Nuclear Structure and Astrophysics

Yuri A. Litvinov

Instrumentation, detection and simulation in modern Nuclear Physics

ecole Joliot-Curie School 2015

Physics at Storage Rings

Single-particle sensitivity | High atomic charge states | Long storage times

Broad-band measurements | High resolving power | Very short lifetimes

Direct mass measurements of exotic nuclei

Radioactive decay of highly-charged ions

Charge radii measurements [DR, scattering]

Experiments with polarized beams

Experiments with isomeric beams [DR, reactions]

Nuclear magnetic moments [DR]

Astrophysical reactions [(p,g), (a,g) ...]

In-ring nuclear reactions

Experimental Storage Ring ESR

Experimental Cooler-Storage Ring CSRe

Low-Energy Storage Ring TSR at ISOLDE

New Storage Ring Complex at FAIR

New Storage Ring Complex at HIAF

Low energy ring CryRING@ESR

RI-RING at RIKEN

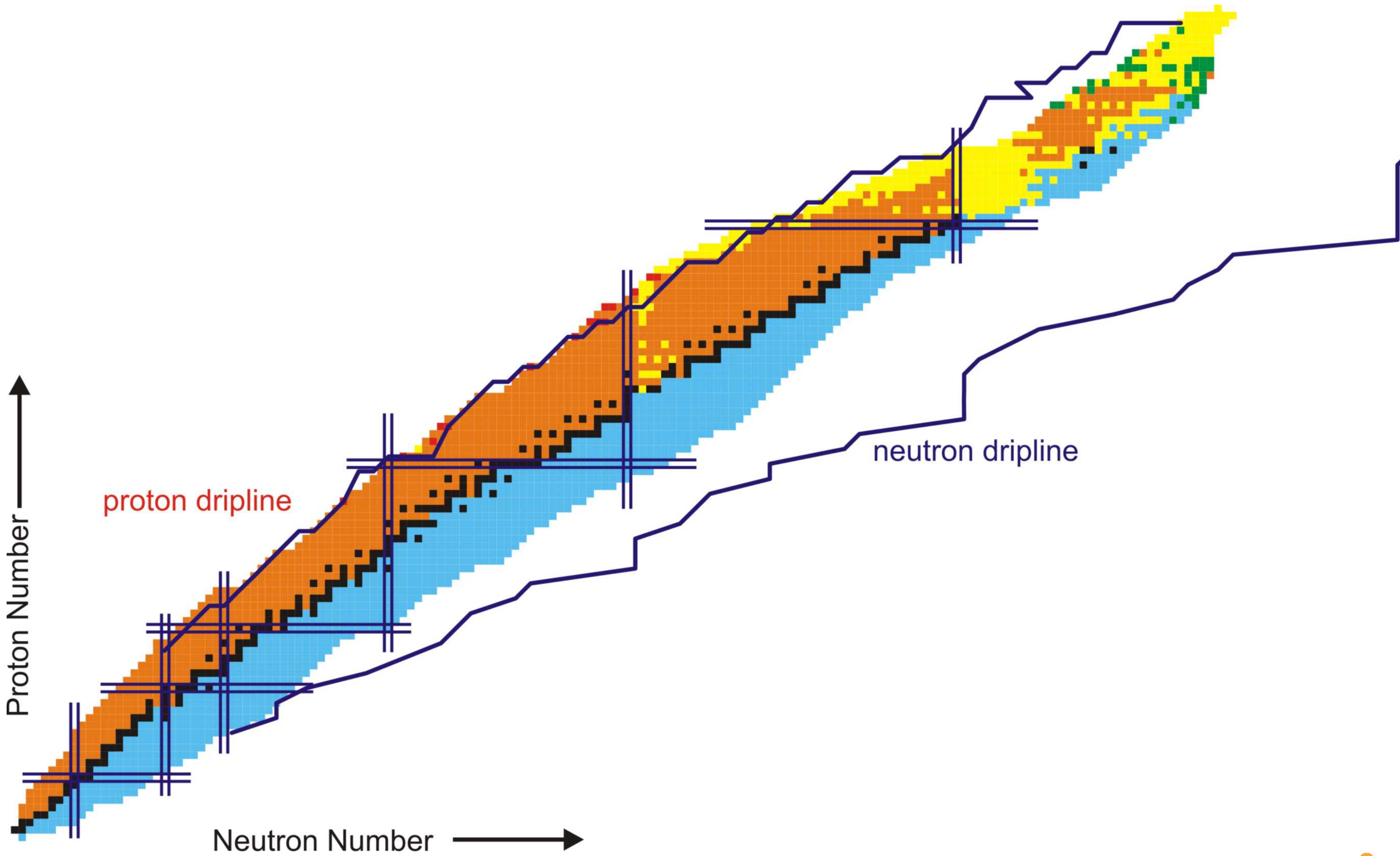
National Research Council's board on physics and astronomy

02.01.2002
The 11 Greatest Unanswered Questions of Physics

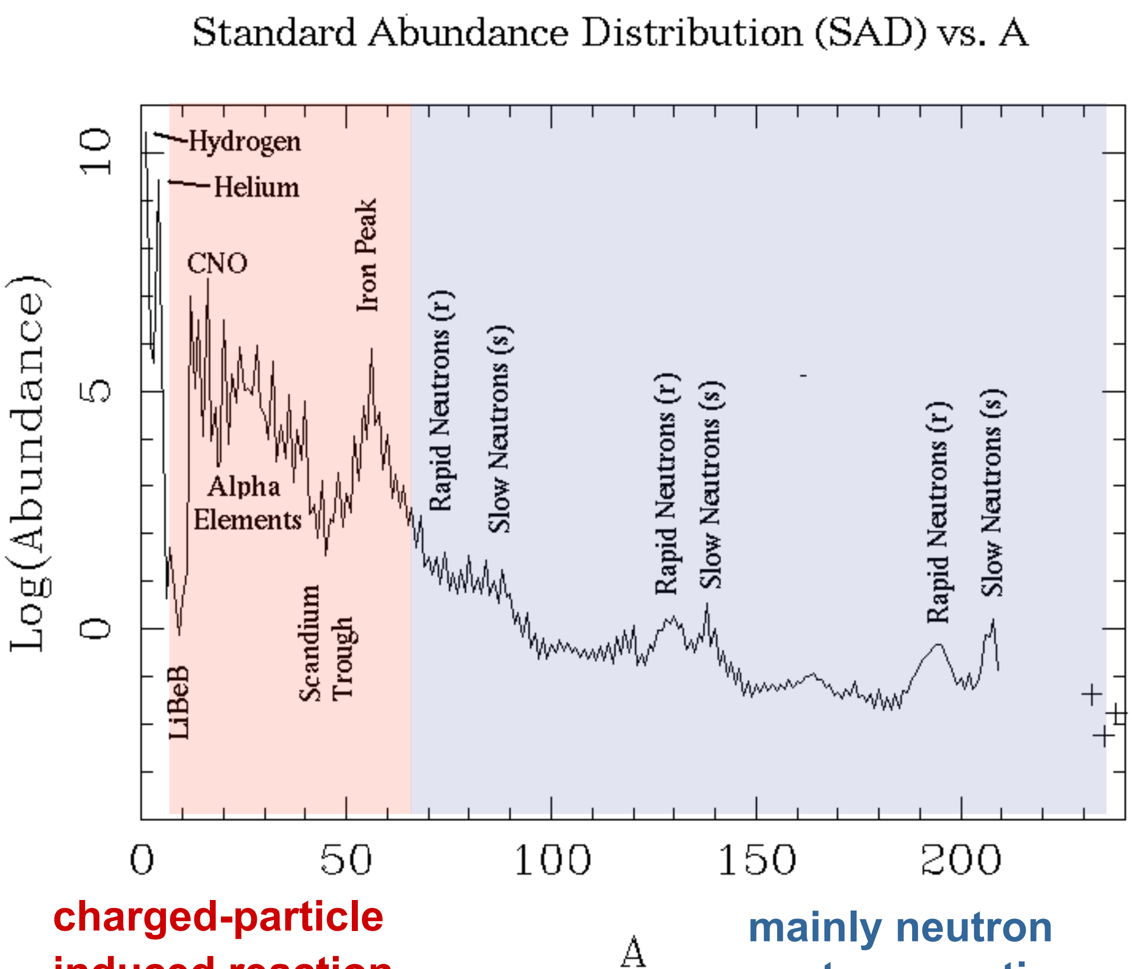
Resolution of these profound questions could unlock the secrets of existence and deliver a new age of science within several decades
by Eric Haseltine, Illustrations by Dan Winters & Gary Tanhauser

3. How were the heavy elements from iron to uranium made?

The Chart of Nuclides



Nuclear processes in astrophysics



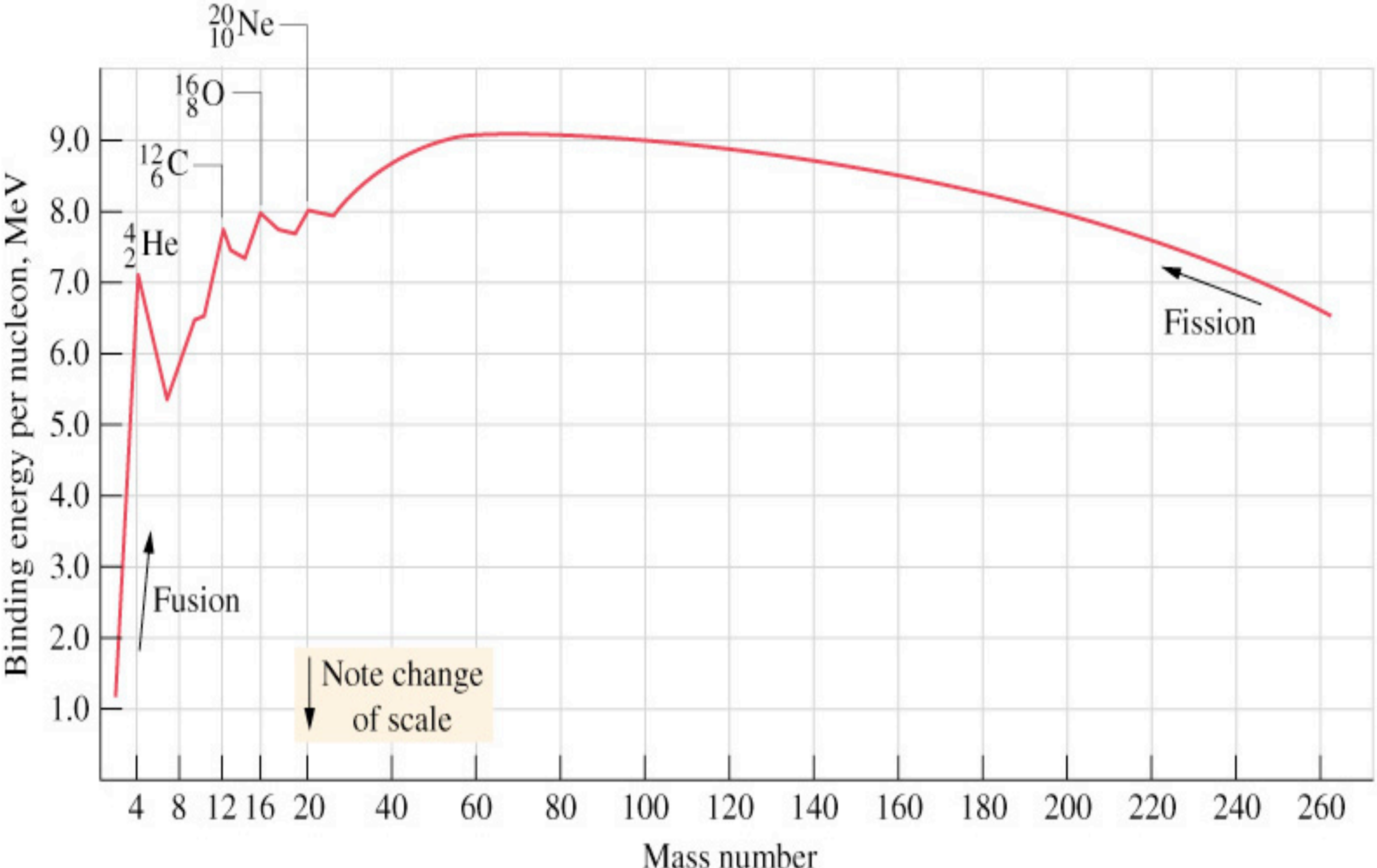
charged-particle induced reaction

mainly neutron capture reaction

involve mainly STABLE NUCLEI

involve mainly UNSTABLE NUCLEI

Stellar nucleosynthesis: fusion until iron

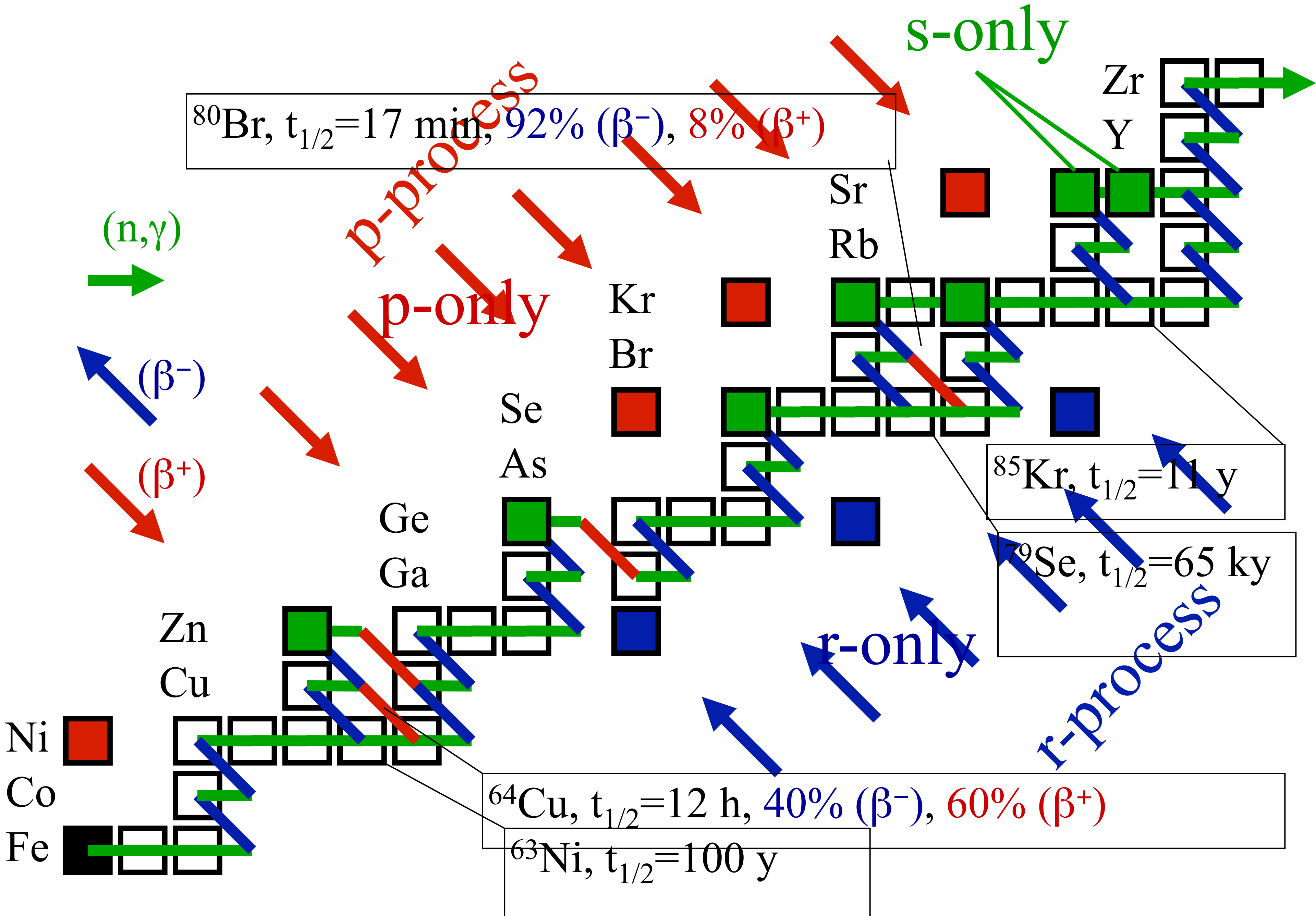


Nucleosynthesis after Big Bang: only He and Li are produced

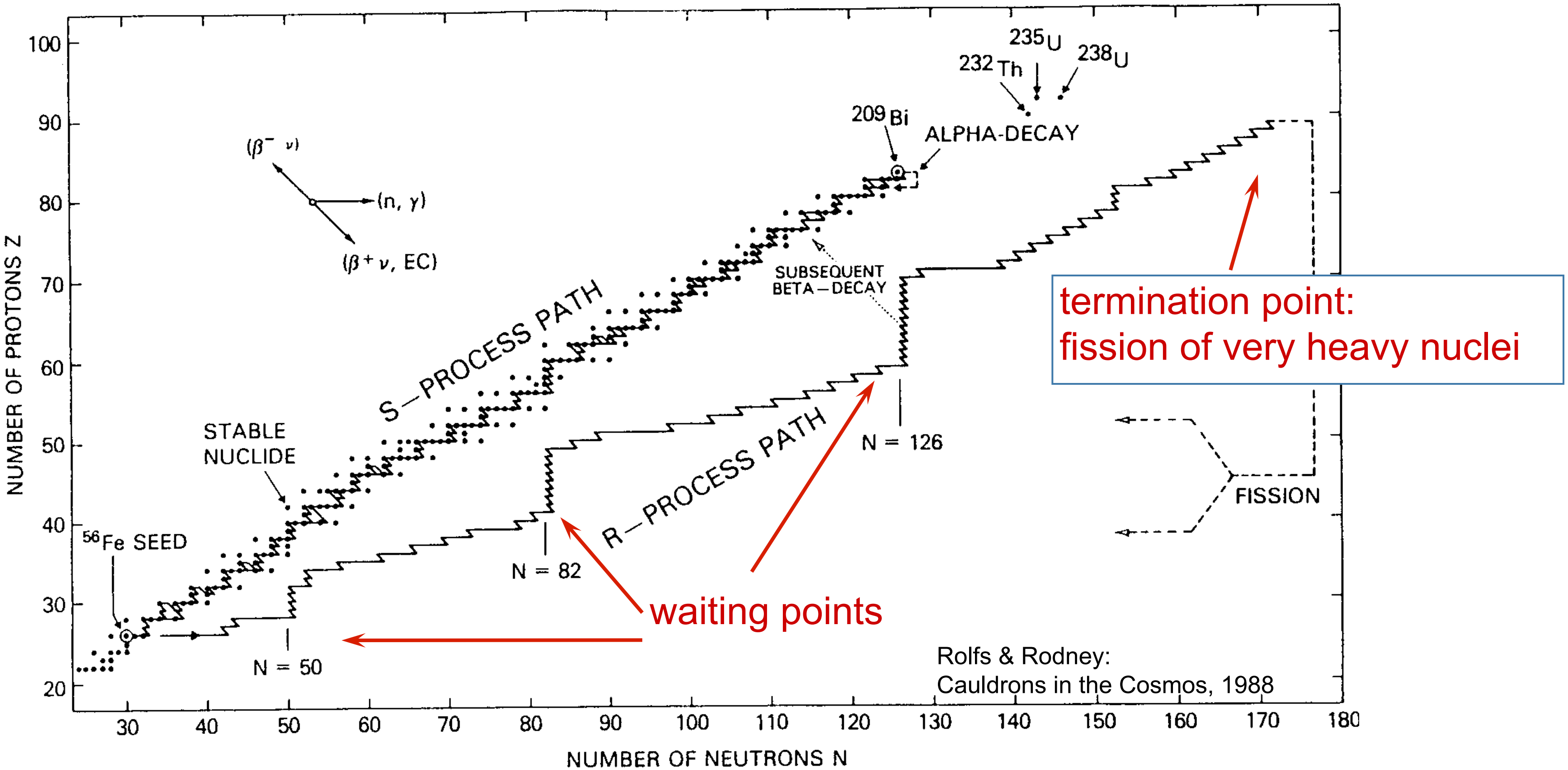
No stable masses with A = 5 and A = 8

Decreasing density and temperature

Deuterons mostly destroyed by photodissociation s process: slow n-capture and β- decay near valley of β stability at kT = 30 keV



The r (rapid neutron capture) - process



typical lifetimes for unstable nuclei far from the valley of β stability: $10^{-4} – 10^{-2}$ s

Requiring n capture time: $\tau_n \sim 10^{-4}$ s $\Leftrightarrow$ $N_n \sim 10^{20}$ n/cm^3

explosive scenarios needed to account for such high neutron fluxes

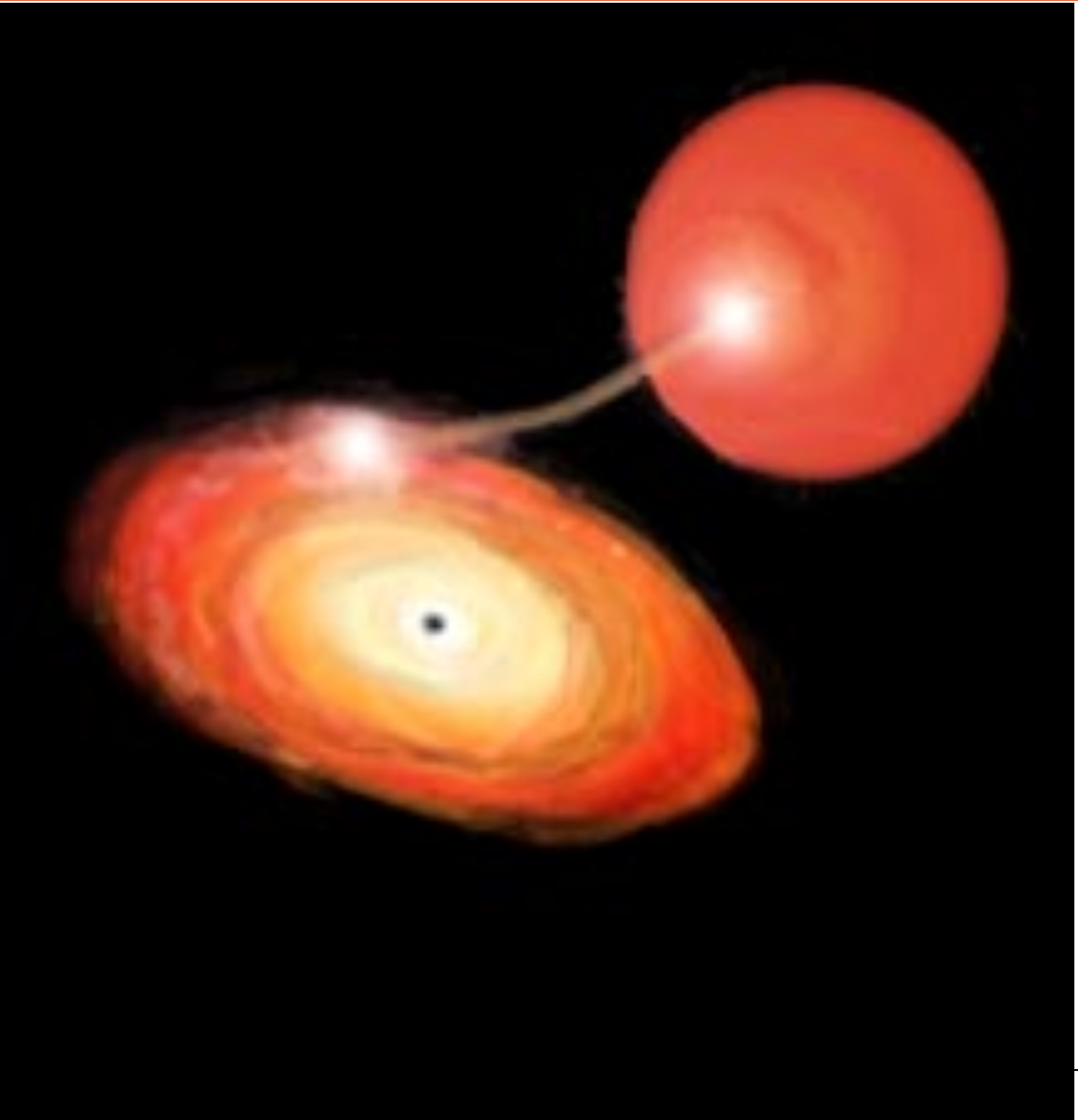
Are Supernovae IIa the sites of the r-process??

A possible scenario:

Supernovae IIa provide in the second of their outbreak a huge neutron flux creating a plenty of unstable neutron-rich nuclei

that decay by a chain of beta decays towards the valley of stability

The rp (rapid proton capture) -process



In binary systems white dwarfs are accreting mass from its companion, leading to explosive hydrogen burning

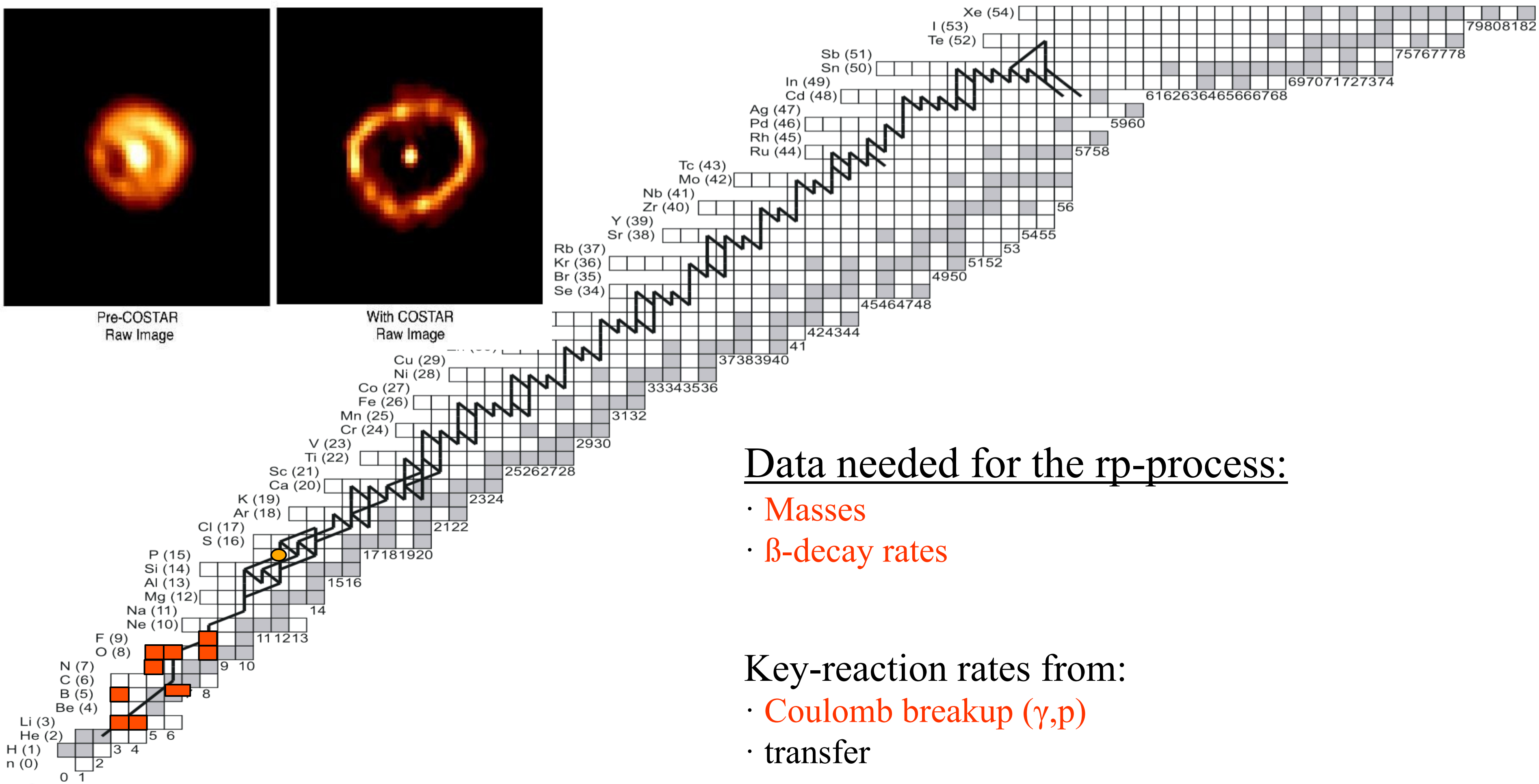
→ Novae

mass accretion of a neutron star leads to

→ X ray bursts

The rp-process: explosive H-burning

Nova Cygni 1992
Hubble Space Telescope
Faint Object Camera



Pre-COSTAR Raw Image — With COSTAR Raw Image

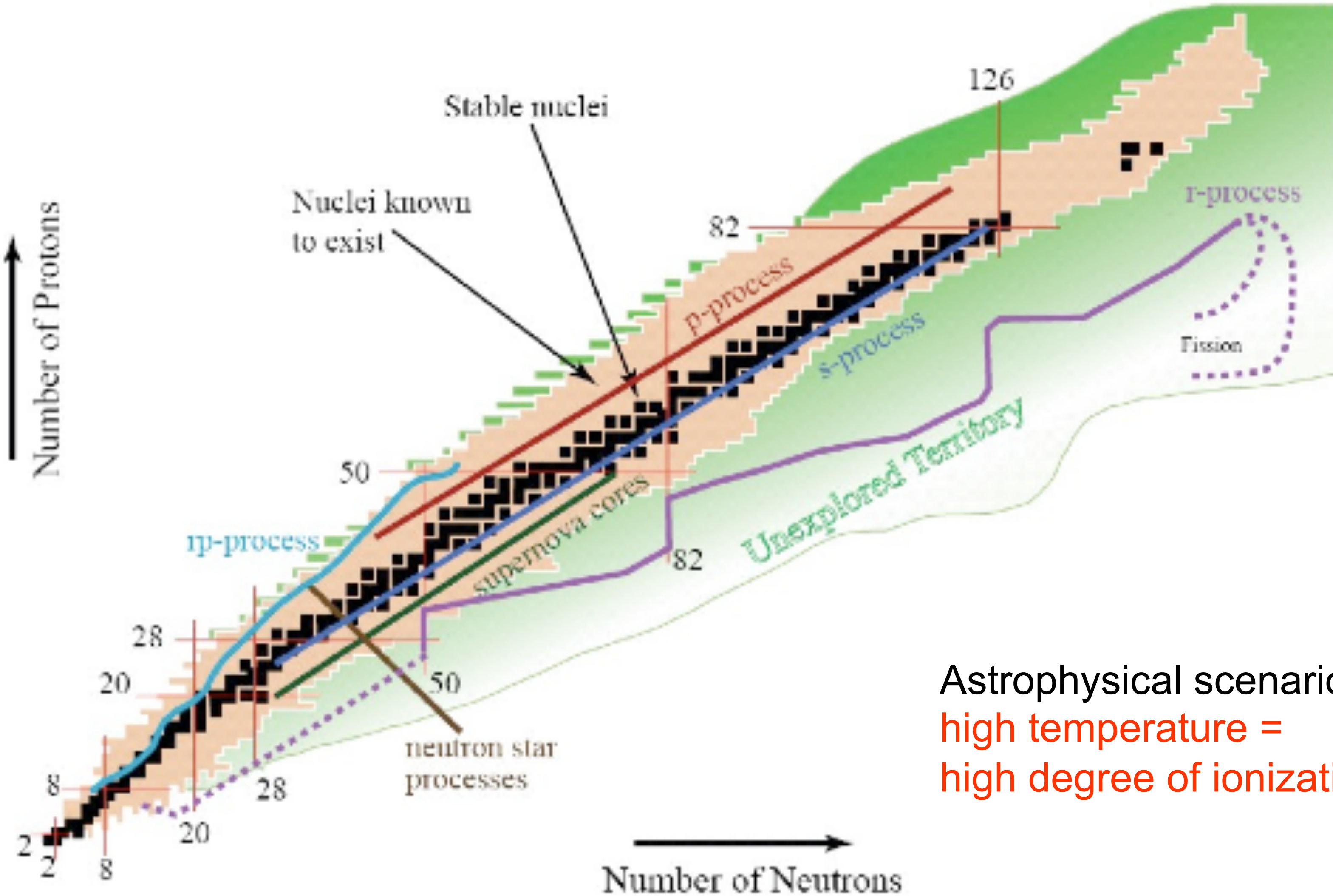
Data needed for the rp-process:

- Masses
- ß-decay rates

Key-reaction rates from:

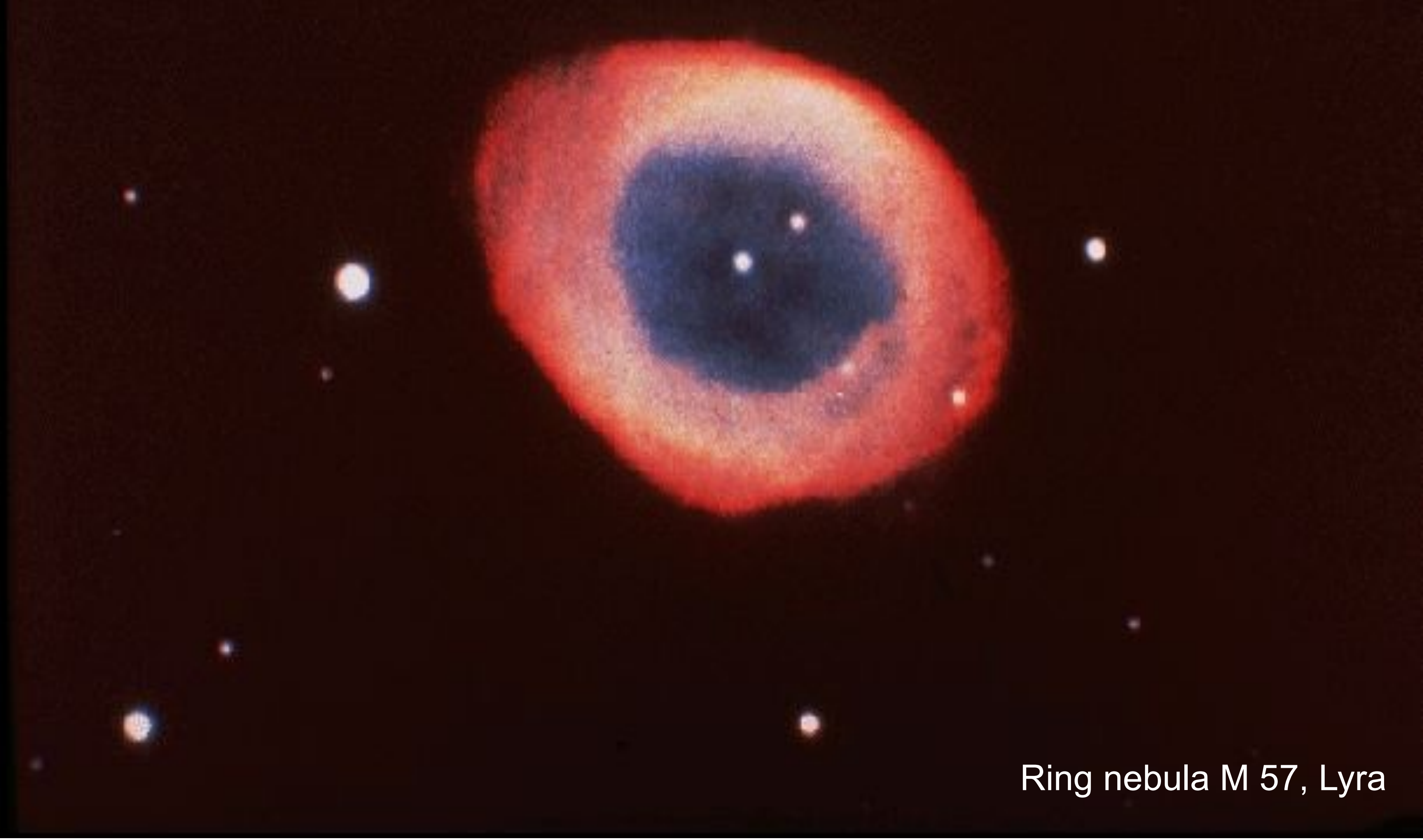
- Coulomb breakup (γ,p)
- transfer
- 2p-captures

Nucleosynthesis on the Chart of the Nuclides



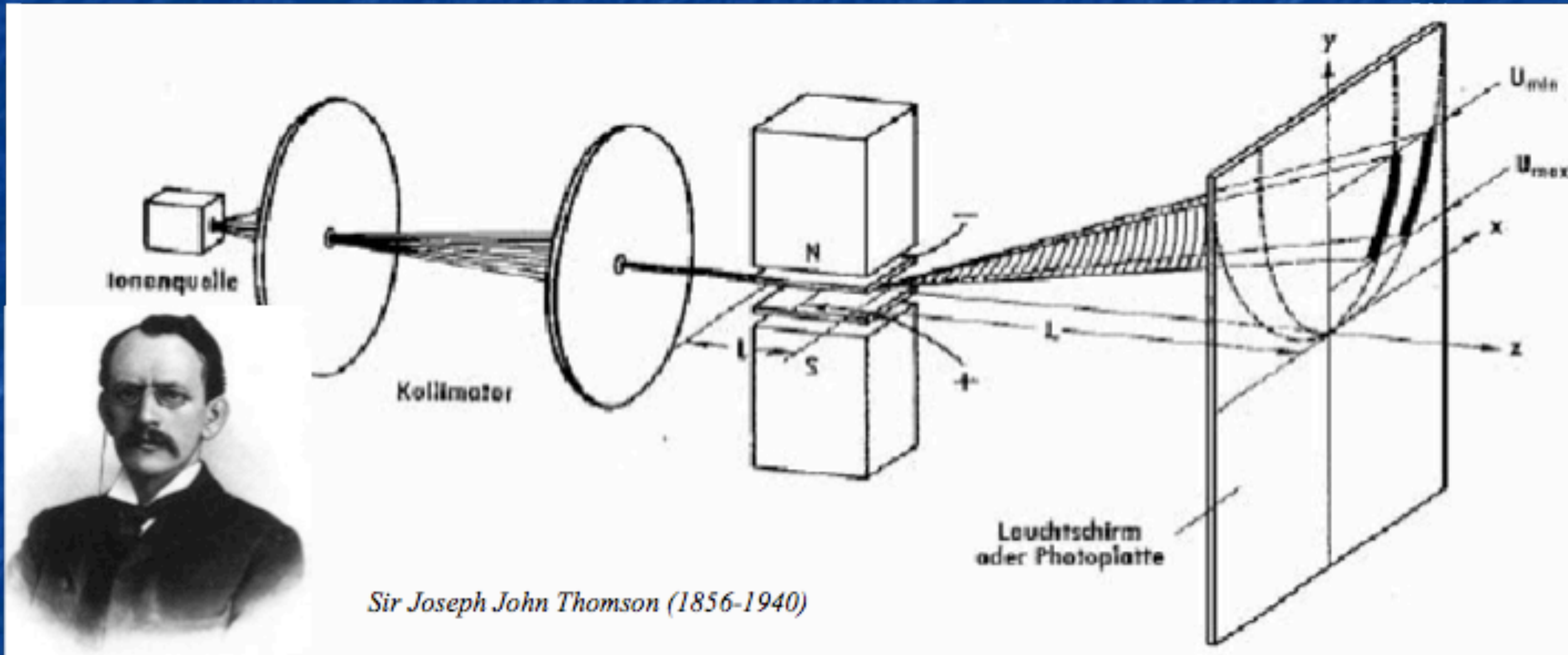
Astrophysical scenarios:
high temperature =
high degree of ionization

Masses and Half-lives: The deep entanglement of nuclear structure and stellar nucleosynthesis



Ring nebula M 57, Lyra

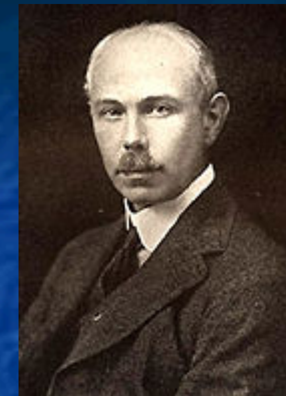
1913 - J. Thompson, Discovery of Isotopes (Nobel prize 1906)

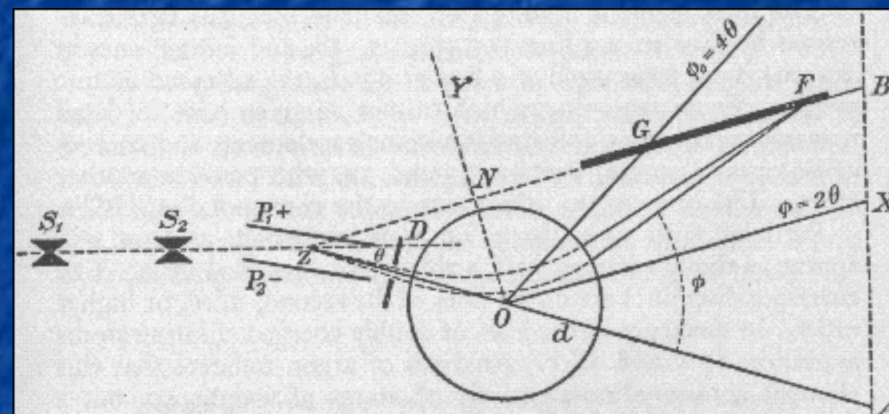


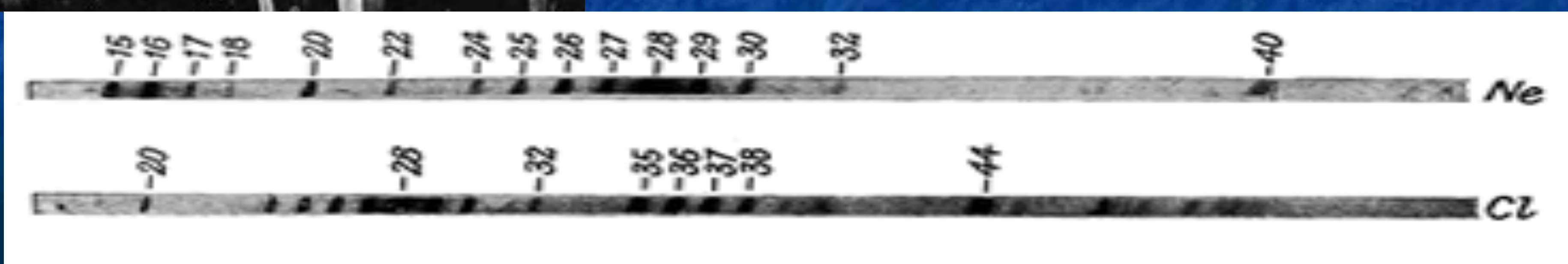
Sir Joseph John Thomson (1856-1940)

1915-1925 – F.W. Aston Mass defect (Nobel prize 1922)

Francis William Aston (1875-1945)







Aston's mass spectra for neon and chlorine, results from the first mass spectrograph in 1920

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

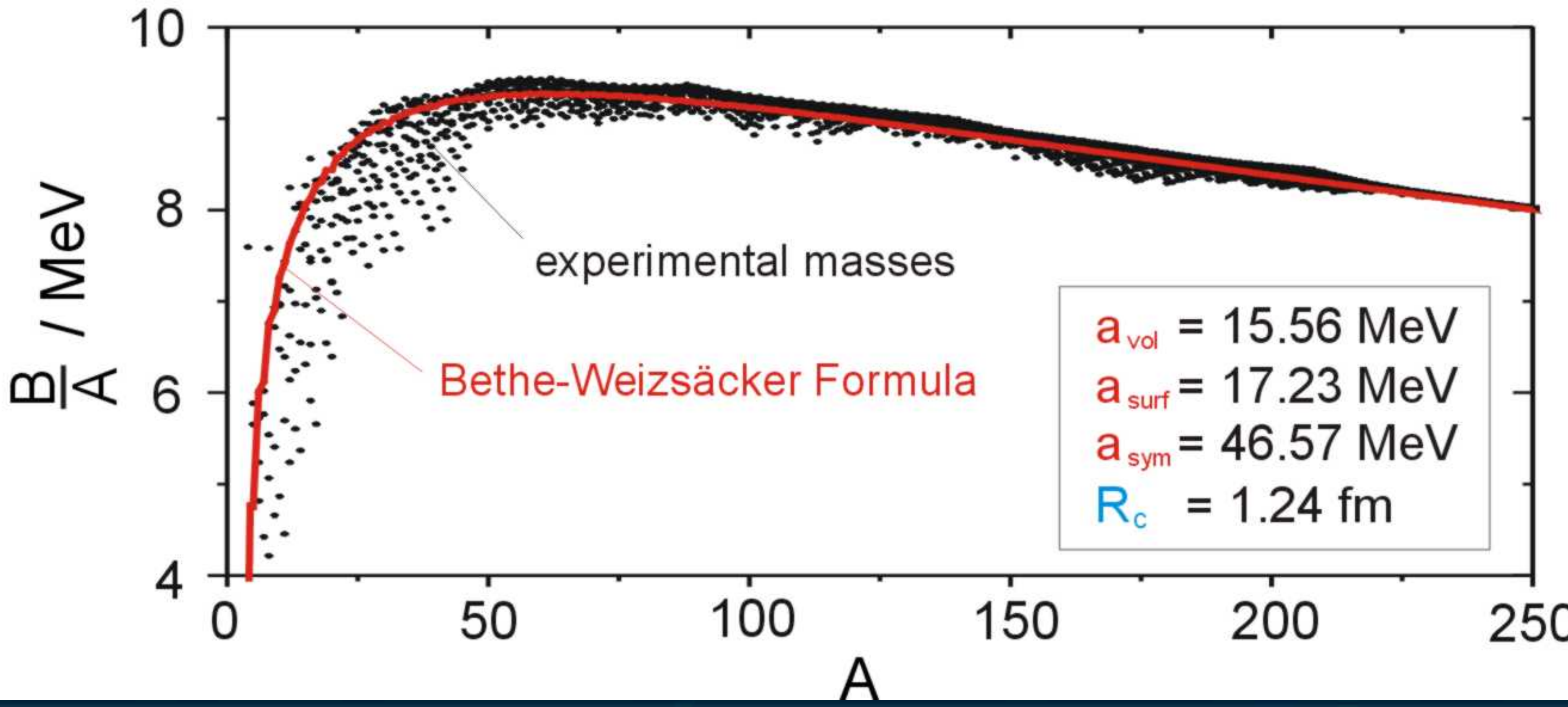
Nuclei are treated as a classical liquid drop

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 % !!!



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

Masses: Fundamental Properties of Atomic Nuclei

- ➢ Binding energies
- • Mass models
- • Shell structure

- ➢ Correlations
- • pairing

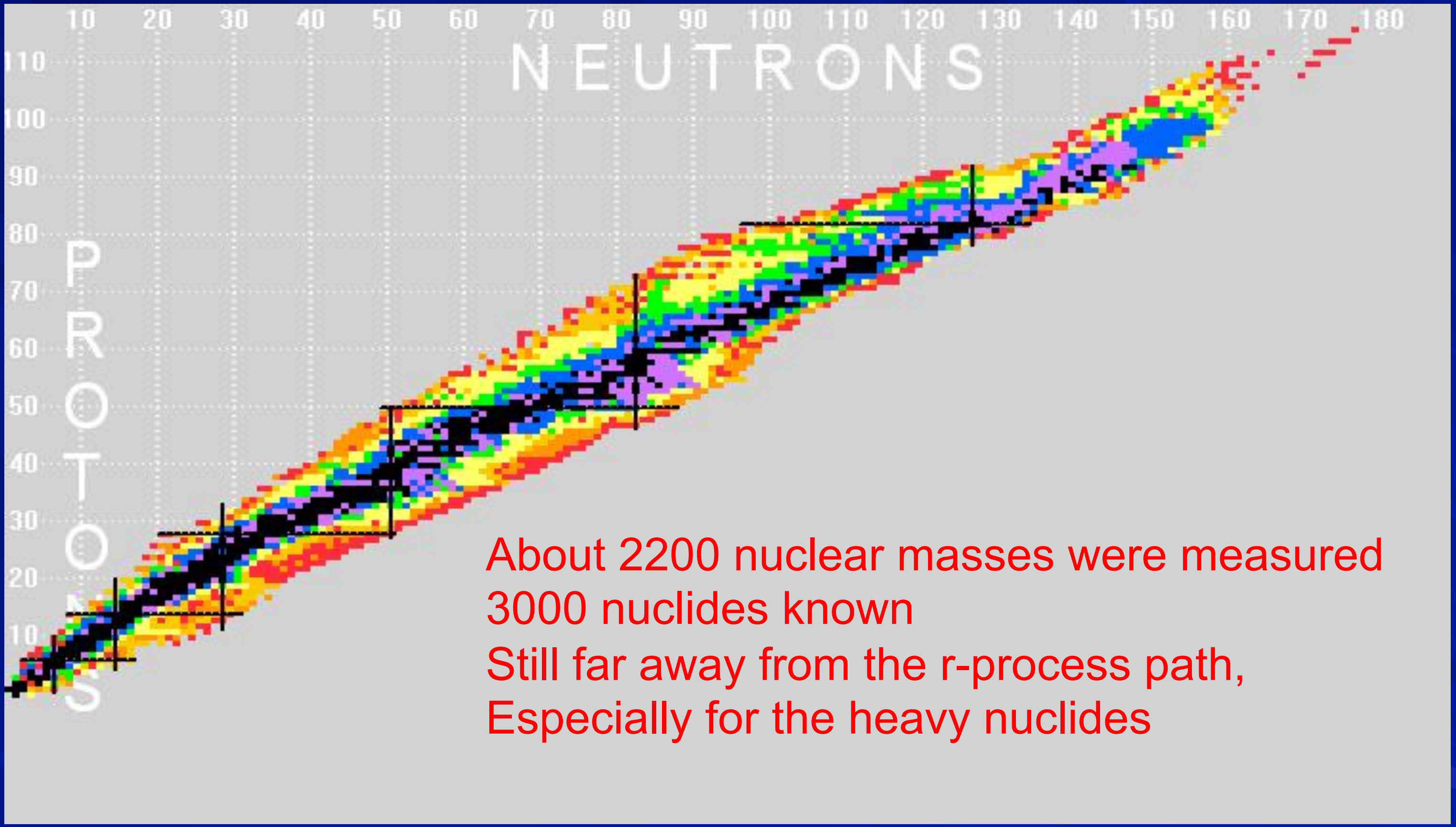
- ➢ Reaction phase space
- • Q-values
- • Reaction probabilities

- ➢ The reach of nuclei
- • Drip lines
- • Specific configurations and topologies

- ➢ Nuclear astrophysics
- • Paths of nucleosynthesis

- ➢ Fundamental symmetries
- ➢ Metrology
- ➢ …..

Current status of experimental nuclear masses

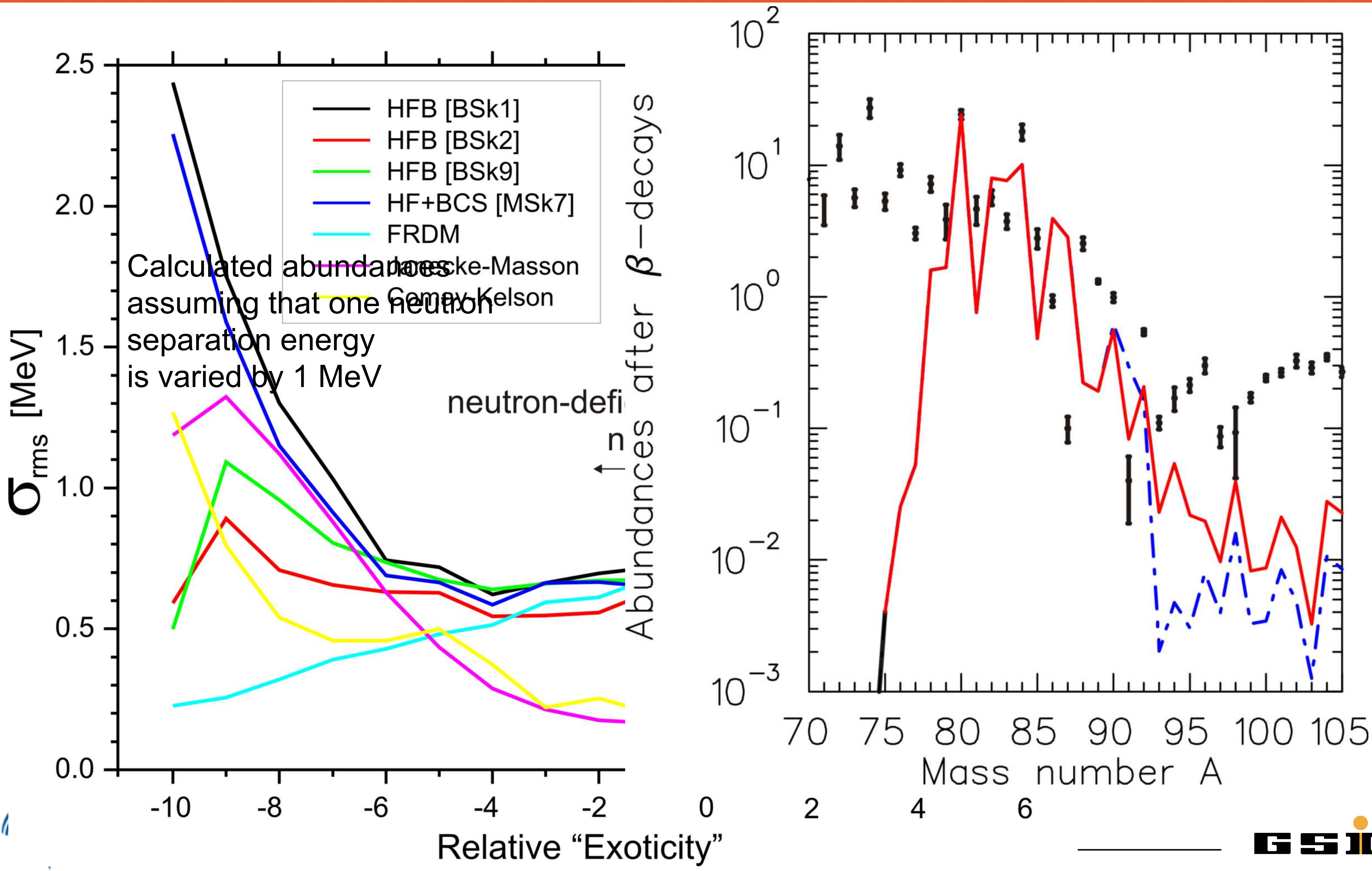


About 2200 nuclear masses were measured
3000 nuclides known
Still far away from the r-process path,
Especially for the heavy nuclides

Up to 2004!

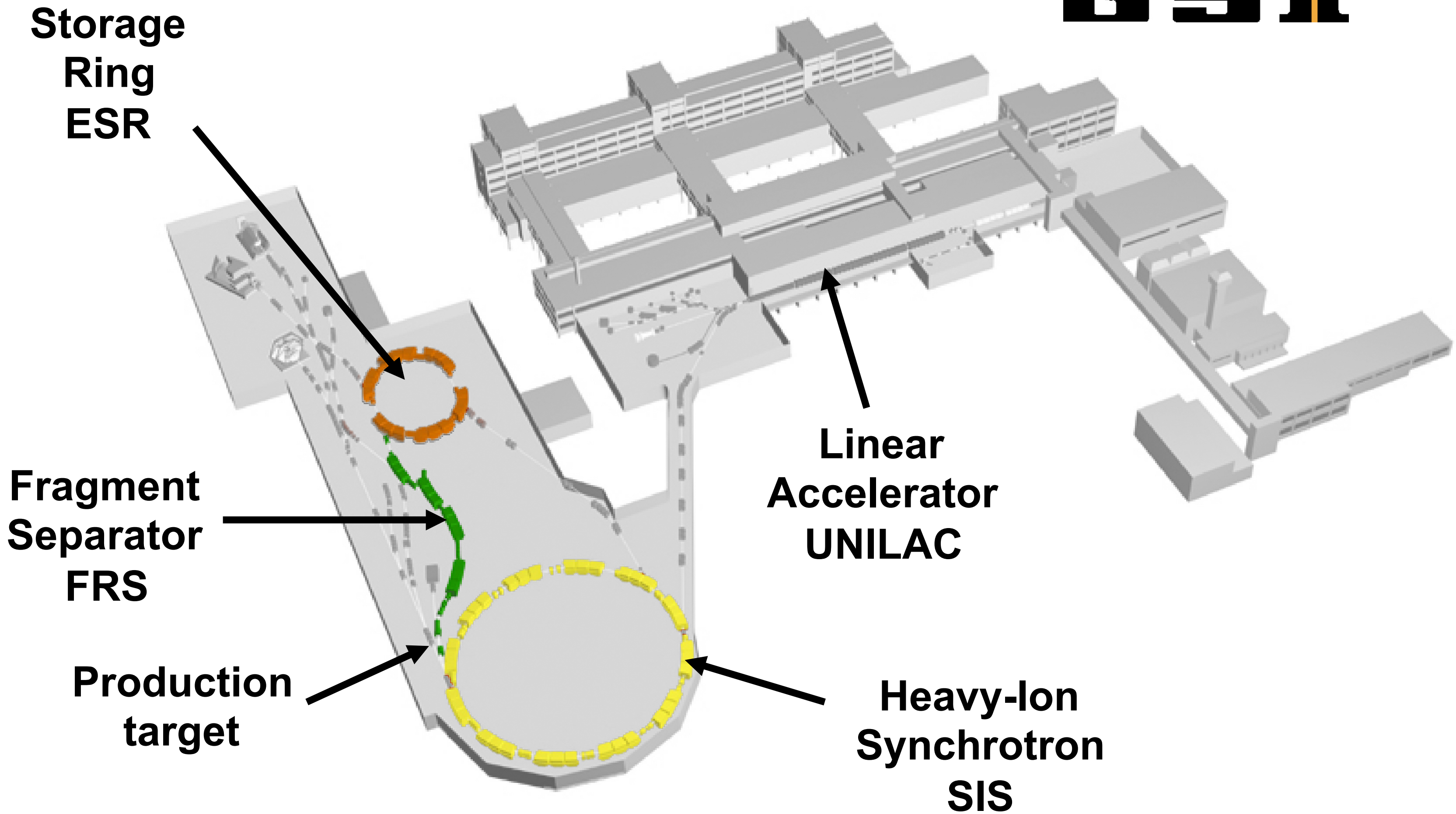
G. Audi et al., Nucl. Phys. **A565**, 1(1993); A 595, 409 (1995)， A729.337(2003)

