Sunshine by cooling

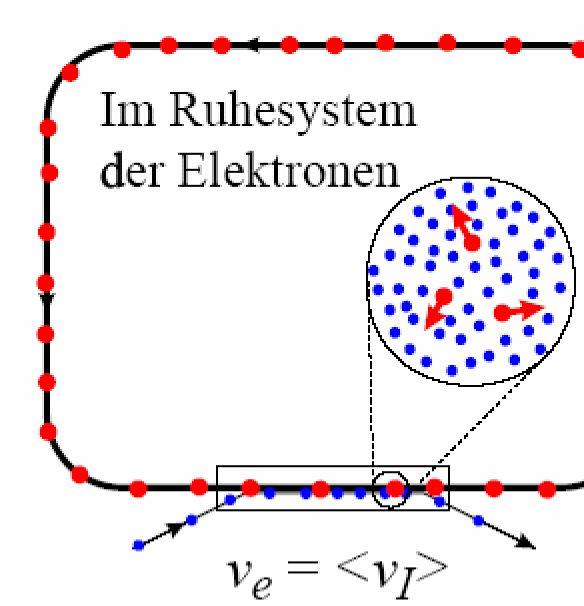
- Van Hove 1984: „Sunshine at GSI if cooling works, if not wicked darkness.“
- The sun is shining – cooling works
- Cooling methods
- LEAR and his daughters
- Ordered beams
- Sunshine at ESR
- Beam cooling quo vadis?

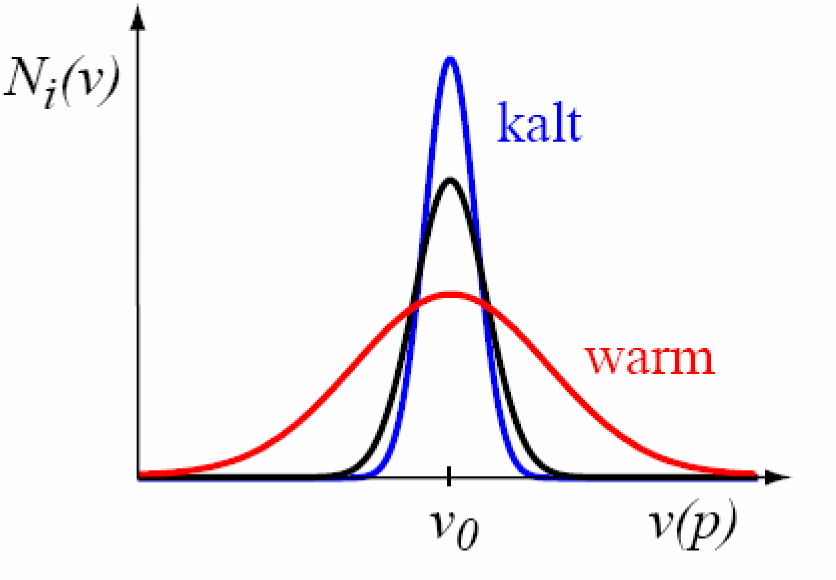
- P.Kienle, Naturwissenschaften, 88(2001) 313

Budgers proposal

- G. I. Budger, Novosibirsk (1966)
- Cooling of stored ion-beams by Mott-scattering using a comoving "cold" electron-beam

Principle of electron cooling





Cooling time

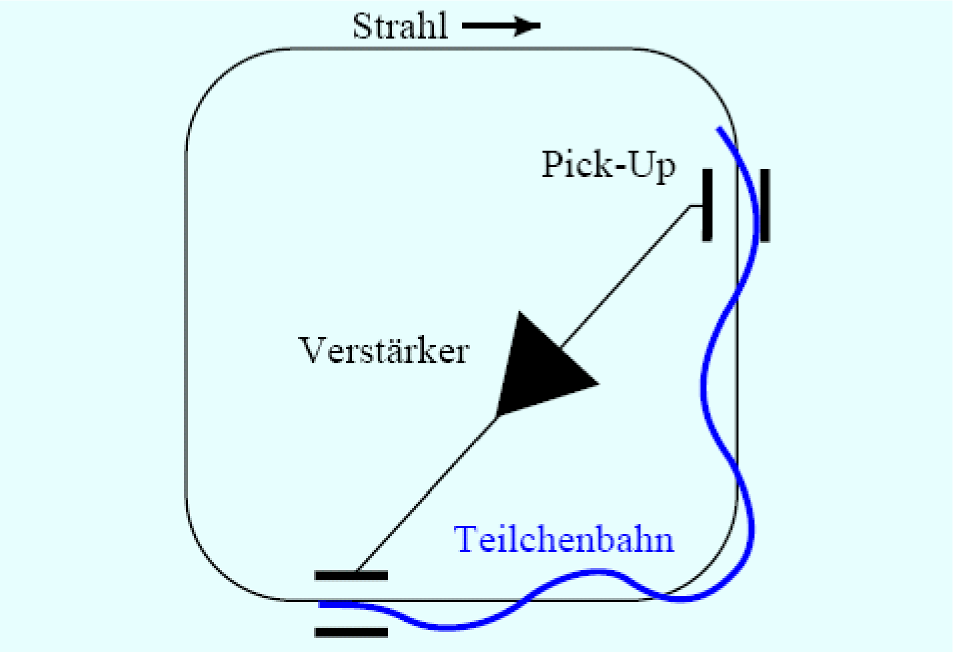
$$\tau_c \sim \frac{m}{Z^2} \cdot \frac{1}{n_e}$$

Van der Meer`s proposal

Van der Meer, CERN (1968)

"Stochastic cooling" for high energy and low phase space density beams

Principle of stochastic cooling



Cooling time

$$\tau = \frac{K \cdot N}{W}$$

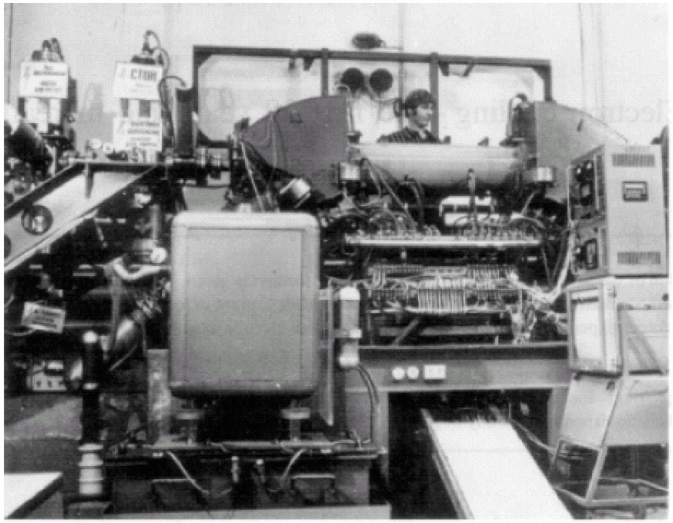
Example $N = 10^{12}$, $W = 10$ GHz , $K = 10$: $\tau = 10^3$ s

Development of electron cooling

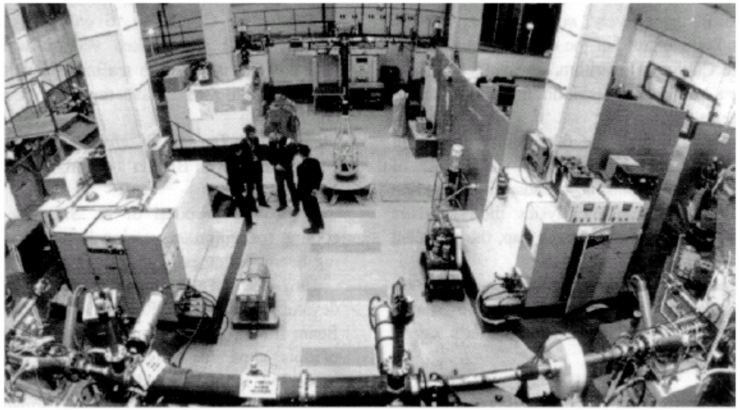
Novosibirsk (1975)

