Experimental Nuclear Physics for the r-Process

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Yuri A. Litvinov

GSI

erc

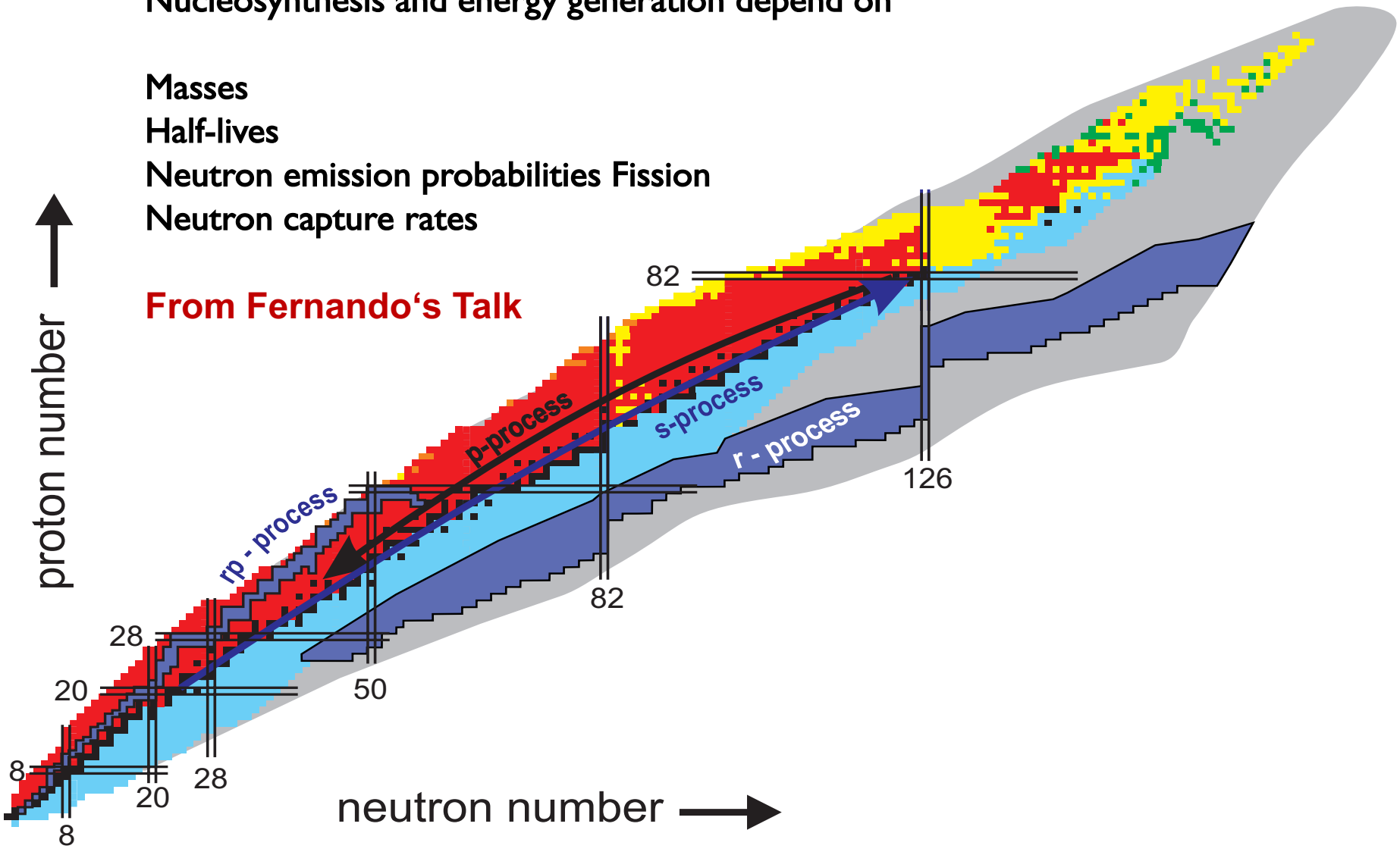
EMMI Rapid Reaction Task Force: The Physics of the Neutron Star Mergers at GSI/FAIR
GSI, Darmstadt, Germany, 04-15 June 2018

Where and how was gold cooked?

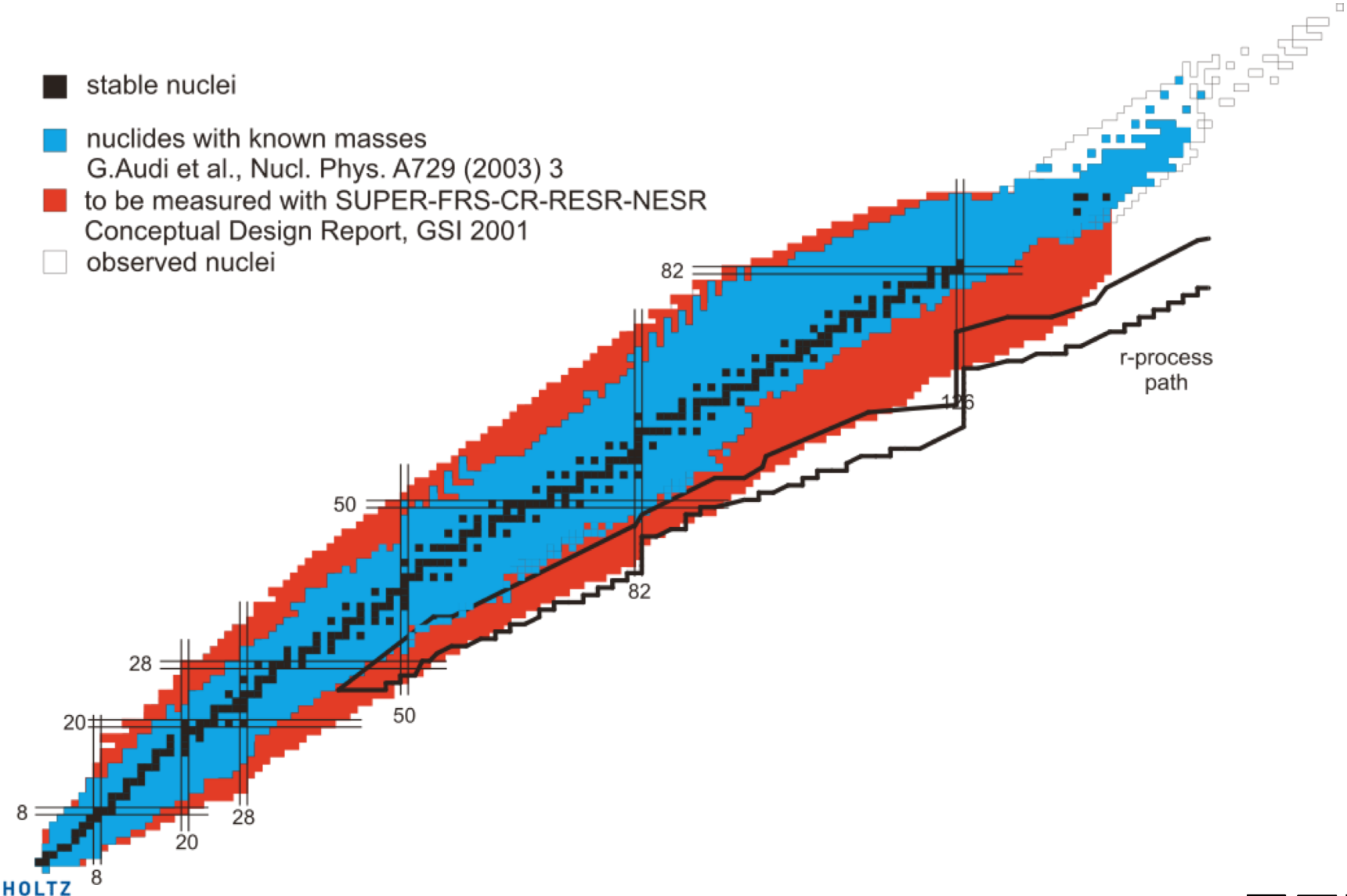
Nucleosynthesis and energy generation depend on

Masses
Half-lives
Neutron emission probabilities Fission
Neutron capture rates

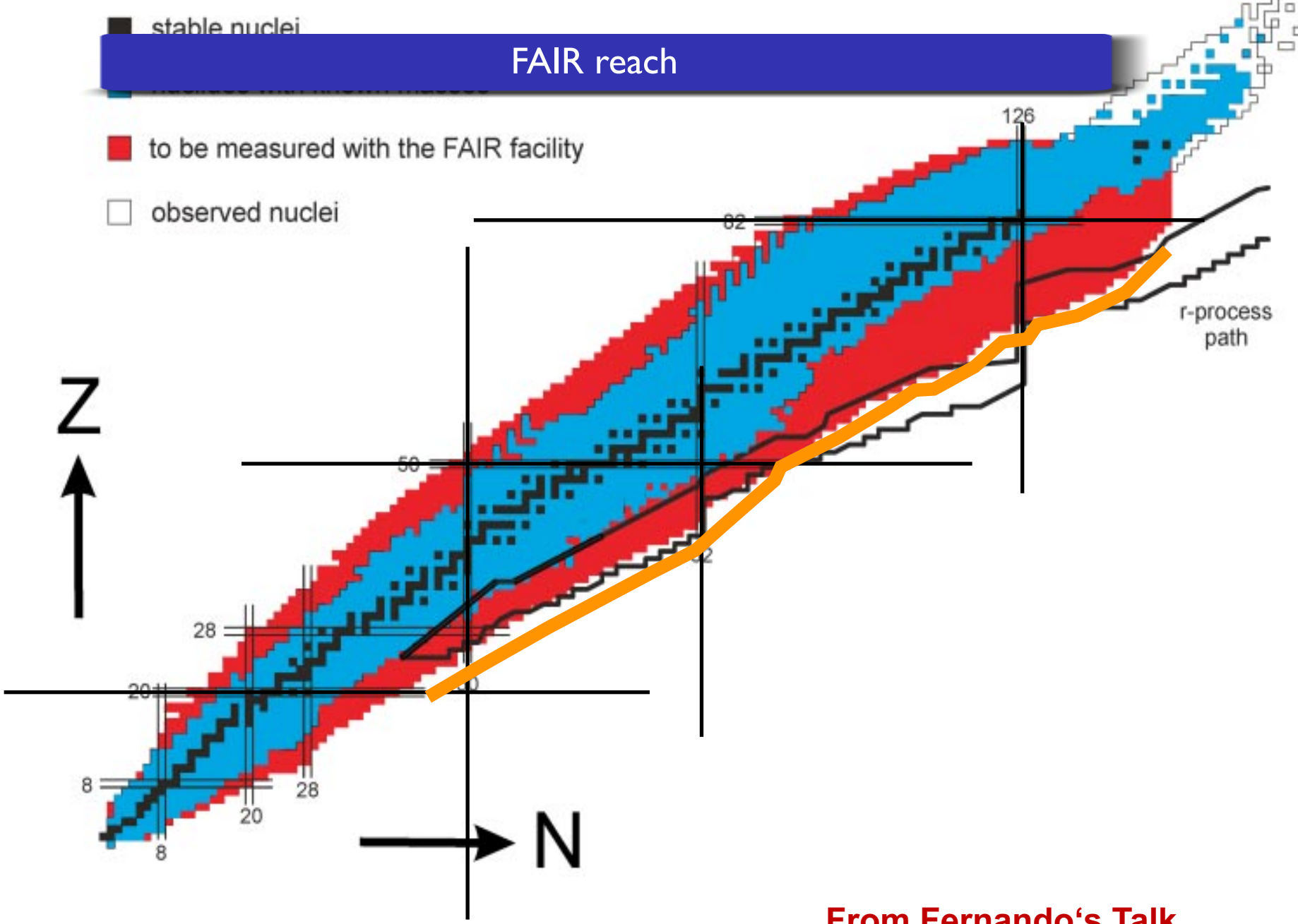
From Fernando‘s Talk



Masses and lifetimes at future facilities



FAIR reach



From Fernando‘s Talk

EMMI Rapid Reaction Task Force: The Physics of the Neutron Star Mergers at GSI/FAIR

What is the uniqueness of GSI/FAIR?