Predictive Powers of Mass Models

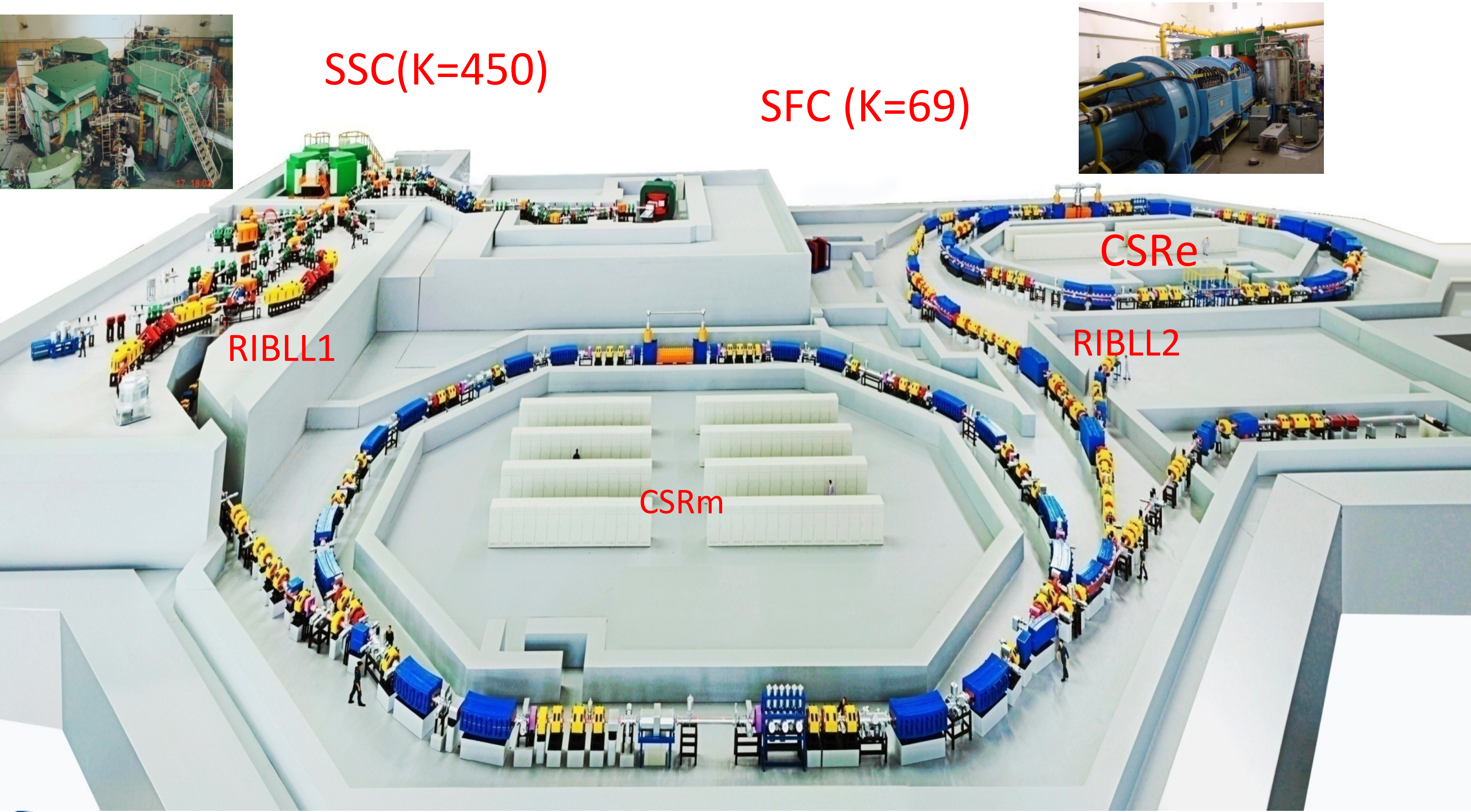


Production and Separation of Exotic Nuclei

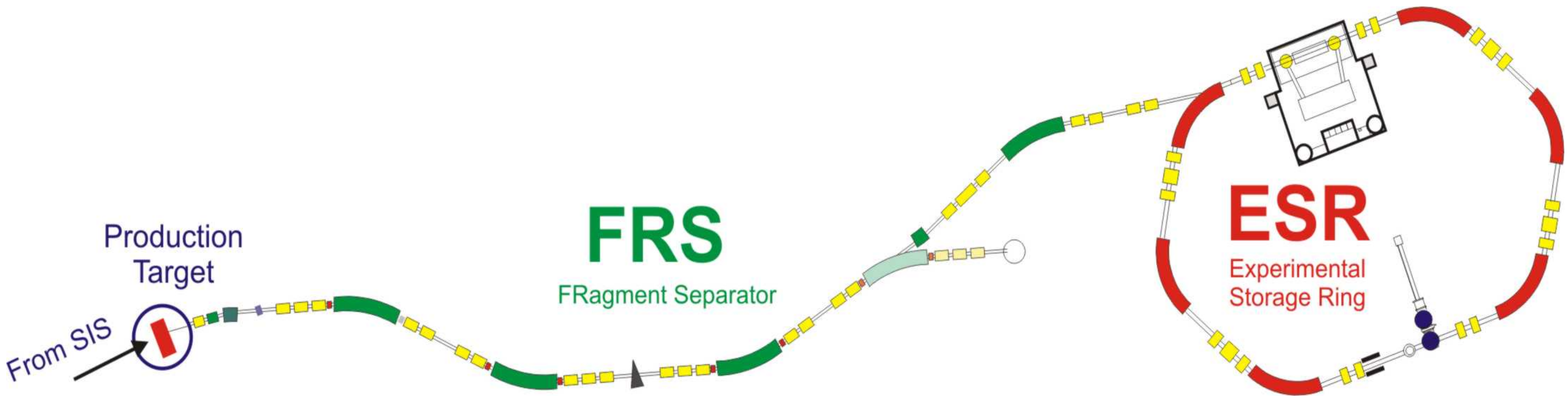
Secondary Beams of Short-Lived Nuclei



Heavy Ion Research Facility in Lanzhou (HIRFL)



Production & Separation of Exotic Nuclei



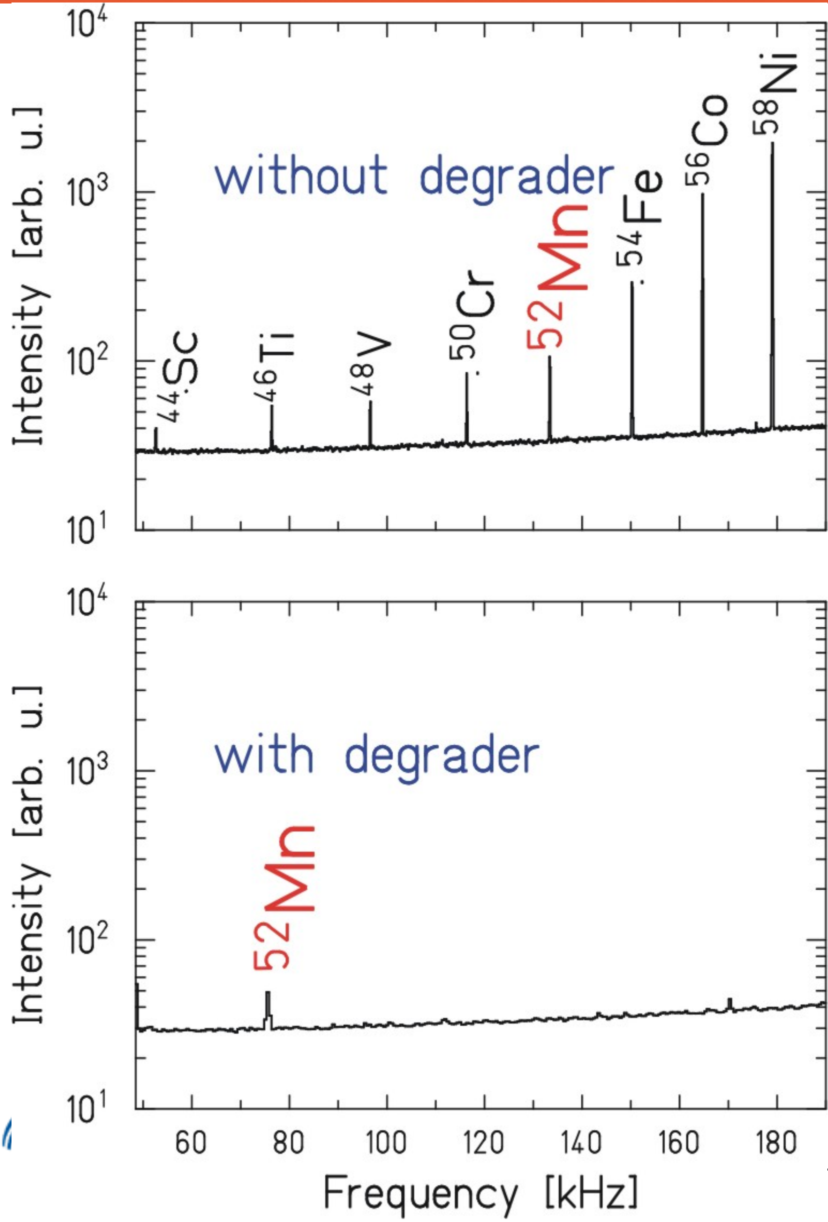
Primary beams @ 400-1000 MeV/u

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

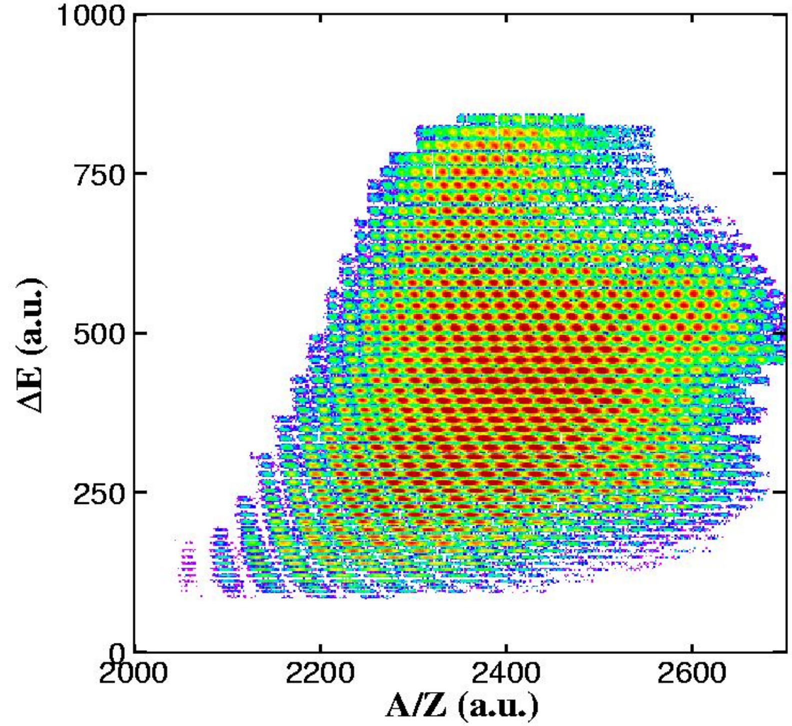
In-Flight separation within ~ 150 ns

Cocktail or mono-isotopic beams

Production & Separation of Exotic Nuclei



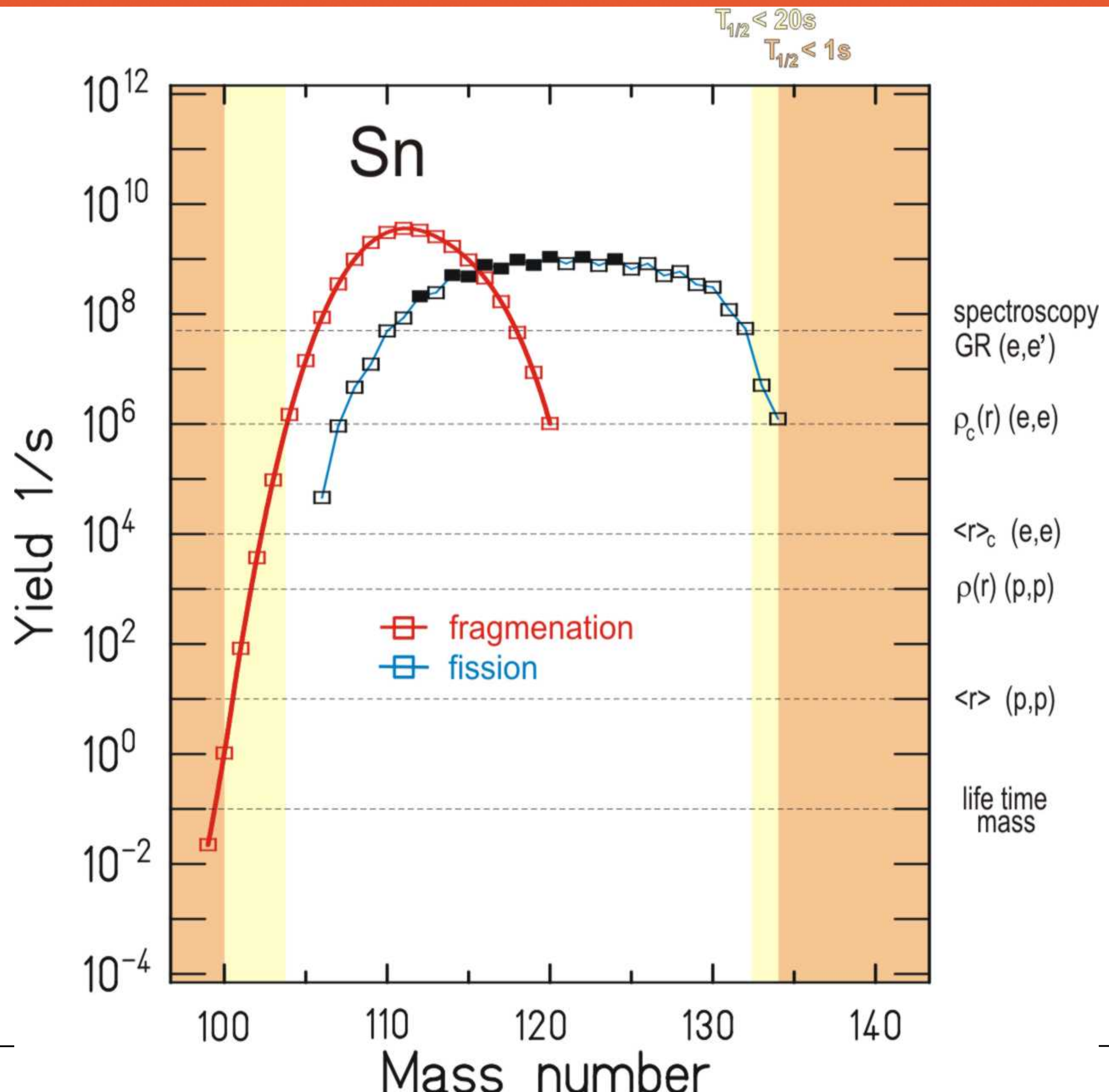
About 1000 nuclear residues identified



A/Z-resolution ~10^{-3}

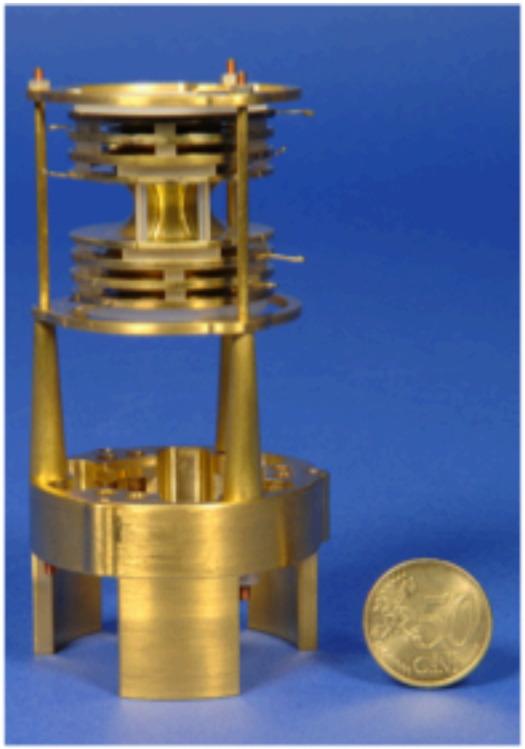
J. Pereira et al., PRC (2007)

Production Cross-Sections for Tin-Isotopes



Devices for precise mass measurements

Penning trap



particles at nearly rest in space

Storage ring

relativistic particles

* ion cooling
* long storage times
* single-ion sensitivity
* high accuracy

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 vocabulary

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

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

$\varepsilon = \pi\, \alpha\, \Delta p$; (α 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.

Space charge sets a limit on the maximum number of stored ions

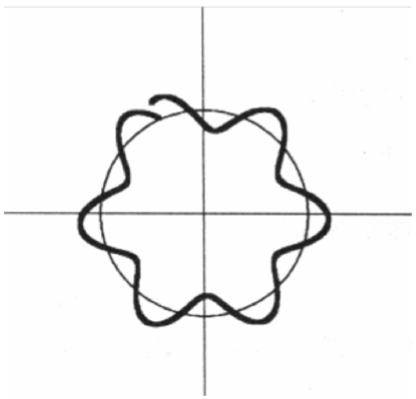
lattice ?

emittance ?

tune ?

cooling ?

space charge ?



Lost planet or lost beam – all the same physics

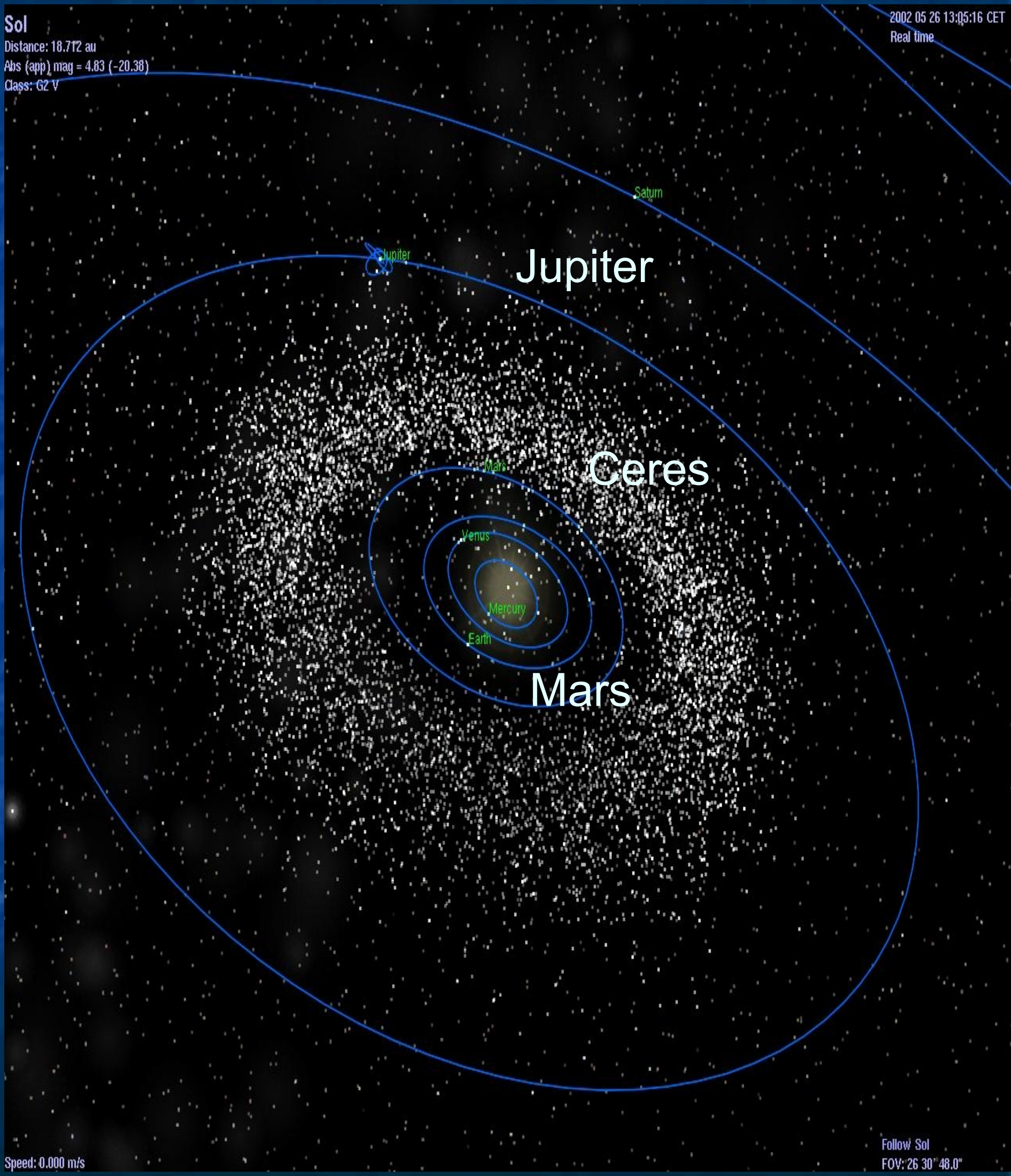
Orbit of a former planet Ceres was periodically influenced by Jupiter

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

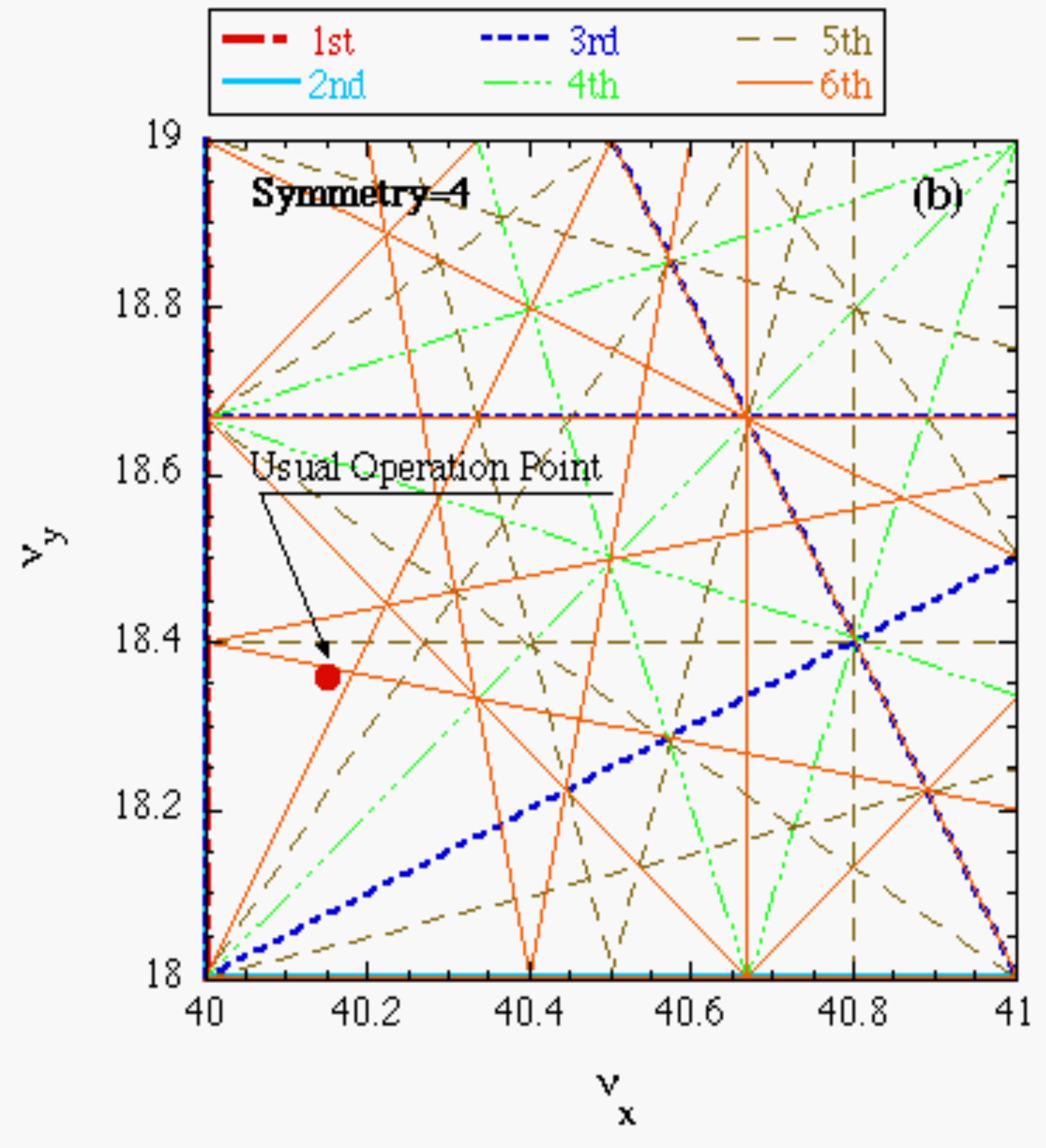
1 AU = $1.5 \cdot 10^8$ km, $T_E = 1$ y

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

$a_C = 2.77$, " $R_{CJ} = 0.53$



Tune diagram and working point

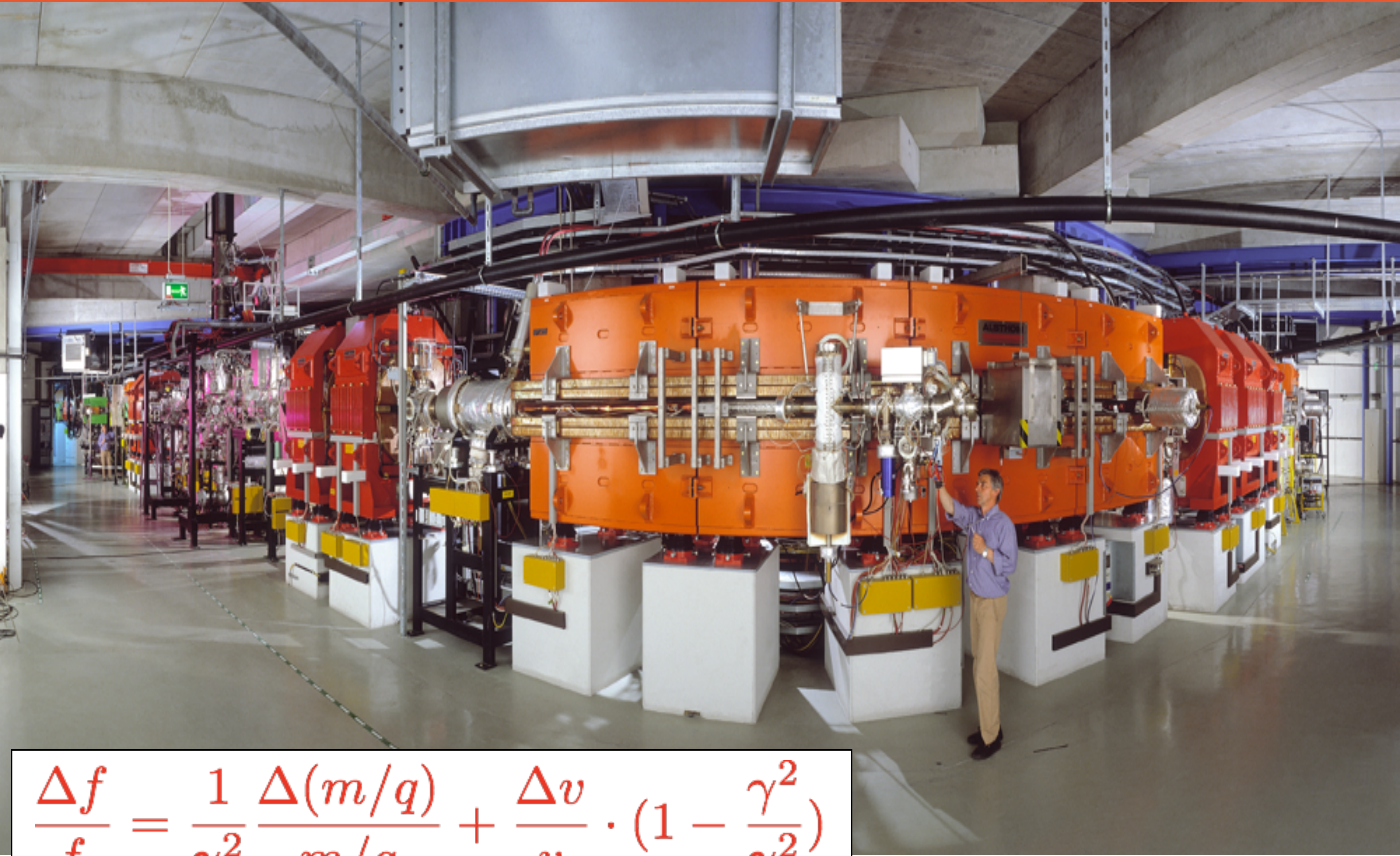


Tuning does not demand a study of tunology, but rather
the right feeling
and the experience
of decades

To save the beam, avoid any crossing of lines

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

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



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

GSI

Cooling techniques applied at ion rings

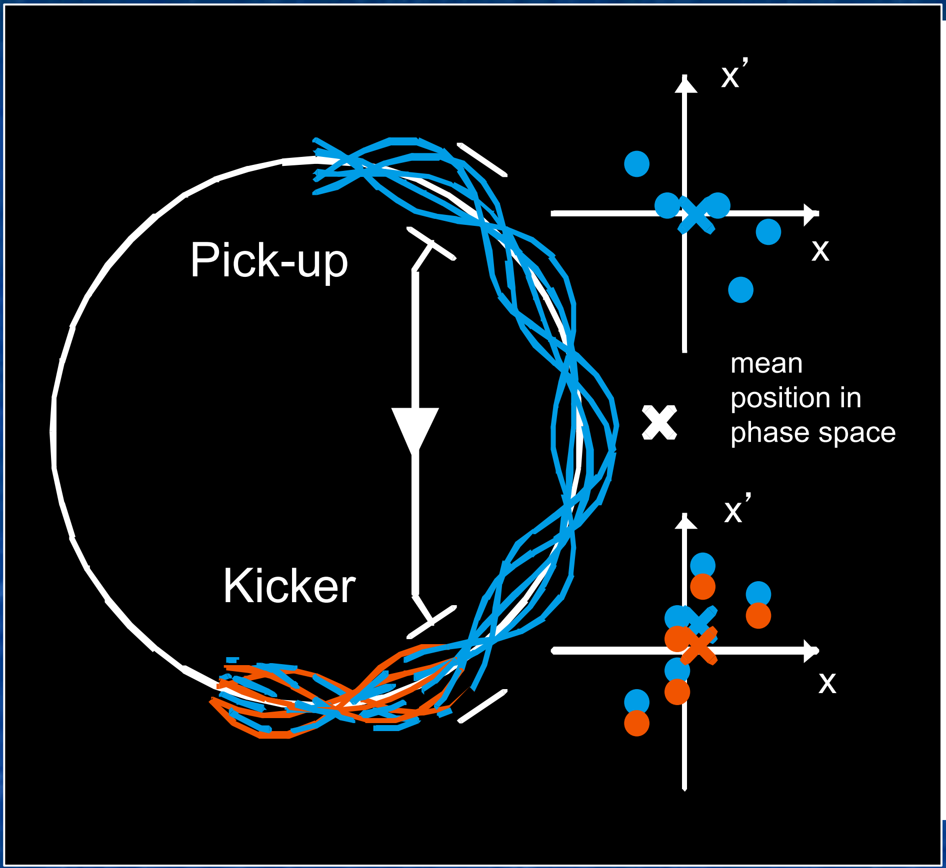
One may overcome Liouville theorem by applying external forces, with the aid of, e.g. :