- EPOKHA: electron cooler with regeneration of the electron beam and strong longitudinal B-field

EPOKHA



NAP-M-Speicherring

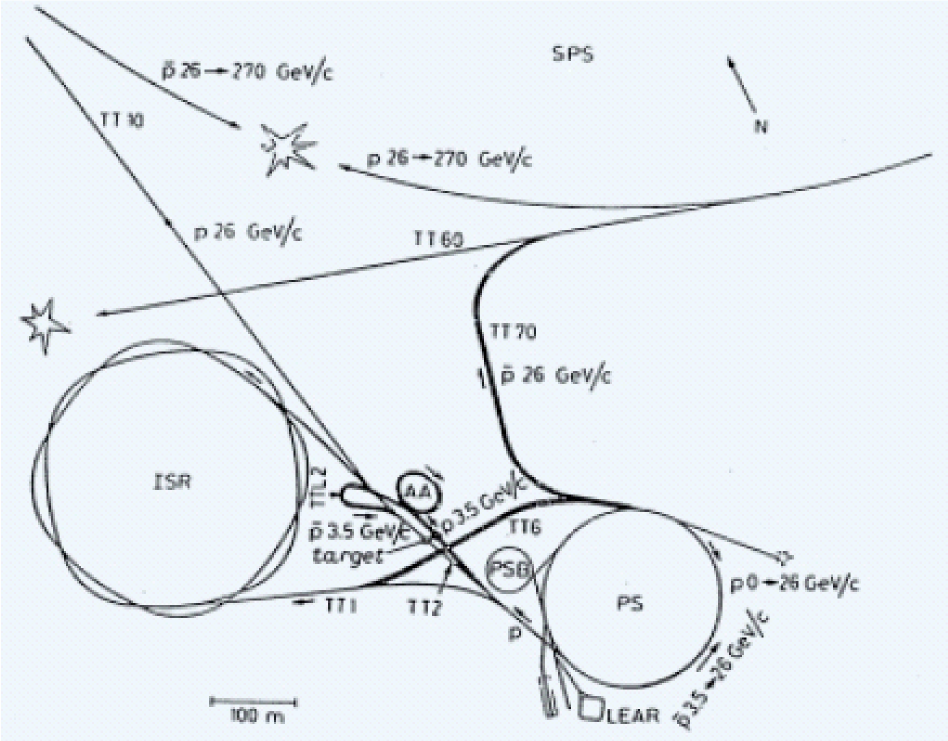


Development of stochastic cooling

CERN (1975)

- Demonstration in the ISR-ring
- Cooling of antiprotons (Thorndale)
- Rubbia et al.: *pp*-collisions (1981-83)

CERN antiproton source



Discoveries

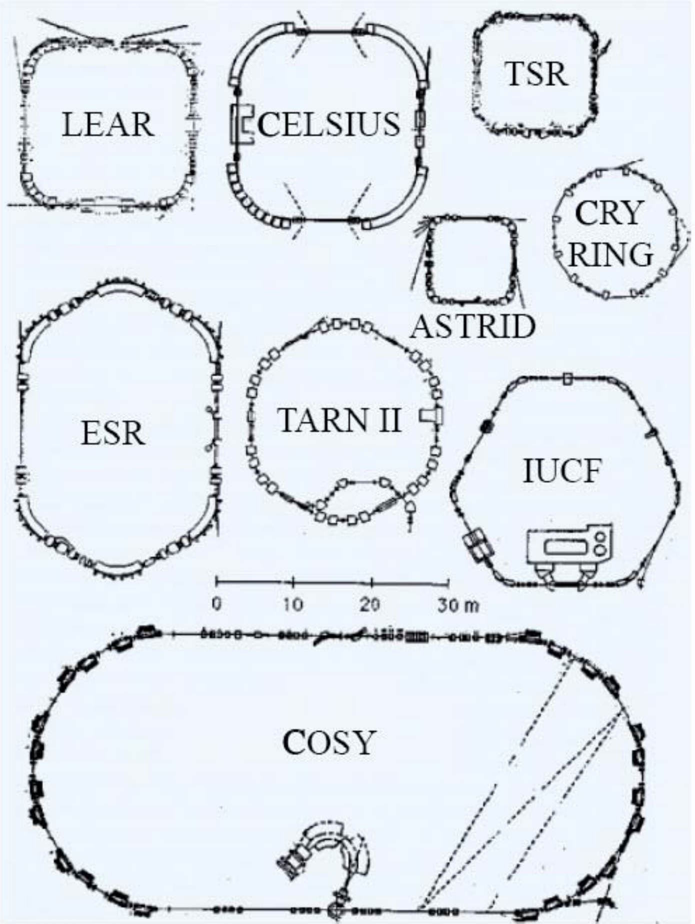
1982-84 Z- and W-Bosons

1995 Discovery of the top-quark

LEAR and his „daughters“

LEAR, a low energy antiproton ring at CERN had stochastic and electron cooling followed by a generation of rings in the 80ies

IUCF-Cooler (Indiana), TSR (Heidelberg), CELSIUS (Uppsala), TARN II (INS Tokyo), ESR (GSI Darmstadt), CRYRING (Stockholm), ASTRID (Aarhus), COSY (Jülich)

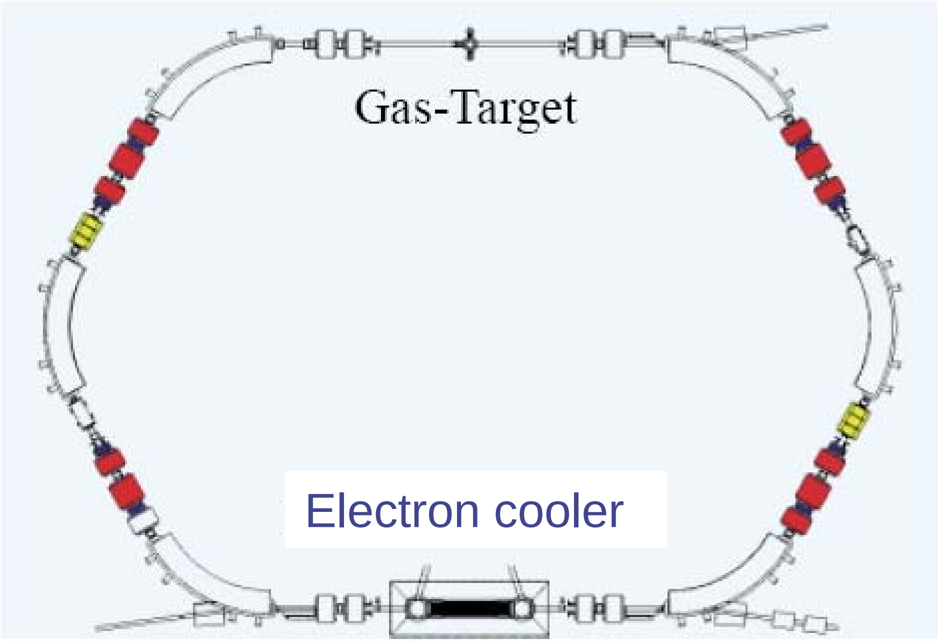


Ion cooling of all elements up to uranium including radioactive nuclei (ESR)

