Exotic nuclei

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Overview

Part 1:
What are exotic nuclei? Why study? Key questions

Part 2:
Production and separation of exotic nuclei in the laboratory

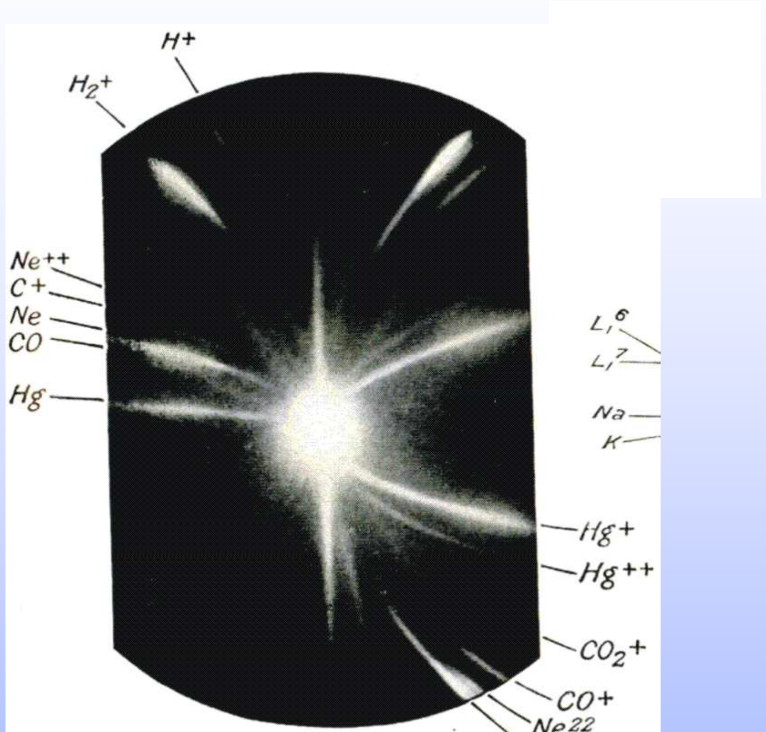
Part 3:
Examples: halo nuclei, 2-proton radioactivity, superheavy elements

Part 4:
Exotic nuclei in nuclear astrophysics

Part 5:
Future opportunities at FAIR

1. Introduction

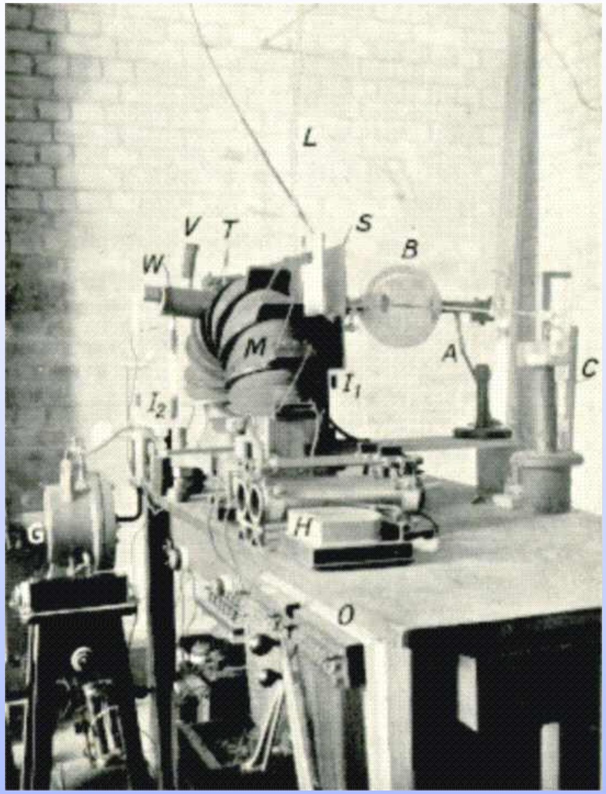
Discovery of isotopes



4. The Parabolas of Neon (1913).

J. J. Thomson
(1913)

High-resolution mass-spectrographs



F. W. Aston (~1915...1925)
* identification of 212 isotopes
* systematics:
  → "packing fraction"

Discovery of mass excess:

Masses deviate from whole numbers

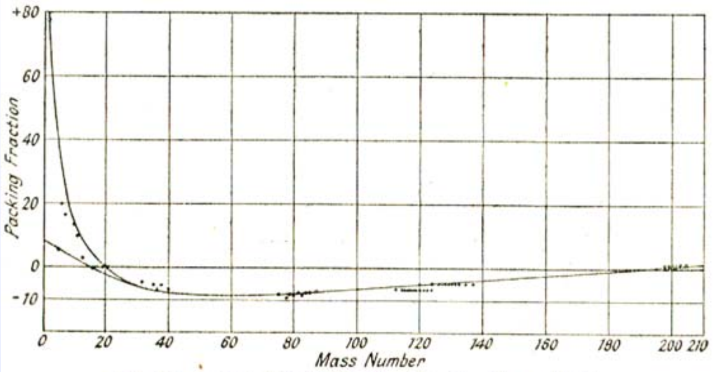


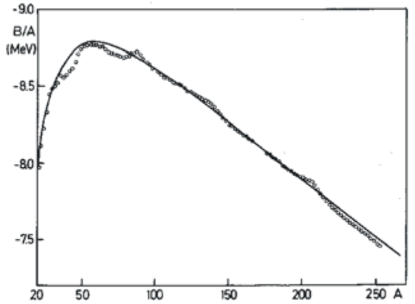
FIG. 20.—Aston's Original Packing Fraction Curve (1927).

First (collective) model:

Liquid-drop model by C.F.v.Weizsäcker, H. A. Bethe (1935/36)

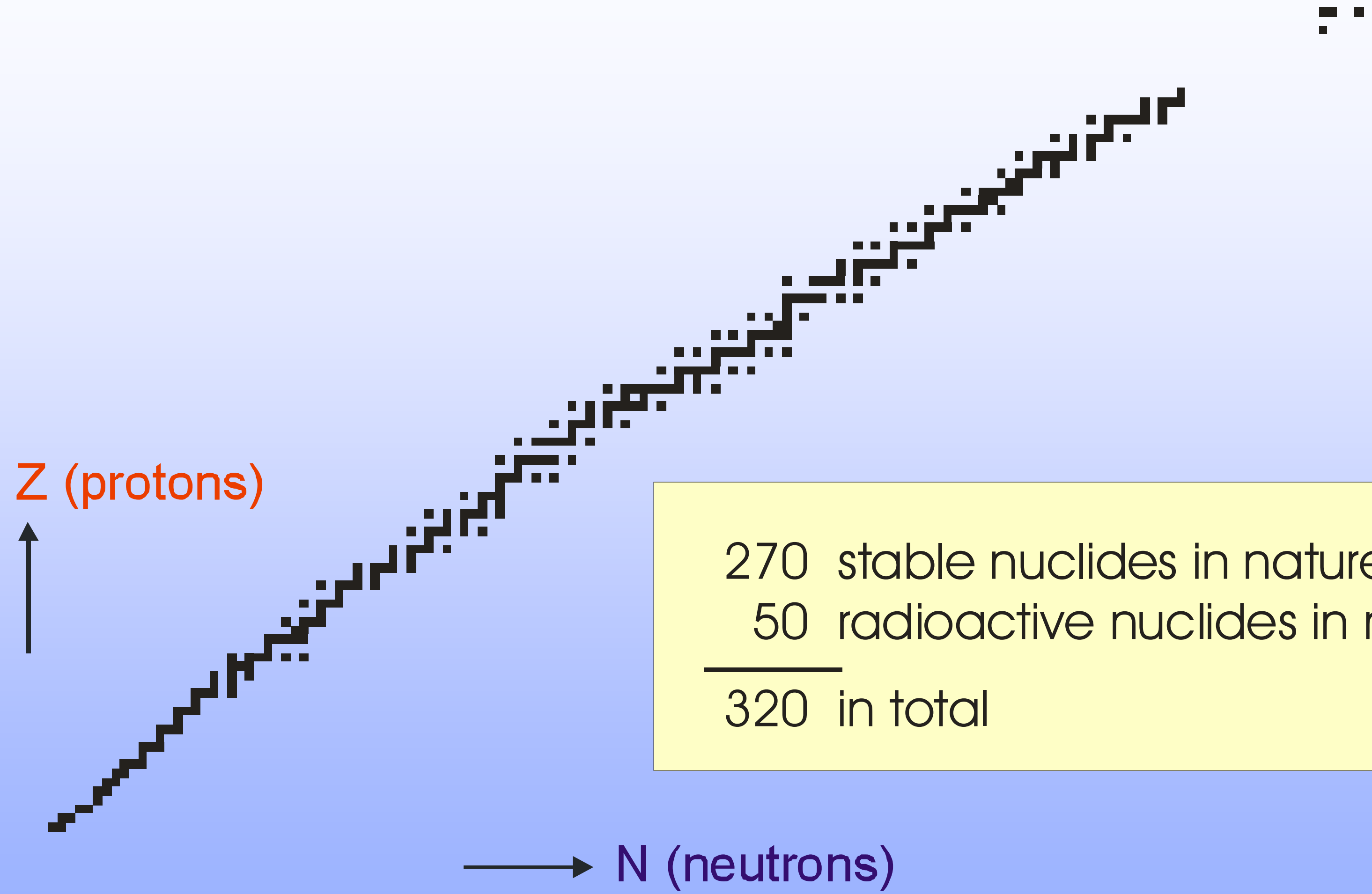
Volume energy ∼ A (*)
Surface " ∼ $A^{2/3}$
Coulomb " ∼ $-Z^2 / A^{1/3}$
Asymetry " ∼ $-(Z - A/2)^2/A$

(*) $R \sim A^{1/3}$



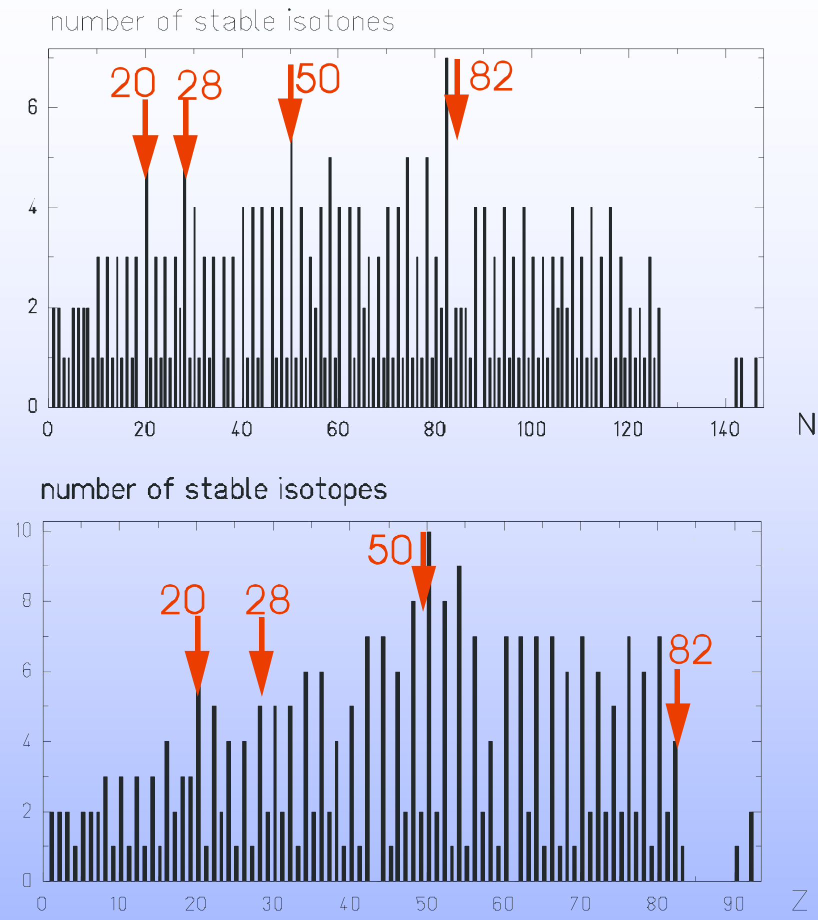
C. F. v. Weizsäcker
Z. Phys. 96, 431 (1935)
H. A. Bethe
Rev. Mod. Phys. 8, 81 (1936)

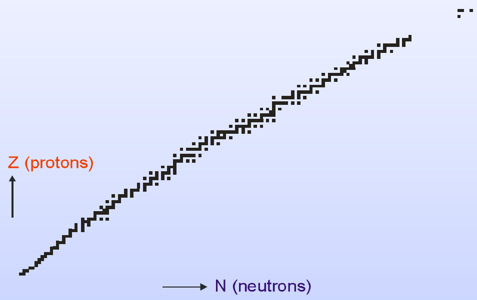
Chart of (stable) nuclei



270	stable nuclides in nature
50	radioactive nuclides in nature
320	in total

Shell effect in stable nuclei





Number of stable isotopes/isotones

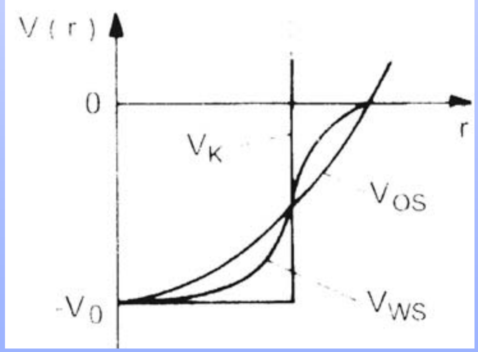
---> magic numbers

Single-particle shell model (1949):

Individual properties:
e.g.: excitation energies, magnetic moments

based on Schrödinger equation:

$$H = \sum_i \left[-\left(\frac{\hbar}{2m} \right) \cdot \Delta_{ii} \right] + \sum_{i<j} V_{ij}$$



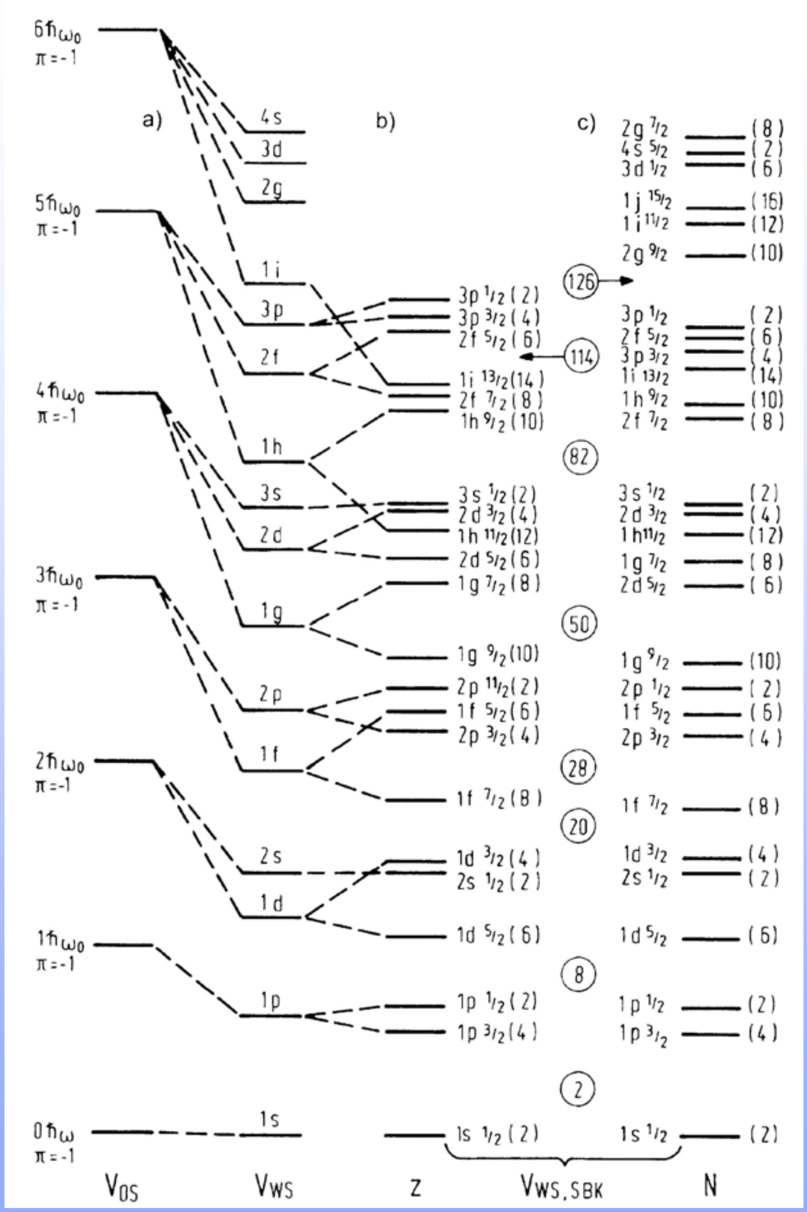
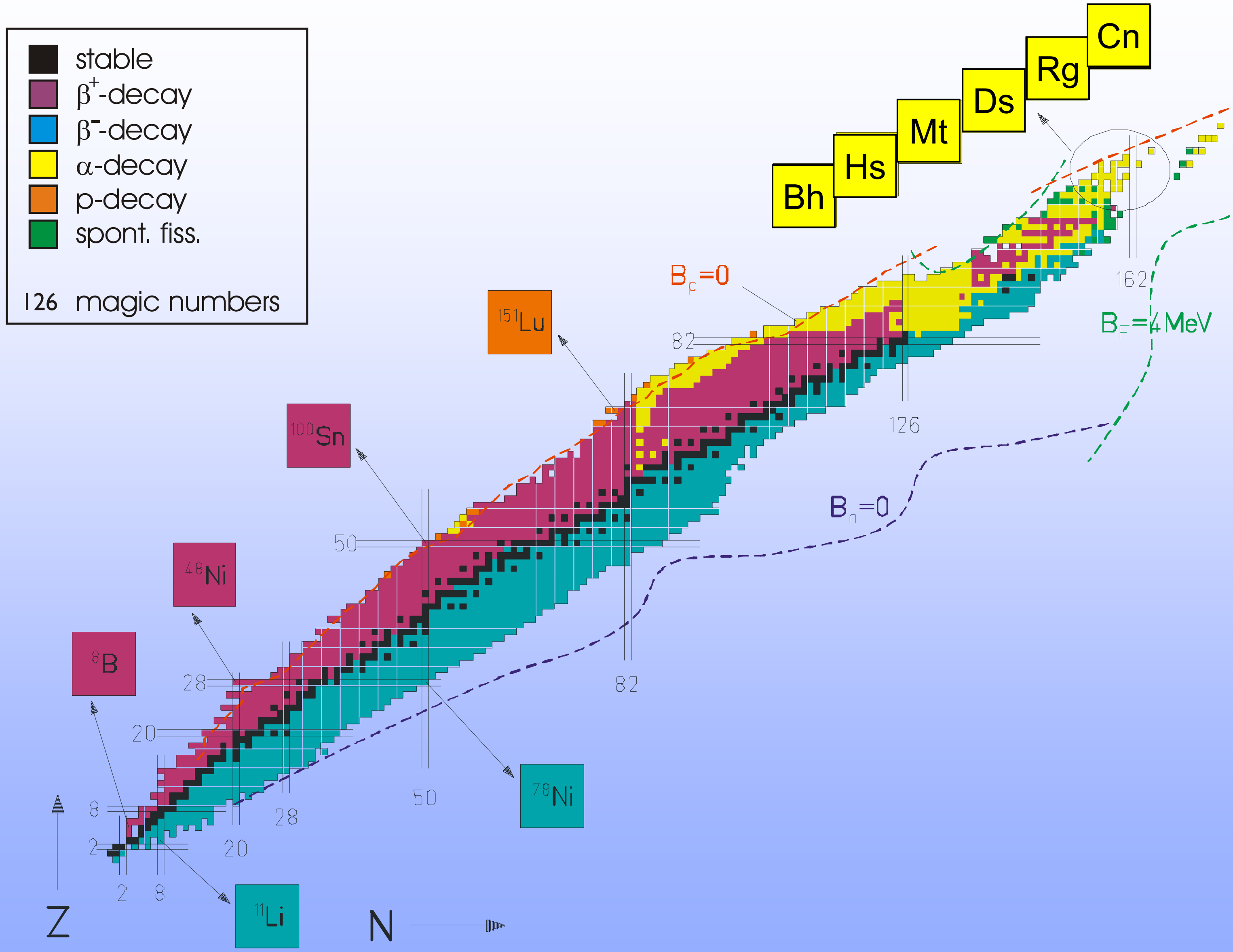


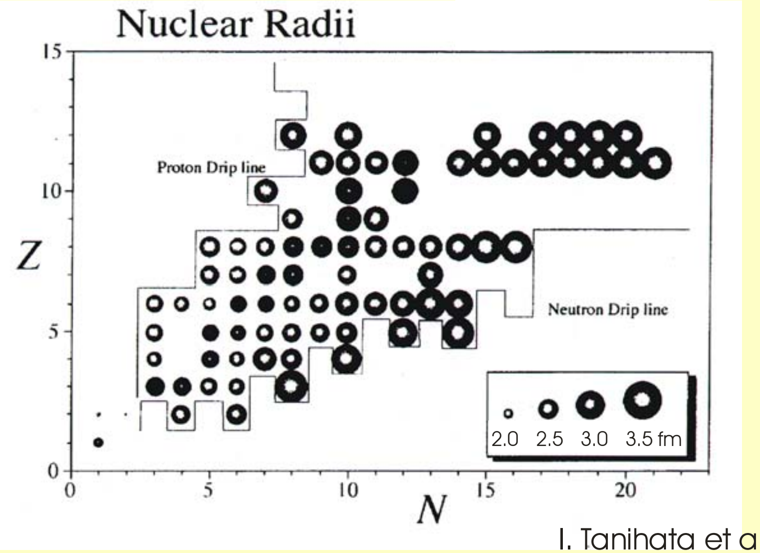
Chart of (known) nuclei



Nuclear radii do not increase as $A^{1/3}$

1) Nuclear Radius:

Textbooks say: $R \approx 1{,}3\ \mathrm{fm} * A_0^{1/3}$



I. Tanihata et al., NPA654, 235 (1999)

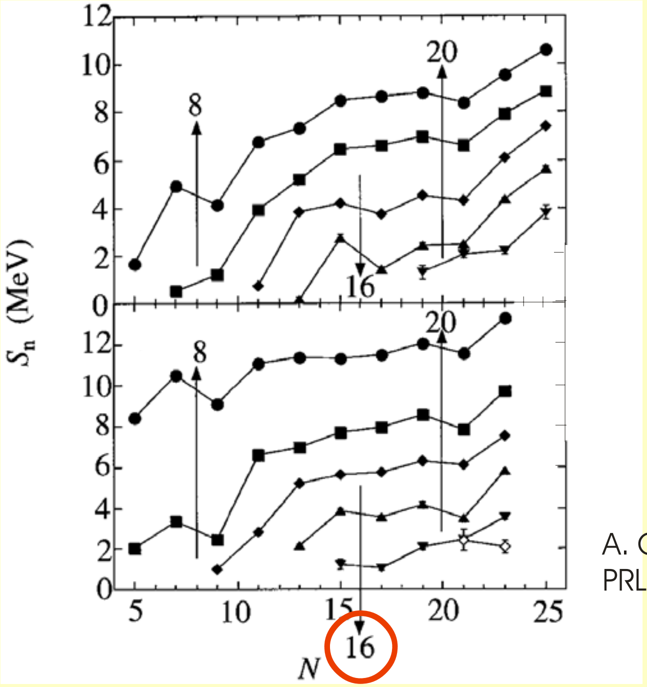
.....valid only for nuclei near stability

Magic numbers depend on N and Z

2) Magic numbers:

According to standard textbooks:

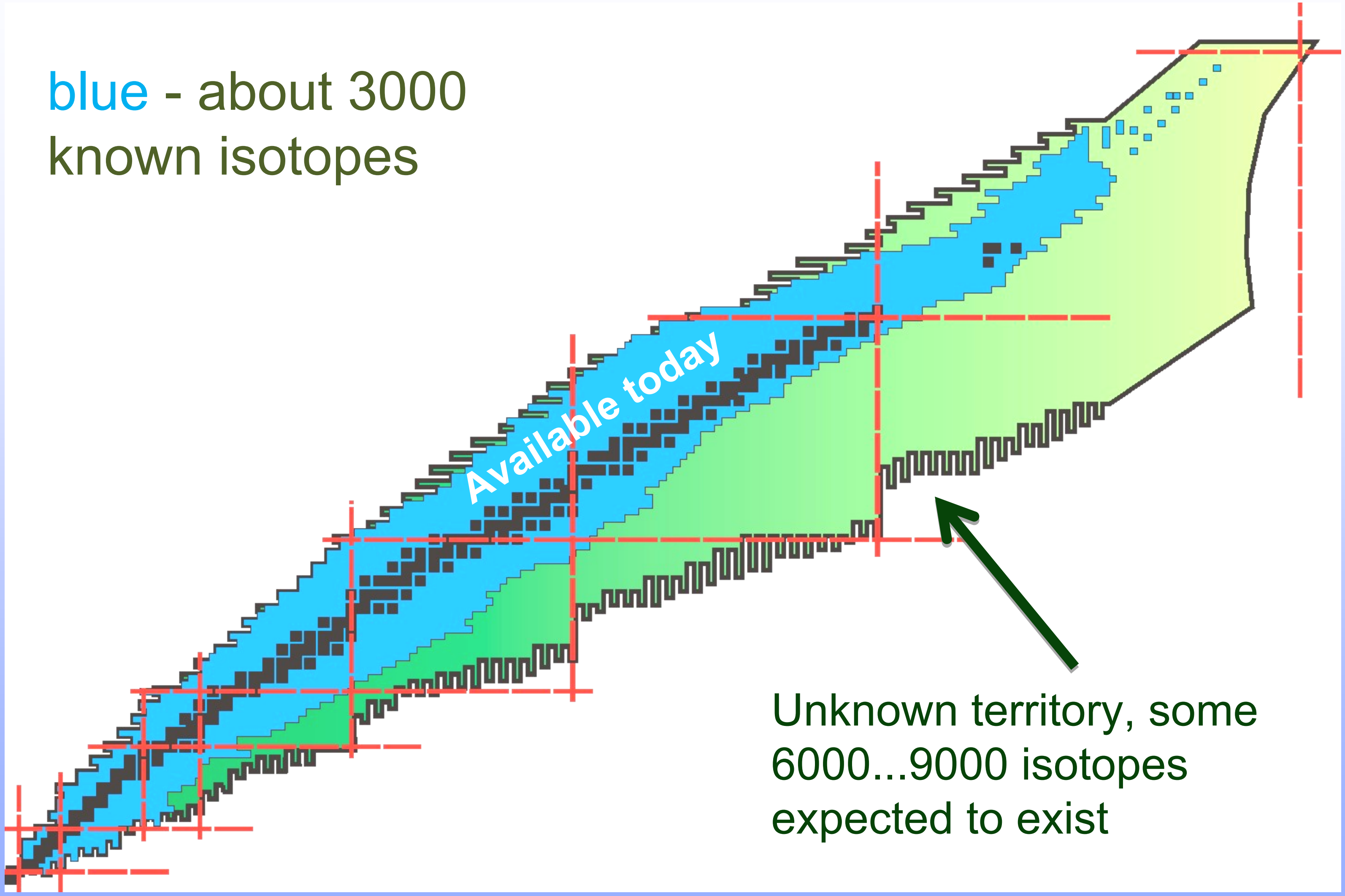
2,8,20,28,50,82,126

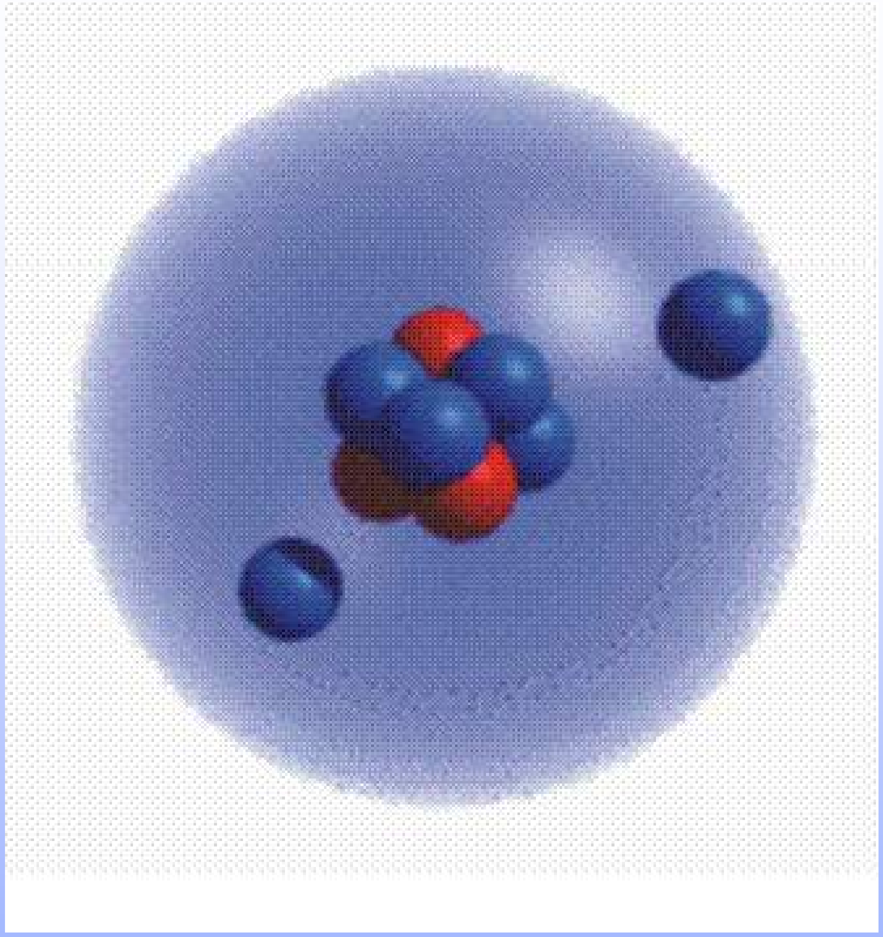


A. Ozawa et al., PRL 84, 5493 (2000)

New "halo-driven" magic numbers

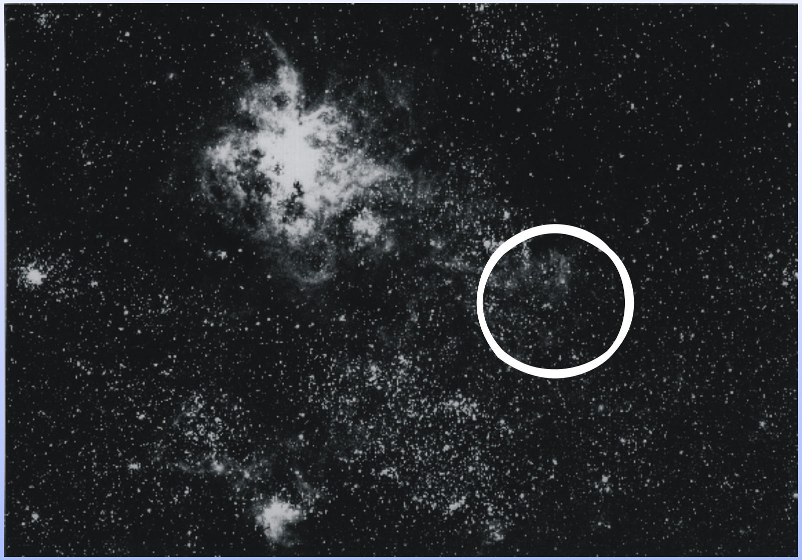
Many more bound nuclei exist than anticipated

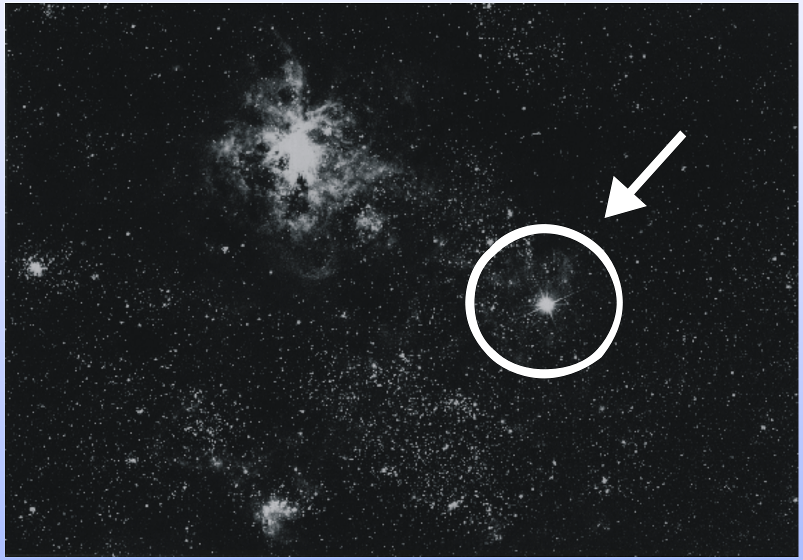




Neutron halo in nuclei

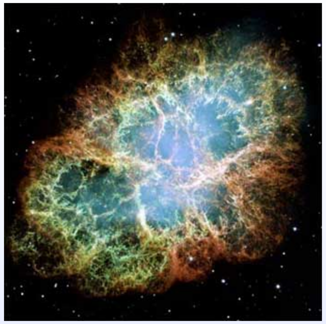
Exotic places where they are produced



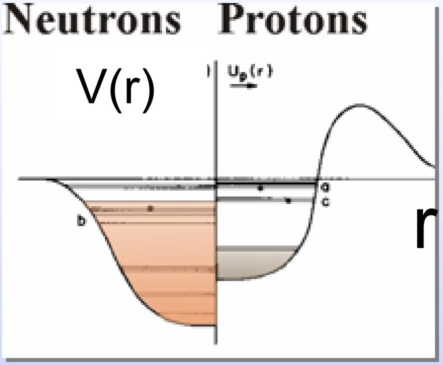


SN1987A

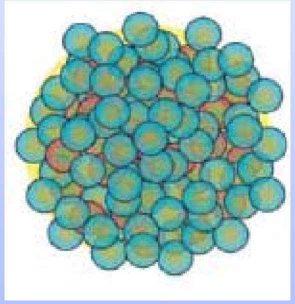
exotic places



exotic composition



exotic properties



→ sufficiently many reasons to study exotic nuclei!

