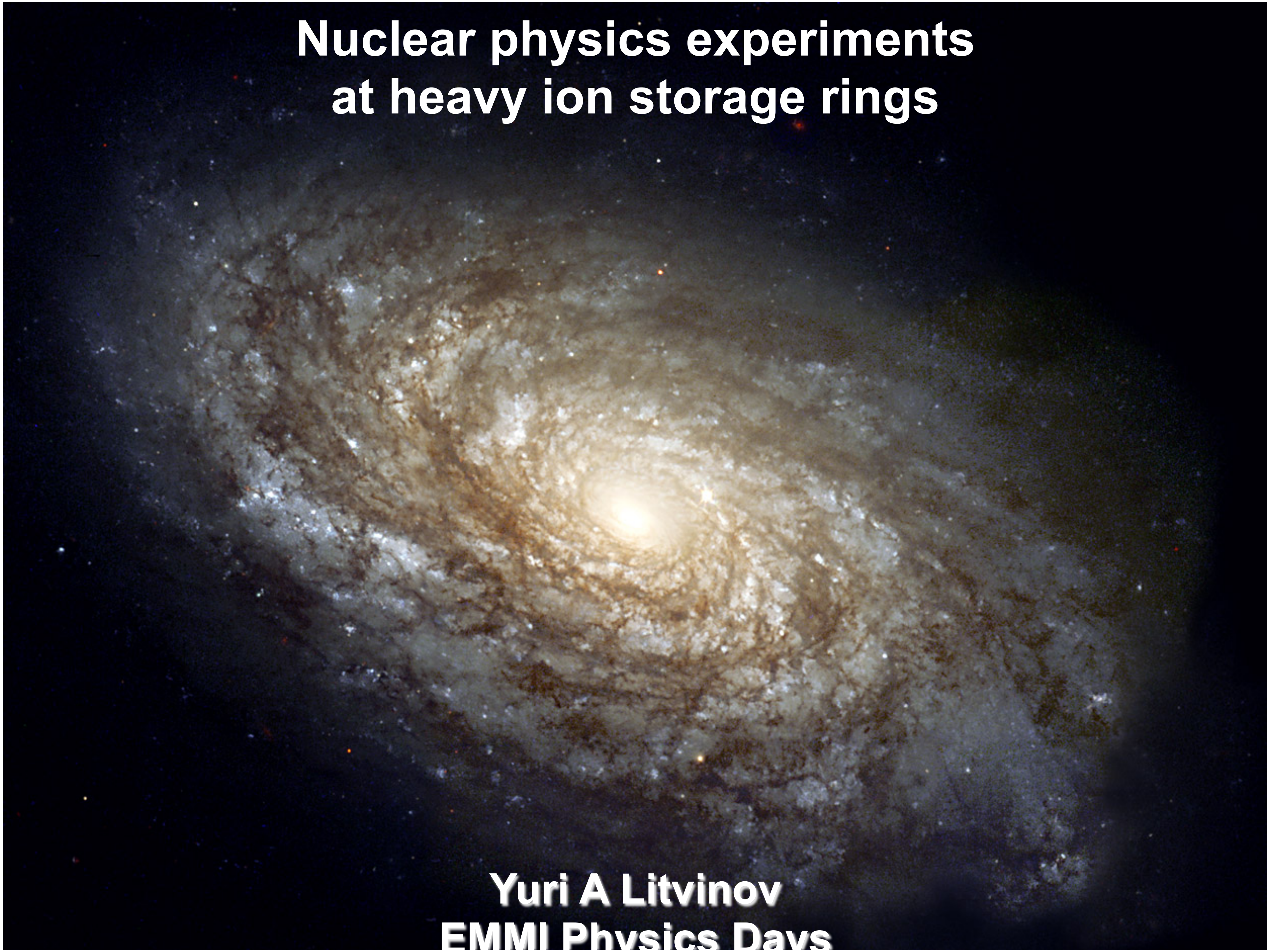
Nuclear physics experiments at heavy ion storage rings



Yuri A Litvinov

EMMI Physics Days

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]

