Lezione 2

Misure di Massa ad alta precisione con

- Trappole

- Storage Rings

Books and review articles:

L.S. Brown and G. Gabrielse: Physics of a single electron or ion in a Penning trap; Rev. Mod. Phys. 58, 233 (1986)

G. Bollen: Traps for Rare Isotopes, Lecture Notes in Physics, 651, 169-210 (2004)

F.G. Major et al.; Charged Particle Traps, Volume I and II Springer, Vol. 37, Berlin (2005)

K. Blaum: High-accuracy mass spectrometry with stored ions, Phys. Rep. 425, 1-78 (2006)

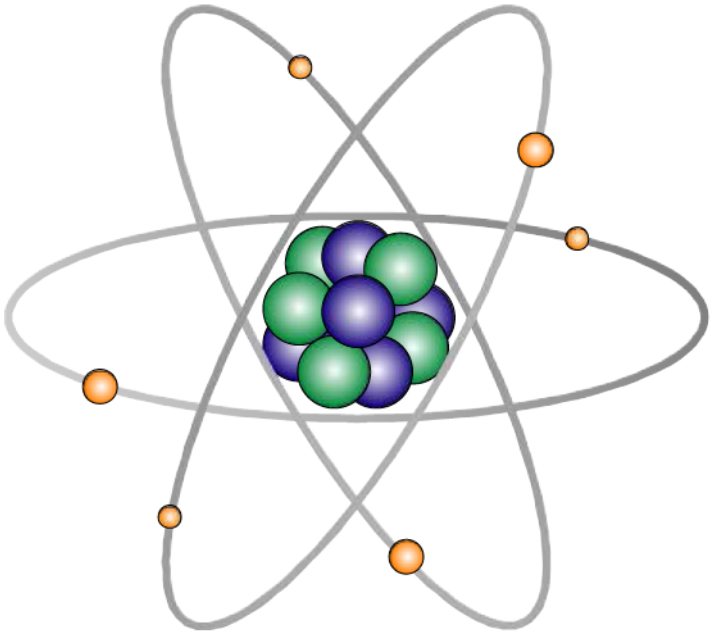
Äystö: Overview of recent highlights at ISOL facilities, Nucl. Phys. A 805, 162c-171c (2008)

Blaum *et al.*: Precision atomic physics techniques for nuclear physics with radioactive beams; Physica Scripta T152, 014017 (2013)

Additional Material: https://w.fys.kuleuven.be/wps/euroschool/lecture-notes/

Atomic and nuclear masses

Masses determine the atomic and nuclear binding energies reflecting all forces in the atom/nucleus.



$= N \cdot$  $+ Z \cdot$  $+ Z \cdot$ 

– binding energy

$$M_{\text{Atom}} = N \bullet m_{\text{neutron}} + Z \bullet m_{\text{proton}} + Z \bullet m_{\text{electron}} - (B_{\text{atom}} + B_{\text{nucleus}})/c^2$$

$\delta m/m < 10^{-10}$

$\delta m/m = 10^{-6} – 10^{-8}$

Binding energy of a nucleus (Note: atomic masses are normally used)

$$B\left({}^{A}_{Z}X_{N}\right) = Zm_{H}c^{2} + Nm_{n}c^{2} - M\left({}^{A}_{Z}X_{N}\right)c^{2}$$

Atomic mass unit

$$1\,u \equiv \frac{1}{12}m({}^{12}C) \approx 1.660566\times10^{-27}\,kg \approx 931.494\,MeV/c^{2}$$

Mass excess

$$M_{e}[keV] = \left(M(in\,u) - A\right)\times 931493.86$$

1 MeV at A=132 corresponds to $\Delta m/m \sim 8\cdot10^{-6}$

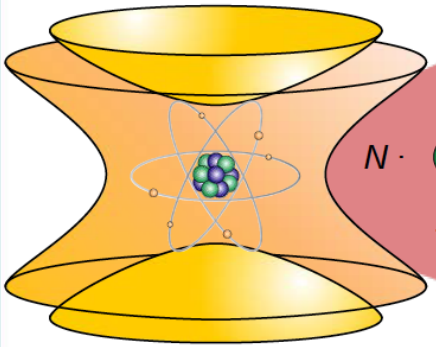
*1/(132*931.494)*

$E = mc^2$

$m_{n,p}$ ≈ 1 GeV/c² = 1.000.000.000 eV/c²

≈ 0,000000000000000000000000017 kg

Why measuring atomic masses?



$N \cdot$ + $Z \cdot$ + $Z \cdot$

– binding energy

Experimental setups

General physics & chemi — KATRIN-TRAP

Nuclear structure physics

- separat — *CSRe/ESR*

Astrophysics

- separati — TRIGA-TRAP

Weak interaction studies — ISOLTRAP/TITAN

Metrology - fundamenta — SHIPTRAP

Neutrino physics

CPT tests — THe-TRAP

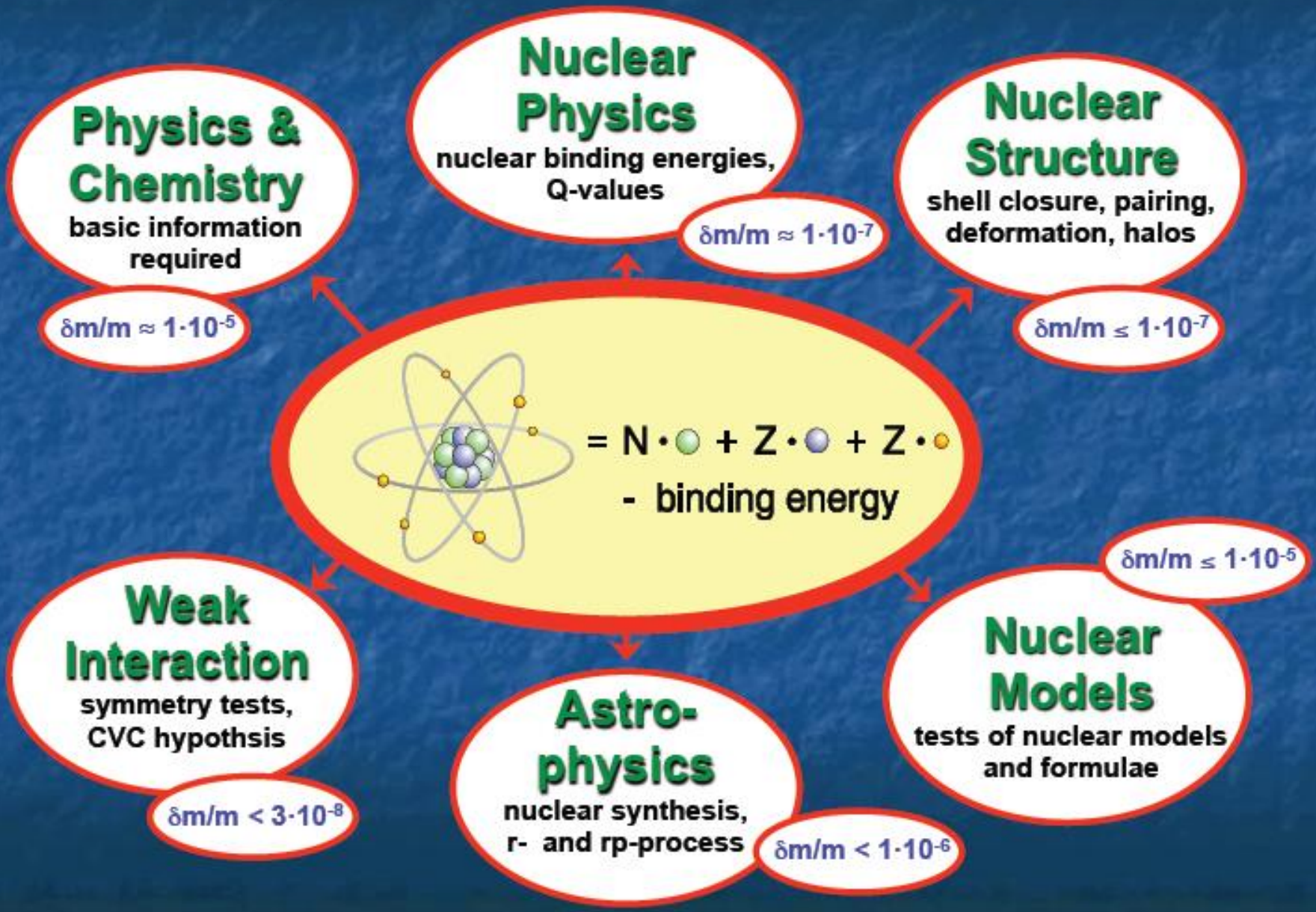
QED in highly-charged ior

- separation of — PENTA-TRAP

Sources:
Accelerator or reactor based radioactive beam facilities and electron beam ion traps.

CERN **IMP/GSI** **MPIK** **TRIGA**

Importance of Atomic Masses



Limits of nuclear stability: superheavies; p- and n- drip lines; pathways of stellar nucleosynthesis

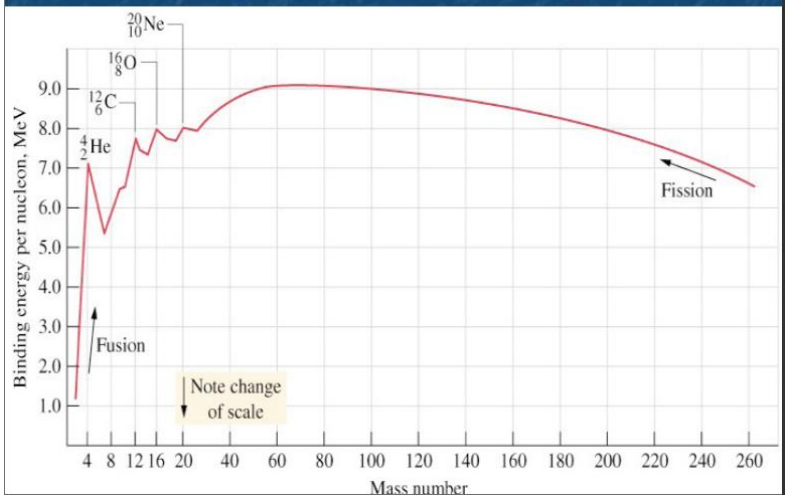
To measure: Ground state properties of exotic nuclei:

masses and β decay half-lives

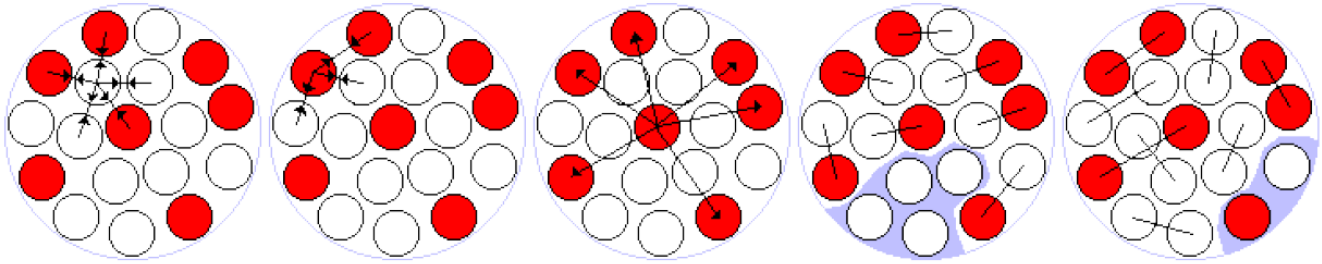
masses determine the
pathways of s-, rp- and r-processes

β half-lives the accumulated abundances

Stellar nucleosynthesis: fusion until iron



The liquid drop model



$$E_{B,Kern} / A = a_{Vol} + a_{Oberf} A^{-1/3} + \frac{3e^2}{5r_0} Z^2 A^{-4/3} + (a_{Symm} + a_{OberfSymm} A^{-1/3}) I^2$$

$A = N + Z$, neutron number N, proton number Z and elementary charge e

Nuclear Radius: $R \approx r_0 A^{1/3}$

Symmetry: $I^2 = (N - Z)^2 / A^2$

C. F. v. Weizsäcker, Zeitschrift der Physik, 96, 431 (1935)

1935-1936 H.A. Bethe, C.F. von Weizsäcker

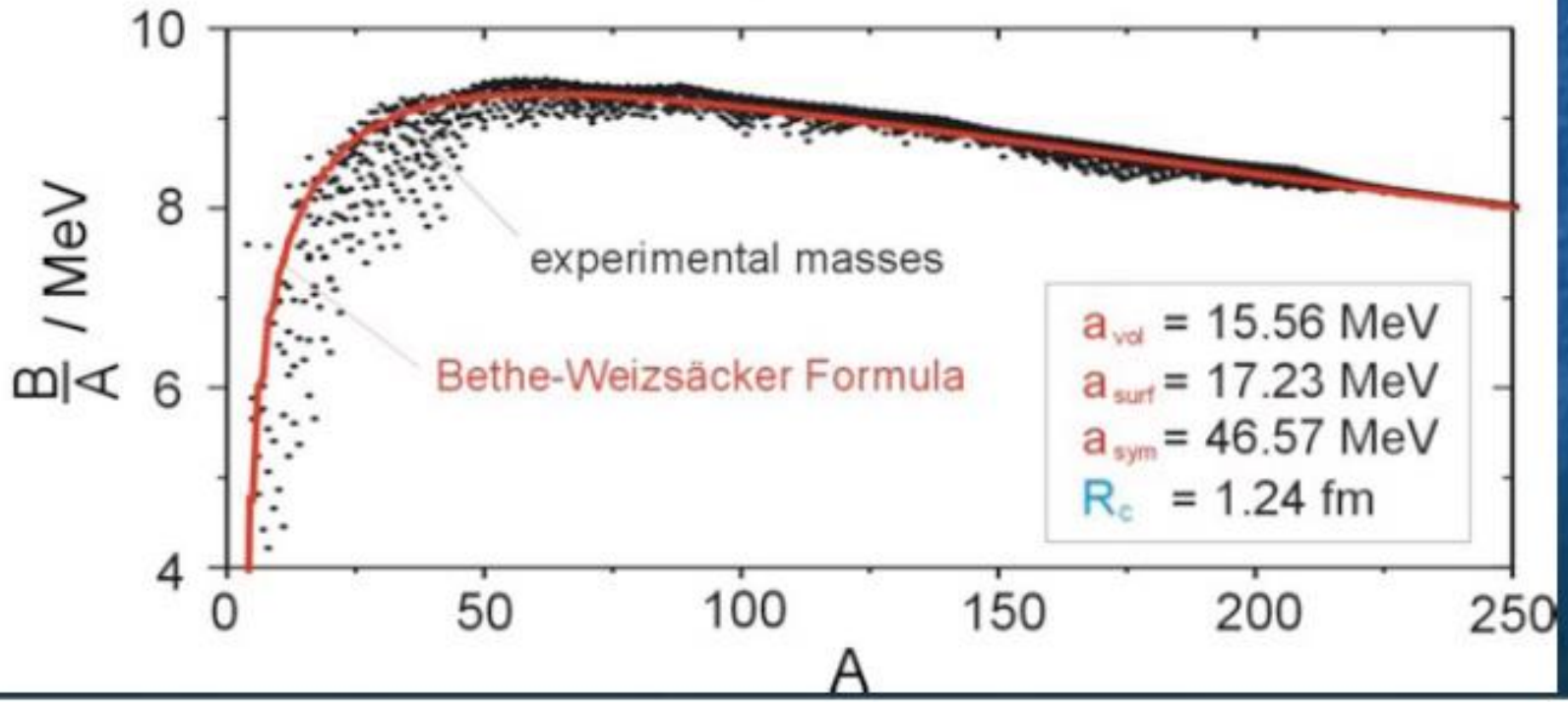
Nuclei are treated as a classical liquid drop

Bethe-Weizsäcker Formula (1935):

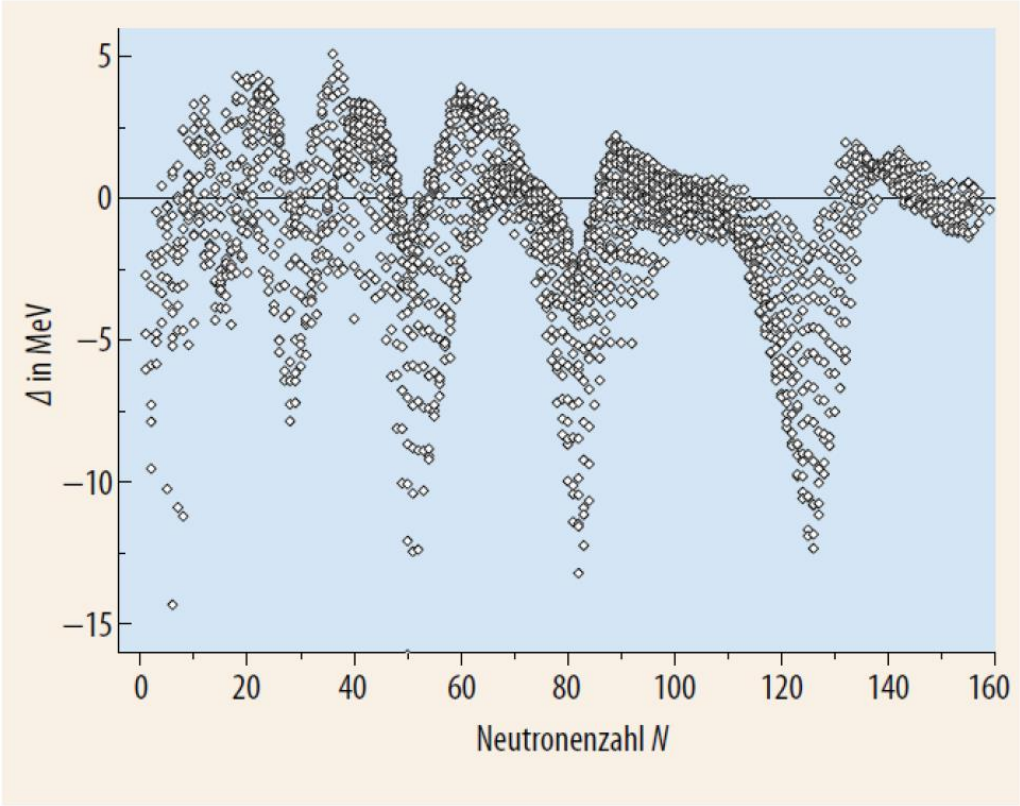
$$B(N,Z) = a_{vol} A - a_{surf} A^{2/3} - \frac{1}{2} a_{sym} \frac{(N-Z)^2}{A} - \frac{3}{5} \frac{Z^2 e^2}{R_c}$$

deformation dependent

Accuracy is better than 1 % !!!



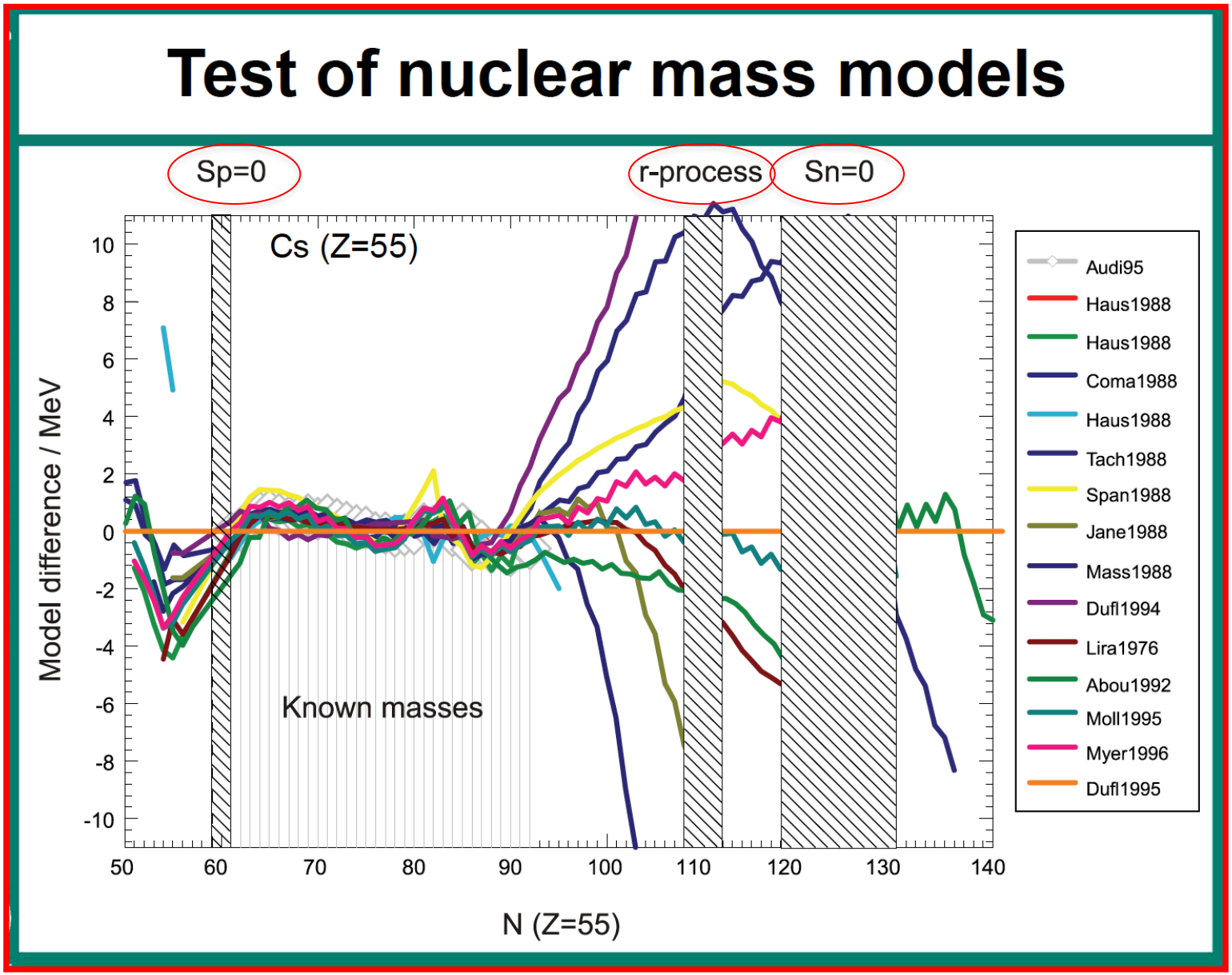
Comparison B_{nucl}: Theory-experiment



Nuclear structure effects like shell closures become visible.

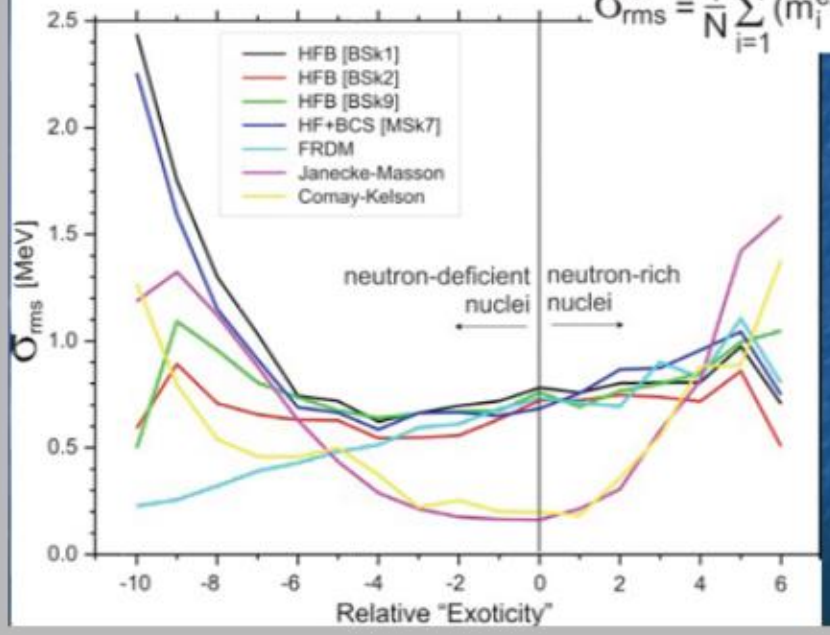
1949: The shell model and magic numbers (Göppert-Mayer + Jensen).

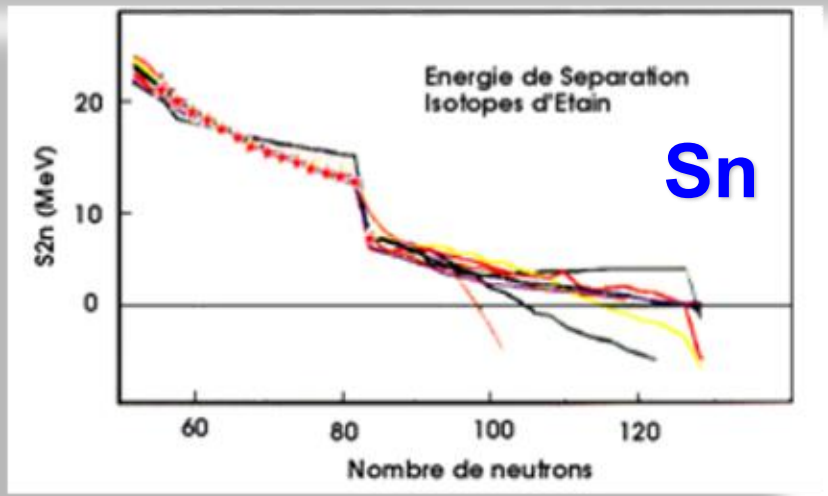
State-of-the-art mean-field and microscopic models



Predictive Powers of Mass Models

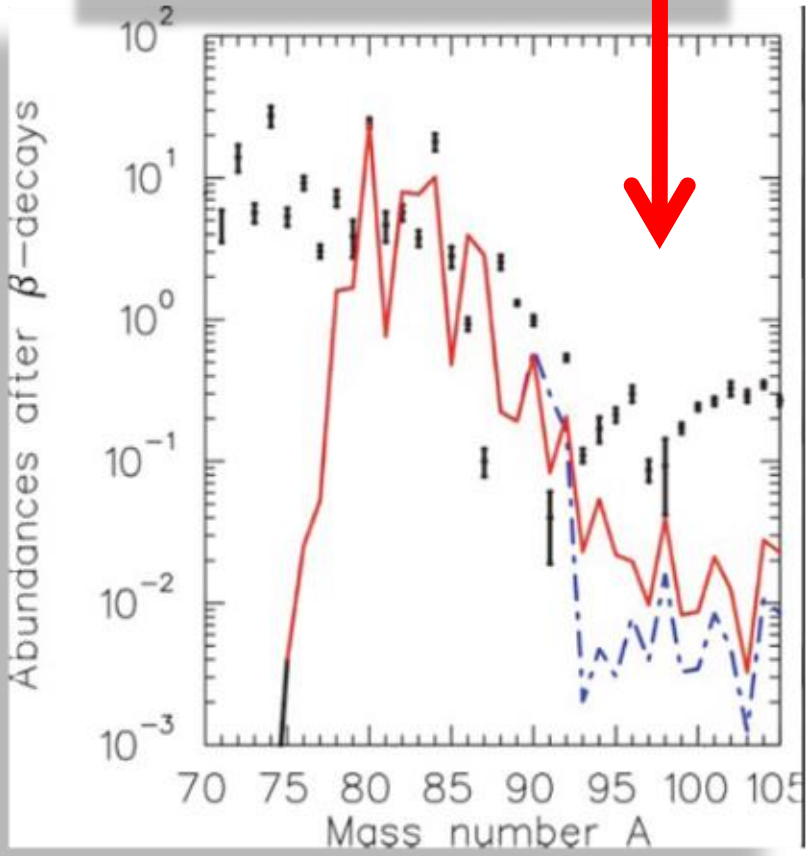
$$\sigma^2_{rms} = \frac{1}{N}\sum_{i=1}^{N}(m_i^{exp} - m_i^{theory})^2$$





Theoretical Predictions become very uncertain close to n-drip line

Calculated abundances assuming that one value for neutron separation is varied by 1 MeV



Need for Precise Mass Measurements !

