DE LA RECHERCHE À L'INDUSTRIE

Physics Opportunities at Heavy-Ion Storage Rings

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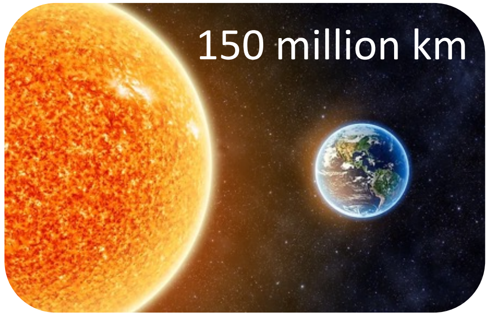
Properties of Heavy-Ion Storage Rings

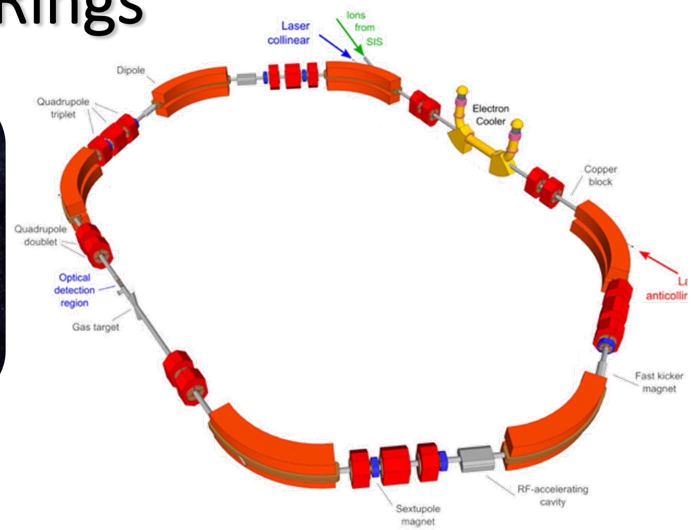
Storage of heavy ions on a closed orbit

- Revolving at high frequencies (0.1 to 1 MHz)
- Storage from milli-seconds (~1000 turns)
- up to hours or days (10^9 turns -> 10^8 km !!)
- ultra-high vacuum **<10^{-11} mbar**

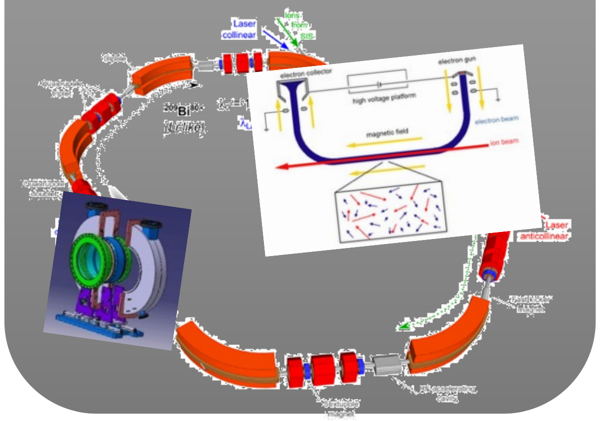
Study of exotic ions

- Radioactive beams and exotic decays
- Very high charge states (bare, H-like, …)

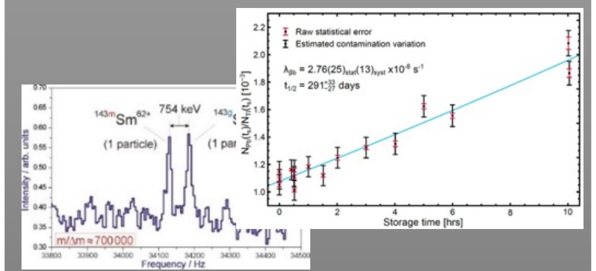




Storage ring basics

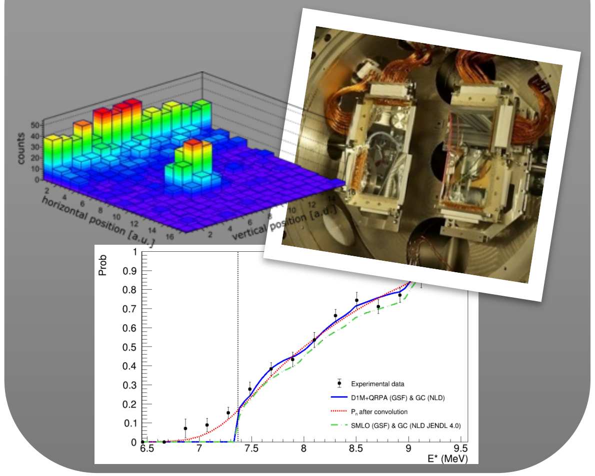


Mass measurements & decay studies

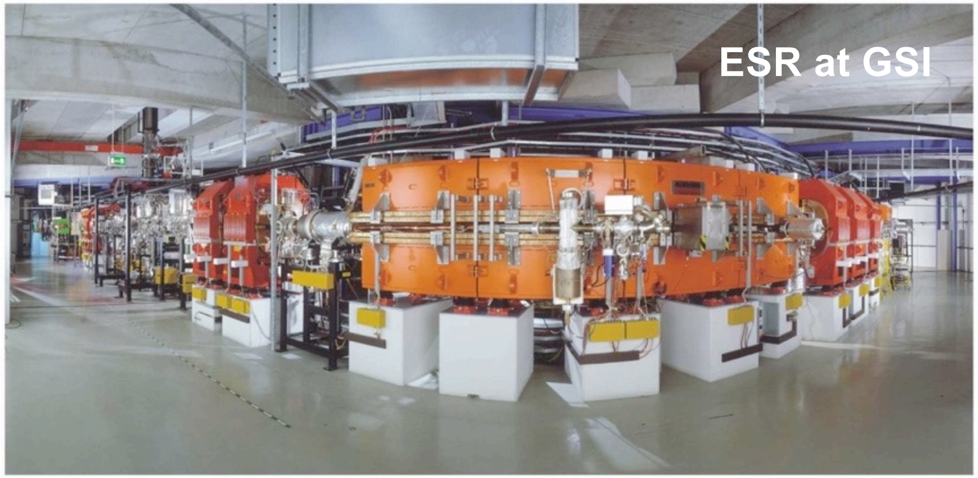


$$\frac{\Delta f}{f} = \frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\cdot\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

reaction studies



Operational Heavy-Ion Storage Rings for Nuclear Physics

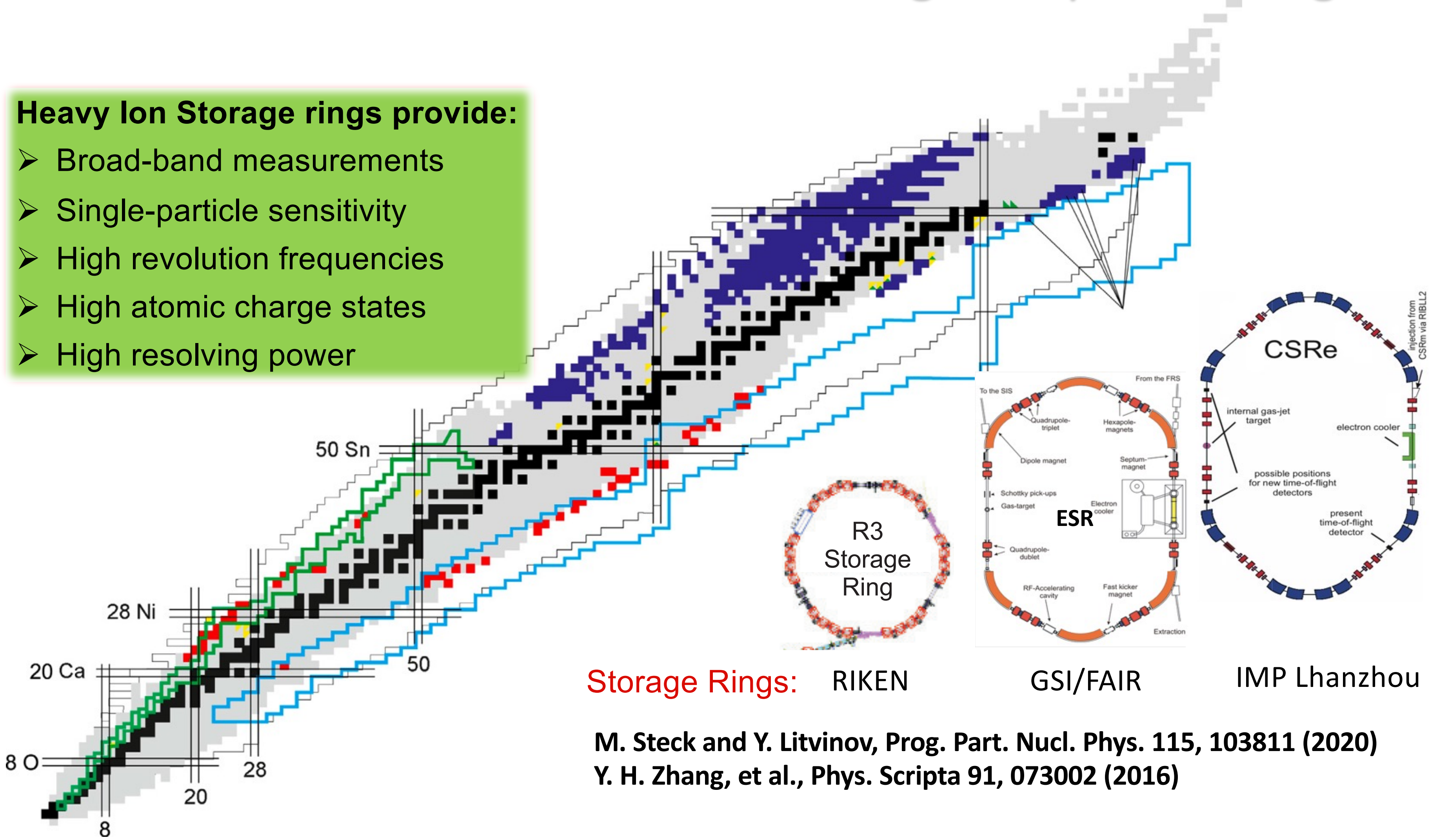


Photos: M. Lestinsky, A. Zschau, GSI; IMP Lanzhou; RIKEN

Direct Mass Measurements using Heavy-Ion Storage Rings

Heavy Ion Storage rings provide:

- Broad-band measurements
- Single-particle sensitivity
- High revolution frequencies
- High atomic charge states
- High resolving power



Storage Rings: RIKEN GSI/FAIR IMP Lhanzhou

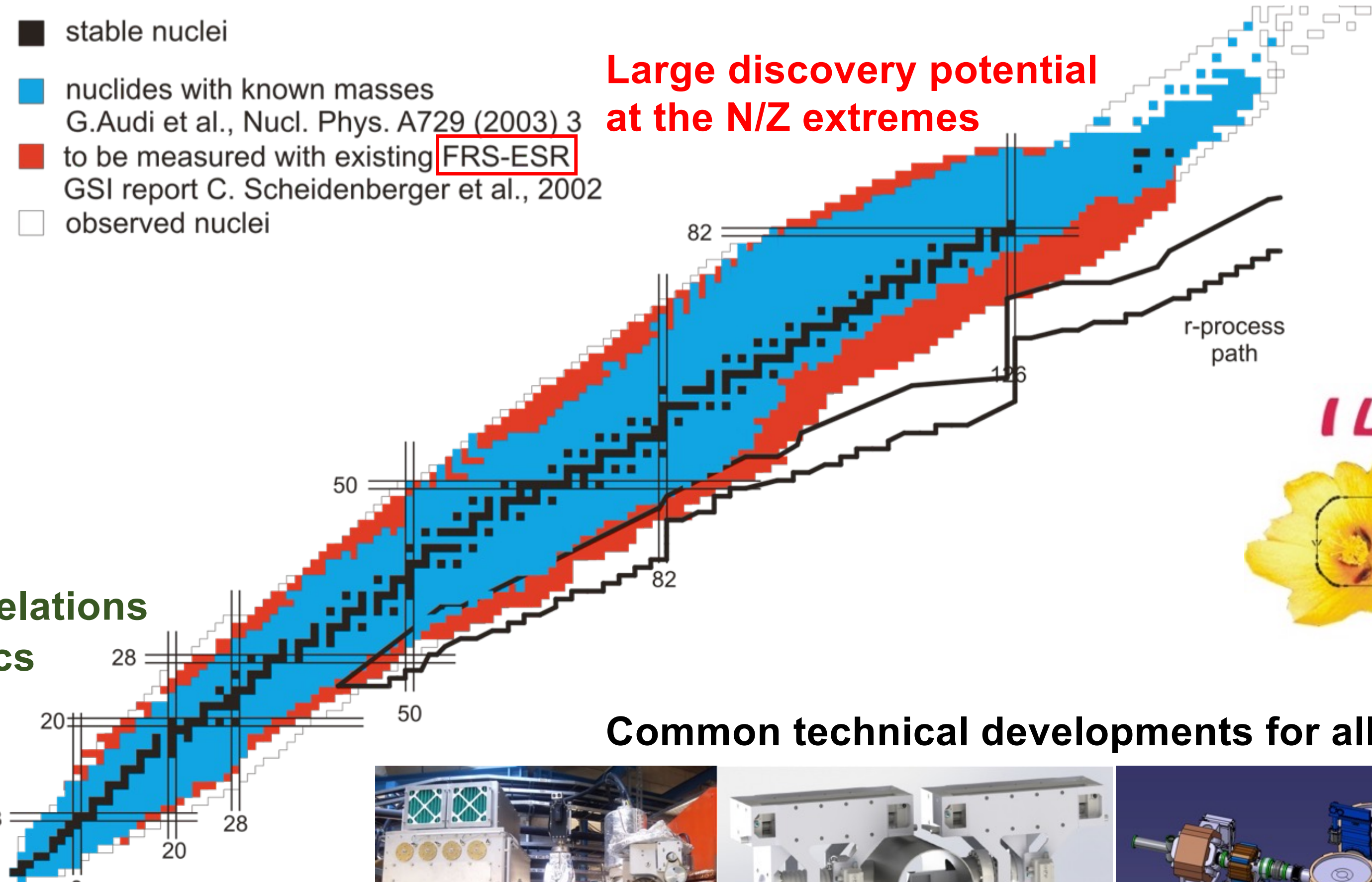
M. Steck and Y. Litvinov, Prog. Part. Nucl. Phys. 115, 103811 (2020)
Y. H. Zhang, et al., Phys. Scripta 91, 073002 (2016)

Mass and lifetime measurements of exotic nuclei

ILIMA

Storage rings:
ESR
CRYRING
with
Schottky detectors
TOF detectors
Particle detectors

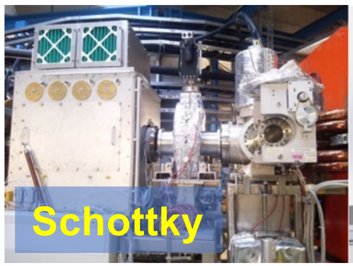
Large discovery potential at the N/Z extremes

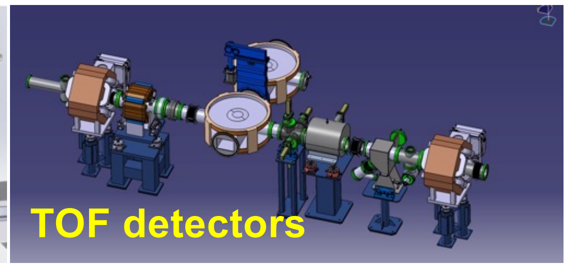


Masses:
- ✓ Shell evolution
- ✓ Deformation & correlations
- ✓ Nuclear astrophysics