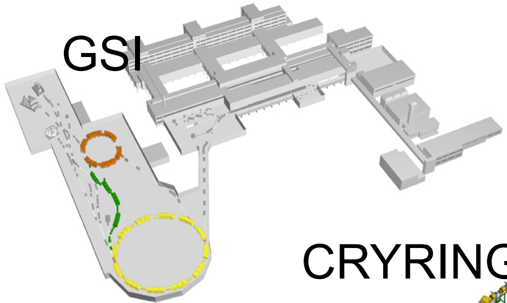
Nuclear magnetic moments [DR]

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

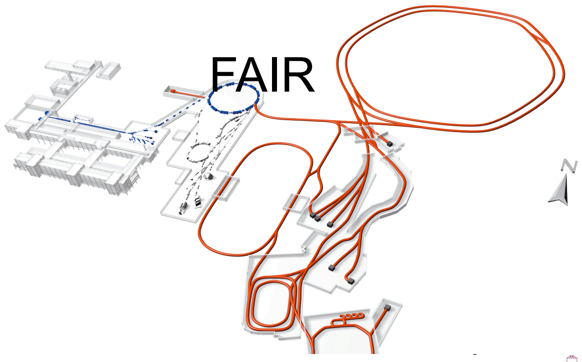
In-ring nuclear reactions

Physics at Storage Rings

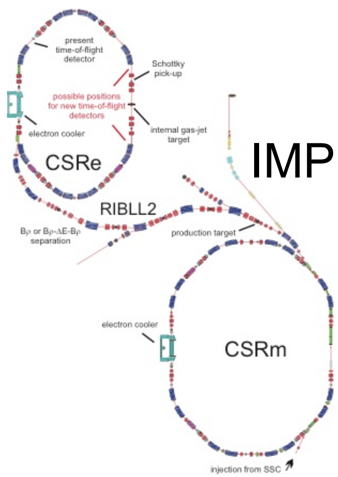
GSI



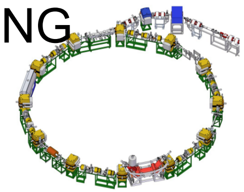
FAIR



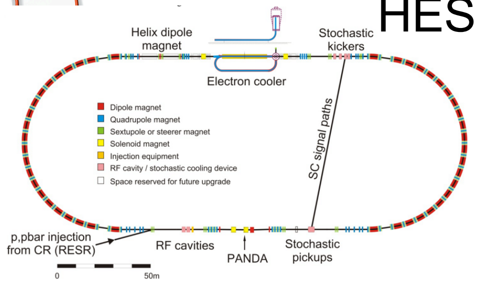
IMP

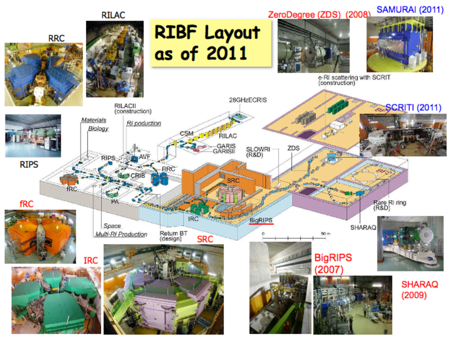


CRYRING



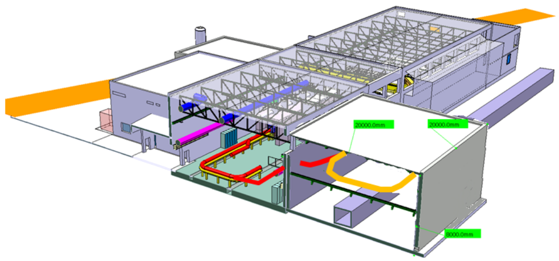