Higher energy

Storage rings

r-Process Nucleosynthesis: Connecting Rare-Isotope Beam Facilities with the Cosmos

C J Horowitz[1,38], A Arcones[6,36,38], B Côté[4,31,38], I Dillmann[10,11,38], W Nazarewicz[4,23], I U Roederer[26,38], H Schatz[4,30,38], A Aprahamian[5,38], D Atanasov[7], A Bauswein[8], J Bliss[6], M Brodeur[5,38], J A Clark[9,38], A Frebel[12,38], F Foucart[13], C J Hansen[14], O Just[37,15], A Kankainen[16], G C McLaughlin[3,38], J M Kelly[5], S N Liddick[17,30,38], D M Lee[12,18,19], J Lippuner[33,34,35,38], D Martin[6], J Mendoza-Temis[20,21], B D Metzger[2], M R Mumpower[22,38], G Perdikakis[23,24,38], J. Pereira[30,38], B W O'Shea[4,32,38], R Reifarth[25], A M Rogers[27], D M Siegel[2], A Spyrou[4,30,38], R Surman[5,38], X Tang[28], T Uesaka[29], M Wang[28]

Physics at Storage Rings

Single-particle sensitivity
Broad-band measurements

High atomic charge states
High resolving power

Long storage times
Very short lifetimes

Direct mass measurements of exotic nuclei

Radioactive decay of highly-charged ions

Charge radii measurements [DR, scattering]

Atomic levels in HCI (x-rays, DR…)

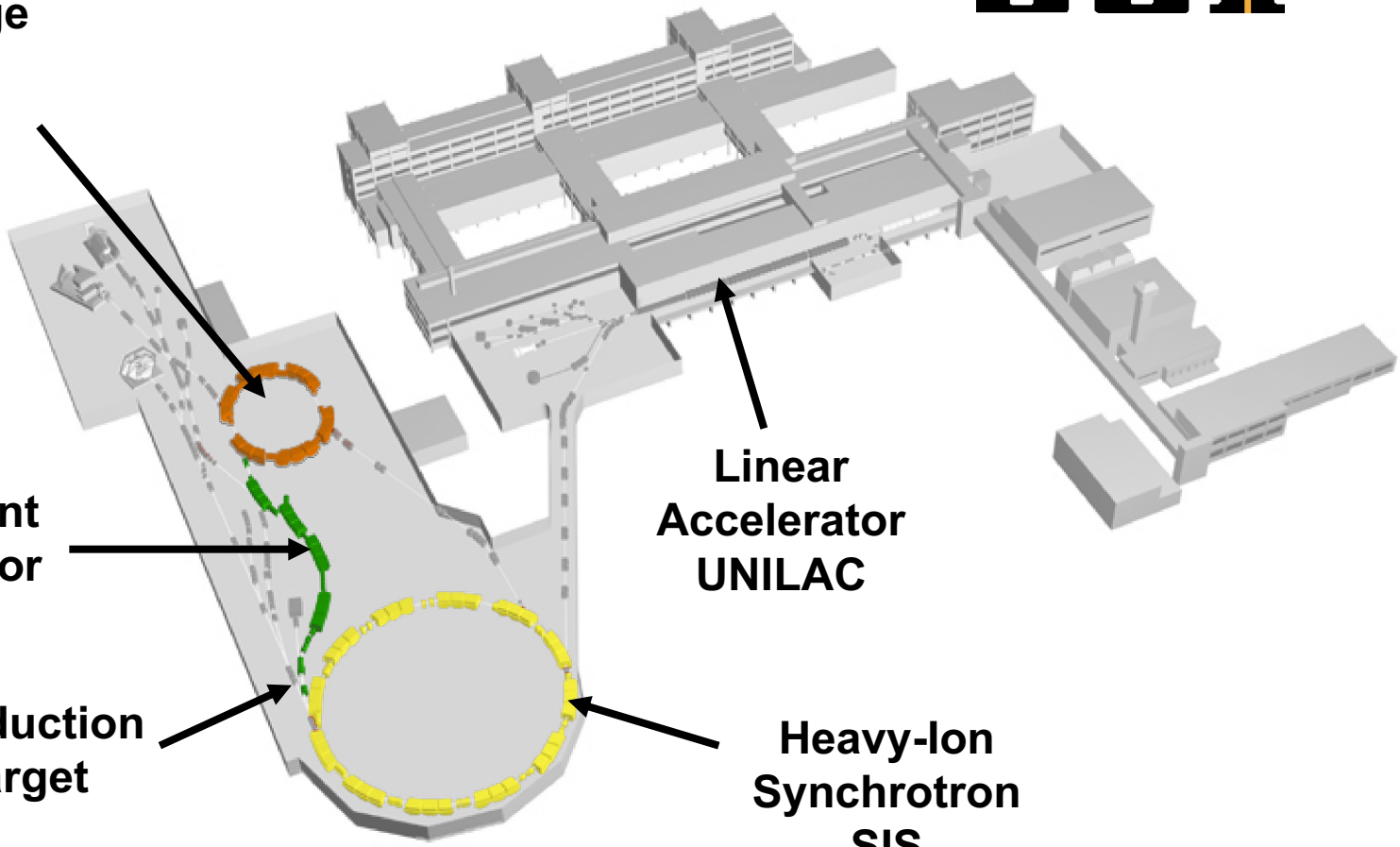
Experiments with isomeric beams [DR, reactions]

Nuclear magnetic moments [DR]

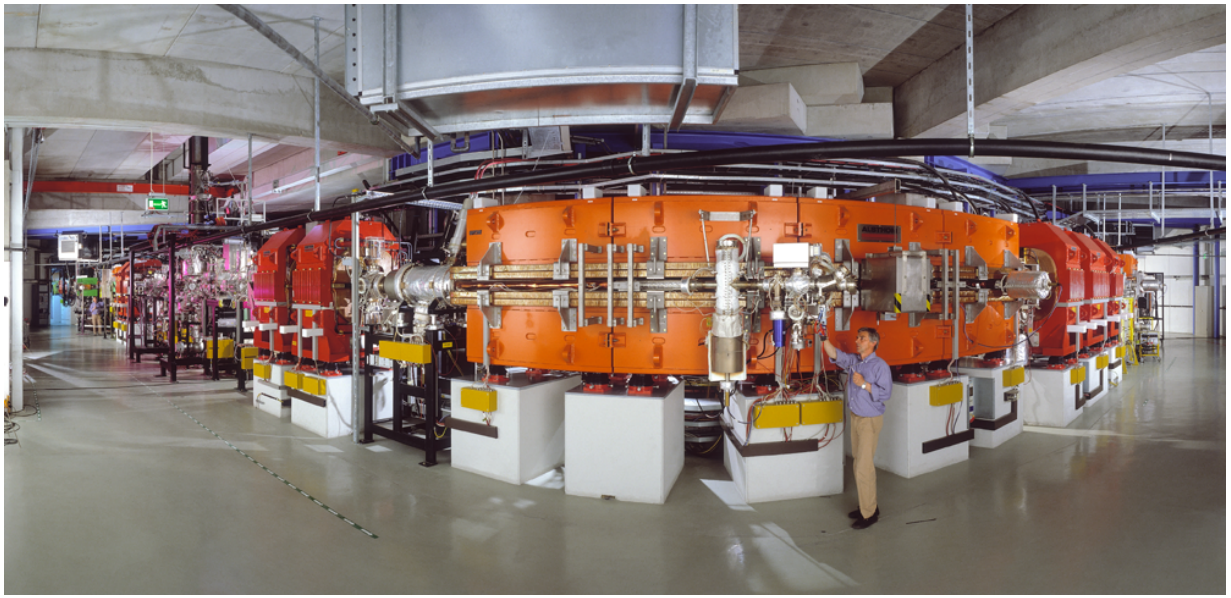
In-ring nuclear reactions

Reactions in Gamow window [(p,g), (a,g) ...]

Secondary Beams of Short-Lived Nuclei



Storage ring facilities at GSI



Experimental Storage Ring (ESR)

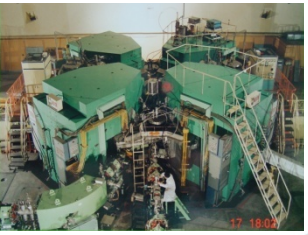
In operation since 1990
Circumference = 108.3 m
Vacuum = 10^{-10}—10^{-12} mbar
Electron, stochastic cooling
Energy range = 4 – 400 MeV/u
Slow and fast extraction

CRYRING
(transported from Stockholm University)

Planned start of operation (stable ions) – 2016
Planned start of operation (exotic nuclei) – 2017
Circumference = 54.15 m
Vacuum = 10^{-11}—10^{-12} mbar
Electron cooling
Energy range = ~0.1 – 15 MeV/u
Slow and fast extraction

Courtesy Michael Lestinsky

Heavy Ion Research Facility in Lanzhou (HIRFL)



SSC(K=450)

SFC (K=69)