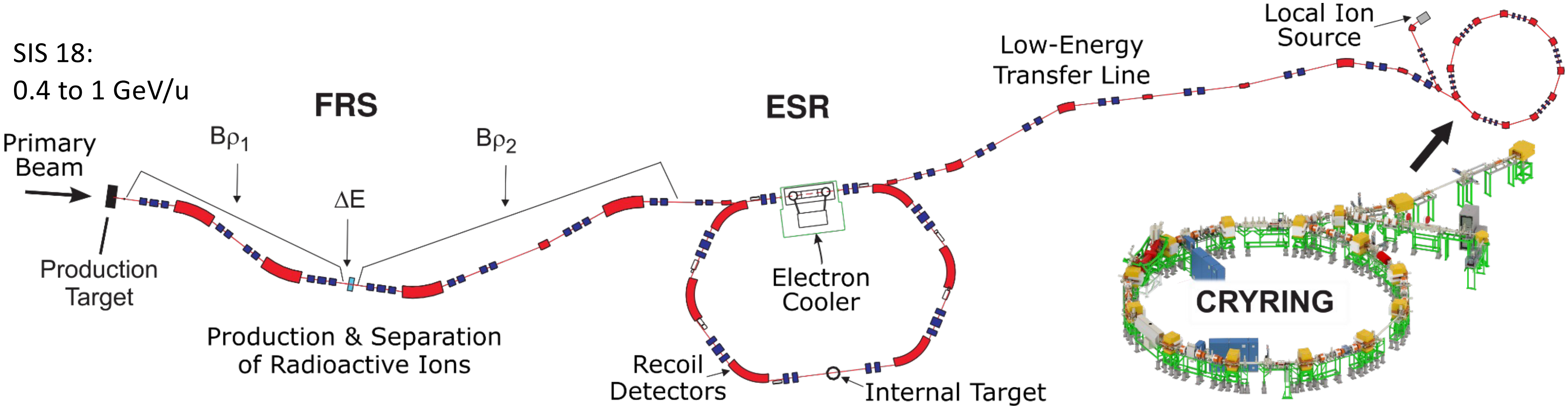
Lifetimes:
- ✓ Isomeric states
- ✓ New decay modes
  - ✓ Double gamma decay
  - ✓ Nuclear excitation by electron capture
- ✓ Bound-state beta decay
- ✓ Bound-state pair conversion decay

Common technical developments for all rings





Secondary beam and isomer production at GSI/FAIR



Select range of exotic ion beams

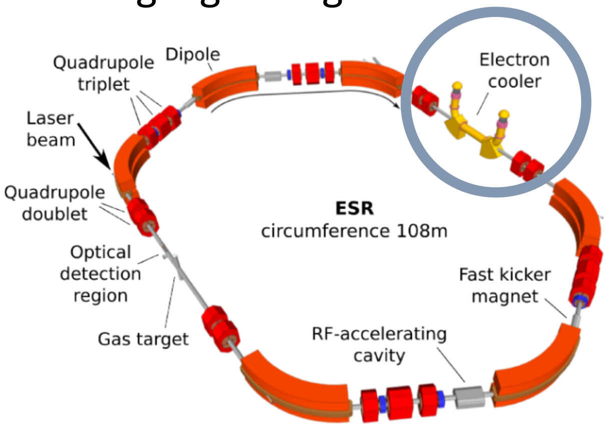
high energy beam storage (~3-400 MeV/u)

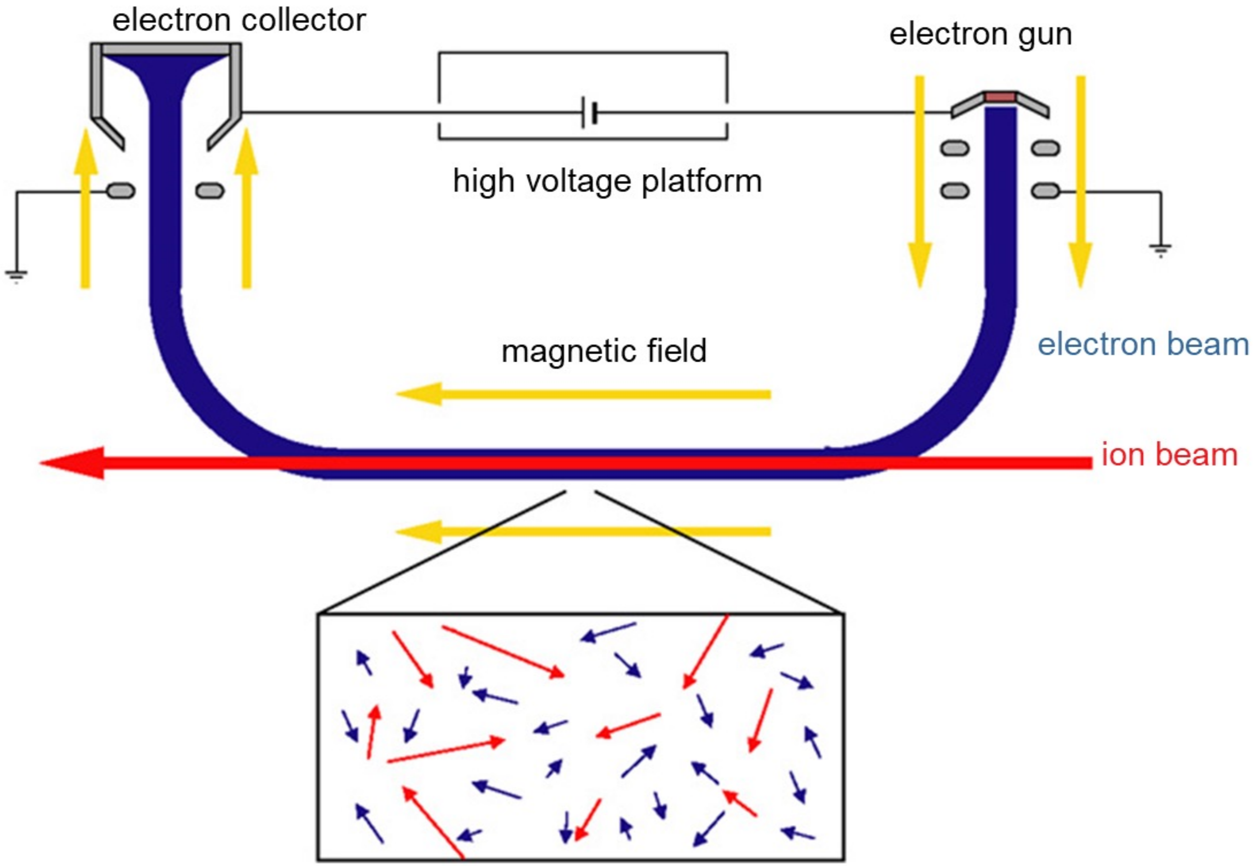
low energy beam storage (0.1– 15 MeV/u)

- Produce secondary beam at FRS (or direct line)
- Accumulation in ESR (with cooling and stacking)
- Deceleration and transfer to Cryring possible
- Scrapers allow to select isomers

Beam cooling as prerequisite for high-resolution mass spectroscopy

- Newly injected beam is “hot” i.e. having a large spread in position and momentum
- Overlap the ion beam with an electron beam with the mean velocity of the ions
- Cooling of the ion beam by a net heat transfer to lighter electrons through collisions
- Recovery of energy loss when using a gas target



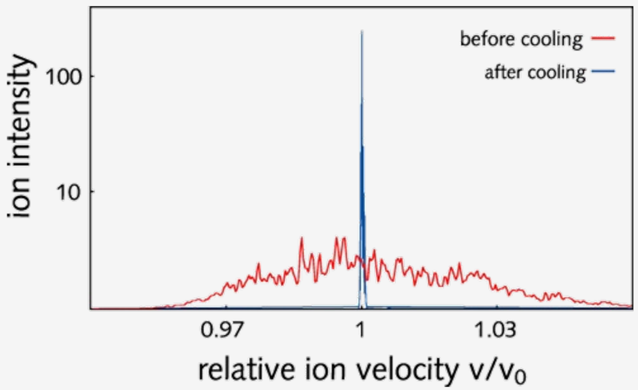


Beam cooling as prerequisite for high-resolution mass spectroscopy

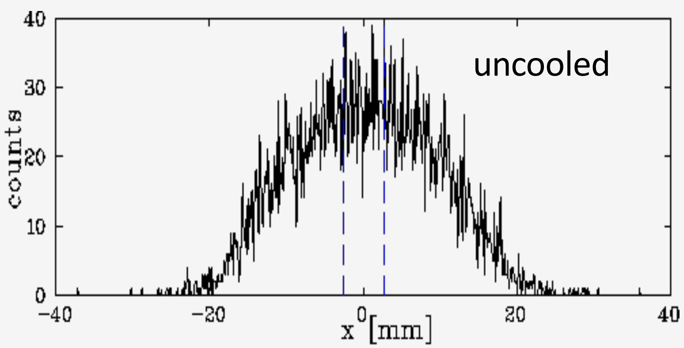
- most brilliant beams
  $\Delta p/p = 10^{-5} - 10^{-6}$
- compensates small energy loss when using an internal gas target
- slow cooling technique, i.e. takes a few seconds or minutes
- most effective for pre-cooled, (stochastic cooling) low-energy beams

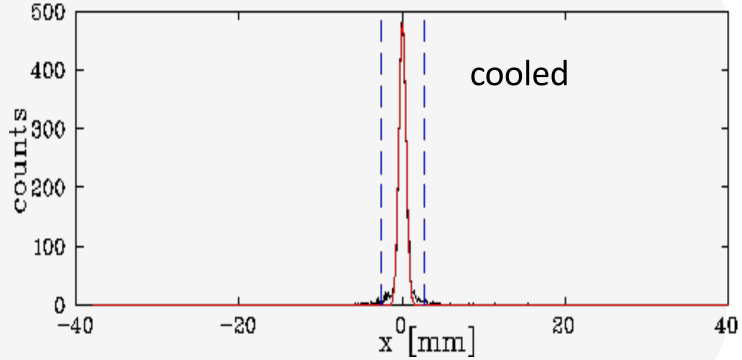
Electron cooler at ESR

Velocity distribution of ions



Spacial distribution of ions



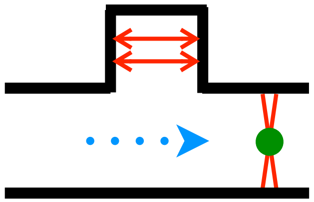


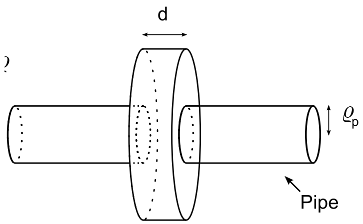
Schottky resonators for non-destructive Particle Detection

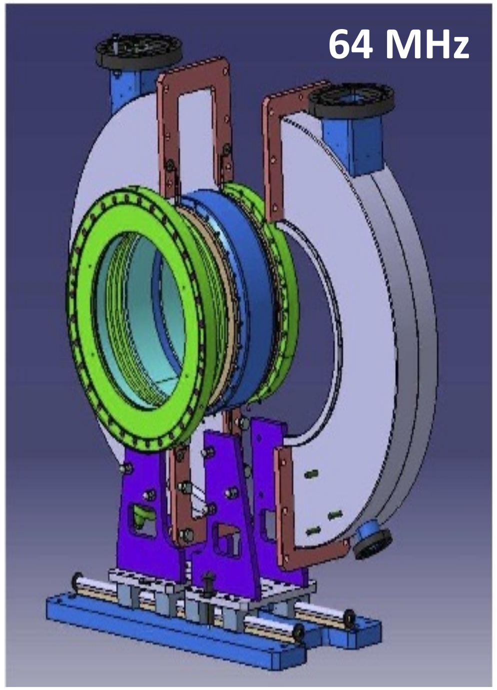
Heavy ions induce a signal at every revolution (~2 MHz)
Increased resonance frequency leads to

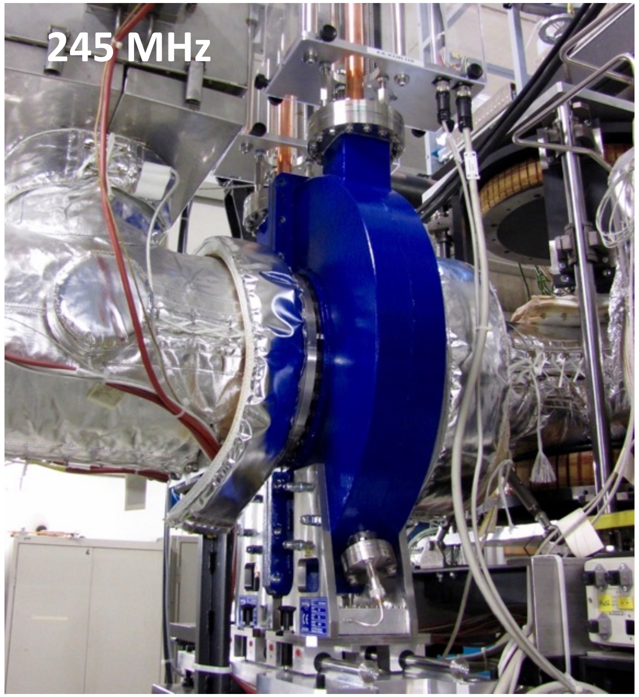
- **better sensitivity** for single ions
- **increased resolving power**

Courtesy F. Nolden and M. S. Sanjari





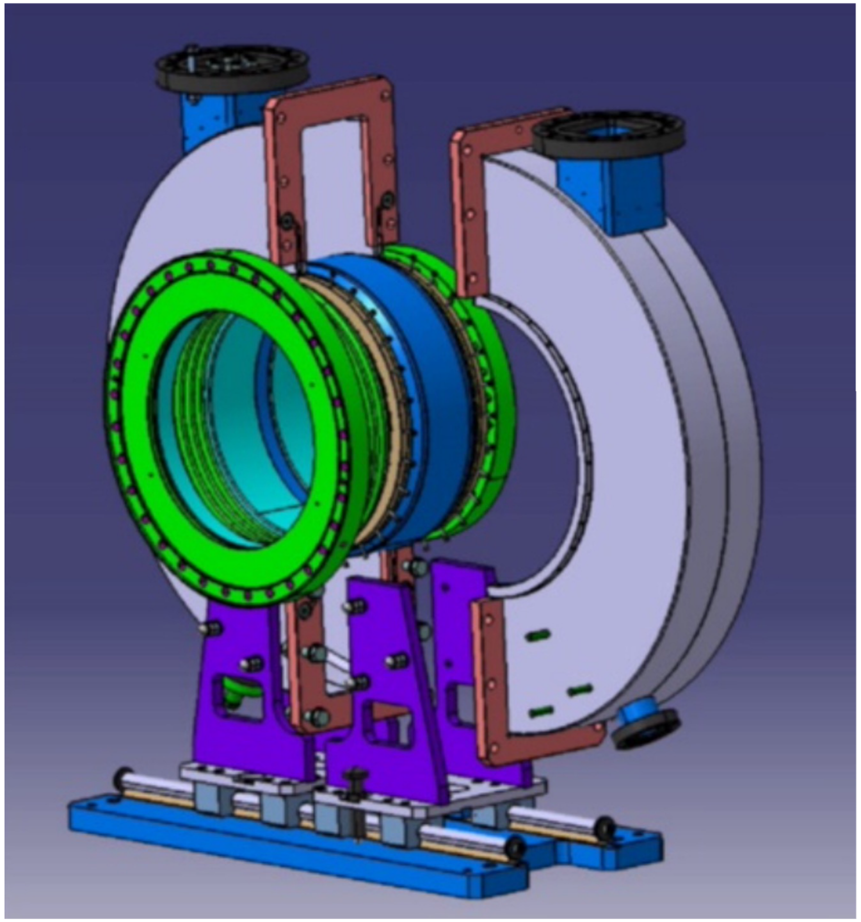




F. Nolden et al.,
Nucl. Instr. Meth. A 659, 69–77 (2011)

S.Sanjari et al.,
Rev. Sci. Instr. 91, 083303 (2020)