Development of laser cooling of Li and Be ions (TSR, ASTRID)

ESR - heavy ion-cooler ring

- Electon cooler: U = 310 kV, I < 3A, L = 2.5 m
- All ions at energies up to 500 MeV/u
- Cooling time ~ A/Z² about 100 ms for U^{92+}
- $\Delta p/p$: $2 \times 10^{-3} \rightarrow 10^{-6} \sim N^{1/3}$
- ε_{xy}: 5 π mm mrad →0.1 π mm mmrad



- High circulating currents: $I = N \times f$
- High luminosities with internal targets

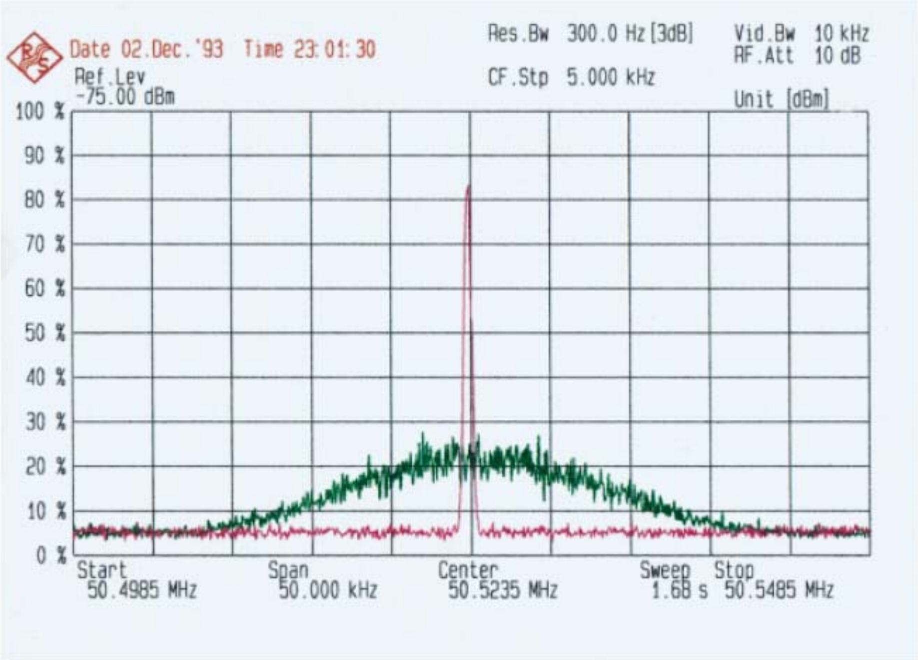
Schottky-Noise-Frequency Spectroscopy

$$S(\omega)_n = \int \langle \gamma I_n(0) \gamma I_n(\tau) \rangle \exp(i\,\omega\,\tau)\; d\tau$$

Relative width of Schottky-Noise-frequency distribution

$\Delta f/f = \eta\,\gamma\,(\Delta p/p)$ $\eta = 1/\gamma^2 - 1/(\gamma_{tr})^2$ ESR: $\gamma_{tr} = 2.67$

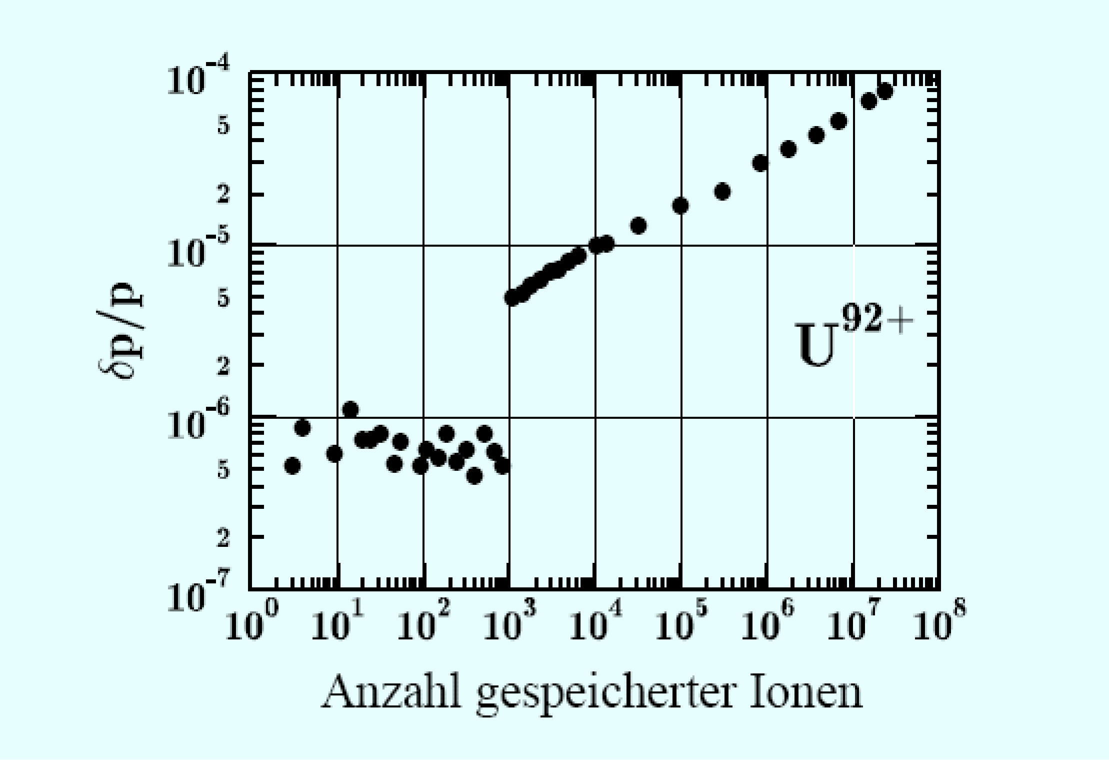
Schottky noise spectrum of an uranium beam in the ESR