Progress in Particle and Nuclear Physics
Volume 86, January 2016, Pages 86-126

Review

The impact of individual nuclear properties on r -process nucleosynthesis

M.R. Mumpower [a], R. Surman [a] ✉, G.C. McLaughlin [b], A. Aprahamian [a]

Impact of Mass uncertainty on Isotopic Abundances

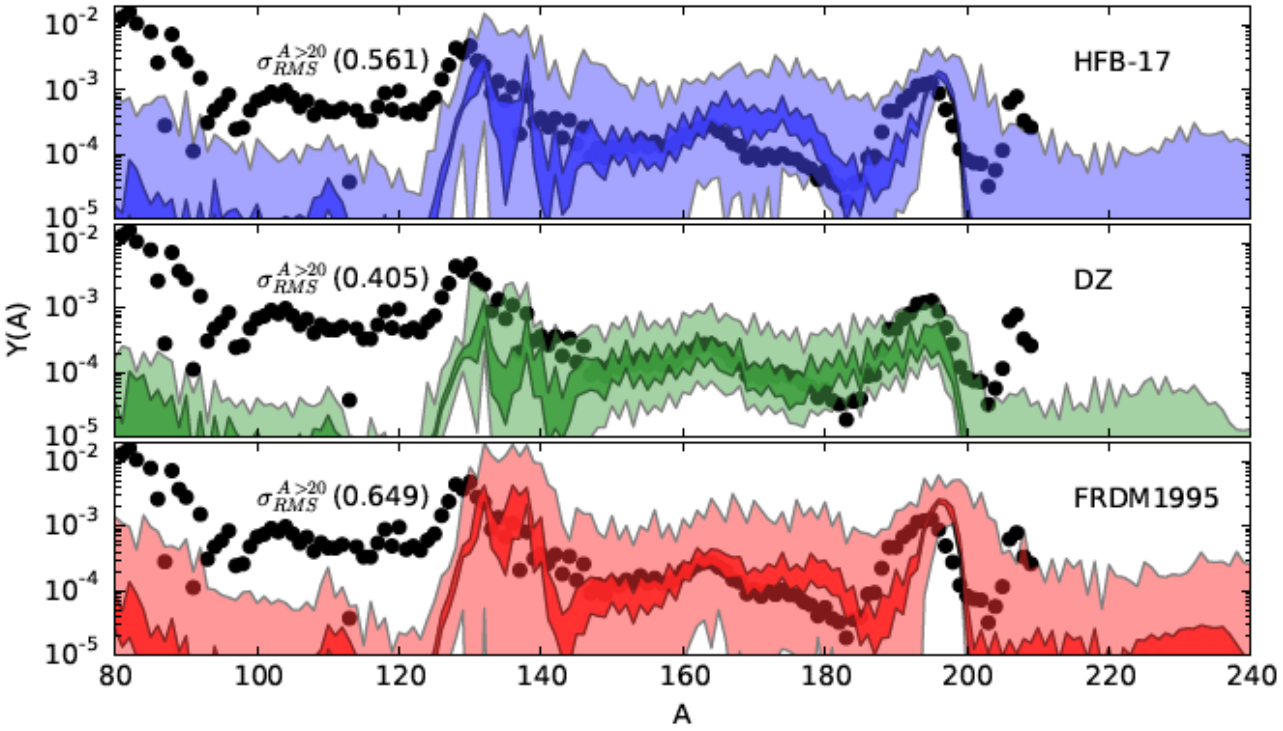
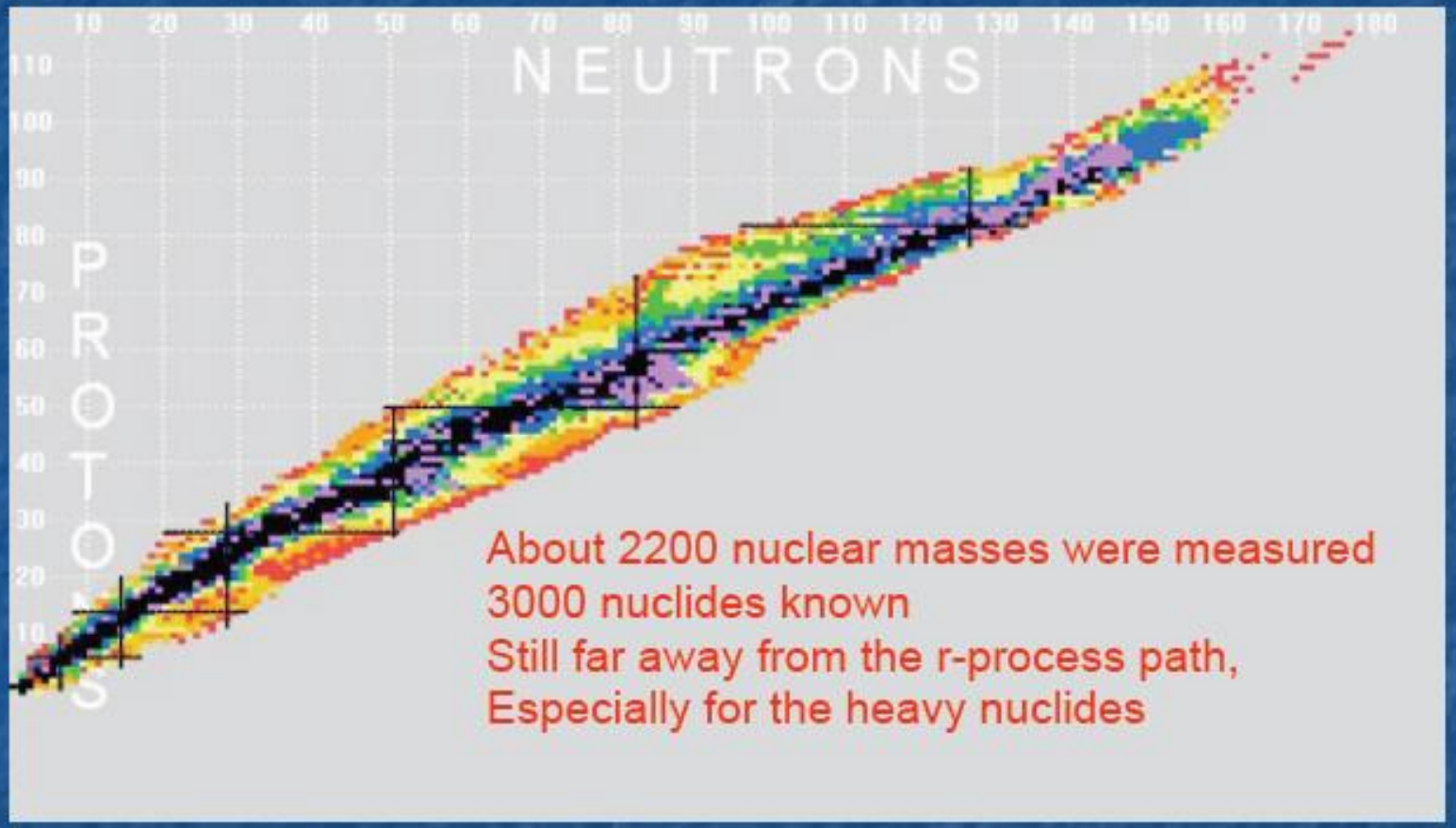


Figure 10: Variance in isotopic abundance patterns from three nuclear mass model predictions (HFB-17, DZ33, and FRDM1995) compared to the solar data (dots) for a hot r-process trajectory that produces primarily main ($A > 120$) r-process nuclei. Darker shaded band represents Monte Carlo simulation with mass model rms error hypothetically reduced to 100 keV. Simulation data from [192].

Knowledge of masses through the years

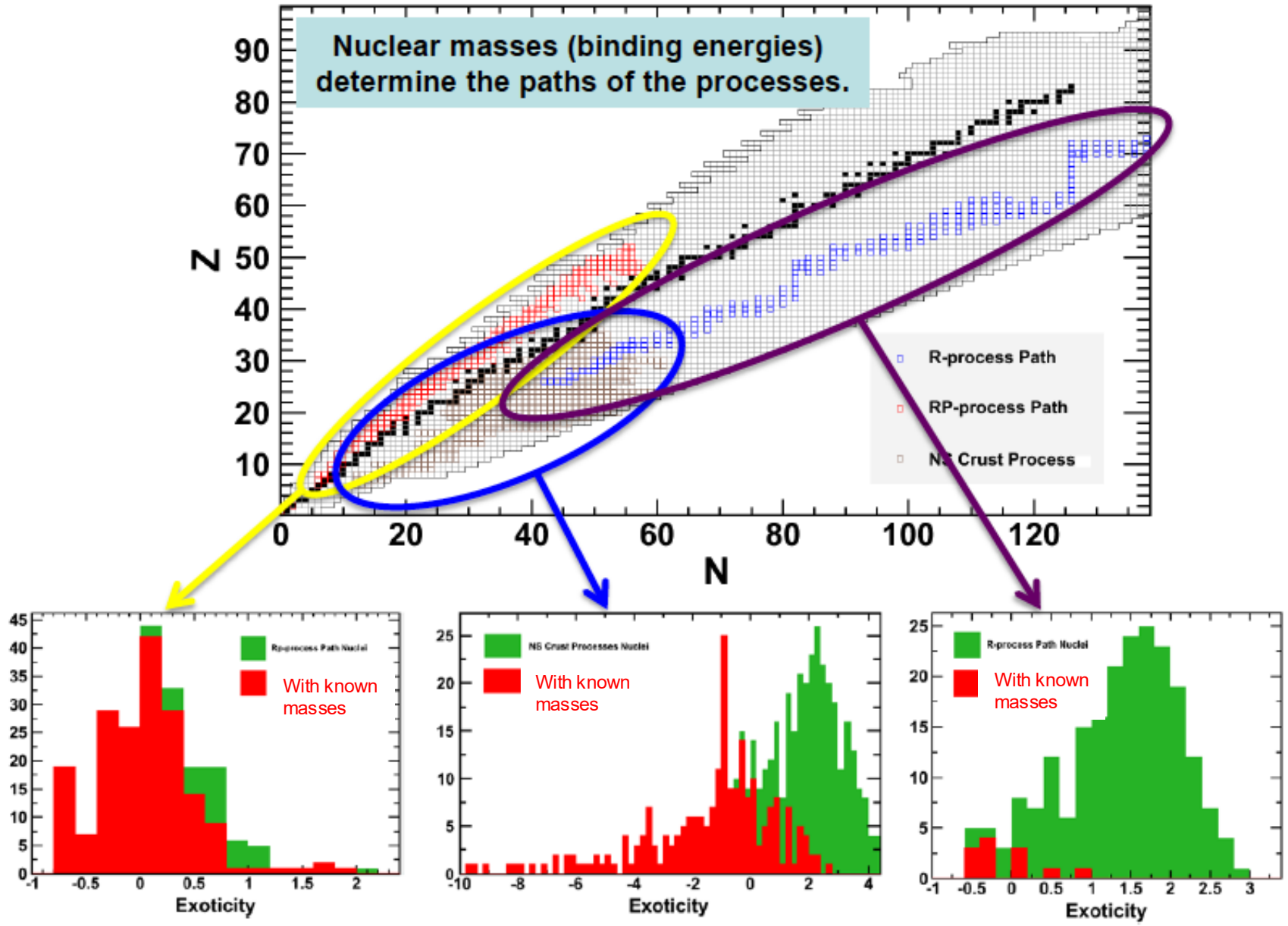


Up to 2004!

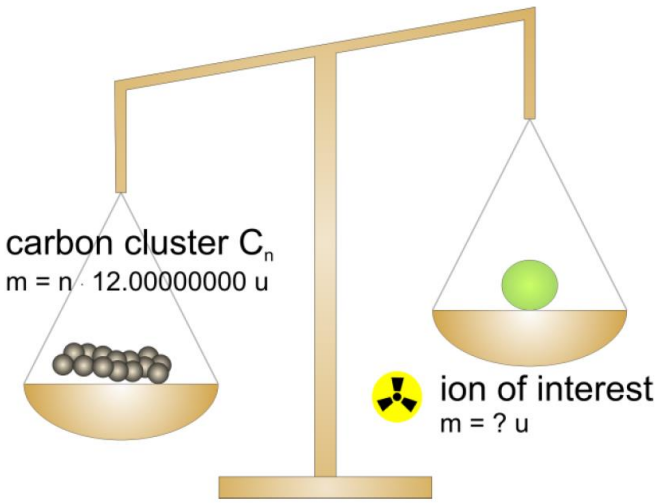
most recent updates in 2016 and 2020

G. Audi et al., Nucl. Phys. **A565**, 1(1993); A 595, 409 (1995), A729.337(2003)

Mass spectrometry for nucleosynthesis



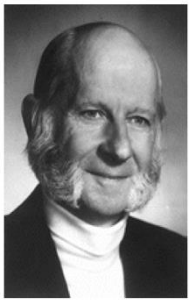
2 How to weigh an atom



$\nu_{c,1}$ $\nu_{c,2}$ $\Rightarrow$ $\frac{\nu_{c,1}}{\nu_{c,2}}$

By capturing and storing of ions and comparing with other masses!

Hans Dehmelt (1922 - 2017)



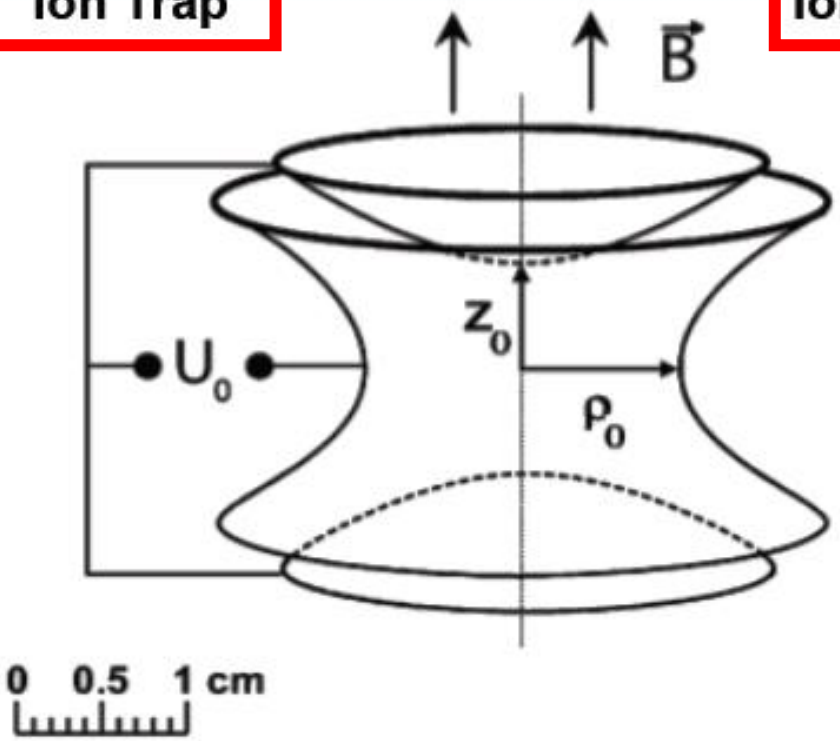
Wolfgang Paul (1913 - 1993)

Nobel Prize in Physics in 1989 to
Hans Dehmelt und Wolfgang Paul
„for the development of the ion trap technique".

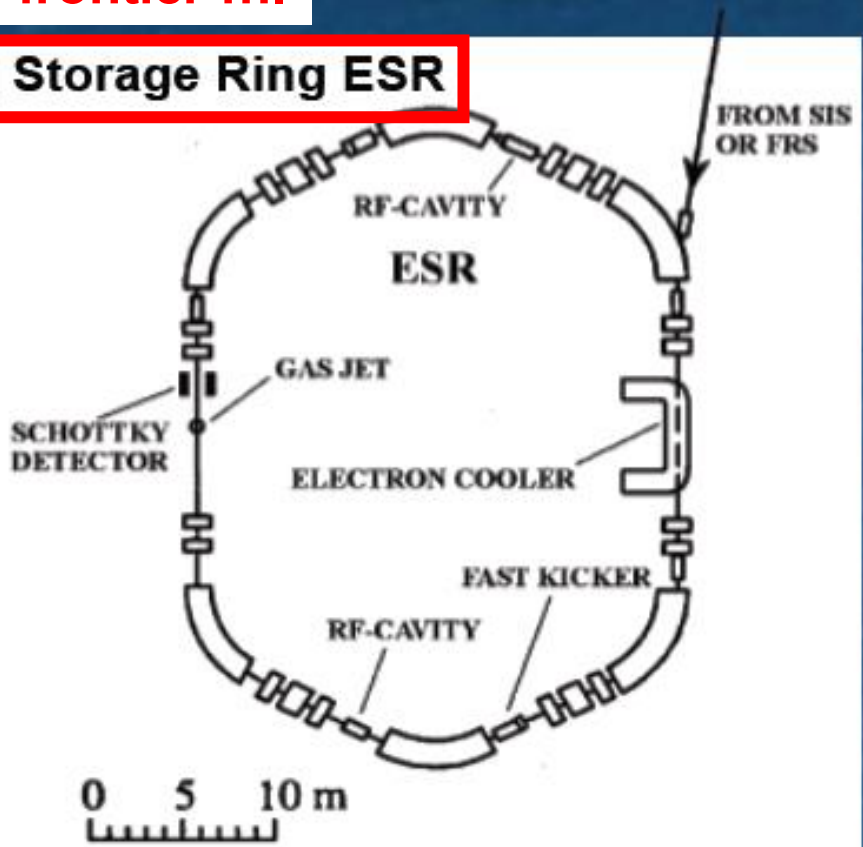
Devices for precise mass measurements

The ultimate frontier ….

Ion Trap



Ion Storage Ring ESR



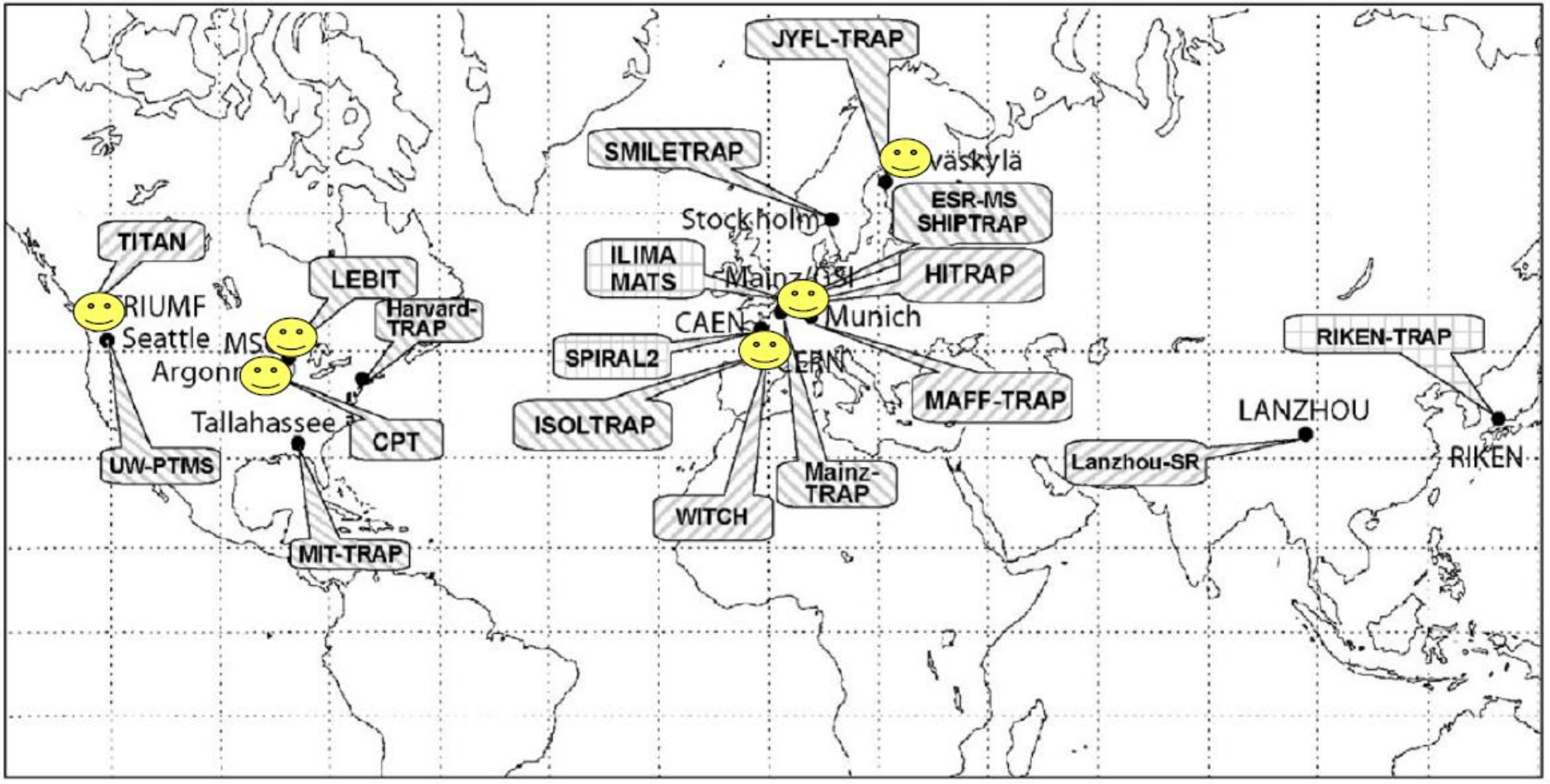
Ions nearly at rest in space

Relativistic (un)stable ions A^{+Z}

* cooling
* long storage time
* single - ion sensitivity
* high accuracy
* mass spectrometry capabilities

K. Blaum, Physics Reports 425 (2006)1-78

Storage rings and Penning traps for high-accuracy measurements worldwide



K. Blaum, Physics Reports 425 (2006)1-78

Misure di Massa … del 1950

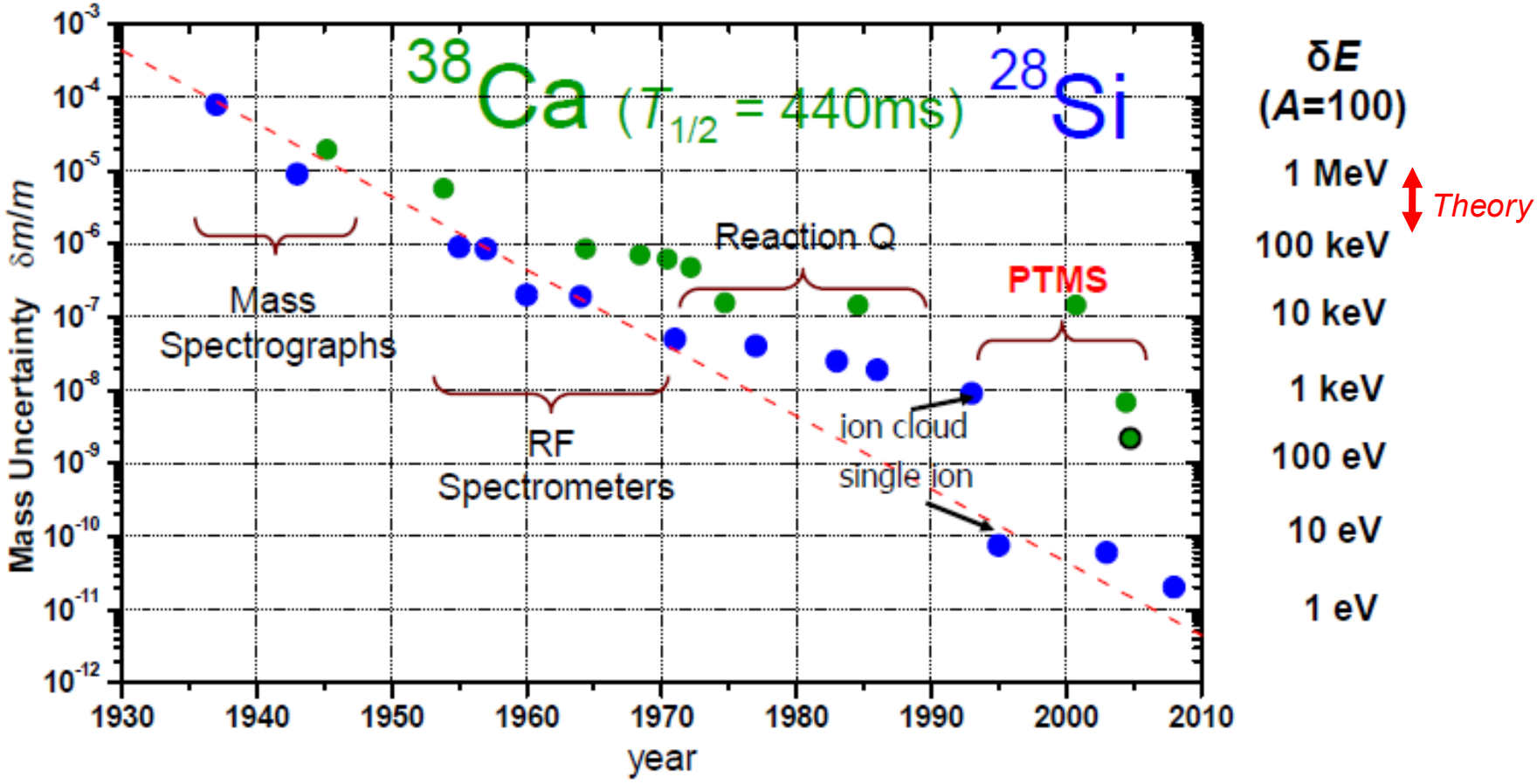
1950-60 Development of magnetic and electric sector-field separators
Q-Value Measurements

1960-80 Mattauch-Herzog mass-spectrometer (quite low resolving power)

1980-90 Time-of-Flight spectrometers (quite low accuracy)

1990-Today Penning traps, storage rings

A brief history of mass spectrometry

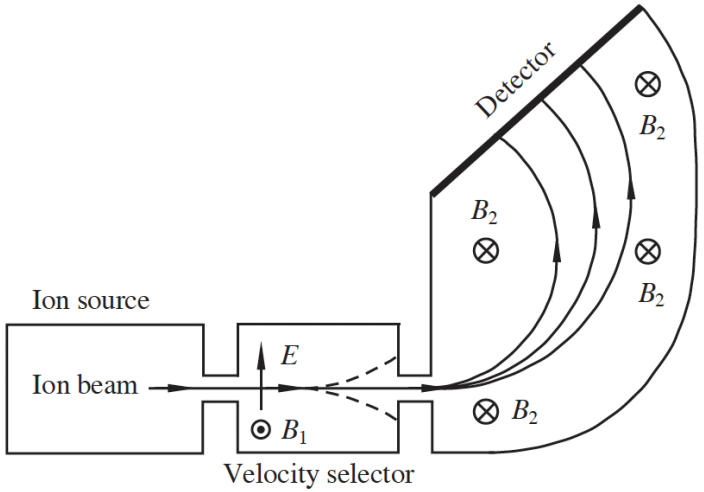


Mass Spectrometers

A «simple» way of measuring masses (of ions) is by
passing ion beams through crossed magnetic and electric fields
Technique introduced by J.J. Thomson in 1912:
discovery of isotopes of Ne with masses 20 and 22

- **Ion source**
  atoms are ionized and accelerated
- **velocity selector**
  - only particles travelling in a straight line cross the collimators
  - Electric and Magnetic force balance each other
- **magnetic spectrometer**
  different masses have different radii
- **Focal Plane detector**
  for measuring the q charge

N.B. the magnetic fields are generally different in the two parts of the system



$$qvB = mv^2/R$$

$$mv = qBR$$

$$m = q\frac{B_v}{E_v}BR$$

$$R = \frac{v}{q\,B_2}M$$

$$\vec{F}_E = q\vec{E}_v \qquad \vec{F}_B = q\vec{v}\times\vec{B}_v \qquad \vec{F}_E = -\vec{F}_B \qquad v = \frac{E_v}{B_v}$$

$$q\,E = q\,v\,B_1$$

N.B. Absolute Mass measurement do not allow high precision

The best precisions (10^{-6}) are achieved by mass ratios

–**molecoles** are used with same masses

Example:

$$A_{C_{12}H_{16}} = 12 \times 12 + 16 \times 1$$

$$m_1 = q\frac{B_v}{E_v}BR_1 \qquad {}^{160}\mathrm{Gd}$$

$$m_2 = q\frac{B_v}{E_v}BR_2 \qquad C_{12}H_{16}$$

– the same E and B fields are used in the two cases

– molecules pass through the same regions of the apparatus

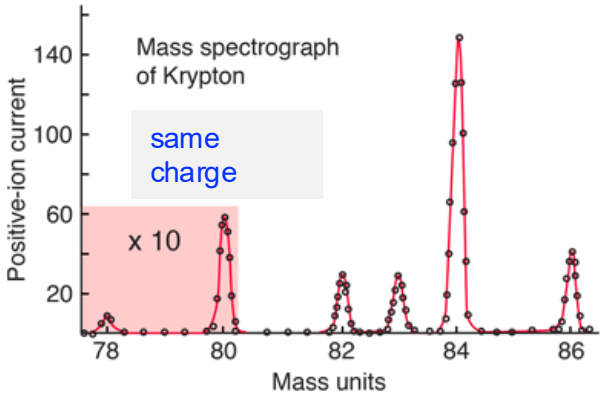
- the mass ratio depends only on radii raggi

$$m_1/m_2 = R_1/R_2$$

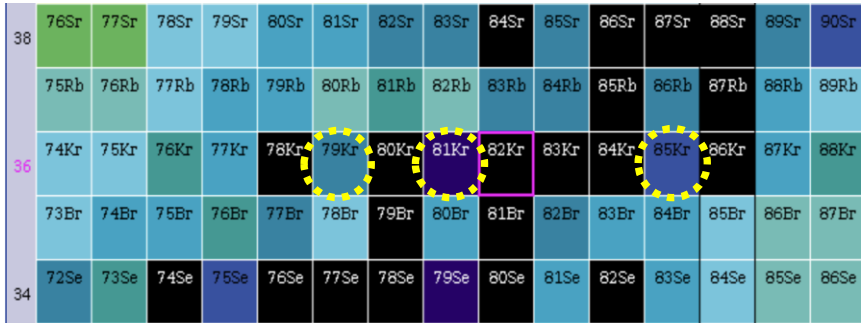
- Carbon allows a large number of possible measurements of masses.

Very Important Application:

Measurement of **relative abundances** of the various isotopes of an element



^{78}Kr	0.356%
^{80}Kr	2.27%
^{82}Kr	11.6%
^{83}Kr	11.5%
^{84}Kr	57.0%
^{86}Kr	17.3%



Kr

Masses not appearing are **radioactive** and are not present in natural krypton:
^{79}Kr, ^{81}Kr, ^{85}Kr, masses below ^{78}Kr and above ^{86}Kr

Average atomic mass of krypton:

$$m = 0.00356m(^{78}\mathrm{Kr}) + 0.0227m(^{80}\mathrm{Kr}) + \cdots$$
$$= 83.8\ \mathrm{u}$$

Masses from Reaction Kinematics

If nuclei are **very short-lived** (shorter than Time-of-Flight to focal plane),
It is NOT possible to use mass spectrometers

Mass differences can be determined by **measuring the energies of particles in nuclear reactions**

nuclear reaction: a + X → b + Y

a = projectile
X = target
b and Y = reaction products

By **measuring the kinetic energies (T) of the reacting particles (a, X, b, Y)**,
we can determine the difference in masses, which is known as the **Q value of the reaction**

Conservation of Total Energy:

$E_{initial} = E_{final}$

$$m_X c^2 + T_X + m_a c^2 + T_a = m_Y c^2 + T_Y + m_b c^2 + T_b$$

$$Q = (m_{initial} - m_{final})c^2$$

$$= (m_X + m_a - m_Y - m_b)c^2$$

equivalent to

$$Q = T_{final} - T_{initial}$$

$$= T_Y + T_b - T_X - T_a$$

Example

the reaction $^1H + ^{14}N \rightarrow ^{12}N + ^3H$. From mass doublet measurements we know that $m(^1H) = 1.007825$ u, $m(^{14}N) = 14.003074$ u, and $m(^3H) = 3.016049$ u. The measured Q value is -22.1355 ± 0.0010 MeV. We thus deduce

$$m(^{12}N) = m(^1H) + m(^{14}N) - m(^3H) - Q/c^2$$

$$= 12.018613 \pm 0.000001 \text{ u}$$

The main contribution to the uncertainty of the deduced mass comes from the Q value; the ^1H, ^3H, and ^{14}N masses are known to much greater precision. The nuclide ^{12}N is unstable and decays with a half-life of only 0.01 s, which is far too short to allow its mass to be measured with a mass spectrometer. The nuclear

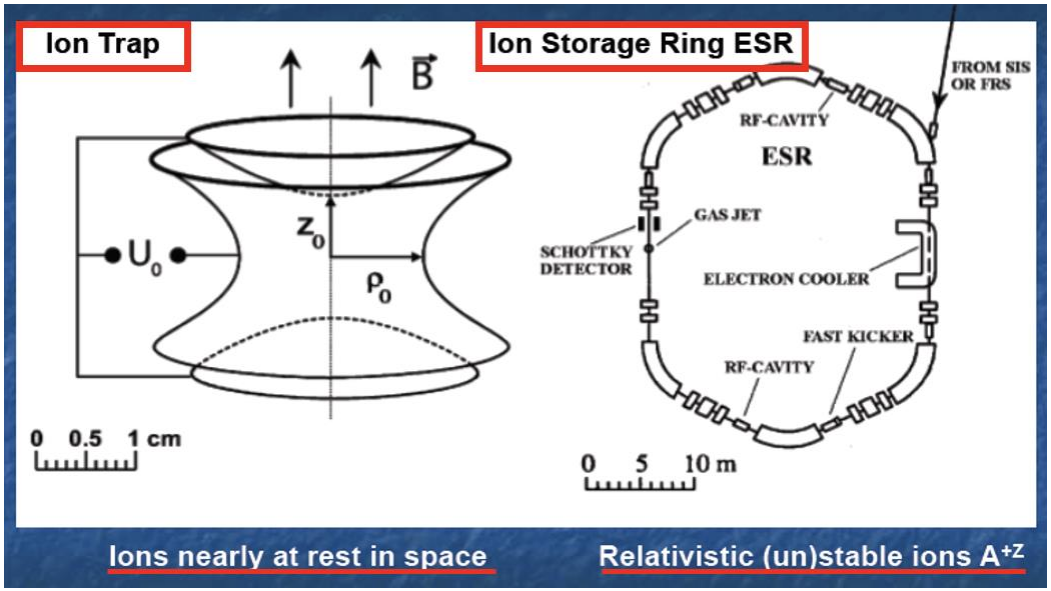
$\delta m/m \sim 10^{-7}$ -10^{-6}

Most precise mass measurements: Traps and Storage Rings

Storage devices **confine ions** in three dimensions using **well-controlled electromagnetic fields**

Current measurements:

masses of unstable nuclei: $\delta m/m \sim 10^{-8}$
masses of stable nuclei $\delta m/m \sim 10^{-11}$



Extreme precision results come from

- extended time of observation of the ions limited in principle only by the lifetime of radioisotopes (i.e. isotopes that decay)
- experiments with single ions are possible
- ions can be stored in ideal conditions

N.B. ***for unstable nuclei****, Ion Traps are* ***factor of 10 better*** *in precision than Storage Rings*

K. Blaum, Physics Reports 425 (2006)1-78

Traps for Rare Isotopes

Ability to confine ions in small volume in well controlled field

Traps are widely used in fundamental and applied research

- **High precision mass measurements**: nuclear binding energy far from stability
  (nuclear structure, nuclear sysnthesis of elements, test of fundamental interactions)

- **nuclear decay in free space**
  (textbook study… !)