Working principle of Schottky detectors



Schematic diagram of a Schottky resonant cavity
(M. S. Sanjari et al, Phys. Scr., 014088, 2013)

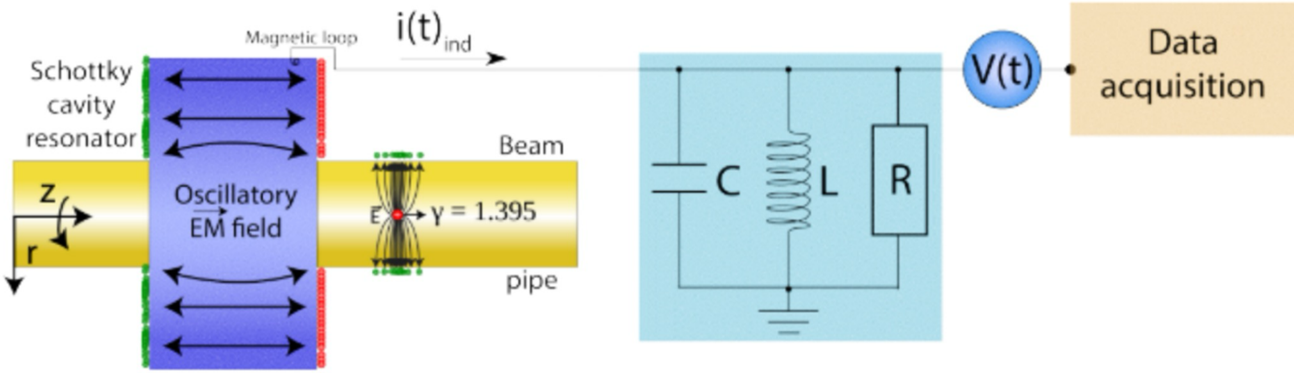
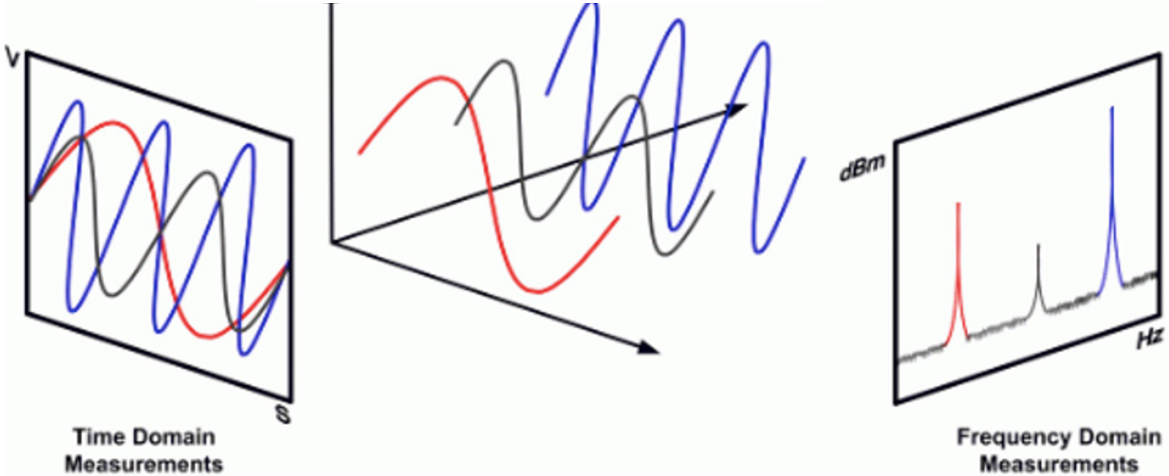


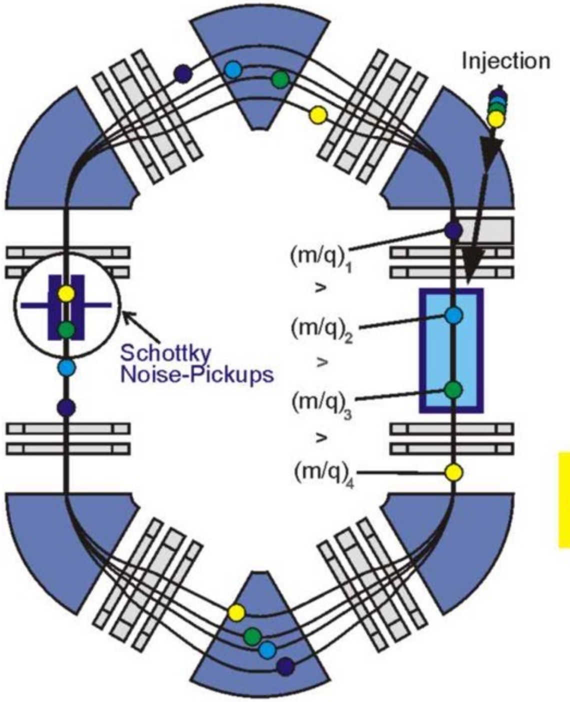
Diagram demonstrating the principle of resonant Schottky detectors
(D. F. Fernandez, PhD Thesis, 2024)



High-resolution mass spectrometry in a storage ring

SCHOTTKY MASS SPECTROMETRY

SMS: revolution frequency (~2 MHz)

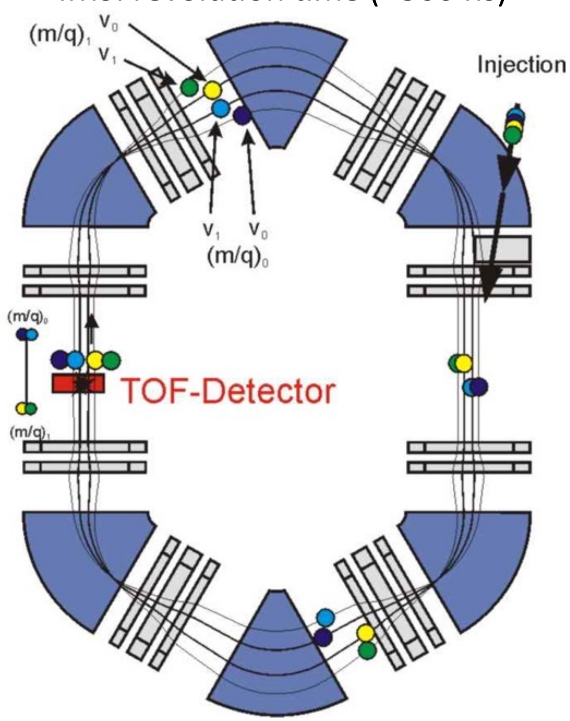


$$\frac{\Delta v}{v} \rightarrow 0 \qquad \gamma_t \rightarrow \gamma$$

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

ISOCHRONOUS MASS SPECTROMETRY

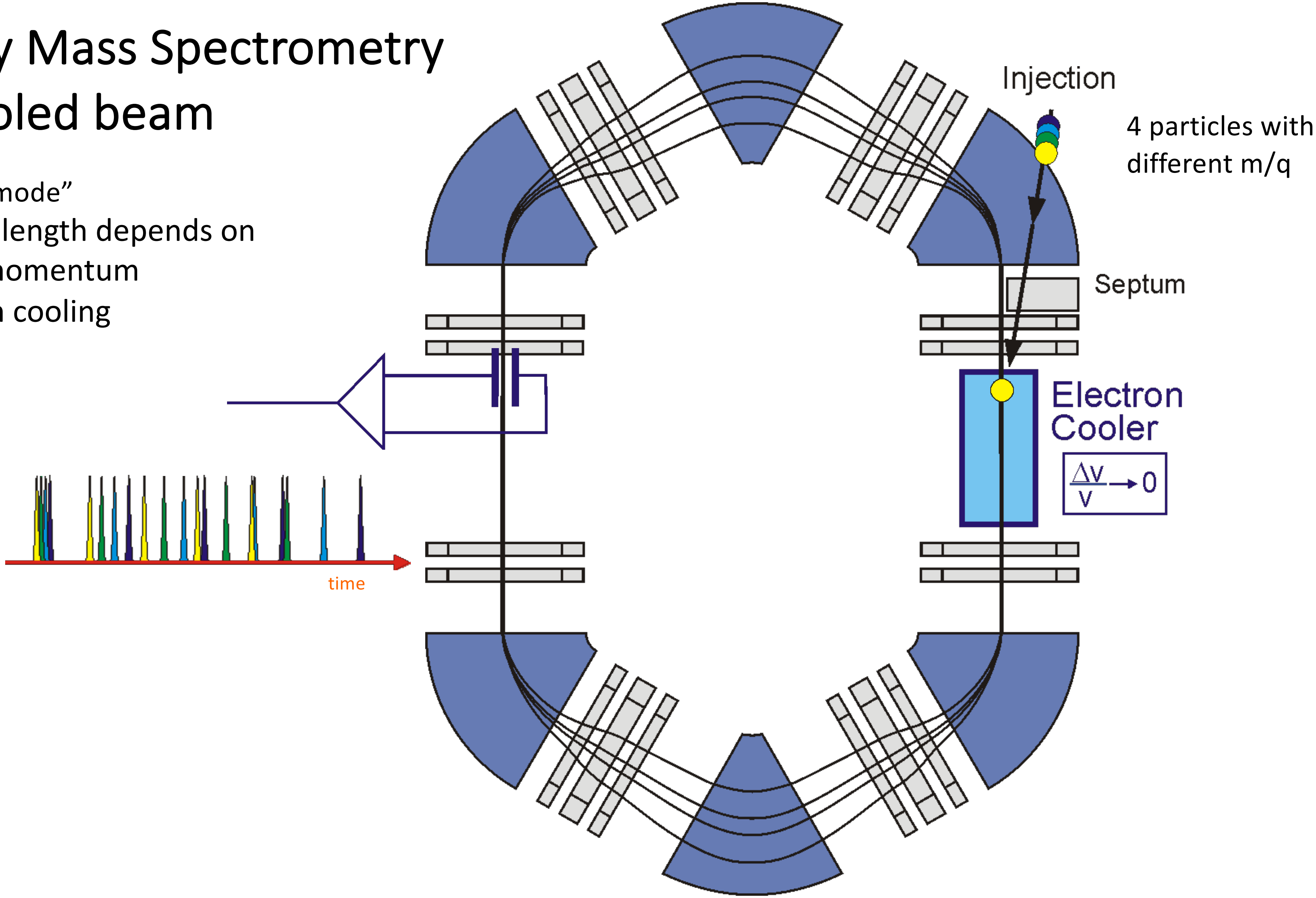
IMS: revolution time (~500 ns)



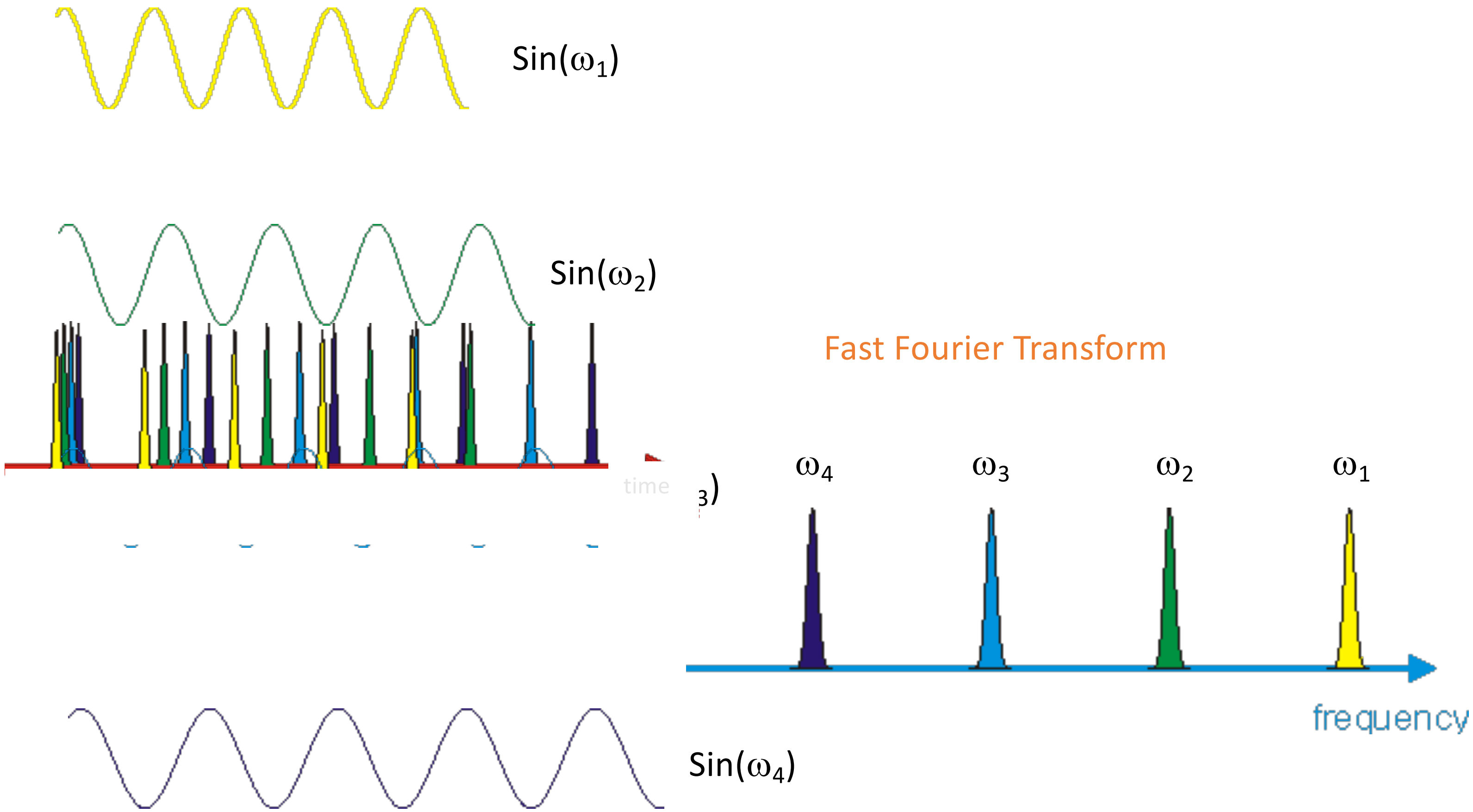
Schottky Mass Spectrometry with cooled beam

"normal mode"