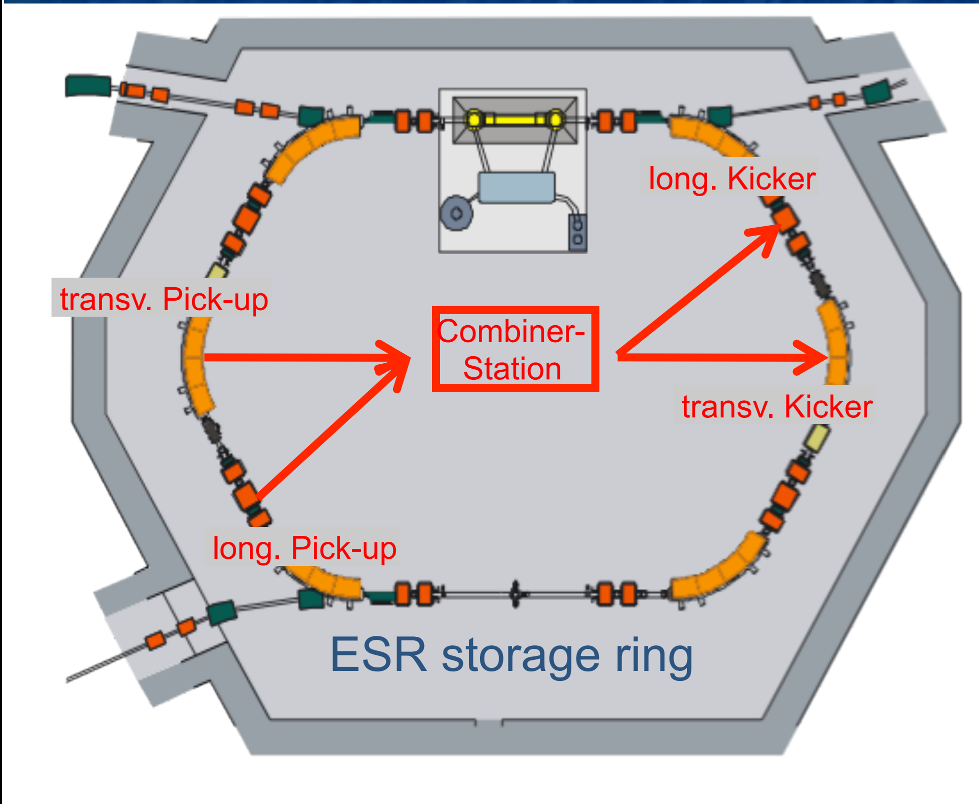
- Lasers = transfer of momentum

- 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

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:
Physics
Chemistry
Physiology or Medicine
Literature
Peace
Economic Sciences

Find a Laureate:
Name GO

SITE FEEDBACK CONTACT TELL A FRIEND

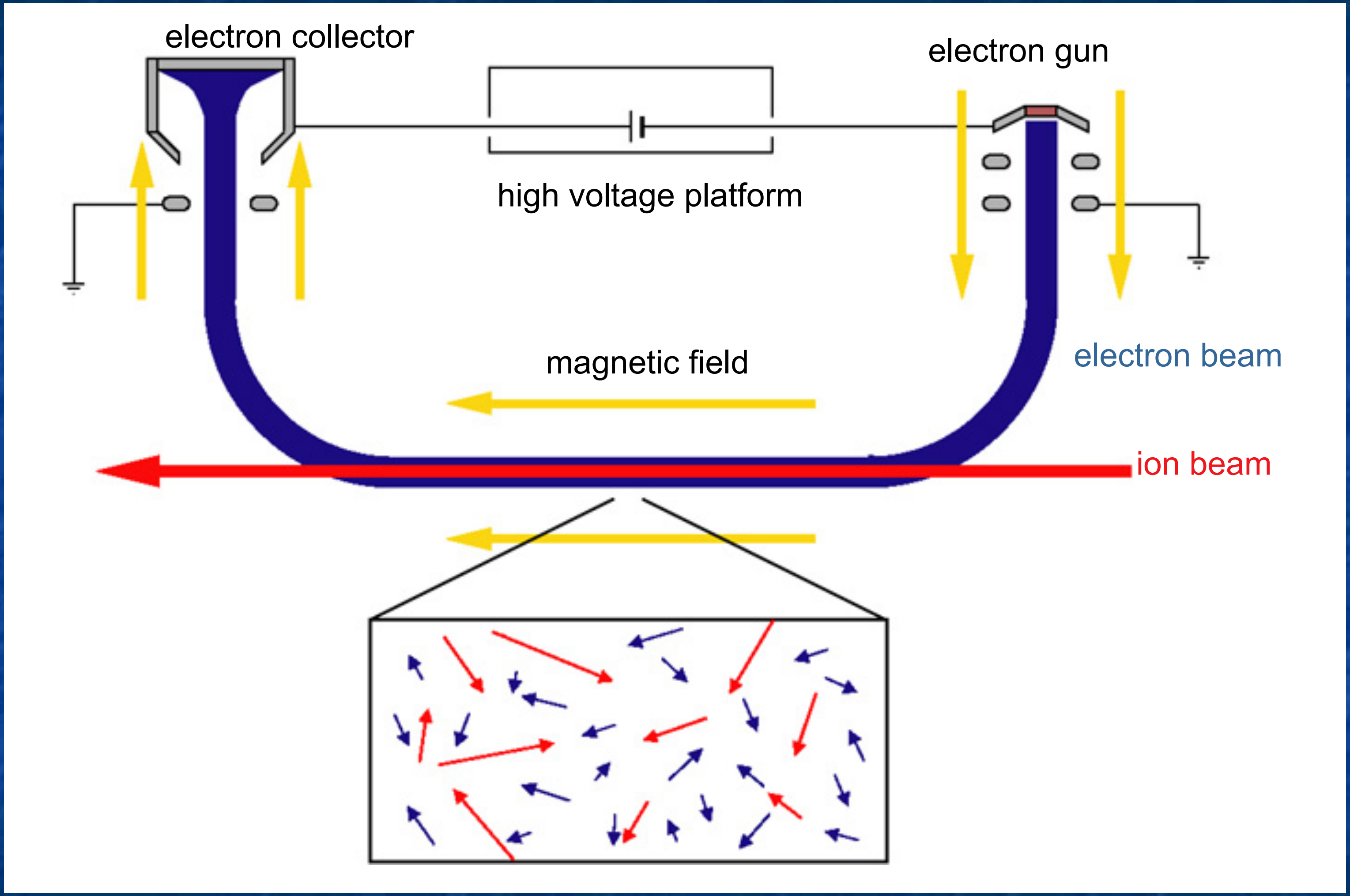
Last modified June 24, 2003

http://www.nobel.se/physics/laureates/1984/

Question 1

In stochastic cooling one has to be very quick to send the pick-up signal to the other side of the ring, which is a non-trivial task. Why does one just not put a kicker next to the pickup and just wait when the particles come back after one revolution?

Electron cooling (cold bath for ions)

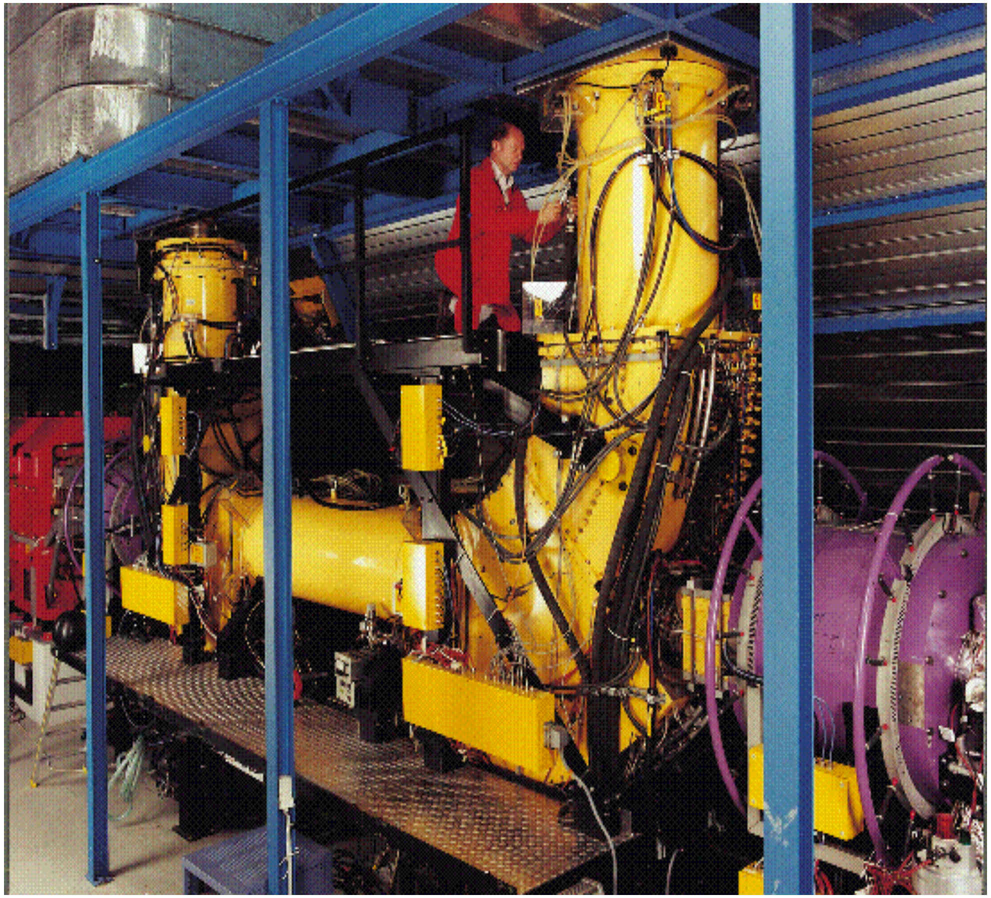


Same mean velocity of e^- and ions;
strong magnetic guiding field; substitution of e^- after a cycle

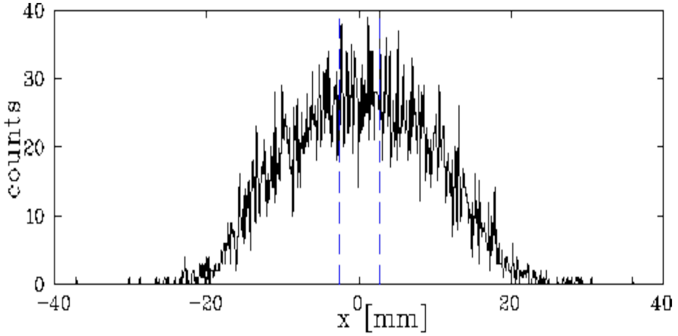
Question 2

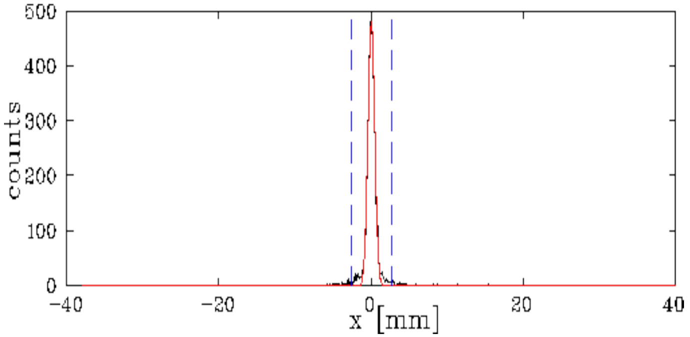
The cross-section for heavy highly-charged ion to capture an electron diverges at zero relative velocities! Why the electron cooling works ☺

Electron Cooling



momentum exchange with 'cold', collinear e- beam. The ions get the sharp velocity of the electrons, small size and divergence





Schottky Mass Spectrometry

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

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

$$\boxed{\frac{\Delta v}{v} \rightarrow 0}$$

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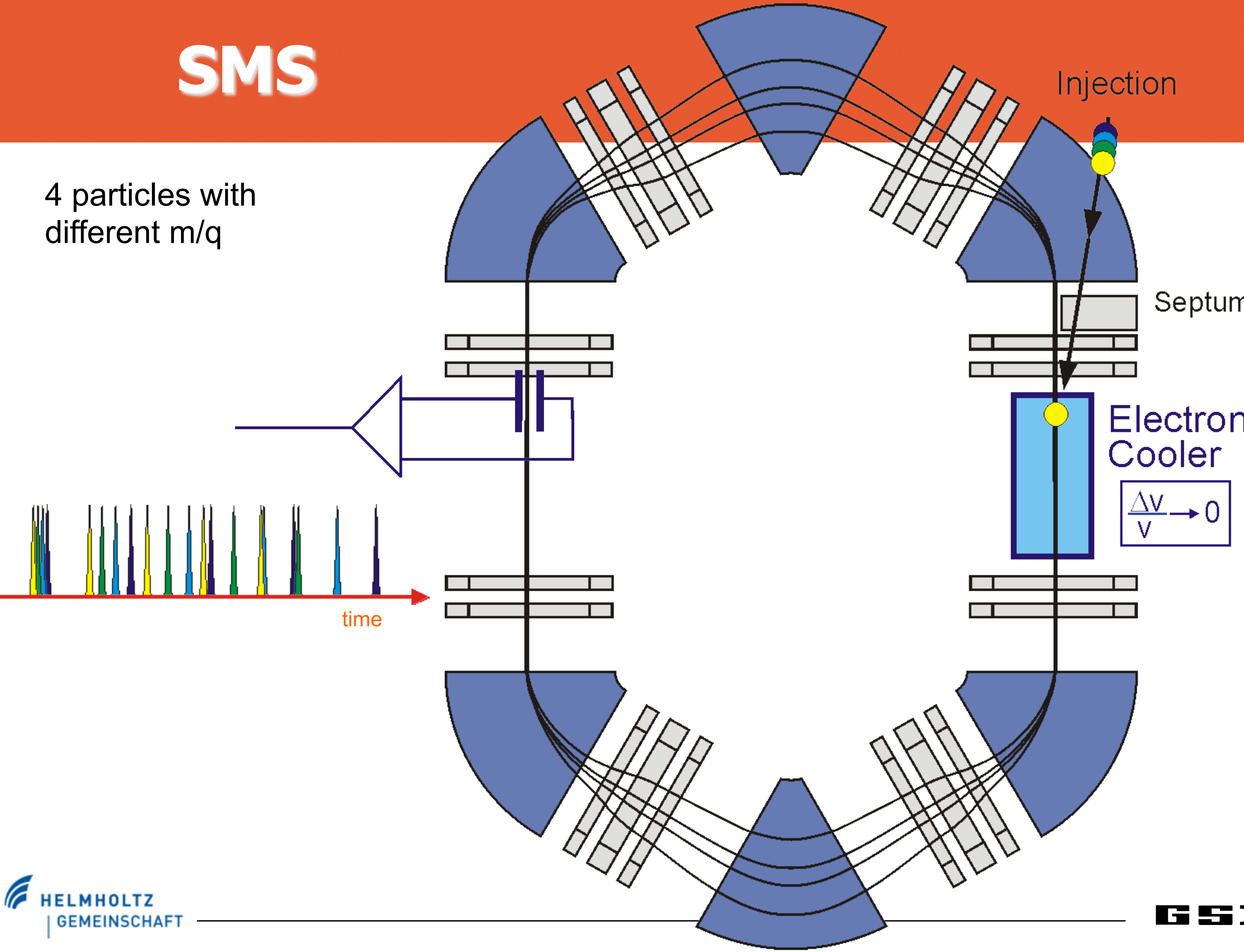
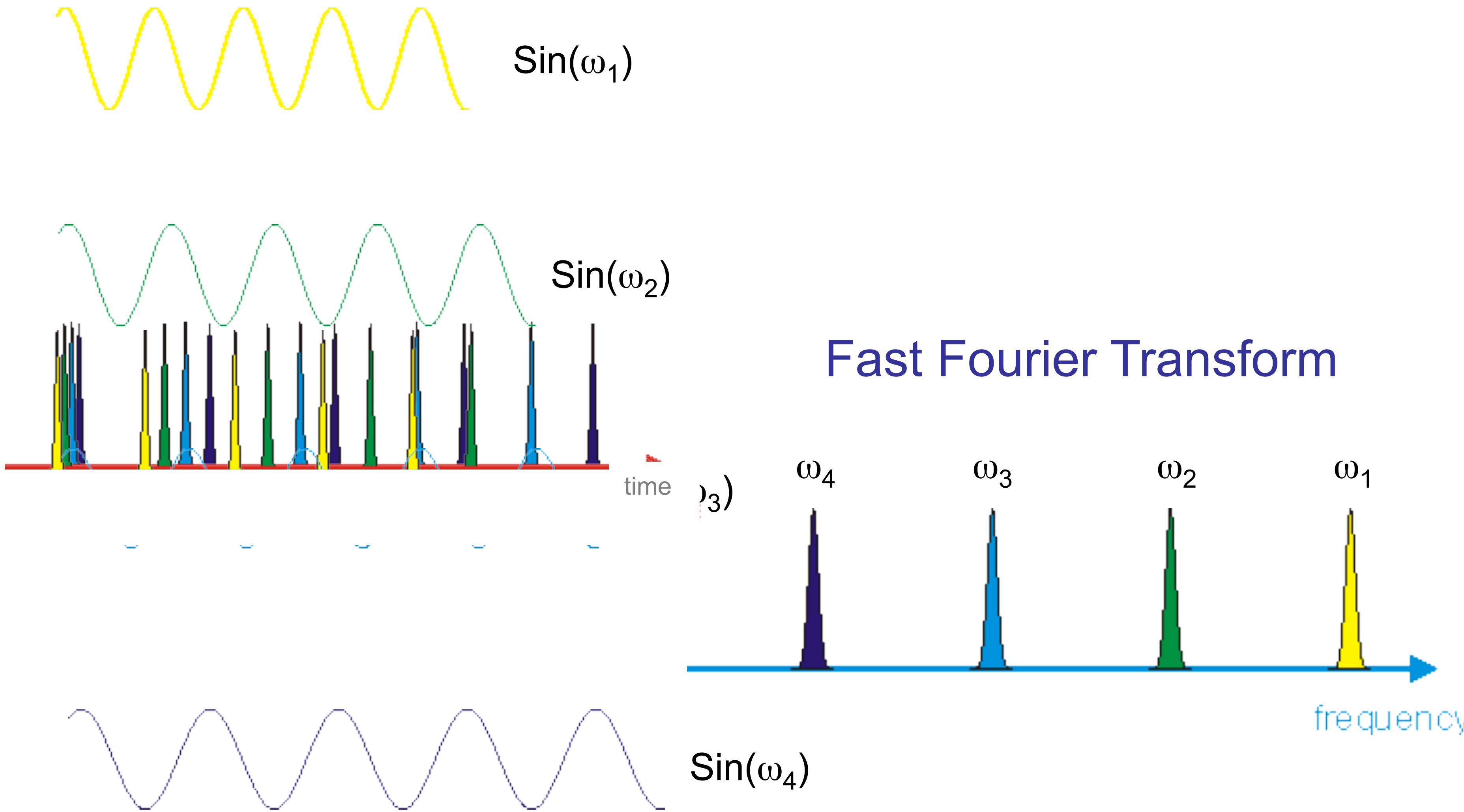
SMS

4 particles with different m/q

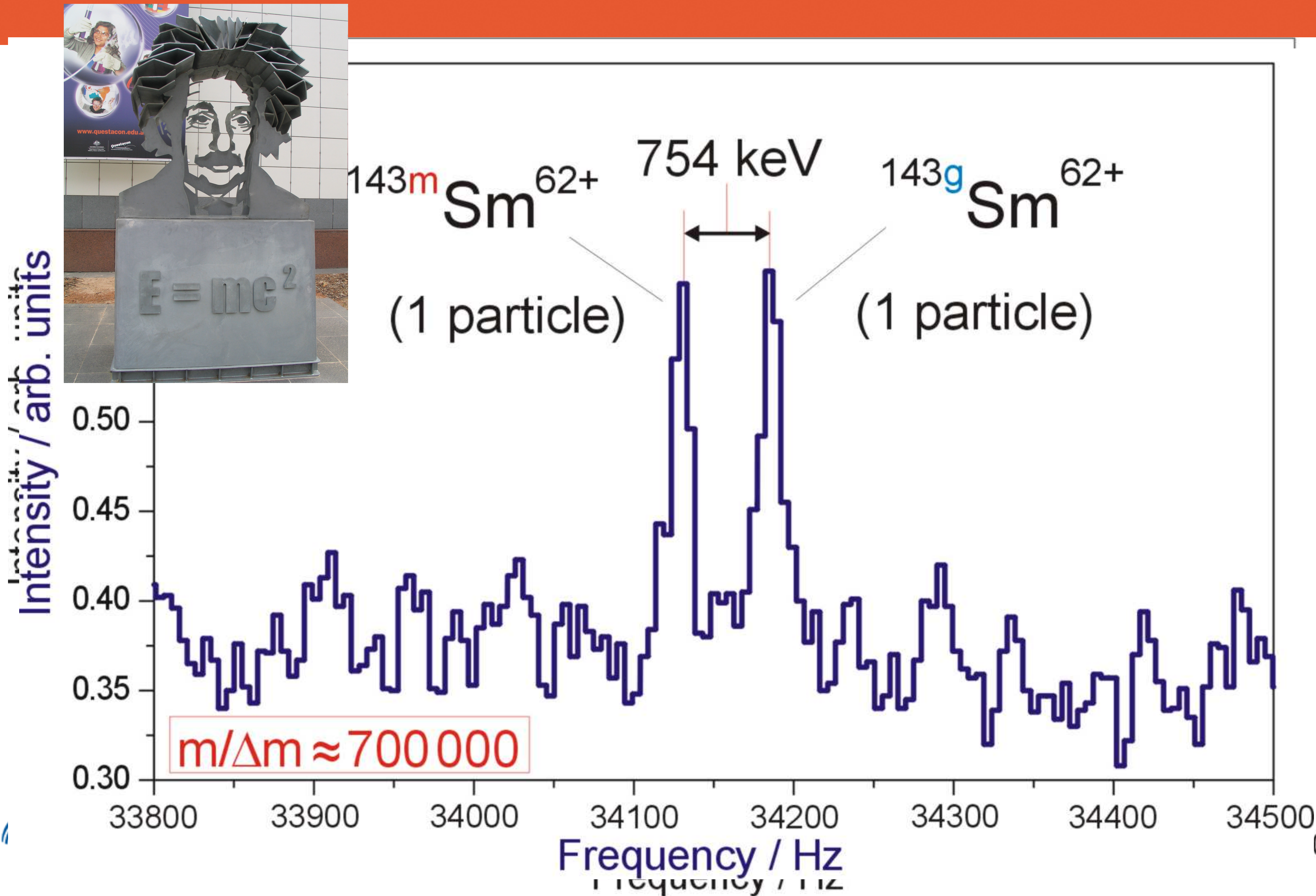


SMS

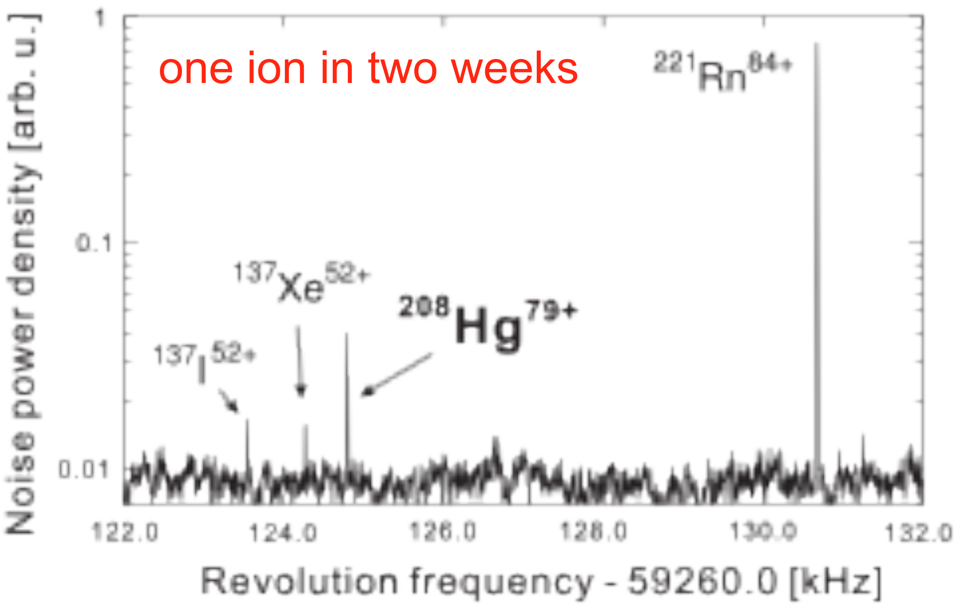


Sin(ω1)
Sin(ω2)
time
Fast Fourier Transform
ω4
ω3
ω2
ω1
frequency
Sin(ω4)

SMS: Broad Band Frequency Spectra



Direct Mass Measurement of ^{208}Hg Nuclide



$$\delta V_{pn}(Z,N) = \frac{1}{4}\Big[B(Z,N) - B(Z,N-2) - B(Z-2,N) + B(Z-2,N-2)\Big]$$

p-n interactions are sensitive to the spatial overlaps of the proton and neutron wave functions

L. Chen, Yu.A. Litvinov, W.R. Plass, et al., PRL 102 (2009) 122503

Isochronous Mass Spectrometry

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

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

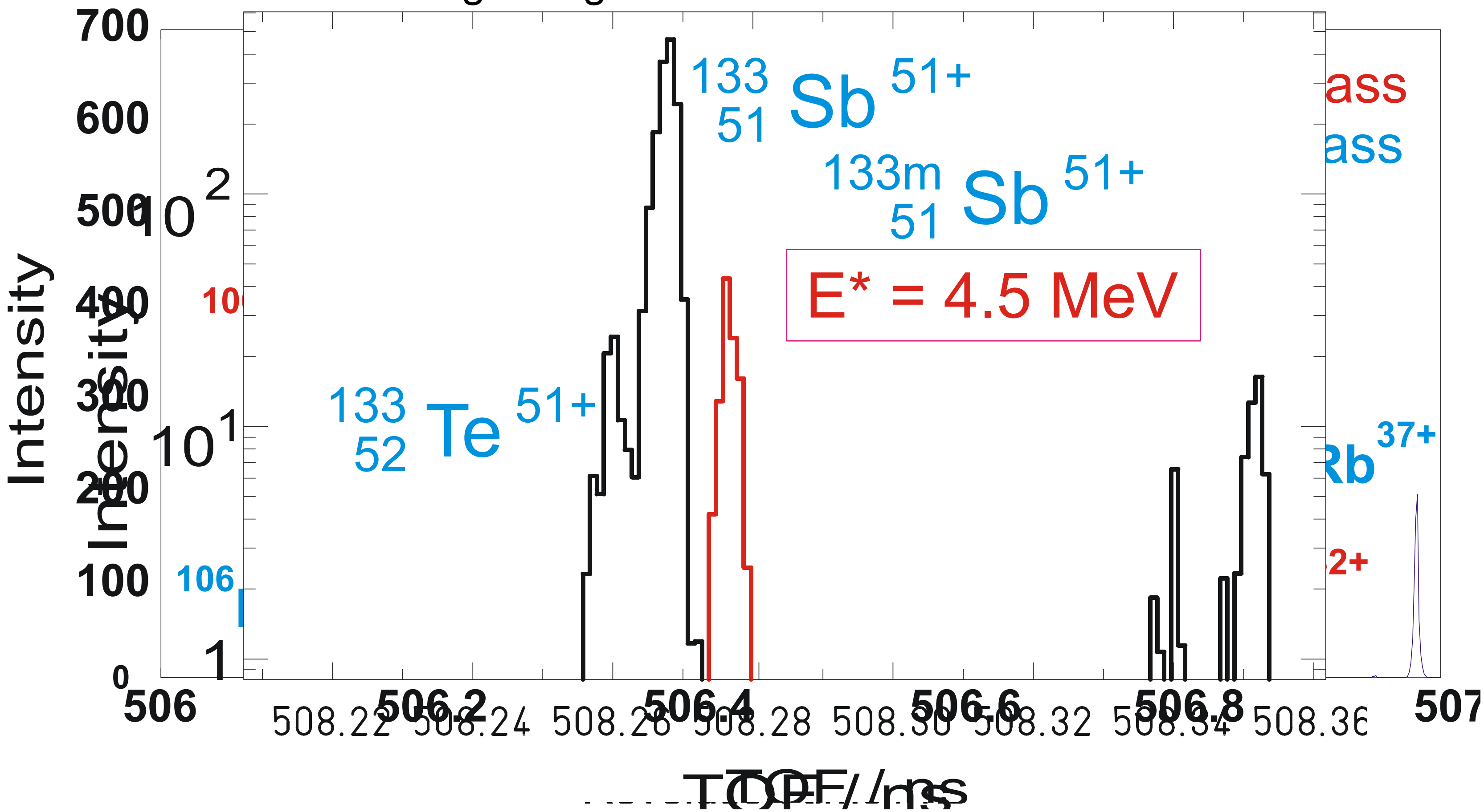
$$\boxed{\gamma_t \rightarrow \gamma}$$

ims_basic2.swf

IMS: Time-of-Flight Spectra

Nuclei with half-lives as short as 20 μs

About 13% in mass-over-charge range



M. Hausmann et al., Hyperfine Interactions 132 (2001) 291

M. Matos et al., Proc. EXON 2004

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Mass Measurements Relevant for Nucleosynthesis in Stars

NUCLEAR ASTROPHYSICS

Star bursts pinned down

One of the main uncertainties in the burn-up of X-ray bursts from neutron stars has been removed with the weighing of a key nucleus, ^{65}As, at a new ion storage ring.