- **Storage and cooling of ions**
  (improvement in beam quality …: accumulation, bunching and beam purification)

G. Bollen, Euroschool Lectures, Volume I
K. Blaum, Physics Reports 425 (2006)1-78

High-precision mass measurements

Challenges in Application of Traps to Rare Isotopes

Ions are delivered from External Source:

- beam energies from 10 keV – GeV
$\Rightarrow$ slowing down of fast beams

- production of minute quantities: few ions/s
$\Rightarrow$ beam cooling and bunching

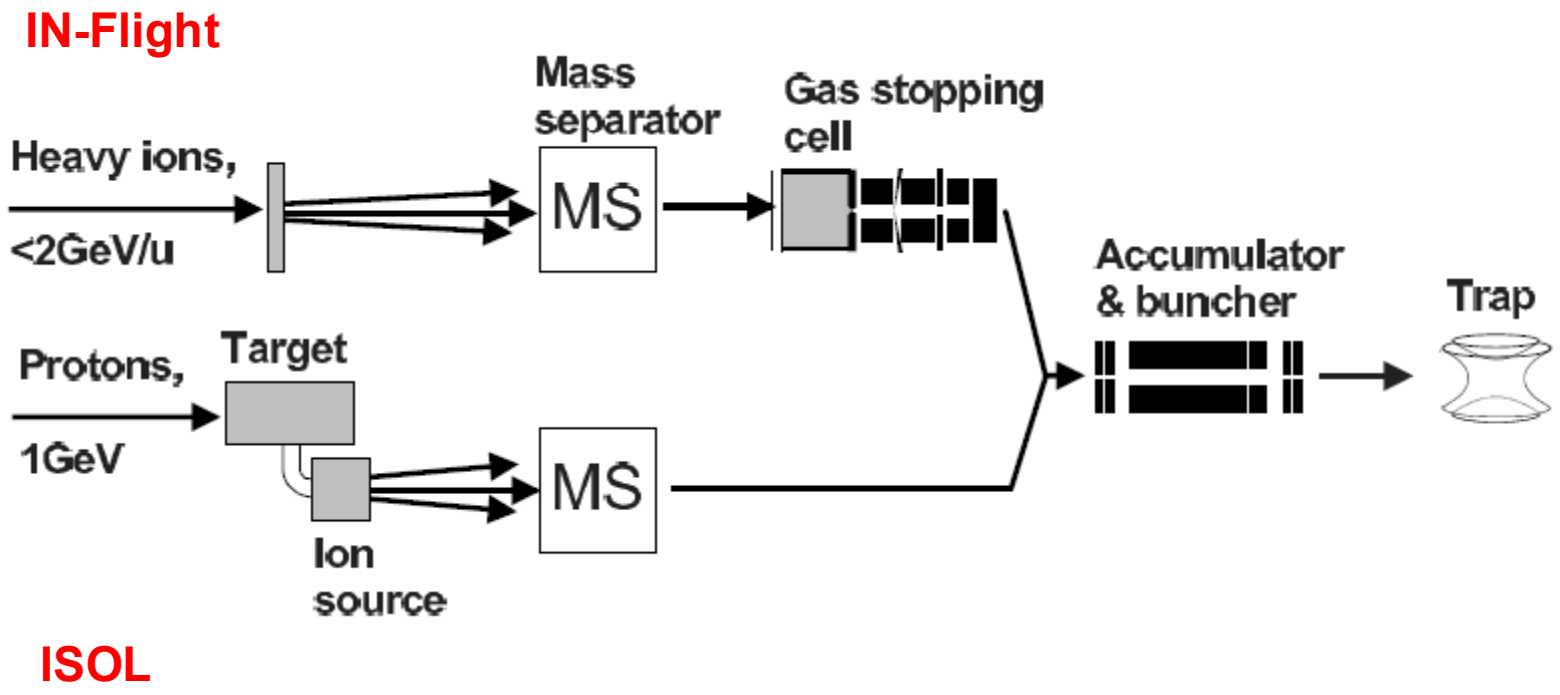
- short half life : down to ms or less (when close to the driplines)
$\Rightarrow$ fast measurements techniques …

The properties of the beams are determined by production scheme:

ISOL beams are more easy to handle due to low energy (few 10 keV) and good beam quality

ISOLTRAP : pioneering experiment istalled at ISOLDE @ CERN
M. Mukherjee et al., EPJA35, 1-29(2008)

Beam Preparation for precision measurements with trapped Ions



Basic Methods for Ion Trapping

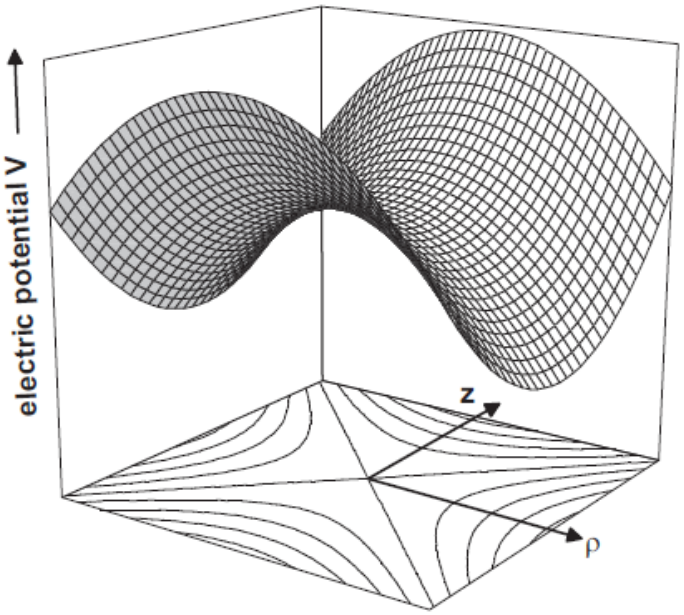
- **Paul Trap or Radiofrequency quadrupole Trap (RFQ)**
  inhomogeneous radiofrequency field employed for ion confinement
  $\Rightarrow$ application in accumulation and storage, beam cooling and bunching

- **Penning Trap**
  combined magnetic and electric fields
  $\Rightarrow$ mass spectrometers

*Extremely elegant example of **electromagnetism** at work!*

The Nobel Prize in Physics 1989 was divided, one half awarded to Norman F. Ramsey *"for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks"*,the other half jointly to Hans G. Dehmelt and Wolfgang Paul *"for the development of the ion trap technique"*

Generation of Trapping Potential



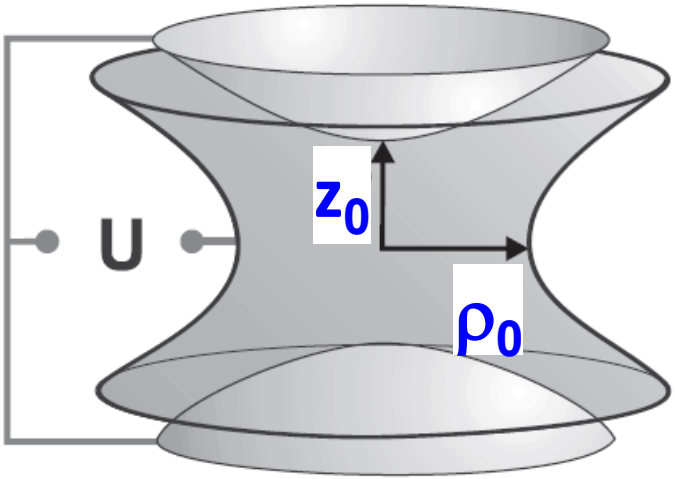
Simplest Confinement in z direction

$$V \propto z^2$$

In 3D: $$V \propto z^2 - \rho^2/2$$

ρ = distance from z-axis

Static electric quadrupole potential confines ions only in axial/radial direction (Z) !!!



3 hyperbolic electrodes

with shape following equipotential surface

$$z = \sqrt{\rho^2/2 - \rho_0^2/2}, \rho \geq \rho_0$$

$$z = \pm\sqrt{z_0^2 + \rho^2/2}$$

1 ring
2 end-caps

$$V(\rho, z) = \frac{U}{2d^2} \cdot (\rho^2/2 - z^2)$$

$$d = \sqrt{\rho_0^2/4 + z_0^2/2}$$ trap dimension

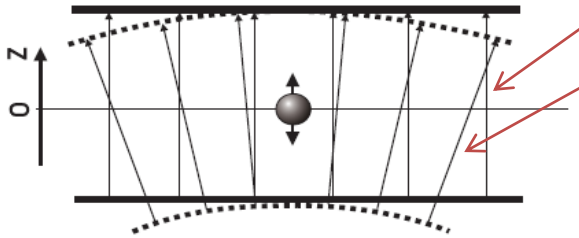
Ion Confinement in Paul or RFQ traps

Oscillating electric field *(inhomogeneous)*:

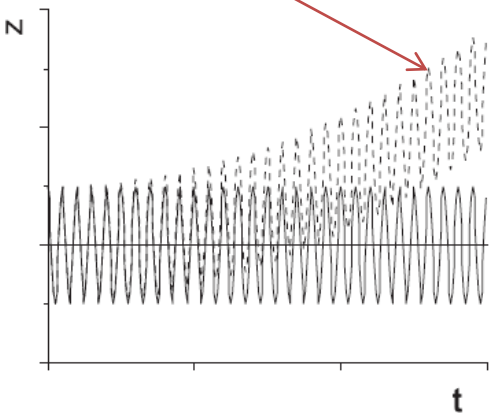
Quick *change of polarity of the potential*, forcing the ions to slide back and forth

$$U(t) = U_{\mathrm{DC}} + U_{\mathrm{rf}} \cdot \sin(\omega_{rf} \cdot t)$$

Origin of confining Force

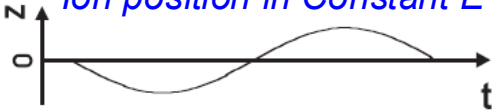


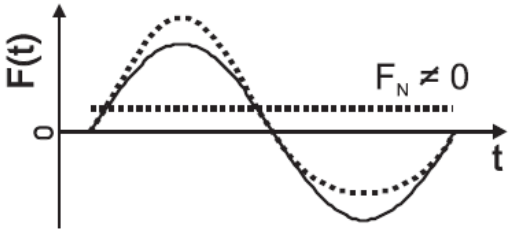
uniform electric field
NOT uniform



Slow driving (macro motion)
towards regions of weaker rf field
(→ confinement)

Ion position in Constant E





Constant E gives 0 net Force

$$\vec{F}_n = -e\vec{\nabla}V_{pseudo}$$

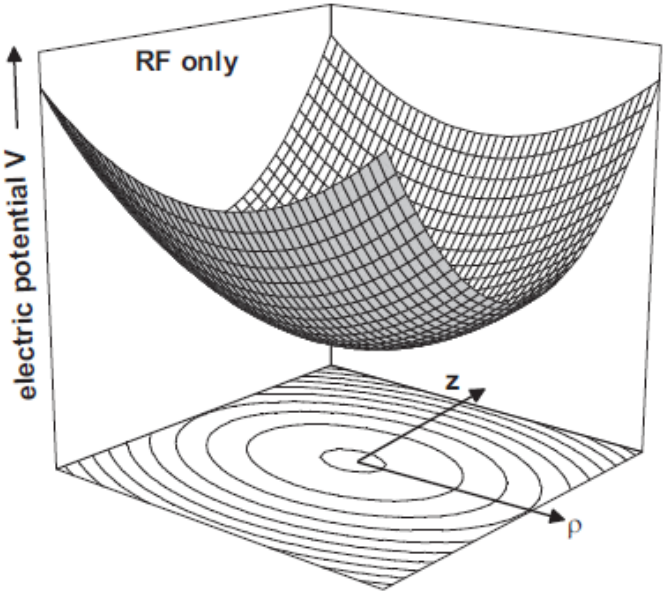
$$V_{\mathrm{pseudo}}(\rho, z) = \frac{e}{m}\left(\frac{U_r}{2\omega_{rf} d_0^2}\right)^2 (\rho^2/4 + z^2).$$

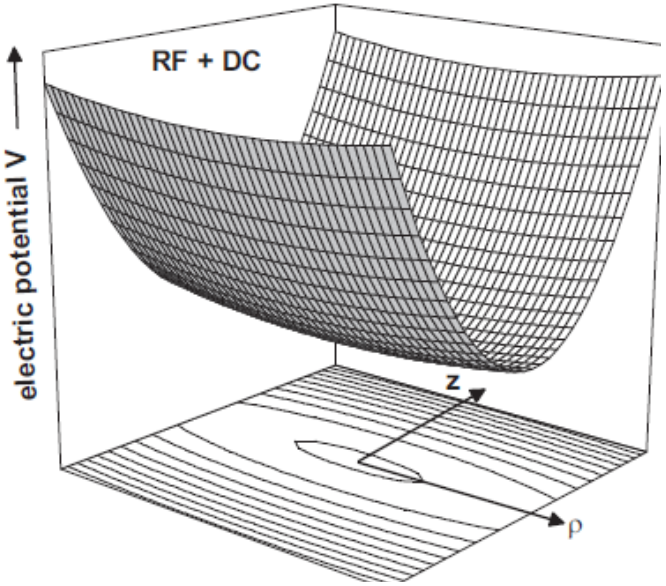
The resulting **force** can be seen as due to a **STATIC pseudo-potential** of ***parabolic well form***

$$V_{\text{pseudo}}(\rho, z) = \frac{e}{m}\left(\frac{U_r}{2\omega_{rf} d_0^2}\right)^2 (\rho^2/4 + z^2).$$

Additional DC potential is often used to increase the depth of the total potential

$$V_{DC+rf} = V(\rho, z) + V_{pseudo}(\rho, z)$$





*N.B. **CAREFUL**: beyond a certain DC voltage, ion confinement in all dimension is lost !!!*

Ions perform harmonic motions in the parabolic potential with frequencies

$$\omega_z = \frac{e}{m}\frac{U_{rf}}{\sqrt{2}\omega_{rf} d^2}$$

$$\omega_\rho = \frac{1}{2}\omega_z$$

for A = 50

frequencies of macro motion

ω_z = 104 kHz
ω_ρ = 52 kHz

Trapping electrodes	
Inner radius of ring electrode ρ_0	1.4 cm
Distance between endcaps $2z_0$	2.0 cm
Characteristic trap dimension d	1.0 cm
Paul trap	
rf amplitude U_{rf}	300 V
rf frequency ν_{rf}	1 MHz
DC-voltage U_{DC}	0 V
Penning trap	
Magnetic field strength B	9.4 T
Trapping voltage U	10 V

Search for optimum parameters for Stability of Ion Motion

$$U(t) = U_{\mathrm{DC}} + U_{\mathrm{rf}} \cdot \cos(\omega_{rf} \cdot t)$$

$$\ddot{\rho} = \frac{e}{m}\frac{\rho}{2d^2} \cdot U(t)$$

$$\ddot{z} = \frac{e}{m}\frac{z}{d^2} \cdot U(t)\,.$$

No simple Solution !!!

Confining Force F_n does not work if $\omega_{rf} \sim \omega_{z,\rho}$ [RadioFreq. close to macromotion]

NO simple analytic solution

Mathieu Equation

$$\frac{d^2 s}{d\xi^2} + (a - 2q\cos 2\xi) \cdot s = 0\,.$$

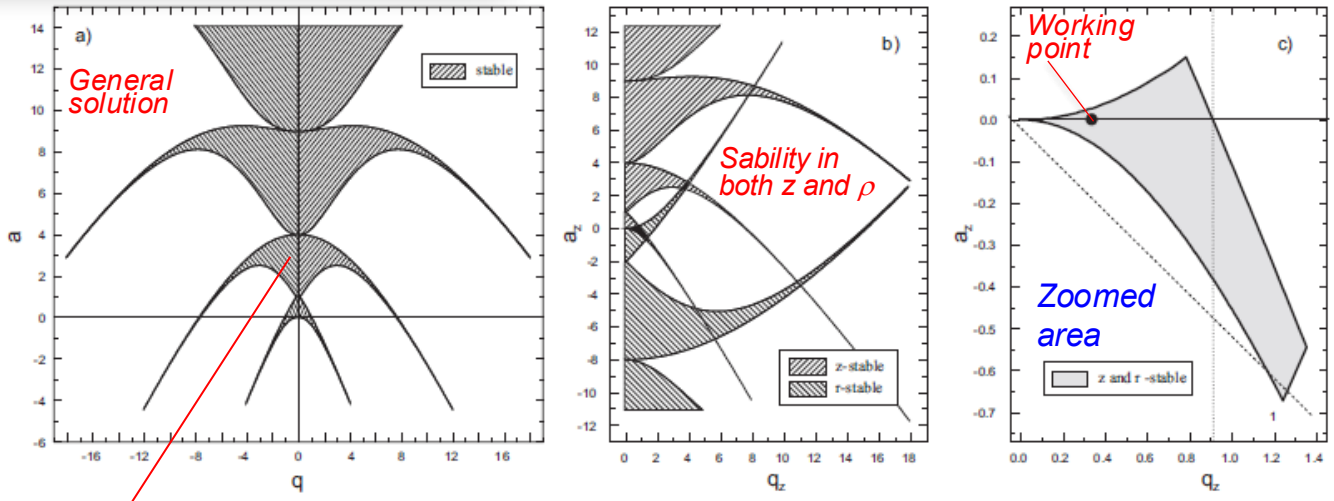
$s = \rho$ or z $\qquad \xi = \omega_{rf}(t/2)$

$$a_z = \frac{4eU_{DC}}{m\omega_{rf}^2 d^2}$$

$$q_z = \frac{2eU_{rf}}{m\omega_{rf}^2 d^2}$$

$$a_r = -\frac{a_z}{2}$$

$$q_r = -\frac{q_z}{2}$$

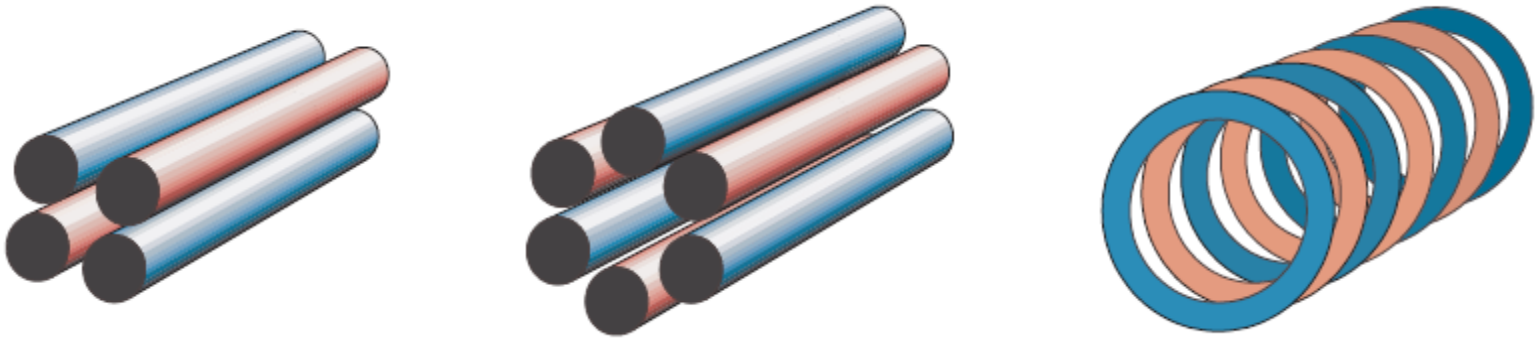


Overlapping regions: **stable motion** in axial and radial direction

Largest stability for Ion storage is achieved close to the origing

Ion confinement: NOT only hyperbolic electrods !

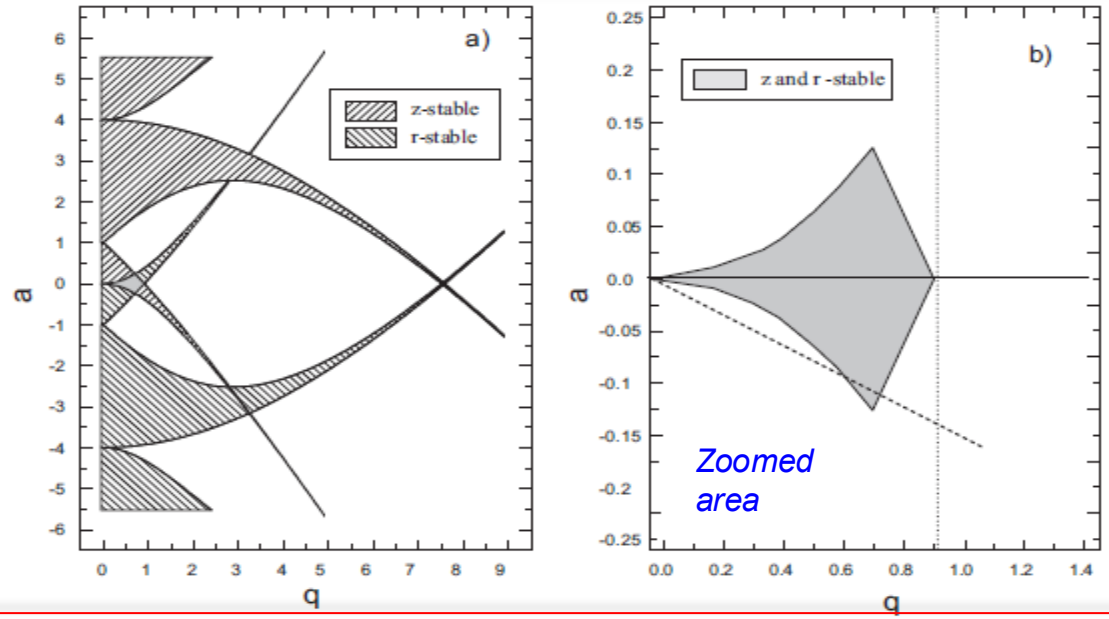
Ions guides and ion beam coolers : quadrupole and hexadecapole configurations



Focusing in AXIAL direction only …

$$a = 8\frac{eU_{DC}}{mr_0^2\omega_{rf}^2}$$

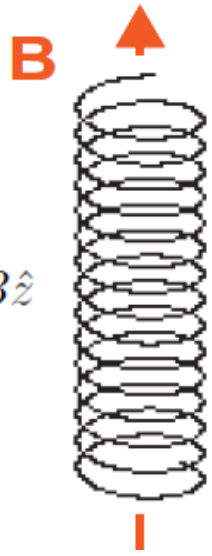
$$q = 4\frac{eU_{rf}}{mr_0^2\omega_{rf}^2} \quad ,$$



Mass dependent: only a range of masses can be stored

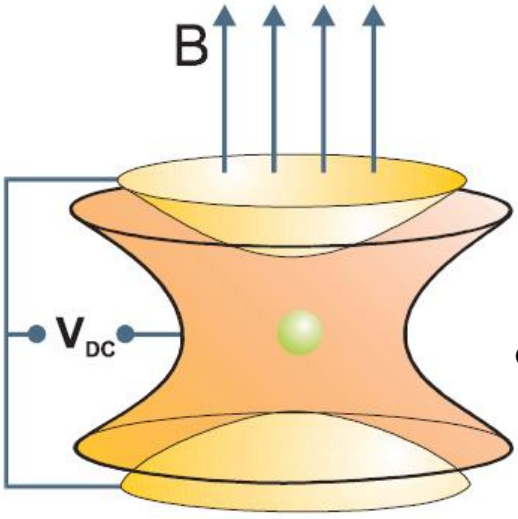
Penning Traps

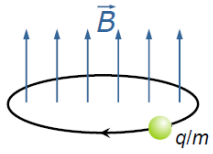
combining a strong magnetic field ***B*** and a static potential V_{DC}



$$\vec{B} = B\hat{z}$$

- Strong homogeneous magnetic field
- Weak electric 3D quadrupole field





$$F_L = q \cdot \vec{v} \times \vec{B}$$

$$\omega_c = \frac{e}{m} \cdot B$$

$$\rho = v/\omega_c$$

Ions Radially Bound: **NO** binding in direction of ***B***

⇒ ***static electric quadrupole field is needed to obtain axial confinement***

Q	A	ν_c	ν_+	ν_z	ν_-
1	4	36136849	36136003	247355	847
1	50	2890947	2890101	69963	847
1	200	722736	721889	34981	848
1	42686	3386	1697	2394	1689

Heaviest confined ion

$$m\ddot{z} = -e\frac{U}{d^2}z$$

$$\omega_z = \sqrt{\frac{eU}{md^2}}$$

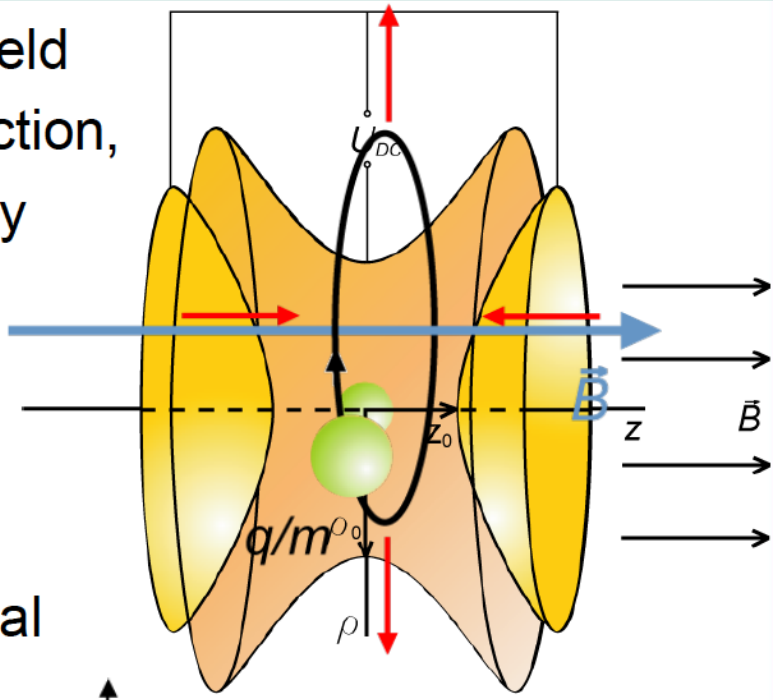
Cyclotron frequency: $\nu_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$ → ***Mass measurements***

The Penning trap

- Trapping of particle via motion in em field
- Strong homog. magnetic field in *z* direction, particle moves with cyclotron frequency

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

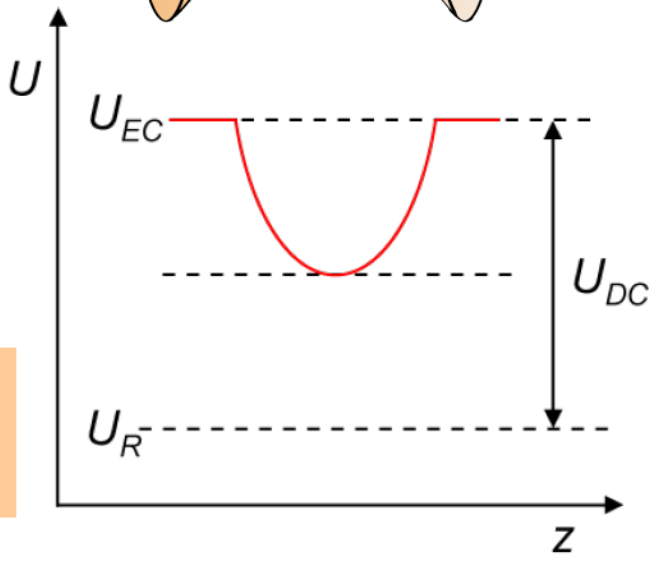
→ bound in radial direction



- Weak, electrostatic quadrupole potential

$$V(z,\rho) = \frac{U_{DC}}{2d^2}(z^2 - \tfrac{1}{2}\rho^2)$$

Geometry parameter $\quad d^2 = \tfrac{1}{2}(z_0^2 + \frac{\rho_0^2}{2})$



- Equations of motion in 3D:

$$\vec{F} = -e_0(\vec{\nabla}\phi(r) + \vec{v}\times\vec{B}) + m\ddot{\vec{r}} = 0$$

Equation of motion in a Penning trap

plus Lorentz force:

$$\vec{F} = -e_0\vec{\nabla}\phi(r) + \vec{v}\times\vec{B}$$

equation of motion:

$$\vec{F} = -e_0(\vec{\nabla}\phi(r) + \vec{v}\times\vec{B}) + m\ddot{\vec{r}} = 0$$

axial oscillation

Three frequencies !!!

