TRIUMF

UNIVERSITY OF TORONTO

Atomic Physics Techniques for Precision Experiments at Accelerator Facilities

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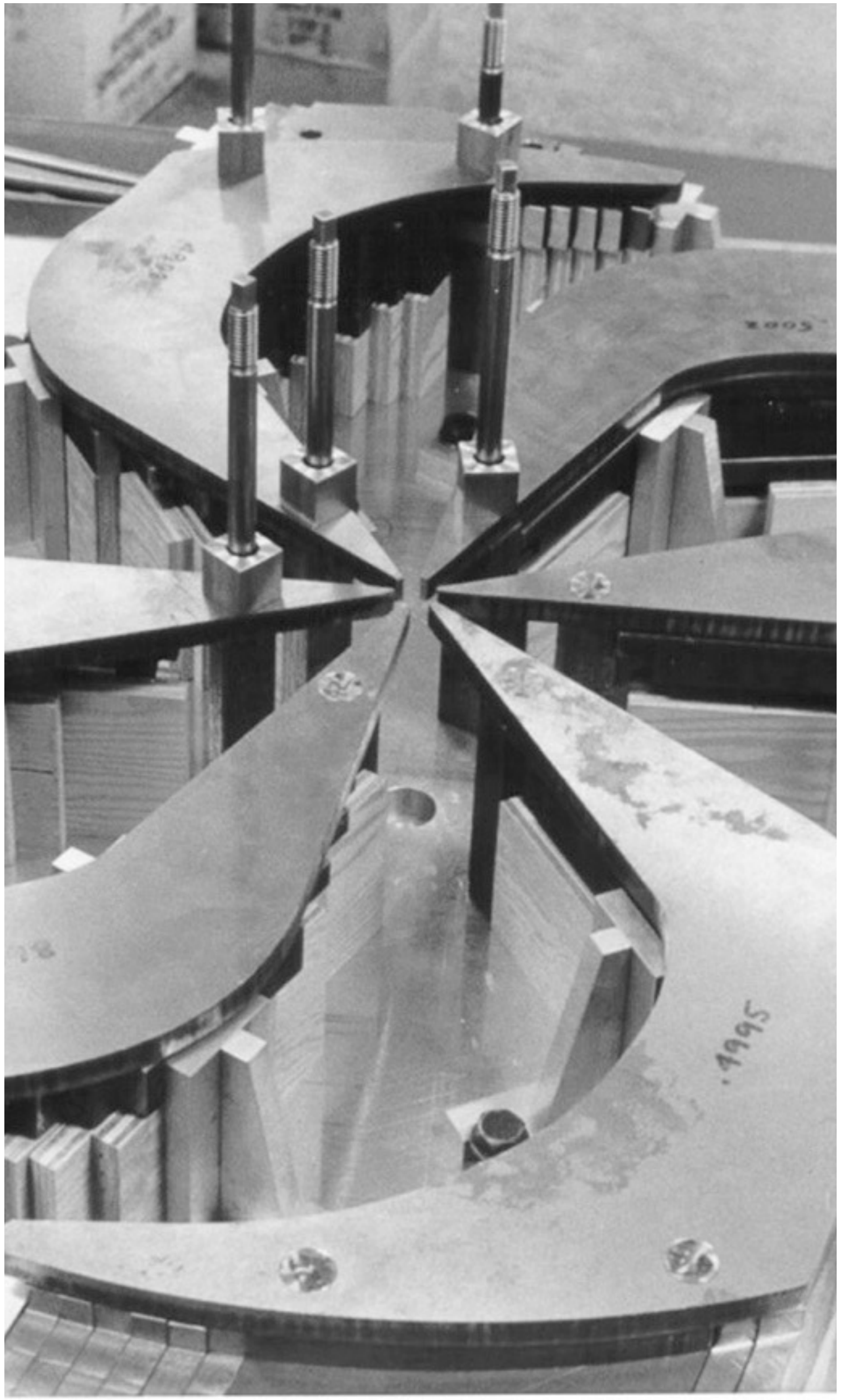
GRIDS 2025



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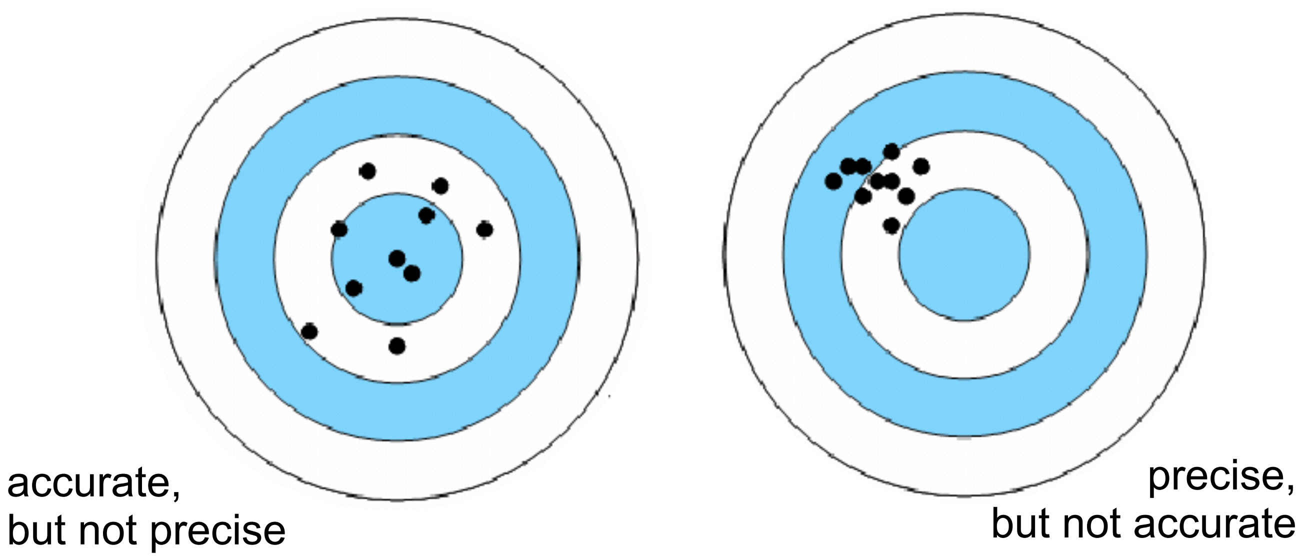
Discovery, accelerated

Atomic Physics Techniques

AMO: Atomic molecular and optical physics:
light-matter and matter-matter interaction

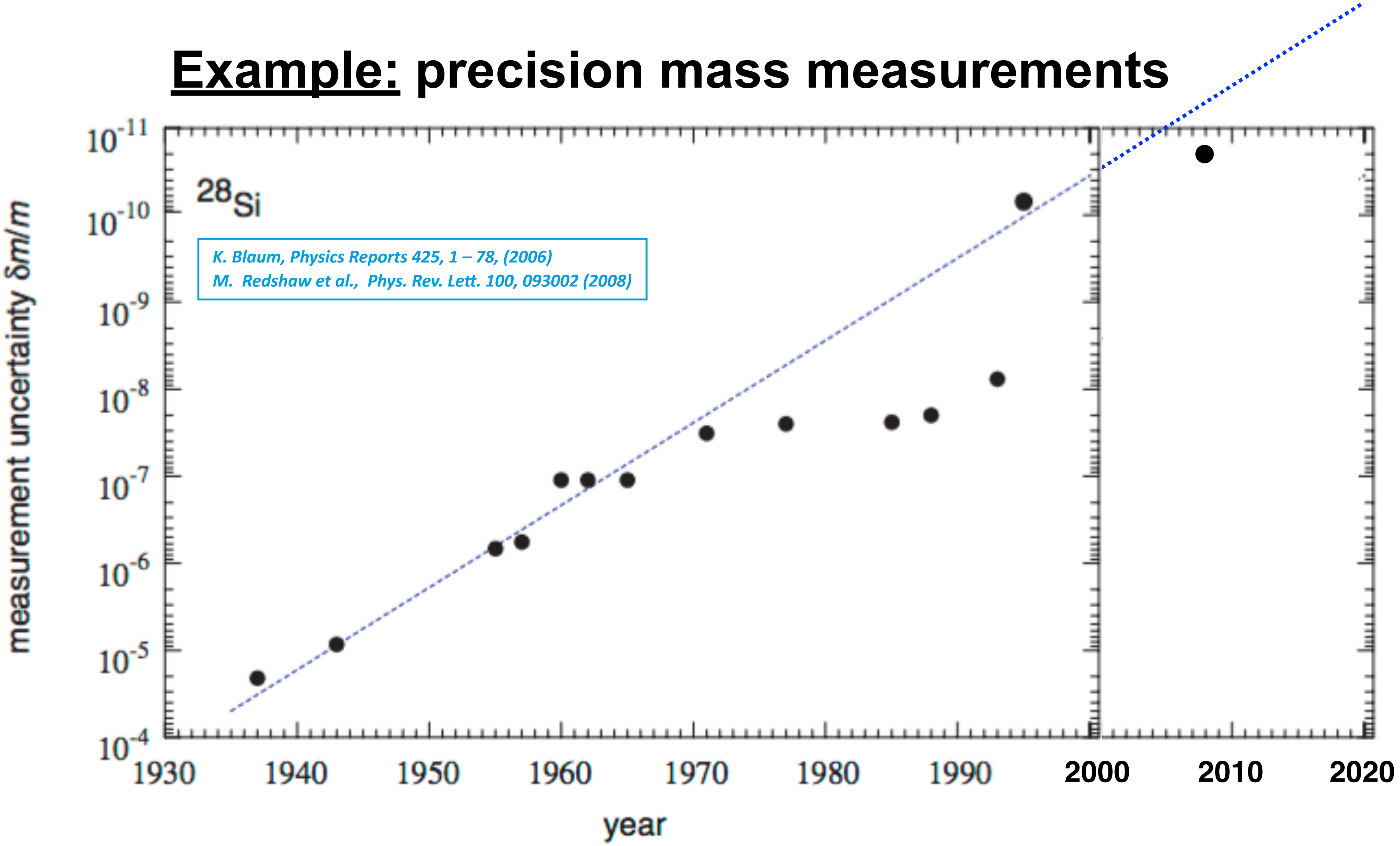
- at the scale of a few atoms, molecules, and photons
- at energy scales around a few electron volts

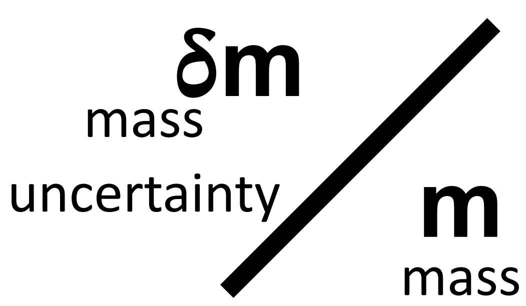
AMO experiments: **high accuracy and precision**



Precision Experiments

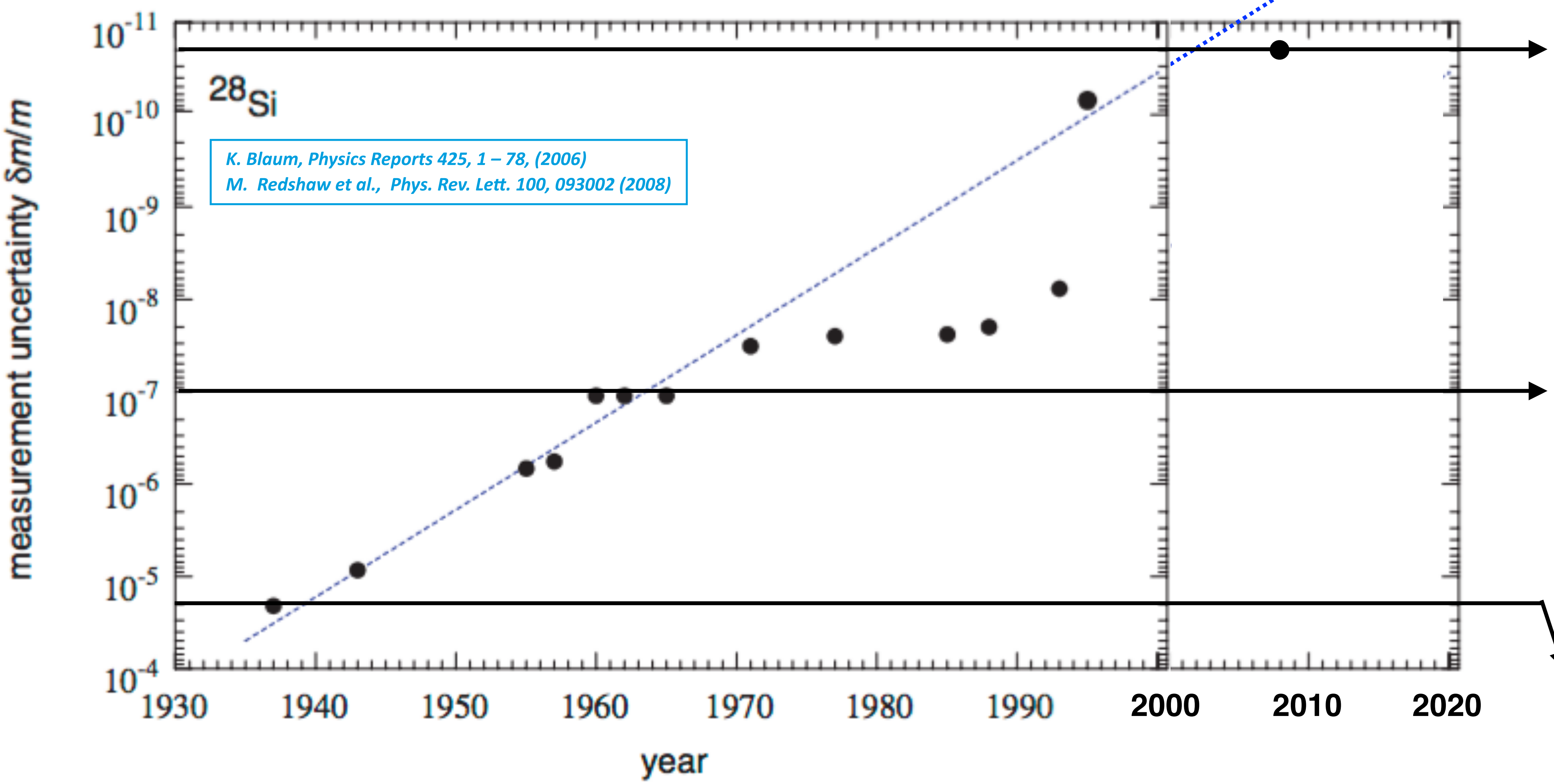
Example: precision mass measurements

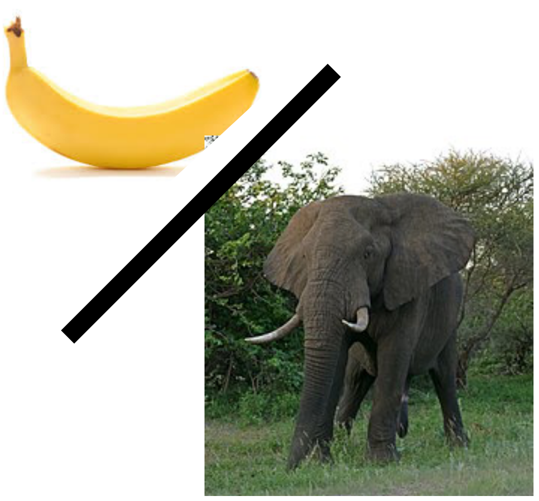




Precision Experiments

<u>Example:</u> precision mass measurements



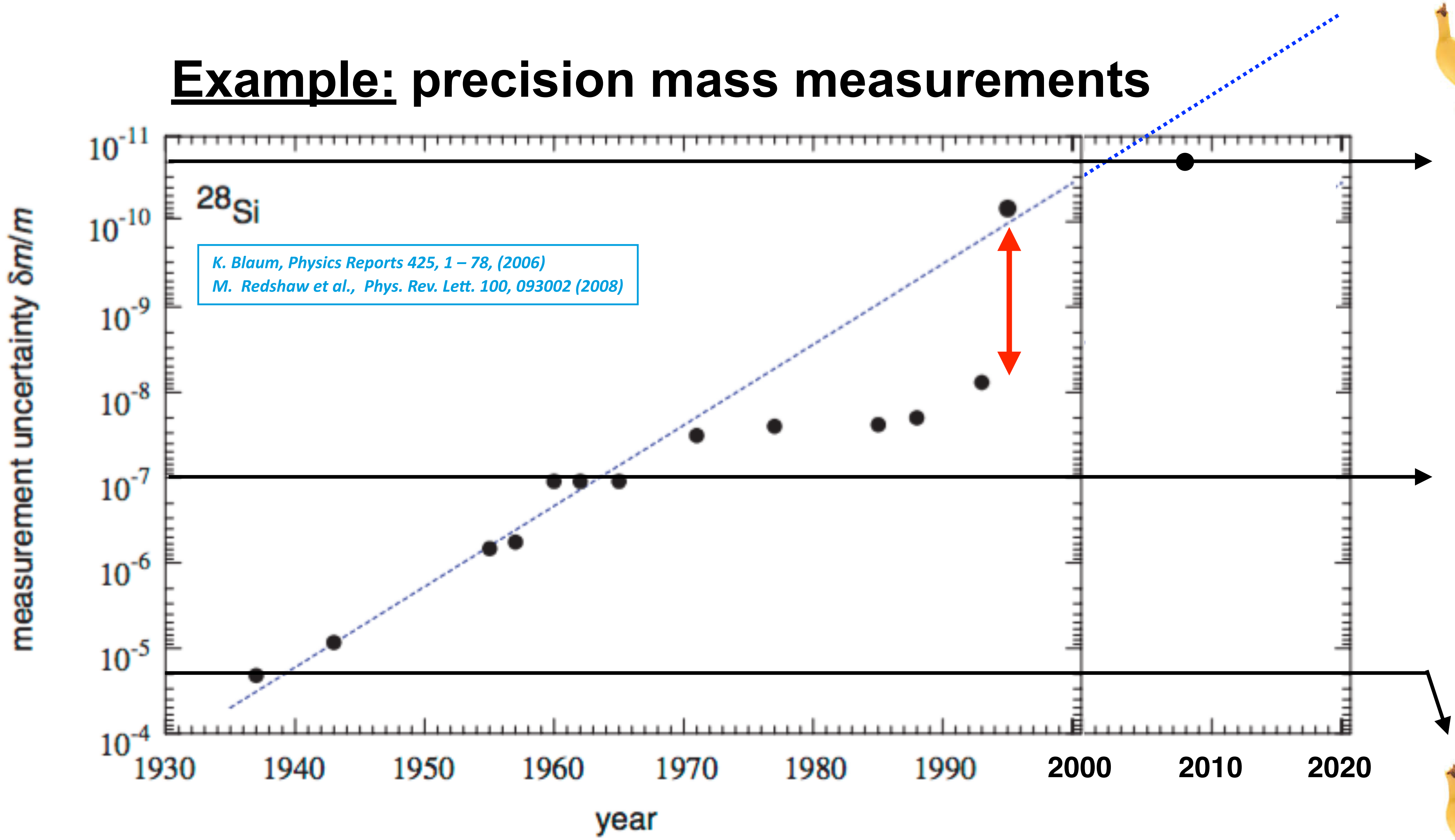


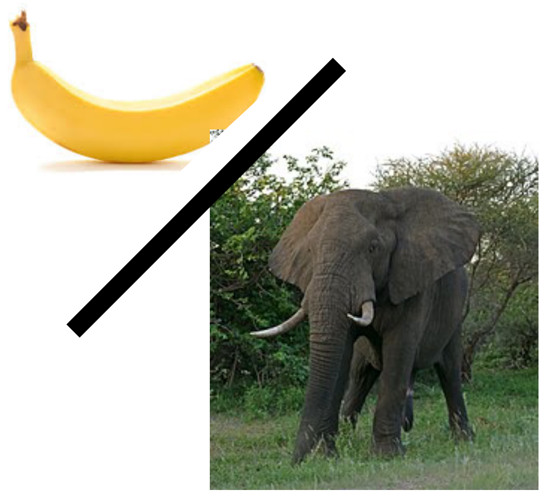
δm
mass uncertainty

m
mass

Precision Experiments

<u>Example:</u> precision mass measurements

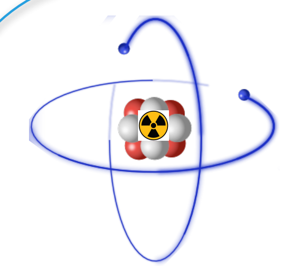




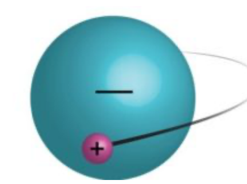
δm mass uncertainty / m mass

Why accelerator facilities?