CSRe

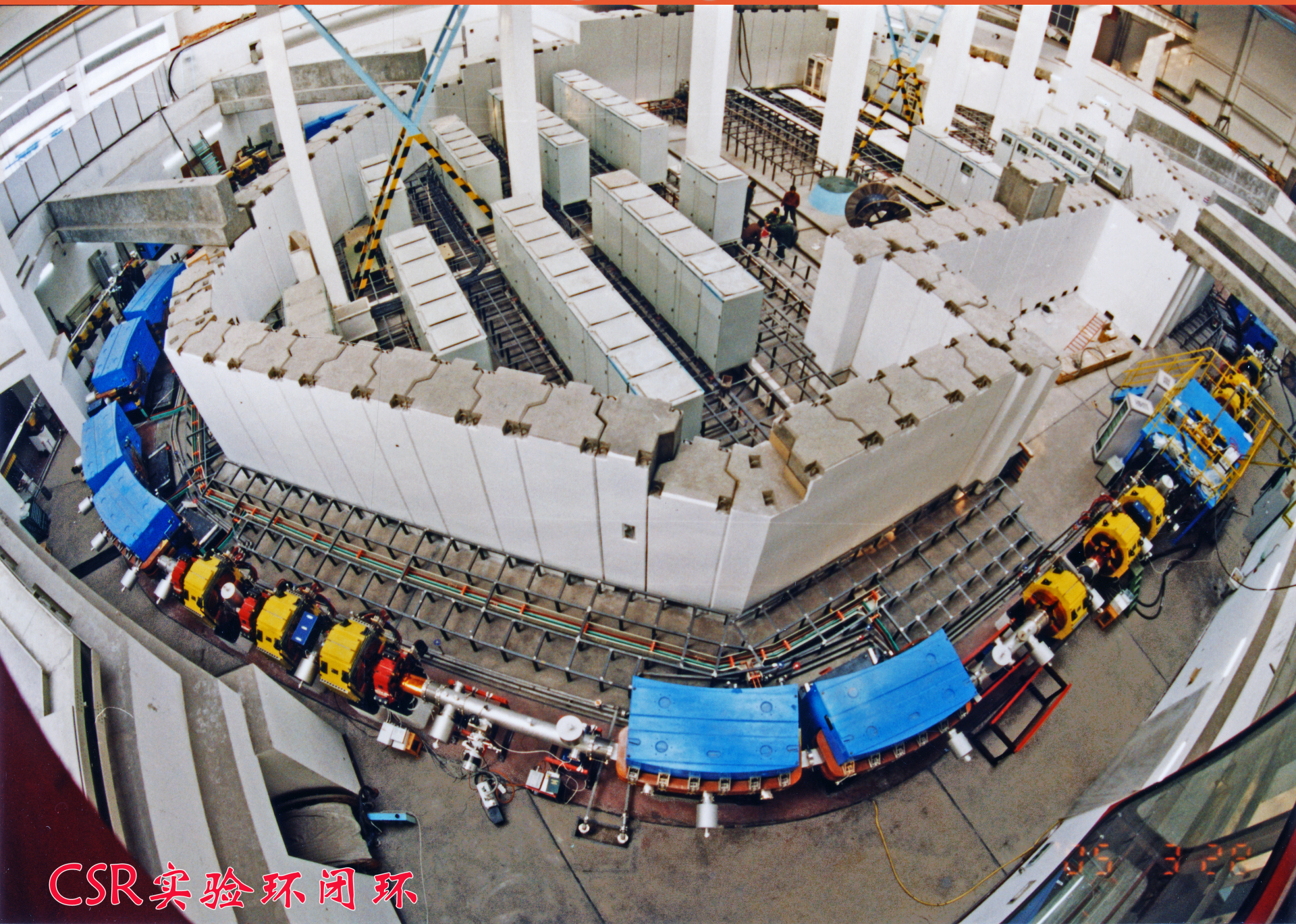
RIBLL1

RIBLL2

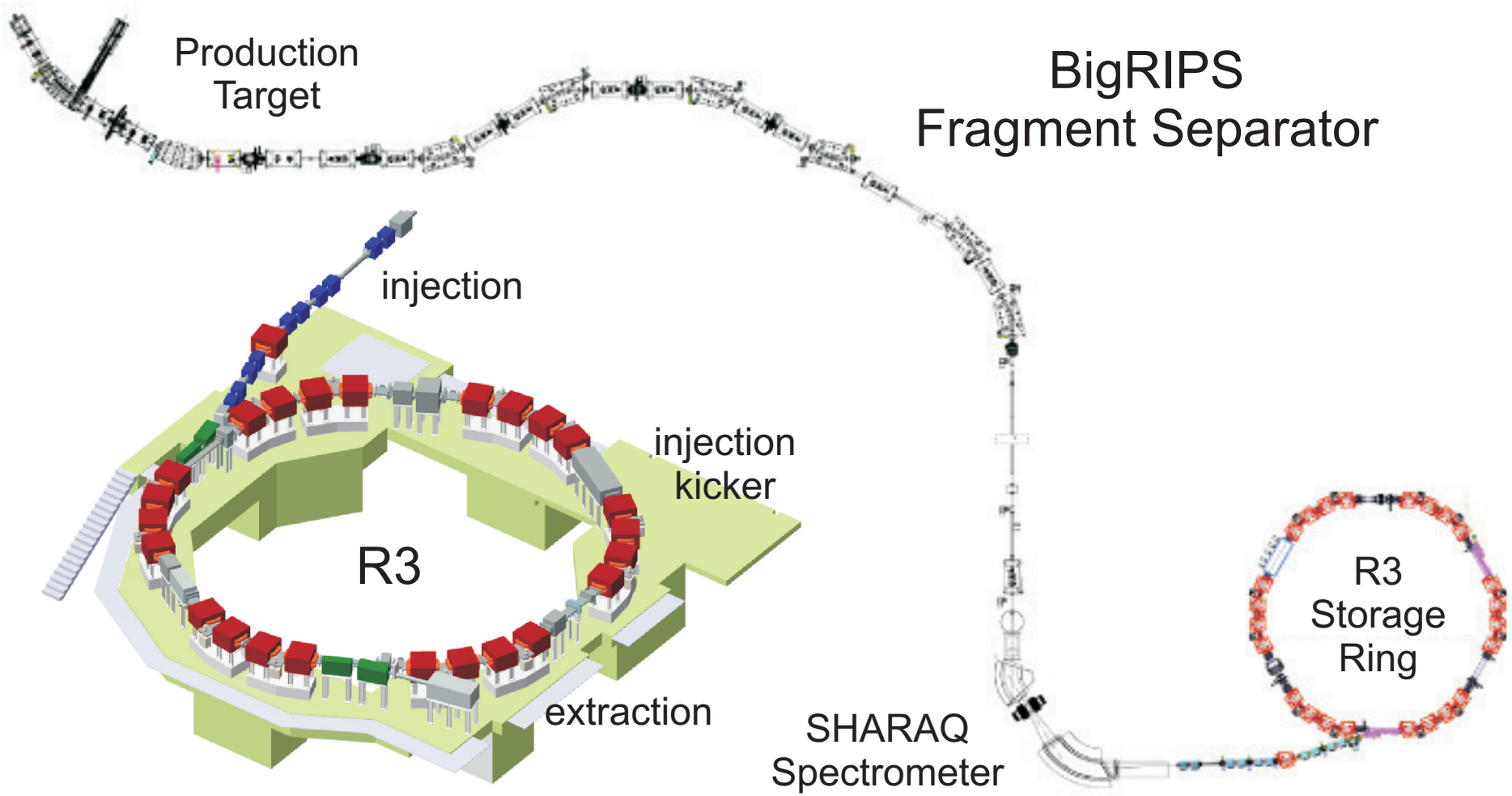
CSRm

Courtesy Guo Qing Xiao

Experimental Cooler Storage Ring CSRe

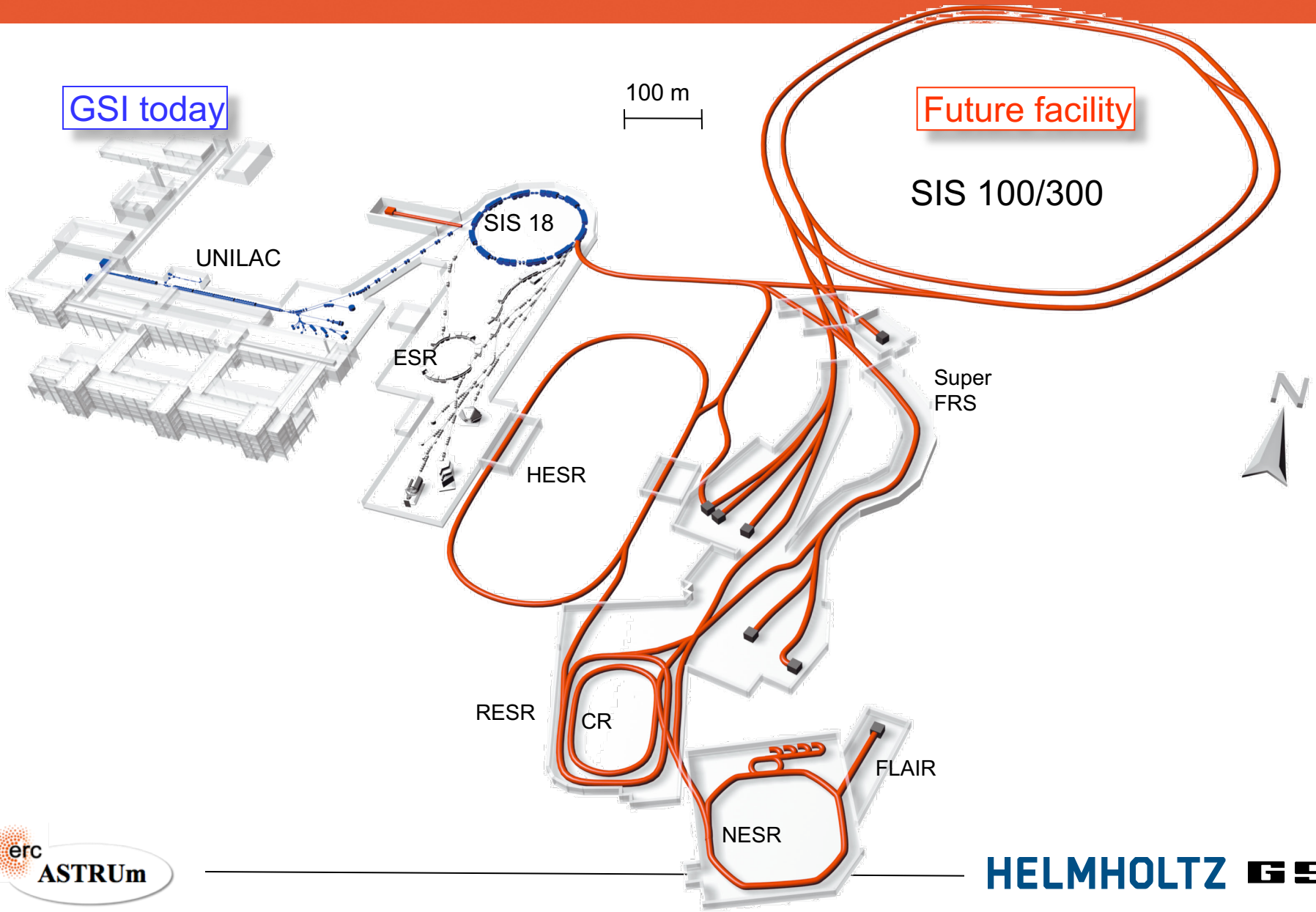


BigRIPS + R3 Setup in RIKEN

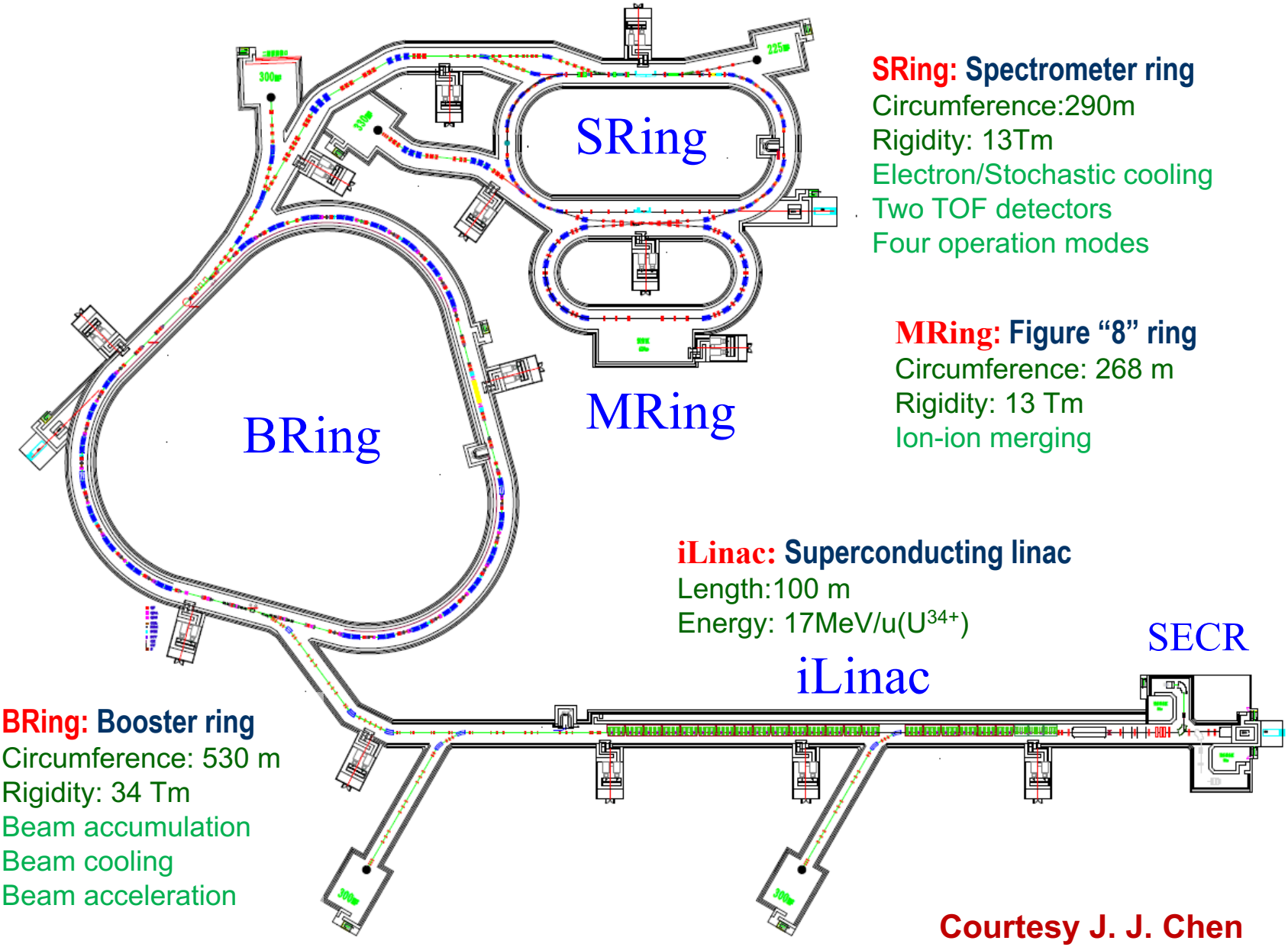


Courtesy Tomohiro Uesaka

FAIR - Facility for Antiproton and Ion Research



HIAF: General description – **Main components**



SRing: Spectrometer ring
Circumference:290m
Rigidity: 13Tm
Electron/Stochastic cooling
Two TOF detectors
Four operation modes

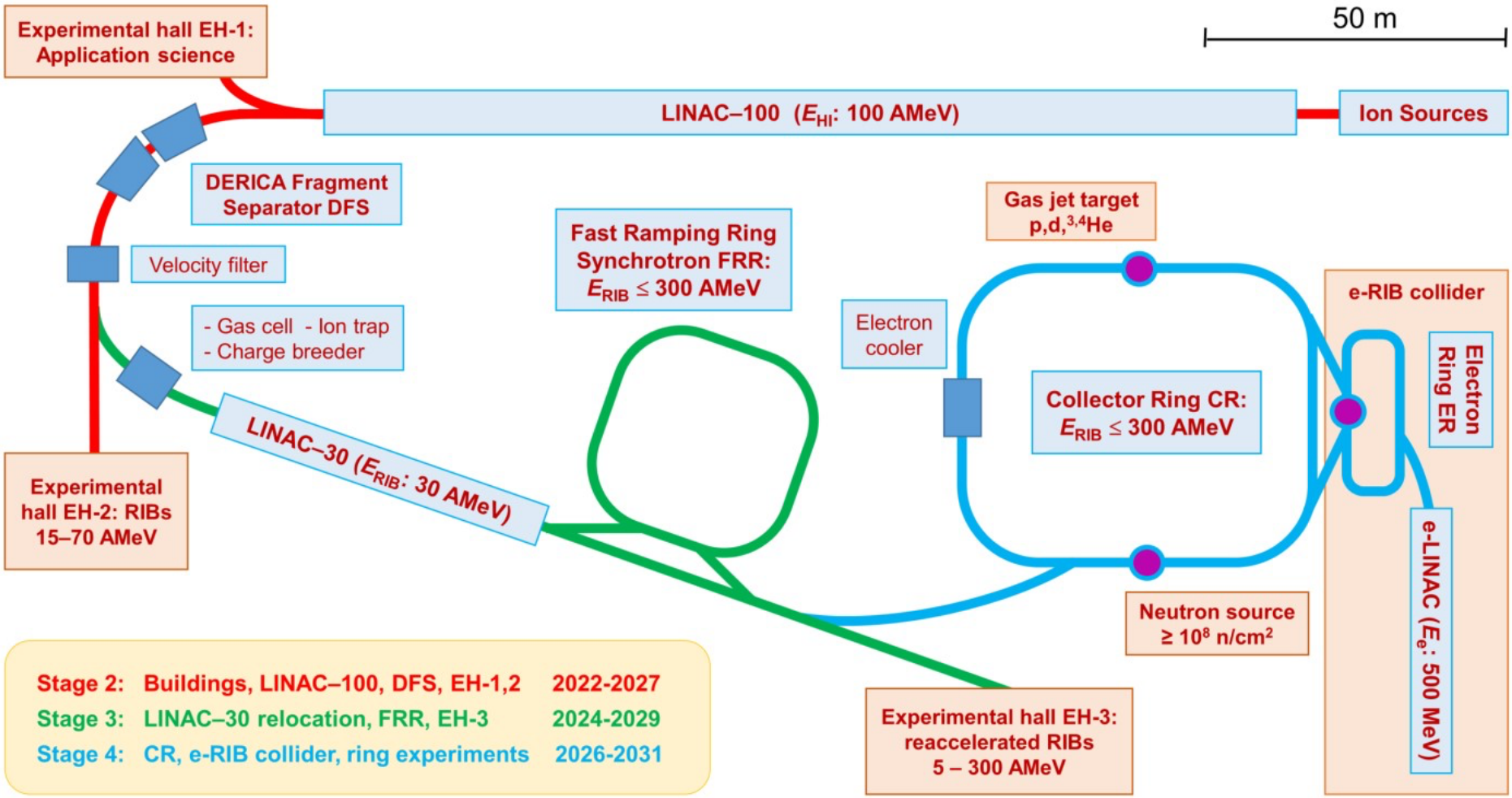
MRing: Figure "8" ring
Circumference: 268 m
Rigidity: 13 Tm
Ion-ion merging

iLinac: Superconducting linac
Length:100 m
Energy: 17MeV/u(U^{34+})

