Leuven, 2 -6 June 2003, FANTOM Study week on

Trapping and Manipulating Atomic and Subatomic Particles

Experiments in Ion Storage Rings: mass and lifetime measurements

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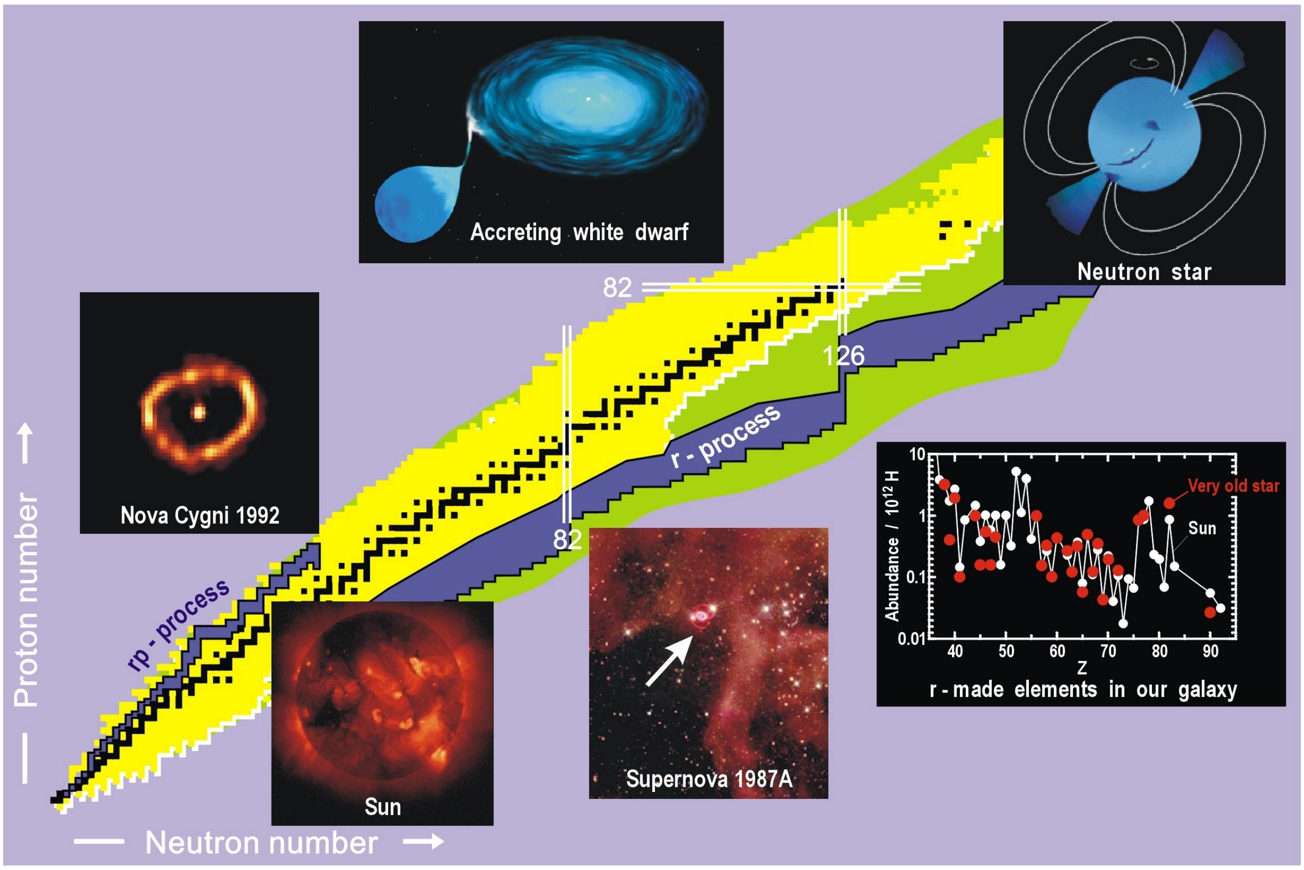
Outline

1. **Why masses and lifetimes of exotic nuclei? -The deep bond of nuclear structure and stellar nucleosynthesis**

2. **'Schottky mass- and lifetime spectrometry' at the ESR**

3. **Exotic beta-decays and the age of the universe**

1. Why masses and lifetimes of exotic nuclei? - The deep bond of nuclear structure and stellar nucleosynthesis



matter creation in stars:

fusion up to iron
explosive rapid neutron capture (r-process)
rapid proton cature (rp-process, e.g. Novae)

the abundance of nuclei in the solar system in closest connection to nuclear structure

→ masses determine the pathways of nucleosynthesis

→ β -lifetimes the accumulated abundance

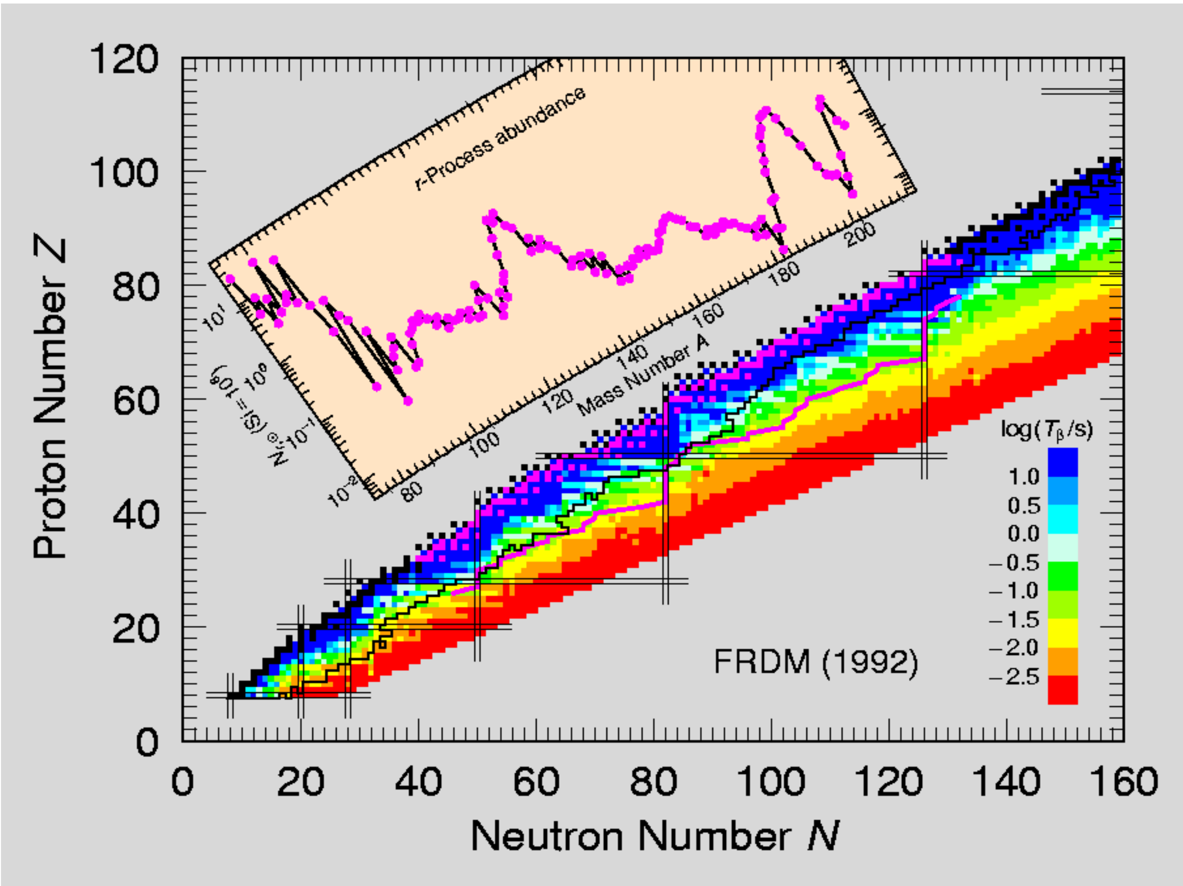
Burning issue of nuclear astrophysics:

How and where the heavy nuclei have been created?

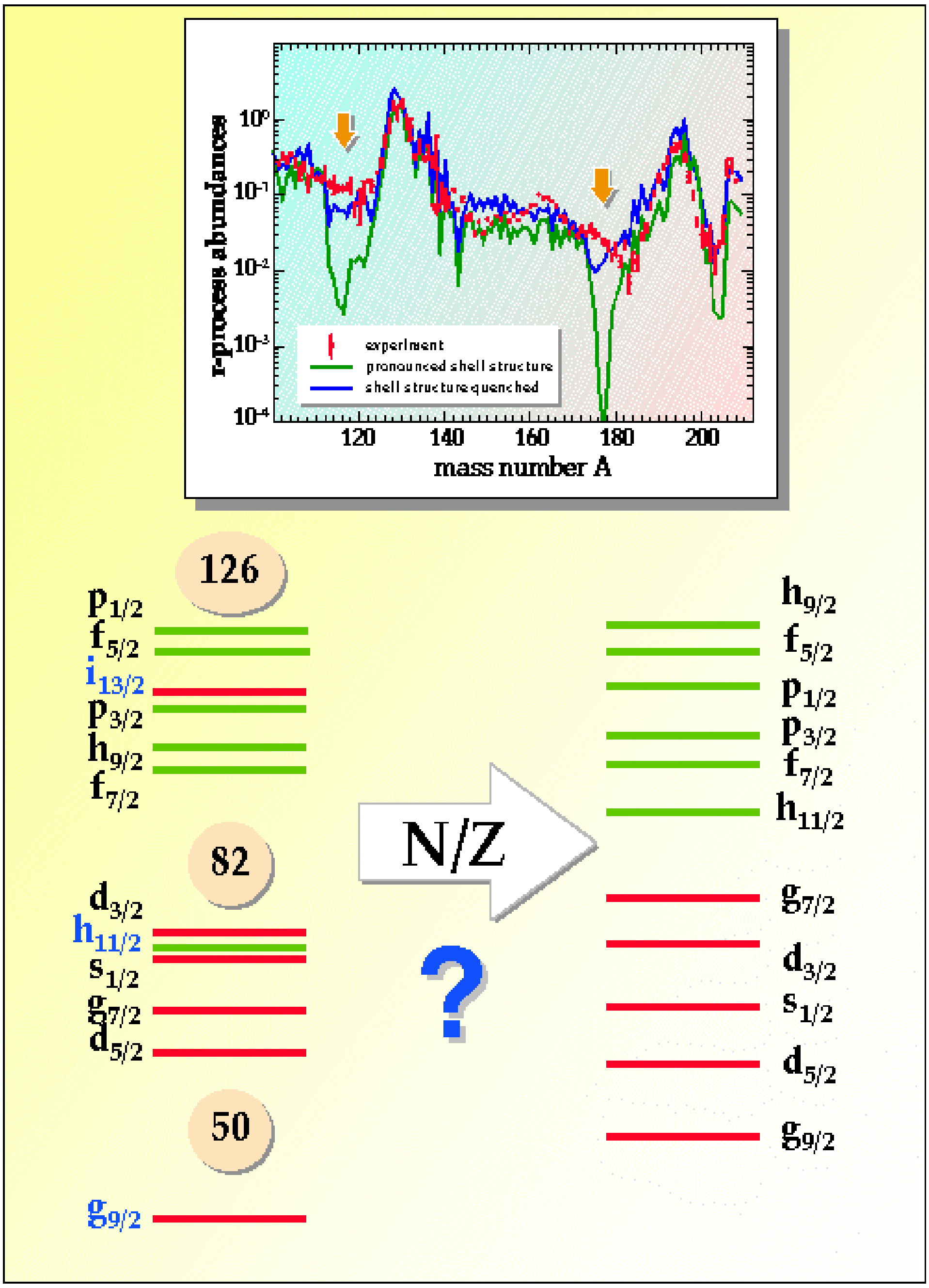
⇒ need to produce *unstable nuclei* in the *laboratory*