HESR



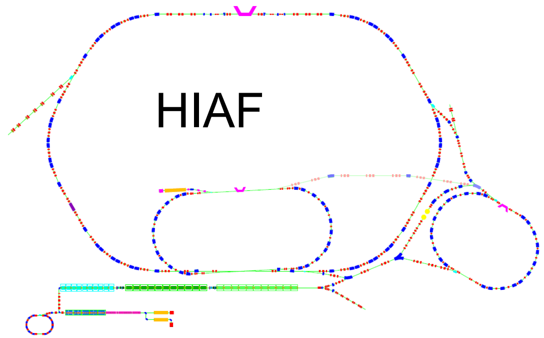


RIKEN

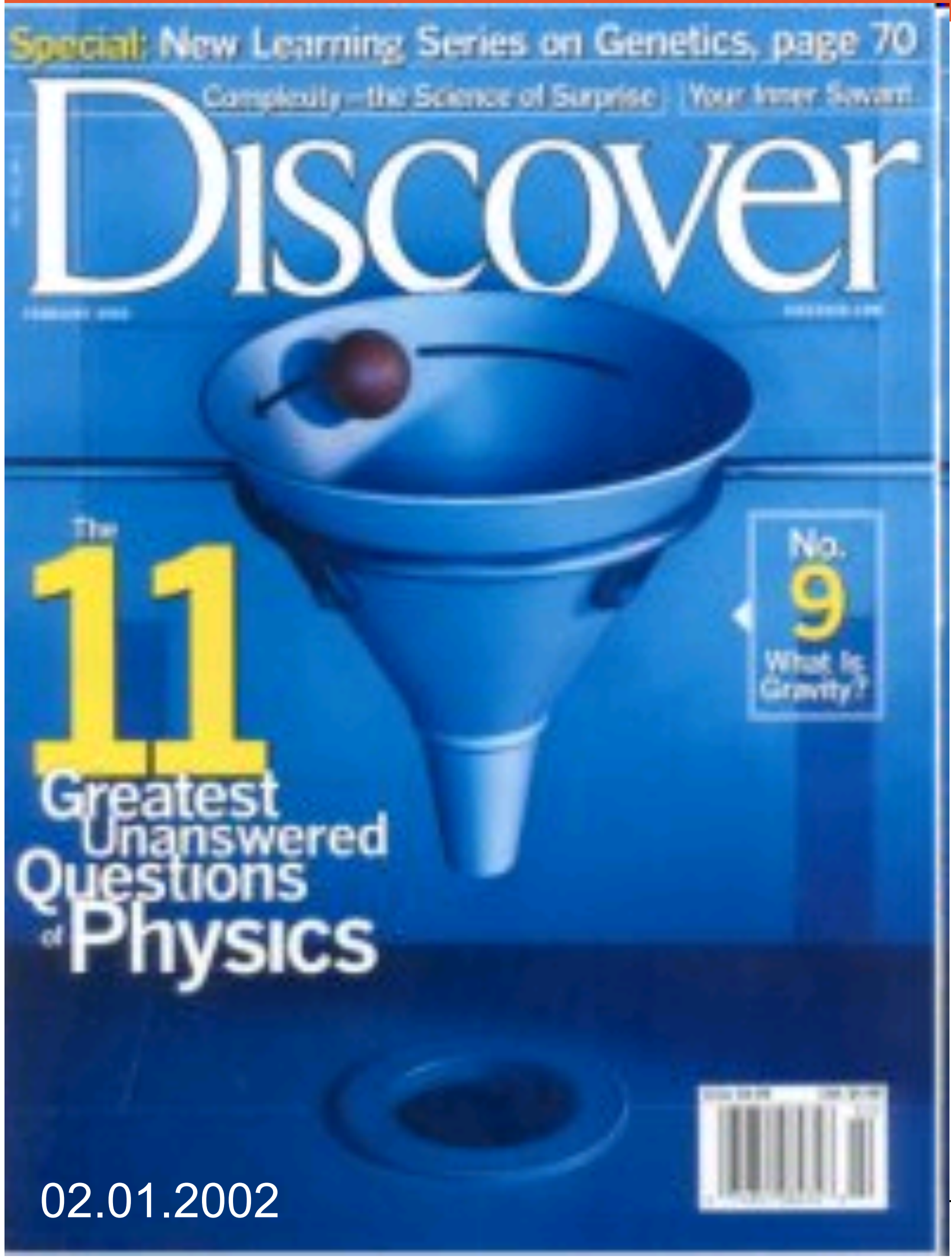
TSR@ISOLDE



HIAF



National Research Council's board für Physik und Astronomie



02.01.2002

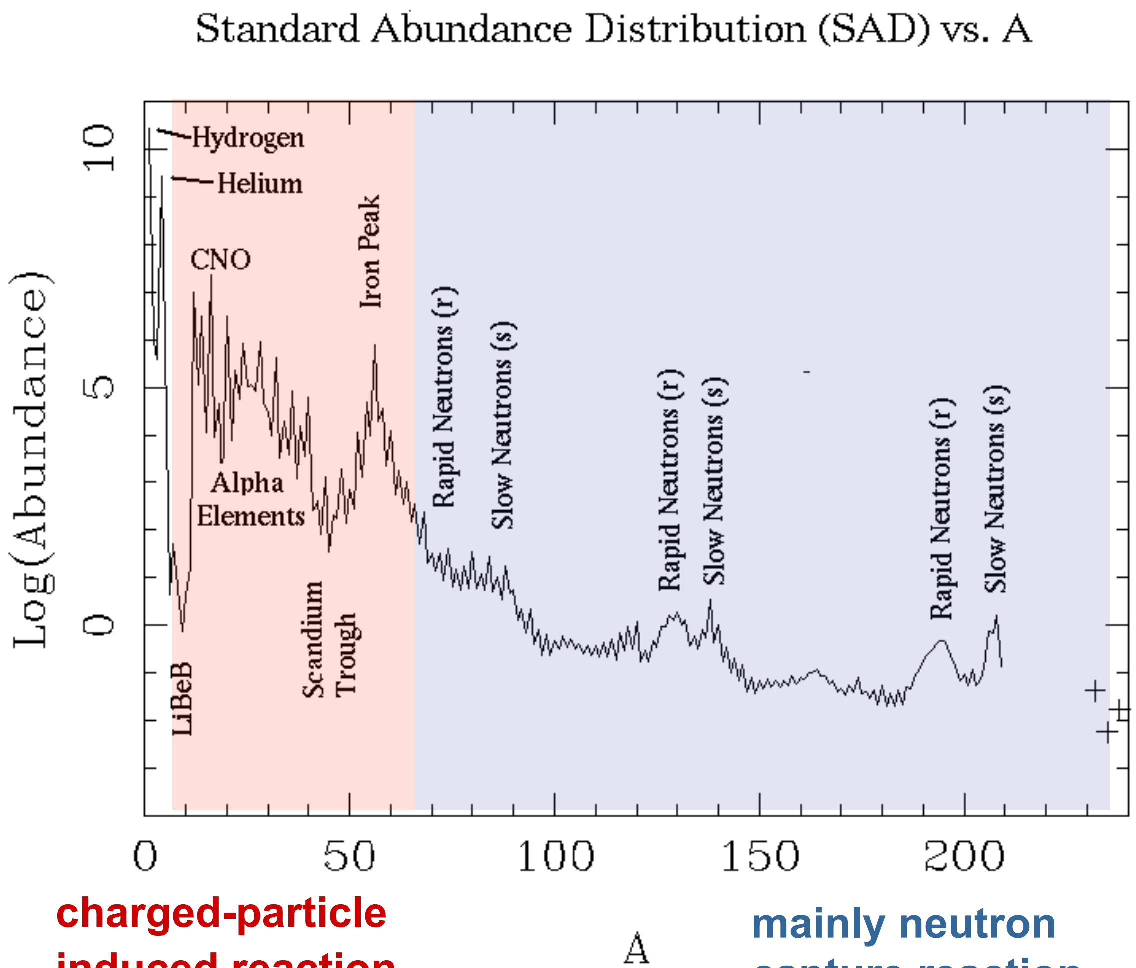
The 11 Greatest Unanswered Questions of Physics

"Resolution of these profound questions could unlock the secrets of existence and deliver a new age of science within several decades"

1. What is dark matter?
2. What is dark energy?
3. **How were the heavy elements from iron to uranium made?**
4. Do neutrinos have mass?
5. Where do ultrahigh-energy particles come from?
6. Is a new theory of light and matter needed to explain what happens at very high energies and temperatures?
7. Are there new states of matter at ultrahigh temperatures and densities?
8. Are protons unstable?
9. What is gravity?
10. Are there additional dimensions?
11. How did the universe begin?