Observation of beam temperature transition

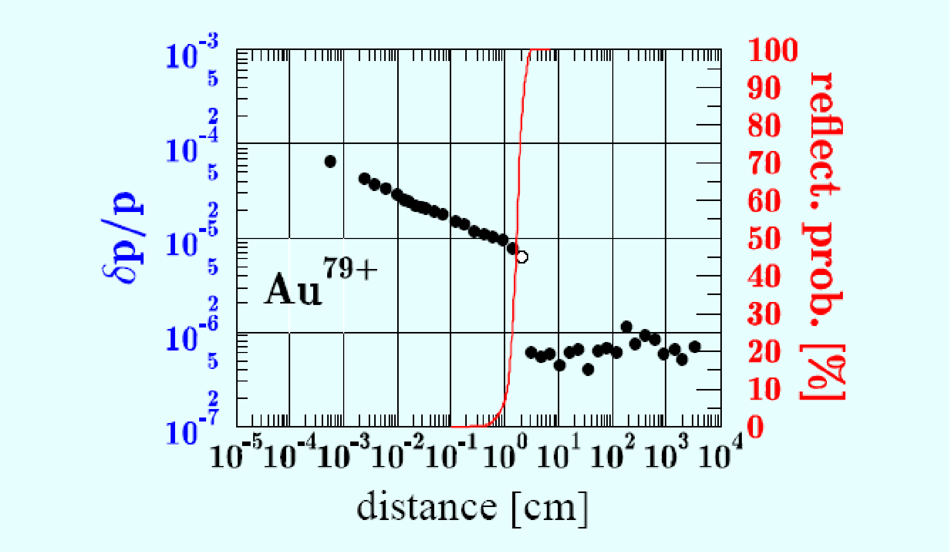
Steck et al., PRL 77, 3803, 1996

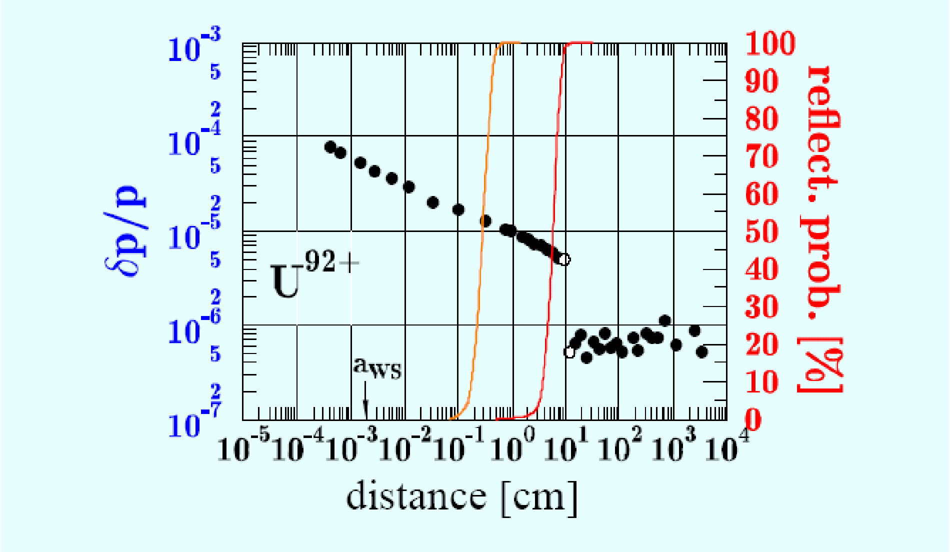
Suppression of „Intra-Beam"-scattering of cooled heavy ions below a critical particle number



Coulomb ordering of ions in ESR

R. W. Hasse, PRL 83, 3430, 1999

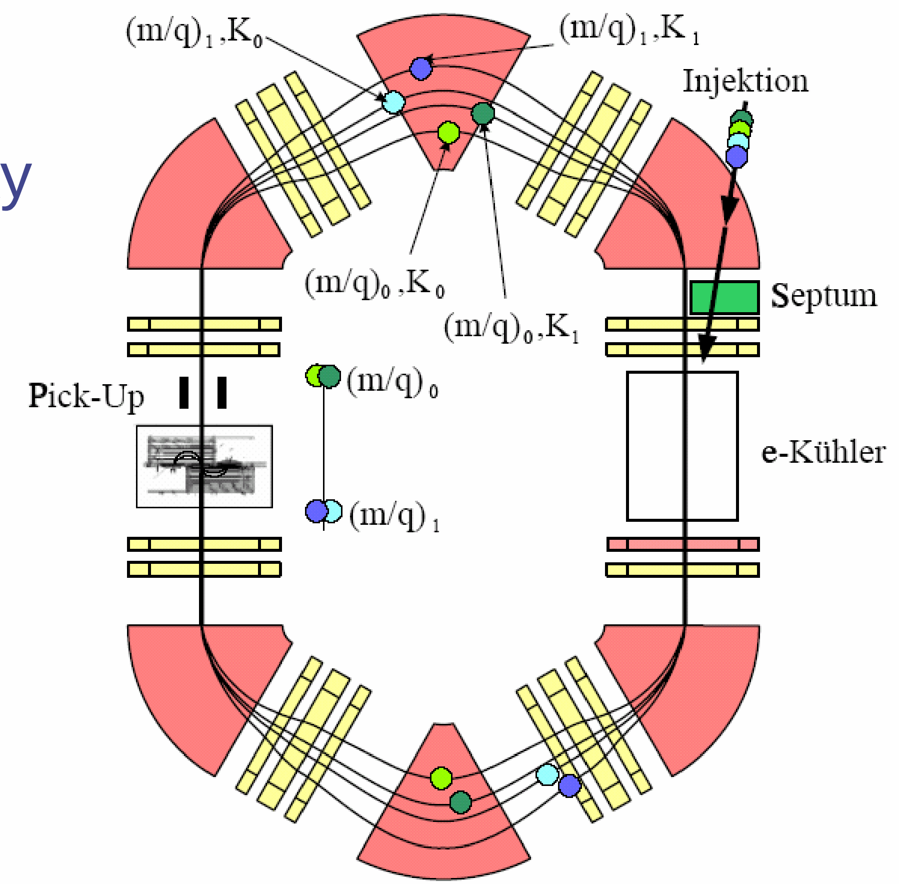




Schottky-Mass-Spectroskopy

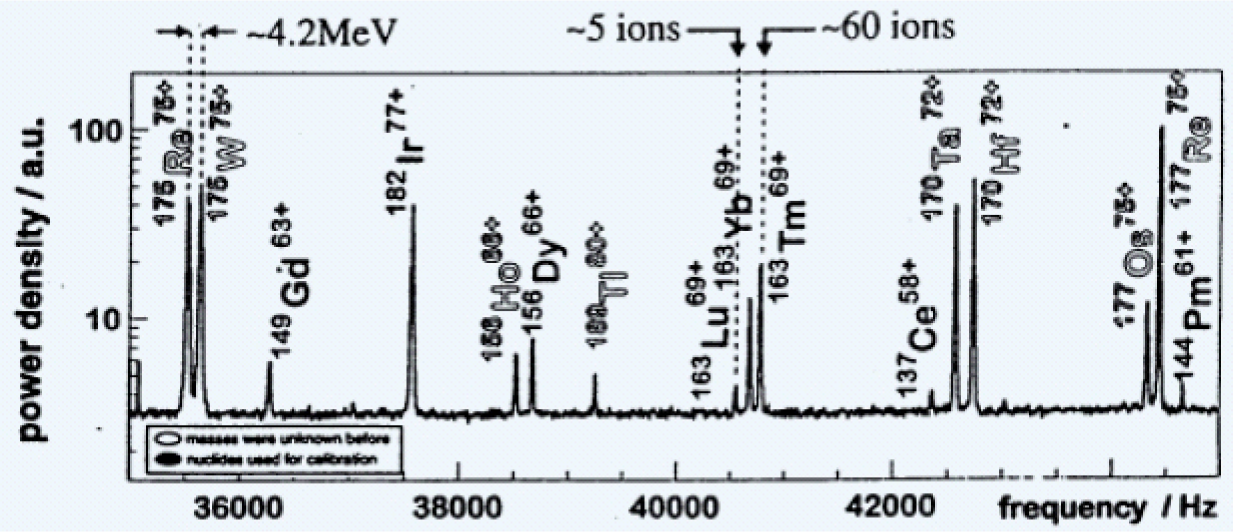
- Direct mass measurement of radioactive nuclei produced by beam fragmentation at 1 GeV/u
- Improved mass resolution and detection efficiency at small particle numbers

Principle of Schottky mass spectroscopy



Status of Schottky-Mass-Spectroskopy

- Mass measurements relativ to known masses
- Mass resolution $\Delta m/m \sim 1 \times 10^{-6} = < 50$ keV/c²
- Single nuclei detectable
- Halflife > 10 s
- Isochroneous operation



