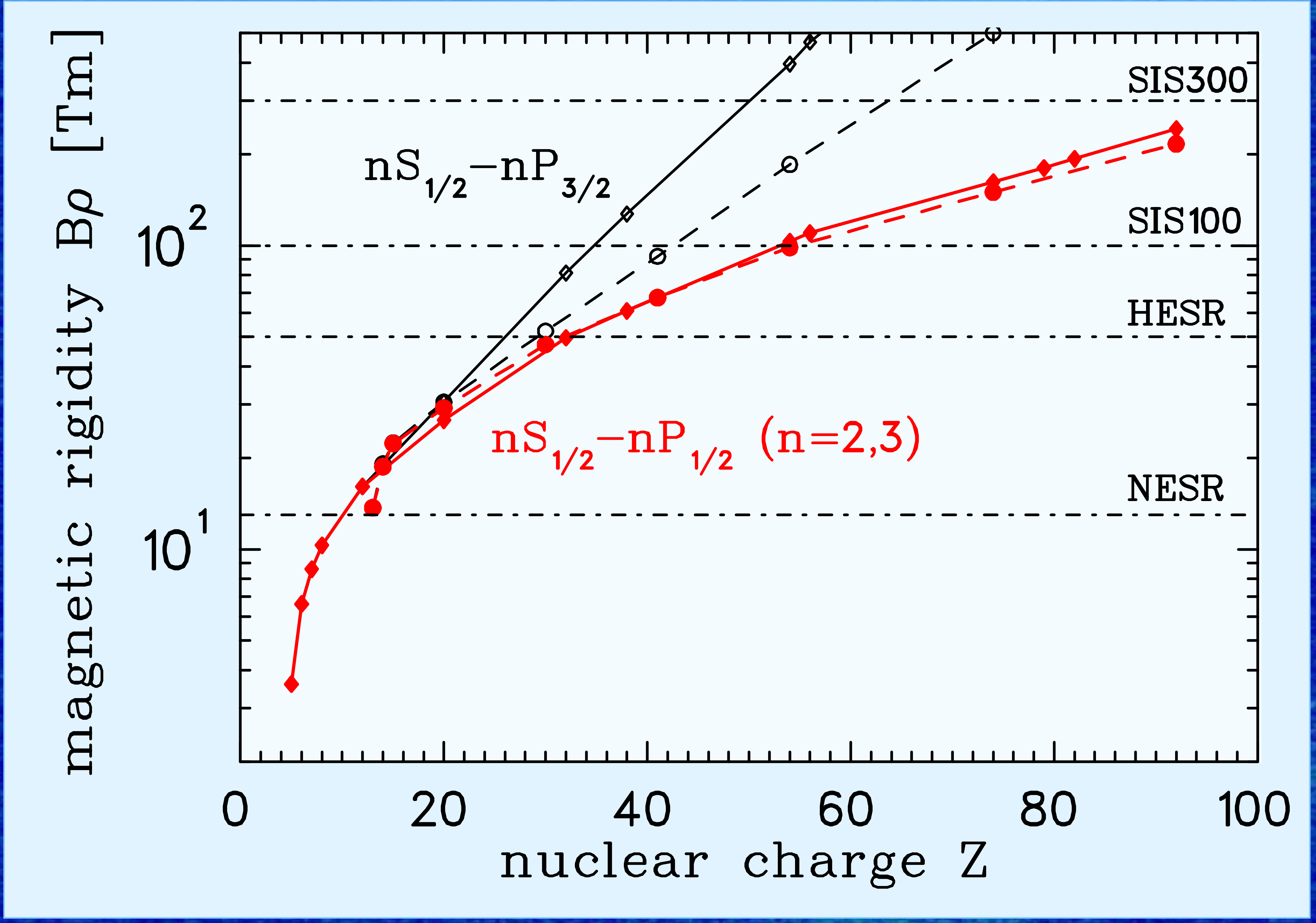
–> huge Doppler shift and pulse shortening

–> laser spectroscopy of heavy few–electron systems

–> short pulse (high intensity) interaction studies

Laser cooling of relativistic heavy ion beams

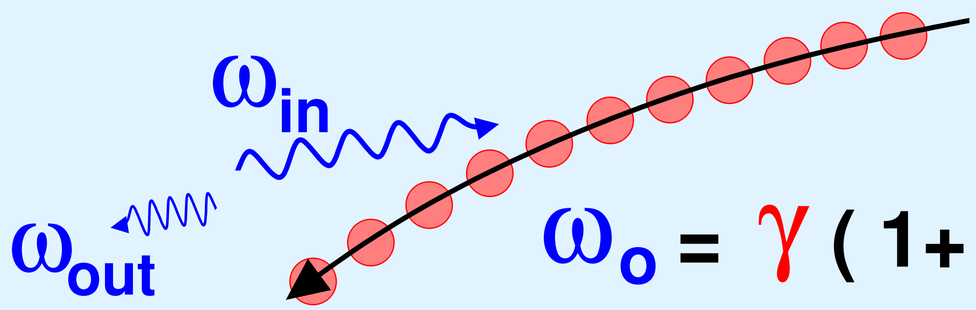
Applying a counterpropagating UV laser beam, at SIS 300 ground state transitions of all Li–like ions can be excited.



Laser excitation of $2S_{1/2}-2P_{1/2}$ (280 eV) of U^{89+} requires $\gamma = 30$ at SIS 300

Laser cooling of relativistic heavy ion beams

Why laser cooling under such 'extreme' conditions ?



$$\omega_o = \gamma\,(1+\beta)\,\omega_{opt.}$$

$$\tau_o \sim \gamma^{-2}\tau_{opt.}$$

$$F_{max,0} \sim \gamma^3\ F_{max,opt.}$$

–> increased efficiency for relativistic beams of few–electron heavy ions

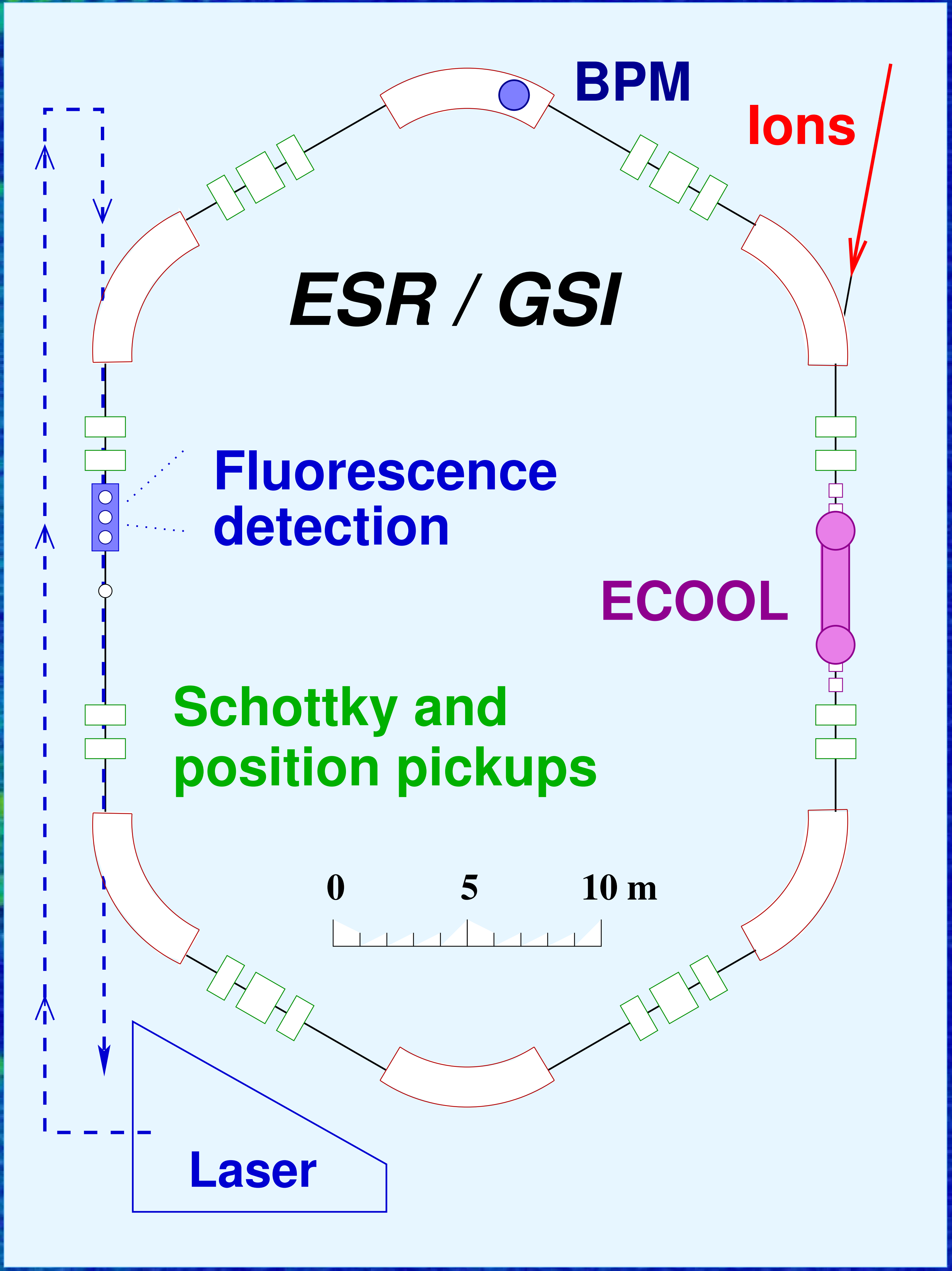
–> impact on phase space density, spec. resolution

–> charge state and ring lattice are favourable for ordering effects (see Pallas RFQ ring)

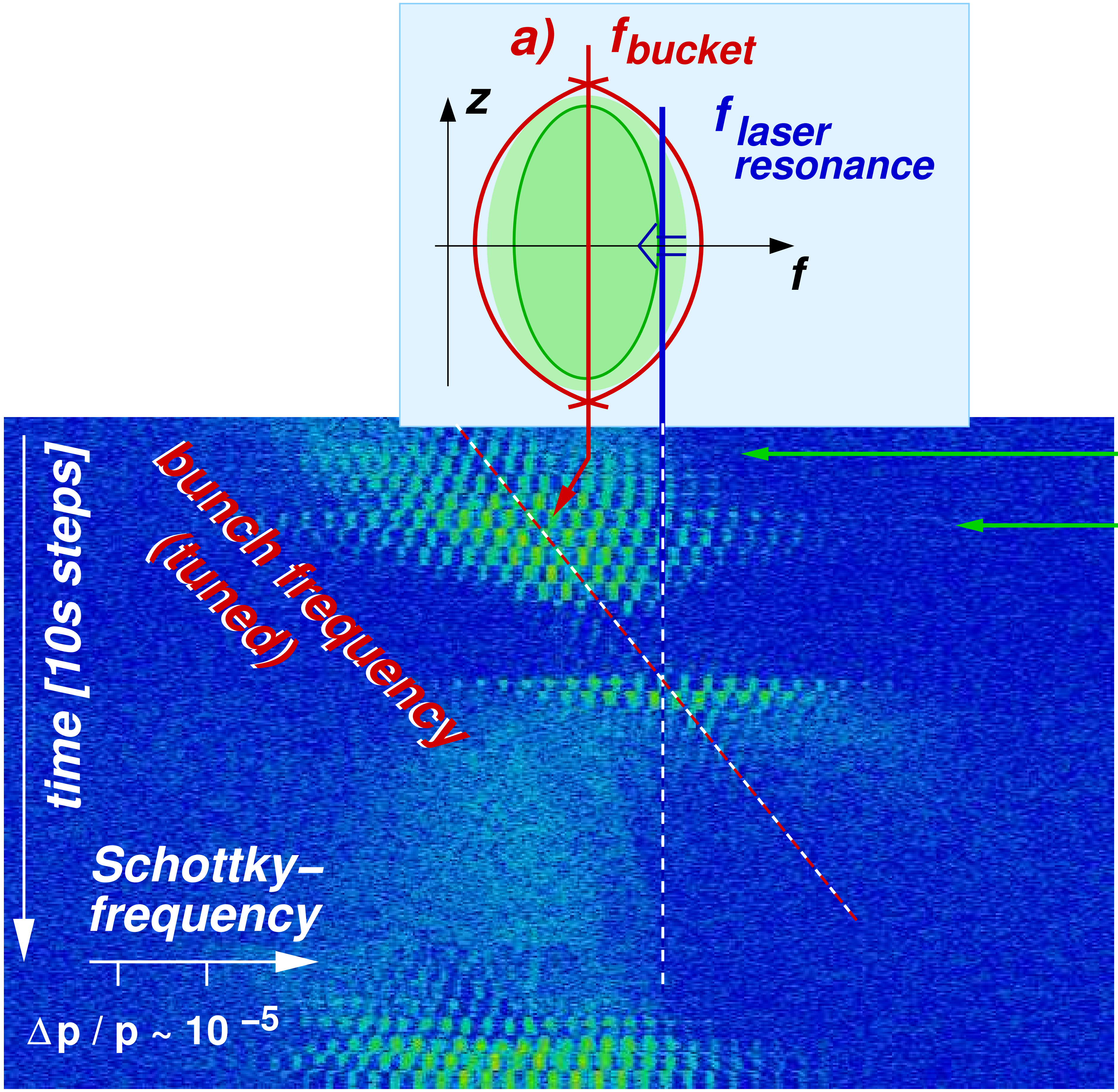
Laser cooling of relativistic heavy ion beams

