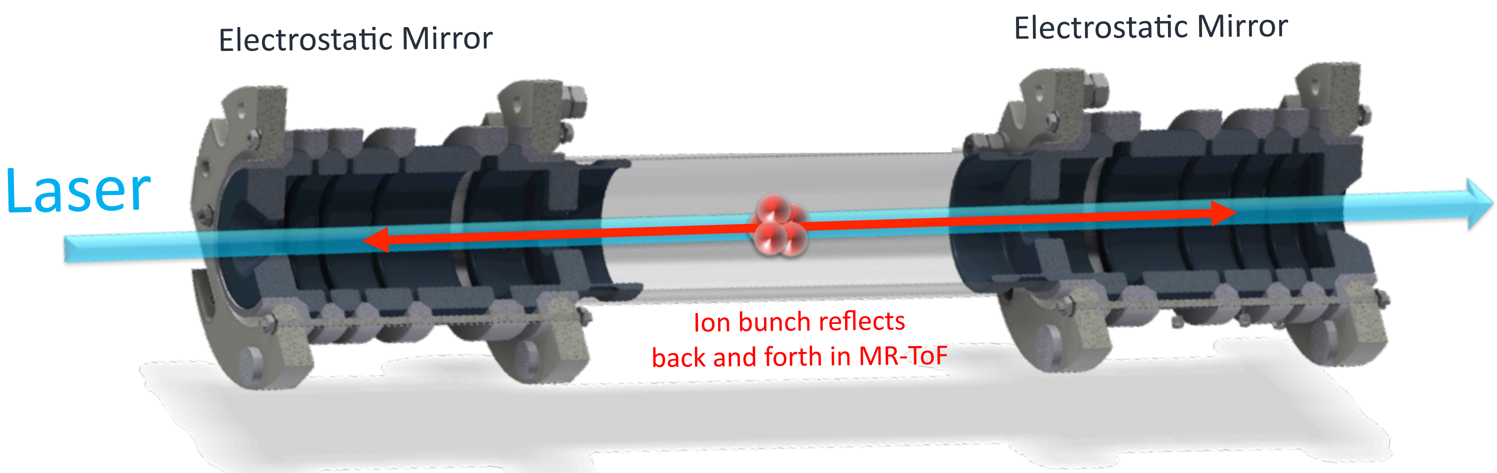
European Research Council

Novel methods to link RIB and AMO techniques for future BSM physics studies

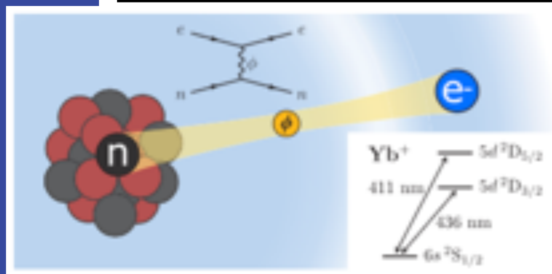


Stephan Malbrunot-Ettenauer
CERN research physicist

Searches for BSM physics

in AMO studies

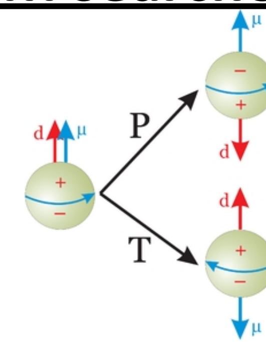
new forces and exotic interactions



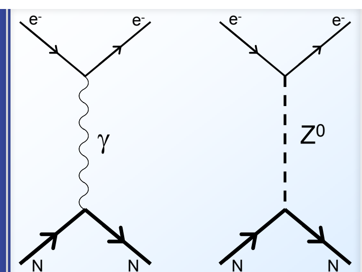
Lorentz invariance

dark matter searches

EDM searches



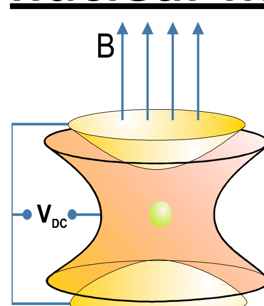
atomic parity violation



variation of fundamental constants

precision tests of QED

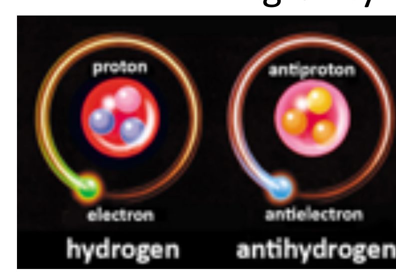
nuclear masses



- neutrino physics
- β-decays & BSM tests

antimatter

- CPT
- gravity

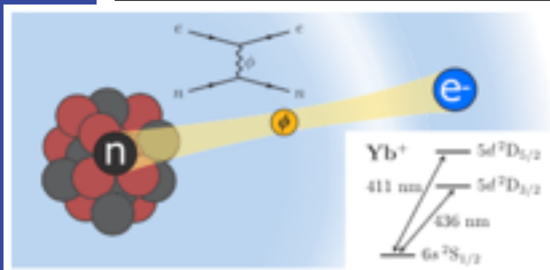


…tenauer: DND 2020

M. S. Safronova et al., Rev. Mod. Phys. 90, 025008 (2018)

Searches for BSM physics

new forces and exotic interactions



Lorentz invariance

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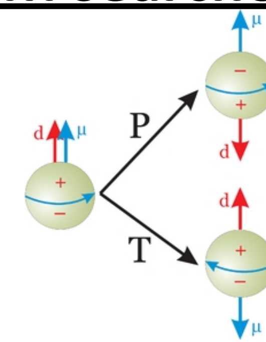

in AMO studies

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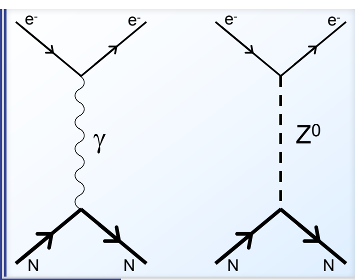

variation of fundamental constants

antimatter

- CPT
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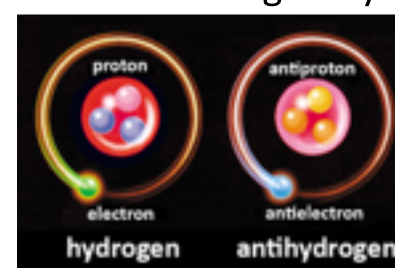


nuclear masses

precision tests of QED

utilising radioactive nuclides

...al., *Rev. Mod. Phys.* 90, 025008 (2018)

Radioactive molecules & EDMs

long coherence time

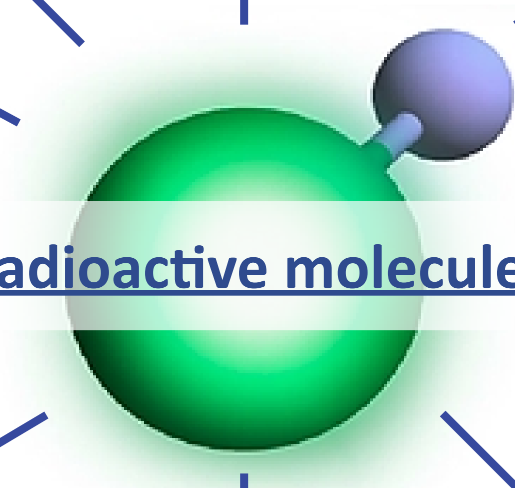
complementary physics
- parity violation
- quantum chemistry
- nuclear structure

laser cooling

co-magnetometry / B-field insensitivity

close-lying opposite parity states

large E_{eff}
$\propto Z^2 R(Z)$

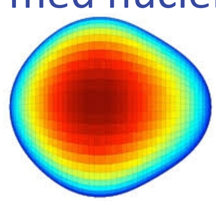


radioactive molecules

nuclear-spin-independent component & electron EDM

CP violating nuclear Magnetic Quadrupole Moment

Schiff moment
deformed nuclei



same chemistry
different physics sensitivity
systematic spin dependence

nuclear-spin-dependent component & hadronic EDM

	222Ra	223Ra	224Ra	225Ra	226Ra	227Ra	228Ra	229Ra	230Ra
	38.0 S	11.43 D	3.6319 D	14.9 D	1600 Y	42.2 M	5.75 Y	4.0 M	93 M
Spin=	0	3/2	0	1/2	0	3/2	0	5/2	0

Challenges

AMO physics		RIB science
stable	**Time**	$T_{1/2}$: ms - s - min - days - …
'∞'	**Intensity**	yields: 1/s to '>10^9/s'
'whatever it takes'	**Purity**	(isobaric) contamination: 1:0-10^6 or more
μK - mK - K cold beams or tapped	**Temperature**	ISOL target ≈2000 ˚C transport beam: 10s of keV
	Accelerator Environment	RIB availability/schedule EM noise
sensitive, high precision devices	**Radiation Safety**	limits access to core of apparatus

Challenges: radioactive molecules

Formation

Limited Knowledge

radioactive molecules

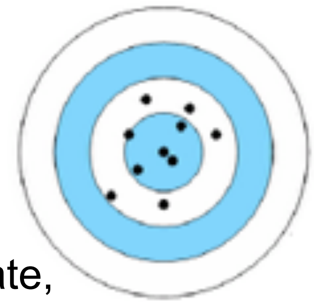
Identification and Separation

Suitable Spectroscopy Techniques

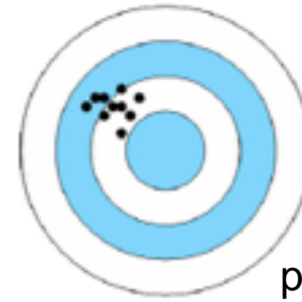
atomic physics techniques at RIB facilities

high **precision and accuracy**

K. Blaum, et al., Phys. Scr. T152, 014017 (2013)
P. Campbell et al., Prog. Part. and Nucl. Phys. 86, 127-180 (2016)
J. Dilling et al., Annu. Rev. Nucl. Part. Sci. 68, 45 (2018)



accurate,
but not precise



precise,
but not accurate

ion traps
- masses
- RIB preparations
- mass separation
- in-trap decay

laser spectroscopy
- hyperfine structure
- isotope shifts
- optical pumping

atom traps
- in-trap decay
- laser spectroscopy
- APV

atomic physics techniques at RIB facilities

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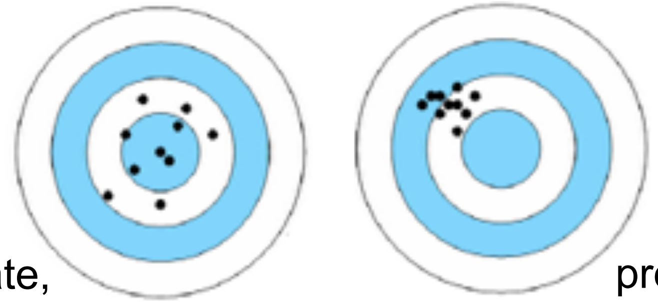

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atom traps
- in-trap decay
- laser spectroscopy
- APV

Challenges

short half-lives

$T_{1/2} < 10$ ms

($\Delta m/m=6\cdot10^{-8}$)