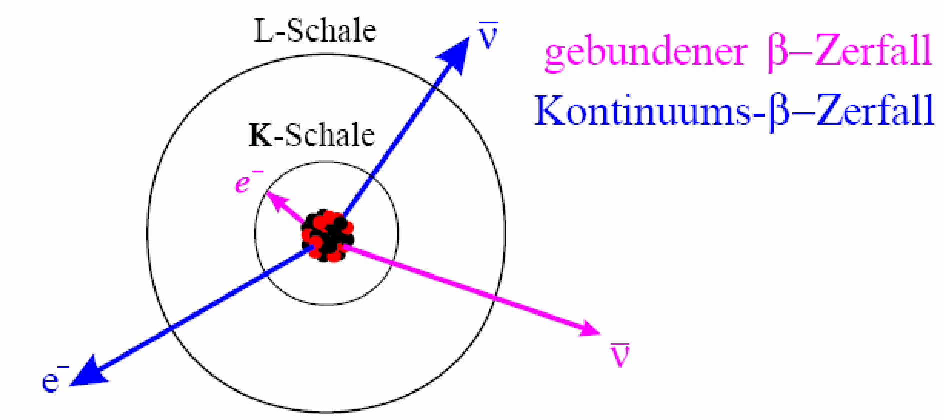
Discovery of the bound β-decay

In completely ionised nuclei the decay electrons are captured in the K-shell

$$Q^{K}_{\beta_b} = Q_{\beta} - [B^{e}(Z+1) - B^{e}(Z)] + B^{e}_{K}(Z+1)$$

$$\lambda_{\beta_b} \approx Q^{2} \cdot |\Psi(0)|^{2}$$

β decay in the continuum and to the K state

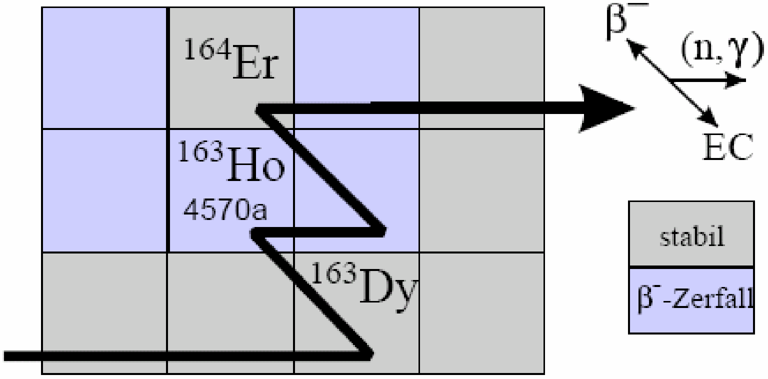


First observation M. Jung et al.: PRL 69, 2164, 1992

^{163}Dy^{0} stable nucleus

$^{163}\mathrm{Dy}^{66+} \rightarrow {}^{163}\mathrm{Ho}^{66+} + \bar{\nu}_e$

$T_{1/2} = (48 \pm 3)$ d



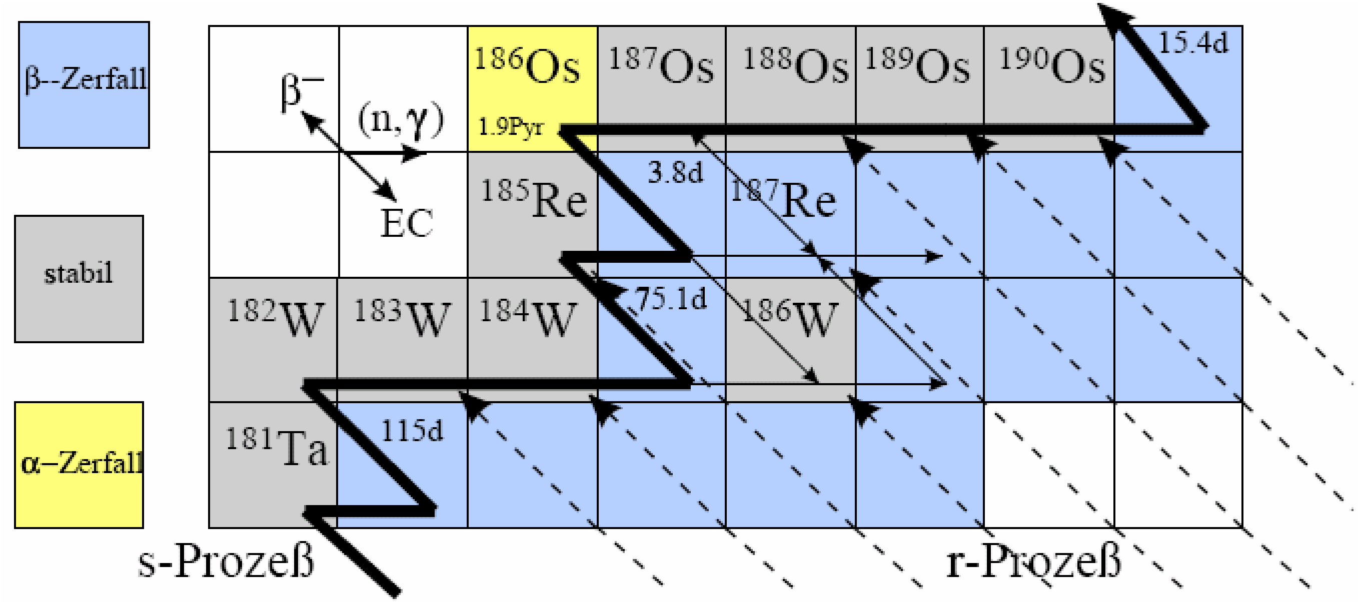
s-Prozess (für hochionisierte Kerne)