Test experiment:

Laser cooling of
and spectroscopy of
Li–like C^{3+} ions
at ESR @ 1.4 GeV



Laser cooling of bunched C^{3+} beams
(rf – tuned)



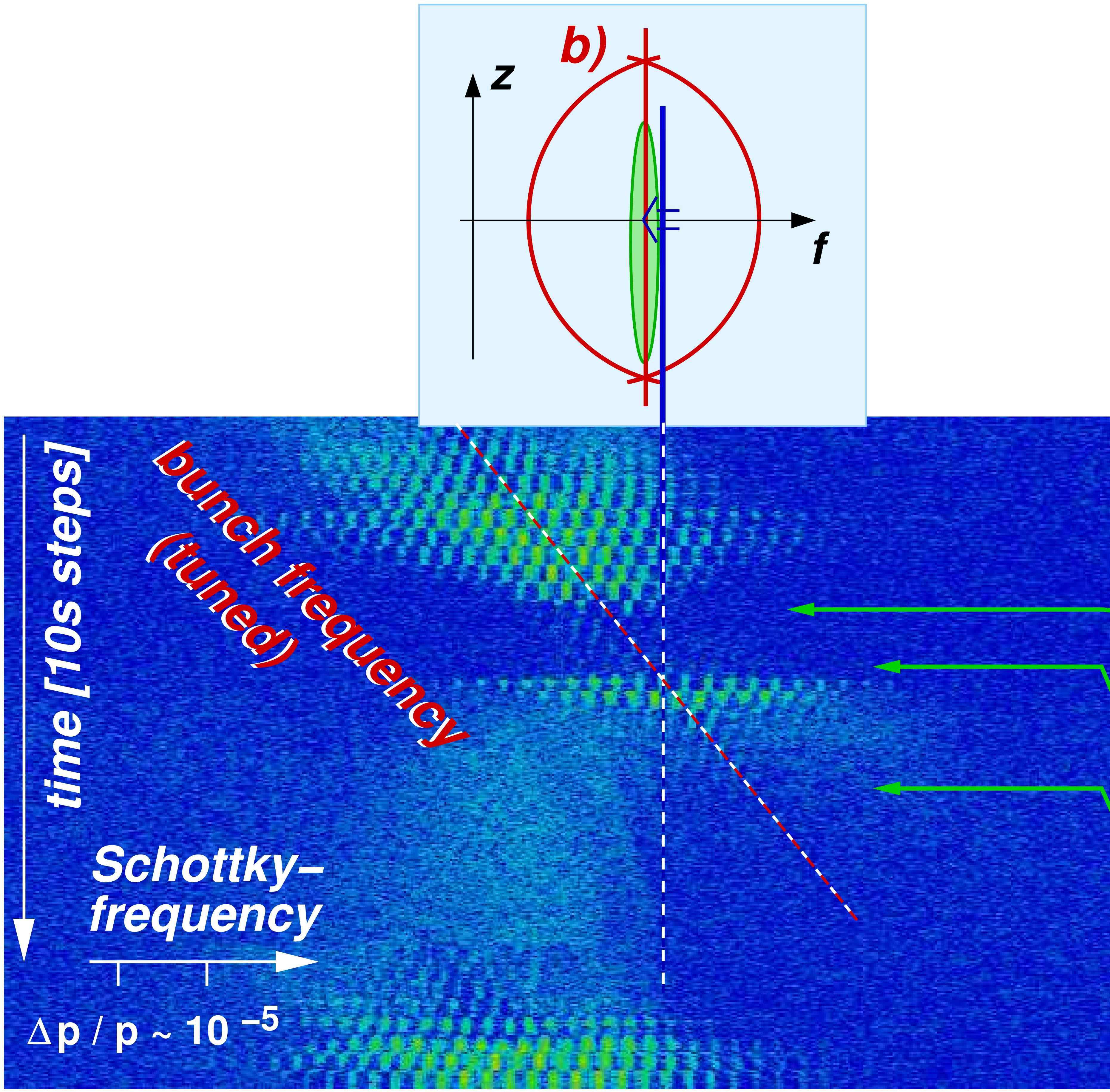
a) large detuning:

cooling into the bucket

sharp sidebands <–> cold individual ions

laser band–width much smaller ($\sim 10^{-7}$) than initial momentum distribution ($\sim$ few 10^{-5}) for $< 10^{8}$ ions

Laser cooling of bunched C^{3+} beams
(rf – tuned)



b) small detuning:

lowest energy spread
space charge dominated

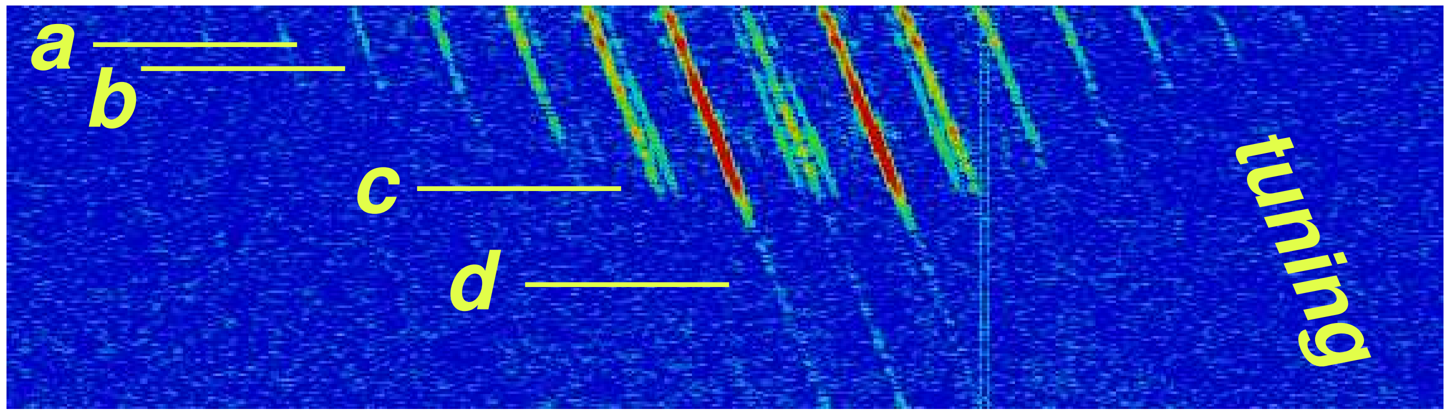
c) resonance crossing:

laser heating

ion deceleration
out of the bucket

Laser cooling of bunched C^{3+} beams
rf–tuning –> side–band spectra

Schottky–spectra

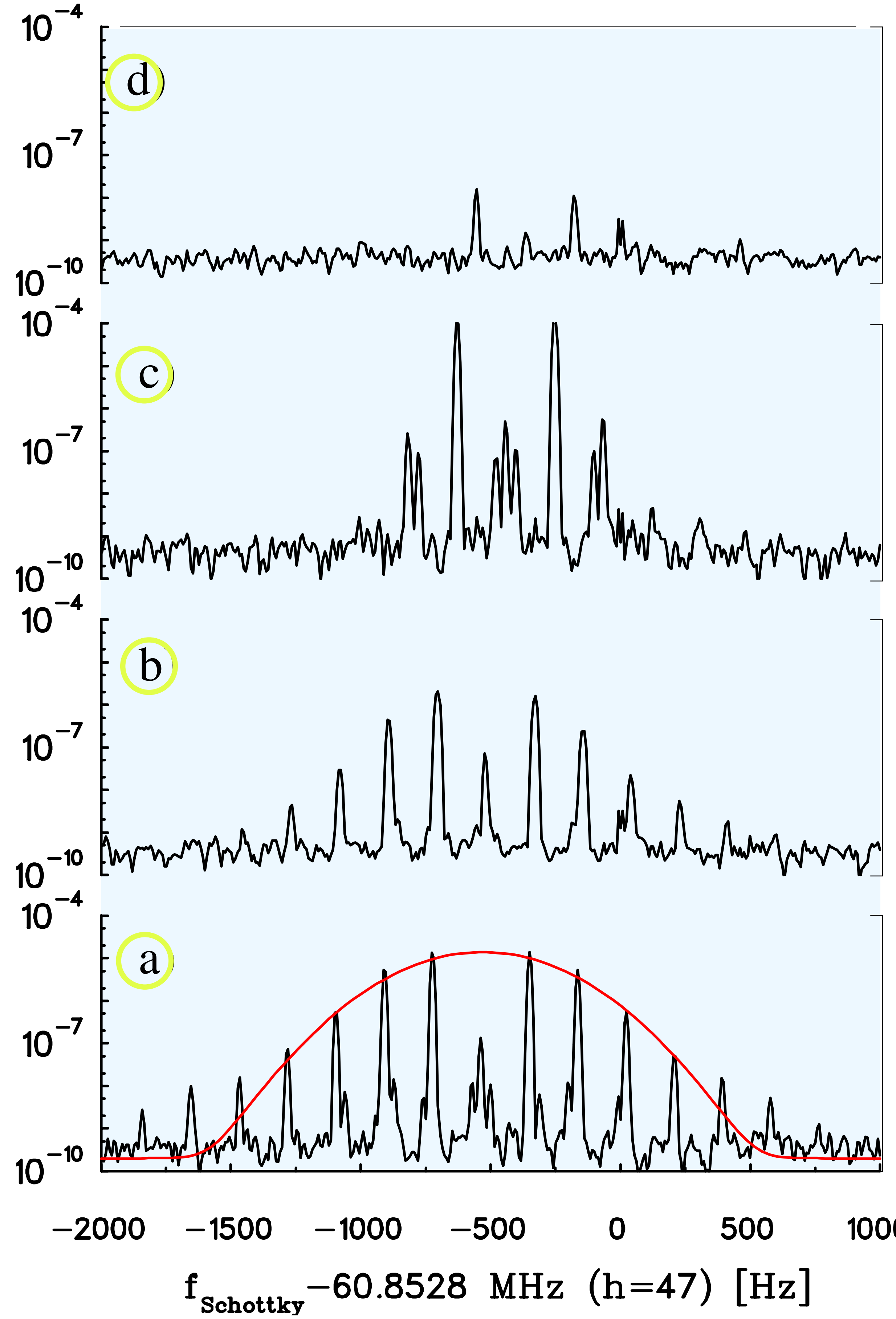


satellites @ 40 Hz
(synchrotron freq. 170 Hz)