$$\frac{2e_0U_0}{md_0^2}\cdot z + m\ddot{z} = 0$$

$$\omega_z = \sqrt{\frac{2e_0U_0}{md_0^2}}$$

z or axial frequency

radial oscillation

substitution:

$$u = x + iy$$

$$\omega_c = \frac{e_0}{m}B$$

$$u(t) = u_0 e^{-i\omega t}$$

$$i\omega_c\dot{u} - \frac{\omega_z^2}{2}u + \ddot{u} = 0$$

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

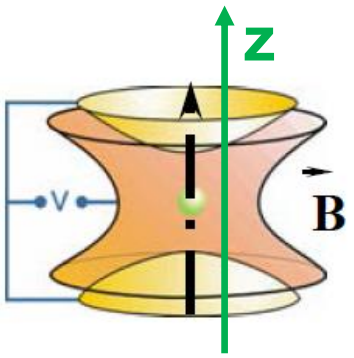
modified cyclotron frequency

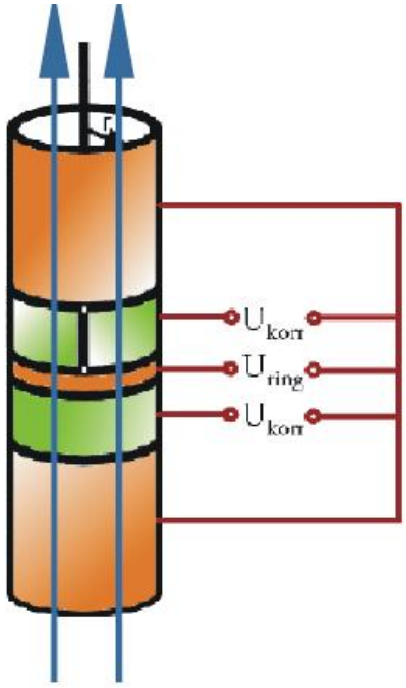
$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

magnetron frequency

Ion motion in a Penning trap

$$\sum \vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$





➢ Three harmonic eigenmotions

1. **Axial** motion:

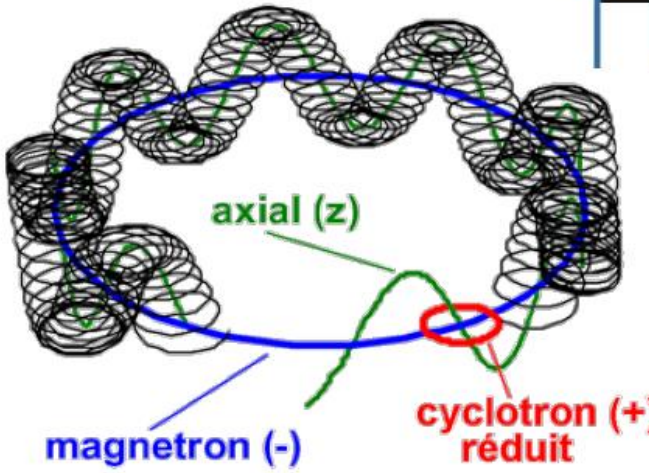
$$\omega_z = \sqrt{\frac{qV_0}{md^2}}$$

2. **Magnetron** motion (slow):

$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

3. **Reduced Cyclotron** motion (fast):

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$



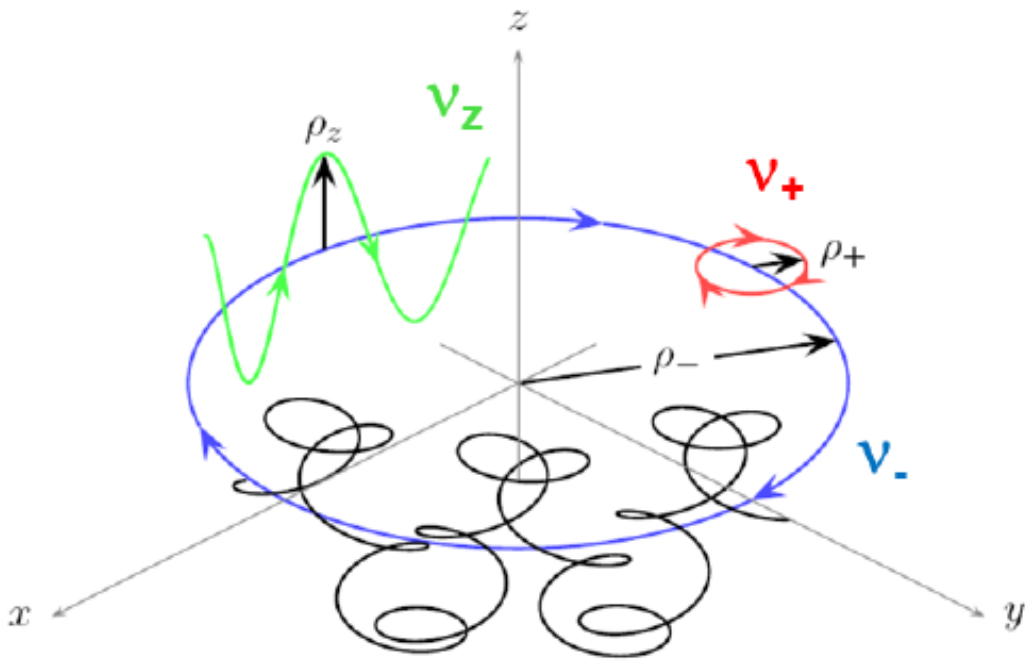
$$\omega_c = \omega_+ + \omega_- = \frac{q}{m} \cdot B$$

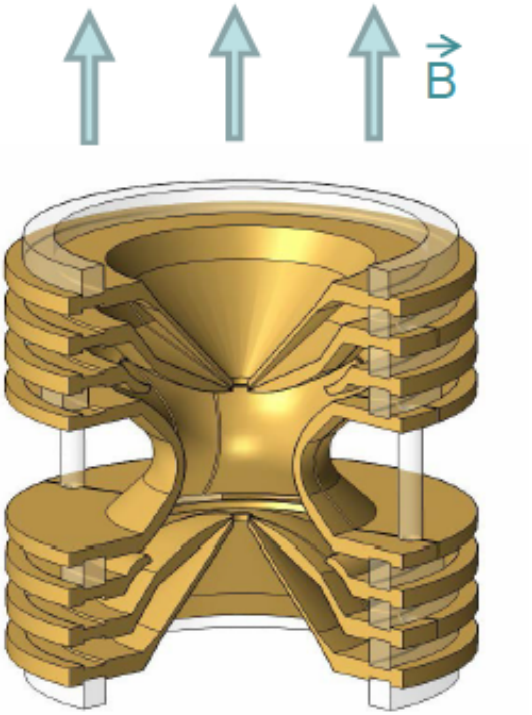
A=100, q=1, B=7 T

- $f_+ \approx$ 1 MHz
- $f_- \approx$ 1 kHz
- $f_z \approx$ 44 kHz

THE KEY EQUATION - Cyclotron frequency: connected to MASS

Storage of ions in a Penning trap





The free cyclotron frequency is inverse proportional to the mass of the ions!

$$\omega_c = qB/m$$

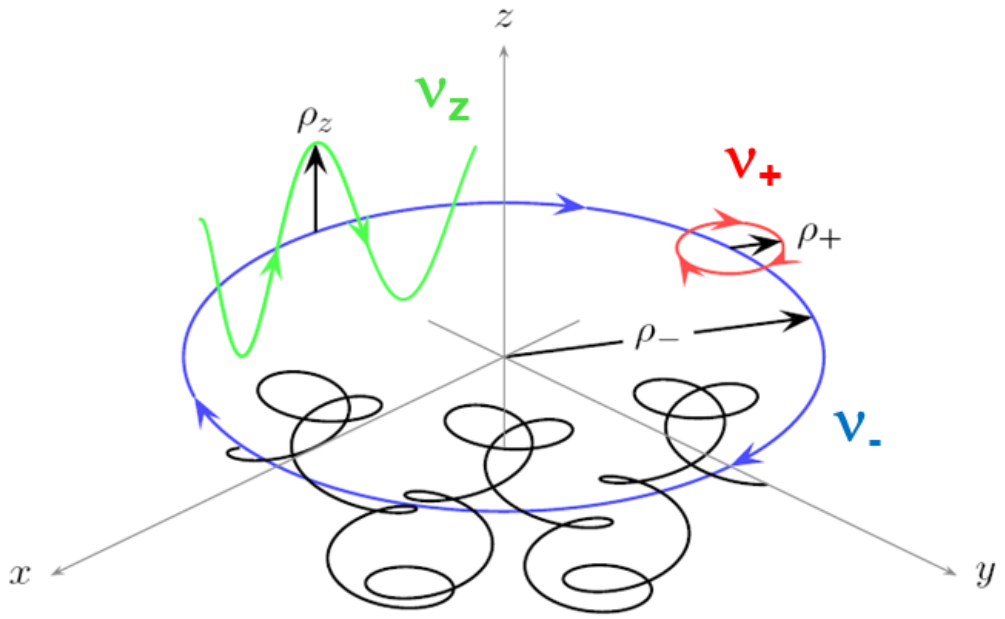
An ***invariance theorem*** saves the day:

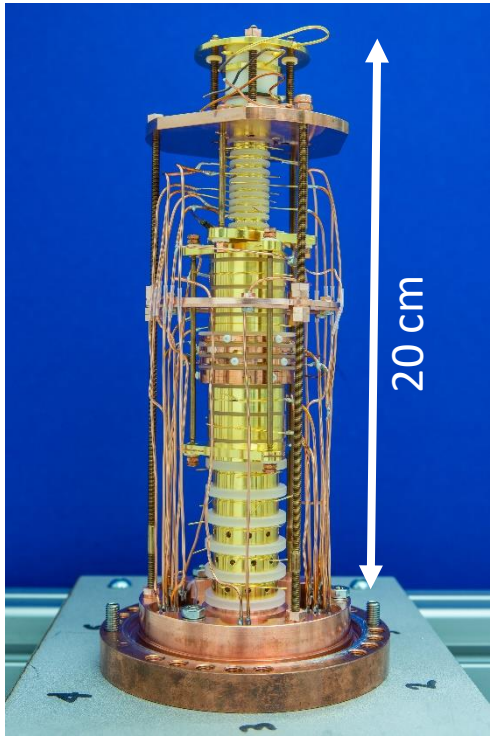
$$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$$

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

L.S. Brown, G. Gabrielse, Rev. Mod. Phys. 58, 233 (1986).
K. Blaum, J. Dilling, W. Nörtershäuser, Phys. Scr. T152, 014017 (2017).

Storage of ions in a Penning trap





The free cyclotron frequency is inverse proportional to the mass of the ion!

$$\nu_c = qB / (2\pi m_{ion})$$

$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

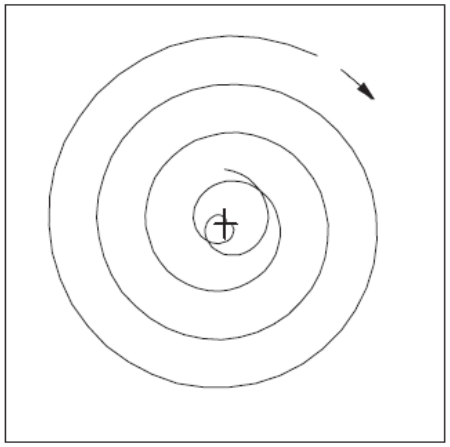
➢ Non-destructive FT-ICR detection technique

K. Blaum, Phys. Rep. **425** (2006) 1-78

Resonant Excitation of Ion Motion

*Change of **frequency** of ion motion* → *Ion Removal, Mass measurements*

Application of radiofrequency fields

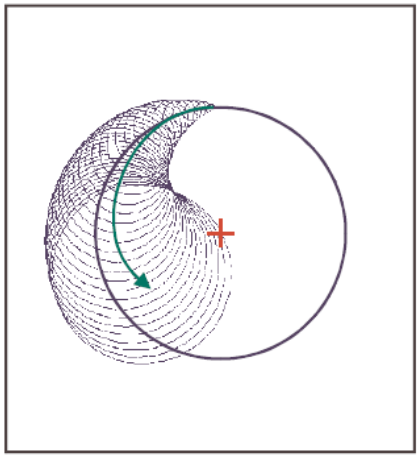


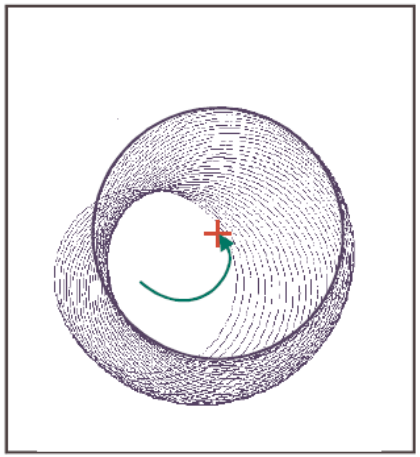
Dipole Excitation (Dipole field rf)

Change the amplitude of the **axial** or radial oscillation:

- drive the ions to specific orbits
- **remove ions from the trap**

$$\tilde{U}_{\mathrm{d}} = \alpha \frac{U_{\mathrm{d}}}{\rho_0} \cos(\omega_{\mathrm{d}} t - \phi_{\mathrm{d}}) \cdot x$$





Quadrupole Excitation

(Quadrupole field rf)

Change the amplitude of side-band excitation at

$$2\omega_z, \quad \omega_+ - \omega_-, \quad \omega_+ + \omega_-$$

Important for mass measurements

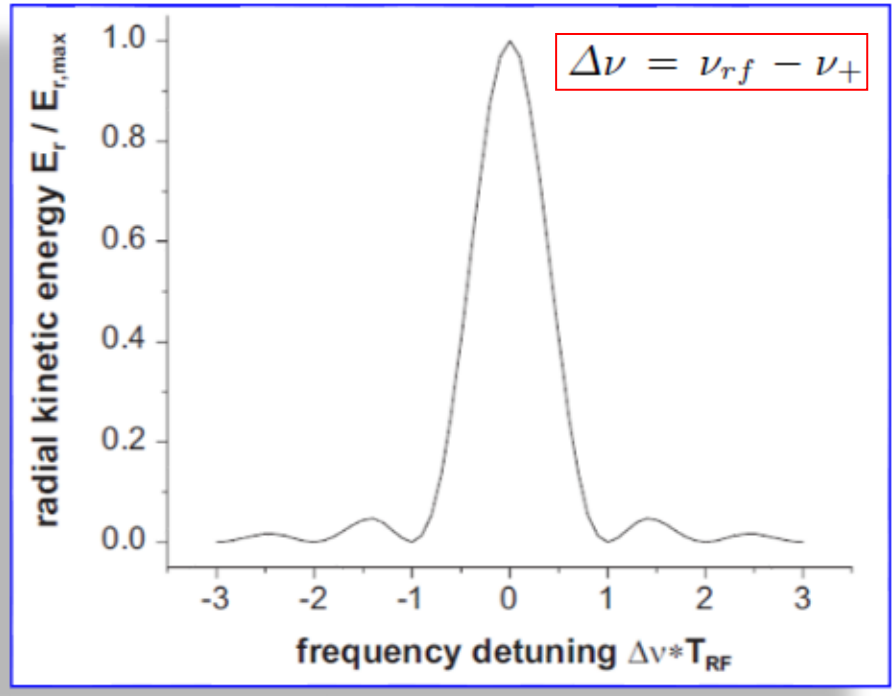
$$\omega_+ + \omega_- = \omega_c = e/m$$

$$\tilde{U}_{\mathrm{q}} = \alpha \frac{U_{\mathrm{q}}}{\rho_0^2} \cos(\omega_{\mathrm{q}} t - \phi_{\mathrm{q}}) \cdot (x^2 - y^2)$$

Example of Energy spectra

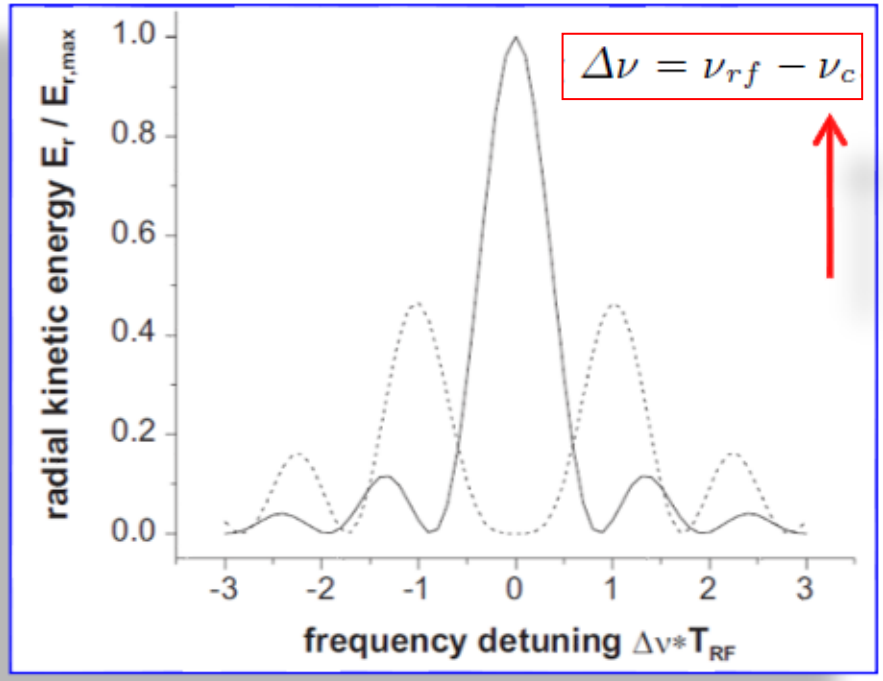
Radial kinetic energy

Dipole Excitation



- *Change of orbit*
- *Ion removal from trap*

Quadrupole Excitation



- *Mass measurements*

Resonance Frequency Measurements In Penning Traps

Short Lived Isotopes investigation by TOF technique

⇒ applicable to a single and/or small number of ions

⇒ ideal for very-short lived isotopes
which can not be stored and observed in traps for long time

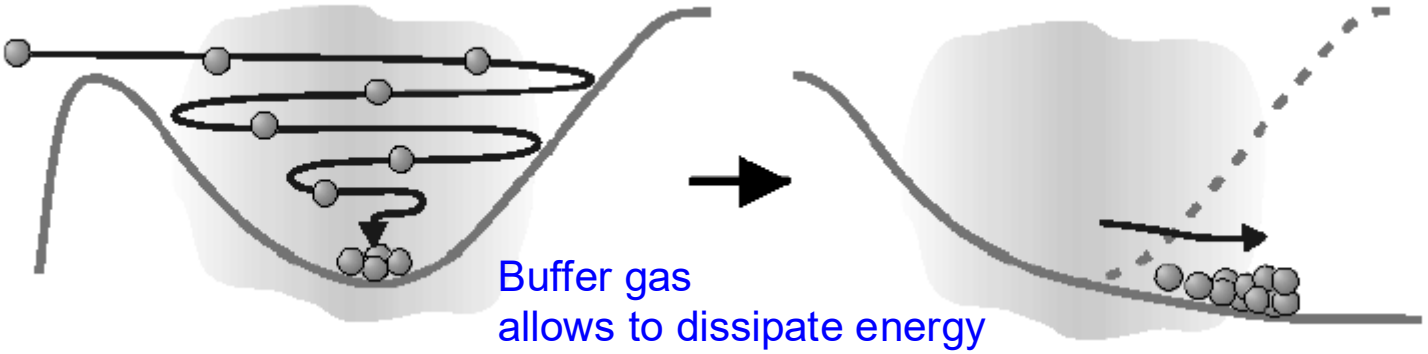
PERFORMANCE:
Mass resolving power R = m/Δm = 10^6
Mass precision δm/m = 10^{-7}.. 10^{-9}
$T_{1/2}$ > 10 ms
Efficiency = 10-50 %

→

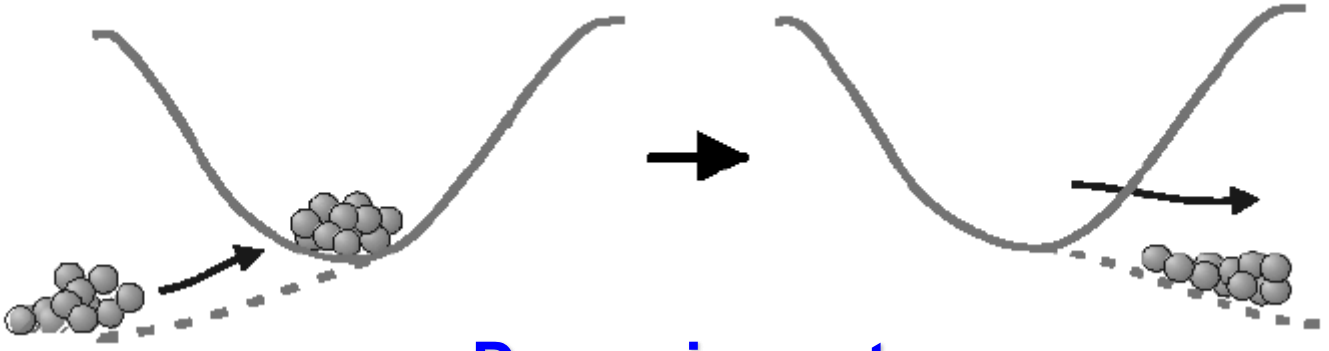
- ***Precise mass measurement***
- ***Isomeric states***
- ***New isotopes***

Injection of Ions In Traps

Continuous capture



Buffer gas
allows to dissipate energy
-> automatic cooling



Short ion bunching

Dynamic capture

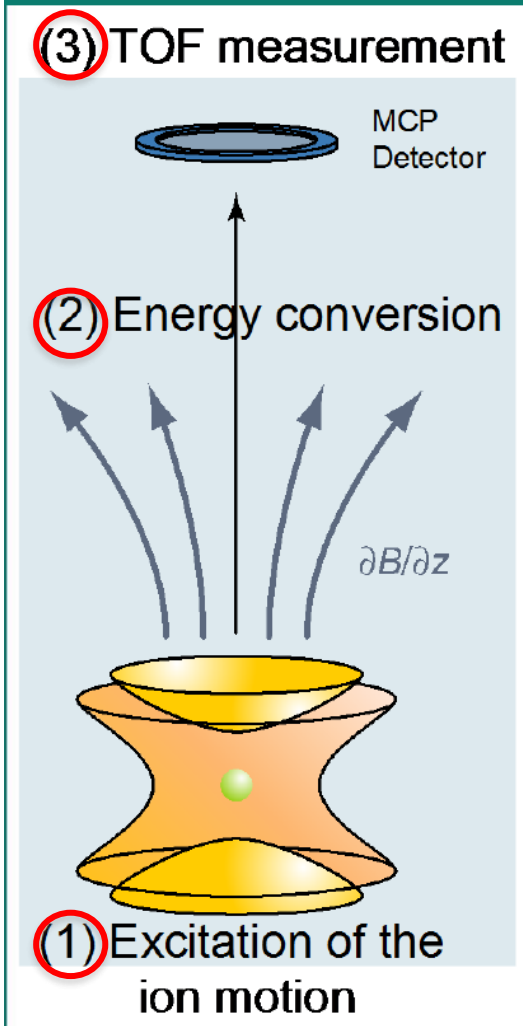
The resolving power in Penning trap mass spectrometry depends on the time of observation T_{obs} of the ion motion.

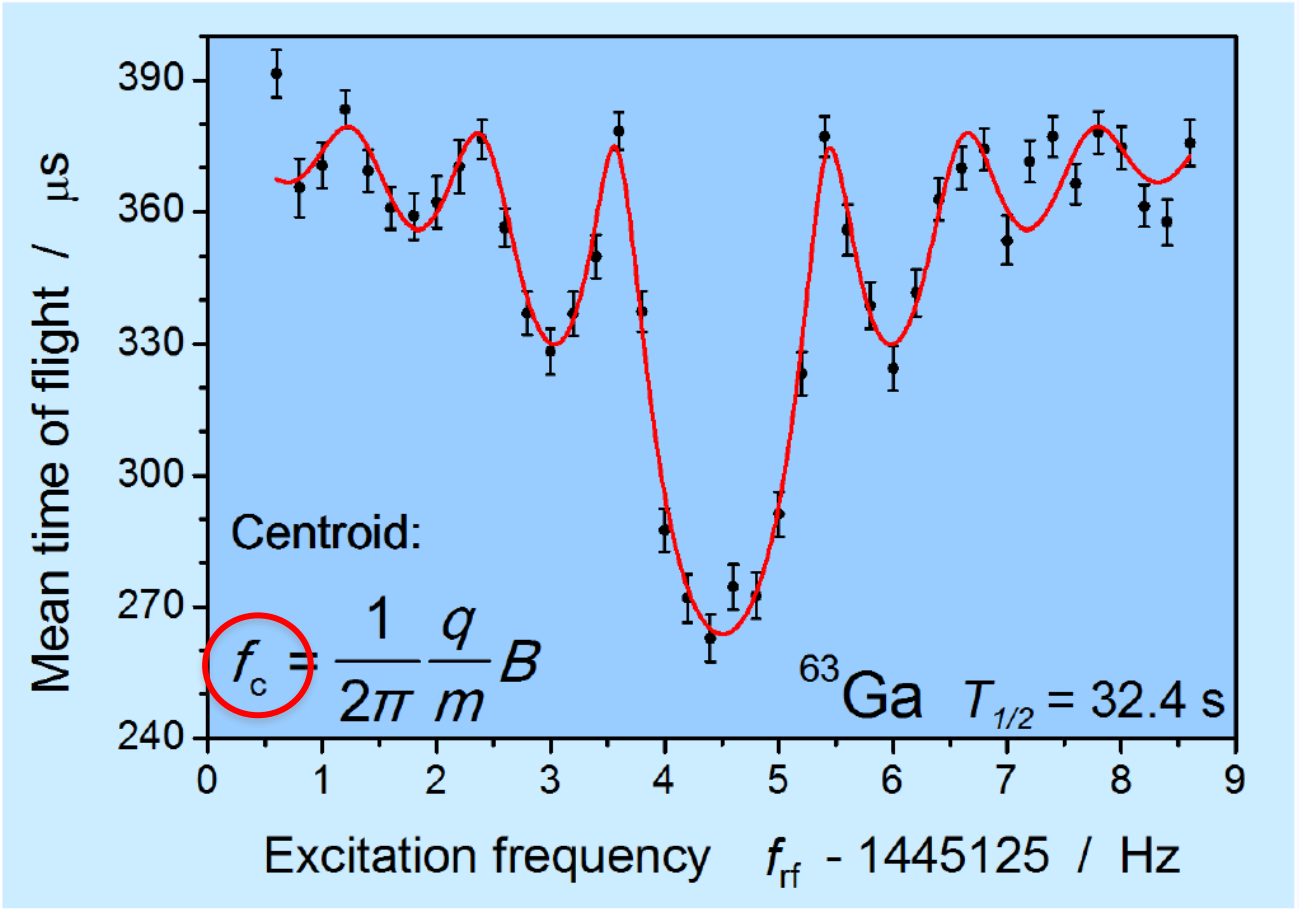
$$R = \frac{m}{\Delta m} = \frac{\nu_c}{\Delta \nu_c} \approx \nu_c \cdot T_{obs}$$

G. Savard *et al.*, Phys. Lett. A 158 (1991) 247.

→ *Less accuracy for very short lived isotopes*

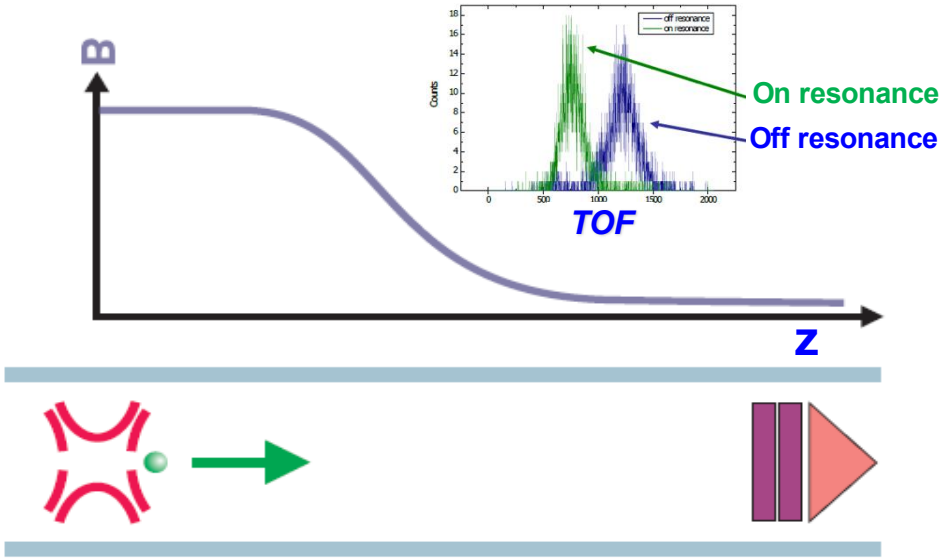
Destructive ion detection





Determine atomic mass from frequency ratio with a well-known "reference mass".

$$\frac{f_{c,ref}}{f_c} = \frac{m - m_e}{m_{ref} - m_e}$$



trap

drift-tube

detector

Release of ions

TOF detection after 1.2 m (region of low B)

Sequence of *ion excitation* In trap

$\mu = E_r(\omega_q)/B$

Energy of cyclotron motion (largest at the cyclotron frequency)

$$F = -\mu(\nabla \cdot B) = -\frac{E_r}{B}\frac{\partial B}{\partial z}\hat{z}$$

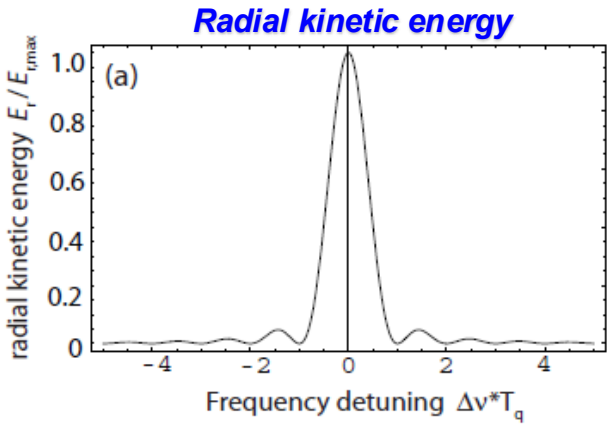
Accelerating force

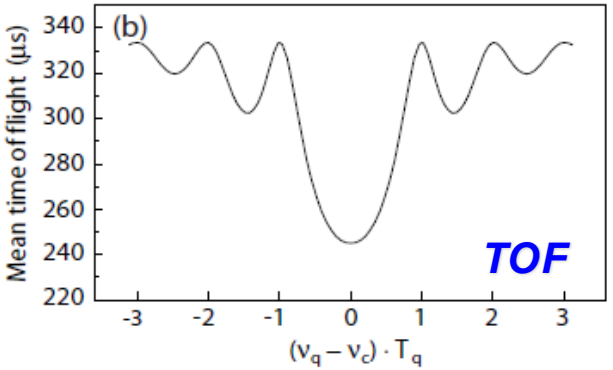
generated by the field gradient

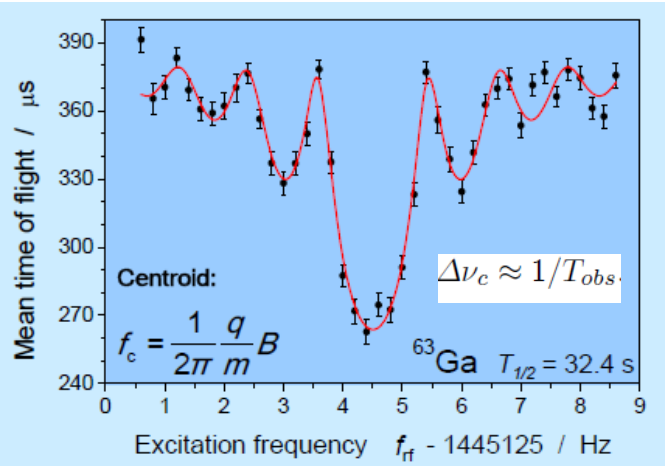
(**largest** for maximum radial energy)

*TOF is reduced due to the presence of the Force (**shortest** for largest gain in radial energy)*

$$T(\omega_{rf}) = \int_{z_0}^{z_1} \left[\frac{m}{E_0 - \mu(\omega_{rf})B(z) - qU(z)}\right]^{\frac{1}{2}} dz$$





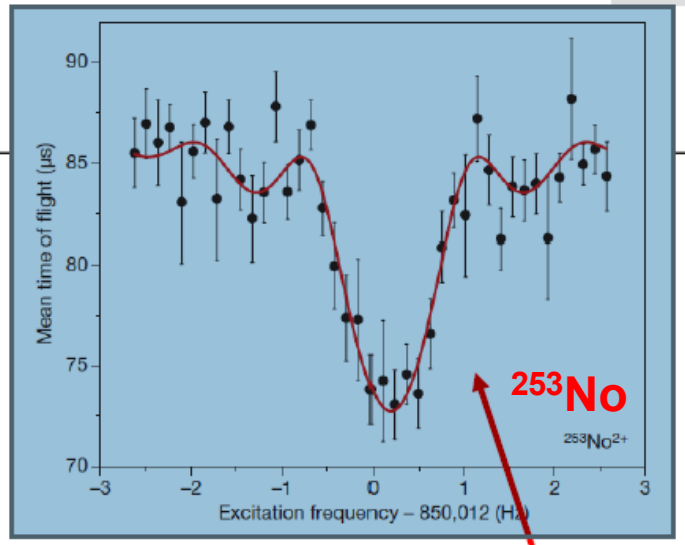


SEVERAL TRIAL Freq. are applied

Weighing superheavy elements

Michael Block et al. SHIPTRAP at GSI

Vol 463|11 February 2010|doi:10.1038/nature08774



Working at the limit: one/few atoms in the trap !!!