Key questions

General questions:

Limits of stability, heaviest elements

Understanding of nuclear forces, isospin dependence

Magicity and shells far-off stability

New phenomena and new decay modes

Nucleosynthesis and elemental abundances

Properties of nuclei:

"Weight" (mass excess)

"Size" (matter and charge radii)

"Shape" (deformation)

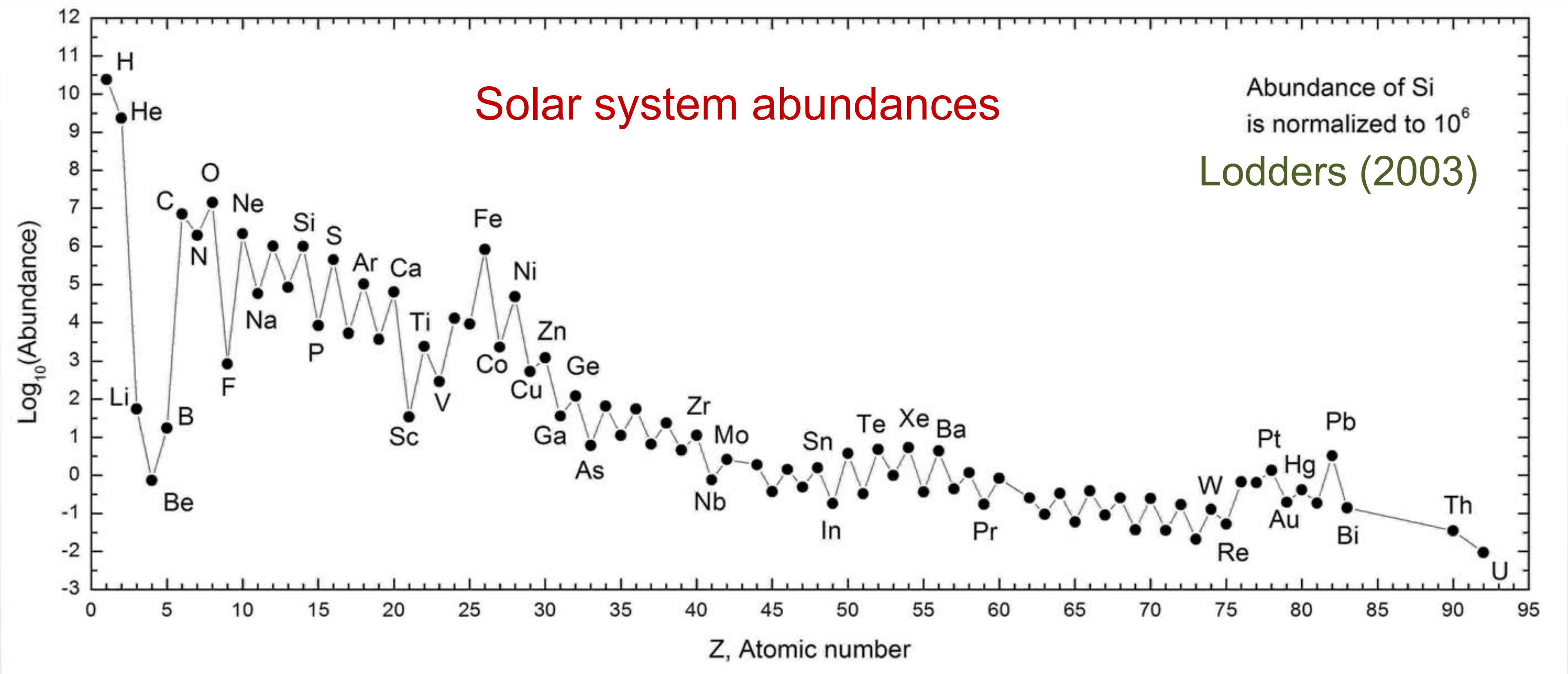
Half-life, decay modes

Electrical and magnetic moments, spins

Single-particle structure

Collective phenomena (giant dipole resonance)

Challenge: understand solar system element and mass abundances

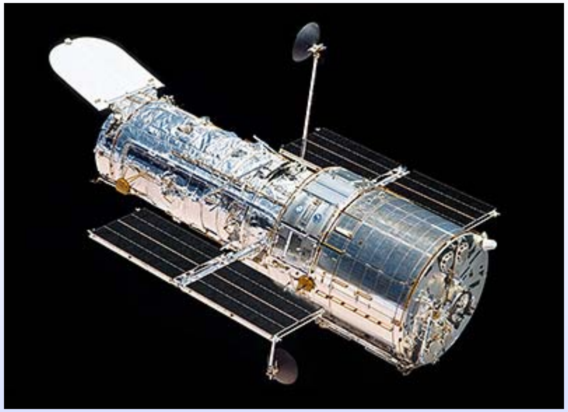


Where, when and how are the elements produced?

Understand the observed distribution, qualitatively and quantitatively!

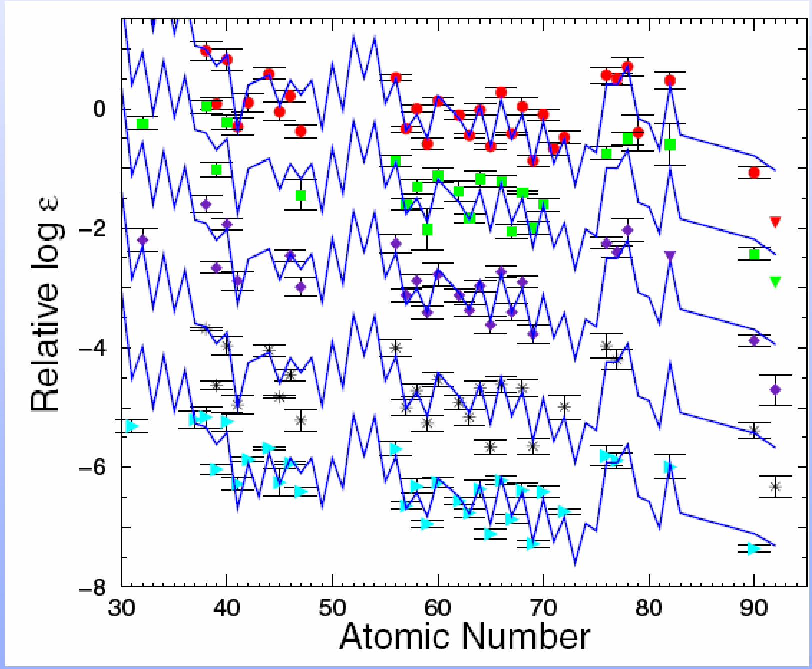
Why no elements Z>92, why no masses A>240?

E.g., discover and understand the formation of the first stars and galaxies, chemical evolution of galaxies, measure the geometry of the Universe and the distribution of (dark) matter, investigate the evolution of galaxies and the production of elements by stars, and the process of star and planet formation



Hubble Space Telescope

Apache Point

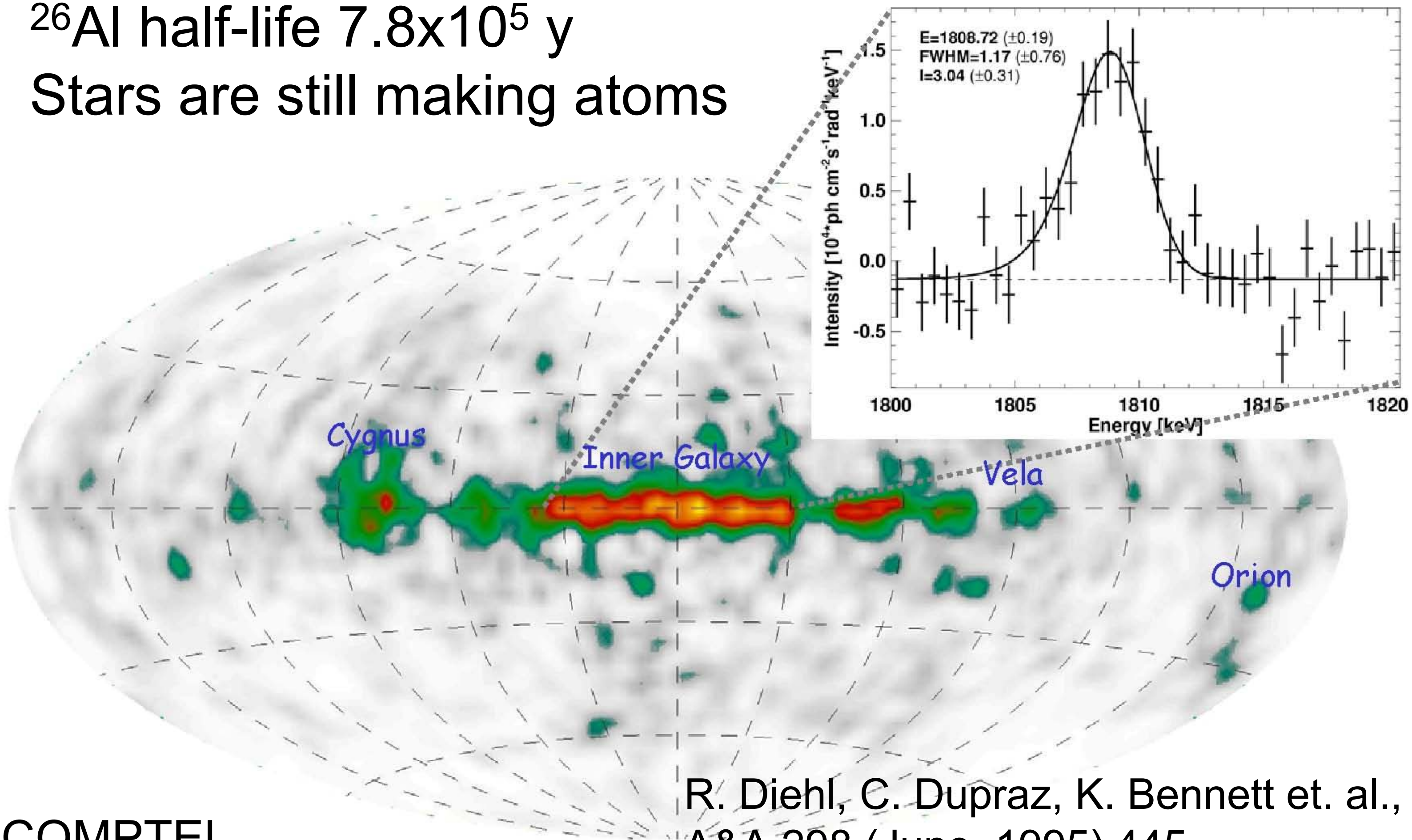


Cowan et al., NIC-9 proceedings

Radioactive nuclei tell us: elements are synthesized in stars

^{26}Al half-life 7.8x10^{5} y

Stars are still making atoms



COMPTEL

R. Diehl, C. Dupraz, K. Bennett et. al., A&A 298 (June, 1995) 445

- Big Bang Nucleosynthesis
- pp-chain
- CNO cycle
- Helium, C, O, Ne, Si burning
- s-process
- r-process
- rp-process
- νp – process
- p – process
- α - process
- fission recycling
- Cosmic ray spallation
- pyconuclear fusion
- + others

} Radioactive (“exotic”) nuclei

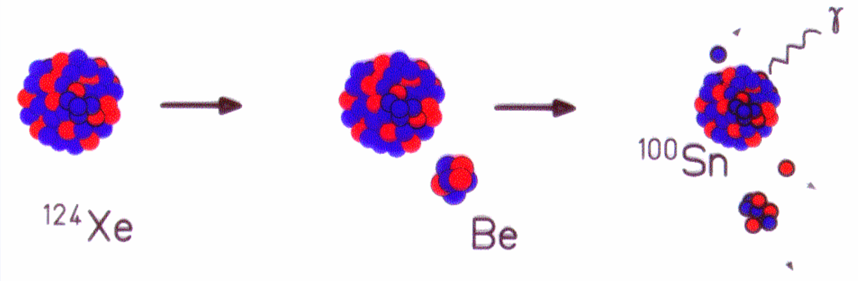
Our telescopes in nuclear physics

We can look into the interior of stars!

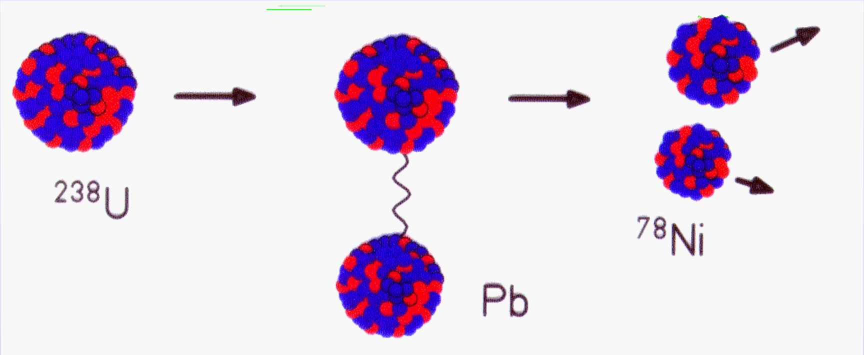
2. Production

Nuclear reactions to produce exotic nuclei

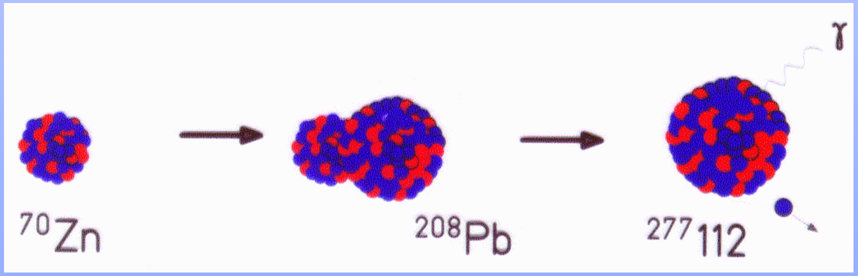
Fragmentation, spallation



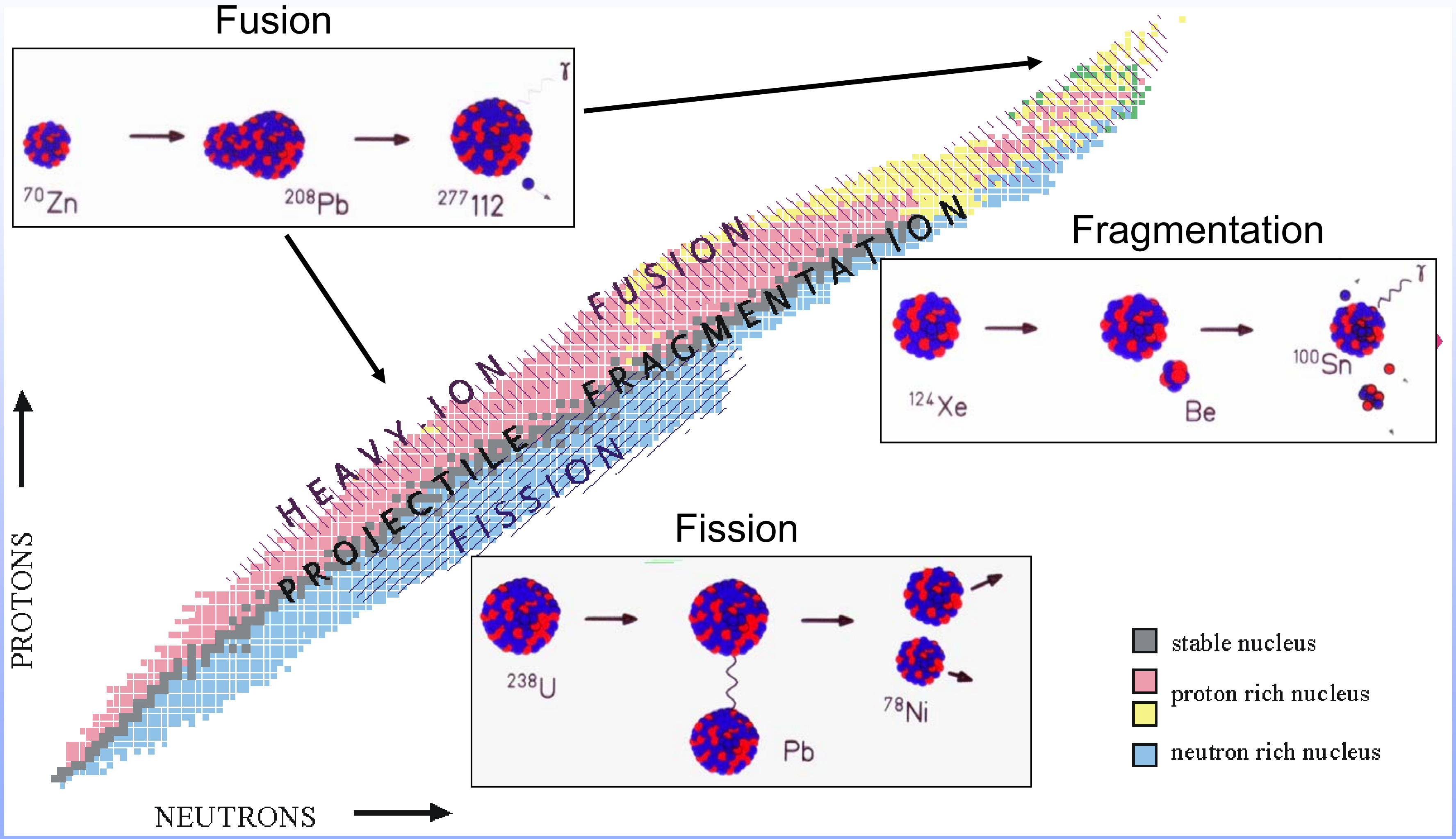
Coulomb dissociation, fission



Compound nuclei, fusion

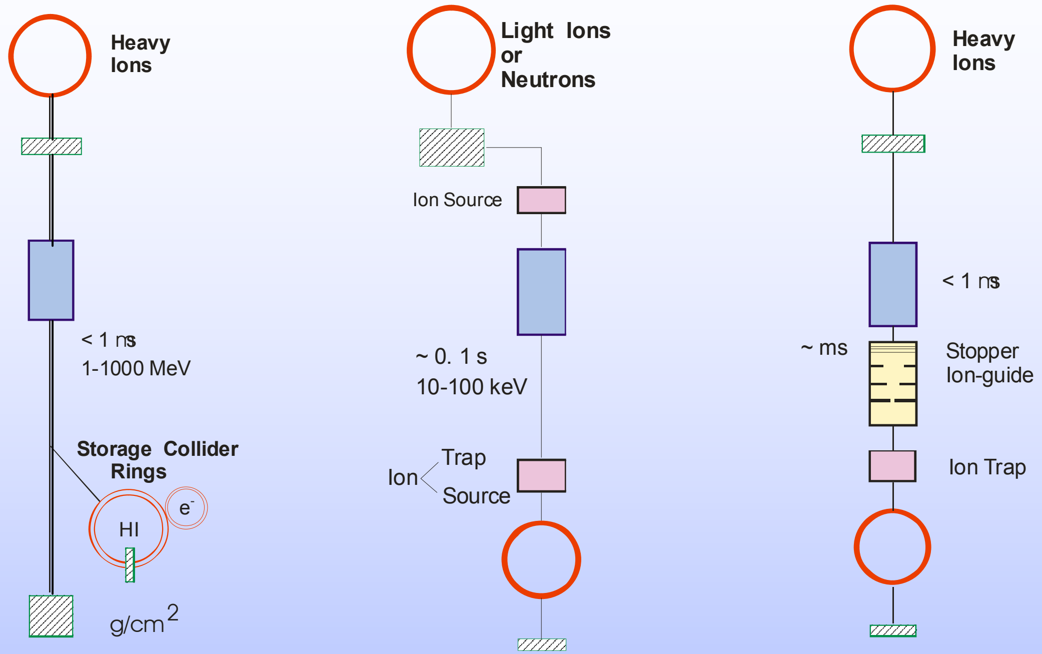


Production reactions



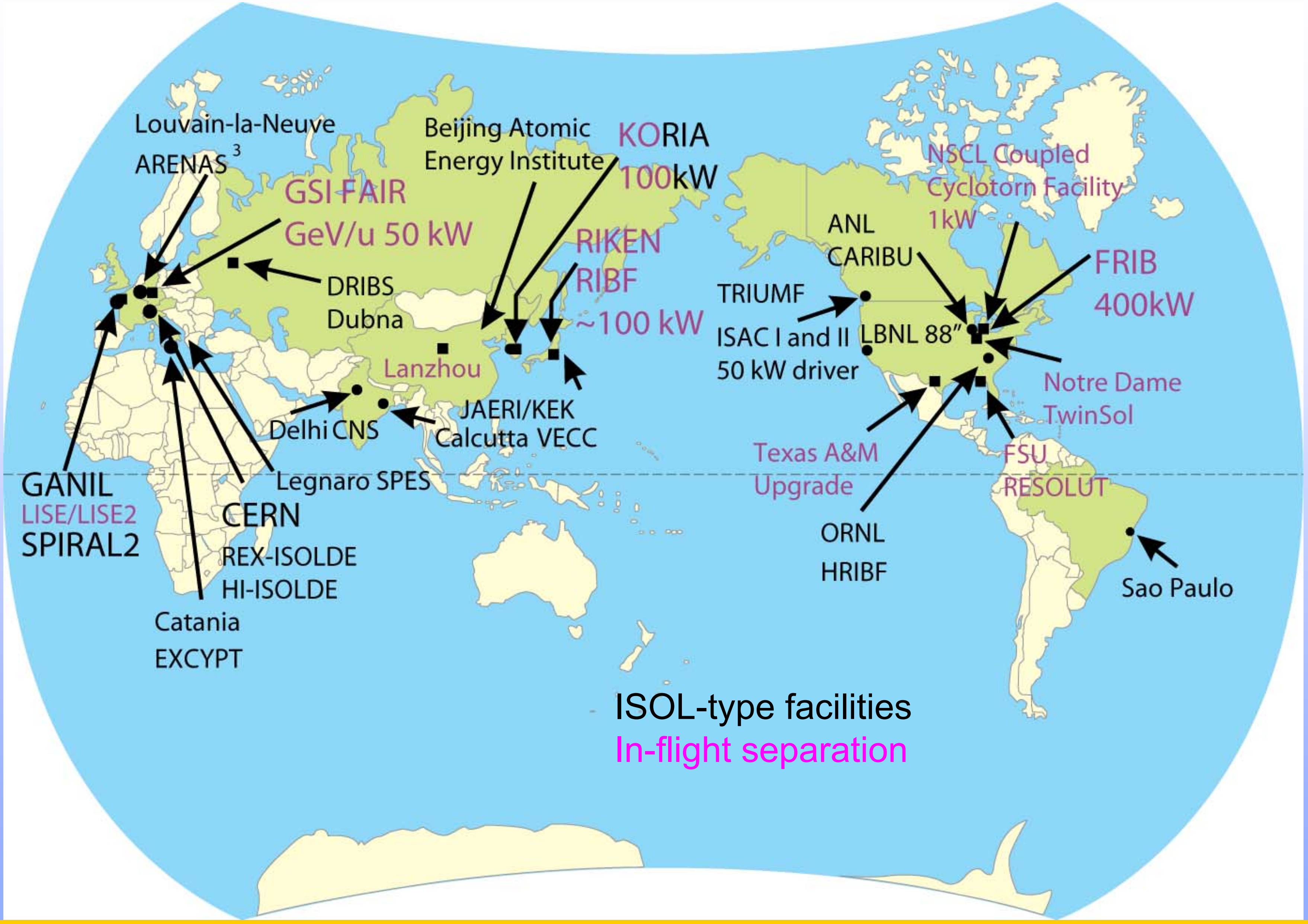
Technical concepts to produce exotic nuclei

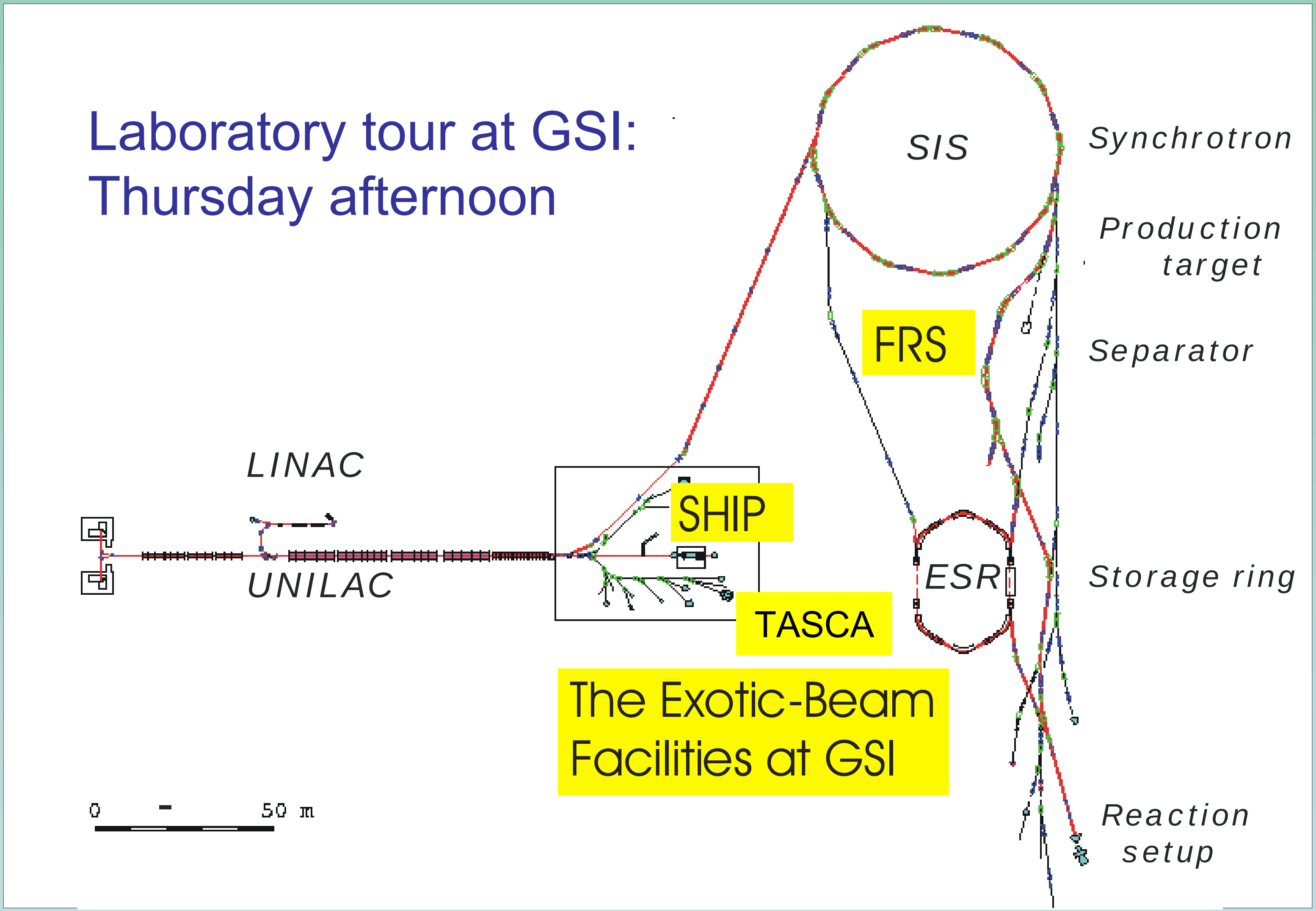
	In-flight	ISOL	Hybrid (in-flight + ISOL)



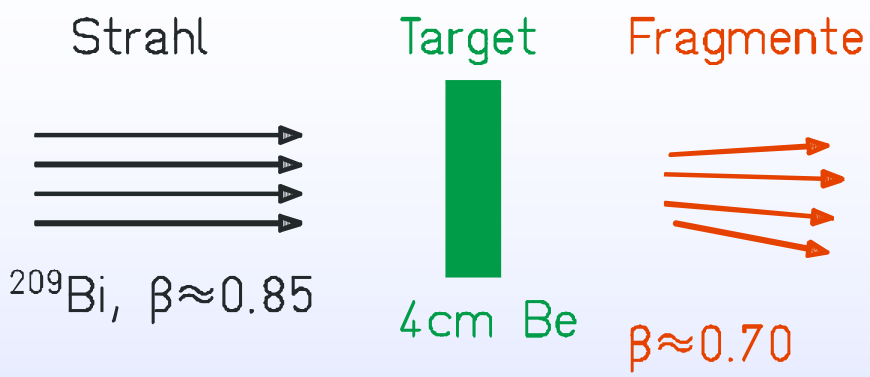
	In-flight	ISOL	Hybrid (in-flight + ISOL)
Elements	**Universal**	**Chemically difficult**	**Universal (?)**
Separation time	**< 1 ms**	**0. 1 s~**	**~ ms**
Selectivity	**pure beams**	**contaminants possible**	**pure beams (?)**
Intensity	**moderate**	**high**	**moderate**
Energy of secondary beam	**50....1500 A MeV**	**10 - 100 keV**	
Options	**Storage rings**	**Post-Acceleration (1....10 A MeV)**	

World view of radioactive-beam facilities

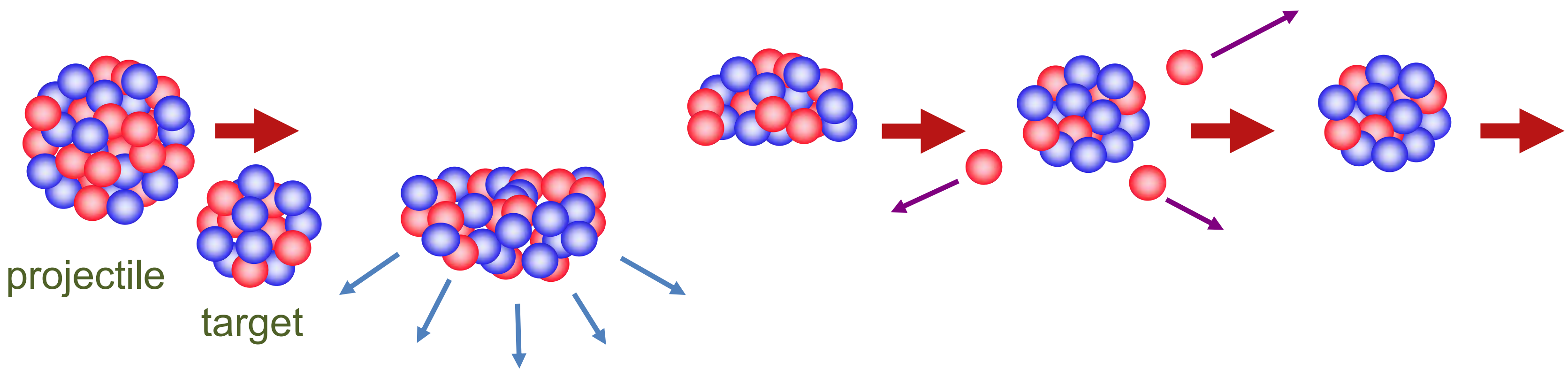



Laboratory tour at GSI:
Thursday afternoon
SIS
Synchrotron
Production target
FRS
Separator
LINAC
SHIP
UNILAC
ESR
Storage ring
TASCA
The Exotic-Beam Facilities at GSI
0
50 m
Reaction setup

Production of exotic nuclei by projectile fragmentation



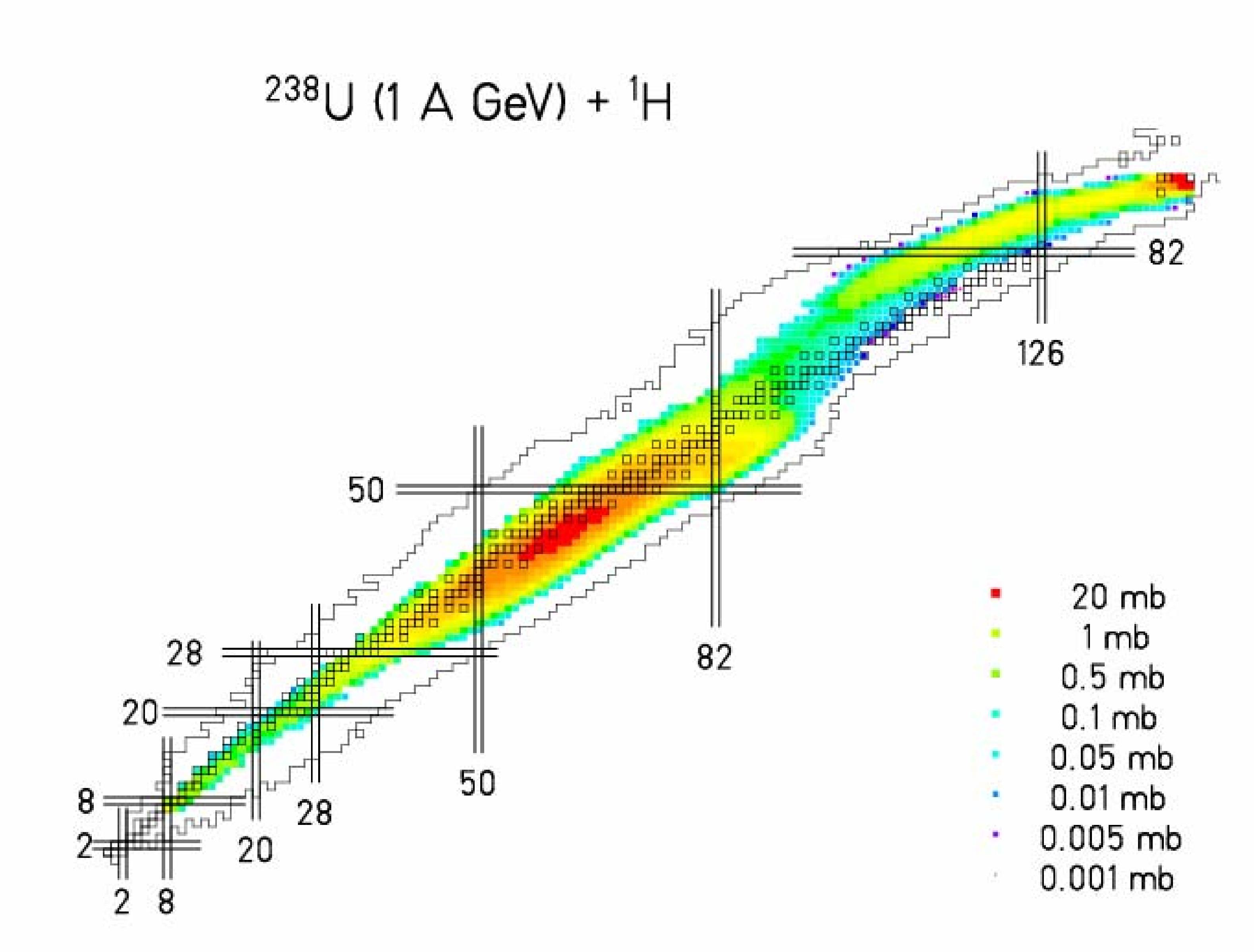
fragmentation, invented at LBNL in the 1980's

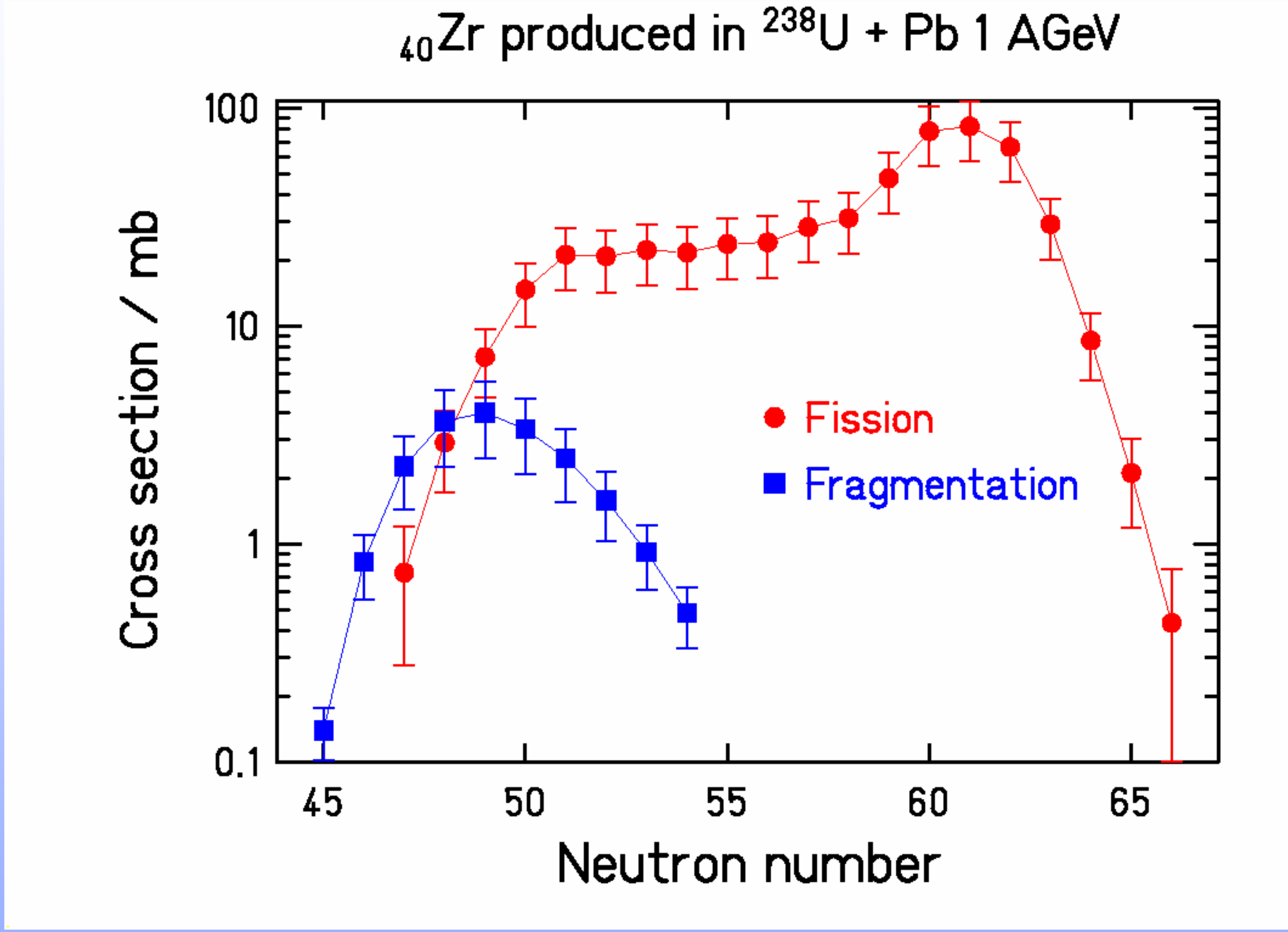


Produktionsraten: 10^{5}/sek. ... 10^{-5}/sek.