BRing: Booster ring
Circumference: 530 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration

Courtesy J. J. Chen

DERICA Project



Courtesy Leonid Grigorenko

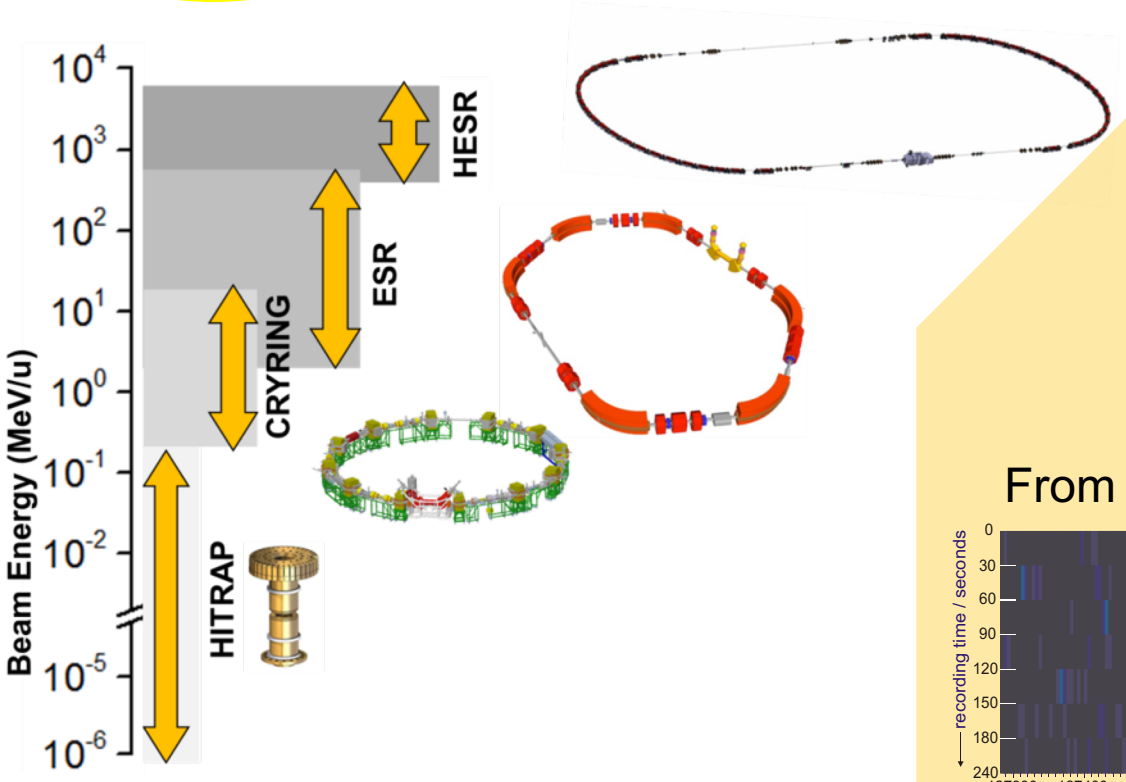
Ion Beam Facilities / Trapping & Storage

Worldwide Unique !

Stored and Cooled

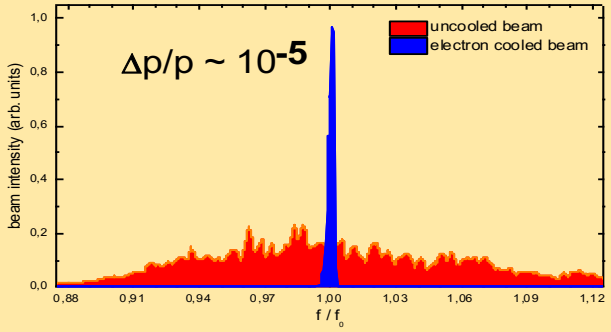
Highly-Charged Ions (e.g. U^{92+}) and Exotic Nuclei

From Rest to Relativistic Energies (up to 4.9 GeV/u)

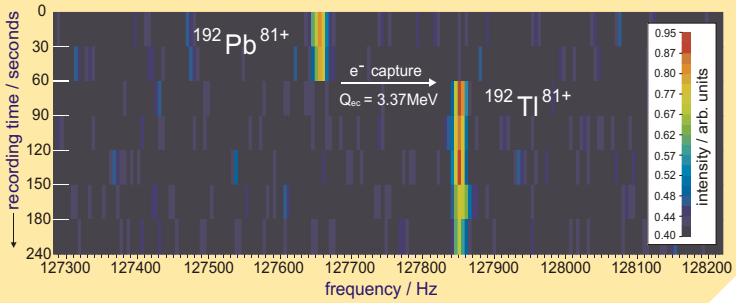


Courtesy Thomas Stöhlker

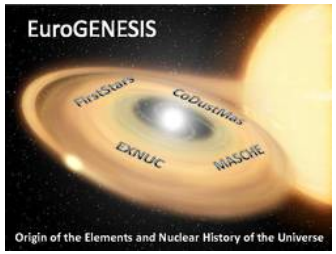
Cooling: The Key for Precision



From Single Ions to Highest Intensities



Direct Mass Measurements on the Chart of the Nuclides



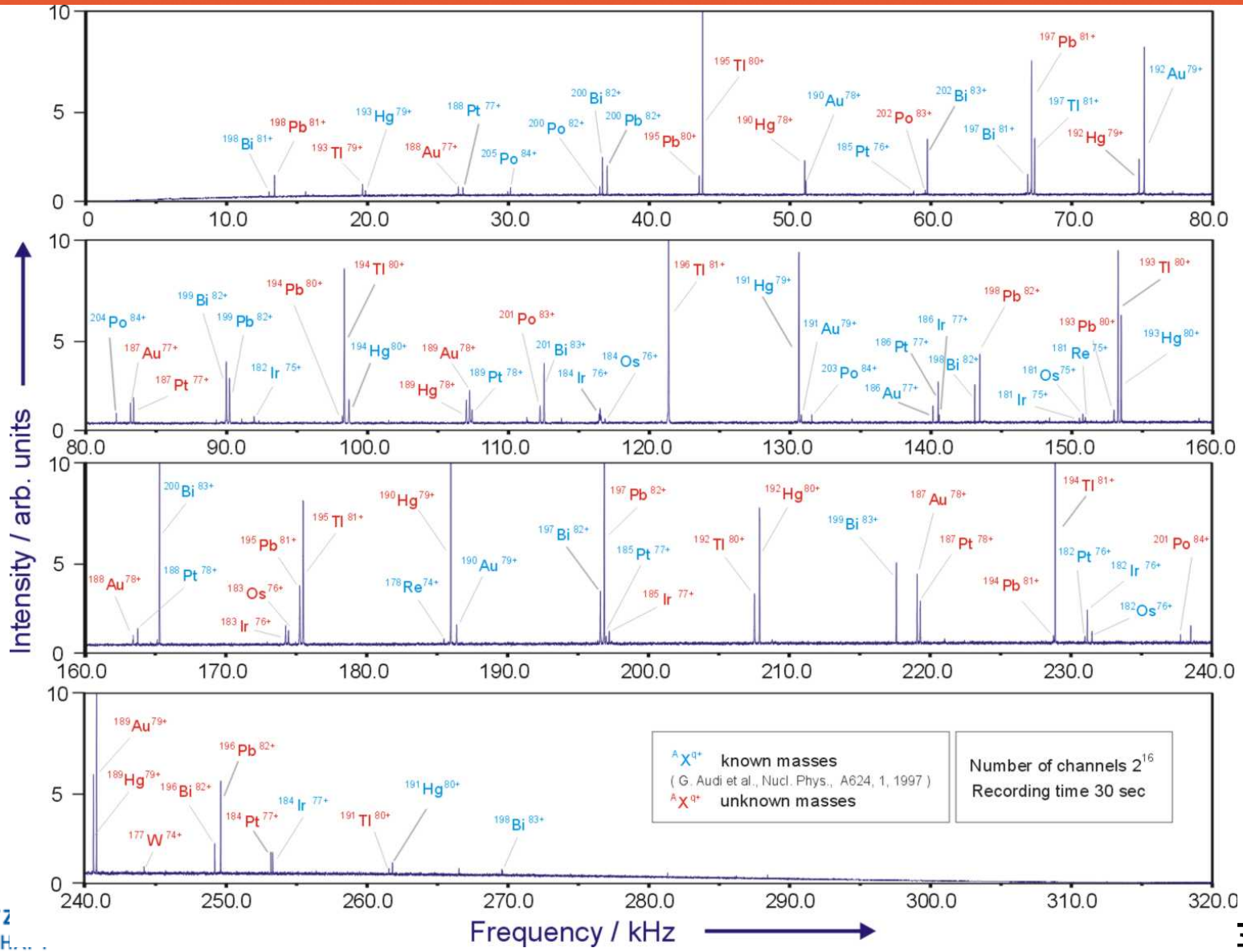
Individual Project
High-Precision Measurements of Nuclear Ground State Properties