In Super-Heavy Region …

PRL 102, 112501 (2009) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2009

Discovery of ^{229}Rn and the Structure of the Heaviest Rn and Ra Isotopes from Penning-Trap Mass Measurements

D. Neidherr,[1] G. Audi,[2] D. Beck,[3] K. Blaum,[4] Ch. Böhm,[1] M. Breitenfeldt,[5] R. B. Cakirli,[6,7] R. F. Casten,[6,8] S. George,[4] F. Herfurth,[3] A. Herlert,[9] A. Kellerbauer,[4] M. Kowalska,[9] D. Lunney,[2] E. Minaya-Ramirez,[2] S. Naimi,[2] E. Noah,[10] L. Penescu,[10] M. Rosenbusch,[5] S. Schwarz,[11] L. Schweikhard,[5] and T. Stora[10]

[1]*Institut für Physik, Johannes Gutenberg-Universität, 55099 Mainz, Germany*
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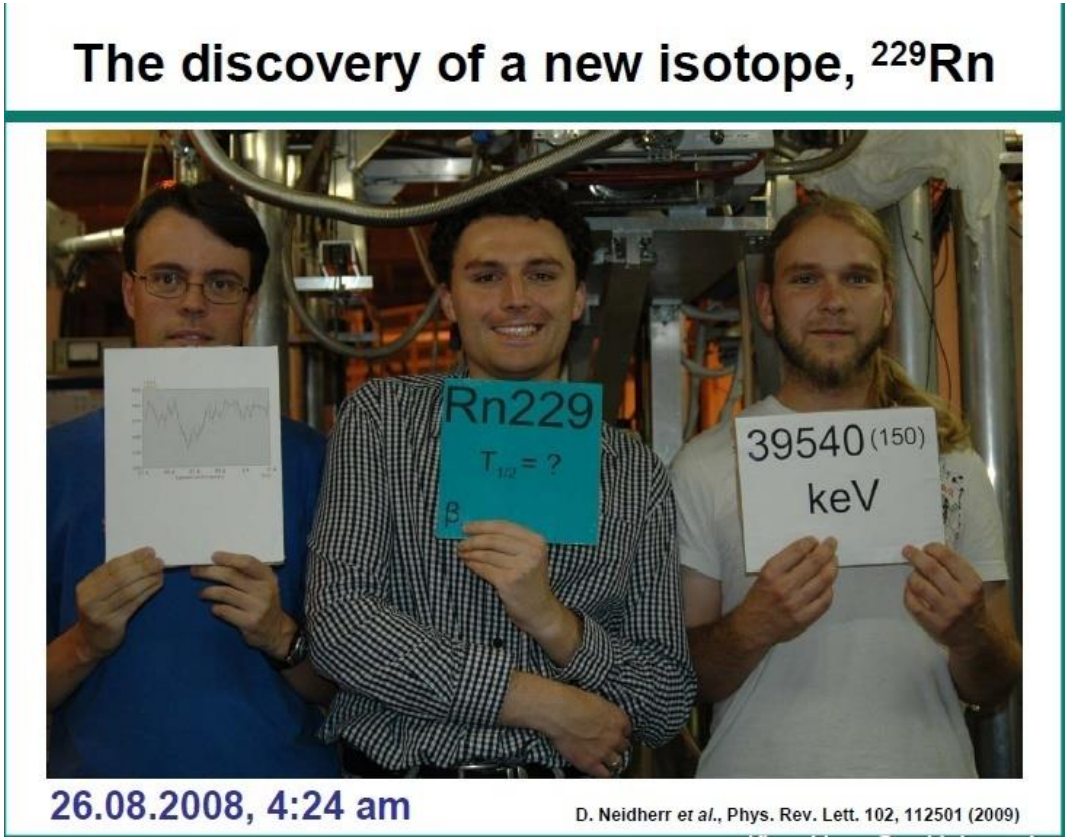
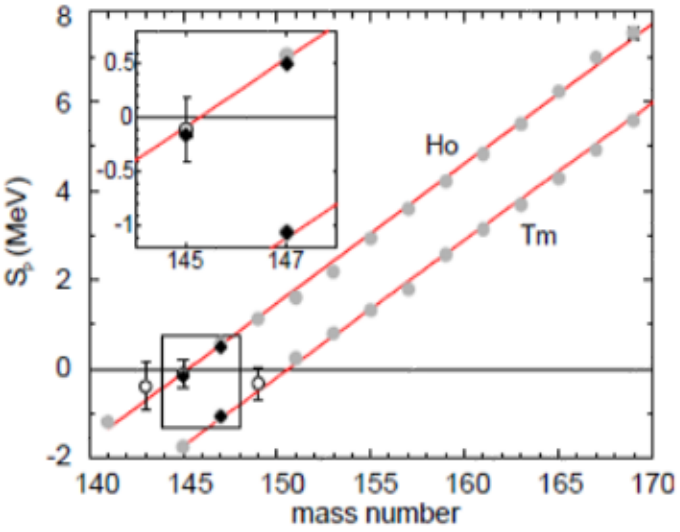
[3]*GSI Helmholtzzentrum für Schwerionenforschung GmbH Darmstadt, 64291 Darmstadt, Germany*

CERN-ISOLTRAP



Nuclear structure studies

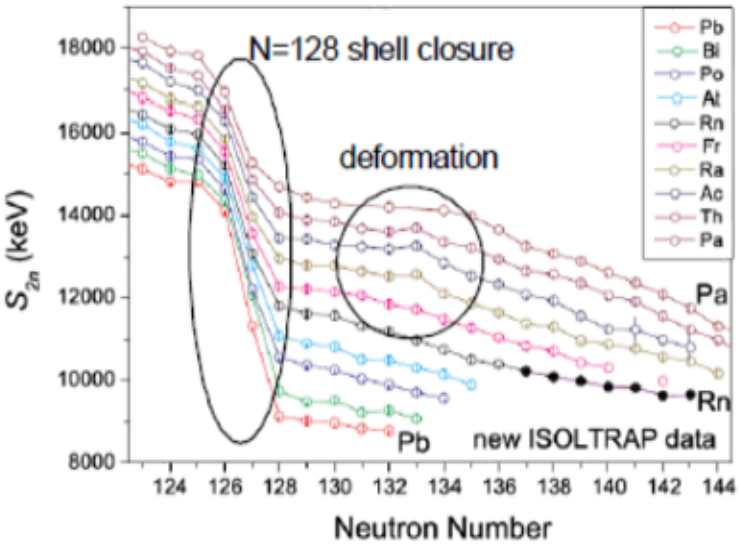
$S_p = B(Z,N) - B(Z\text{-}1,N)$



First direct mass measurement beyond the proton dripline.

C. Rauth *et al.*, Phys. Rev. Lett. 100, 012501 (2008)
M. Dworschak *et al.*, Phys. Rev. Lett. 100, 072501 (2008)

$S_{2n} = B(Z,N) - B(Z,N\text{-}2)$



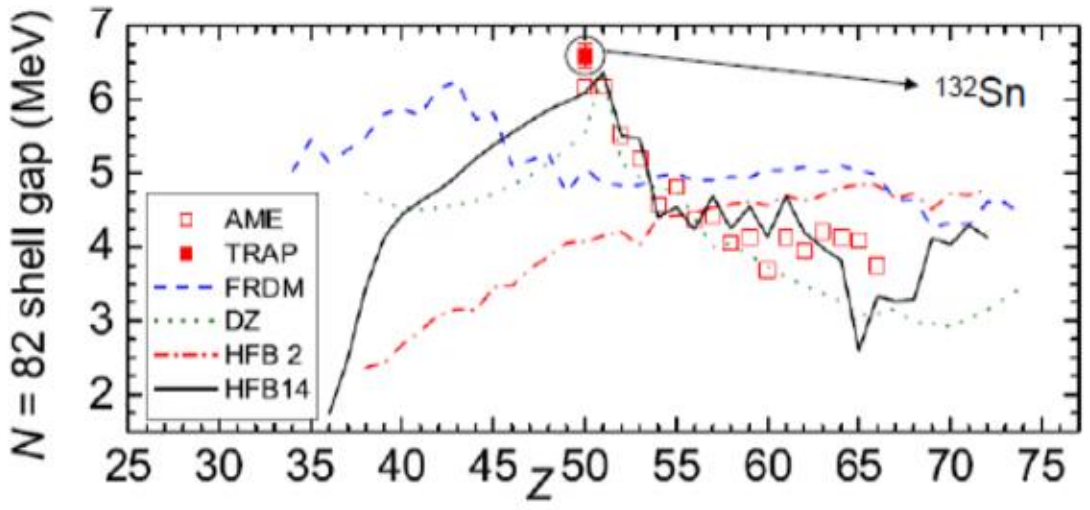
Investigation of shell closures, onset of deformation, collective effects.

B. Cakirli *et al.*, Phys. Rev. Lett. 102, 082501 (2009)
D. Neidherr *et al.*, Phys. Rev. Lett. 102, 112501 (2009)

^{132,134}Sn

Magicity of $N = 82$

neutron shell gap $\Delta_n(N_0, Z) = S_{2n}(N_0, Z) - S_{2n}(N_0 + 2, Z)$



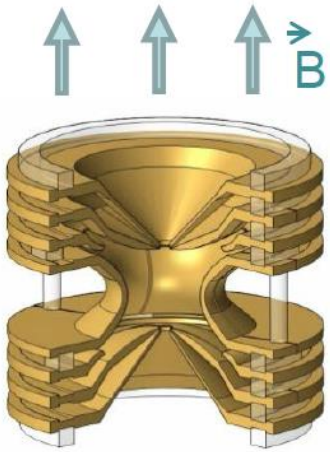
Restoration of $N = 82$ gap

M. Dworschak *et al.*, Phys. Rev. Lett. 100, 072501 (2008)

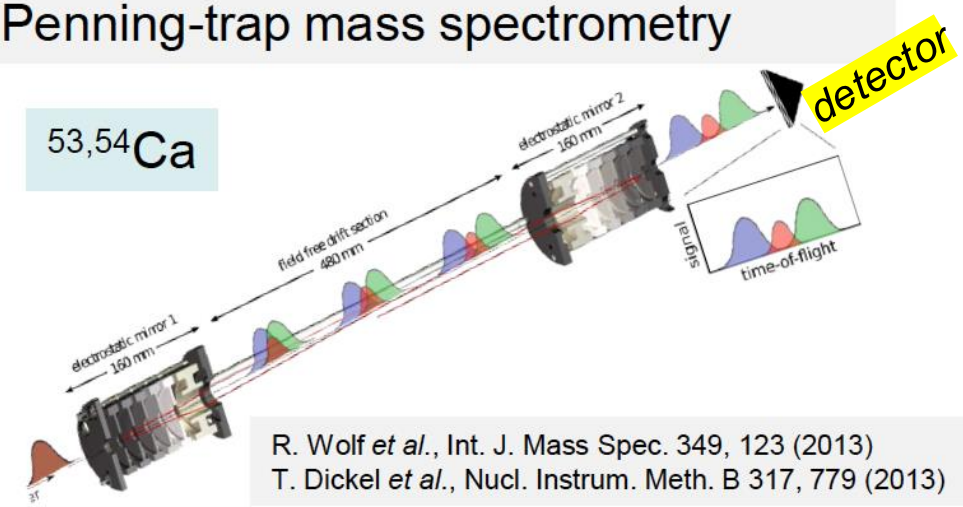
Ca masses pin down nuclear forces

Multi-reflection time-of-flight and Penning-trap mass spectrometry

^{51,52}Ca

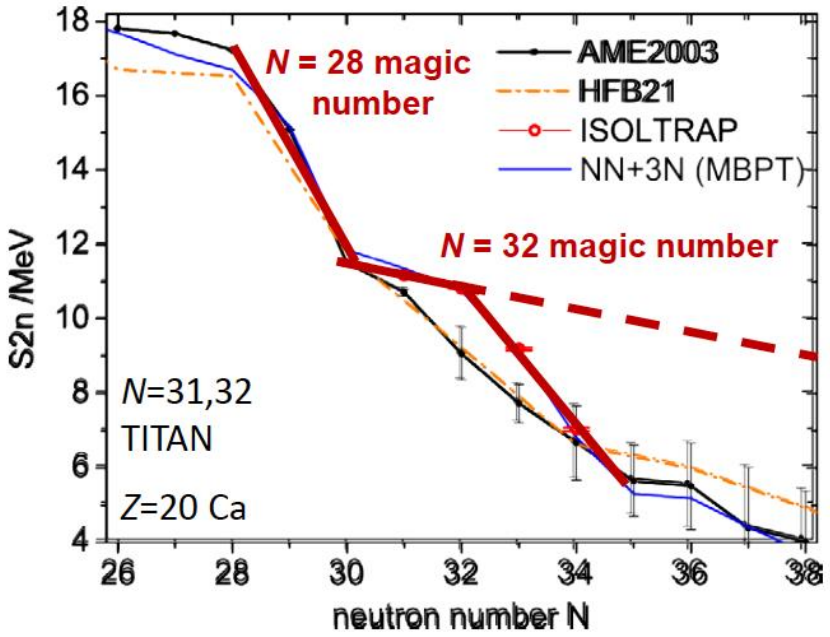


^{53,54}Ca



R. Wolf *et al.*, Int. J. Mass Spec. 349, 123 (2013)
T. Dickel *et al.*, Nucl. Instrum. Meth. B 317, 779 (2013)

- Production rates of ~10 ions/s
- Mass measurements via S_{2n} establish new magic number at $N = 32$
- Correct prediction from 3N-forces (A. Schwenk *et al.*, TUD)

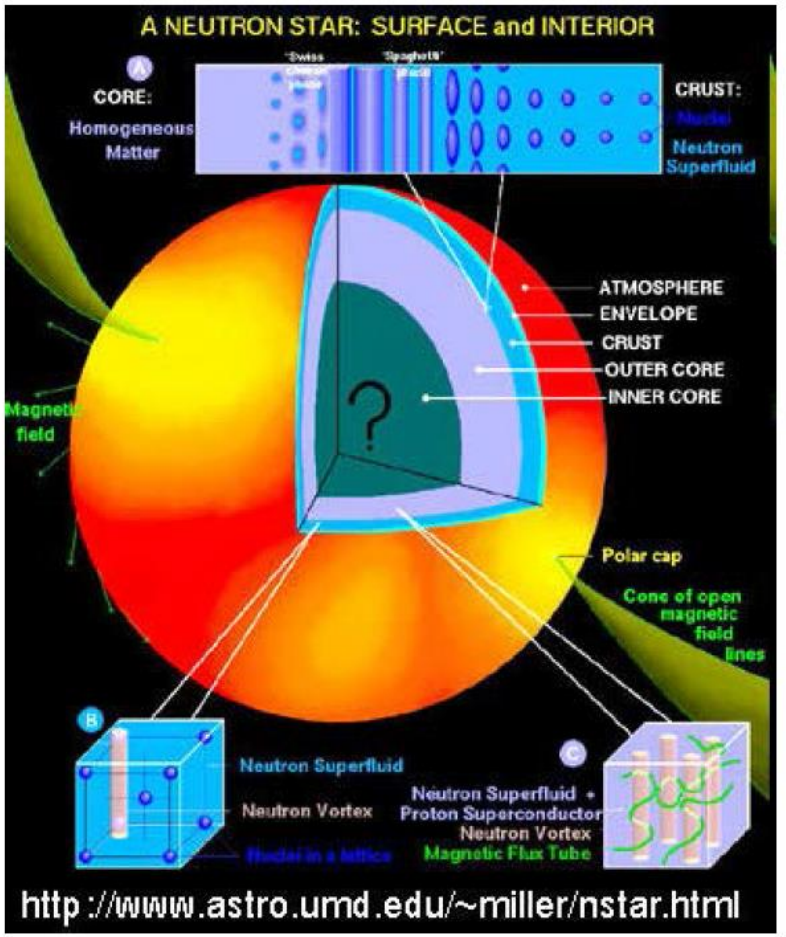


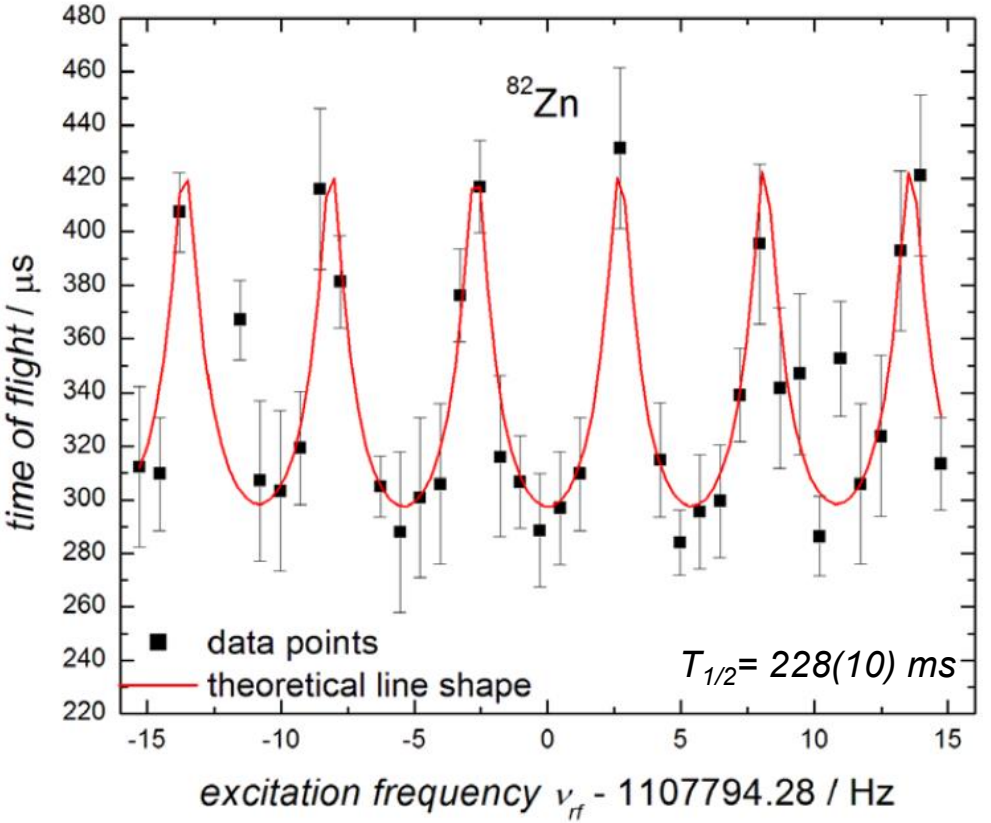
F. Wienholtz *et al.*, Nature 498, 346 (2013)

ISOLTRAP (CERN), TITAN (TRIUMF)

Nuclear astrophysics

Composition of the outer crust of a neutron star





80 ions in 35 minutes!

δm/m = 4•10^{-8}

R. Wolf *et al.*, Phys. Rev. Lett., 110, 041101 (2013)

Plumbing Neutron Stars to New Depths with the Binding Energy of the Exotic Nuclide ^{82}Zn

R. N. Wolf,[1,*] D. Beck,[2] K. Blaum,[3] Ch. Böhm,[3] Ch. Borgmann,[3] M. Breitenfeldt,[4] N. Chamel,[5] S. Goriely,[5] F. Herfurth,[2] M. Kowalska,[6] S. Kreim,[3,6] D. Lunney,[7] V. Manea,[7] E. Minaya Ramirez,[2,8] S. Naimi,[7,9] D. Neidherr,[2,3] M. Rosenbusch,[1] L. Schweikhard,[1] J. Stanja,[10] F. Wienholtz,[1] and K. Zuber[10]

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[6]*CERN, 1211 Geneva 23, Switzerland*
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[8]*Helmholtz-Institut Mainz, 55099 Mainz, Germany*
[9]*RIKEN Nishina Center for Accelerator-based Science, RIKEN, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan*
[10]*Institut für Kern- und Teilchenphysik, Technische Universität Dresden, 01069 Dresden, Germany*

(Received 28 October 2012; published 22 January 2013)

Modeling the composition of neutron-star crusts depends strongly on binding energies of neutron-rich nuclides near the $N = 50$ and $N = 82$ shell closures. Using a recent development of time-of-flight mass spectrometry for on-line purification of radioactive ion beams to access more exotic species, we have determined for the first time the mass of ^{82}Zn with the ISOLTRAP setup at the ISOLDE-CERN facility. With a robust neutron-star model based on nuclear energy-density-functional theory, we solve the general relativistic Tolman-Oppenheimer-Volkoff equations and calculate the neutron-star crust composition based on the new experimental mass. The composition profile is not only altered but now constrained by experimental data deeper into the crust than before.

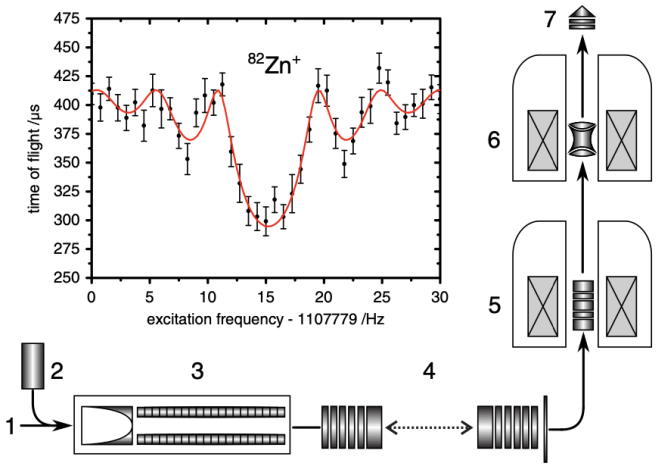


FIG. 3 (color online). Schematic ISOLTRAP overview and time-of-flight resonance of ^{82}Zn$^+$. The main components relevant for this study are the incoming ISOLDE beam (1), reference ion source (2), RFQ cooler and buncher (3), MR-ToF mass separator (4), preparation Penning trap (5), precision Penning trap (6), and ToF detector (7). Top-left inset: Time-of-flight resonance of ^{82}Zn$^+$ (see text).

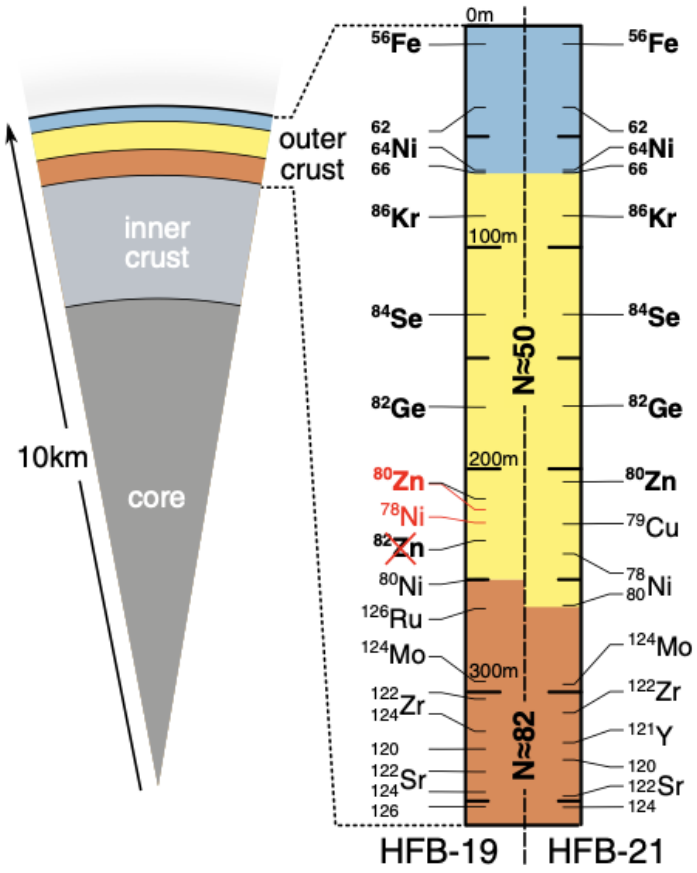
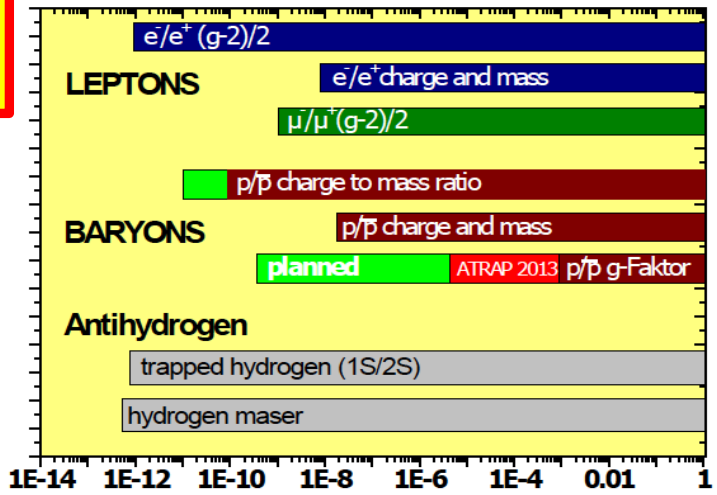


FIG. 1 (color online). The depth profile of a neutron star of 1.4 solar mass and 10 km radius. The scale on the right indicates the nuclide composition in the outer crust as predicted by the HFB-19 and HFB-21 mass models. Experimentally known nuclides are printed in bold. Including the new mass value for ^{82}Zn, the position of ^{80}Zn has changed and ^{78}Ni replaces ^{82}Zn (changes marked red).

Most stringent baryonic CPT test

*The CPT invariance implies that the **fundamental properties** of antiparticles and their matter-conjugates are **identical**, apart from signs.*

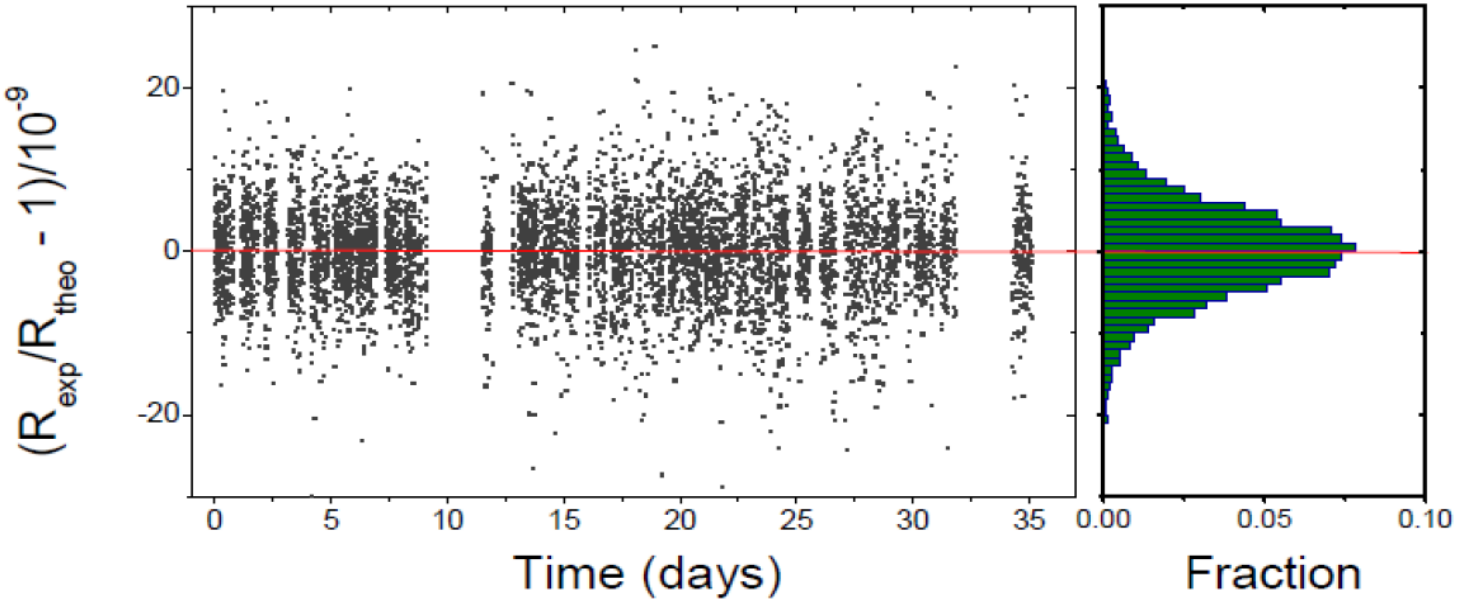
Compare charge-to-mass ratios *R* of p and $\bar{p}$:



$$(q/m)_{\bar{p}} / (q/m)_p = 1.000\ 000\ 000\ 001\ (69)$$

precision 10^{-12}

S. Ulmer *et al.*, Nature 524, 196 (2015)



*Probes the standard model at an energy scale of **8 atto-electronvolts***

Most of stringent test of CPT invariance with baryonic antimatter performed so far.

