Penning-trap mass spectrometry with a single trapped ion: approaches for experiments at GSI/FAIR

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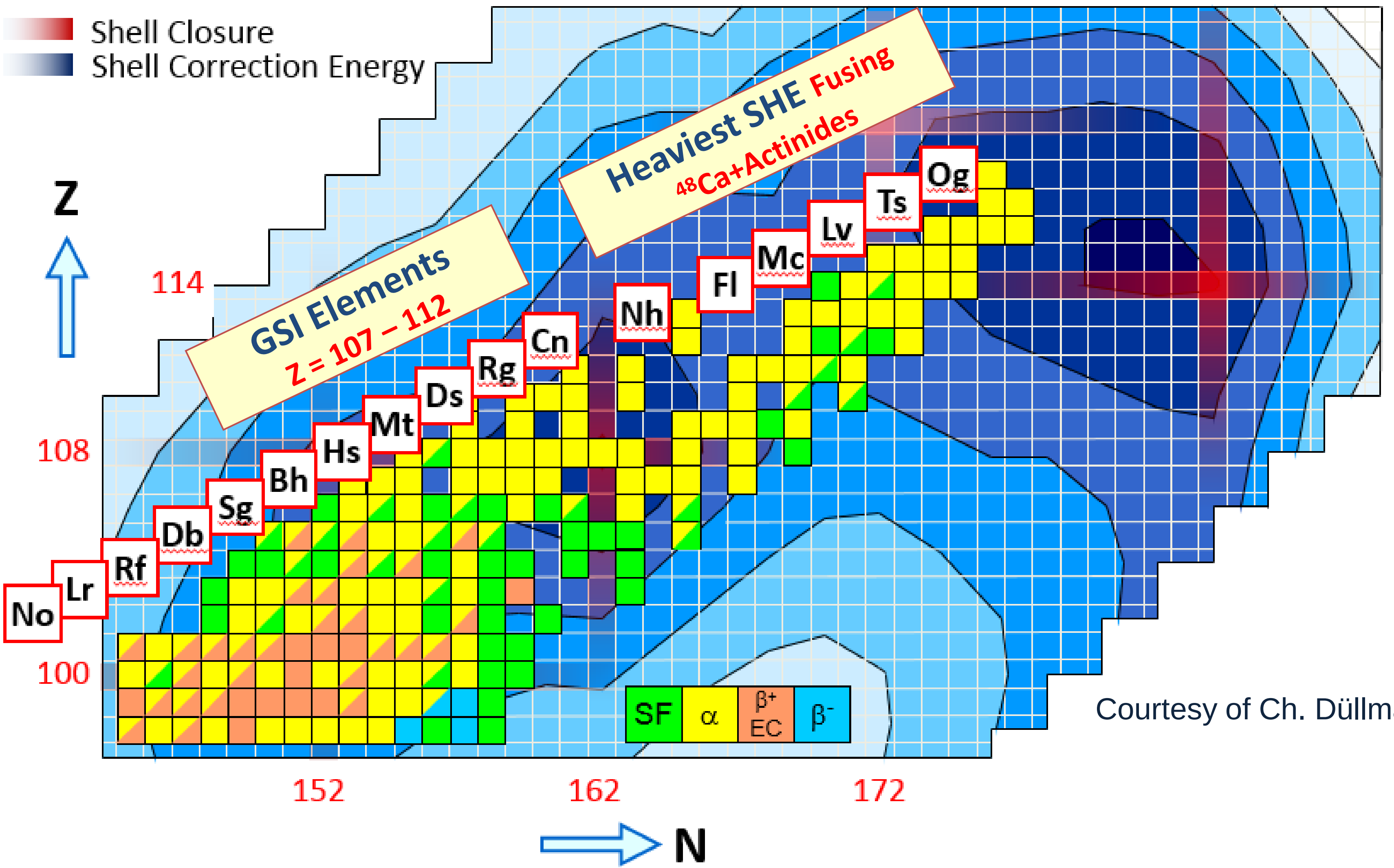
"Una manera de hacer Europa"
CPAN Ingenio 2010
TRAP SENSOR

Outline

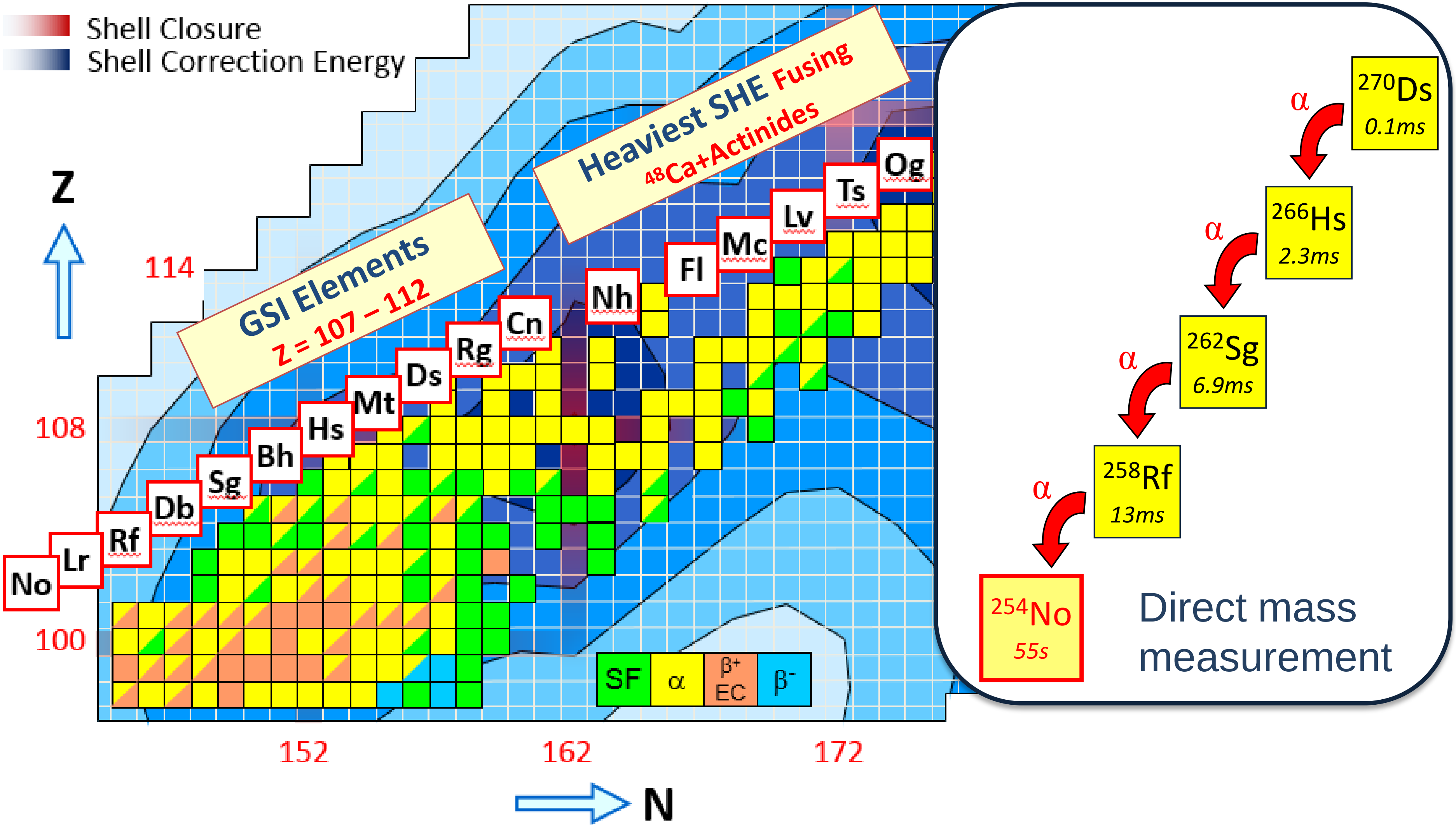
- Motivation
- Penning traps and masses
- Single-ion (electronic) detection
- Experimental setups
- Results
- Single-ion (optical) detection
- Conclusions and perspectives

Motivation
Masses of Superheavy elements



Courtesy of Ch. Düllmann

Motivation
Masses of Superheavy elements



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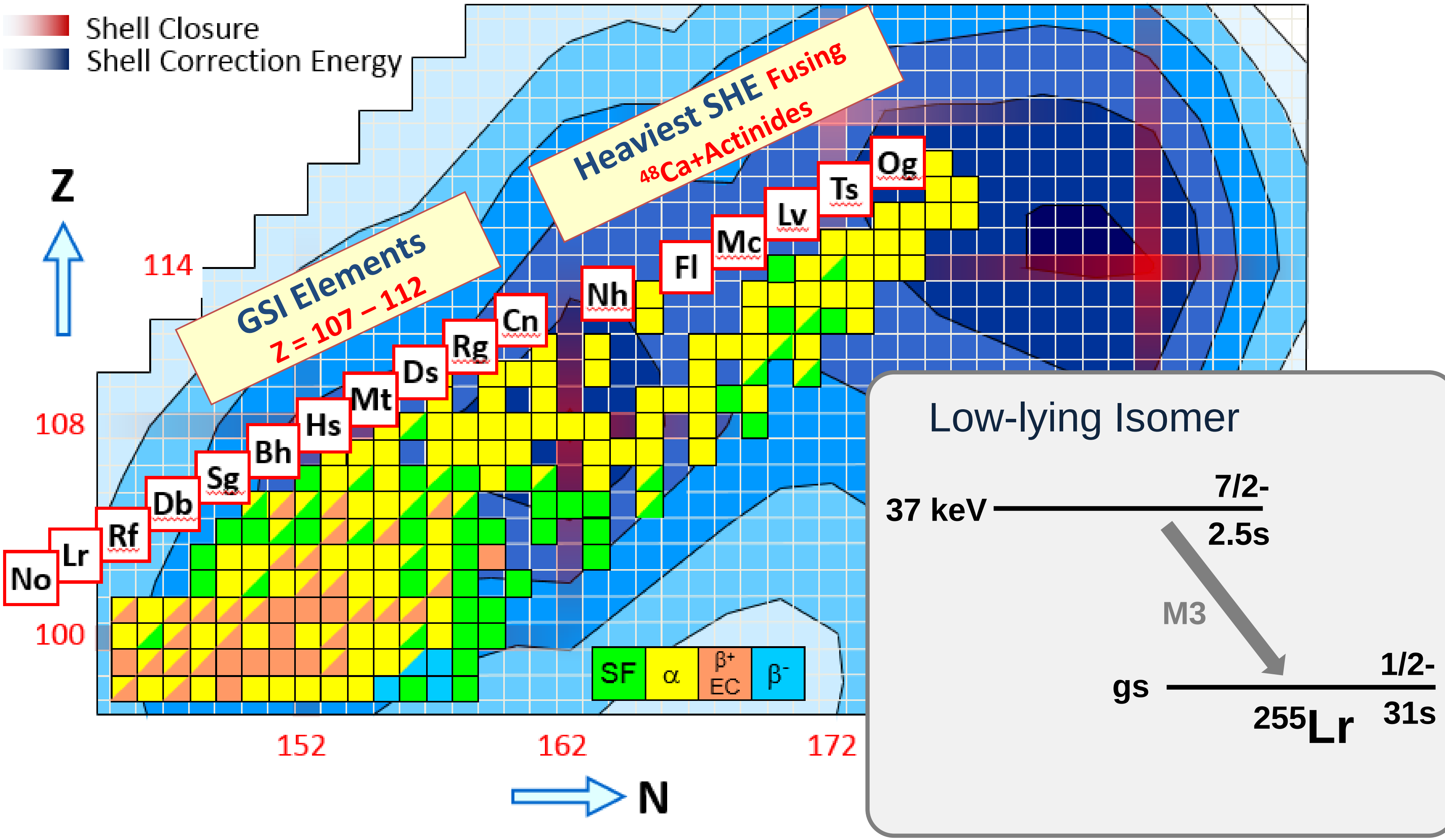

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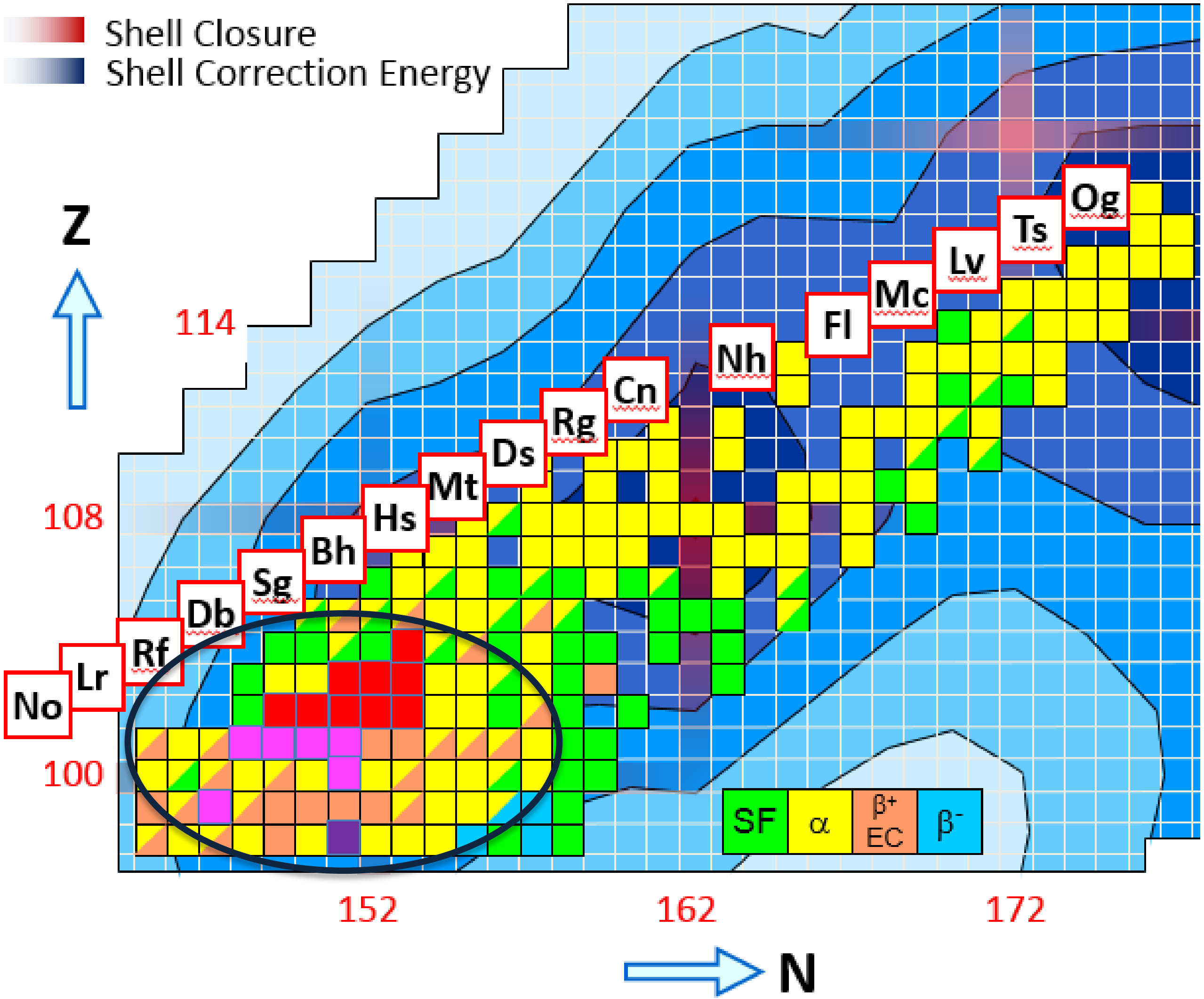