Penning Traps

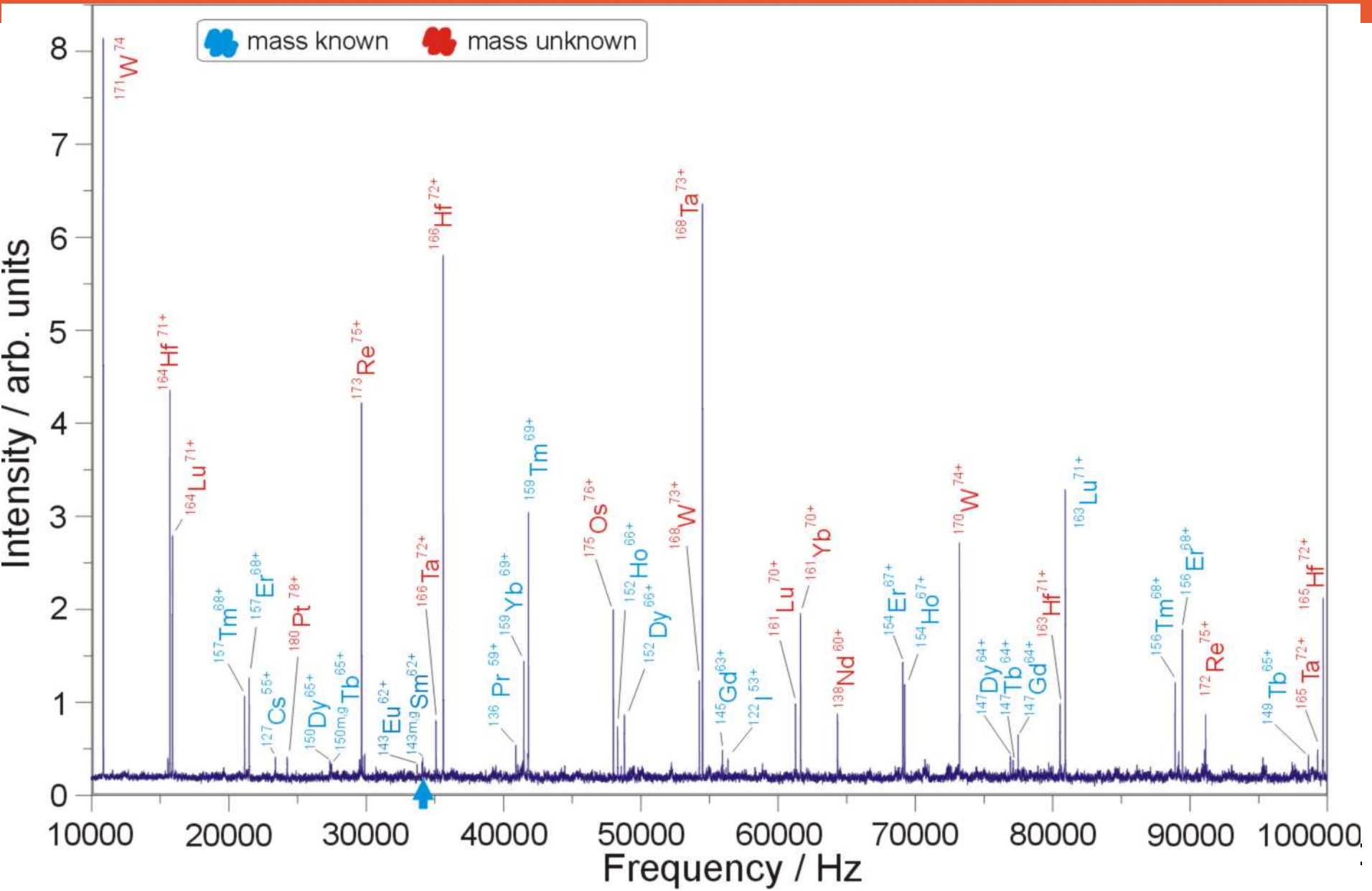
Storage Rings

Courtesy Klaus Blaum

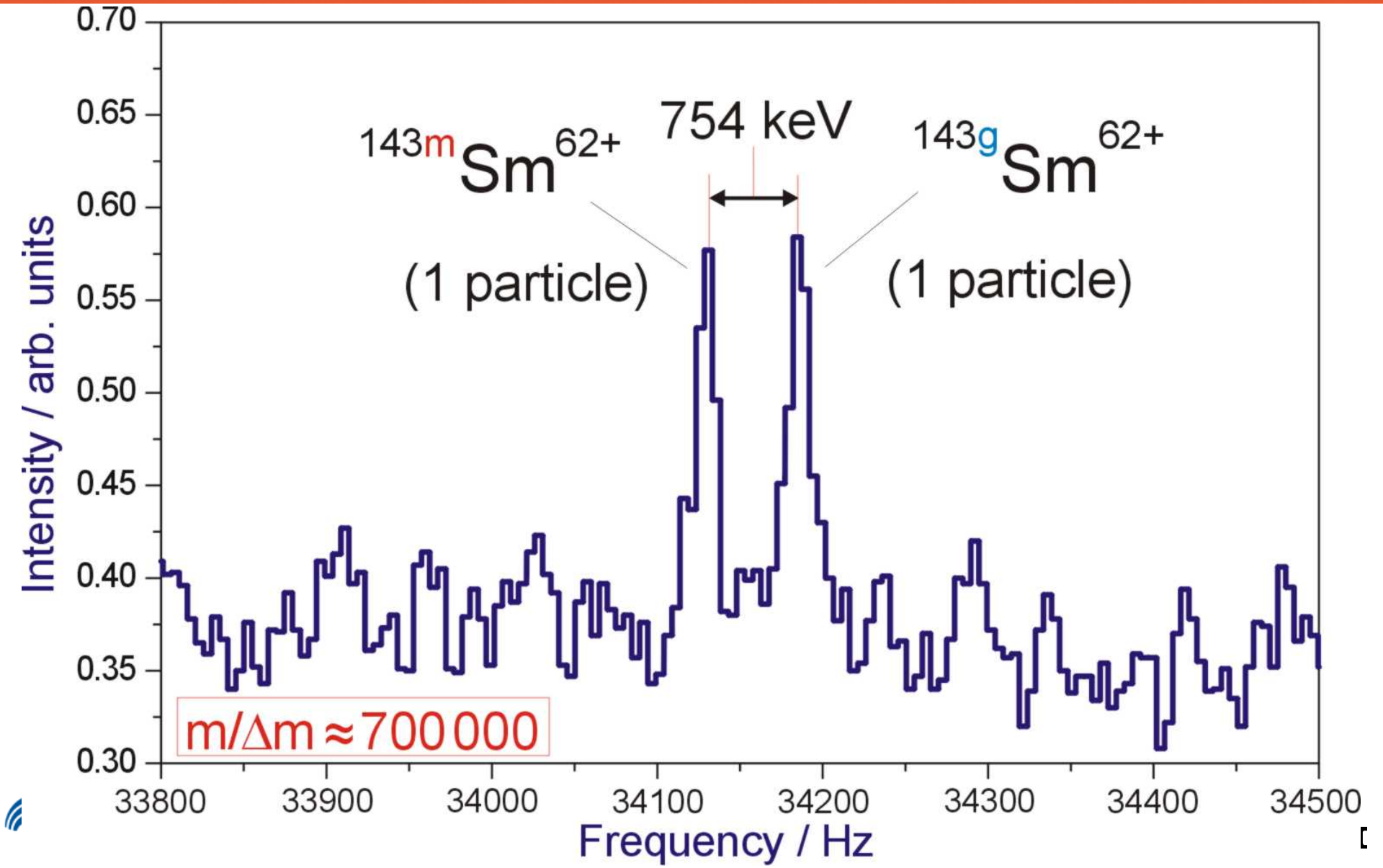
SMS: Broad Band Frequency Spectra



SMS: Broad Band Frequency Spectra

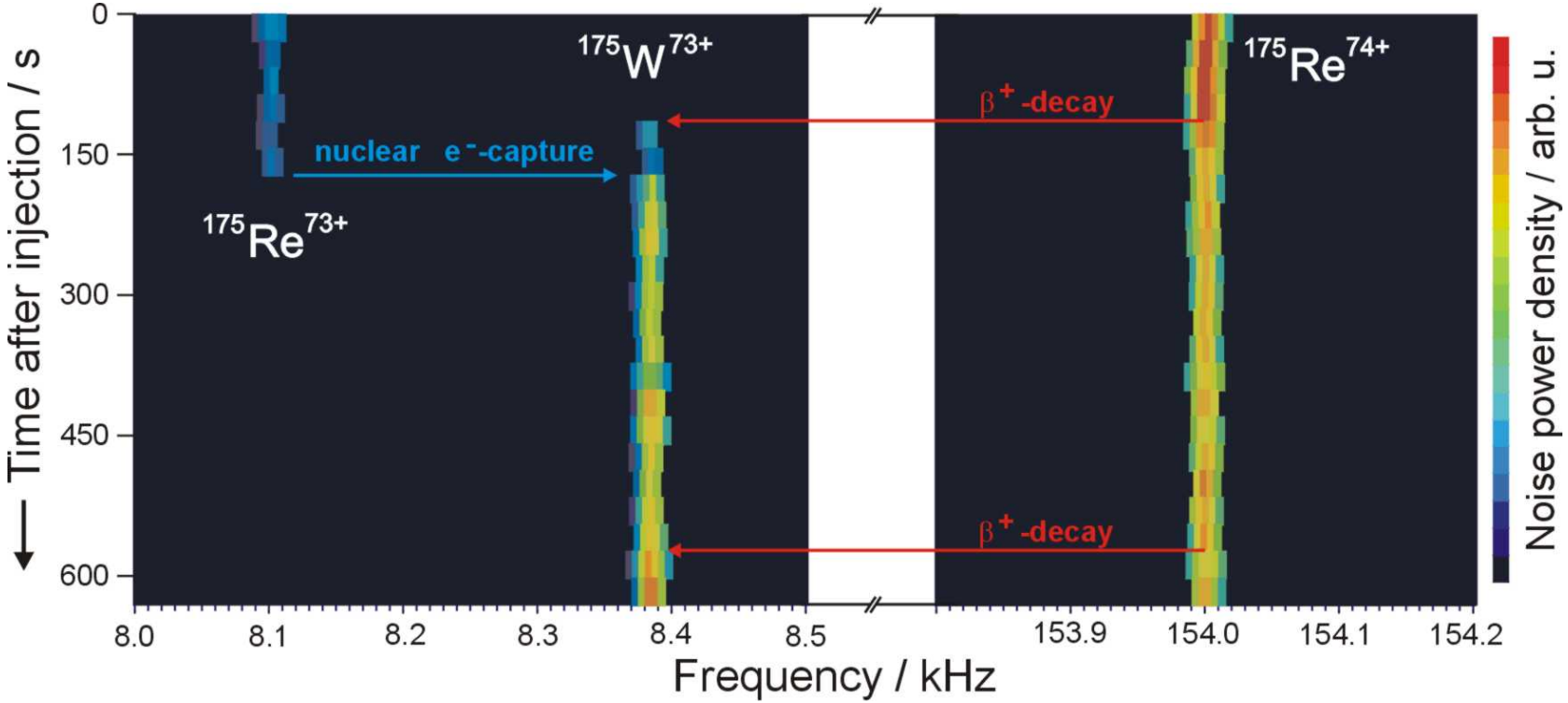


SMS: Broad Band Frequency Spectra



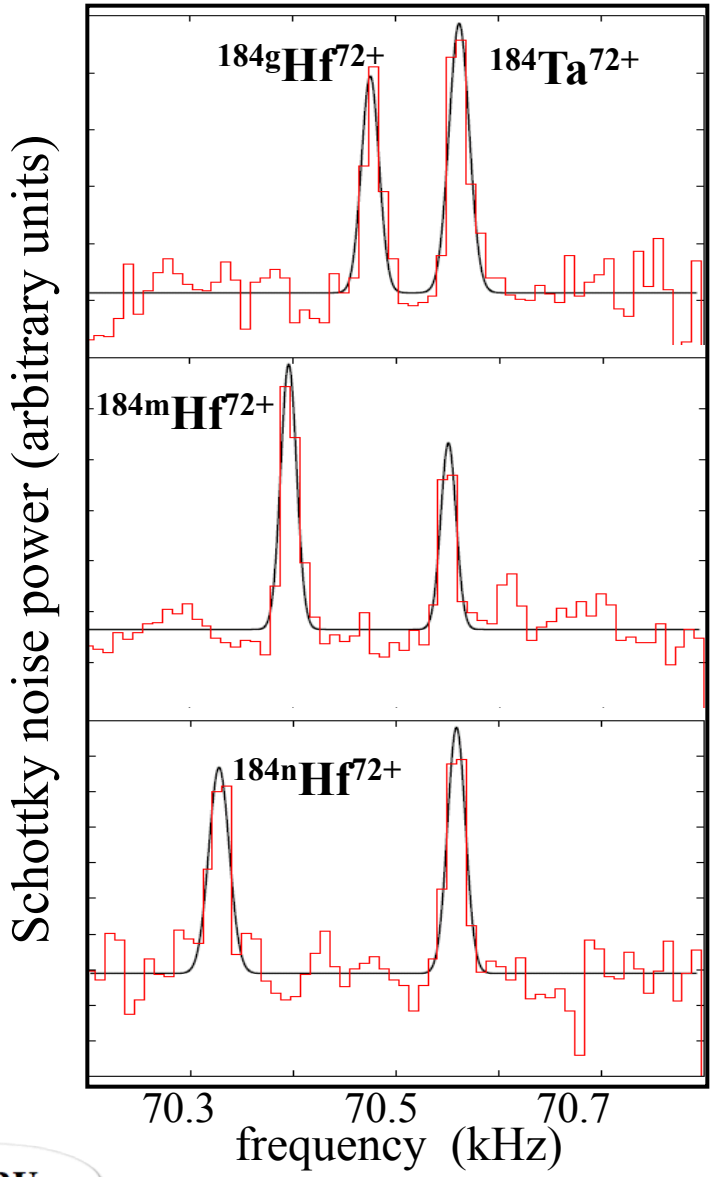
Nuclear Decays of Stored Single Ions

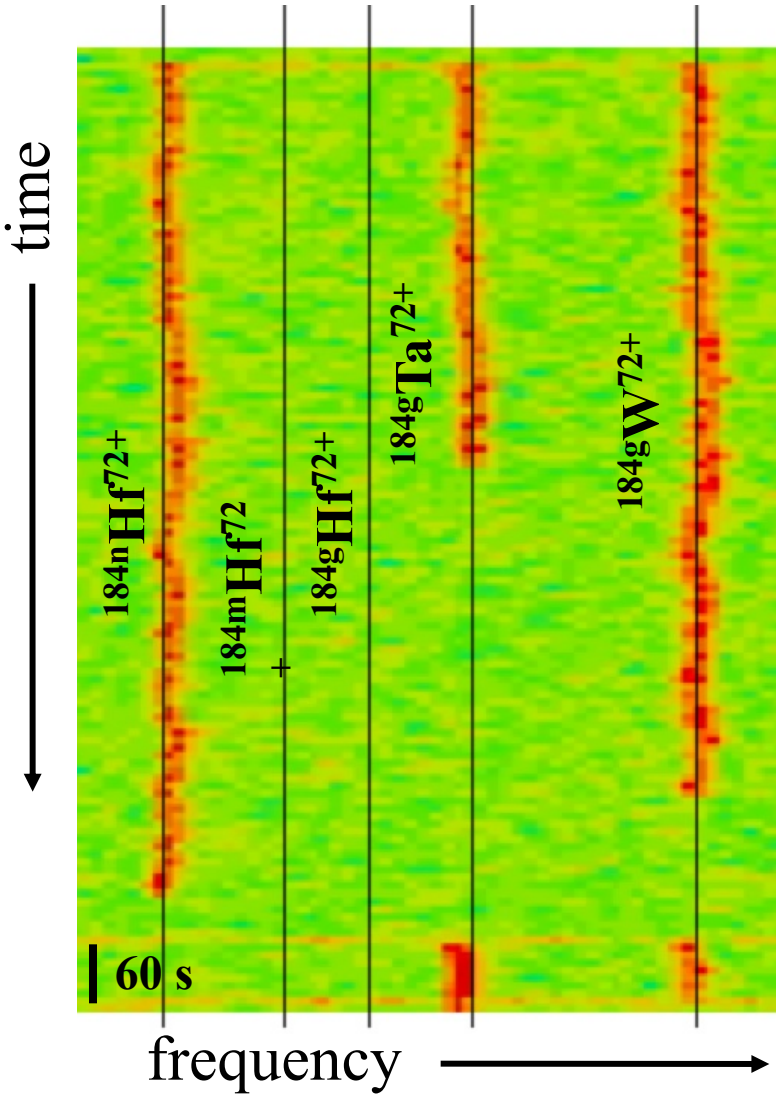
Time-resolved SMS is a perfect tool to study decays in the ESR