GSI

Nuclear processes in astrophysics



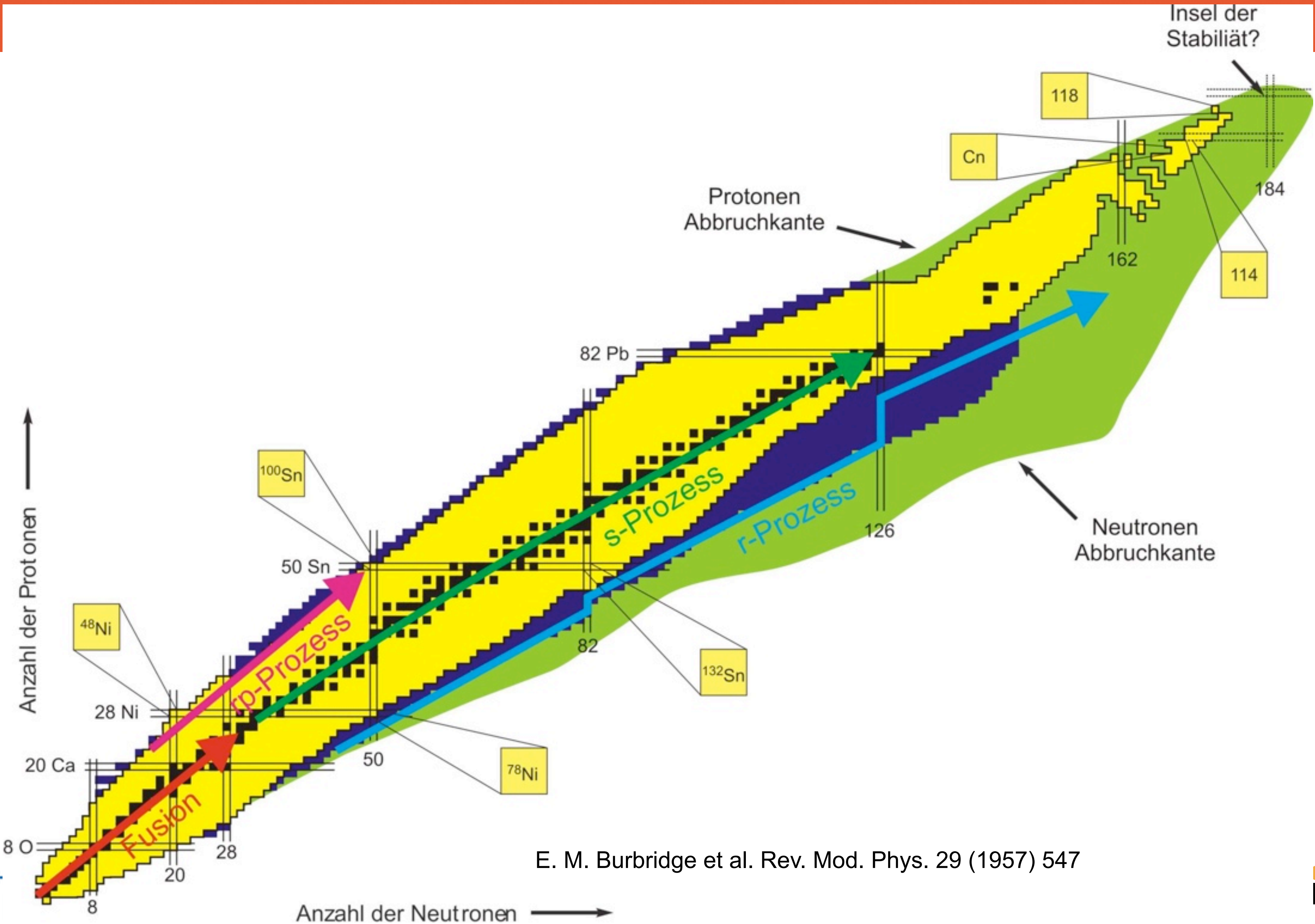
charged-particle induced reaction

mainly neutron capture reaction

involve mainly STABLE NUCLEI

involve mainly UNSTABLE NUCLEI

Nucleosynthesis on the Chart of the Nuclides



E. M. Burbridge et al. Rev. Mod. Phys. 29 (1957) 547

Limits of nuclear stability: superheavies; p- and n- drip lines; pathways of stellar nucleosynthesis