‘Exotic’ species
(for AMO studies)

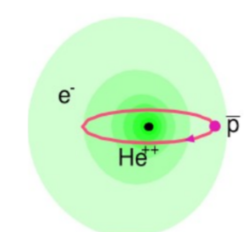


radioactive atoms and molecules

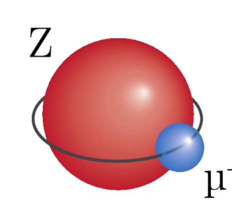


Antiprotons

Antihydrogen



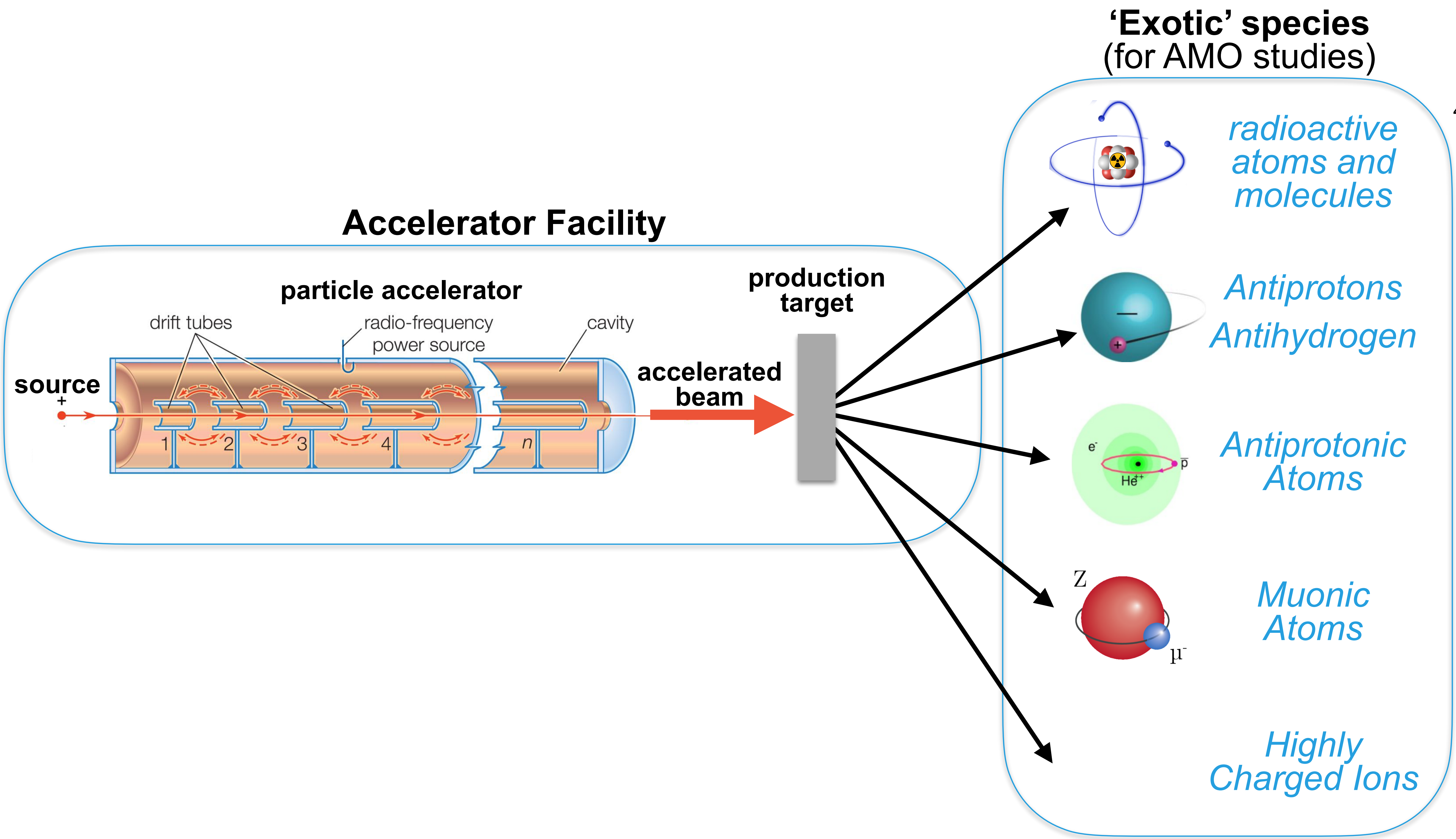
Antiprotonic Atoms



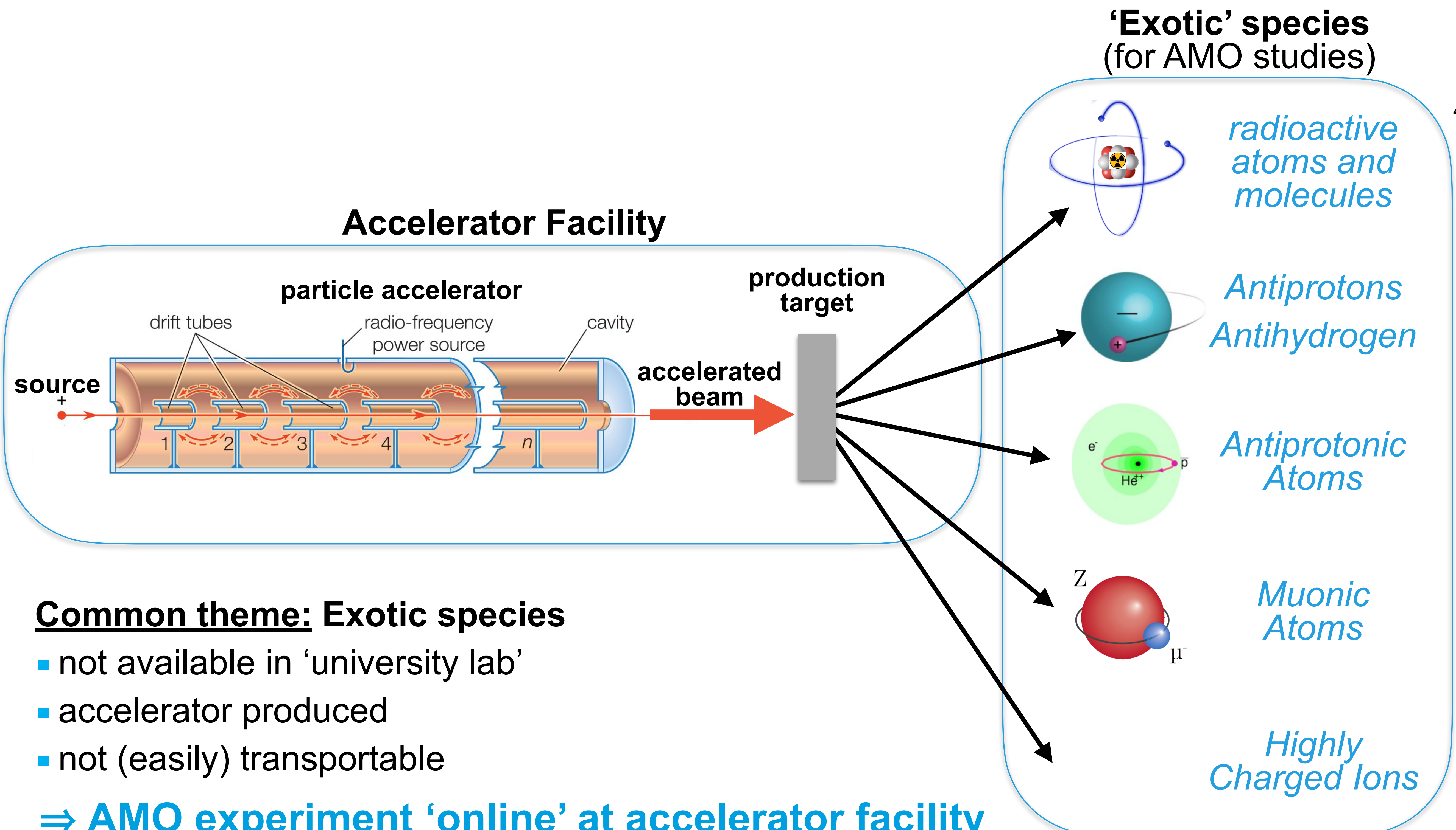
Muonic Atoms

Highly Charged Ions

Why accelerator facilities?



Why accelerator facilities?

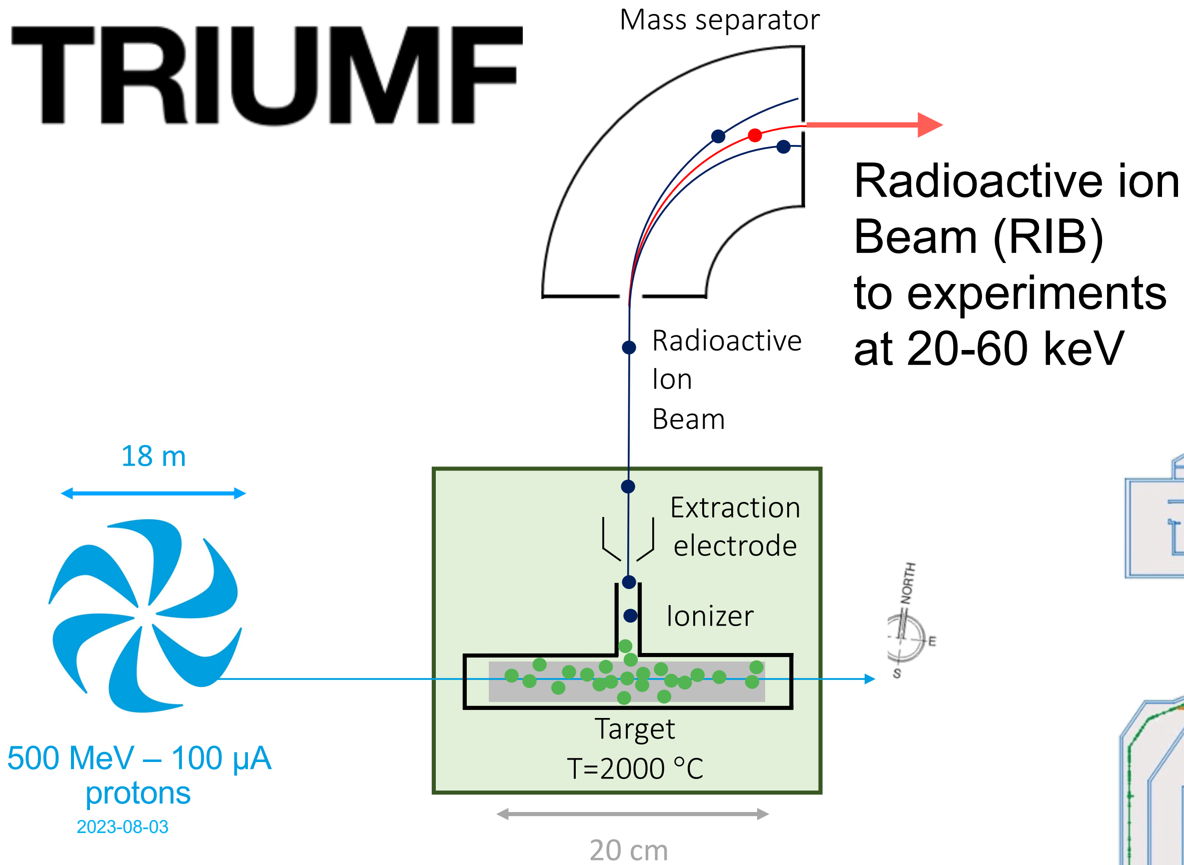


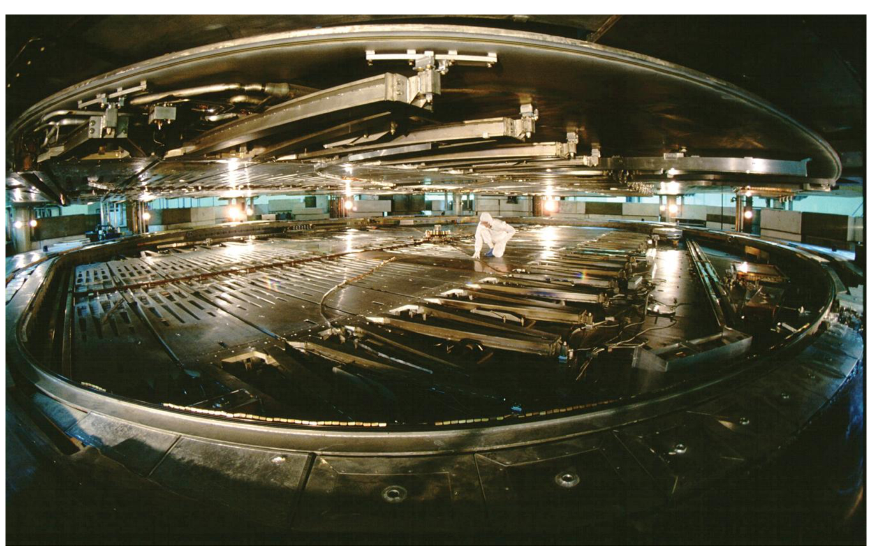
<u>Common theme:</u> Exotic species

- not available in 'university lab'
- accelerator produced
- not (easily) transportable

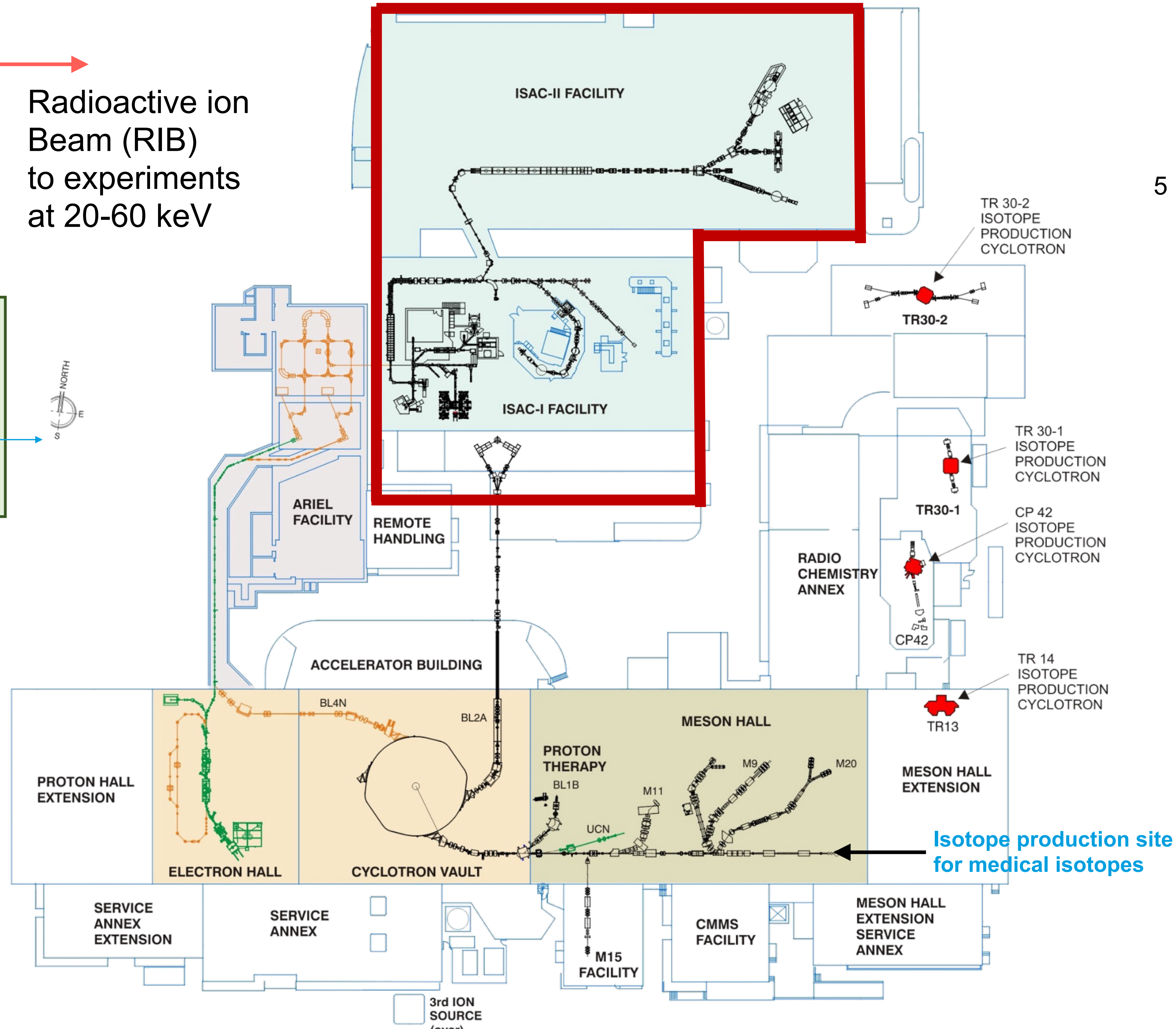
⇒ **AMO experiment 'online' at accelerator facility**

Example: Isotope Separator and Accelerator





TRIUMF main cyclotron (since 1974)

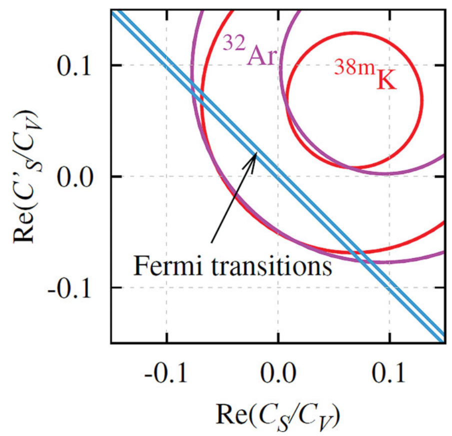


- About 3000 h of isotope beam per year
- >700 nuclides extracted

Precision Experiments at Accelerator Facilities

with AMO techniques

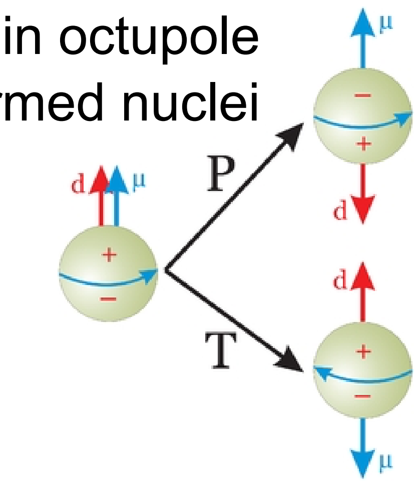
new forces and exotic interactions



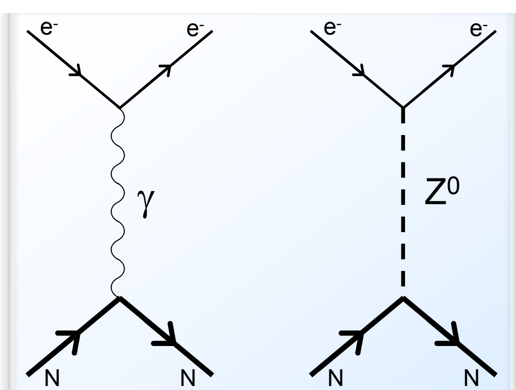
Lorentz invariance

EDM searches

in octupole deformed nuclei

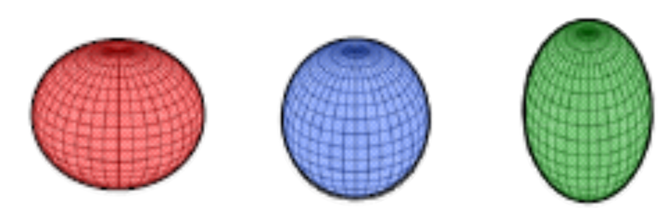


atomic parity violation

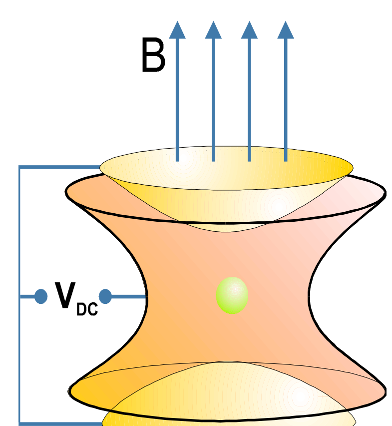


precision tests of QED

electromagnetic properties of radionuclides



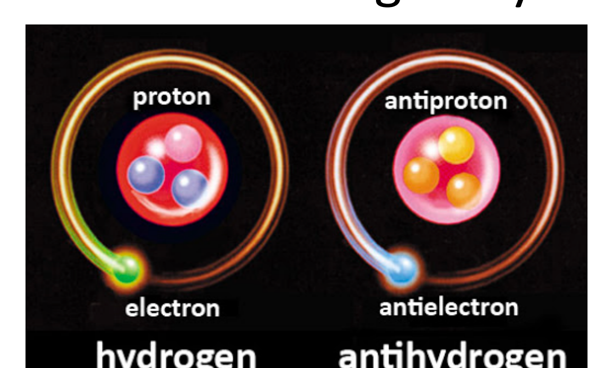
nuclear masses



- neutrino physics
- β-decays & BSM tests

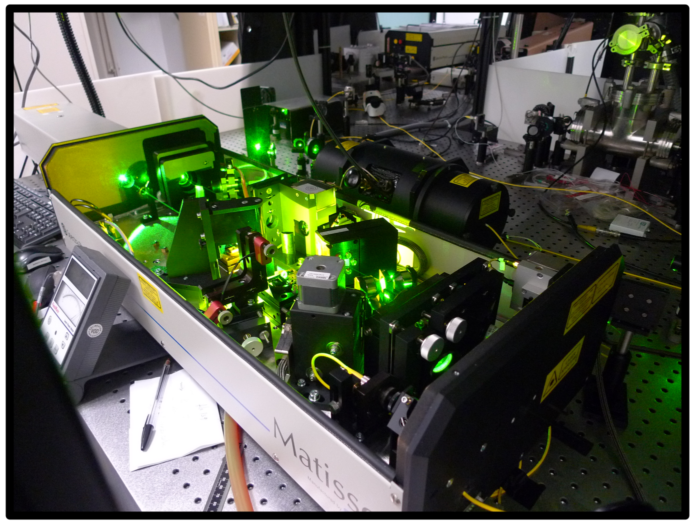
antimatter

- CPT
- gravity

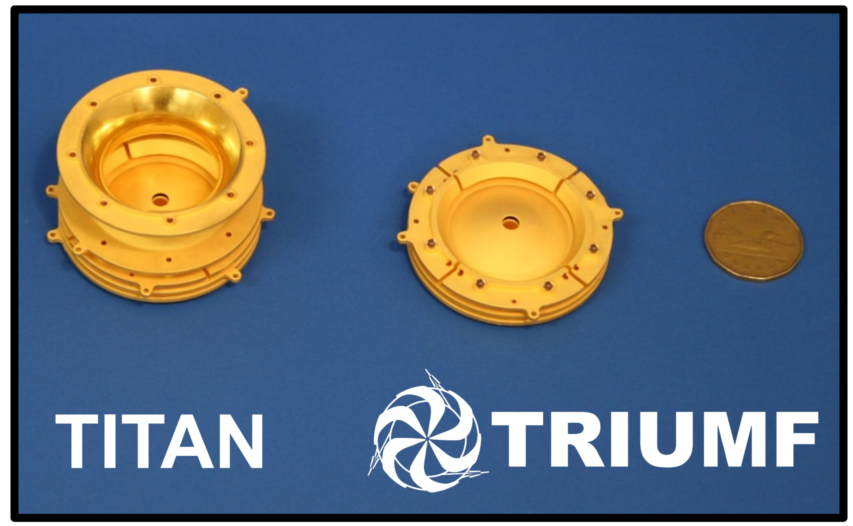


AMO tool kit

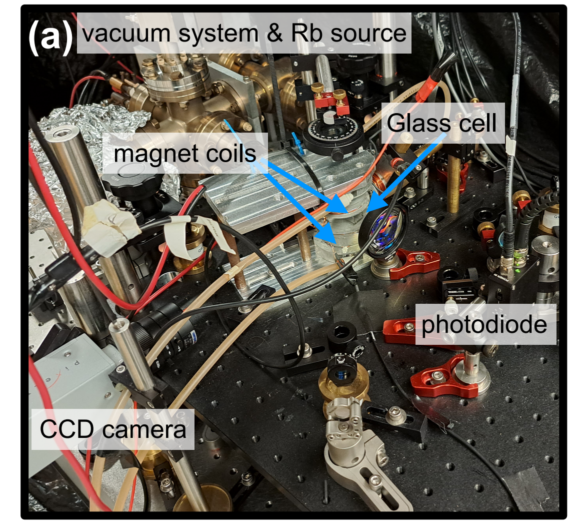
lasers



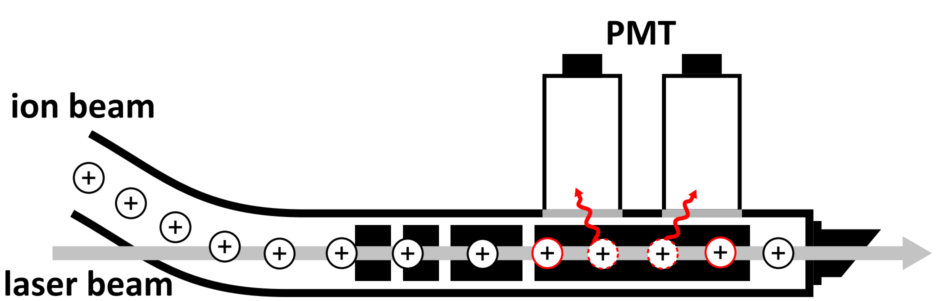
ion traps



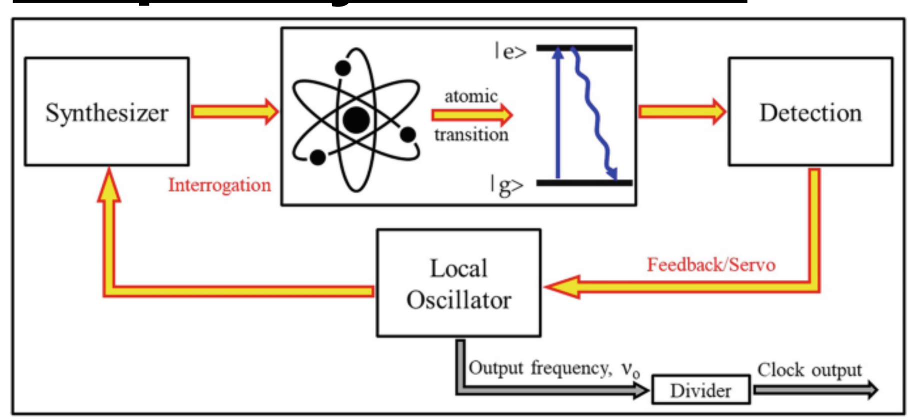
atom traps



laser spectroscopy



frequency standards



Cooling

- buffer gas cooling
- laser cooling
- Evaporative cooling
- Sisyphus cooling
- Sympathetic cooling

…. and many more

Typical size: table-top$^+$

AMO tool kit / classification

Classical:

no explicit quantum behaviour

- optical lenses, mirrors, and classical imaging systems
- ion optics via magnetic and electric fields
- etc.

