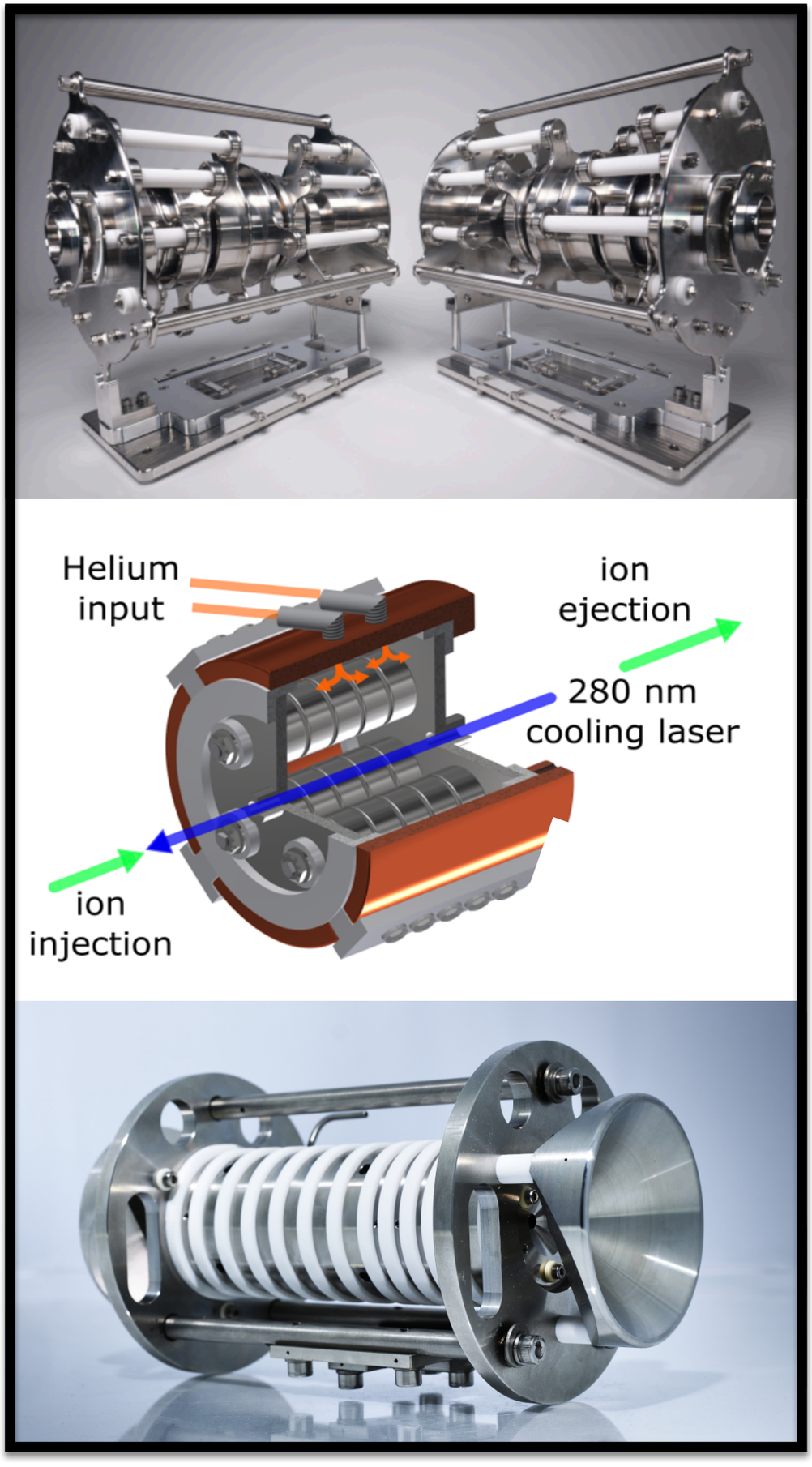
Doppler and sympathetic cooling for the investigation of short-lived radionuclides

Stephan Malbrunot-Ettenauer
TRIUMF, University of Toronto

EMIS XX, 2025



Discovery, accelerated

Laboratory temperature regimes

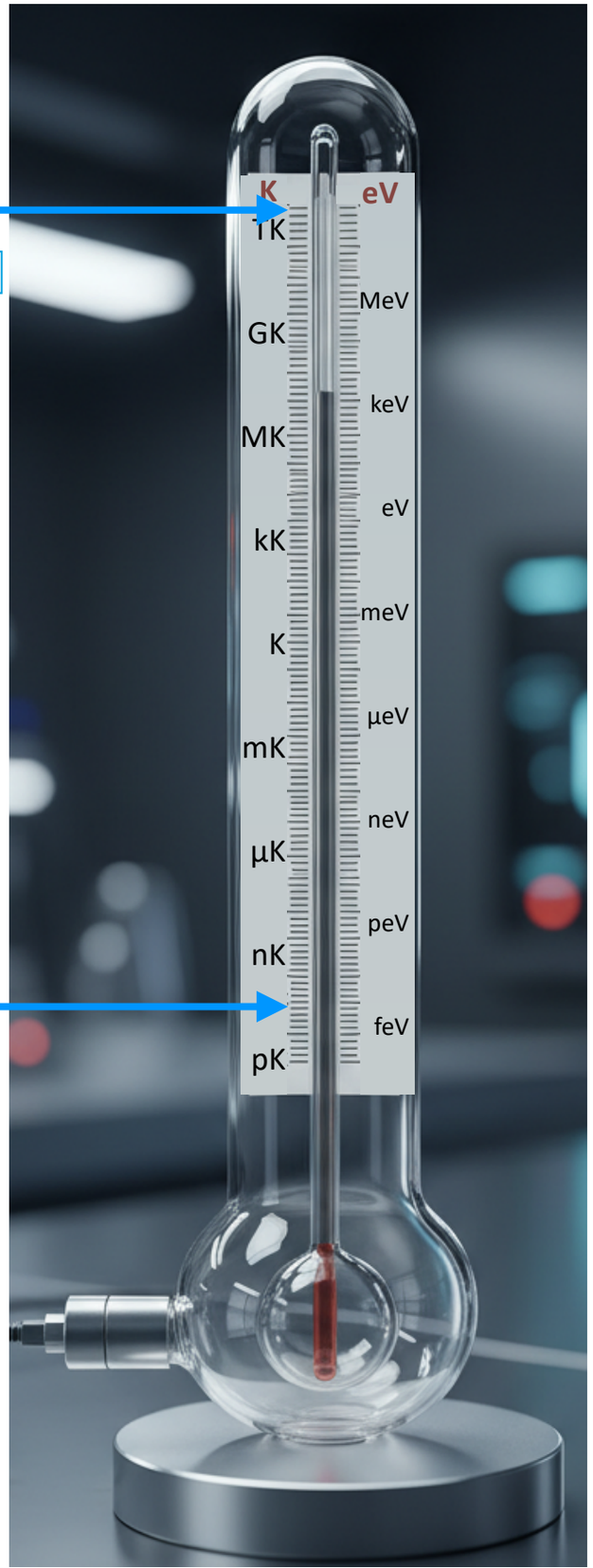
>5 trillion K

ALICE@LHC CERN (2012)

23 orders of magnitude

38 pK

C. Deppner Phys. Rev. Lett. 127, 100401 (2021)



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"Highest artificial temperature"

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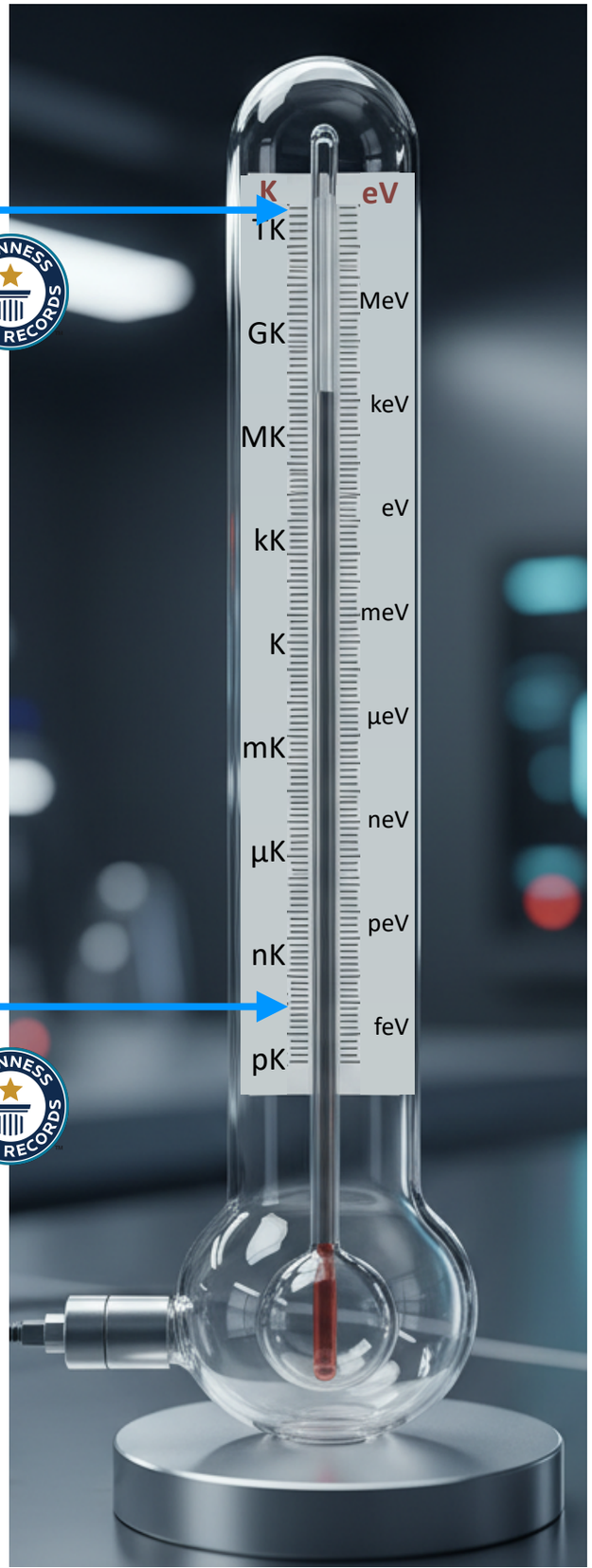

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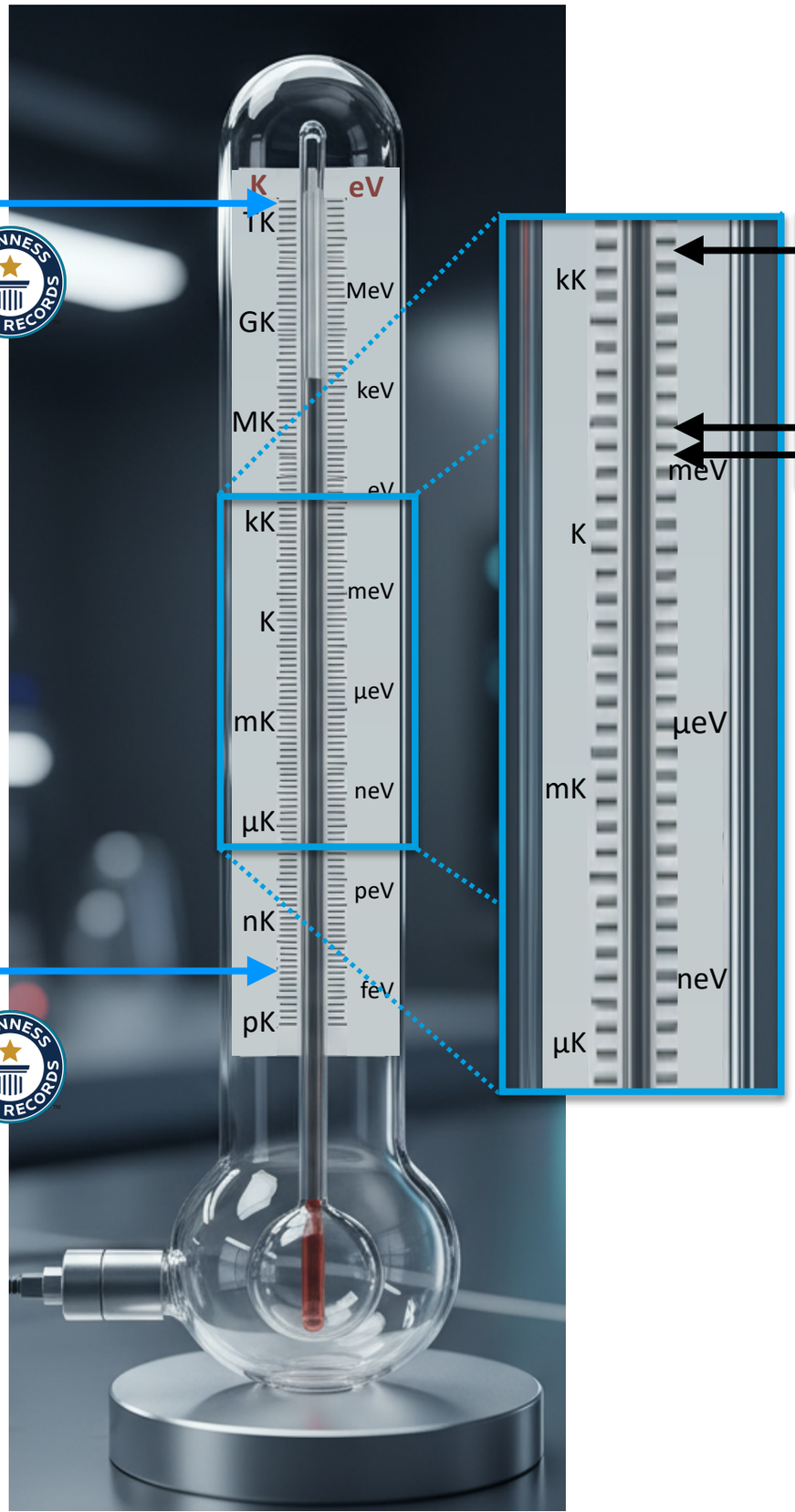

RIB facilities

≈2000 C ISOL target

room-temp } cooler-
LN2 } buncher

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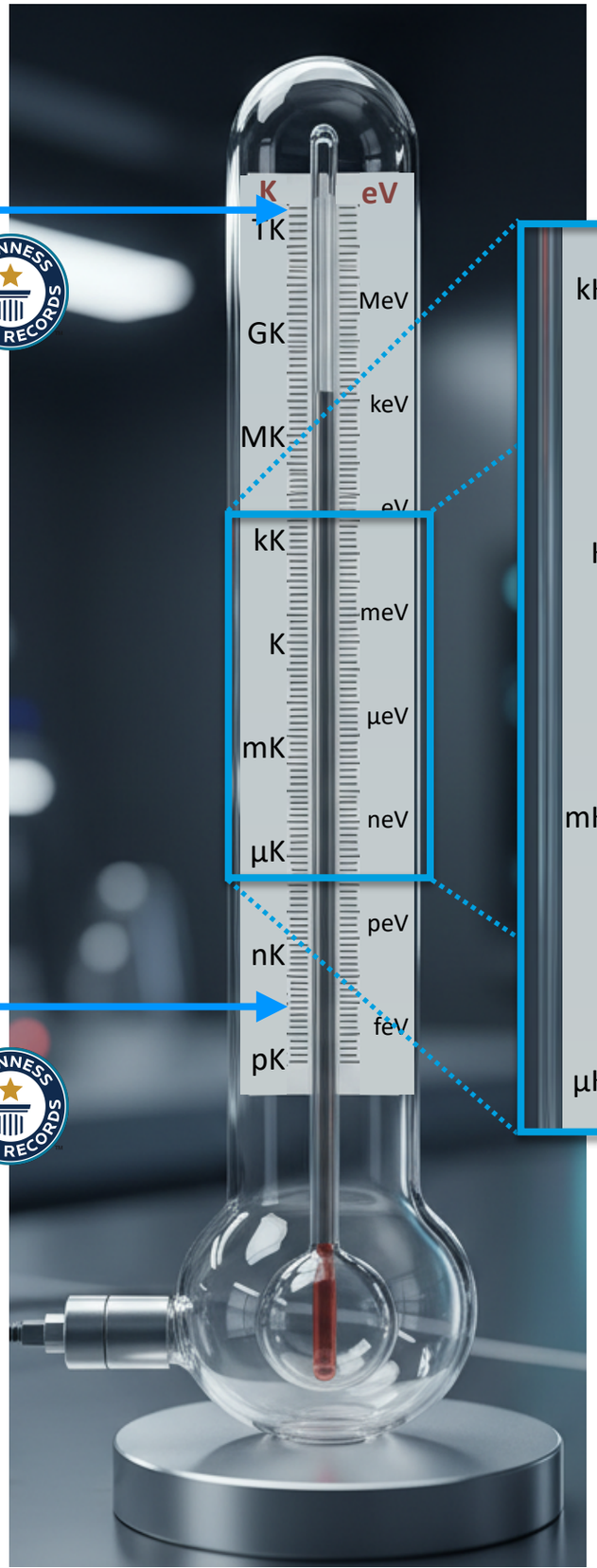

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Low Temperature
Nuclear Orientation

≈25 µK: ^{211}Fr in ODT

see talk by
L. Croquette

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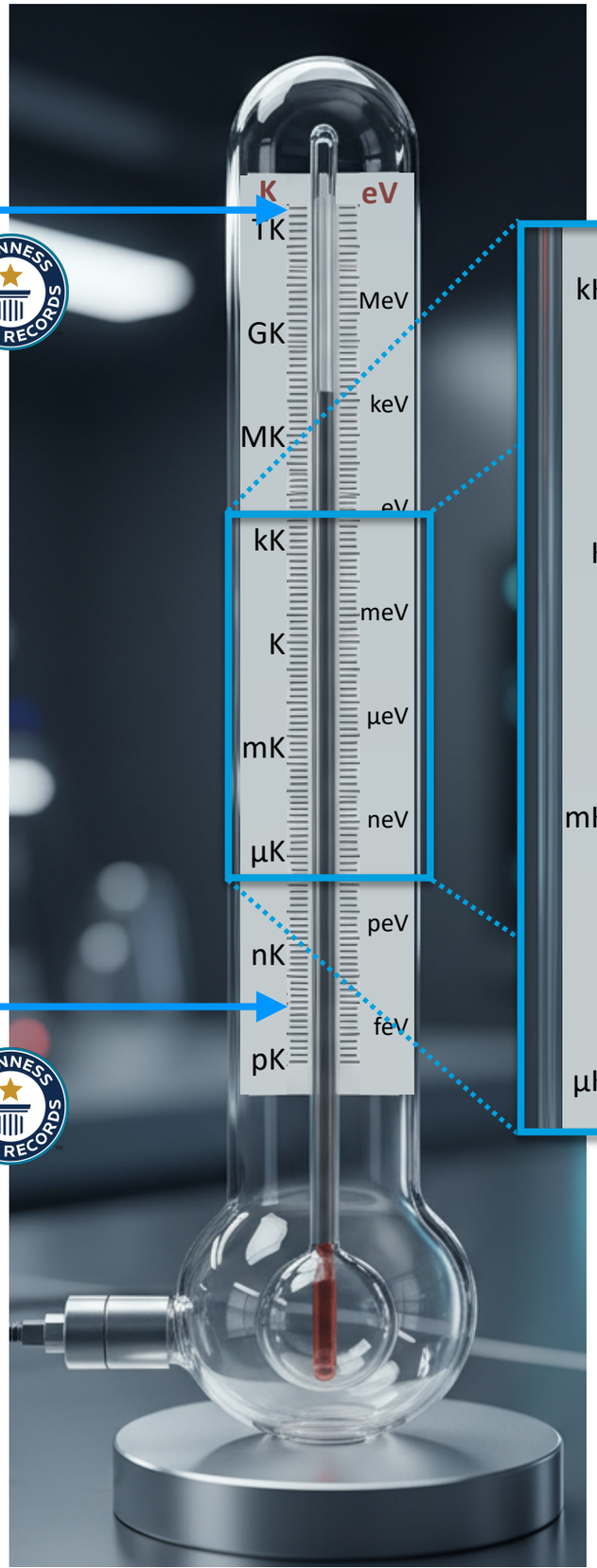

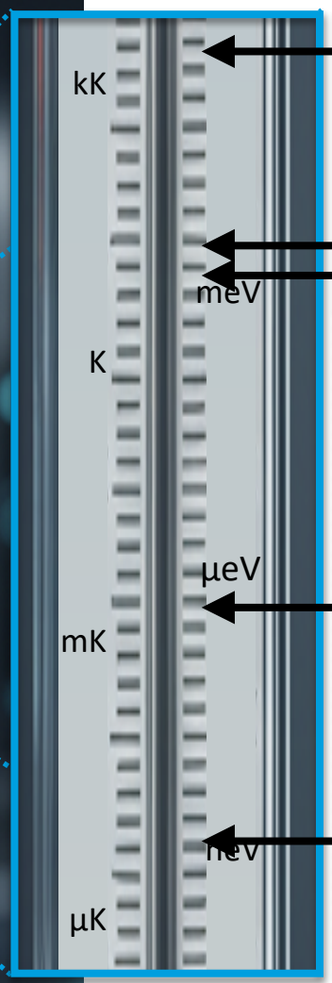

RIB facilities

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Low Temperature Nuclear Orientation

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see talk by L. Croquette

Opportunities

enhanced RIB exp.