⇒ to measure their fundamental properties:
mass and lifetime

to understand the *abundance of nuclei*
in the solar system and in the universe



Peaks in the r-process abundance correspond to closed neutron shells (50, 82, 126...)
courtesy P. Moeller



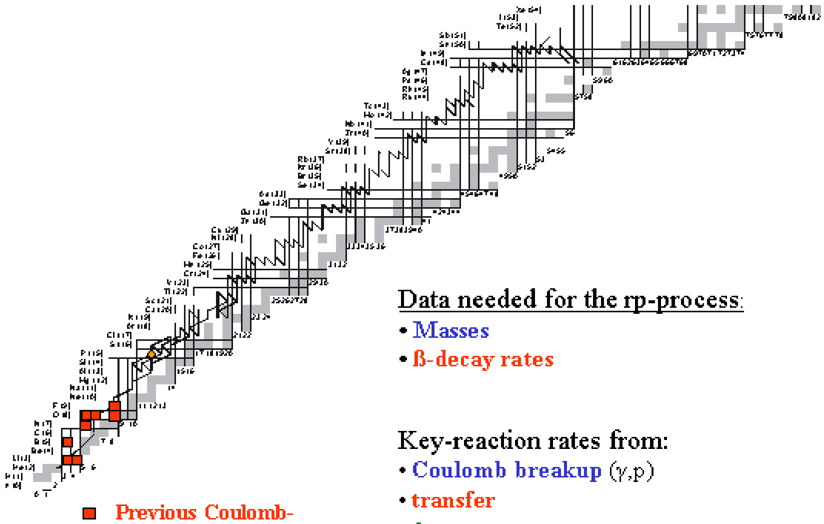
still open questions of nuclear structure and explosive nucleosynthesis

courtesy R. Nasarewicz

persisting shell gaps??

Extrapolating the shell gaps of stable to very neutron-rich nucleione cannot describe the abundance of r-made nuclei

The rp-process



Previous Coulomb-breakup experiments

Data needed for the rp-process:

- Masses
- ß-decay rates

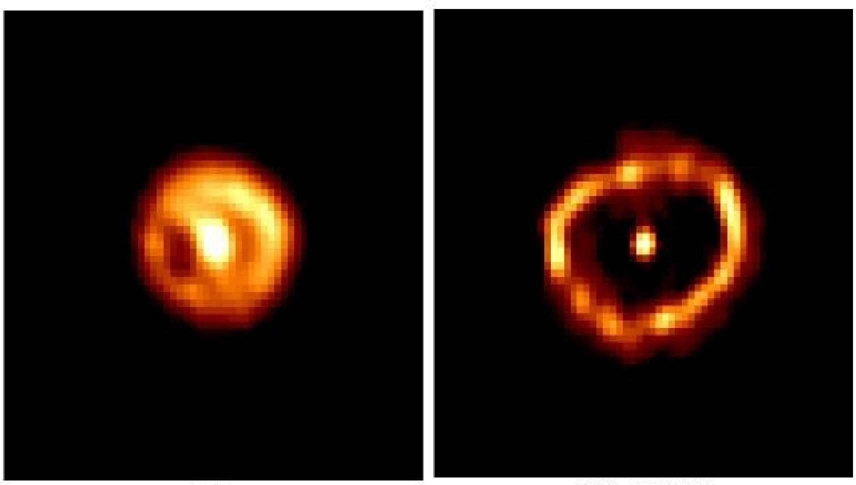
Key-reaction rates from:

- Coulomb breakup (γ,p)
- transfer
- 2p-captures

courtesy H. Schatz

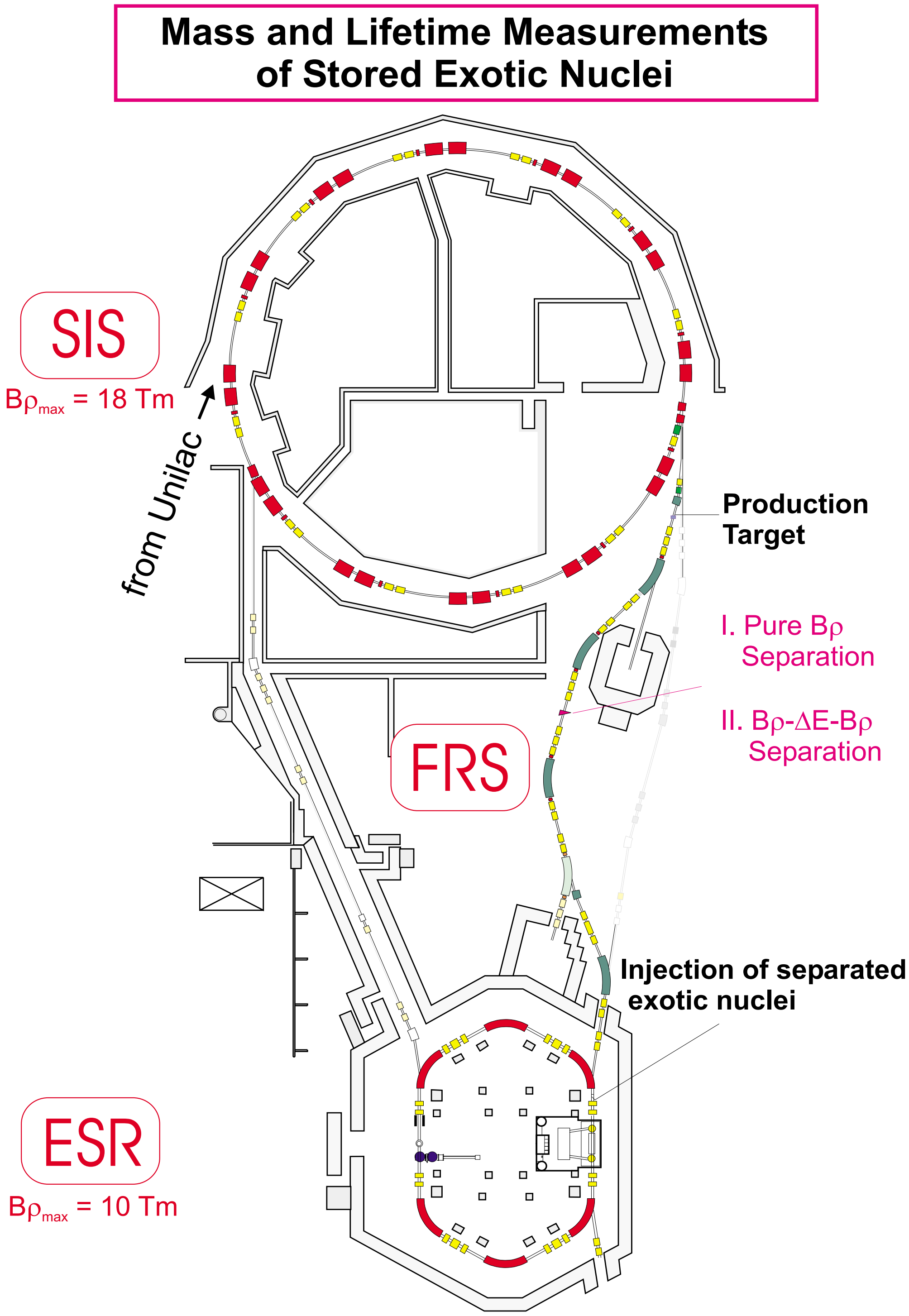
Nova Cygni 1992

Hubble Space Telescope
Faint Object Camera



Pre-COSTAR Raw Image | With COSTAR Raw Image

2. 'Schottky' mass- and lifetime spectrometry at the ESR



In-flight production of exotic, highly charged ions by projectile fragmentation; $B\rho$-separation of many species with same mv/q, or of one species by $B\rho$-ΔE-$B\rho$ method

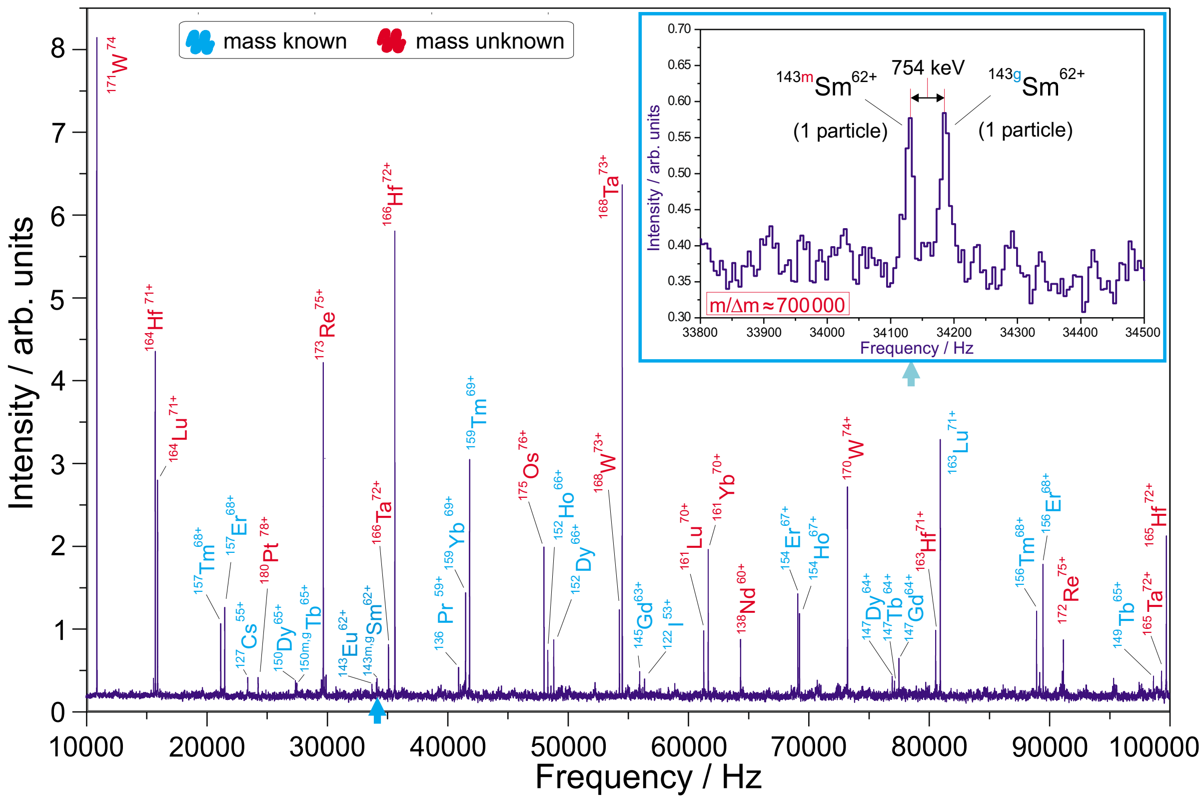
Schottky mass-spectrometry:

- **projectile-fragments from the fragment separator within $\{(m/q)_0 +/- 1.5\%\}$ stored and cooled in ESR**

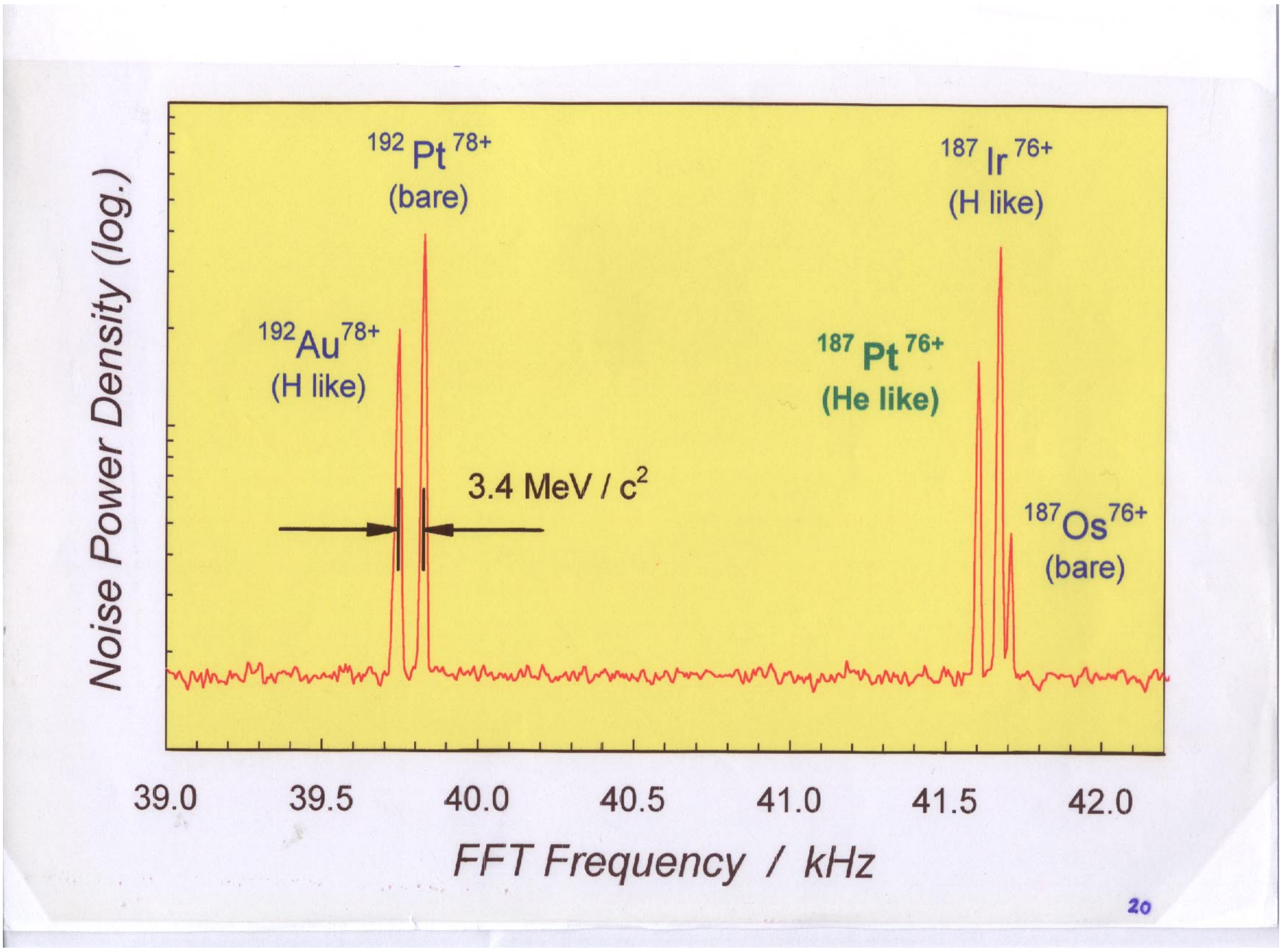
- **each cooled ion of a certain $(m/q)_i$ -species induces a signal $V_i(t)$ {'Schottky noise'} on pick-up plates at each passage with a well-defined period $f_i = 1/\tau_i$**

- **the autocorrelation $< I_i(t)\ I_i(t+\Delta t) >$ has strong peaks at $\Delta t = \tau_i, 2\tau_i, ...n\tau_i$, i.e.the Fourier Transform of it at the revolution frequencies $f_i, 2f_i, ...nf_i$**

- **this Fourier Transform of the Schottky noise identifies each circulating ion species → Schottky mass-spectrometry**



Schottky spectrum of some 50 simultaneously stored ion species



radioactive 'families':

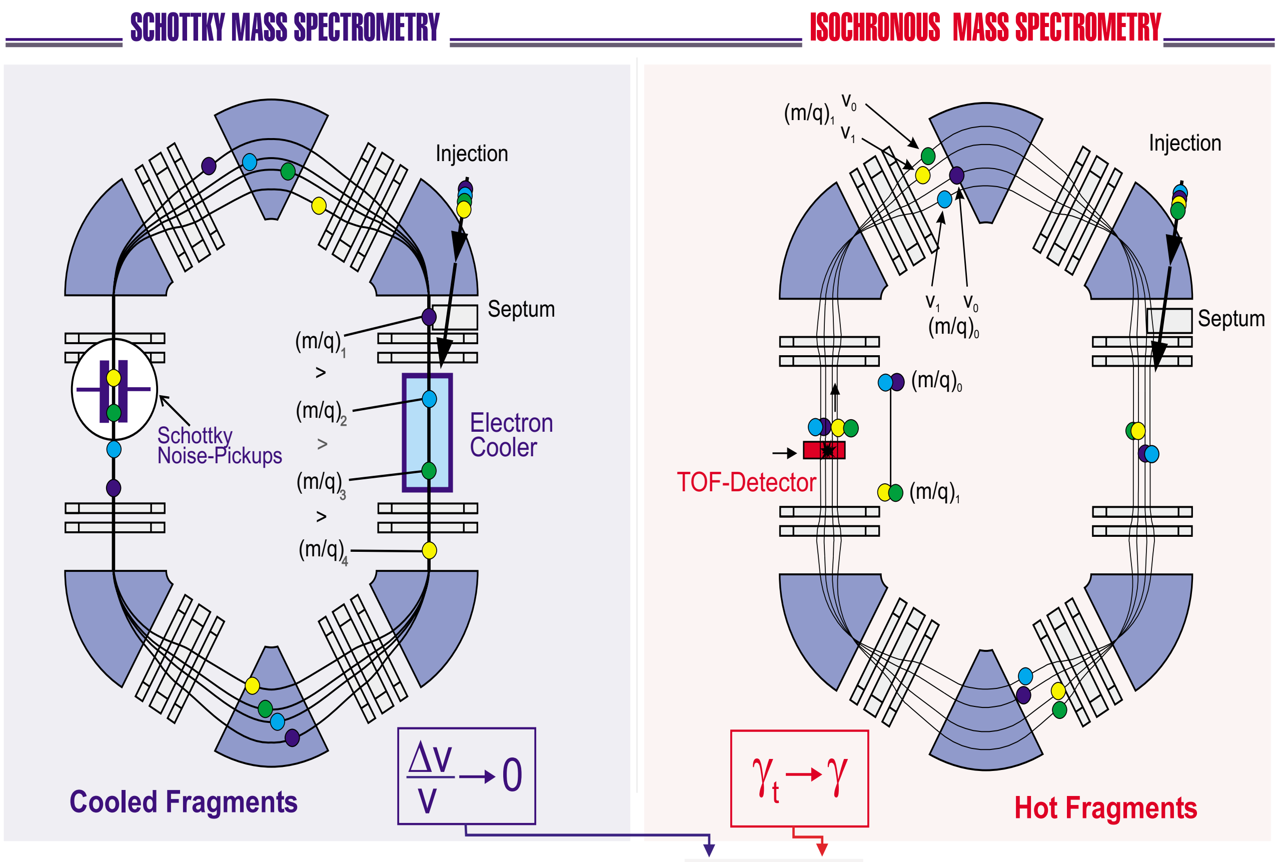
mother ^{192}Au $^{78+}$ $\xrightarrow{\text{EC}}$ daughter ^{192}Pt^{78+}

grandma ^{187}Pt^{76+} $\xrightarrow{\text{EC}}$ mother ^{187}Ir^{76+} $\xrightarrow{\text{EC}}$ daughter ^{187}Os^{76+}