Quantum:

quantum phenomena

- measure or use of quantized energy levels

Quantum 2.0:

engineered quantum states

- Involves quantum coherence and superposition, entanglement, etc.

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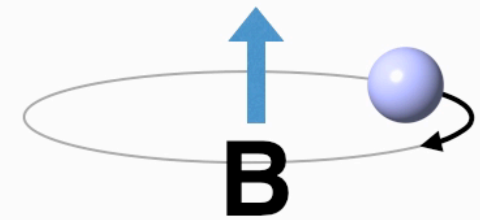

measure

$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

of ion in magnetic field

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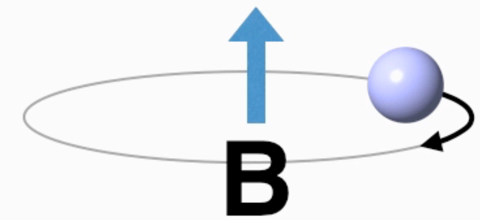

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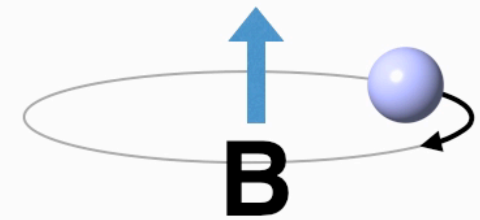

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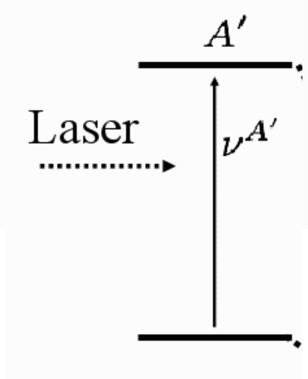

measure atomic transition frequency

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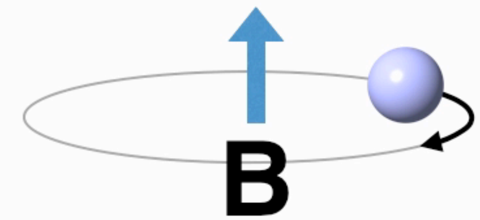

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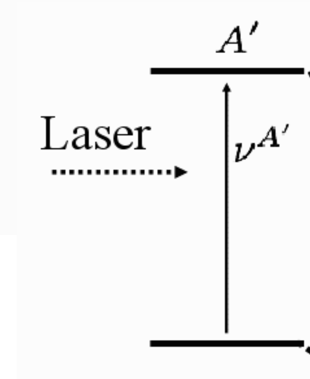


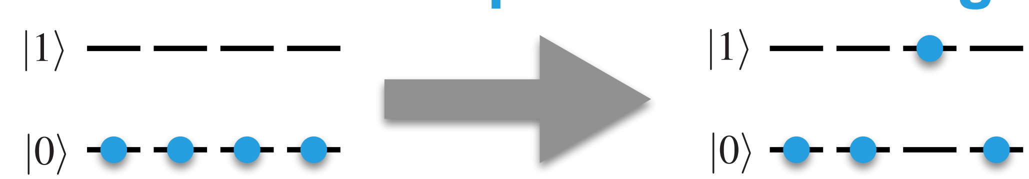
measure atomic transition frequency

Quantum 2.0:

engineered quantum states

- Involves quantum coherence and superposition, entanglement, etc.

quantum sensing



quantum state preparation

Evolves under the influence of an external perturbation

quantum state readout
⇒
information on perturbation

AMO tool kit / classification

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routinely done at Accelerator Facilities

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→ **routinely done at Accelerator Facilities**

Quantum 2.0:

engineered quantum states

- Involves quantum coherence and superposition, entanglement, etc.

→ **opportunity for higher precision and new probes at Accelerator Facilities**

Common challenges

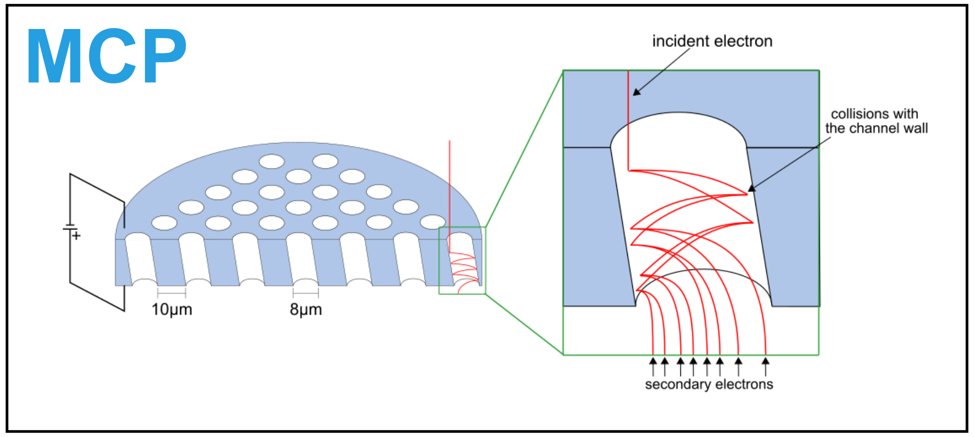
in translating AMO methods into accelerator environment

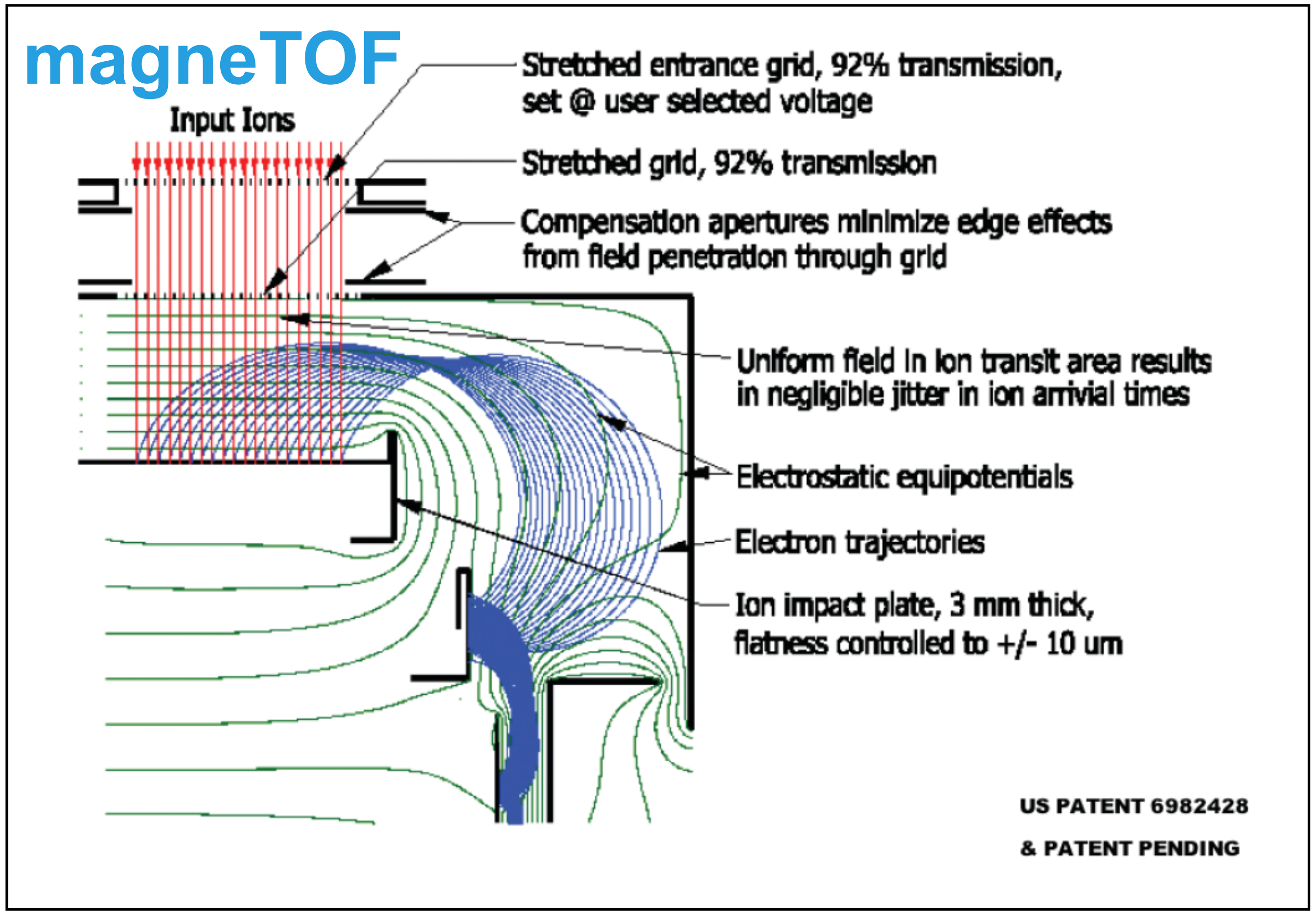
AMO physics		accelerator facility
stable	**Time**	$T_{1/2}$: ms - s - min - days - …
'∞'	**Intensity**	yields: 1/s to '>10^9/s'
'whatever it takes'	**Purity**	(isobaric) contamination: 1:0-10^6 or more
µK - mK - K cold beams or tapped	**Temperature**	transport beam: 10s of keV to GeV (Production targets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

Typically used detectors

ion and neutral particle detectors:
micro channel plate (MCP),
magneTOF

typical requirements:
- low dark-count rate
- efficiency approaching unity
- good time resolution
- wide dynamic range
- [position sensitivity]





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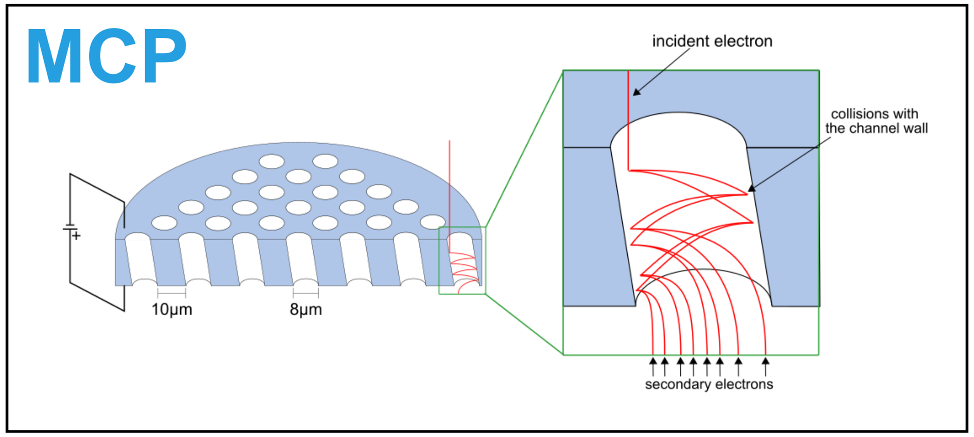
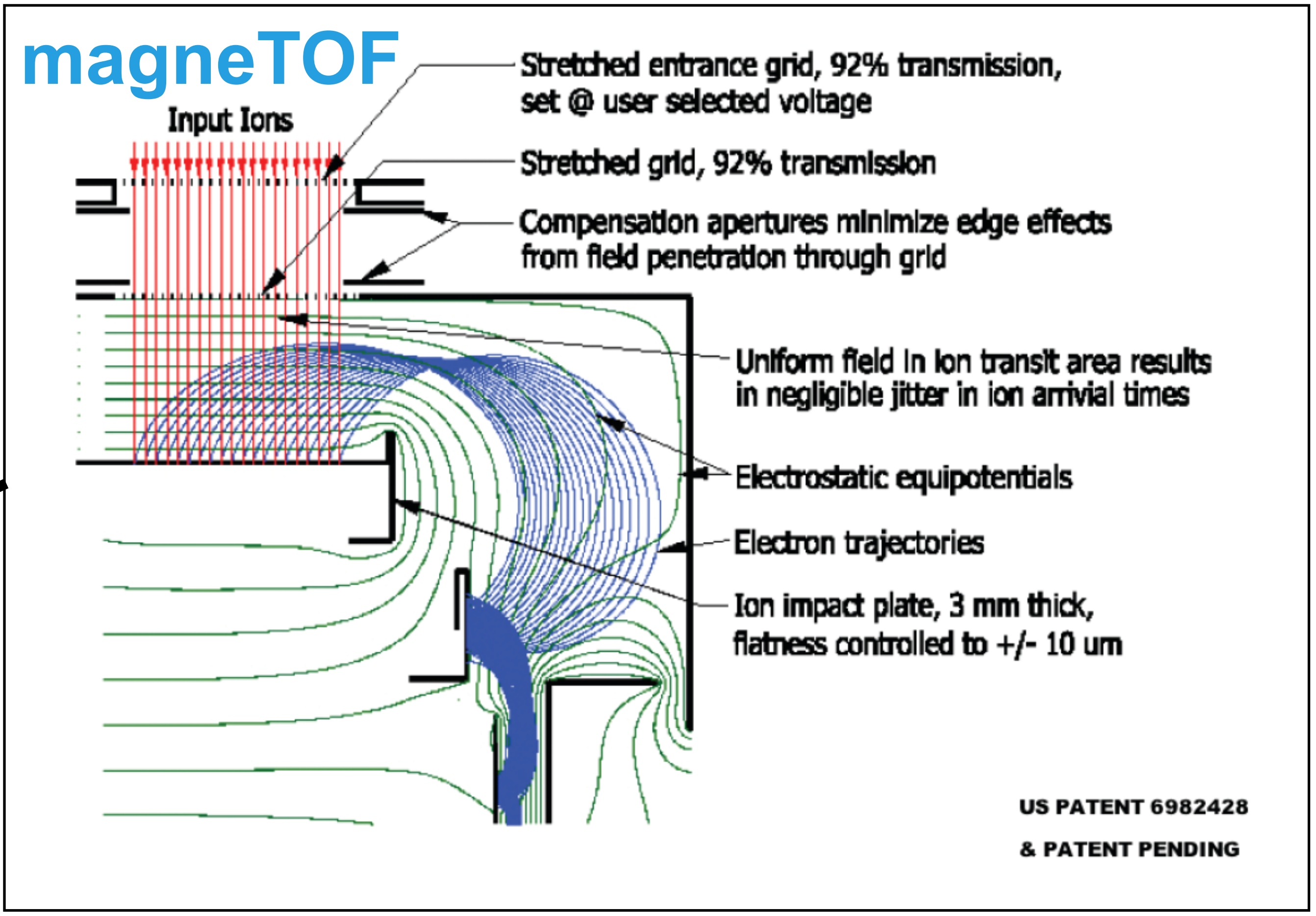
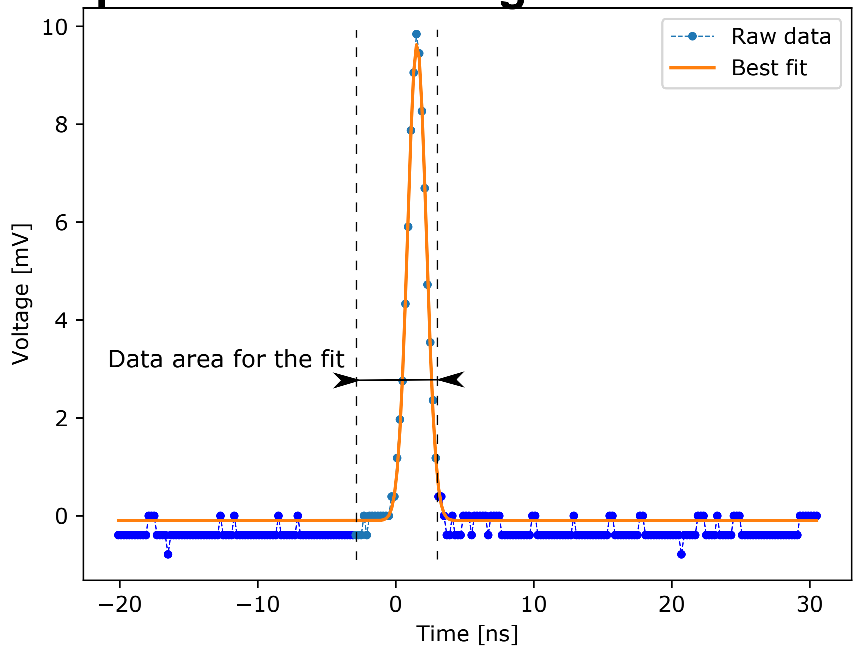




pulse width at magneTOF

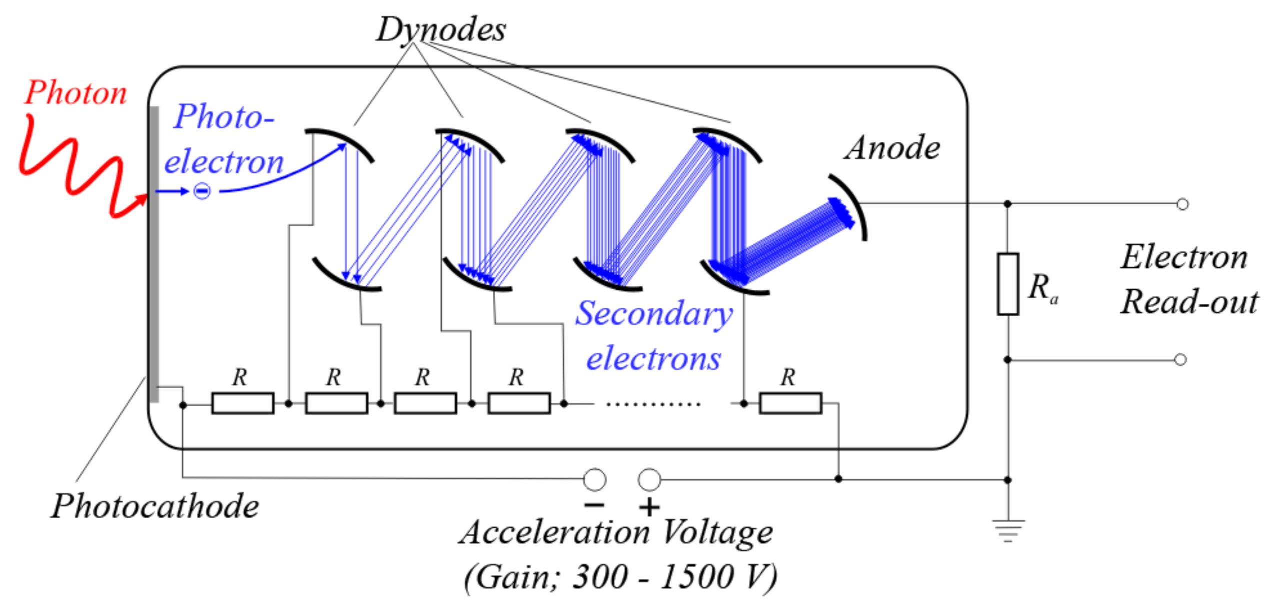


Typically used detectors

Photo-detectors:
PMT, SiPMT, etc.

typical requirements:

- single photon sensitivity
- low dark-count rate



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Typically used detectors

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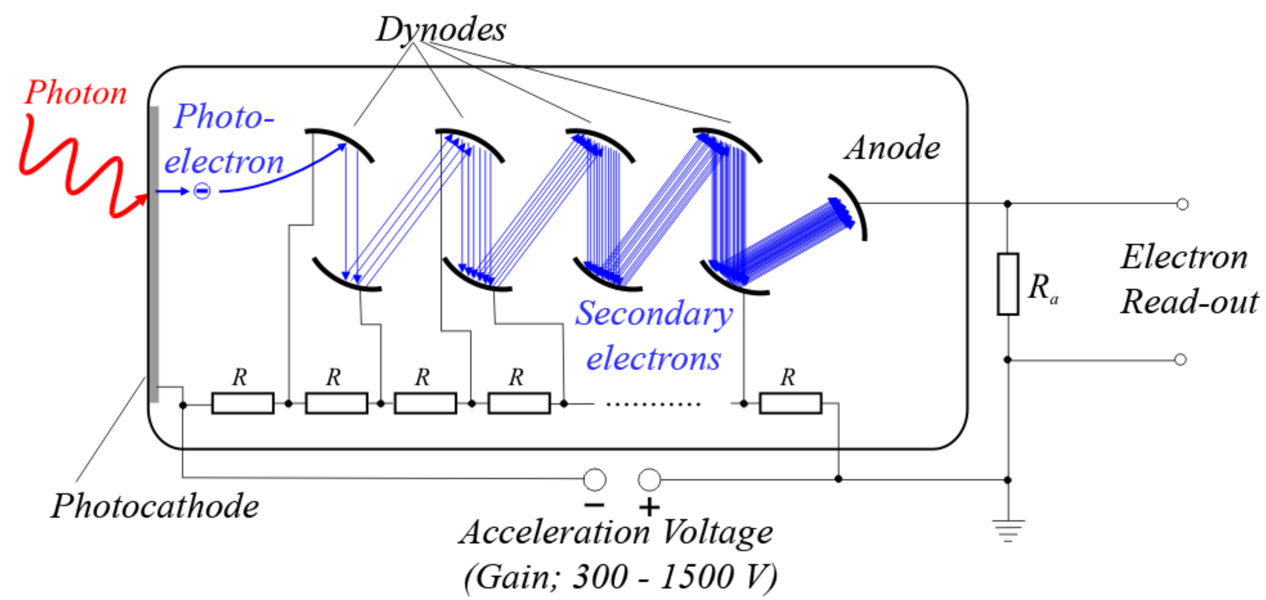


Common theme:

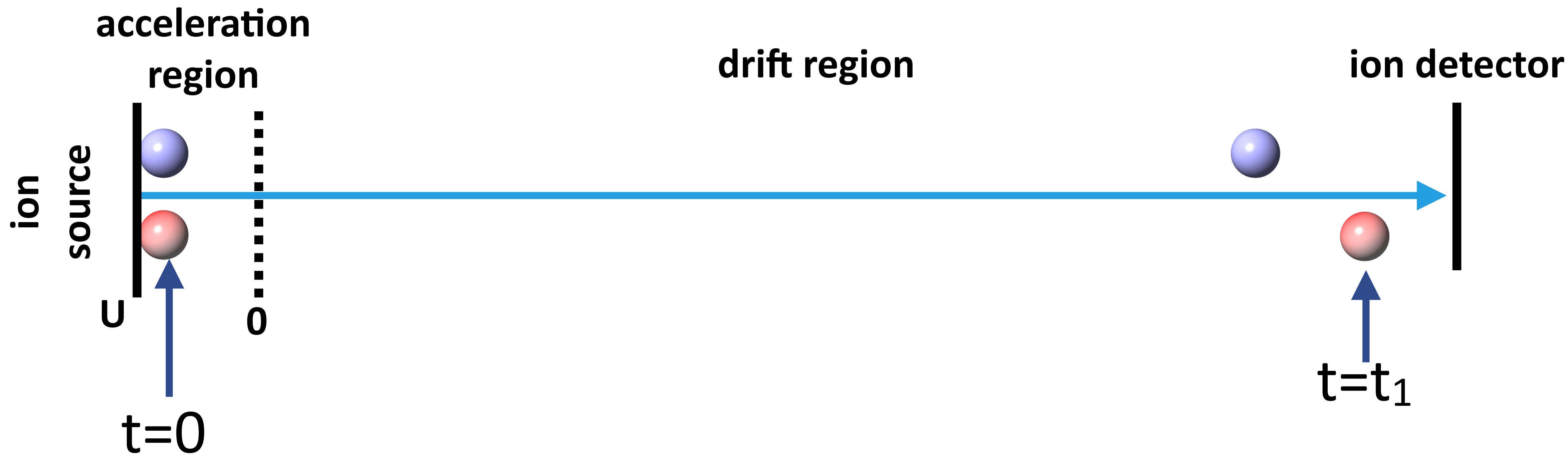
- used particle and photon detectors not too ‘special’
- usually compact, cost-effective devices
- not the detector leads to high resolution but overall experimental method (typically comparison to frequency standard or phase measurement)

Examples in this lecture

[very personal, very biased selection]

- Time of Flight mass spectrometry
  - Multi-reflection Time of Flight (MR-ToF) devices
- Penning traps
- Collinear laser spectroscopy (CLS)
  - conventional, fluorescence based CLS
  - Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy (MIRACLS)
- Radioactive molecules
  - Molecular formation and identification in ion traps
  - Molecular formation in atom traps
  - Towards EDM measurements

Time of Flight (ToF) mass spectrometry



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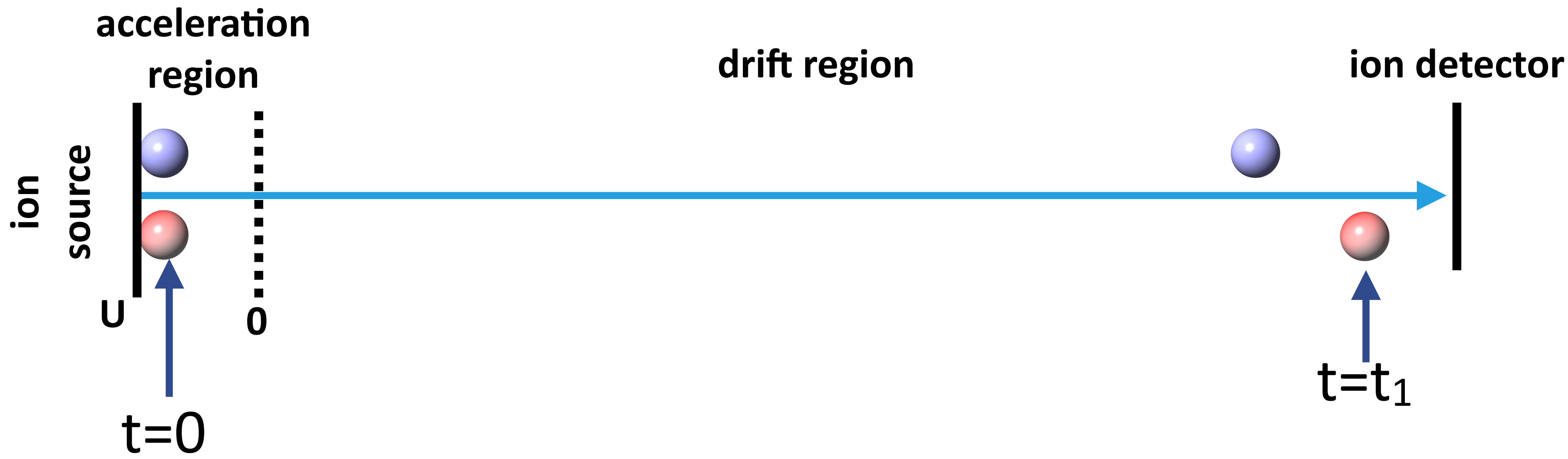
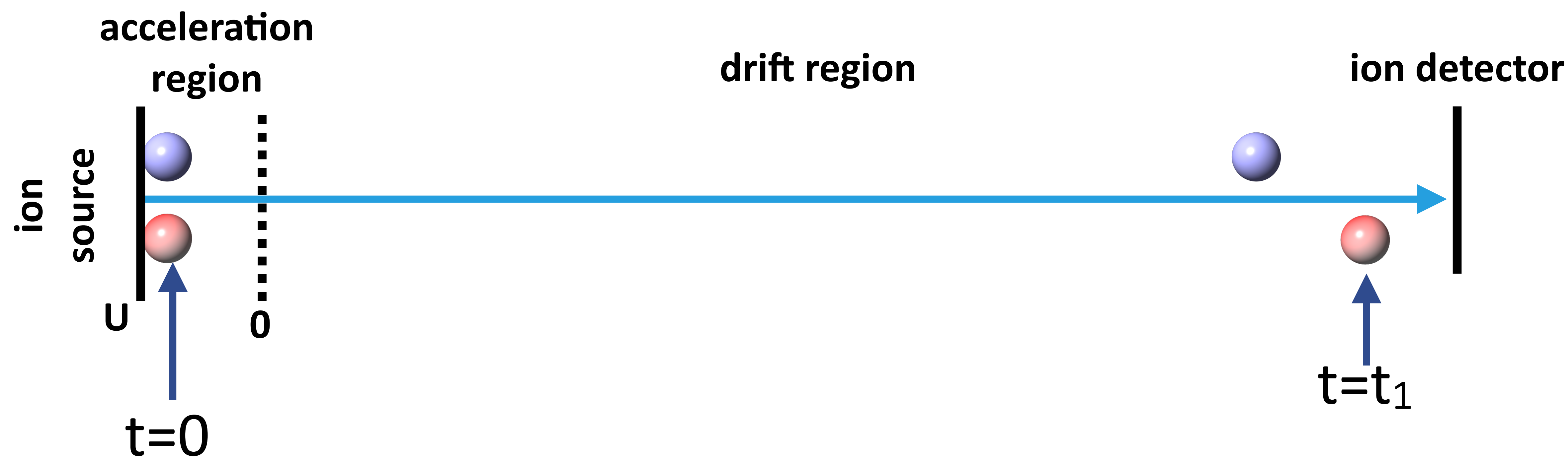
Time of Flight (ToF) mass spectrometry



$$v = \sqrt{\frac{q}{m} \cdot 2U}$$

Time of Flight (ToF) mass spectrometry



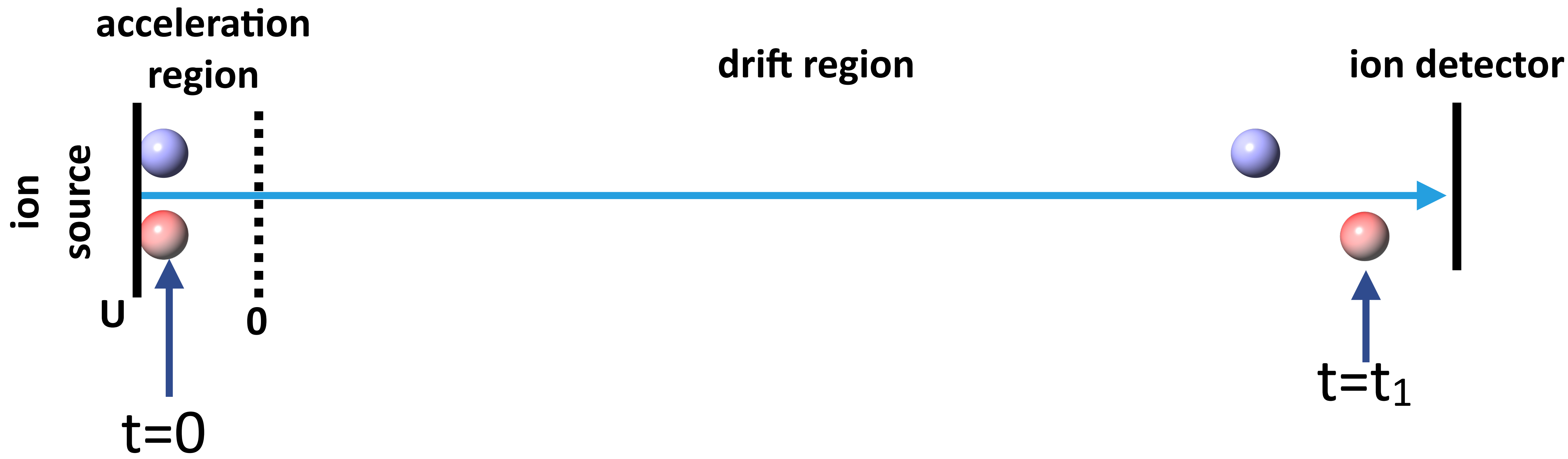
15

$$v = \sqrt{\frac{q}{m} \cdot 2U}$$

constant (fixed by reference ion)

$$v = \frac{s}{t} \Rightarrow t = \frac{s}{v} \Rightarrow \mathrm{ToF} = \sqrt{\frac{m}{q}} \cdot \frac{s}{\sqrt{2U}} = k\sqrt{\frac{m}{q}}$$

Time of Flight (ToF) mass spectrometry



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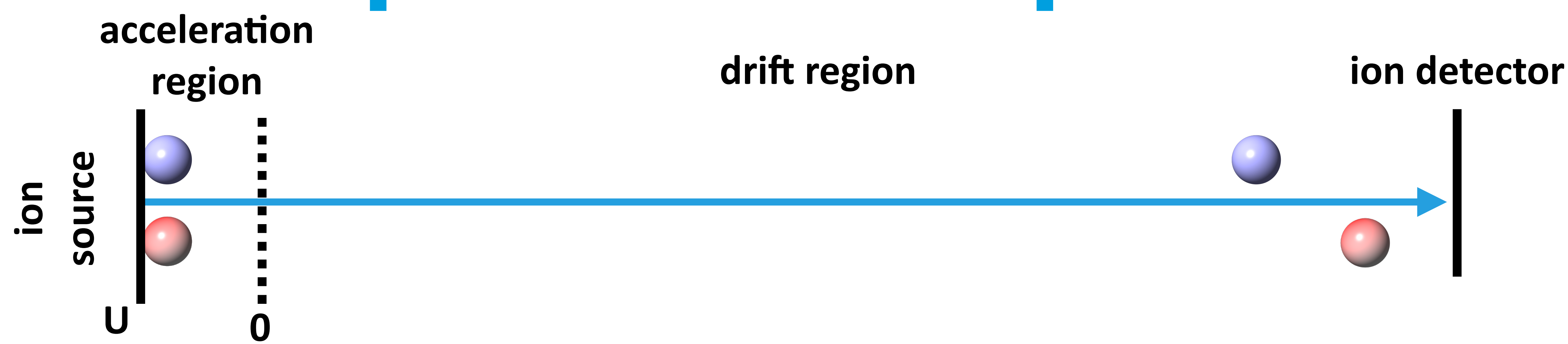
$$\Rightarrow \frac{\mathtt{ToF}}{\sqrt{m}} = \mathtt{const} \Rightarrow$$

if q=1

$$m_{\mathtt{IoI}} = m_{\mathtt{ref}} \left(\frac{\mathtt{ToF}_{IoI}}{\mathtt{ToF}_{ref}} \right)^2$$

ion of interest **reference ion**

Example of ToF spectrum



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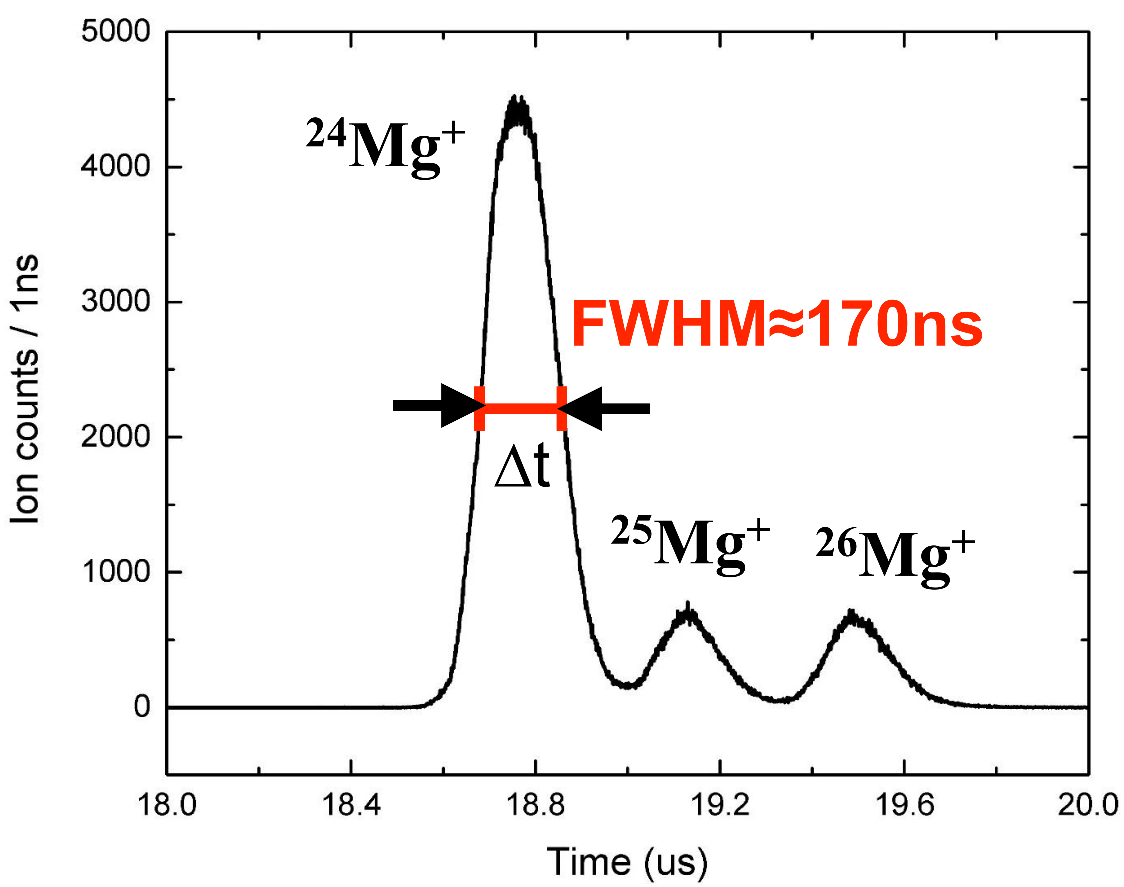


- resolving power of ToF spectrometer R=m/Δm=t/(2Δt)≈55
- …. not too impressive

$$m_{\mathrm{IoI}} = m_{\mathrm{ref}} \left(\frac{\mathrm{ToF}_{IoI}}{\mathrm{ToF}_{ref}} \right)^2$$

ion of interest

reference ion

Method to improve R for ToF

- **<u>in practice:</u>**
  velocity spread Δv (e.g. form ion source)
  ⇒ increased Δt

  ⇒ degraded R=m/Δm=t/(2Δt)

- **<u>correction with reflector</u>**
  faster ions (of m_x)
  ⇒ deeper path into reflector

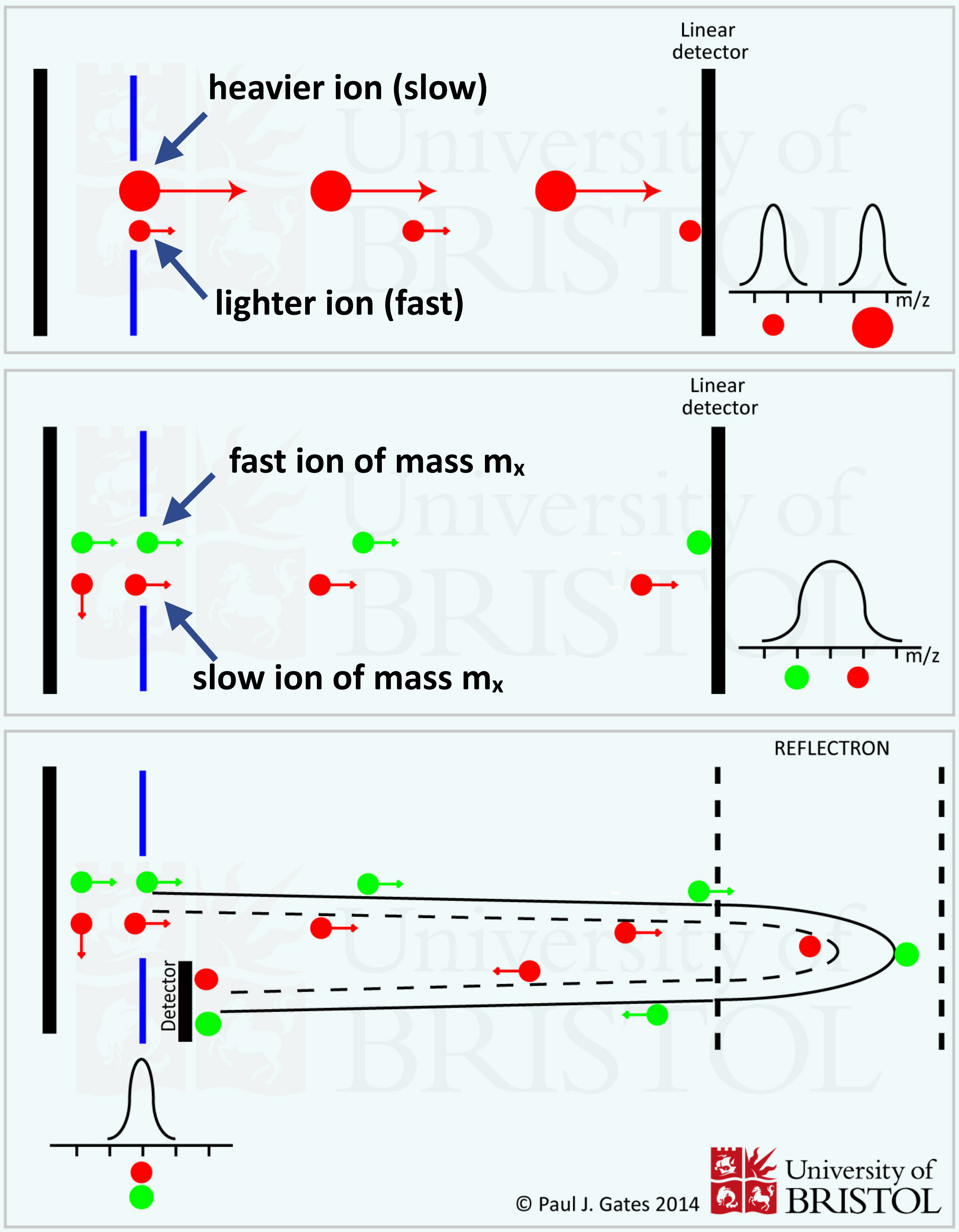
  ⇒ longer flight path

  ⇒ 'identical' t as slower ions (of m_x)

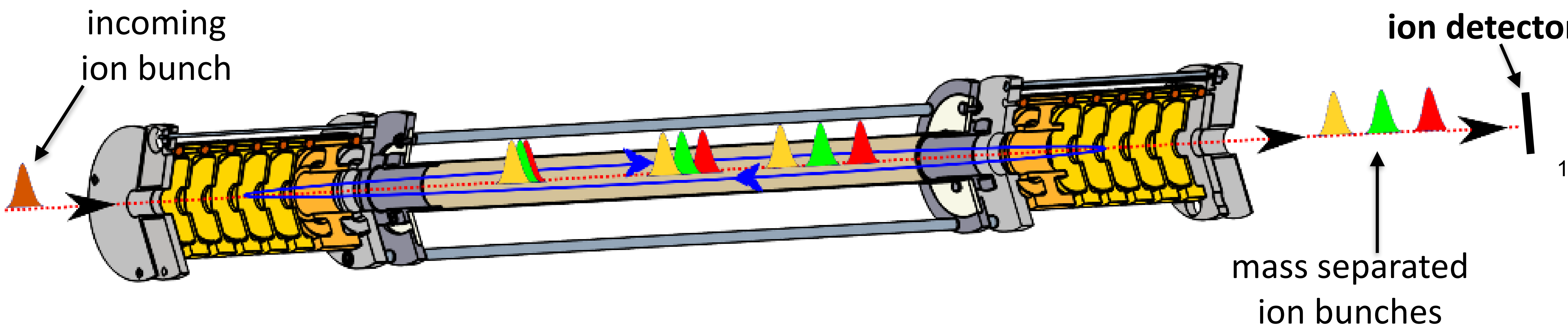
  ⇒ more narrow Δt

  ⇒ better R

Figure 2.