(≈1/Tag)

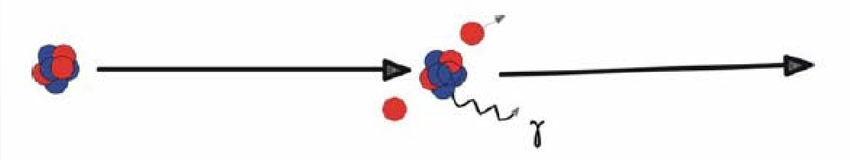
Spallation and fission of uranium

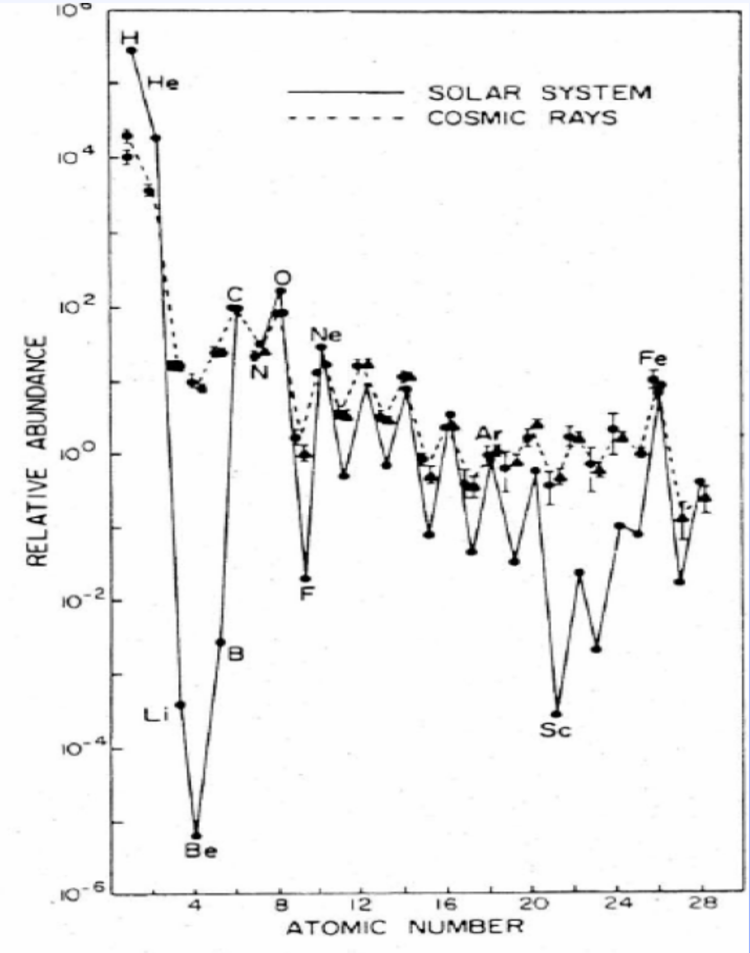




$_{40}$Zr produced in ^{238}U + Pb 1 AGeV
100
10
1
0.1
Cross section / mb
45
50
55
60
65
Neutron number
Fission
Fragmentation

Nucleo"synthesis" by spallation of cosmic rays

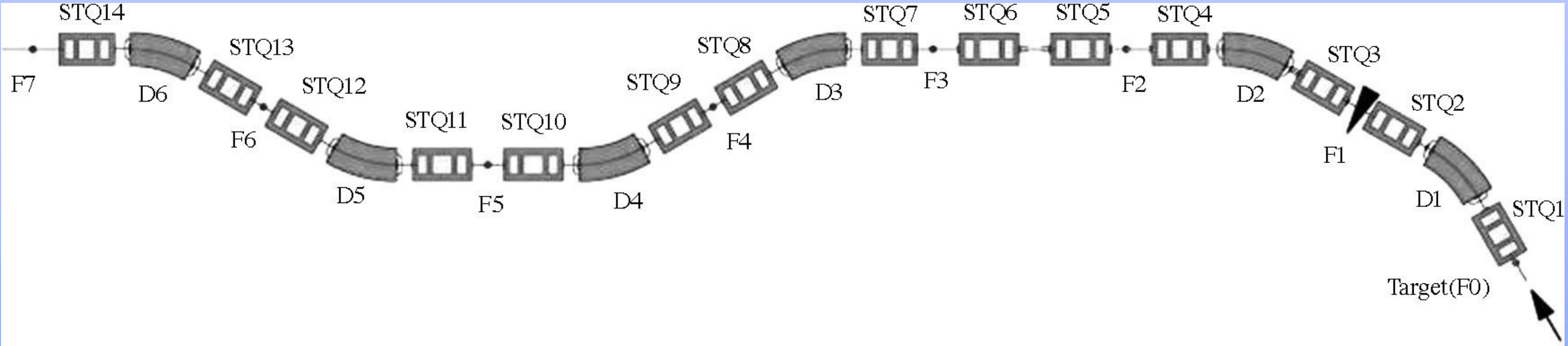


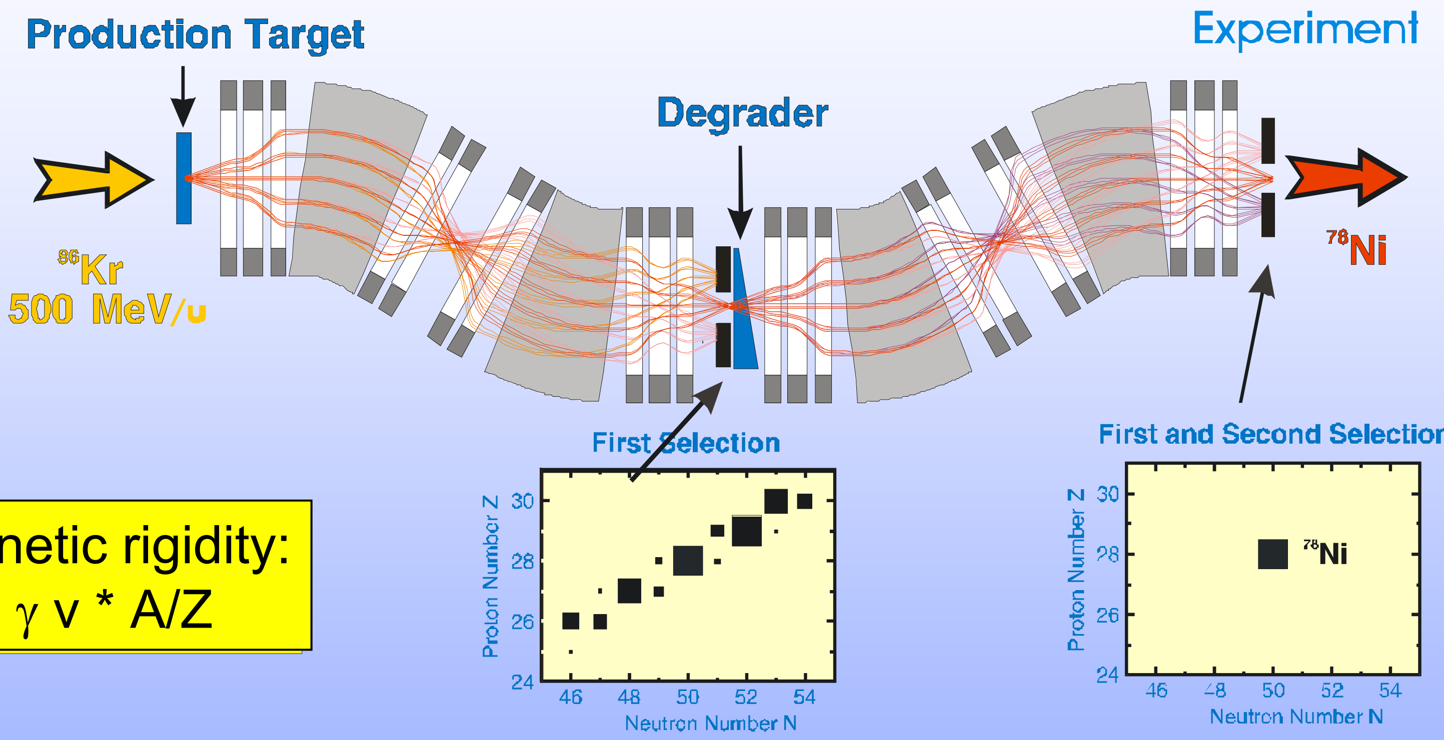


Big-RIPS in RIKEN (Japan, near Tokyo)

BigRIPS 1st stage

BigRIPS 2nd stage



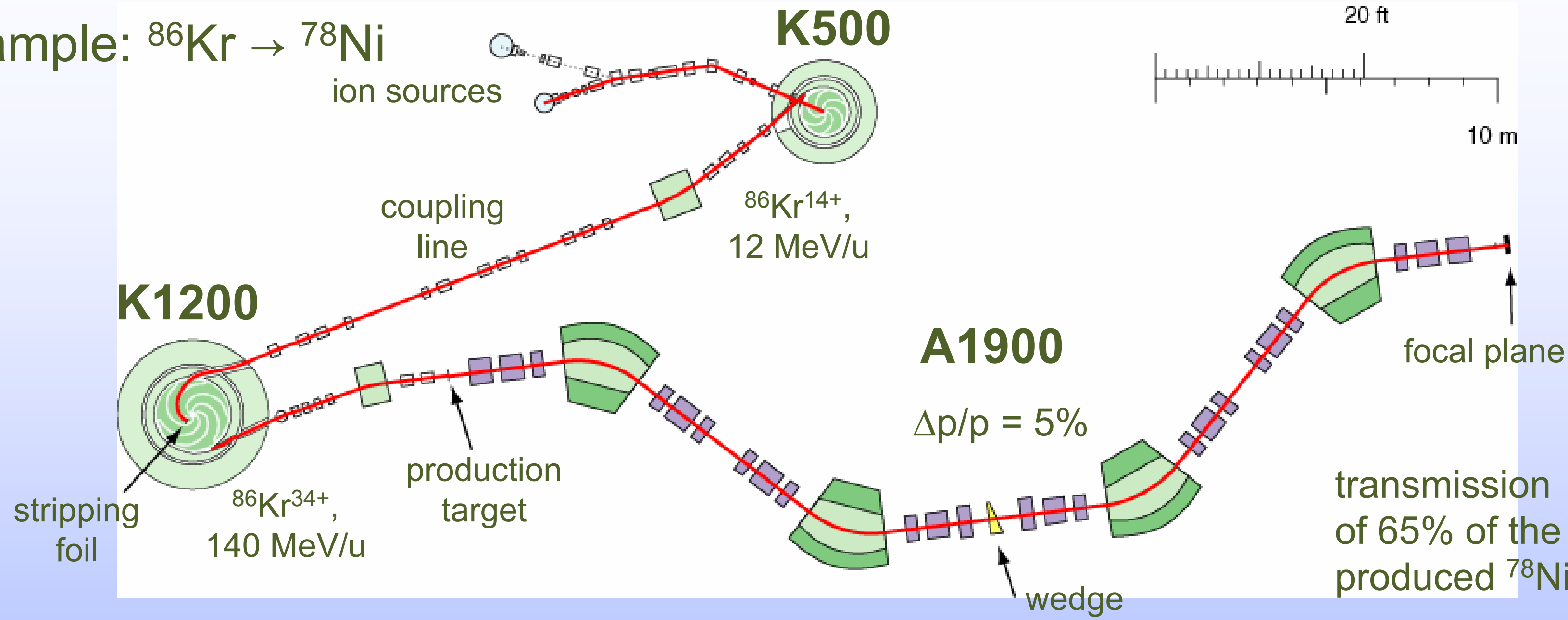


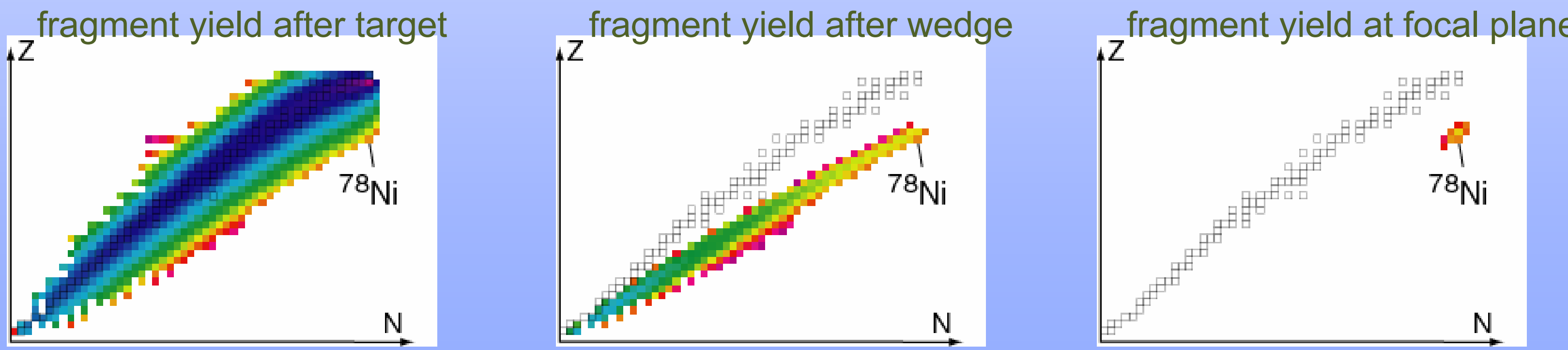
Magnetic rigidity:
$B\rho = \gamma v * A/Z$

$V_{Fragment} \sim V_{Projectile}$ → A/Z ~ const. → Magnetic-rigidity analysis of energy loss yields single isotope !

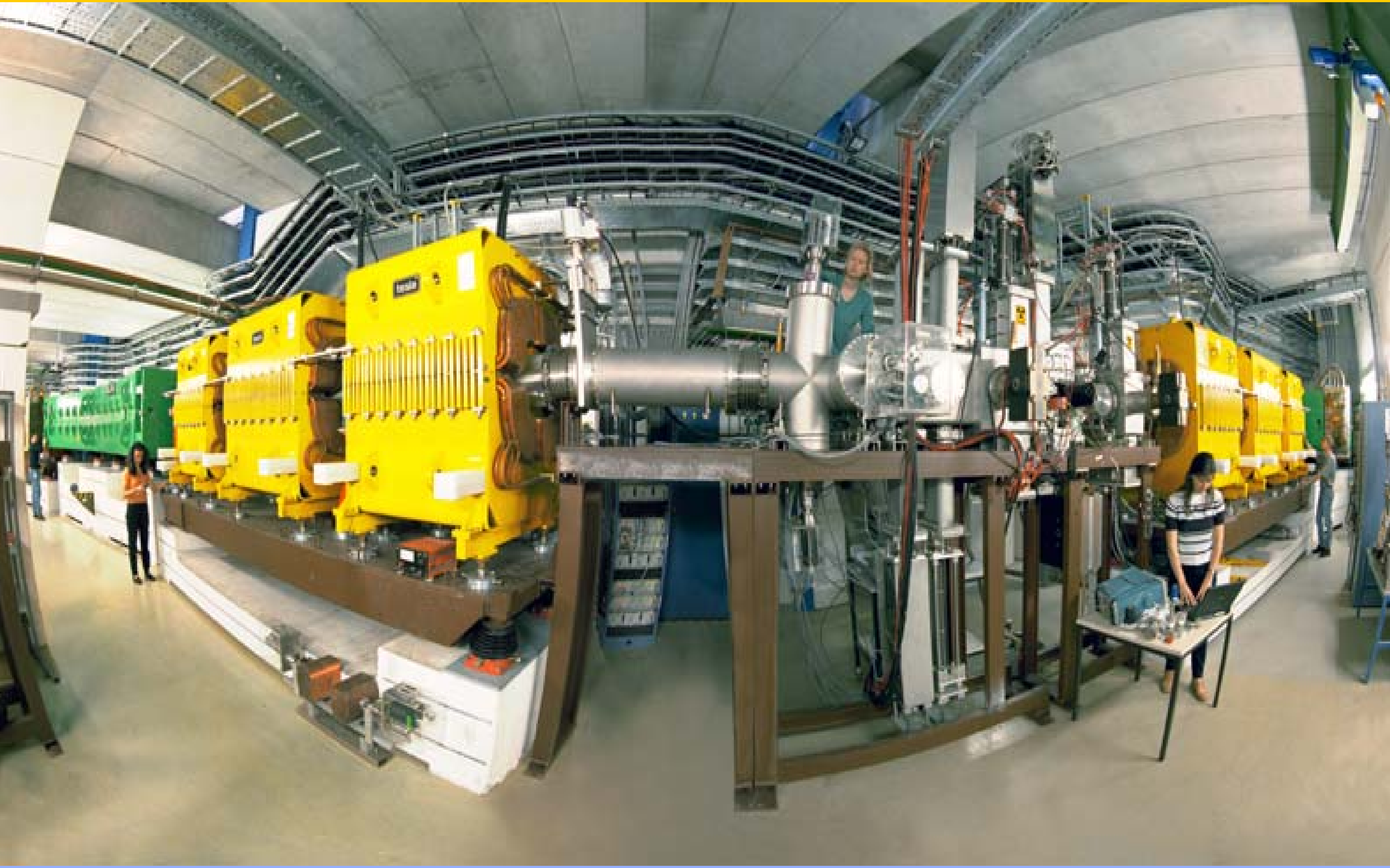
Separation principle: Bρ-ΔE-Bρ method

Example: $^{86}Kr \rightarrow {}^{78}Ni$

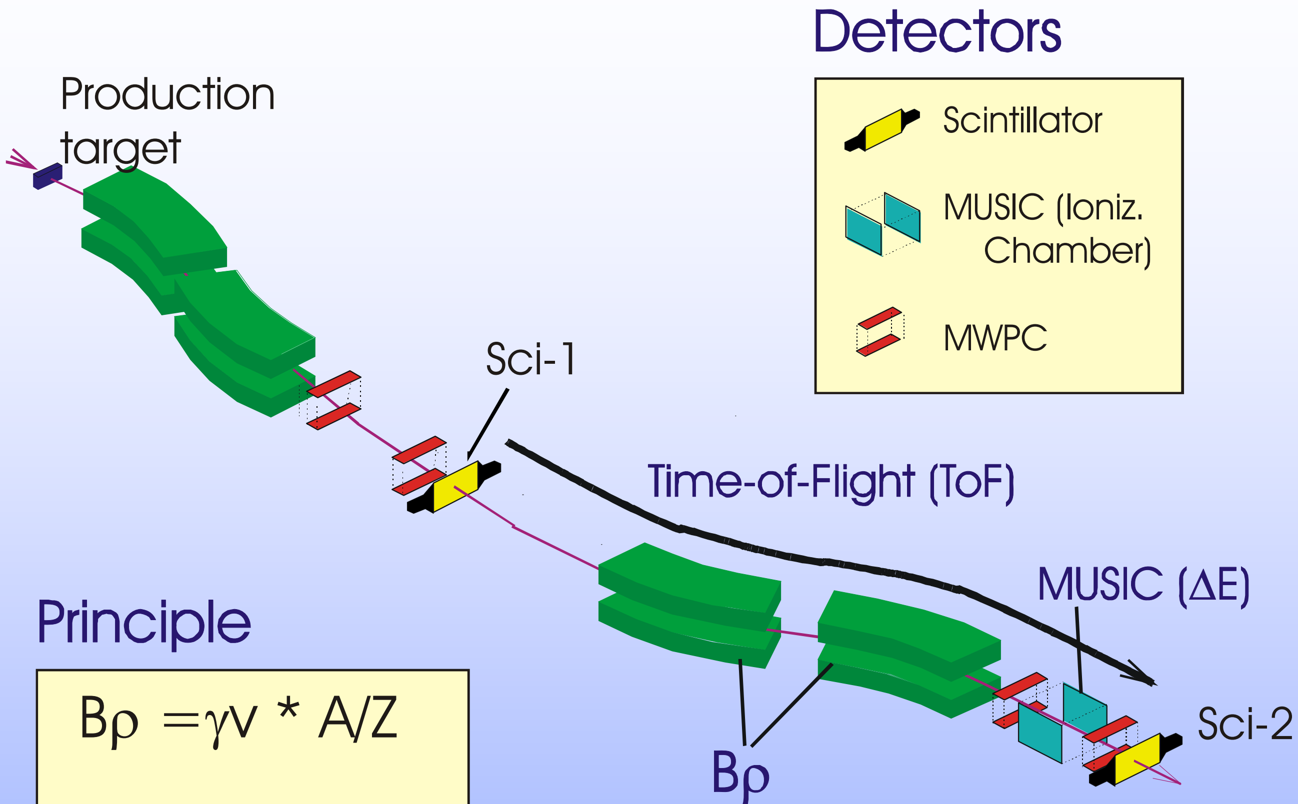




The FRS at GSI



Separation and identification at the FRS



Principle

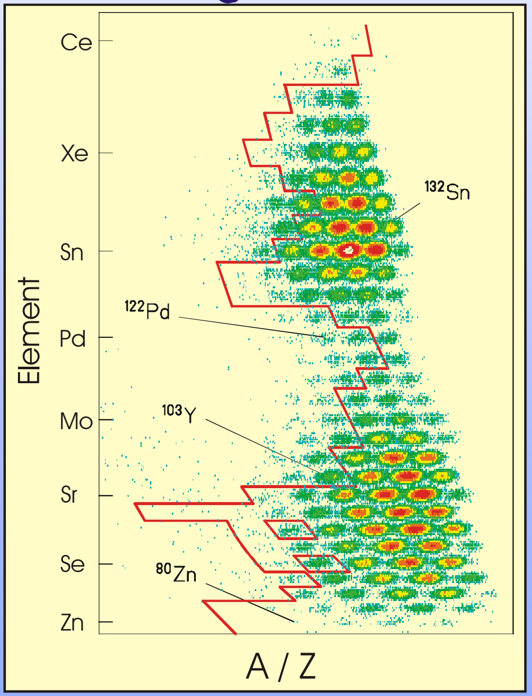
$B\rho = \gamma v * A/Z$

ToF: γv

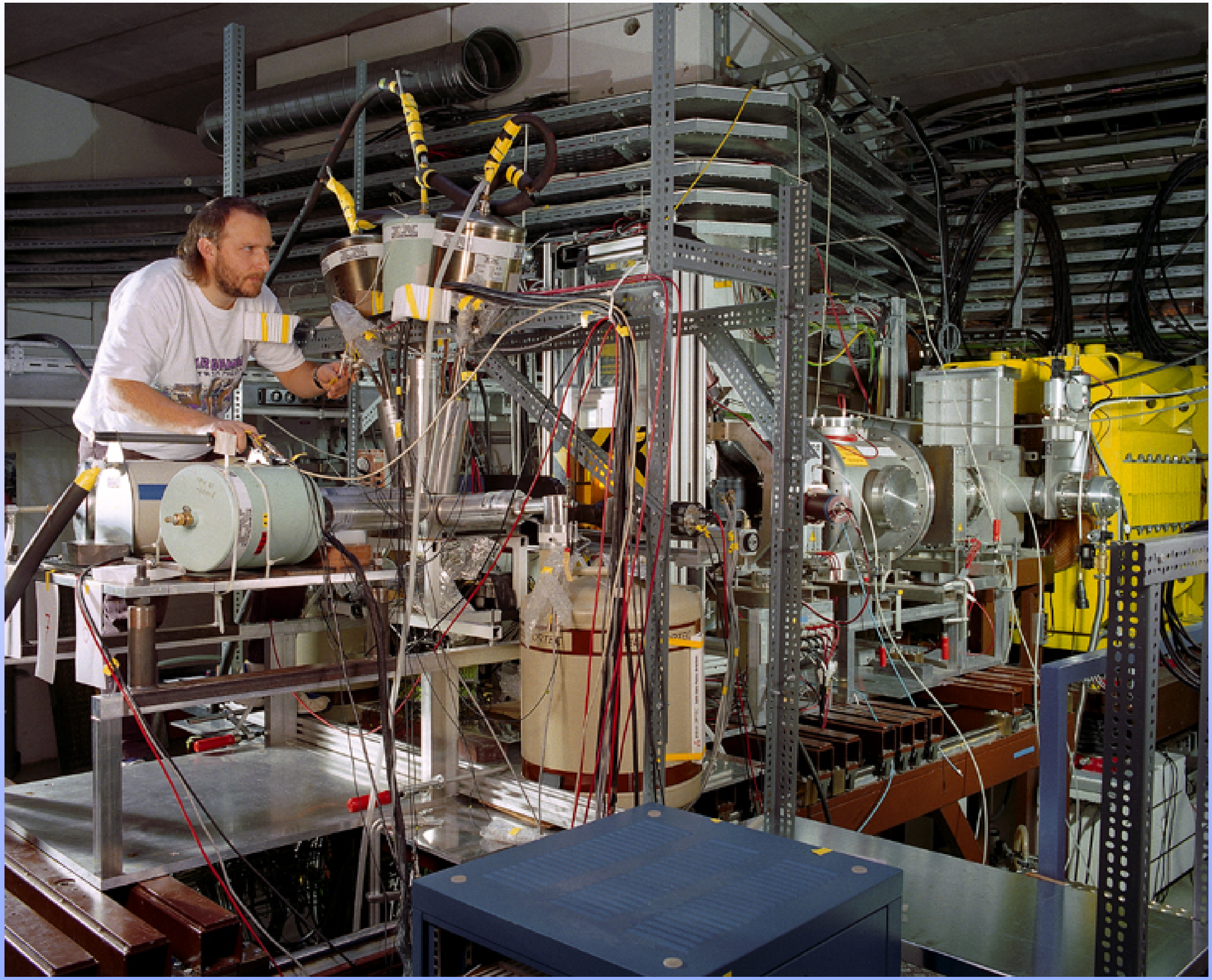
ΔE: Z

$B\rho$: A

Identification of fragments

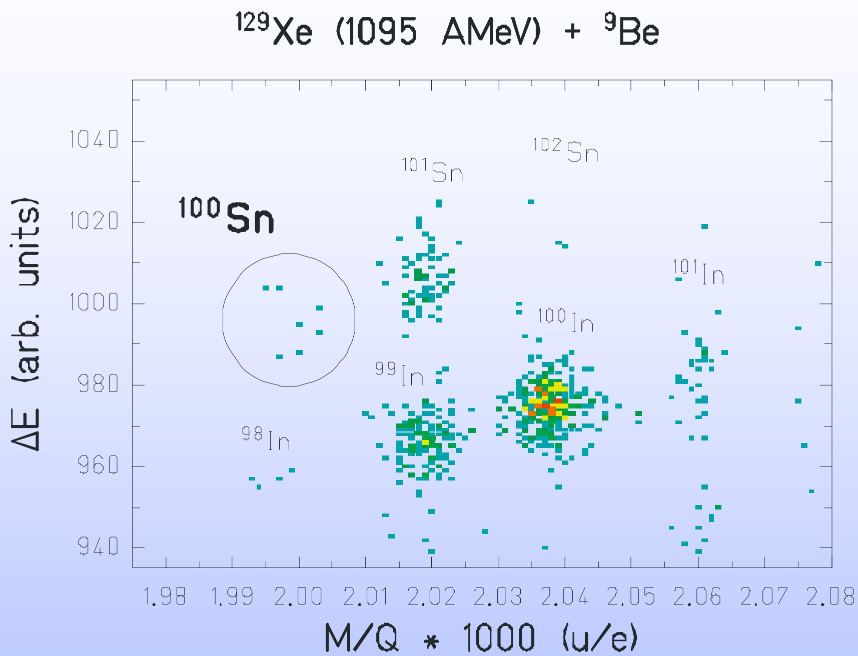


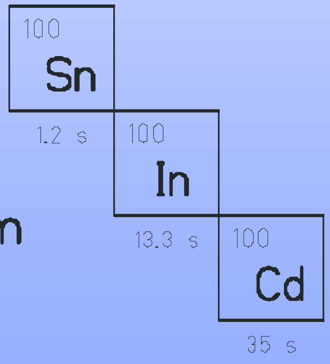
Experimental area at the Fragment Separator FRS



Identification and experiments with few atoms per week

In-flight identification (Bρ, TOF, ΔE)





single-atom
β chain

$T_{1/2}$ = $(0.94\ ^{+0.54}_{-0.27})$ s

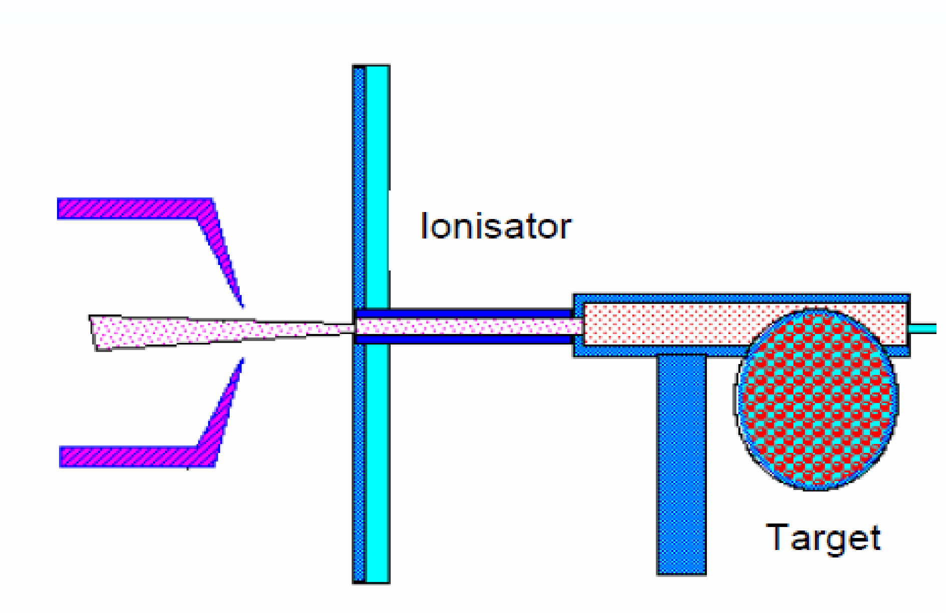
Q_β = $(3.4\ ^{+0.7}_{-0.3})$ MeV

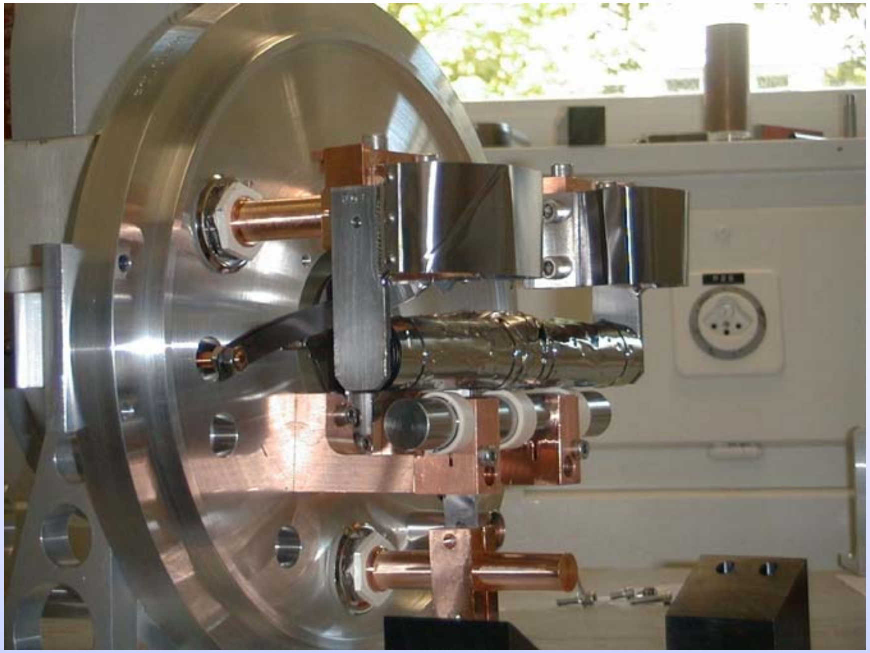
σ = 11 pb

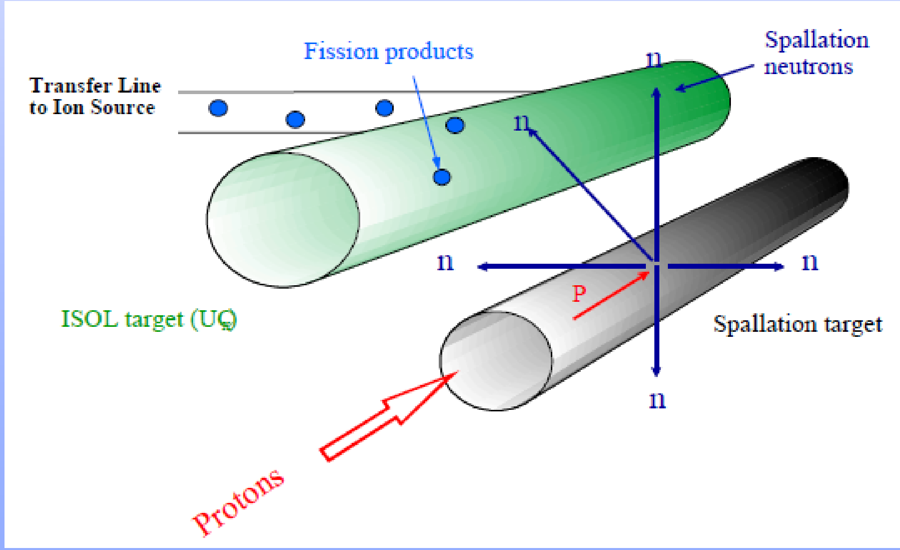
(7 atoms)