Gaussian used for estimation of momentum spread

Bessel function series cannot explain central dip

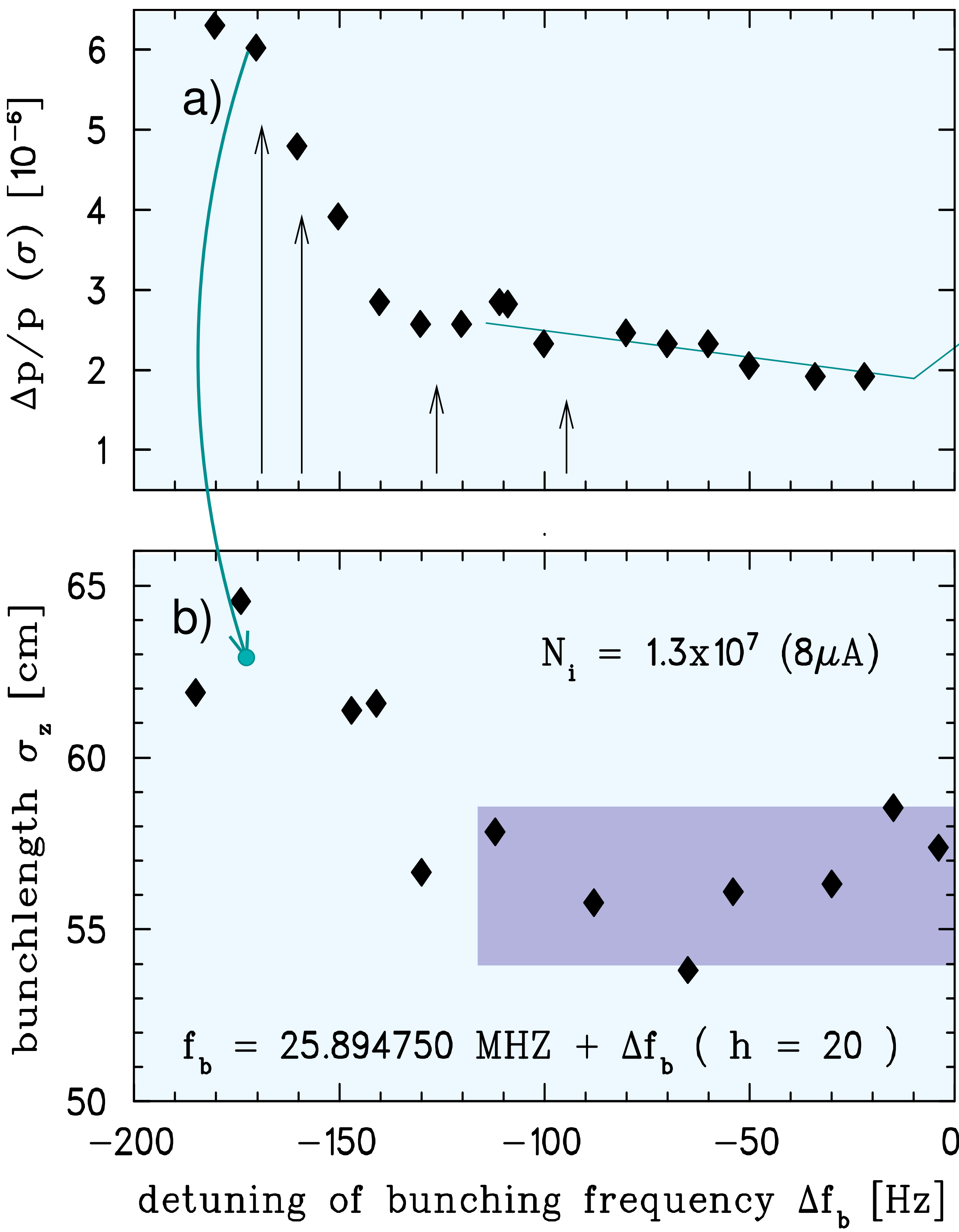
(initial distr. was laser heated)



Laser cooling of bunched C^{3+} beams
momentum spread vs. bunch length

width of Schottky signal

corresponding pick–up meas.



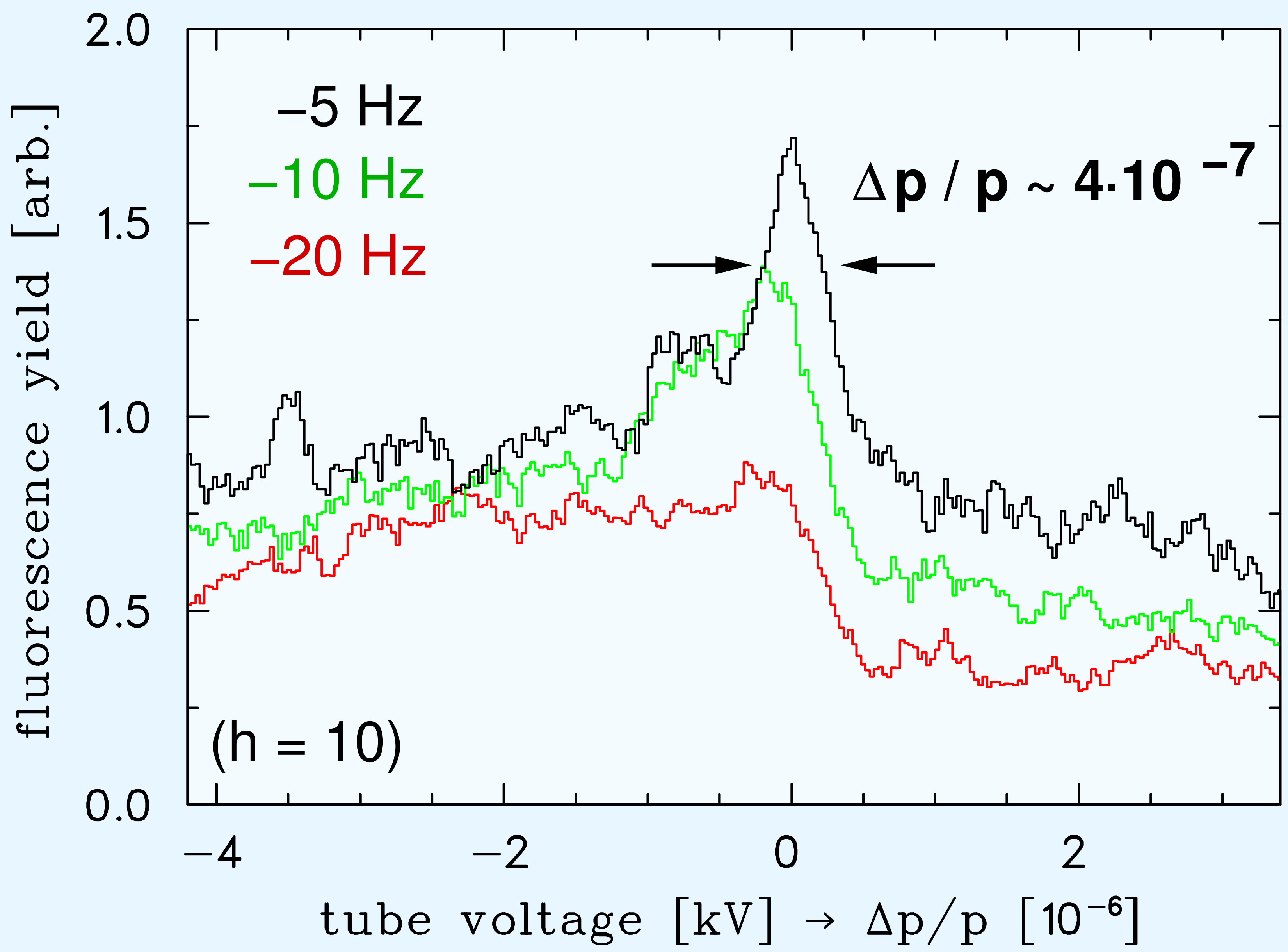
resolution limited

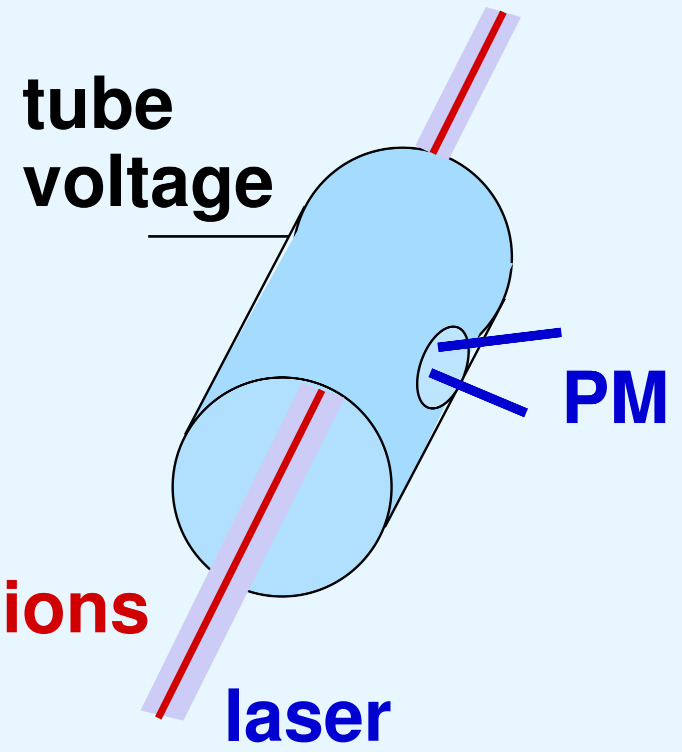
–> laser fluorescence diagnostics for space–charge dominated regime

equilibrium length for constant density

(const. signal strength –> no ion losses)

Laser cooling of bunched C^{3+} beams
laser fluorescence diagnostics





–> the momentum spread of the core corresponds to a plasma parameter of unity

(first test of the method)

Laser cooling of bunched C^{3+} beams
summary rf–tuning

scanning the bunching frequency the whole bunch can be laser–cooled into the space–charge dominated regime

–> what about the transverse motion ??