- orbit length depends on ion momentum
- beam cooling



Schottky Mass Spectrometry with cooled beam



Isochronous Mass Spectrometry

No beam cooling

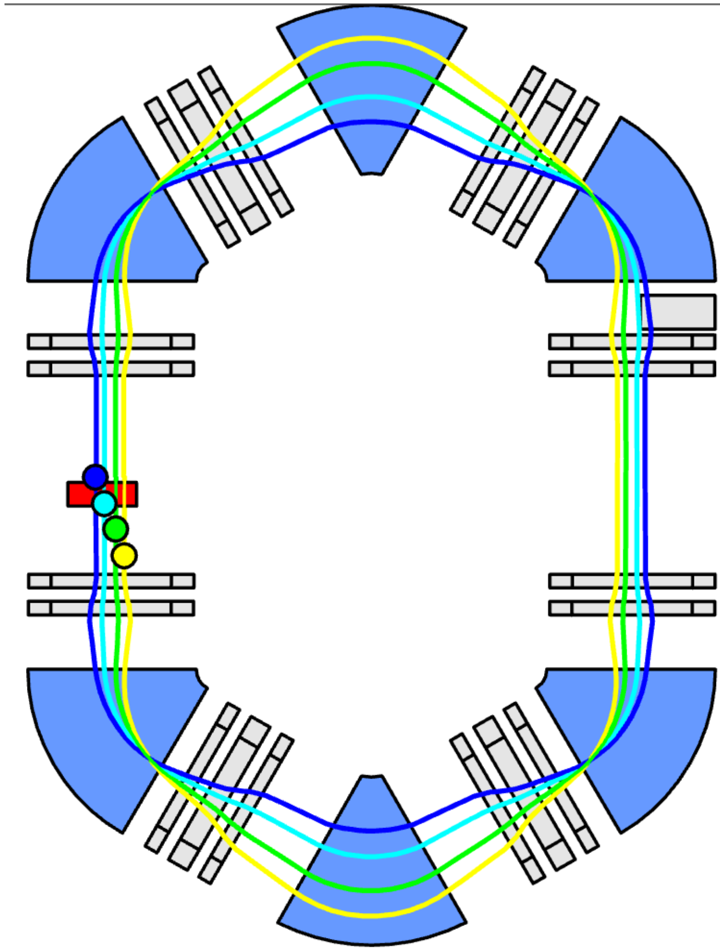
- ✓ very fast technique
- ✓ milli-seconds half-life
- ✓ broad velocity distribution

Special optical setting

- ✓ fixed orbital length for ions with $\gamma=\gamma_t$ independent of ion velocity

Measurement scheme

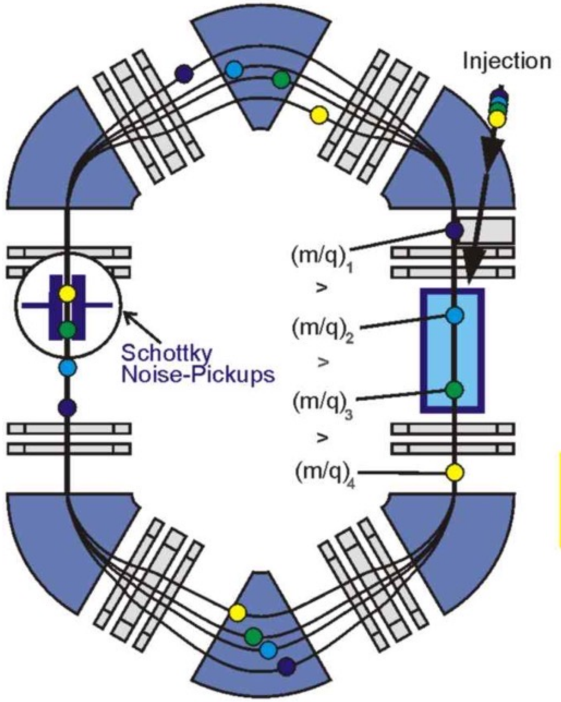
- ✓ ring acceptance is set to certain m/q range
- ✓ new injection every second
- ✓ rare isotopes can come with extremely low rates (e.g., 1 per day or week)



High-resolution mass spectrometry in a storage ring

SCHOTTKY MASS SPECTROMETRY

SMS: revolution frequency (~2 MHz)



- Highest precision
  (Electron cooling)
- Non destructive
  (Schottky cavities)
- Slow (many seconds)

$$\frac{\Delta v}{v} \rightarrow 0 \qquad \gamma_t \rightarrow \gamma$$

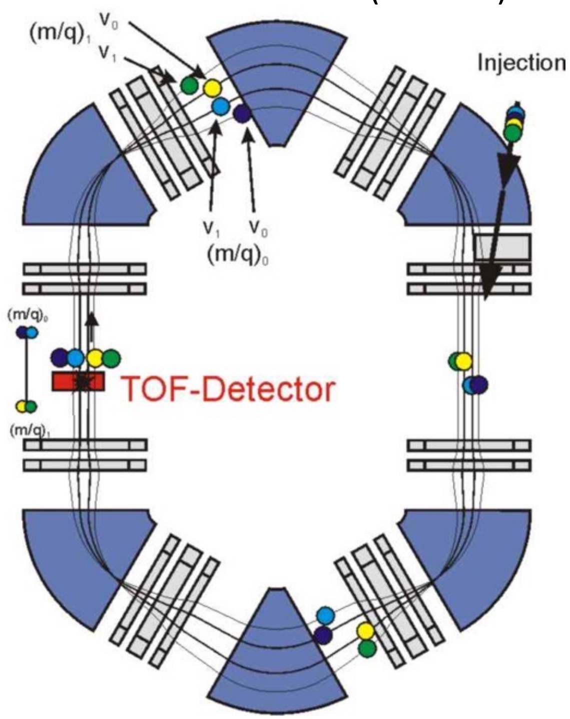
$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

Combined Schottky + Isochronous Mass Spectrometry (S+IMS)

Very fast and non-destructive

ISOCHRONOUS MASS SPECTROMETRY

IMS: revolution time (~500 ns)



Very fast (few ms)

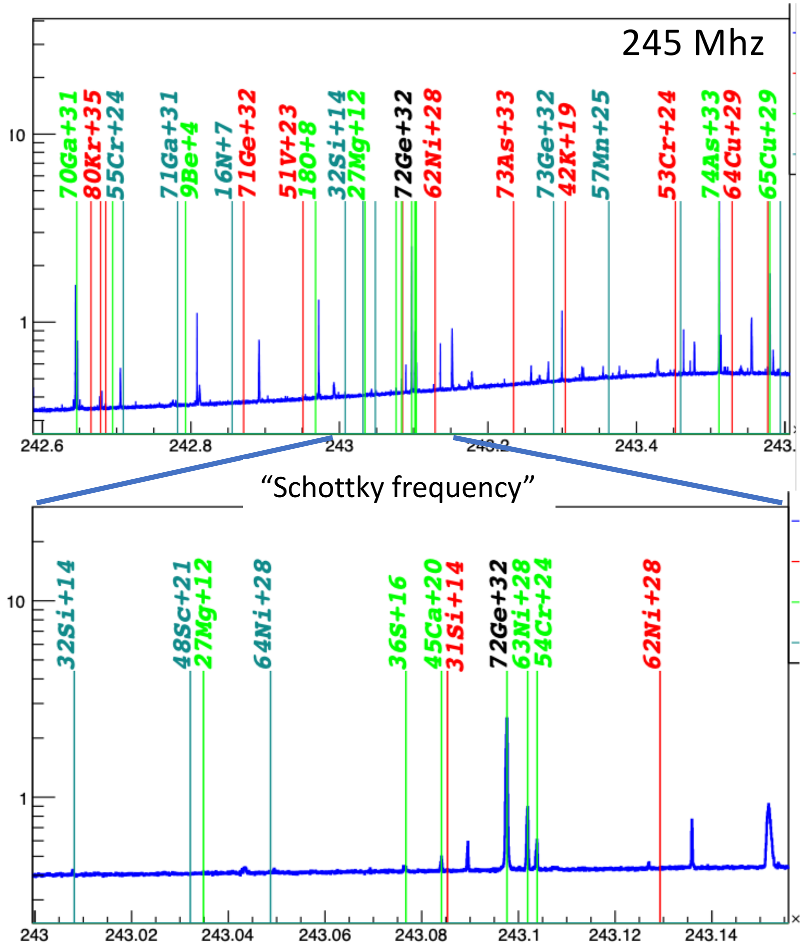
Good precision (for $\gamma_{beam} \sim \gamma_t$)

Destructive method

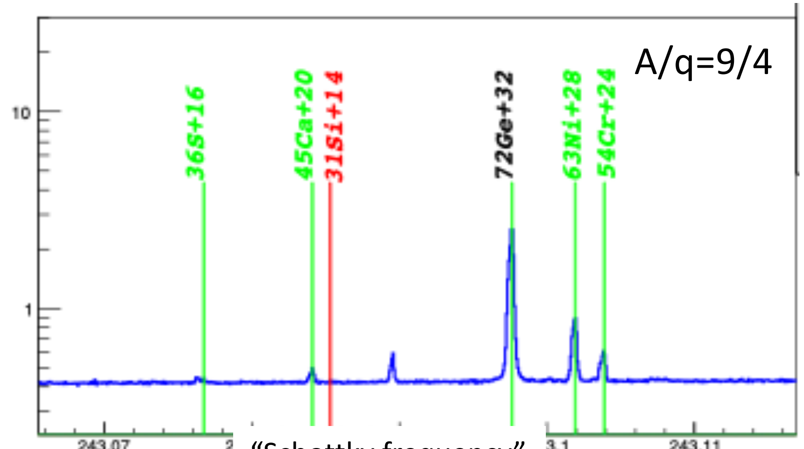
- ToF detectors

Identification of all isotopes through Schottky spectra

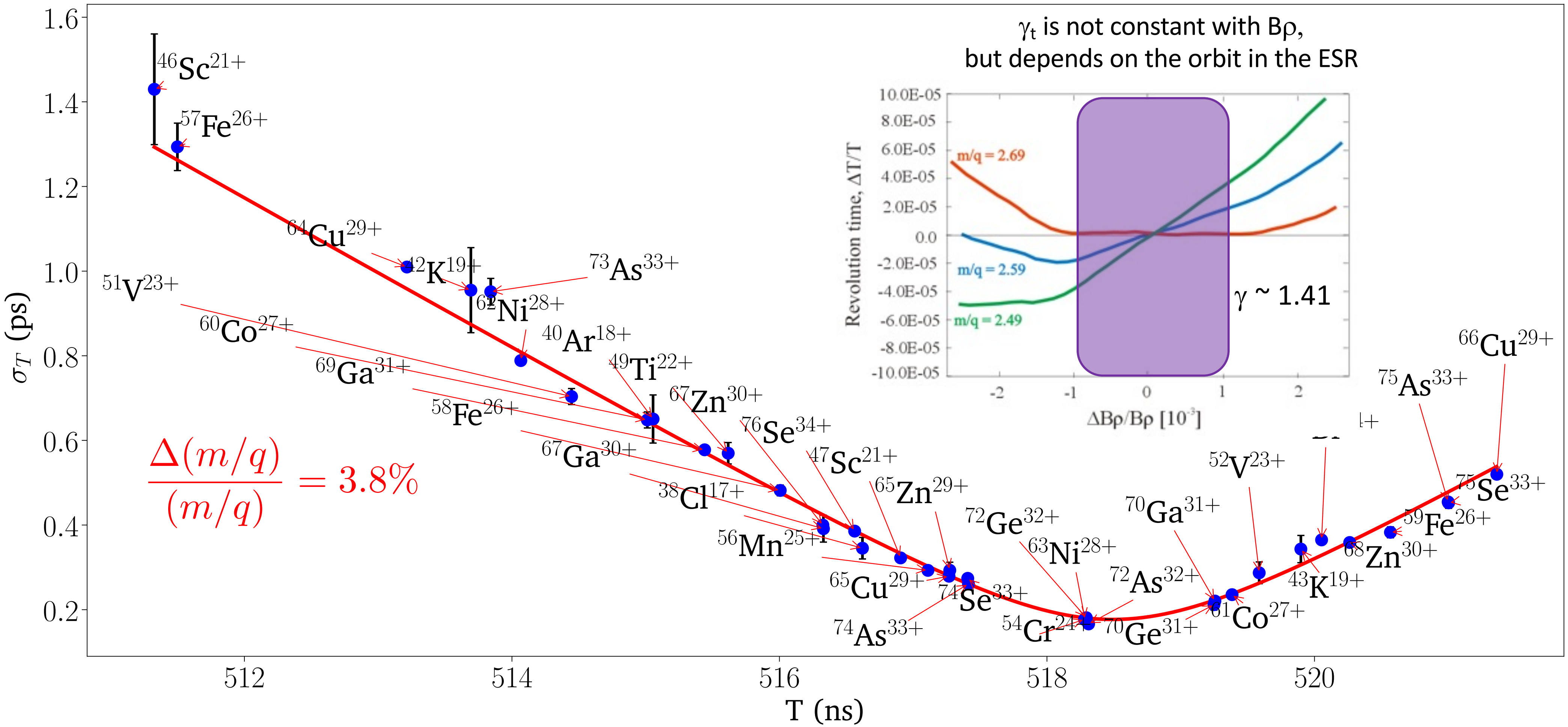
Example from ^{78}Kr fragmentation to produce ^{72}Ge (A/Z=9/4)



- **All stored nuclei** can be identified by their **characteristic Schottky frequency**
- Colour code indicates **different harmonics** of the original revolution frequency



Mass resolution in Isochronous Mass Spectrometry (IMS)



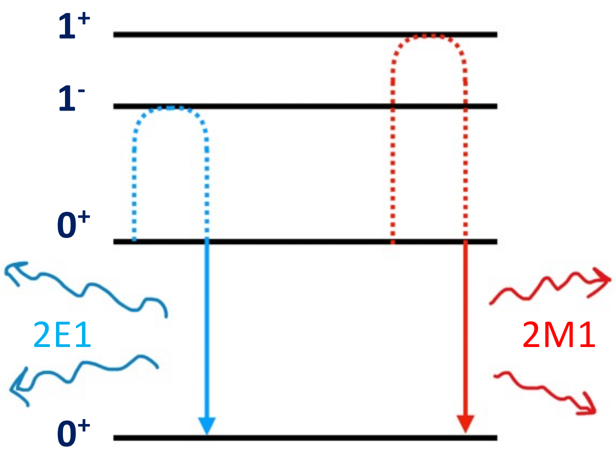
Selected physics examples

- Nuclear two-photon or double-gamma decay
- Bound state beta decay of ^{205}Tl
- Nuclear reactions of astrophysical interest
- Fission studies (NECTAR)

Nuclear two-photon or double-gamma decay

Rare decay mode whereby two gamma rays are simultaneously emitted

- Second order quantum mechanical process proceeds through virtual excitation of (higher-lying) intermediate states
- Observable only when first order decays are (strongly) hindered
  ex. $0^+ \rightarrow 0^+$ E0 decay : single γ-ray emission is forbidden
- Access to transitional nuclear polarisability ($\alpha_{E\lambda}$) and susceptibility ($\chi_{M\lambda}$)
- Small branching ratio ($<10^{-4}$) and very strong energy dependance ($\sim E_x(0^+)^7$)



$E_{\gamma1} + E_{\gamma2} = \omega_0 = E_x(0^+)$

$$\Gamma_{\gamma\gamma} = \frac{\omega_0^7}{105\pi}\left(\alpha_{E1}^2 + \chi_{M1}^2 + \frac{\omega_0^4}{4752}\alpha_{E2}^2\right)$$

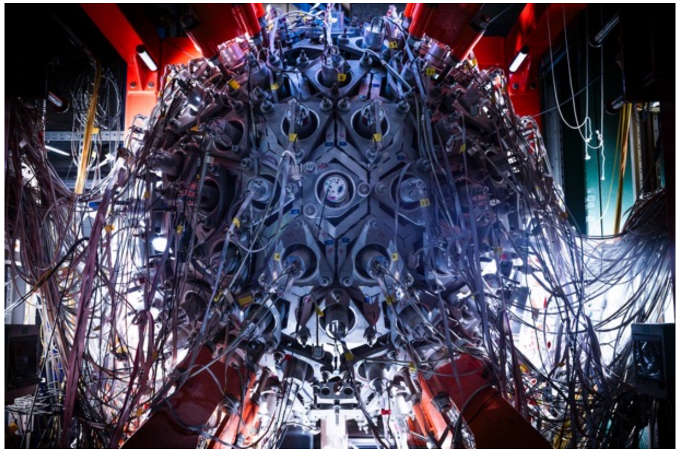
Usually $\alpha_{E1} \gg \chi_{M1} \sim \alpha_{E2}$