Cosmochronometry with the Re/Os-clock

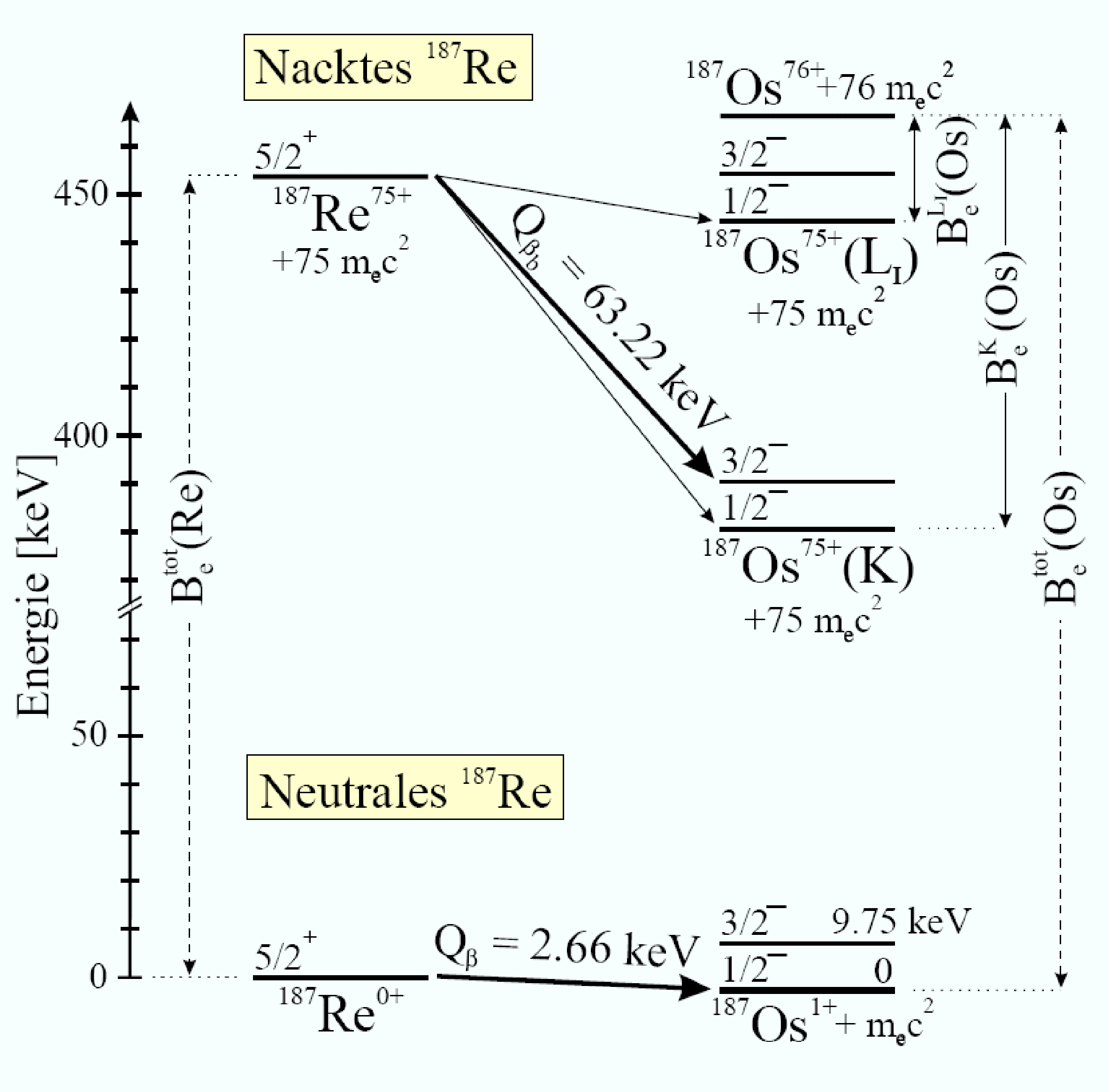
- Isotopic ratio of $^{187}Re/^{187}Os$ in old meteorites can be used to determine the time of the nuclear synthesis t_s of ^{187}Re produced by the r-process

$$N_{^{187}Os}(t_s) = \lambda(^{187}Re)\; N_{^{187}Re} \cdot t_s$$

- 187Re: T1/2 = 42 Gy
- 187Os: mostly radiogen
- But T1/2 of highly ionised Re in a star plasma is determined by bound β-decay

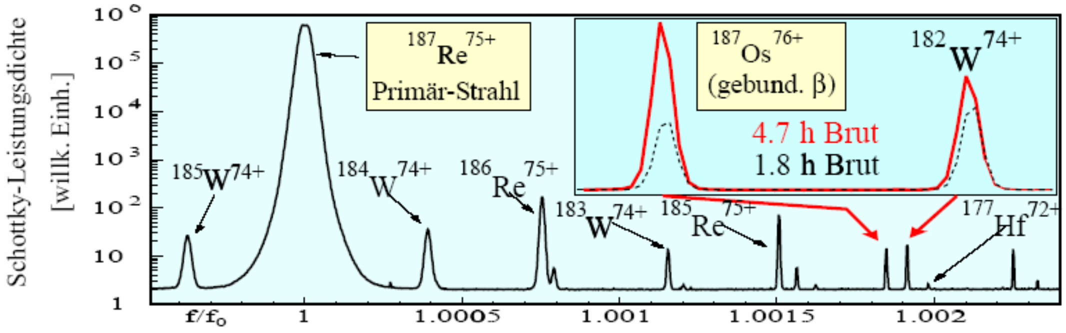


^{187}Re-^{187}Os Beta-decays



Detection of Os^{76+}

Schottky spectrum

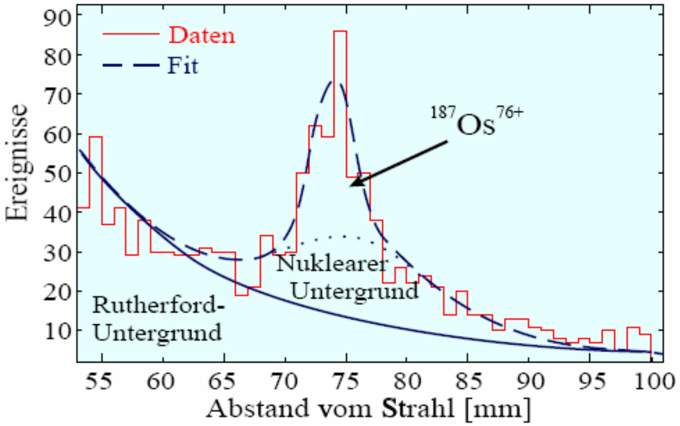


Magnetic analysis

Speicherzeit = 4 h

$N_{Re}(t_s) = 6 \cdot 10^7$

$N_{Os}(t_s) = 182$

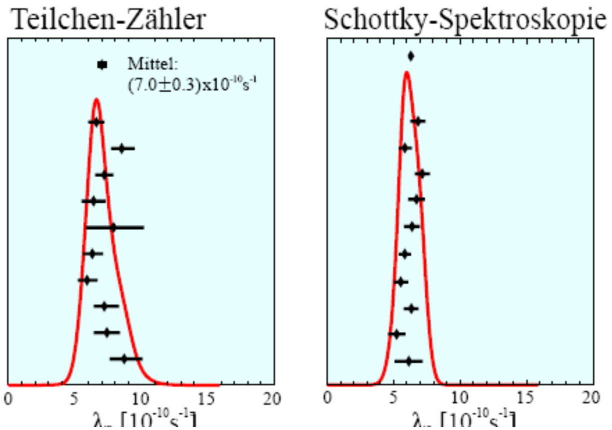


Results

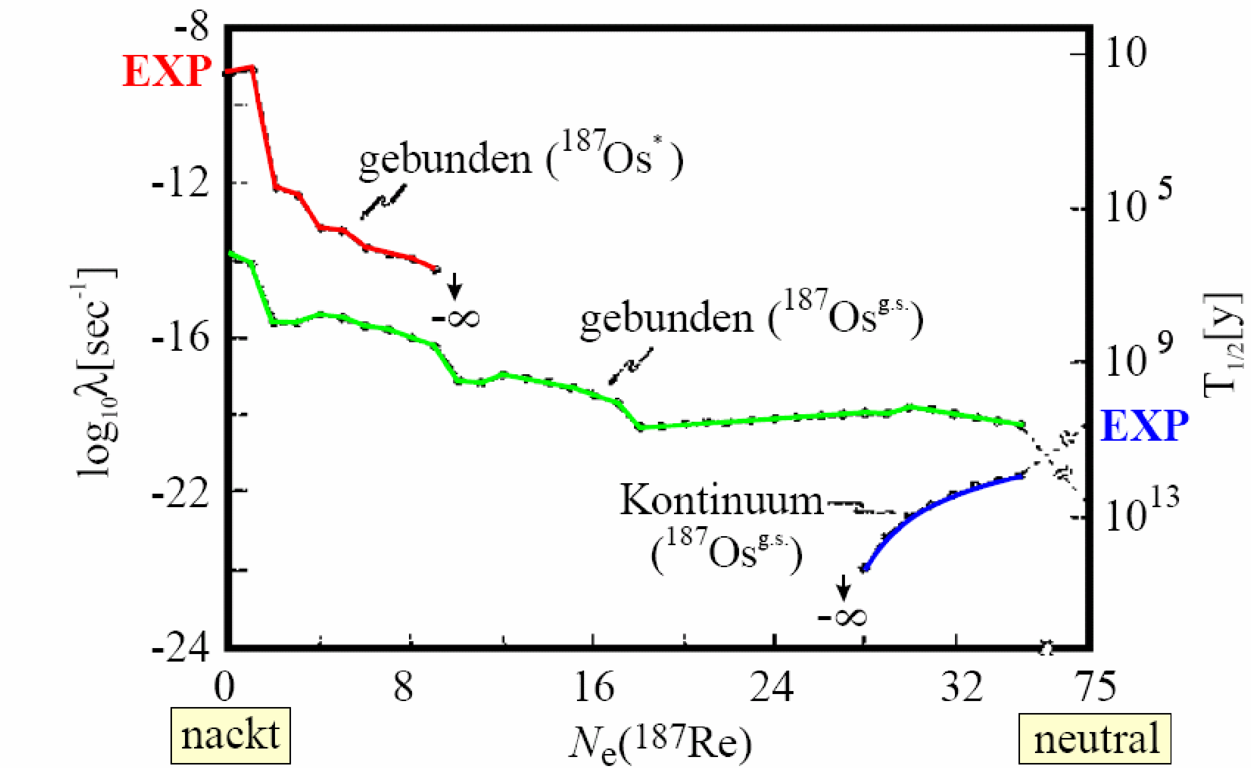
$\lambda_{\beta_b} = 6.7 \pm 0.4 \cdot 10^{-10}\ s^{-1}$