both Q -values and β -lifetimes are directly observed

Mass spectrometry in the ESR for

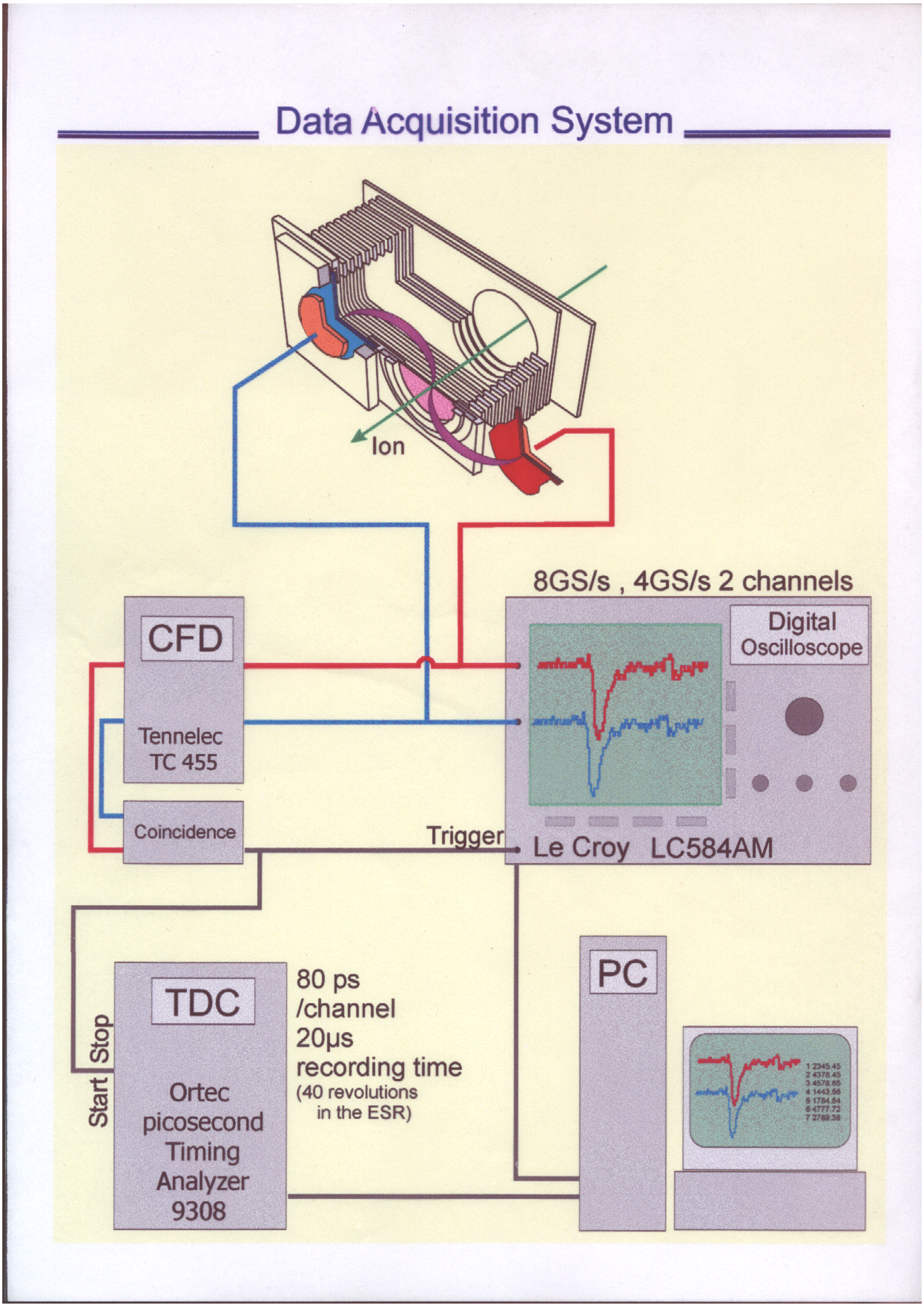
longer-lived **short-lived nuclei**



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

two possibilities to minimize the Δv/v (...) -term:

cooling: Δv gets small **'isochronous' mode: $\gamma = \gamma_t$**


Data Acquisition System
Ion
8GS/s , 4GS/s 2 channels
CFD
Tennelec
TC 455
Digital
Oscilloscope
Coincidence
Trigger
Le Croy LC584AM
PC
TDC
Ortec
picosecond
Timing
Analyzer
9308
Start
Stop
80 ps
/channel
20μs
recording time
(40 revolutions
in the ESR)

by recording **at each turn the passage-time** through a foil of **each stored ion** → **$(m/q)_i$**

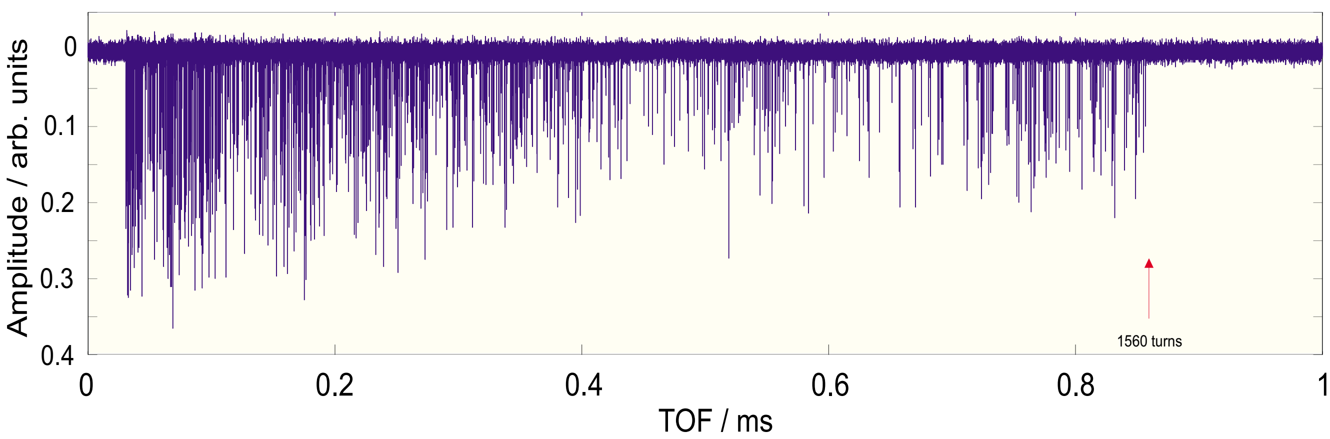
detection limit: **one single ion**

lifetime limit: **revolution time ≈ μs**

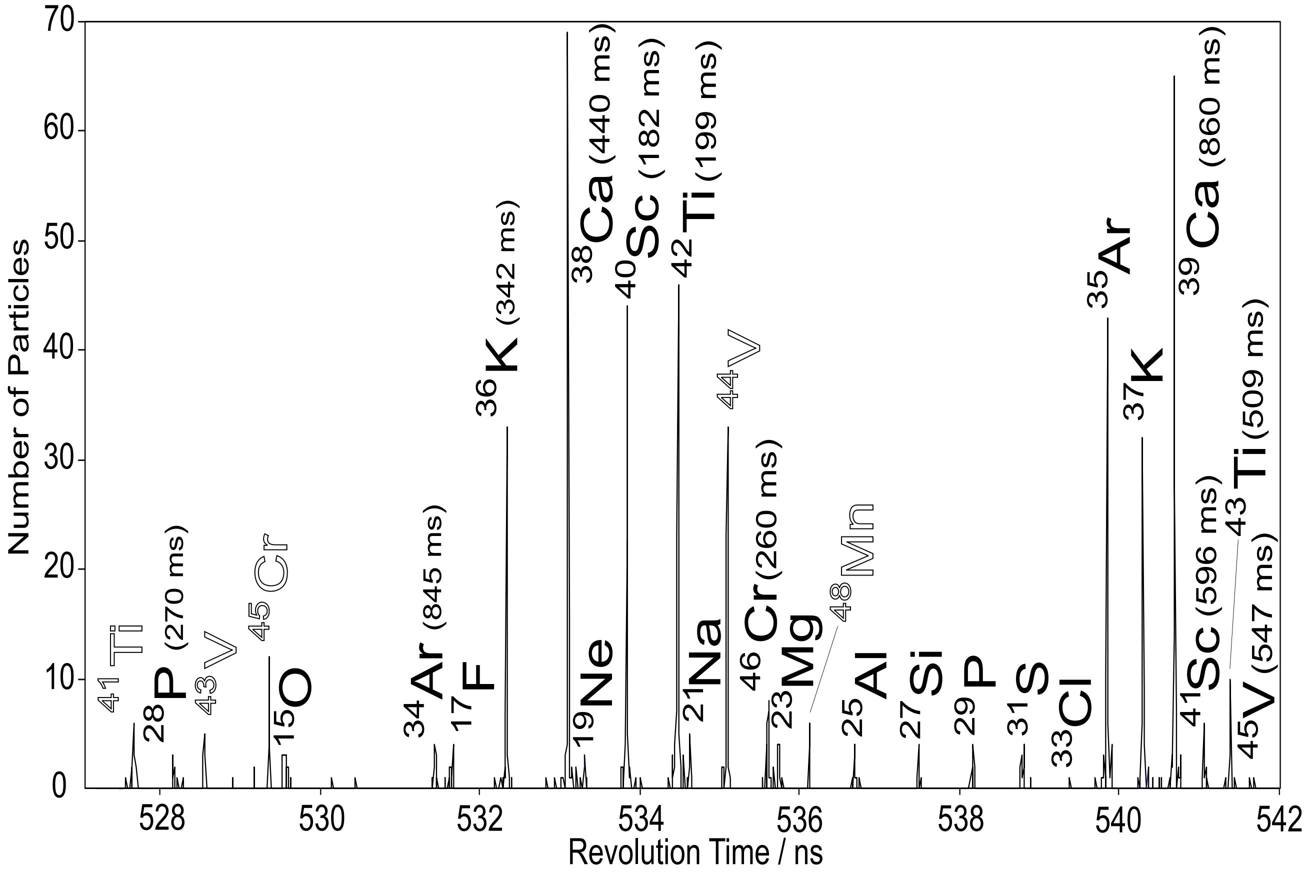
production cross section: **< 10^{-33} cm^2 (nb)**

resolving power m/Δm: **10^5 ...3 x 10^5**

The Time of Flight Detector for the ESR

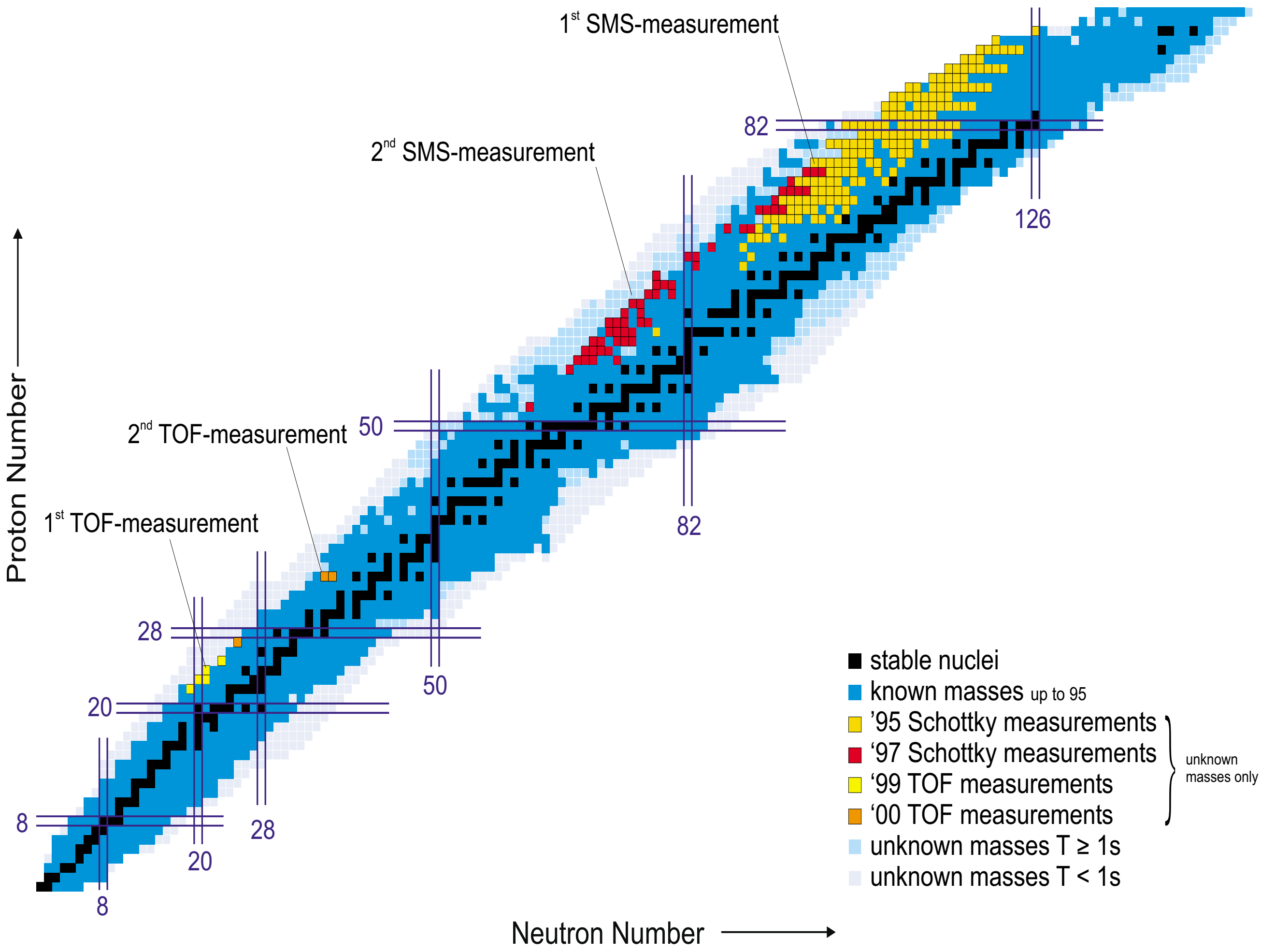


Periodic 'fingerprints' of a few ions in the isochronous mode



Proton-rich isochronous fragments of a ^{52}Cr primary beam along the pathway of the rp-process