M. Smith et al., PRL 101, 202501 (2008)

low intensity

masses: 0.5 ions / h

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

temperature

buffer gas cooling

selected cases of laser cooling

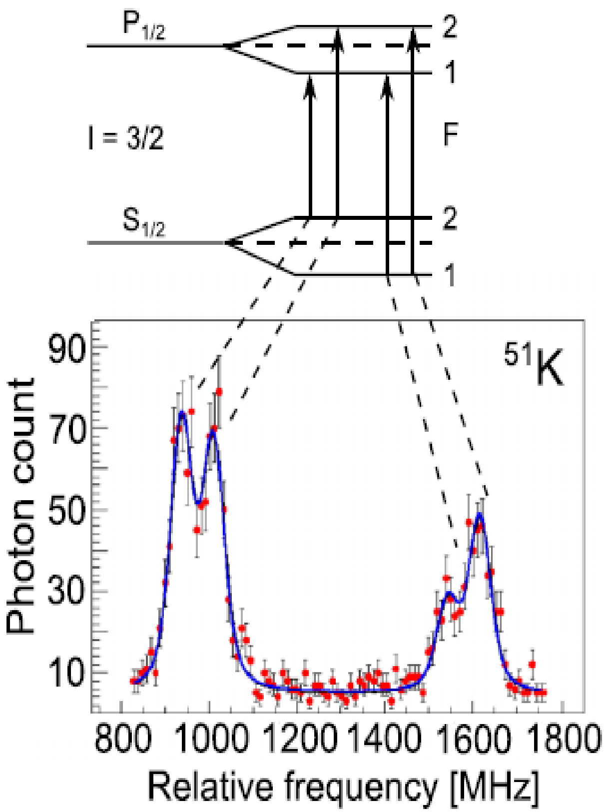
purity

$R=m/\Delta m>5\cdot10^{6}$

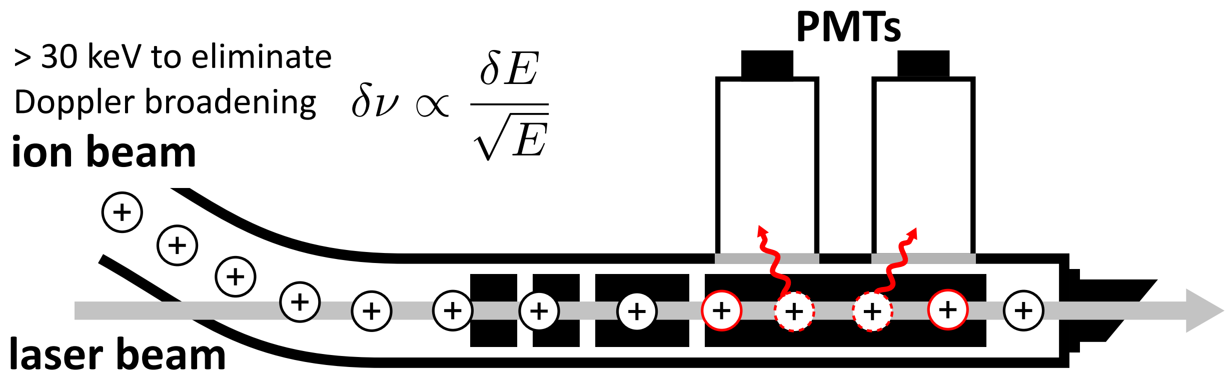
limited ion capacity

S. Eliseev et al., PRL 110, 082501 (2013)

Collinear Laser Spectroscopy (CLS)



> 30 keV to eliminate Doppler broadening $\delta\nu \propto \frac{\delta E}{\sqrt{E}}$



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P. Campbell et al., Prog. Part. and Nucl. Phys. 86, 127-180 (2016)
R. Neugart et al., J. Phys. G: Nucl. Part. Phys. 44, 064002 (2017)

Sensitivity limit
- 10^3-10^5/s for atoms/ions
- much lower for molecules

Collinear Laser Spectroscopy (CLS)

K. Blaum et al., Phys. Scr. T152, 014017 (2013)
P. Campbell et al., Prog. Part. and Nucl. Phys. 86, 127-180 (2016)
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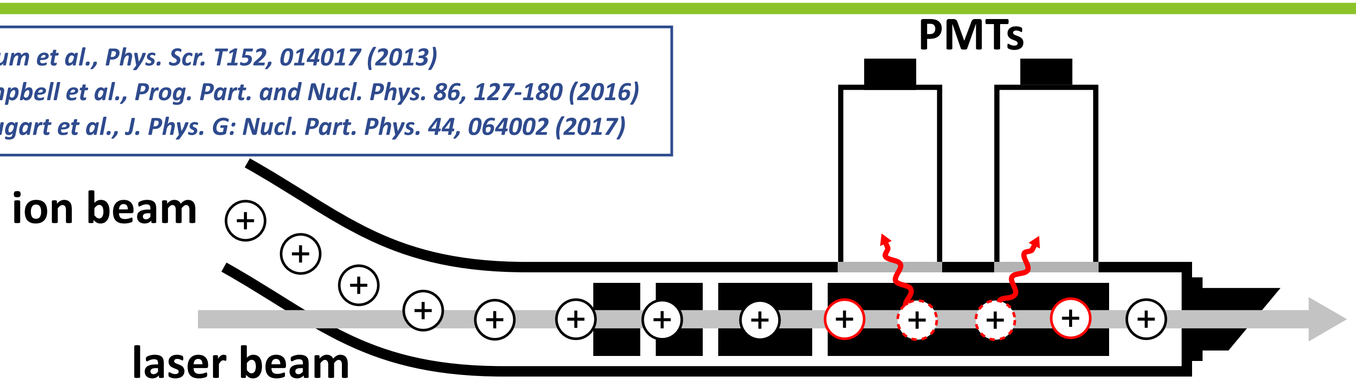
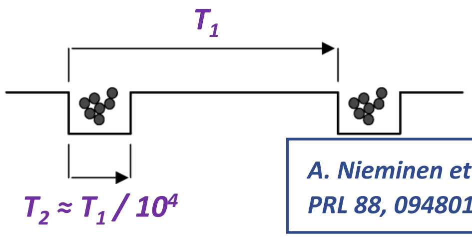


Fast beams (≥30 keV) minimises Doppler-broadening

$$\delta\nu \propto \frac{\delta E}{\sqrt{E}}$$

Bunched beams: reduce background by gating on bunch



A. Nieminen et al., PRL 88, 094801 (2002)

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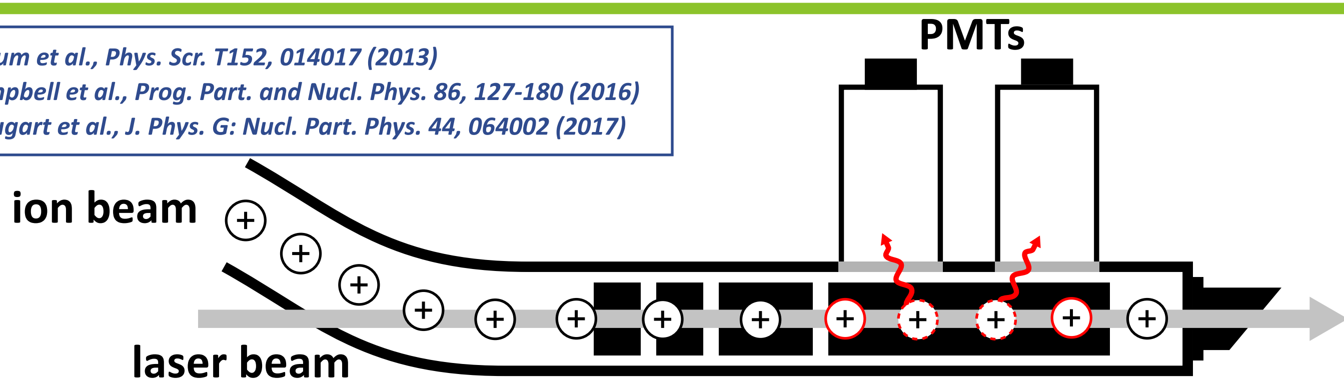

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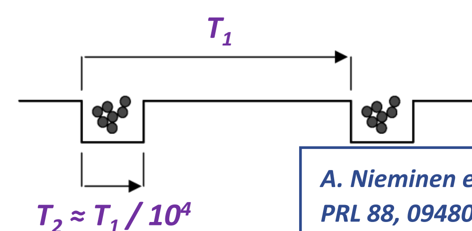


A. Nieminen et al., PRL 88, 094801 (2002)

$T_{1/2}$ of accessible radionuclides:
5 ms to seconds

⟷

effective use for CLS
100s of ns to a few µs

¿ can one use exotic nuclides even more efficiently ?

the Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy

laser spectroscopy

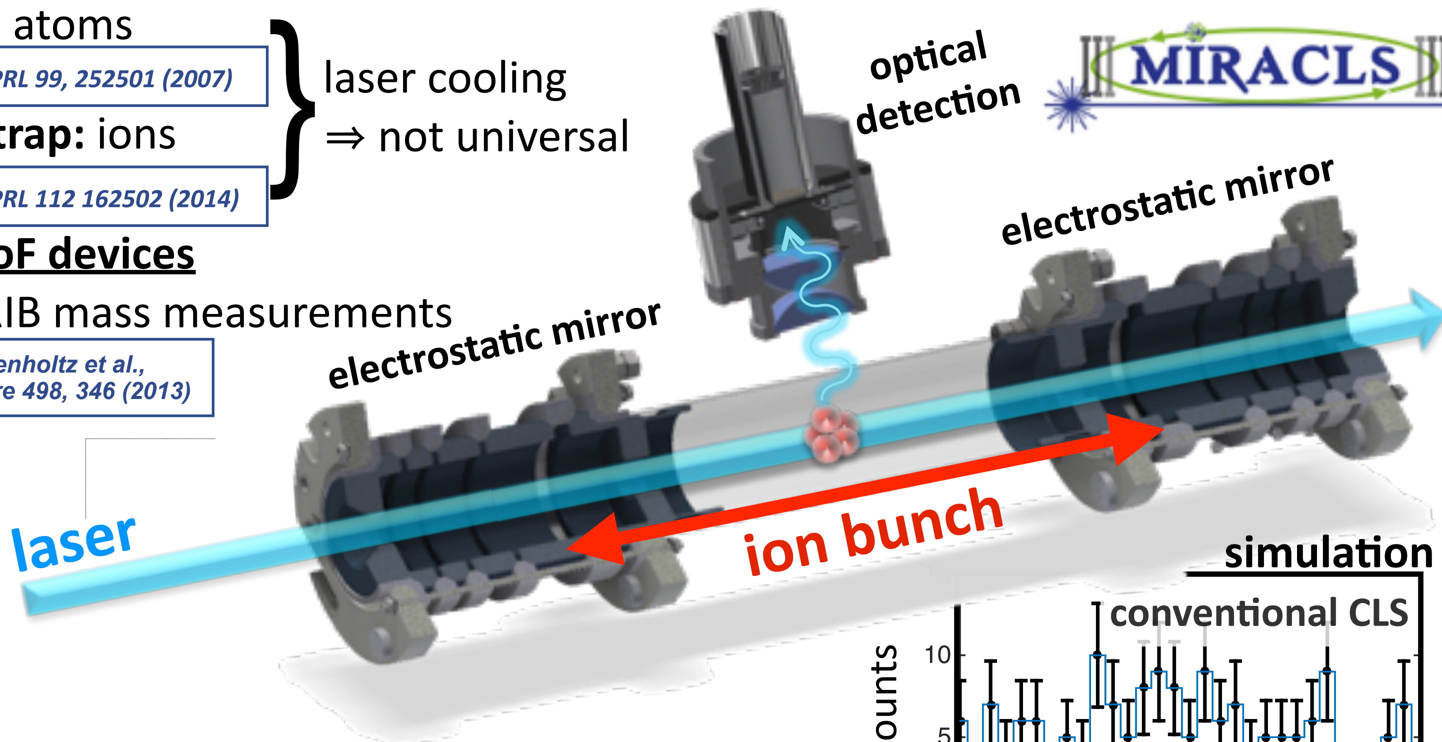
trap ⇒ long observation time ⇒ higher sensitivity