- **SHIPTRAP**

  O. Kaleja, F. Giacoppo *et al.*, in preparation
  E. Minaya-Ramirez *et al.*, Science 337, 1207 (2012)
  M. Block *et al.*, Nature 463, 785 (2010)

- **RIKEN MR-TOF**

  Y. Ito et al., Phys. Rev. Lett. 120, 152501 (2018)

- **TRIGA-TRAP**

  M. Eibach *et al.*, Phys. Rev. C 89, 064318 (2014)

M. Block, Radiochmica Acta 107, 603, (2019)

Motivation
Masses of Superheavy elements

TOF-ICR

E. Minaya-Ramirez *et al.*,
Science 337, 1207 (2012)
M. Block *et al.*,
Nature 463, 785 (2010)

^{256}Lr (60 nb)
(2010)

PI-ICR

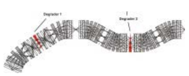
$^{255(m)}$Lr (200/52 nb)
^{256}Lr (60 nb)
$^{254(m)}$Lr (22/7 nb)
$^{251(m)}$No (30 nb)
^{257}Rf (15 nb)

(1 nb)

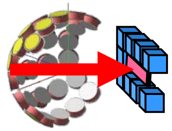
- All recent SHIPTRAP measurements performed with doubly charged ions
- 1st direct mass spectrometry of a superheavy element (1 det. ion per 8 hours)
- **Single-ion sensitivity (low charge states) needed for isotopes produced with cross section below 1 nb.**

Motivation
Masses of ions with ultra-low production yields

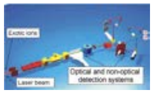
Super-FRS



HISPEC/ DESPEC

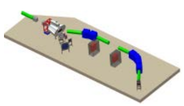


LASPEC

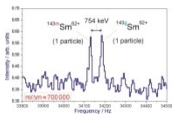


MATS

R3B

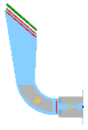


ILIMA



SHE

ELISE



EXL

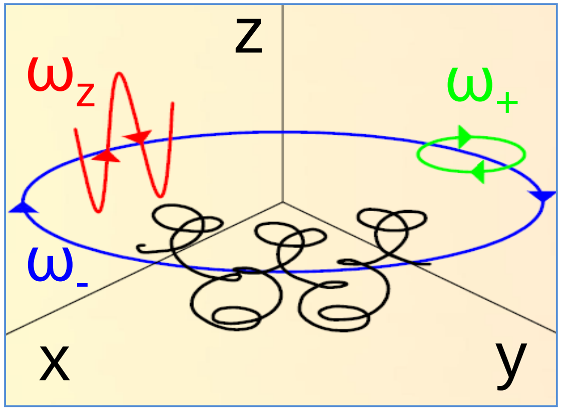
	Super-FRS	HISPEC/DESPEC	LASPEC	MATS	R3B	ILIMA	SHE	ELISe	EXL
Masses		Q-values, isomers		dressed ions, highest precision	unbound nuclei	bare ions, mapping study	precision mass of SHEs		
Half-lives	ps...ns-range	dressed ions, µs...s			resonance width, decay up to 100ns	bare ions, ms…years	µs...days		
Matter radii	interaction x-section				interaction x-section				matter densitiy distribution
Charge radii	charge-changing cross sections		mean square radii		charge-changing cross sections			charge density distribution	
Single-particle structure	high resolution, angular momentum	high-resolution particle and γ-ray spectroscopy	magnetic moments, nucl. spins	evolution of shell str., pairing int., valence nucl.	quasi-free knockout, short-range and tensor	evolution of shell closures, pairing corr.	shell structure of SHEs		low momentum transfers
Collective behavior		electromag. transitions	quadrupole moments	halo structure	dipole response	changes in deformation		electromag. transitions	monopole resonance
EoS					polarizability, neutron skin			neutron skin →	neturon skin, Compressibility
Exotic Systems	bound mesons, hypernuclei, nucleon res.								

From Nasser Kalantar-Nayestanaki

- Or if fast measurements are required.

Penning traps and masses
Considerations for Superheavy elements

$$\omega_c = \frac{q}{m} B$$



- High charge state
- High magnetic field
- Magnetic field imperfections
- Misalignment
- Electric field imperfections
- …

Penning traps and masses
Considerations for Superheavy elements

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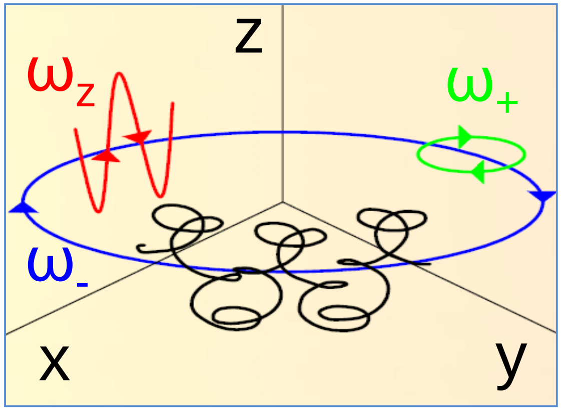

- High charge state
- High magnetic field
- Low production rates Single ion sensitivity
- Fixed charge states Highest sensitivity
- Half-lives Half-lives above 1 second

Penning traps and masses
Considerations for Superheavy elements

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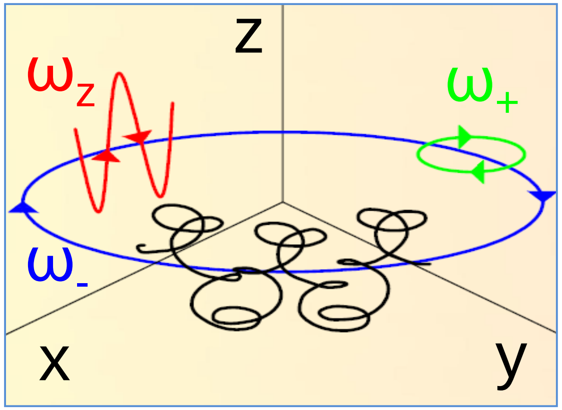


$$\omega_c = \omega_+ + \omega_-$$

In the order of 500 kHz (for SHE)

~100 kHz (for SHE)

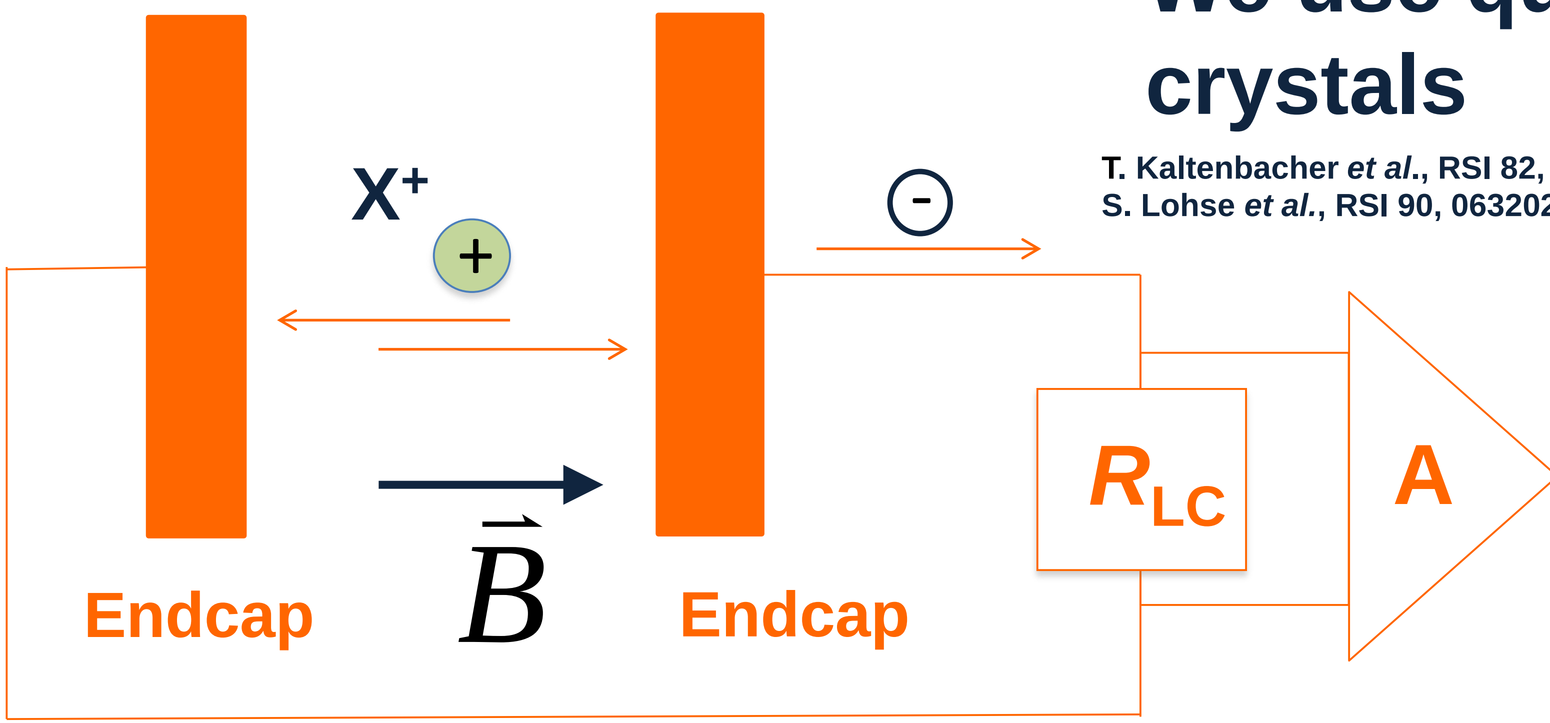
$$\omega_+ > \omega_z > \omega_-$$

Single-ion electronic detection
Quartz amplifiers

- **Highest accuracy achieved using low mass-to-charge ratios (see e.g. K. Blaum's division, E. Myers's group).**
- **Drawback:** The highest sensitivity is frequency dependent → Narrowband.

We use quartz crystals

T. Kaltenbacher *et al.*, RSI 82, 114702 (2011)
S. Lohse *et al.*, RSI 90, 063202 (2019)



D. J. Wineland & H. G. Dehmelt, J. Appl. Phys. 46 (1975) 919-930.

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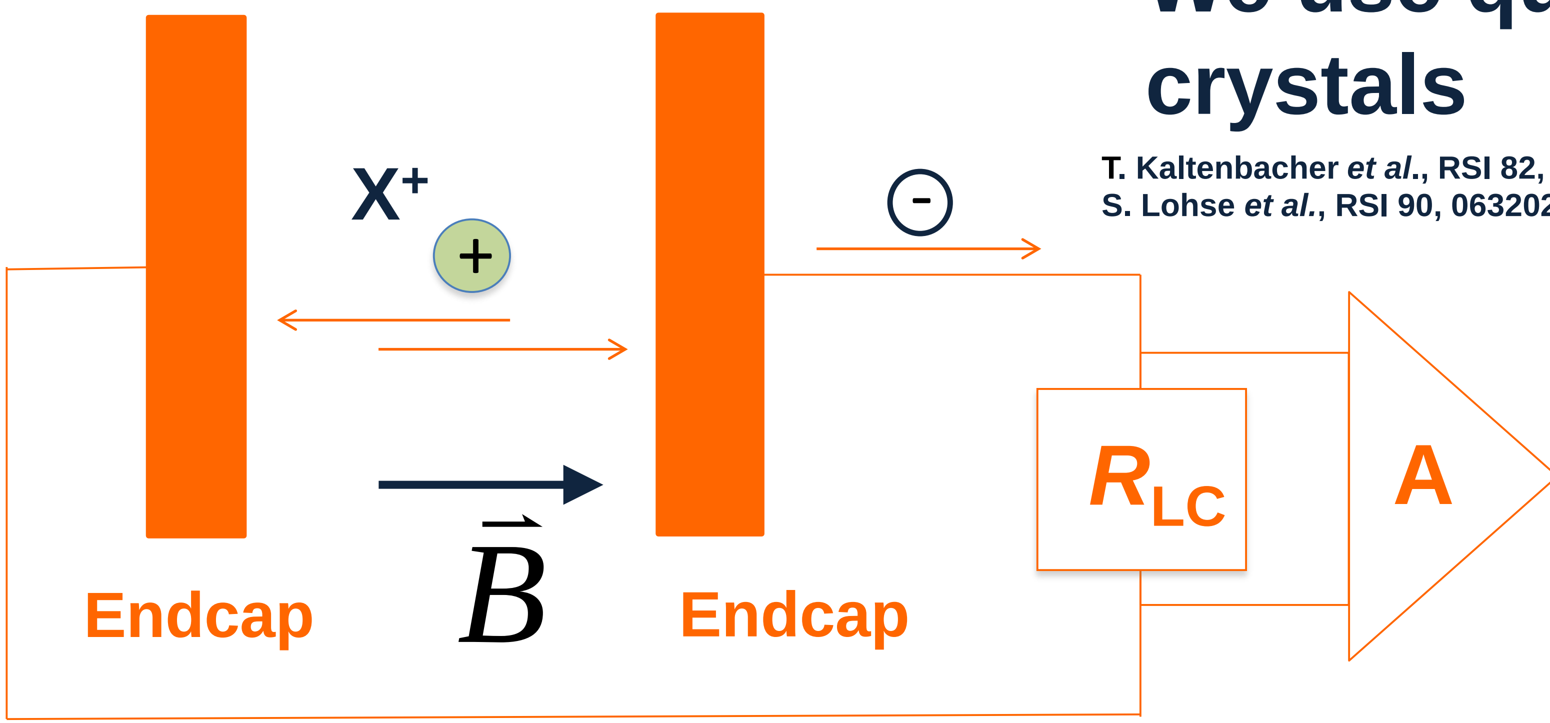
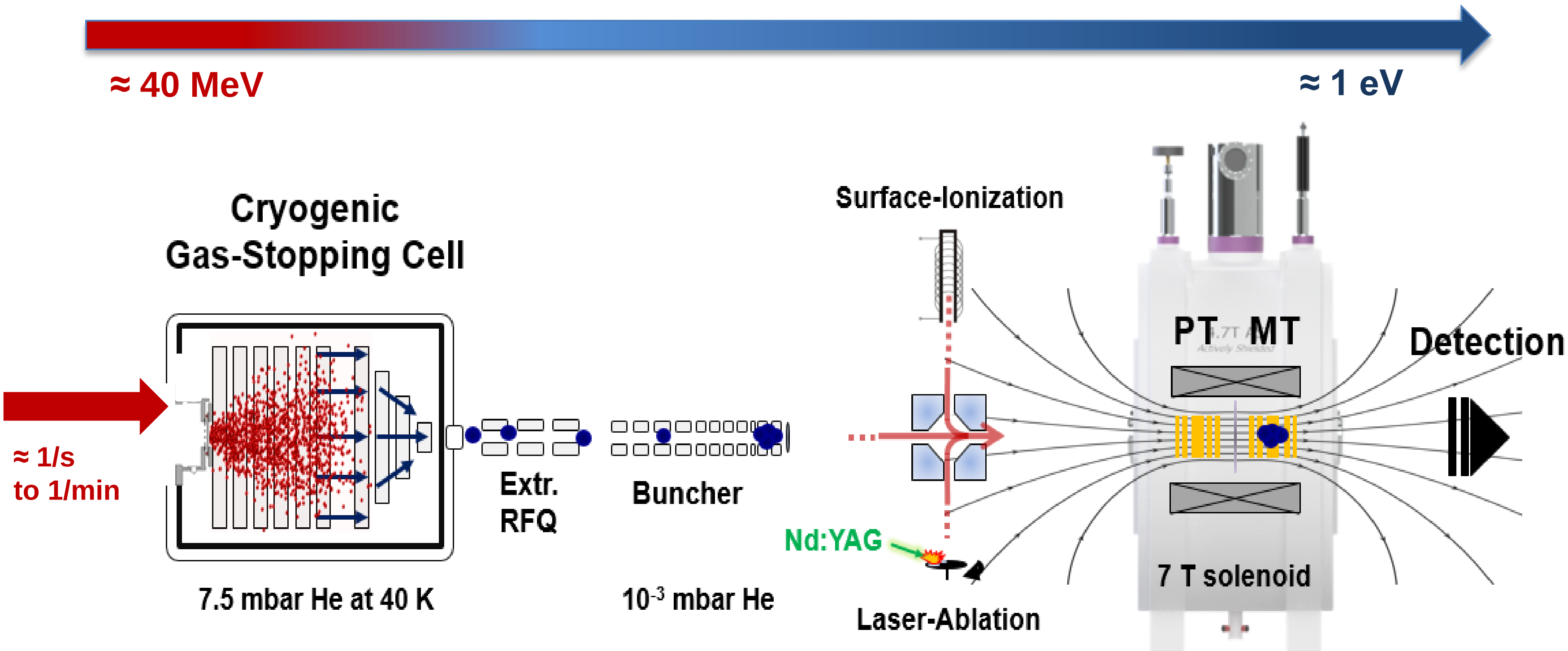