Multi-Reflection Time-of-Flight devices



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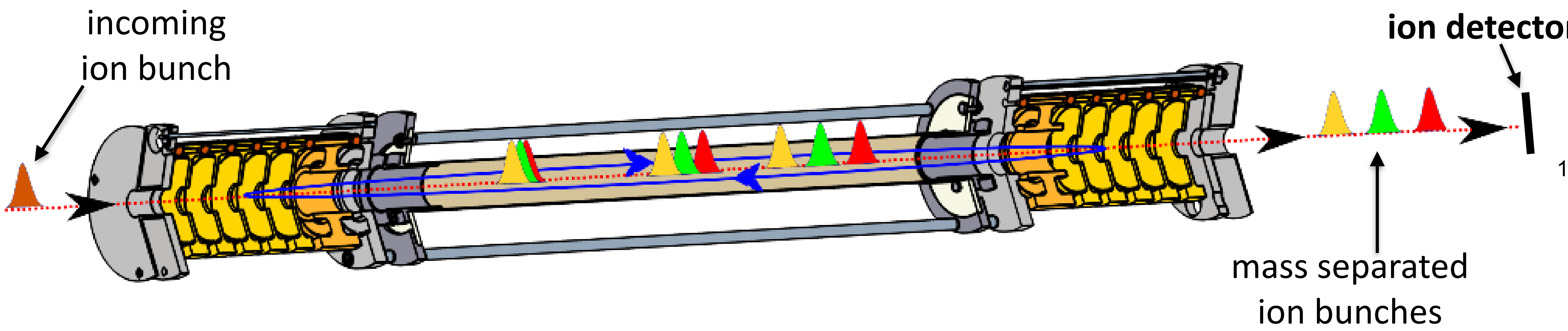
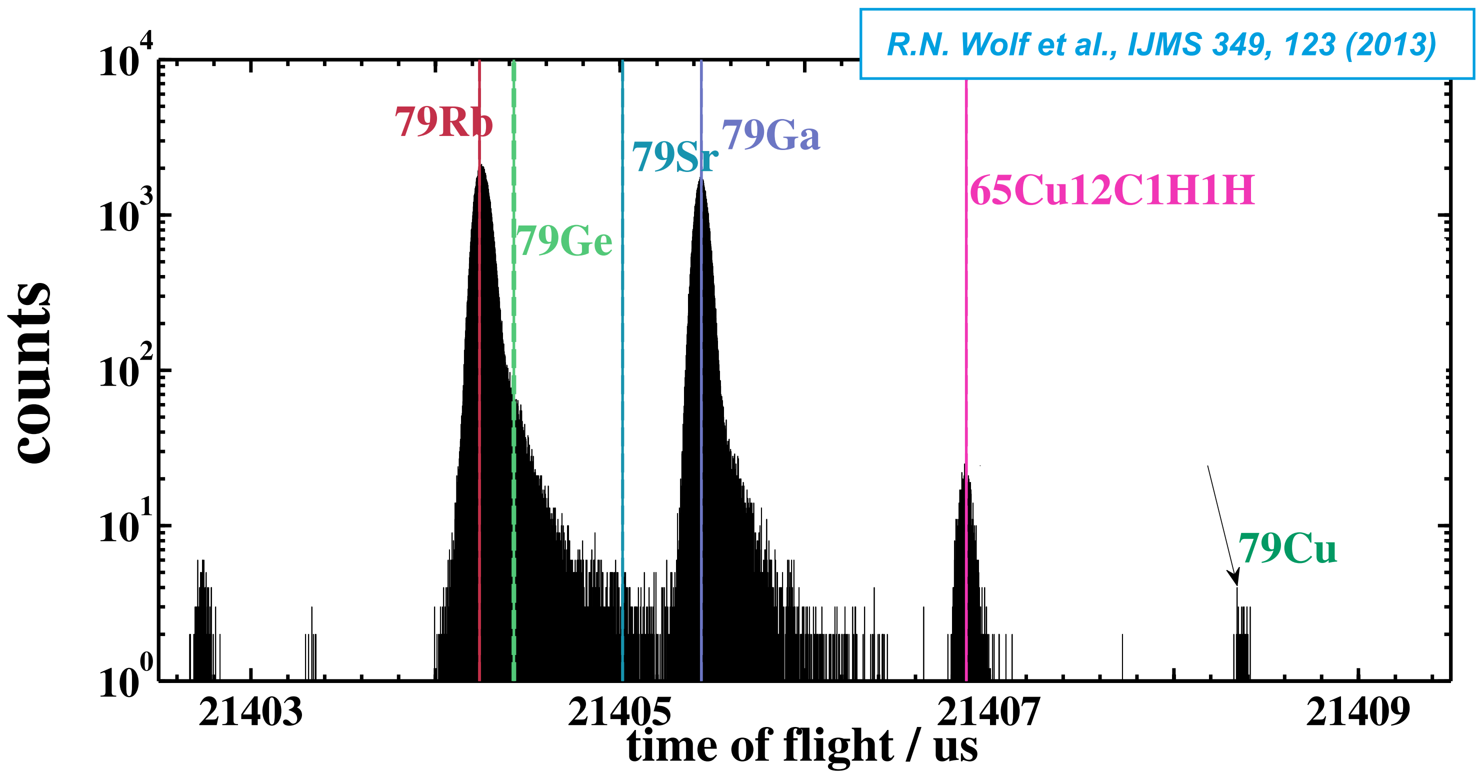
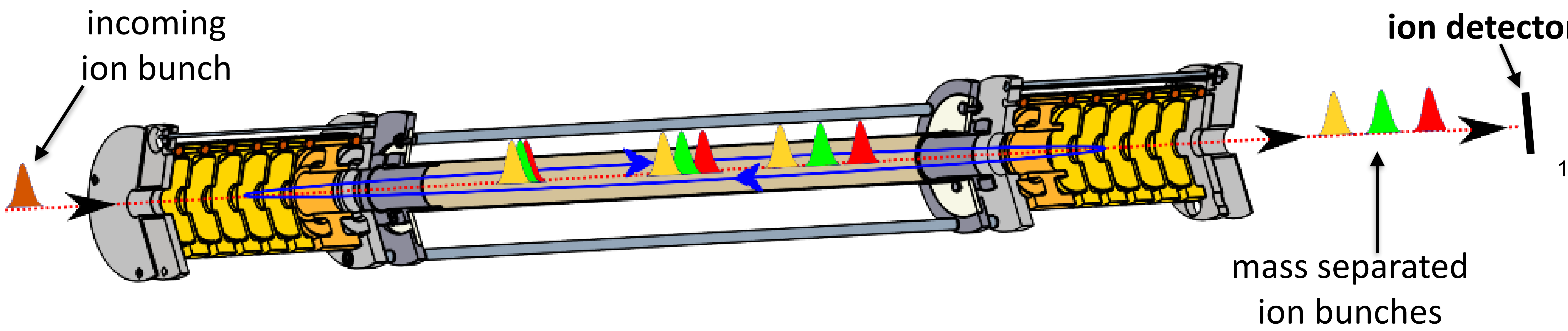


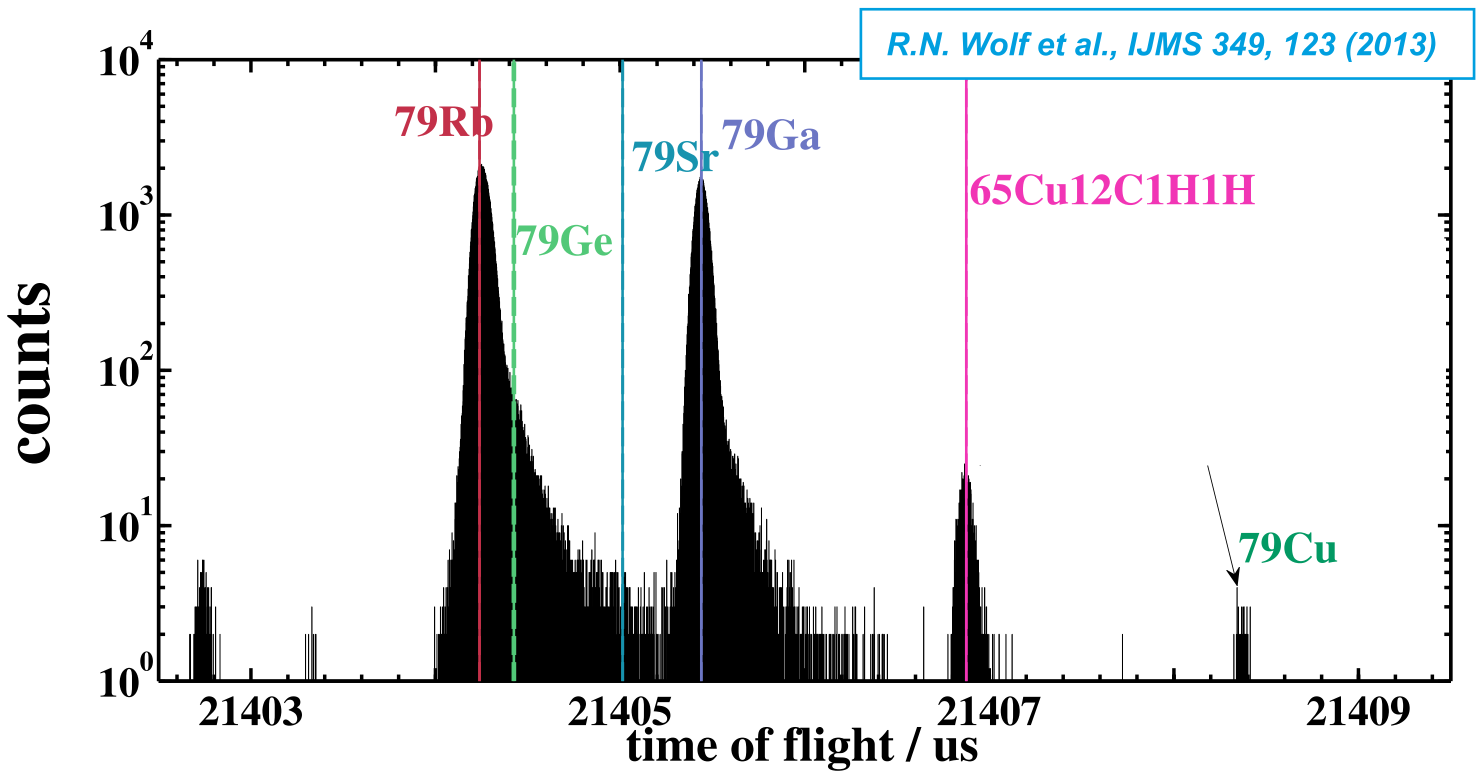


Mass resolving power (FWHM):

m/Δm=120 000 in 22ms ($^{85}Rb^+$)

Multi-Reflection Time-of-Flight devices

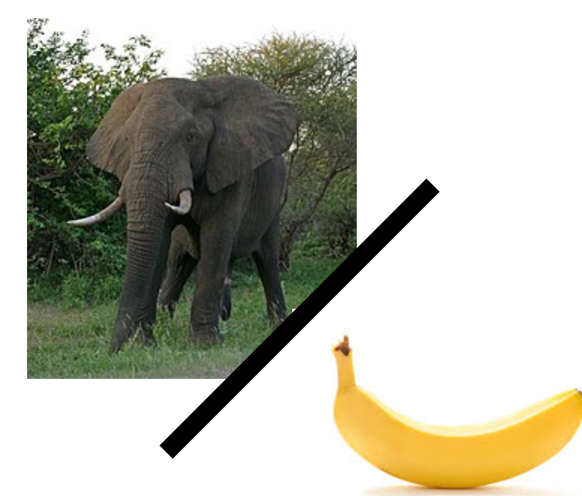




Mass resolving power (FWHM):

$m/\Delta m$=120 000 in 22ms ($^{85}Rb^+$)

$m / \Delta m \Leftrightarrow$



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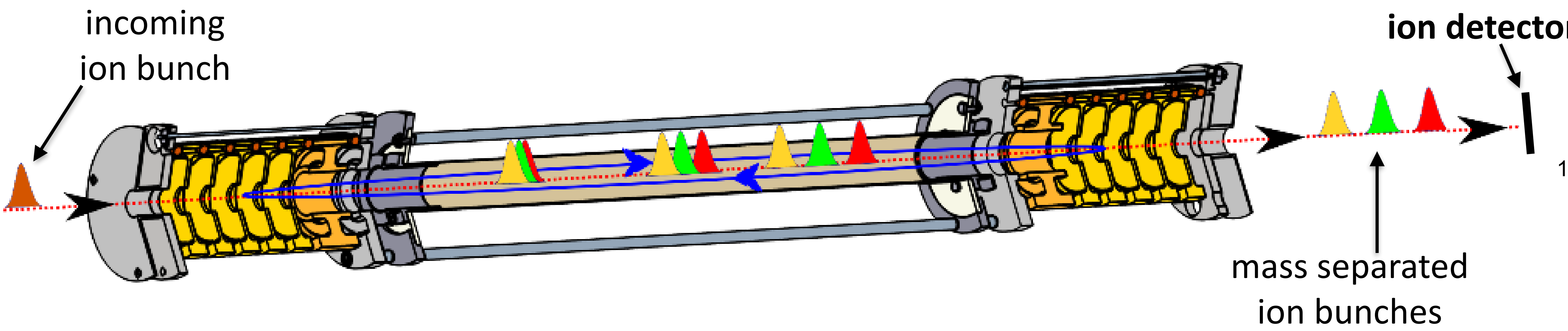

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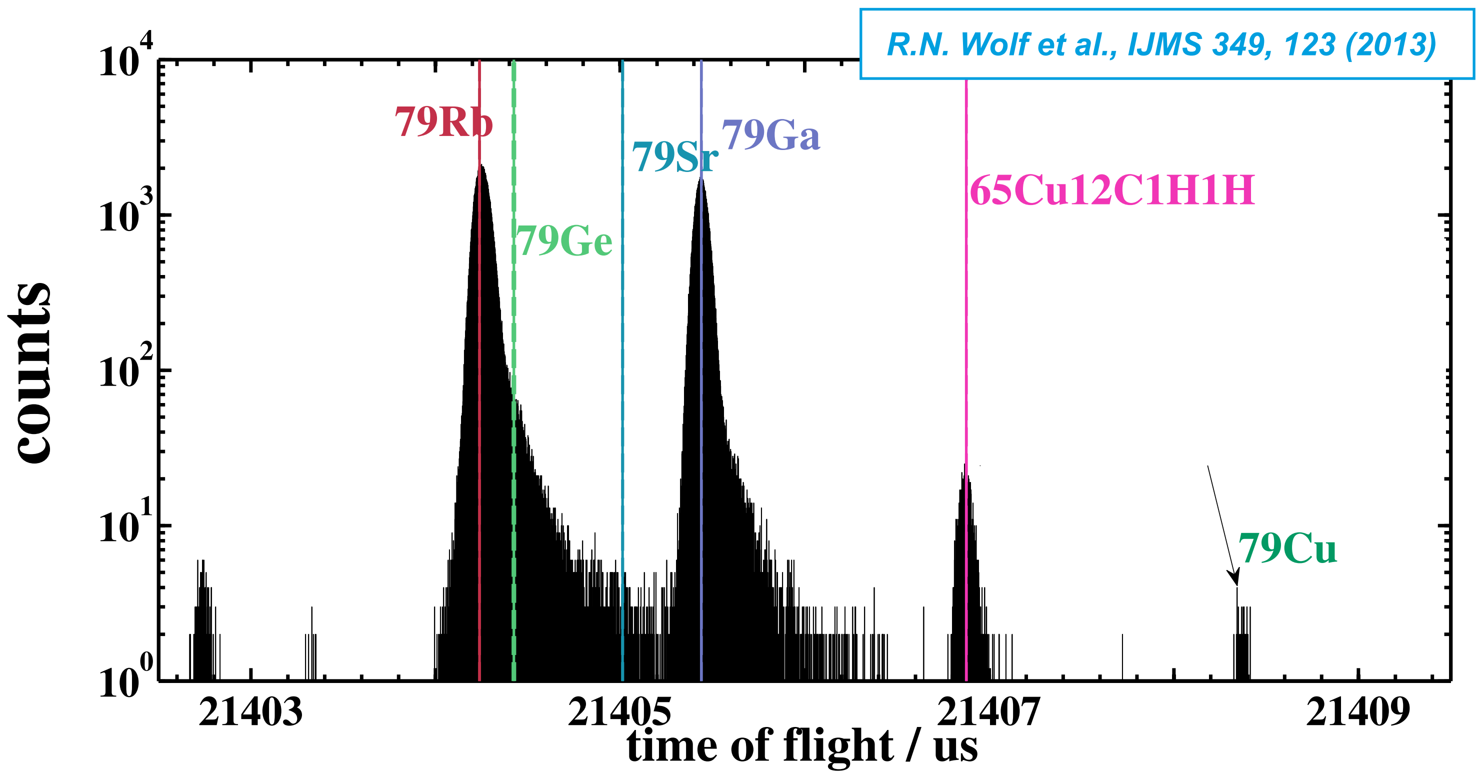

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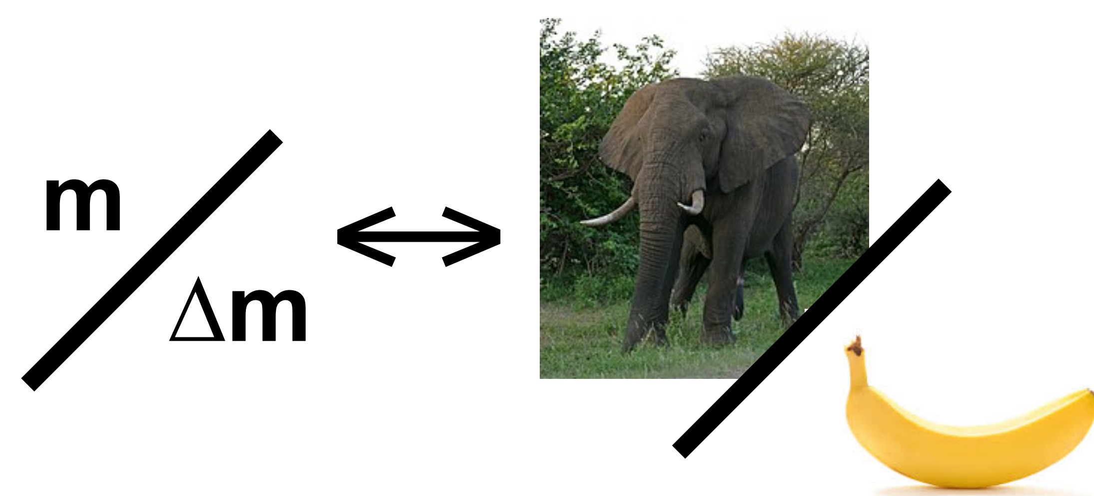


- detector time resolution relevant
- but ion-bunch properties more important
- high precision in little processing time
- single ion sensitivity

$\Rightarrow$ **ideal for mass measurements of accelerator short-lived radionuclides**

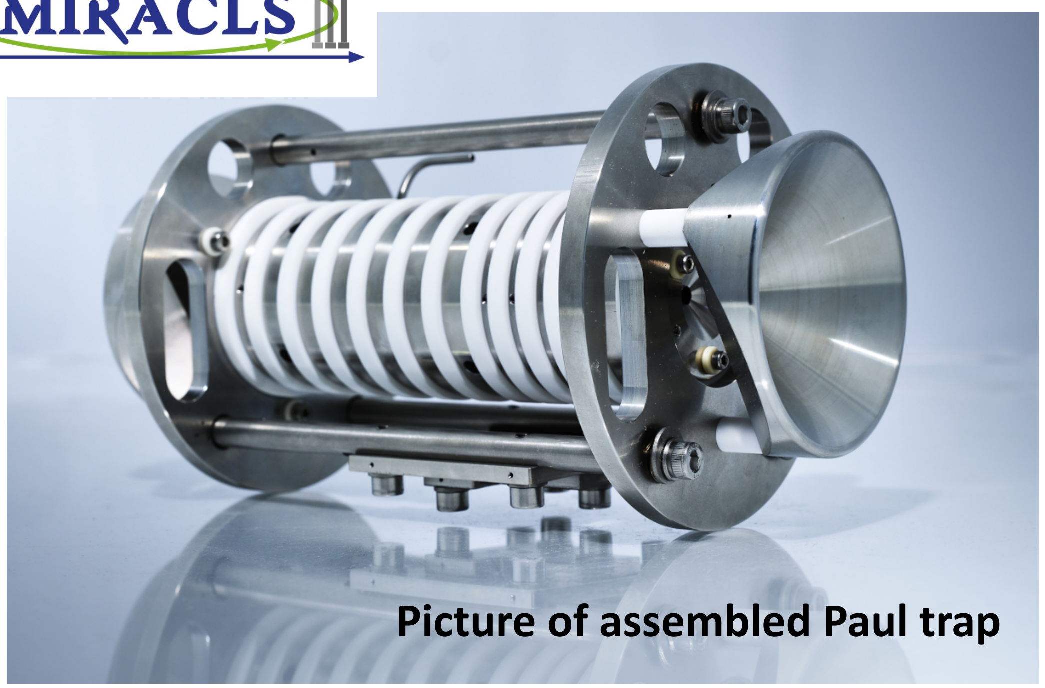
Ion cooling, accumulation, and bunching

buffer-gas-filled Paul traps as cooler-bunchers at RIB facilities

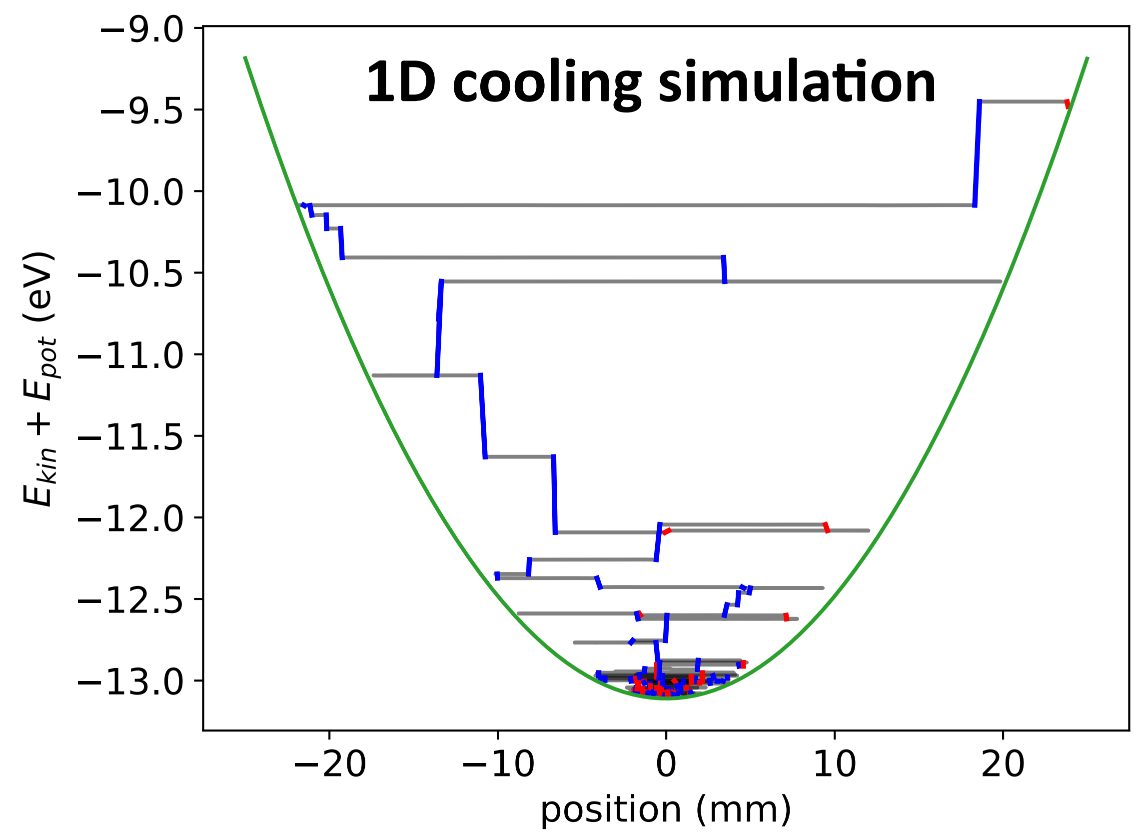
fast & efficient ion preparations for subsequent AMO experiments

cooling limit: buffer-gas temperature (room temperature)

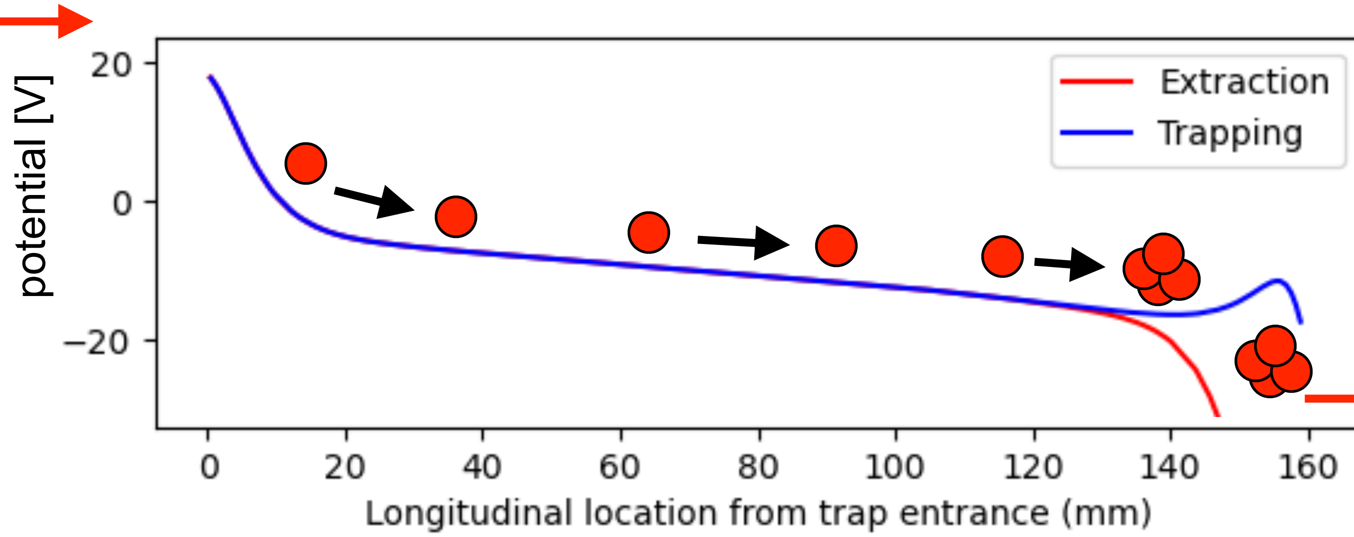
MIRACLS



Picture of assembled Paul trap

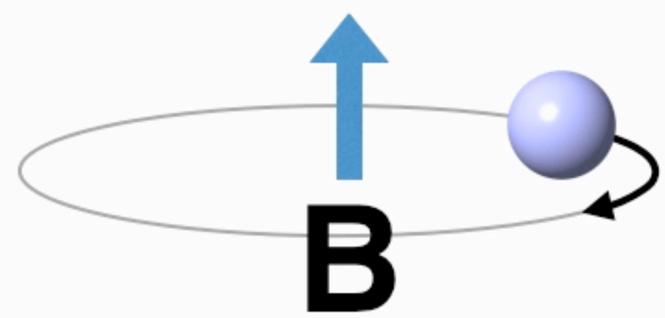


Continuous RIB



to MR-ToF (or other experimental device)

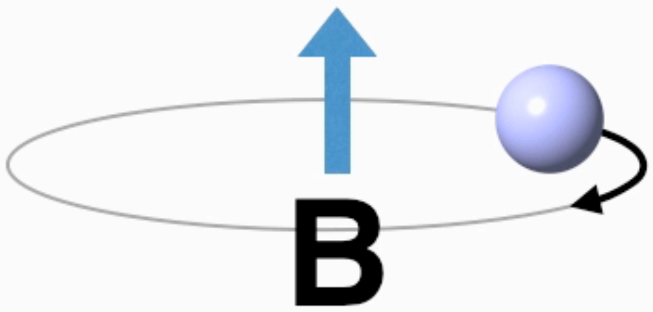
Penning traps



$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

“If you want to measure something precisely, measure a frequency.”