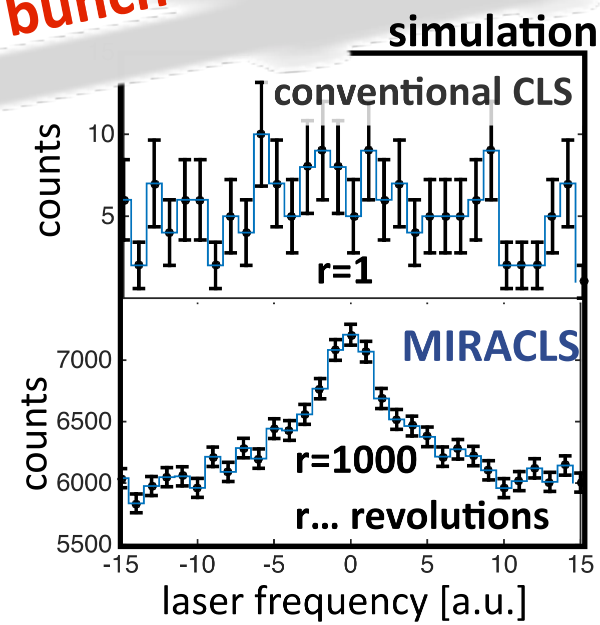
- **MOT:** atoms
  - *e.g.: PRL 99, 252501 (2007)*
- **Paul trap:** ions
  - *e.g.: PRL 112 162502 (2014)*

} laser cooling ⇒ not universal

- **MR-ToF devices**
  first RIB mass measurements
  - *F. Wienholtz et al., Nature 498, 346 (2013)*

MIRACLS



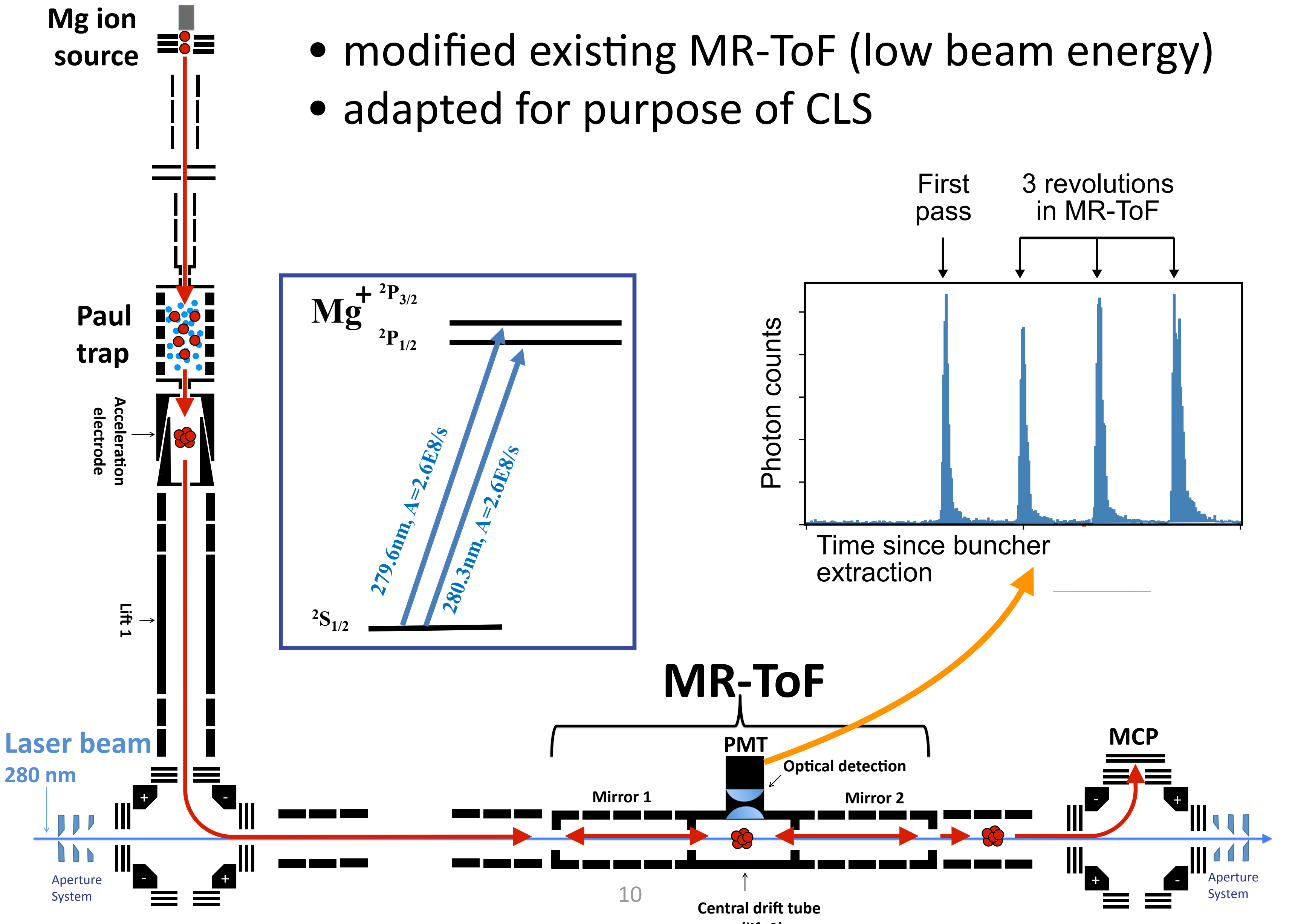


novel approach for collinear laser spectroscopy:

- ion trap ⇒ long observation time
- 30 keV beam ⇒ high resolution

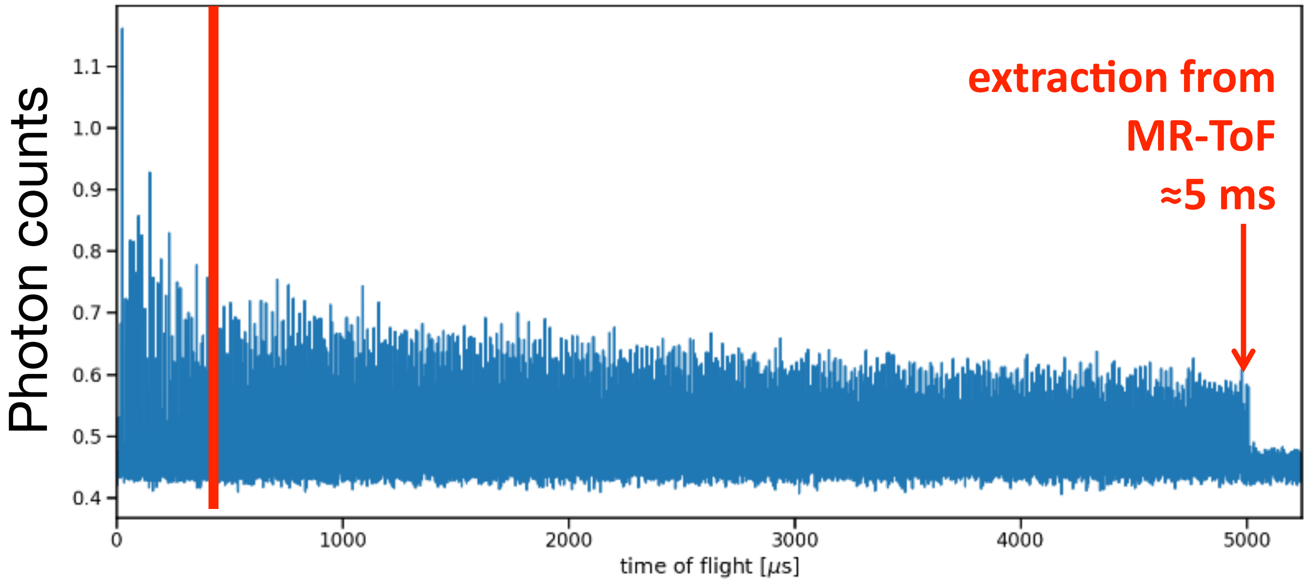
proof-of-principle experiment

- modified existing MR-ToF (low beam energy)
- adapted for purpose of CLS



MIRACLS performance

laser spectroscopy



S. Sels et al., Nucl. Instr. Meth. B 463, 310 (2020)
F. Maier et al., Hyperfine Interact. 240, 54 (2019)
S. Lechner et al., Hyperfine Interact 240, 95 (2019)
V. Lagaki et al., Acta Phys. Pol. B 51, 571 (2020)
V. Lagaki et al., in preparation
S. Sels et al., in preparation

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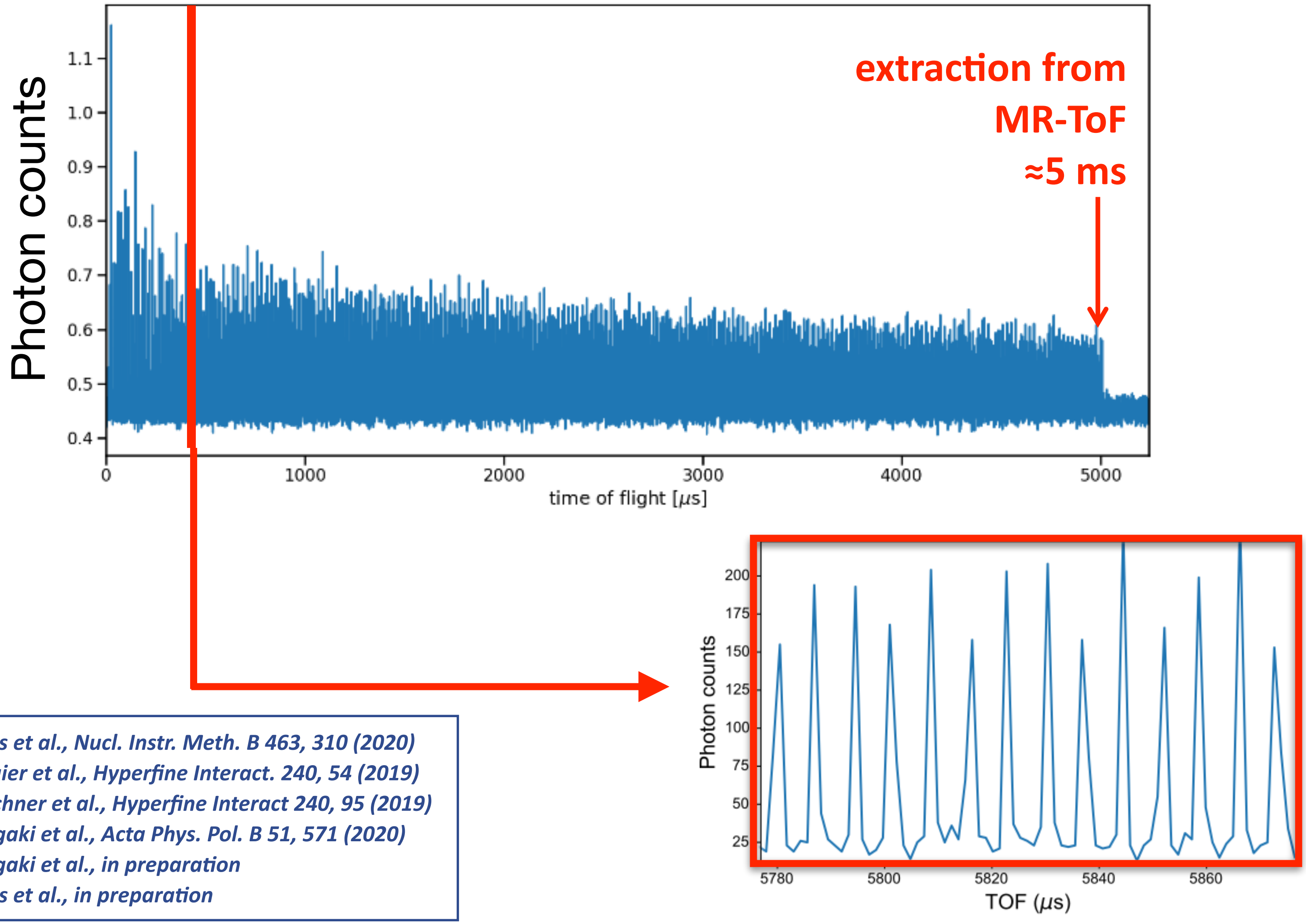