Areas of Mass Measurements in the ESR



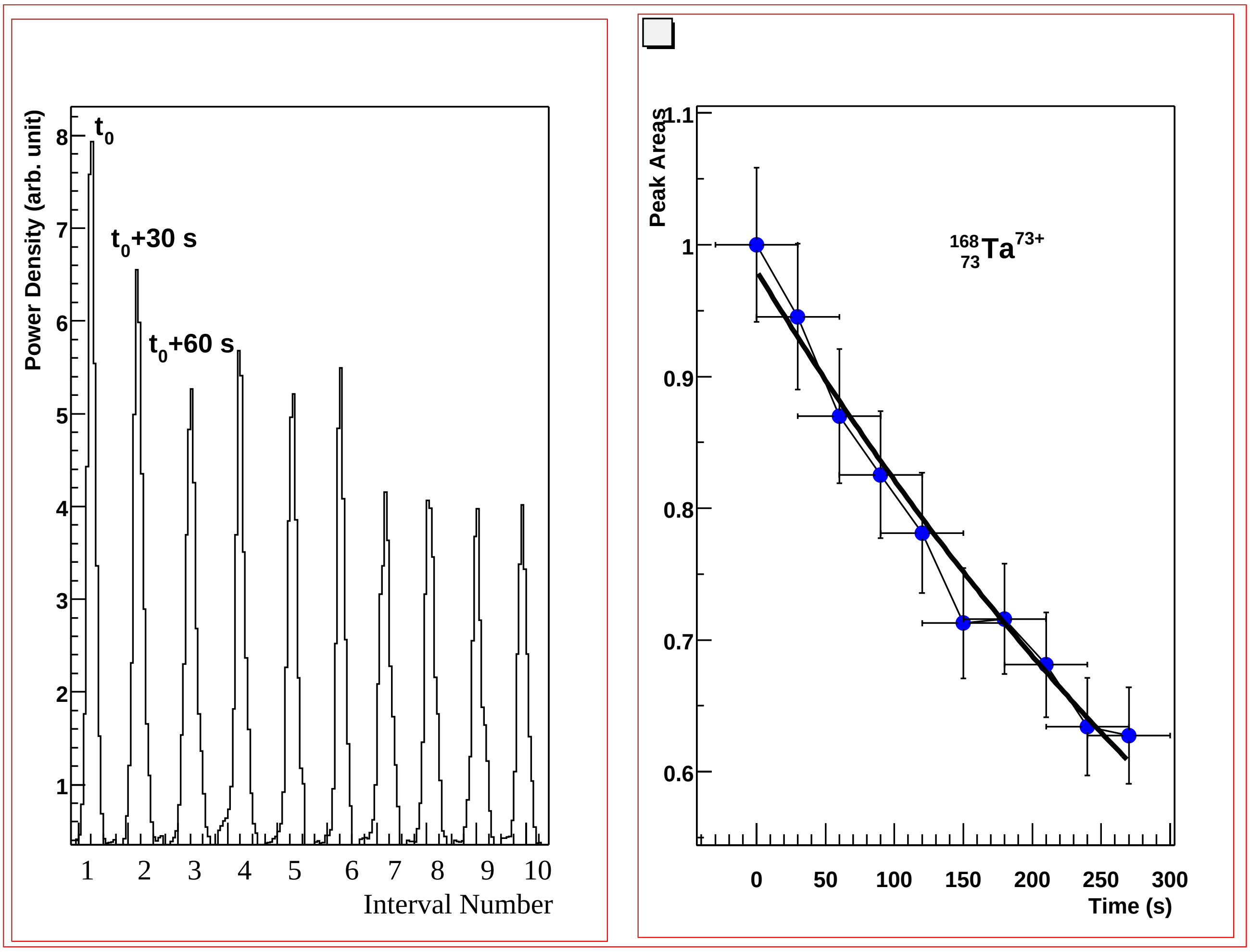
Harvest of four experiments of Schottky- and isochronous mass-spectrometry.

More than 170 previously unknown masses were determined

mass resolving power m/Δm of 3×10^5 to 9×10^5

accuracy of 20 to 100 keV.

Recording Schottky areas vs time → (β) lifetimes



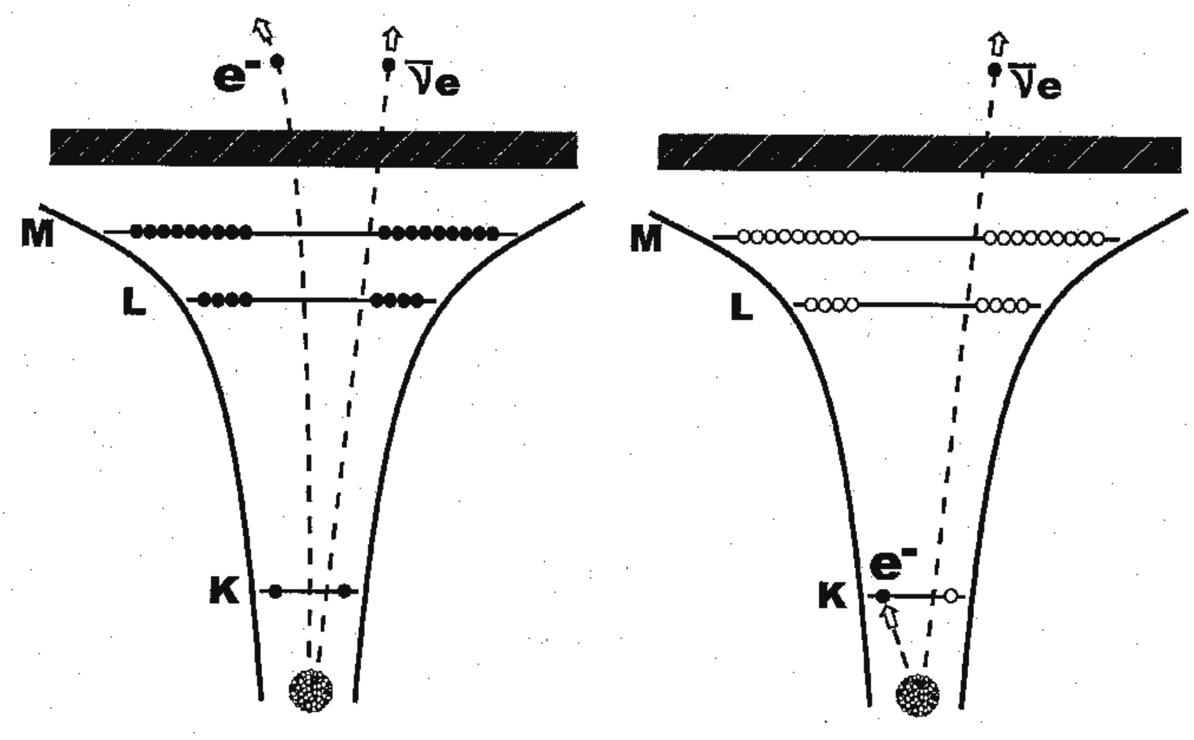
Lifetime measurement of bare $^{168}Ta^{73+}$ by recording the Schottky-line area every 30 s.

$T_{1/2}$ (bare ^{168}Ta) = 5.2 m

$T_{1/2}$ (neutral ^{168}Tl) = 2.0 m

(β^+ + orbital EC)

3. Exotic β -decays and the age of the Universe



4 kinds of β decay:

1.	n	$\rightarrow$	$p + e^- + \nu_e$ (bar)	β^-_c
2.	p	$\rightarrow$	$n + e^+ + \nu_e$	β^+
2a	$p + e^-_b$	$\rightarrow$	$n + \nu_e$	EC
1a	$n + \nu_e$	$\rightarrow$	$p + e^-_b$	β^-_b

1a = 'bound' beta decay, first observed at the ESR

Bound beta decay (β_b) of highly charged ions:

→ **the created electron remains bound in an inner shell of the daughter atom.**

→ **time-mirrored EC; monochromatic ν_e(bar)**

→ **inner shell vacancies have to exist**

→ **the binding energy of the electron is 'saved'; 'Q' -value of the decay gets larger**

→ **lifetimes of highly ionized atoms might change; stable neutral atoms can get unstable if ionized**

→ **important in hot stellar plasmas during nucleosynthesis**

→ **only detectable if charge state can be preserved**

→ ion traps or ion storage rings

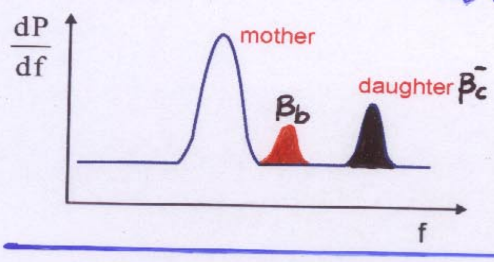
$$\beta_b : (A, Z)^q \rightarrow (A - Q/c^2, Z + 1)^q$$

Principle of Lifetime Measurements for Cooled Fragments

projectiles → FRS → fragments → ESR → Schottky Sp.