EDM measurements

King plot-nonlinearities

higher-order moments

higher order radii

….

General theme:
higher precision ⇒
access to new phenomena & observables

Standard RIB buffer gas cooling

cooler - bunchers at RIB facilities, operated at 300 K buffer gas

Cooling limit: 300 K

$$(\Delta E\,\Delta t)_{95\%} \approx 2\pi \ln(20) k_B T \sqrt{\frac{m}{2qC_2}}$$

R. B. Moore et al., Phys. Scr. 1995, 93 (1995).
S. Schwarz et al., NIM A 816, 131 (2016).

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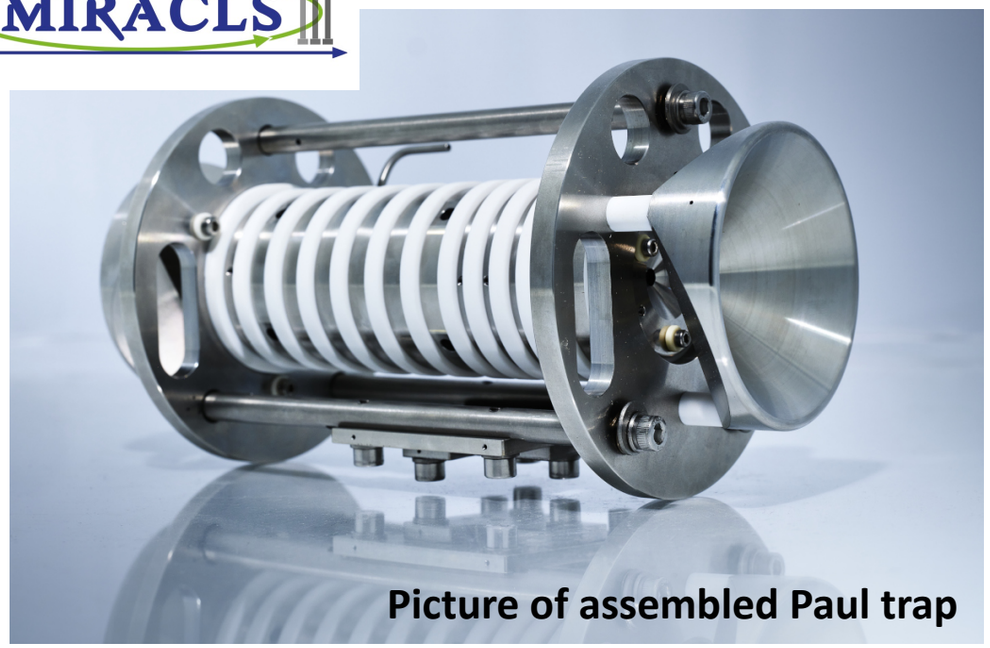

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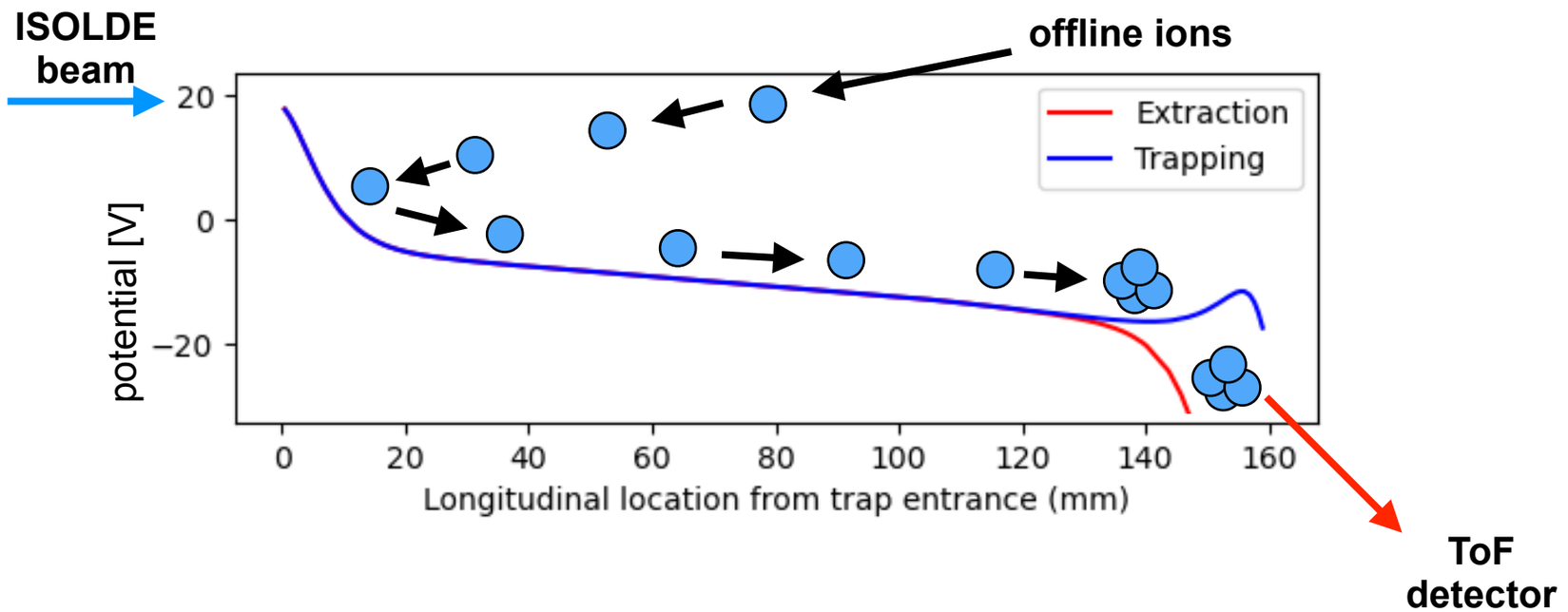

C. Kanitz, L. Croquette et al., in preparation

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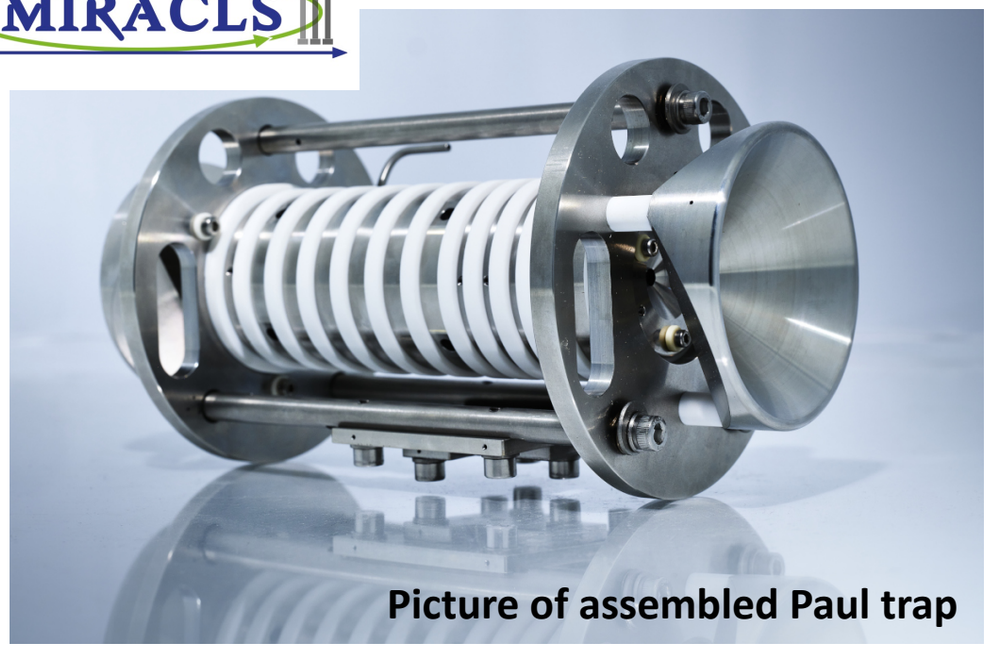
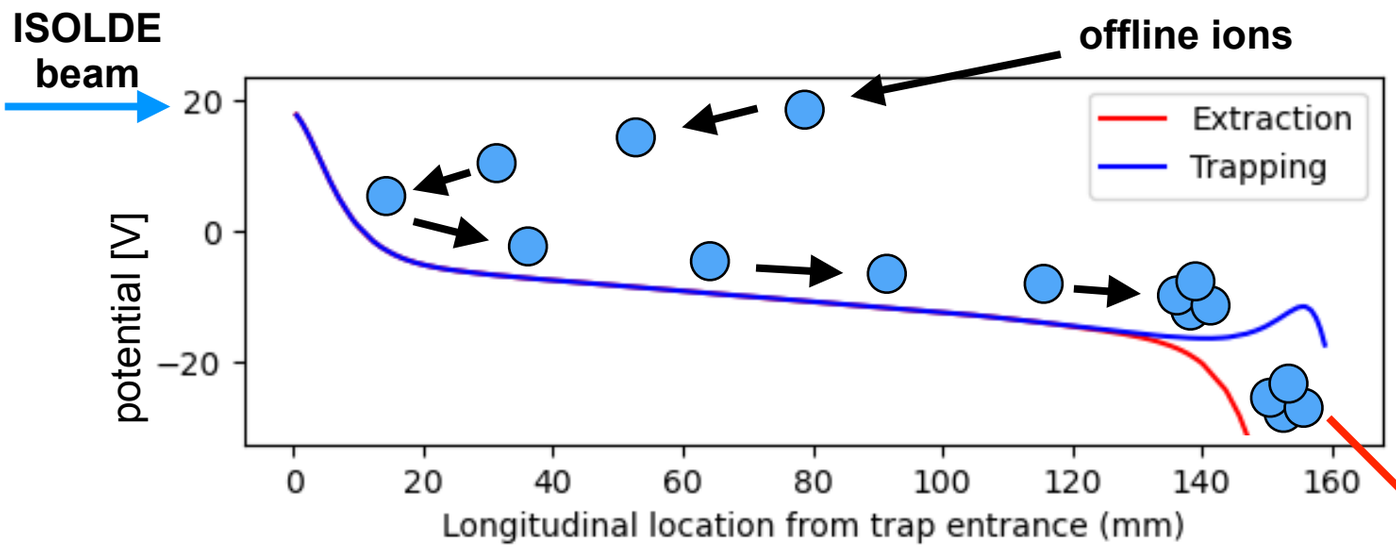
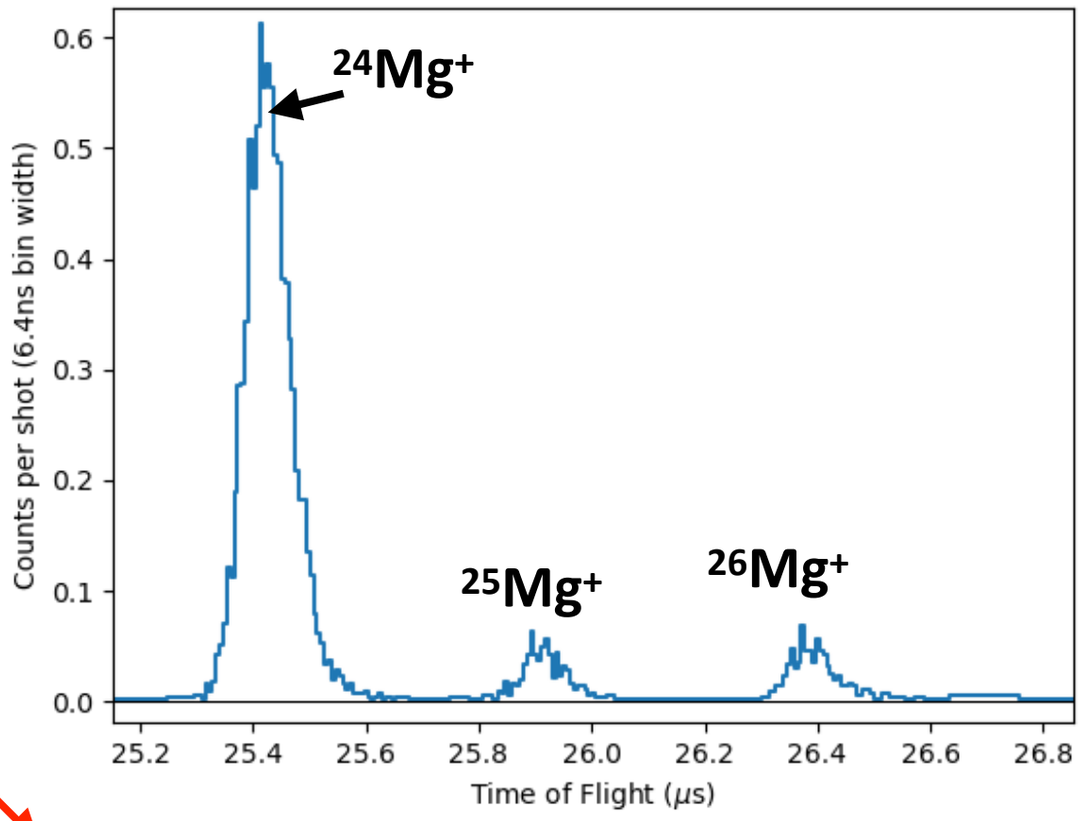




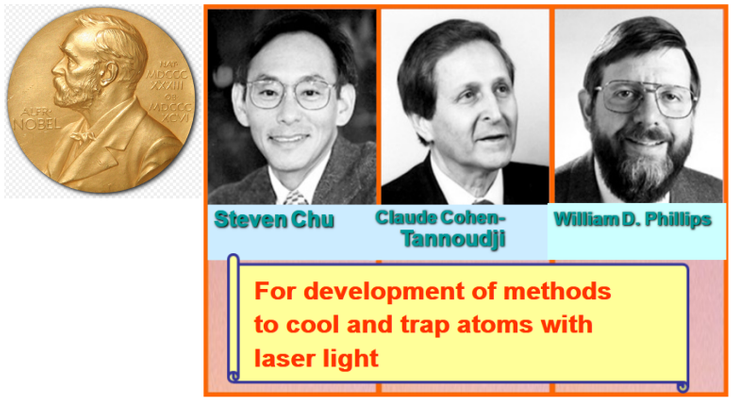


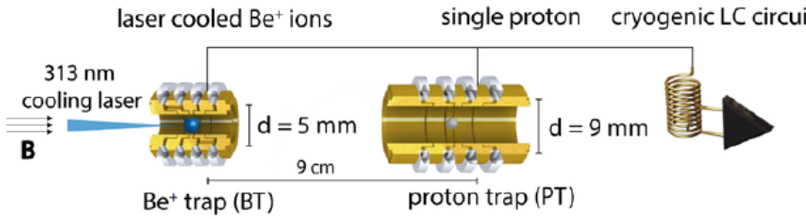
ToF detector

C. Kanitz, L. Croquette et al., in preparation

Doppler Cooling

- Powerful technique to reach sub-K atom and ion temperatures [1]
- Standard tool for high-precision measurements: atomic clocks [2], quantum information science [3], physics beyond the standard model [4]





[1] T. Haensch and A. Schawlow, Optics Communications 13, 68 (1975).
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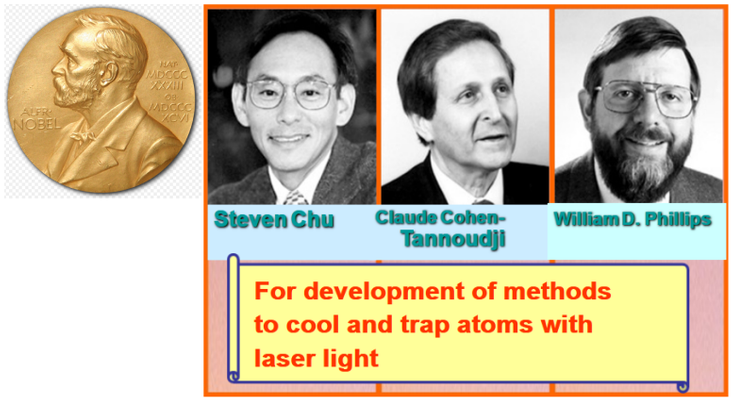

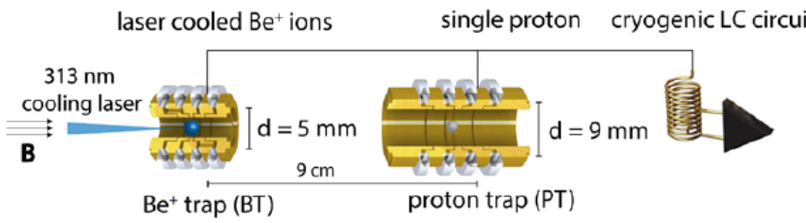

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- Specific applications with RIBs

G. D. Sprouse and L. A. Orozco, Annu. Rev. Nucl. Part. Sci.. 47, 429 (1997)
J. A. Behr et al., Phys. Rev. Lett. 79, 375 (1997).
M. Trinczek et al., Phys. Rev. Lett. 90, 012501 (2003).
L. B. Wang et al., Phys. Rev. Lett. 93, 142501 (2004).