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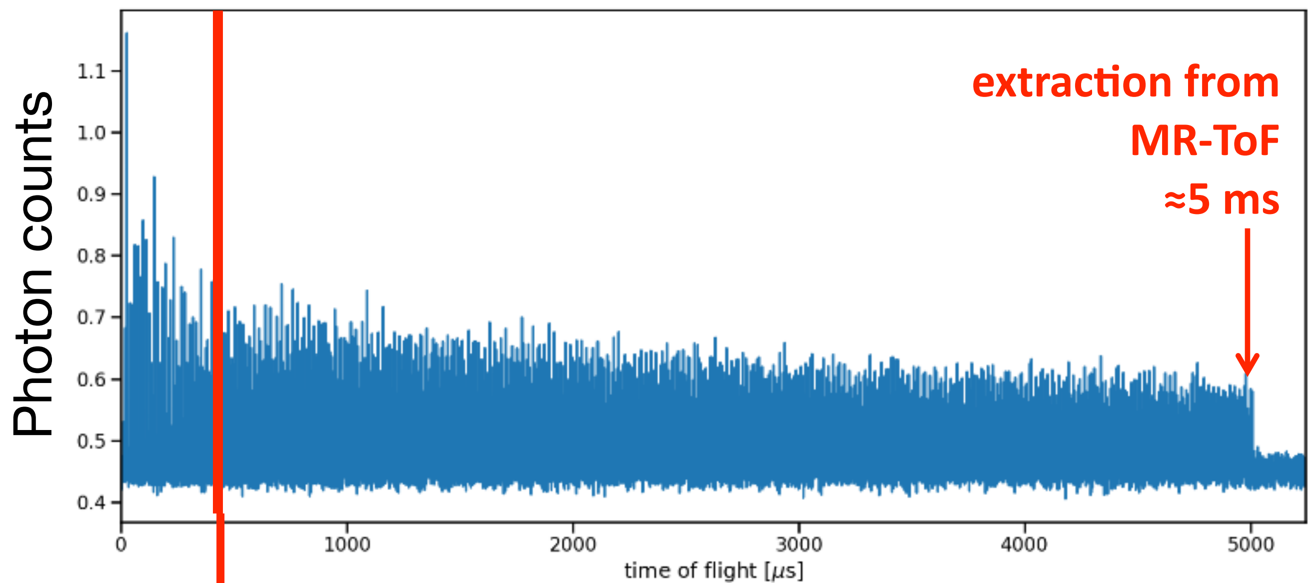

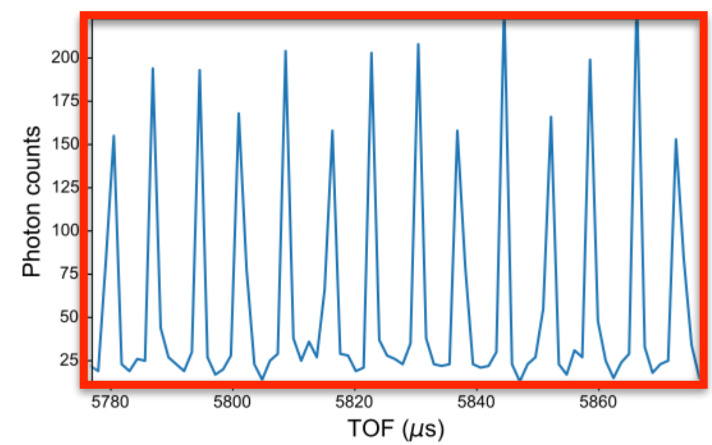

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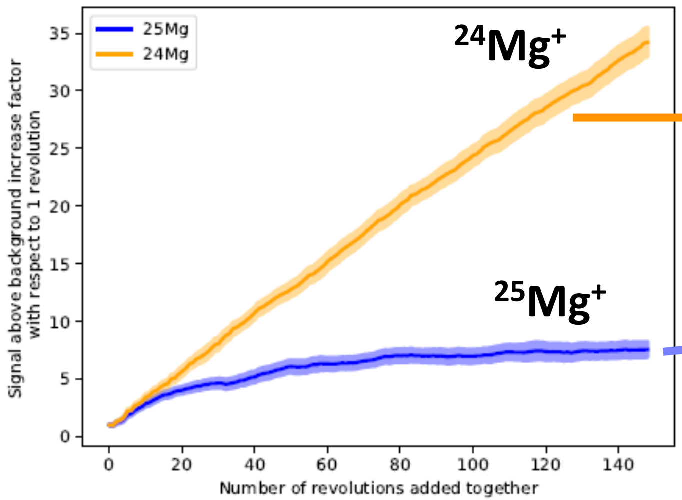
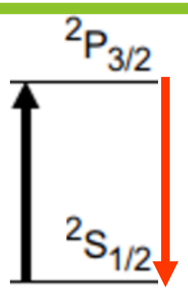
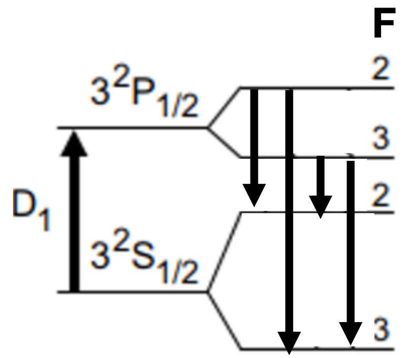
S. Sels et al., in preparation

online measurements with *O*(10) ions/sec possible

MIRACLS for non-closed level systems



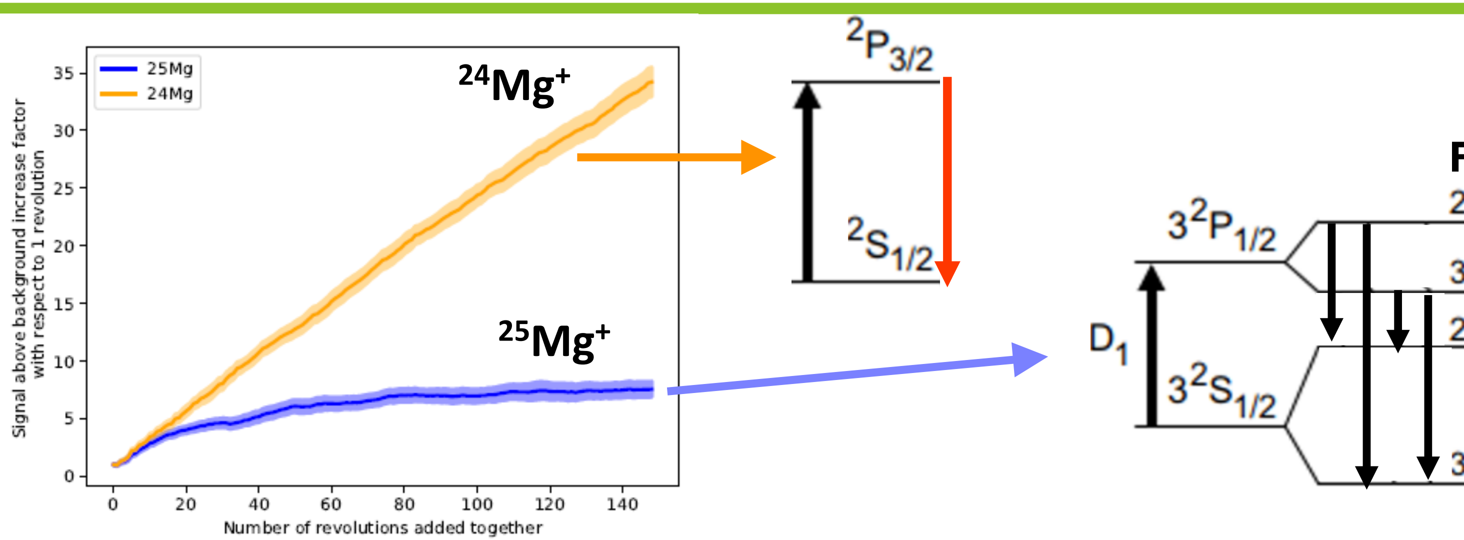




laser spectroscopy

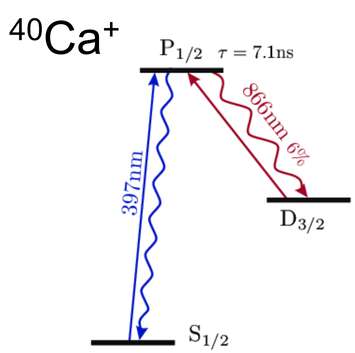
MIRACLS for non-closed level systems

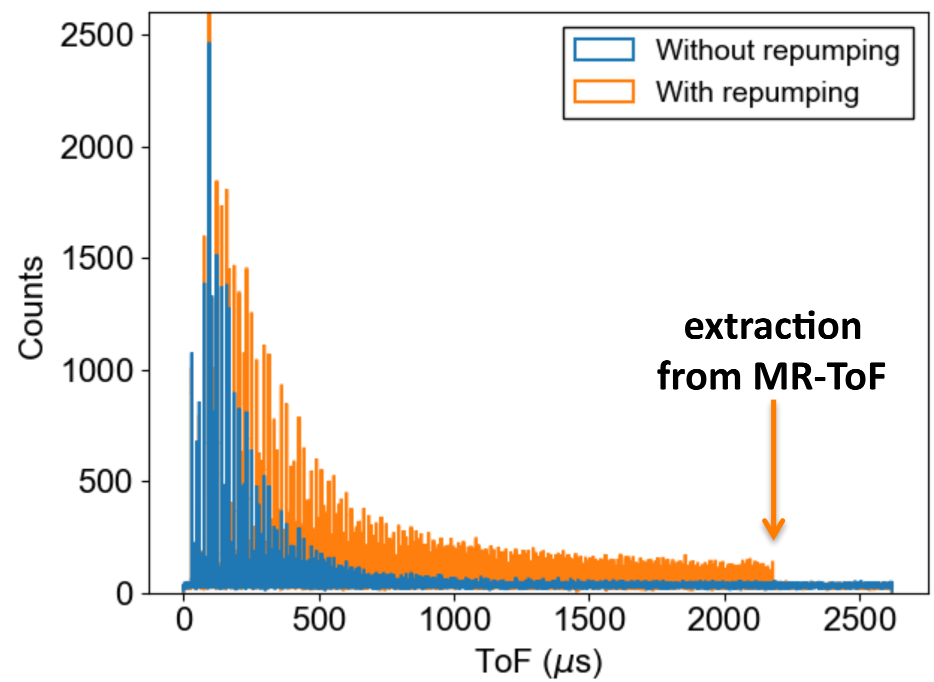
laser spectroscopy



significant improvement,
but can do better:

- re-pumping
- re-thermalisation in Paul trap

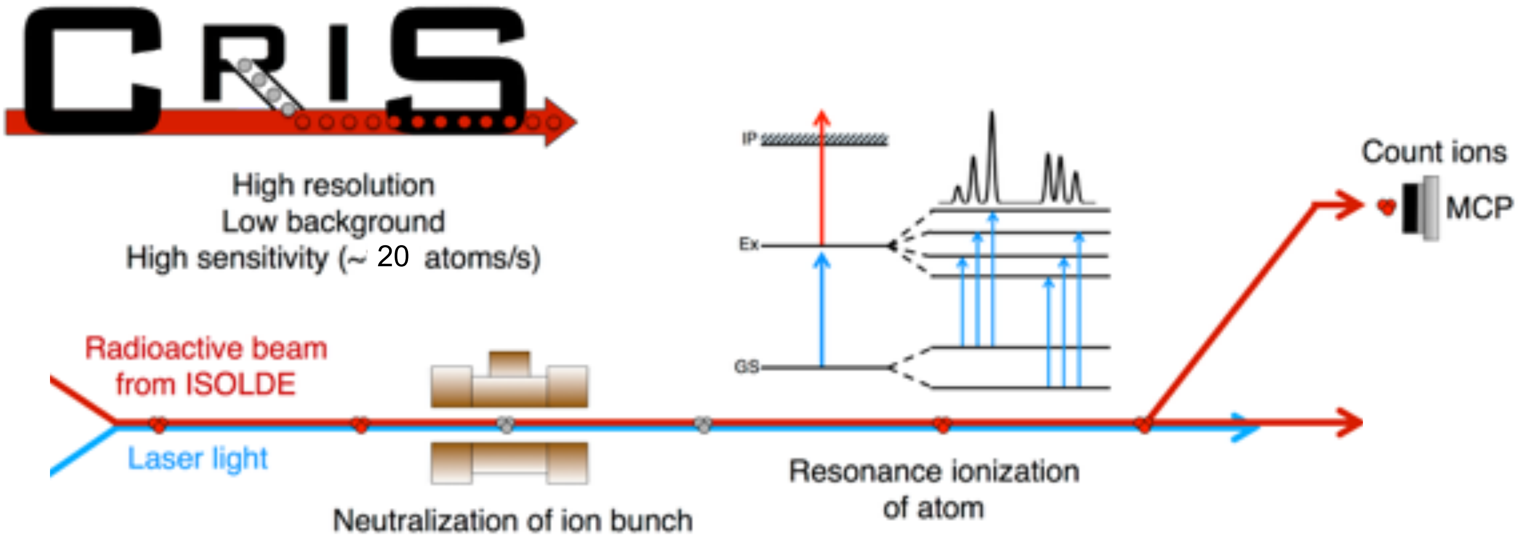


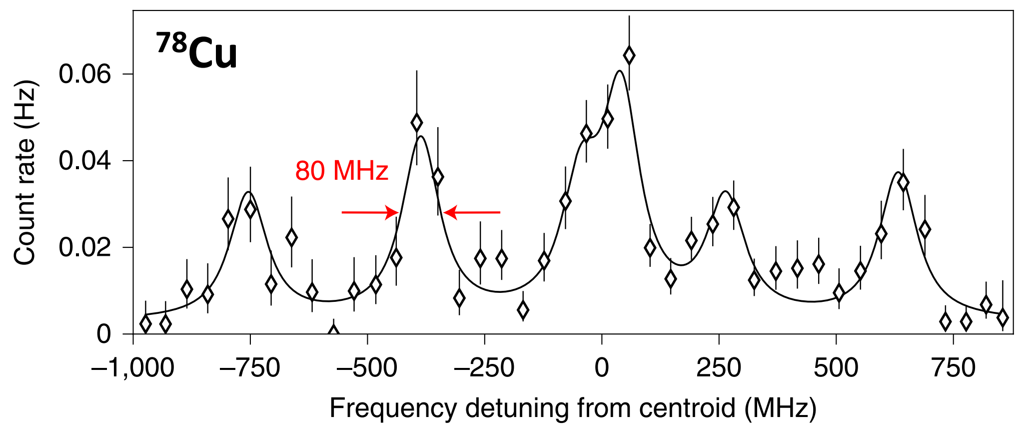


S. Malbrunot-Ettenauer: DND 2020

Collinear Resonance Ionization Spectroscopy

laser spectroscopy



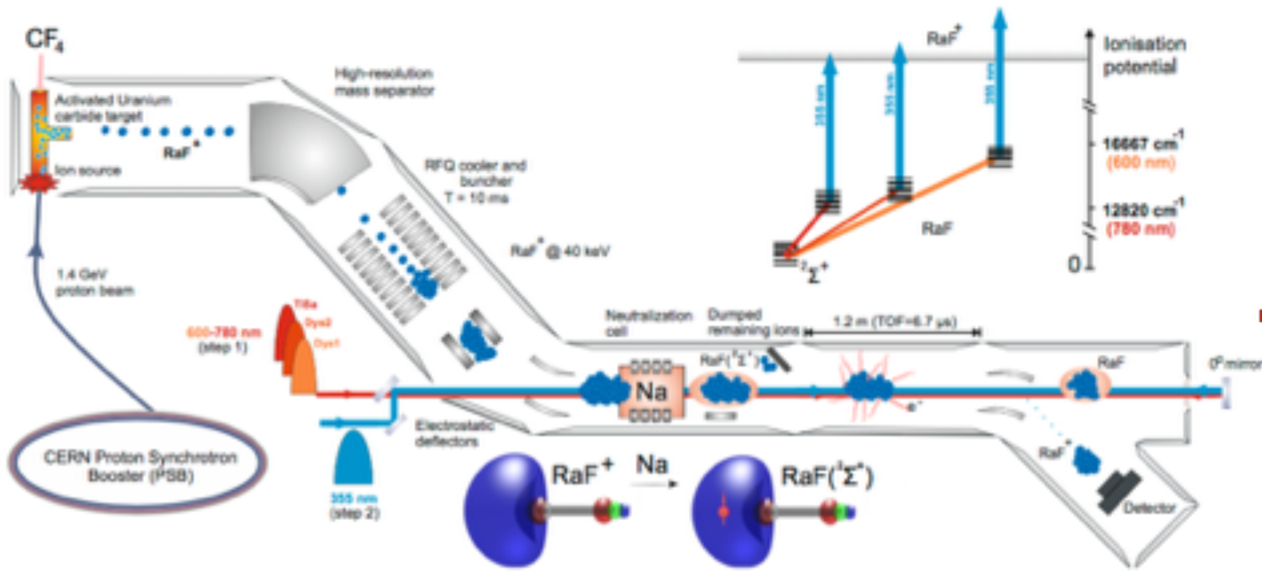


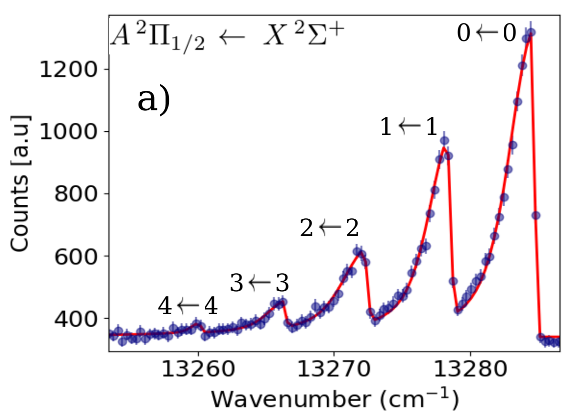
- 20 ions/sec to CRIS
- $T_{1/2}$=335 ms
- high resolution

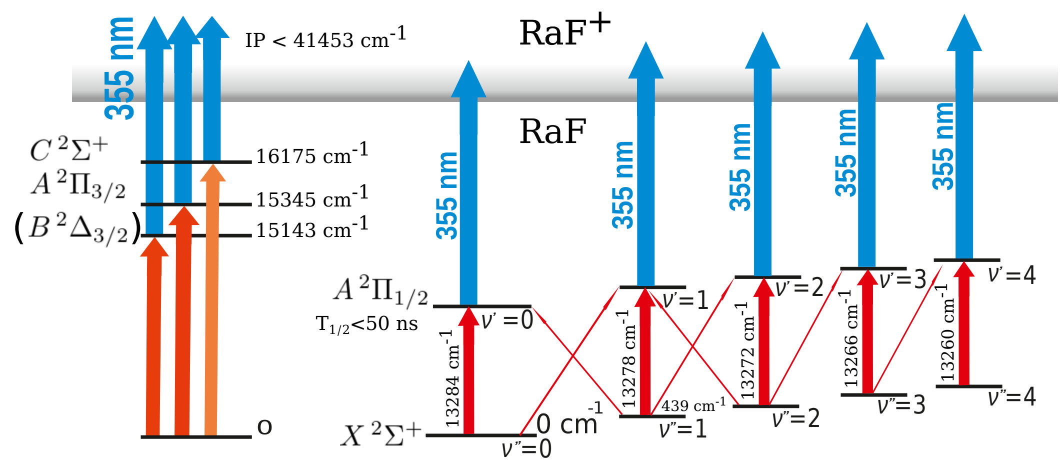
R. P. de Groote et al., Nat. Phys. 16, 620-624 (2020)
A. R. Vernon et al., Sci. Rep. 10, 12306 (2020)
R. F. Garcia Ruiz et al., Nature 581, 396 (2020)
R. F. Garcia Ruiz et al., Phys. Rev. X 8, 041005 (2018)

First spectroscopy of radioactive molecules

laser spectroscopy







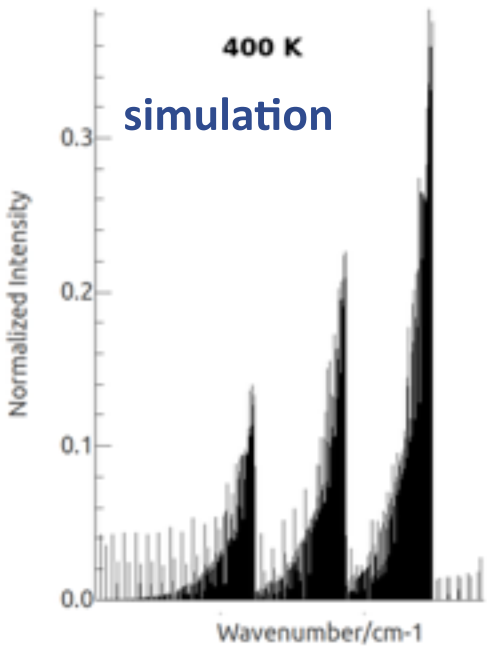
S. Malbrunot-Ettenauer: DND 2020

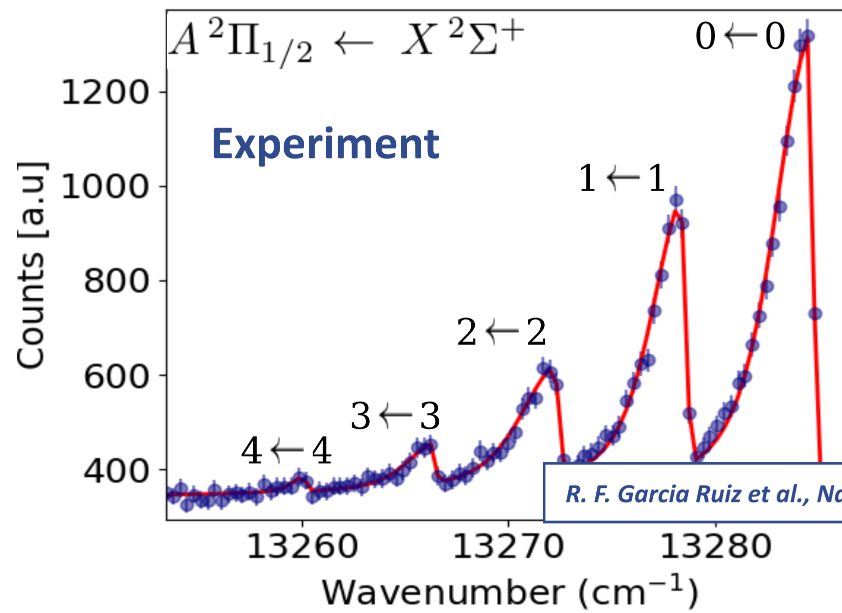
R. F. Garcia Ruiz et al., Nature 581, 396 (2020)

laser spectroscopy of molecules

- cooling of internal degrees of freedom (especially vibrations)
  ➡ higher population of the low-lying states
  ➡ simpler spectra ⇒ more easily identification
- buffer-gas cooling in cryogenic Paul trap:
  ➡ overall the gain could be more than x100 in scanning time.
  ➡ enables efficient initial state preparation for later EDM searches