Storage Rings

A **storage ring** is a type of circular particle accelerator in which a continuous or pulsed particle beam may be kept circulating for a long period of time. Storage of a particular particle depends upon the mass, energy and usually charge of the particle being stored.

Revolution time of an ion, stored in a ring with fixed magnetic rigidity **Bρ** depends on its momentum-to-charge ratio **mv/q**

$$\frac{m \cdot v}{q} = B \cdot r$$

- **Longed lived isotopes (Schottky method)**:
  cooling techniques reduce velocity spread

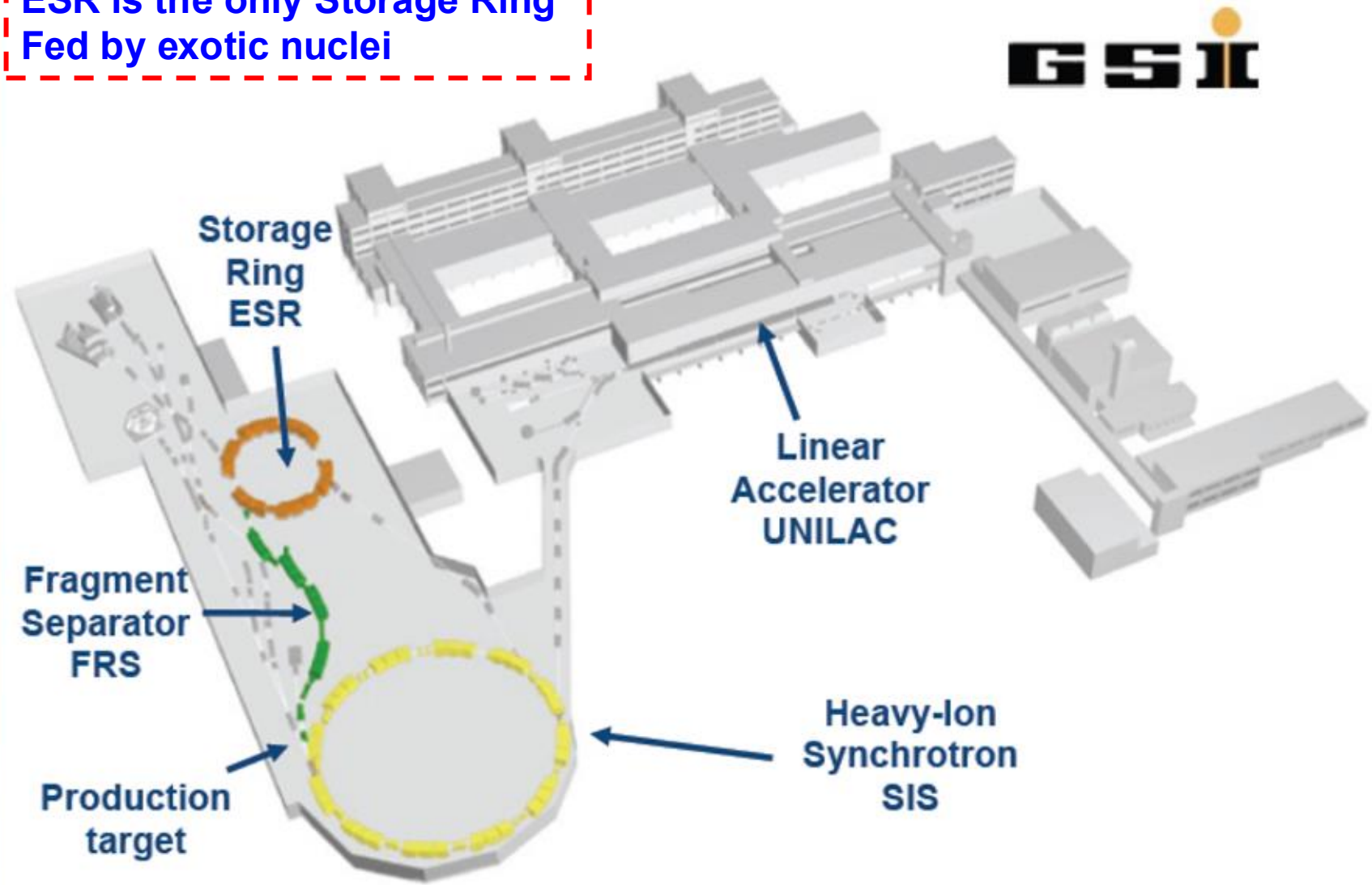
-**Short lived isotopes (Isochronous mass spectrometry)**:
  cooling needs time (few seconds) ! Adjusted ion-optical mode

→ revolution time depends only on **m/q**

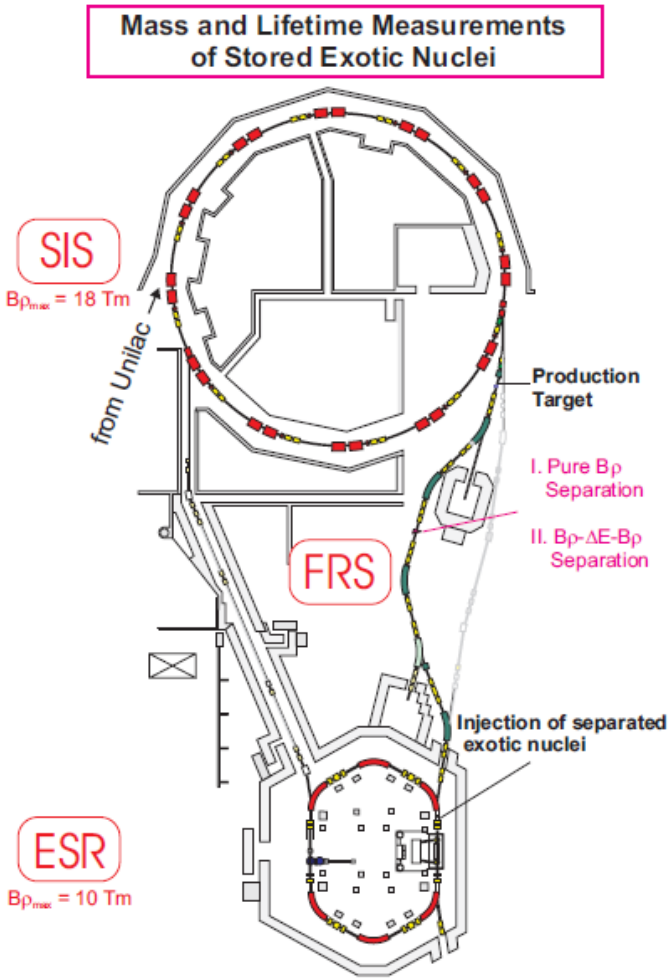
F. Bosch, Euroschool Lectures, Volume I

Secondary beam facility at GSI

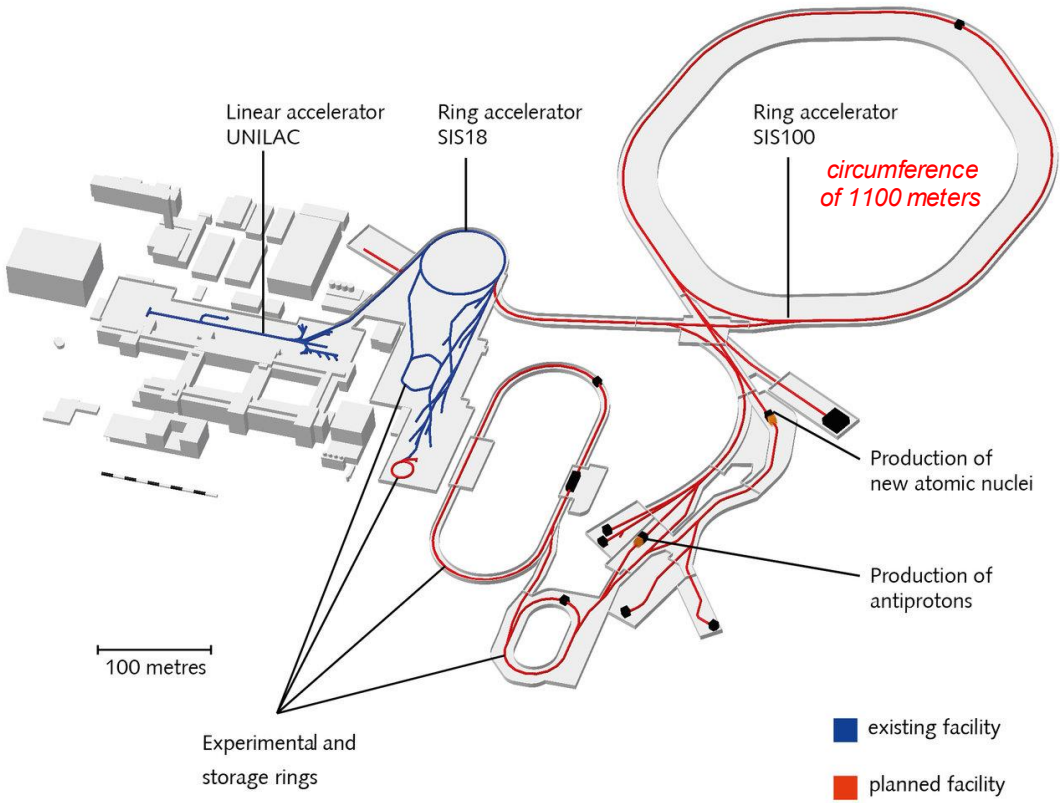
ESR is the only Storage Ring
Fed by exotic nuclei



present
GSI



future
FAIR



a magnet of Super FRS

https://www.gsi.de/en/researchaccelerators/fair

In-Flight production & separation

Primary beams @ 400-1000 MeV/u

Highly-Charged Ions (0, 1, 2 … bound electrons)

In-Flight separation within ~ 150 ns

Cocktail or mono-isotopic beams

Transmission to the ESR of about 1%

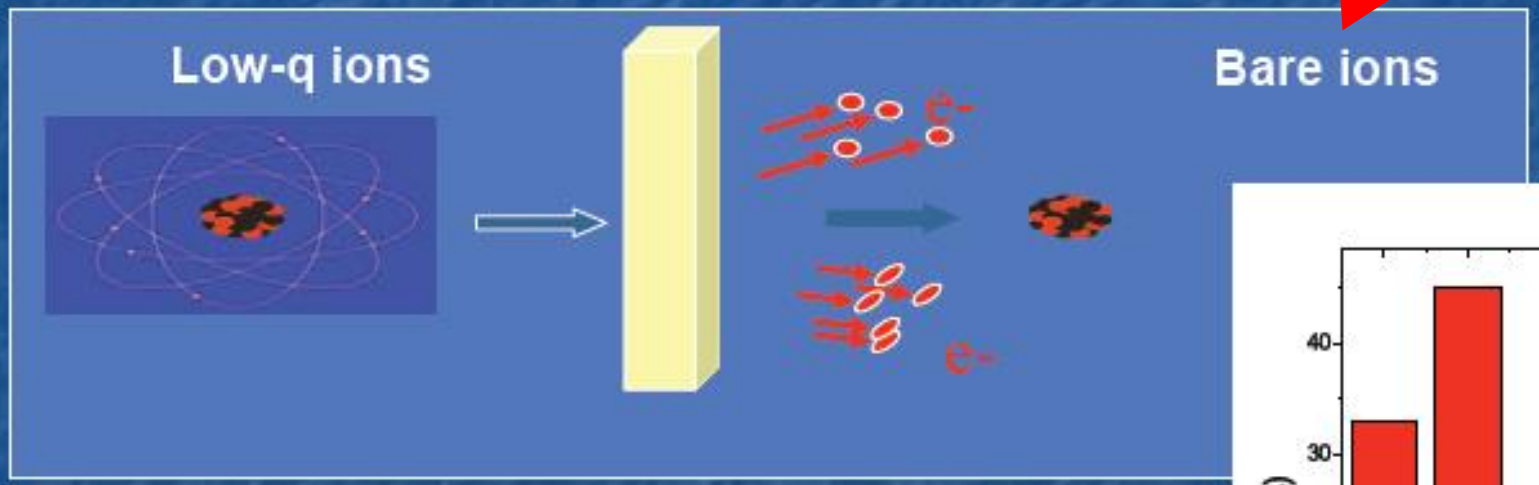
Why relativistic velocities ?

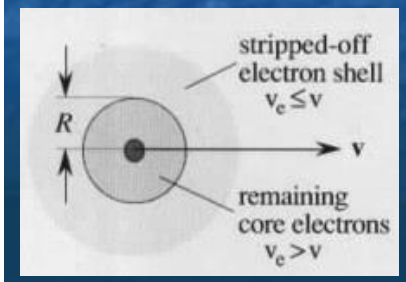
Bohr criterion: Largest ionization cross section at $v/c \approx v_K/c = \alpha Z$

Uranium

$v_K/c \approx 0.67$

$E_{KIN} \approx 330$ MeV/u

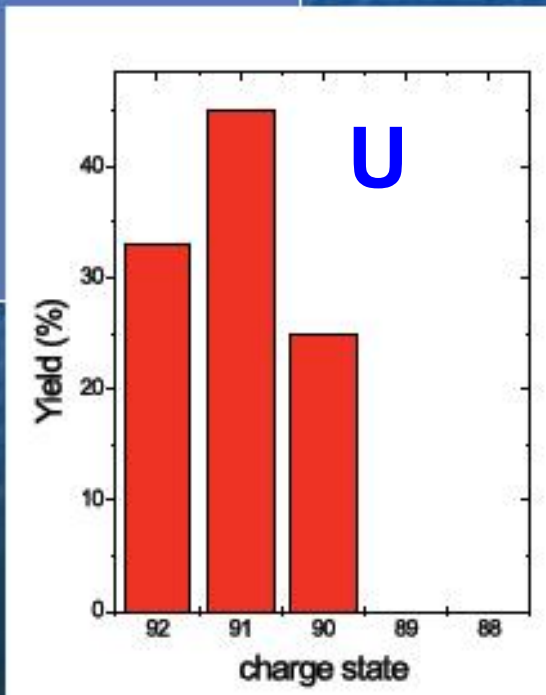




Bohr's stripping criterion

ALL electrons with orbital velocities v_e smaller than the velocity of the projectile-ion, v, will be stripped-off in the target.

According to the Virial theorem, they correspond to the electrons outside a critical radius *R*



Magnetic rigidity

$$\frac{m \cdot v^2}{r} = q \cdot (\vec{v} \times \vec{B}) \rightarrow \frac{m \cdot v}{q} = B \cdot r$$

r the bending radius of the magnets, also called ρ
q the charge of the ions
v the ion velocity
m the mass of the ions
B the magnetic field

Storage Ring	magnetic rigidity	Circumference
ESR	10 Tm	108 m
TSR	1.5 Tm	55 m
CRYRING	1.4 Tm	52 m
ASTRID	2 Tm	40 m

ESR : E_{max} = 420 MeV/u, 10 Tm; e^-, stochastic cooling

ESR: B. Franzke, NIM B 24/25 (1987) 18

Stochastic cooling: F. Nolden et al., NIM B 532 (2004) 329
Electron cooling: M. Steck et al., NIM B 532 (2004) 357

Storage ring vocabulary

To store ions, a set of magnetic elements such as dipoles, quadrupoles ... is needed which form the **lattice of the ring**

Maximum emittance

Storage rings have a limited acceptance which can be expressed in terms of the beam **emittance ε** and **momentum spread Δp**

$\varepsilon = n\,\alpha\,\Delta p$; ($\alpha$ angular divergence)

Liouville's law states that **emittance is strictly conserved** under the action of conservative forces. 'Tricks' to overcome this law are e.g. the various methods of **beam cooling**

The ions move on periodic orbits around the ideal trajectory 's' ("Sollbahn"), performing **betatron oscillations**. The ratio of the betatron wavelength to the ring circumference is the **Tune Q** It should 'nt be a simple algebraic number such as 1, 2, ... or ½, ¾ in order to avoid beam losses.

(resonance oscillations→ beam loss)

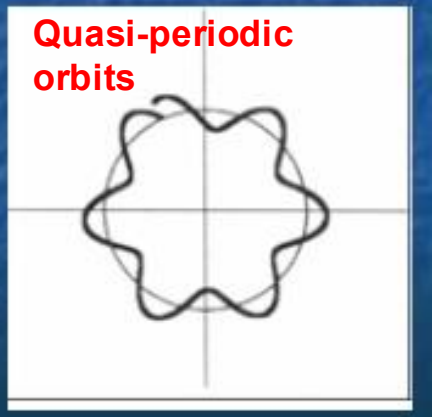
lattice ?

emittance ?

tune ?

cooling ?

space charge ?



Lost planet or lost beam – all the same physics

Q-resonance destroyed Ceres

Orbit of a former planet Ceres was periodically influenced by Jupiter

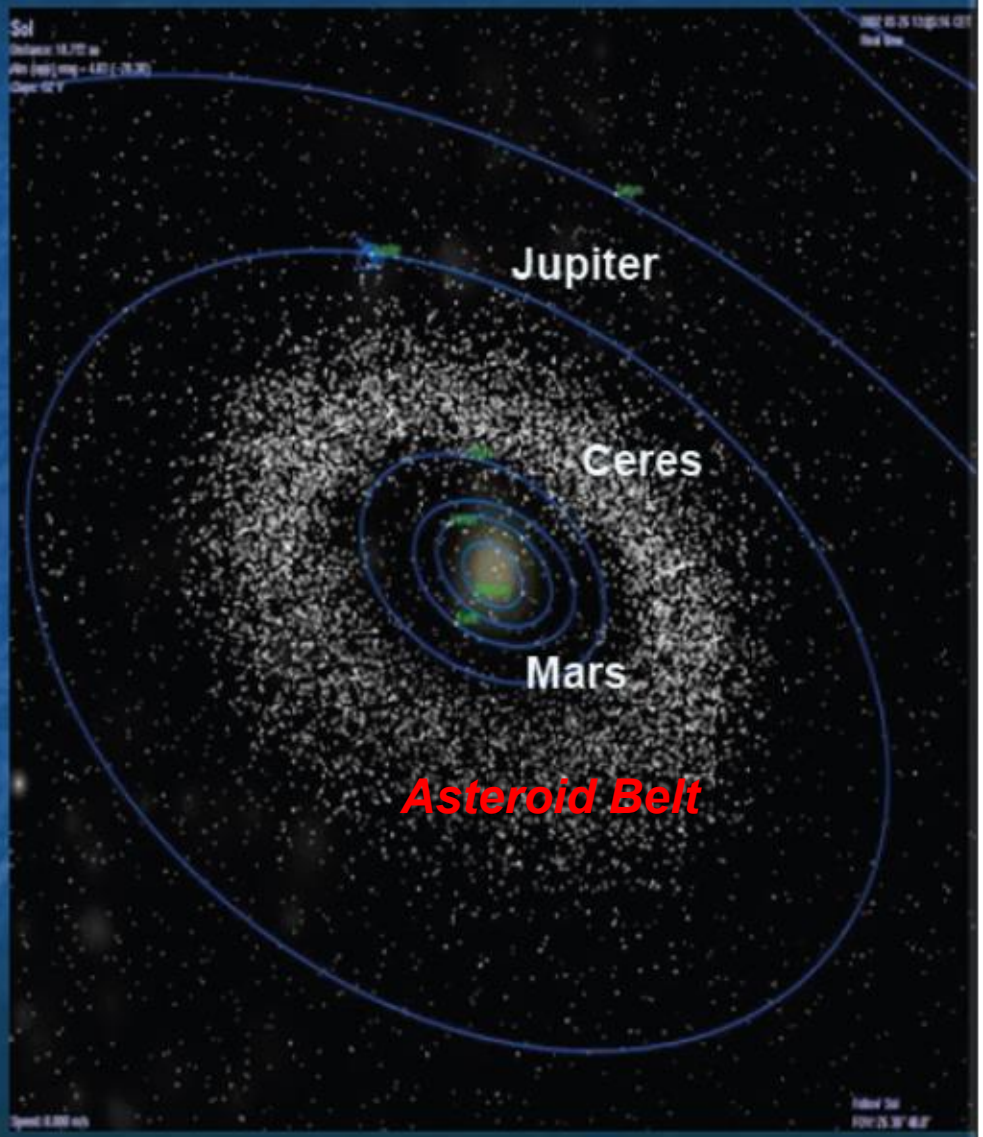
Orbits are solutions of Hill's equation (3 body force)

3.Kepler law: T^2/a^3 = const.

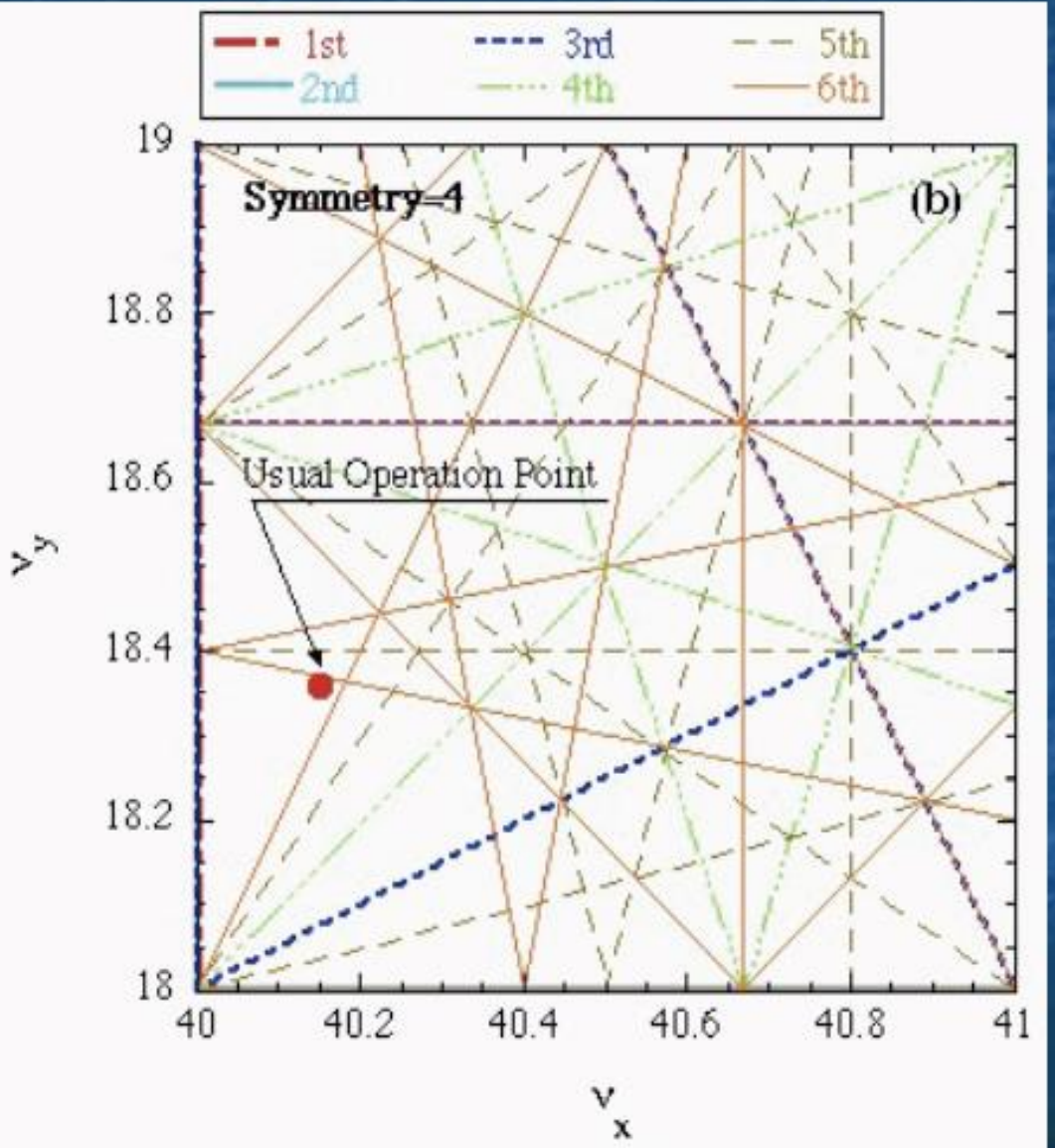
1 AU = $1.5 \cdot 10^8$ km, T_E = 1 y

a_M = 1.52, a_J = 5.20, R_{MJ} = 0.29

a_C = 2.77, " R_{CJ} = 0.53



Tune diagram and working point



Tuning does not demand a study of tunology, but rather the right feeling and the experience of decades

To save the beam, avoid any crossing of lines

How to do so, if the ions get acc(de)celerated ??

The experimental storage ring ESR

Particle detectors

Re-injection to SIS

Schottky pick-ups

Gas jet

TOF detector

L = 108 m = ½ L_{SIS}

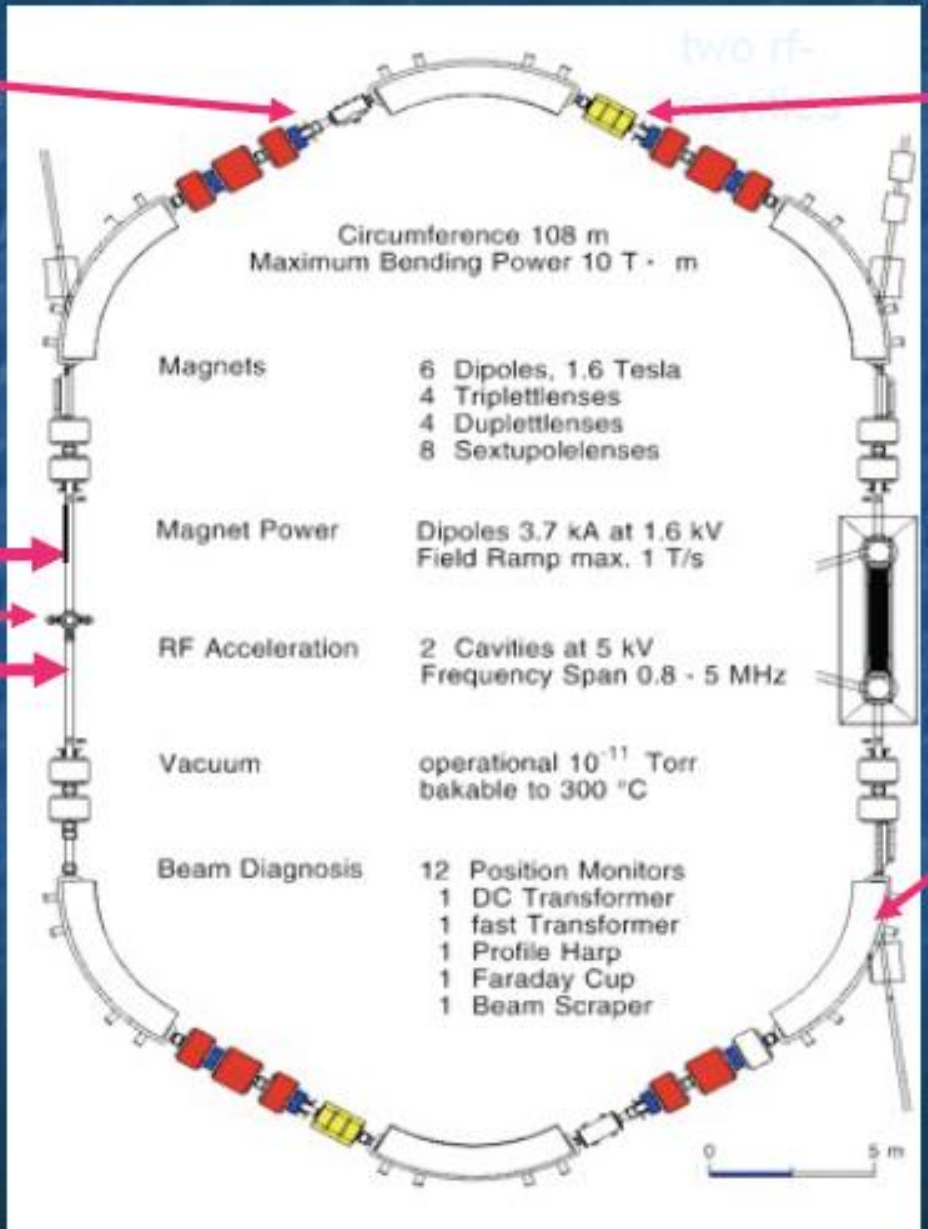
dB/ds ≤ 1 T/m

p = 2· 10^{-11} mbar

E = 3...420 MeV/u

β = 0.08...0.73

$Q_{h,v}$ ≈ 2.65



Two 5 kV rf-cavities

Fast Injection

e^- cooler

I = 10...500 mA

Six 60^0 dipoles

Bρ ≤ 10 T· m

Extraction

Cooling techniques applied at ion rings

emittance $\varepsilon = n \alpha \Delta p$

One may overcome Liouville theorem by applying external forces, with the aid of, e.g. :

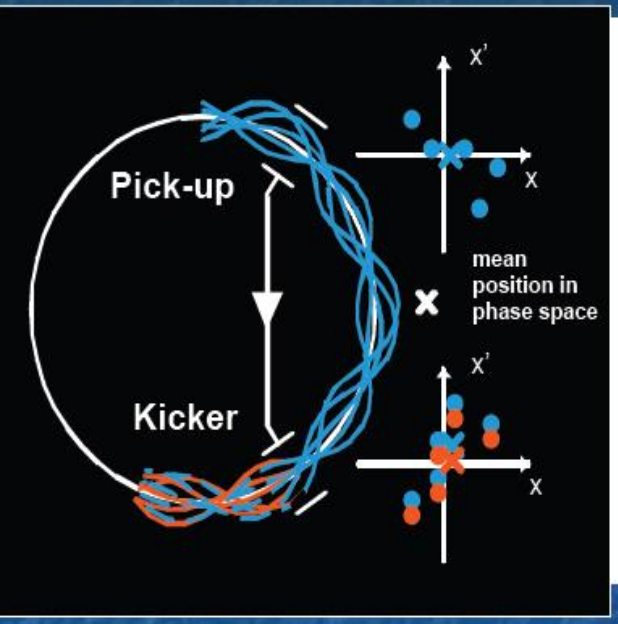
- **Lasers = transfer of momentum**

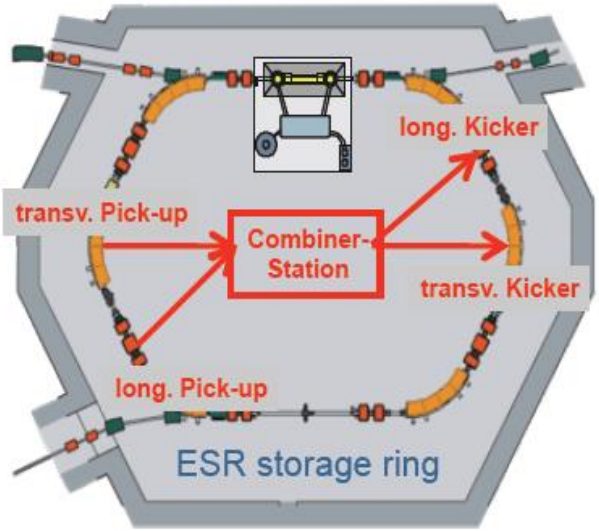
  direct momentum transfer by absorption of resonant photons and isotropic re-emission

- **Electrons = mixing of temperatures**

- **Stochastic = self-correction**

Stochastic cooling (self-correction of trajectory)



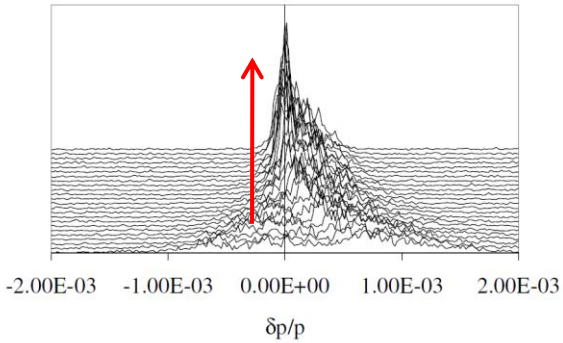


Stochastic cooling is in particular efficient for hot ion beams

Cooling time τ scales as N_{ion} / bandwith

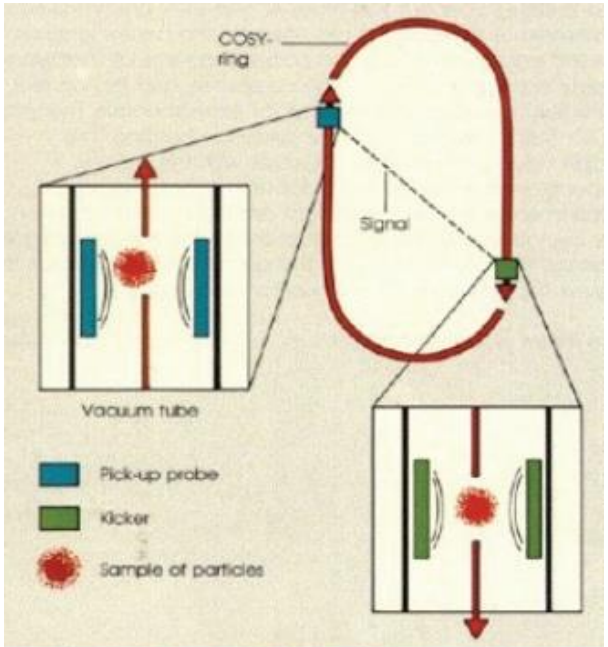
Since **stochastic cooling** is most effective for 'hot' beams ($\Delta p/p \geq 10^{-3}$... 10^{-2}), *it may serve as an ideal tool for pre-cooling, followed by electron cooling* which is much less suited for this regime of large momentum spreads.