D. J. Wineland & H. G. Dehmelt, J. Appl. Phys. 46 (1975) 919-930.

Experimental setups
SHIPTRAP



Experimental setups
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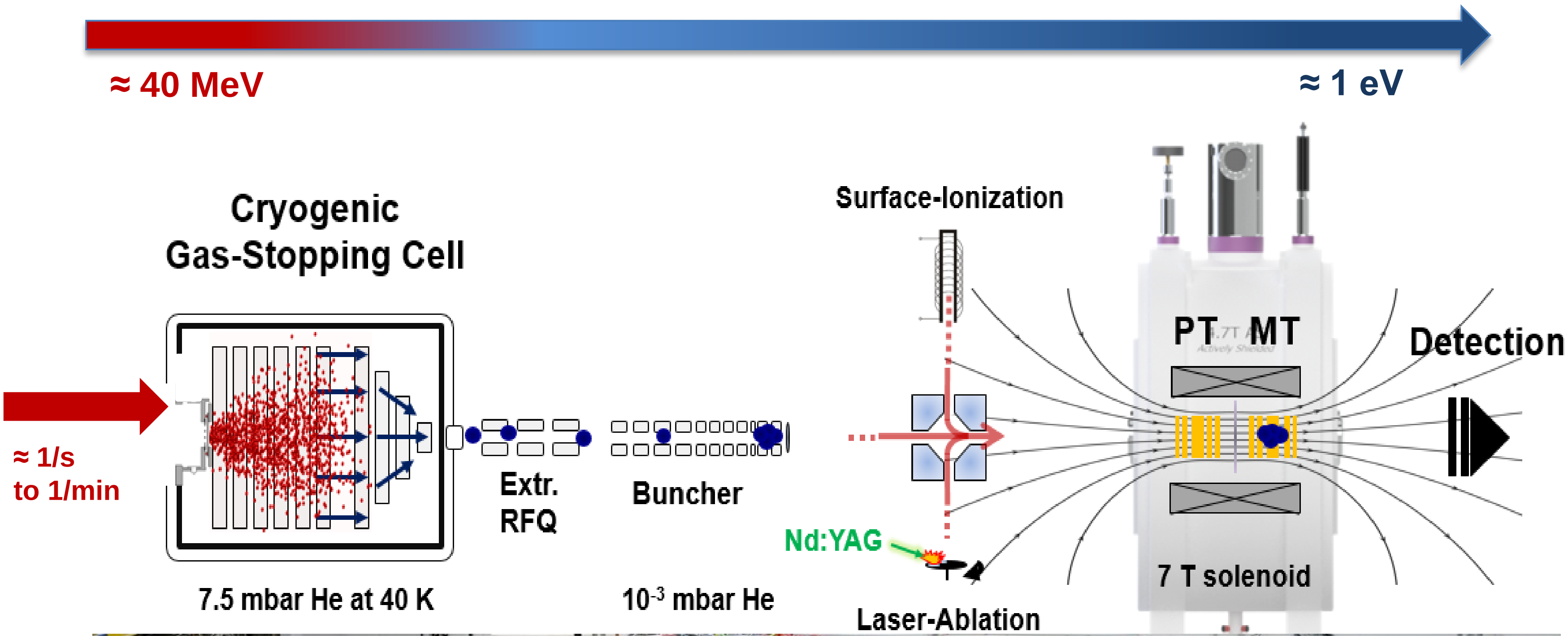


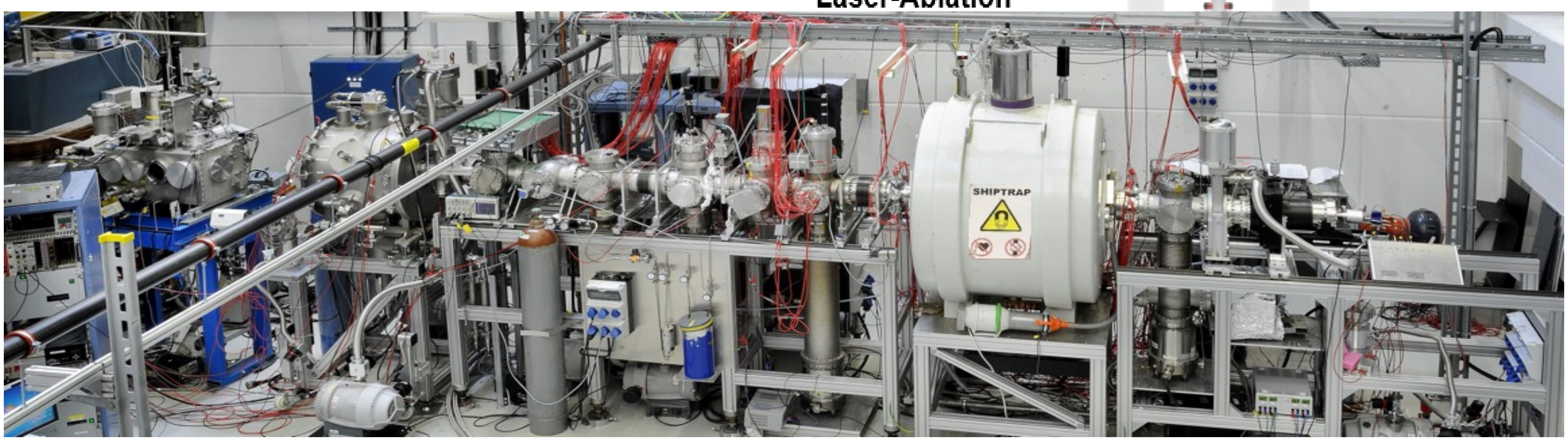


Photo: G. Otto, GSI

Experimental setups
TRIGA-TRAP and TRAPSENSOR

TRIGA-TRAP (laser ablation)

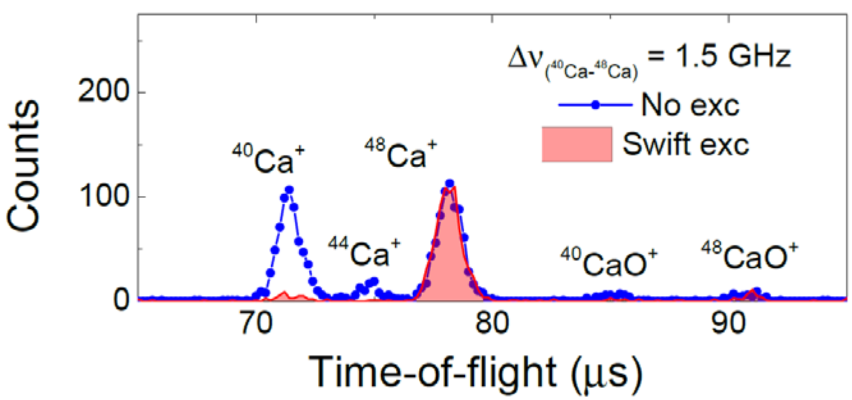
Johannes Gutenberg Universität Mainz

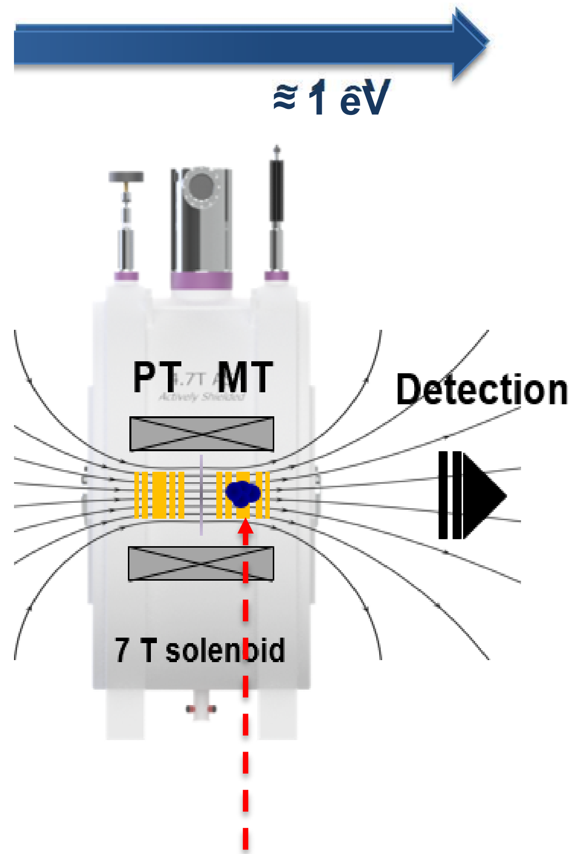
$^{206,207}Pb^{+}$

TRAPSENSOR (laser ablation)

Universidad de Granada

$^{40}Ca^{+}$, $^{187}Re^{+}$, $^{187}Os^{+}$

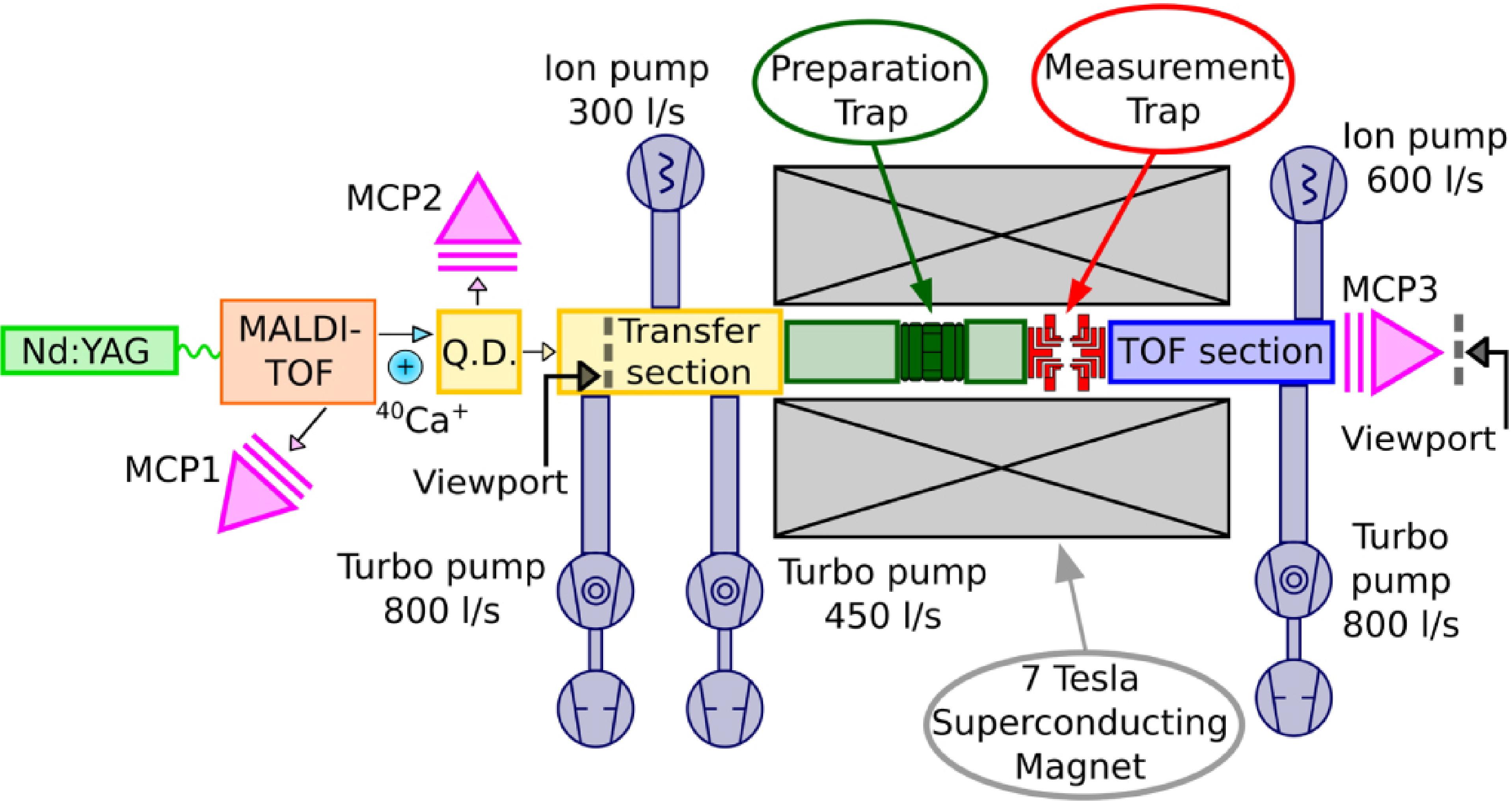




TRAPSENSOR (photoionization)