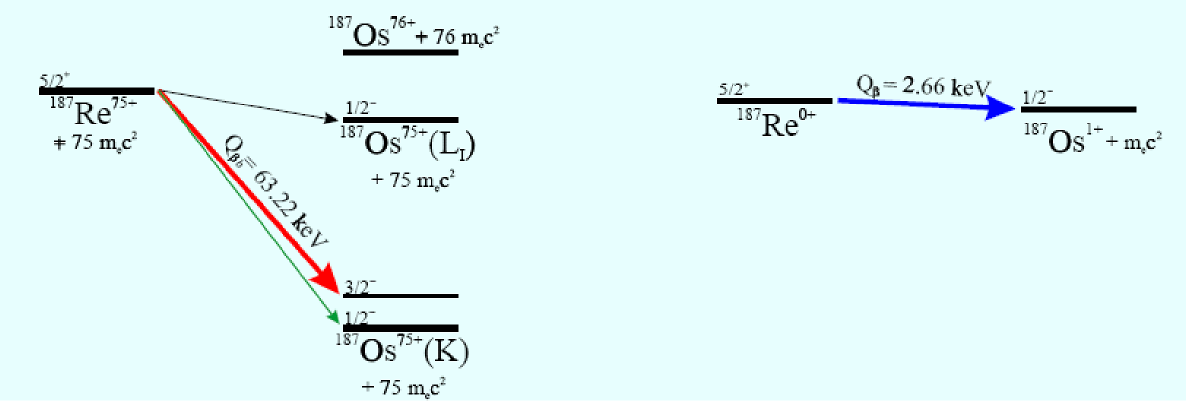
$T_{1/2} = 32.9 \pm 2.0$ yr

$\log ft = 7.87 \pm 0.03$



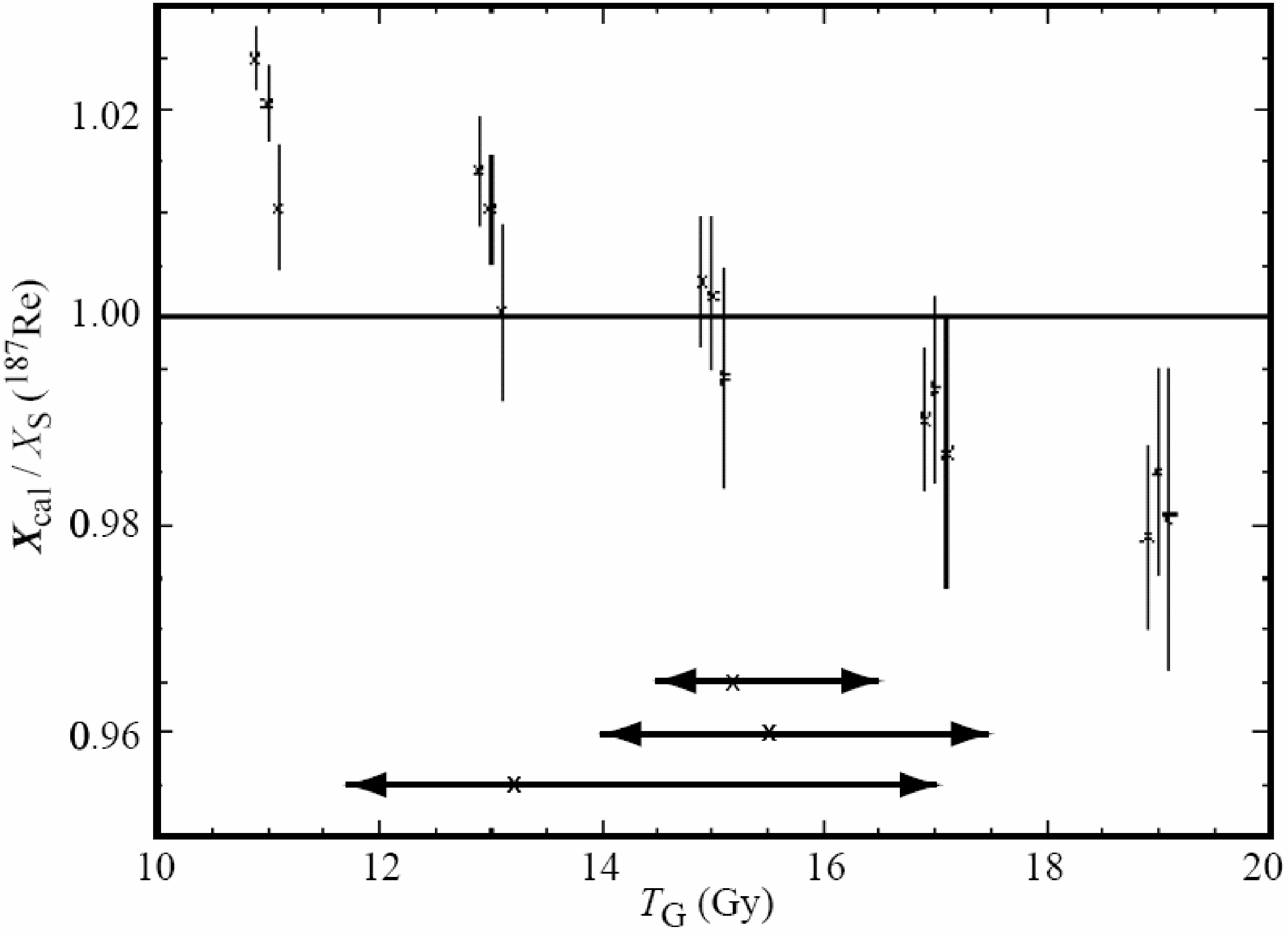
Halflife of ^{187}Re





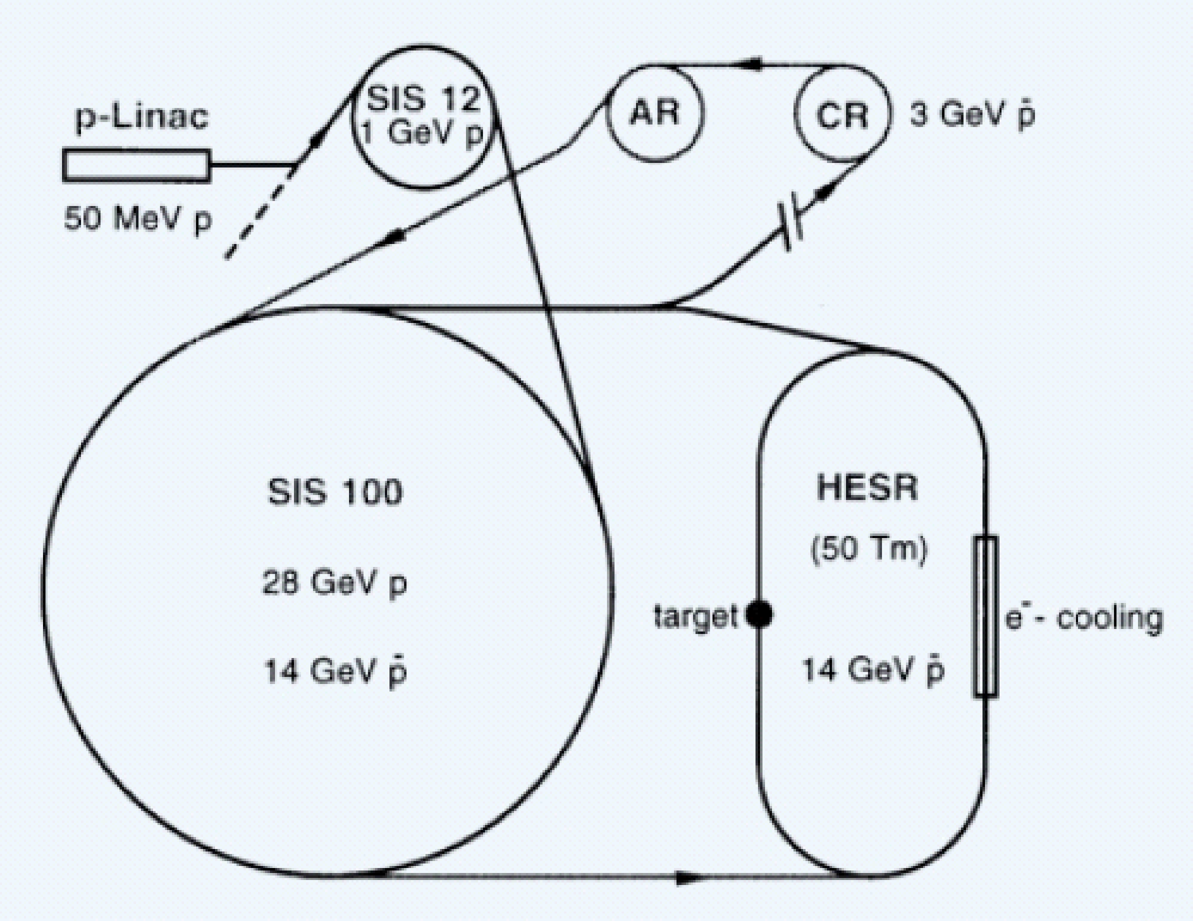
Age of the Galaxy

K. Takahashi, 1999