P. A. Vetter et al., Phys. Rev. C 77, 035502 (2008).
J. R. A. Pitcairn et al., RRC 79, 015501 (2009)
A. Takamine et al., Phys. Rev. Lett. 112, 162502 (2014)
B. Fenker et al., Phys. Rev. Lett. 120, 062502 (2018)

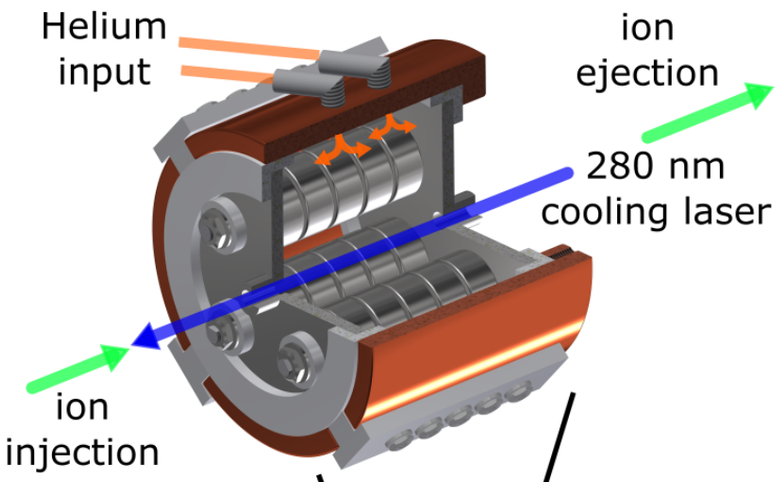
- unexplored as cooling technique to deliver high quality RIBs

Goal: provide ultra-cold RIBs

- ... compatible with short half-lives
- ... universally applicable (via sympathetic cooling)

Experimental Setup

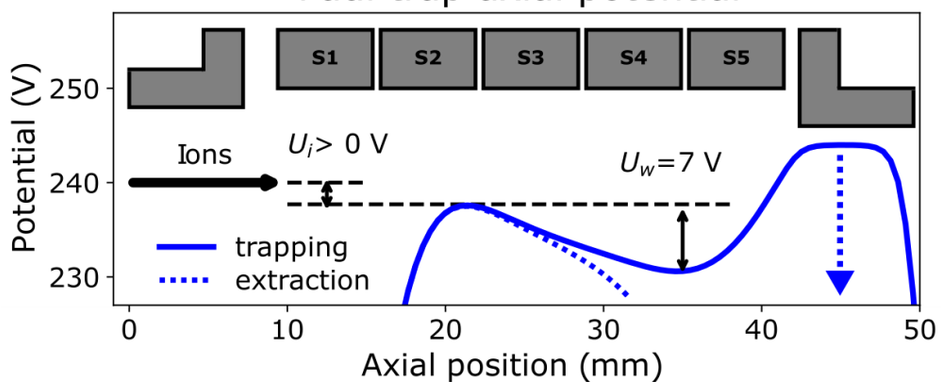
Paul trap cooler-buncher



stopping of incoming beam

1. Electrostatic (down to ≈ eV)
2. Laser cooling

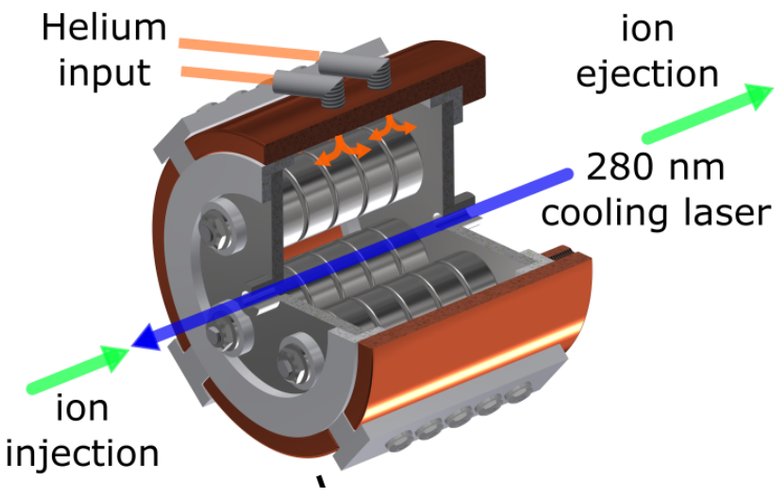
Paul trap axial potential



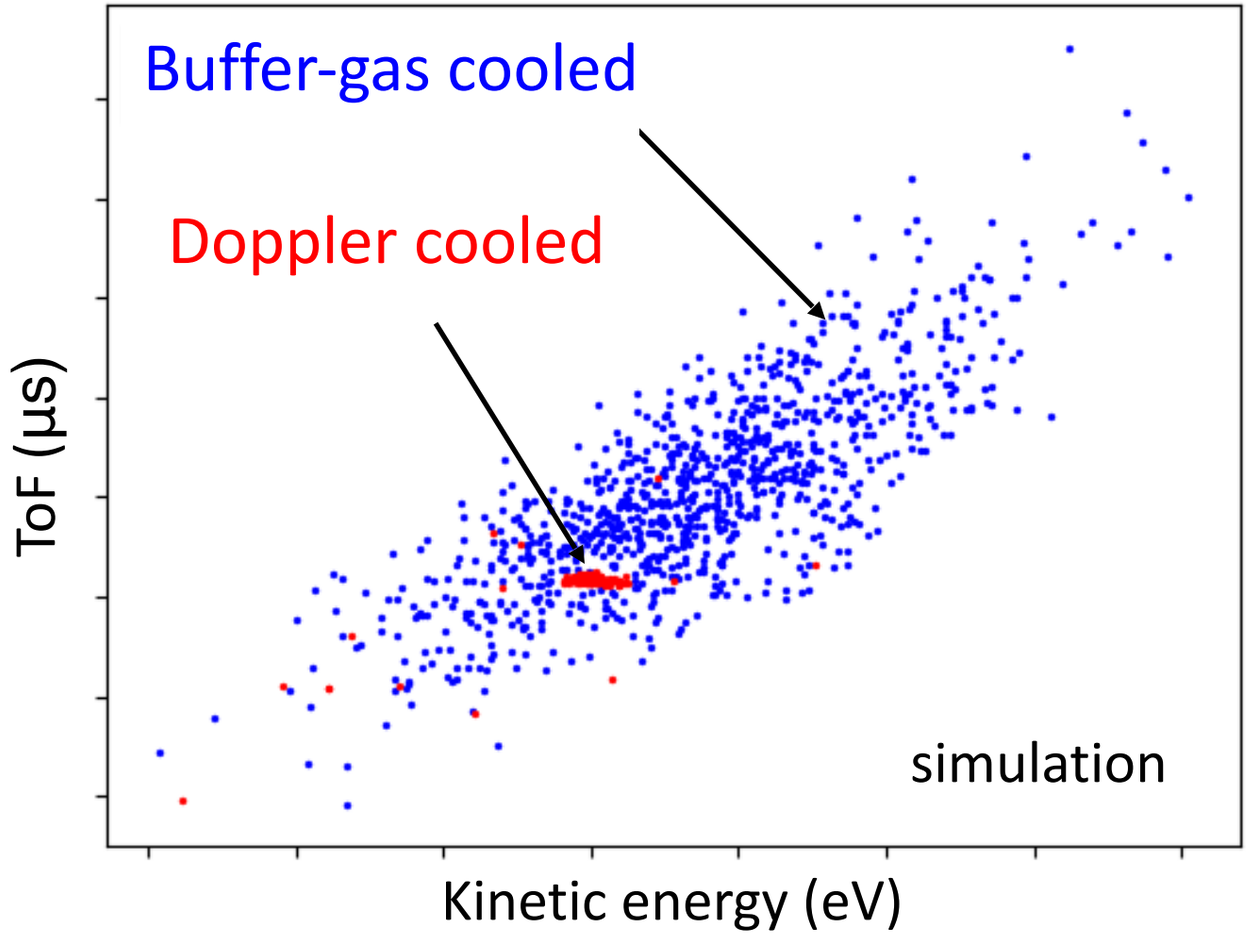
S. Sels, F. Maier et al., Phys. Rev. Res. 4, 033229 (2022)

Experimental Demonstration at MIRACLS

Paul trap cooler-buncher



externally produced, fast and ‘hot’ Mg^+ ion beam



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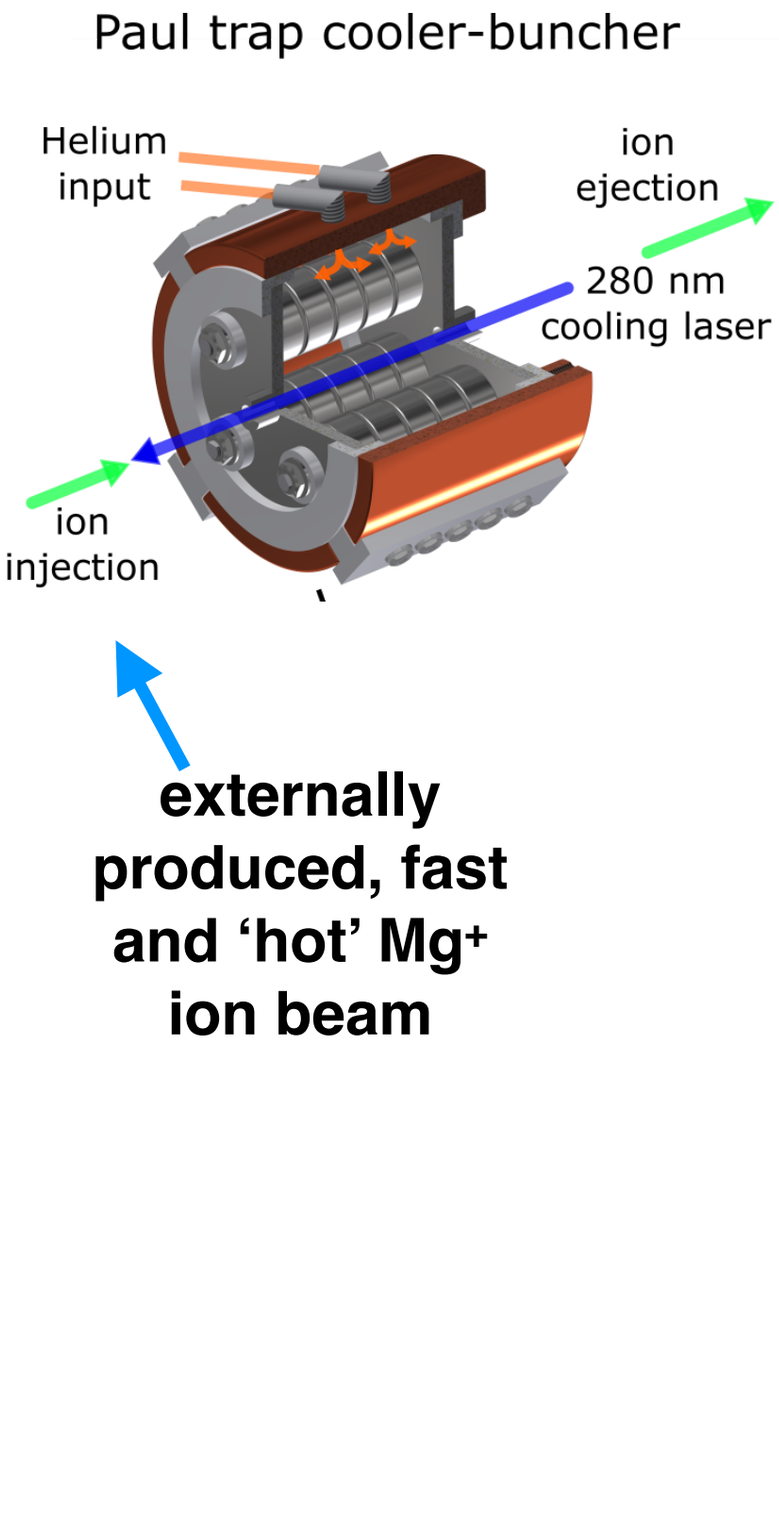

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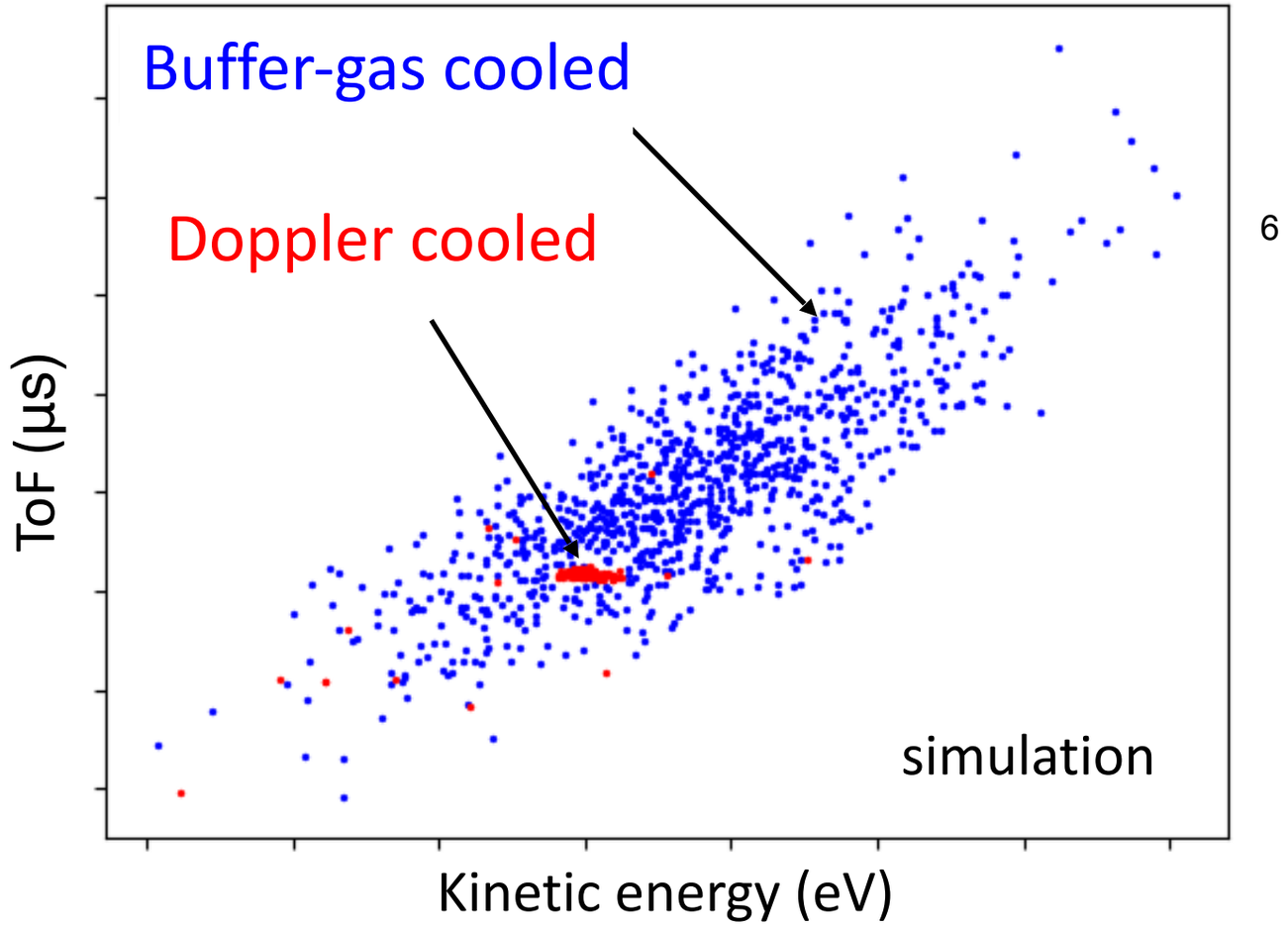
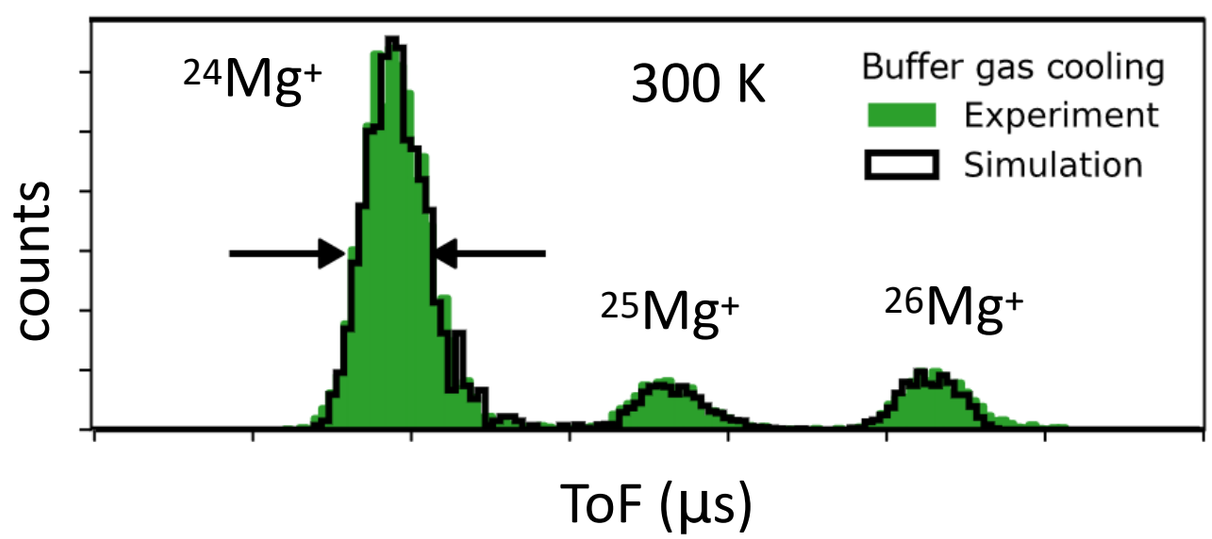
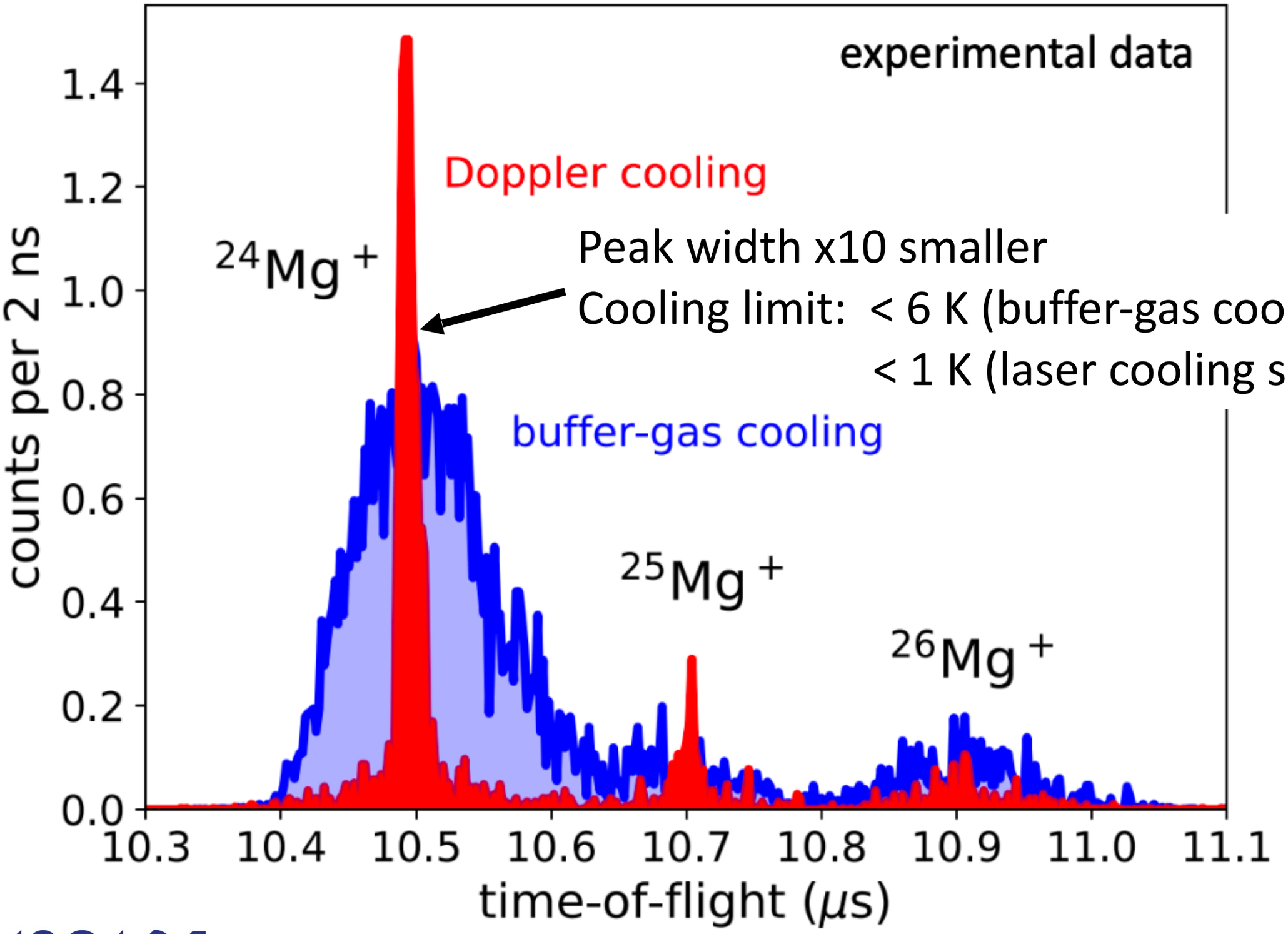