R.Schneider
J.Friese, 1995

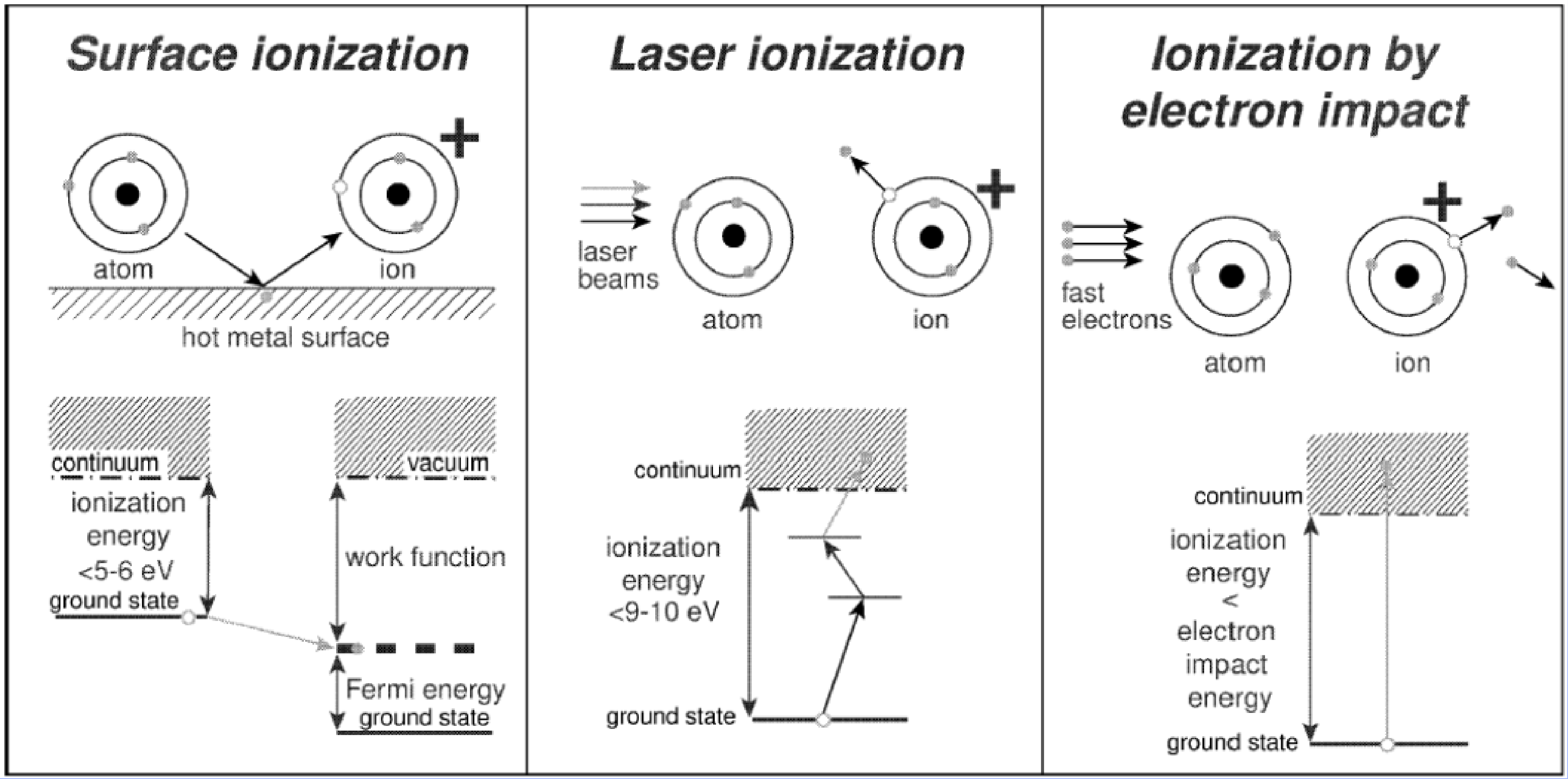
ISOL target and ion source



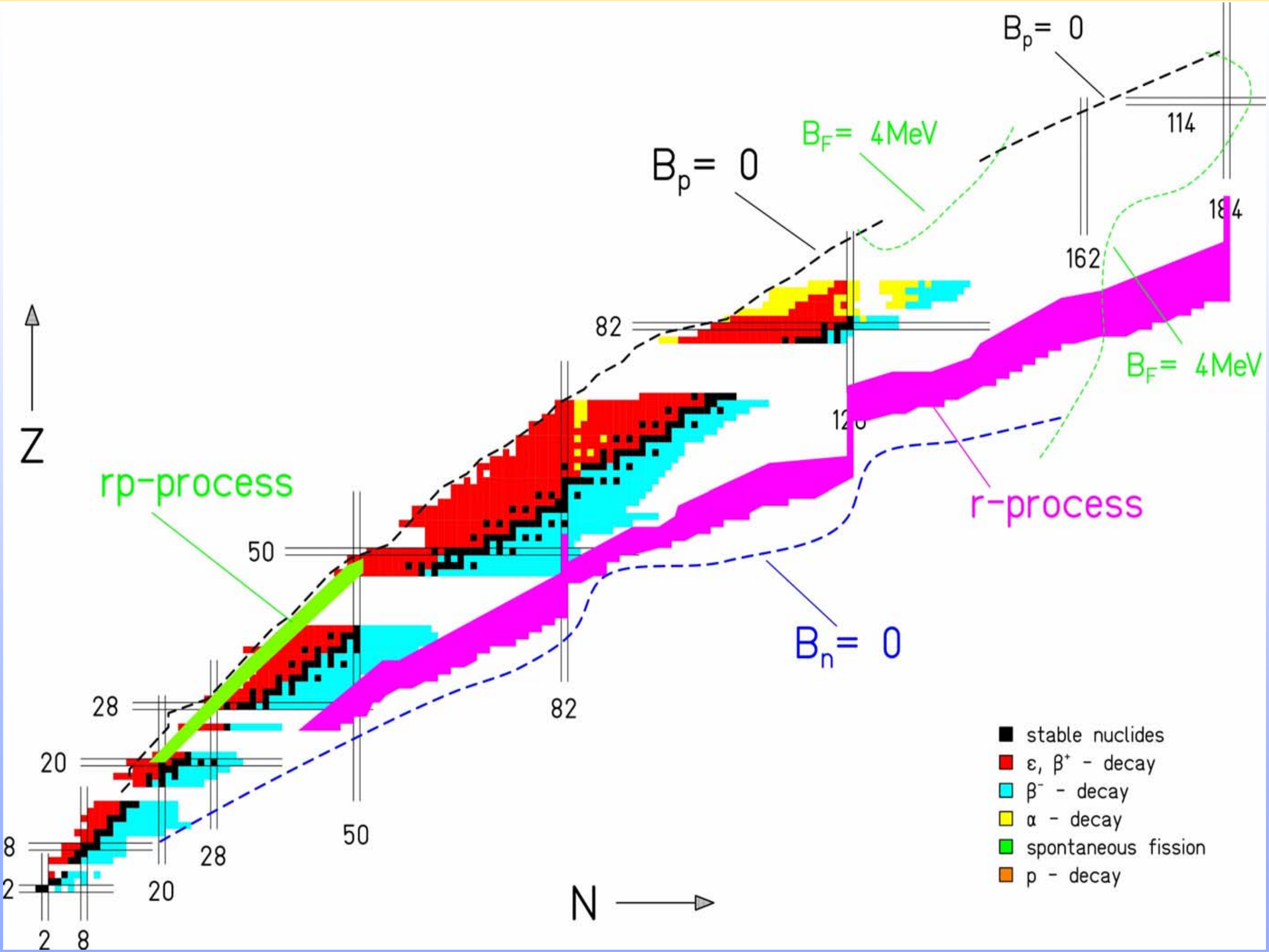




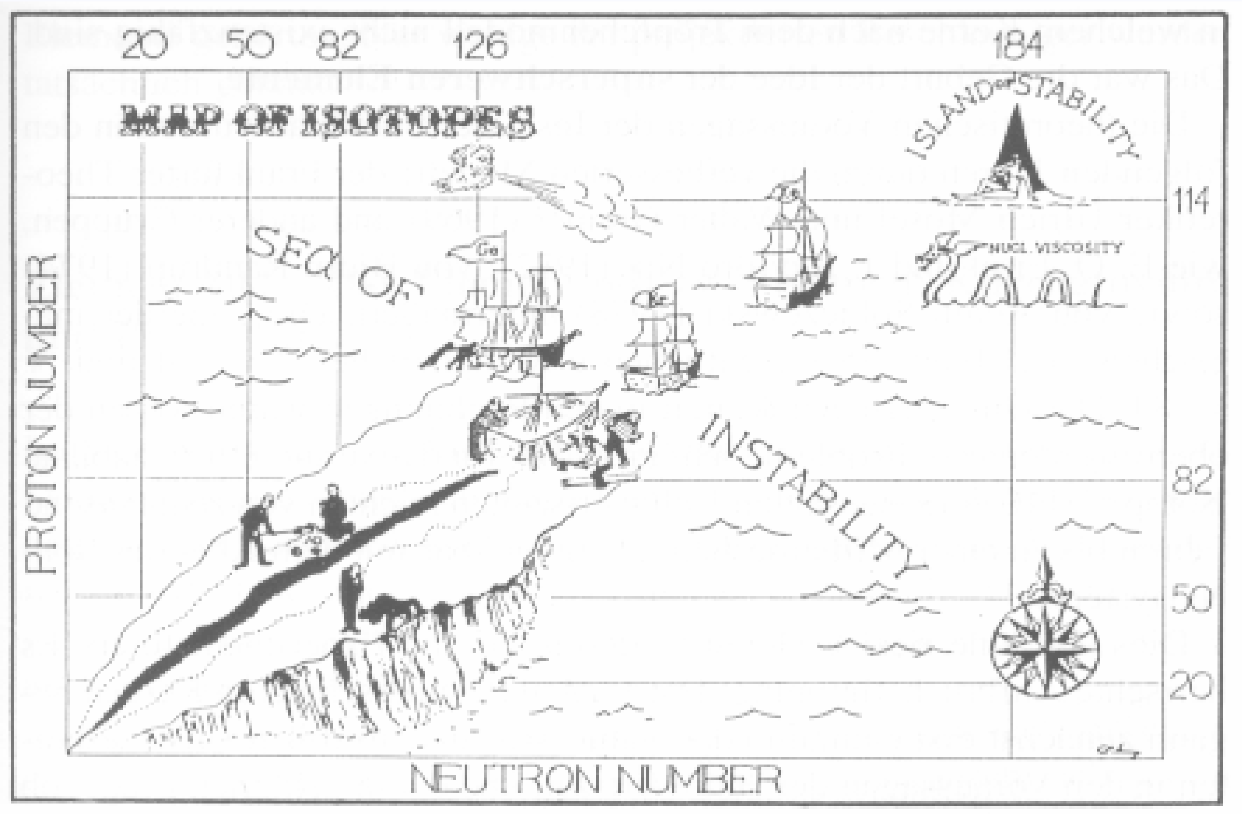
Ionisation mechanisms



Nuclear chart @ CERN-ISOLDE



3a. Superheavy elements

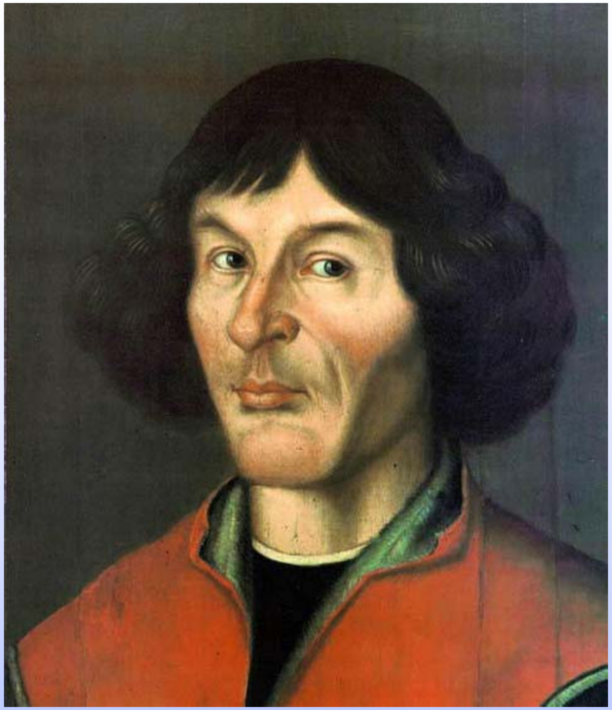


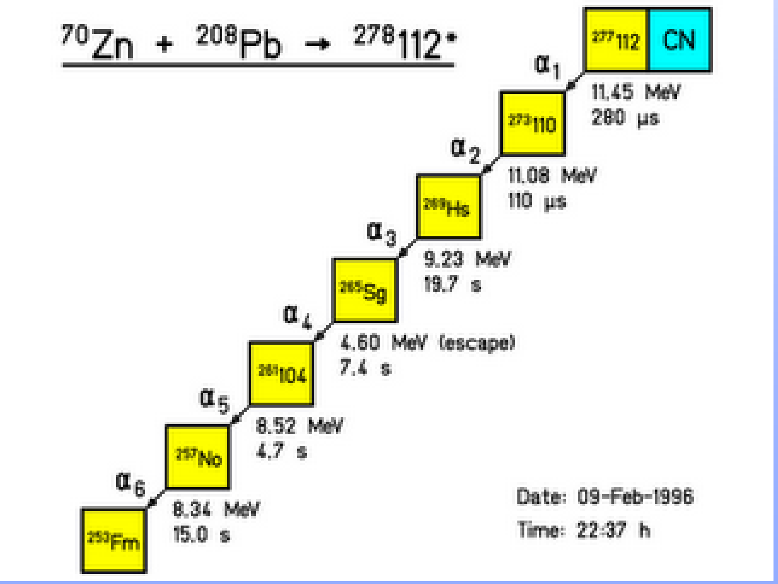
Gottfried Münzenberg und Matthias Schädel „Moderne Alchemie – Die Jagd nach den schwersten Elementen

Key questions:

- where are the upper limits of the periodic table of elements?
- why do SHE exist?
- where is the next proton magic number?
- what atomic and nuclear properties do they have?

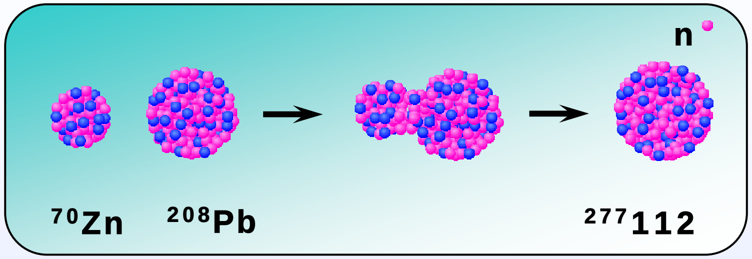
- Officially named in 2009 by IUPAC
- "The idea was to go backwards, to honor someone who was not greatly honored in his lifetime." – Sigurd Hofmann
- Hofmann wanted to highlight the contribution of nuclear chemistry to other fields, astrophysics in particular
- Element was first produced at GSI in 1996 by fusion of zinc and lead

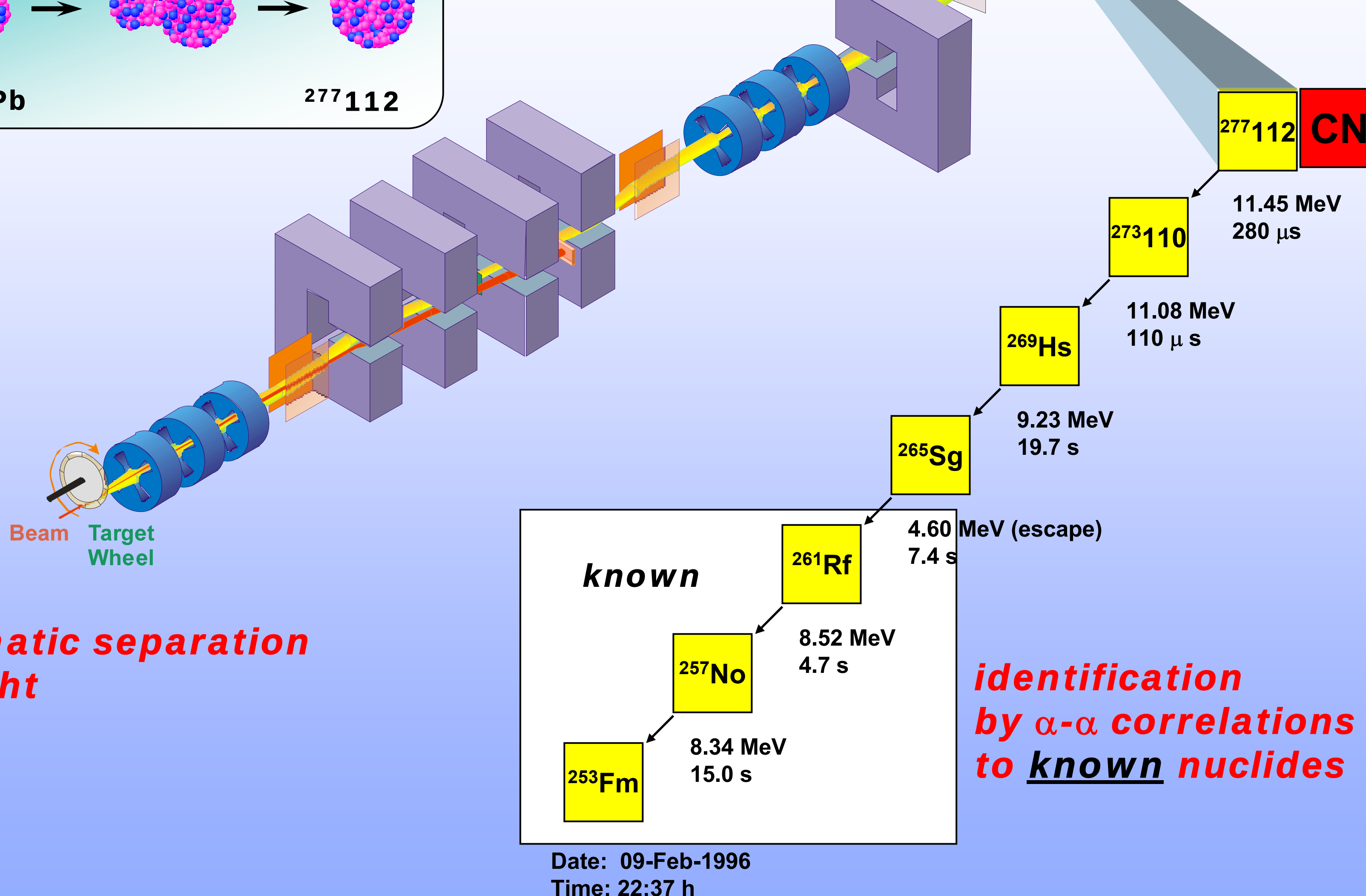




S. Hofmann et al.,
Z. Phys. A354, 229-230 (1996)

Synthesis and identification of SHE at SHIP

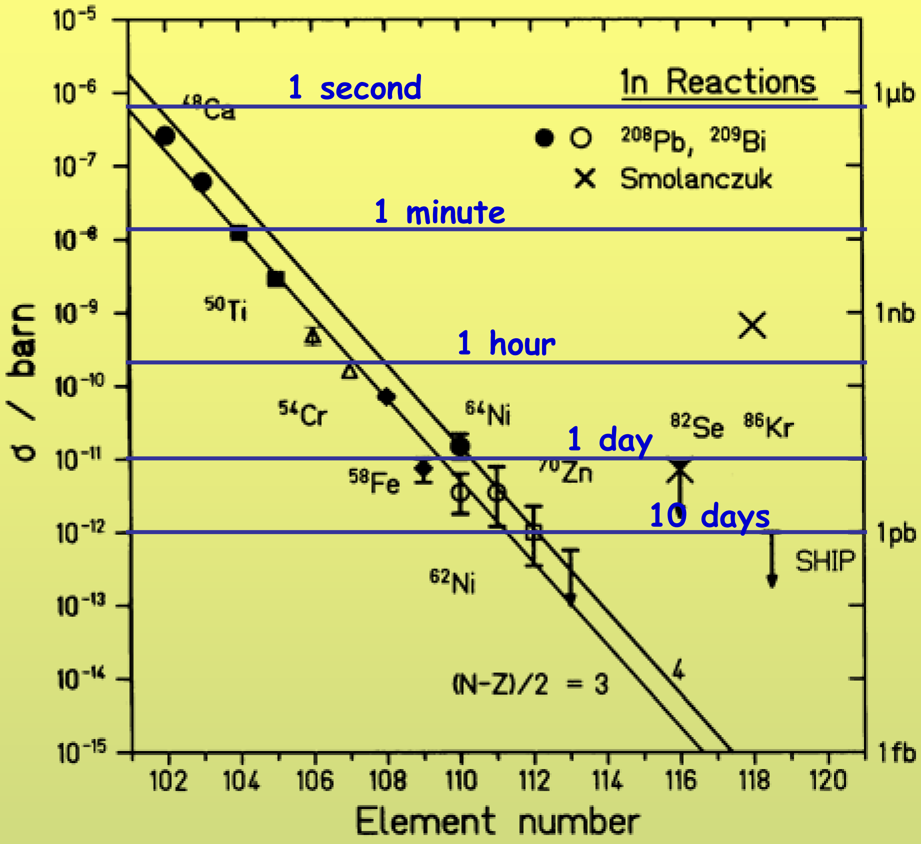




kinematic separation in flight

identification by α-α correlations to <u>known</u> nuclides

Cross section systematics (1n evaporation residue)



times needed to observe on average 1 event

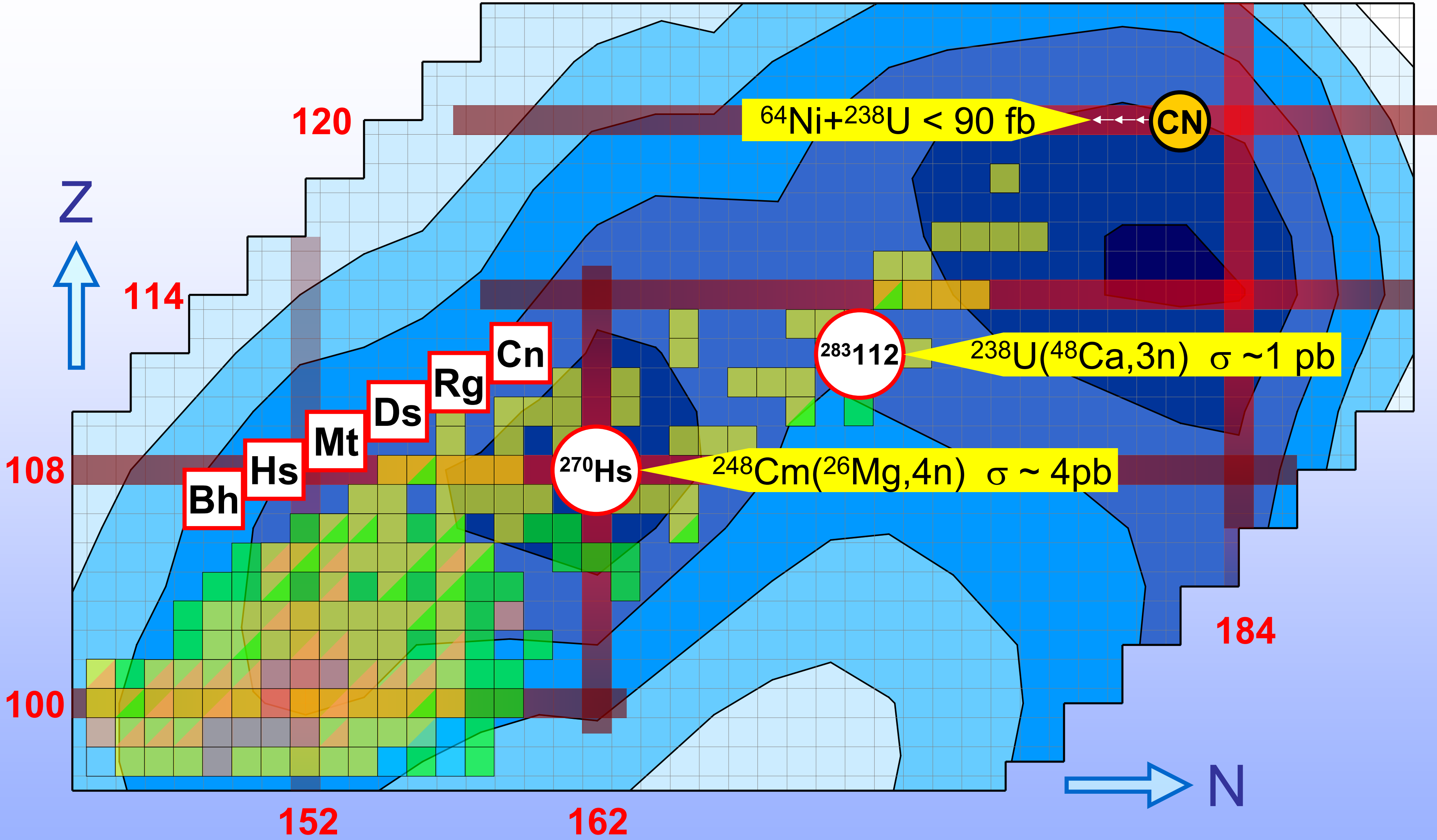
→present sensitivity:

limit ≈ 1 pbarn

→beam dose:

1.5×10^{18} projectiles

Status of worldwide SHE research



Background: calculated shell correction energies E_{shell} of SHE

The inner electrons move at relativistic speed in the strong electric field of the high-Z nucleus:

$v/c \sim Z\alpha \sim 100/137 \rightarrow \beta \sim 0{,}7$

example $_{106}$Sg: $\beta = 0{,}77$

$\gamma = 1{,}58$

$r = 0{,}63\, r_0$

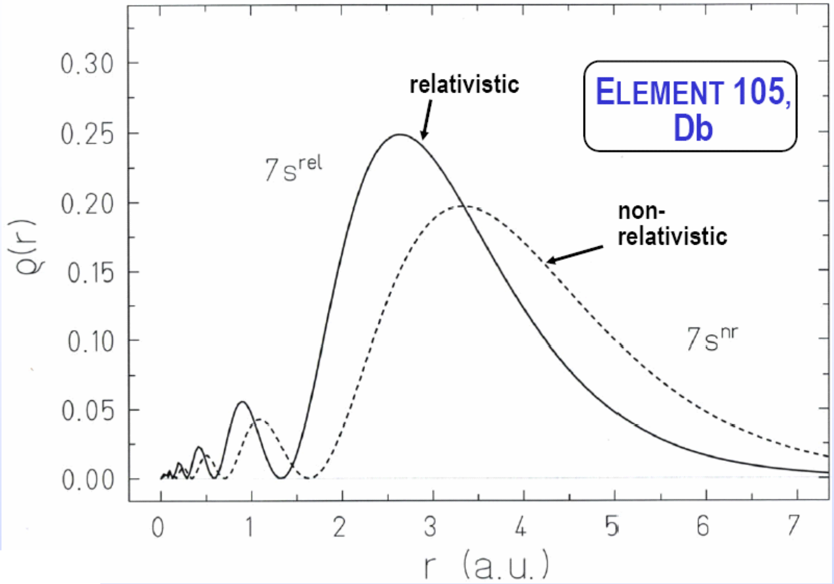
→ s,p-electrons are attracted closer to the nucleus
→ spin-orbit splitting
→ high electron-density near nuclear surface
→ screening of nuc.charge for outer (d,f) electrons

Glenn Seaborg during his visit to GSI

Chemistry of Transactinides

→ electron configuration, ionic radii, binding energies
→ chemical properties (redox potential, volatility, complex formation, periodicity of chem.properties,...)

Theory predictions: relativistic vs. non-relativistic calculations



CONSEQUENCES

* Shift of energetic and spacial distribution of electronic orbital on an absolute and relative scale

→ Change of electronic ground state configurations and the ionization energies

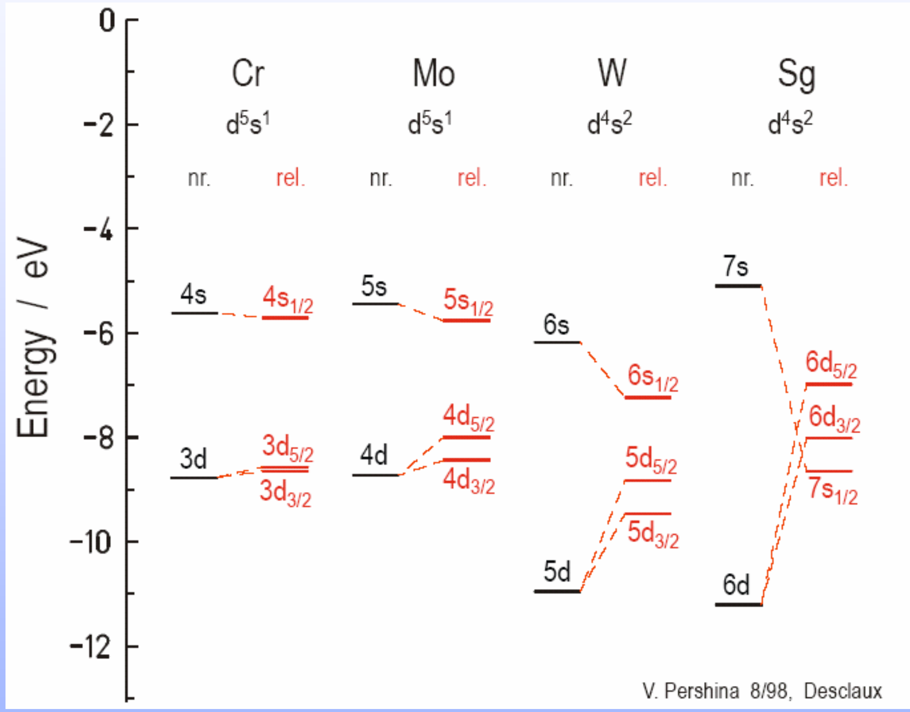
→ Change of atomic- and ionic radii

→ Change of availability of electronic orbitals for chemical bonding

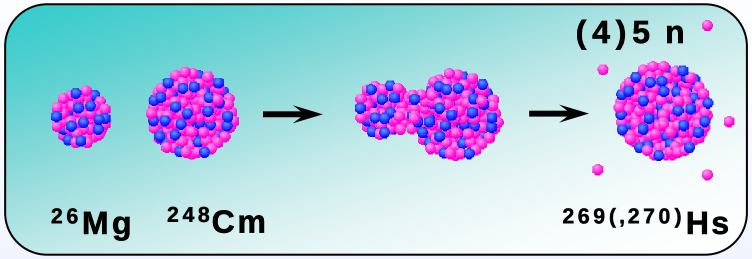
→ Change of bonding energies in molecular bonds

→ Change of contribution of ionic- and covalent part in the bonding

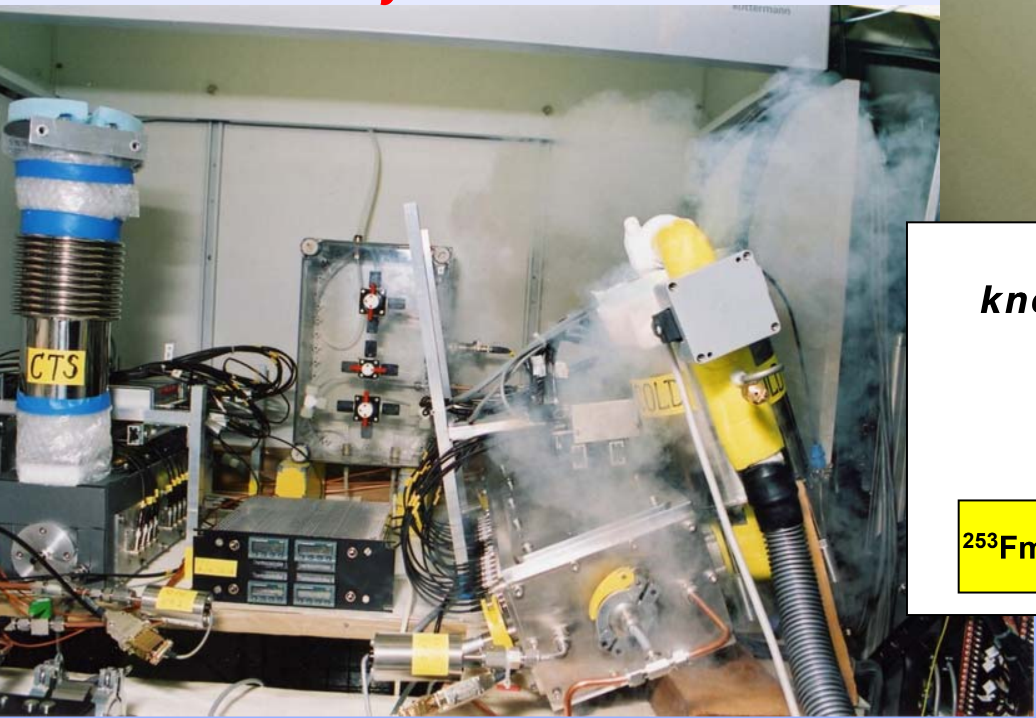
Group 6 elements

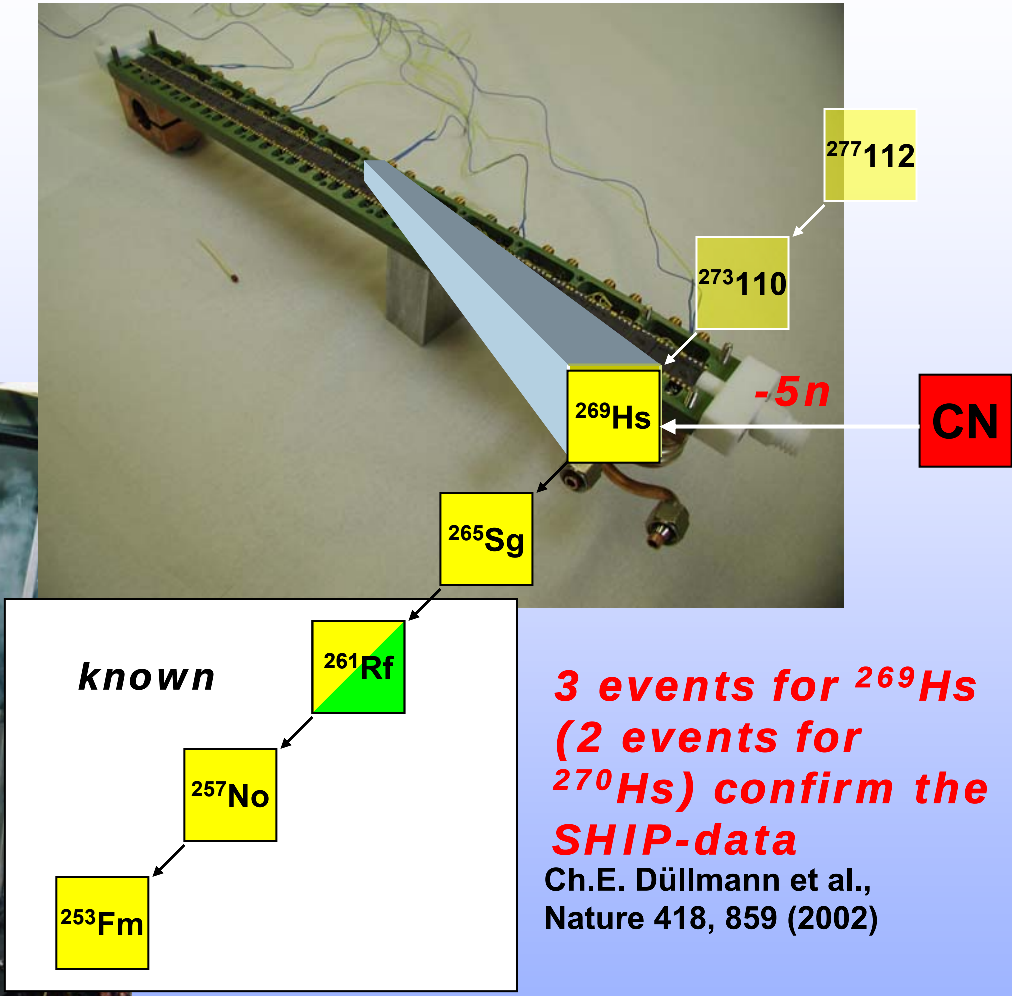


Confirmation by chemistry



+ chemistry



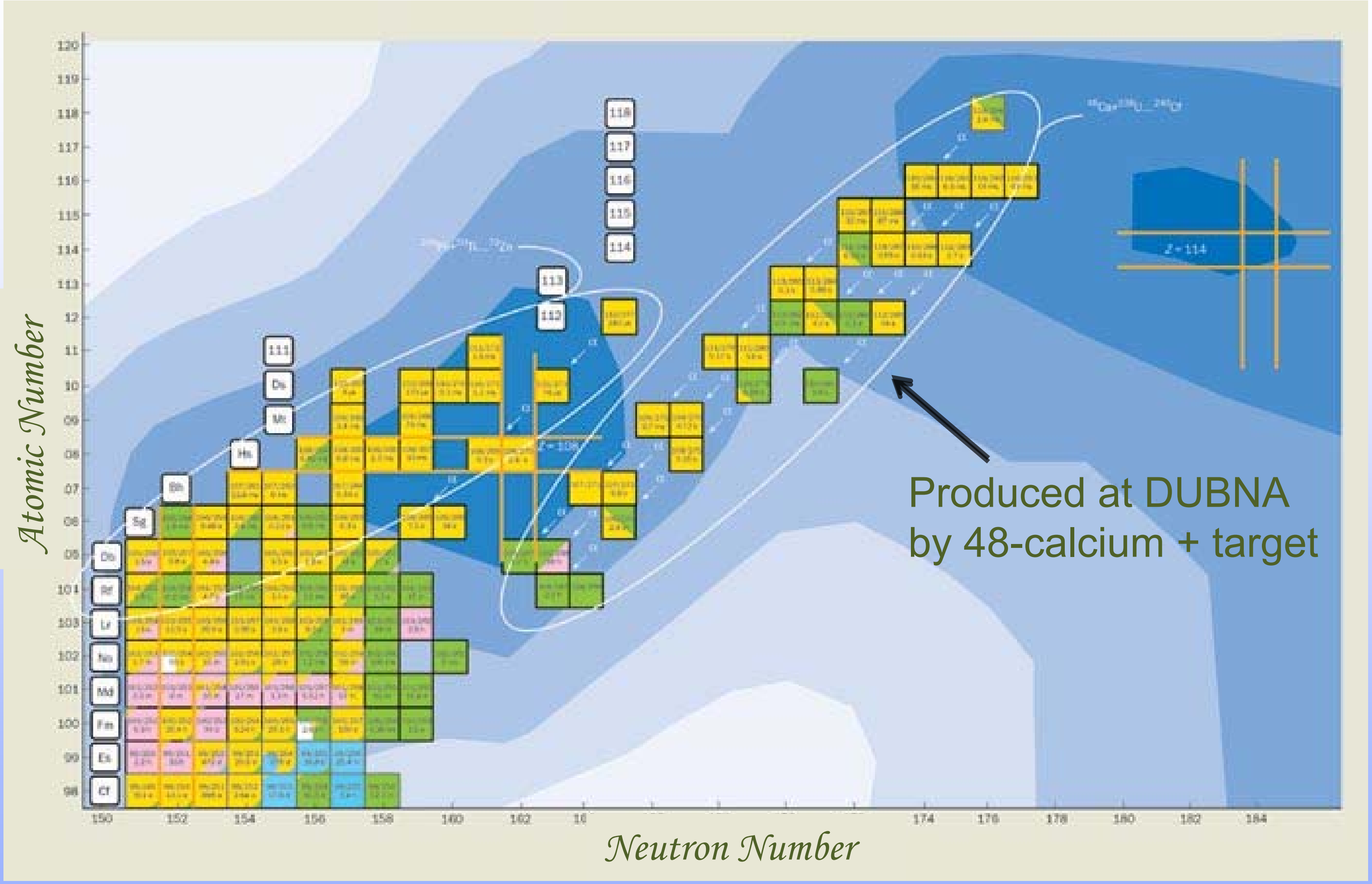


3 events for ^{269}Hs (2 events for ^{270}Hs) confirm the SHIP-data

Ch.E. Düllmann et al., Nature 418, 859 (2002)