β_c^-: $\frac{A}{q} \rightarrow \frac{A-Q}{q+1}$

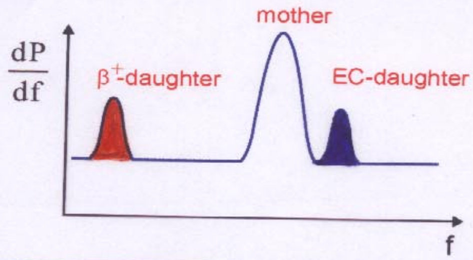
$Q \gtrsim 1$ MeV



For $Z \geq 28$ both are circulating within the acceptance of the ESR

β^+: $\frac{A}{q} \rightarrow \frac{A-Q}{q-1}$

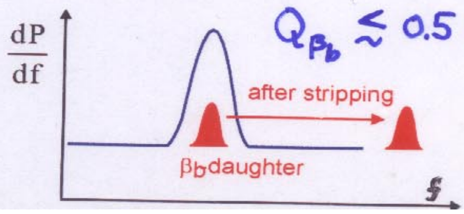
EC: $\frac{A}{q} \rightarrow \frac{A-Q}{q}$ $q < Z$



β_b^-: $\frac{A}{q} \rightarrow \frac{A-Q}{q}$

$Q_{\beta^+} >> Q_{EC}$ [redacted]

$Q_{\beta_b} \lesssim 0.5$ MeV



Unique:

1) Both mother and daughter nuclei can be measured simultaneously

2) $T_{1/2}$ can be studied for different atomic charge states

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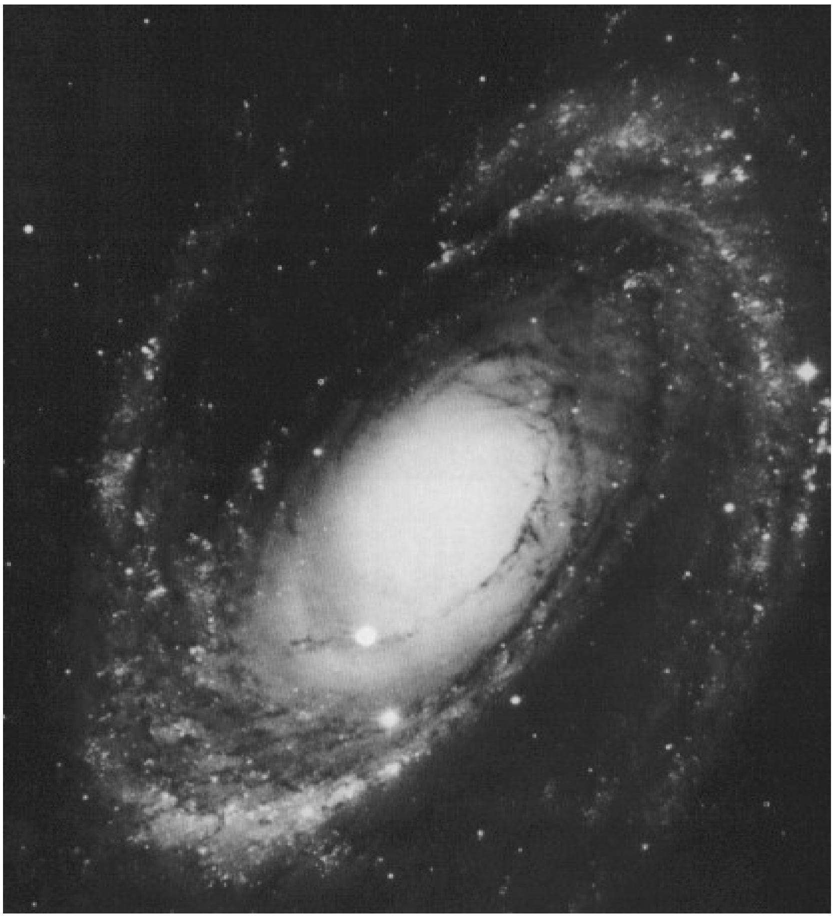
The cosmic 'clock' $^{187}Re/^{187}Os$

How old is the Universe?



observations favouring a beginning of the world:

universal *red-shift* ('Hubble constant' H_0, 1929)
3 K background radiation (Penzias and Wilson, 1964)

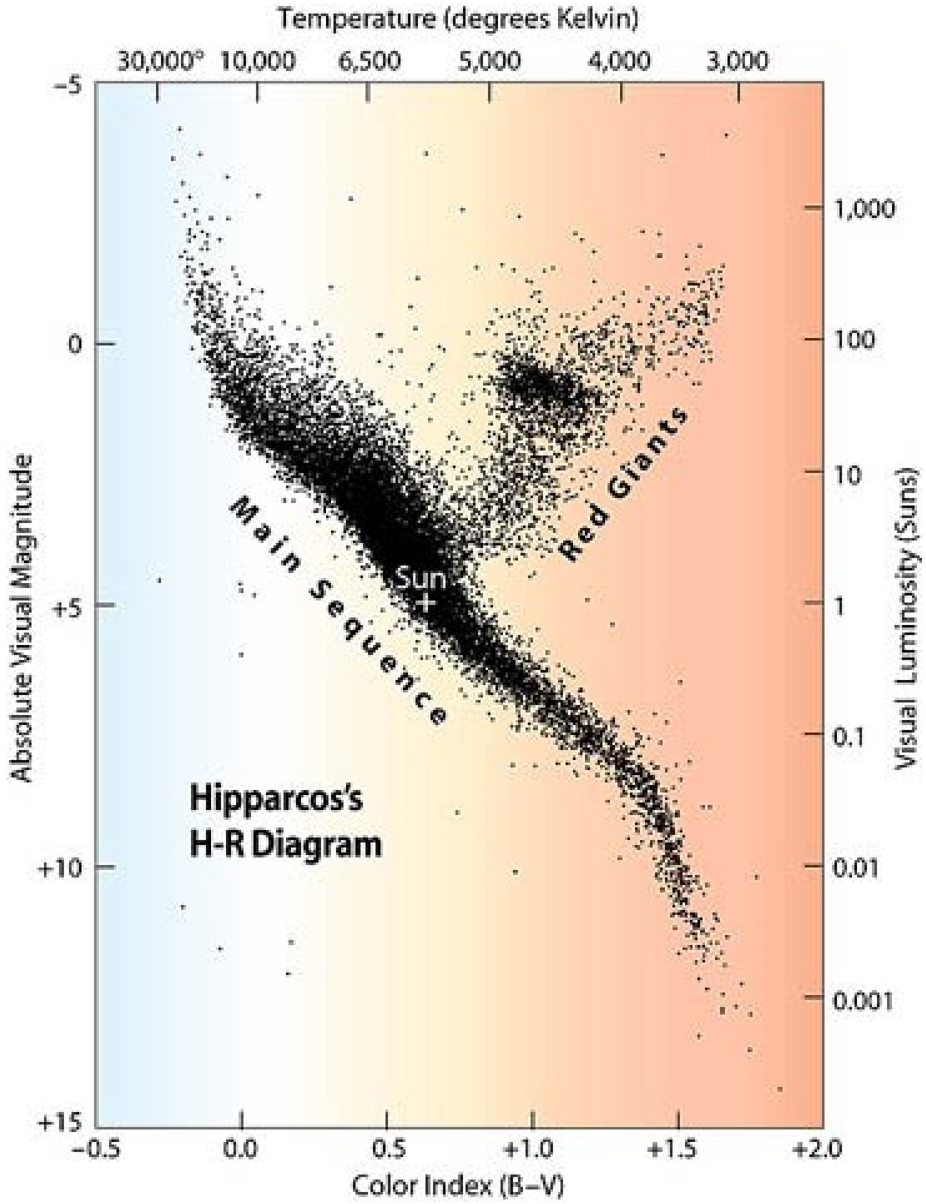
'clocks' for the age T_U of the Universe:

astronomical ('globular clusters' GC)
nuclear (long-lived radioactive nuclei)

From H_0 and T_U one get constraints for the mass density Ω_M of the Universe and the 'cosmological constant' Ω_Λ

The GC M13 in the constellation Herkules

All the many 100 000 stars originated at the same time. The massive ones have already left the 'main sequence' (MS) of the 'Hertzsprung-Russell-diagram'. If one knows the time a star stays on the MS as a function of its mass, on can deduce the age of M13 by determining the mass at which its stars are leaving the MS.



Hertsprung-Russell-diagram for all stars within a distance of 500 light years, taken by the Hipparcos satellite.

The age T_{GC} of the oldest GC observed is

$$T_{GC} = (12 +/- 1)\ 10^9\ y$$

$$\rightarrow T_U \geq 11 \times 10^9\ y$$

is a 'safe' lower limit for the age T_U of the Universe.

S.M. Carroll, W.H. Press

Ann. Rev. of Astron. and Astrophysics 30 (1992) 521:

"...it may be more secure [to use nuclear clocks instead of astronomical clocks], because

the physics of nuclear decay is so much better understood

than that of stellar evolution..."

14a

The 7 nuclear 'clocks' for the age of the Earth, the solar system, our Galaxy and the Universe

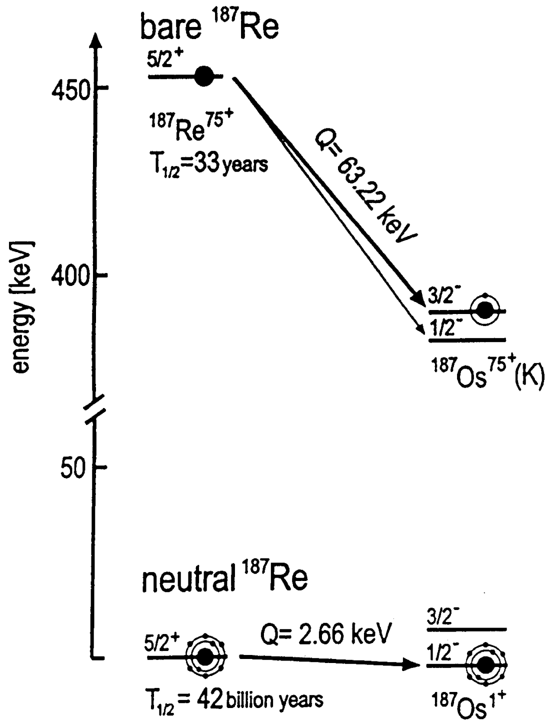
nuclei (decay mode)	half-life $T_{1/2}$ [10^9 y]
$^{40}K/^{40}Ar$ (β)	1.3
$^{238}U...Th...^{206}Pb$ (α, β)	4.5
$^{232}Th...Ra...^{208}Pb$ (α, β)	14
$^{176}Lu/^{176}Hf$ (β)	30
$^{187}Re/^{187}Os$ (β)	42
$^{87}Rb/^{87}Sr$ (β)	50
$^{147}Sm/^{143}Nd$ (α)	100

From the U/Th -ratio in a old rock one gets its age from λ_U, λ_{Th}:
but U/Th are not in a common decay chain