Electric dipole transition polarizability

Magnetic dipole transition susceptability

Electric quadrupole transition polarizability

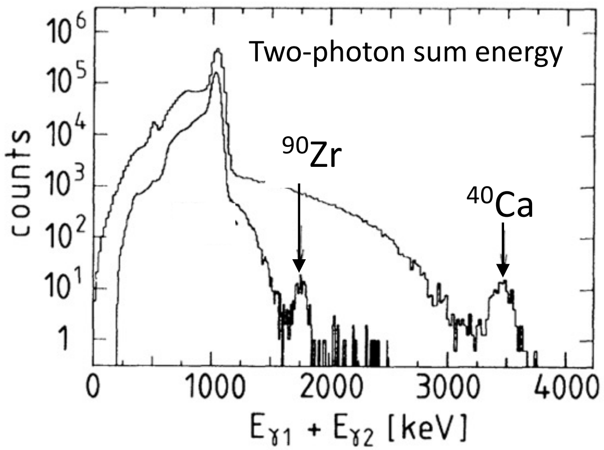
Previously known cases of double-gamma decay

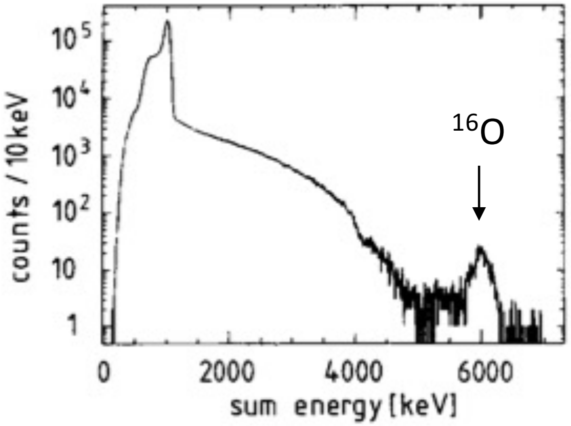


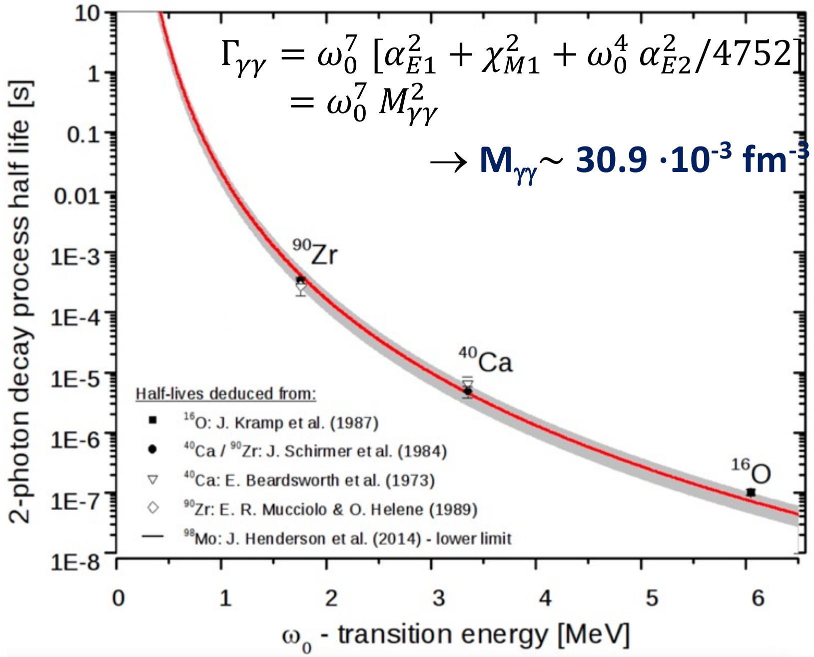
Heidelberg-Darmstadt Crystal Ball
162 NaI detectors → moderate resolutio
Solid angle > 98% → very high efficiency

J. Schirmer et al., PRL 53 (1984) 1897

J. Kramp et al., Nucl. Phys. A474 (1987) 412







Low-energy 0$^+$ states not accessible in direct spectroscopy : $\Gamma_{\gamma\gamma}/\Gamma_{tot} \sim 10^{-6} - 10^{-7}$

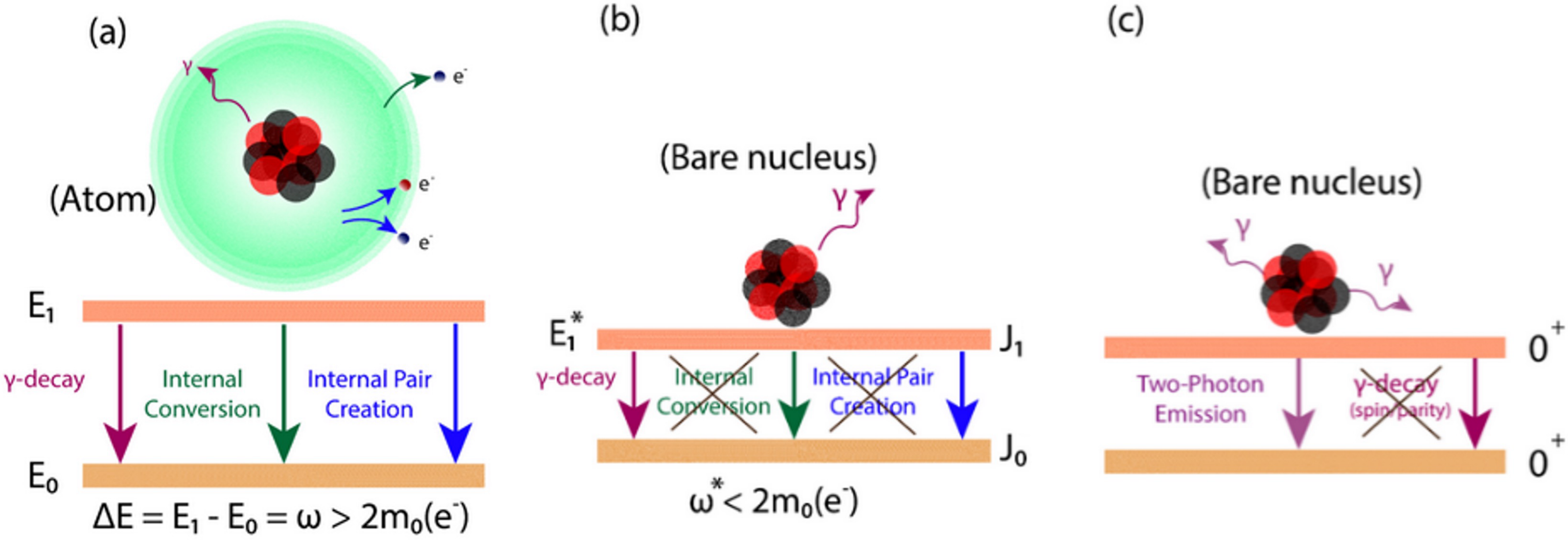
But expected partial lifetimes of several 100 ms

How to isolate the double-gamma decay ?

First order electromagnetic transitions in atomic nuclei:

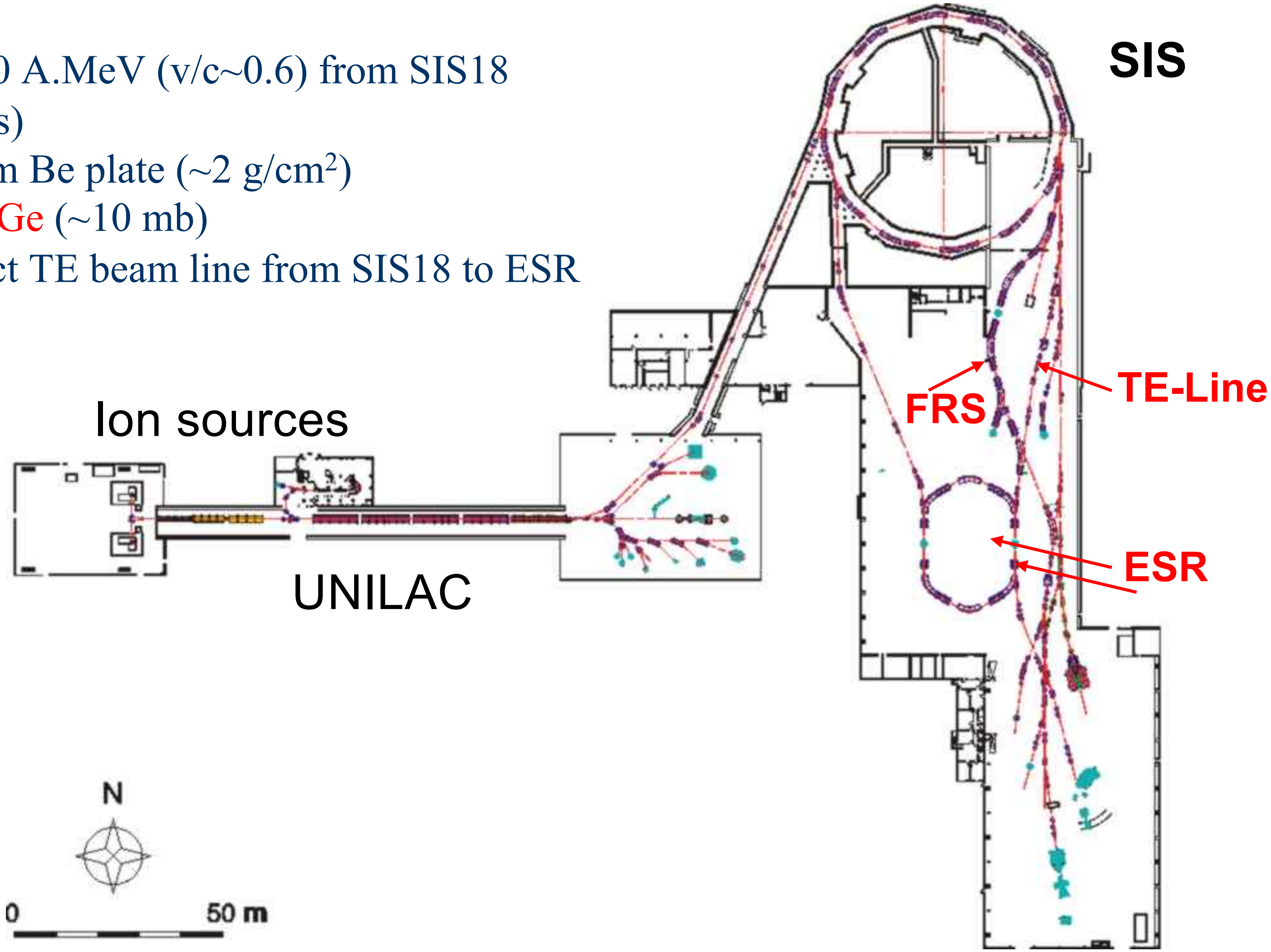
- gamma-ray emission (according to spin/parity conservation)
- electron emission from atomic shells ("internal conversion")
- electron-positron pair creation (for $\Delta E > 1.022$ MeV)

Two-photon decay is the only allowed $0^+ \rightarrow 0^+$ decay in stable bare nuclei



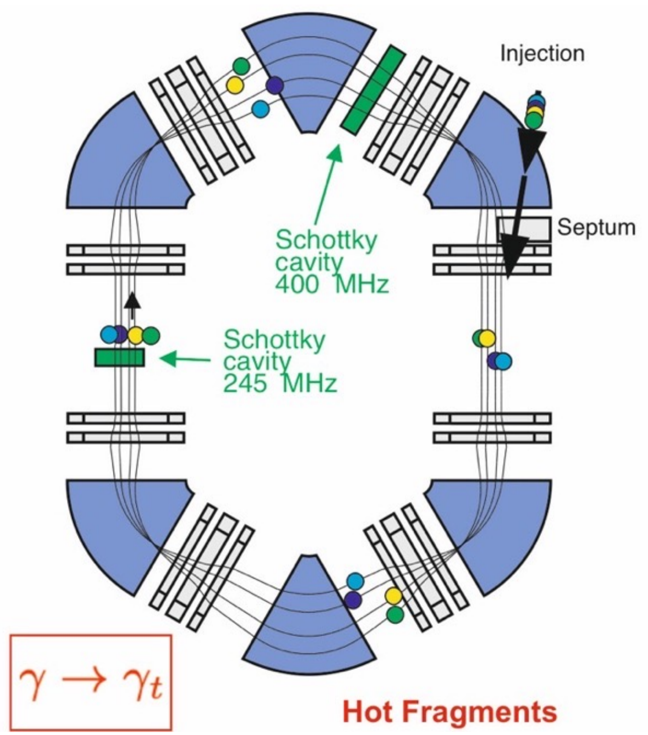
The SIS18 + ESR experiment on ^{72}Ge

^{78}**Kr** beam acerated to ~460 A.MeV (v/c~0.6) from SIS18
- ➢ ~10^9 ions/spill (every 10s)
- ➢ Fragmentation in a 10mm Be plate (~2 g/cm^2)
- ▪ high cross section for ^{72}Ge (~10 mb)
- ▪ Bρ selection in the direct TE beam line from SIS18 to ESR



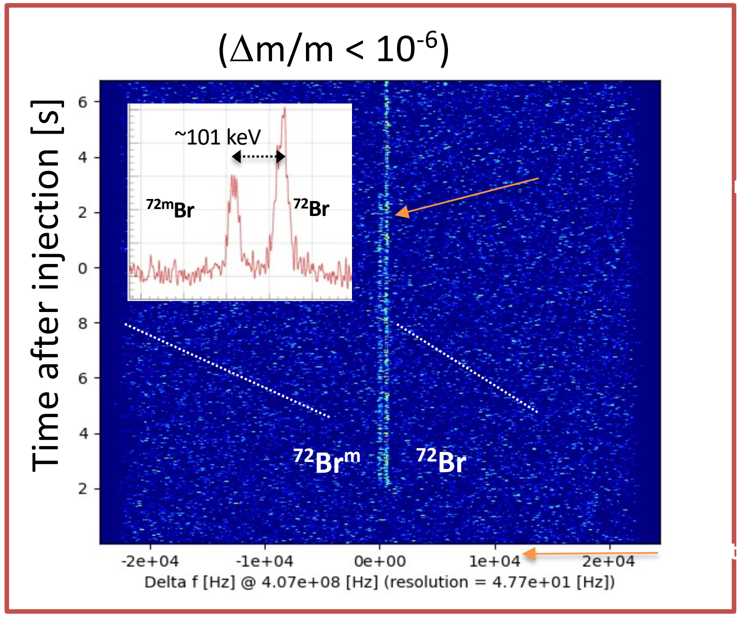
Time-resolved Schottky + Isochronous Mass Spectrometry (S+IMS)

First time-resolved Schottky plus Isochronous Mass Spectroscopy (S+IMS)