Penning traps



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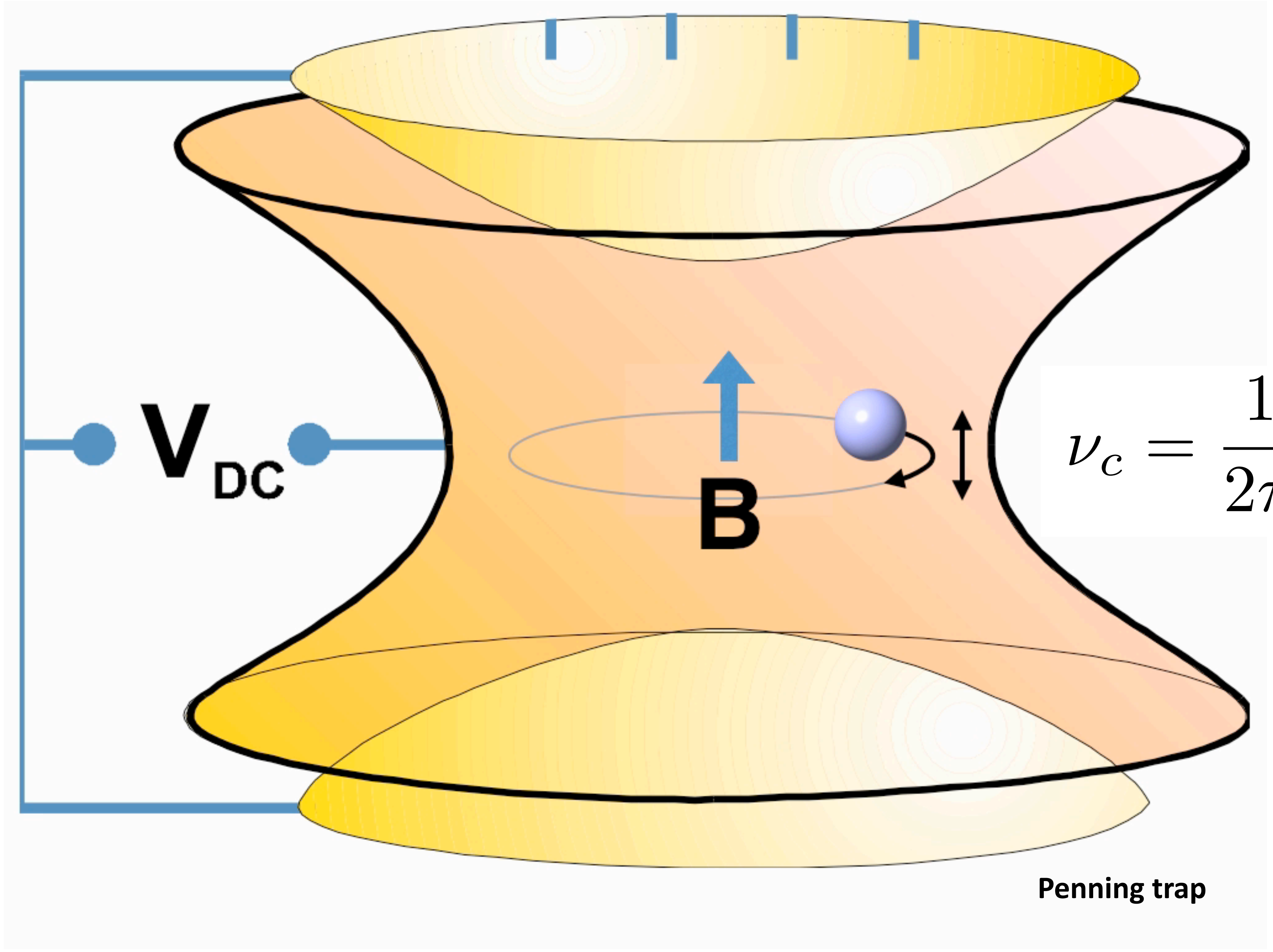

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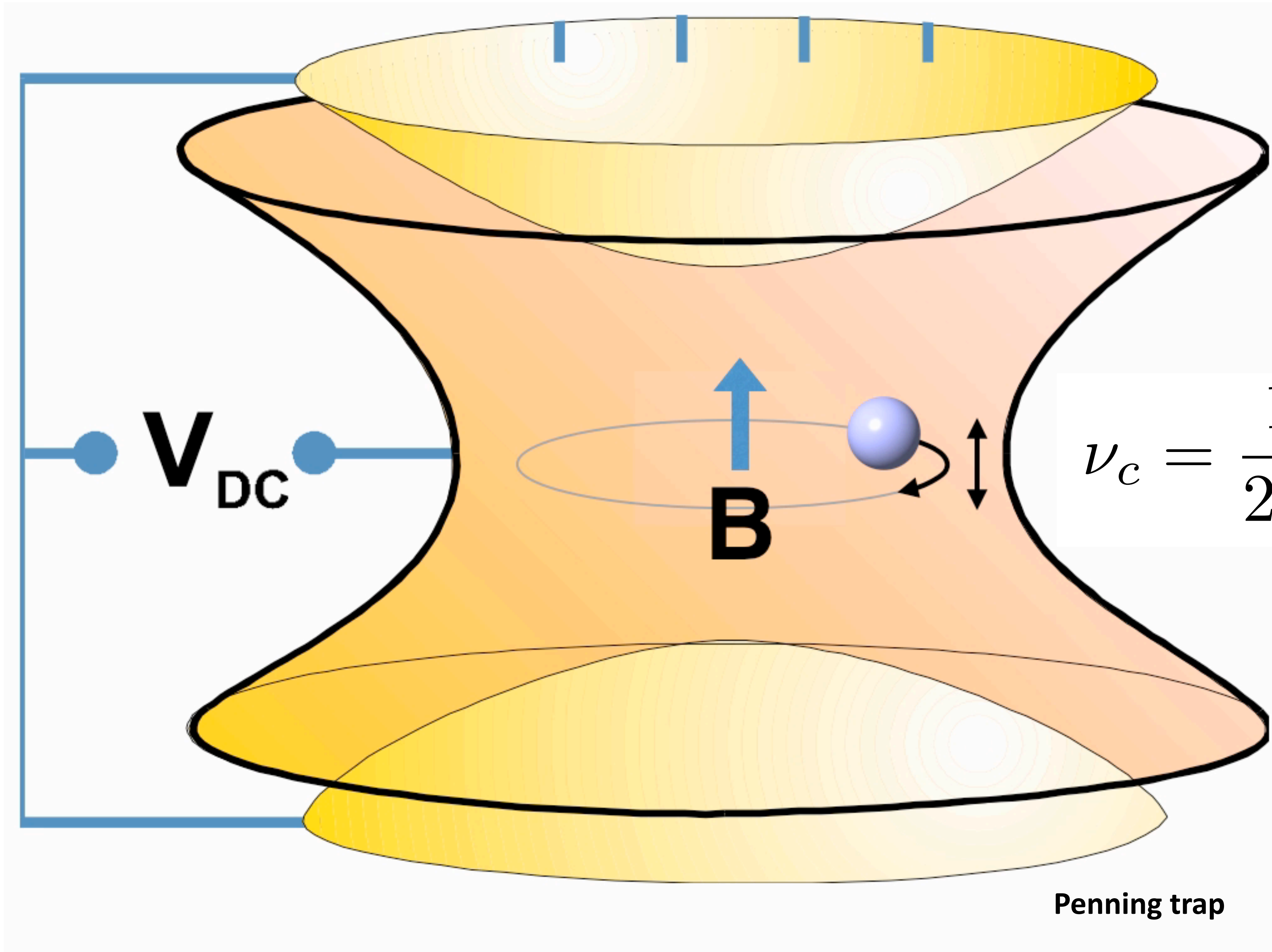

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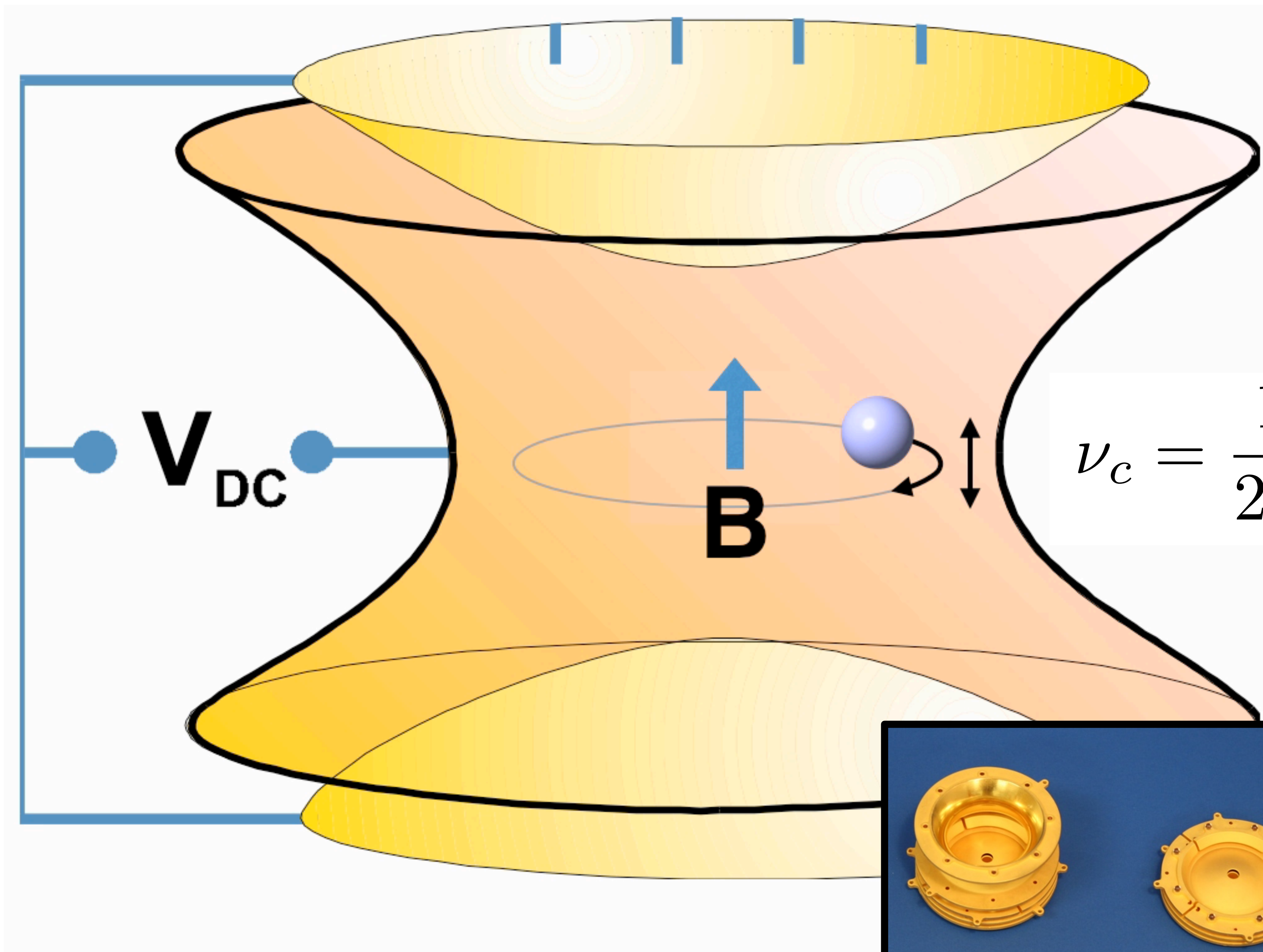

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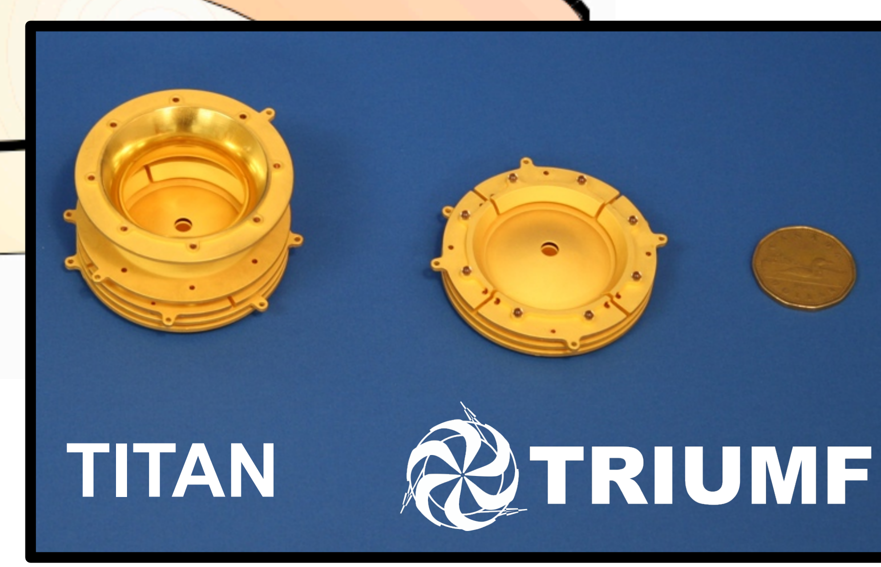
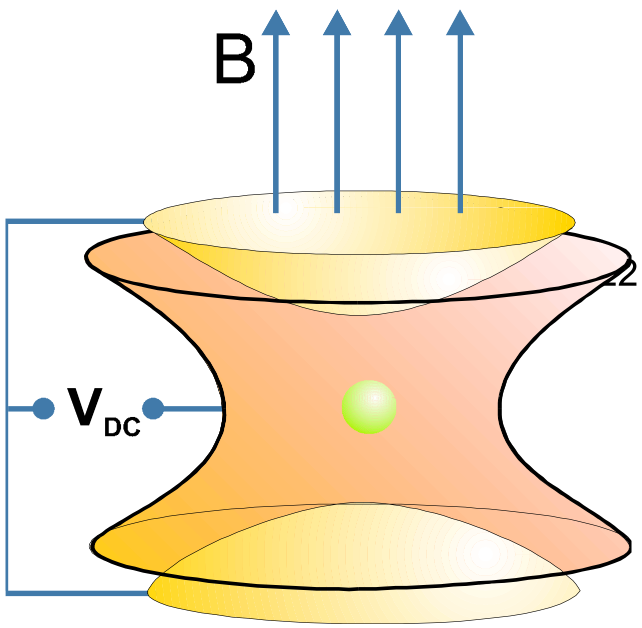


Penning traps and radionuclides



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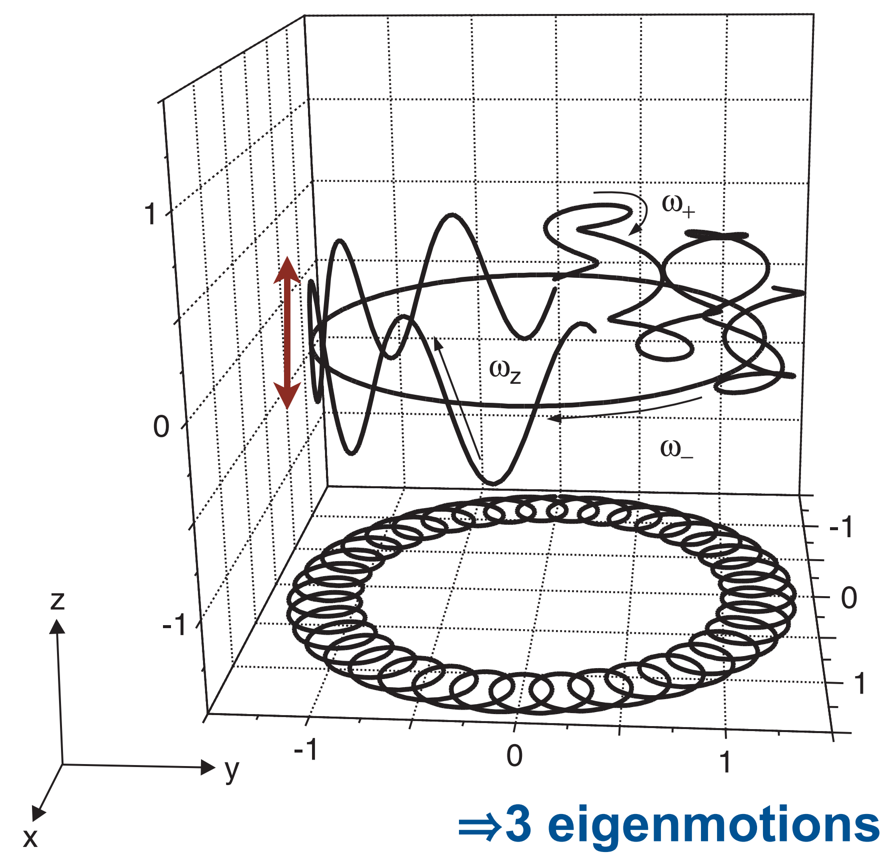


⇒3 eigenmotions

Accuracy

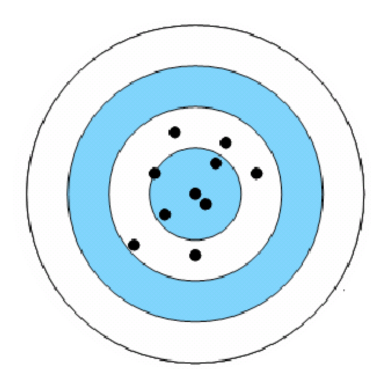
•exact theoretical description

L.S. Brown and G. Gabrielse, Rev. Mod. Phys. 58, 233 (1986)
G. Bollen et al., J. Appl. Phys. 88, 4355 (1990)
M. König et al., Int. J. Mass Spect. 142, 95 (1995)
M. Kretzschmarr, Int. J. Mass Spect. 246, 122 (2007)

•Including realistic, non-ideal traps

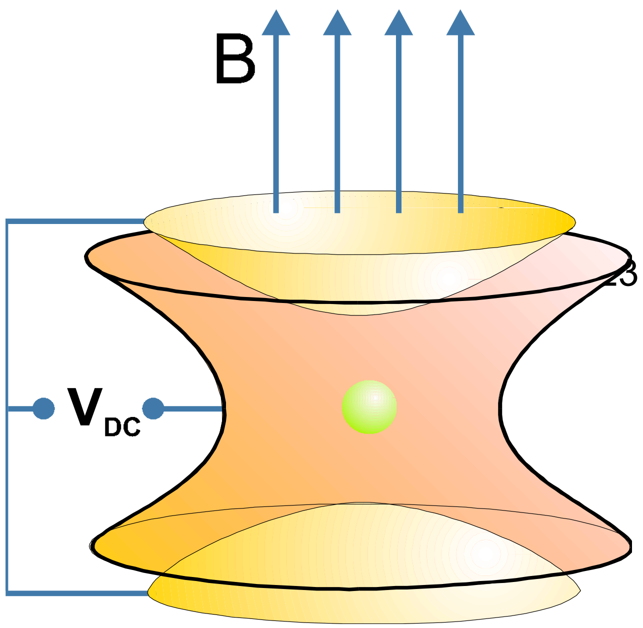
G. Bollen et al., J. Appl. Phys. 88, 4355 (1990)