$^{40,42,44,48}Ca^{+}$

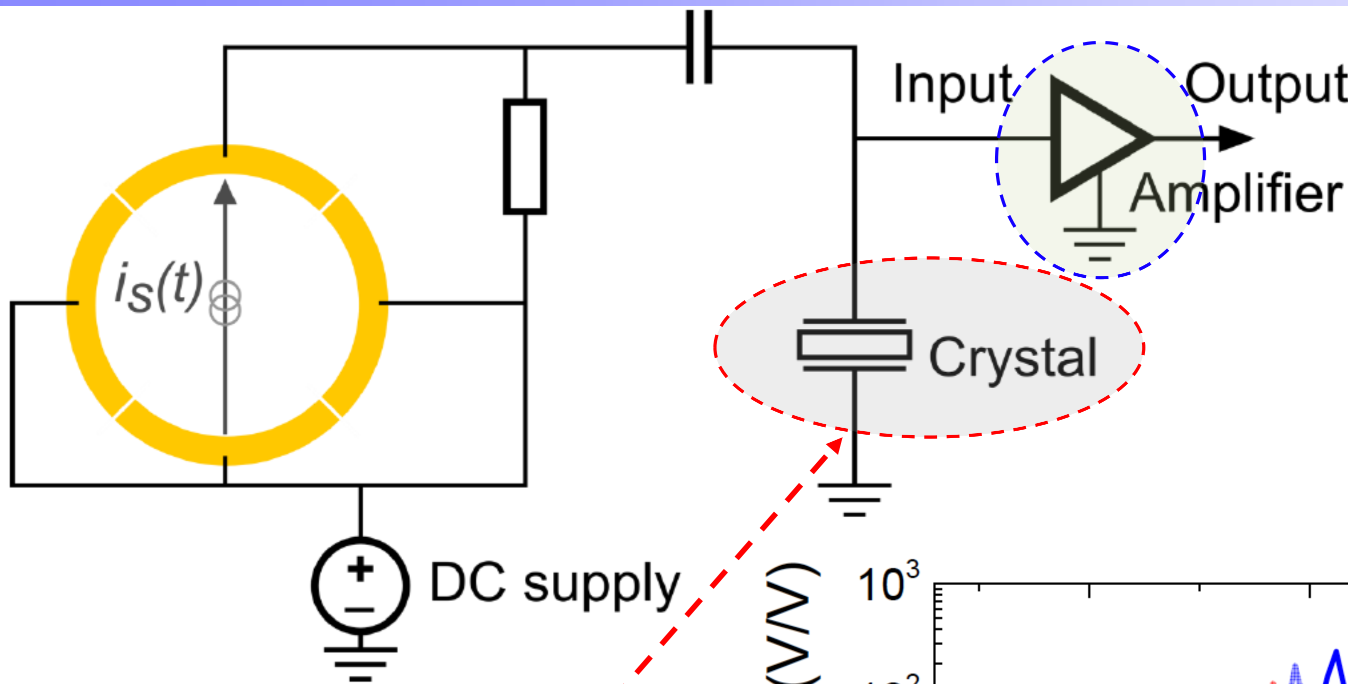
Experimental setups
TRAPSENSOR

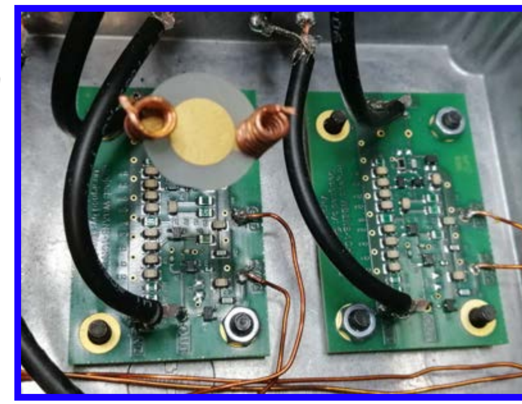


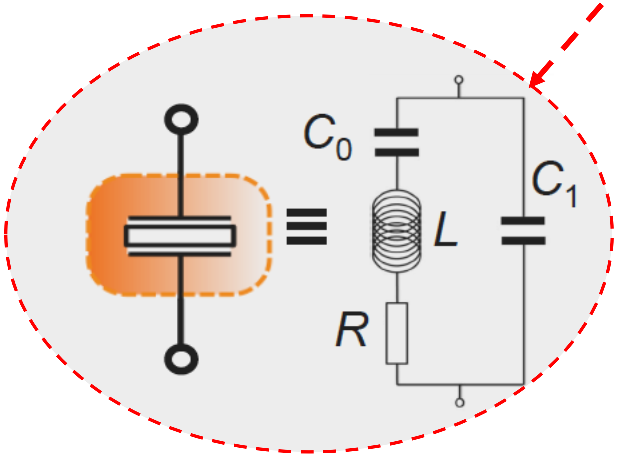
M. J. Gutiérrez *et al.*, New J. Phys. 21 023023 (2019)

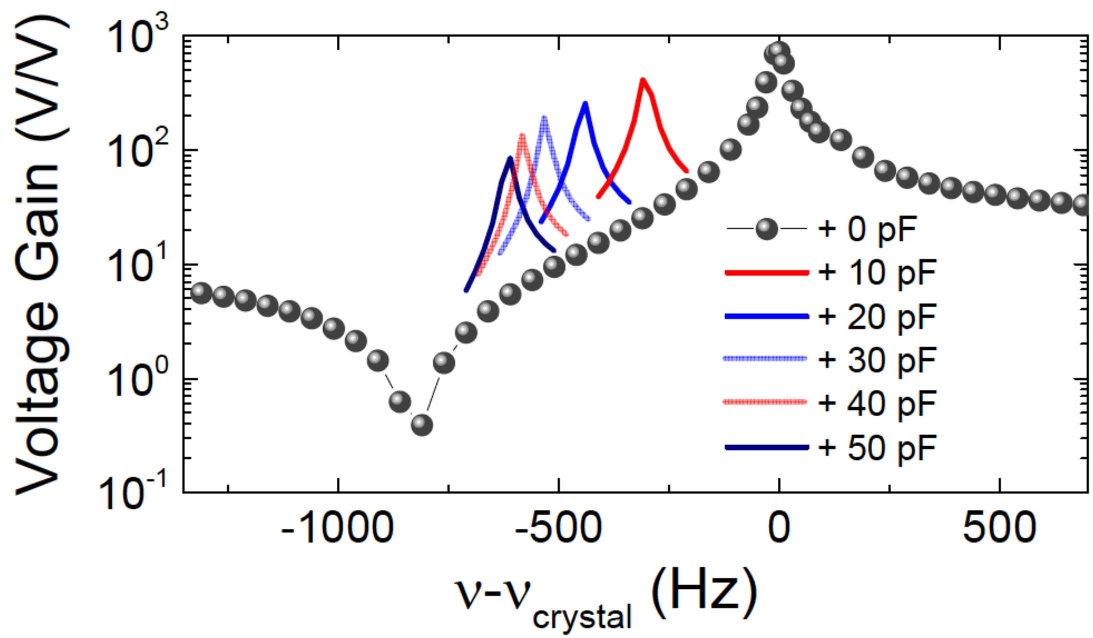
Results

Quartz amplifiers (UGR - Seven Solutions - JGU/HIM)









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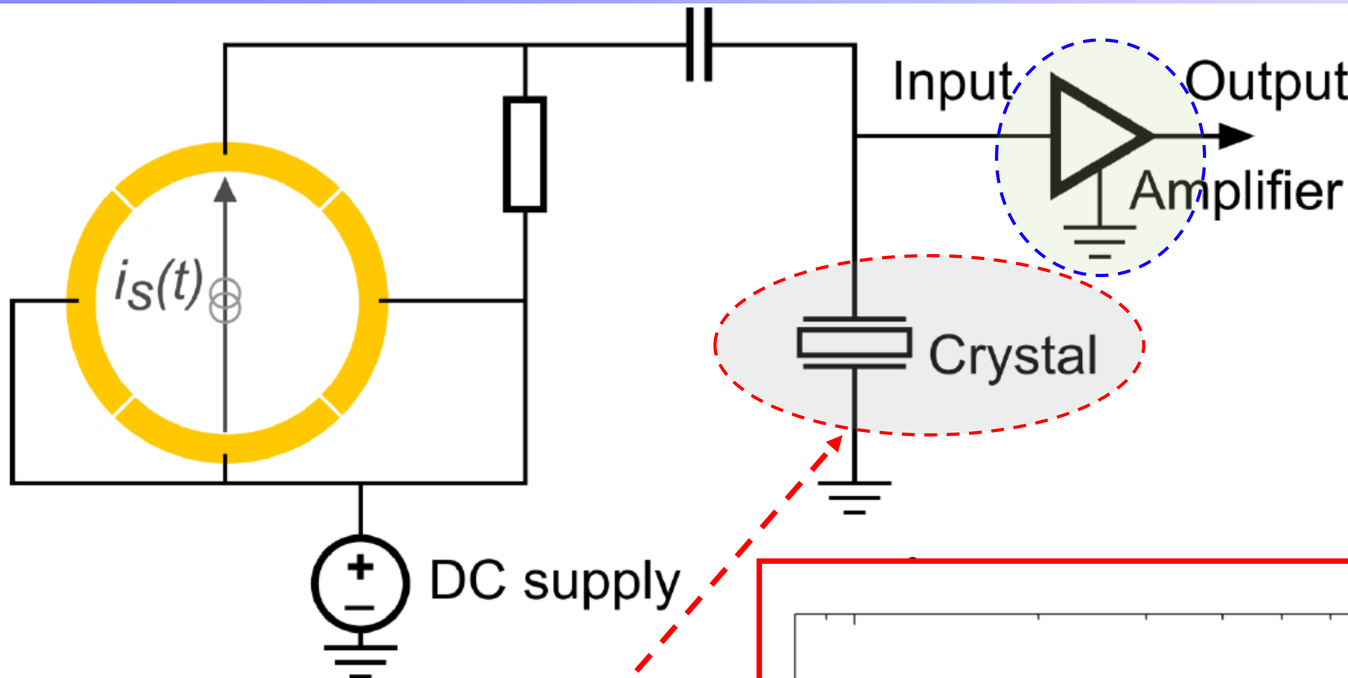