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

Discovery of ^{184n}Hf Isomer

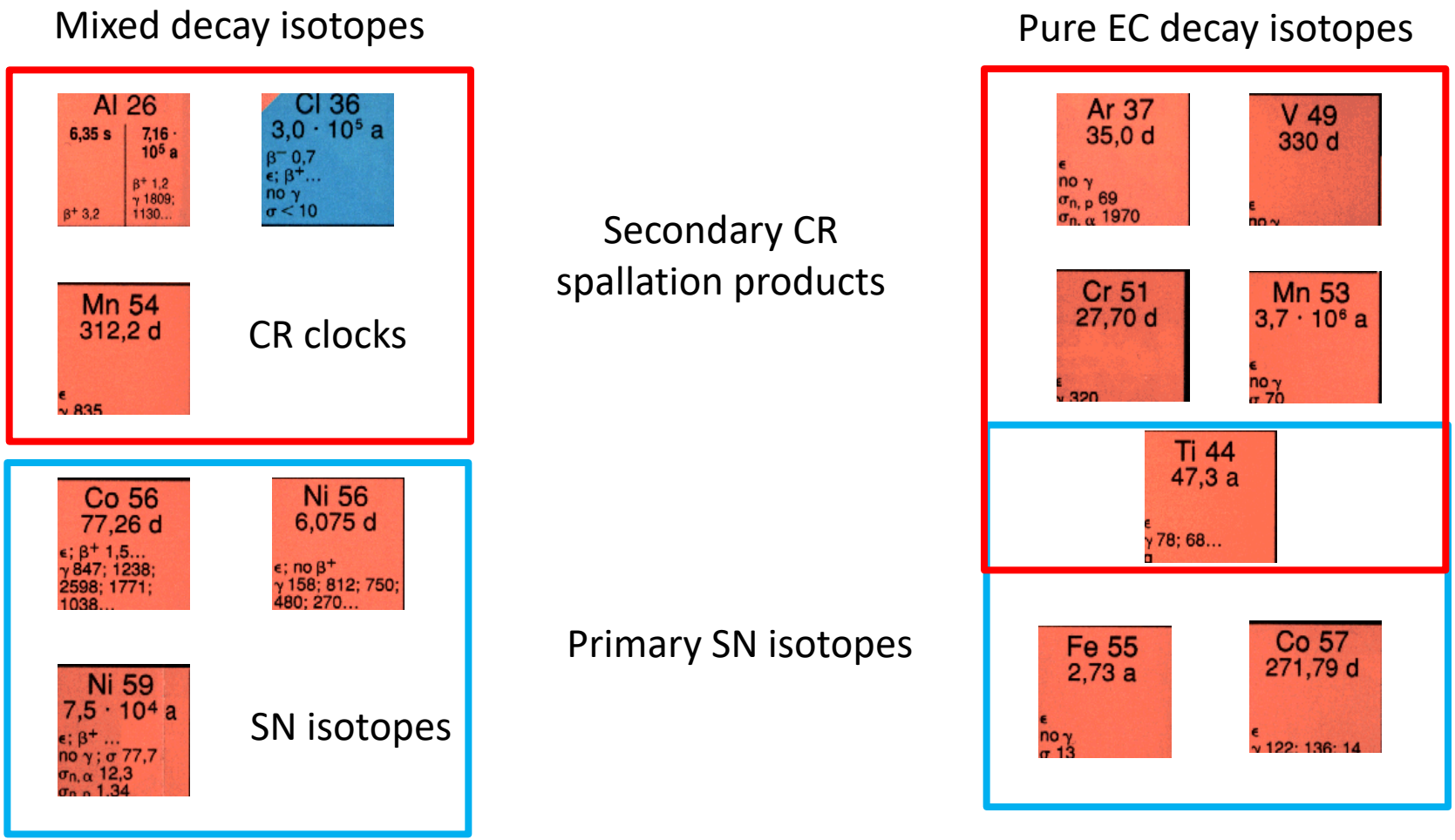




Courtesy Philip Walker

Physics cases

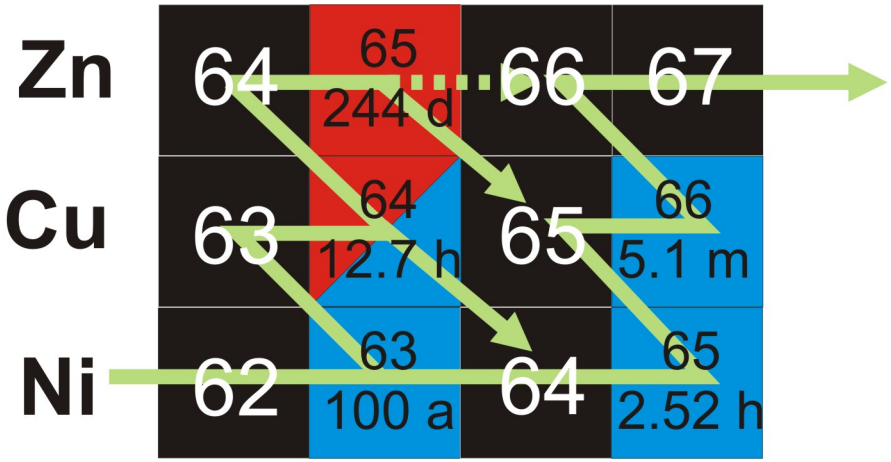
⇨ "Stellar lifetimes of SN isotopes"

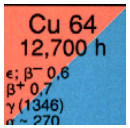


Courtesy Iris Dillmann

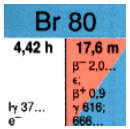
Mixed EC/β-decay isotopes: s process

- s-process "branchings"
- Determines how much material is transferred to next isotope
- Interior of stars: high recombination rates but also high temperatures
- T≈30-1000 MK