→ assumptions on their relative production in the r-process

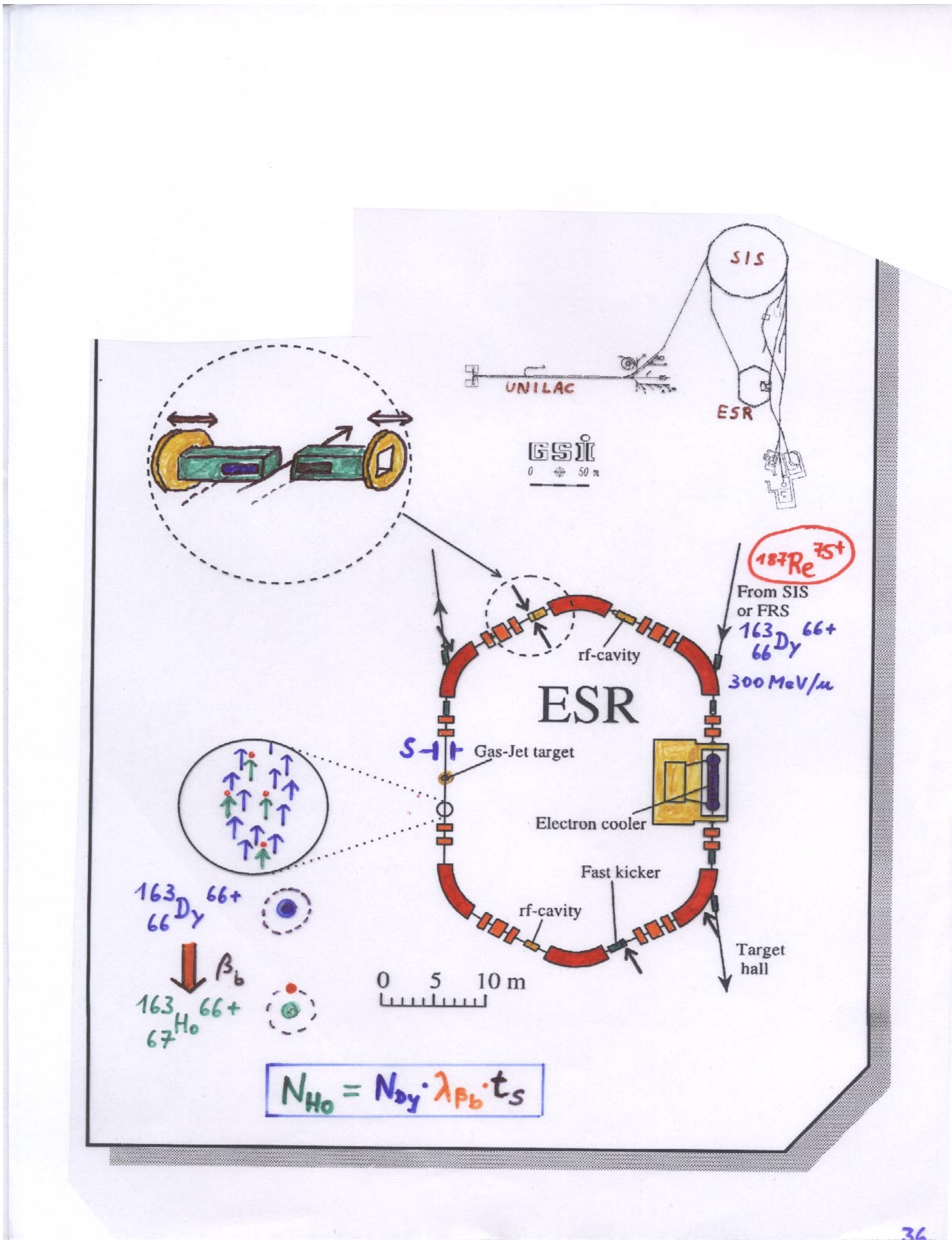
β decays better (mother/daughter)
all of them have a small Q -value (long $T_{1/2}$)

is their half-life independent on their charge state q?



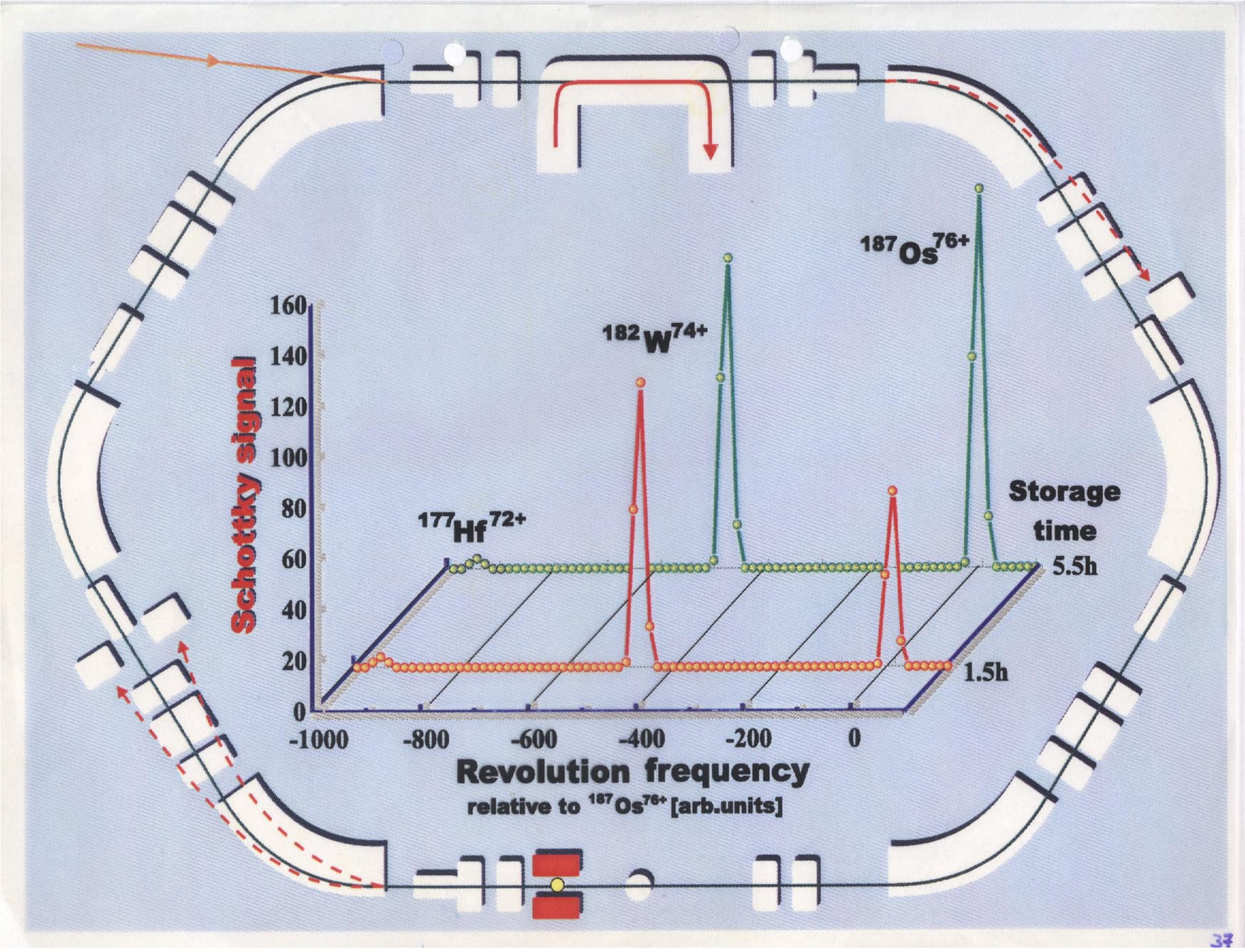
Neutral ^{187}Rhenium undergoes β^- decay to ^{187}Osmium with $T_{1/2} = 42 \times 10^9$ y.

Bare $^{187}Re^{75+}$ can decay by β_b decay to the first excited state of $^{187}Os^{75+}$ at 10 keV. The nuclear matrix element (ft-value) is not known.



Lifetime of bare $^{187}Re^{75+}$: injection of bare ^{187}Re (ion source →SIS → ESR), cooling and recording the number of β_b $^{187}Os^{75+}$ -daughters vs storage time.

Since these are not seen in the Schottky spectra (not resolved, Q -value only 53 keV), the one electron of $^{187}Os^{75+}$ is stripped off after some storage time . Then, bare $^{187}Os^{76+}$ can be seen easily in the Schottky spectrum.



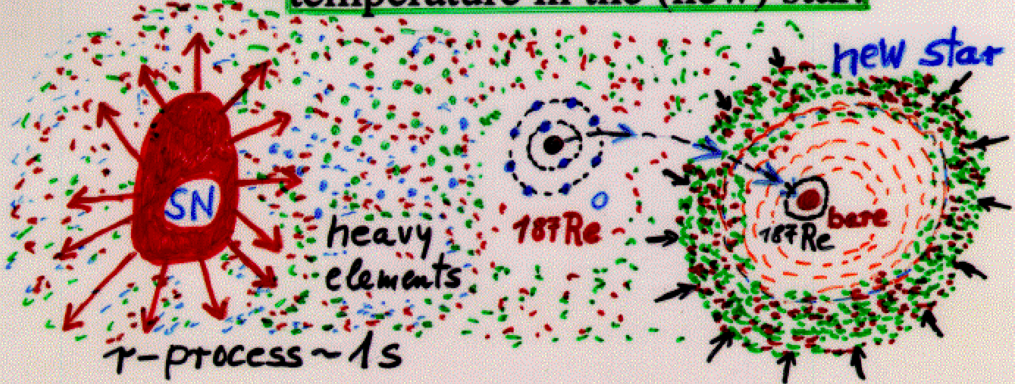
Part of the Schottky spectrum after 1.5h and 5.5h storage of bare $^{187}Re^{75+}$ (its dominant line is not shown).

To strip off the electron of the β_b daughters, hydrogen-like $^{187}Os^{75+}$ ions, a gas jet was turned on, whereby nuclear reaction products, such as ^{182}W, were generated. Their yield does not depend on storage time in contrast to ^{187}Os which grows in proportion to it.

Synopsis

The *lifetime of* ^{187}*Re depends* crucially on its ***atomic charge state***.

During the 'lifestory' of ^{187}Re in our galaxy several ***'astrations'*** occured, where ^{187}Re (and ^{187}Os) got ***highly ionized***, depending on location and temperature in the (new) star.



The halflife of 42 billion years has to be substituded by a ***much shorter 'effective' halflife***.

One has to model the ***history*** of ^{187}Re by a

stellar (galactic) evolution model.