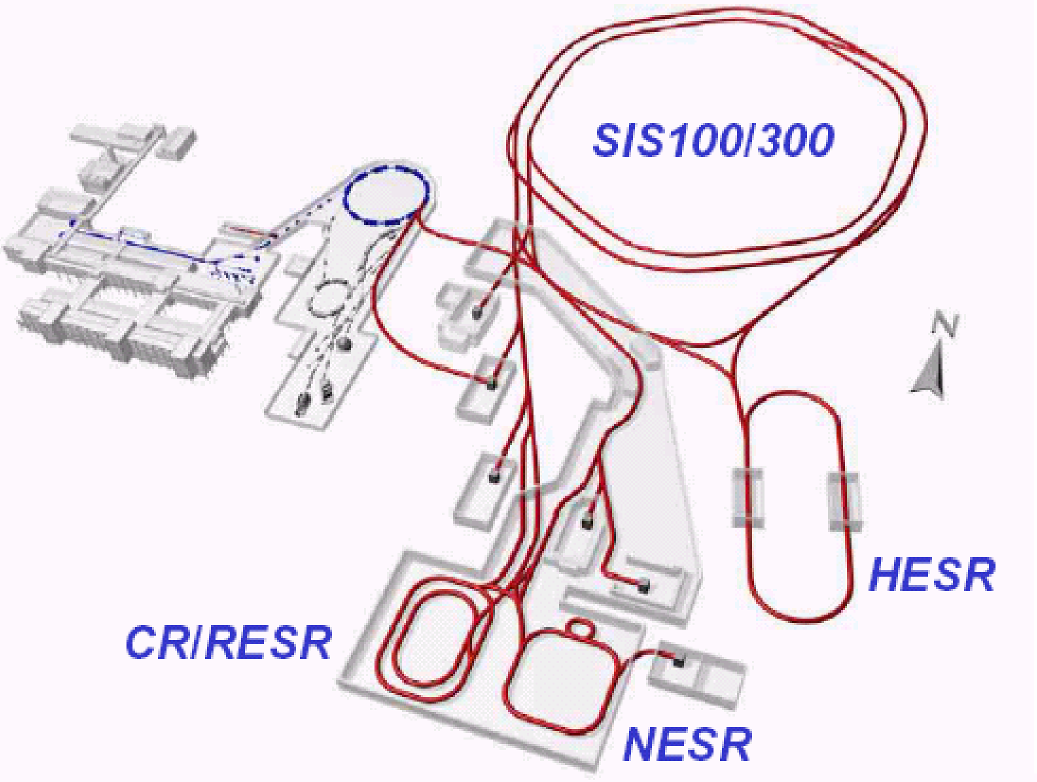


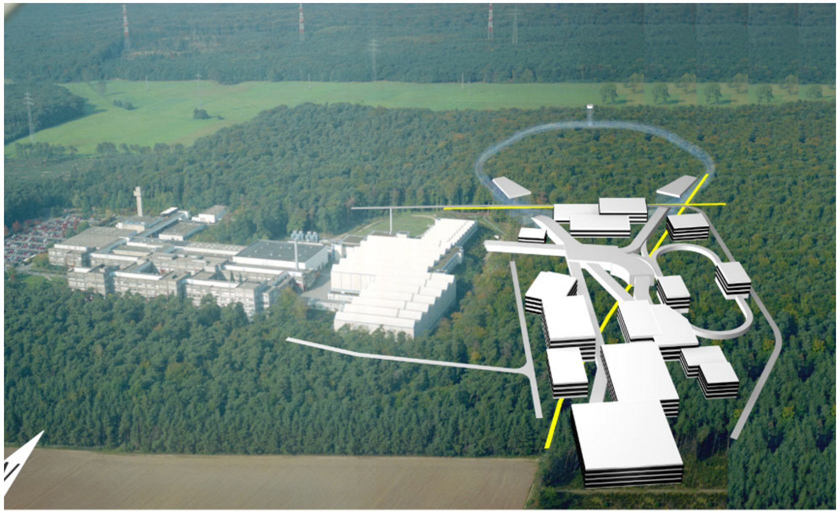
Age of the Galaxy: (15±2)Gy

HESR – high energy storage ring for antiprotons



FAIR – Facility for Antiproton Ion Research





FAIR – Storage Rings