Experimental results



Peak width x10 smaller

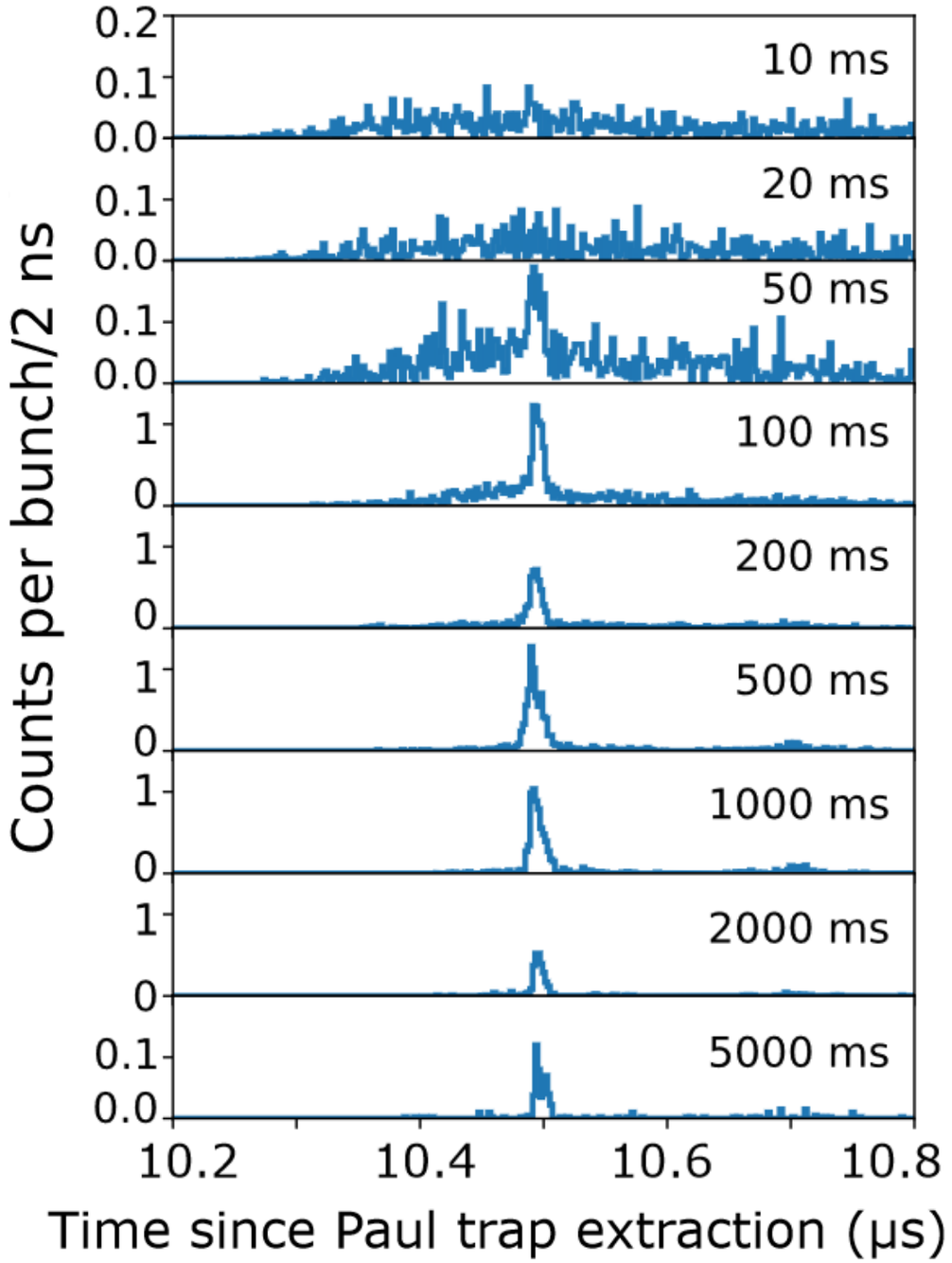
Cooling limit: < 6 K (buffer-gas cooling sim)

< 1 K (laser cooling simulation)

S. Sels, F. Maier et al., Phys. Rev. Res. 4, 033229 (2022)

Cooling Systematics

3 mW & -200 MHz detuning,
varying cooling times:



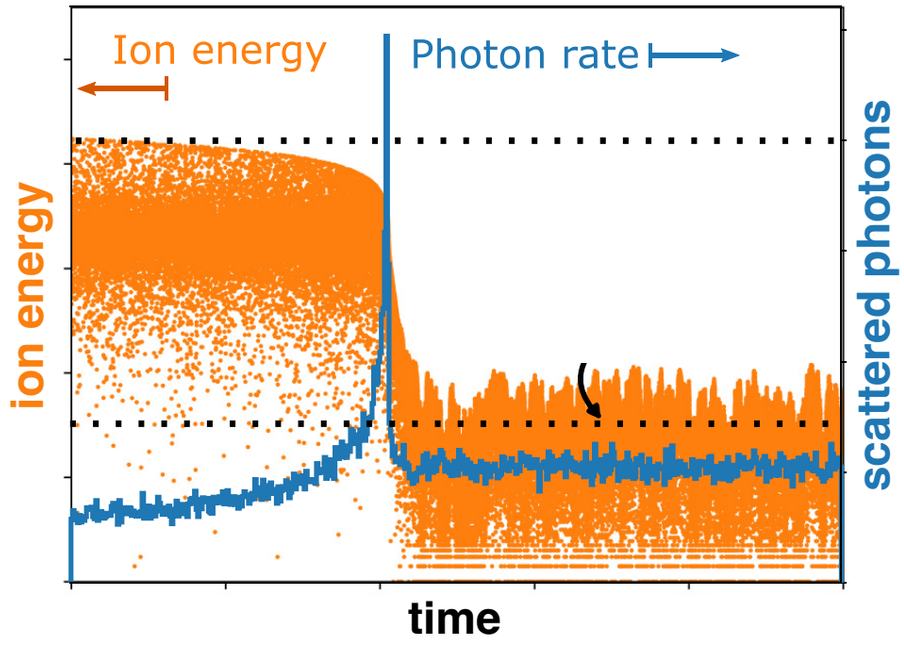
Requirements for radionuclides

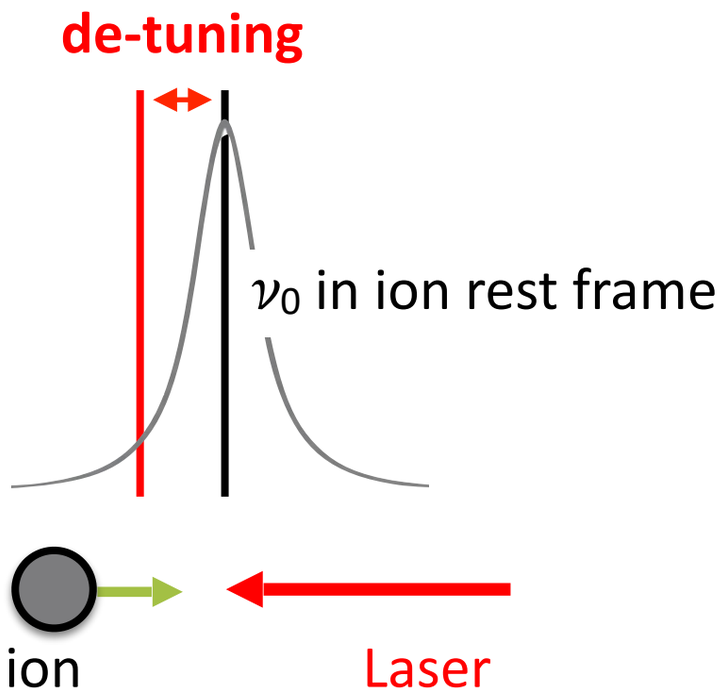
- cold
- fast

S. Sels, F. Maier et al., Phys. Rev. Res. 4, 033229 (2022)

erc European Research Council

Cooling simulation & numerical model





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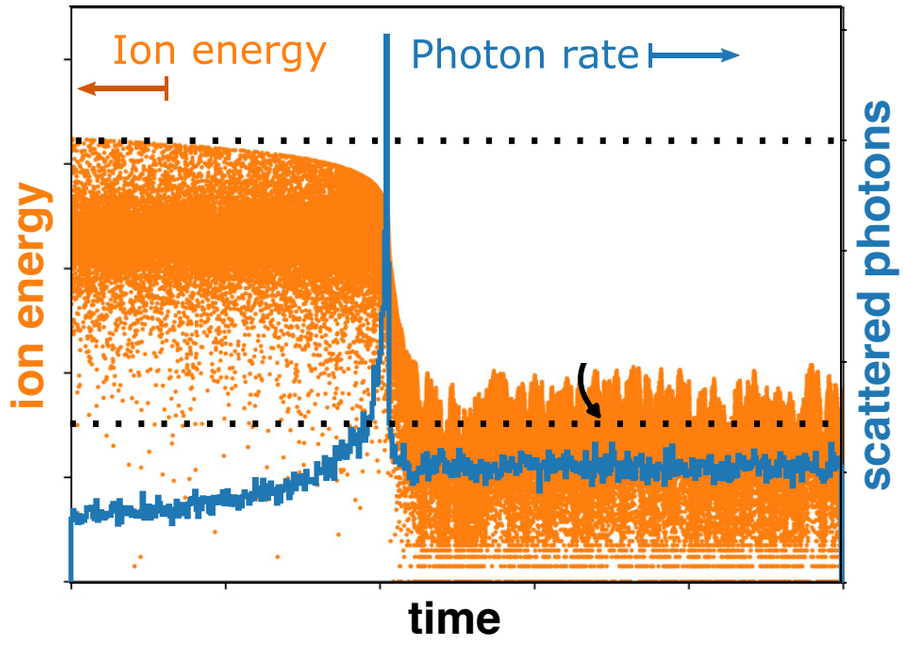

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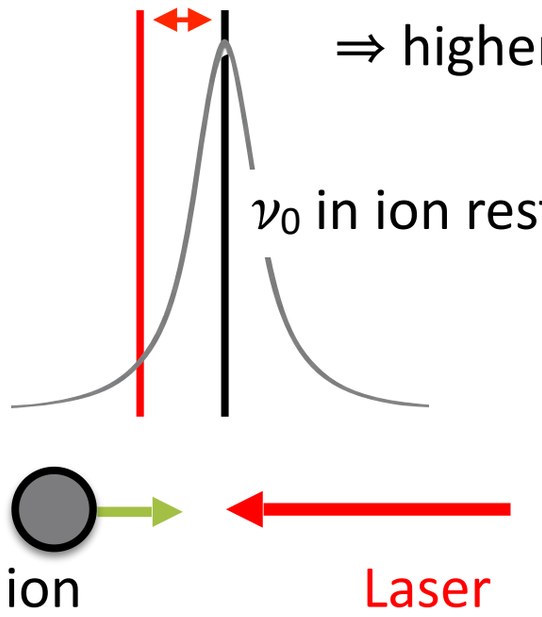
large de-tuning ⇒ rapid initial cooling

⇒ higher T_{final}



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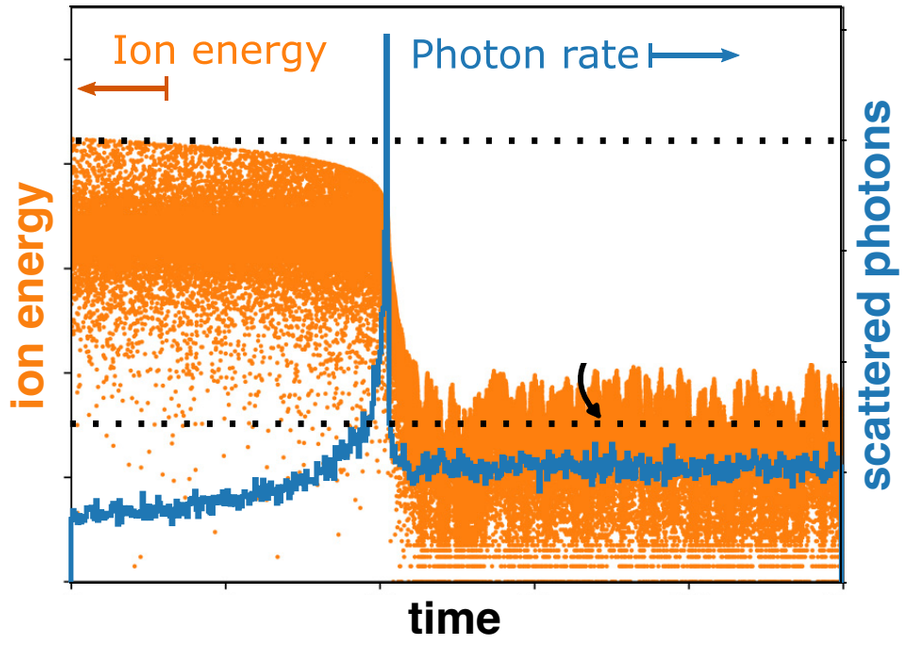

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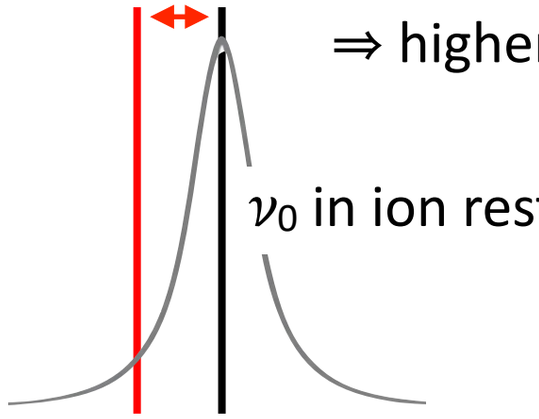
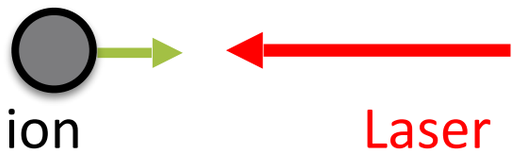
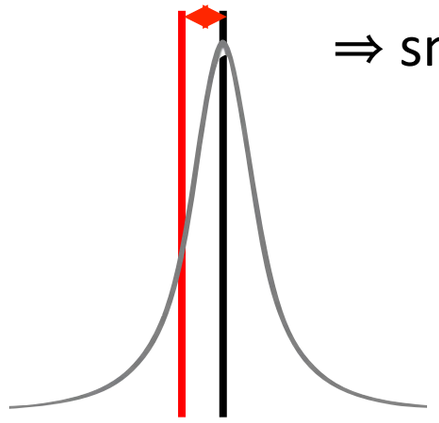




small de-tuning ⇒ slow initial cooling

⇒ smaller T_{final}



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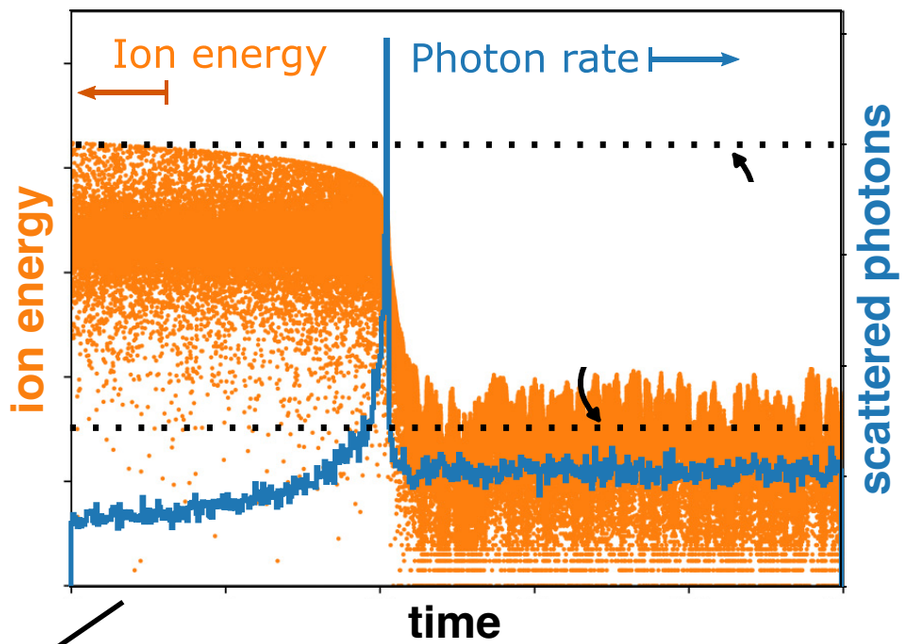
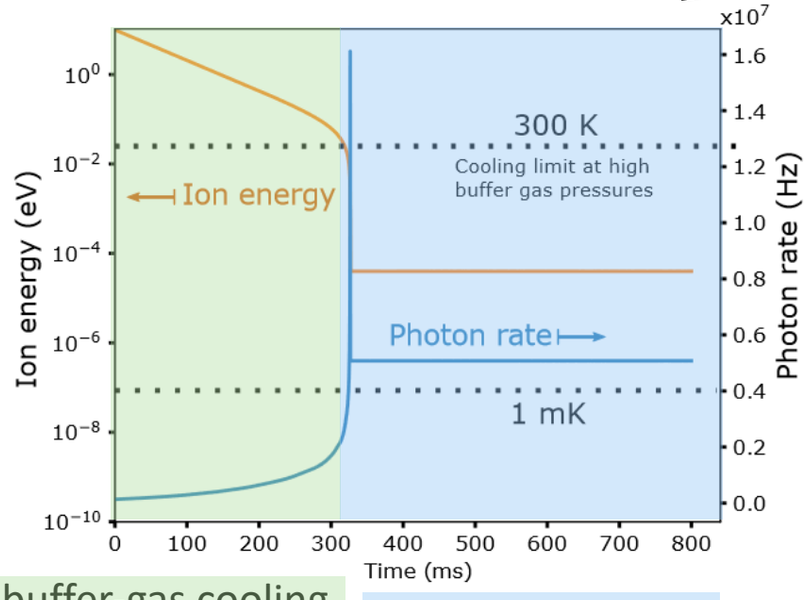