Often used as pre-cooling, ***before*** *electron-cooling*



Time development of momentum spread

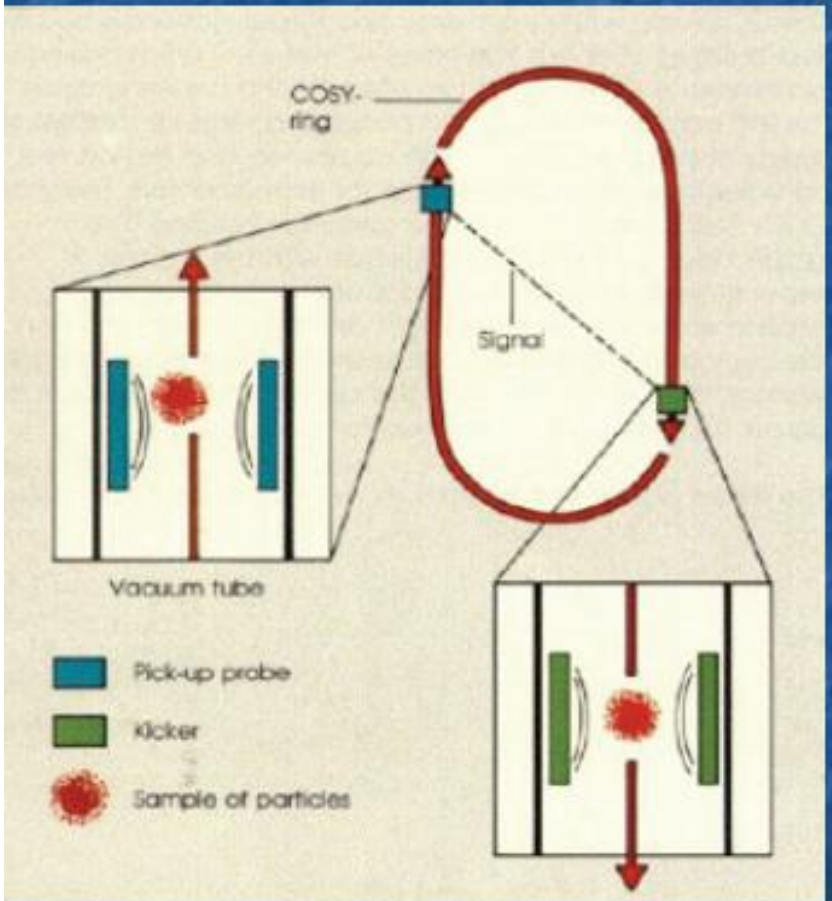
10^5 'hot' ^{40}Ar recorded every 100 ms



The Nobel Prize in Physics 1984
Simon van der Meer 1925*, CERN

Stochastic cooling (self-correction of trajectory)

Self correction of ion trajectory



Using a **pick-up probe**, the position of the ion beam is measured at a fixed position via the induced signal. A deviation of the beam from the ideal orbit can be corrected by **amplification of this signal.**

The amplified signal is now used as a **correction signal** which acts on the beam at a second position (zero crossing of the betatron function) via a „**kicker**".

This method was invented for the cooling of hot p(bar) by van der Meer. He showed that after a cooling time of $\tau \propto$ **N/C** (N: particle number, C = Bandwidth of the amplifier) a momentum width of the beam of about $\Delta p/p \approx 10^{-3}$ can be achieved by stochastic cooling

Detection of the **W boson** from p ↔ p(bar)

The Nobel Prize in Physics 1984
Simon van der Meer 1925*, CERN

Stochastic cooling (self-correction of trajectory)

The Nobel Prize in Physics 1984

"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

Carlo Rubbia
1/2 of the prize
Italy
CERN
Geneva, Switzerland
b. 1934

Simon van der Meer
1/2 of the prize
the Netherlands
CERN
Geneva, Switzerland
b. 1925

The Nobel Prize in Physics 1984
Press Release
Presentation Speech

Carlo Rubbia
Autobiography
Nobel Lecture
Banquet Speech

Simon van der Meer
Autobiography
Nobel Lecture

1983 1985

The 1984 Prize in:
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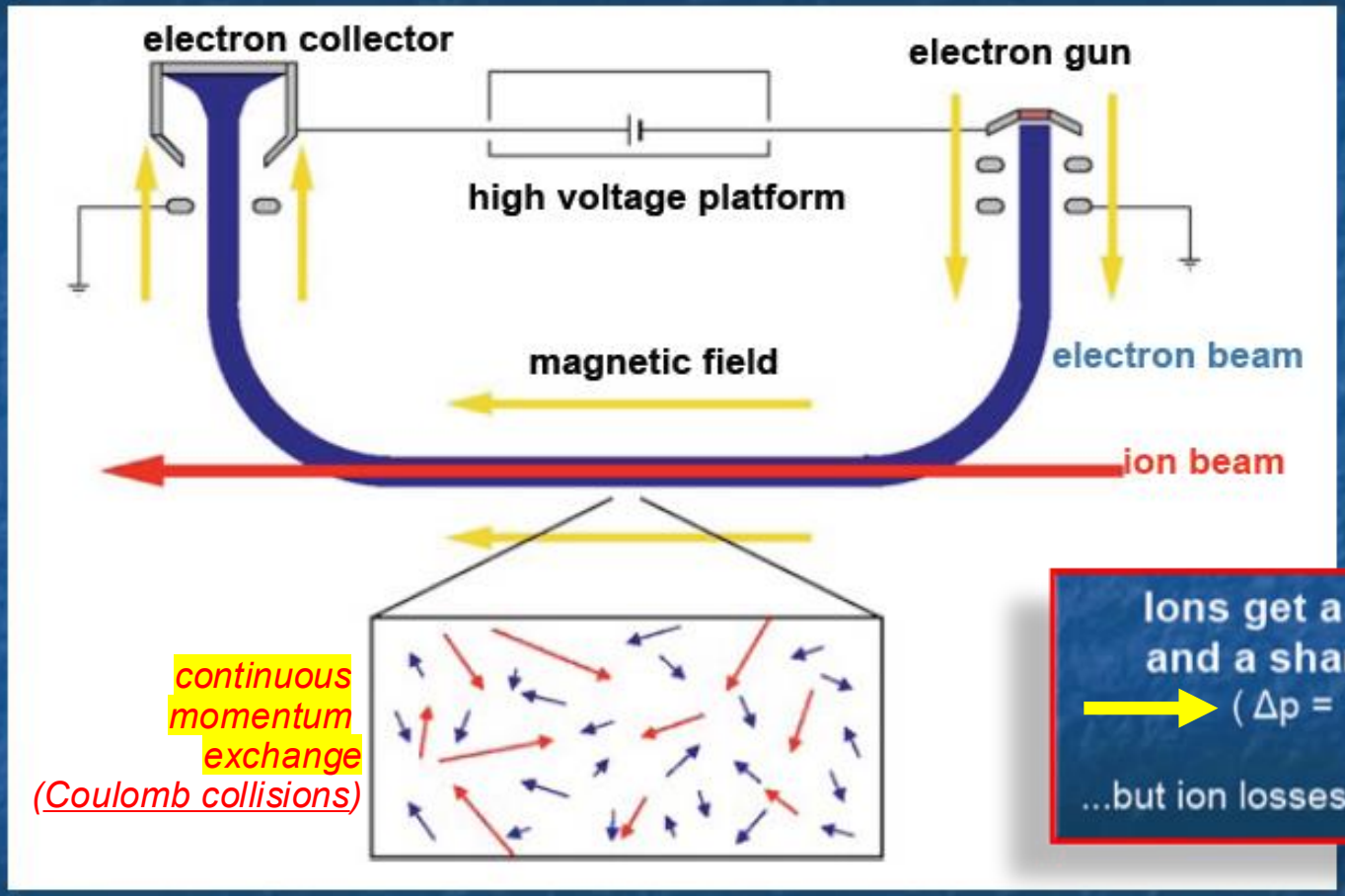
http://www.nobel.se/physics/laureates/1984/

Electron cooling (cold bath for ions)

cold collinear electrons (kT = 100 meV)



Ions get a sharp velocity and a sharp momentum
($\Delta p = 10^{-5} \ldots 10^{-7}$)

...but ion losses by electron capture

Same mean velocity of e^- and ions;
strong magnetic guiding field; **substitution** of e^- after a cycle

250 keV electron cooler at the ESR

Electron cooling (cold bath for ions)

The 250 keV electron cooler at the ESR

G. Budker, Novosibirsk 1965

cold, collinear electrons, contained by a strong magnetic field (0.1 T) interact with the ions via Coulomb collisions

'old' electrons exchanged at each turn

→ continuous momentum exchange

→ ions get $(kT)_l$ << 1 meV as well as $(kT)_t \approx 100$ meV of the electrons

Ions get a sharp velocity and a sharp momentum
($\Delta p = 10^{-5} \ldots 10^{-7}$)

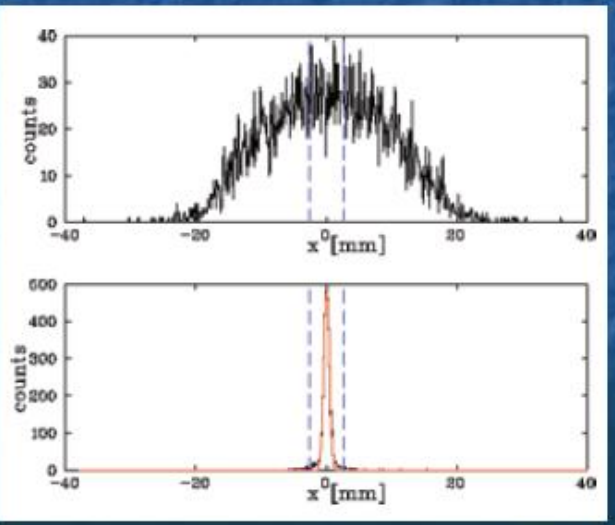
...but ion losses by electron capture

Electron cooling (Coulomb cooling)

Cooling by electrons can be treated in analogy to **energy loss** of ions in matter

$$\frac{dE}{dx} \propto \tilde{n}\frac{Z^2}{m_e v^2}$$

What acts against cooling ?



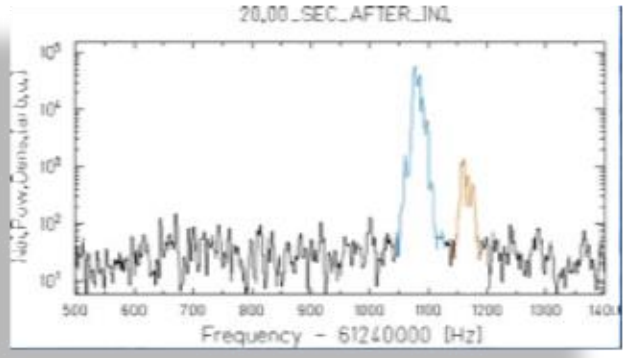
a) ***Intra beam scattering***
Ion-ion scattering

b) ***Collisions*** (scattering) of ions with the ***residual gas atoms***

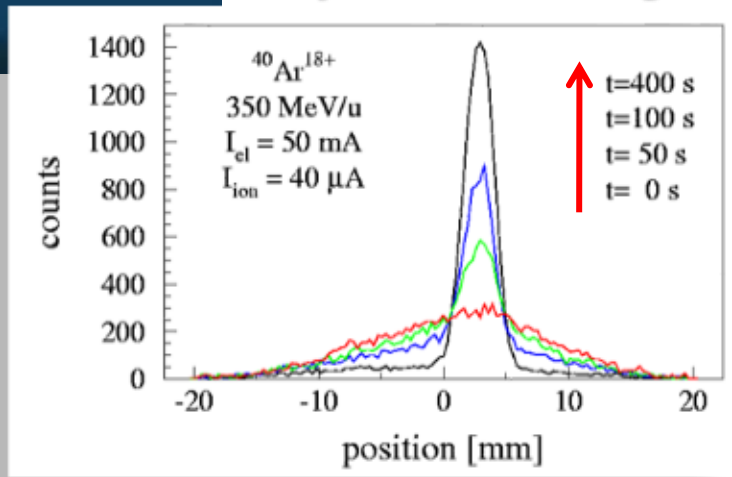
c) ***Charge exchange losses*** of the ions in collisions with the residual gas atoms or cooler electrons

d) ***Space charge limit***

All processes (a - d) scale with Z^2 of the ions



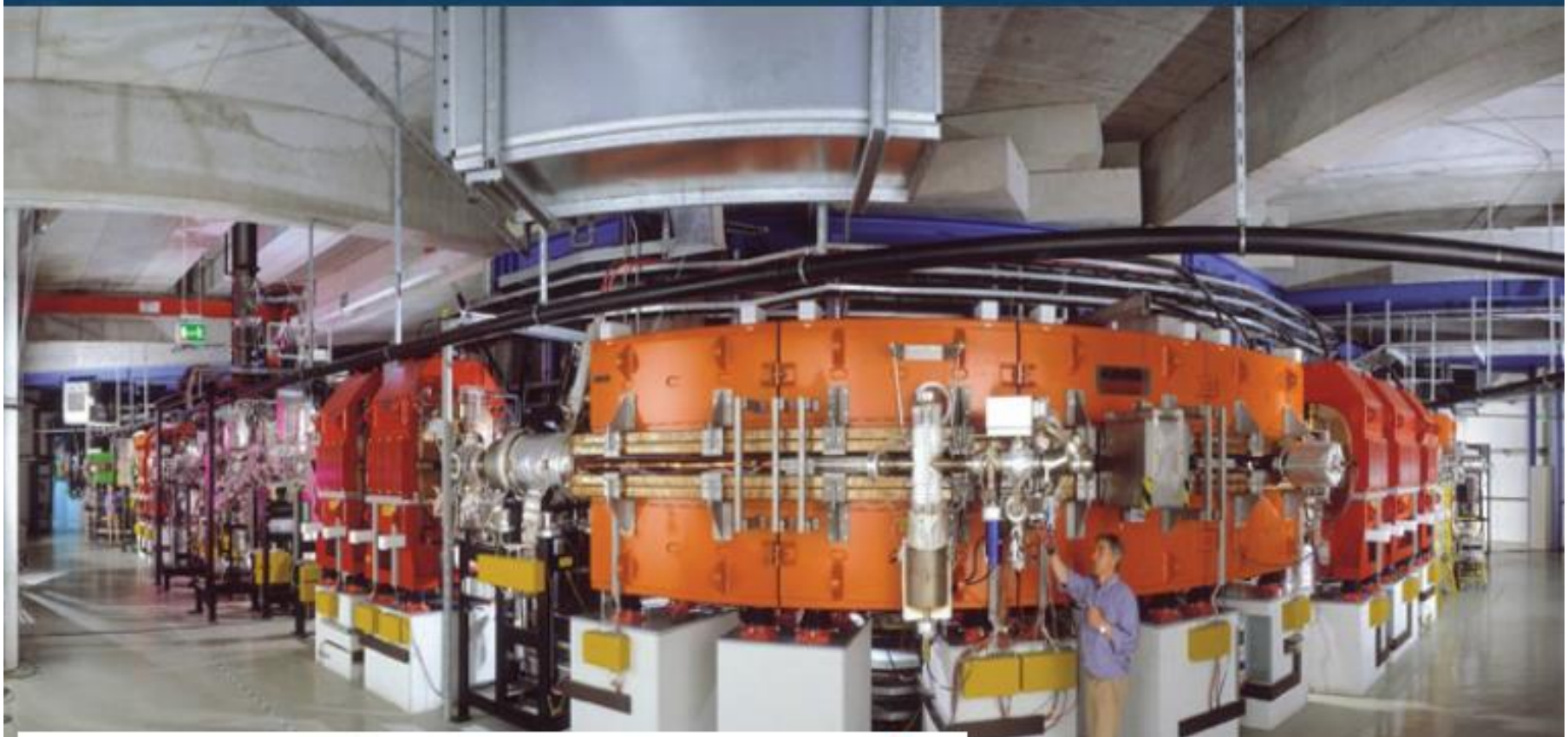
time development of electron cooling



Literature to "Basics of ion storage-cooler rings"

1. **Hill's equation**: W. Magnus, St. Winkler, Hill's equation, Dover ed. 2004
2. **ESR**: B. Franzke: COOL05 (Galena, Il, USA), **AIP** Conf. Proc. **821**
3. **FRS**: H. Geissel et al., PRL **68** (1992) 3412
4. **Electron Cooling**: G. I. Budker et al., Part. Accel. **7** (1976) 197
   H. Poth, Electron Cooling, Amsterdam, North Holland 1990
5. **Stochastic Cooling**: S. van der Meer, Nobel lect. 1984:
   Nobel lectures- physics 1981-1990, World Scient., Singapore 1993
6. **Implementation ESR**: F. Nolden: COOL05, **AIP** Conf. Proceedings **821**
7. **Phase transition**: M. Steck et al., PRL **77** (1996) 3803
8. **Laser cooling**: S.V. Andreev et al., JETP Lett. **34** (1981) 442
   J. Opt. Soc. Am. **B6** (1989) 2020, special issue
9. **Laser cooling of ions:** S. Schröder et al., PRL **64** (1990) 2901
10. **Beam crystals**: T. Schätz, U. Schramm, D. Habs, Nature **412** (2001) 717
11. **Combined cooling**: T. Ohtsubo et al.,PRL **95** (2005) 052501

ESR : E_{max} = 420 MeV/u, 10 Tm; e^-, stochastic cooling



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

γ_t = transition energy

ESR: B. Franzke, NIM B 24/25 (1987) 18

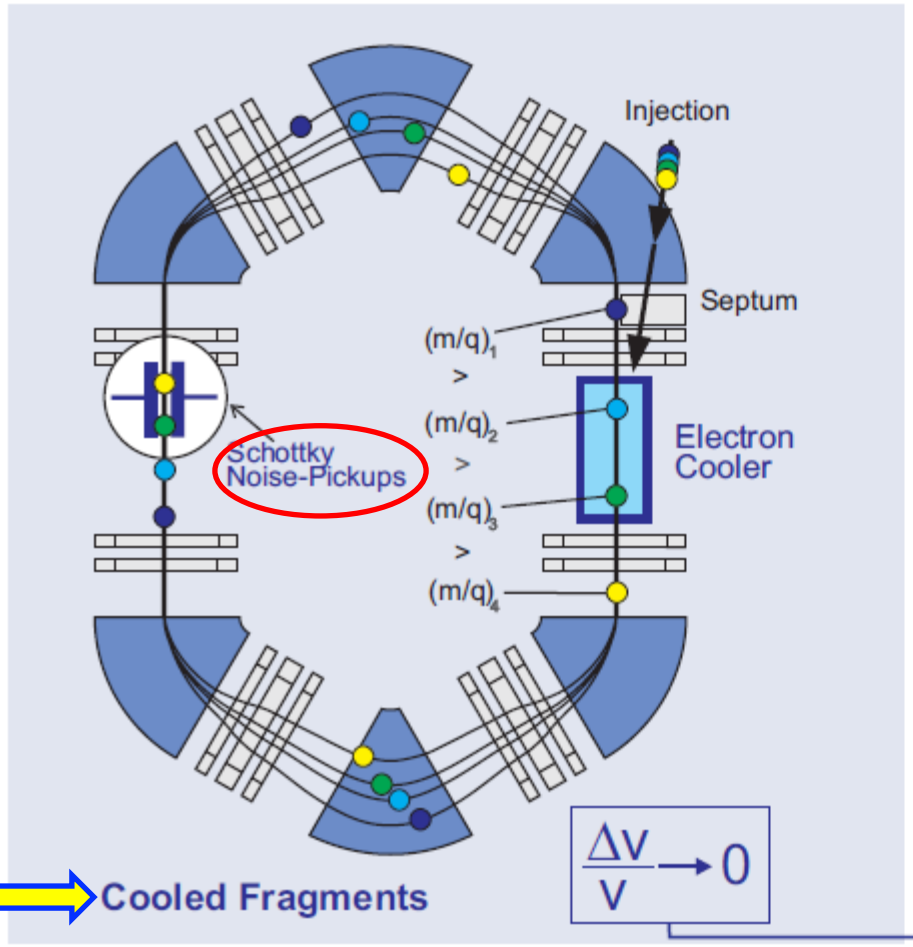
Stochastic cooling: F. Nolden et al., NIM B 532 (2004) 329
Electron cooling: M. Steck et al., NIM B 532 (2004) 357

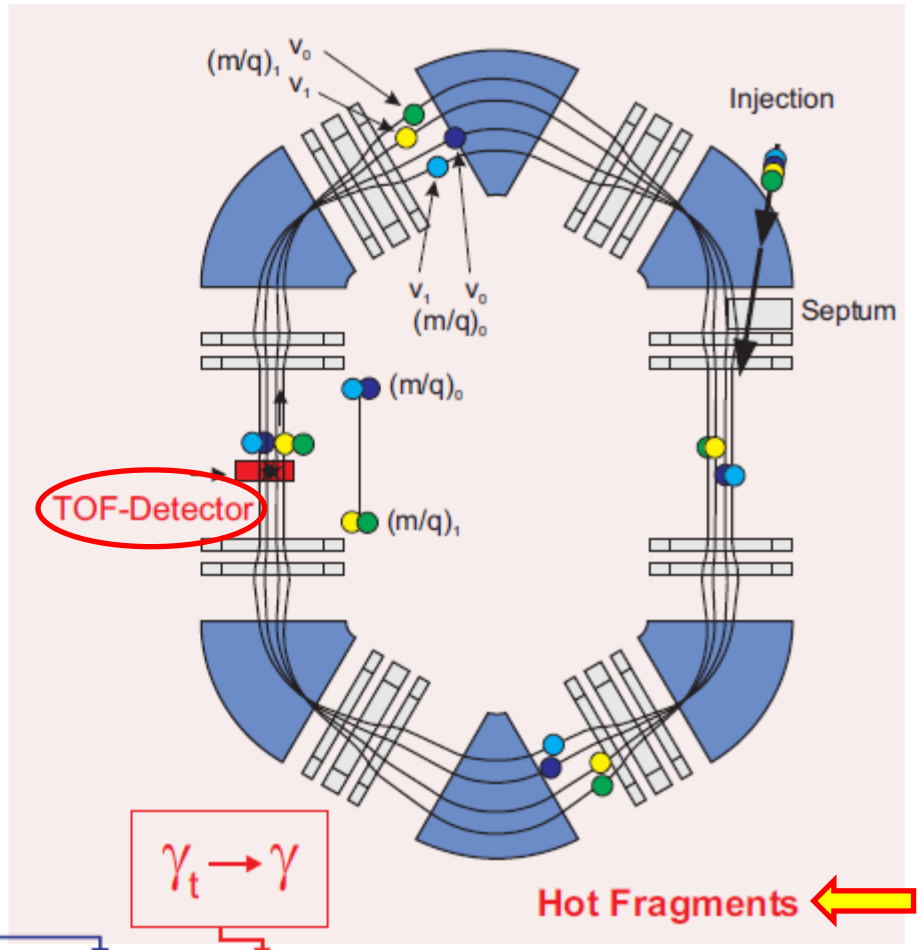
Longed lived isomers: τ > 1 sec

Short lived isomers

SCHOTTKY MASS SPECTROMETRY

ISOCHRONOUS MASS SPECTROMETRY





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

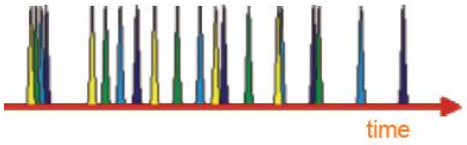
Schottky Mass Spectrometry

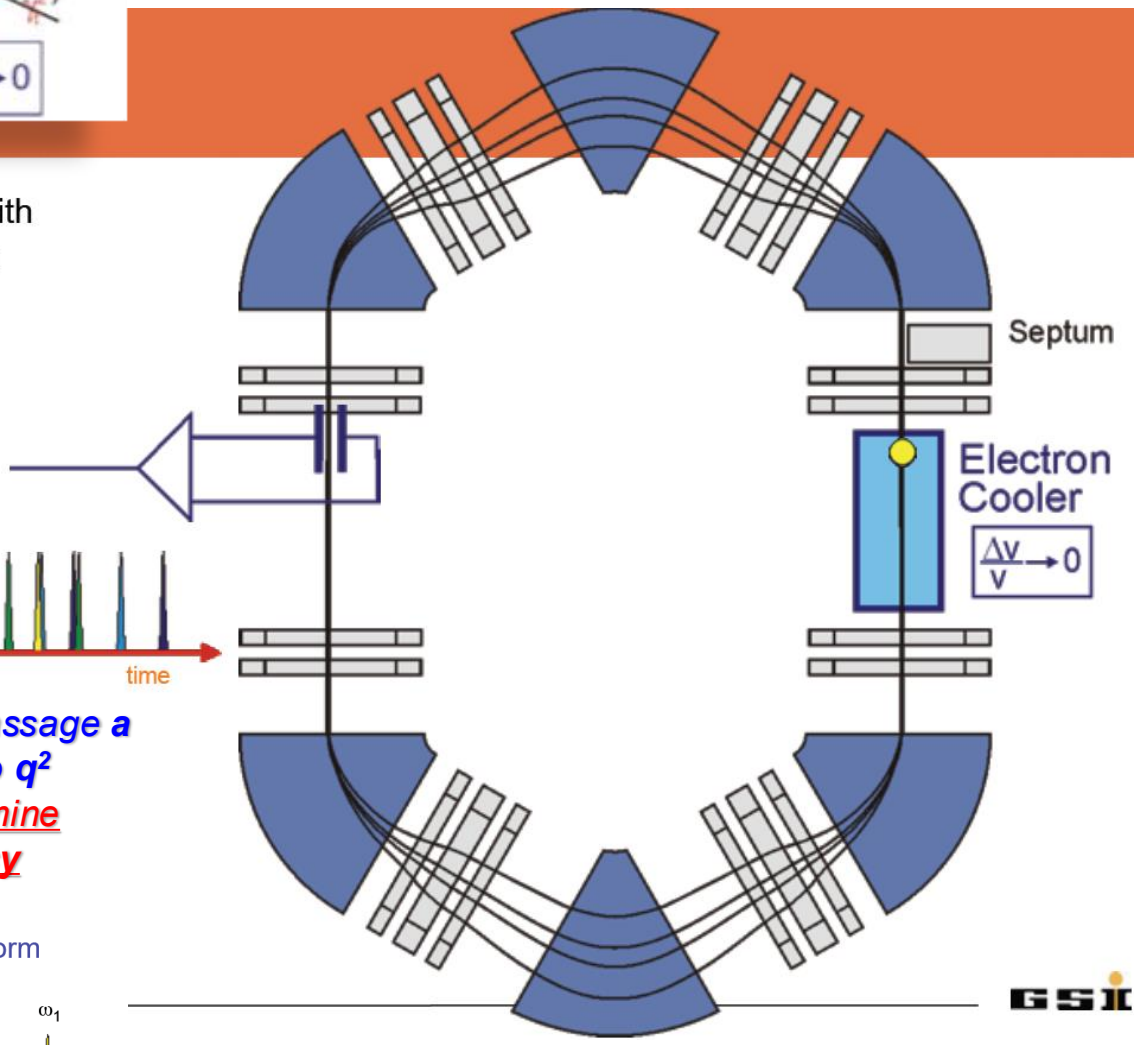
1987 - B. Franzke, H. Geissel, G. Münzenberg