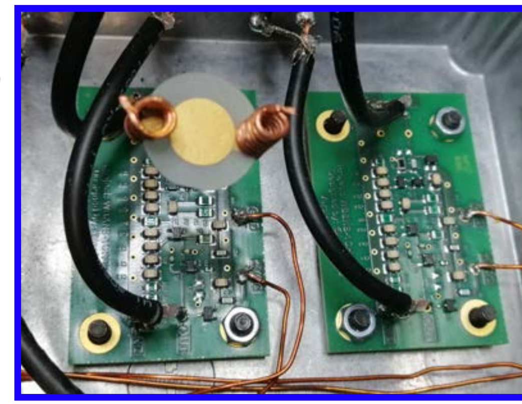

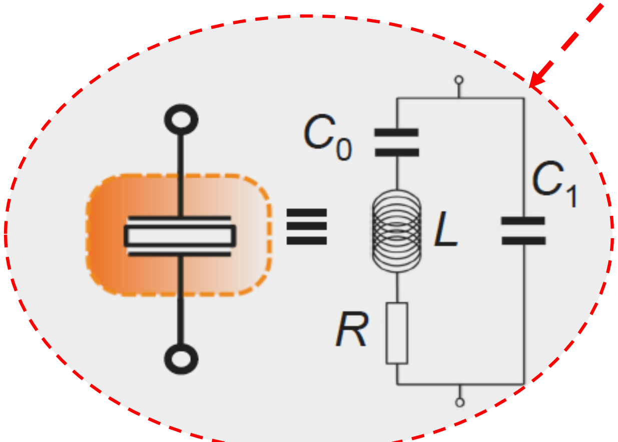

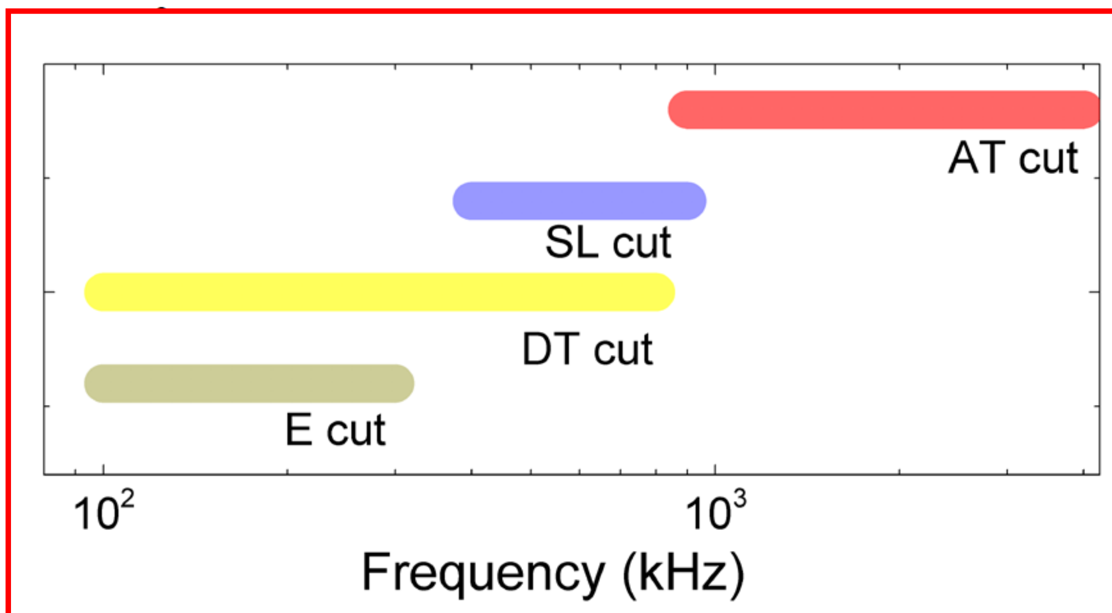

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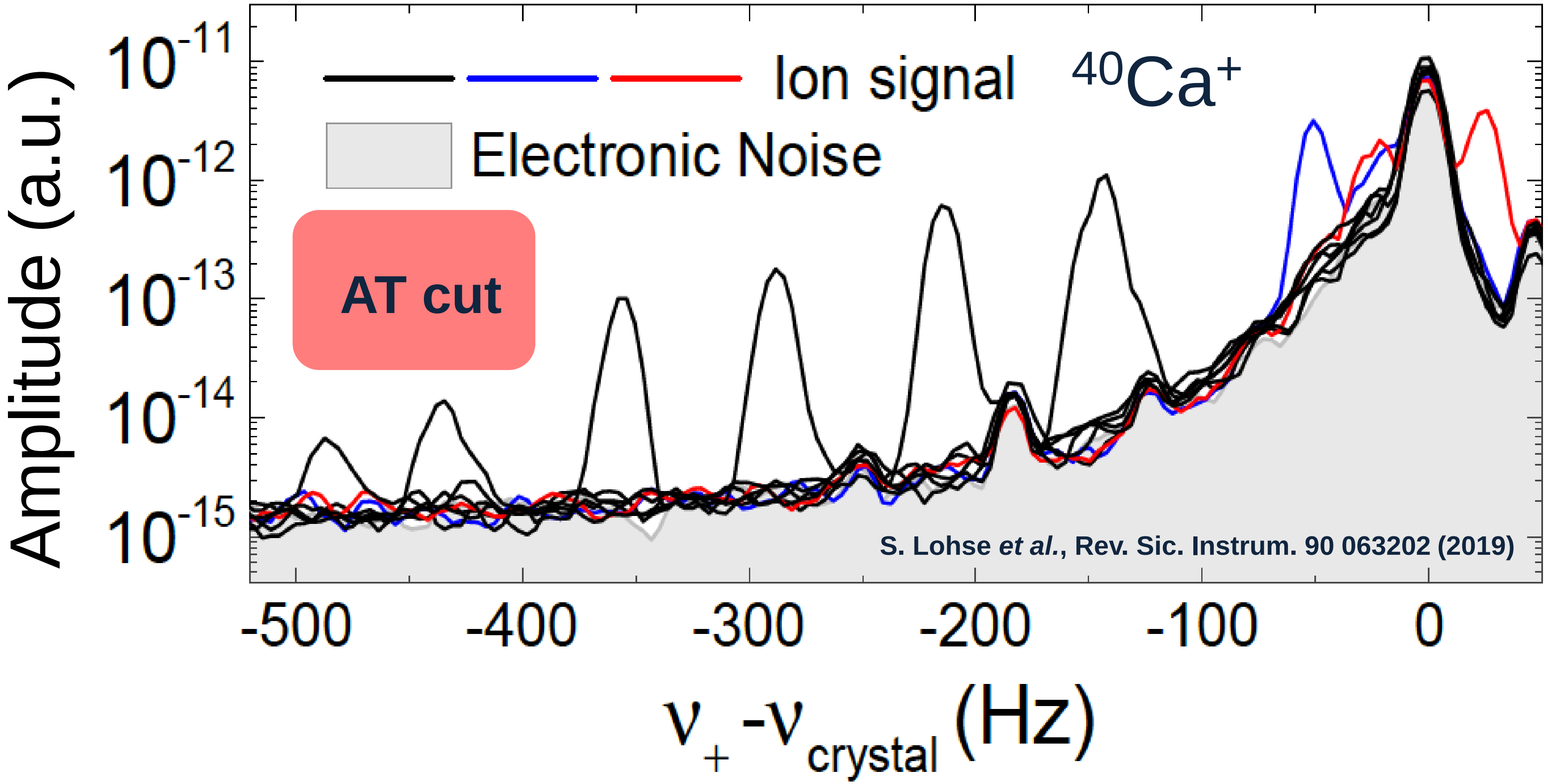
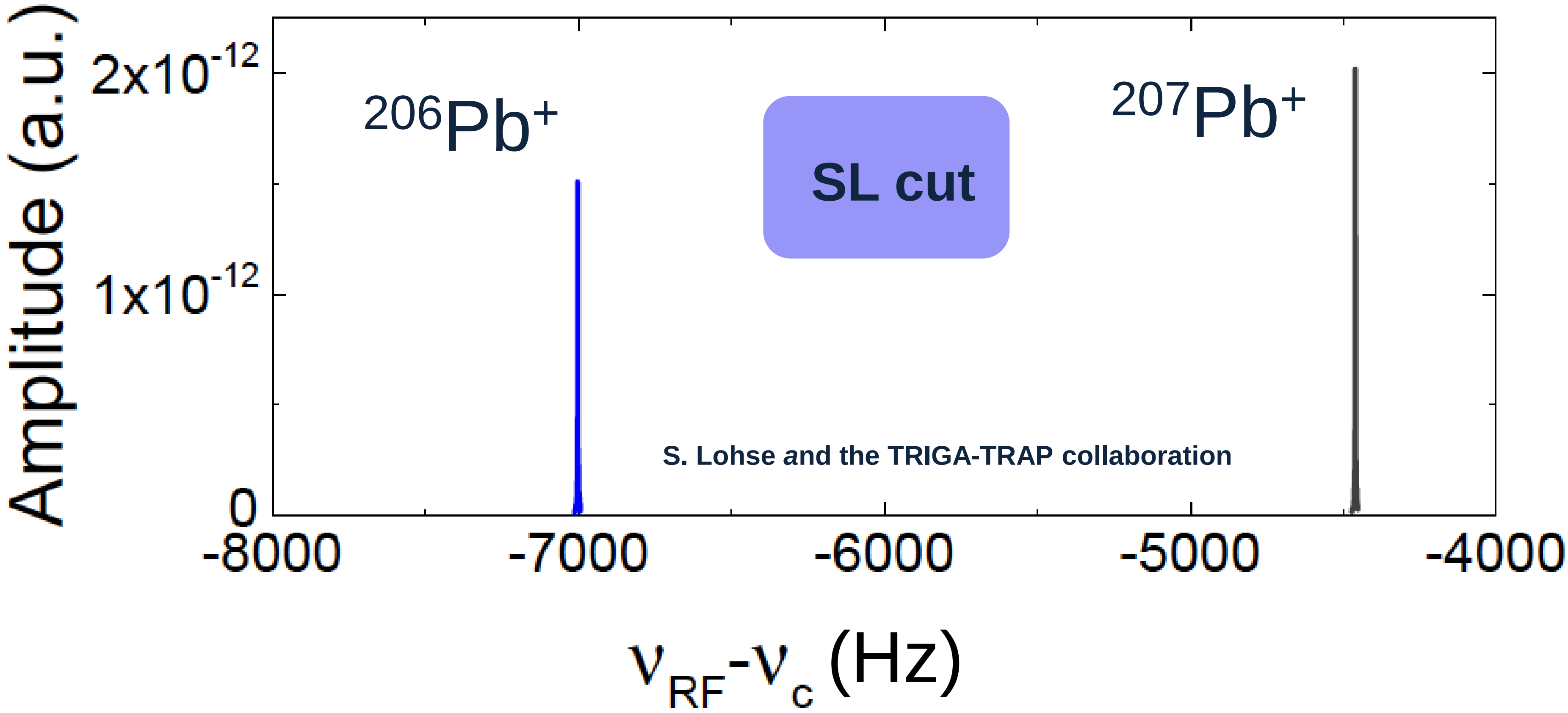


Sensitivity: 30 - 40 ions at 300 K

Results

Quartz amplifiers (UGR - Seven Solutions - JGU/HIM)



ν_+ ($^{206,207}Pb^+$) ~ 518105 Hz

ν_z ($^{206}Pb^+$) ~ 85 kHz

Sensitivity: ~ 20 ions at 300 K

Single-ion optical detection

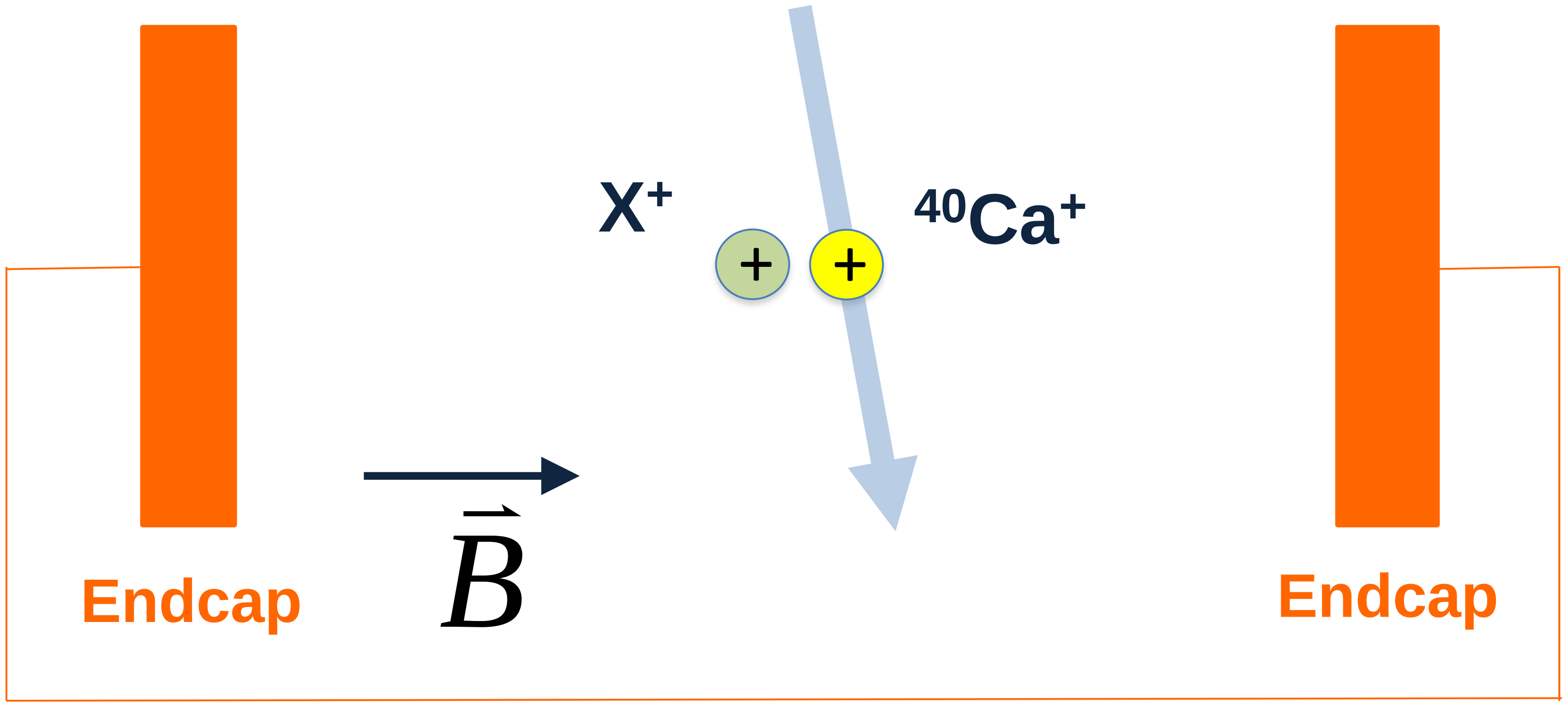
A two-ion crystal

- **Optical detection is non frequency dependent → Broadband**

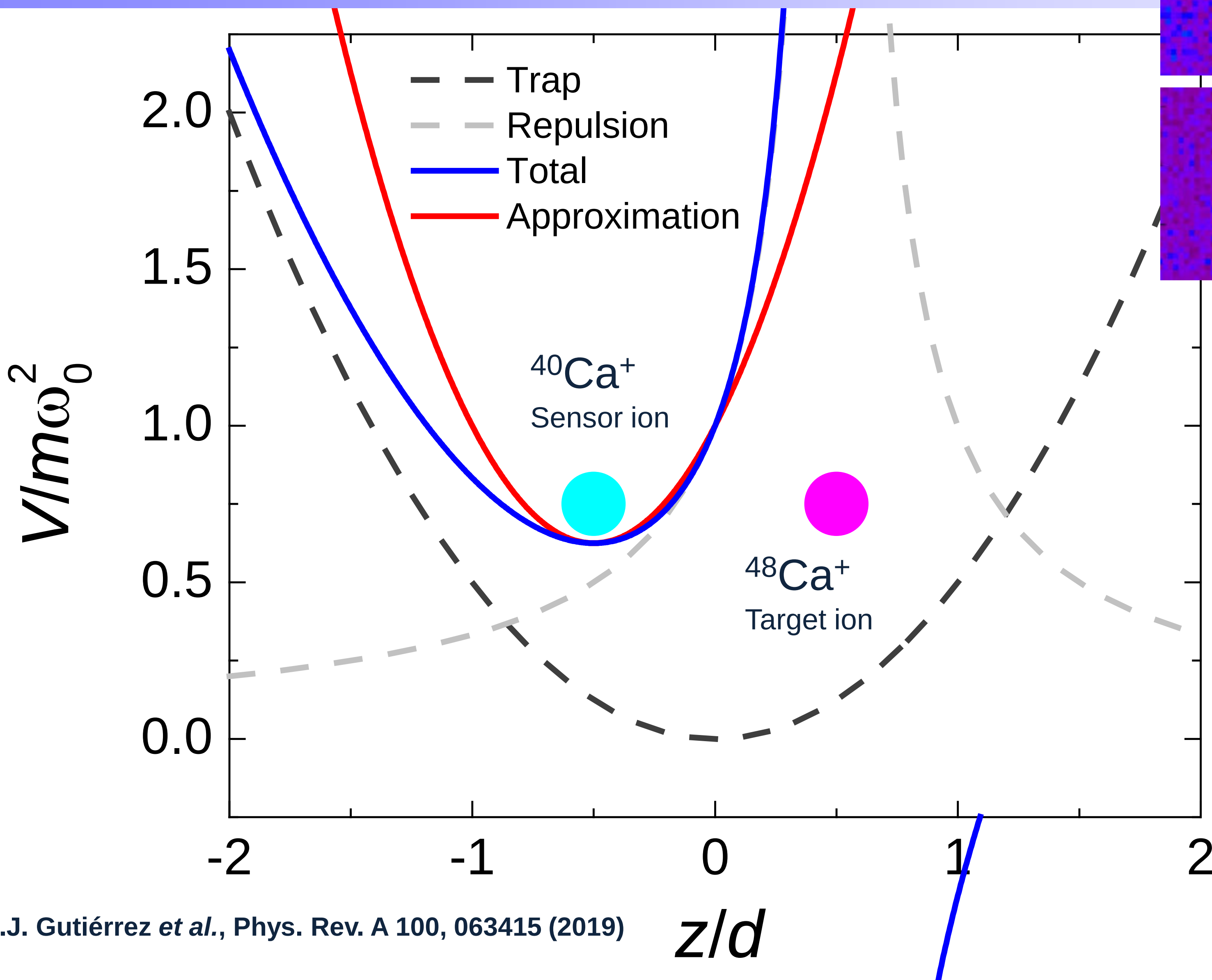
$$\sum_{i=1}^{6} \Omega_i = \omega_{ct}^2 + \omega_{cs}^2$$

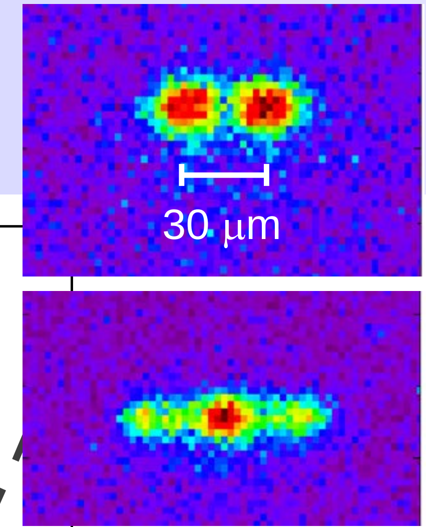
S. Jain et al., arXiv:1812.06755v2

- **Drawback:** Short distance between the ions → large frequency shifts → Quantum regime.