S. Sels, F. Maier et al., Phys. Rev. Res. 4, 033229 (2022)

low-pressure buffer gas

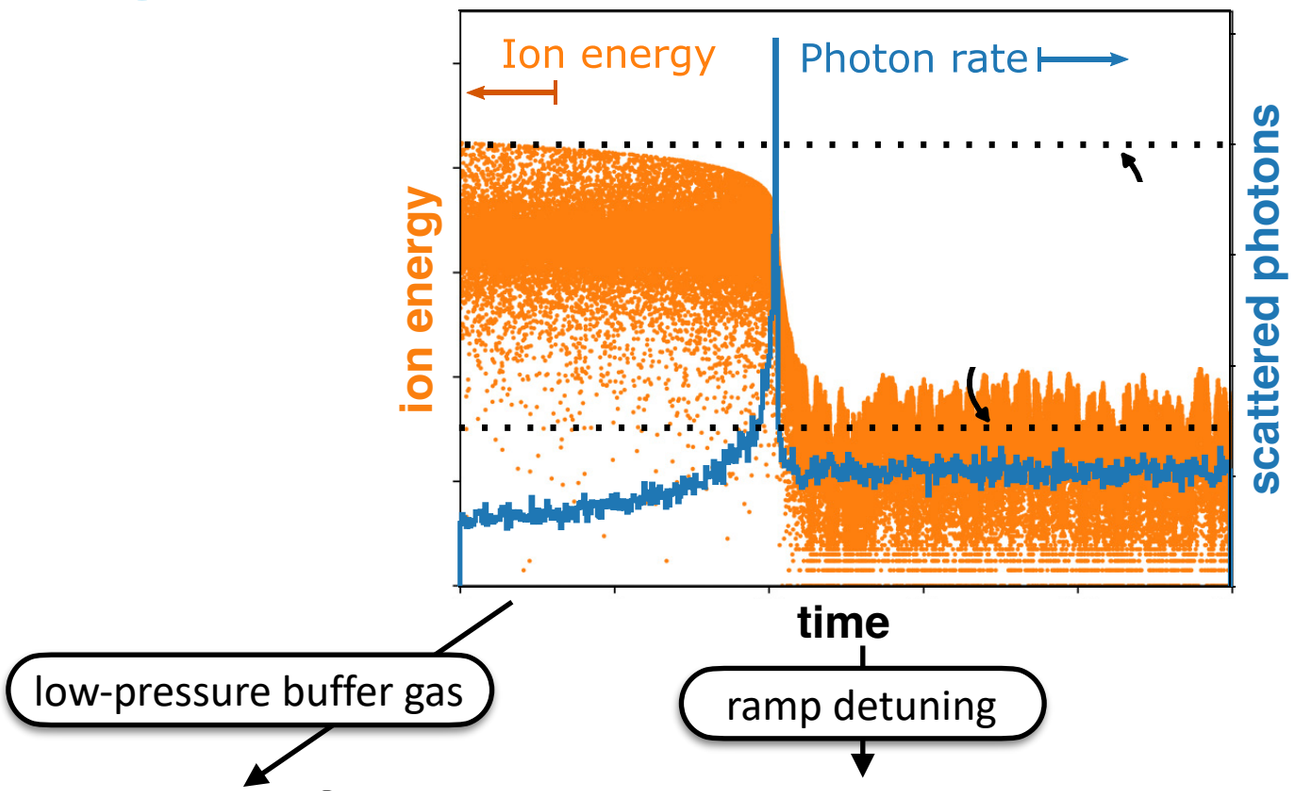


buffer-gas cooling
10^{-5} mbar

Doppler cooling

drawback: higher T_{final}

Cooling simulation & numerical model



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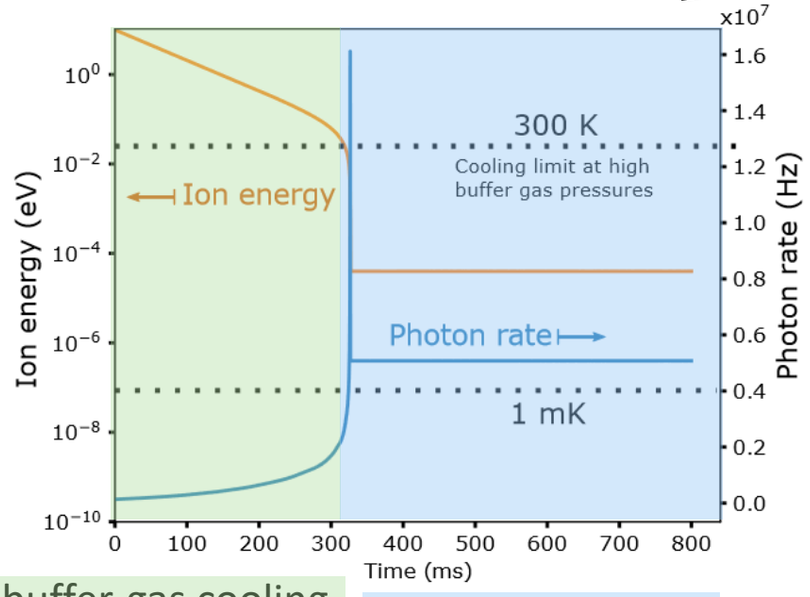

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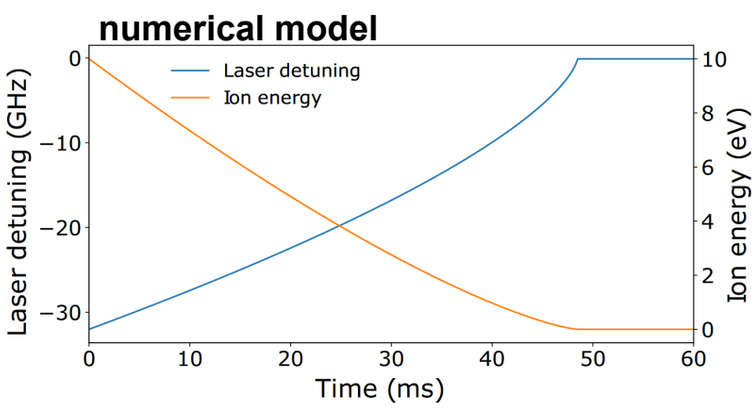
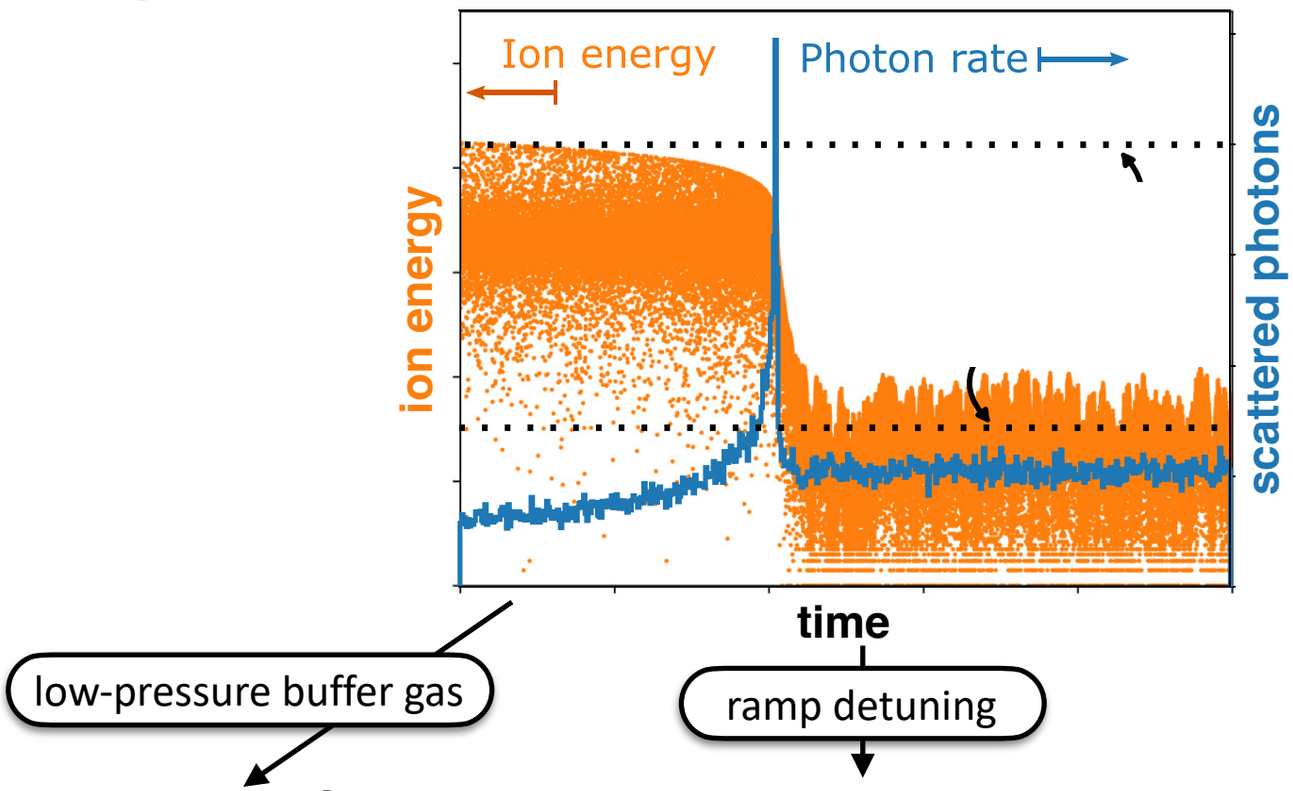


potential drawback: lower efficiency

Cooling simulation & numerical model



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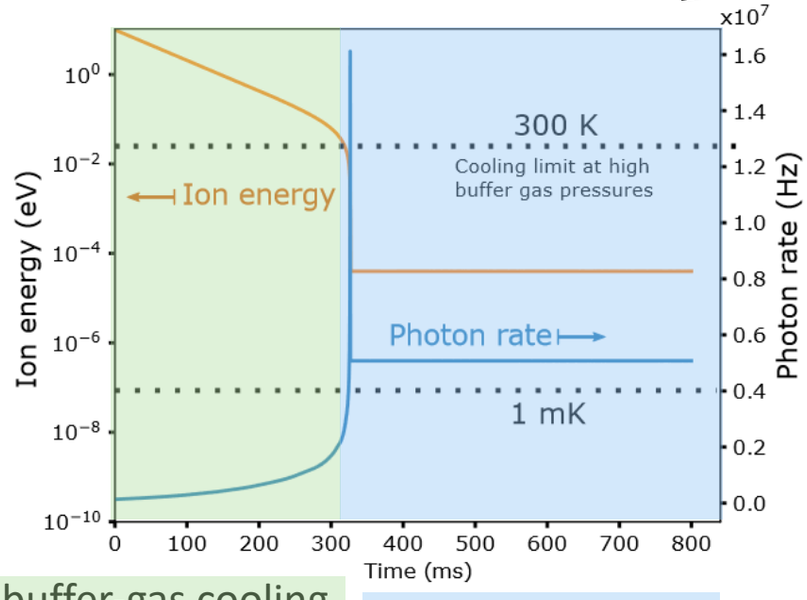

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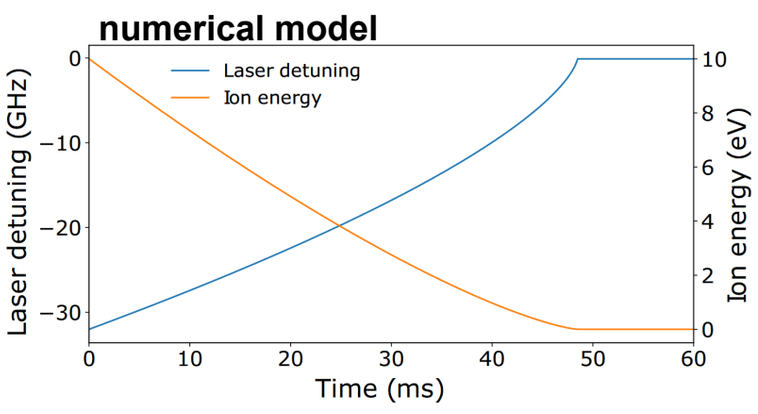


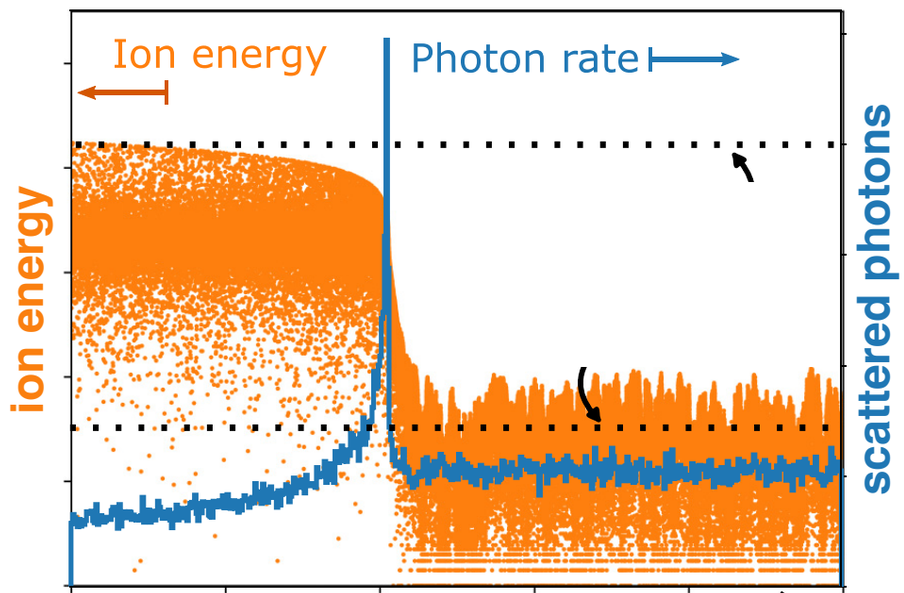
potential drawback: lower efficiency

recently implemented at REBEL@Leuven

P. Imgram et al., arXiv:2506.18552 (2025)

see talk by S. Pelonis

Cooling simulation & numerical model

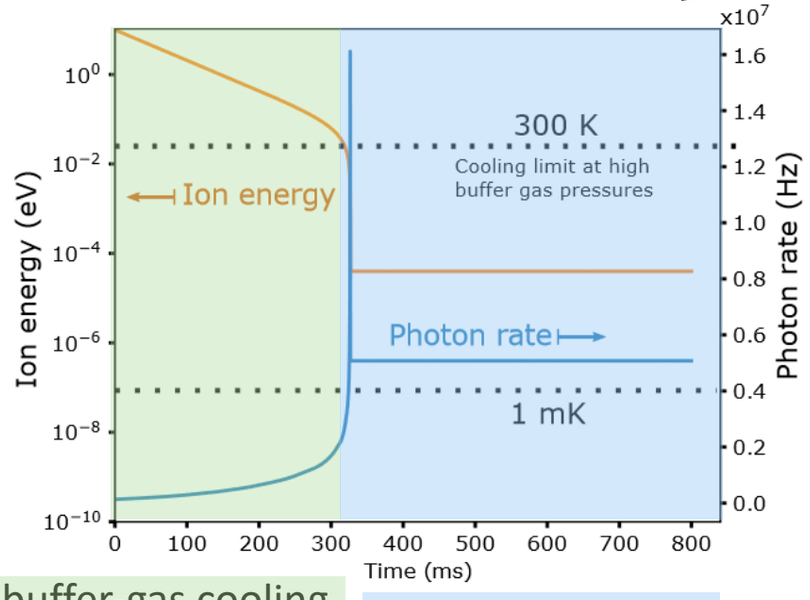


low-pressure buffer gas

ramp detuning

staged ion-trap system

S. Sels, F. Maier et al., Phys. Rev. Res. 4, 033229 (2022)



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10^{-5} mbar

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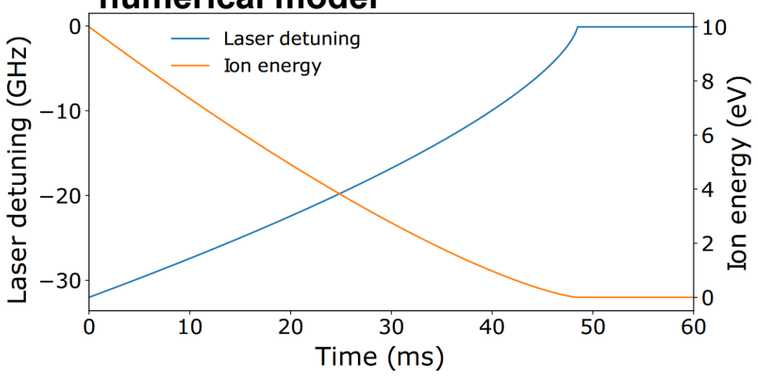
drawback: higher T_{final}

numerical model



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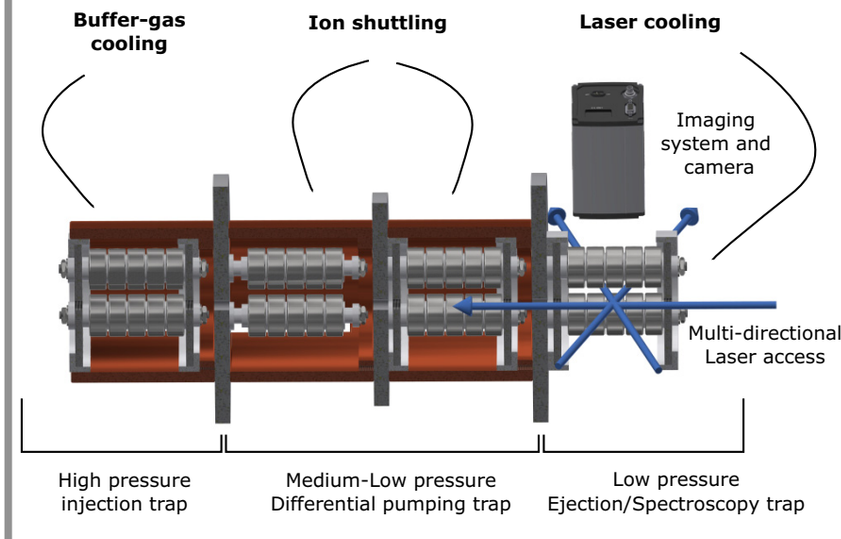
recently implemented at REBEL@Leuven