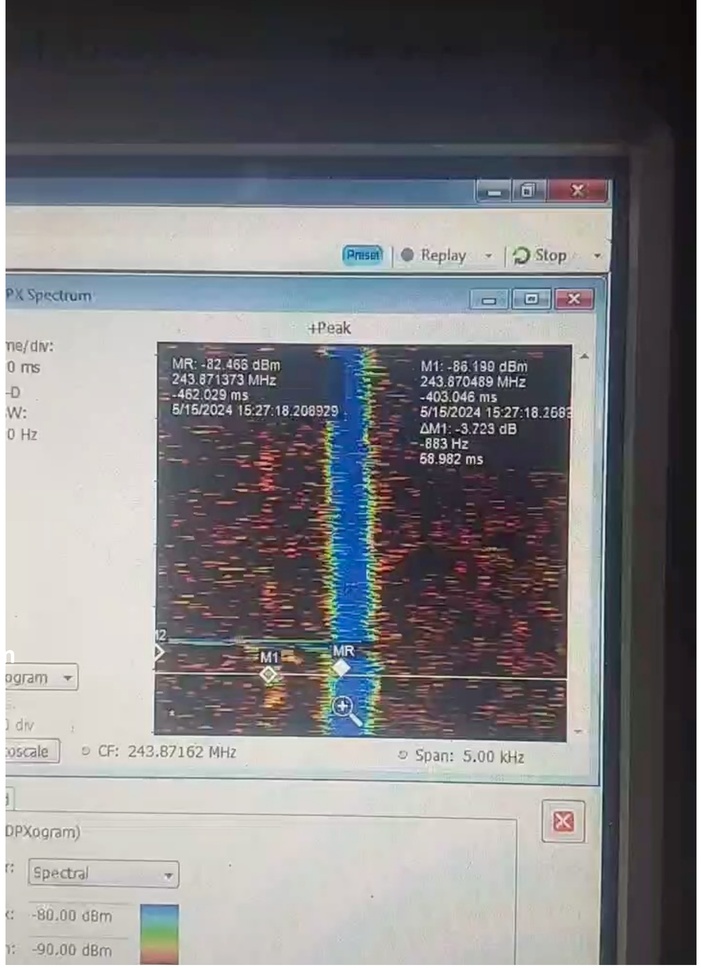
Schottky spectrum for a single event

Observation of a 101 keV isomer in ^{72}Br



Revolution frequency

Observation of a 0^+ isomer in ^{72}Ge



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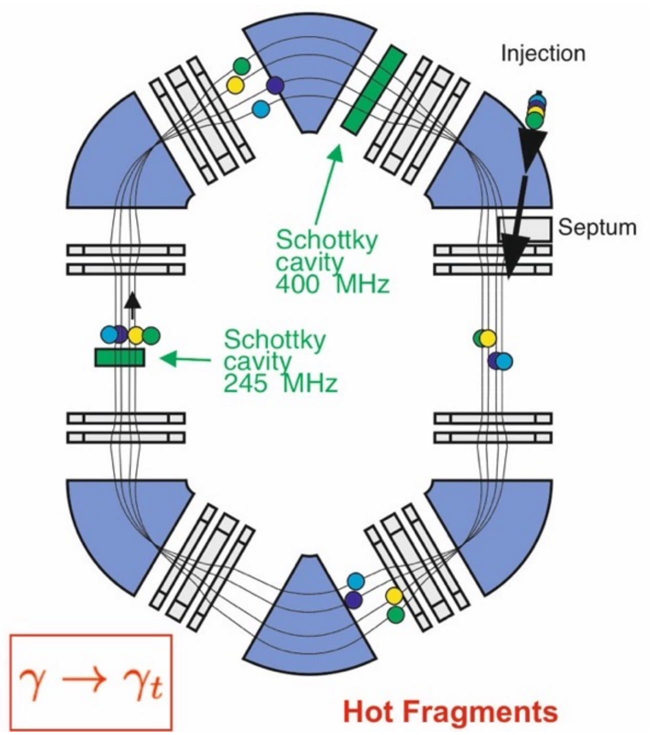

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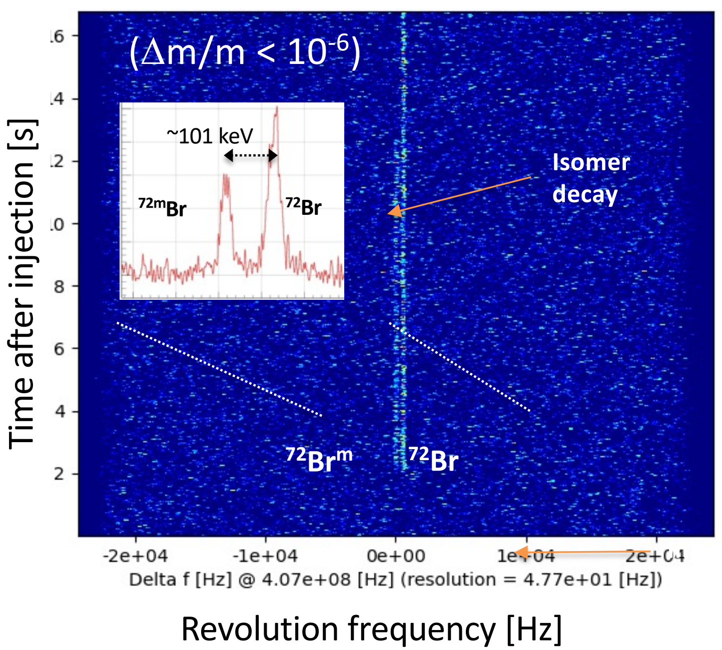
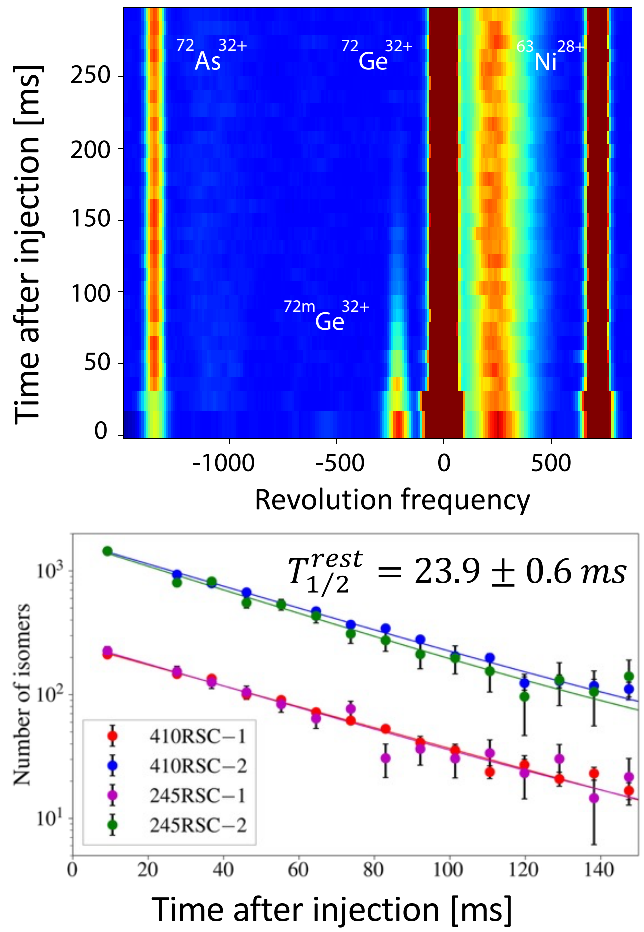


Double gamma decay of ^{72m}Ge

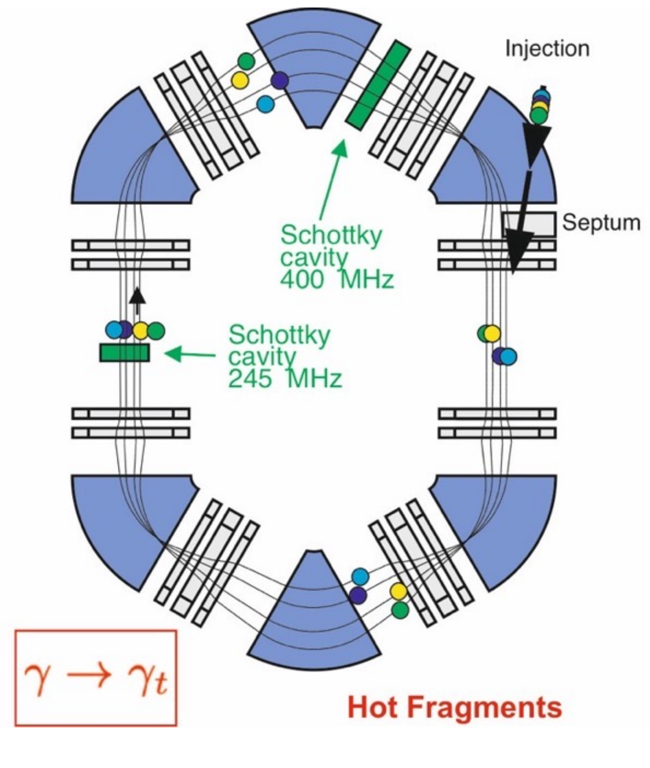


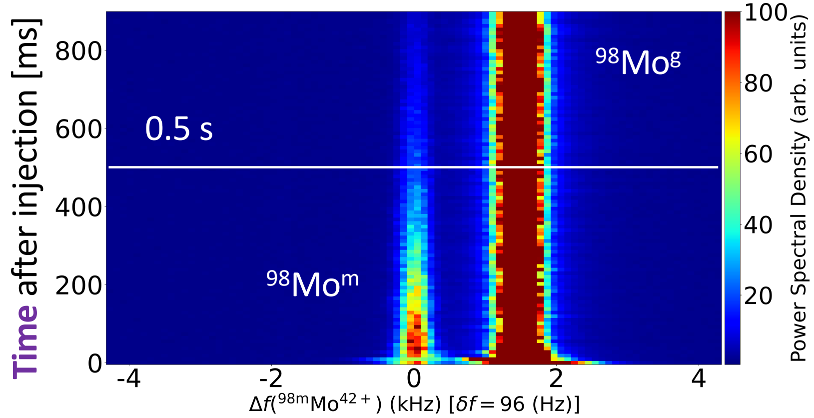
D. Freire Fernandez et al., PRL 133, 022502 (2024)

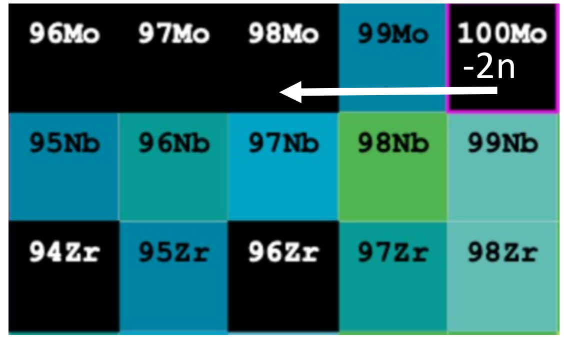
Double gamma decay experiments on ^{98}Mo and ^{98}Zr (May 2024)

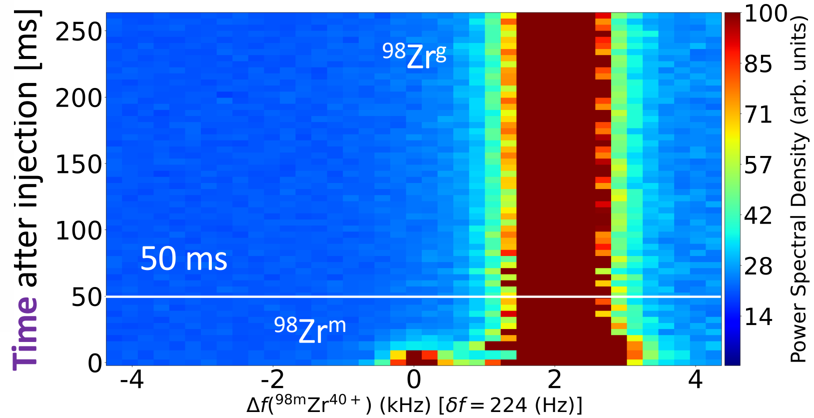
^{100}**Mo** at ~460 A.MeV, ~10^9 ions per spill (every 2-5s), online results

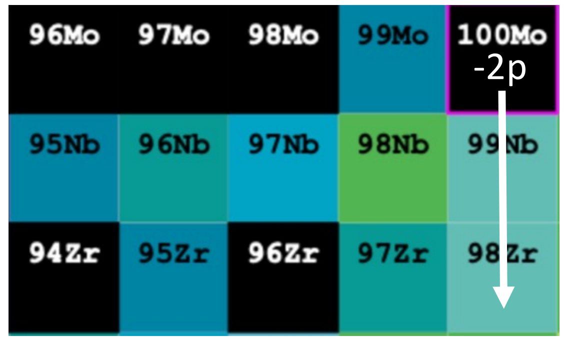
Time-resolved Schottky + Isochronous Mass Spectroscopy (S+IMS)



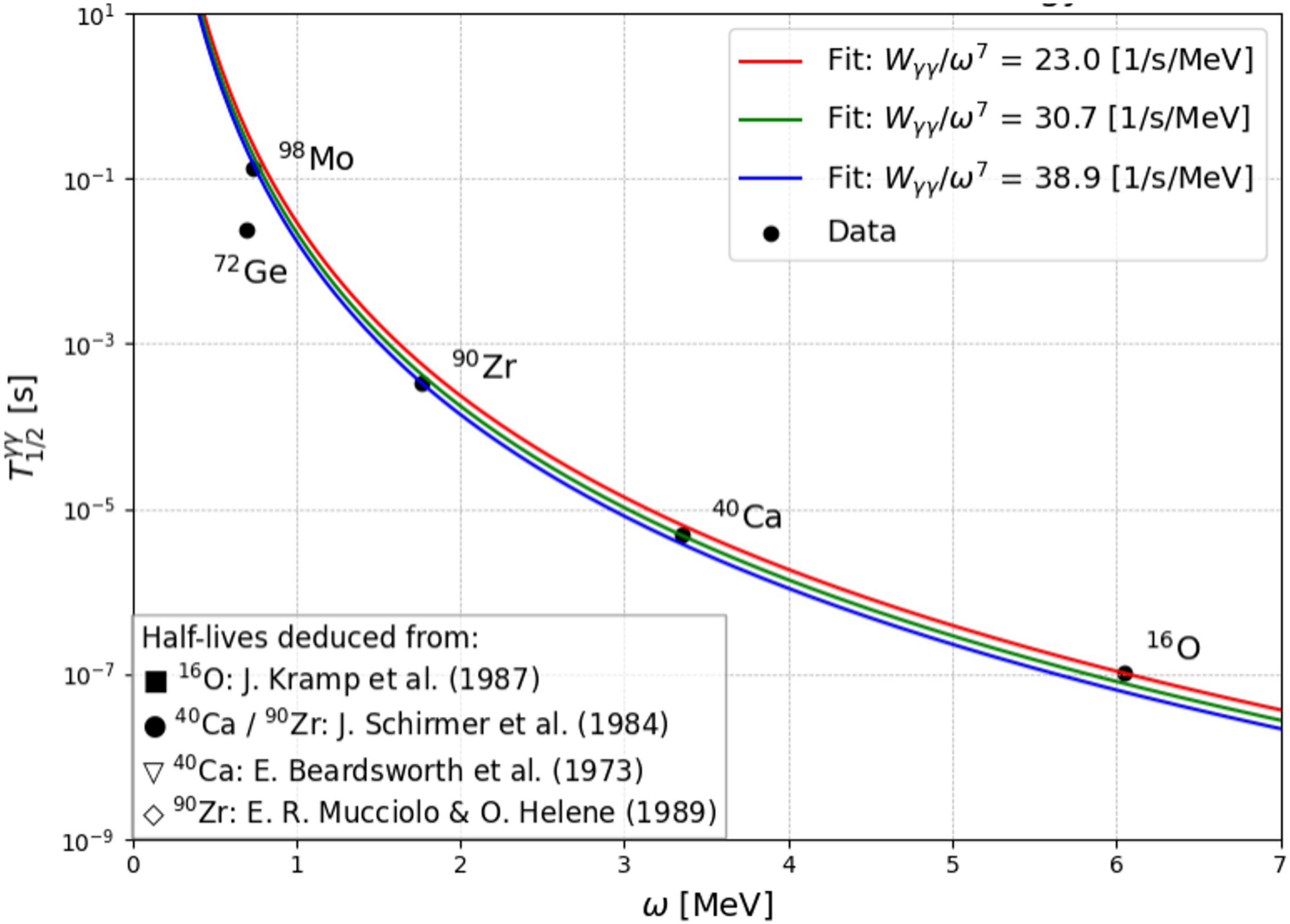








Summary of results on double-gamma decay half lifes



Bound state electron-positron pair decay in ^{194}Pb

Search for bound-state electron+positron pair decay

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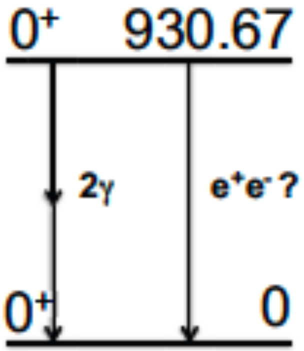
Abstract. the heavy ion storage rings coupled to in-flight radioactive-ion beam facilities, namely the ability to produce and store for extended periods of time radioactive nuclides in high atomic charge states, for the search of yet unobserved decay mode – *bound-state electron-positron pair decay*.