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

$$\frac{\Delta v}{v} \to 0$$

4 particles with different m/q

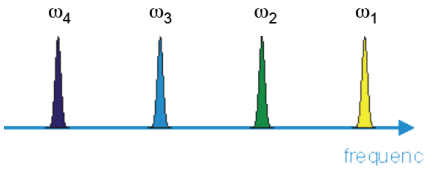




Every ion induce at each passage ***a signal proportional to q²***

→ *Signal used to determine* ***revolution frequency***

Fast Fourier Transform



Schottky Spectrum for ESR

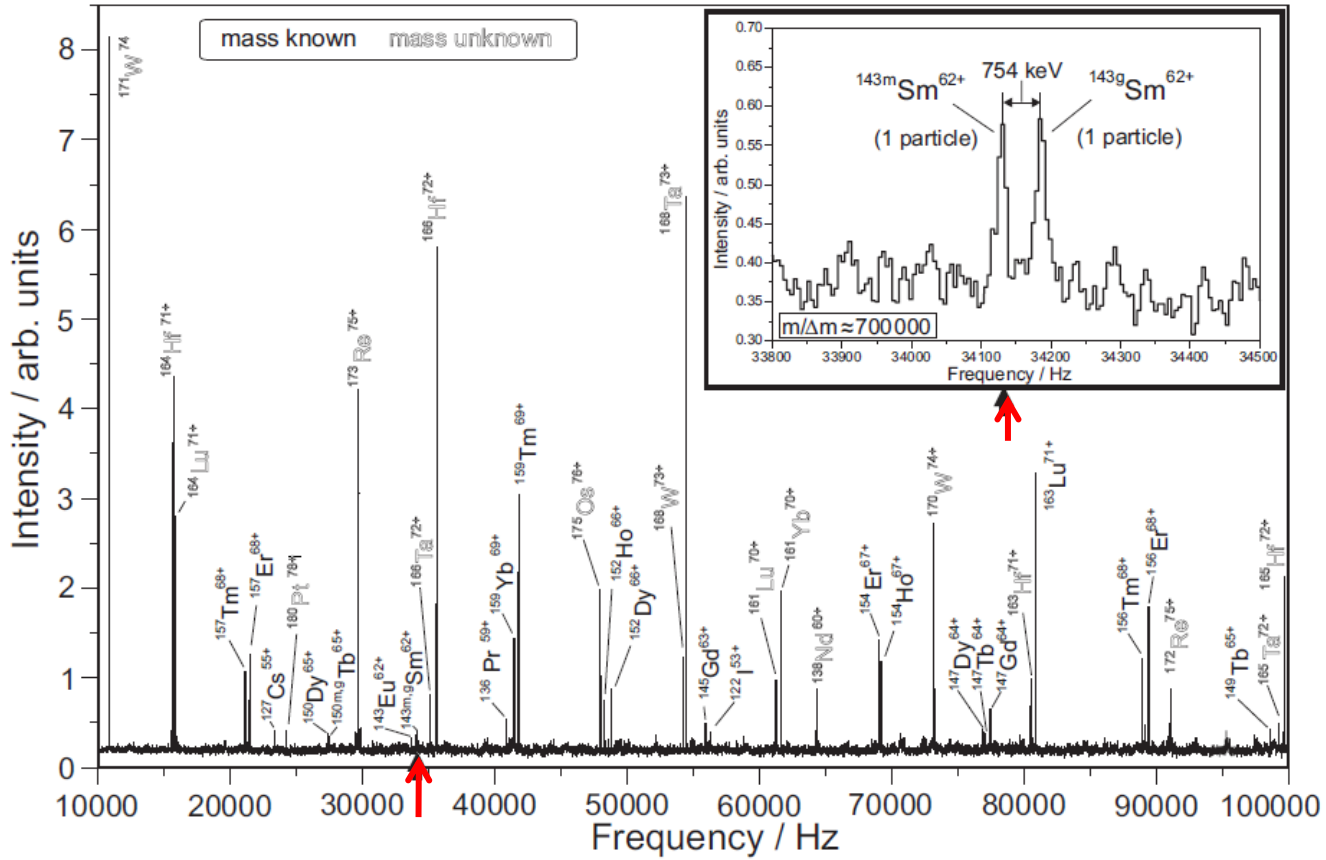
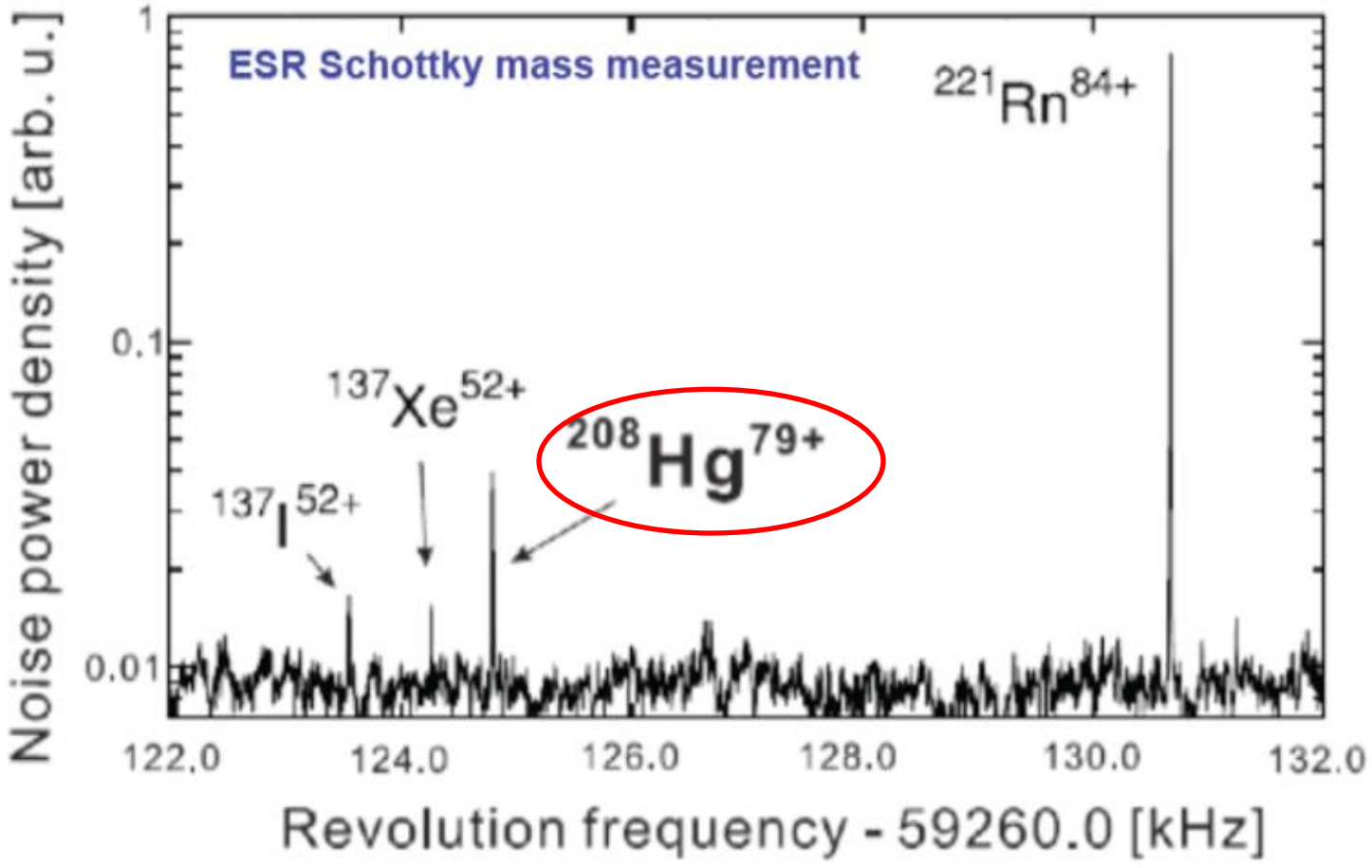


Fig. 9. Schottky spectrum of fragments from a primary ^{209}Bi beam, stored and

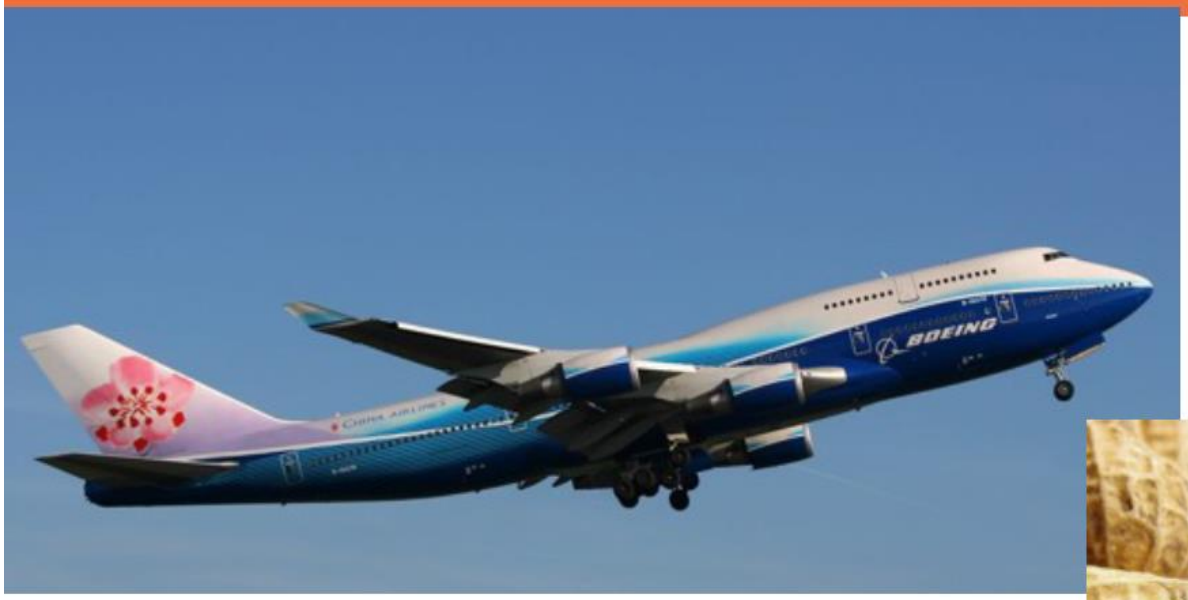
Simultaneous detection of 50 ions with high resolving power

Use of known masses for calibration

Direct Mass Measurement of ^{208}Hg Nuclide



Relative mass accuracy of $4 \cdot 10^{-8}$



M ~ 160’000 kg

M ~ 5 g

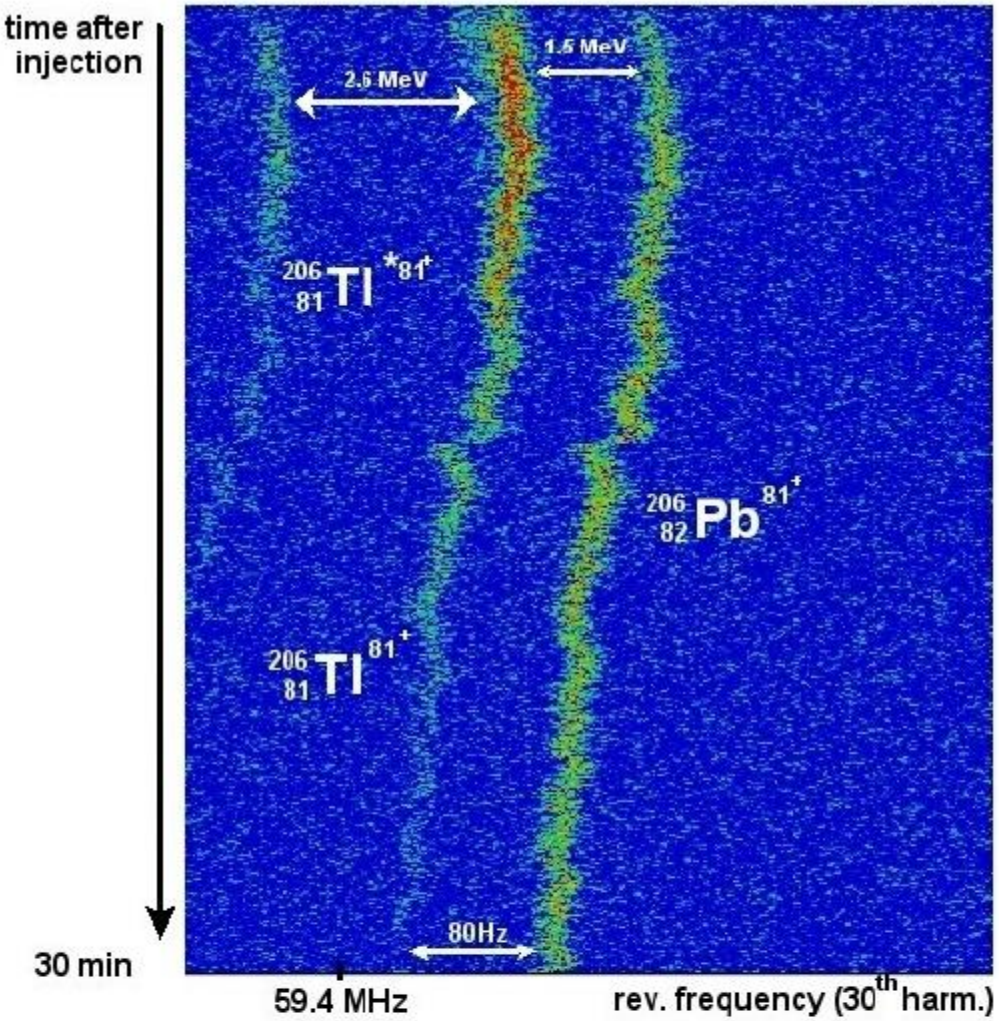
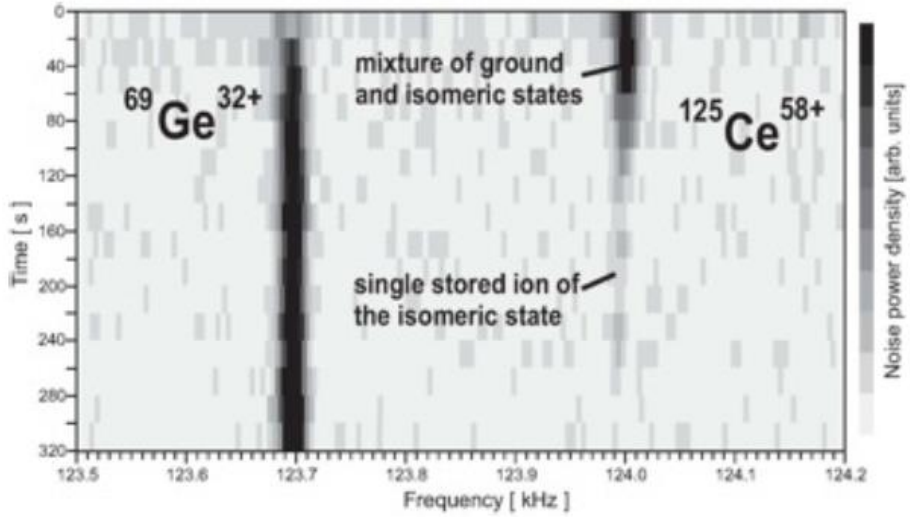
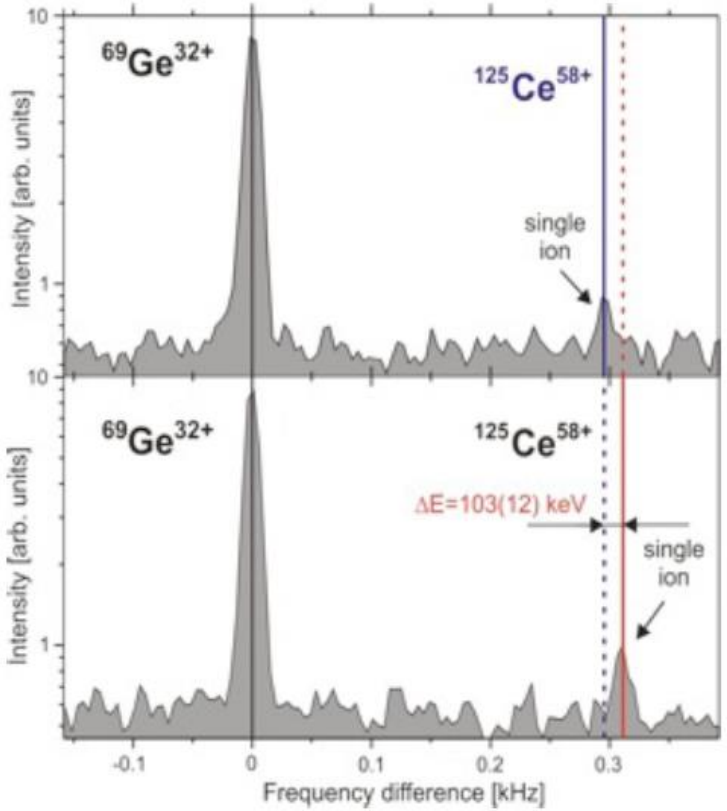


Fig. 17. Time–traces of Schottky lines vs. the 30th harmonics of the revolution frequencies (about 60 MHz) of stored and electron-cooled bare ^{206}Tl ions. From left to right: short-lived isomeric state of $^{206}Tl^{81+}$ at 2.6 MeV excitation energy; $^{206}Tl^{81+}$ ground state; bound β daughter of it, hydrogen-like $^{206}Pb^{81+}$. The (parallel) fluctuations of a few Hz in the revolution frequencies are due to random jitters of magnetic fields and power supplies.

New isomeric states



Lifetime = 193 s



B. Sun et al., EPJA 31 (2007) 393

Isochronous Mass Spectrometry

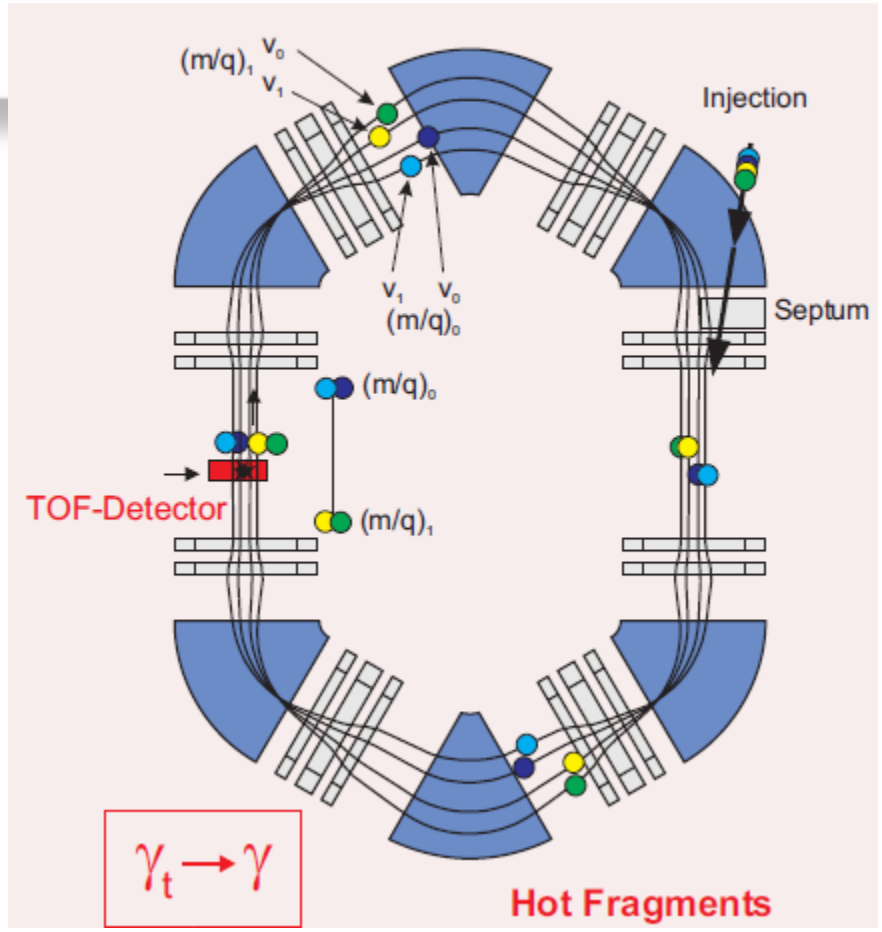
1985 - H. Wollnik, Y. Fujita, H. Geissel, G. Münzenberg, et al.

γ_t is the 'transition energy', at which the revolution frequency gets independent on the energy for each ion species with fixed m/q-ratio. This transition energy γ_t can be varied within certain limits by a careful choice of the ion optics of the storage ring.

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

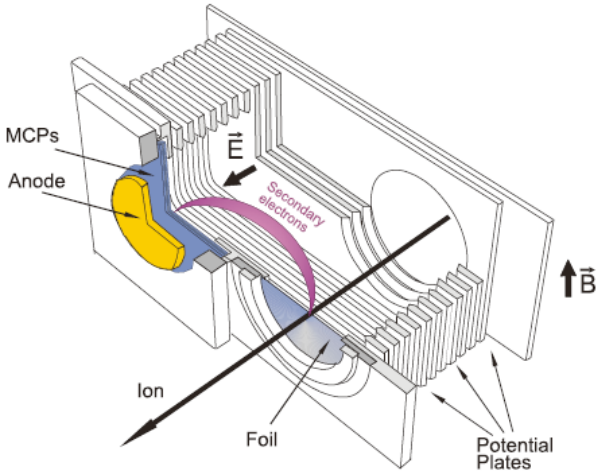
$\gamma_t \rightarrow \gamma$

ISOCHRONOUS MASS SPECTROMETRY



The idea is to force the ions to the transition energy regime i.e.

$\gamma = \gamma_t$



TOF detector is based on MCP device setup:
Very thin metalized foil (~μg/cm2) emitting δ-electrons focused on a detector

TOF Spectrum for ESR

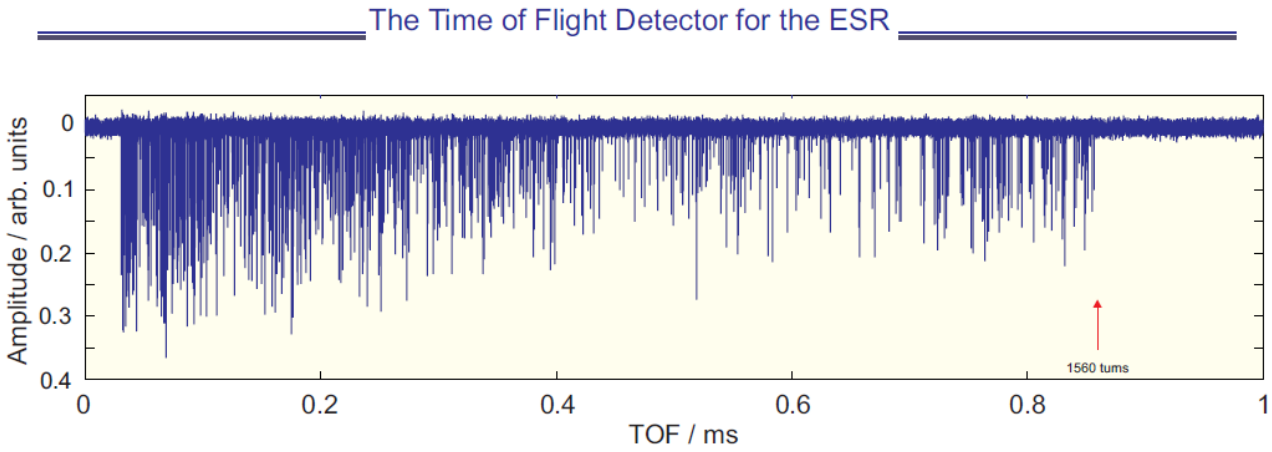
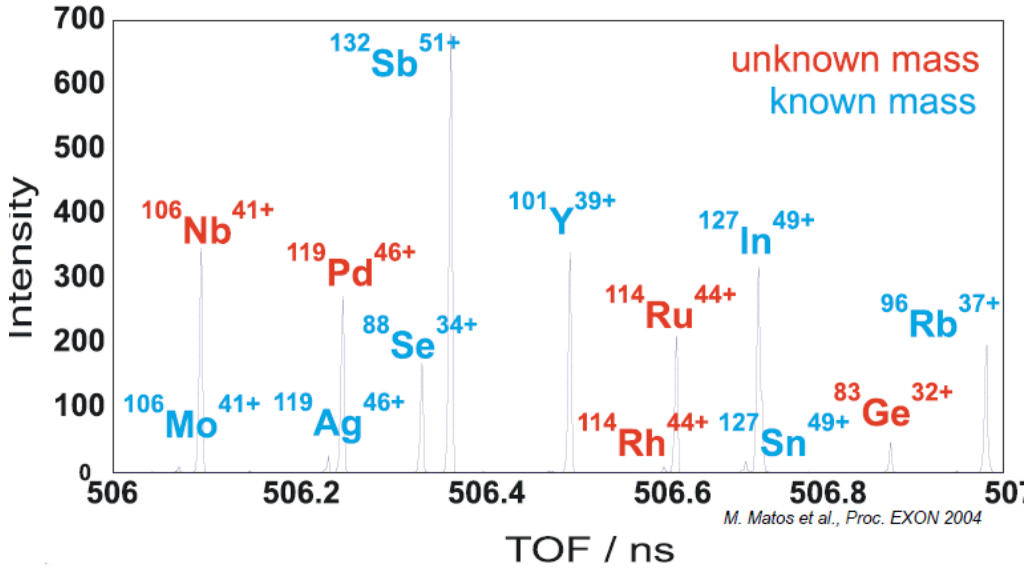
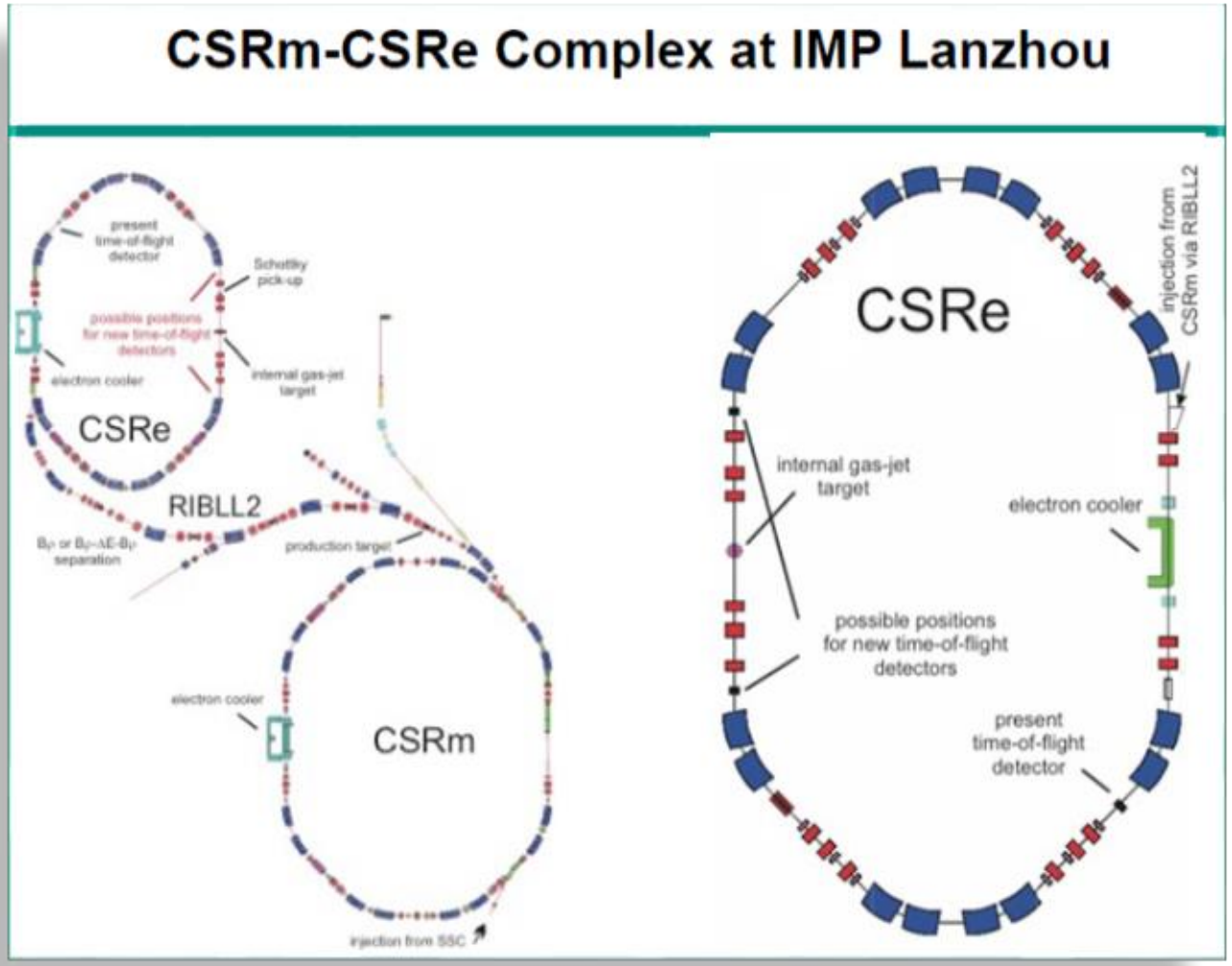


Fig. 10. Periodical 'fingerprints' in the TOF detector of a few ions stored at the transition energy γ_t. The maximum number of turns of one ion, as observed in this spectrum, amounts to 1560. This figure was originally published in [29].



Revolution time spectrum taken by TOF detector

in CHINA


CSRm-CSRe Complex at IMP Lanzhou
present time-of-flight detector
Schottky pick-up
possible positions for new time-of-flight detectors
electron cooler
internal gas-jet target
CSRe
RIBLL2
Bρ or Bρ-ΔE-Bρ separation
production target
electron cooler
CSRm
injection from SSC
CSRe
injection from CSRm via RIBLL2
internal gas-jet target
electron cooler
possible positions for new time-of-flight detectors
present time-of-flight detector

...