P. Imgram et al., arXiv:2506.18552 (2025)

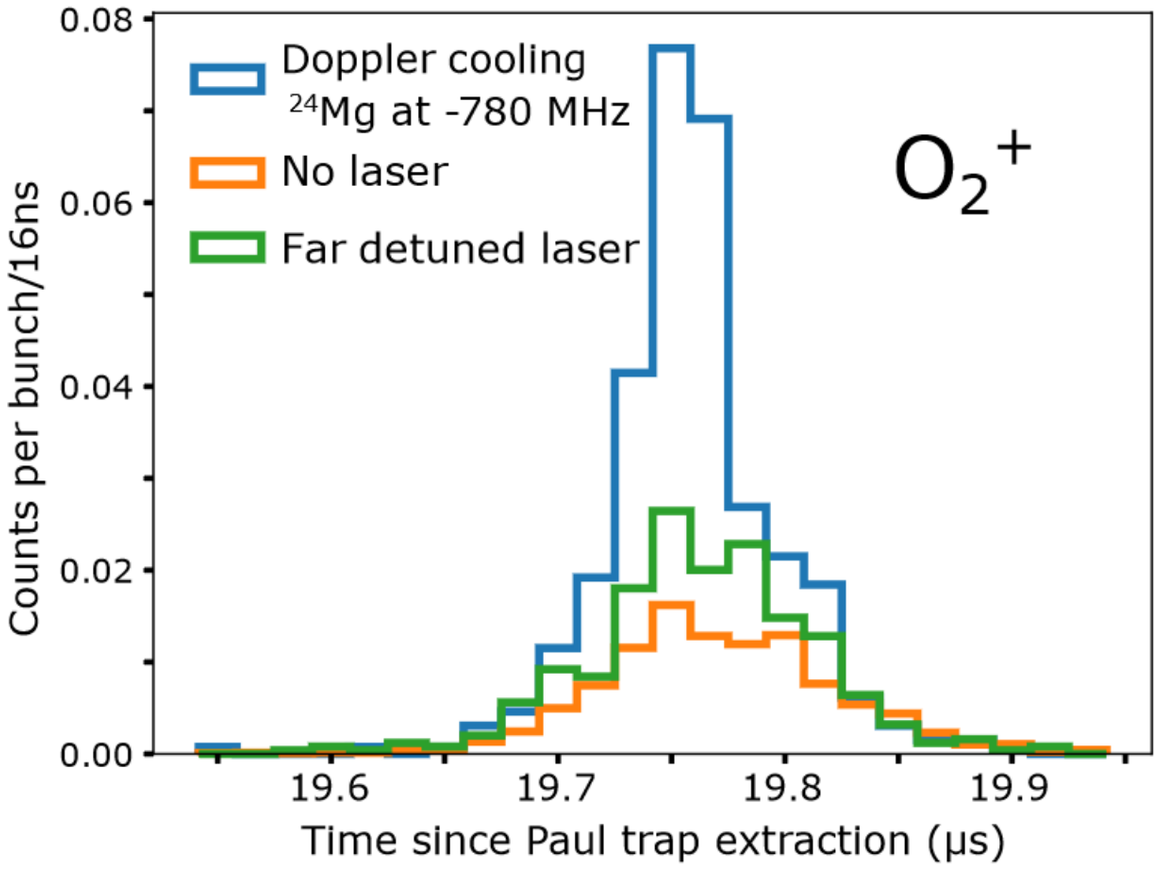
see talk by S. Pelonis

apply both in different sections



Sympathetic cooling

- ‘universal’ availability of cold ion ensembles
- including ionic systems which cannot be directly laser-cooled



	O_2^+
Peak width residual-gas or buffer-gas cooling	113(5) ns
Sympathetic cooling	58(4) ns
Improvement in countrate	Factor 2.6

Issues with our O_2^+ source

can be done better analogous to work with stables

J. Wuebbena et al, Phys. Rev. A 85, 043412 (2012)
M. Guggemos. New Journal of Physics 17, 103001 (2015)
K. Groot-Berning et al. Phys. Rev. A 99, 023420 (2019)

S. Sels, F. Maier et al., Phys. Rev. Res. 4, 033229 (2022)

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Sympathetic cooling

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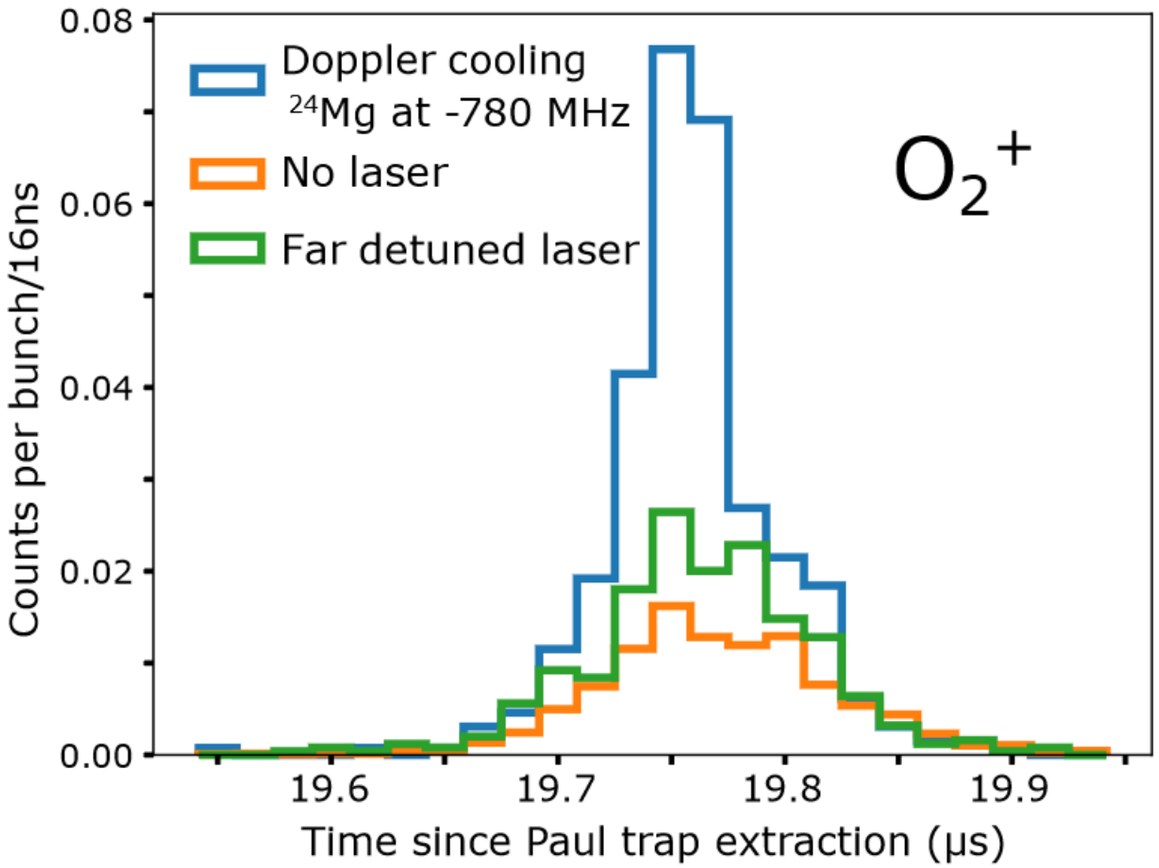

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opportunity for cold molecular RIBs

see talk by R. Garcia Ruiz

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J. Wuebbena et al, Phys. Rev. A 85, 043412 (2012)
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Improved R in MR-ToF devices

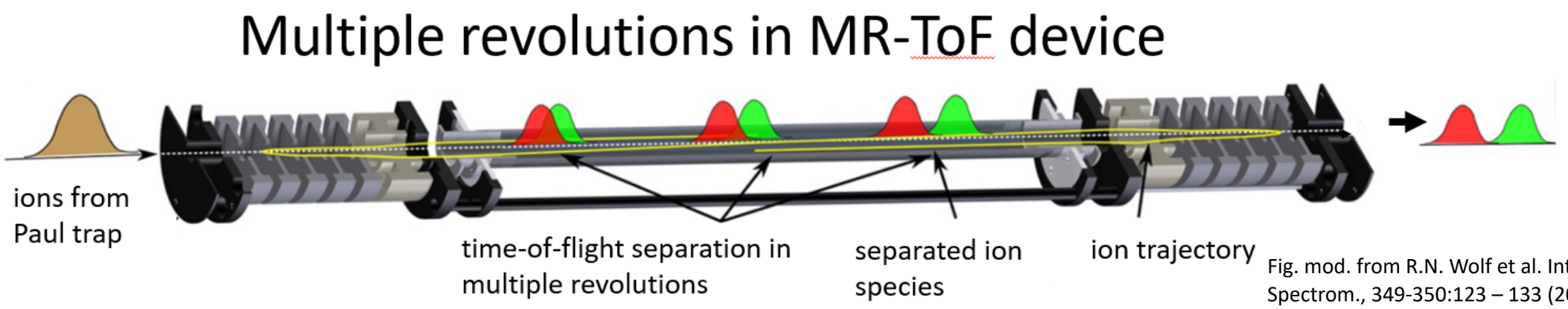


Fig. mod. from R.N. Wolf et al. Int. J. Mass Spectrom., 349-350:123 – 133 (2013).

$$R = \frac{m}{\Delta m} = \frac{t}{2\Delta t}$$

Improved R in MR-ToF devices

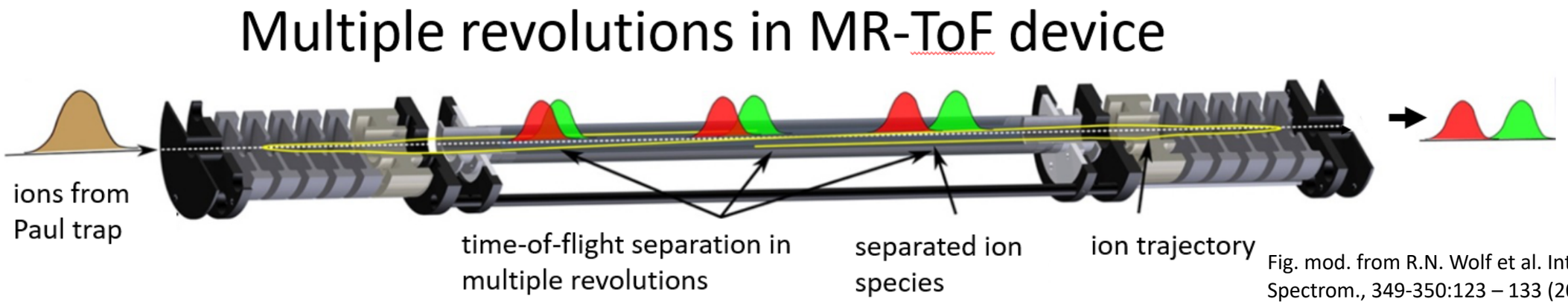
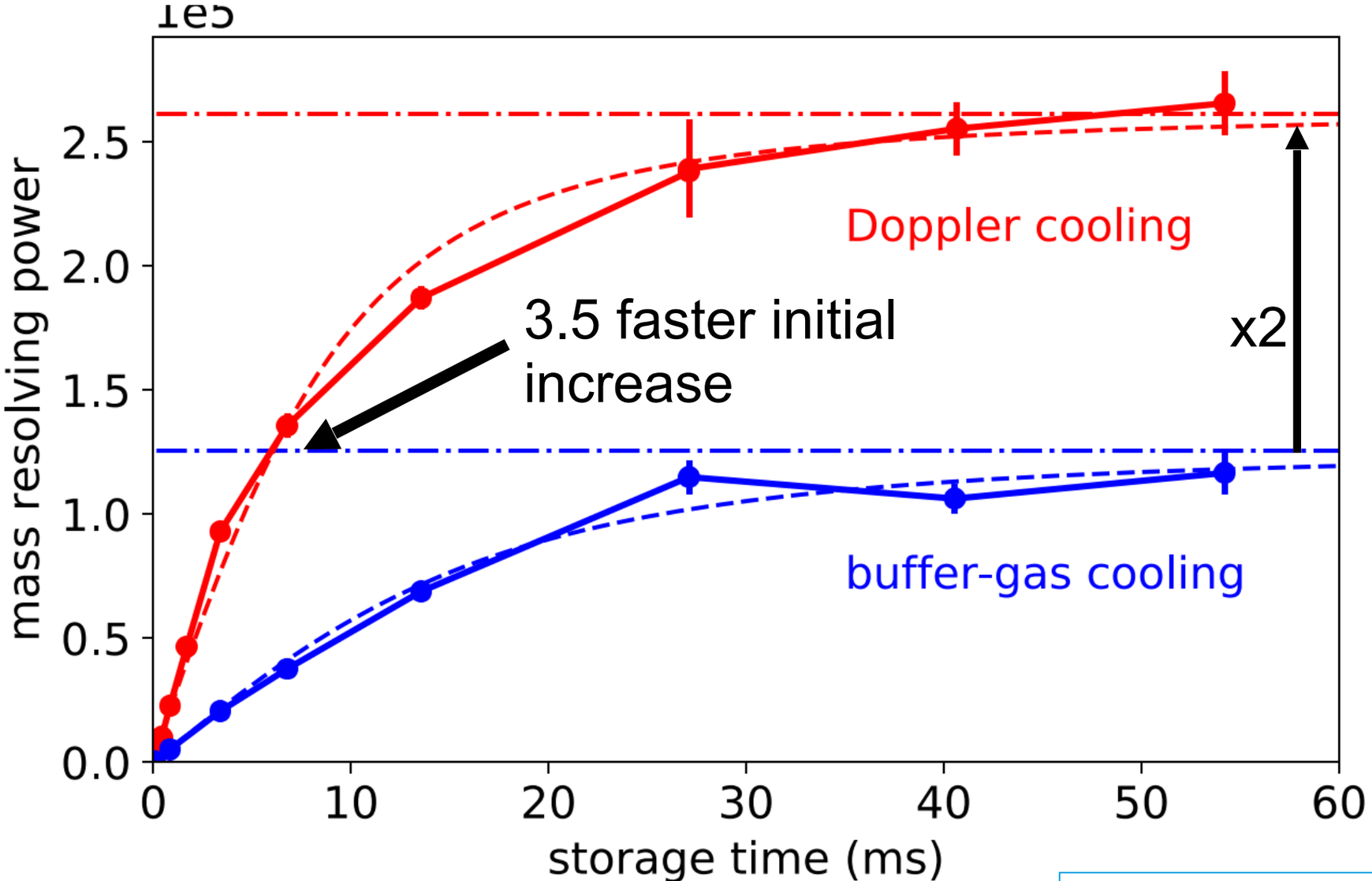


Fig. mod. from R.N. Wolf et al. Int. J. Mass Spectrom., 349-350:123 – 133 (2013).



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S. Sels, F. Maier et al., Phys. Rev. Res. 4, 033229 (2022)

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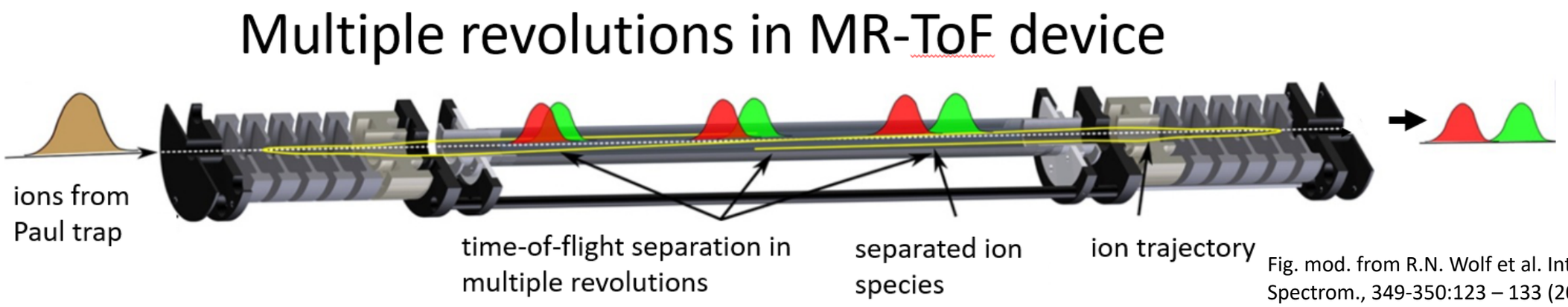
Improved R in MR-ToF devices



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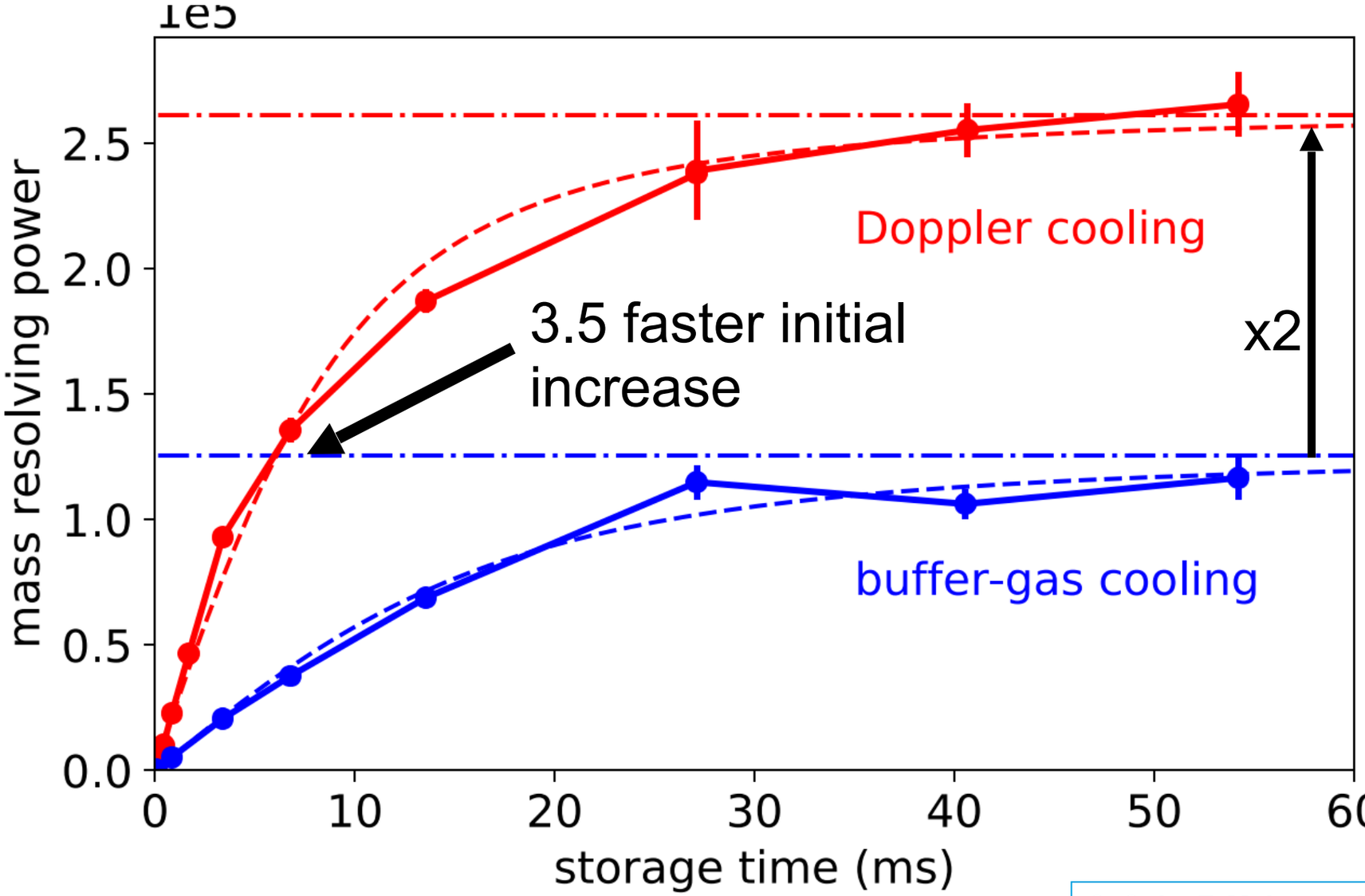