Single-ion optical detection
A two-ion crystal





M.J. Gutiérrez *et al.*, Phys. Rev. A 100, 063415 (2019)

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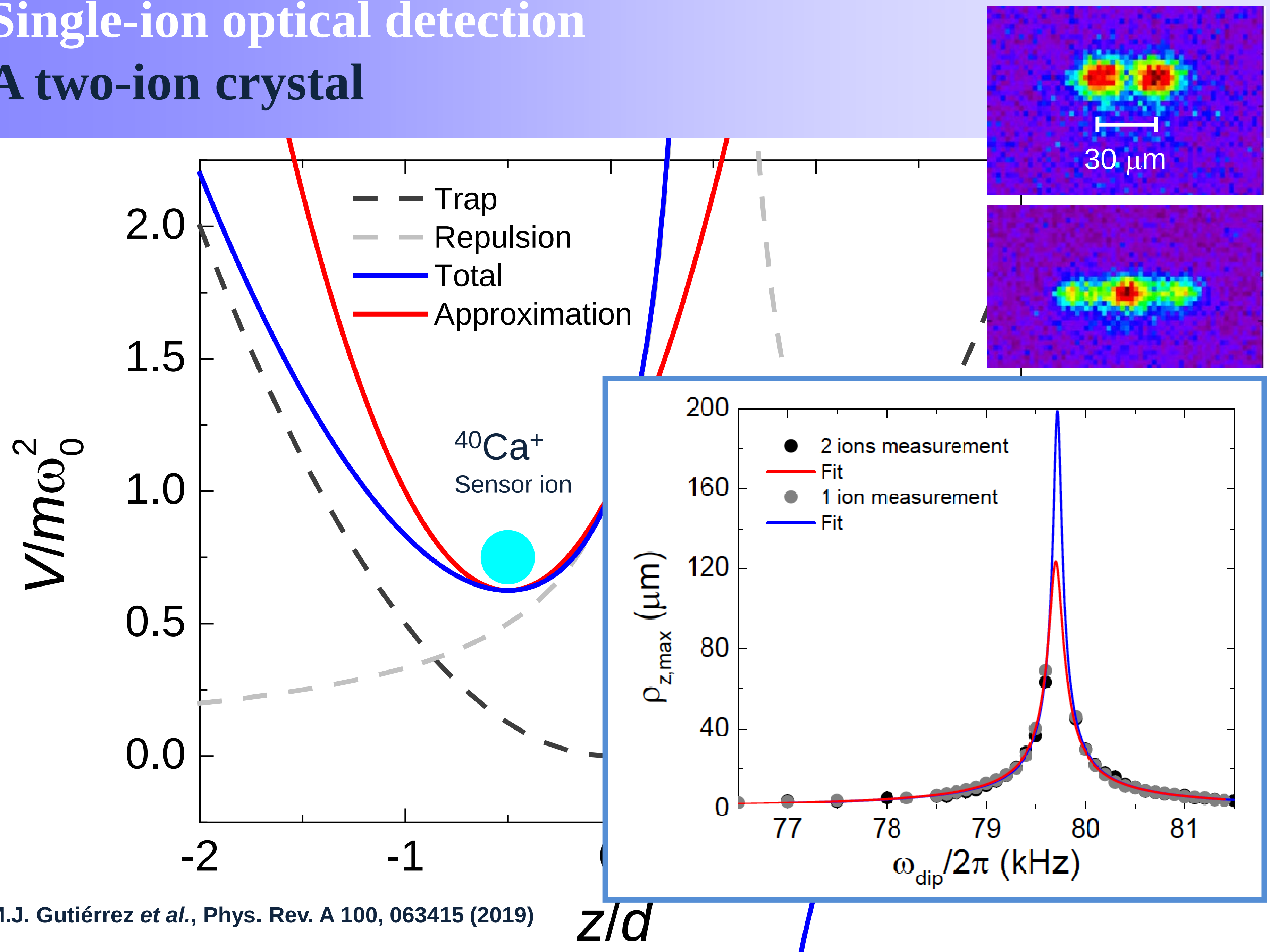
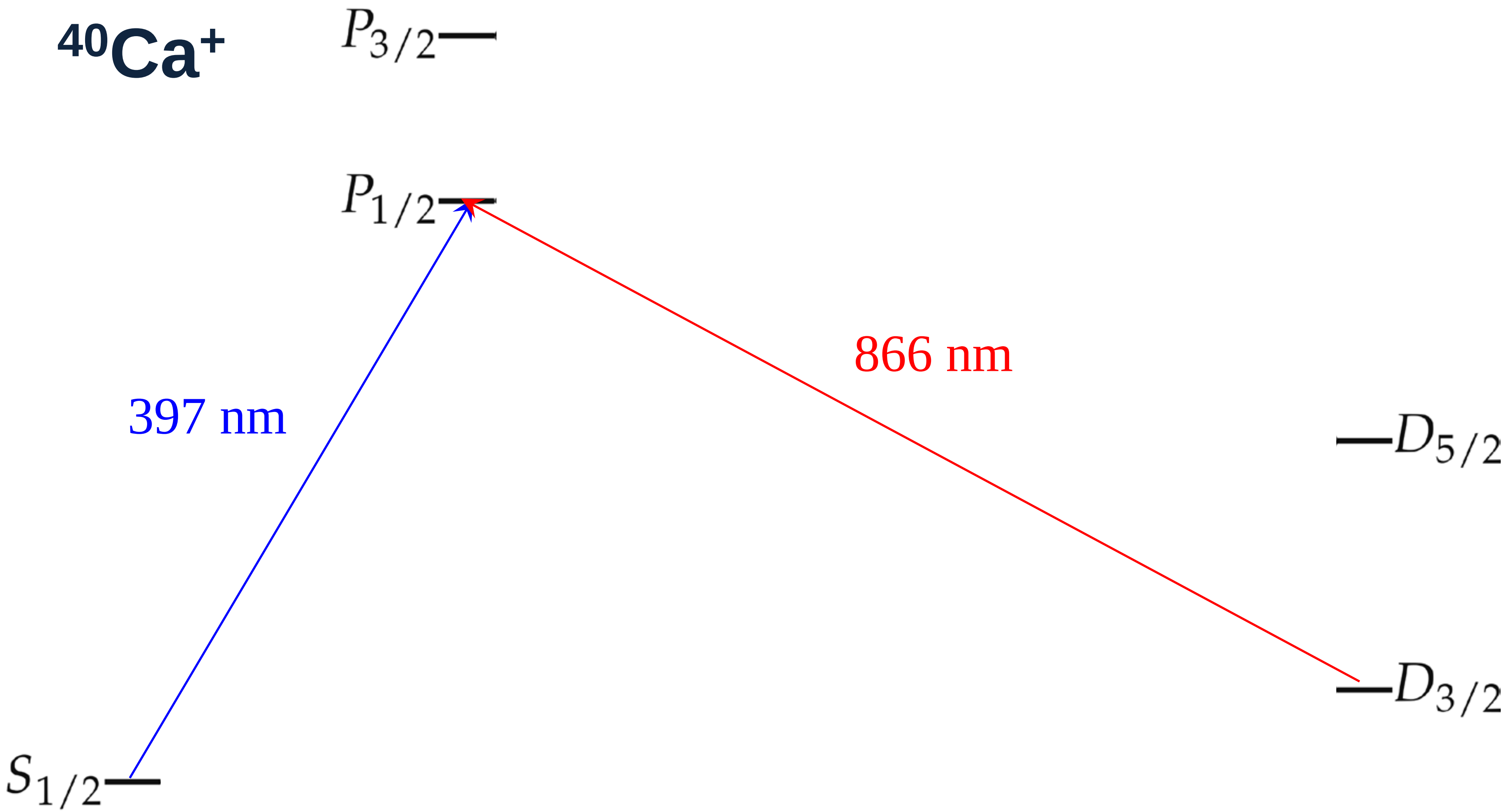


M.J. Gutiérrez *et al.*, Phys. Rev. A 100, 063415 (2019)