diagnostics tools *(and problems)*

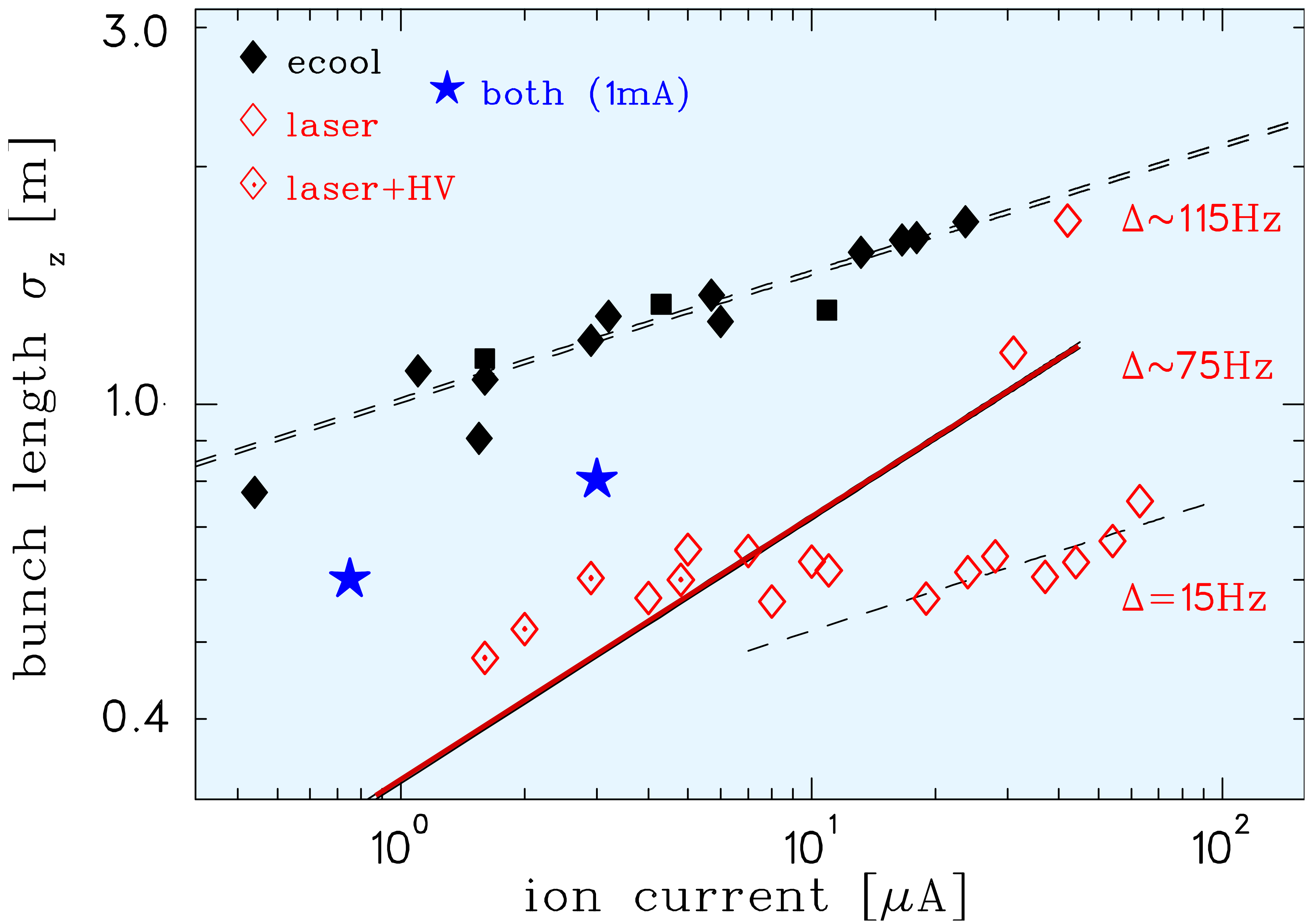
Schottky –> momentum distr. from side–band distribution
(interpretation of cold beams open)

Fluorescence –> momentum distr. below $5x10^{-6}$
(preliminary, affects the cooling)

Pick–up –> spatial bunch length

Residual gas ionization monitor –> transverse profile
(resolution, weak signal)

Laser cooling of bunched C^{3+} beams
laser vs electron cooling – bunch length

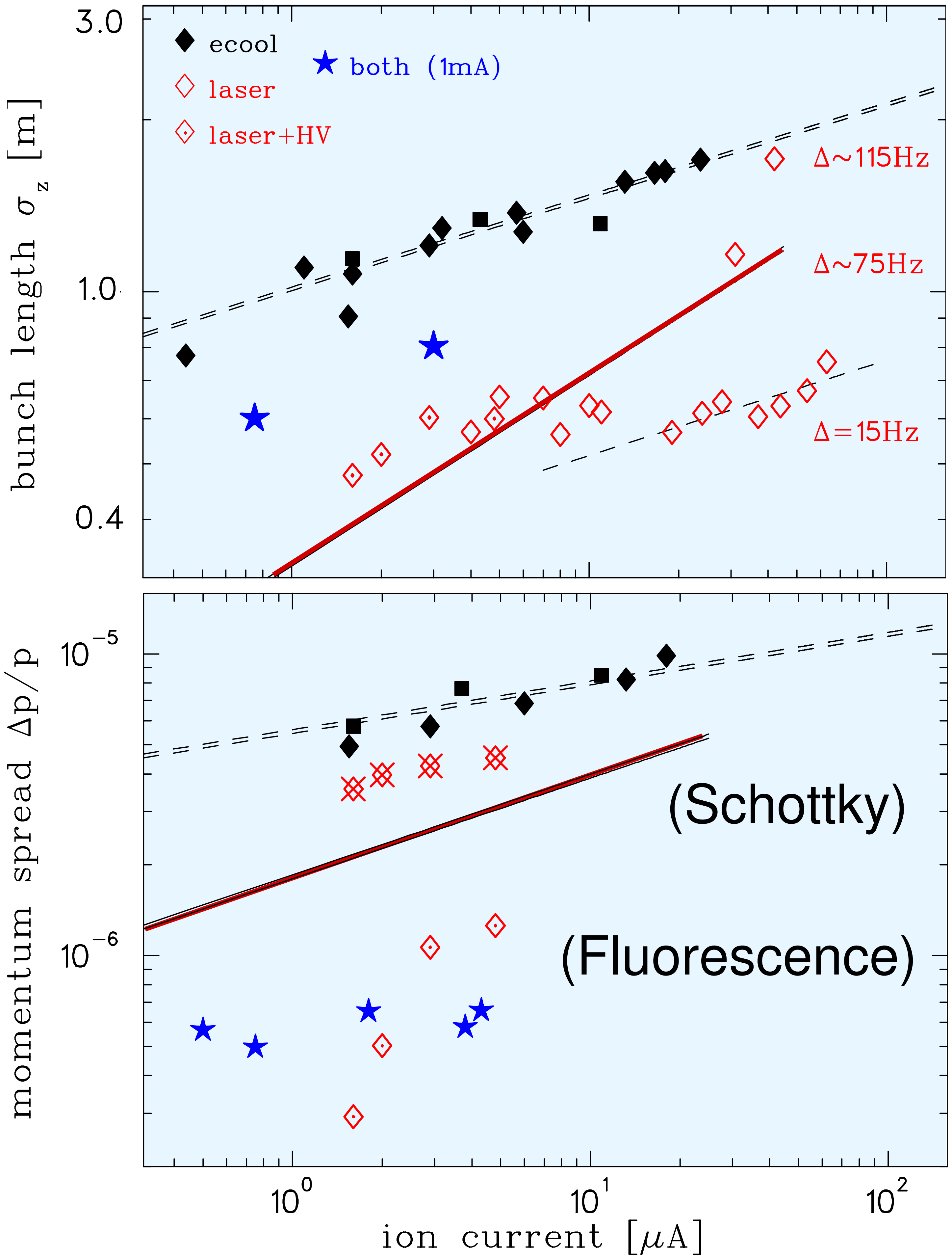


ecool ref. data
~ $N^{1/6}$ (IBS regime)

space charge dominated length
~ $N^{1/3}$

(constant detuning)

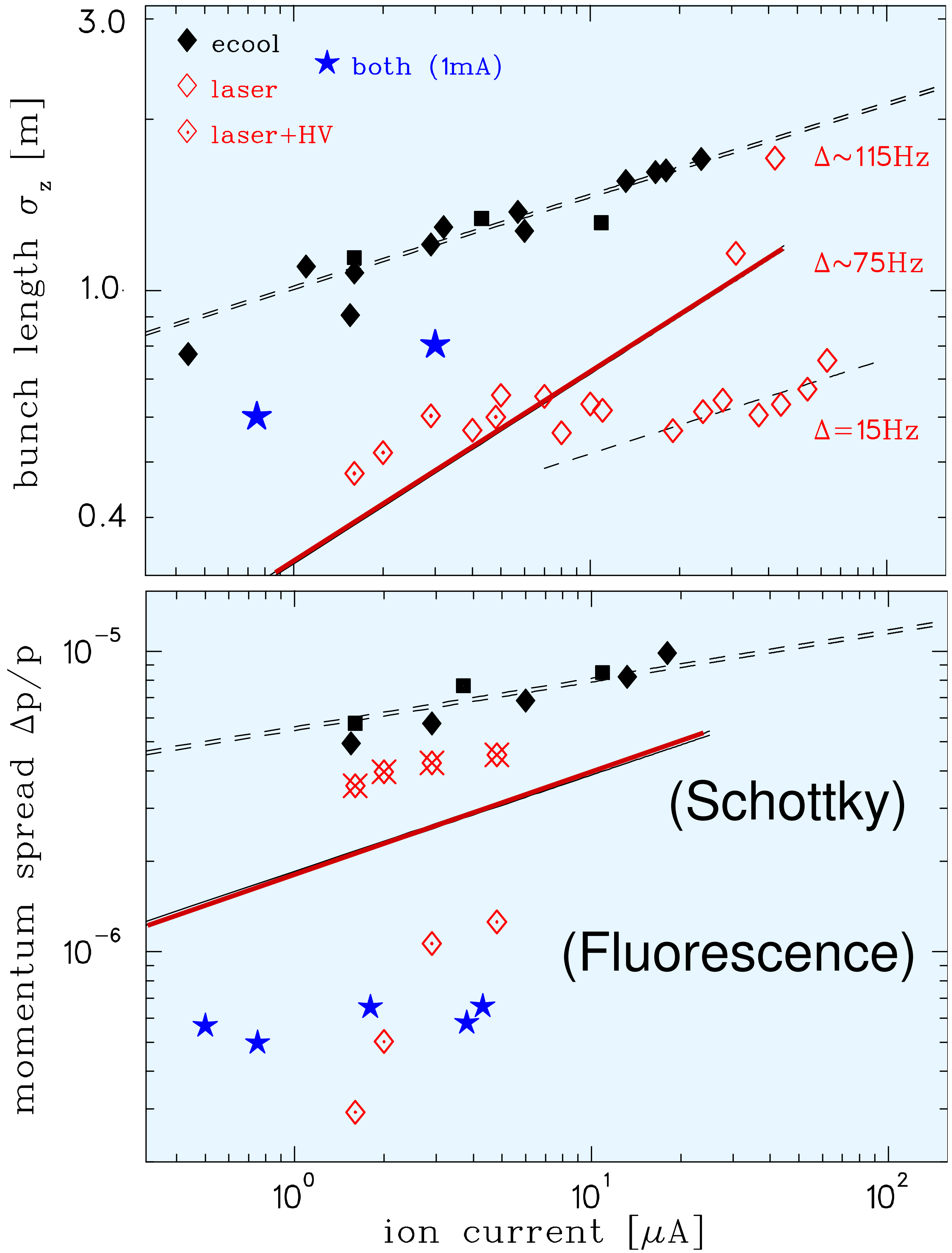
Laser cooling of bunched C^{3+} beams
laser vs ecool – momentum spread