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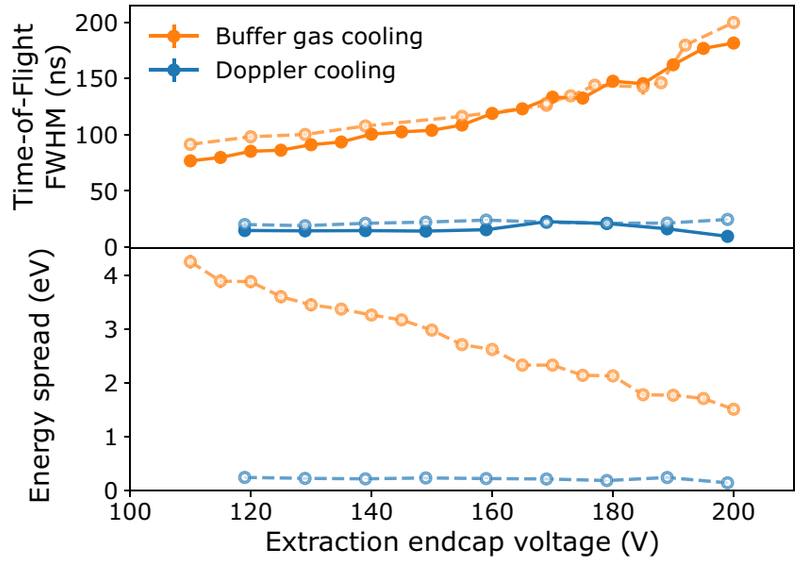

Laser Cooling

$\Longrightarrow$

low ΔE and Δt

S. Sels, F. Maier et al., Phys. Rev. Res. 4, 033229 (2022)

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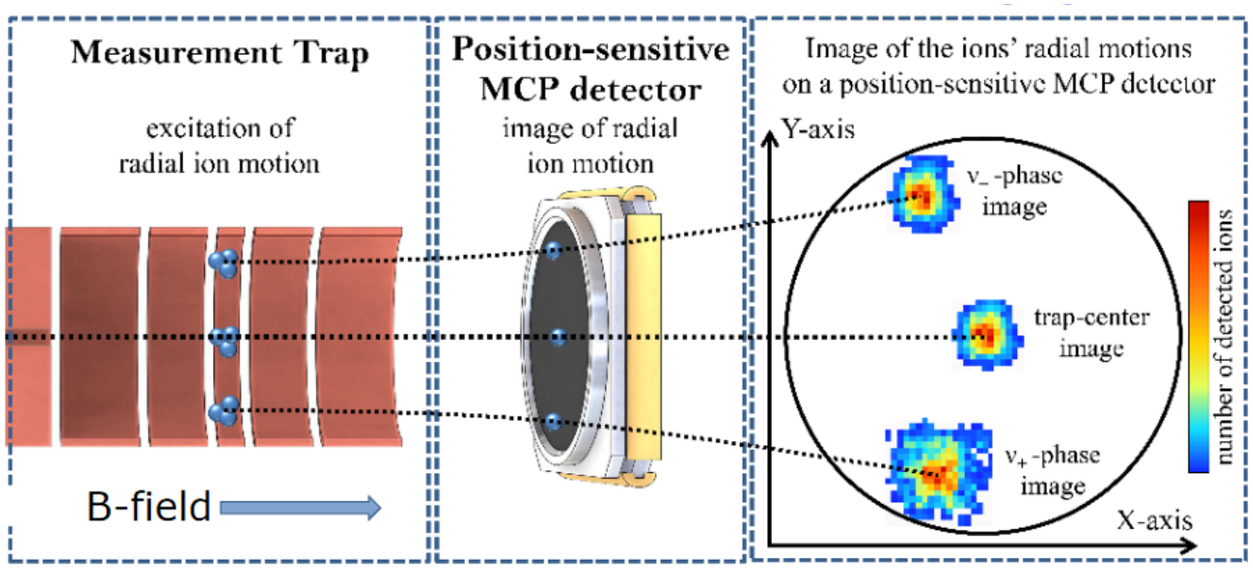
Penning trap PI-ICR

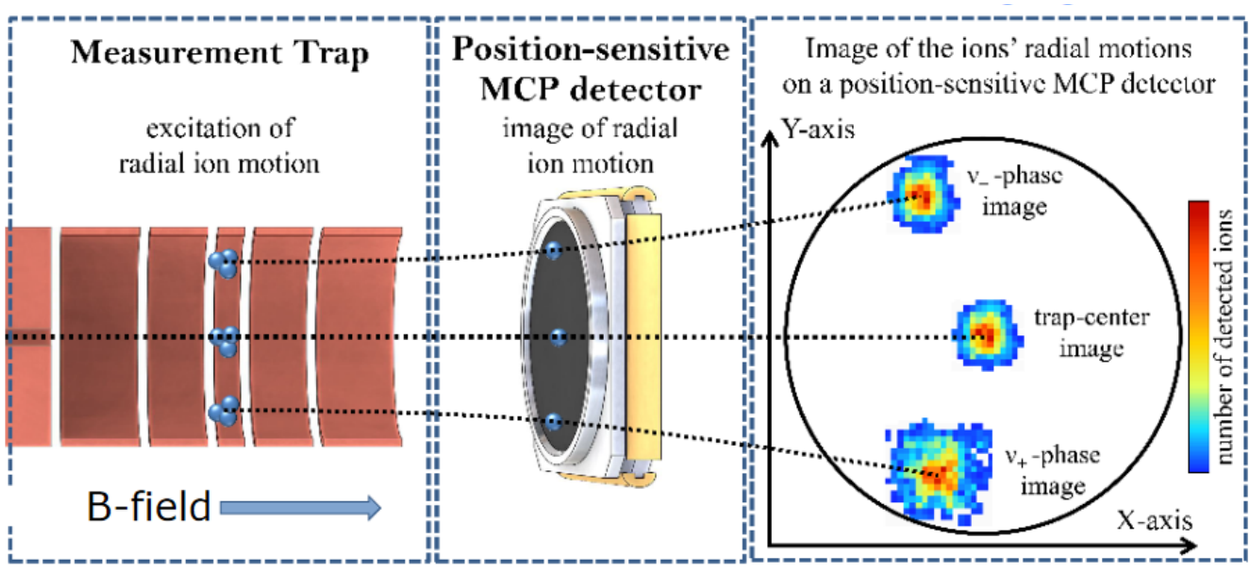


Sergey Eliseev (MPIK)

first introduced at SHIPTRAP

S. Eliseev et al., Phys. Rev. Lett. 110, 082501(2013)
Appl. Phys. B 114, 107 (2014)

Penning trap PI-ICR



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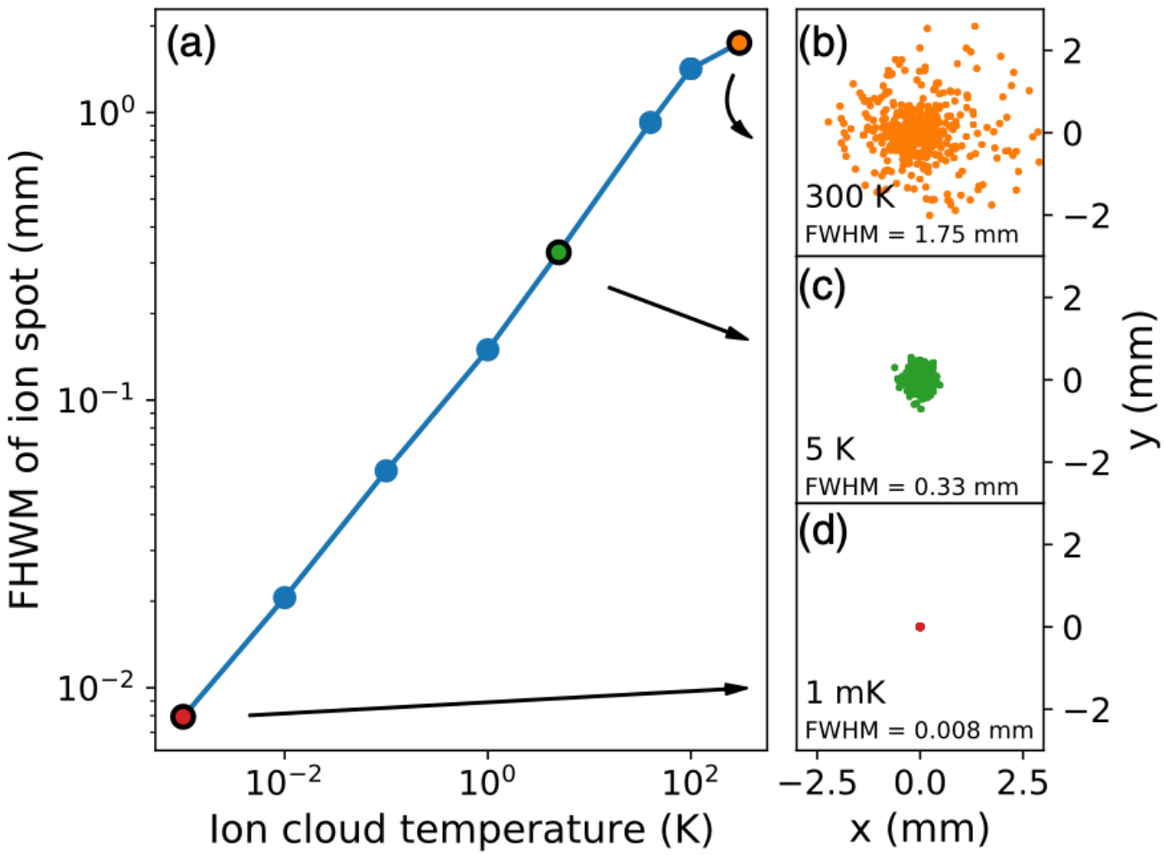

simulation combined for
- MIRACLS laser cooling
- TITAN PI-ICR

E. M. Lykiardopoulou et al., Hyperfine Interact. 241, 37 (2020).

S. Sels, F. Maier et al., Phys. Rev. Res. 4, 033229 (2022)

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Summary

- **Doppler and sympathetic cooling**
  - ➡ key ingredients in high-precision experiments in AMO physics
  - ➡ unexplored opportunity for (universal) cold RIB

- **Detailed study at MIRACLS for its use at RIB facilities**
  - ➡ provide cold beams (ionic atoms and molecules)
  - ➡ enables **low ∆E and ∆t**
  - ➡ explored for
    - MR-ToF MS (experiment)
    - Penning trap PI-ICR (sim.)
    - Laser spec. (Exp. + sim.)
    - …

- **Outlook: dedicated programs at Leuven, JFYL, Bordeaux / GANIL, ANL,** others?

Acknowledgements

Laser-cooling team:

F.M. Maier, S.Sels, M. Au, P. Fischer, C. Kanitz, V. Lagaki, S. Lechner, E. Leistenschneider, D. Leimbach, E.M. Lykiardopoulou, A.A. Kwiatkowski, T. Manovitz, G. Neyens, P. Plattner, M. Rosenbusch, S. Rothe, L. Schweikhard, M. Vilen, R. Wolf, S. Malbrunot-Ettenauer

https://miracls.web.cern.ch/

Thank you
Merci

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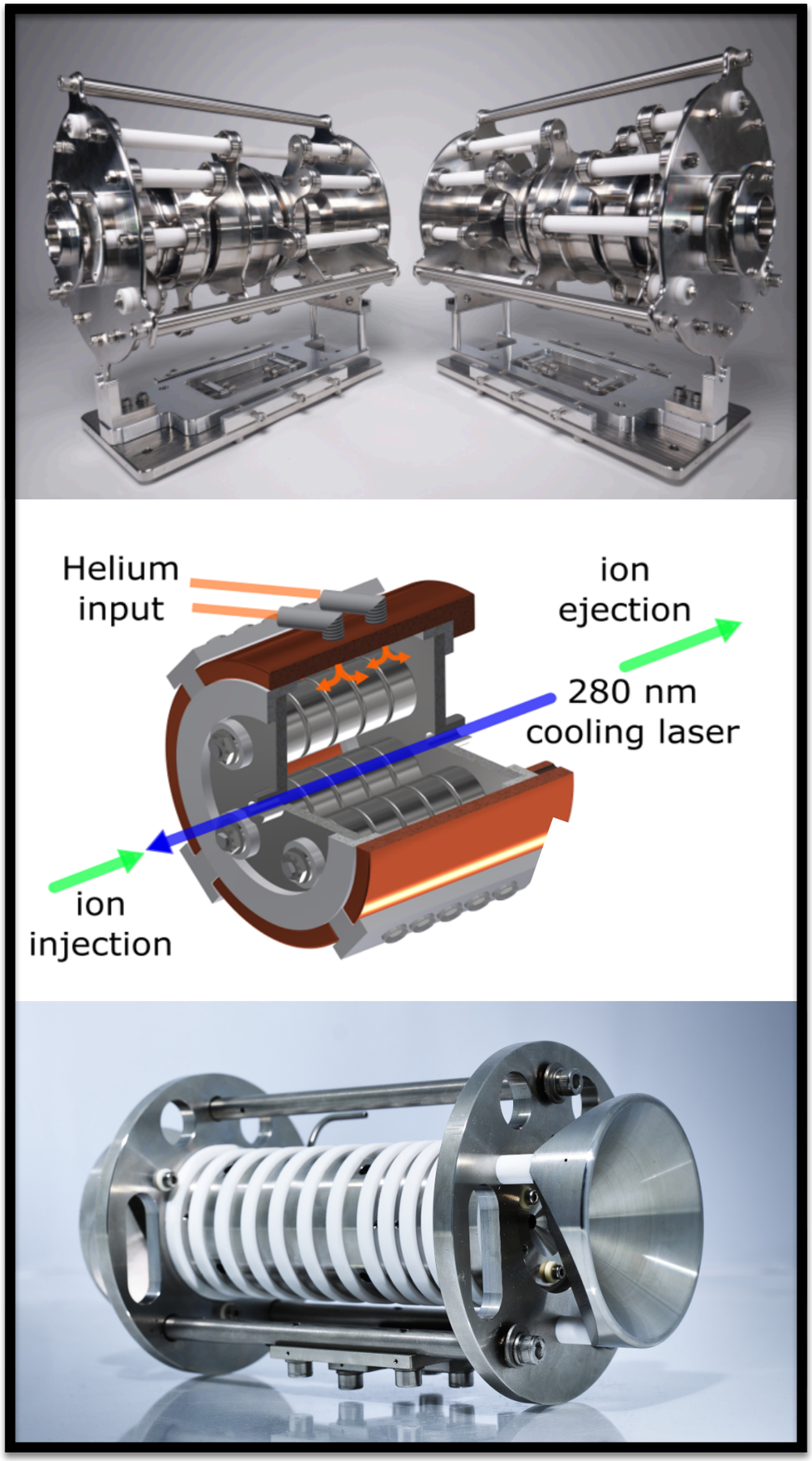


Discovery, accelerated

Extraction field- room temperature

- turn-around time:

$$\Delta t_{\mathrm{ta}} = \sqrt{8 \ln 2}\ \frac{\sqrt{m k_{\mathrm{B}} T}}{q E_{\mathrm{extr}}}$$

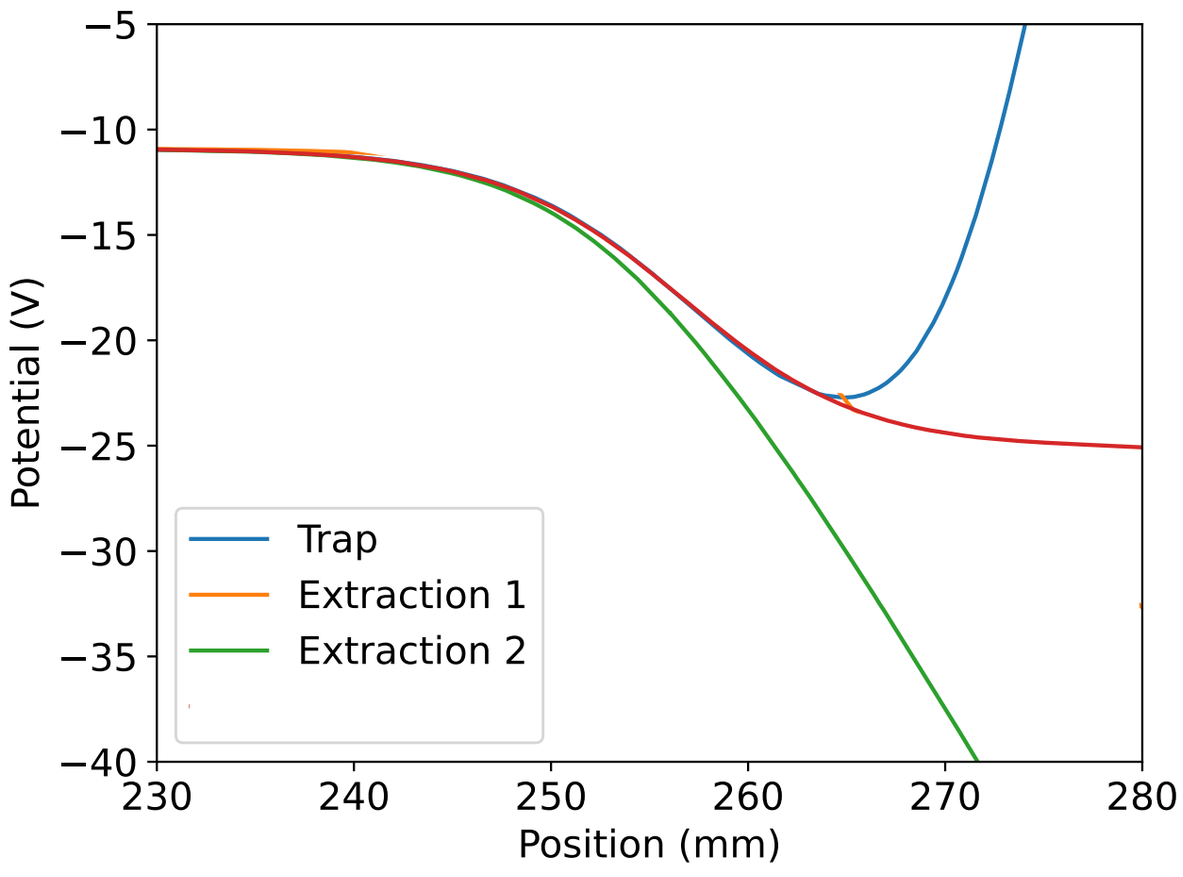
W. C. Wiley and I. H. McLaren, Rev Sci Instrum 26, 1150 (1955)
T. Dickel et al., NIM A 777, 172 (2015)