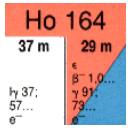
43.9% EC/17.6% β^+



6.1% EC/ 2.2% β^+

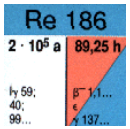
6.9% EC

28 (4)% EC
72.1% EC

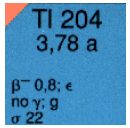


60 (5)% EC

86 (3)% EC



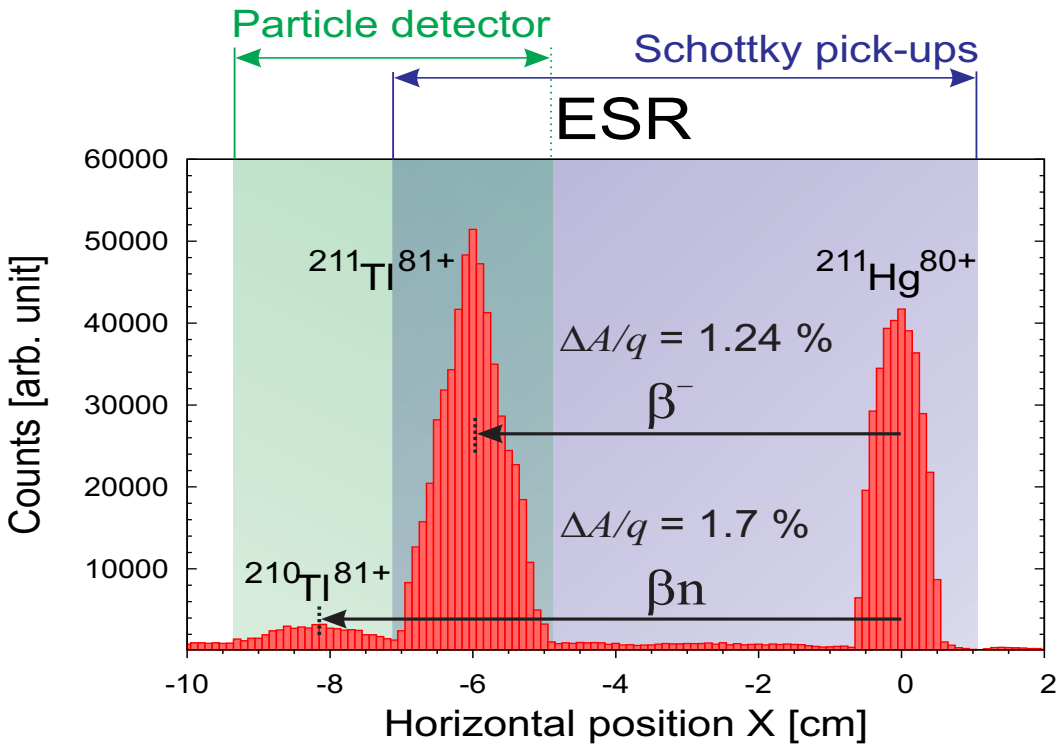
7.47% EC

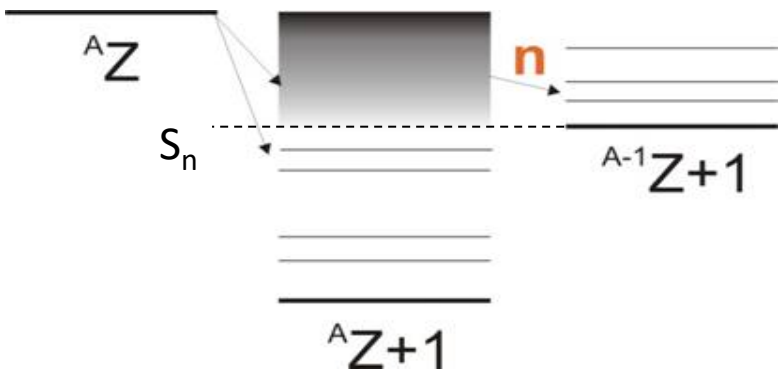


2.92% EC

Courtesy Iris Dillmann

β-delayed neutron emission probability



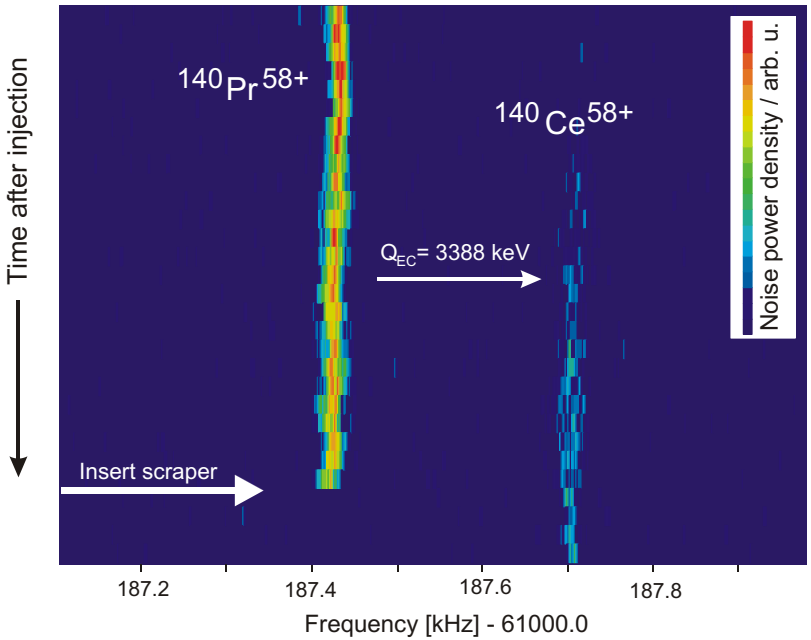


$S_n < Q_\beta$

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

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

Search for Nuclear Excitation in Electron Capture process

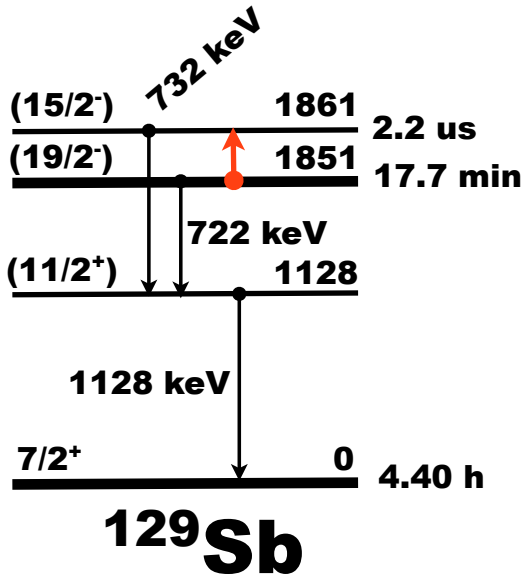


CRYRING:
Slowing down to a few 10 keV/u

Fast extraction towards an external Detection system

ESR:
Ability to prepare pure isomeric beams

Slowing down to 4 MeV/u



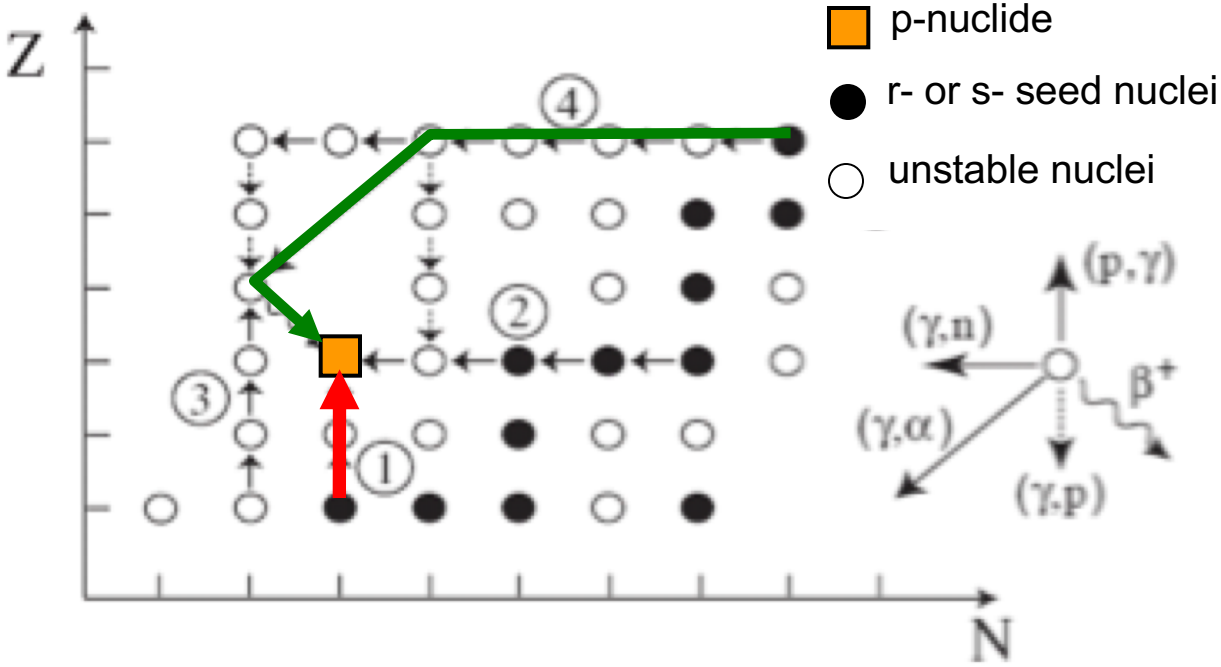
Astrophysics motivation: the p-process

35 stable neutron-deficient isotopes between ^{74}Se and ^{196}Hg

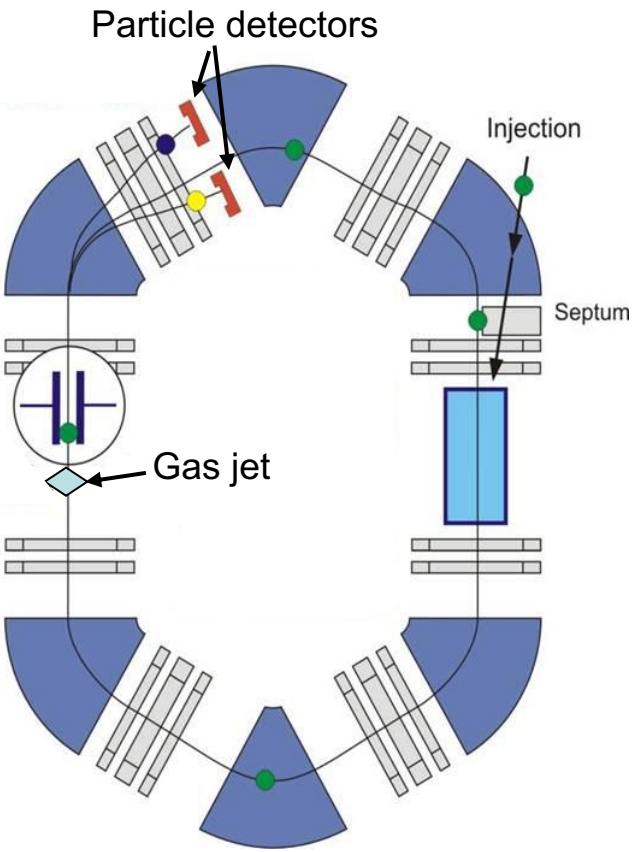
Dominating reactions: (p,γ) for light nuclei;
(γ,n), (γ,p), (γ,α) and β^+ decays for heavier nuclei

Temperatures of 2-3 × 10^9 K during time scales of a few seconds are required
(type II supernovae explosions)

Network calculations
more than 2000 nuclei
(mostly unstable)
more than 20000 reactions



Reaction studies in a storage ring



ESR

High revolution frequency

→ high luminosity even with thin targets

Detection of ions via in-ring particle detectors

→ low background, high efficiency

Well-known charge-exchange rates

→ in-situ luminosity monitor

Ultra-thin windowless gas targets

→ excellent resolution

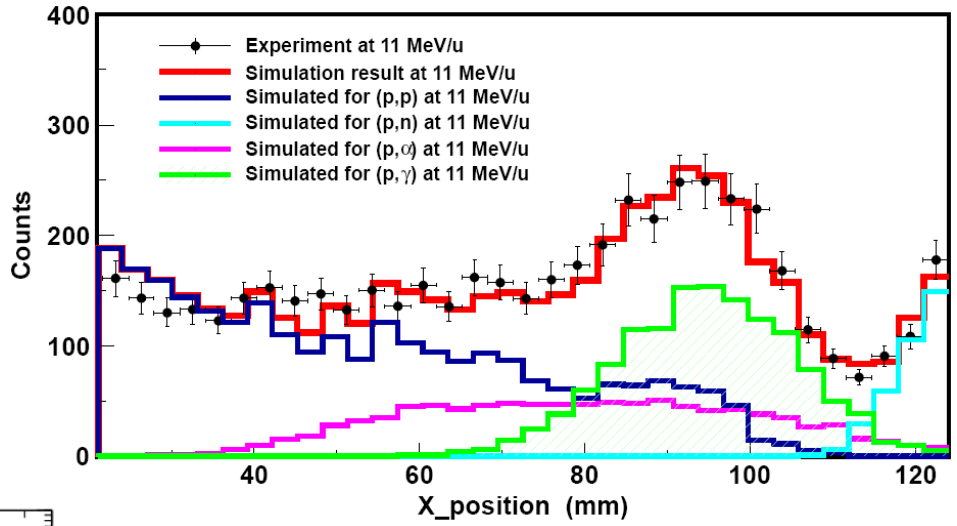
Applicable to radioactive nuclei

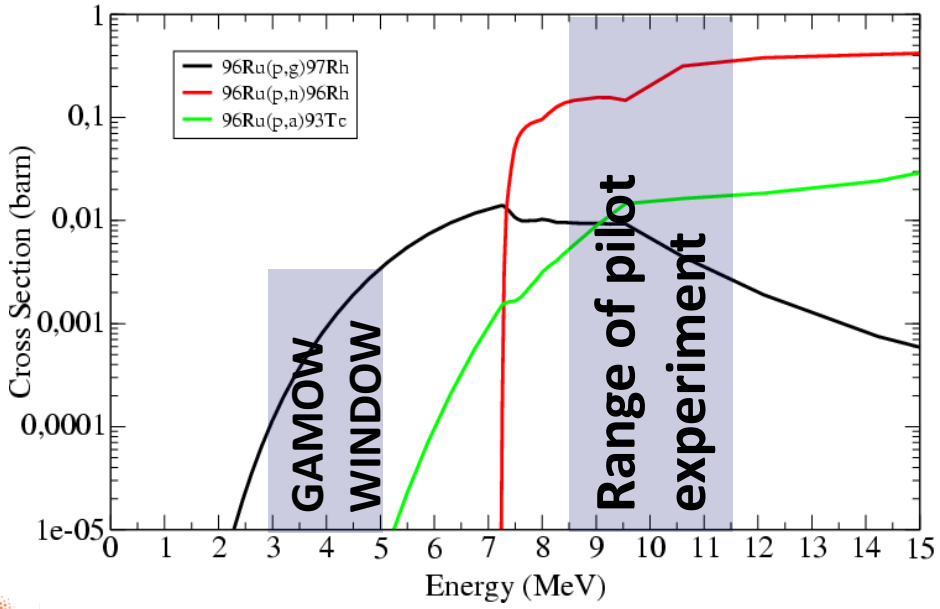
^{96}Ru(p,g)^{97}Rh Experiment at the ESR

Slowing down to ~10 MeV/u

^{96}Ru(p,g)^{97}Rh

Above (p,n) treshold





σ_{PG} ~ 4.0 mb

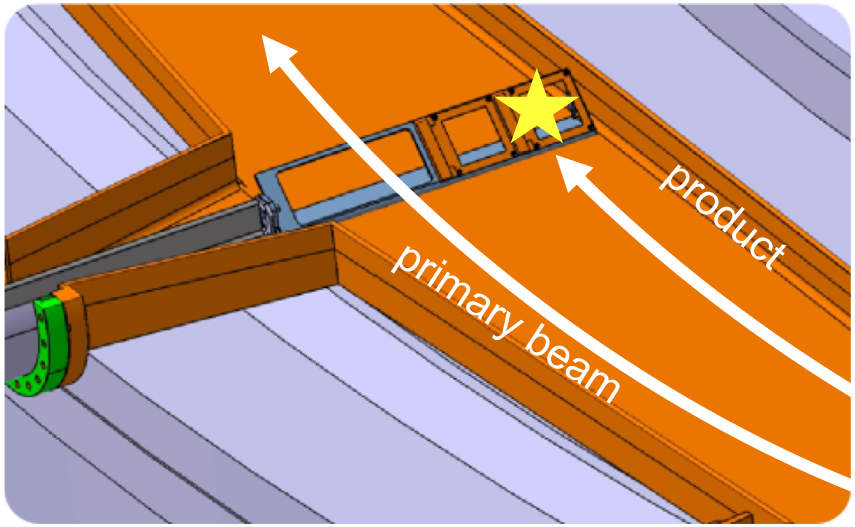
(Non-smoker: 3.5 mb)

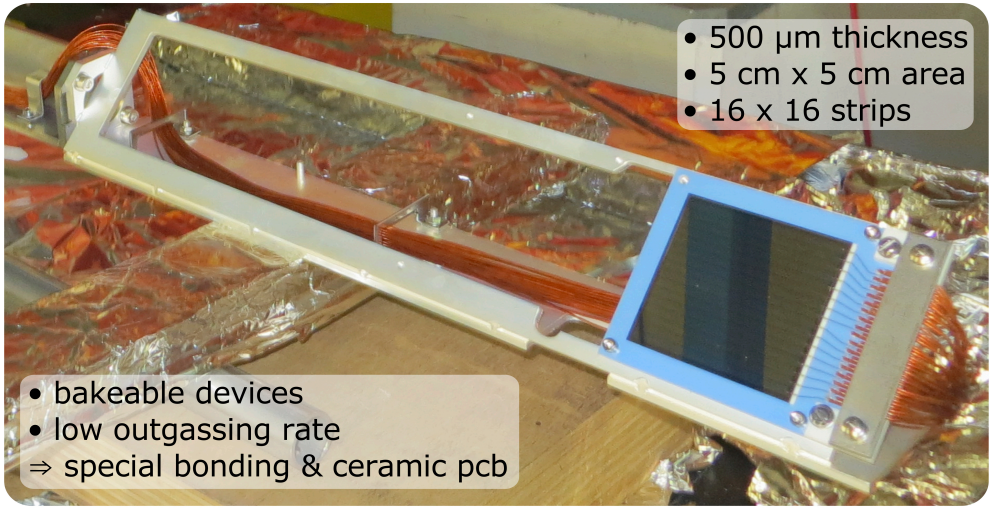
B. Mei et al, PRC 92 (2015) 35803

Courtesy Rene Reifarth

$^{124}Xe(p,g)^{125}Cs$ Experiment at the ESR

Double-sided silicon strip detector installed directly into the UHV of the ESR





Federal Ministry of Education and Research

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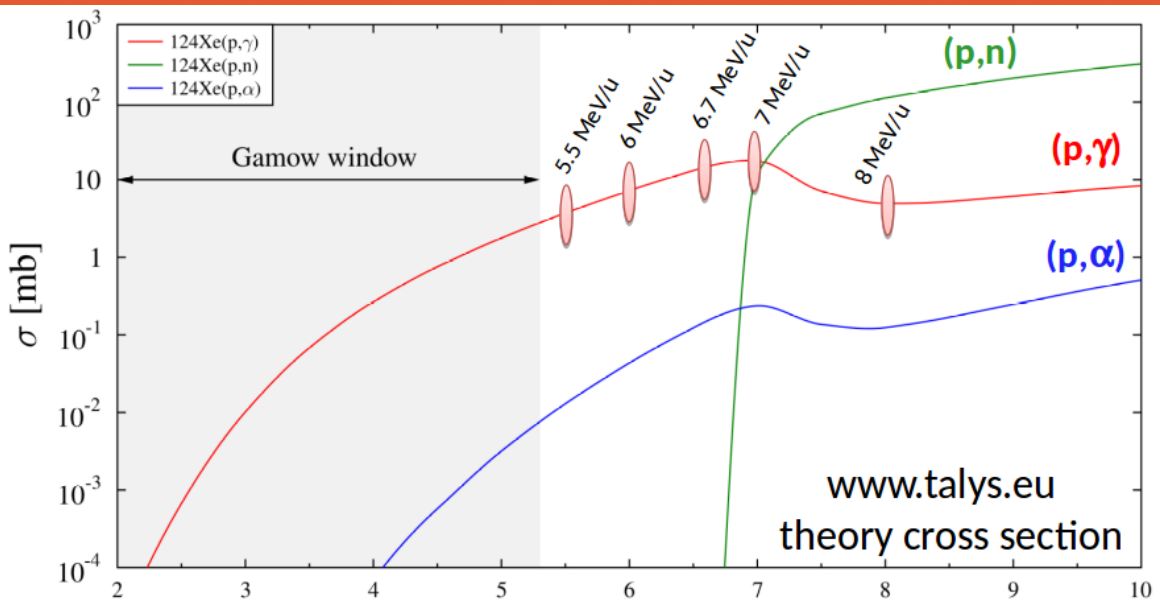
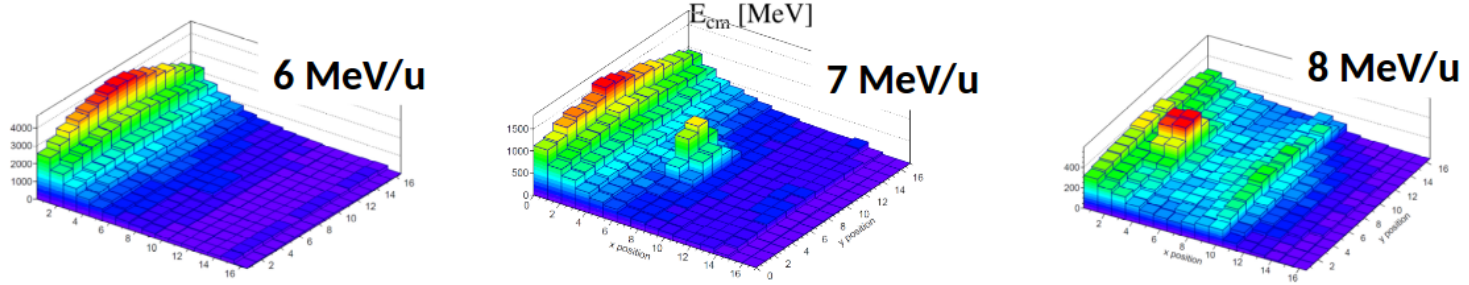
erc ASTRUm