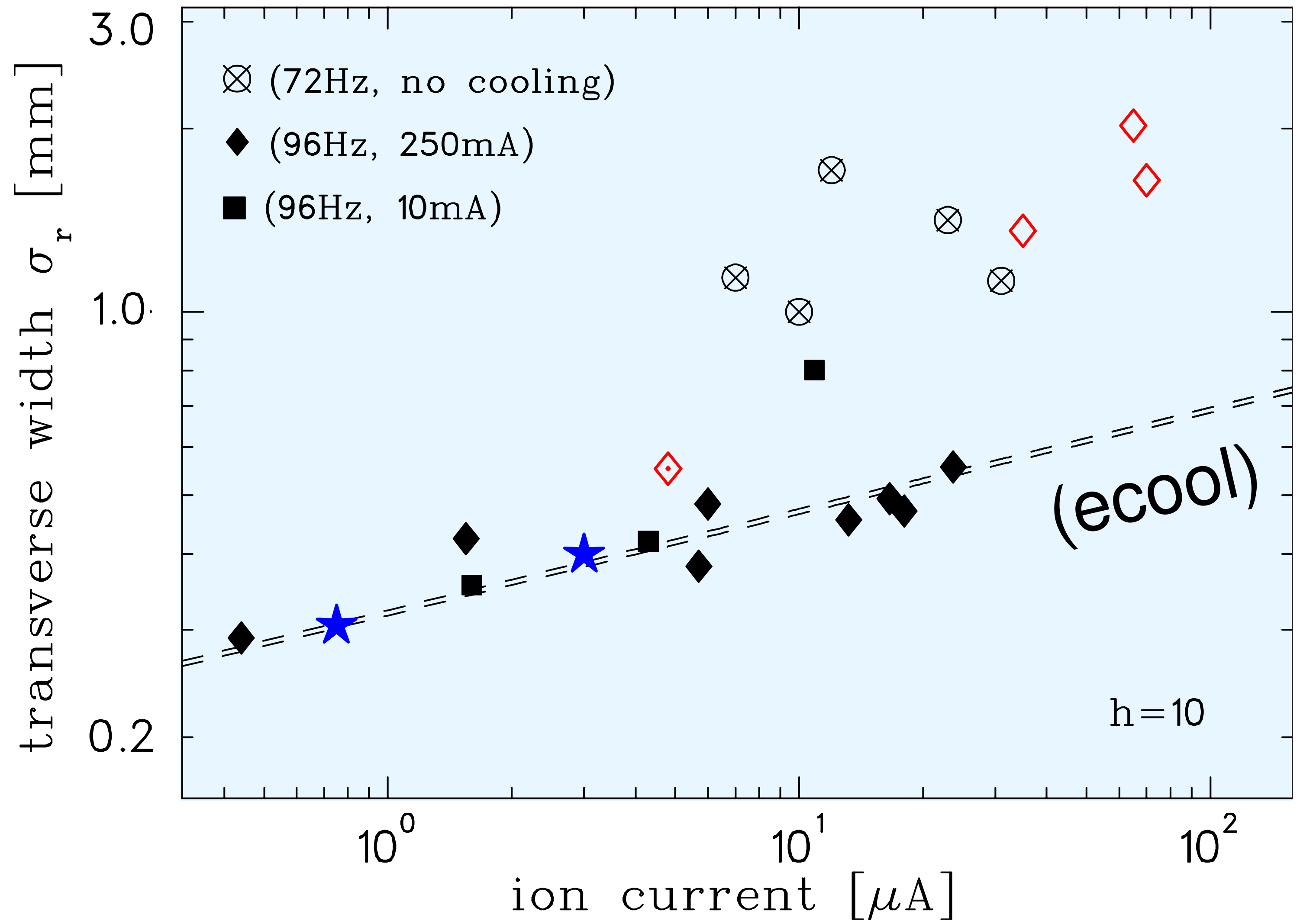


ecool ref. data
~ $N^{1/6}$ (IBS regime)

–> about one order of magnitude lower momentum spread than for electron cooled bunch (below 10 μA)

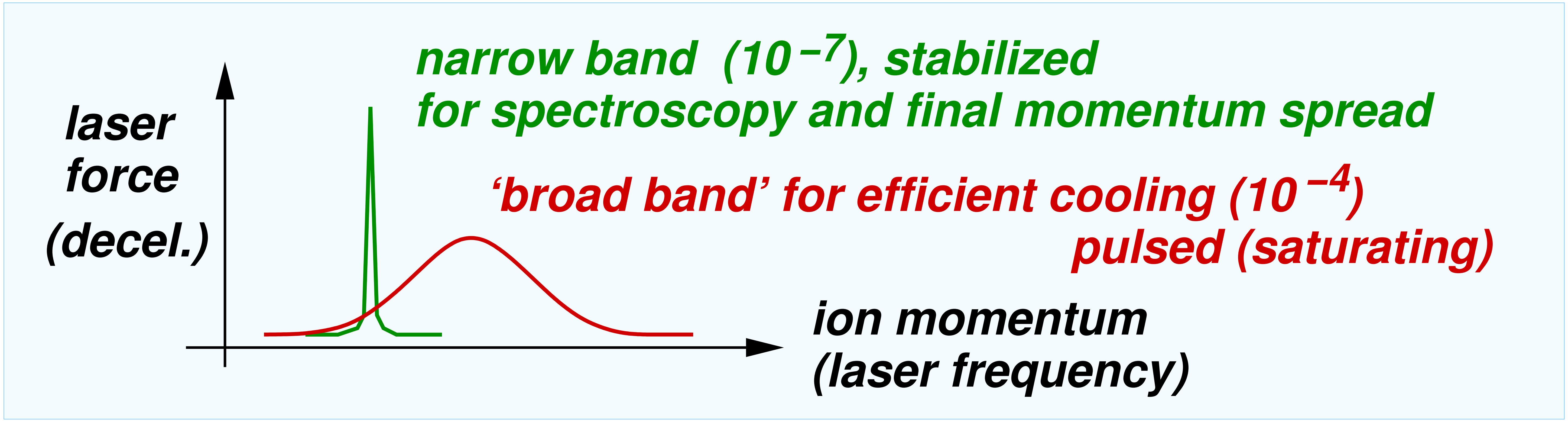
Laser cooling of bunched C^{3+} beams
laser vs ecool – transverse profiles





–> with little ecool (1mA) and even without (low ion current) beams are cold in 3D !

Laser excitation of relativistic beams
laser system for cooling & spectroscopy



At ESR further tests are required (and scheduled) for

- **testing broad−band laser cooling**
- **establishing longitudinal−transverse coupling (simulations)**
- **improved spectroscopy**

For SIS300 experiments, planning has started ...

ion–ion cooling

projectile energies (HCIs) ~ eV

target energies (stored cold OCP) ~ µeV

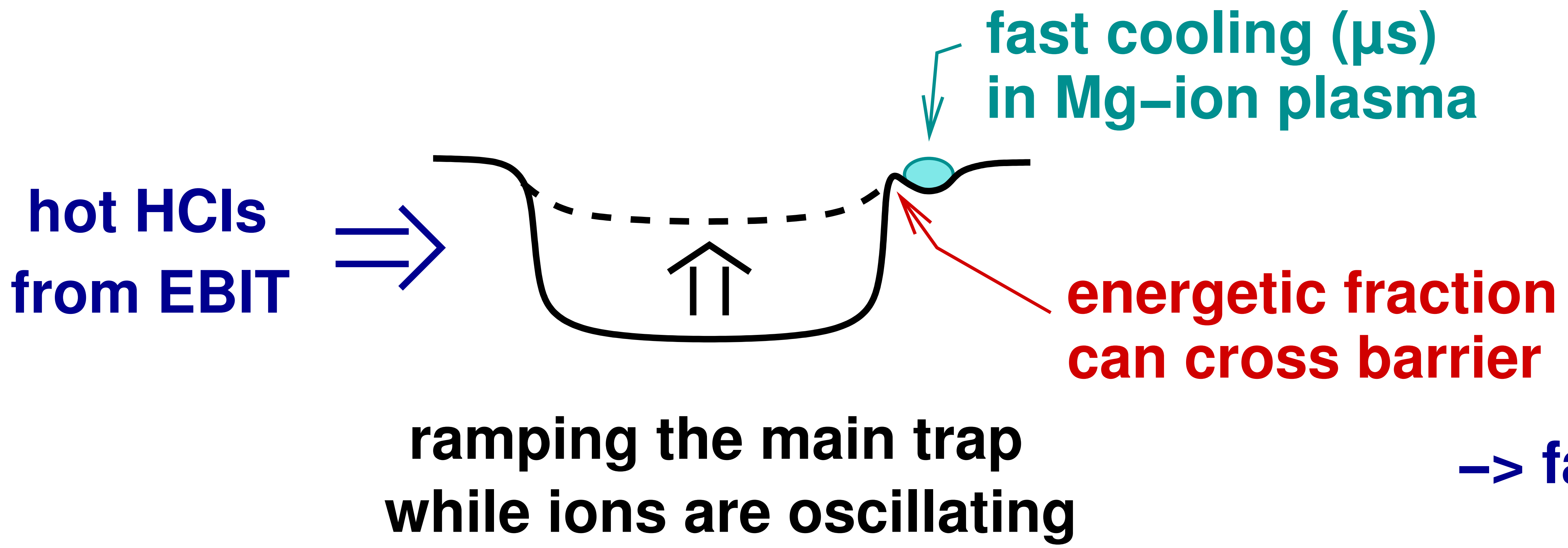
ion–ion cooling and stopping
the idea

precision Penning–trap mass measurements of short–lived nuclei

require high charge states –> charge breeding

and cold ions –> fast cooling without charge exchange

–> fast cooling of ~1eV HCIs in a continuously laser–cooled Mg–ion cloud or crystal