- Commonly applied method to obtain small Δt
  Δt < 10 ns reported, e.g. *T. Dickel et al., IJMS 412, 1 (2017)*

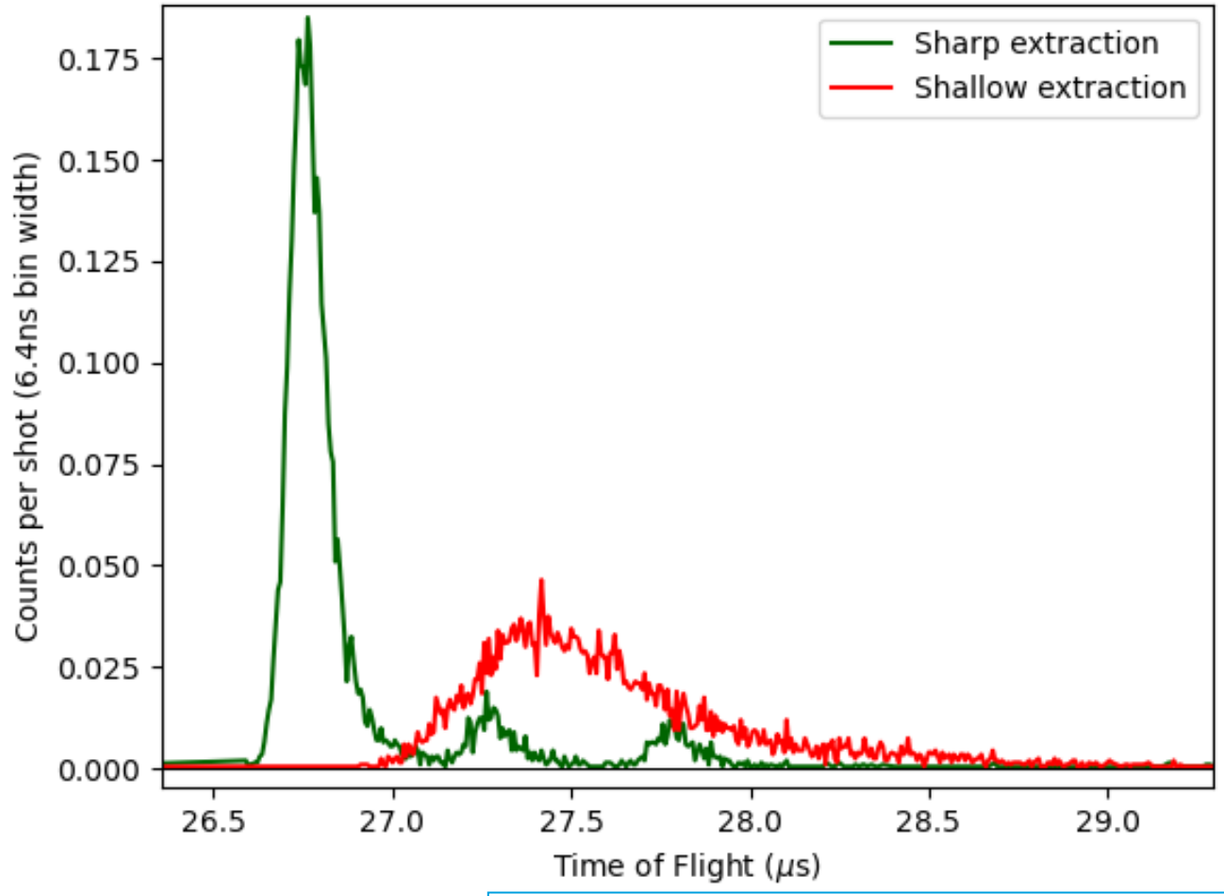
- Consequence: increased ΔE

$$(\Delta E\, \Delta t)_{95\%} \approx 2\pi \ln(20) k_B T \sqrt{\frac{m}{2qC_2}}$$

Calculated potential in MIRACLS Paul trap:

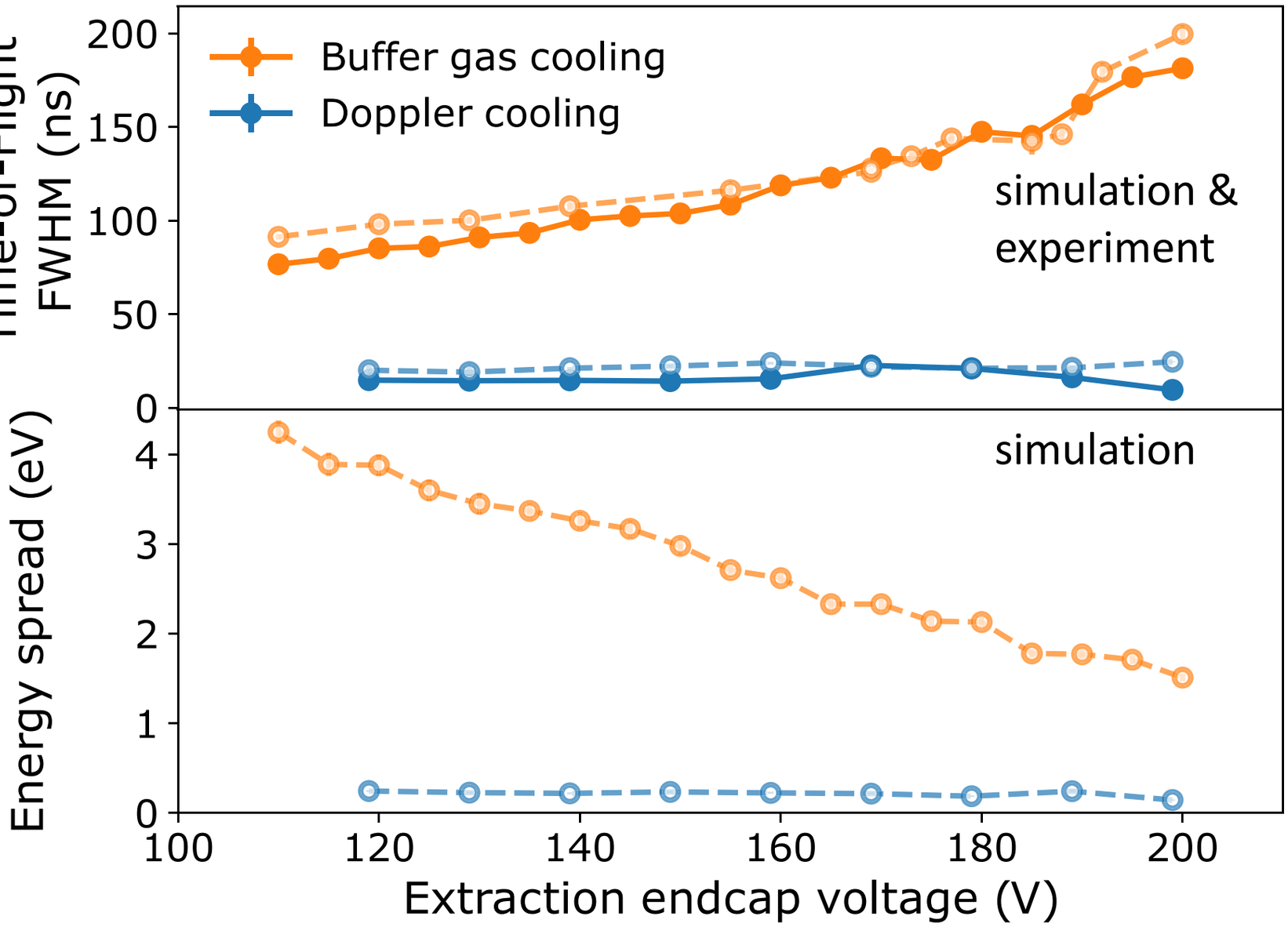


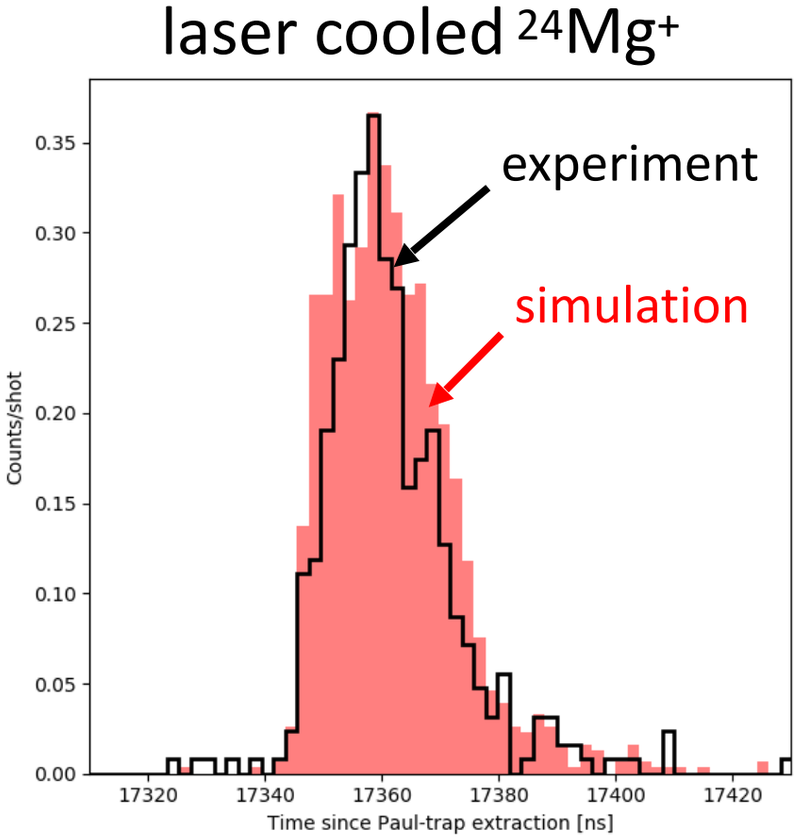
Experiment



C. Kanitz, L. Croquette et al., in preparation

Extraction Field vs Laser Cooling





Laser Cooling ⟹ **<u>low ΔE and Δt</u>**

⟹ explored for
- MR-ToF MS (experiment)
- Penning trap PI-ICR (sim.)
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- …

S. Sels, F. Maier et al., Phys. Rev. Res. 4, 033229 (2022)

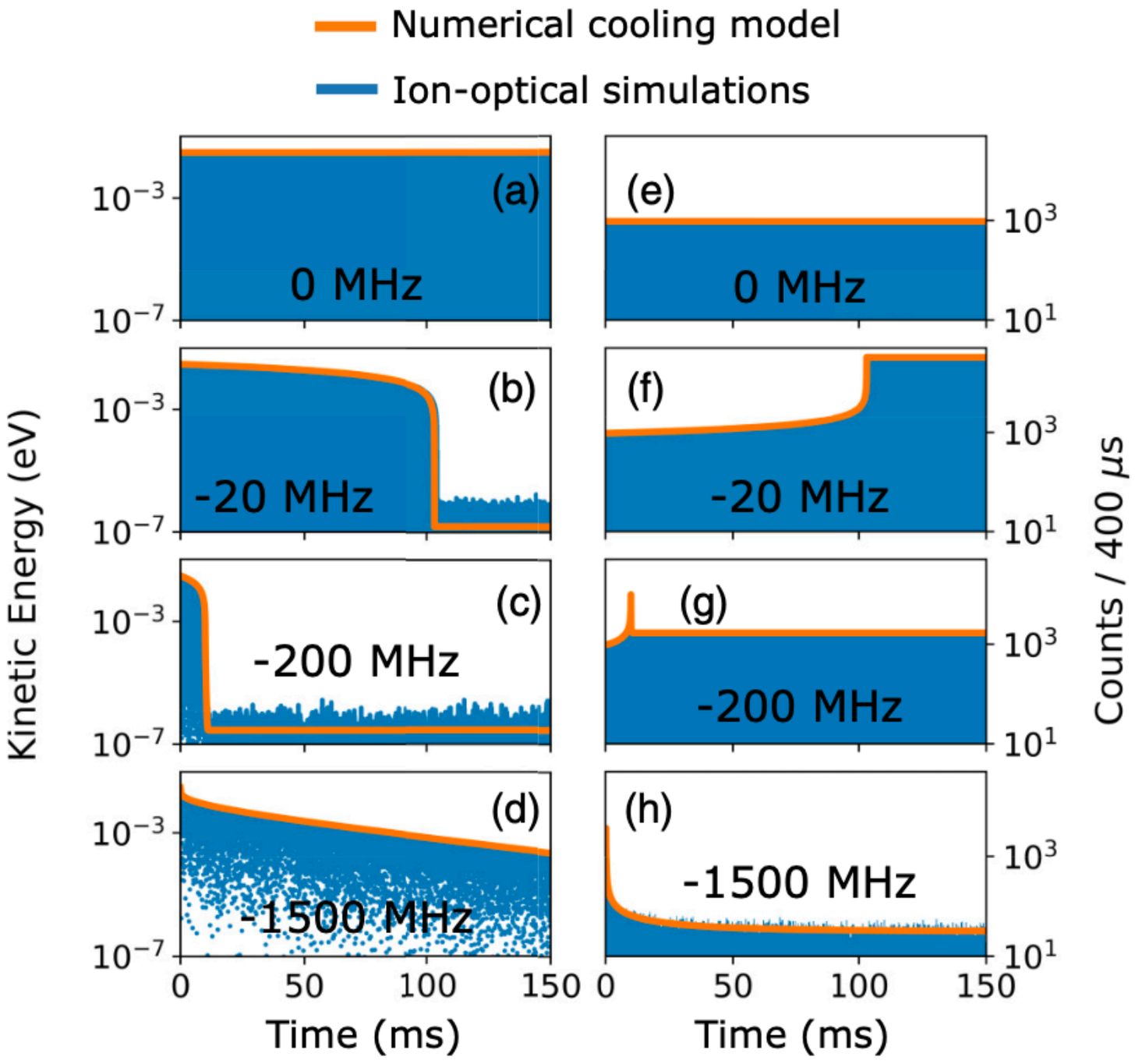
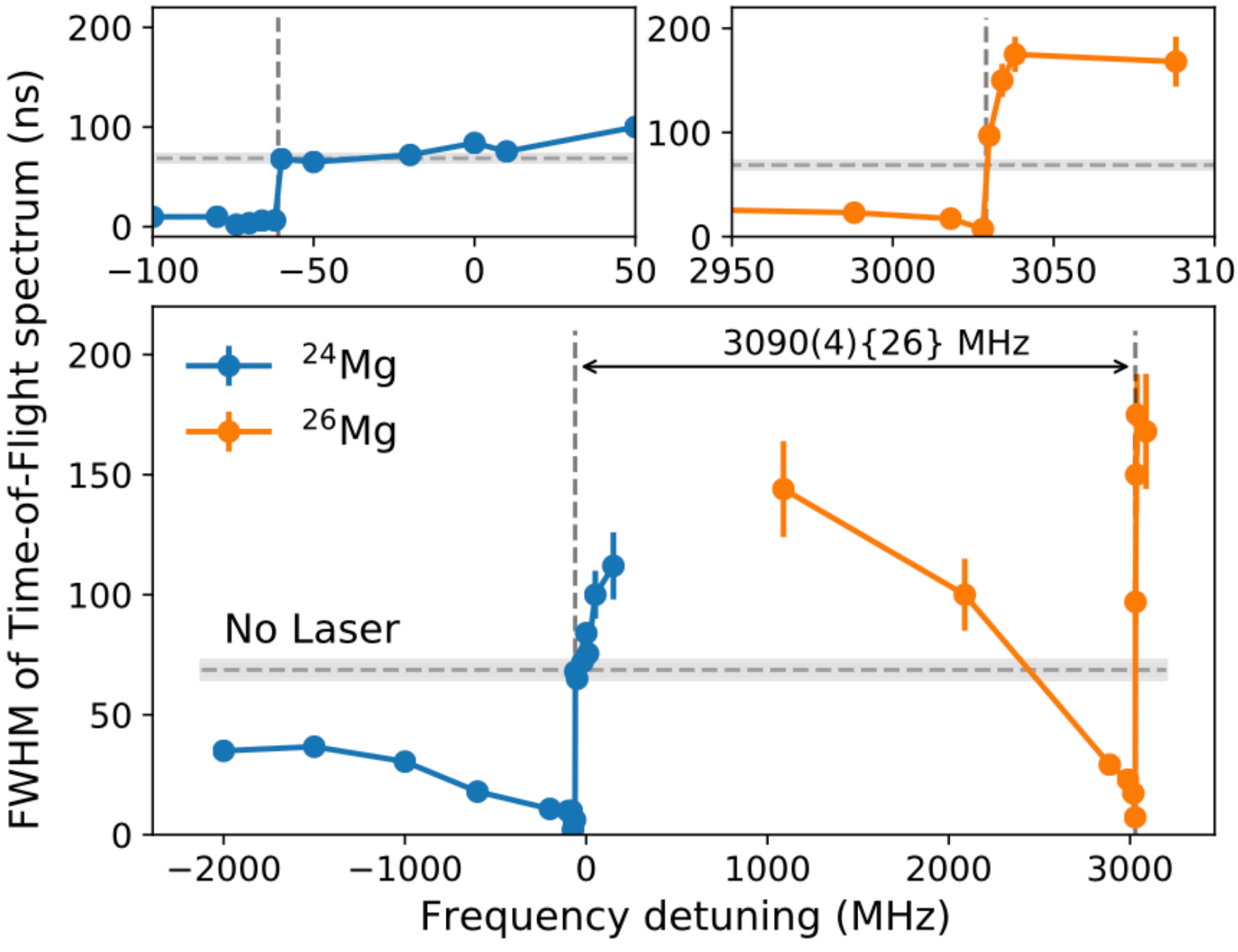


FIG. 10. (a)–(d) Kinetic energy and (e)–(h) scattered photon rate for the 1D numerical model (orange) and ion-optical simulations (blue) as a function of time for different laser detuning frequencies.

S. Sels, F. Maier et al., Phys. Rev. Res. 4, 033229 (2022)

New method laser-spec



S. Sels, F. Maier et al., Phys. Rev. Res. 4, 033229 (2022)