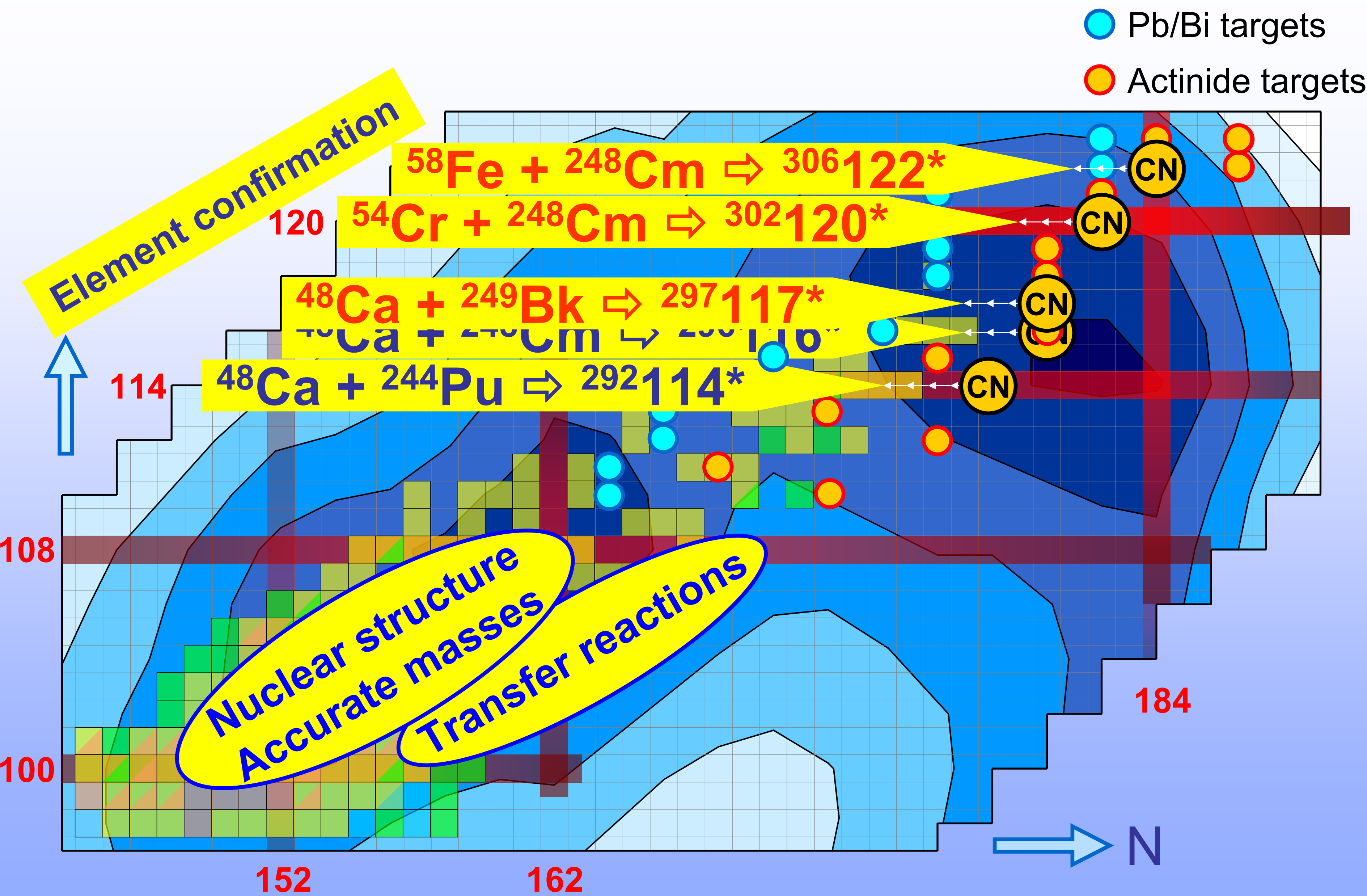
determination of the chemical Properties of Hassium

Hot fusion advances the field



Produced at DUBNA by 48-calcium + target

Future perspectives

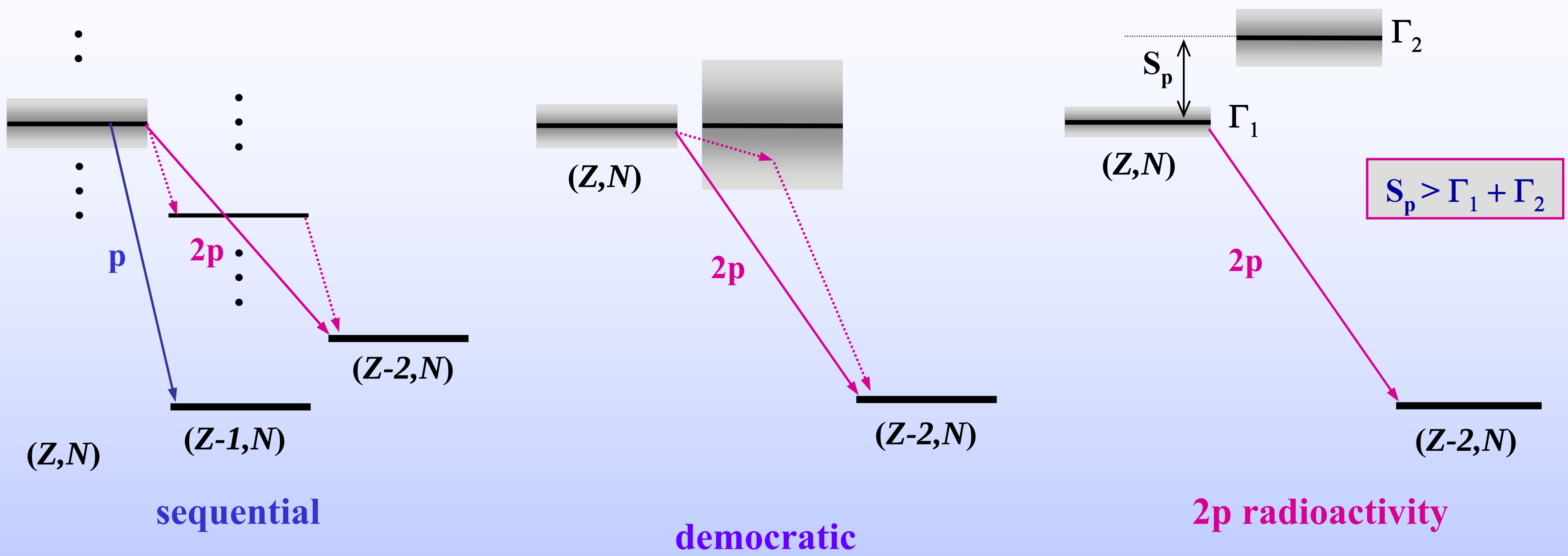


3b. 2-proton radioactivity

Discovery of a new type of radioactivity

- Production of nuclei at the proton dripline
- Study of the 2-proton emitter ^{45}Fe

Emission of two protons from nuclear states

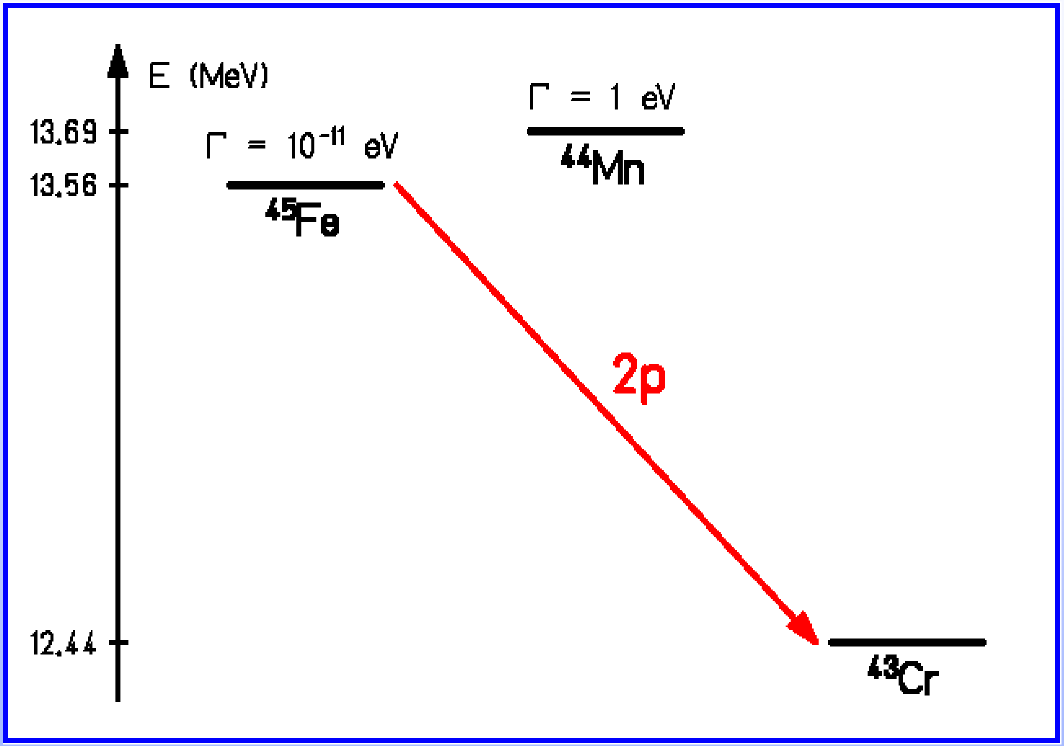


$^{22}Mg^*$, $^{26}Si^*$ – Cable et al., 1983
$^{35}K^*$ – Äystö et al., 1985
$^{31}Cl^*$ – Borge et al., 1990
$^{14}O^*$ – Bain et al., 1996
$^{18}Ne^*$ – Gómez del Campo et al., 2000

^{6}Be – Bochkarev et al., 1989
^{12}O – Kryger et al., 1994
^{16}Ne – ?

Not observed before !
Predicted candidates :
^{19}Mg, ^{45}Fe, ^{48}Ni, ^{54}Zn

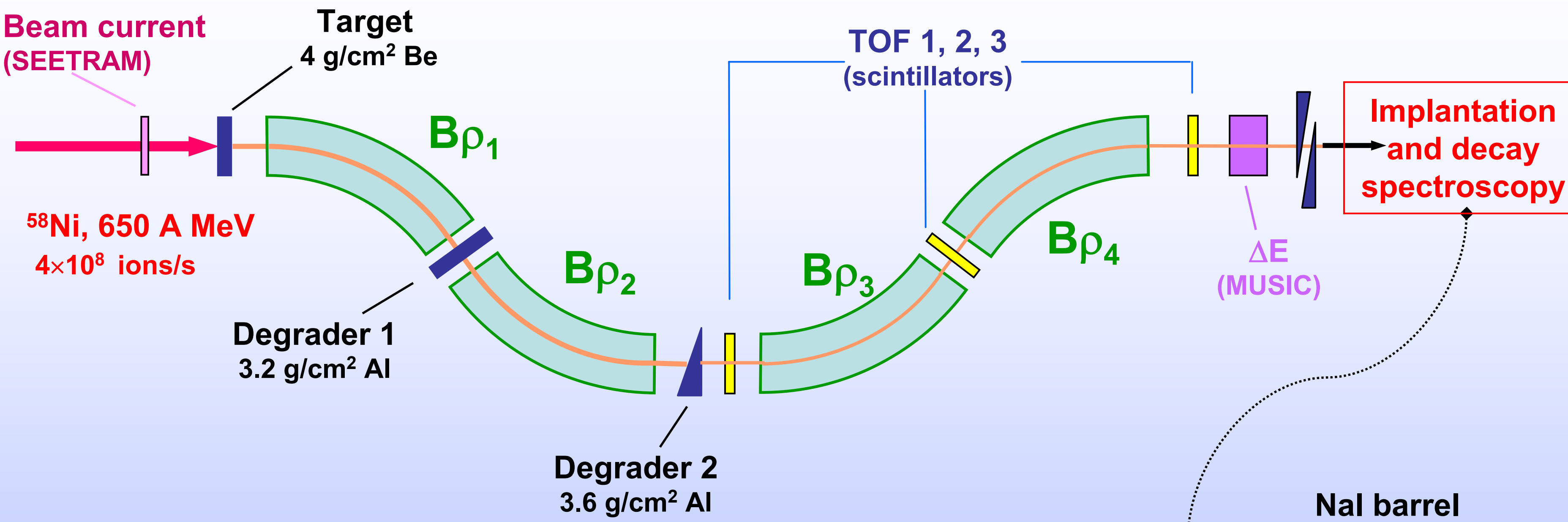
Ground state energies of ^{45}Fe, ^{44}Mn, ^{43}Cr

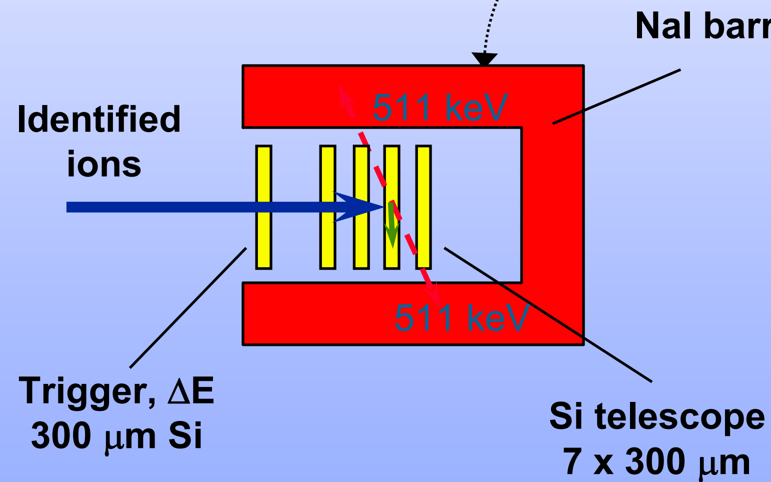


Author	Q_{2p} [MeV]	$T_{1/2}$ [μs]
Brown	1.15 ±0.09	2 - 300
Ormand	1.28 ±0.18	0.01 - 100
Cole	1.22 ±0.05	-

M. Pfützner et al. Eur. Phys. J. A 14 (2002) 279

Experiment at the FRS





IN-FLIGHT IDENTIFICATION OF IONS

$B\rho_{3,4} \Rightarrow A\,v / Z$

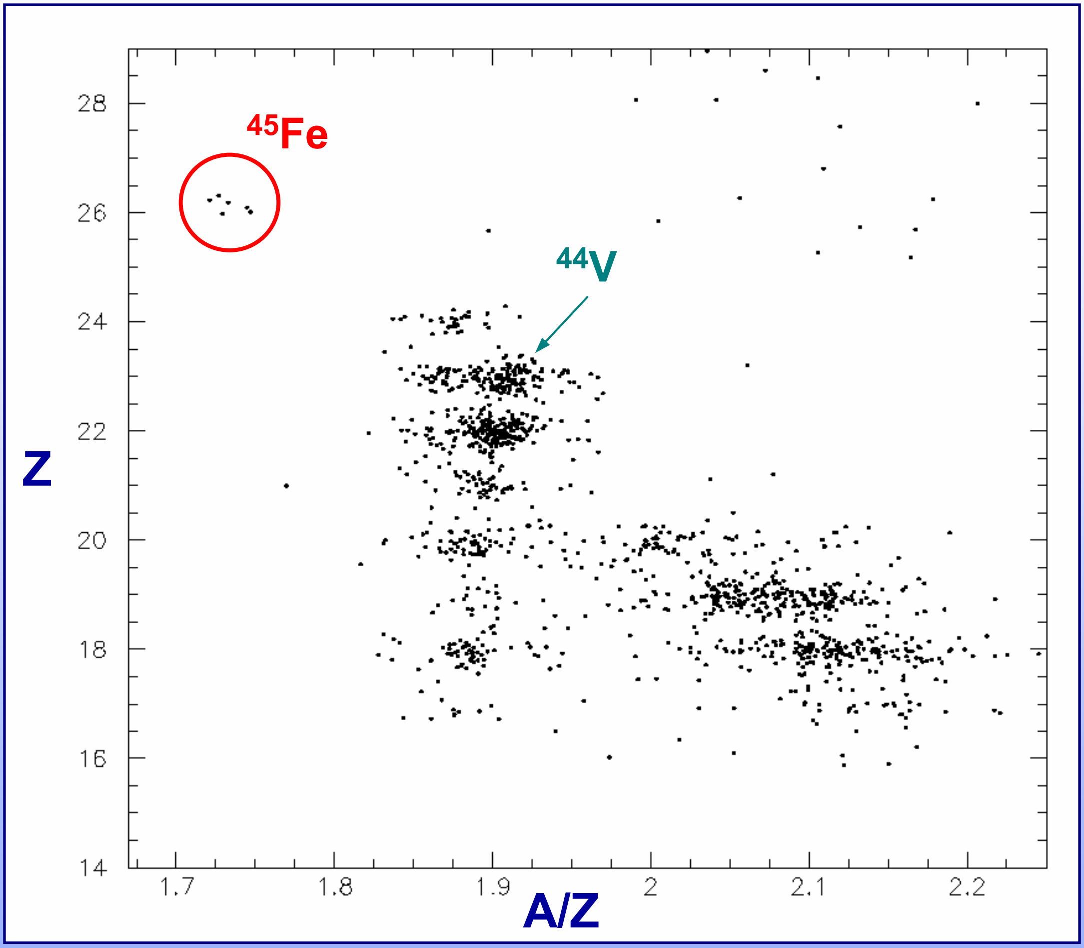
TOF 1,2,3 $\Rightarrow v$

$\Rightarrow A/Z$

$\Delta E \Rightarrow Z$

M. Pfützner et al. Eur. Phys. J. A14 (2002) 279

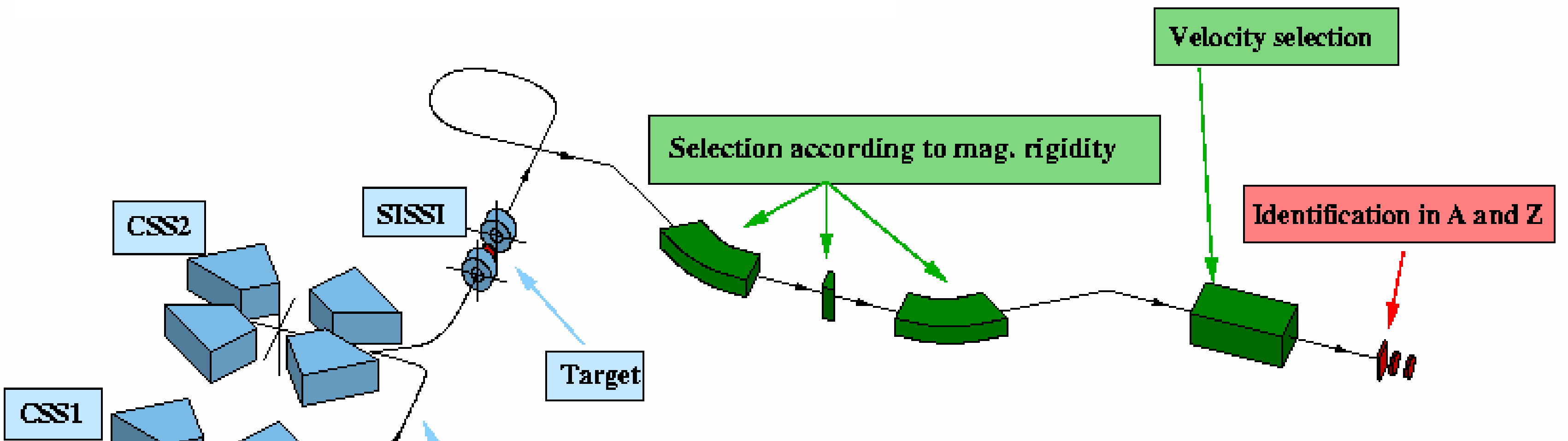
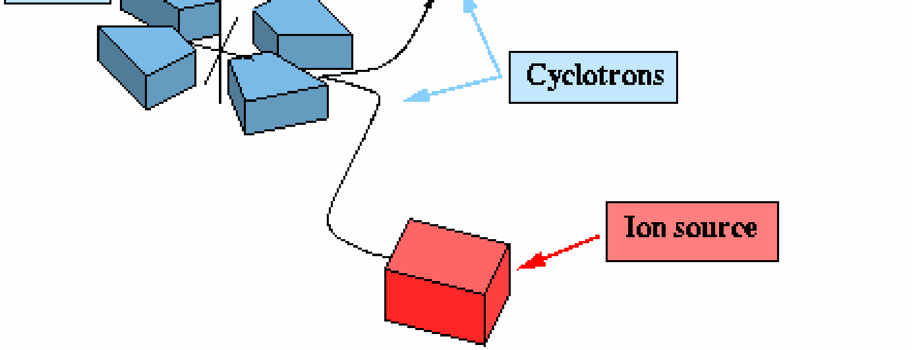
Identification of ^{45}Fe

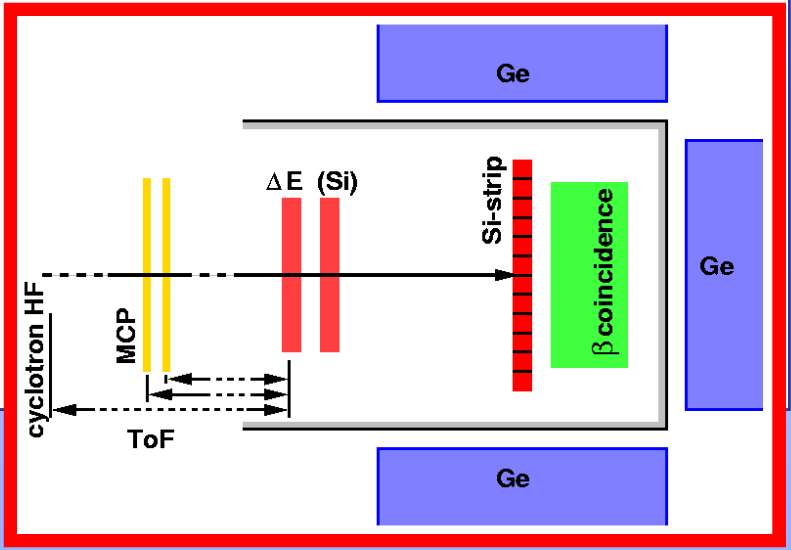


2115 events in 8117 min. (5.6 d)
6 events ^{45}Fe

M. Pfützner et al.,
Eur. Phys. J. A 14 (2002) 279

LISE 3 Separator at GANIL

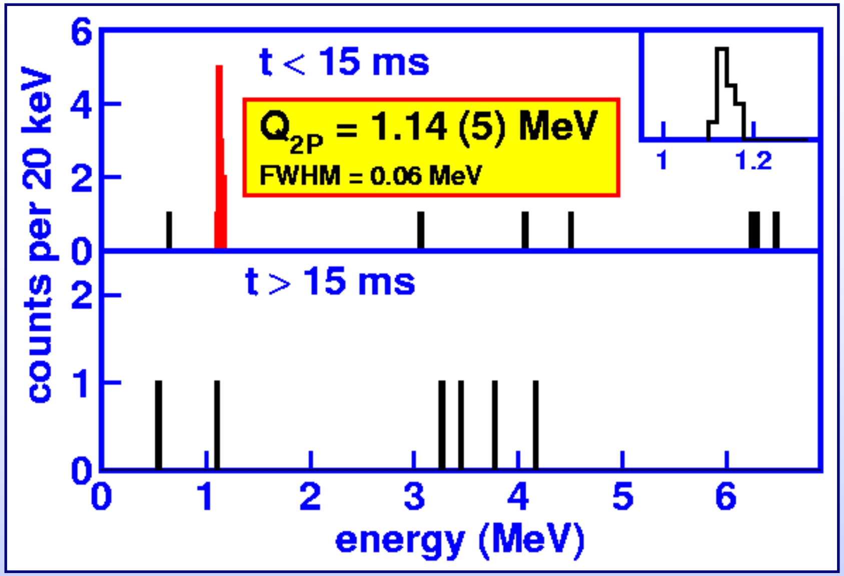





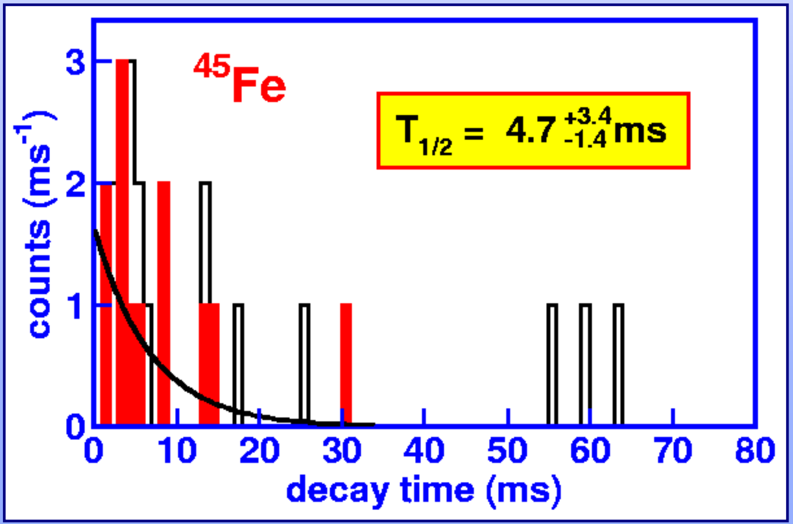
^{58}Ni @ 75 MeV/A on nickel target
High primary beam intensity: 3-5μA

Results from GANIL experiment

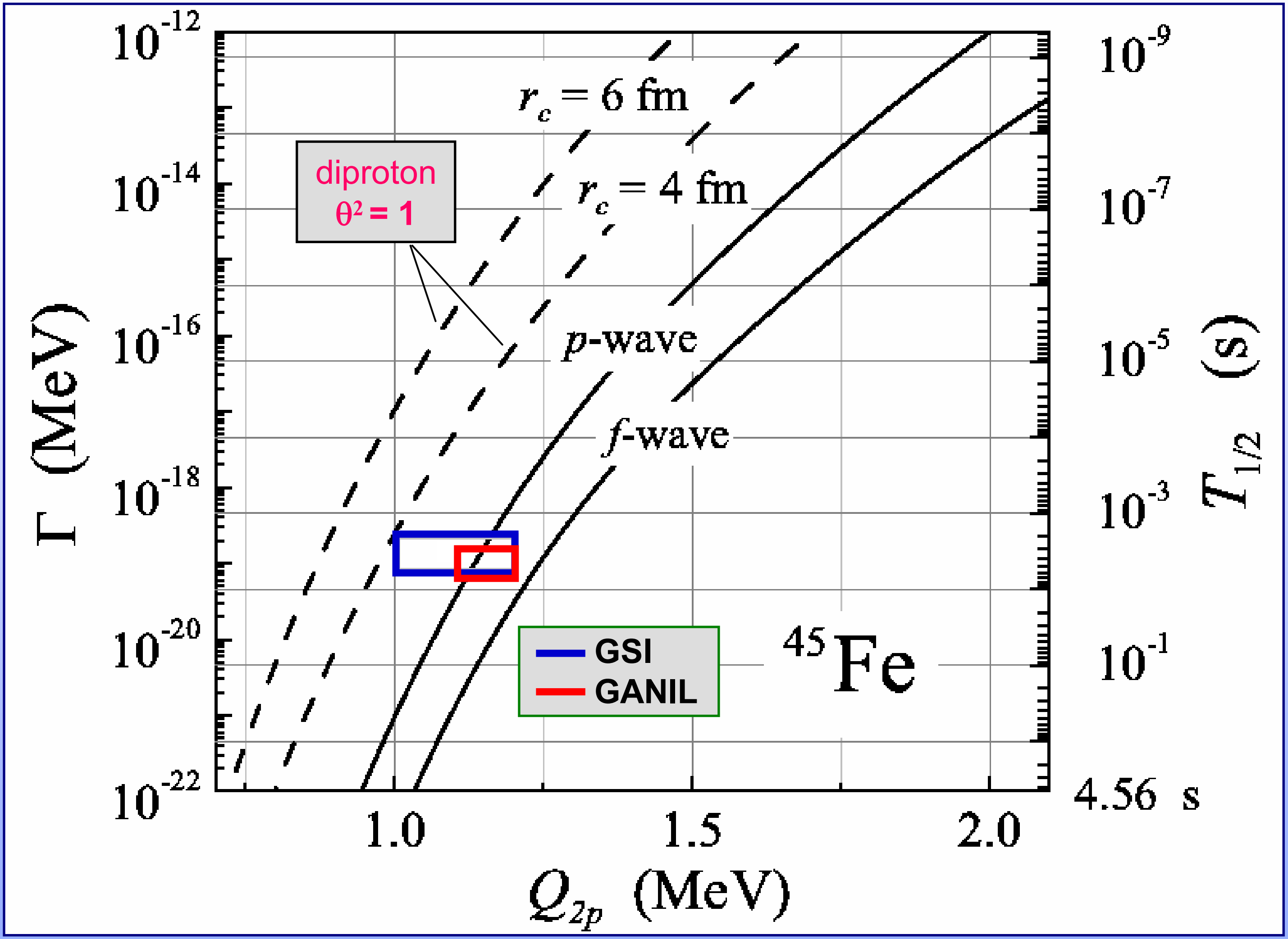
Decay energies



Decay times

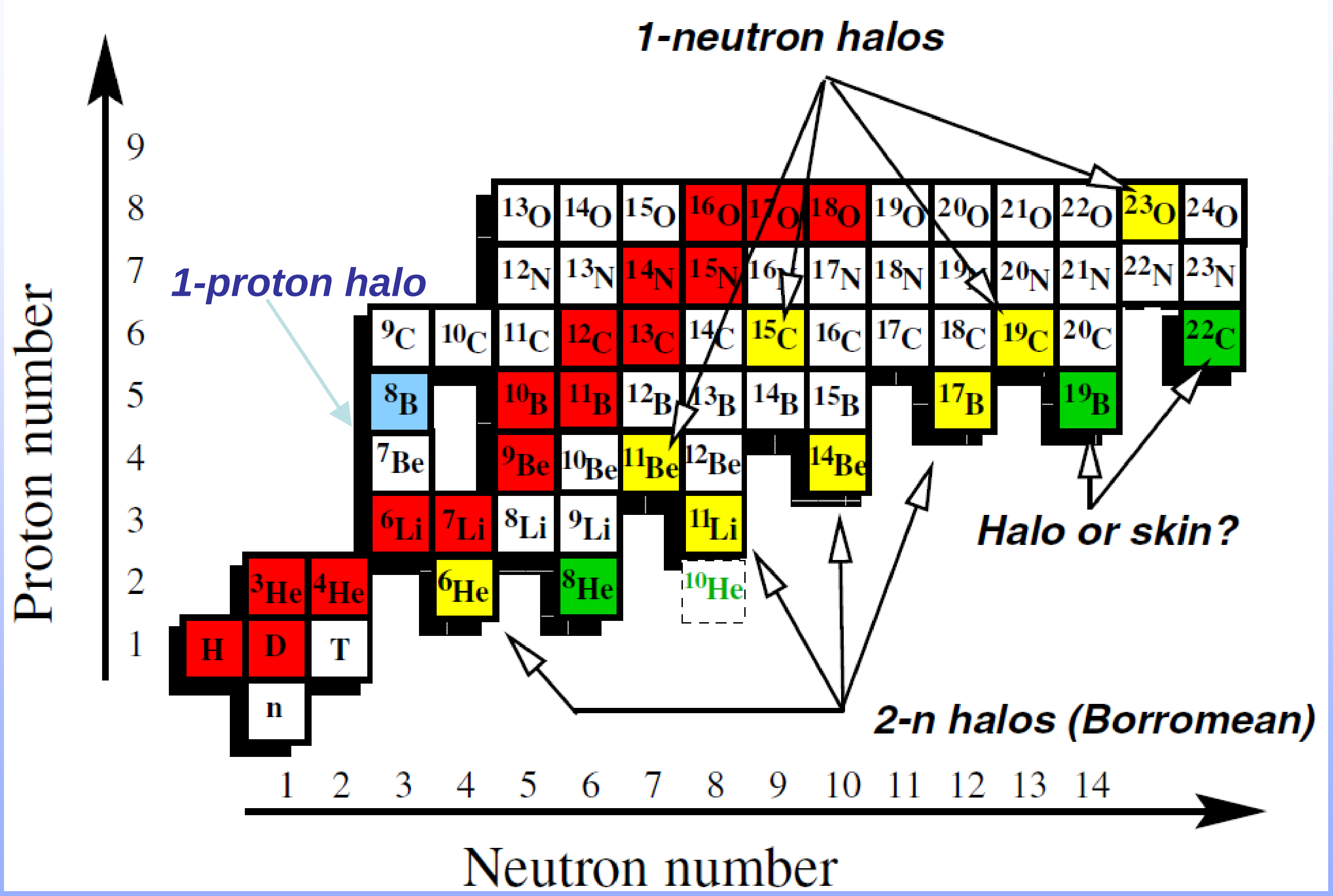


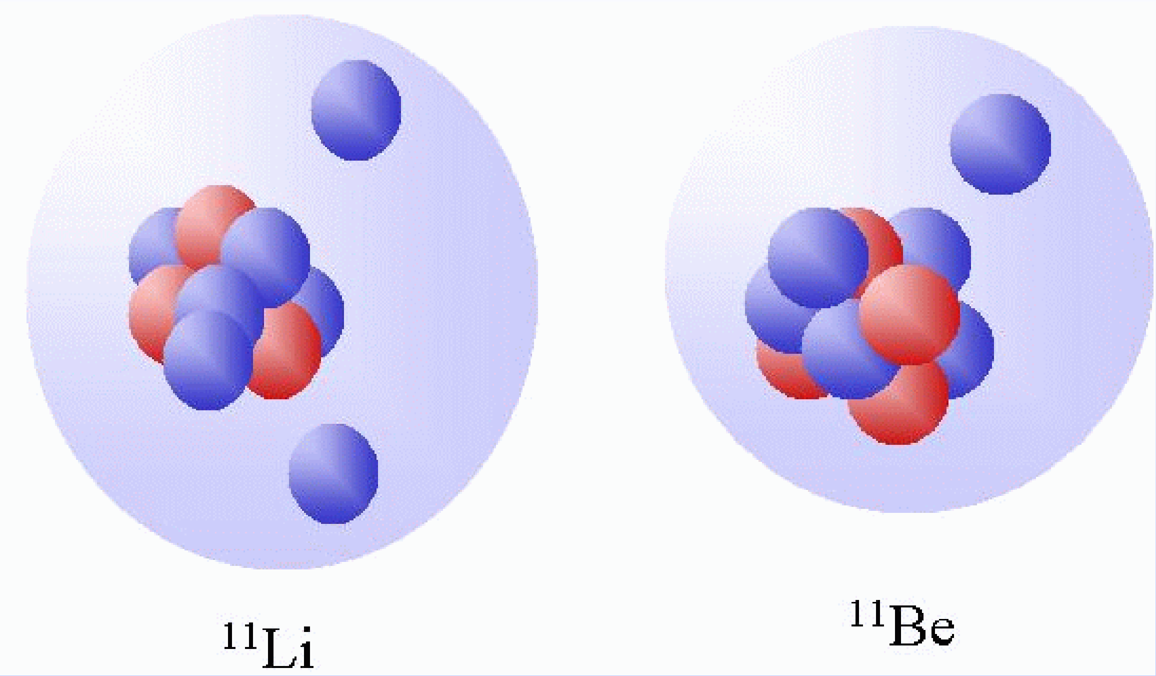
2p-decay of ^{45}Fe in a 3-body model

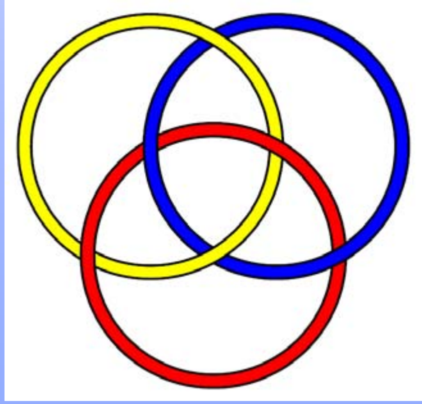


3c. Halo nuclei

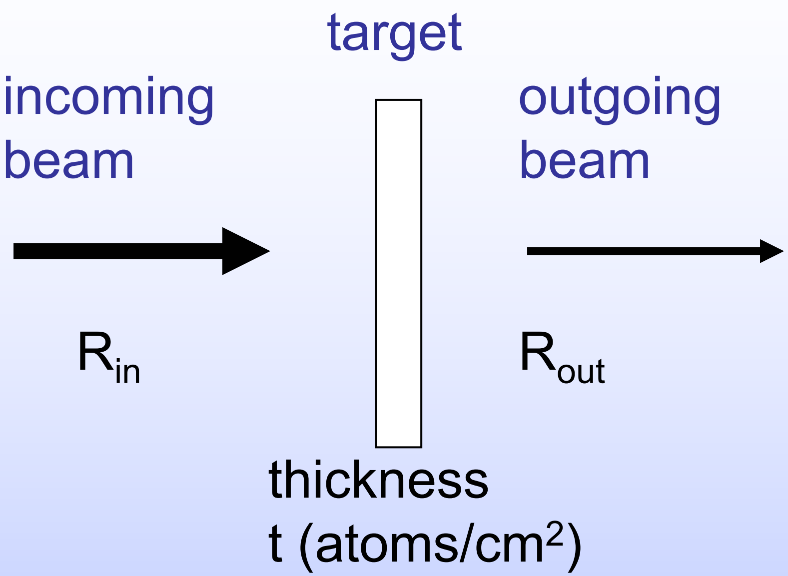
- Radii measurements
- Momentum measurements
- Complete kinematic measurements