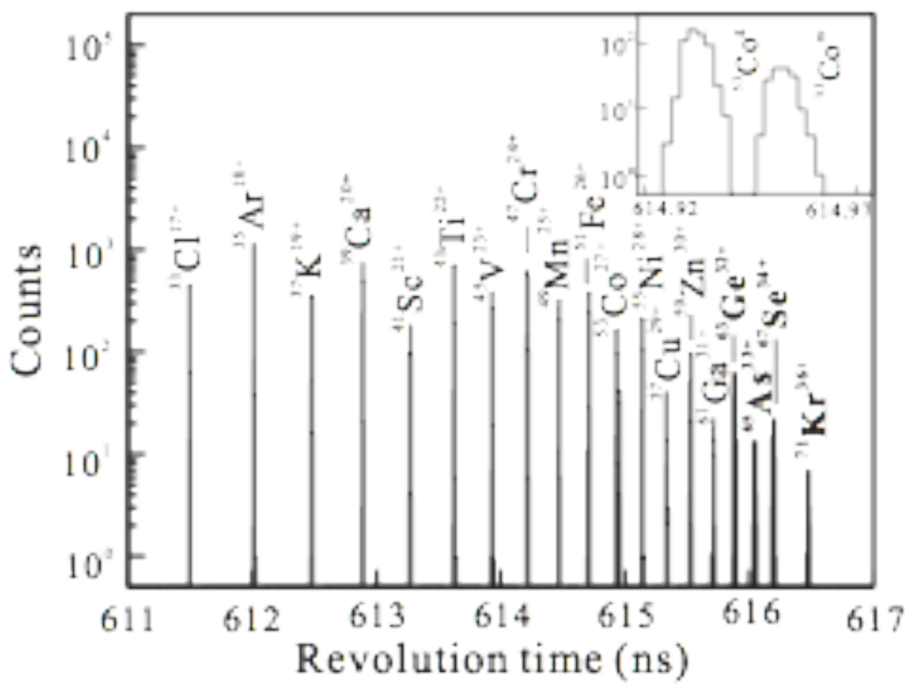
NATURE PHYSICS | VOL 7 | APRIL 2011 | www.nature.com/naturephysics

BRENNPUNKT

Kein Halten am Wartepunkt

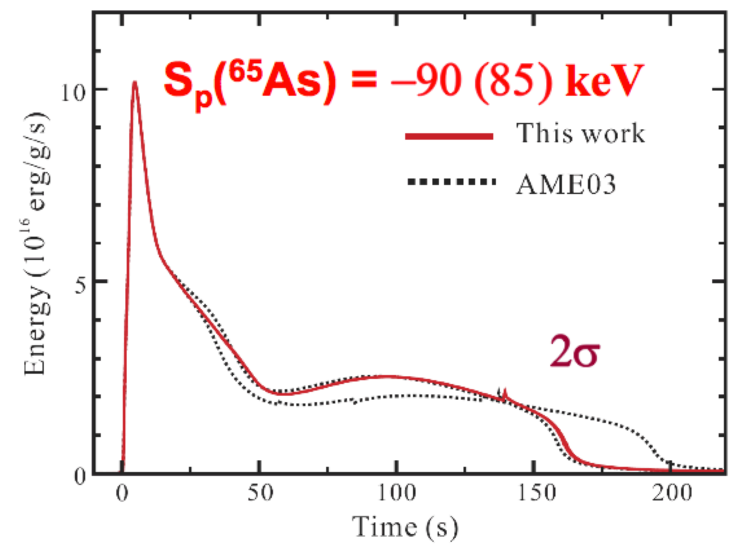
Hochpräzise Massenmessungen erklären die Kernreaktionen bei Ausbrüchen von Röntgenstrahlung.

Physik Journal 10 (2011) Nr. 6



Rate of ^{71}Kr was just 2 ions/day

Light curve shape of Type I x-ray burst



X.Tu, et al., PRL 106 (2011) 112501

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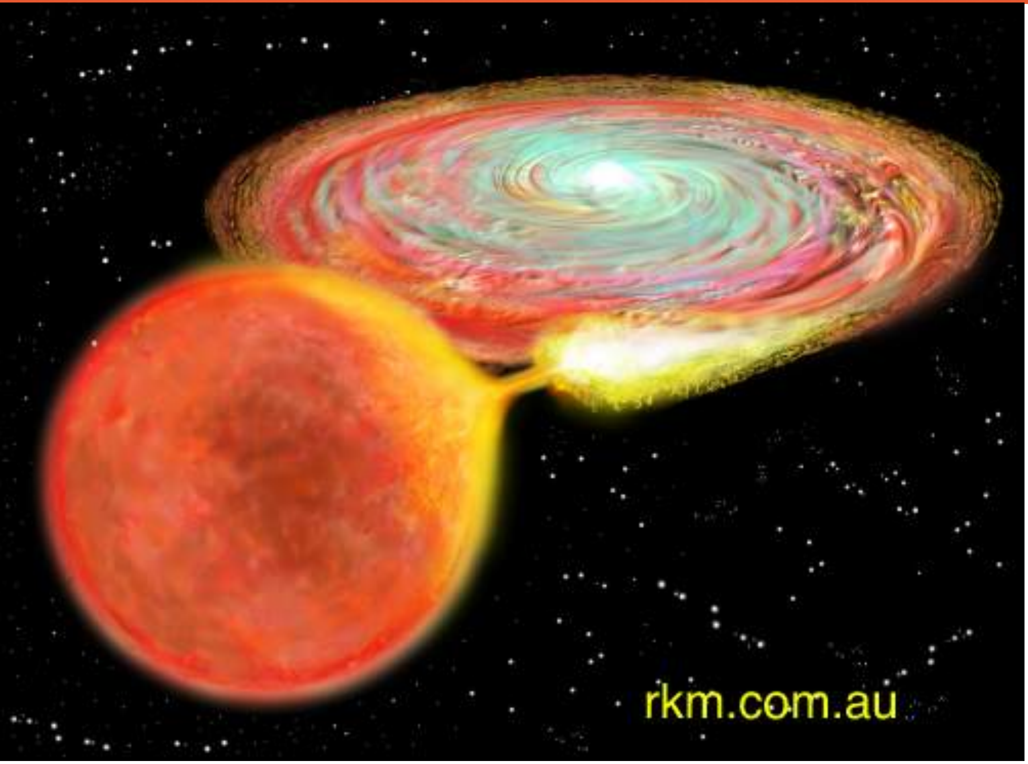
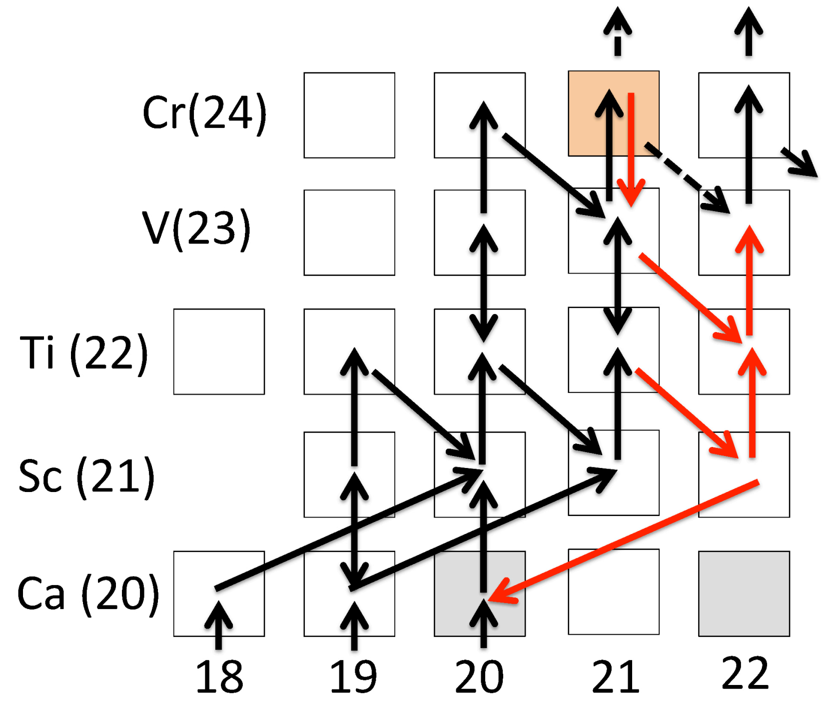
Internationales Büro des BMBF

GSI

Mass Measurements of ^{58}Ni Projectile Fragments
New masses of ^{43}V, ^{45}Cr, ^{47}Mn, ^{49}Fe, ^{51}Co, ^{53}Ni, and ^{55}Cu



Ca-Sc Cycle [L. Van Wormer, ApJ 432 (1994) 326]



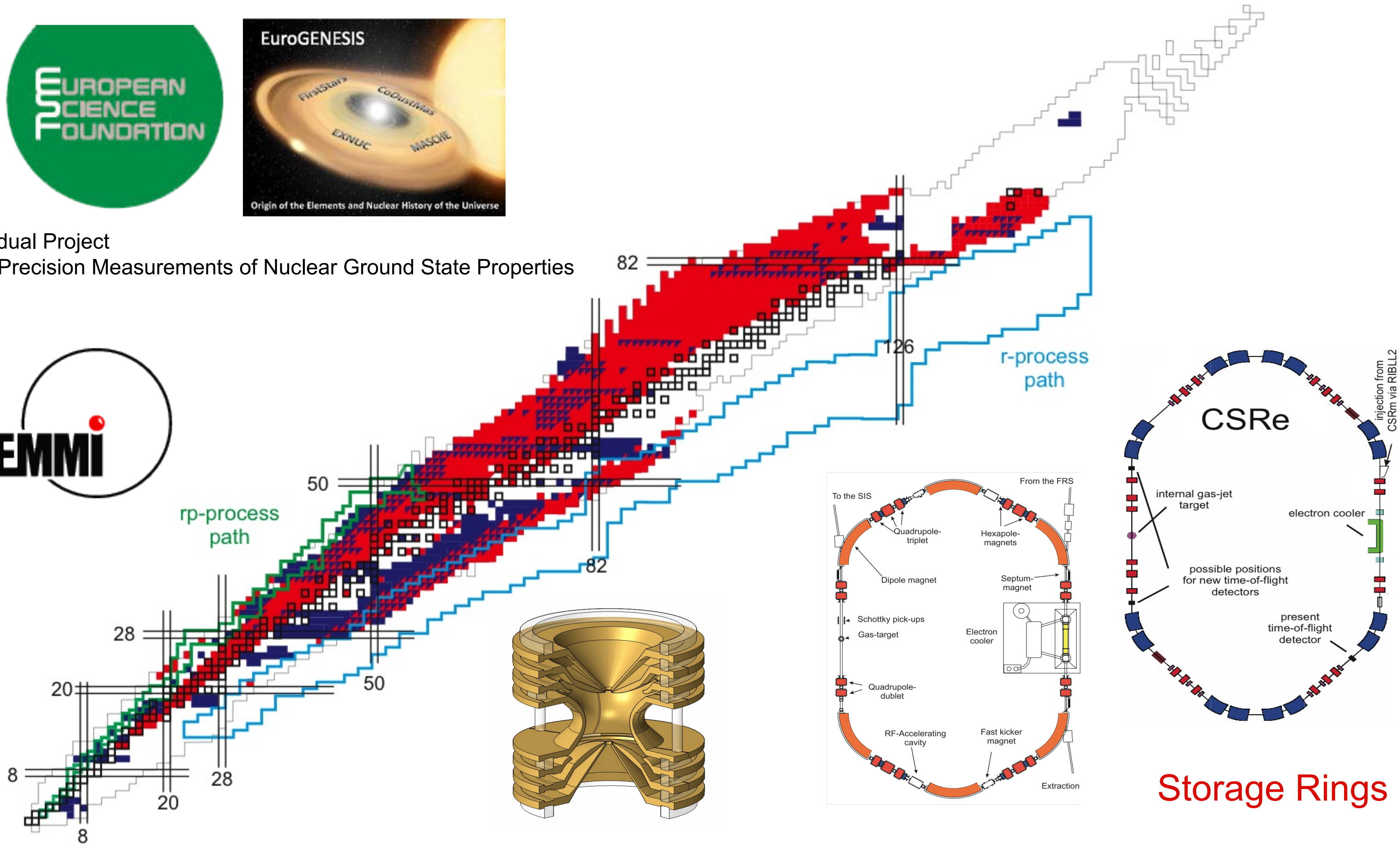
$S_p(^{45}Cr)$= 2.1(5) MeV [AME03]

$S_p(^{45}Cr)$= 2.69(13) MeV

X.L. Yan et al., ApJL 766 (2013) L8

Direct Mass Measurements on the Chart of the Nuclides

Individual Project
High-Precision Measurements of Nuclear Ground State Properties



Penning Traps

Storage Rings

Half-life modifications

Fundamental question:

“Can we change the decay rate or the half-life of a nucleus is its basic property ?!“

Nuclear decay constant is a fundamental constant which cannot be changed by external, non-nuclear processes

Rutherford E and Soddy F The radioactivity of thorium compounds II. The cause and nature of radioactivity J. Chem. Soc. Transactions 81 837–860 (1902)

Pressure, Temperature, Electromagnetic fields, Chemistry ...

G.T. Emery, Annu. Rev. Nucl. Sci. 22 (1972) 165:

Effects of less than 1%

Modification of the electron density at the nucleus

Radioactive decays of highly-charged ions

Nuclear weak decay in general form:

$$n + \nu_e \leftrightarrow p + e^-$$

i) continuum beta decay:

$$n \rightarrow p + e^- + \bar{\nu}_e \qquad \beta^- - \text{decay}$$

$$p \rightarrow n + e^+ + \nu_e \qquad \beta^+ - \text{decay}$$

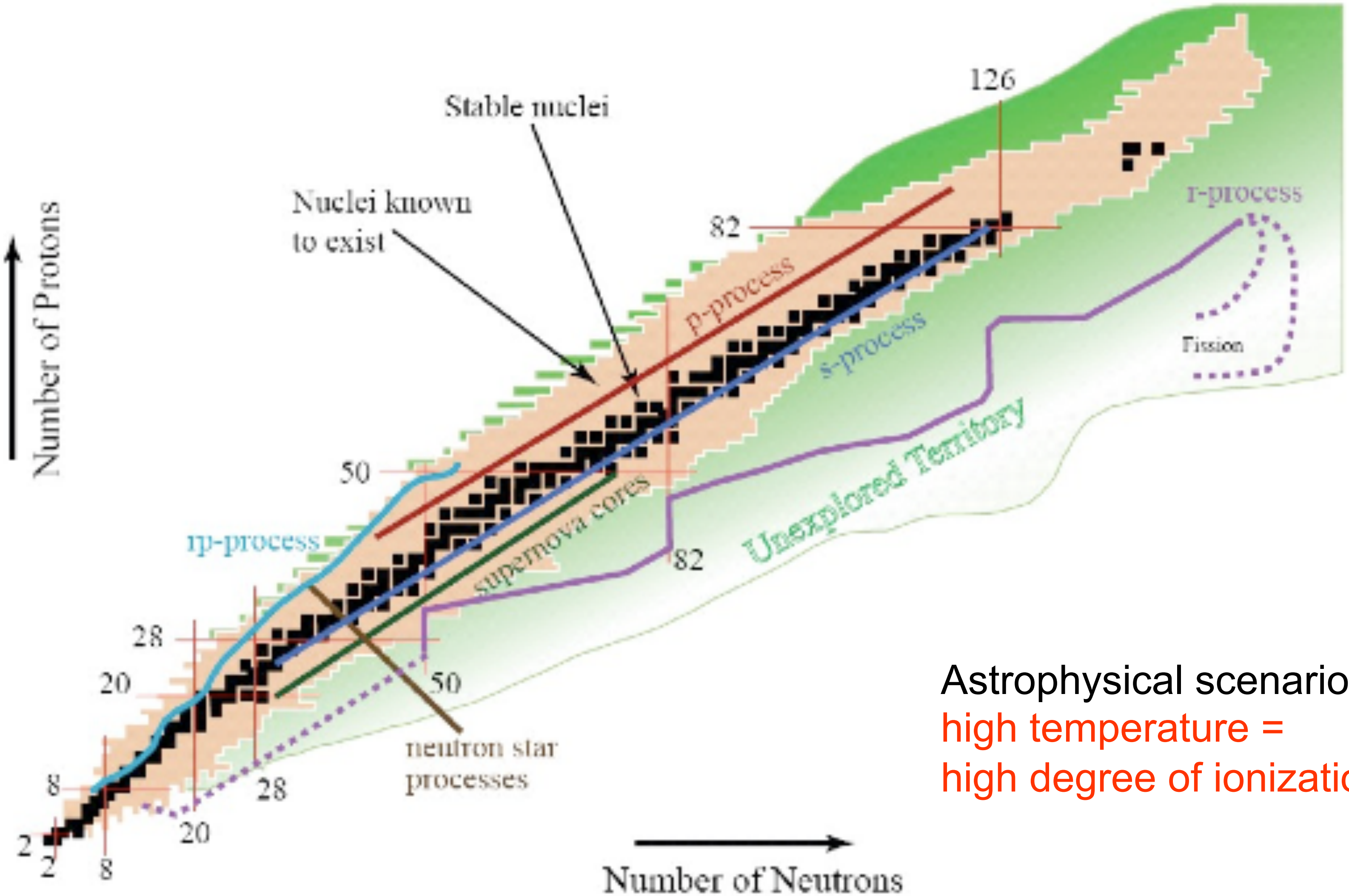
ii) two-body beta decay:

$$p + e_b^- \rightarrow n + \nu_e \qquad \text{Orbital electron capture (EC)}$$

$$n \rightarrow p + e_b^- + \bar{\nu}_e \qquad \text{Bound state beta decay } (\beta_\mathrm{b}^-)$$

$$p + e^- \rightarrow n + \nu_e \qquad \text{Free electron capture}$$

Nucleosynthesis on the Chart of the Nuclides



Astrophysical scenarios:
high temperature =
high degree of ionization

Radioactive decays of highly-charged ions

Few-electron ions
well-defined quantum-mechanical systems

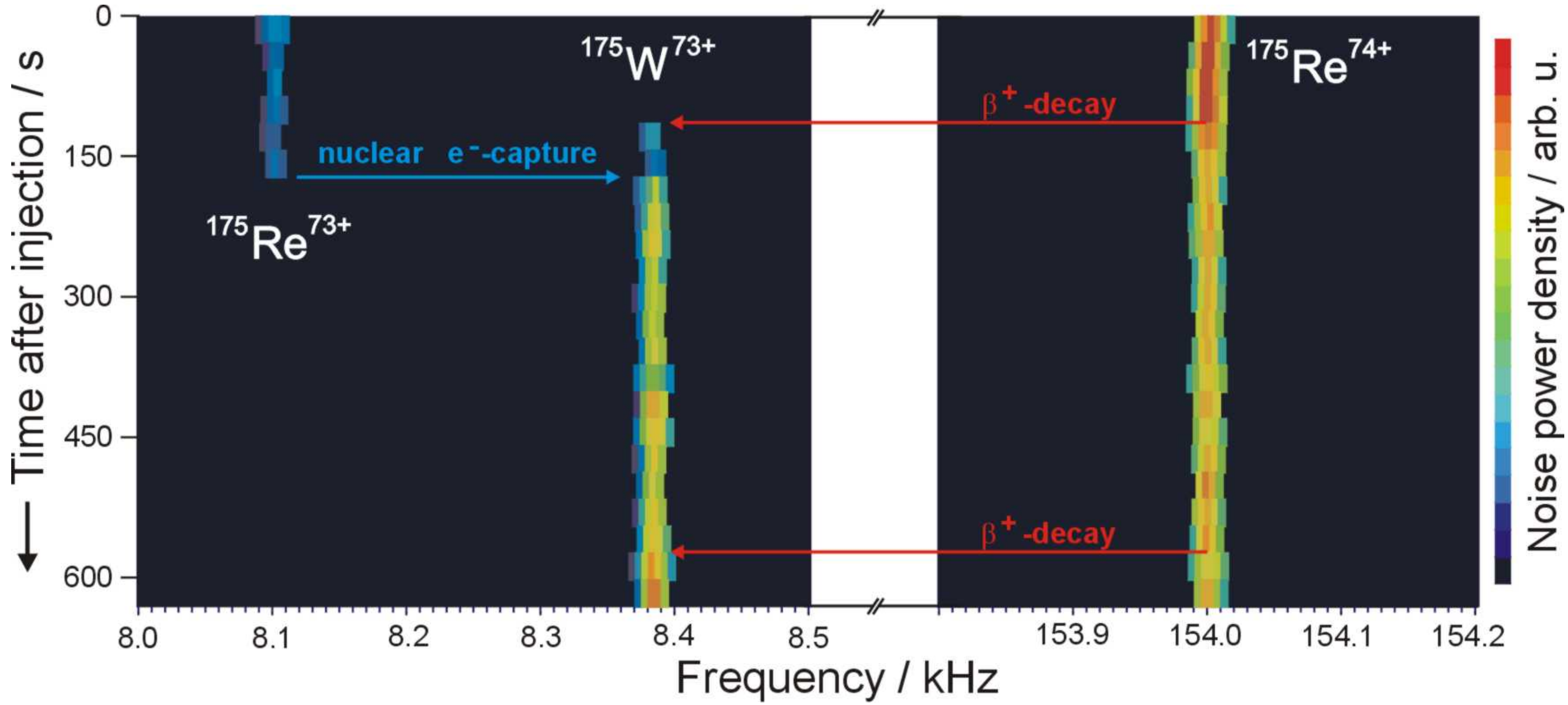
New decay modes
(bound-pair-creation, bound-state beta decay, etc.)

Influence of electrons on radioactive decay

Astrophysical scenarios:
high temperature = high degree of ionization

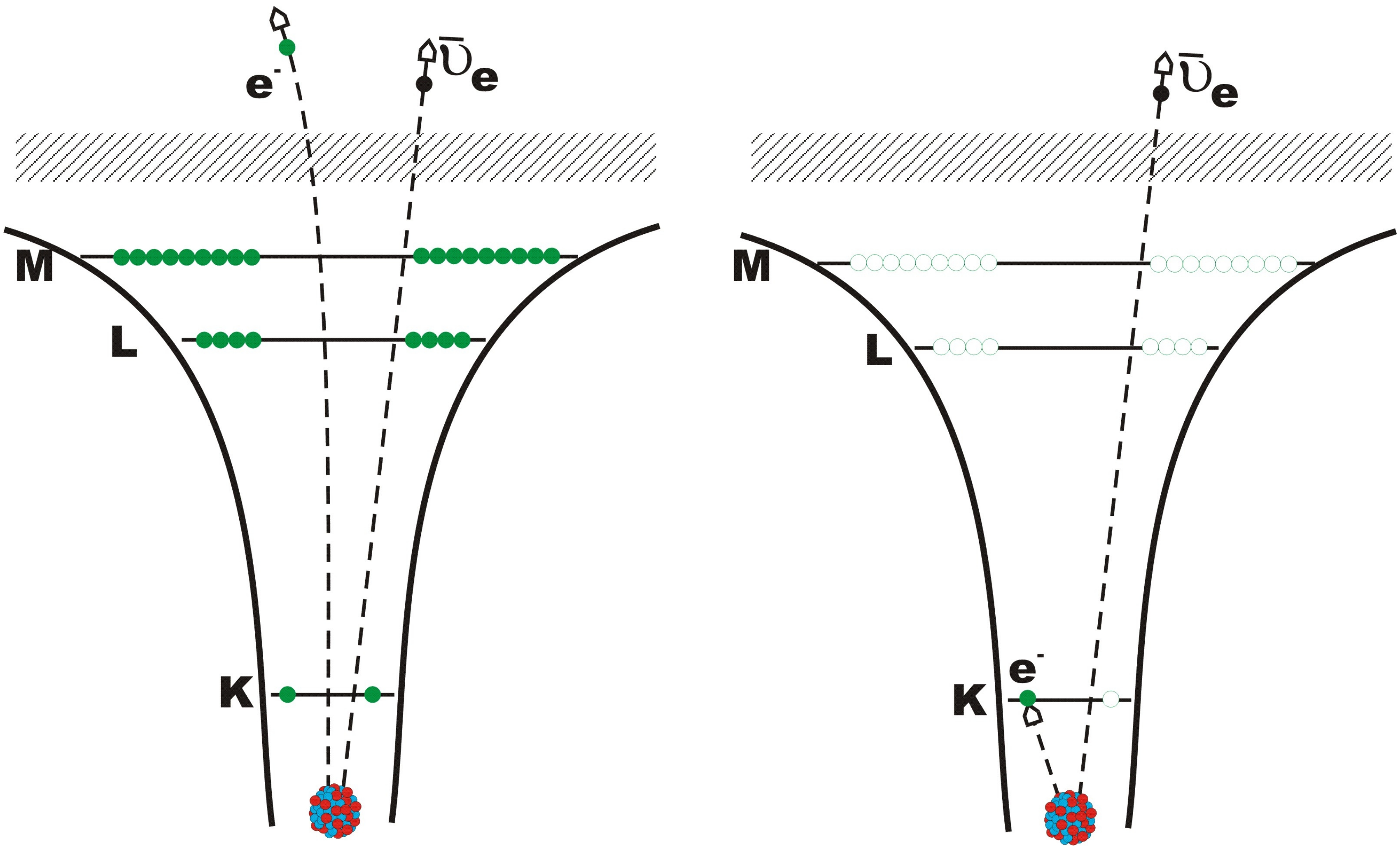
Nuclear Decays of Stored Single Ions

Time-resolved SMS is a perfect tool to study decays in the ESR



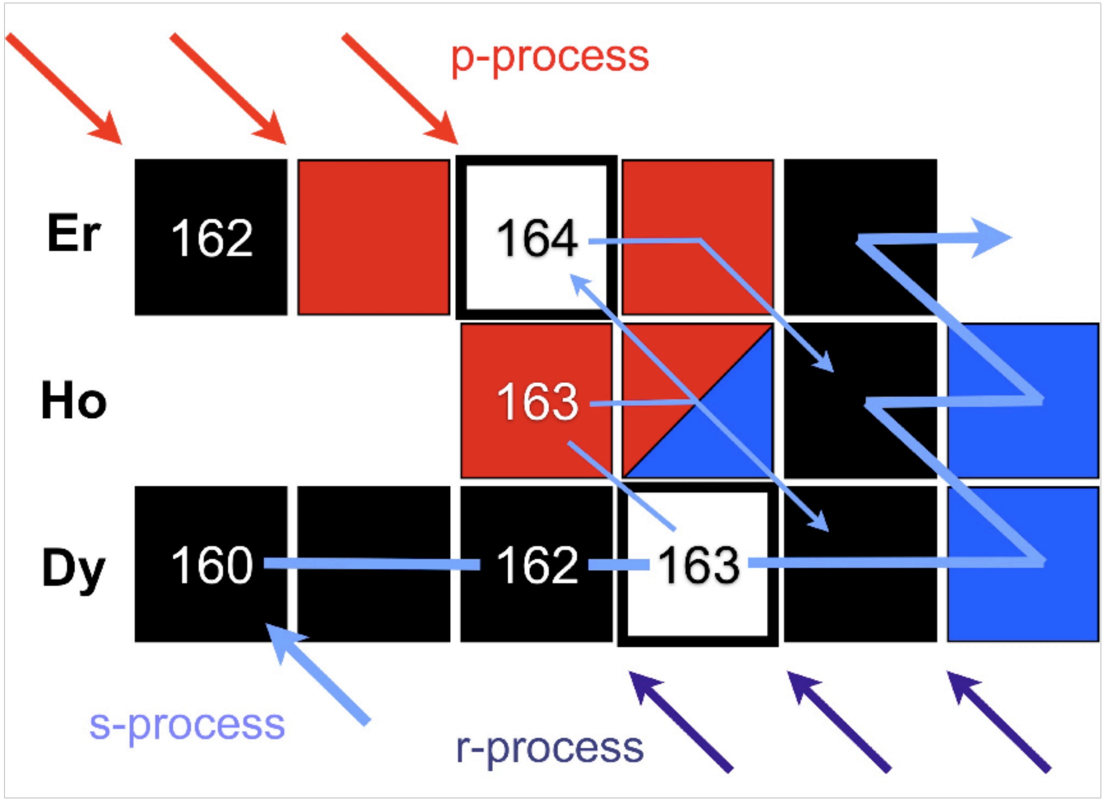
EC, β+,β-, bound-state β, and IT decays were observed