RaF spectra





R. F. Garcia Ruiz et al., Nature 581, 396 (2020)

simulation by R. F. Garcia Ruiz

cooling

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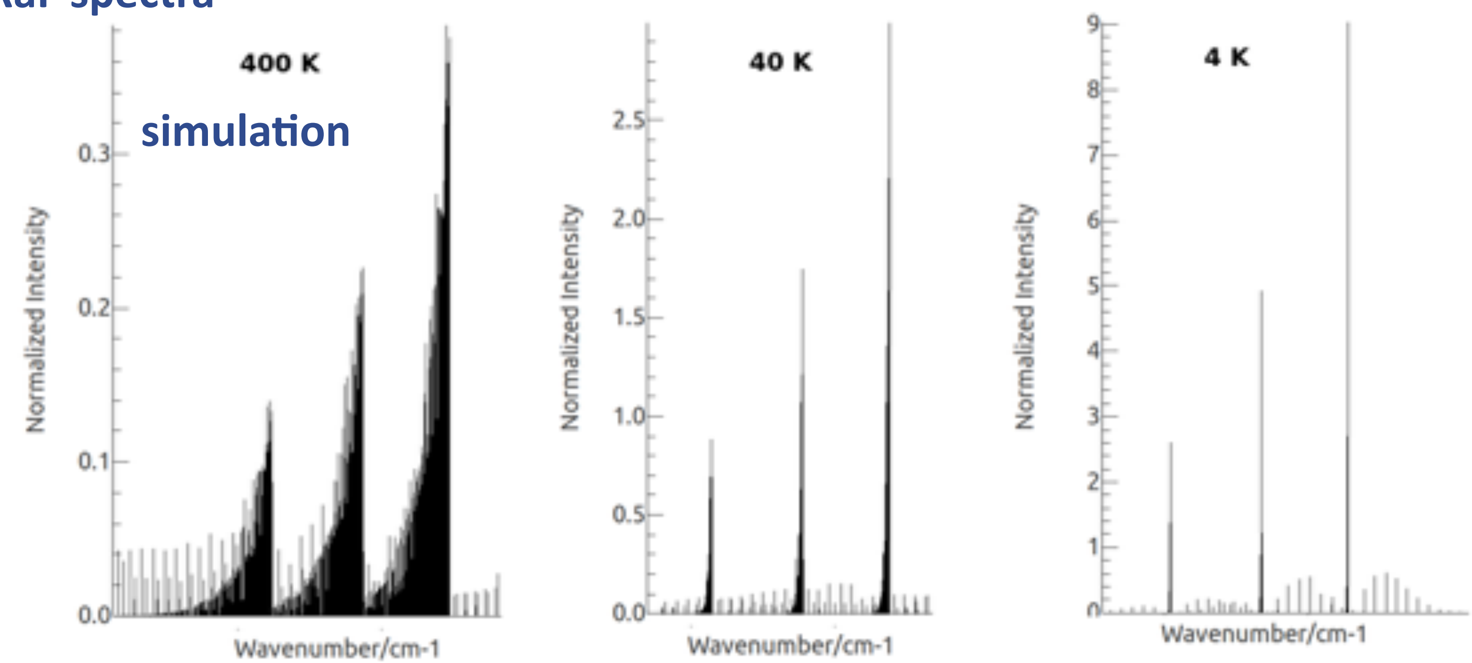


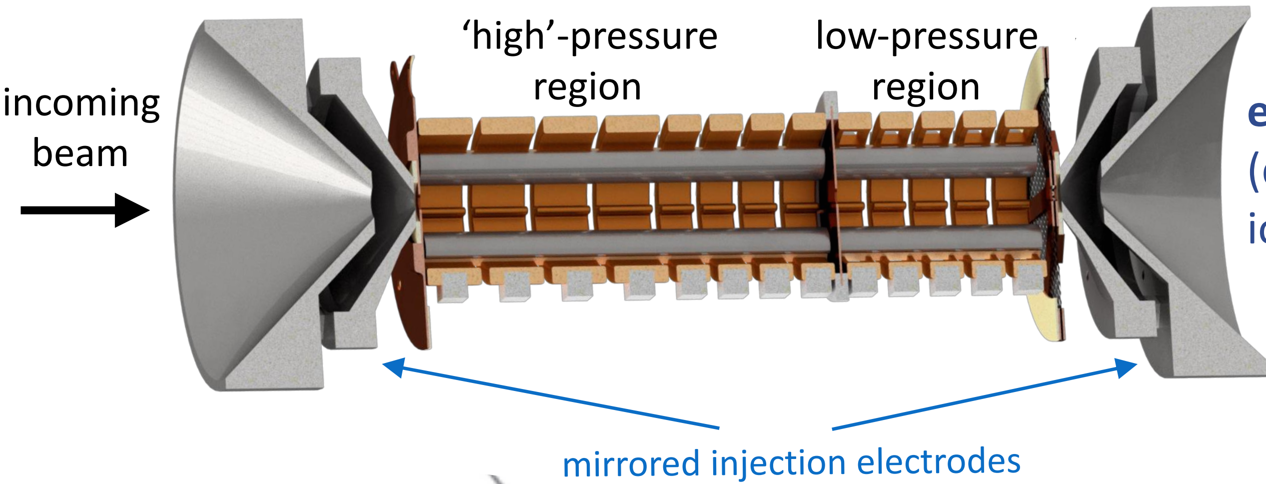
simulation by R. F. Garcia Ruiz

S. Malbrunot-Ettenauer: DND 2020

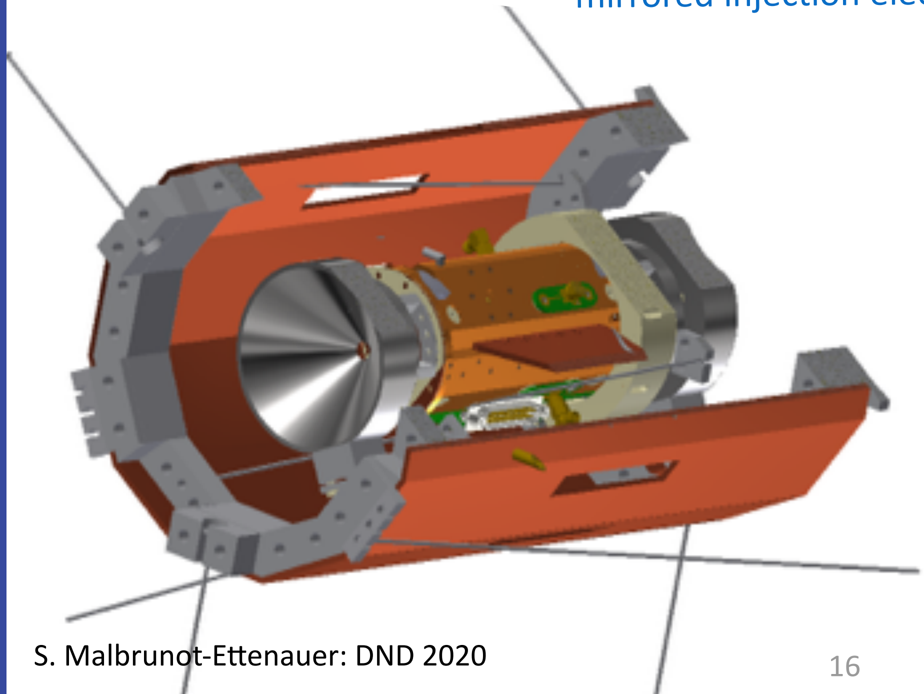
cooling

cryogenic, buffer-gas filled Paul

cooling



eliminates re-heating
(during extraction and ion acceleration)



- operation at 4 K
- cooling of ions and molecules
- emittance improvement

$$\xi_{95\%,long} \approx 2\pi \ln(20) \frac{k_B T}{\omega_z}$$

- axial and radial laser access

S. Lechner, S. Sels et al, in preparation

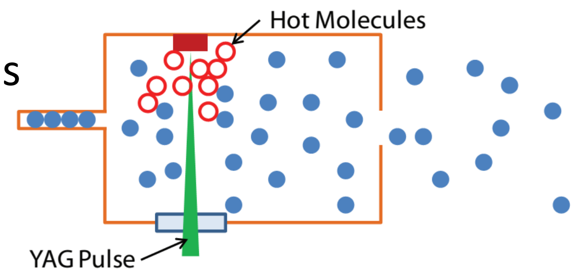
Cryogenic cell for neutral beams

cooling

- charge exchange of cryo-cooled ion beam: re-heating?
- cryogenic buffer gas beam cell :
  - ➡ universal tool to obtain cold, slow, high-flux beams

N. R. Hutzler et al., Chem. Rev. 112, 4803 (2012)
S. Truppe et al., J. of Modern Optics, 65, 648 (2018)

  - ➡ how to use it for radioactives?



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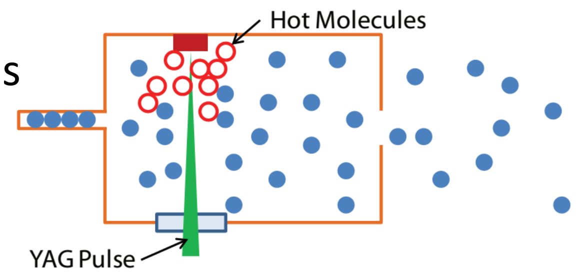