1-neutron halos
1-proton halo
Halo or skin?
2-n halos (Borromean)
Proton number
Neutron number
1 2 3 4 5 6 7 8 9
1 2 3 4 5 6 7 8 9 10 11 12 13 14
H D T n
3He 4He 6He 8He 10He
6Li 7Li 8Li 9Li 11Li
7Be 9Be 10Be 11Be 12Be 14Be
8B 10B 11B 12B 13B 14B 15B 17B 19B
9C 10C 11C 12C 13C 14C 15C 16C 17C 18C 19C 20C 22C
12N 13N 14N 15N 16N 17N 18N 19N 20N 21N 22N 23N
13O 14O 15O 16O 17O 18O 19O 20O 21O 22O 23O 24O





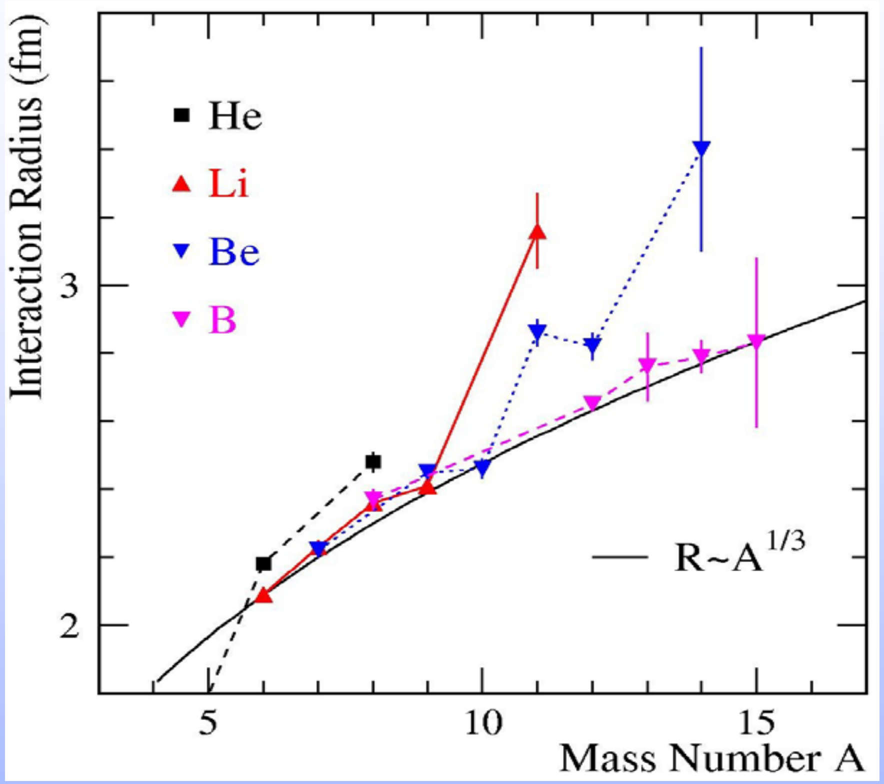
Borromean rings – Borromean nuclei
(sign of an Italien
noble family)

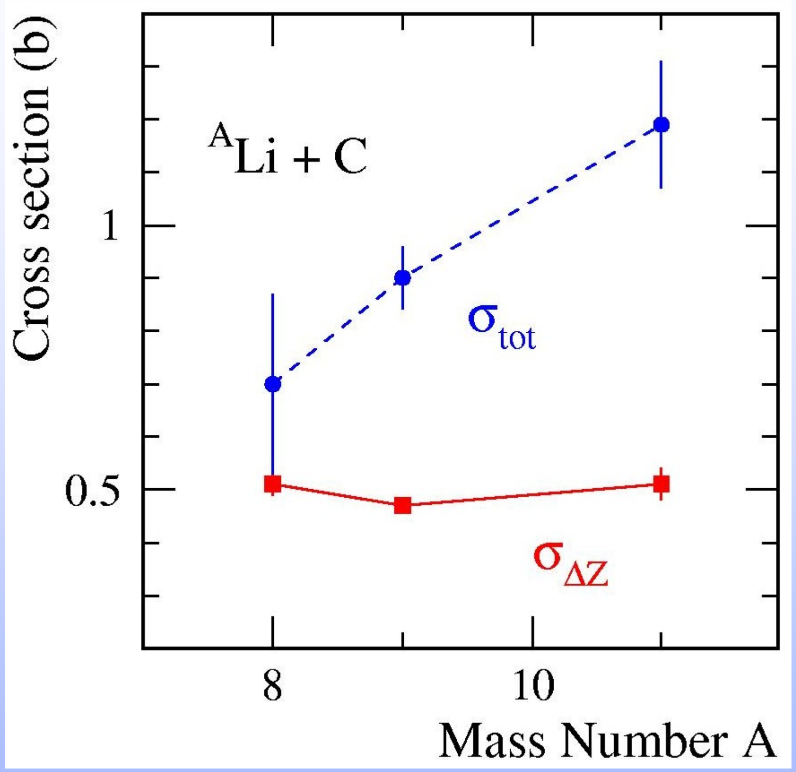


$$\sigma_R = -\frac{1}{t}\ln\left(\frac{R_{in}}{R_{out}}\right)$$

I. Tanihata et al., PRL 55 (1985) 2676

Interaction cross sections of n-rich nuclei



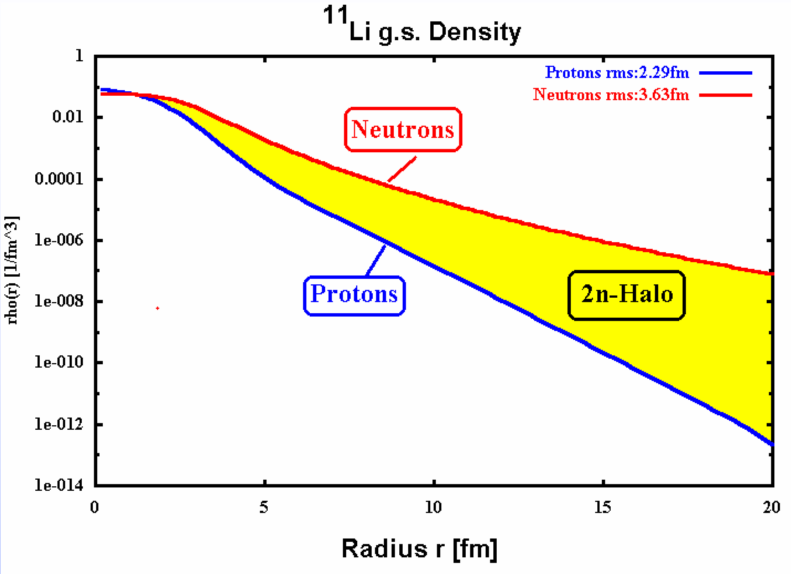


I. Tanihata et al.,
PRL 55 (1985) 2676, PLB 206 (1988) 592

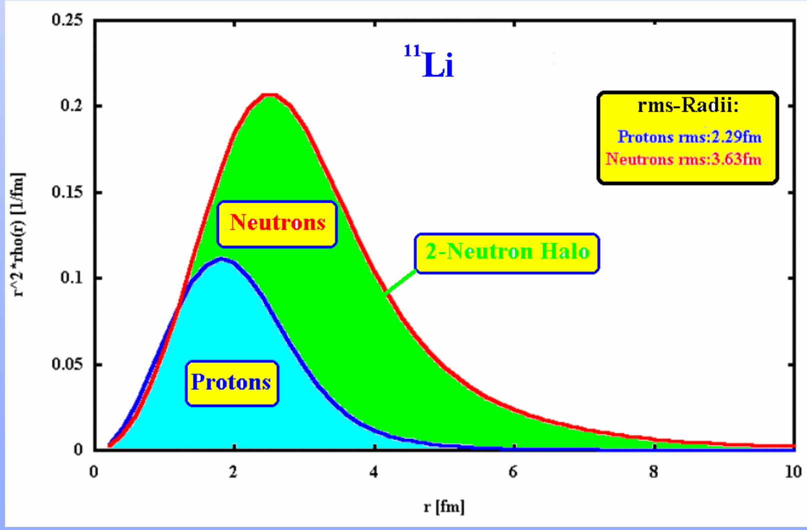
B. Blank et al.,
Z. Phys. A 343 (1992) 375c

Radial density distributions

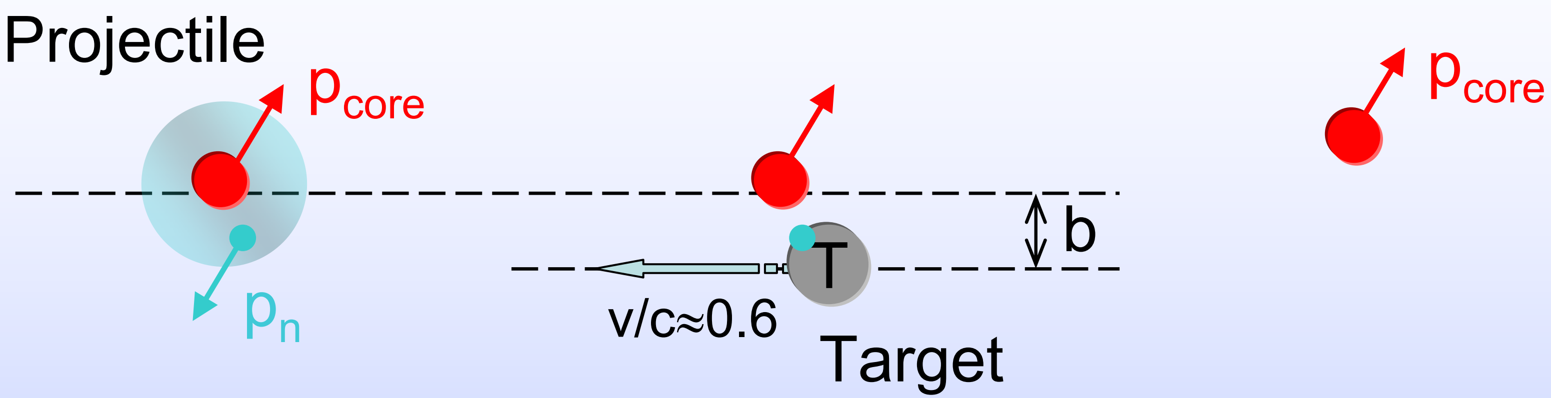
ground state densities :



g.s. densities × r^2 :



Theory: H. Lenske



"Sudden collision": $\Delta t_{collision} << \Delta t_{orbit}$

Reaction time $\Delta t_{collision} \approx 10^{-22}$ s

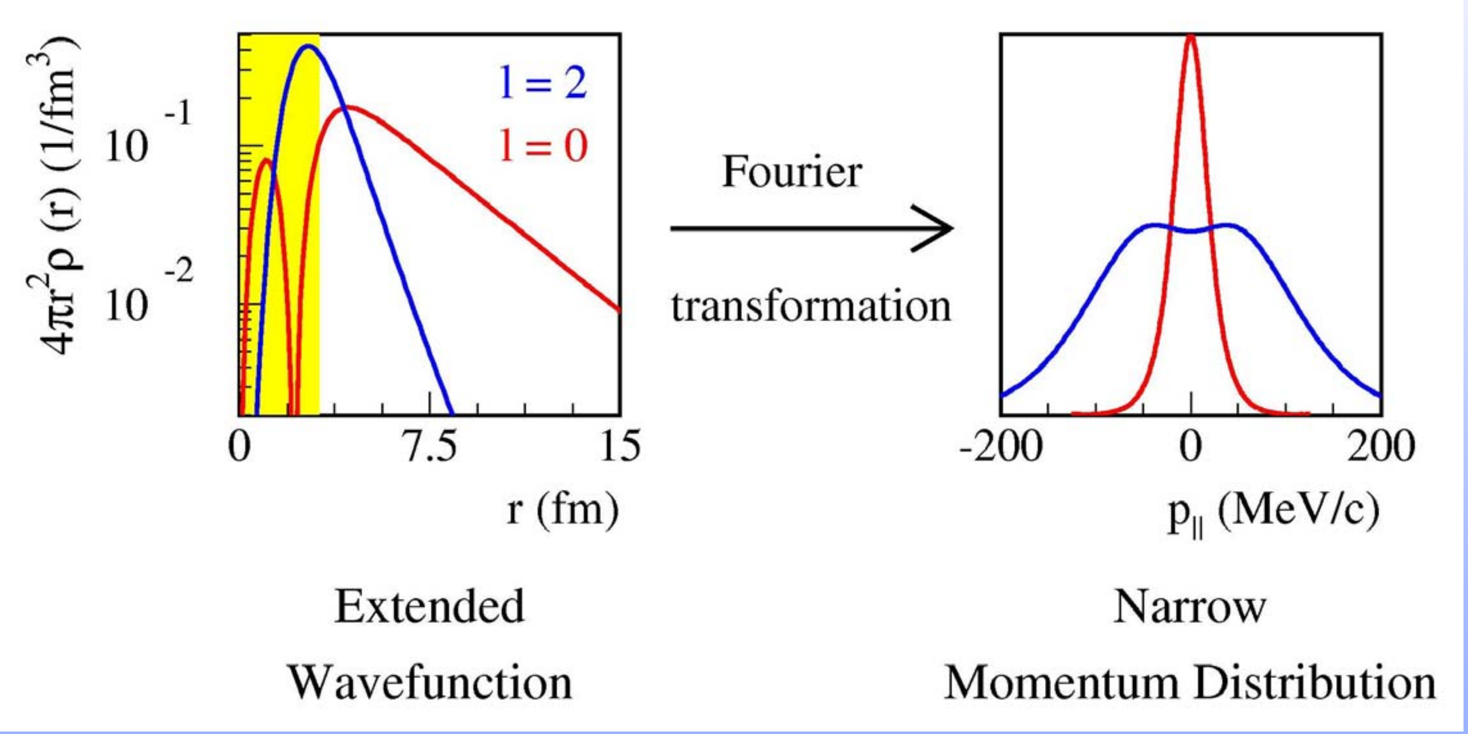
Internal motion $\Delta t_{orbit} \approx 10^{-21}$ s

$\Rightarrow p_{core} = -p_n$

$\Rightarrow$ Measurement of momentum of halo-nucleon

Relation of space and momentum is given by
Heisenberg's uncertainty principle:

$$\Delta p \cdot \Delta x \approx \hbar$$



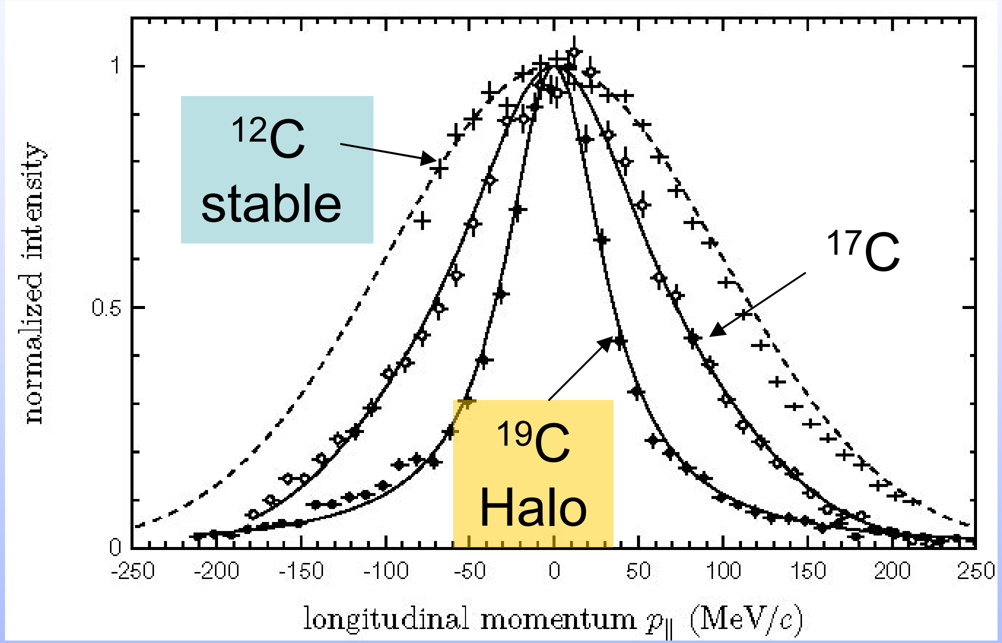
Momentum distributions of carbon isotopes

Example: Carbon isotopes

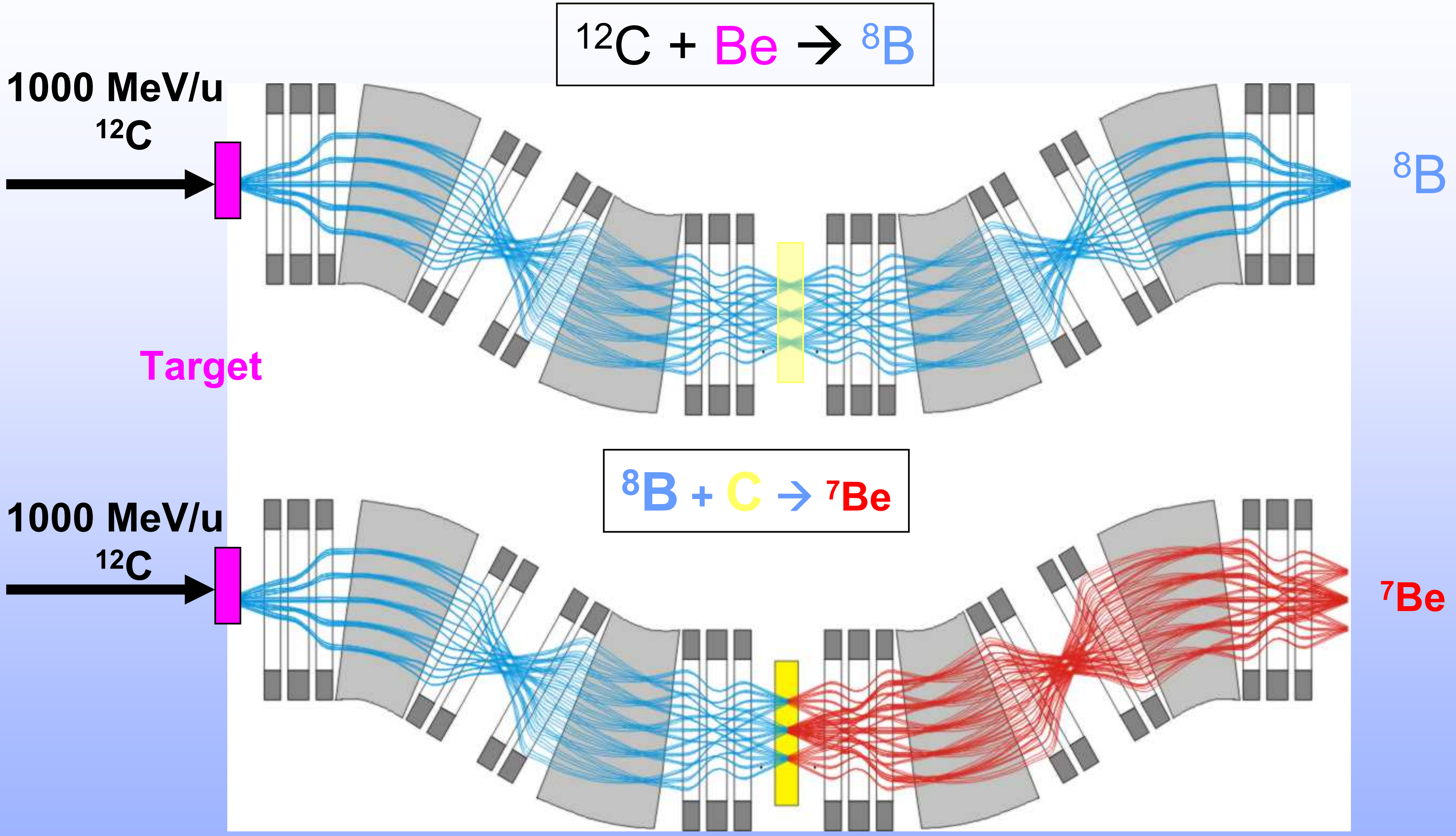
$^{A}C + C \rightarrow {}^{A-1}C + x$

$E \approx 900$ MeV/u

FRS@GSI

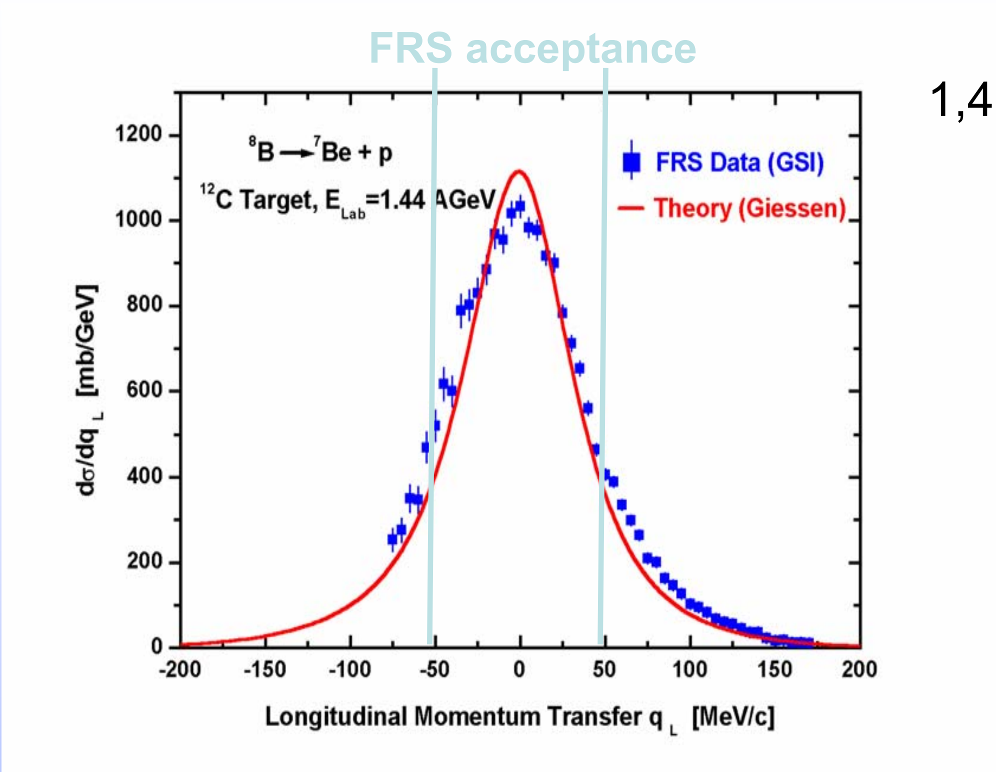


High resolution momentum measurements - proton-halo in ^{8}B



W. Schwab et al., Z. Phys. A350 (1995) 283

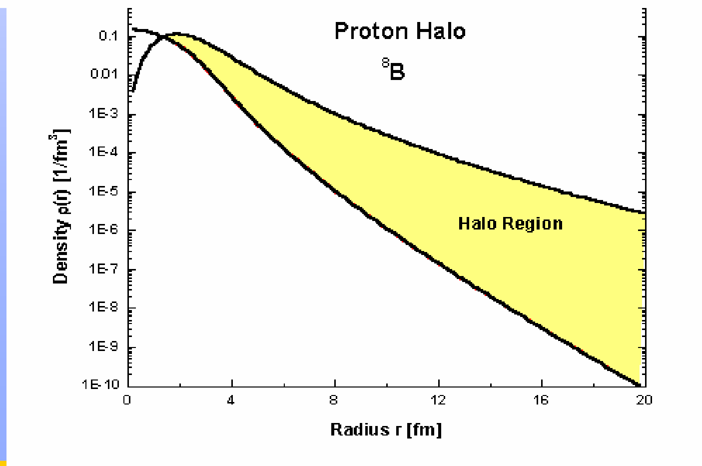
Discovery of a proton-halo nucleus: ^8B



1,4 GeV/u $^8B \rightarrow C$

Mean-Field & RPA

^{7}Be(3/2-,0.0)	p3/2: 71%
^{7}Be(3/2-,0.0)	p1/2: 13%
^{7}Be(3/2-,0.0)	f 7/2: 11%
^{7}Be(3/2-,0.0)	f 5/2: 5%
^{7}Be(1/2-,0.420)	p3/2: 15%



W. Schwab et al., Z. Phys. A350 (1995) 283
H. Lenske et al., Prog. Part. Nucl. Phys. 46 (2001)

When/where do halos form?

Small nucleon separation energy
→ close to drip-lines

Low orbital angular momentum (l=0,2)

Asymptotic form of wave function:

$\Psi(r) \sim \exp[-(2\cdot\mu\cdot S_{2n})^{1/2}\cdot r/\hbar]$

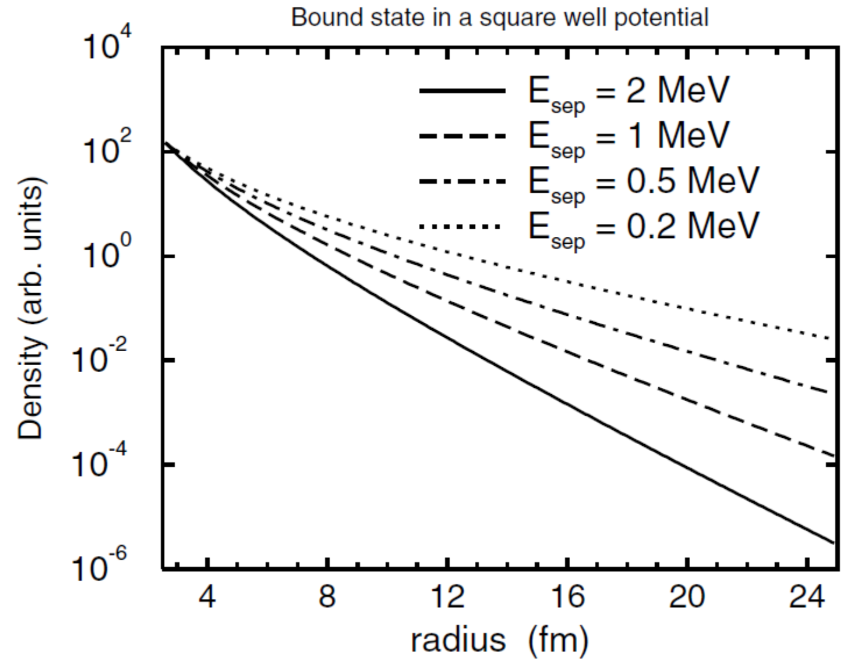
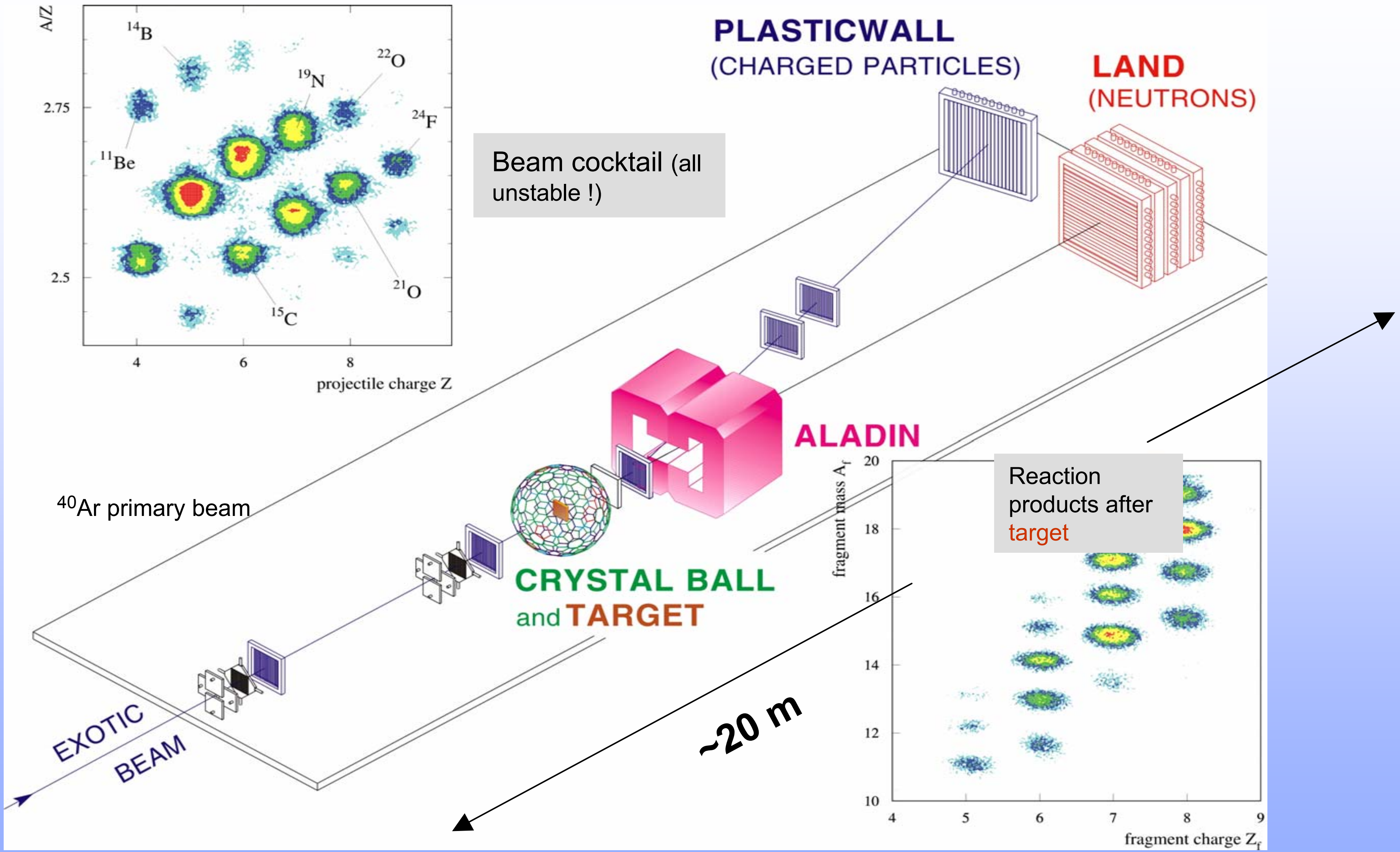


Fig. 4. The dependence of the wavefunction tail of a particle bound inside a square well potential on separation energy (the distance from the top of the well).

see P. G. Hansen and B. Jonson, Europhys. Lett. 4, 409 (1987)