Bound-State β-decay



Bound-State β-decay of ^{163}Dy

s process: slow neutron capture and β- decay near valley of β stability at kT = 30 keV; → high atomic charge state → bound-state β decay

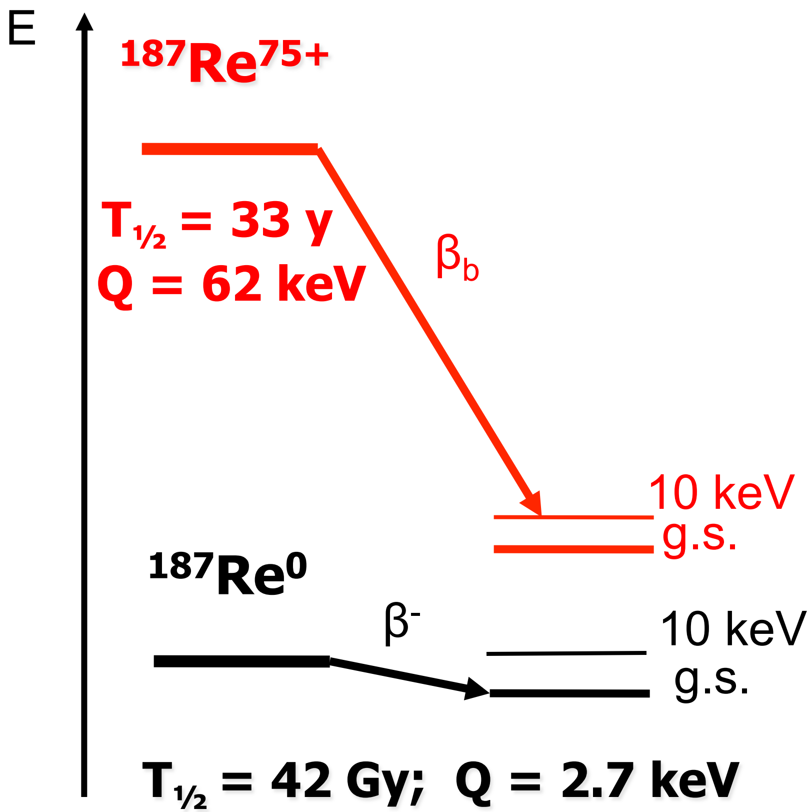


$T_{1/2}$ = 48 days

branchings caused by bound-state β decay

M. Jung et al., Phys. Rev. Lett. 69 (1992) 2164

Bound-State β-decay of ^{187}Re



F. Bosch et al., Phys. Rev. Lett. 77 (1996) 5190

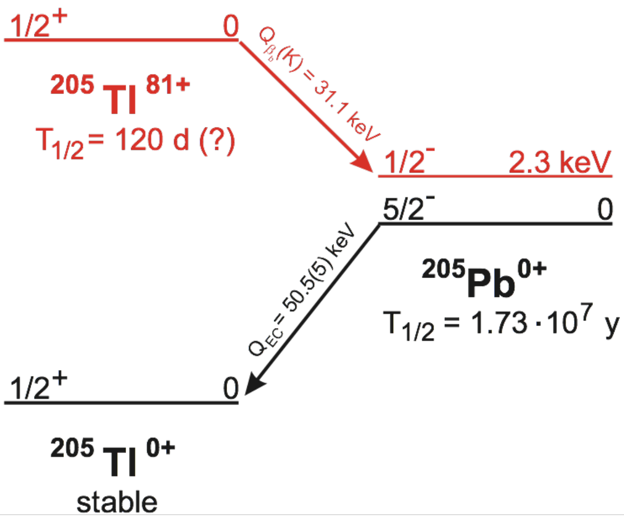
The 7 Nuclear Clocks

the Earth, the Solar System, the

Galaxy, and the Universe

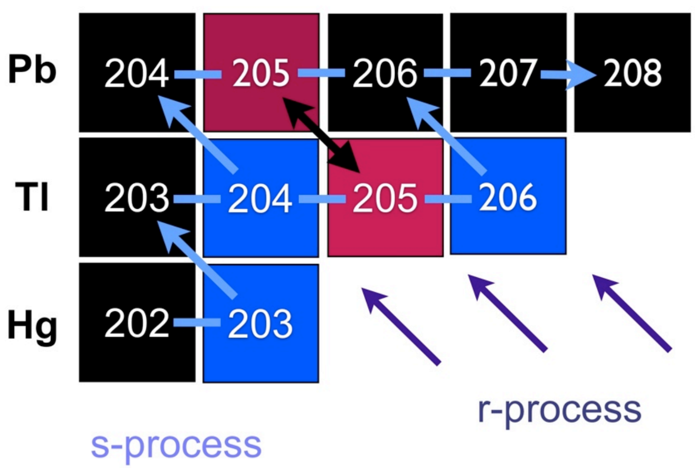
clock	$T_{1/2}$ [10^9 y]
$^{40}K/^{40}Ar$ (β)	1.3
^{238}U…Th…^{206}Pb (α,β)	4.5
^{232}Th…Ra…^{208}Pb (α,β)	14
$^{176}Lu/^{176}Hf$ (β)	30
$^{187}Re/^{187}Os$ (β)	42
$^{87}Rb/^{87}Sr$ (β)	50
$^{147}Sm/^{143}Nd$ (α)	100

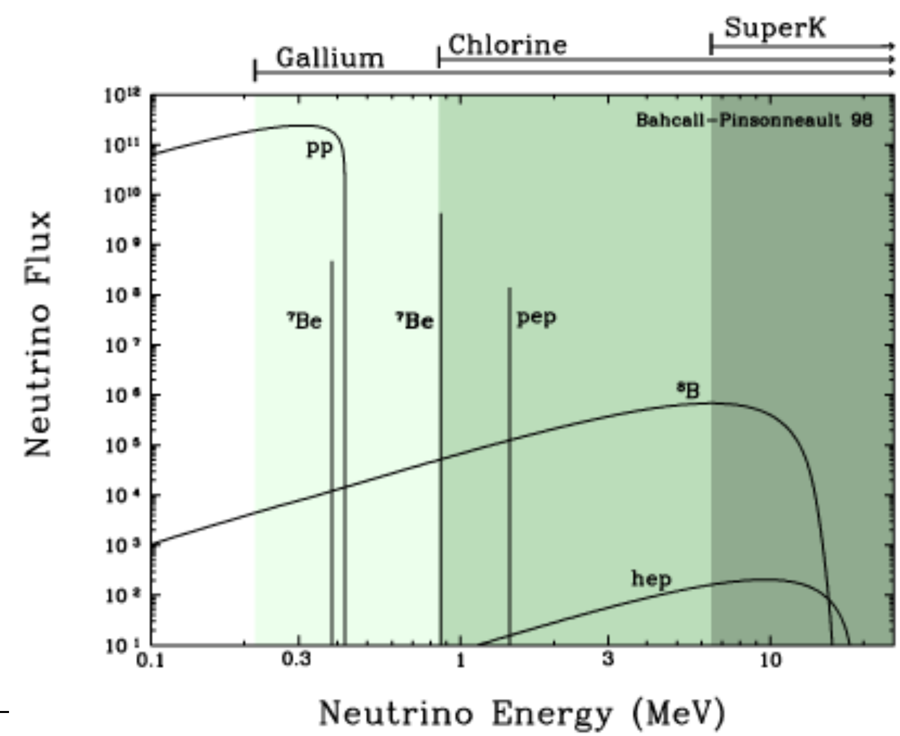
Bound-State Beta Decay of ^{205}Tl Nuclei



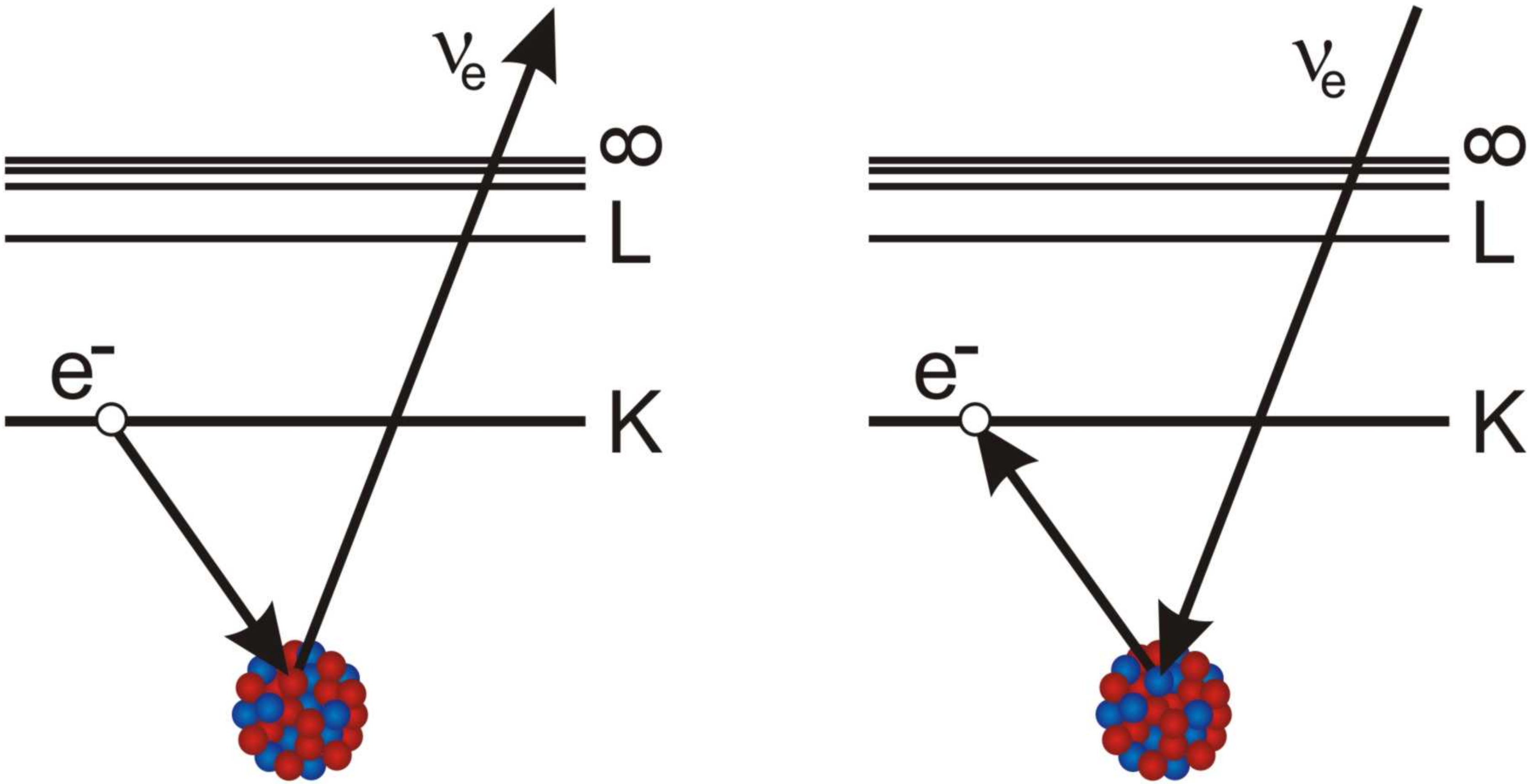
New ESR proposal to study $^{205}Tl^{81+}$

F. Bosch, Yu.A. Litvinov et al., GSI Proposal E100 (2010)





Two-Body Beta Decay



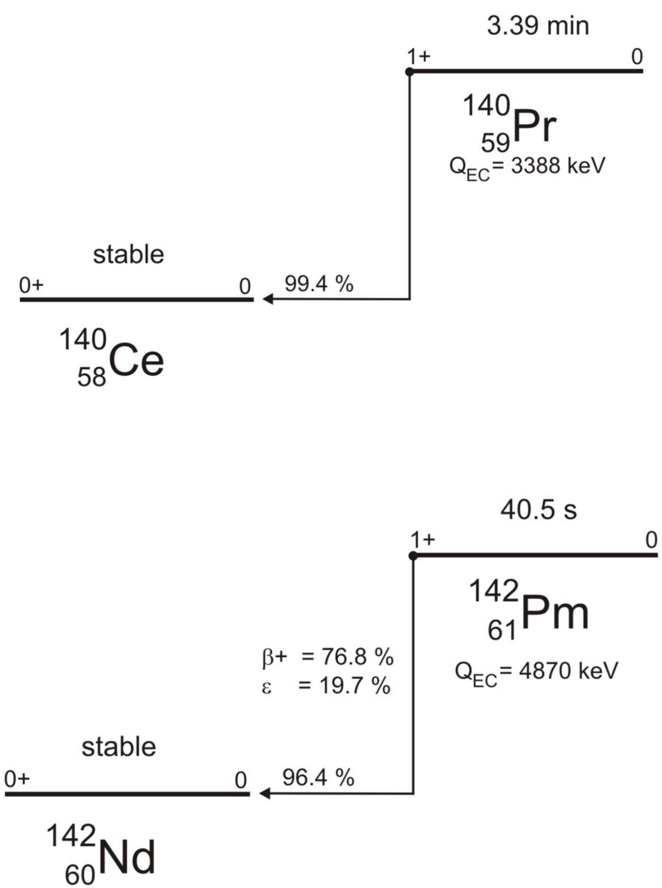
$(Z,N) \rightarrow (Z-1,N+1)$

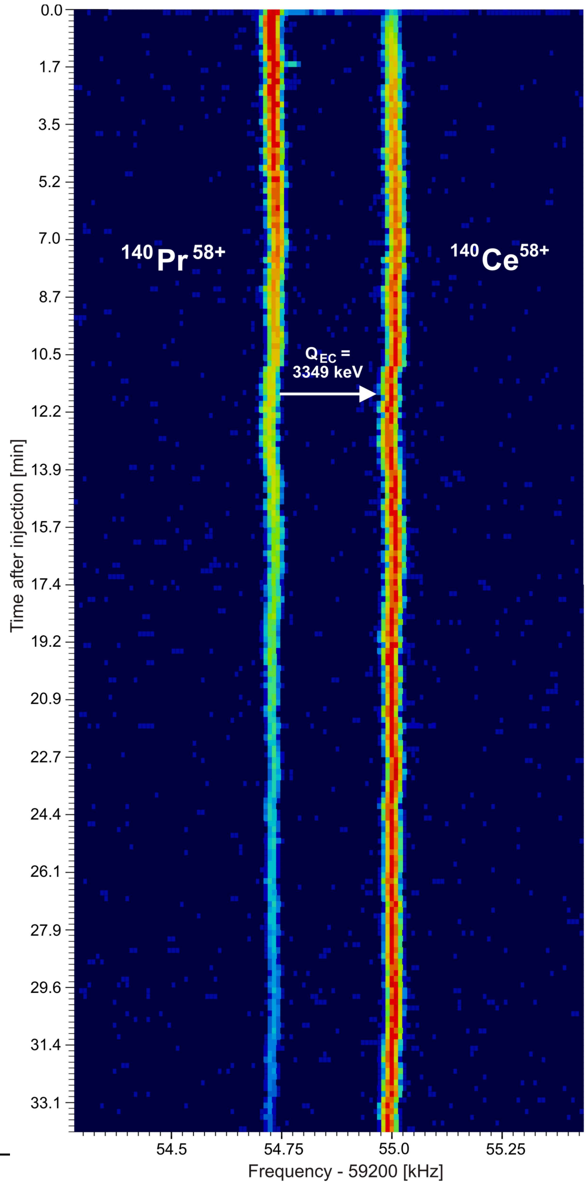
EC

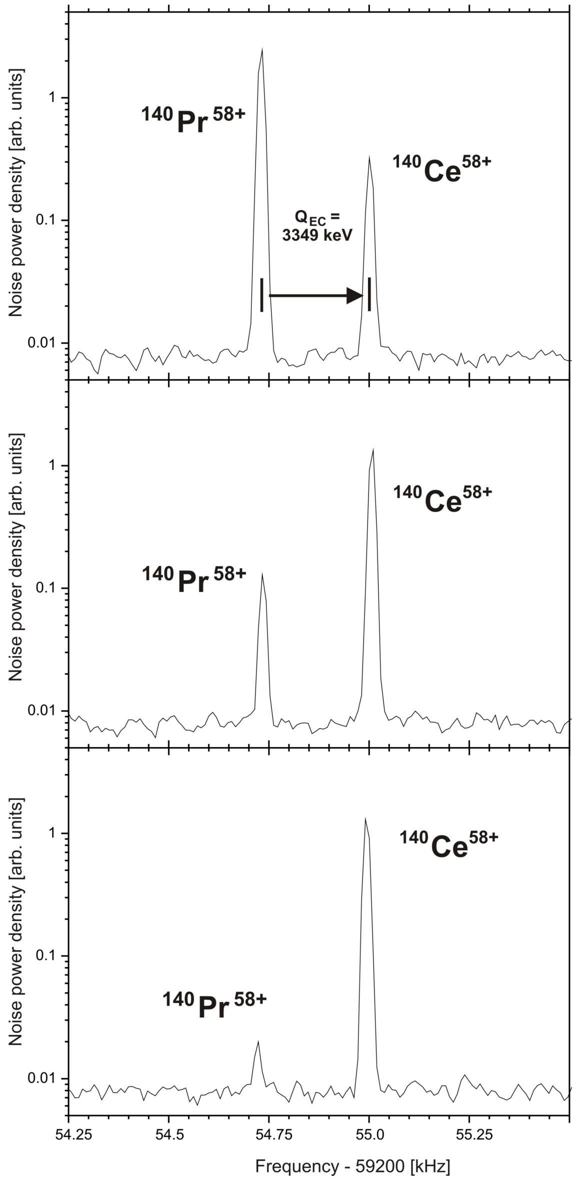
$(Z,N) \rightarrow (Z+1,N-1)$

β_b^-

Orbital Electron Capture Decay of Few-Electron Ions

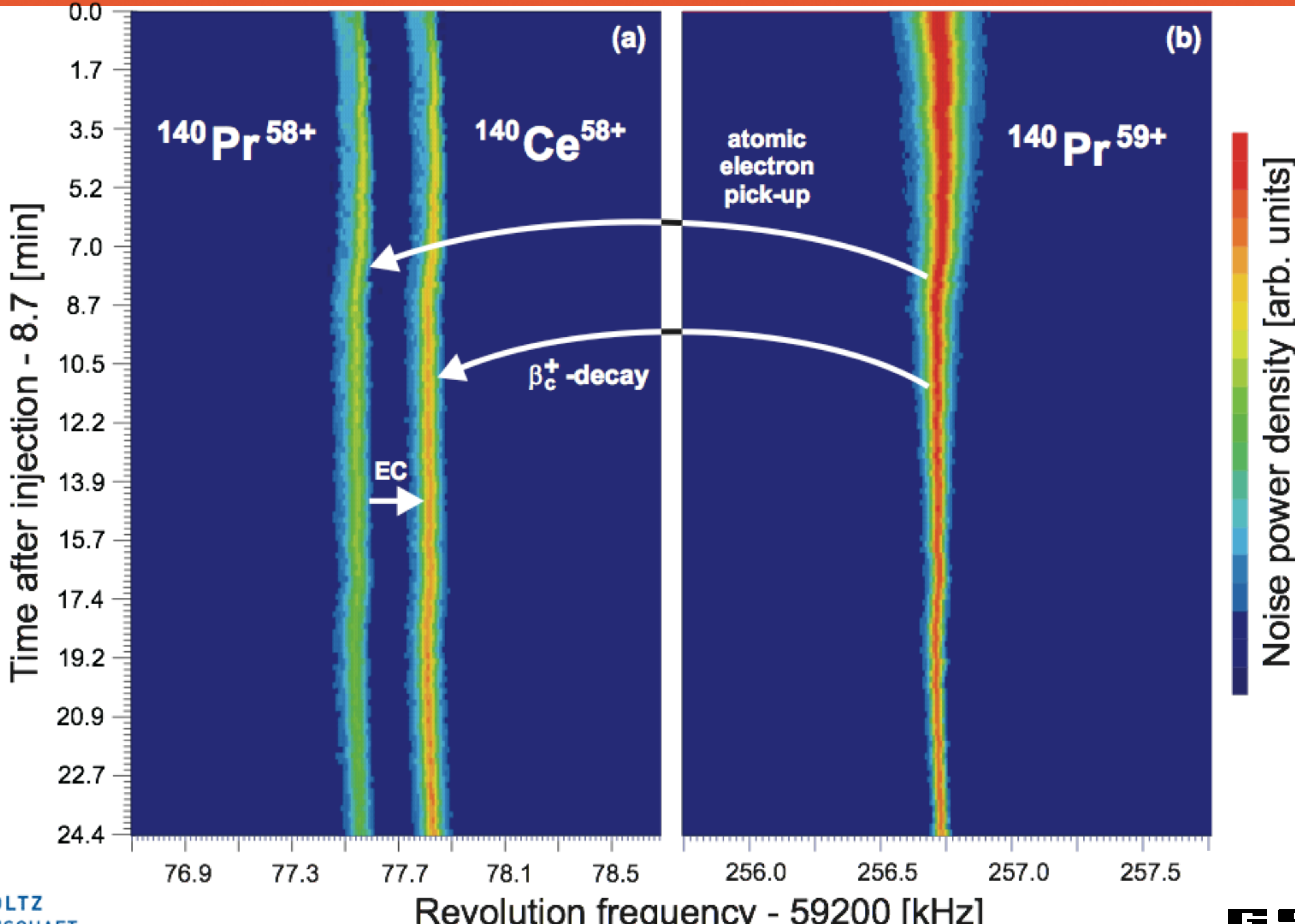






HELMHOLTZ
GEMEINSCHAFT

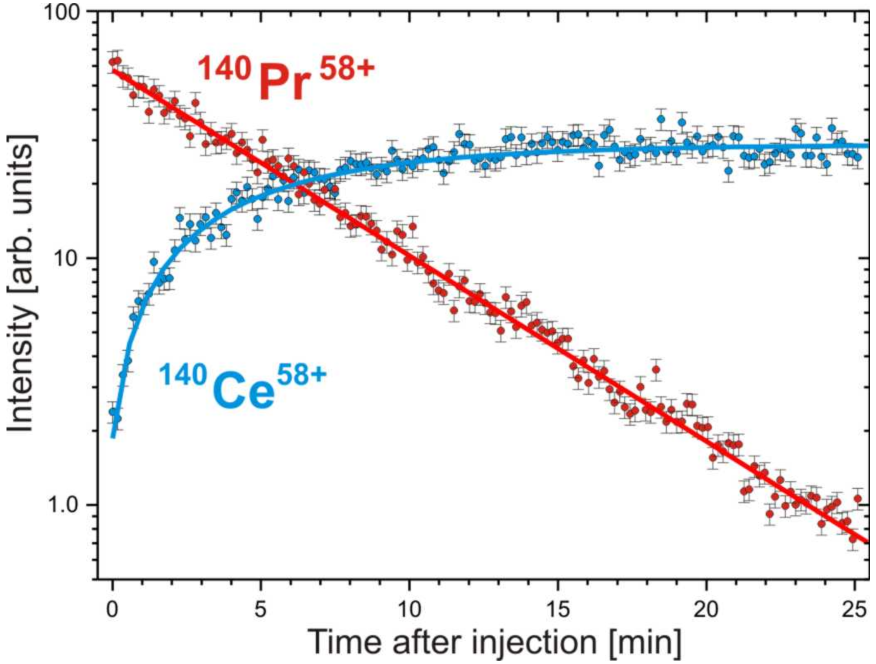
3-body Beta Decay



Orbital Electron Capture Decay of Few-Electron Ions

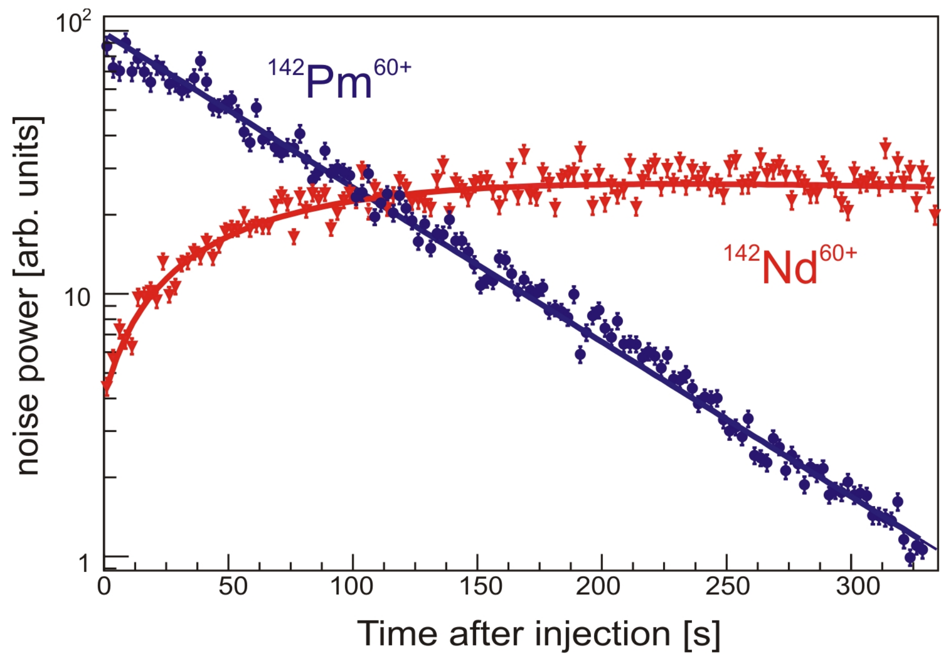
Expectations: $\lambda_{EC}(\text{H-like})/\lambda_{EC}(\text{He-like}) \approx 0.5$

$\lambda_{EC}(\text{H-like})/\lambda_{EC}(\text{He-like}) = 1.49(8)$



Yu.A. Litvinov et al., Phys. Rev. Lett. 99 (2007) 262501

$\lambda_{EC}(\text{H-like})/\lambda_{EC}(\text{He-like}) = 1.44(6)$



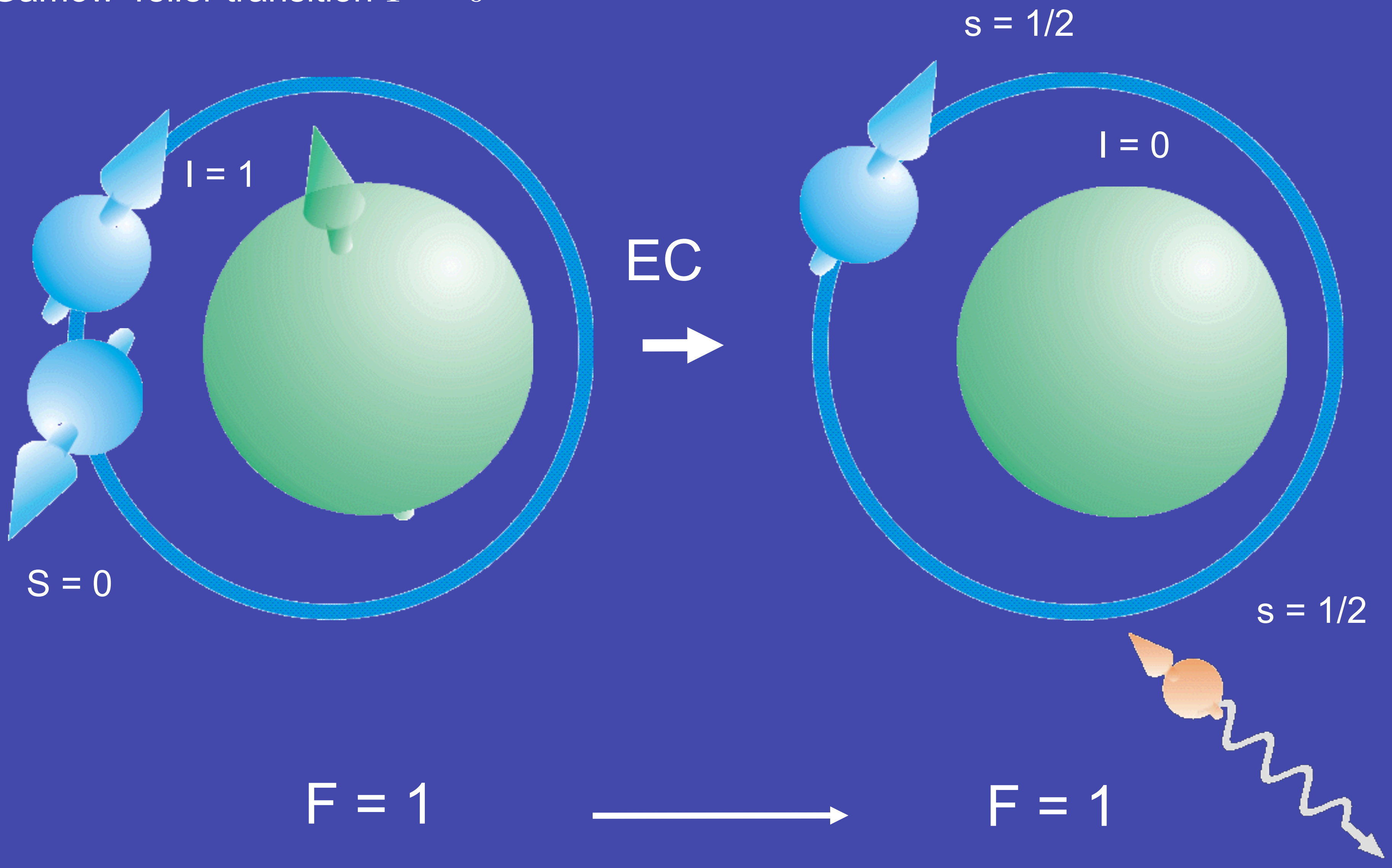
N. Winckler et al., Phys. Lett. B579 (2009) 36