Experimental setup
Lasers

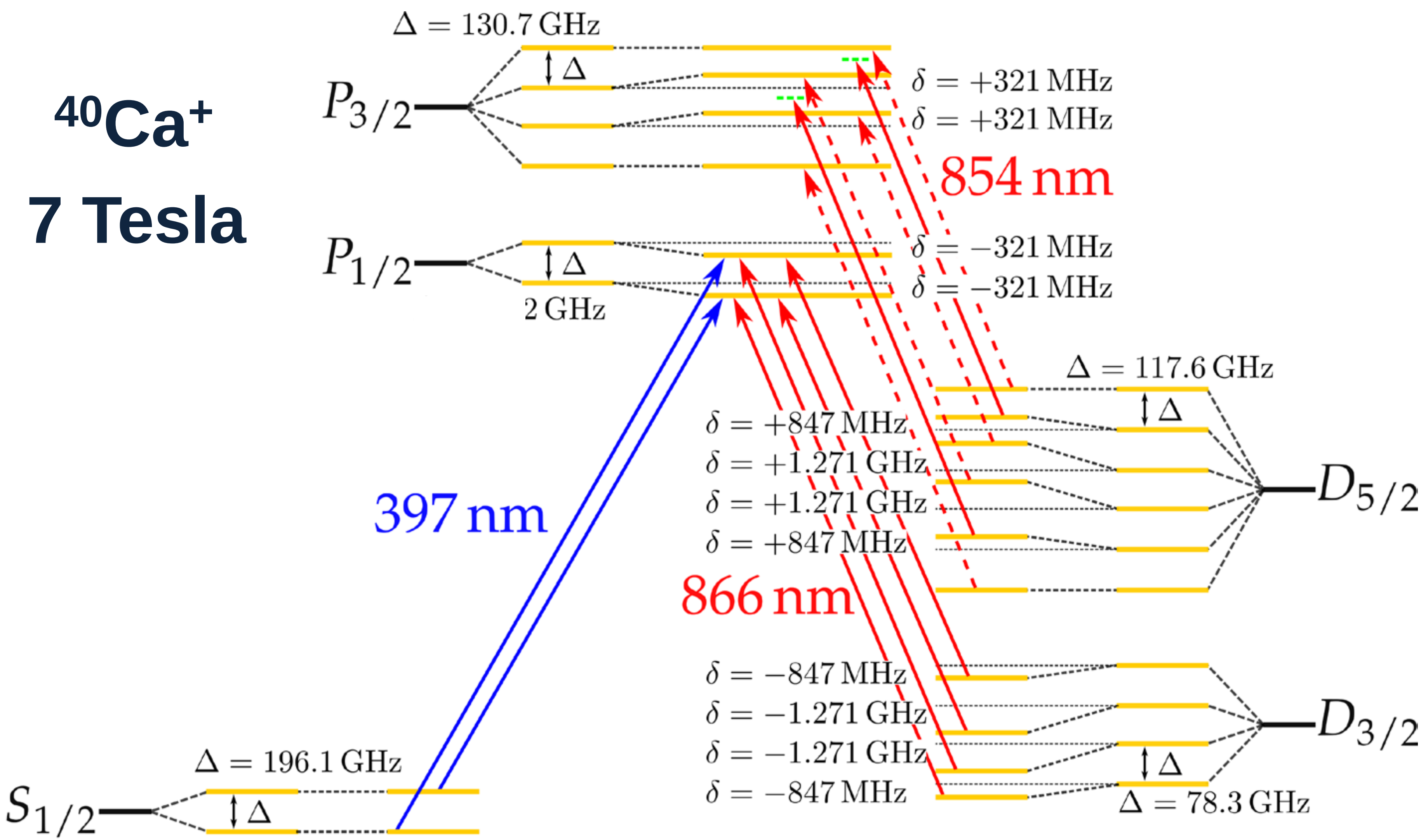


Experimental setup

Lasers

$^{40}Ca^{+}$

7 Tesla



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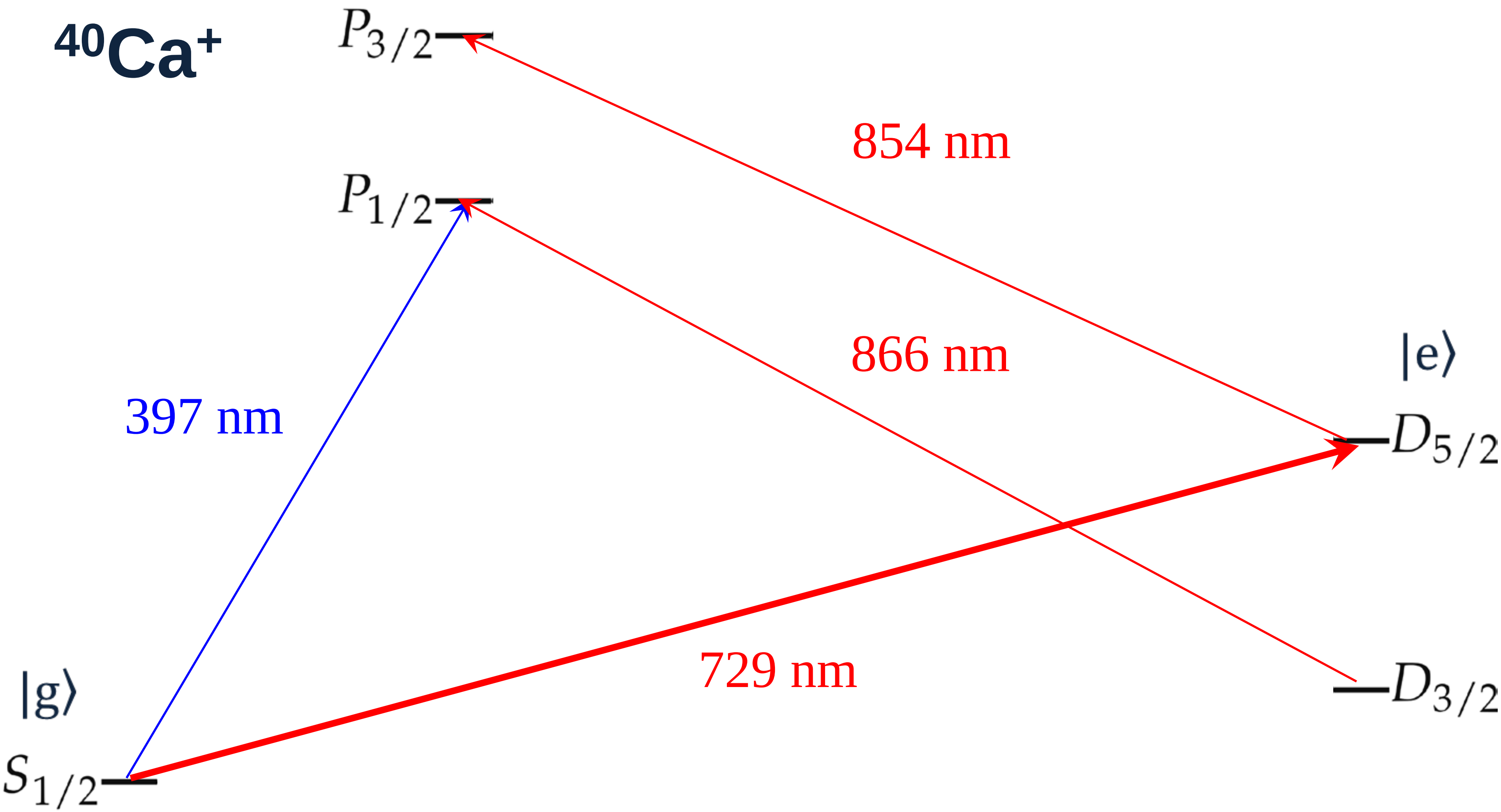

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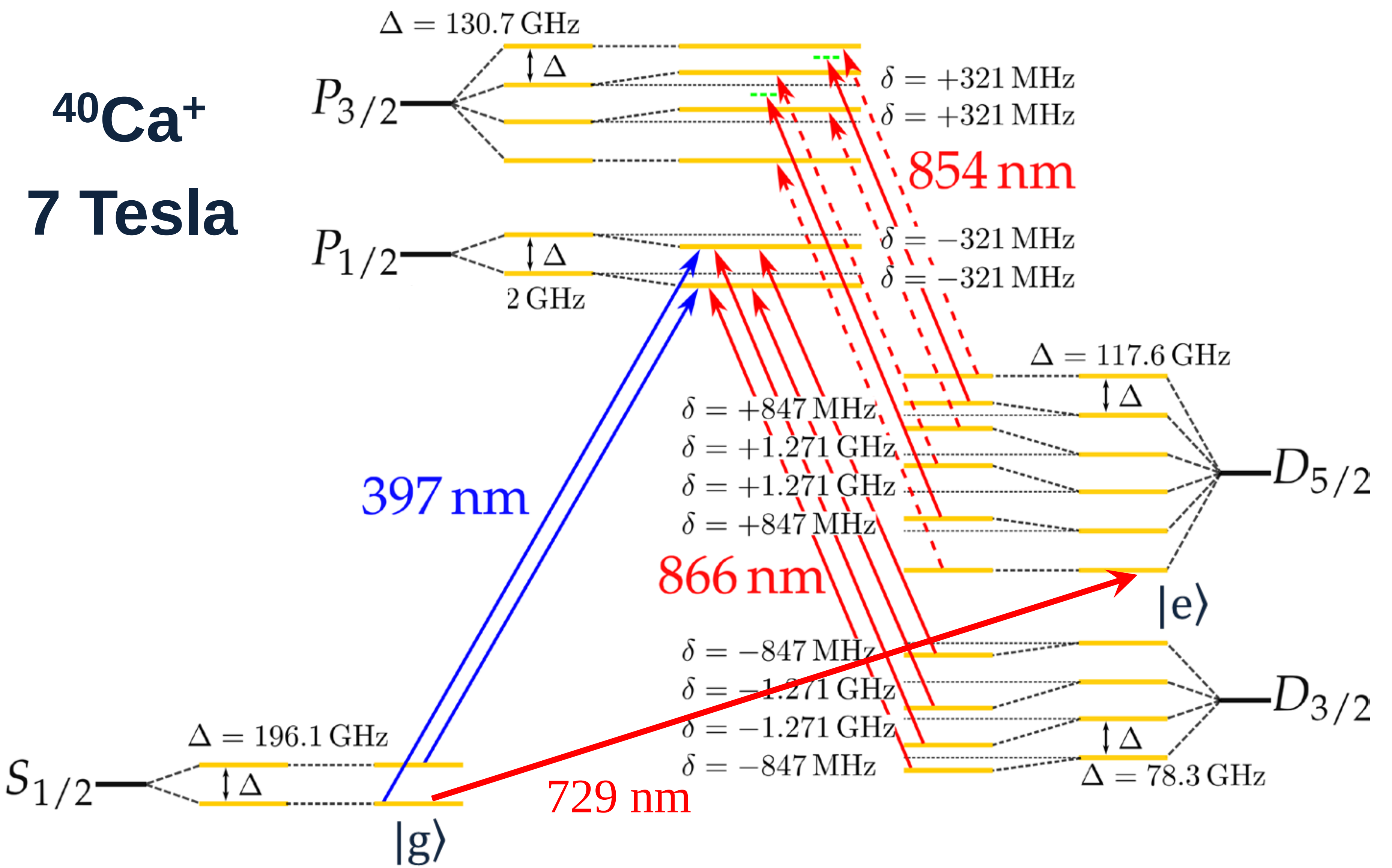

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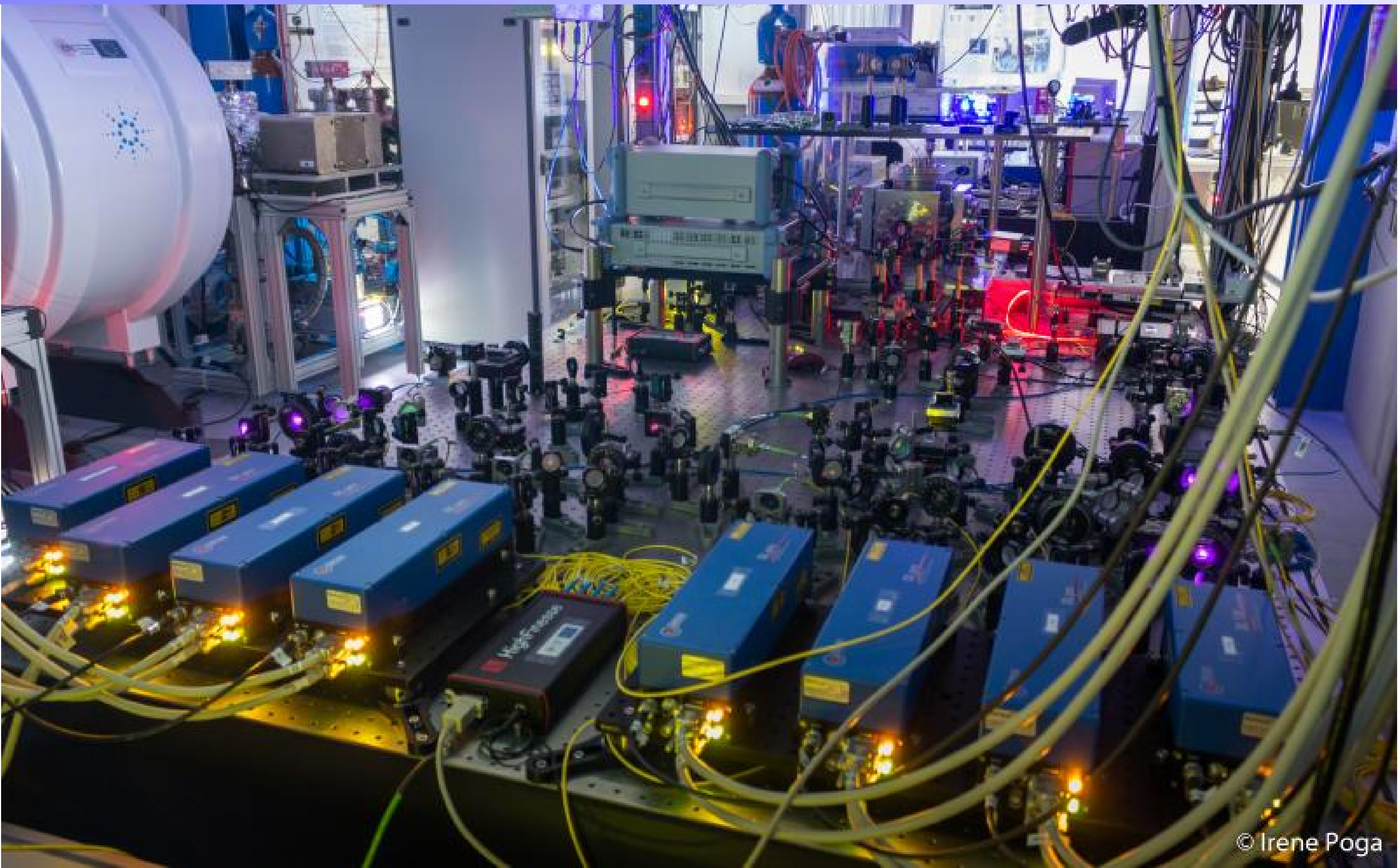
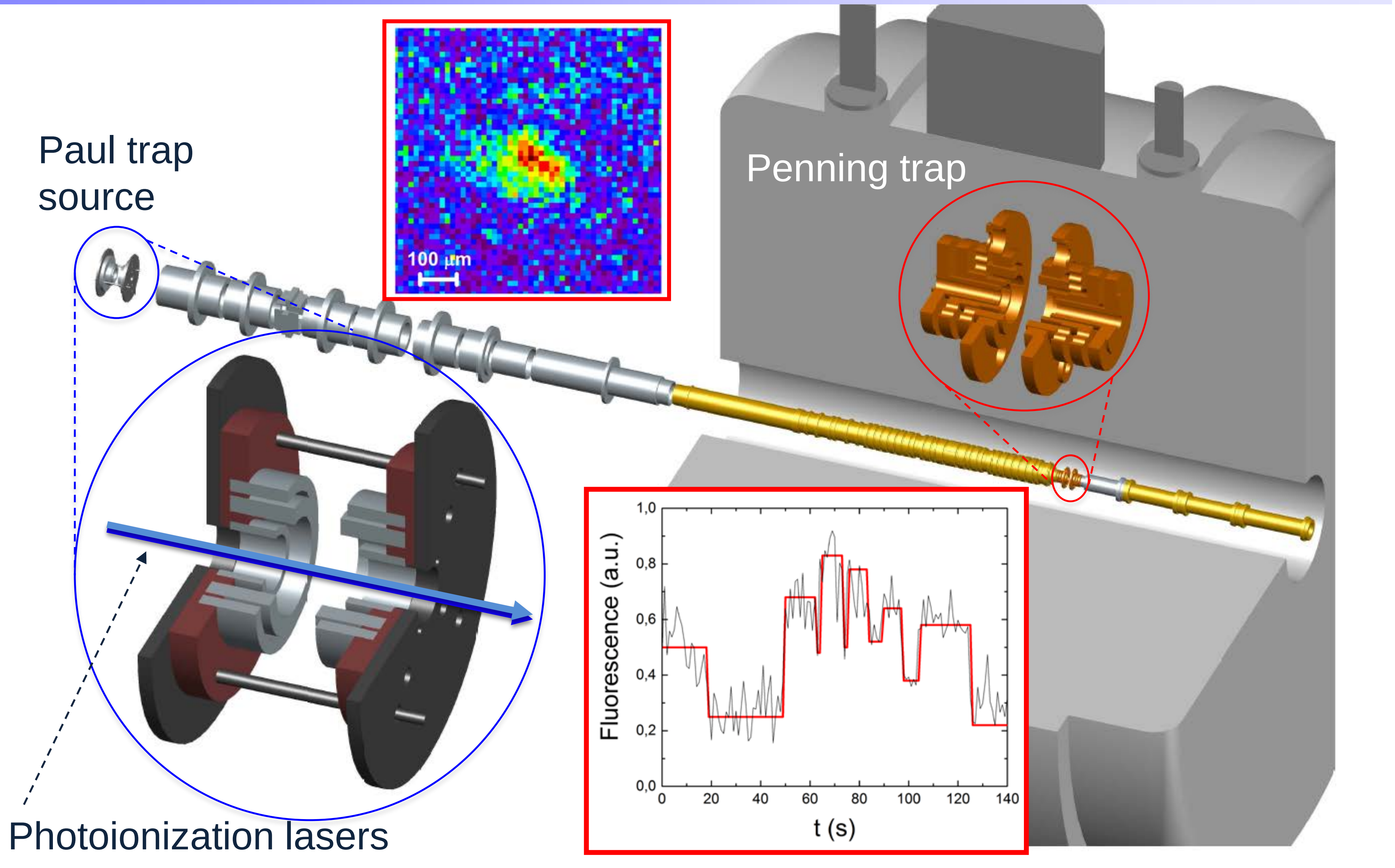
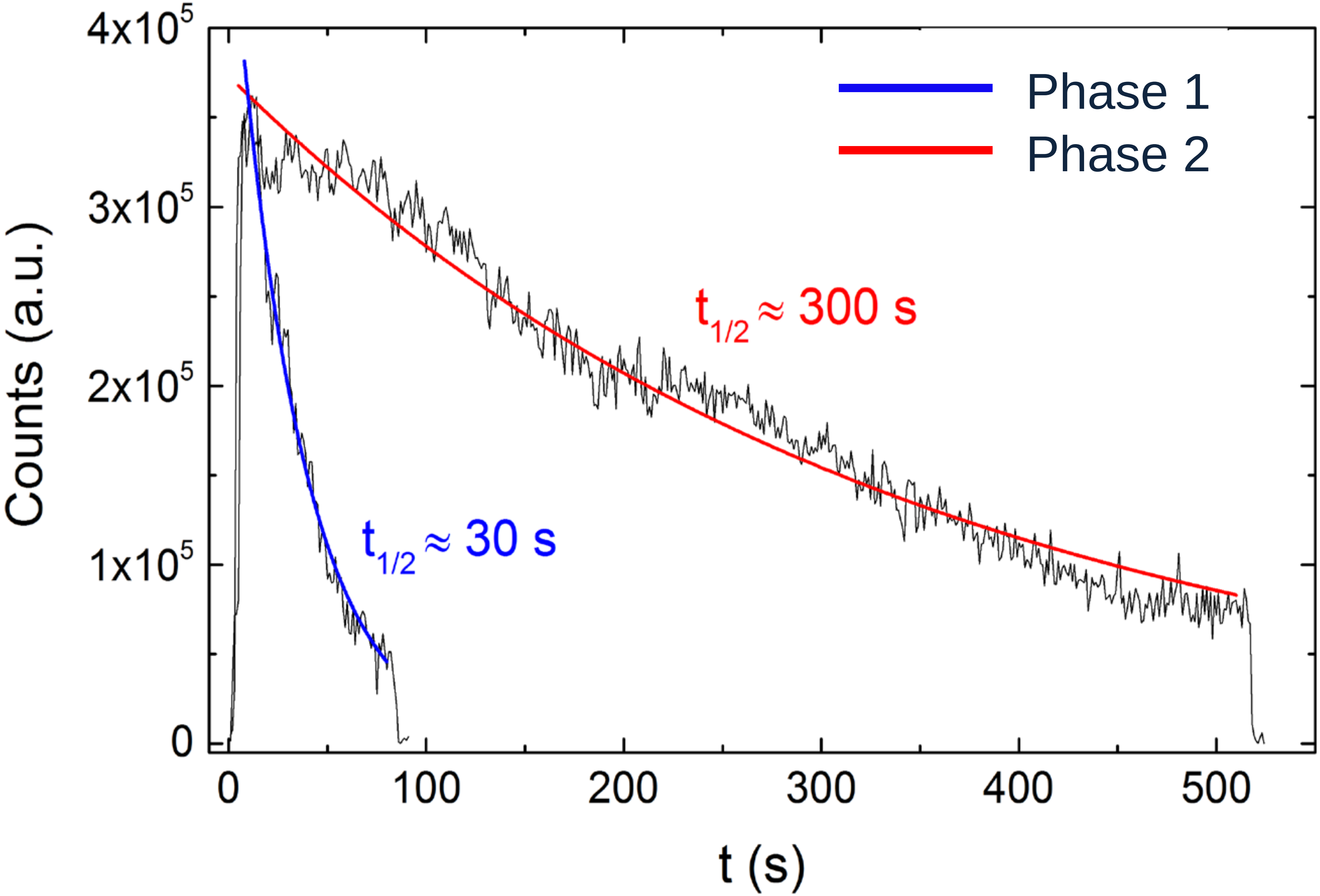