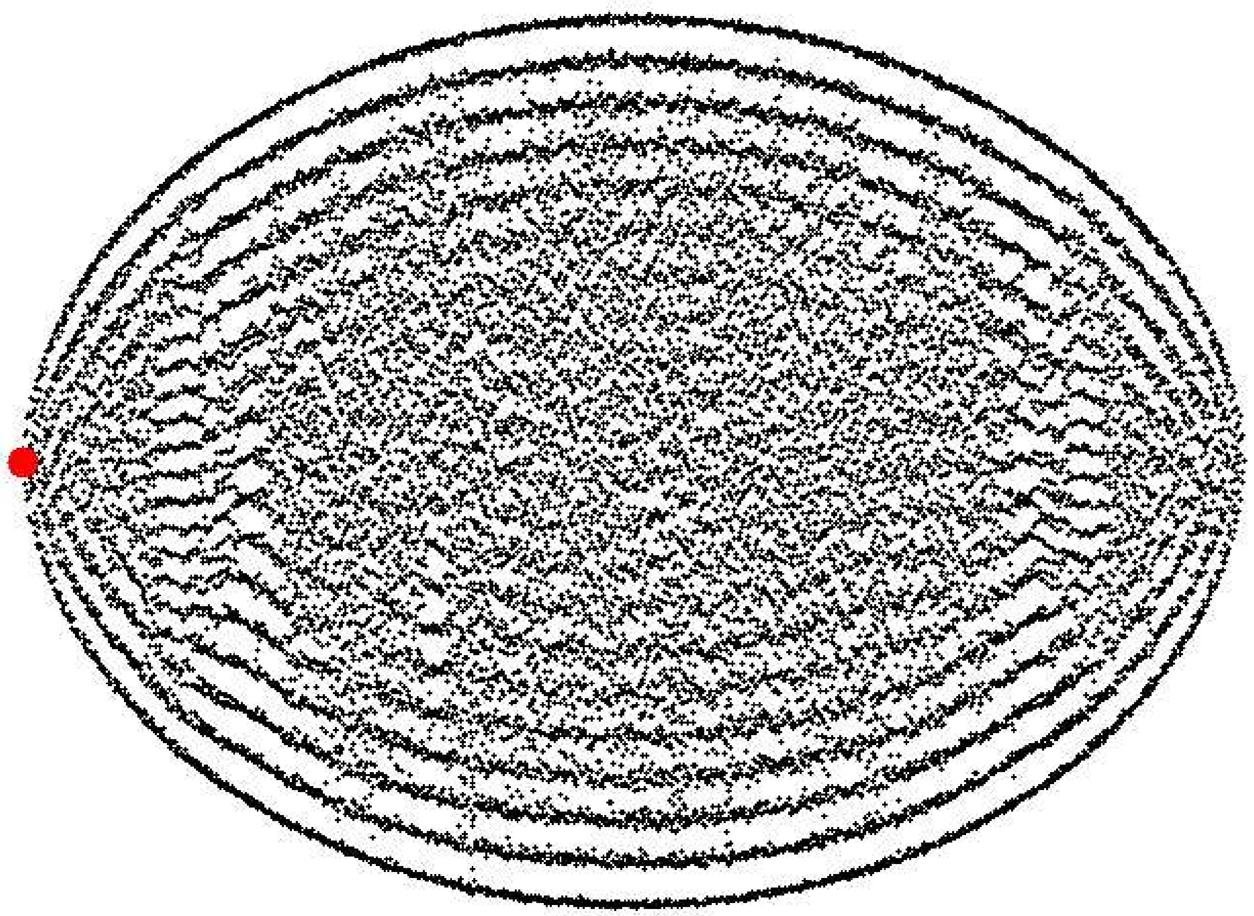
–> fast extraction

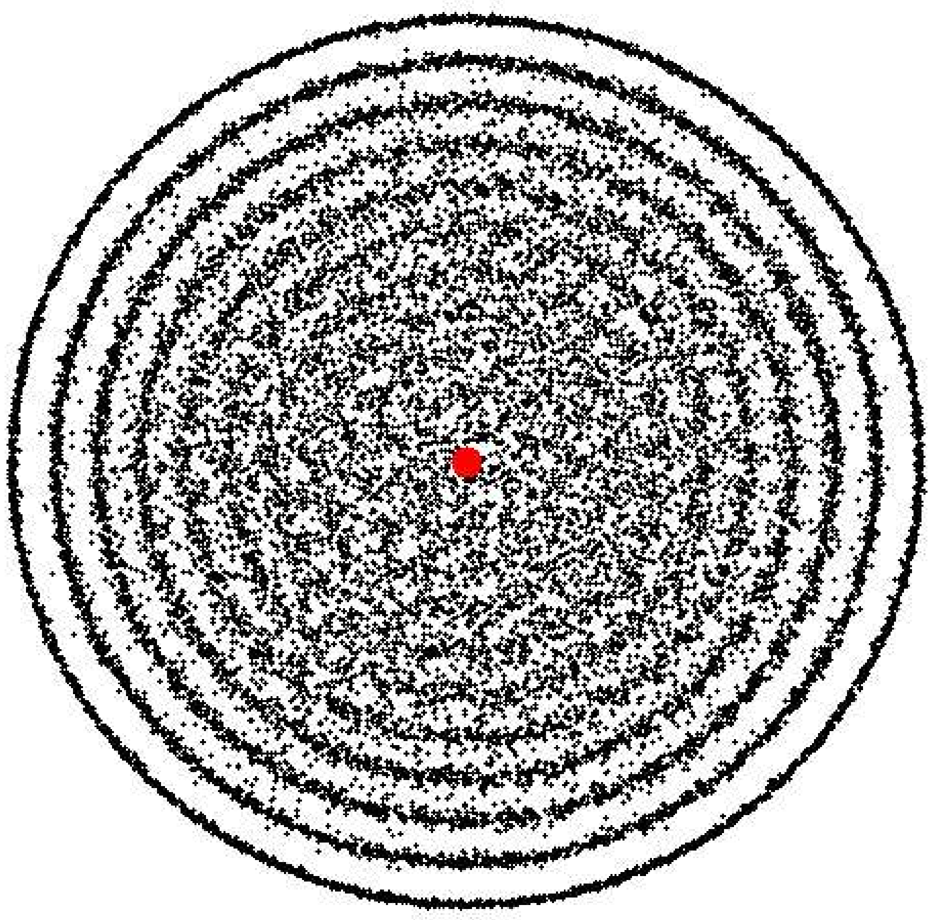
ion–ion cooling and stopping
MD simulation parameters

Target parameters: ***laser–cooled Mg–ion OCP in harmonic confinement***

100.000 ions, ~1mK, $\Gamma \sim 900$, ion spacing 30 µm

aspect ratio 1:25, plasma freq. ~ 1.7 MHz



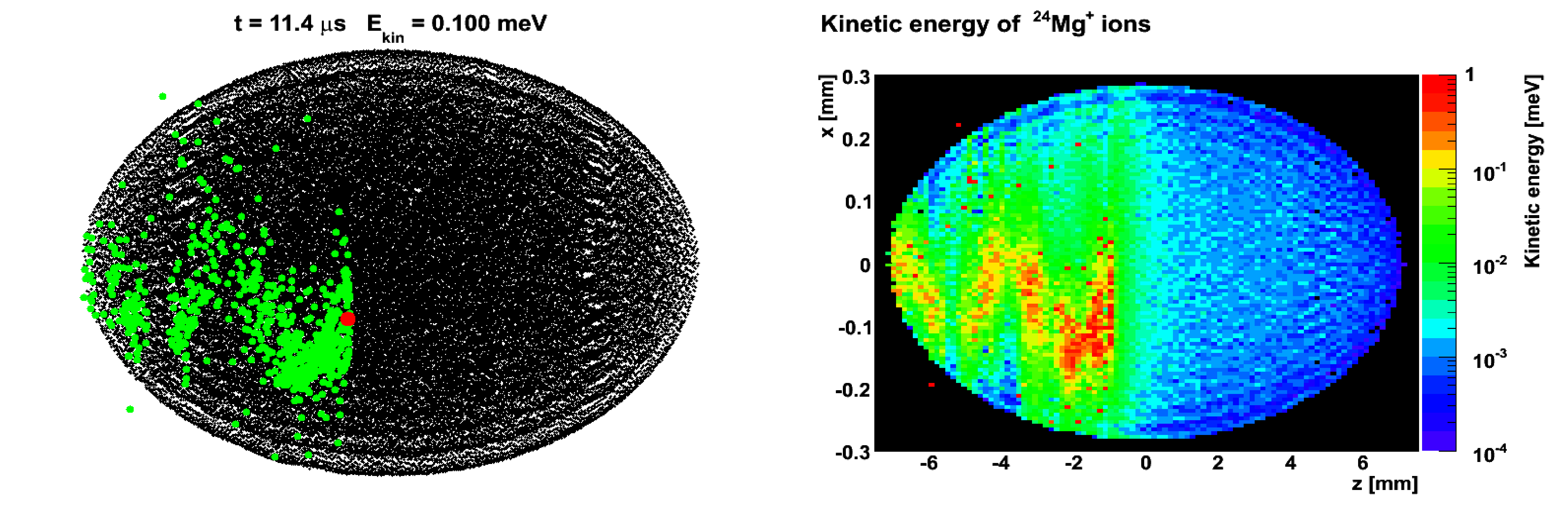


[code by M. Bussmann, explicit NxN computation, energy conserving]