HELMHOLTZ GEMEINSCHAFT

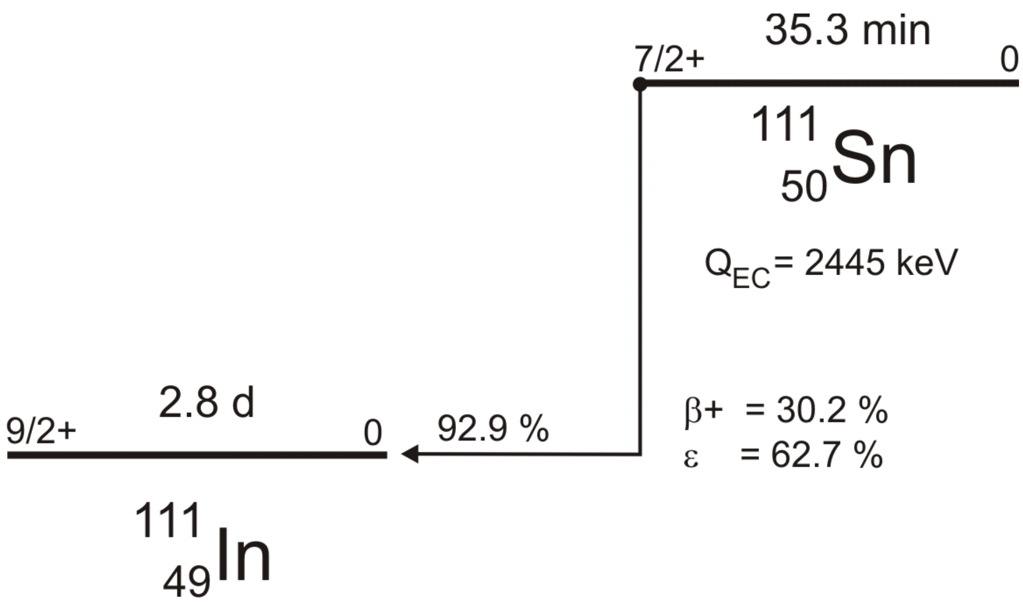
GSI

Electron Capture in Helium-like Ions

Gamow-Teller transition $1^+ \rightarrow 0^+$



Orbital Electron Capture Decay of Few-Electron Ions



New ESR proposal to study EC decay

GSI Proposal E078 (2007)

New ESR proposal to study Alpha-decay

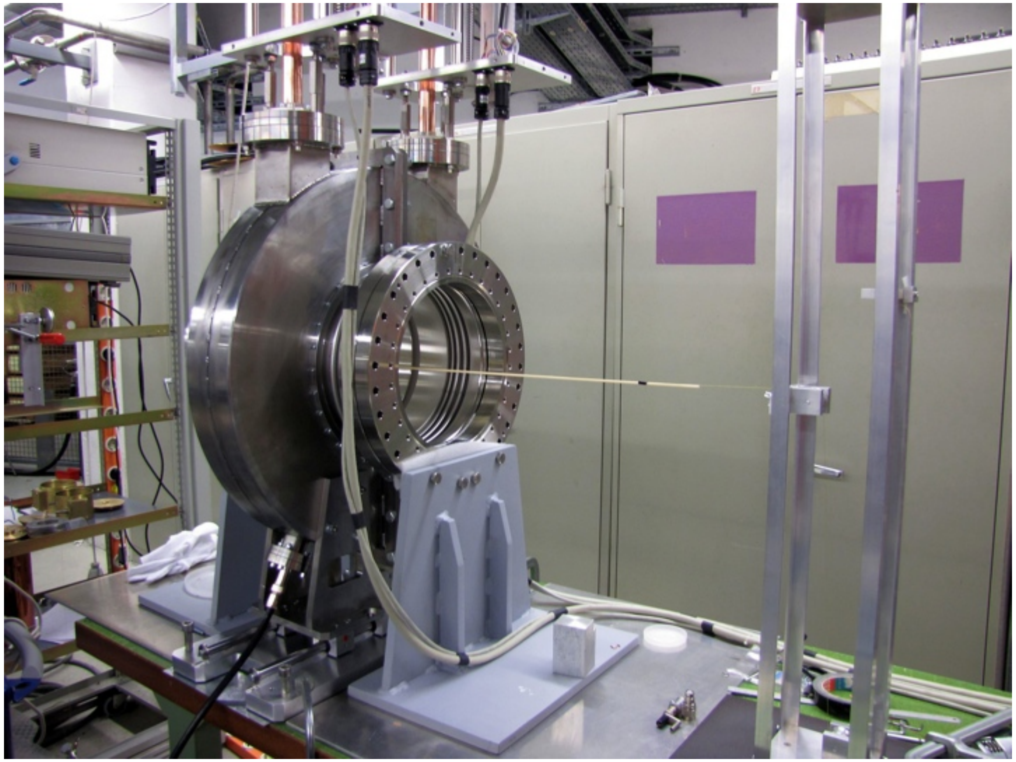
A. Musumarra et al., GSI Proposal E073 (2007)

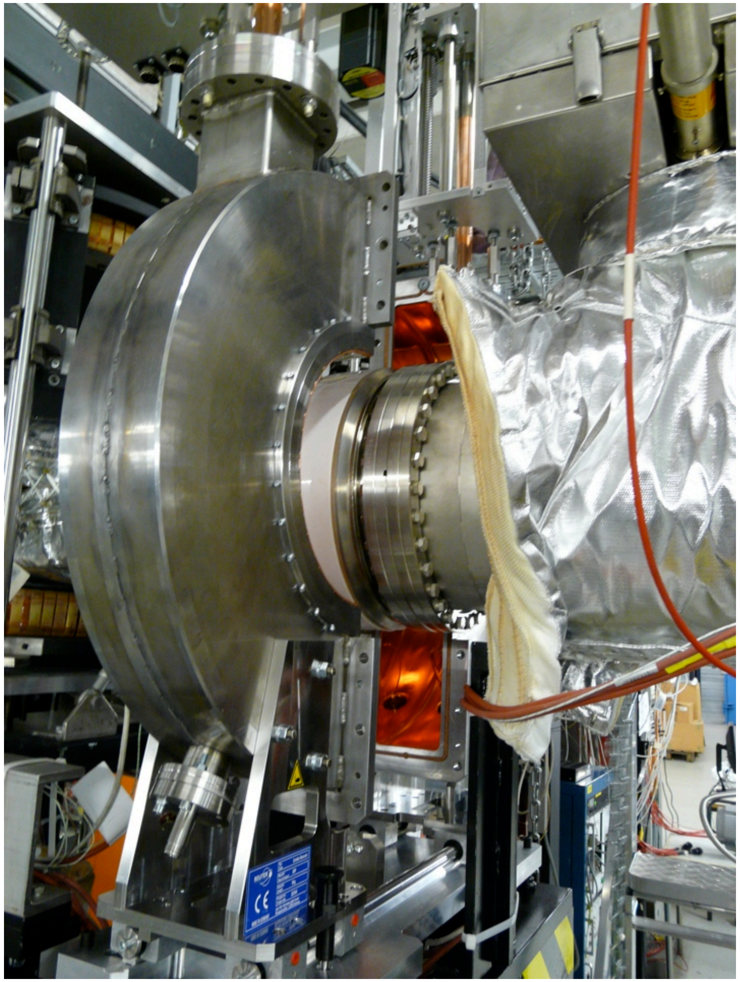
$$F = I + s \;\begin{cases} 4 \\ 3 \end{cases} \longrightarrow F = I + s \;\begin{cases} 5 \\ 4 \end{cases}$$

Possibility to address the electron screening in beta decay under very clean conditions !

Yu.A. Litvinov, Int. J. Mod. Phys. E18 (2009) 323

New Resonant Schottky Cavity

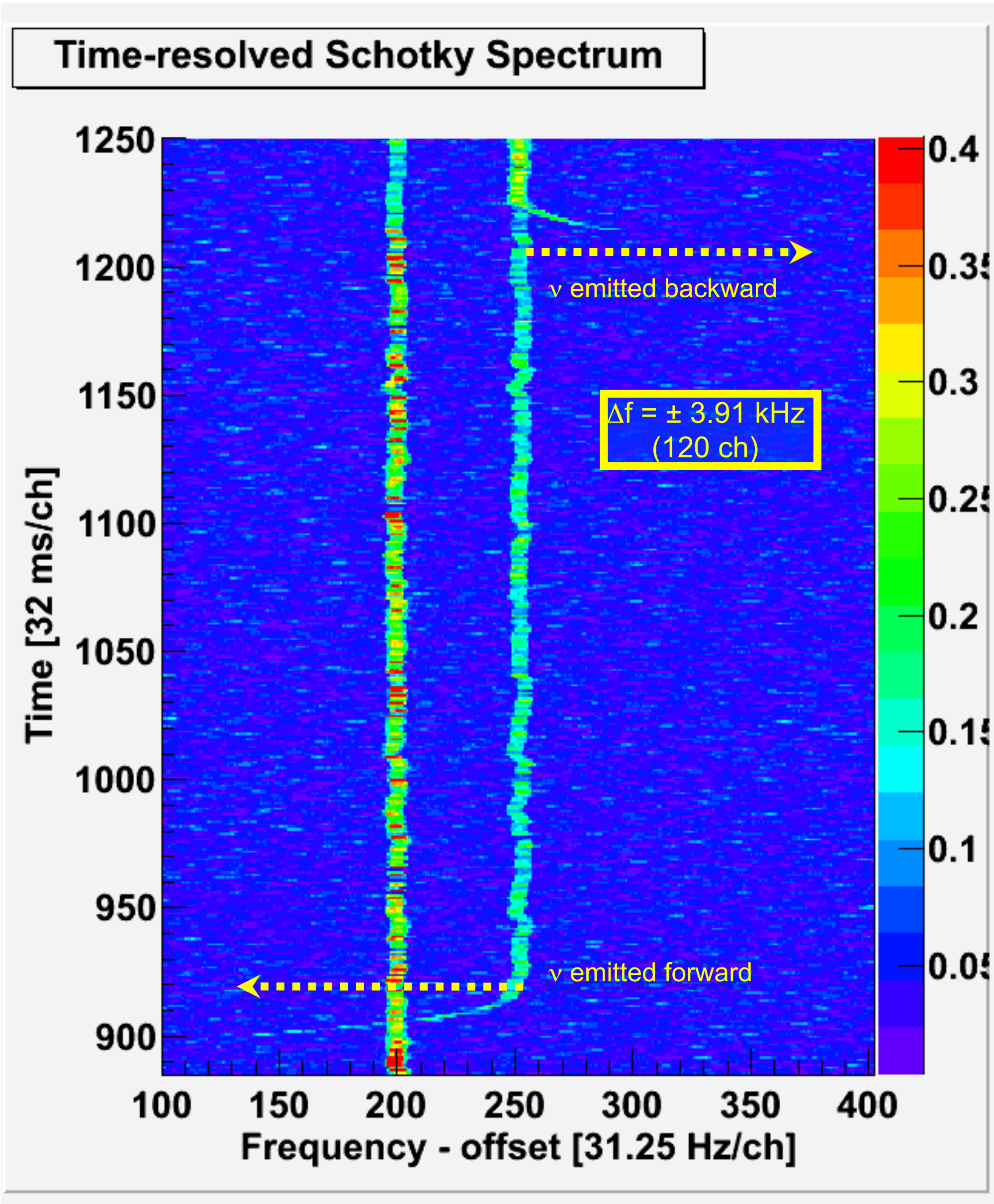


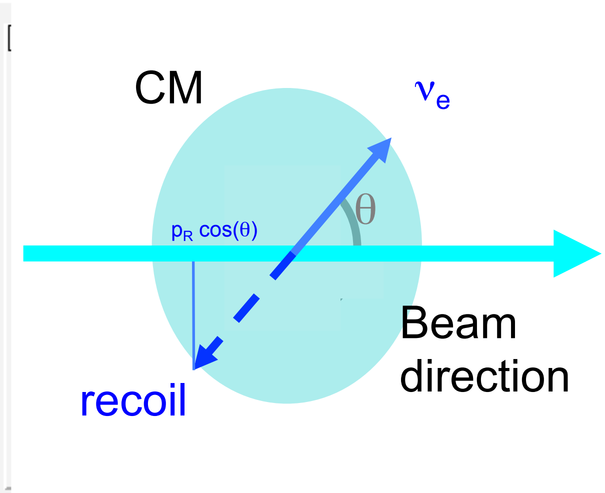


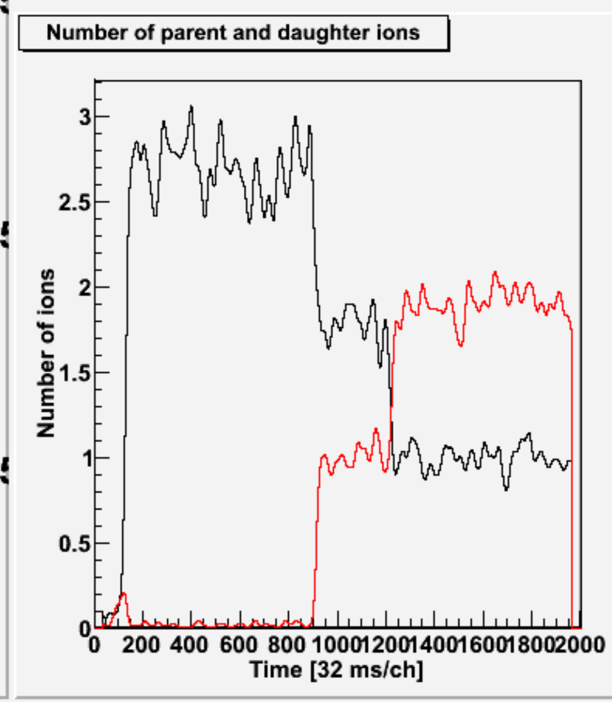
The signal-to-noise ratio is improved by a factor of about 100

F. Nolden et al., Nucl. Instr. Meth. A (2011) in press

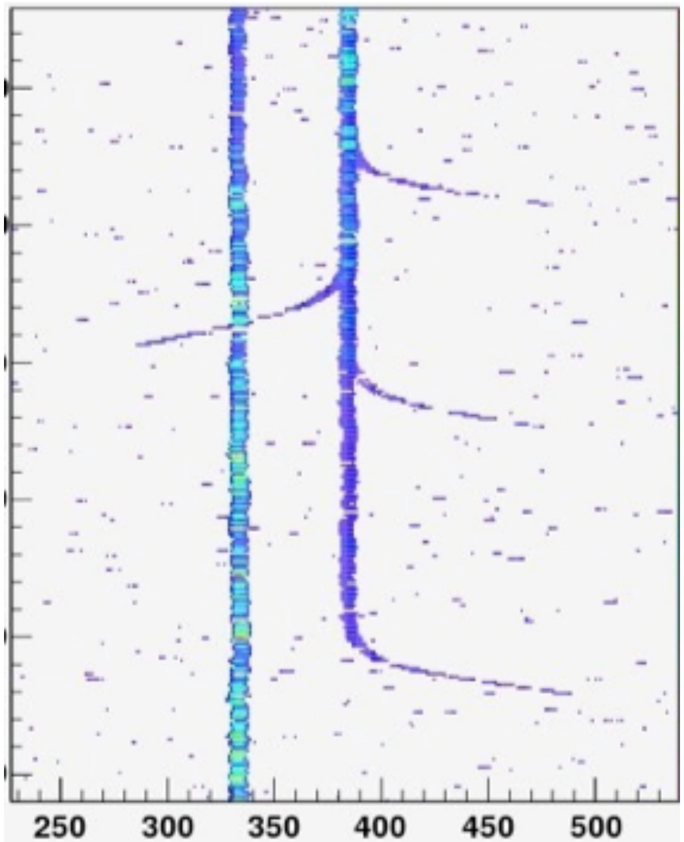
Three Parent He-Like ^{142}Pm Ions

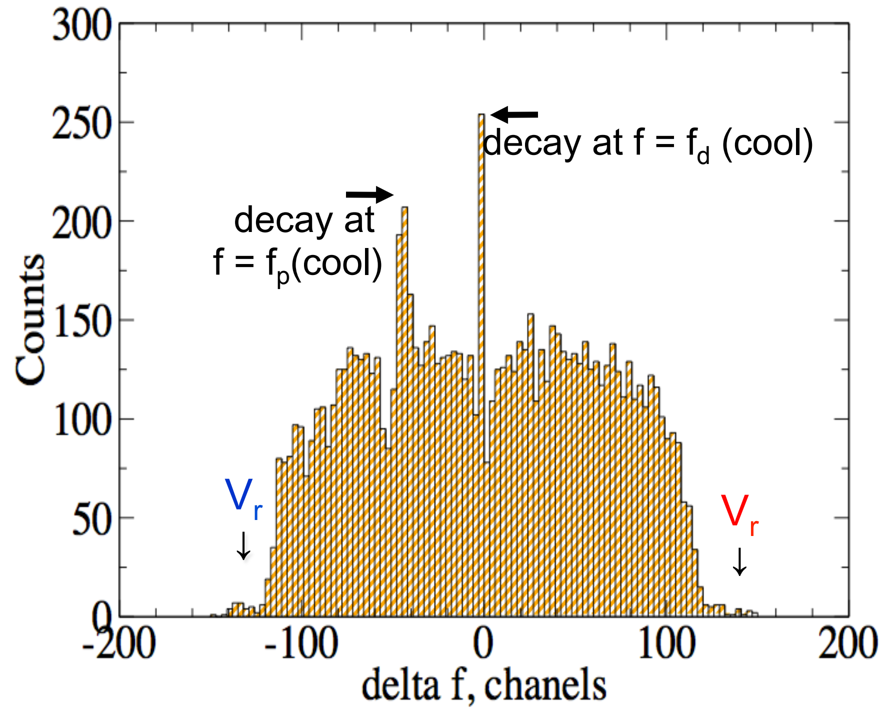






Revolution-frequency difference δf of the recoils just after decay: $\delta f = f_{dec} - f_{cool}$





For a (longitudinally) unpolarized beam the distribution should have a rectangular shape

For a (steadily controlled) polarized beam the distribution would provide the helicity of the neutrino

From v_r and m_r one gets the momentum of the (monochromatic) neutrino: $(pc)_d = m_d\, cv_d = (pc)_\nu$

From m_p and m_d one gets its energy: $E_\nu = (m_p - m_d)\, c^2$ and then $\beta_\nu = E_\nu / (pc)_\nu$

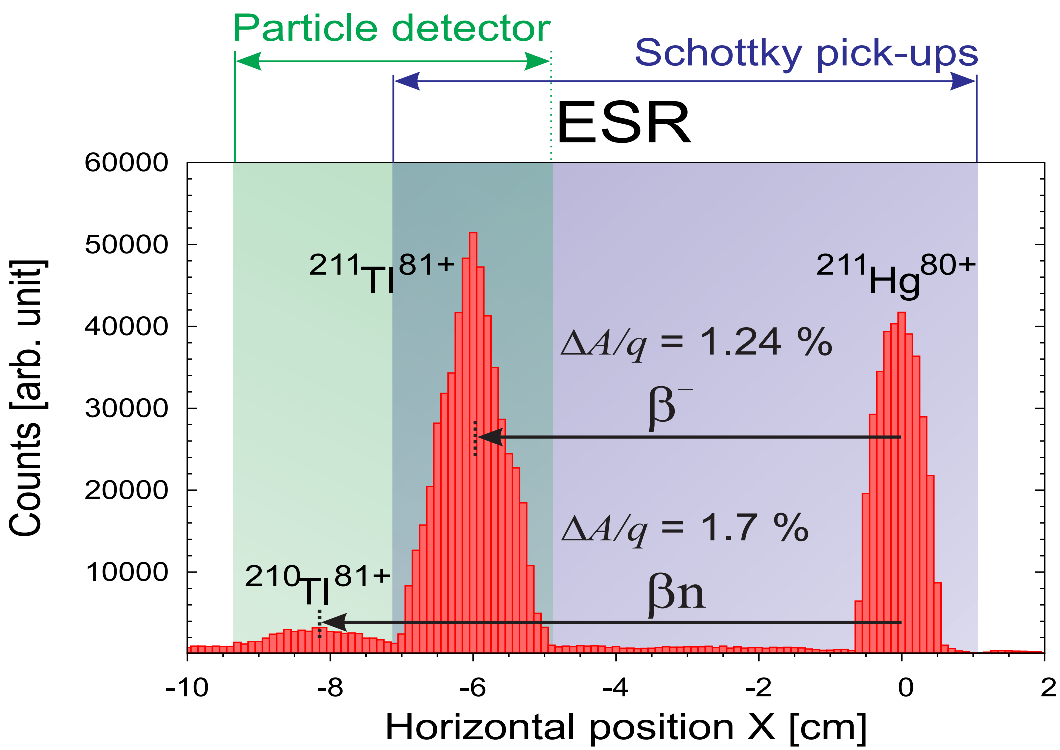
Exotic (radioactive) nuclides in high atomic charge states stored for an extended period of time

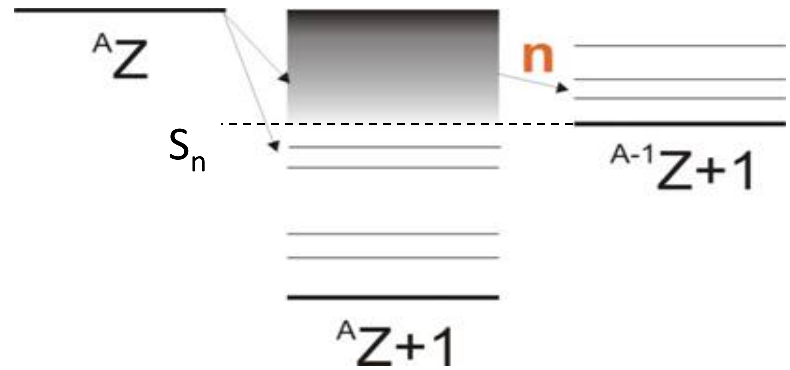
Radioactive ion beam facilities

High kinetic energies or electron beam ion source

Ultra-high vacuum conditions

β-delayed neutron emission probability





$S_n < Q_\beta$

Important nuclear structure information
P_n : β-strength above S_n
$t_{1/2}(^{A}Z+1)$: sensitive to low-lying β-strength

A. Evdokimov et al., Proc. NIC XI, PoS (NIC XII) 115

Physics at Storage Rings

Single-particle sensitivity
High atomic charge states
Long storage times
Broad-band measurements
High resolving power
Very short lifetimes

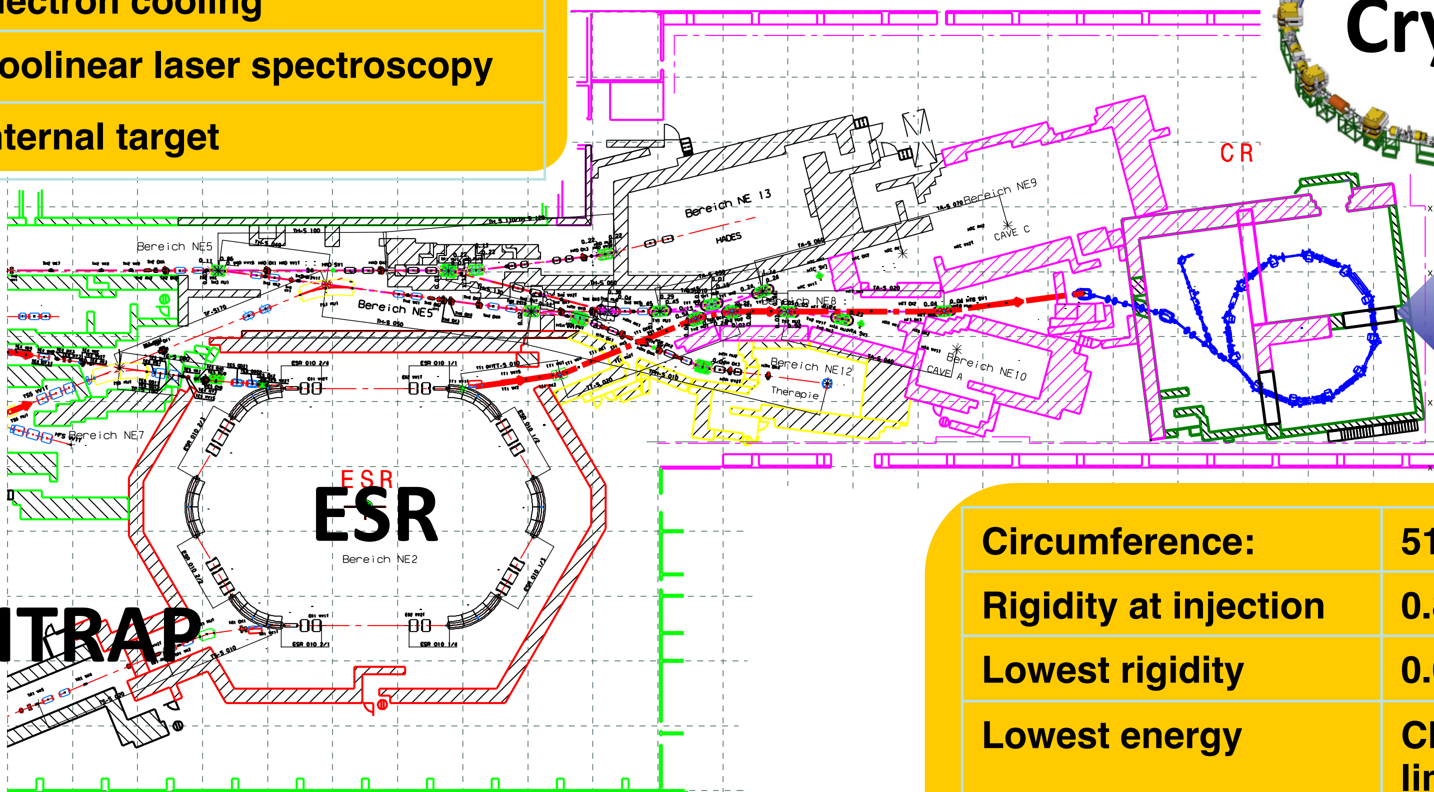
Direct mass measurements of exotic nuclei
Radioactive decay of highly-charged ions
Charge radii measurements [DR, scattering]
Experiments with polarized beams
Experiments with isomeric beams [DR, reactions]
Nuclear magnetic moments [DR]
Astrophysical reactions [(p,g), (a,g) ...]
In-ring nuclear reactions

Experimental Storage Ring ESR
Experimental Cooler-Storage Ring CSRe
Low-Energy Storage Ring TSR at ISOLDE
New Storage Ring Complex at FAIR
New Storage Ring Complex at HIAF
Low energy ring CryRING@ESR
RI-RING at RIKEN

CRYRING@ESR

Project coordination:
F. Herfurth & M. Lestinsky

Electron cooling
Coolinear laser spectroscopy
Internal target



Circumference:	**51.63 m**
Rigidity at injection	**0.88 Tm (1.44 Tm)**
Lowest rigidity	**0.054 Tm**
Lowest energy	**Charge exchange limited**
Magnet ramping	**7 T/s; 1 T/s**
Vacuum system	**10^{-11} -10^{-12} bar**
Slow extraction	

Working group report: http://www.gsi.de/en/start/fair/fair_experimente_und_kollaborationen/sparc/news.htm

The case of CRYRING

ESR: beam energies > 4.0 MeV/u reaction rates measurements in the Gamow window of the **p-process**

Q. Zhong et al., J. Phys. CS 202 (2010) 012011

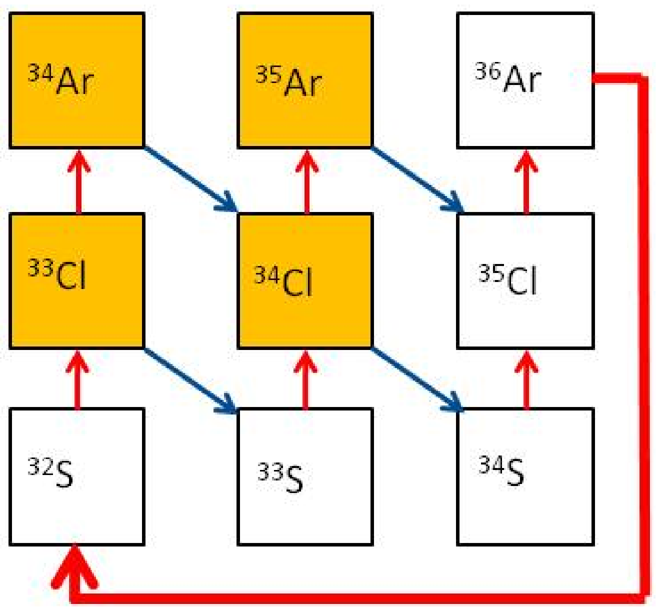
→ Cryring+ESR: beam energies 0.1-1.0 MeV/u reaction rates measurements in the Gamow window of the **rp-process**