HELMHOLTZ GSI

Courtesy Jan Glorius

The ^{124}Xe(p, γ) ^{125}Cs experiment - Data analysis





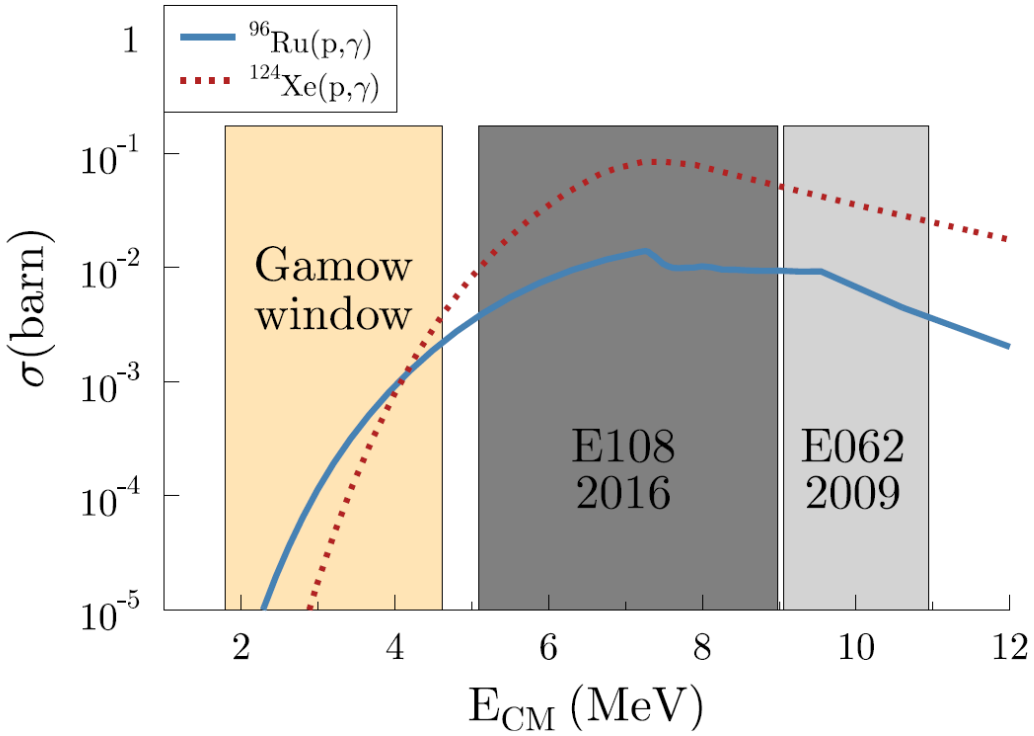
- succesfull measurement of the proton-capture products
- by decreasing the beam energy:

⇒ cross section of (p, γ) decreases

⇒ background increases

Courtesy Jan Glorius

Future measurements



E062 M. Heil et al.
E108 R. Reifarth et al.

NucAR

E127 R. Reifarth et al.

Regarding the proposal "Measurements of proton-induced reaction rates on radioactive isotopes for the astrophysical p process" (Proposal E127), the G-PAC recommends this proposal with ***highest priority (A)*** *and that* ***15 shifts of main beam time*** *be allocated for this measurement.*

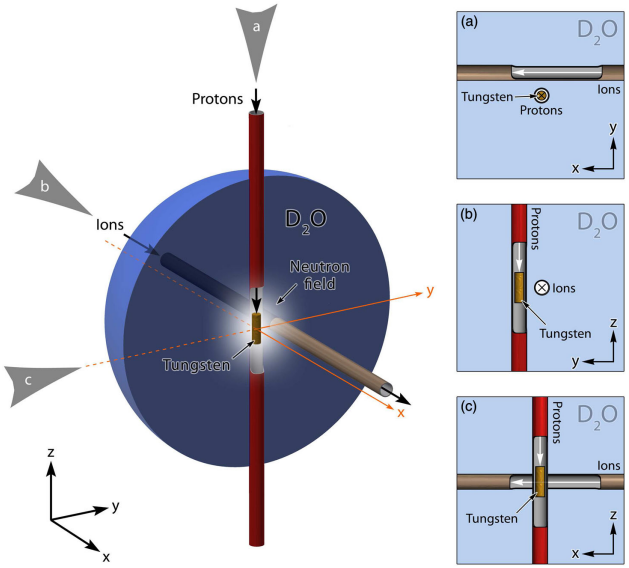
Neutron captures in inverse kinematics

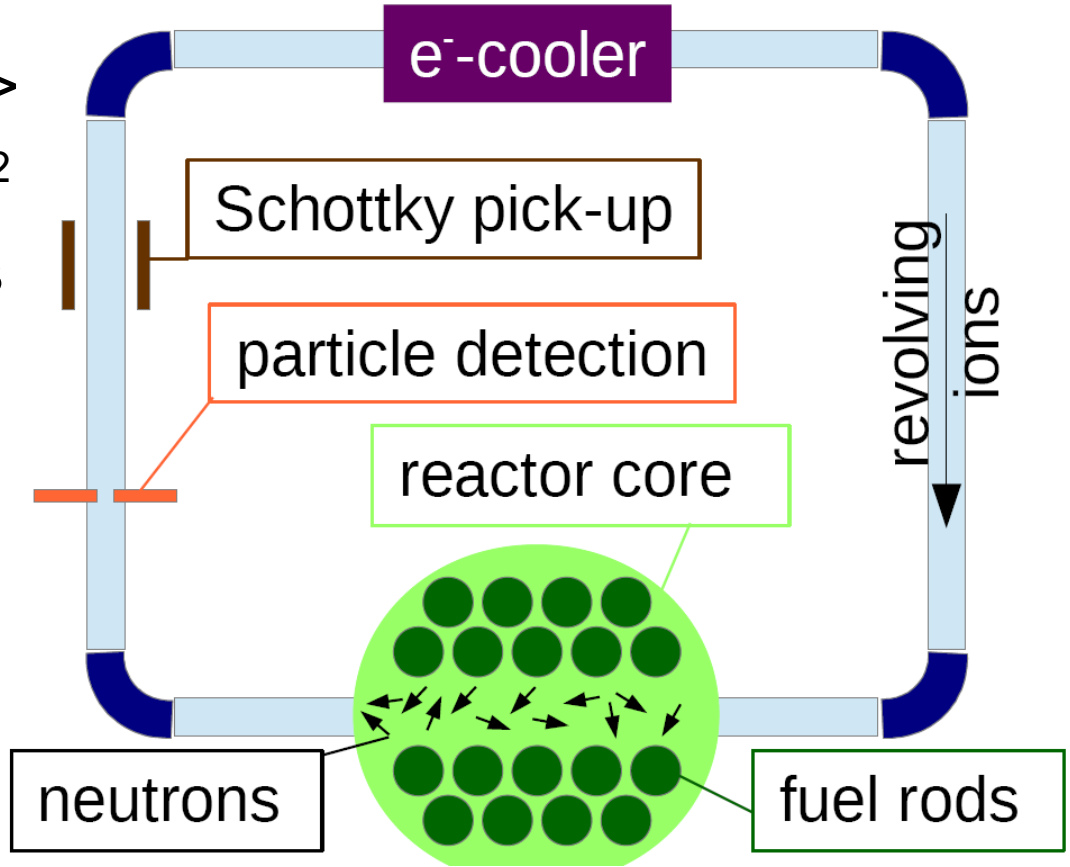
Neutron flux: 10^{14} n/cm^2/s ->

Neutron target: 2 10^{10} n/cm^2

10^7 ions, 1 MHz: 10^{13} ions/s

Counts per day: 20 σ / mb





Reifarth & Litvinov , Phys. Rev ST Accelerator and Beams, 17 (2014) 014701

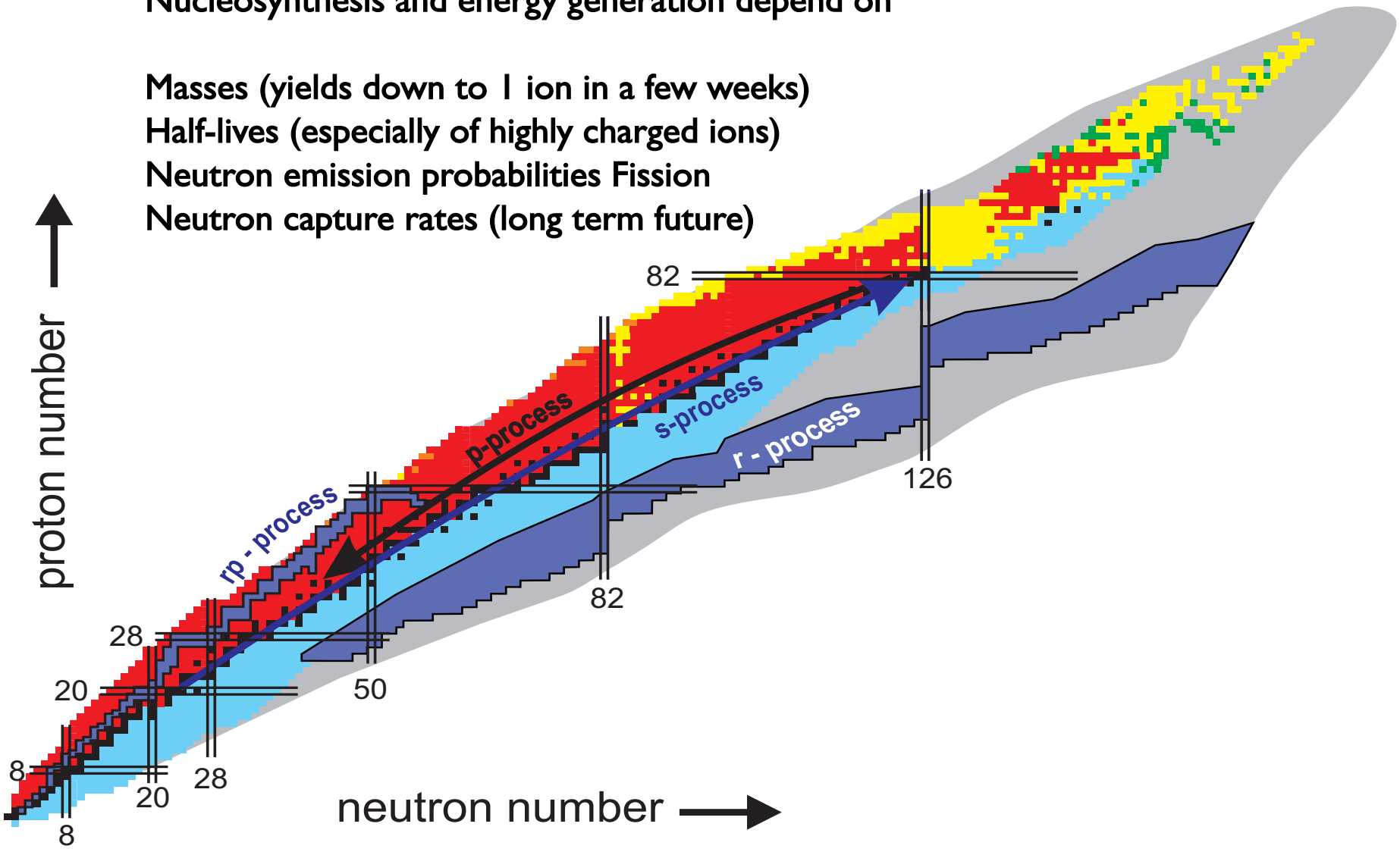
Reifarth et al., Phys. Rev ST Accelerator and Beams, 20 (2017) 044701

Courtesy Rene Reifarth

Where and how was gold cooked?

Nucleosynthesis and energy generation depend on

Masses (yields down to 1 ion in a few weeks)
Half-lives (especially of highly charged ions)
Neutron emission probabilities Fission
Neutron capture rates (long term future)



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