•off-line tests with stables



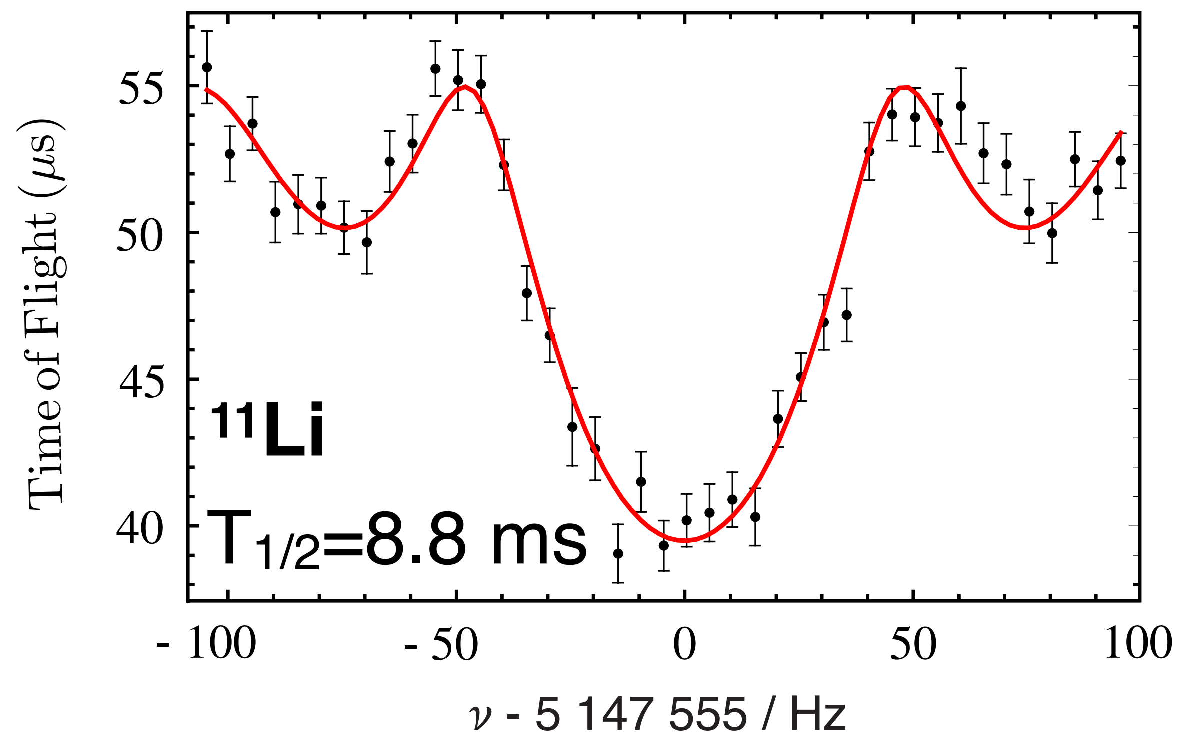
accurate,
but not precise

Penning traps and radionuclides



$$\boxed{\nu_c = \frac{1}{2\pi}\frac{q}{m}B}$$

M. Smith et al., Phys. Rev. Lett. 101, 202501 (2008)

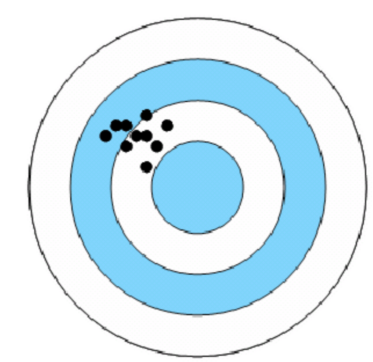


line-width (FWHM):

$$\Delta\nu \approx 1/T_{rf}$$

Precision

$$\frac{\delta m}{m} \propto \frac{m}{q}\frac{1}{BTN^{1/2}}$$



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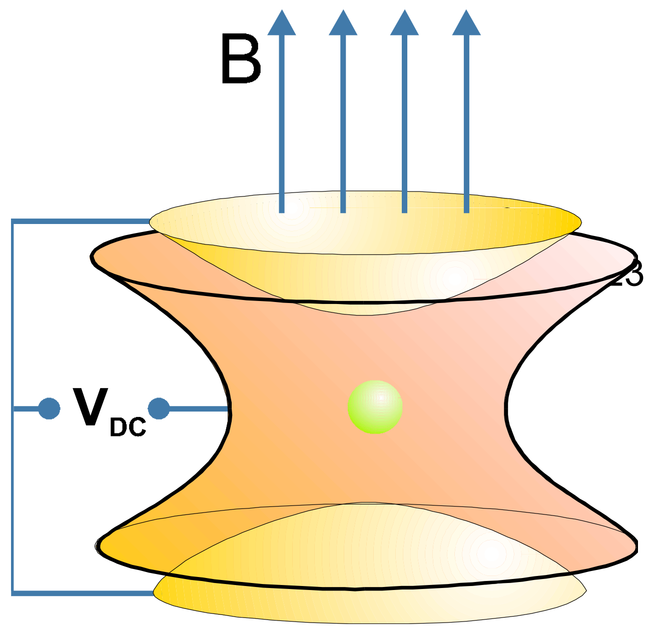

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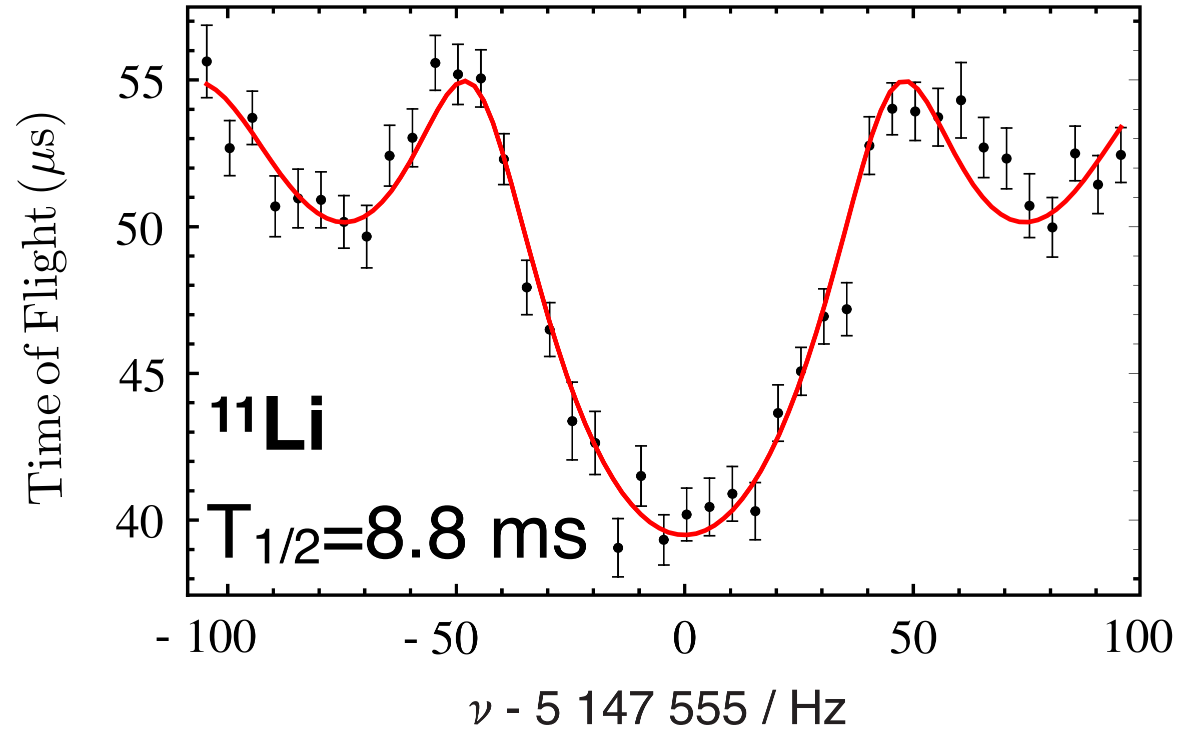
M. Smith et al., Phys. Rev. Lett. 101, 202501 (2008)



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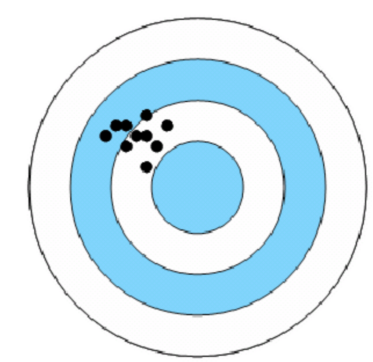
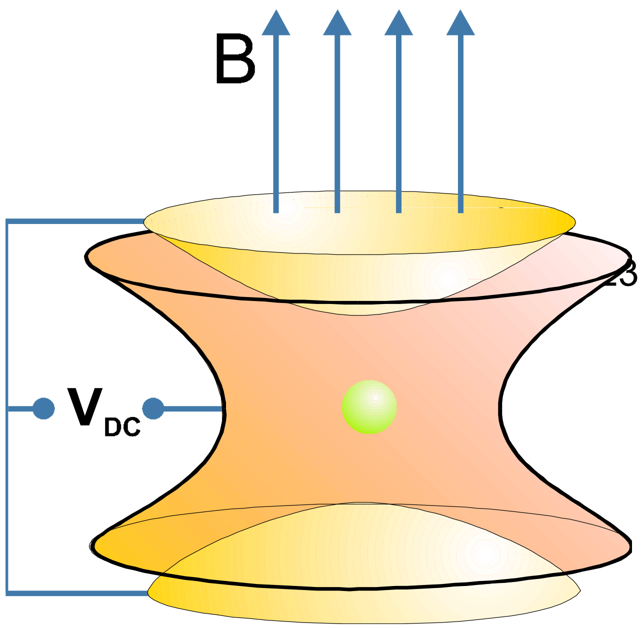


precise,
but not accurate

Attainable precision and accuracy
$\delta m/m \approx 10^{-7}$ to 10^{-9}

Penning traps and radionuclides



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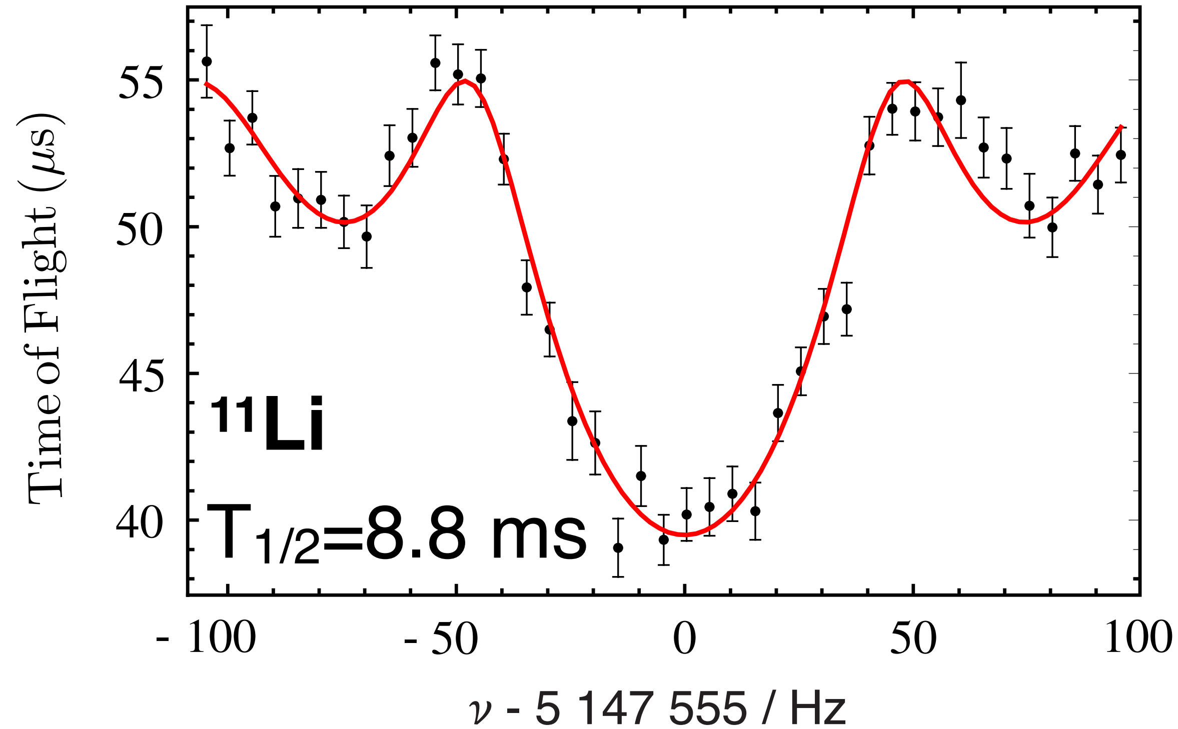

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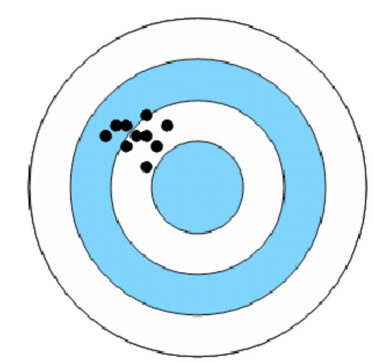

precise,
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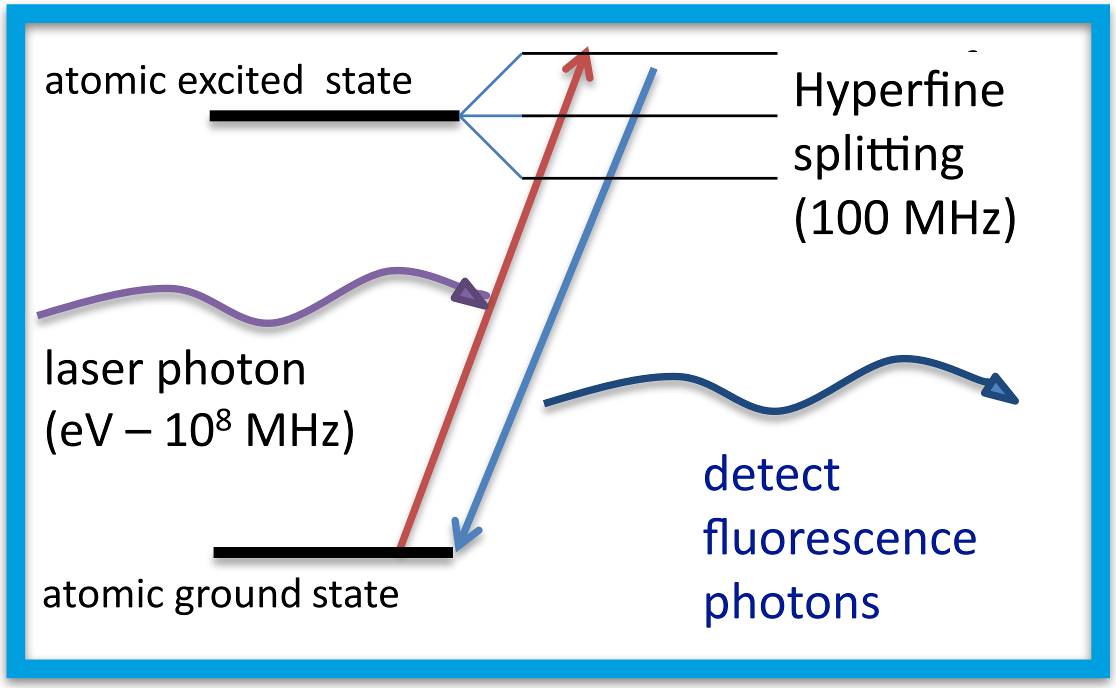
Attainable precision and accuracy
$\delta m/m \approx 10^{-7}$ to 10^{-9}

Related methods also used to study mass and magnetic moment of antiproton!

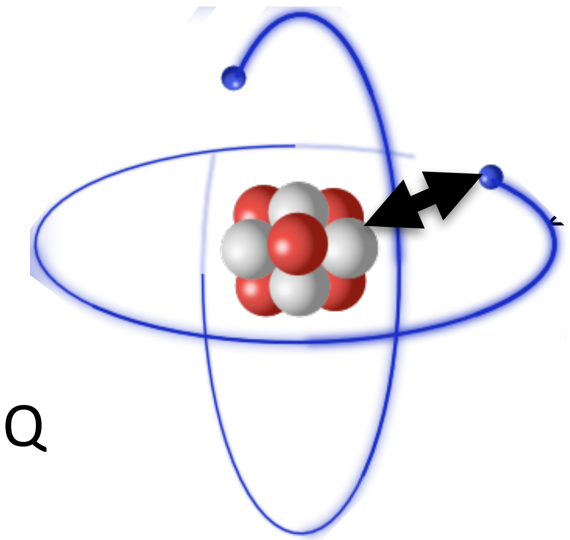
laser spectroscopy



nucleus - electrons interaction

⇒ atomic hyperfine structure

- nuclear spin I
- electromagnetic moments μ and Q
- nuclear charge radius r_c



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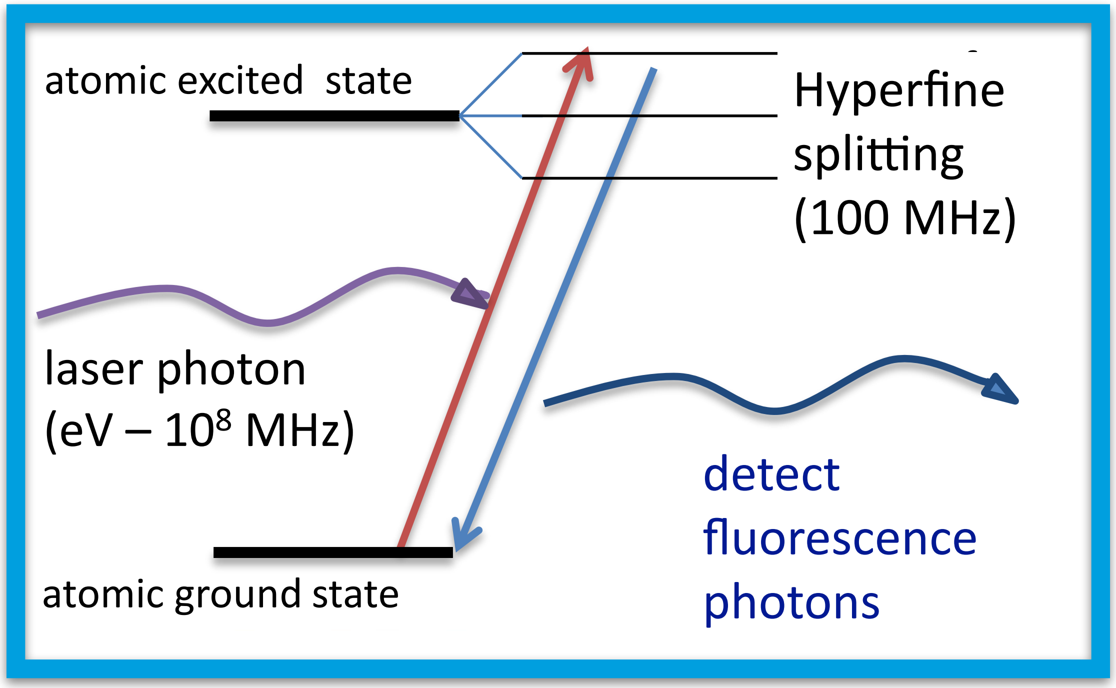

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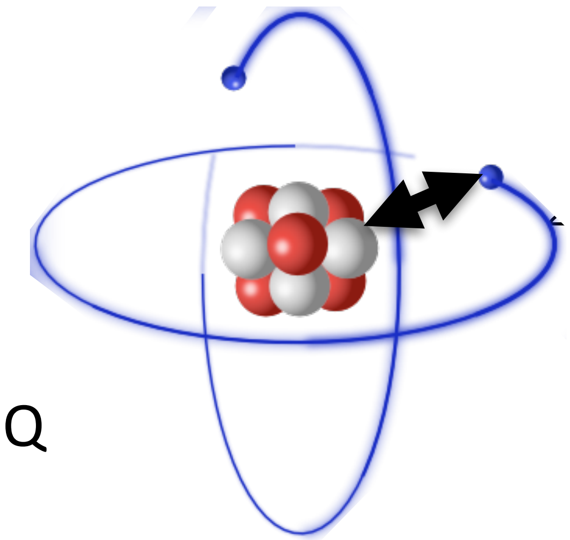
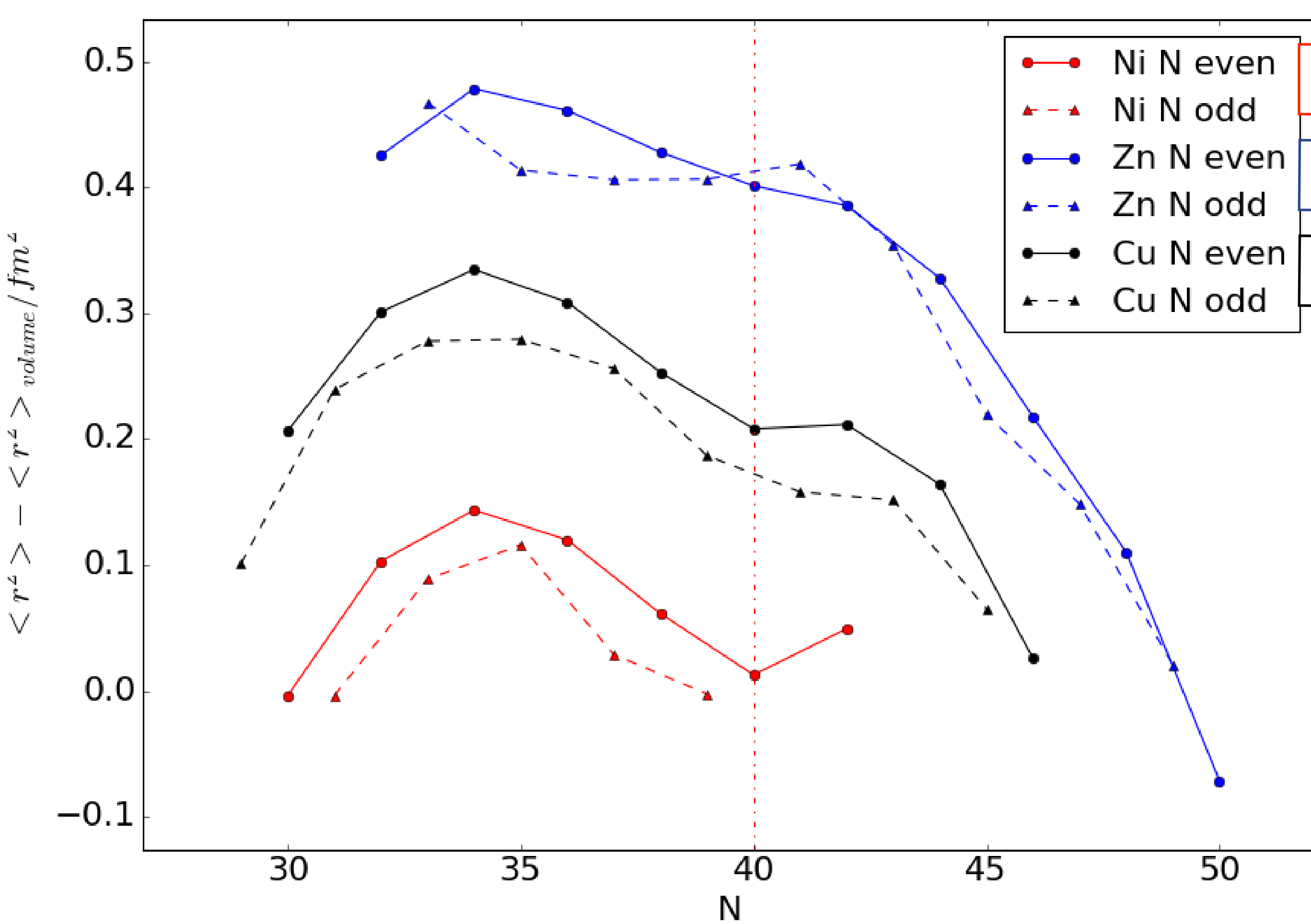