This (and other) radioactive clock is ***not more independent*** from ***astronomical clocks***

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Present lower limits of H_0 and T_U on the 1 σ level:

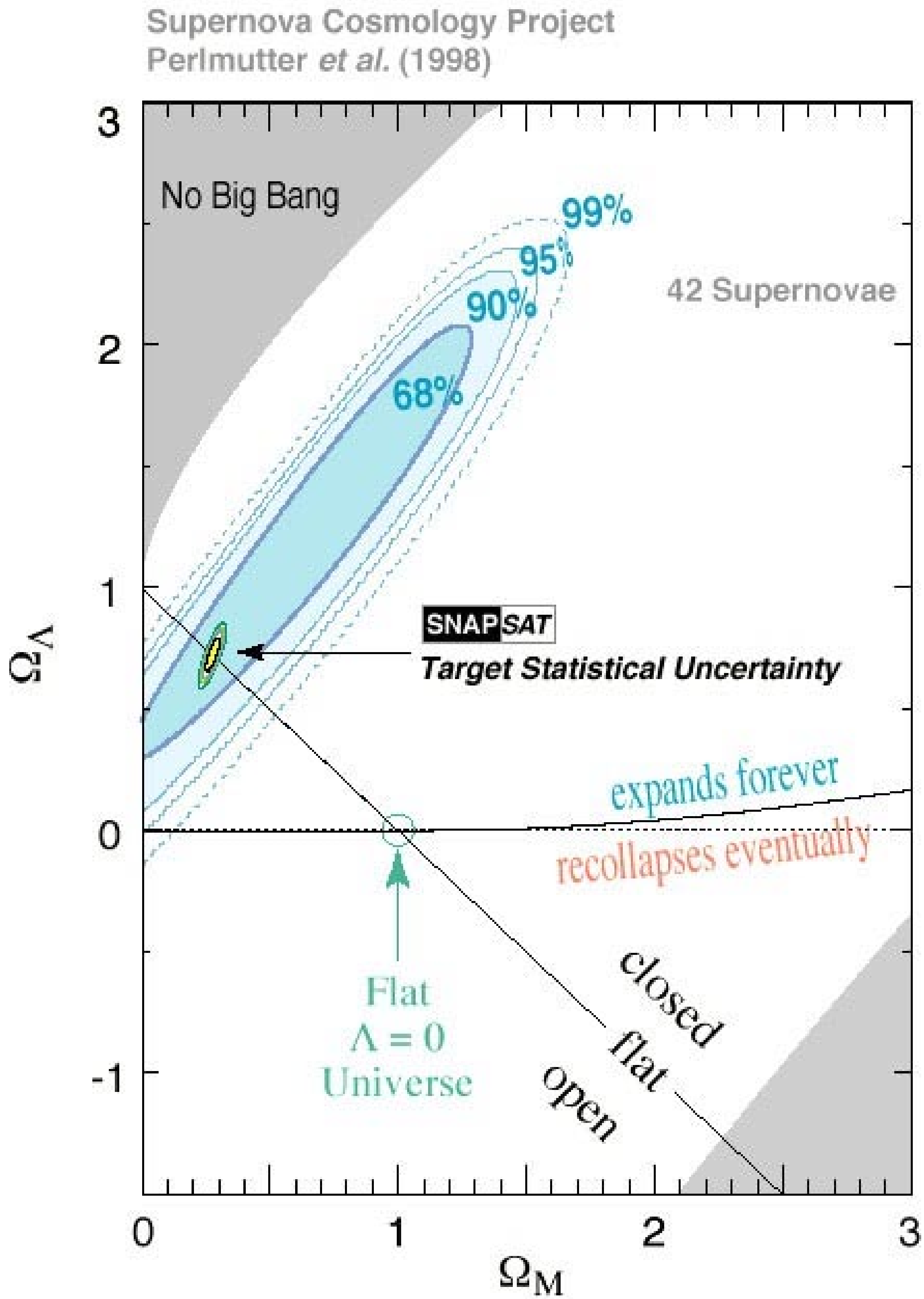
$H_0 \geq 63$ [km/(s Mpc)]
(**'Hubble key project'**, W. Friedman 1999)

$T_U \geq 11 \times 10^9$ y
(GC, U/Th - and 'recalibrated' ^{187}Re- clock)

$\rightarrow H_0 T_U \geq 693$

('Standard model' $\Omega_M = 1, \Omega_\Lambda$, $H_0 T_U = 652$)

'weak' indication for cosmology beyond the Standard model

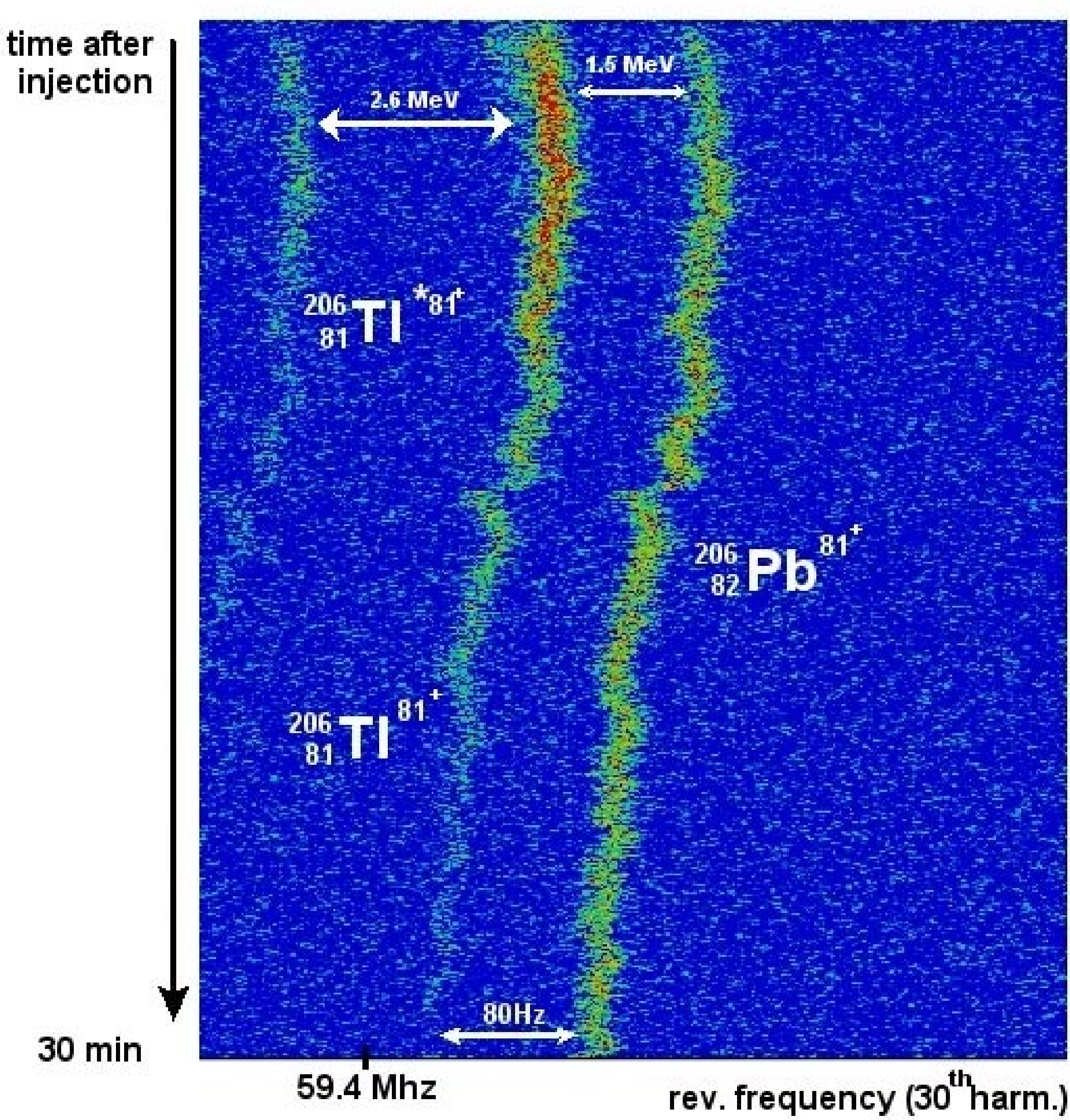


Supernova Cosmology Project
Perlmutter et al. (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
SNAPSAT
Target Statistical Uncertainty
expands forever
recollapses eventually
closed
flat
open
Flat
Λ = 0
Universe
3
2
1
0
-1
0
1
2
3
ΩΛ
ΩM

First direct observation of β_b - decay

$^{206}Tl \rightarrow {}^{206}Pb$ (Q = 1.5 MeV);

$^{207}Tl \rightarrow {}^{207}Pb$ (Q = 1.45 MeV)



☺ Summary

Ion storage-cooler rings, connected with a projectile-fragment separator, are ideal tools

- **to determine precisely as well as effectively the mass of unstable nuclei either by Schottky- ($T_{1/2}$ > 20 s) or TOF ($T_{1/2} > 10^{-6}$ s)- techniques**

- **to address the astrophysically most interesting field of β decay of highly charged ions**

- **to explore ground state properties also of nuclei far from stability (at both sides) due to the ultimate sensitivity of both techniques: one single stored ion**

☻ Outlook

- by **stochastic pre-cooling** (already successfully tested) **Schottky mass-spectrometry** will be extended down to $T_{1/2} \approx 1$ s.

- **nuclear reaction- and structure physics** (at the ESR internal target) with radioactive beams will become feasible **after intensity upgrading**

- presently the **expected luminosity** for ions near stability, $L \approx 10^{26}\ cm^{-2}\ s^{-1}$ (10^6 stored ions, 1 MHz revolution frequency, $10^{14}\ cm^{-2}$ gas-target atoms) still is **too small** by a **factor of 10...100.**

- a mid- and long-term perspective of GSI is the **facility to come** with new rings and a new fragment separator to address (inter alia) **the structure of nuclei far off stability.**

- worlwide are **other ion cooler-rings for RNB already under construction** or at least seriously considered (**MUSES, HIRFL**, K4, MAFFIA...)

Some references

A stochastic cooling

G. Carron, L. Thorndale	CERN-ISR-RF/**78-12** (1978)
D. Möhl	Phys. Rep. **58** (1980) 73
F. Nolden et al.	Nucl. Phys. **A626** (1997) 491c
S. van der Meer	Nobel lecture 1984, Les Prix Nobel 1**984** p. 192

B electron cooling

G.I. Budker	At. Energy **22** (1967) 346
H. Poth	Phys. Rep. **196** (1990) 135
I. Meshkov	Nucl. Phys. **A626** (1997) 459c
M. Steck et al.	Nucl. Phys. **A626** (1997) 495c

C laser cooling

S. Schröder et al.	Phys. Rev. Lett. **64** (1990) 2901
W. Petrich et al.	Phys. Rev. **A 48** (1993) 2127
J. Hangst et al.	Phys. Rev. Lett **74** (1995) 4432

D masses, bound beta decay and nuclear astrophysics

E.M.Burbidge, G.R. Burbidge, W.A. Fowler and F. Hoyle	Rev. Mod. Phys. **29** (1957) 547 (**seminal paper** of nuclear astrophysics)
F. Kaeppeler et al.	Annu. Rev. Nucl. Part. Sci. **48 (**1998**)** 175 (r-, s- process)
B. Pfeiffer et al.	Z. Phys. **A357** (1997) 235 (r- abundance of elements)
F. Attallah et al.	Nucl. Phys. **A701** (2002) 561c (Schottky mass mesurements)
M Hausmann et al	NIM **A446** (2000) 569 (isochronous mass measurements)
T. Radon et al.	Nucl. Phys. **A677** (2000) 75 (Schottky mass measurements)
Yu. A. Litvinov et al.	Hyperfine Interactions **132** (2001) 283 (Schottky mass m.)
M. Jung et al.	Phys. Rev. Lett. **68** (1992) 2164 (detection of β_b decay)
O. Klepper	Nucl. Phys. **A626** (1997) 199c (lifetime measurem. at ESR)
F. Bosch et al.	Phys. Rev. Lett. **77** (1996) 5170 (β_b decay of ^{187}Re)
F. Bosch	Atomic Physics **16**, ICAP Proceedings, Windsor 1998, p.344 (Rhenium and the age of the Universe)
W.F. Henning ed.	Conceptual Design Report, GSI, **not** publ. (future GSI facility)