^{194}Pb^{82+}

No e^+- e^- pair conversion in neutral ^{194}Pb possible

Energy gain for e^- capture in K shell
B_k=101.3 keV $\rightarrow$ $Q_b(e^+e^-)$=1032.0 keV

Long standing idea by F. Bosch et al.

One of the prominent candidates for this study is the magic $^{194}_{82}\mathrm{Pb}^{82+}_{112}$. The decay scheme of the first excited state in ^{194}Pb is illustrated in Fig. 1. The energy of the 0^+ state is $E(0^+)$ = 930.67 keV which is known from precision spectroscopy investigations [30]. This energy is below 1022-keV threshold for $e^- + e^+$ decay. However, the binding energy of the last K-electron is $B(K)$ = 101.336 keV [31, 32], which makes the new decay mode, bound-state $e^- + e^+$ decay, energetically allowed. In this case the electron shall occupy the vacant K-shell thus saving ~ 100 keV energy. The excess energy of about 10 keV is taken away by a monochromatic positron, which may appear as a forward-emitted particle in the laboratory frame.

Rate estimates:

$\lambda(e^+e^-)$ = $\rho^2(E0) \cdot \Omega_{ipc} \cdot R_{capture}$
= $10^{-3} \cdot 0.7 \cdot 0.2\ s^{-1} = 1.4\ 10^{-4}\ s^{-1}$

For $\tau_{\gamma\gamma}$=100 ms : $\lambda(e^+e^-)/\lambda_{\gamma\gamma} \sim 1.4\ 10^{-5}$

For 7.2 10^6 isomers produced in 5 days:
~100 e^+e^- events

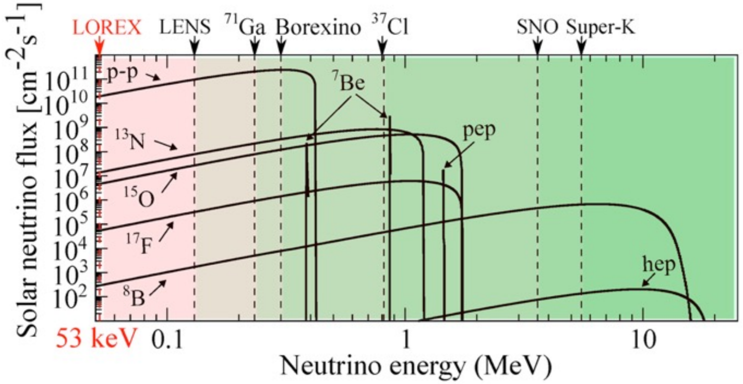
For 1 event: $\lambda(e^+e^-)/\lambda_{\gamma\gamma} < \sim 1.4 \cdot 10^{-7}$

No event sets limit on $\Omega_{ipc} \cdot R_{capture}$

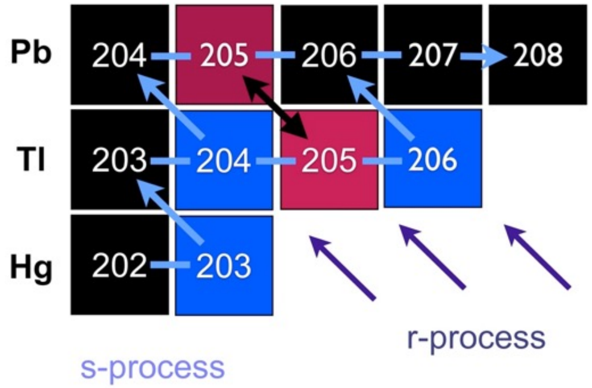
Measurement of the bound-state beta decay of bare ^{205}Tl ions

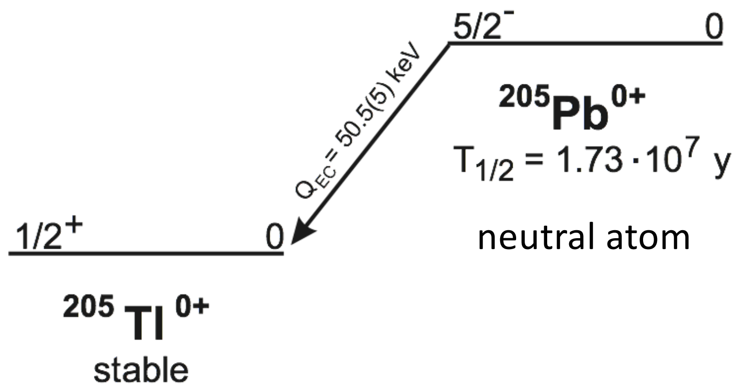
1. **The flux of solar pp neutrinos (LOREX project)**

$$^{205}\text{Tl} + \nu_e(> 52\ \text{keV}) \rightarrow ^{205}\text{Pb}^* + e^-$$



2. **^{205}Pb/^{205}Tl pair as s-process cosmochronometer**





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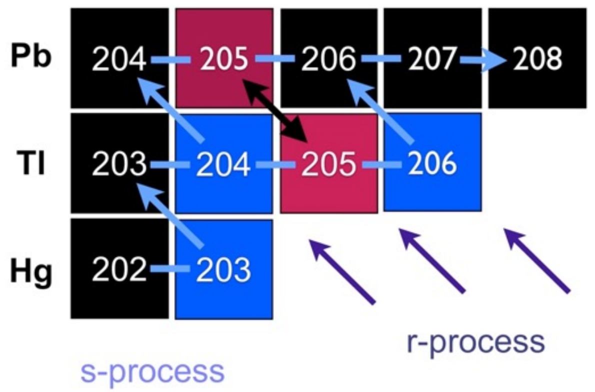
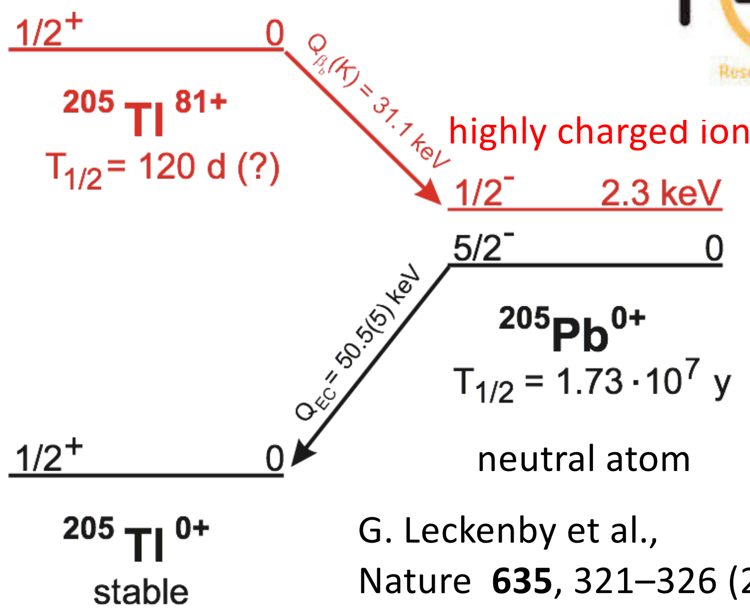
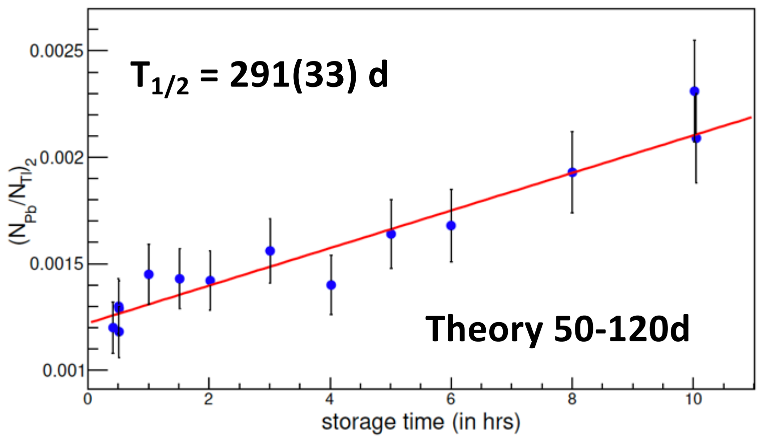




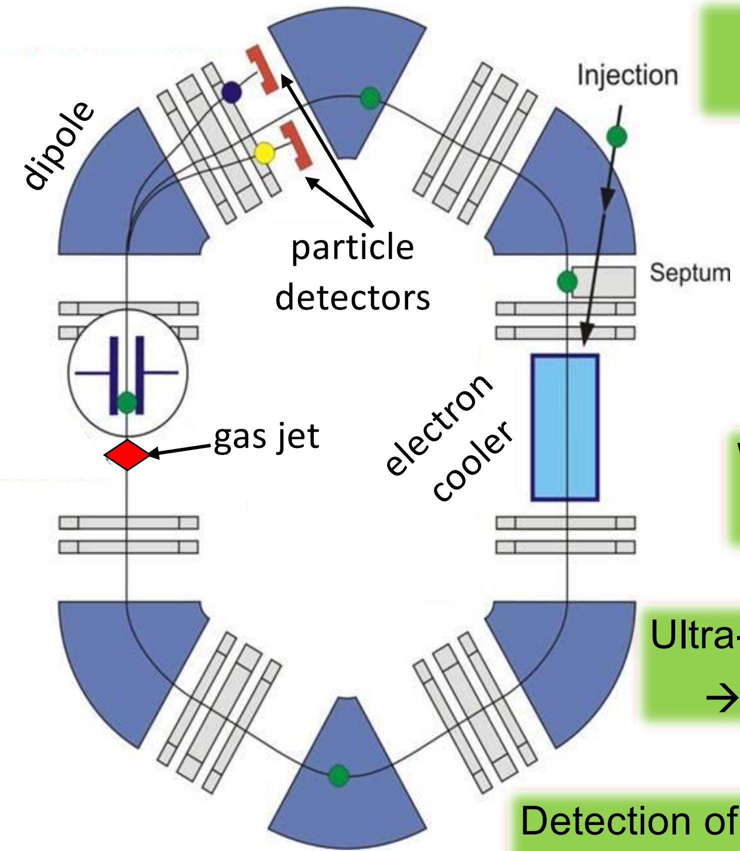
G. Leckenby et al., Nature **635**, 321–326 (2024)



E121: Yu. A. Litvinov et al. (ILIMA, SPARC, LOREX collaborations)

- ✓ Accumulation of secondary beam from FRS (highest purity)
- ✓ Long storage time (up to ~10 h)
- ✓ Gas jet target (to strip captured electron)
- ✓ Resonant Schottky detectors
- ✓ In-ring particle detectors

Nuclear reaction studies in a storage ring



In-flight fragmentation at FRS
→applicable to radioactive nuclei

Courtesy/contact
J. Glorius (GSI)

deceleration of beams
→ Gamow window

High revolution frequency
→ high luminosity even with thin targets

Well-known atomic charge-exchange rates
→ in-situ luminosity monitor

Ultra-thin windowless gas targets and electron cooling
→ excellent energy resolution

Detection of ions via in-ring particle detectors, clean beam and target
→ low background, high efficiency

very efficient use of exotic beams for high resolution experiments

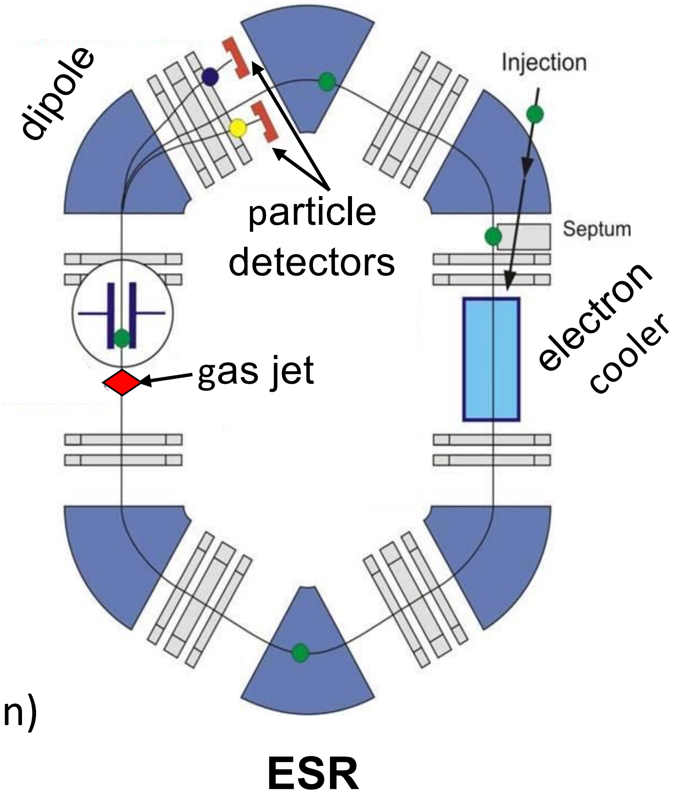
Proton-Capture experiments at the ESR

refill ring periodically

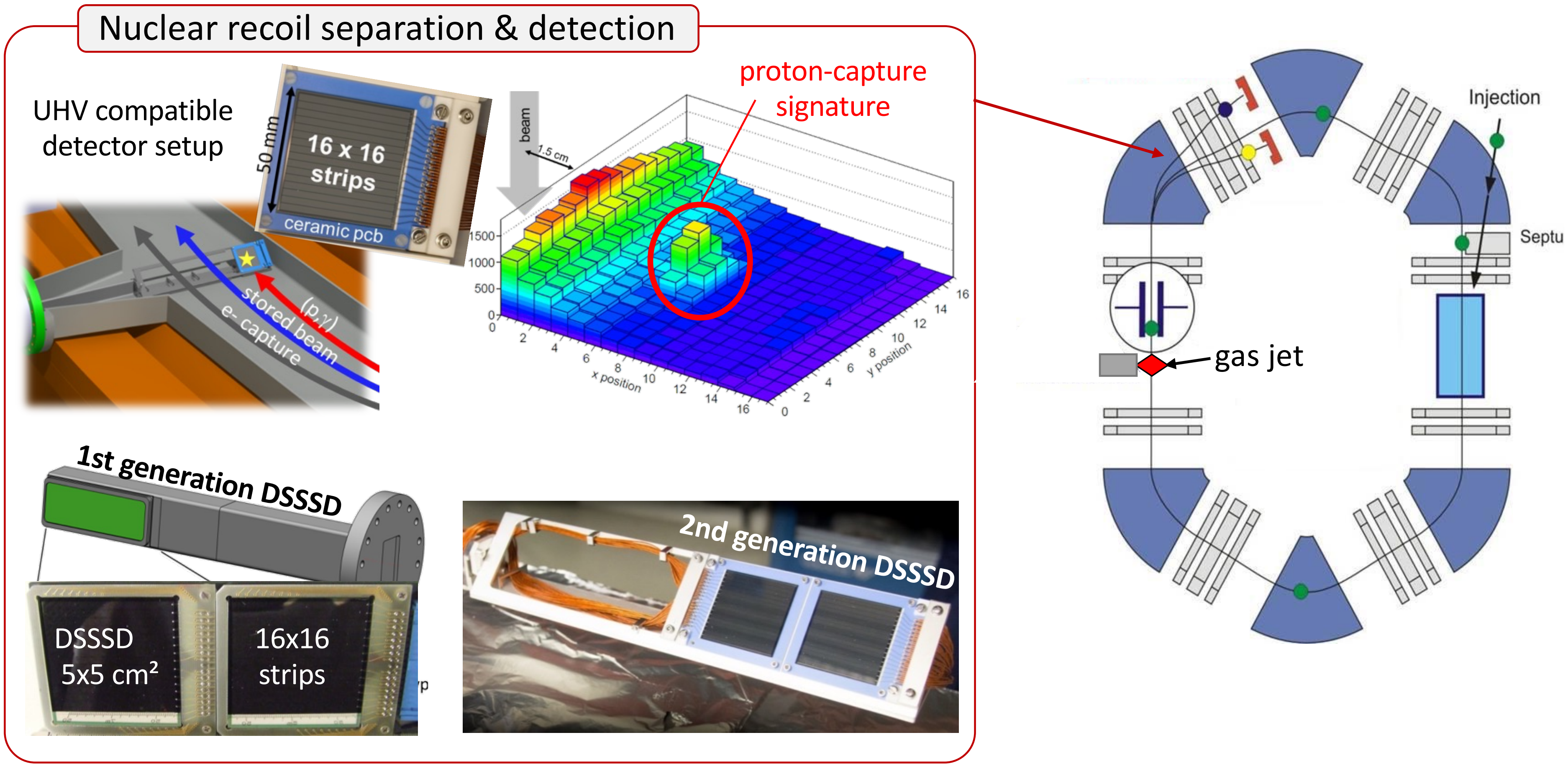
Experimental Procedure:

1. injection of ions @ >100 MeV/u
   - ✓ fully stripped ions/fragments
   - ✓ **beam accumulation** if needed
2. deceleration & electron cooling of the beam
   - ✓ **E = 4 - 10 MeV/u**
3. activate internal hydrogen target (10^{14} cm^{-2})
   - ✓ **proton & electron capture** reactions
   - ✓ **separated by dipole**
   - ✓ particle detectors on…
     - … inner tracks for (p,γ) products
     - … outer tracks for e^- capture products
4. beam lifetime (residual gas + target interaction)
   - ➢ intensity goes down exponentially

A recycling recoil separator



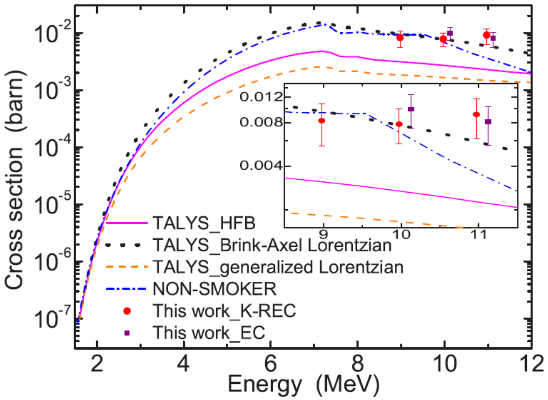
Proton capture experiments at the ESR



Proton-Capture experiments at the ESR

^{96}Ru(p,γ)^{97}Rh

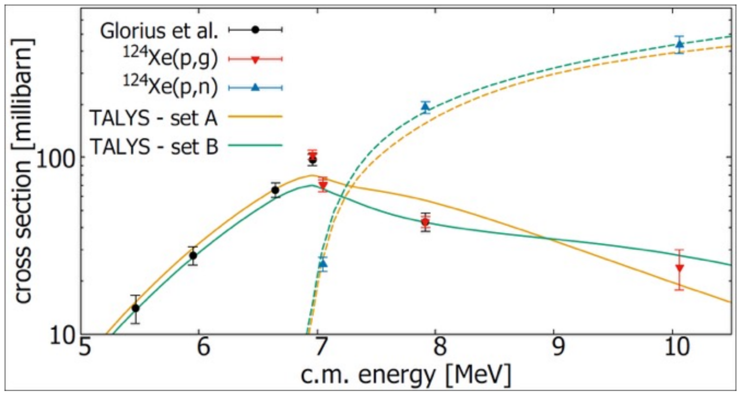
- successful pilot experiment
- Large Rutherford background
- Gamow window not reached (detector behind window)



Mei et al. PRC **92**, 035803 (2015)

^{124}Xe(p,γ)^{125}Cs

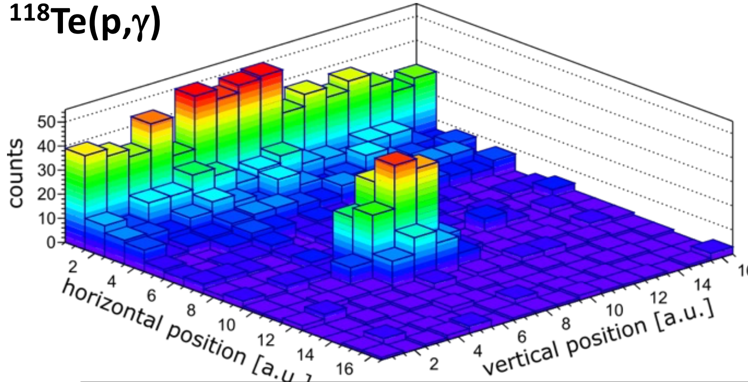
- UHV compatible Si-setup
- 1st meas. inside Gamow window
- also (p,n) cross section

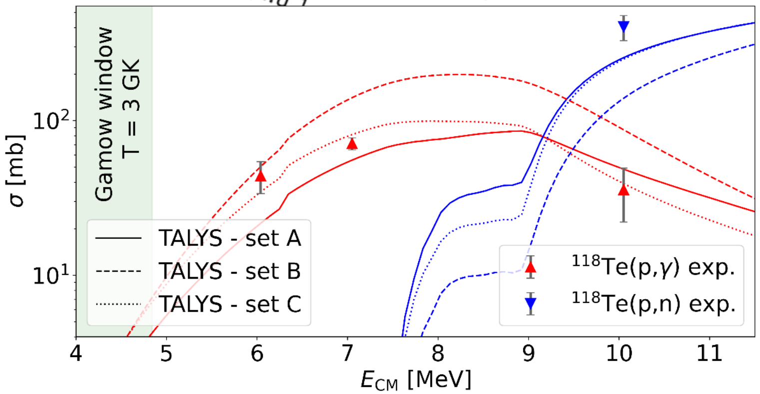


J. Glorius et al. PRL **122**, 092701 (2019)

Pioneering experiments with Stable Beams

^{118}Te(p,γ)





1st measurement with **radioactive beam**

- 40 hours of data taking at **6 & 7 MeV/u**
- clear proton-capture signature
- > 300 counts [≈7.5 counts/hour]

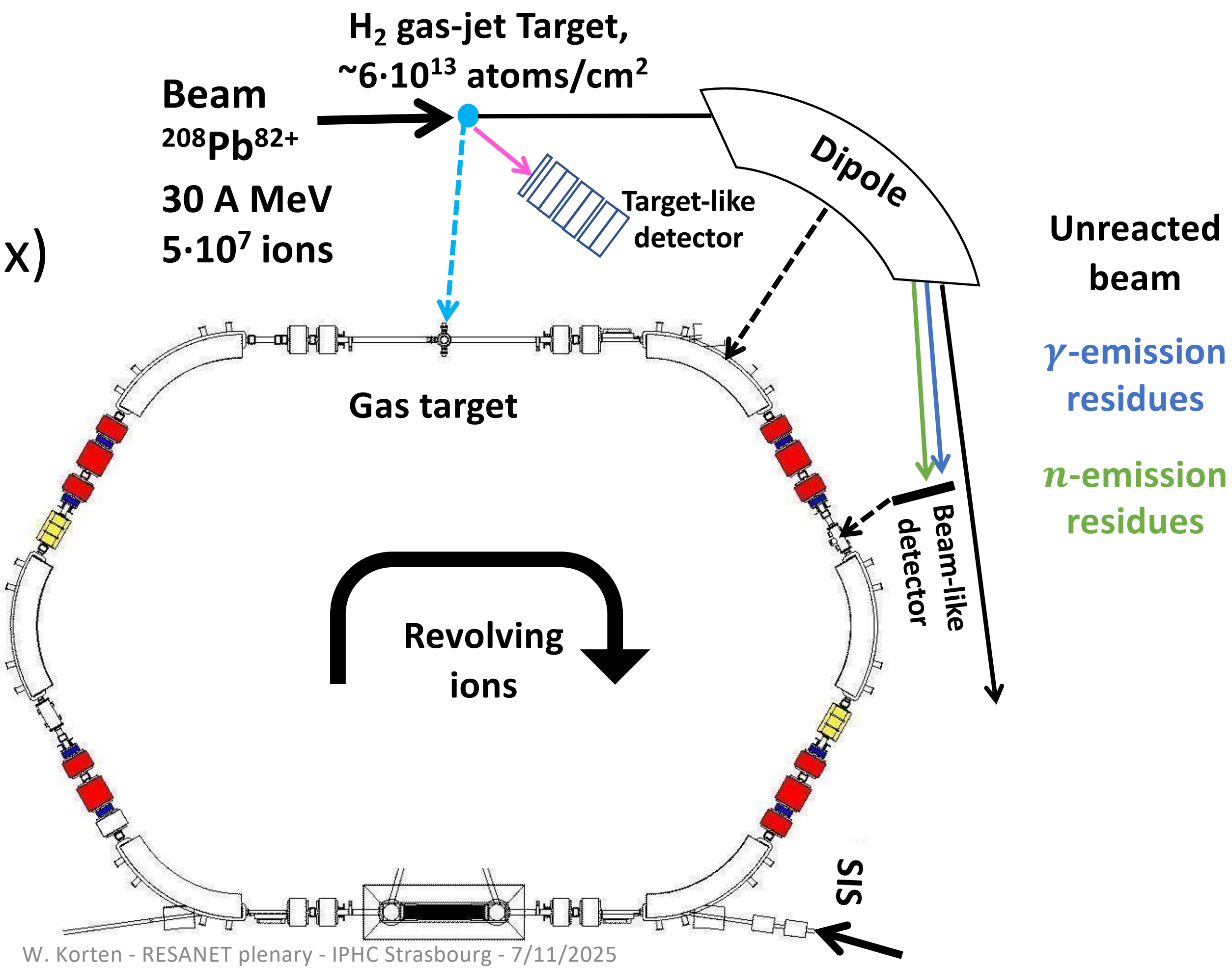
NECTAR: Nuclear rEaCTions At storage Rings

Surrogate reactions in inverse kinematics at the ESR

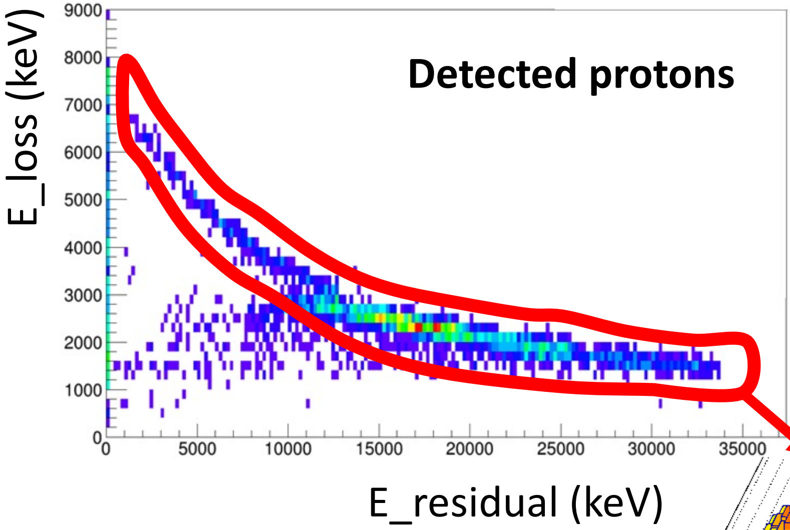
- First demonstration:
  ^{208}Pb(p, p') @ 30 MeV/u

- B. Jurado et al. (LP2I Bordeaux)

See presentation by Camille Berthelot

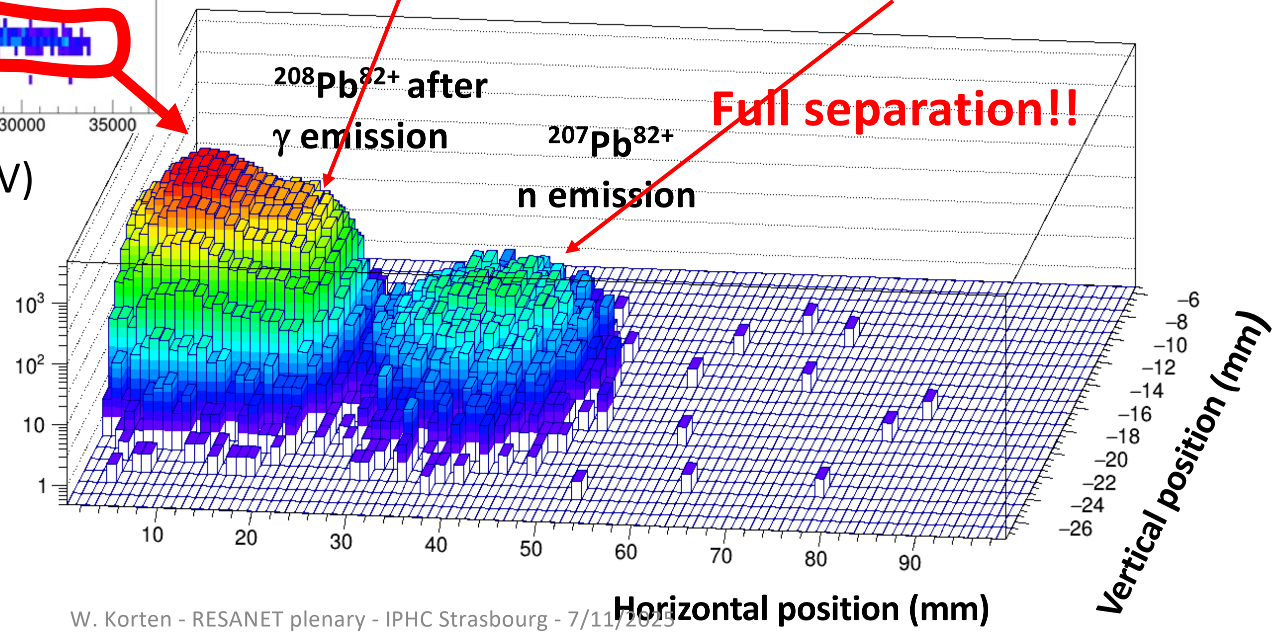


^{208}Pb(p, p') with NECTAR at the ESR



Efficiency ~33-100%!
≈ Max 20 % in direct kinematics

Efficiency 100%!
0% in direct kinematics...



M. Sguazzin *et al.*, Phys. Rev. Lett. 134 (2025) 072501

M. Sguazzin *et al.*, Phys. Rev. C 111 (2025) 024614

Summary

Heavy ion storage rings provide unique opportunities for

- **Mass** measurements
  - Broad range surveys with $\Delta M/M < 10^{-6}$
- **Lifetime** measurements with single ion capability
  - From milliseconds to years
- **Exotic** decays of highly charged ions
  - Bound-state decays, double-gamma decay, …
- Nuclear **reactions**
  - Astrophysical regime (< 5 MeV to ~0.1 MeV/u @ Cryring)
  - Fission studies (30 MeV/u)
  - Low momentum transfer at relativistic energies (EXL)