Results
Doppler cooling (phase 1)



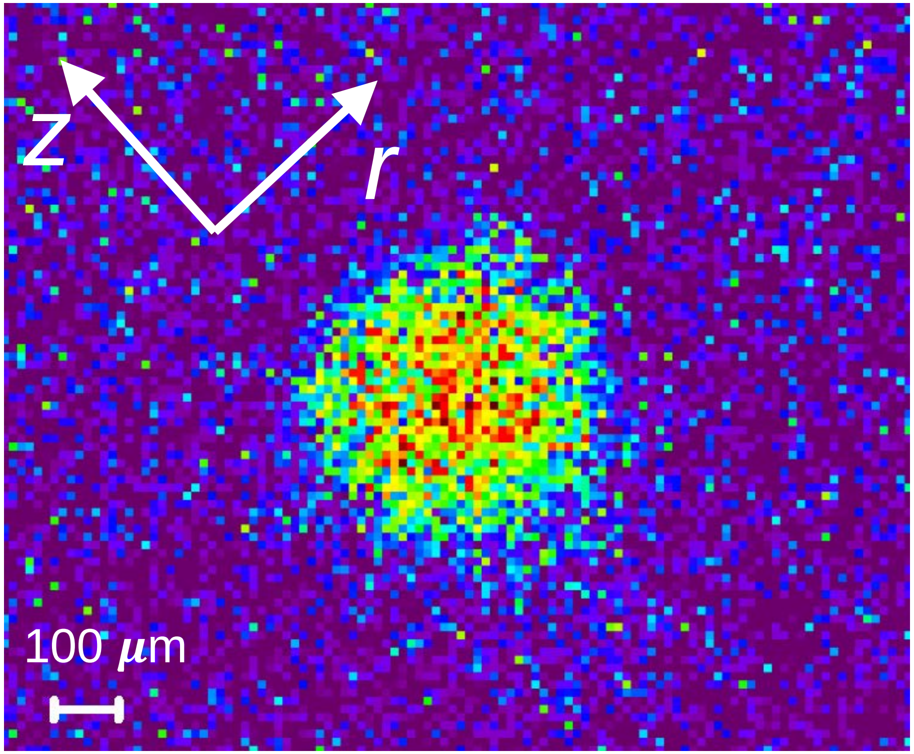
Results
Storage time



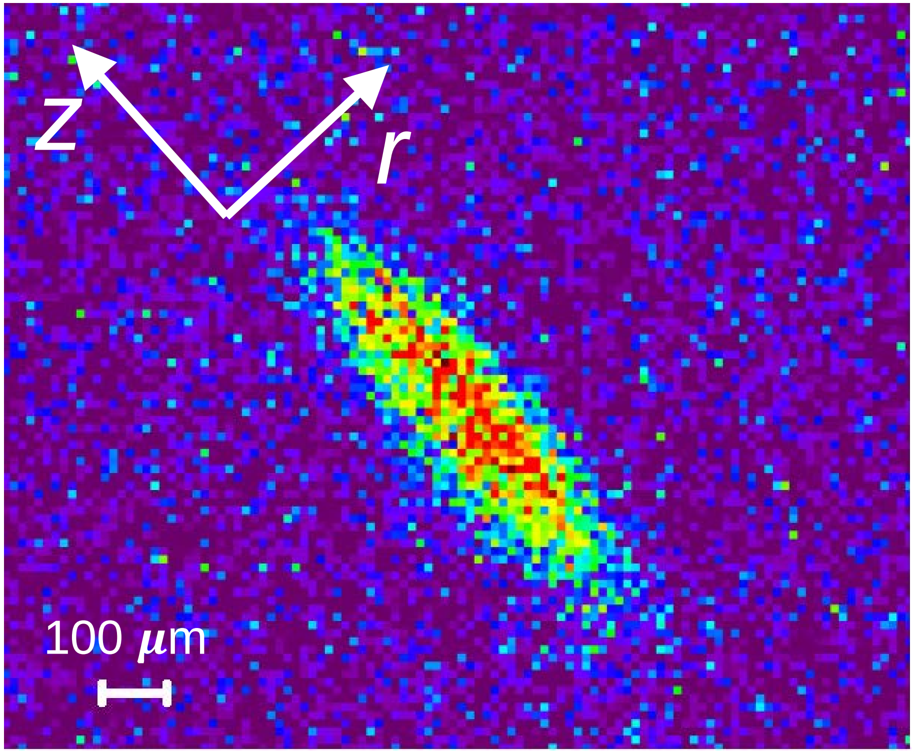
Results
Centering/Axialization (phase 2)

- The magnetron motion is unstable.
- Conversion of magnetron motion (unstable) into reduced-cyclotron (stable) by applying an external RF field with frequency $\nu_c \rightarrow$ radial cooling.

RF OFF

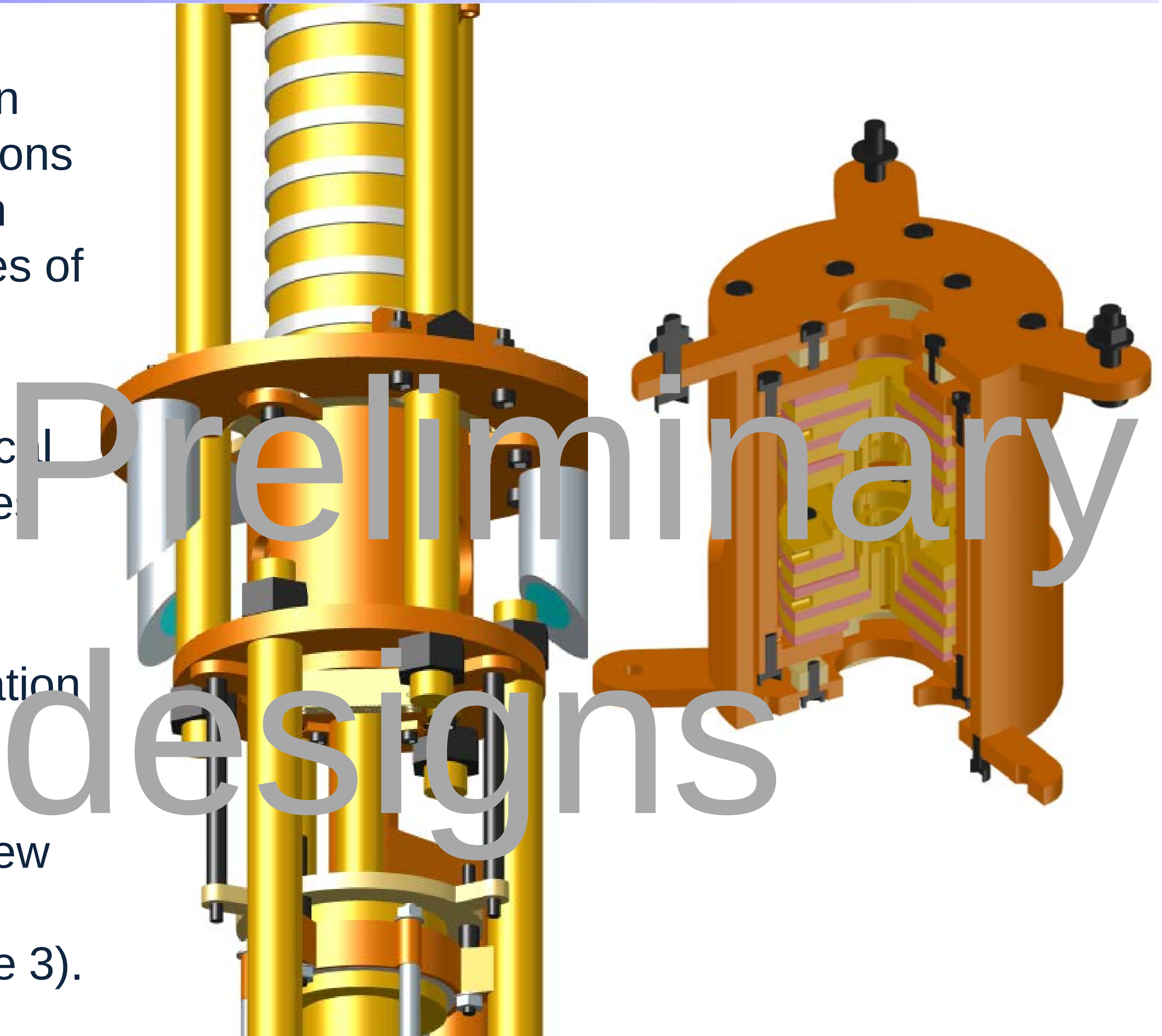


RF ON



Conclusions and perspectives

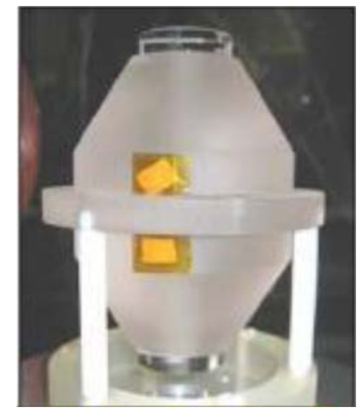
- Single-ion detection will be needed for ions with low production yields (and half-lives of about/above one second).
- Electronic and optical detection techniques are under development.
- For both, the operation at cryogenic temperature is necessary and a new system is under construction (phase 3).

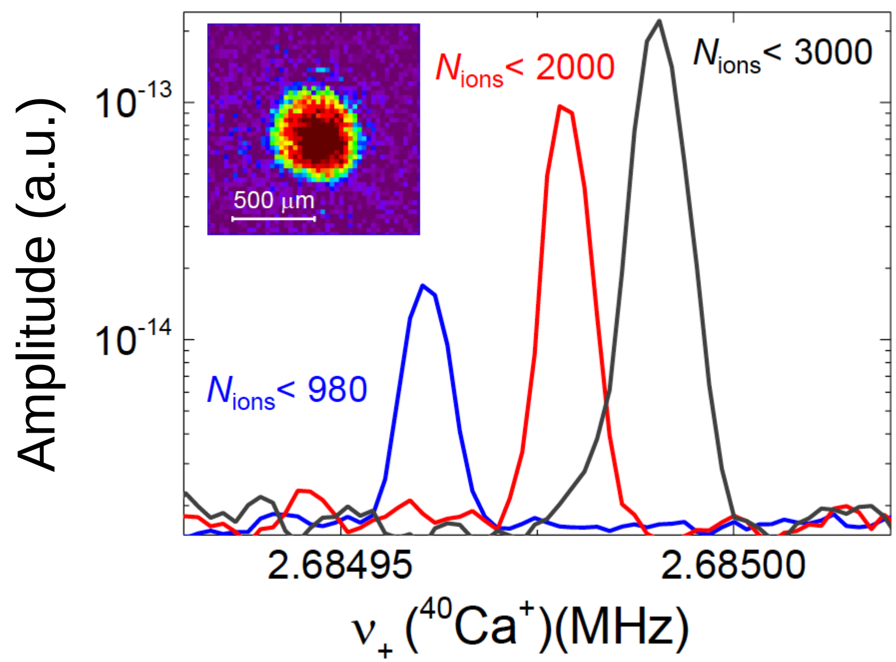


Conclusions and perspectives

- Optical detection needs to reach the quantum regime (Quantum Mass Spectrometry) and for that, we need to drive the clock transition in $^{40}Ca^{+}$ (729 nm). System will be delivered by mid 2020.
- In general we can also combine both detection schemes and/or use the optical method for atomic spectroscopy using the photons from the laser-cooled $^{40}Ca^{+}$ ion as detector.

+





Thank you very much for your attention

Group at the University of Granada

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Jaime Doménech
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Berta Molina
Ernesto Ruiz
Carlos Vivo

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MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

UNIÓN EUROPEA
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CPAN
Ingenio 2010

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ugr Universidad de Granada

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Steffen Lohse
Oliver Kaleja
F. Giacoppo
Michael Block
SHIPTRAP and TRIGA-TRAP collaborations

SEVEN SOLUTIONS S.L.

J. Gabriel Ramírez

IKERBASQUE

Íñigo Arrazola
Enrique Solano

UGR

Ana Carrasco Sanz
Francisco Javier Fernández