–> probing cooling dynamics

ion–ion cooling and stopping
MD simulation results

energy deposition can be compensated by continuous laser cooling

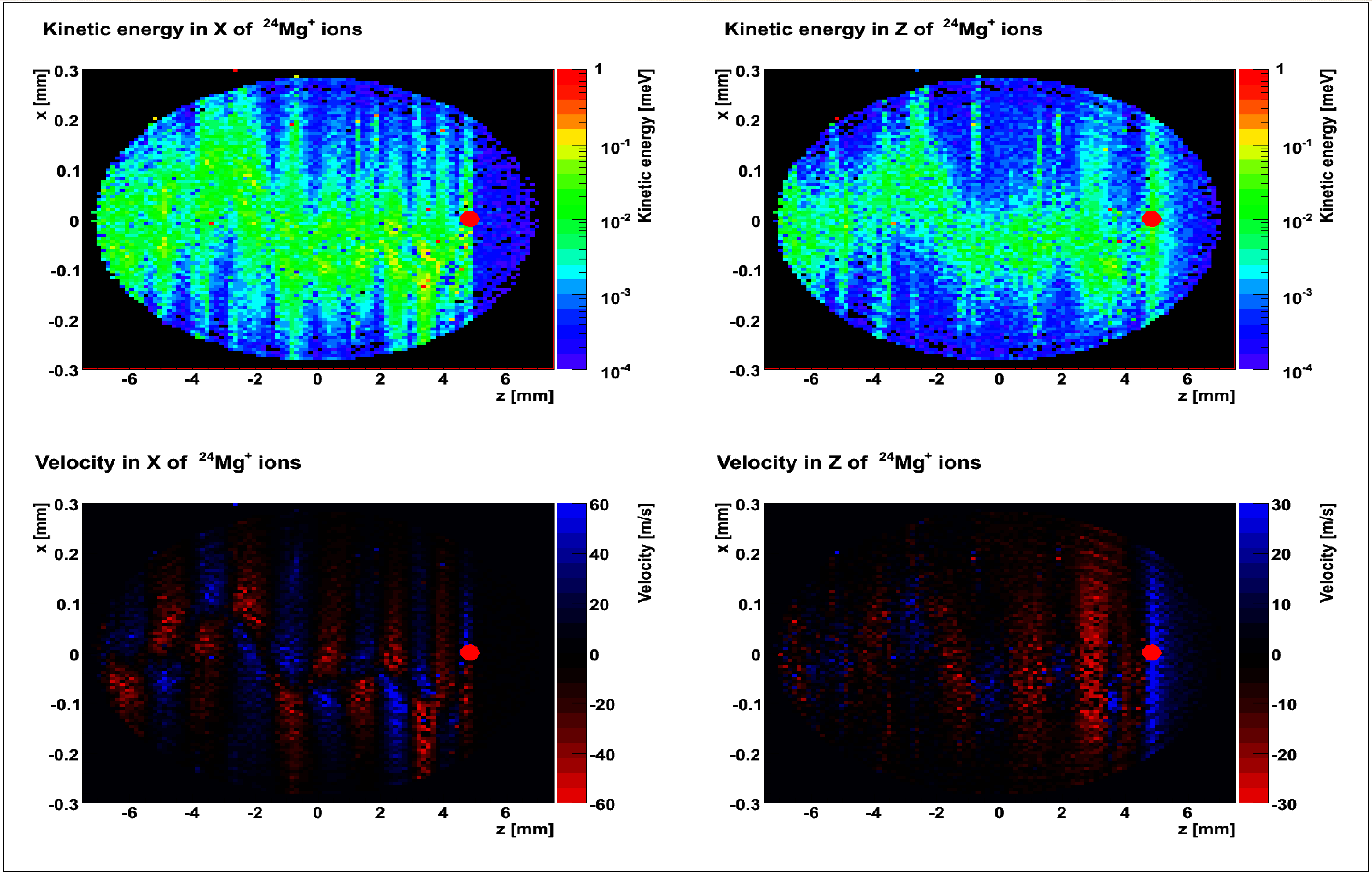


green dots mark Mg–ions above 0.1 meV –> kicked out of the lattice

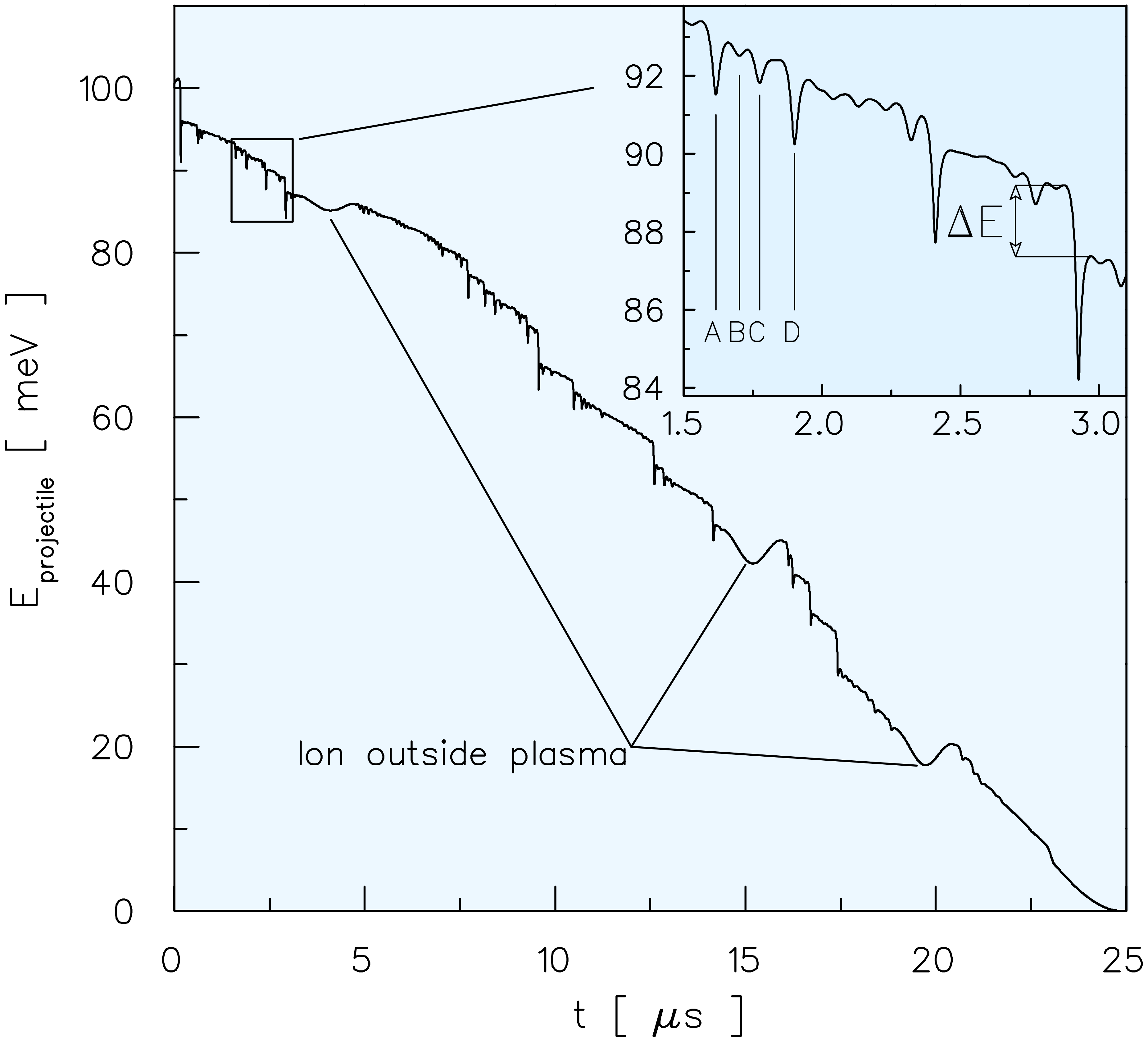
–> stopping of the HCl in ~10 μs

ion–ion cooling and stopping

MD simulation results



ion–ion cooling and stopping
energy loss mechanisms



sample case:
A=100, q=10, 100meV

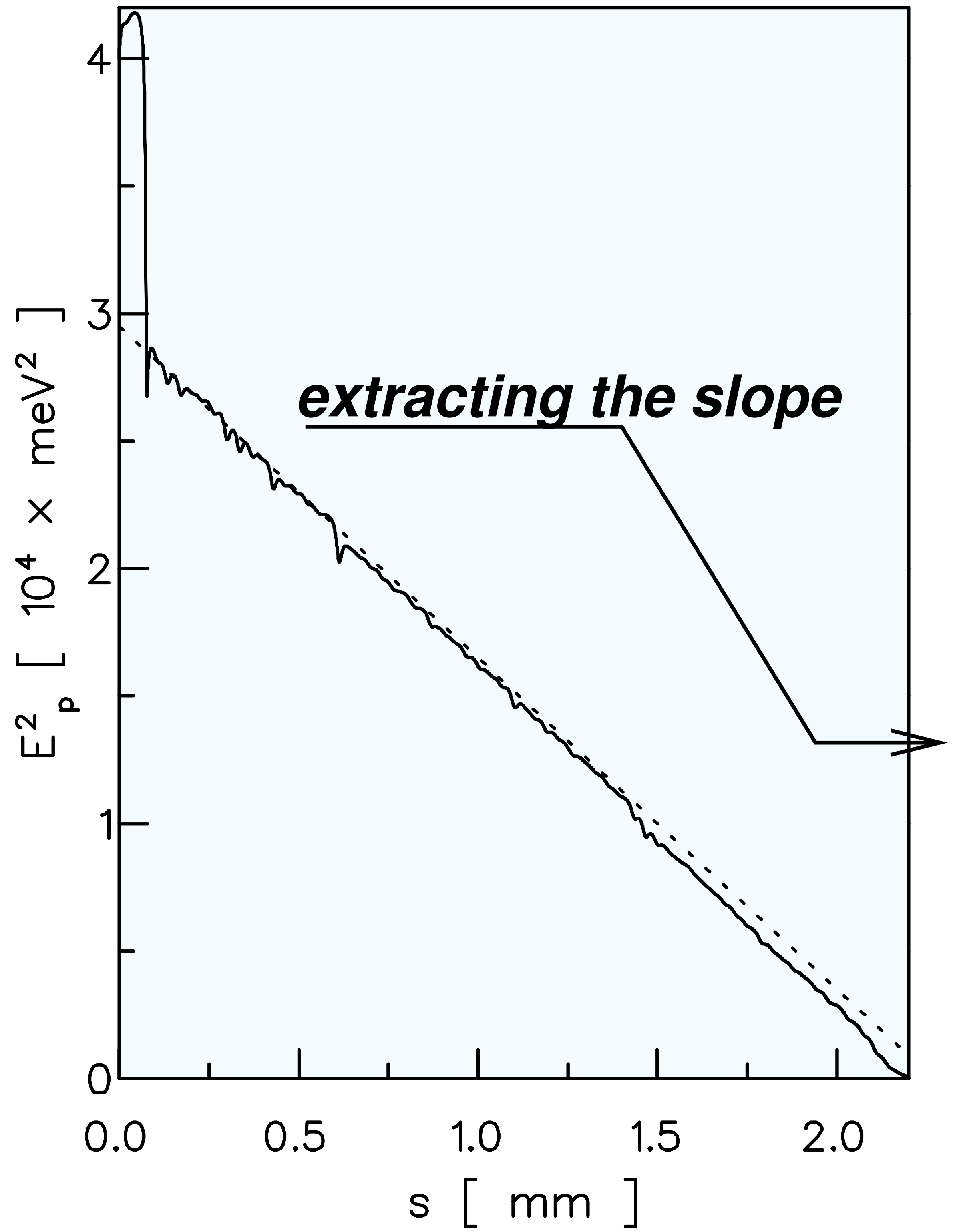
–> frequent binary collisions (heavy target)

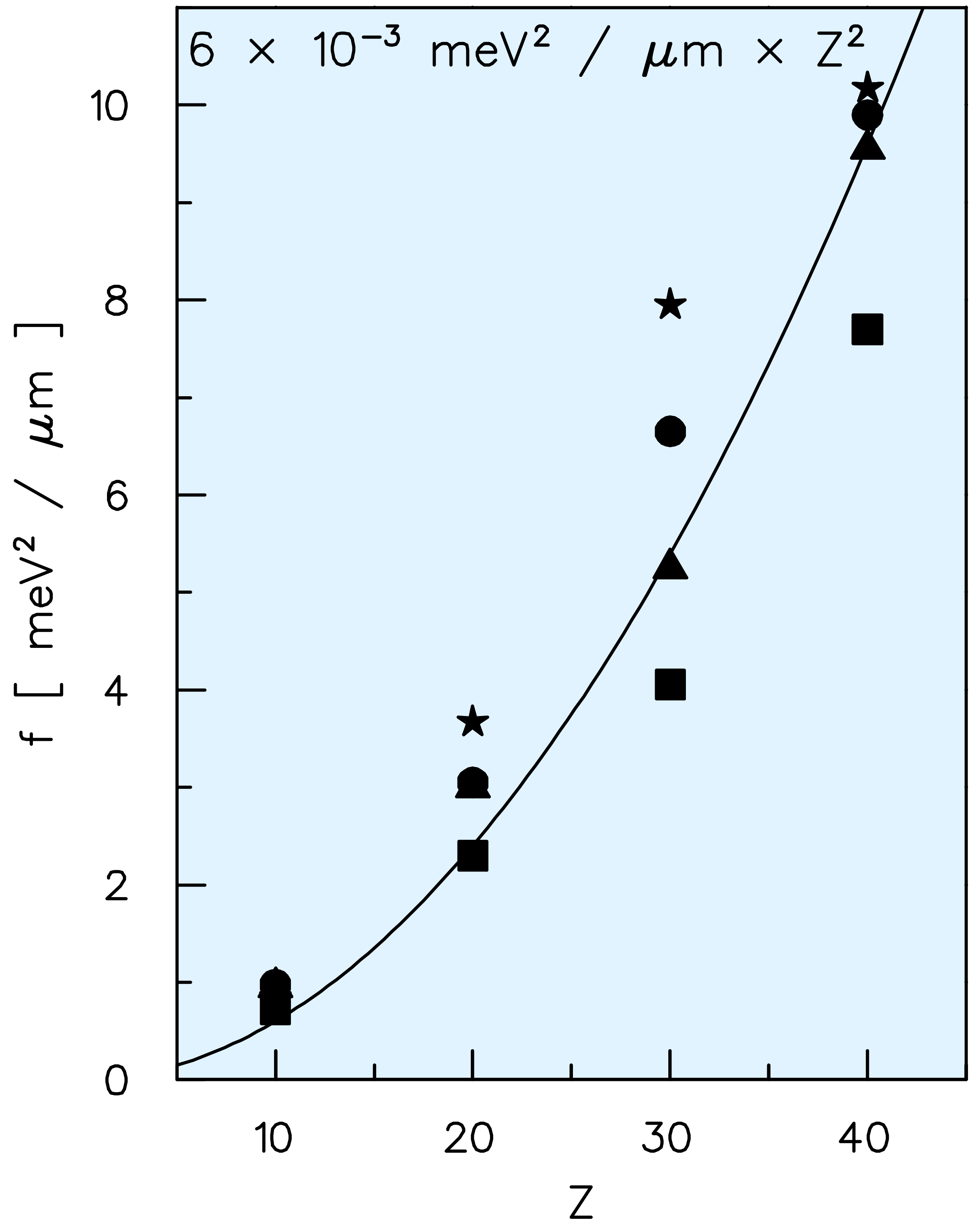
–> collective effects in the whole crystal (ad. shielding ~ size)

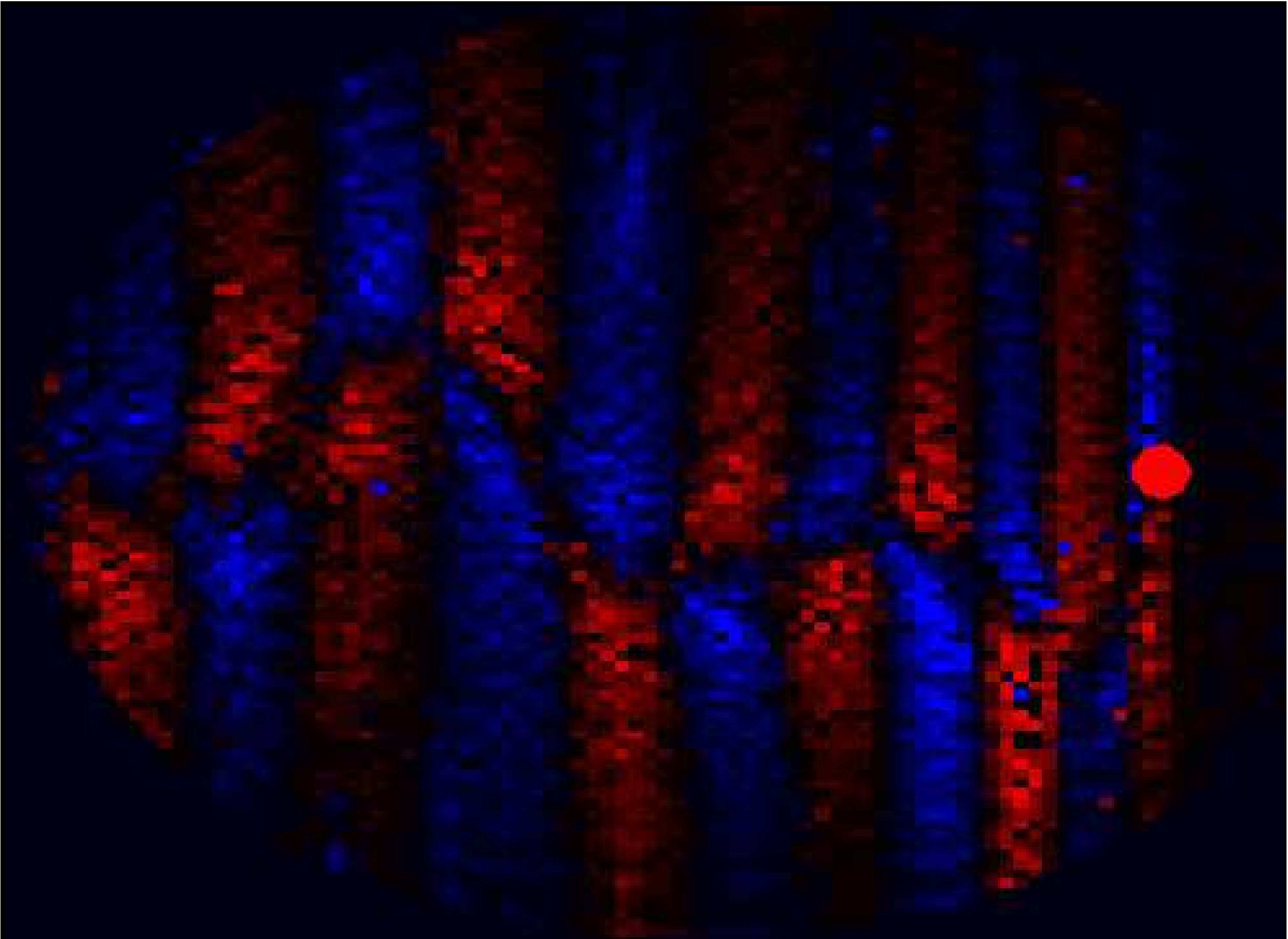
ion–ion cooling and stopping
charge and energy scaling