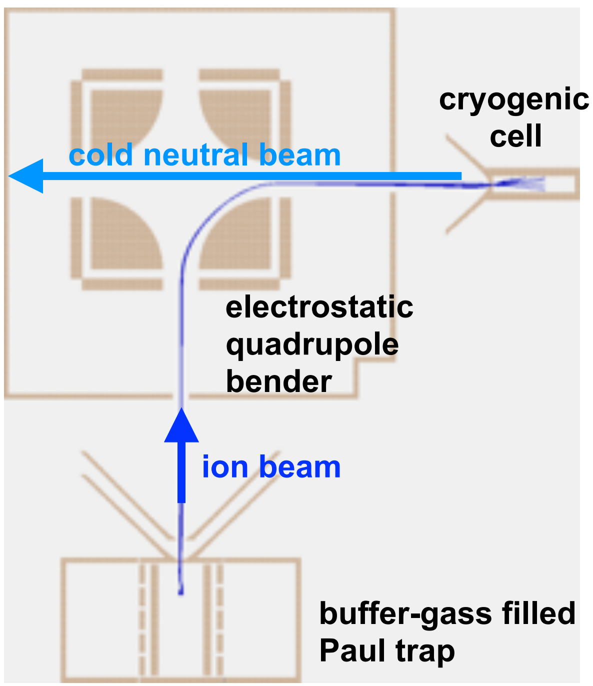

cooling

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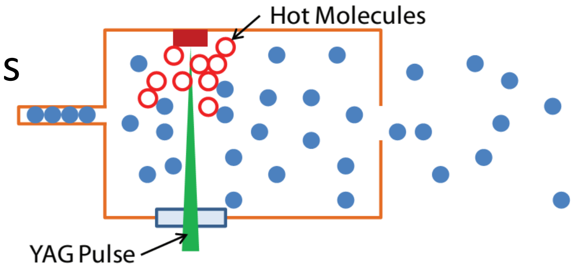
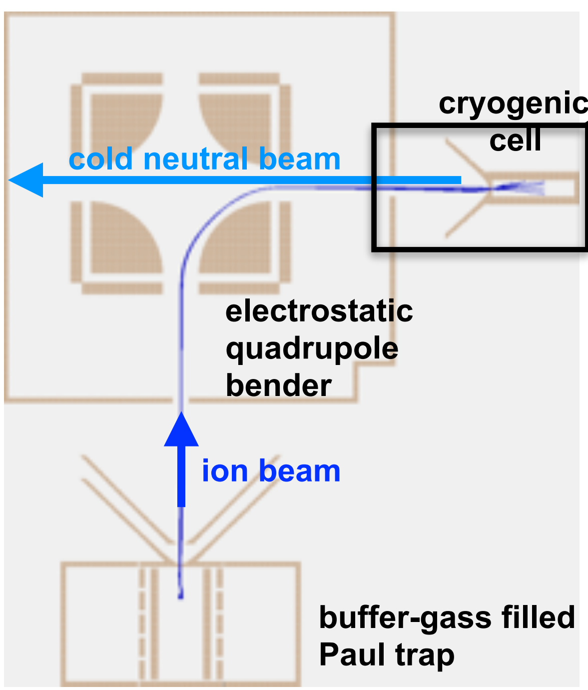
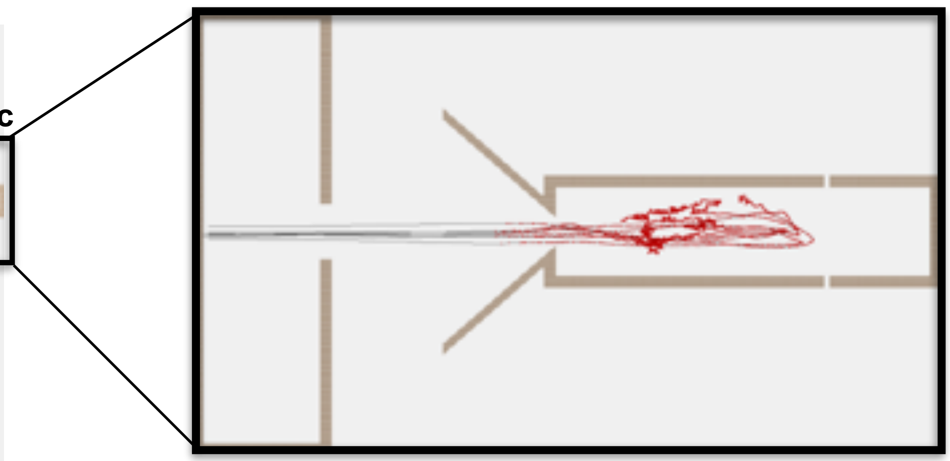
- charge exchange of cryo-cooled ion beam: re-heating?
- cryogenic buffer gas beam cell :
  - ➡ universal tool to obtain cold, slow, high-flux beams

N. R. Hutzler et al., Chem. Rev. 112, 4803 (2012)
S. Truppe et al., J. of Modern Optics, 65, 648 (2018)

  - ➡ how to use it for radioactives?





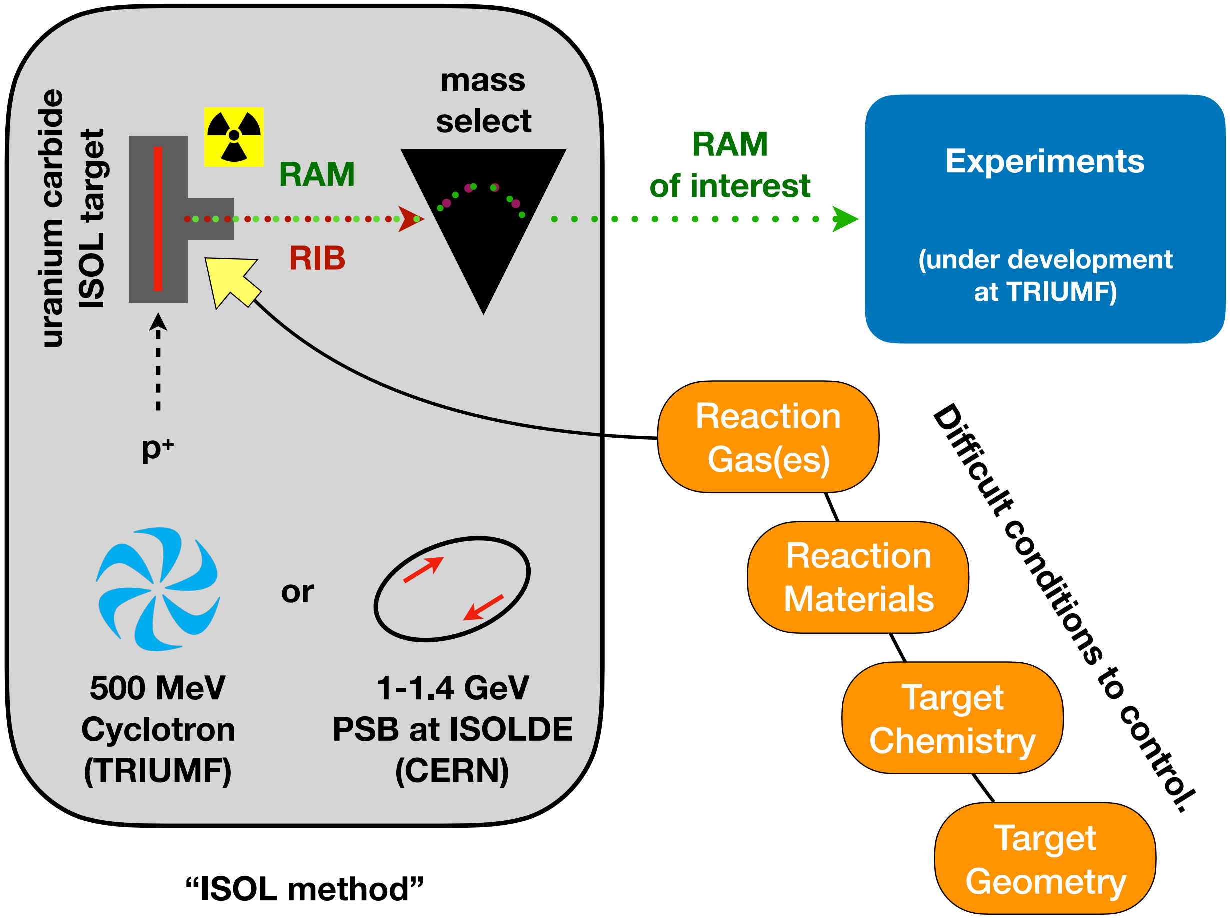


ion neutralisation close to extraction point:

- magnetic guidance
- electric reflection

formation of radioactive molecules

molecule formation

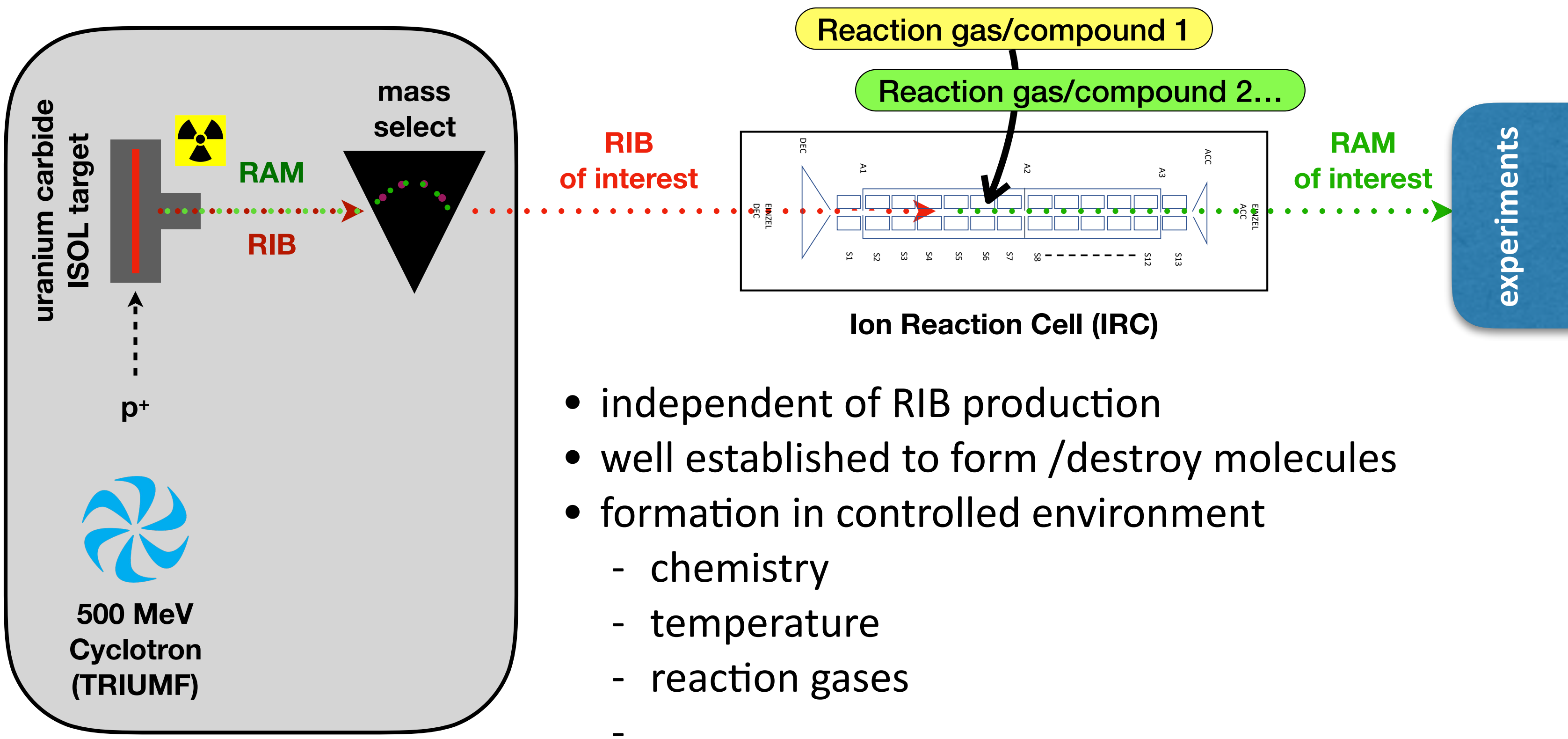


"ISOL method"

courtesy of Chris R.J. Charles

formation of radioactive molecules

molecule formation



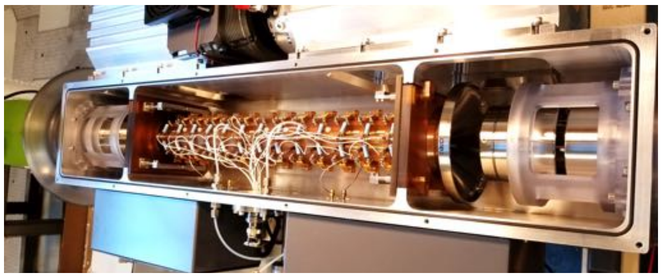
"ISOL method"

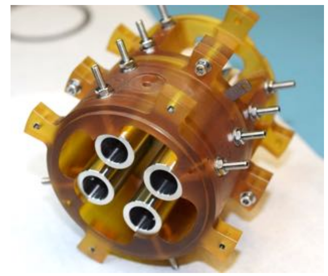
- independent of RIB production
- well established to form /destroy molecules
- formation in controlled environment
  - chemistry
  - temperature
  - reaction gases
  - …
- offline testing and operation

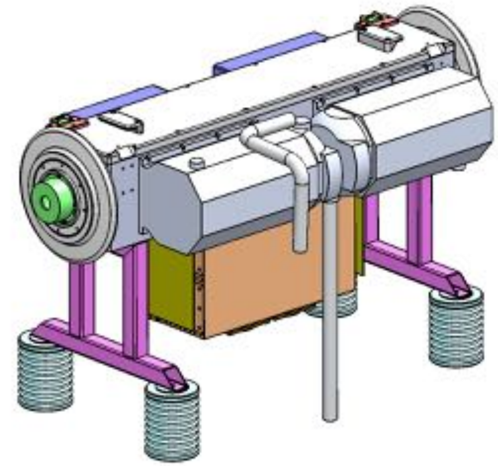
courtesy of Chris R.J. Charles

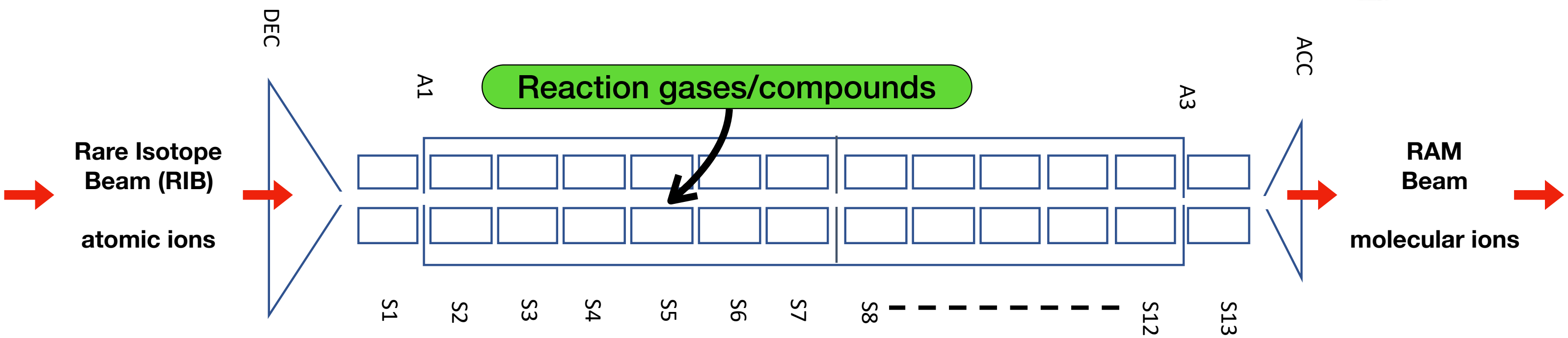
formation of radioactive molecules

IRC (ion reaction cell)









RFQ column geometry is reconfigurable.