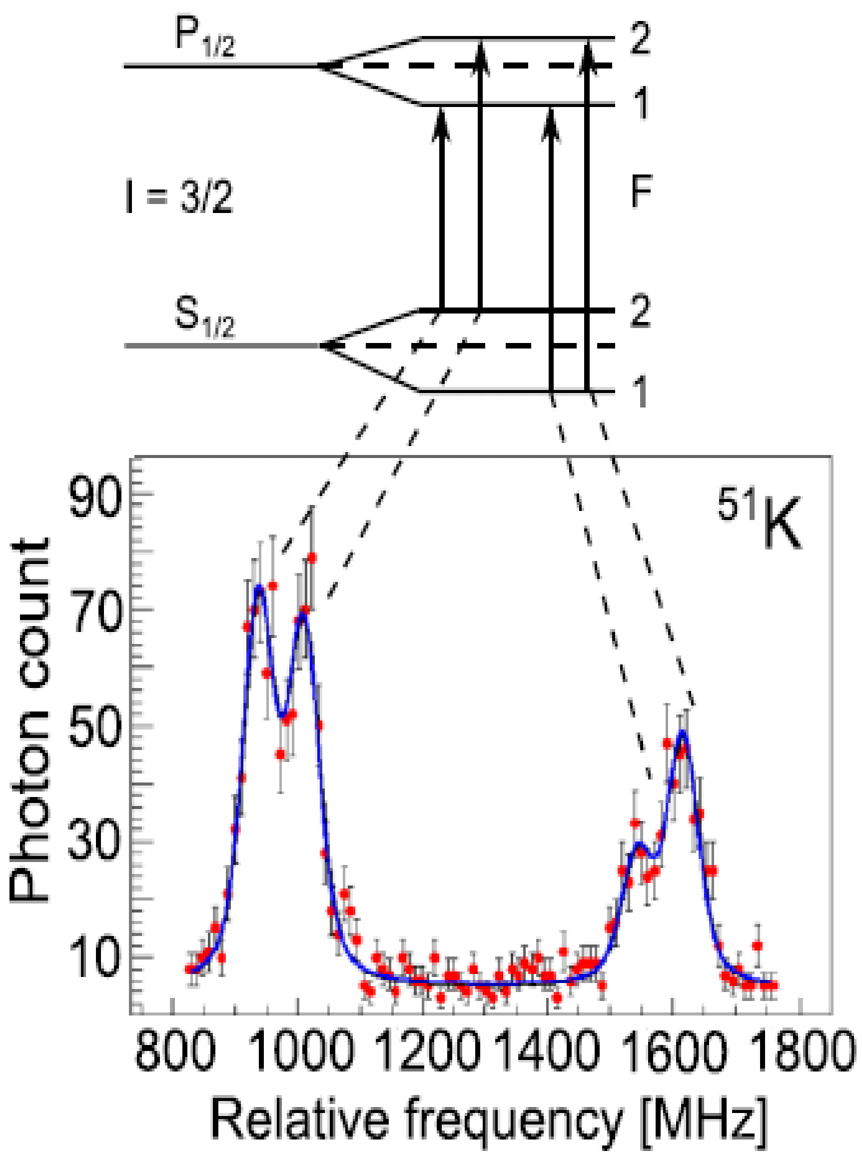
S. Malbrunot-Ettenauer, PRL 128, 022502 (2022)

L. Xie et al., PLB 797, 134805 (2019)

M. L. Bissell et al., PRC 93, 064318 (2016)

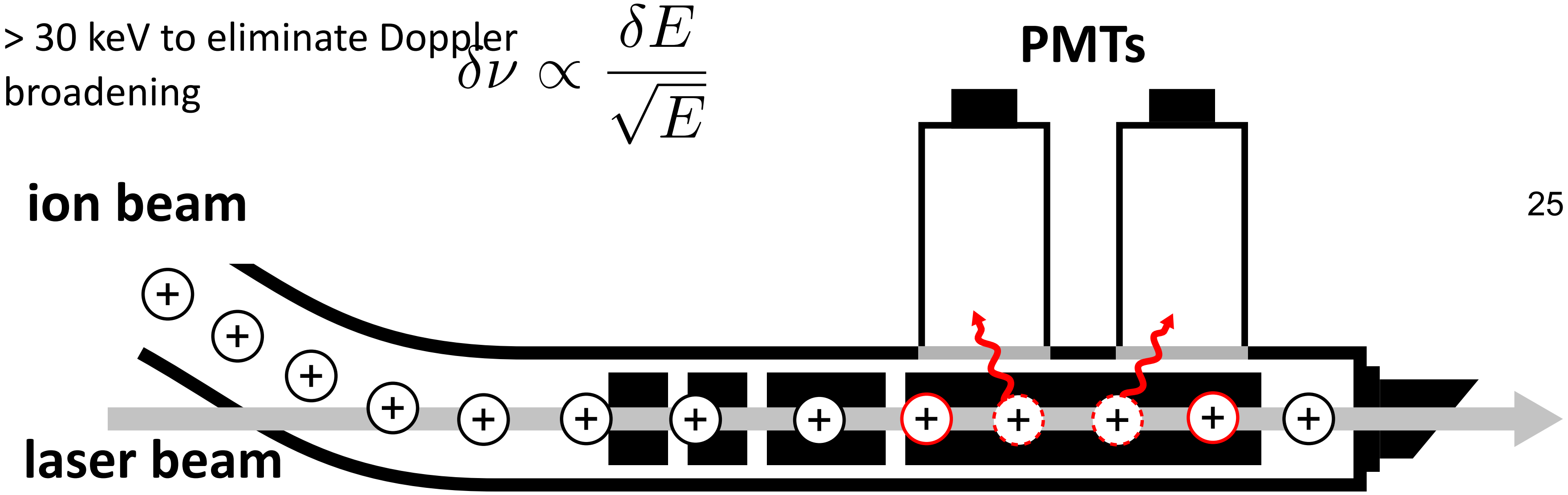
- **highlights changes in nuclear structure**
- **benchmark for modern nuclear theory**

Collinear Laser Spectroscopy (CLS)



> 30 keV to eliminate Doppler broadening

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



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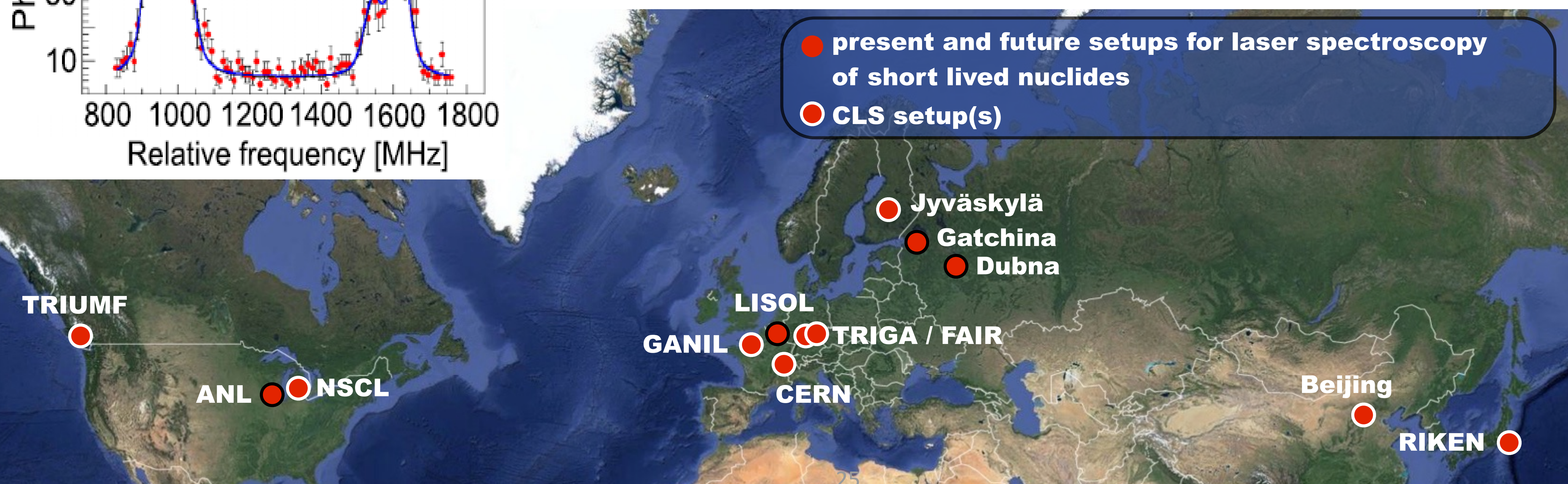
K. Blaum, et al., Phys. Scr. T152, 014017 (2013)
P. Campbell et al., Prog. Part. and Nucl. Phys. 86, 127-180 (2016)
R. Neugart et al., J. Phys. G: Nucl. Part. Phys. 44, 064002 (2017)



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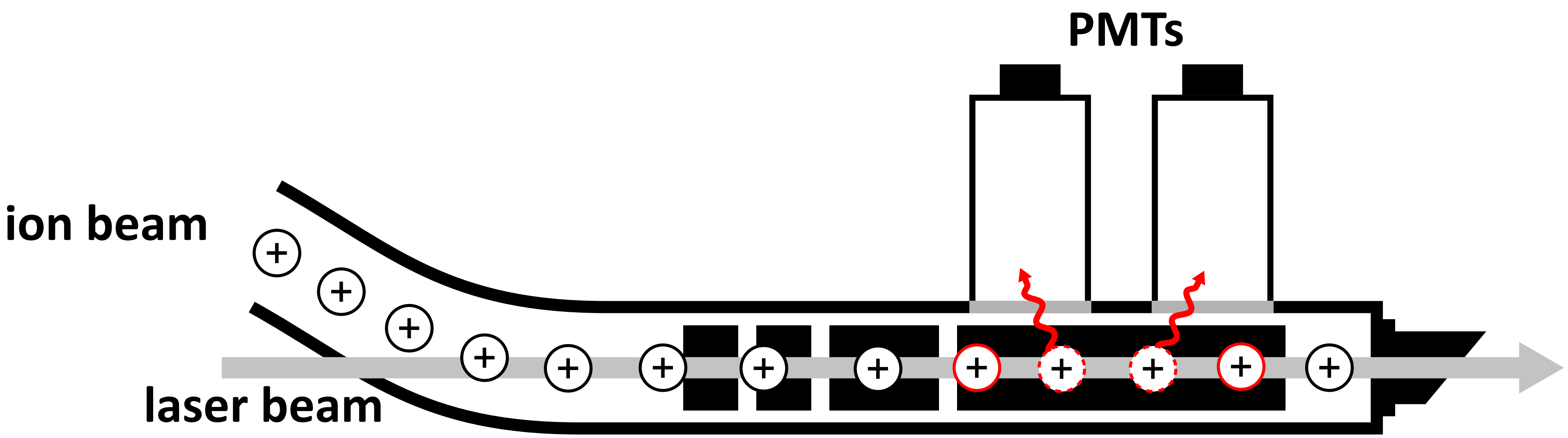
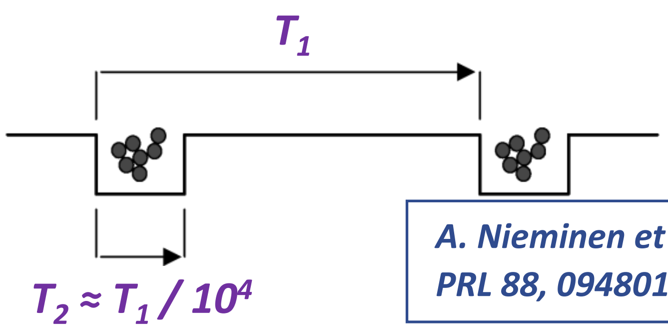


beams of ≥30 keV
minimises Doppler-broadening
⇒ high resolution

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

Bunched beams:
reduce background
by gating on bunch



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

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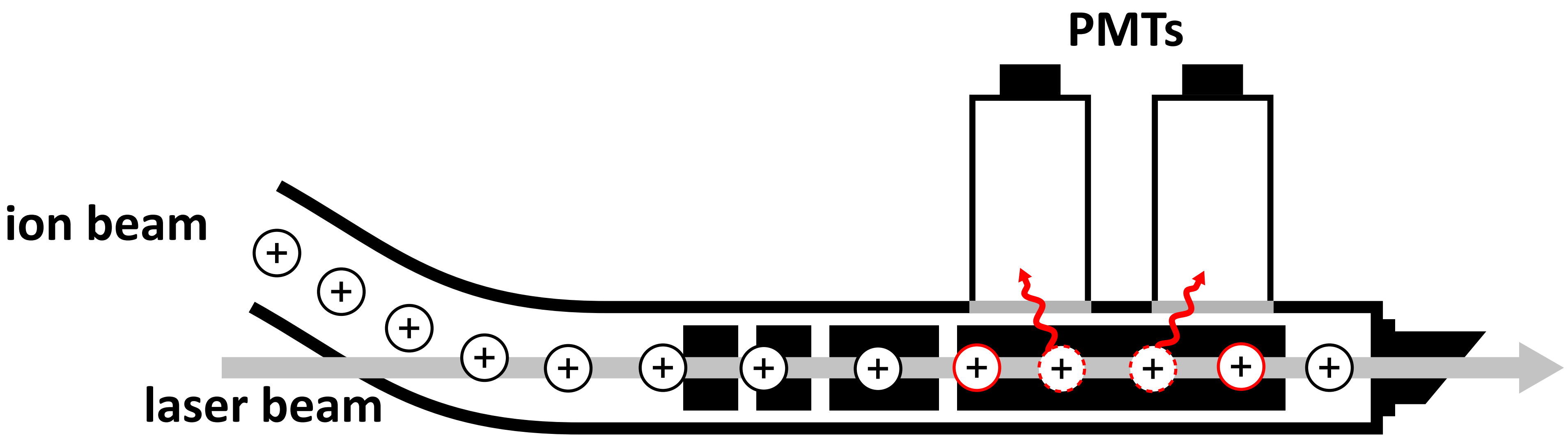

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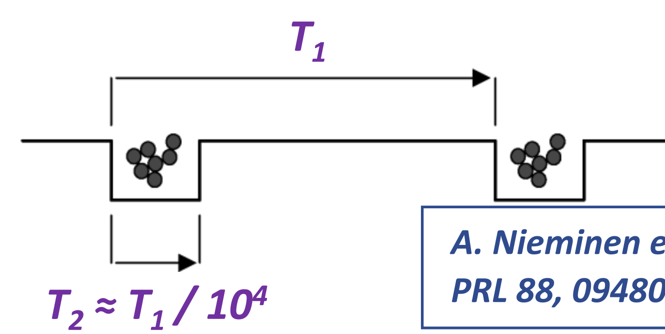


A. Nieminen et al., PRL 88, 094801 (2002)

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

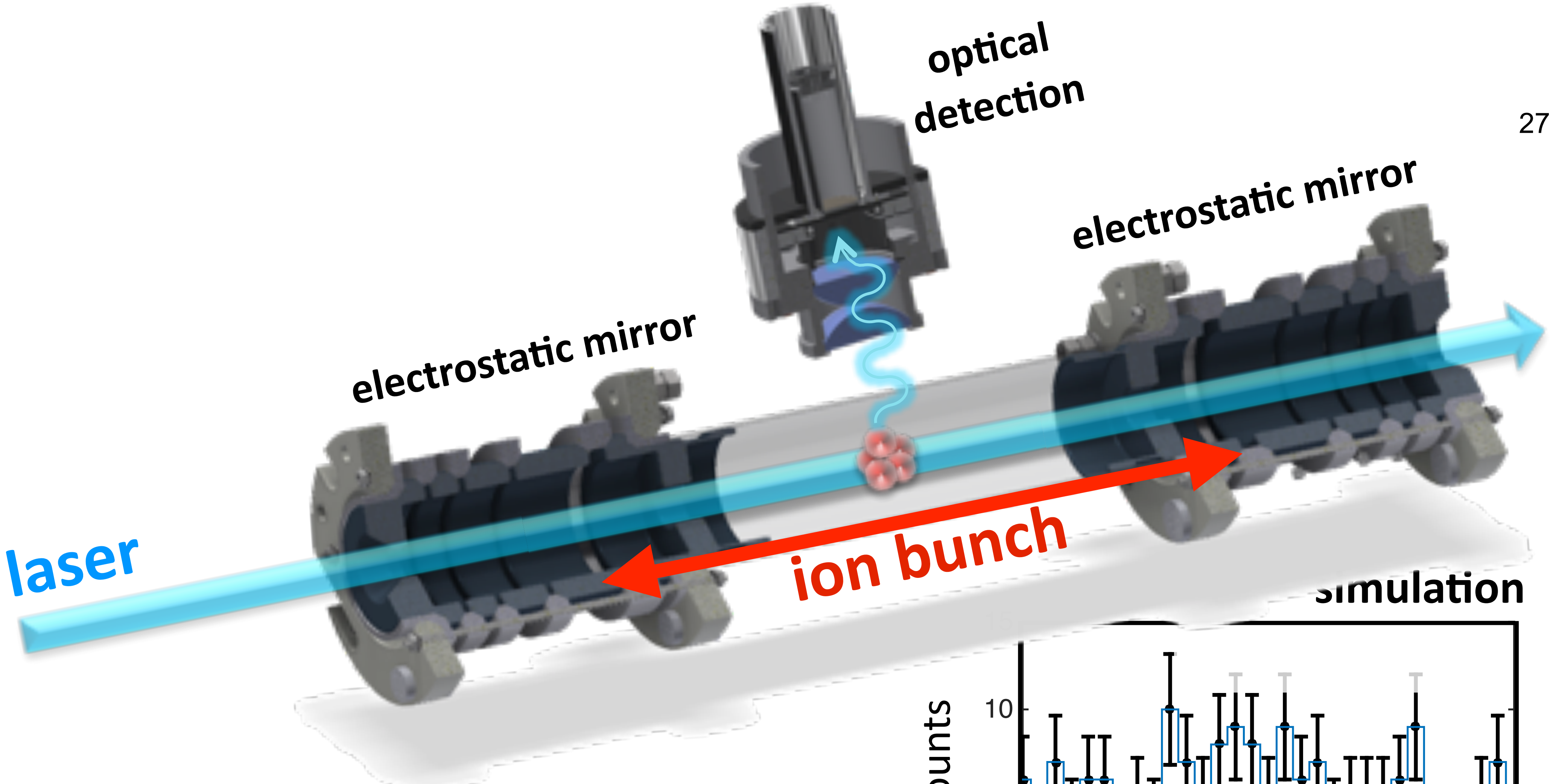
↔

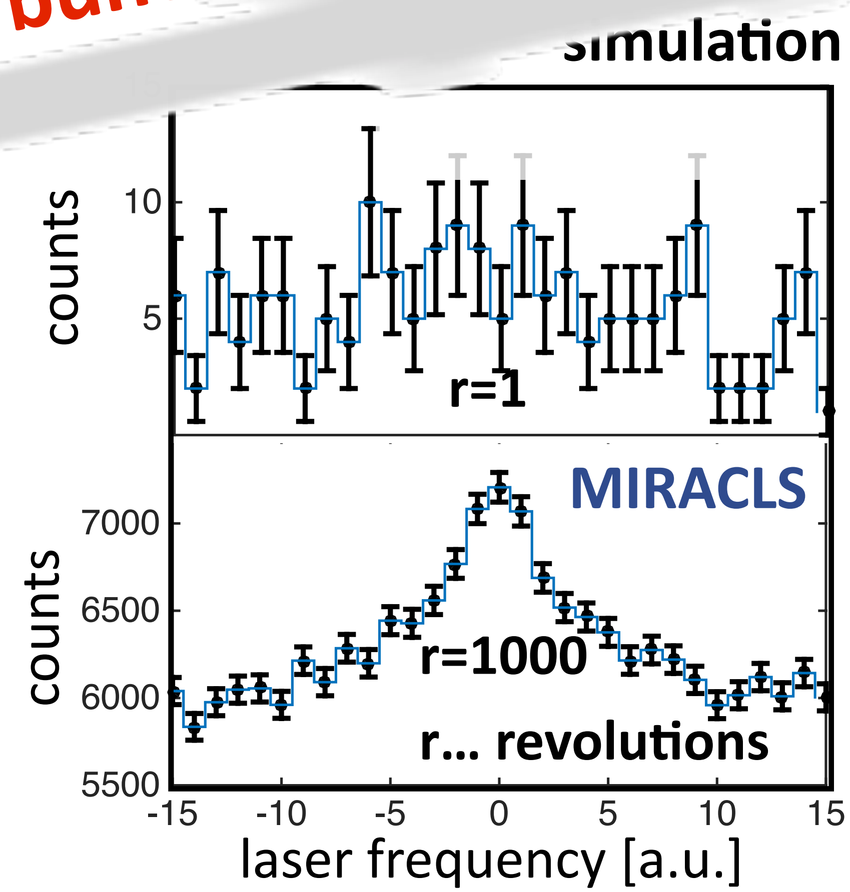
effective use for CLS
100s of ns to a few µs

¿ can one use exotic nuclides even <u>more efficiently</u> ?

the Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy (MIRACLS)

trap ⇒ long observation time ⇒ higher sensitivity ⇒ more exotic nuclides accessible

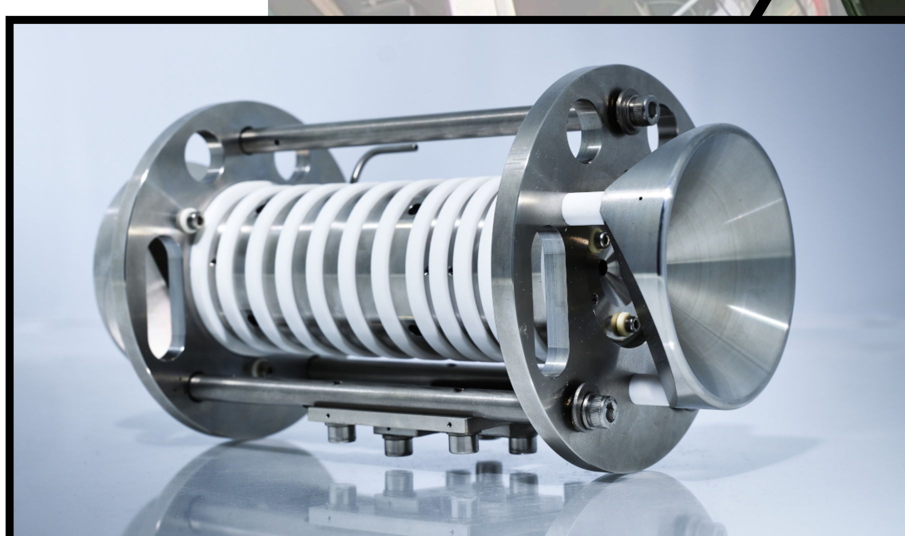




novel approach for collinear laser spectroscopy:

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

MIRACLS at ISOLDE / CERN


Picture of assembled Paul trap


Picture of MR-ToF mirrors

Summary

- **Techniques from Atomic, Molecular and Optical Physics (AMO) with high accuracy and precision**

- **Precision tools also at accelerator facilities to study ‘exotic atoms and molecules’**

- **today’s examples:**
  ➡ MR-ToF devices
  ➡ Penning traps
  ➡ Collinear laser spectroscopy
  ➡ Radioactive molecules as novel probes for new physics

- **… and many more**

TITAN

R. Simpson, I. Belosevic, A. Mollaebrahimi, C. Walls, C. Chambers, M. Au, P. Justus, C.Charles, L. Croquette, SME, A. Kwiatkowski
and all members of the TITAN collaborations

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I. Belosevic, **L. Croquette**, P. Fischer, **C. Kanitz**, **F. Hummer**, **E. Leistenschneider**, **S. Lechner**, **F. Maier**, **P. Plattner**, **A. Roitman**, M. Rosenbusch, **S. Sels**, **R. Simpson**, F. Wienholtz, **M. Vilen**, R. Wolf, F. Buchinger, W. Nörtershäuser, L. Schweikhard, SME

RadMol Collaboration:

UBC
University of Manitoba
TRIUMF
McGill
THE UNIVERSITY OF CHICAGO
University of Colorado Boulder
Massachusetts Institute of Technology
UNIVERSITY OF TORONTO
uOttawa
UNIVERSITY OF WATERLOO
HARVARD
JOHNS HOPKINS UNIVERSITY
UNIVERSITY OF MARYLAND 1856
Philipps Universität Marburg
TEMPLE UNIVERSITY®
university of groningen
THE UNIVERSITY OF EDINBURGH


TRIUMF-local RadMol team