$$dE/ds = -f \cdot 1/E$$

$$E^2 = -2f \cdot s$$







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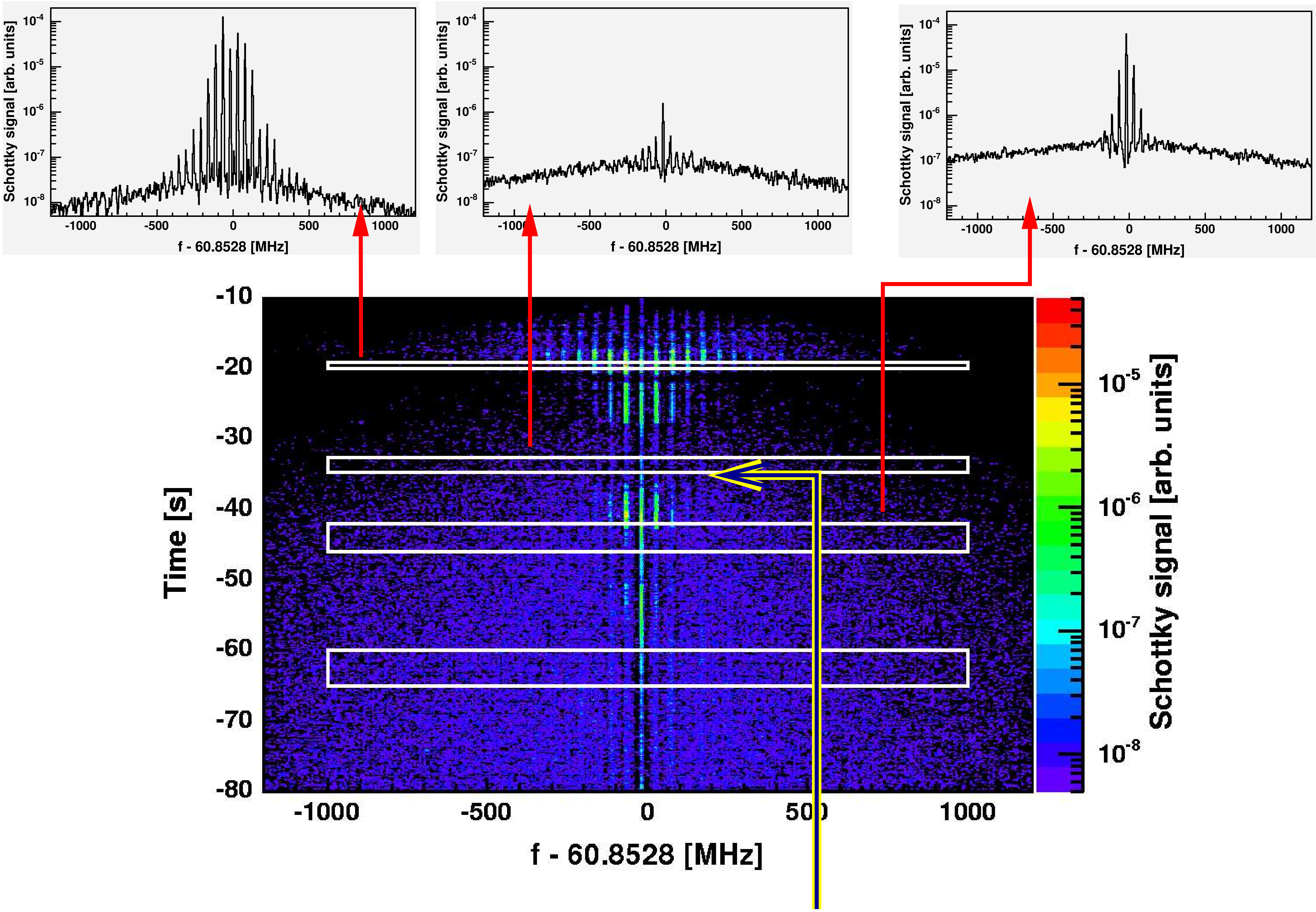
Laser cooling of bunched C^{3+} beams
long. cooling times – coupling



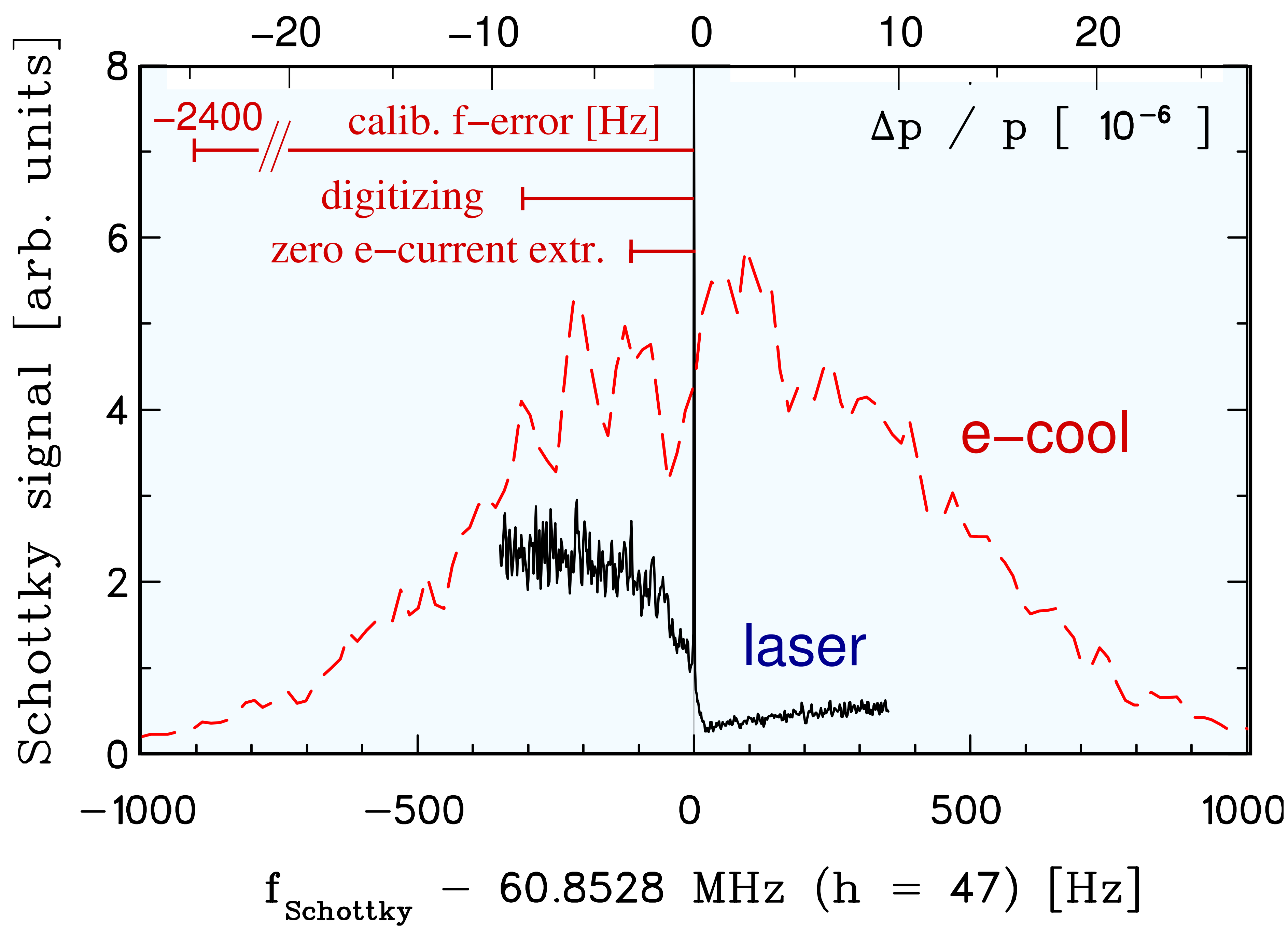
long. blow–up after strong cooling <–>

<–> coupling to transverse motion ?

Laser spectroscopy of bunched C^{3+} beams

1) mark Doppler–shifted laser transition in Schottky–spectrum

2) adjust electron cooled distribution to same revolution frequency



3) extrapolate to zero electron current (eliminating space charge effects)

Laser spectroscopy of bunched C^{3+} beams

–> *absolute accuracy limited by uncertainty in the ion energy, resp. the electron energy*

other influences

Ref.	excitation energies $2s\,^2S_{1/2} - 2p\,^2P_{1/2}$ [cm^{-1}]	$2s\,^2S_{1/2} - 2p\,^2P_{3/2}$ [cm^{-1}]	fine structure splitting ($2p\,^2P$) [cm^{-1}]
ESR (this work)	64486.80(1.6)(0.1)	64594.18(1.60)(0.08)	107.38(0.7)[a]
Exp.[6, 7] (1997)[b]	64483.8(1.5)	64591.0(1.5)	107.2(0.7)[c]
Th. [8][d] (1996)	64483.7	64591.6	107.9
Th. [9][e] (1998)	64503.2	64610.3	107.1
Th. [11][f] (2004)	64485.4(1.1)	64592.3(2.2)	106.9(2.5)

[6,7] from B. Edlen, Phys. Scr. 28, 51 (1983), M. Tunklev, et al, Phys. Scr. 55, 707 (1997)

[8] from W.R. Johnson, et al, At. Data Nucl. Data Tab. 64, 279 (1996)

[9] from C. Froese Fischer, et al, At. Data Nucl. Data Tab. 70, 119 (1998)

[11] from I. Tupitsyn, V. Shabaev (priv.com.)

Laser spectroscopy of bunched C^{3+} beams

–> at ESR laser spectroscopy of Li–like light ions is competitive (and limited by the abslute knowledge of the Doppler–shift)

–> improved voltage calibration ?

–> cross check with other spectr. data (DR) ?

–> at SIS 100/300 the absolute (and precise) measurement of the laser frequency and the X–ray energy gives an absolute value for the transition energy

$$f_{rest}^2 = f_{laser} \cdot f_{X-ray}$$

–> precision spectroscopy (X–ray ...)

–> valuable input for NESR experiments