Decelerating stage	**Ion confinement & cooling stage (RFQ)**	**Reaction cell stage (RFQ)**	**Reaccelerating stage**

Quantitative Identification

i.e. MR-TOF

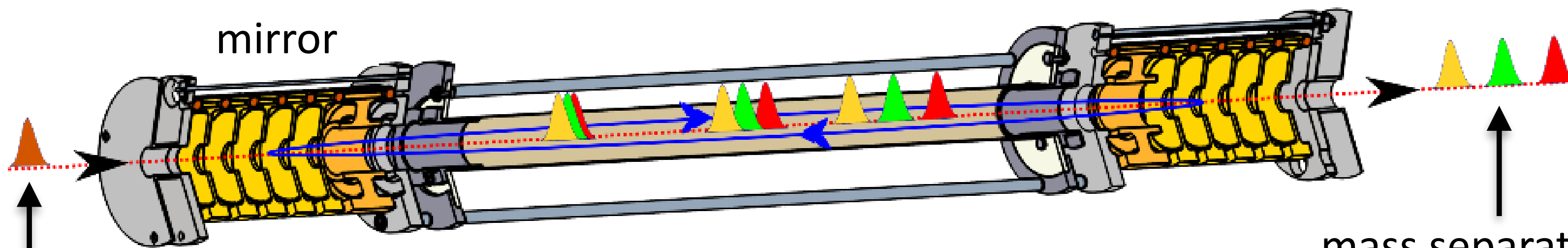
other mass or energy analyses

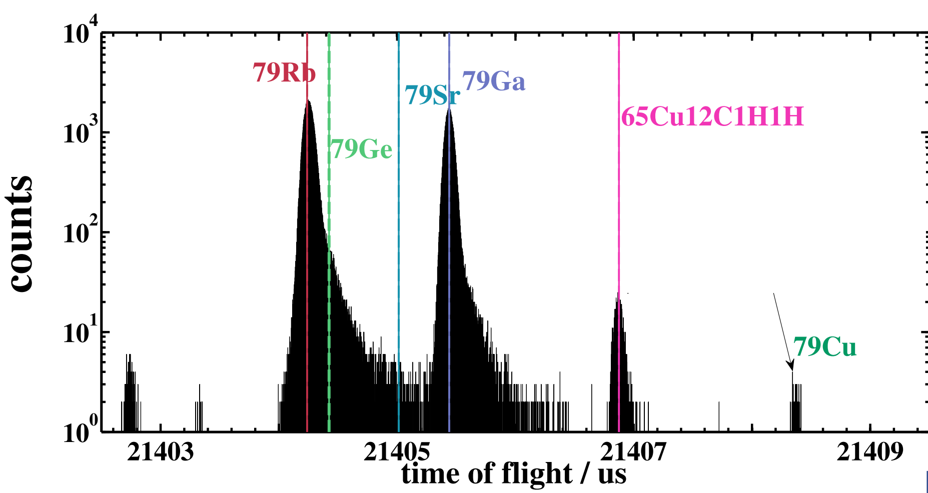
Measurements:
- **yields.**
- **Isotope ratios.**
- **Isotope/molecule ID.**
- **Trace analyses.**

courtesy of Chris R.J. Charles

MR-ToF devices

separation and identification





ion beam energy:

2.3 keV

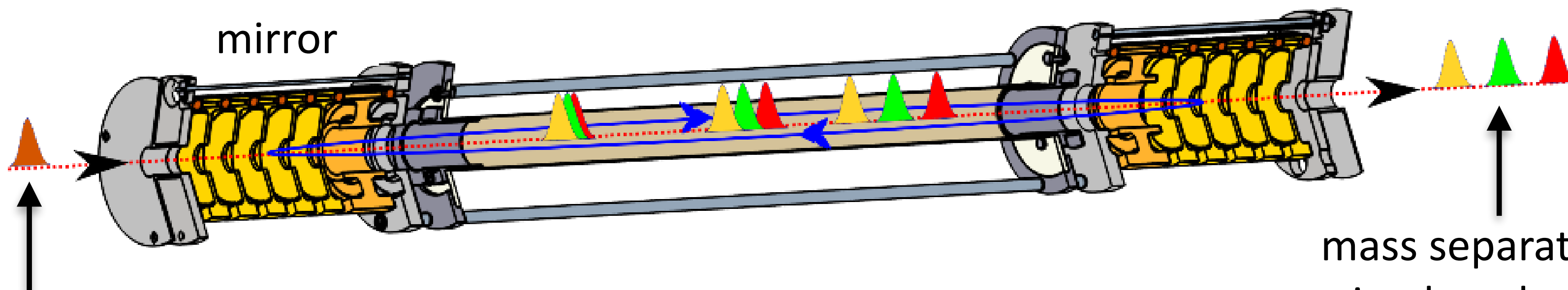
Mass resolving power (FWHM):

m/Δm=120 000 in 22ms ($^{85}Rb^{+}$)

F. Wienholtz et al., Nature 498, 346-349 (2013)
R. N. Wolf et al., Int. J. Mass Spectrom. 349-350, 123-133 (2013)
T. Dickel et al., NIM A 777, 172 (2015)
T. Dickel et al.Hyperfine Interactions, (2019)
E. Leistenschneider PRL 120 (2018) 062503

MR-ToF devices

separation and identification



fast

highly selective

magnetic separators

MR-ToF

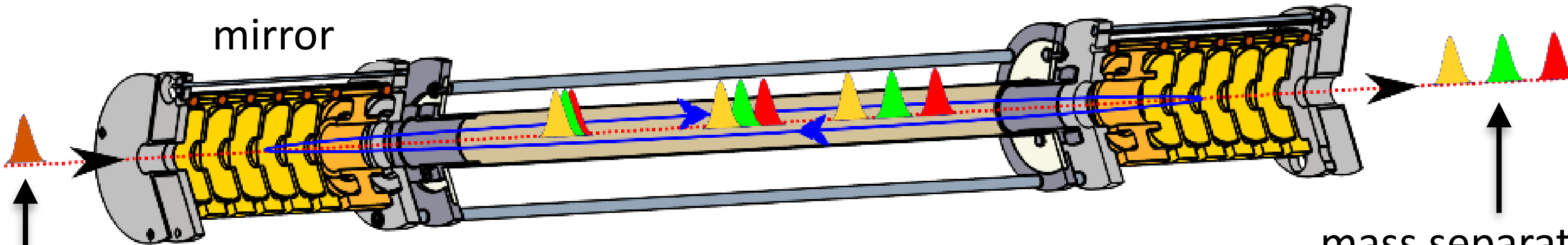
Penning traps

MR-ToF devices

separation and identification

electrostatic mirror

electrostatic mirror



incoming ion bunch

mass separated ion bunches

fast

highly selective

magnetic separators

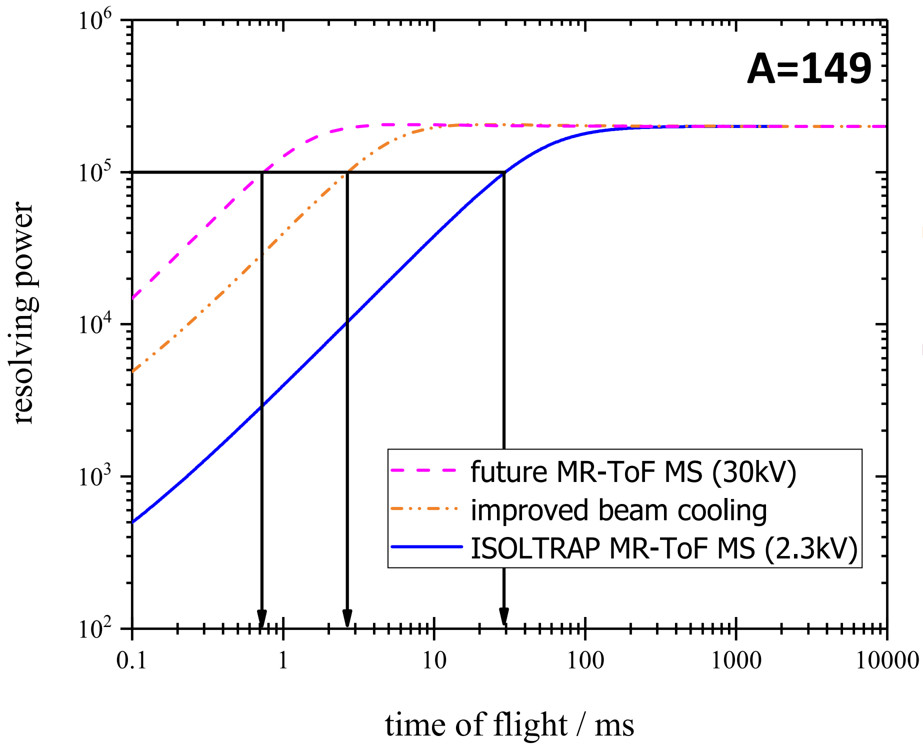
MR-ToF

Penning traps

space-charge effects limit ion capacity to ≈10^6/s

new opportunities for purified RIB

separation and identification



➡ **advanced beam preparations**
(in cryogenic Paul trap)

➡ **higher beam energy**

faster isobaric separation in MR-ToF while keeping high mass resolving power

➡ higher ion flux through MR-ToF device ('bypass' space-charge limits)

➡ **<u>MIRACLS: excellent synergy to development of MR-ToF with high-ion capacity</u>**

➡ initial goal: a few pA (ultimate goal: >100 pA)

S. Malbrunot-Ettenauer: DND 2020

Summary & Conclusions

- **AMO studies: high-precision searches for new physics**

- **Radioactive beams & Radioactive Molecules**
  - ➡ intriguing new opportunities for BSM physics
  - ➡ truly interdisciplinary
  - ➡ experimental challenges: link RIB and AMO technology

- **new developments**
  - ➡ laser spectroscopy methods

    CRIS MIRACLS
  - ➡ cooling methods
    - cryogenic Paul trap
    - integration of cryogenic buffer gas cell in RIB environment
    - laser cooling
  - ➡ molecule formation
  - ➡ mass separation and identification
  - ➡ ....

MIRACLS

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European Research Council

MIRACLS Alumni:

H. Heylen (2018-2020) F. Hummer (2019), **L. M. Bartels** (2018), **F. Maier** (2018), **L. Fischer** (2017), **F. Stabel** (2017), **S. Sailer** (2017)

ATTRACT

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CERN **Medical Applications Funds**

https://miracls.web.cern.ch

ISOLDE