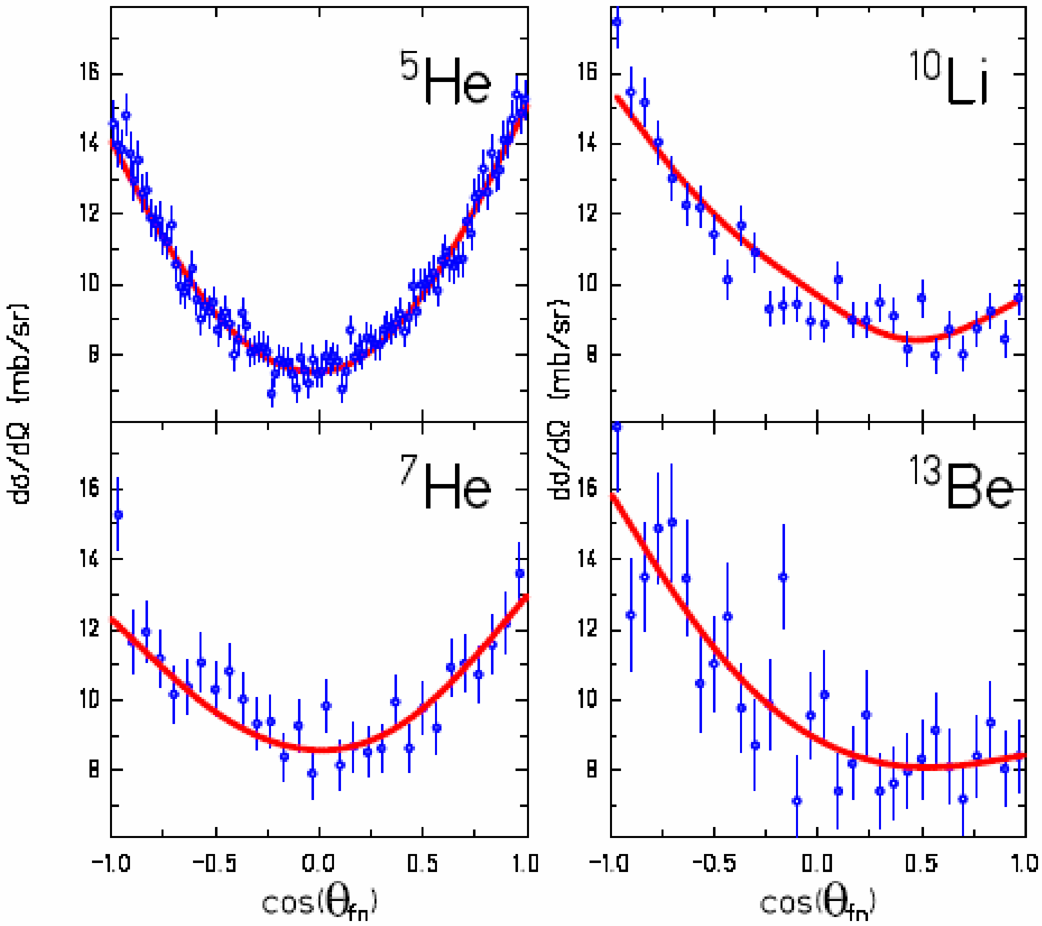
Kinematical complete experiments

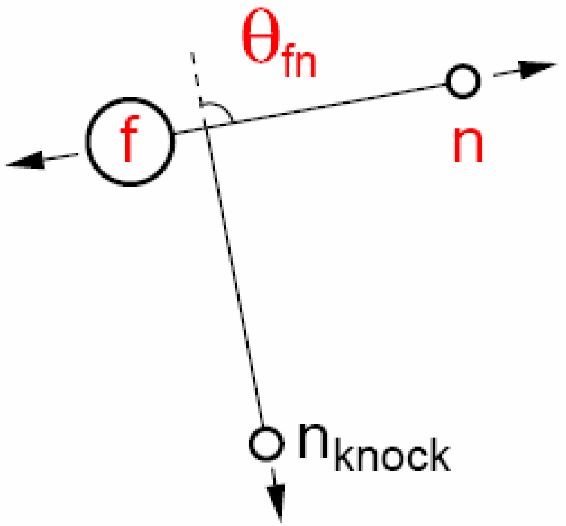


$$m^* - M = \sum_{i<j} \frac{E_i E_j - m_i m_j c^4 - \boldsymbol{p}_i \boldsymbol{p}_j c^2}{M c^4}$$

$$M = \sum m_i$$

Angular correlations reveal inner structure





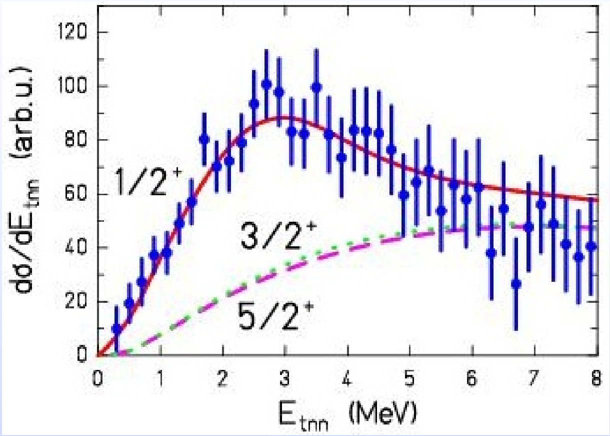
He: p-states

Li/Be: different parity states

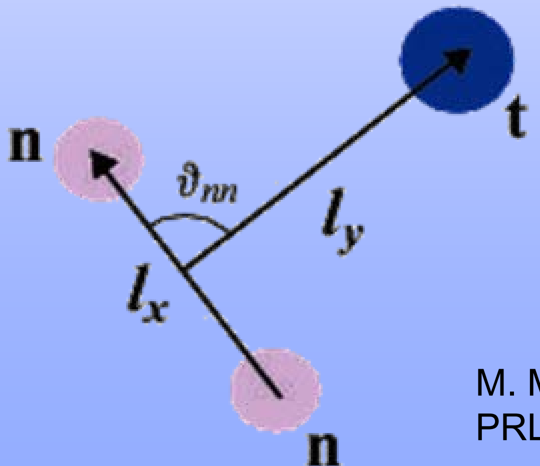
Energy and angular correlations

^5H obtained in proton knockout:

$^6He \rightarrow p + {}^3H + n + n$



Measured correlations are consistent with a 3-body microscopic calculation assuming $J^\pi=1/2^+$



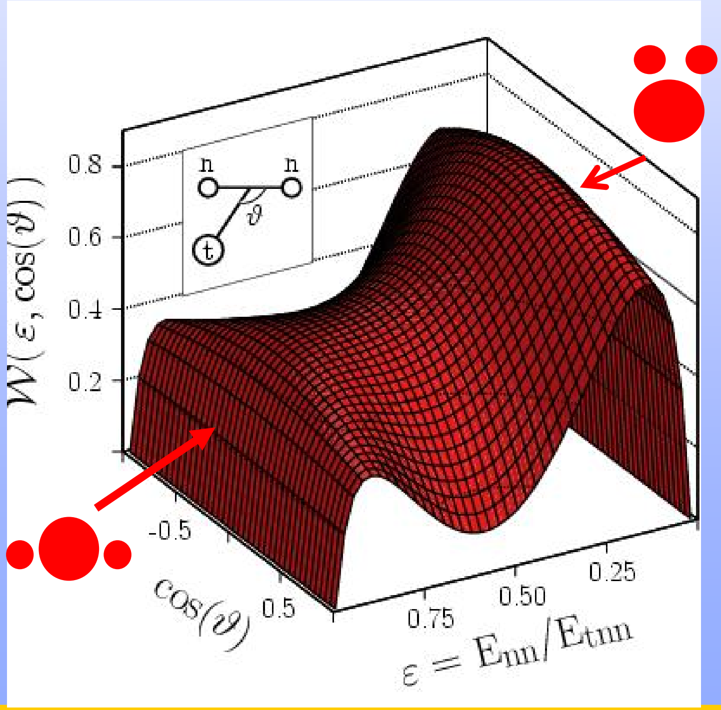
M. Meister et al., PRL 91 (2003) 2504

Measured three-body correlations (projections of energy and angle) are analyzed via a Jacobi coordinate system and an expansion with a restricted set of hyperspherical harmonics:

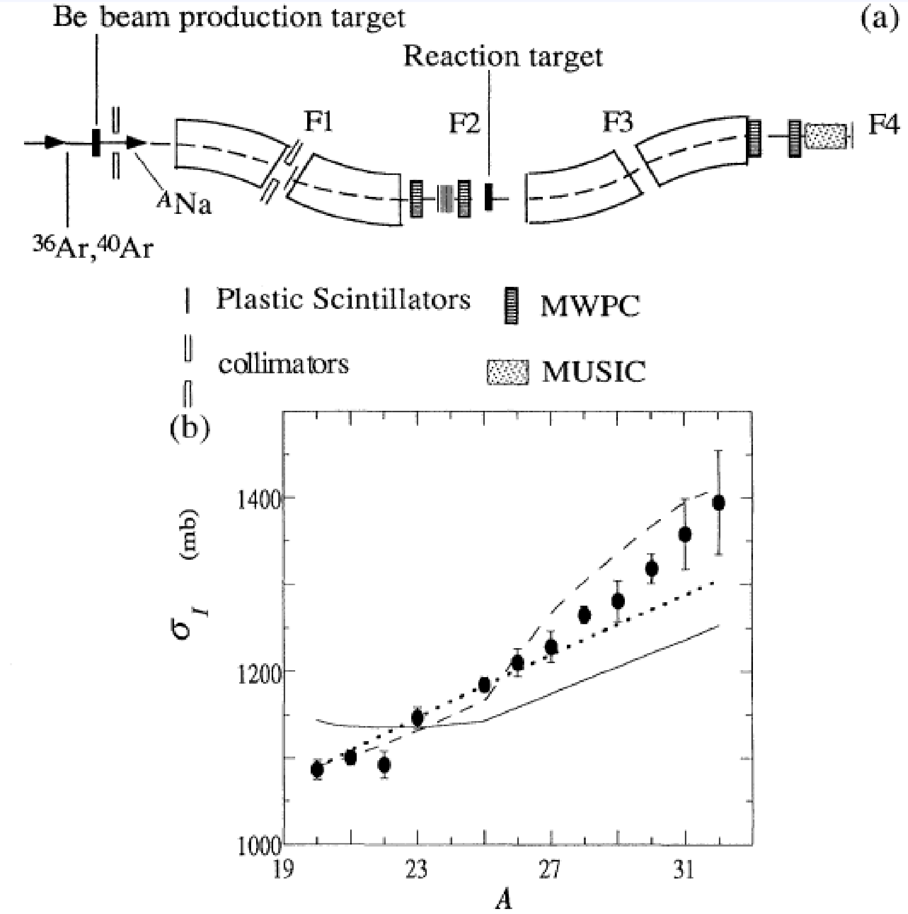
→ angle between relative momenta θ_{nn}

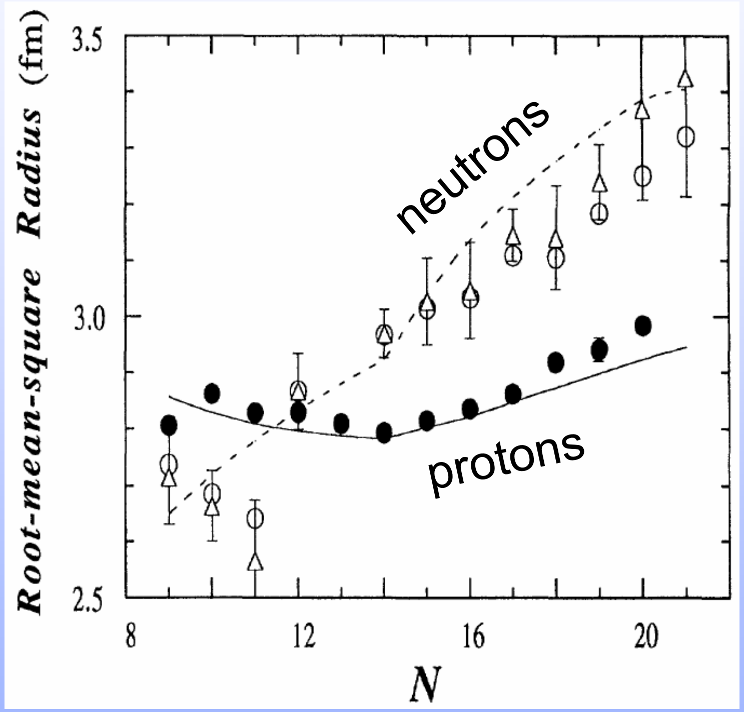
→ energy sharing $\varepsilon=E_{nn}/E_{total}$ between sub-systems

→ spin and parity of the state



Total interaction cross sections measured at 950 MeV/u ^{A}Na → C

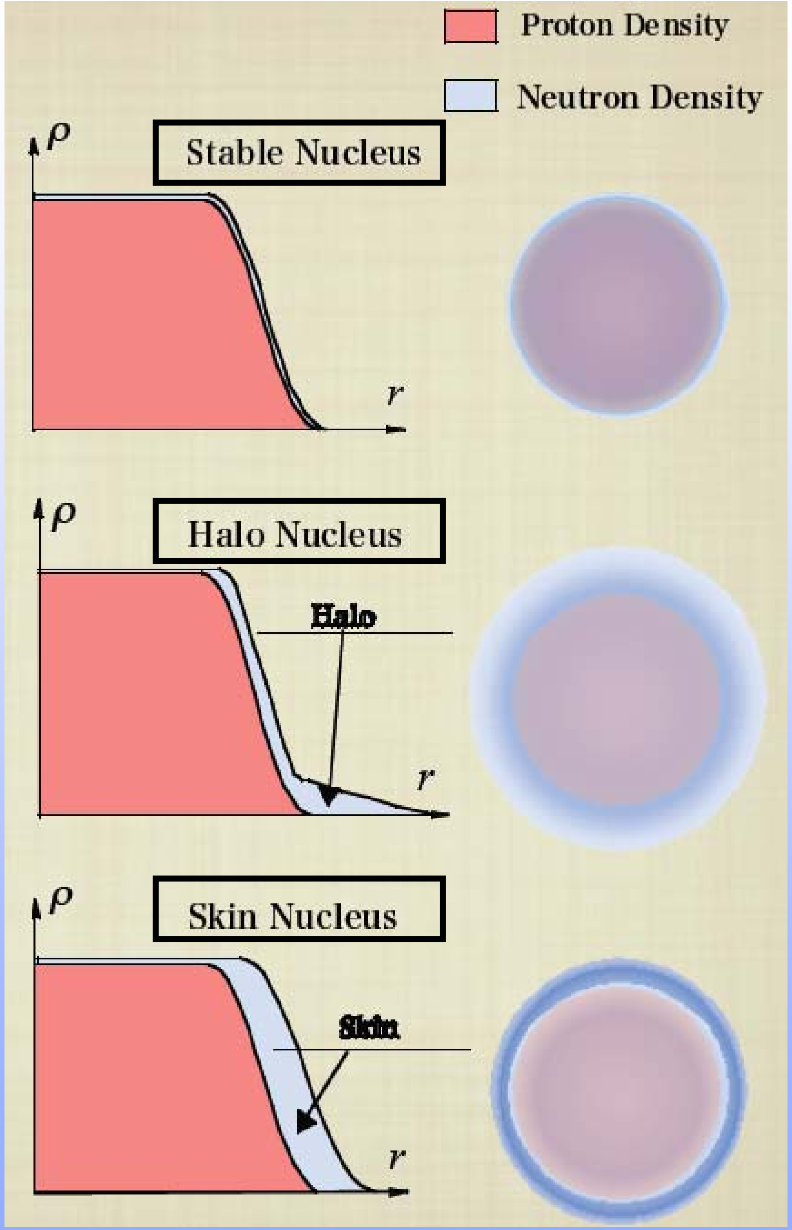




RMS charge radii from isotope-shift measurements, e.g. G. Huber et al., Phys. Rev. C 18 (1978) 2342

T. Suzuki et al., Phys. Rev. Lett. 75 (1995) 3241

Stable, skin and halo nuclei



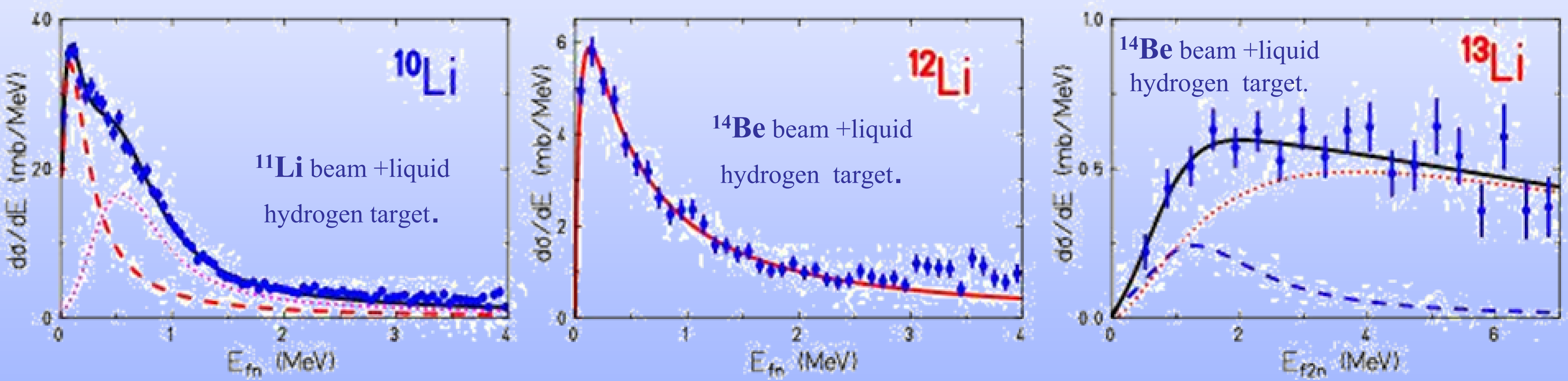
~300 MeV/u ^{11}Li,^{14}Be + liq.H_2 → ^{9}Li+n, ^{11}Li+n, ^{11}Li+2n

Newly observed ^{12}Li and ^{13}Li

Previous results confirmed: **^{10}Li** is known as virtual s-state **(a = -22 fm)** with an excited state at **0.5MeV** and **Γ= 0.5MeV**.

^{12}Li is observed as a virtual s-state with scattering length **a = -11 fm**

^{13}Li is seen as a broad 3-body resonance state at **1.5 MeV**.

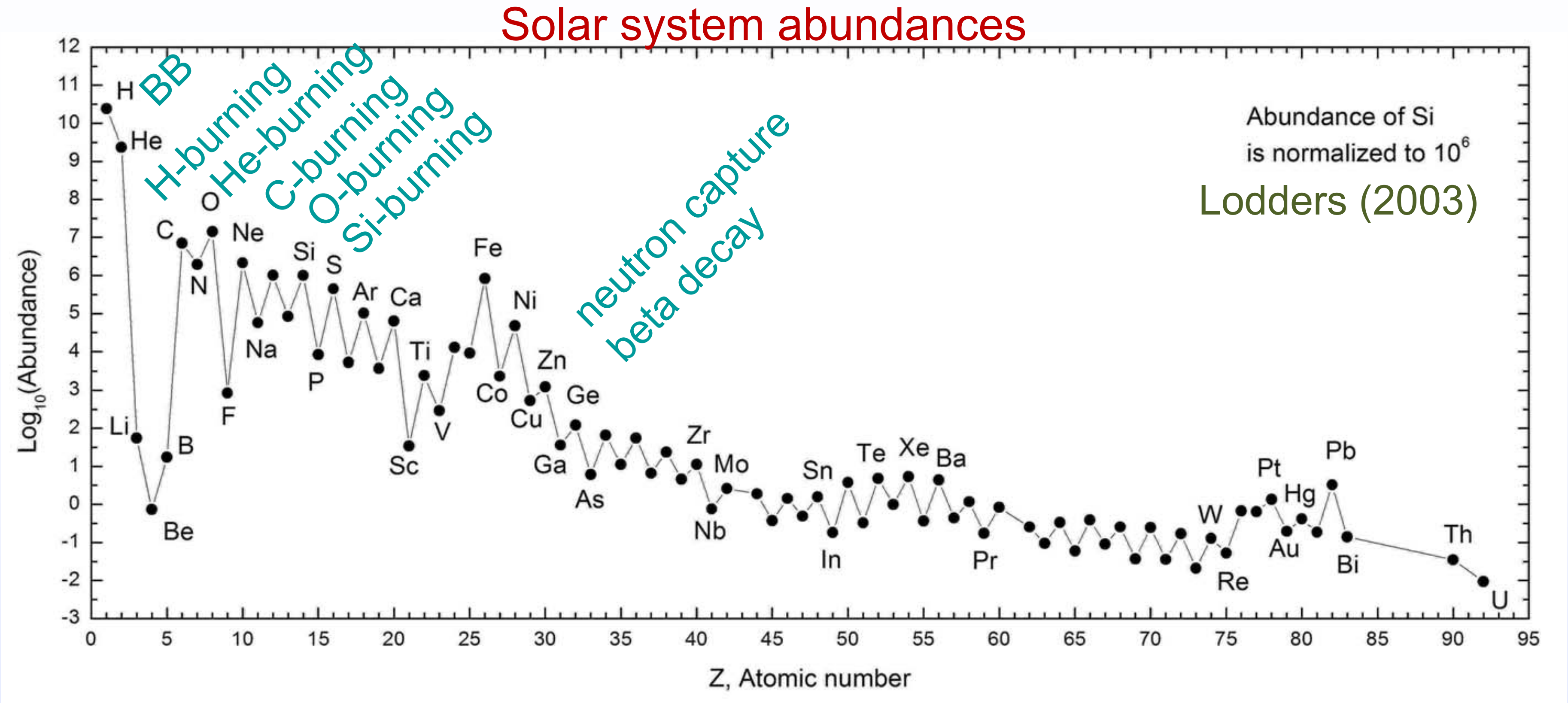


Resonance state – – – – – –
Correlated background ···············
(from nn-correlations in initial bound-state wave function)

Yu. Aksyutina et al., publication in preparation

4. Some links to nuclear astrophysics

Challenge: understand solar system element and mass abundances

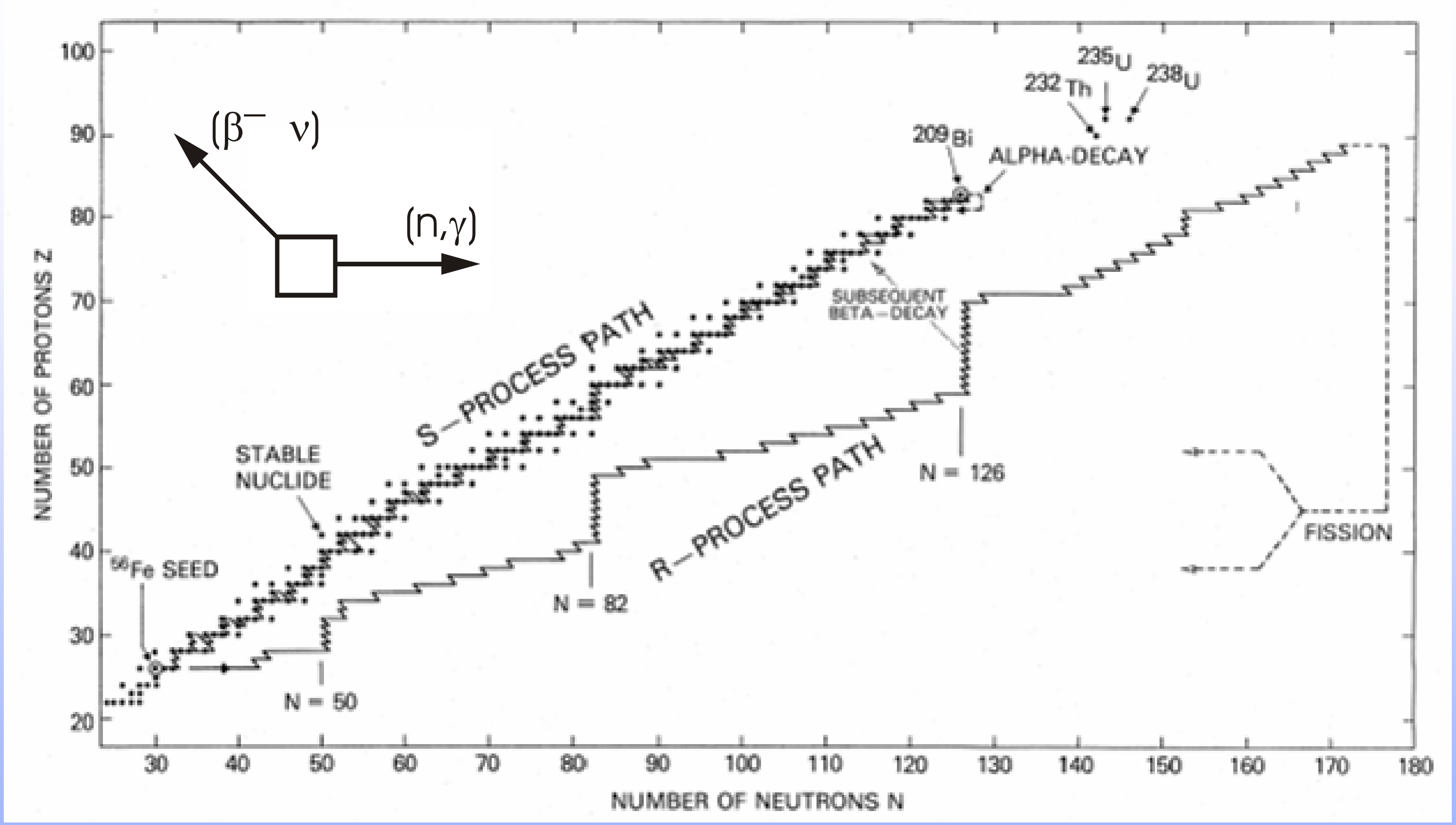


Where, when and how are the elements produced?

Understand the observed distribution, qualitatively and quantitatively!

Why no elements Z>92, why no masses A>240?

Formation of heavy elements by s- and r-process

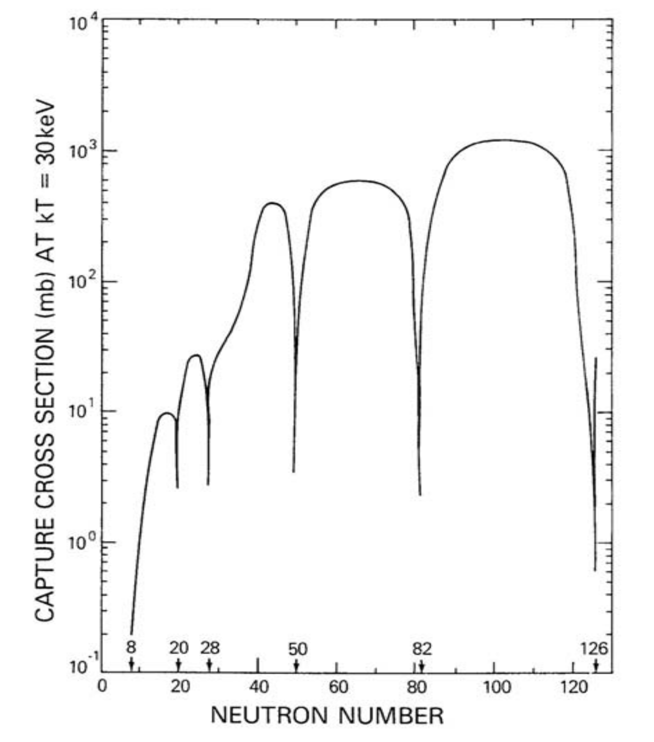


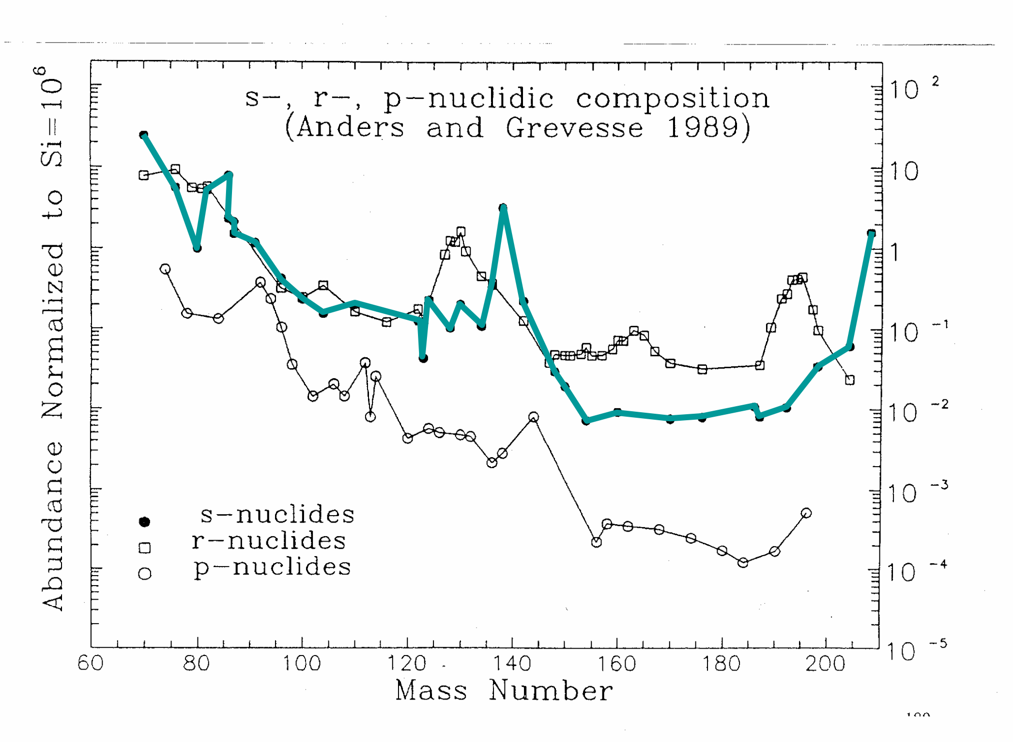
- s-process terminates at ^{209}Bi
- r-process produces the heaviest elements (Th, U)
- p-process produces ~30 n-deficient isotopes, which cannot be formed by s- or r-process

Explanation of s-process abundance maxima

$$N_A \propto \frac{1}{\langle\sigma\rangle_A} \quad \Leftrightarrow$$

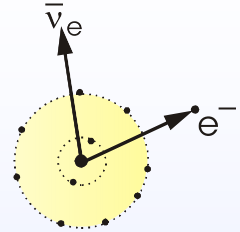
small n-capture cross sections lead to large abundances and vice versa





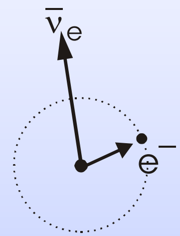
- Temperature-averaged n-capture cross sections needed!
- Near stability

Neutral atom:

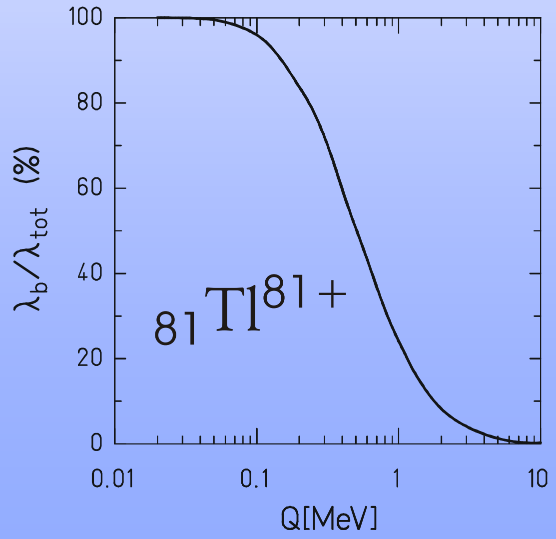


Continuum-state β-decay

Bare nucleus:

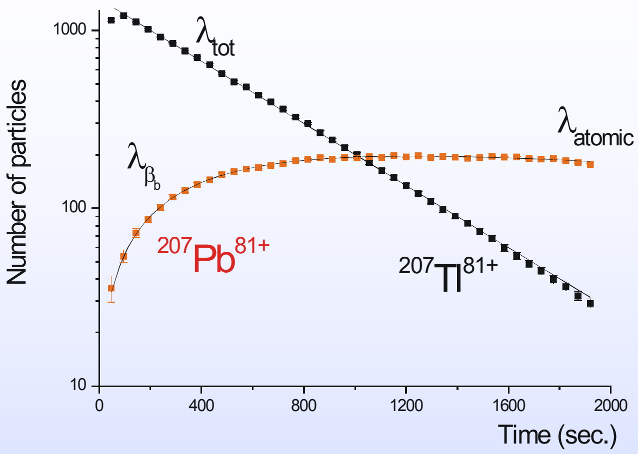


Bound-state β-decay



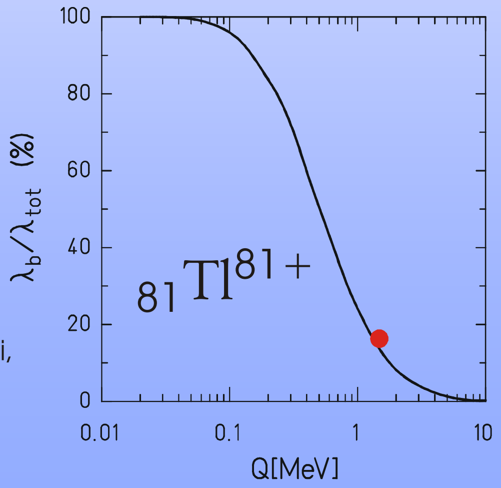
K. Takahashi and K. Yokoi, ADNDT 36 (1987)

Bound-state beta decay of $^{207}Tl^{81+}$



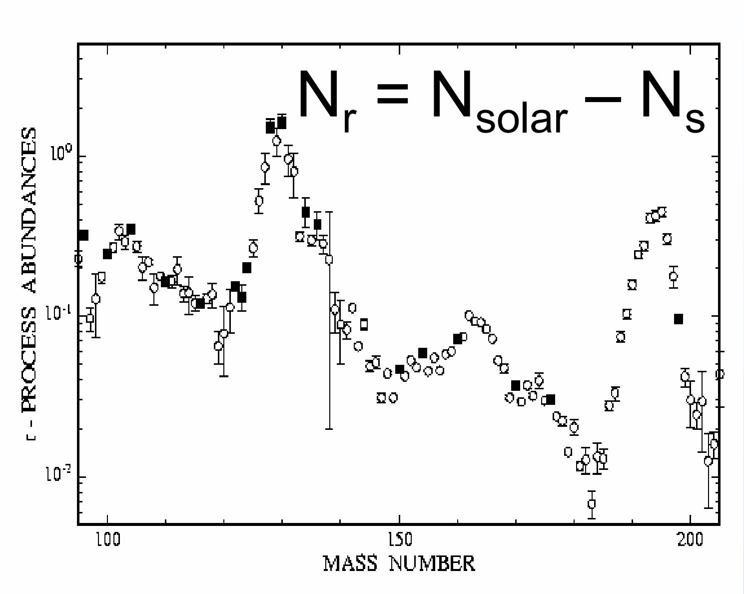
Half-life	$T_{1/2}$	=	271	±	2 sec.
Branching	β_b/β_c	=	0.224	±	0.004
Q-value	Q_{β_b}	=	1507	±	8 keV

Calculation by
K. Takahashi and K. Yokoi,
ADNDT 36 (1987)



Assumption: (n,γ) ↔ (γ,n) rate equilibrium

$$\lambda_{\gamma n} \propto \frac{T^{3/2}}{N_n} \exp\left(-\frac{Q_n}{kT}\right) \cdot \lambda_{n\gamma}$$



Example: $N_n = 10^{24}$ /cm³ , $T_9 = 1$
→ $Q_n = 2$ MeV

Neutron capture processes stall, and nucleus „waits" for β⁻-decay:

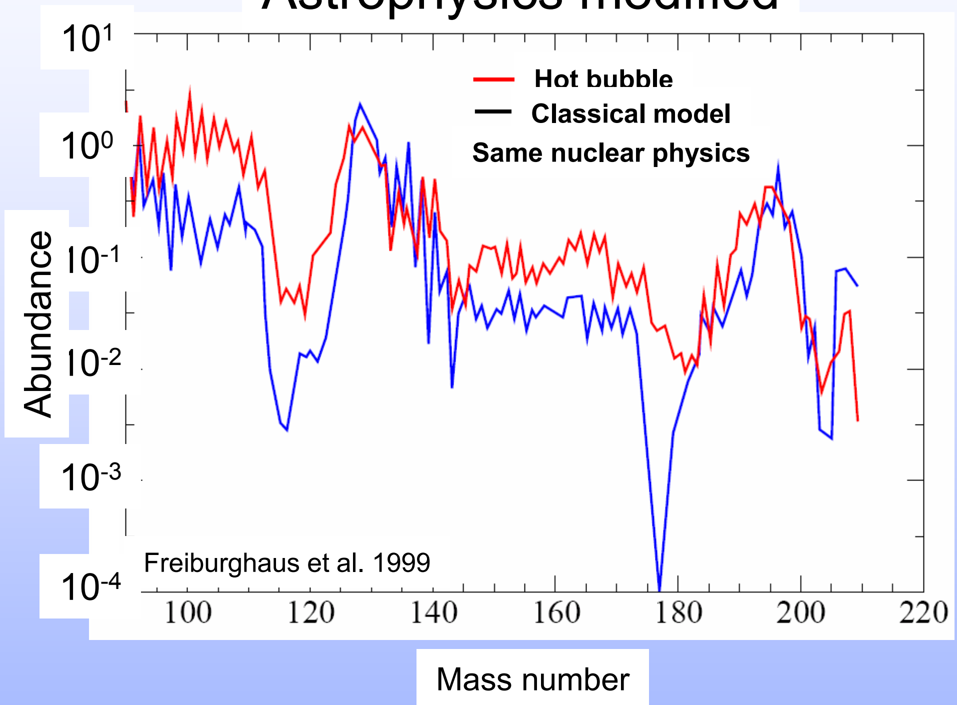
$_{Z}X \rightarrow {}_{Z+1}X + e^- + \nu_e$

→ for every element, there is a so-called „waiting point"

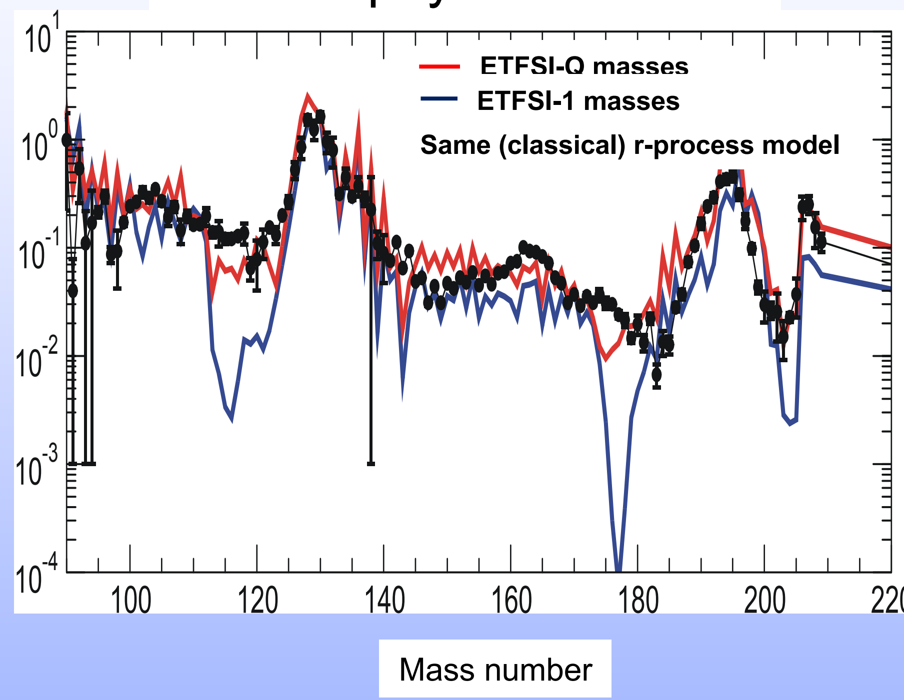
→ r-process path determined by mass differences
→ abundances determined by half-lives

Uncertainty between models and nuclear properties

Astrophysics modified



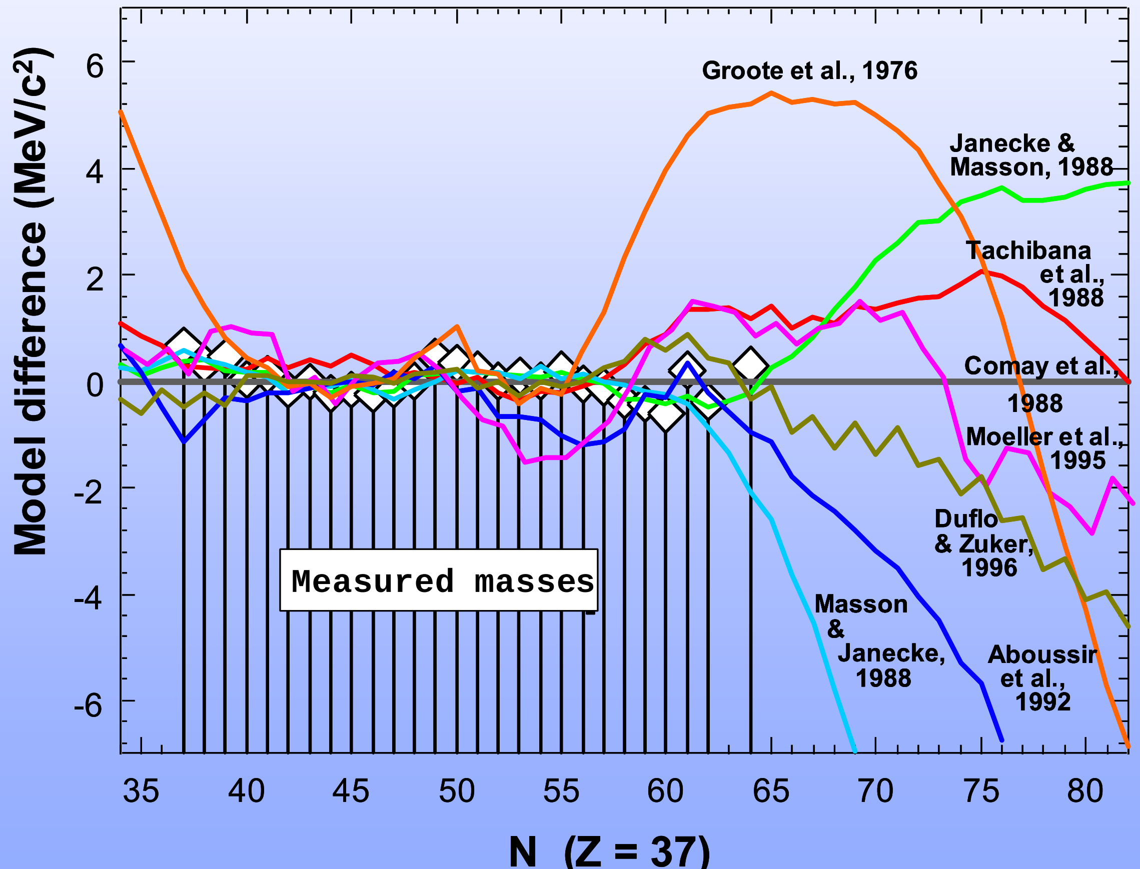
Nuclear physics modified



Are the fine details a reflection of the stellar site or of nuclear physics input?

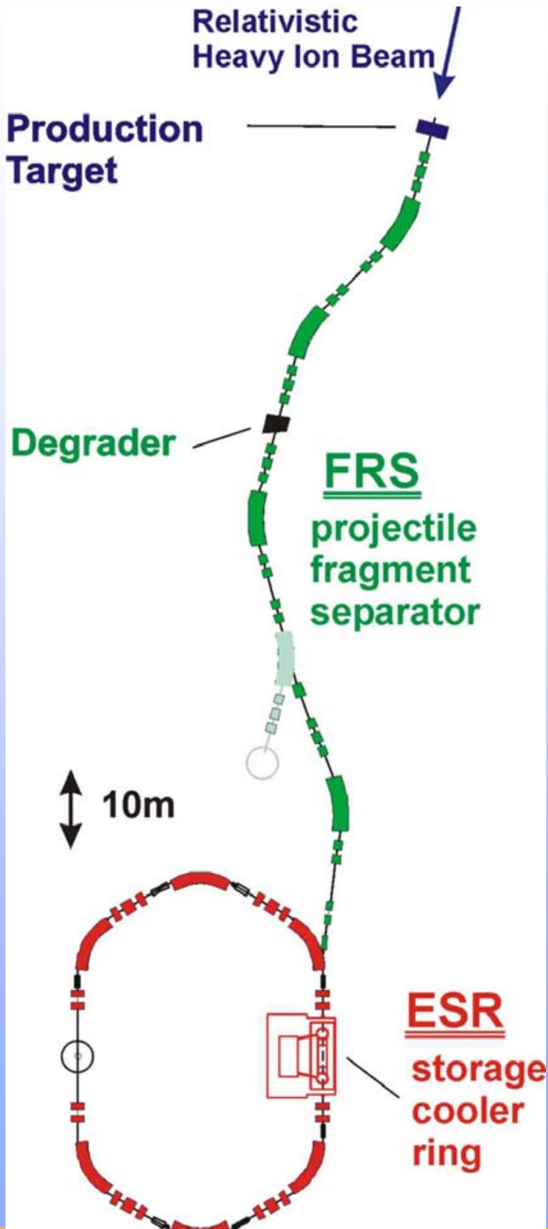
Importance of mass measurements

- Nuclei far-off stability may show different phenomena than nuclei close to stability (magic numbers, shell quenching)
- Extrapolation of mass models to regions far from stability may introduce errors



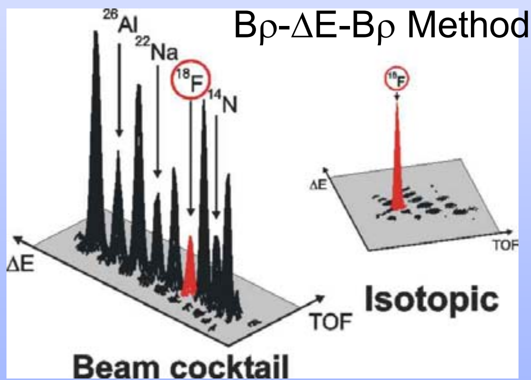
D. Lunney, 2001

Storage-ring mass spectrometry at FRS-ESR



Production:
* Primary beams:
  H.....U, 100...1000MeV/u
* Reaction mechanisms:
  Projectile fragmentation,
  ED and fission
* Yields:
  ~ 10^5/s.... 10^{-5}/s (=1/day)
* Ionic charge states:
  bare, H-, He-, Li-like

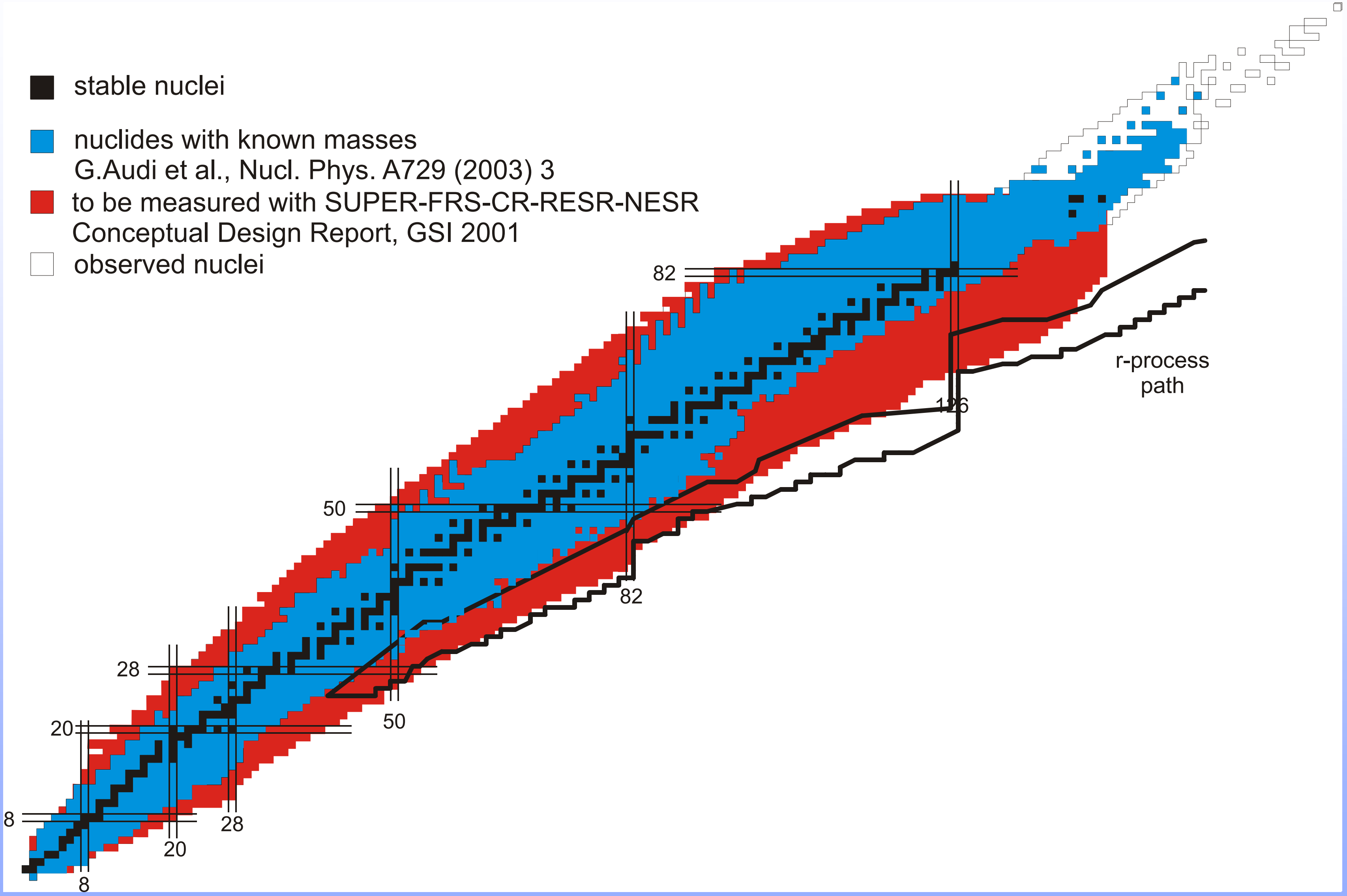
Separation:
Bρ-Analysis



	IMS	SMS
Mass resolving power $m/\Delta m_{FWHM}$	**$1\cdot10^5$**	**$1\text{-}2\cdot10^6$**
Mass accuracy	**~100keV**	**~ 30 keV**
Accessible half-lives	**> 10 μs**	**> 1 s**
Sensitivity	**single ions**	**single ions**

Storage:
* Fast injection (bunch length ~ 400ns)
* Storage times: minutes .... hours
* Cooling: - stochastic (pre-)cooling
  - electron cooling

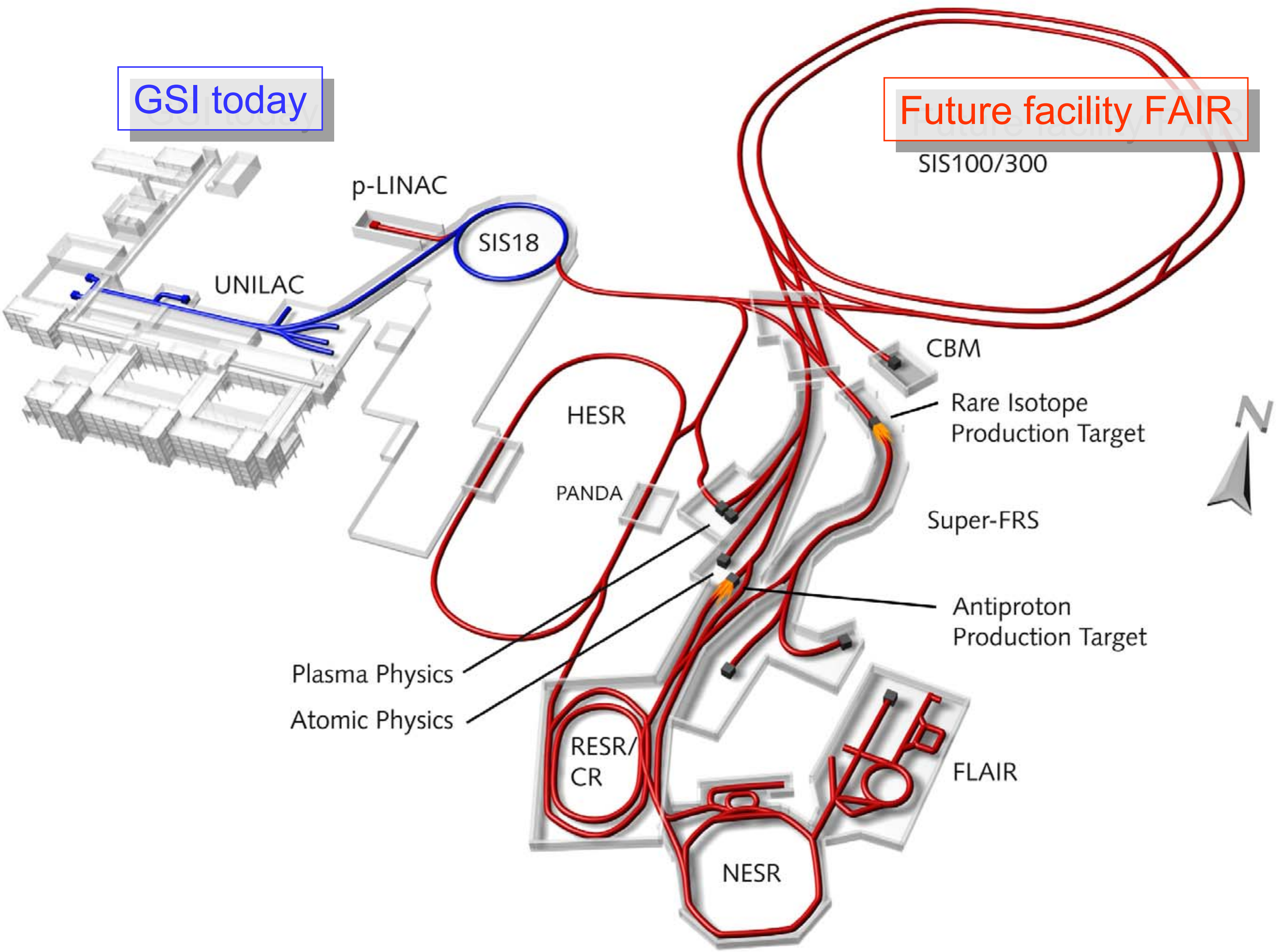
Mass Measurements at the Ring Branch



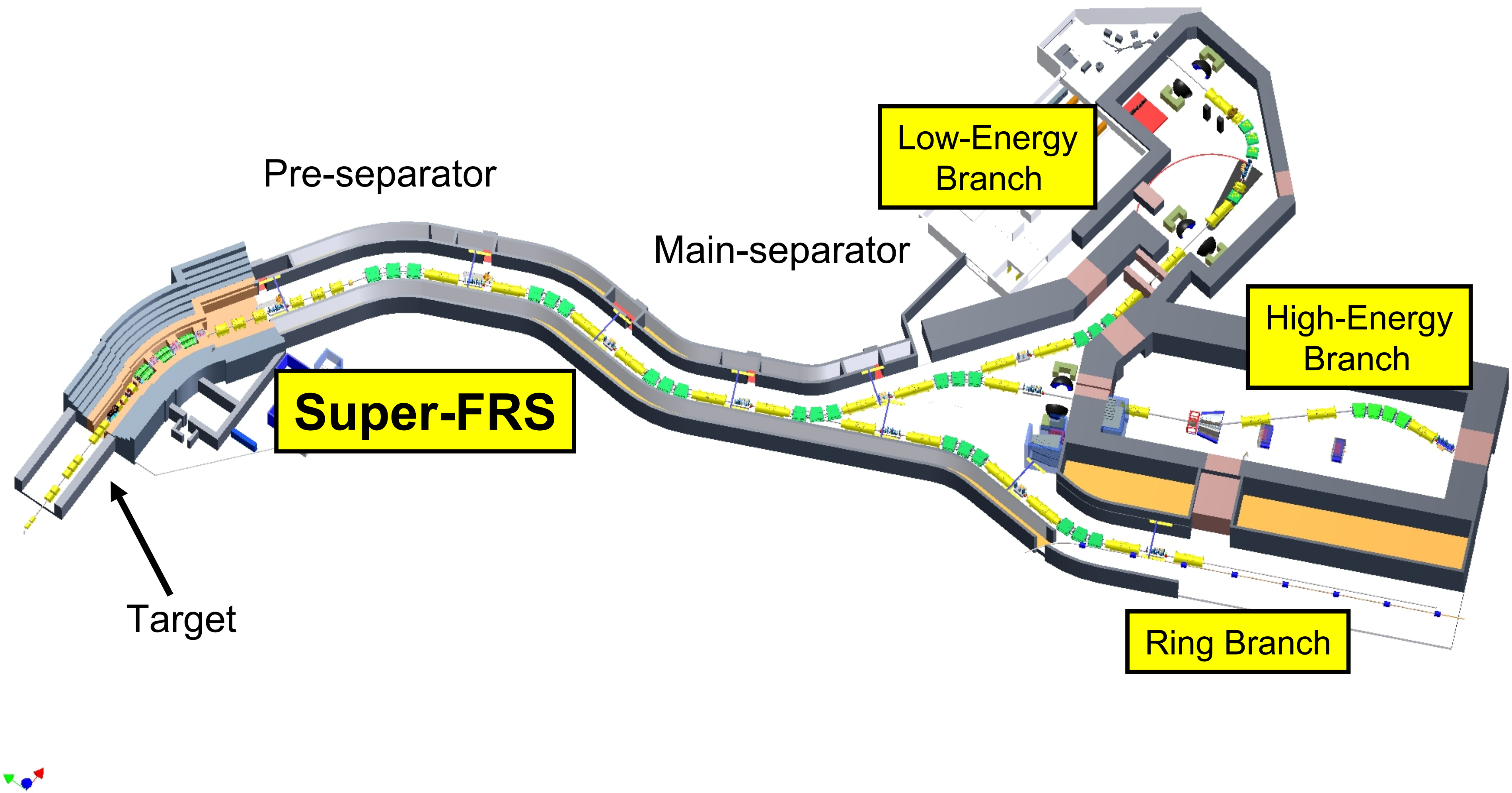
Yu. Litvinov

5. Future opportunities at FAIR

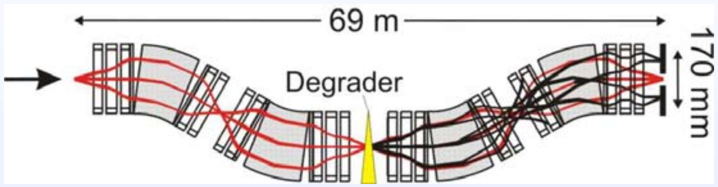
FAIR – International Facility for Antiproton and Ion Research



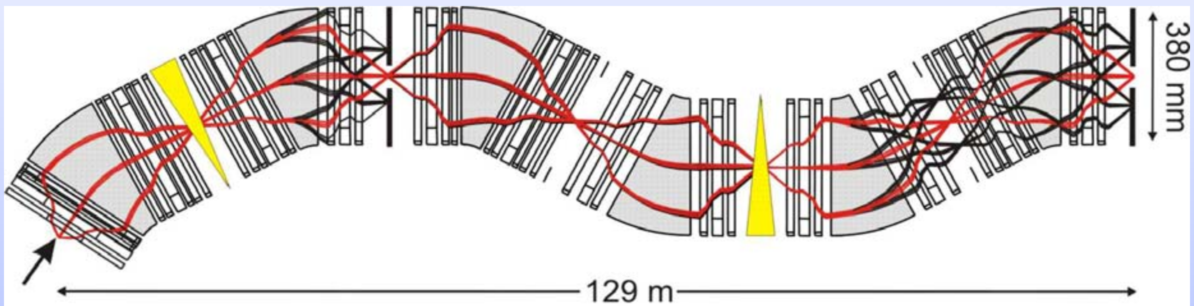
Super-conducting FRS

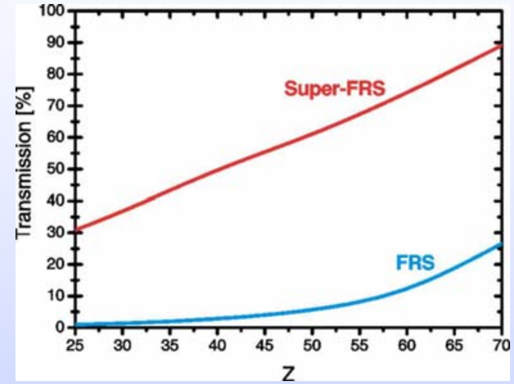


FRS

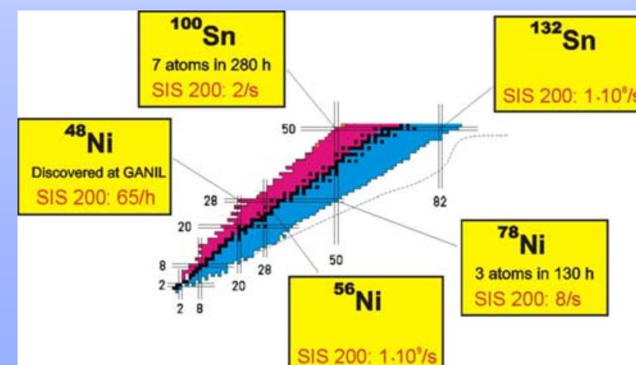


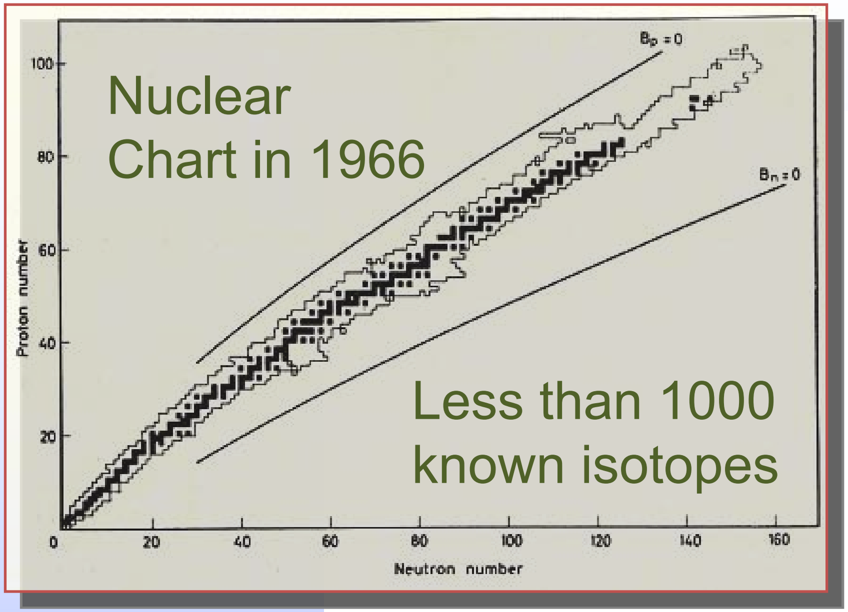
Super-FRS



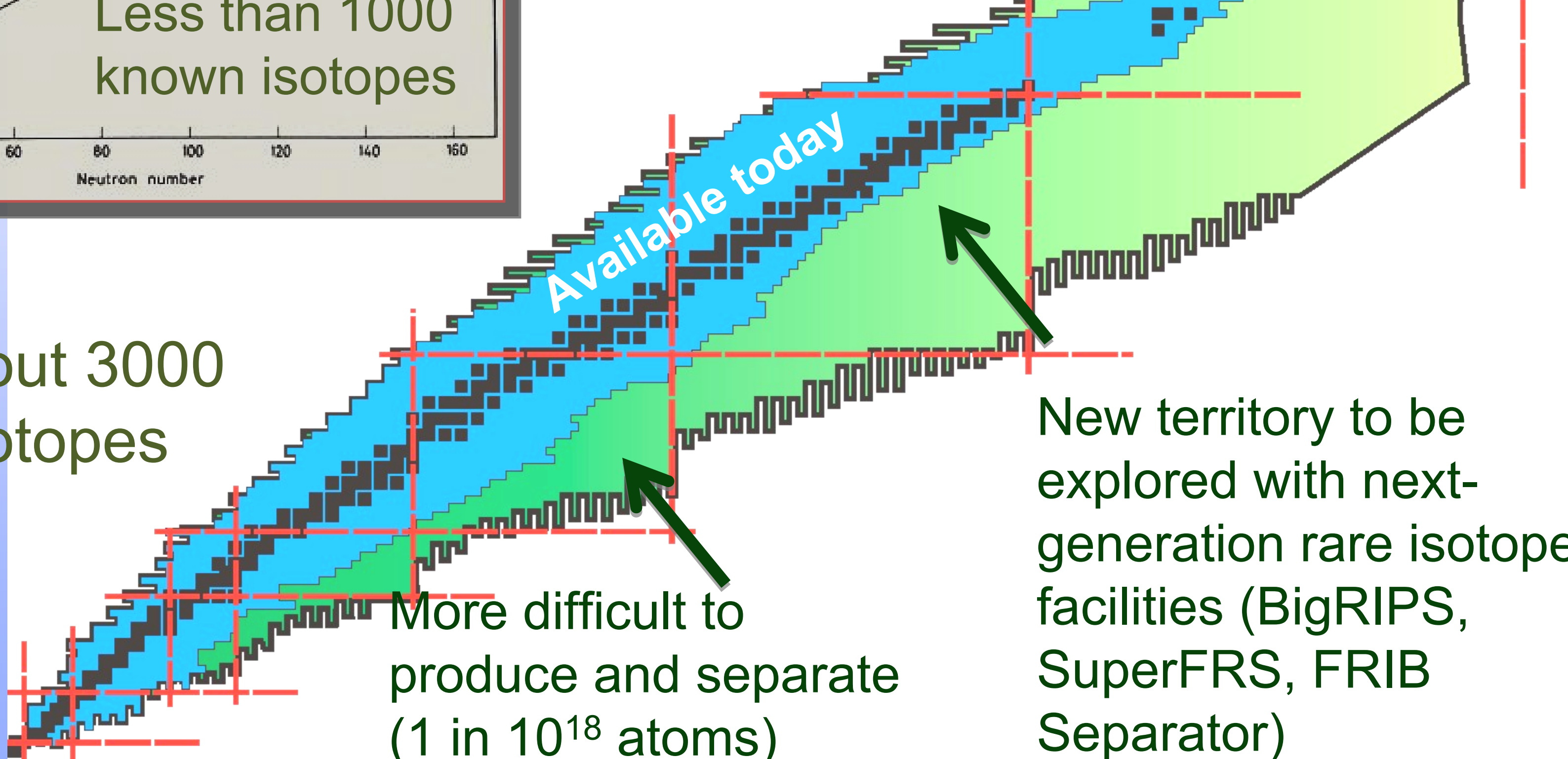


	$B\rho_{max}$	$\Delta p/p$	$\Delta\Phi_x$, $\Delta\Phi_y$	resolving power	gain factor ^{19}C	gain factor ^{132}Sn
FRS	18 Tm	1.0 %	± 13, ± 13 mrad	1500	1	1
Super-FRS	20 Tm	2.5 %	± 40, ± 20 mrad	1500	5	10
				including primary rate	250	20 000

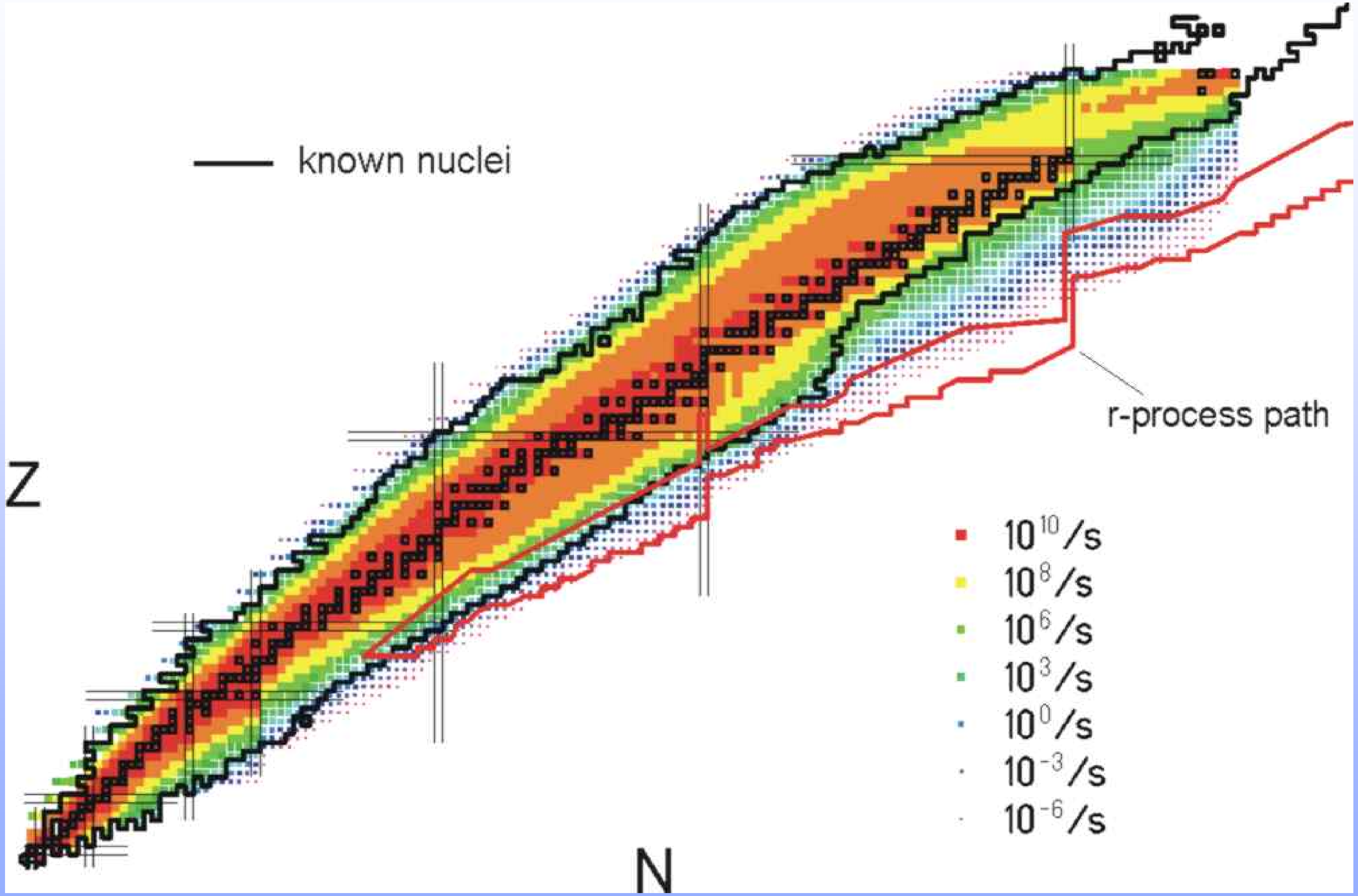




blue - about 3000 known isotopes



Rate estimates



Thank you for attention !

Enjoy the school and the NIC conference!

End