R. Reifarth et al., Cryring Physics Book

One example: ^{33}Cl(p,γ)^{34}Ar by-pass of ^{34m}Cl γ-ray emitting isomer

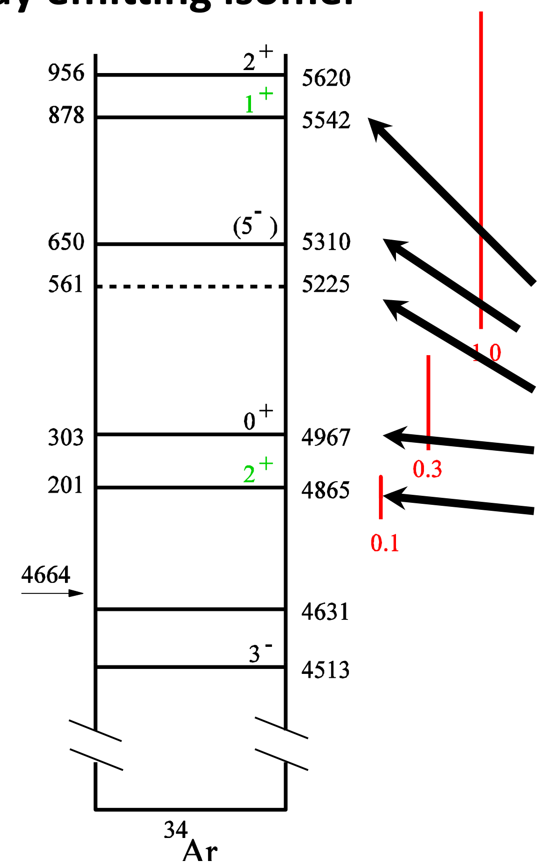
Novae physics

Production of ^{34m,g}Cl



S. Bishop et al., Cryring Physics Book

resonance strengths



assuming 10^6 stored ^{33}Cl we can expect:

1200 count/hr

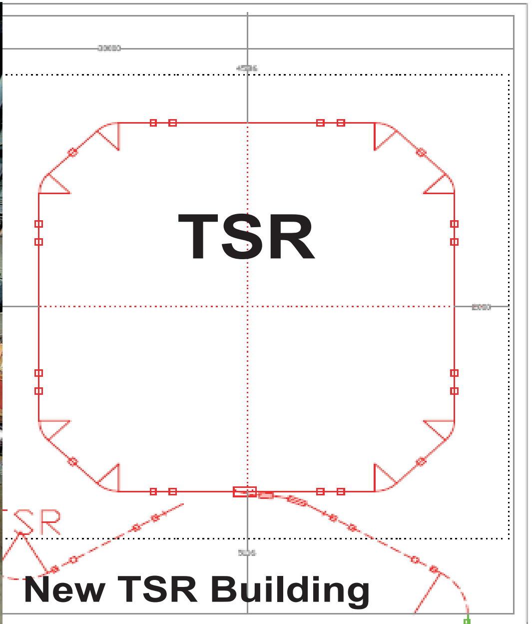
1 count/s

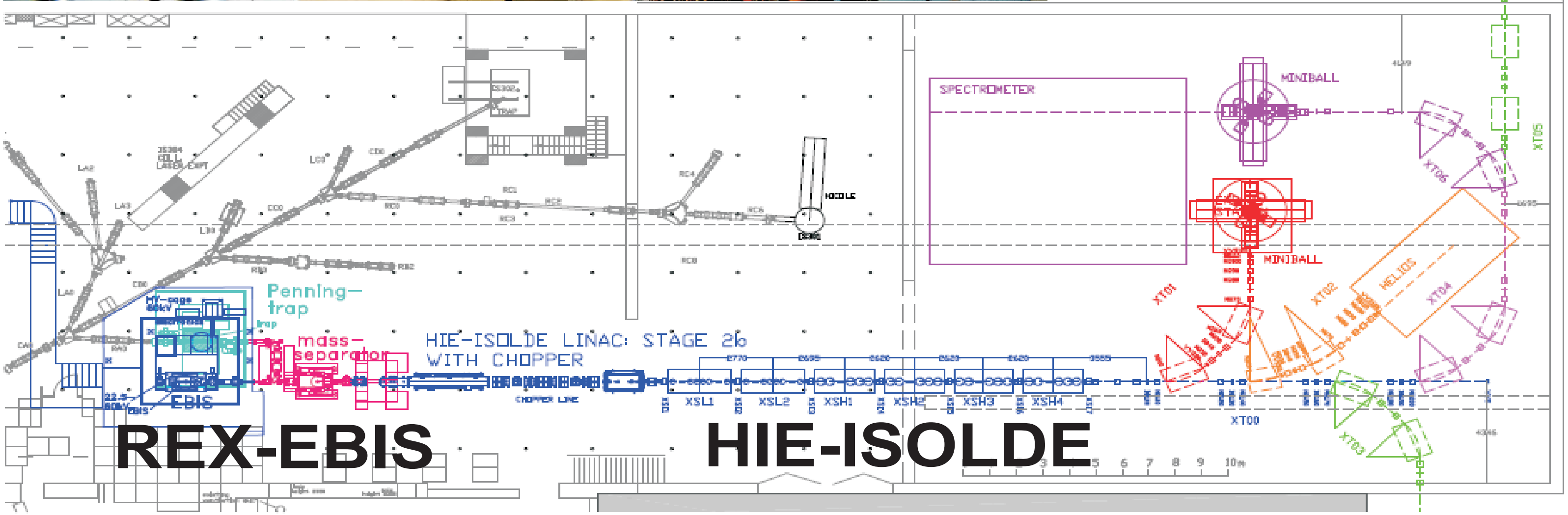
2 counts/s

10 counts/day

1 count/s

TSR@ISOLDE

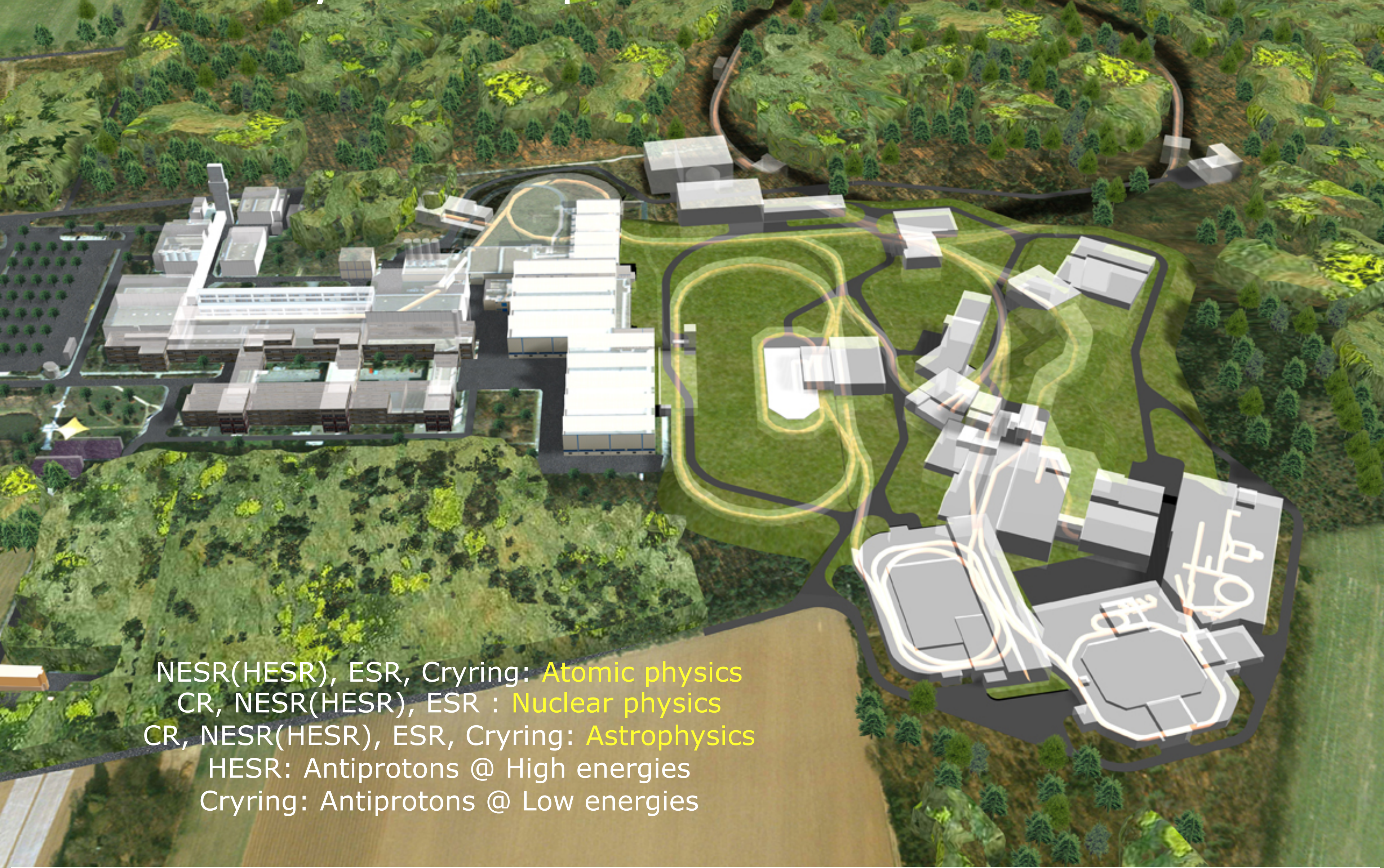




27-28.04
2015

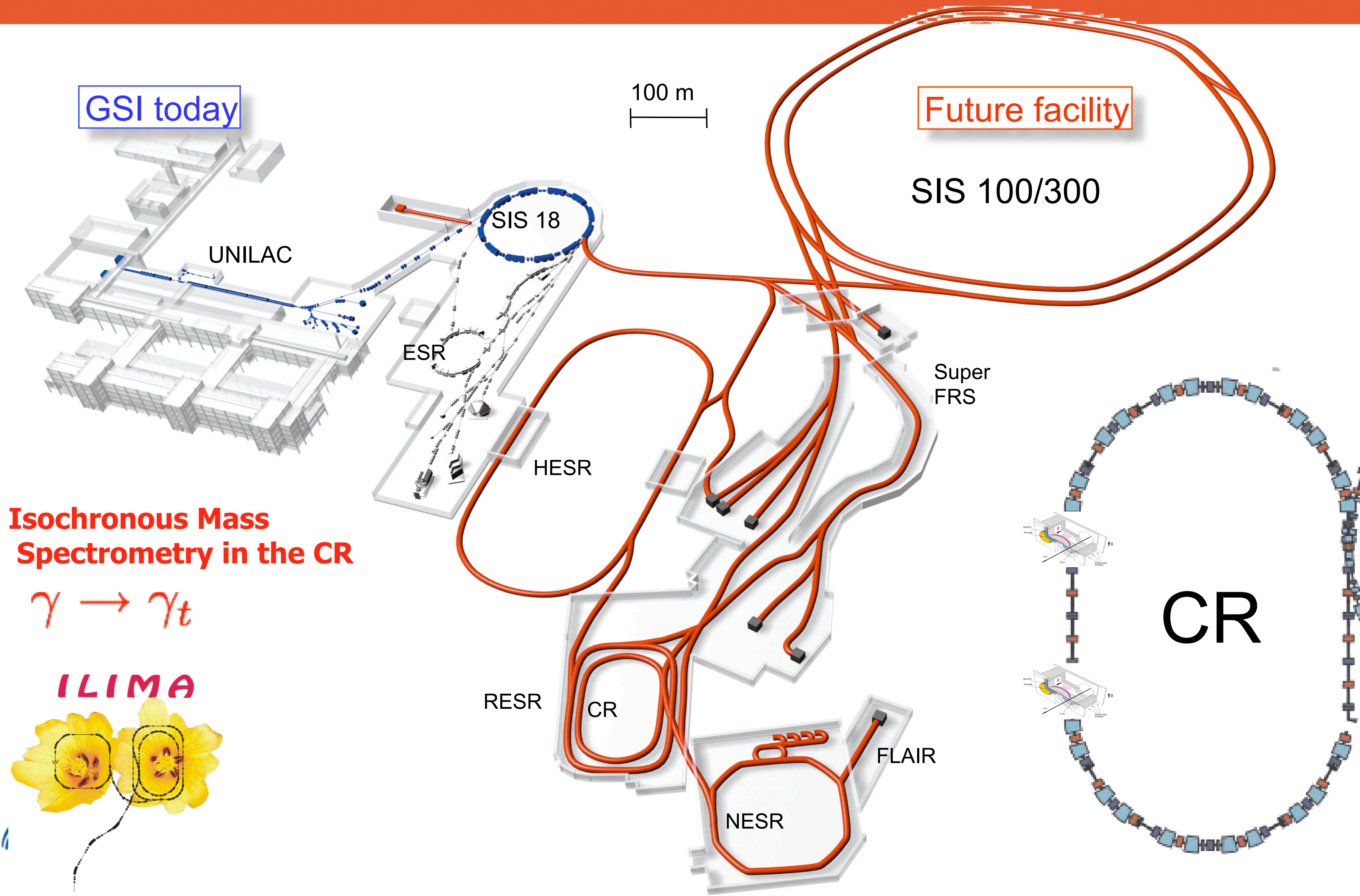
Dedicated
Workshop
At CERN

Facility for Antiproton and Ion Research



CN DE ES FI FR GB GR IN IT PL RO RU SE

FAIR - Facility for Antiproton and Ion Research



Isochronous Mass Spectrometry in the CR

$$\gamma \rightarrow \gamma_t$$

ILIMA Set-Up at FAIR

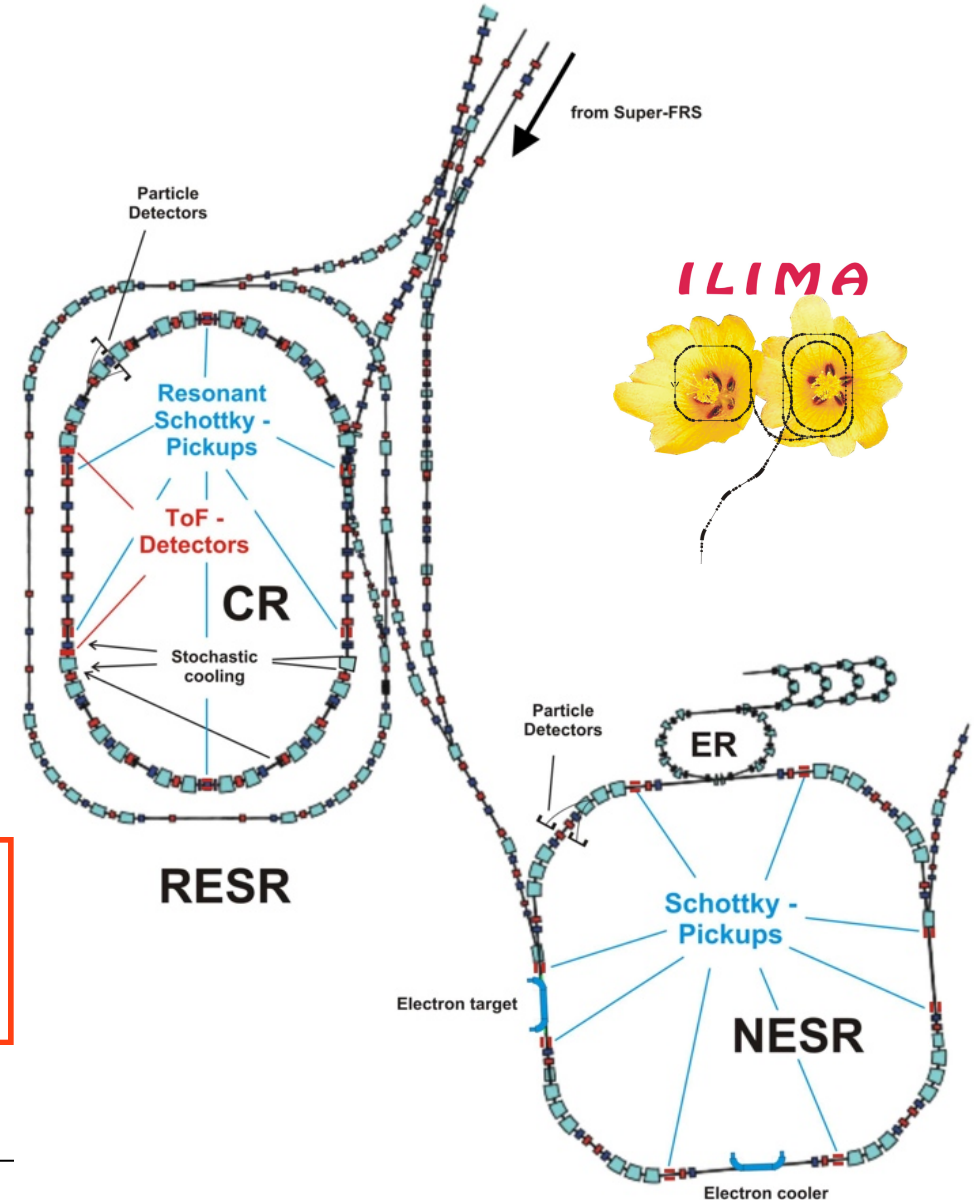
Isochronous Mass Spectrometry in the CR

$$\gamma \rightarrow \gamma_t$$

Schottky Mass Spectrometry in the CR & NESR

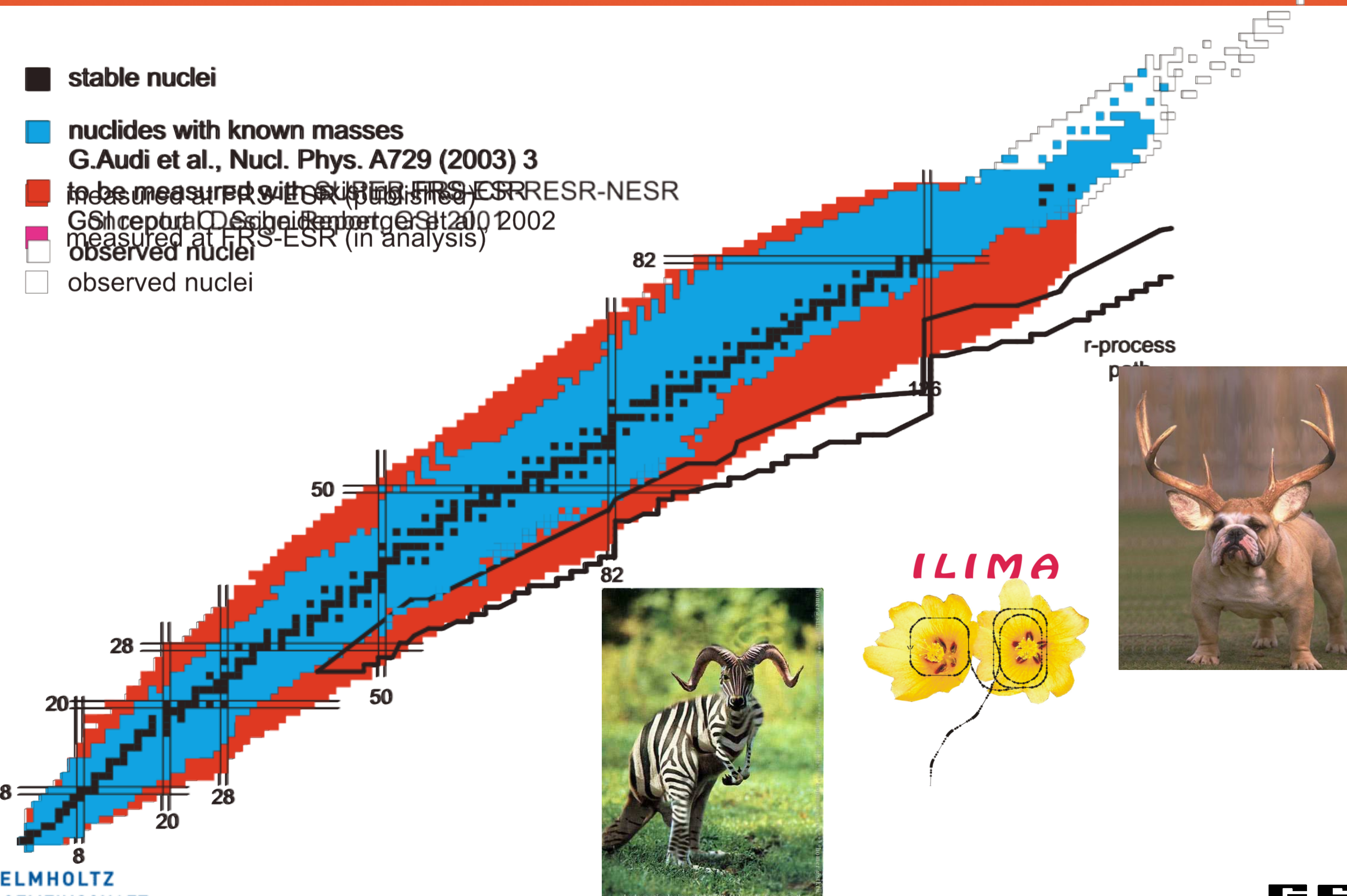
$$\frac{\Delta v}{v} \rightarrow 0$$

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



ILIMA

ILIMA: Masses and Halflives

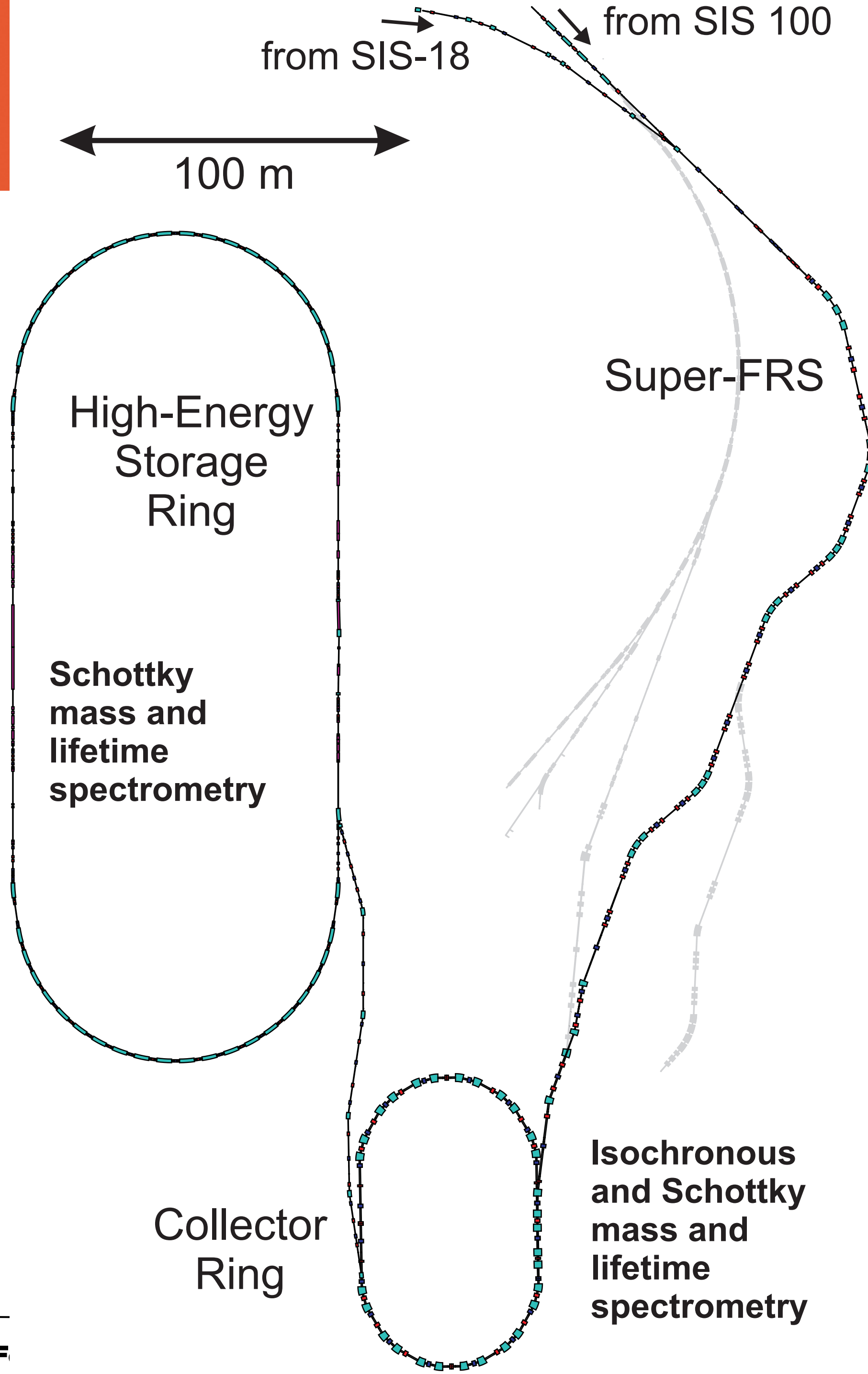


ILIMA in MSV-FAIR

SPARC Experiments at the HESR:

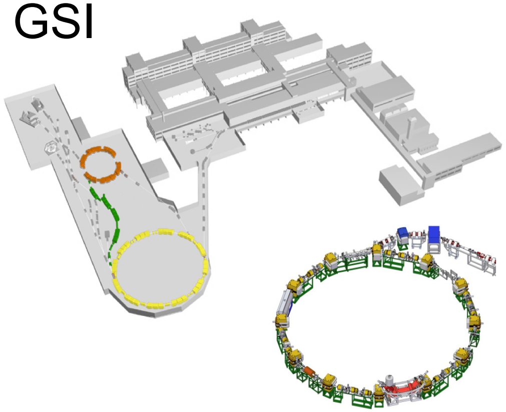
A Feasibility Study

Thomas Stöhlker[1,2,3], Reinhold Schuch[4], Siegbert Hagmann[1,5], Yuri A. Litvinov[1,2]
for the SPARC Collaboration*
Christina Dimopoulou[1], Alexei Dolinskii[1], & Markus Steck[1]

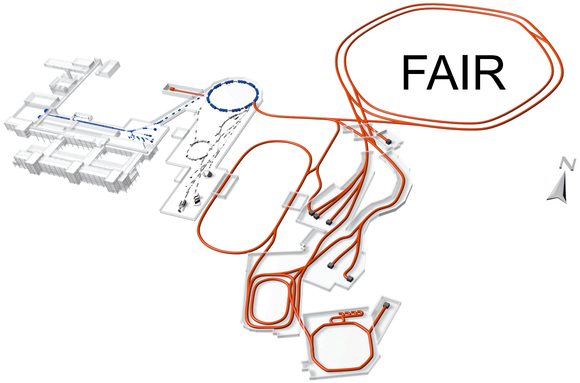


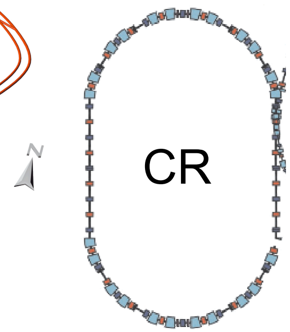
Physics at Storage Rings

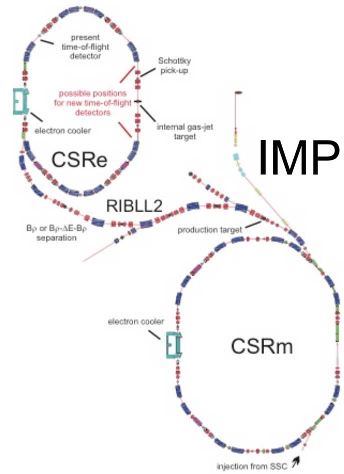
GSI



CRYRING

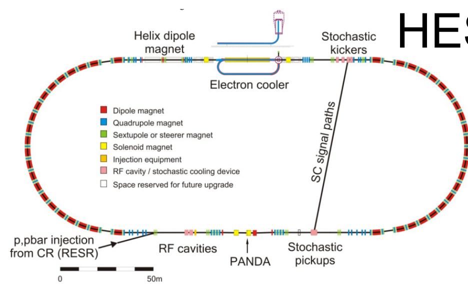


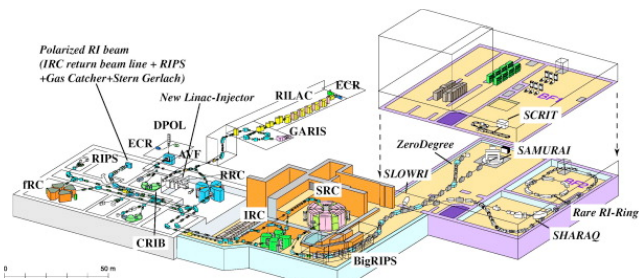




IMP

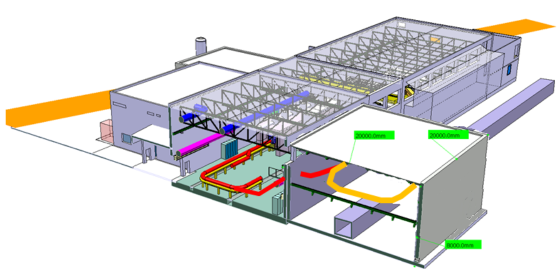
HESR



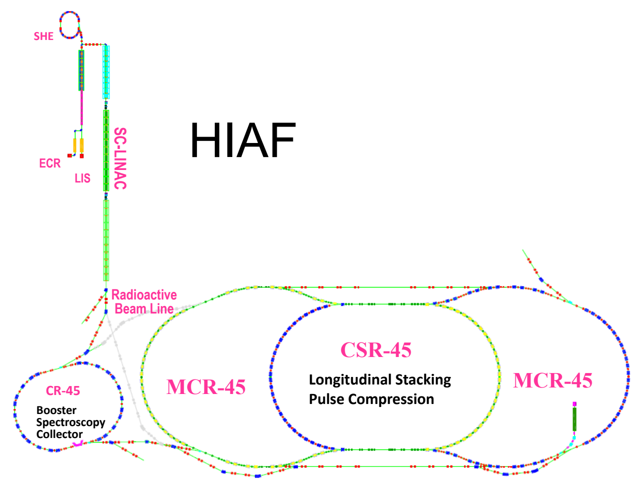


RI-RING

TSR@ISOLDE



HIAF



Many-many thanks to all my colleagues from all over the world !!!

中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

HIC for FAIR
Helmholtz International Center

MICHIGAN STATE UNIVERSITY

Niigata University

筑波大学

GSI

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UNIVERSITY OF LIVERPOOL

RIKEN

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Saitama University

THE UNIVERSITY of York

UNIVERSITY OF SURREY

TUM