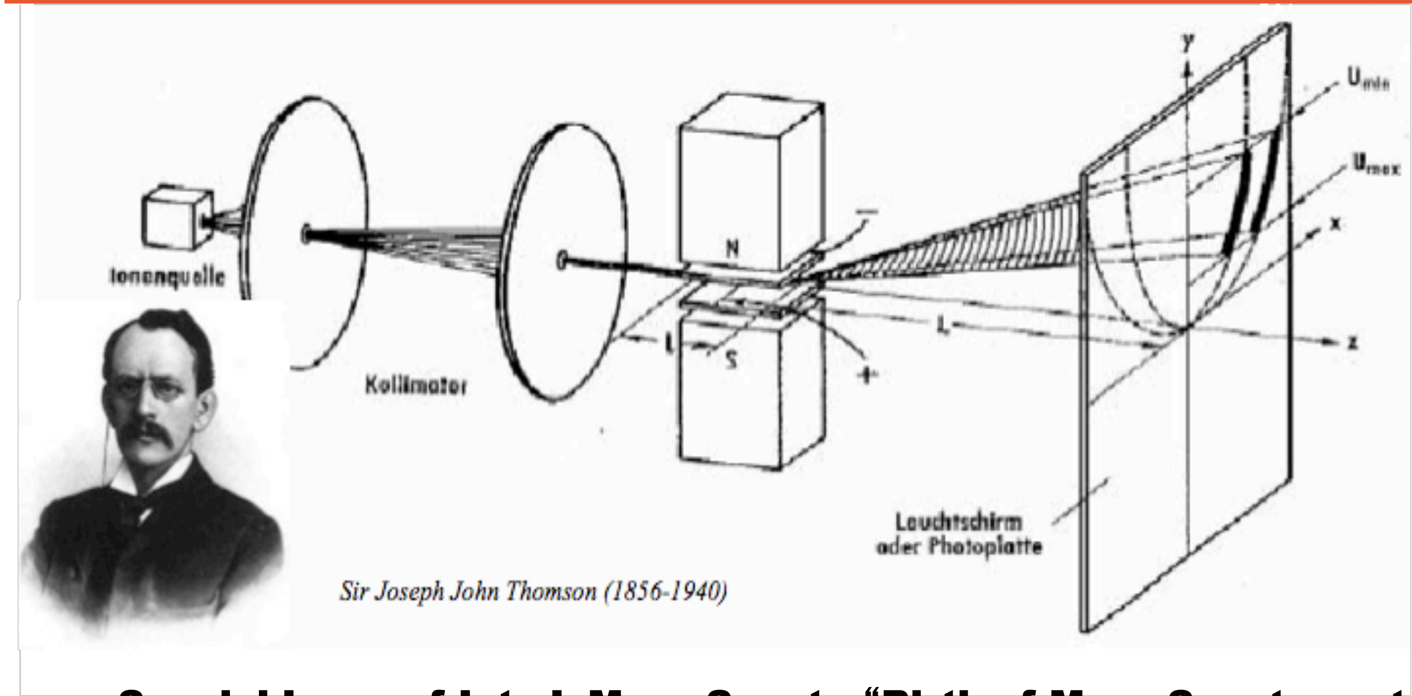
To measure: Ground state properties of exotic nuclei:

masses and β decay half-lives

masses determine the
pathways of s-, rp- and r-processes

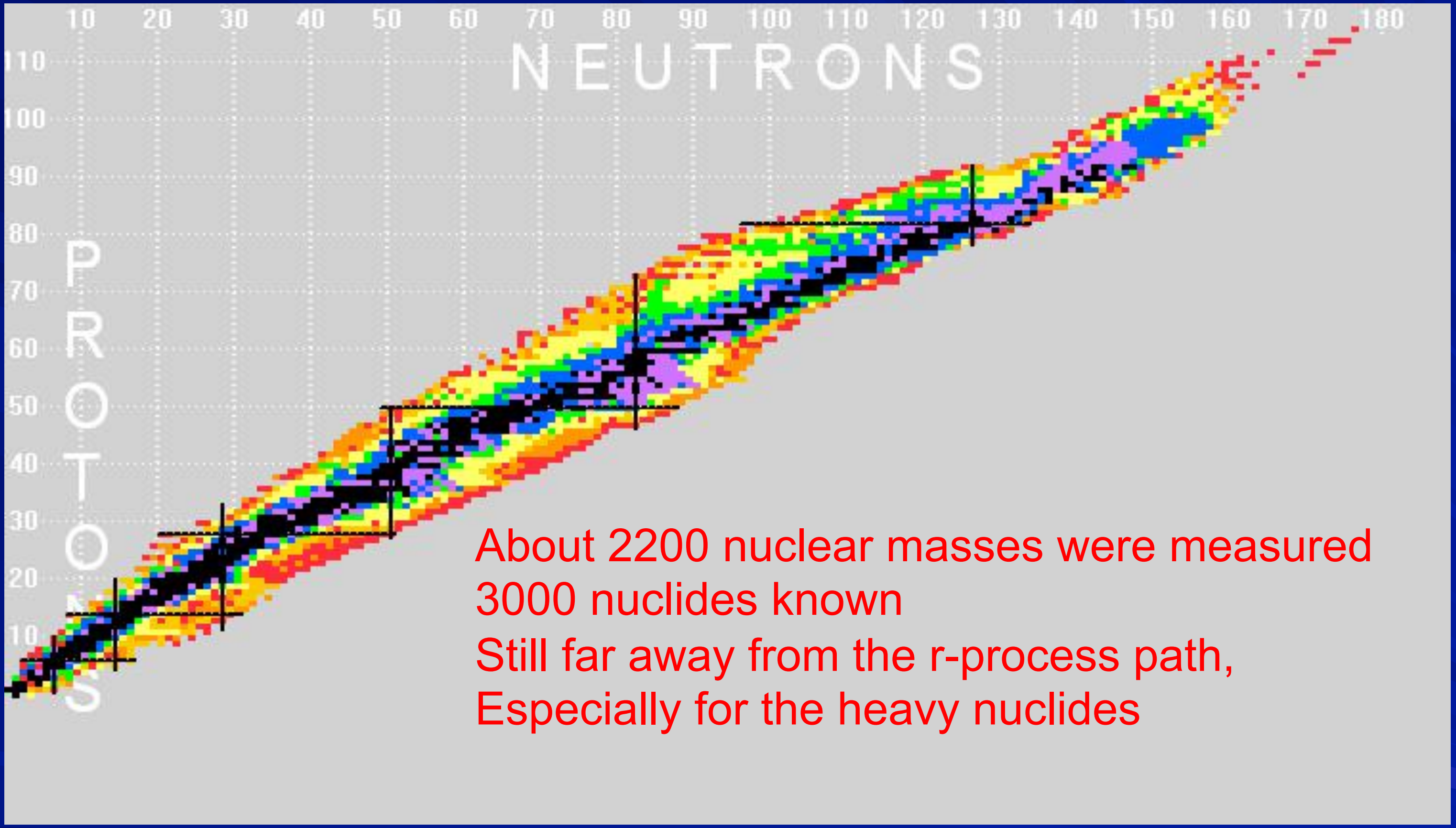
β half-lives the accumulated abundances

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



- **Special Issue of Int. J. Mass Spectr. "Birth of Mass Spectrometry"**
- **DPG Symposium "100 Years of Mass Spectrometry", Hanover, 2013**
- **513. WE-Heraeus Seminar: "Astrophysics with Ion-Storage Rings", January 2013**
- **530. WE-Heraeus Seminar on "Nuclear Masses and Nucleosynthesis", April 2013**
- **New Atomic Mass Evaluation (AME2012) is to appear in 2013**

Current status of experimental nuclear masses

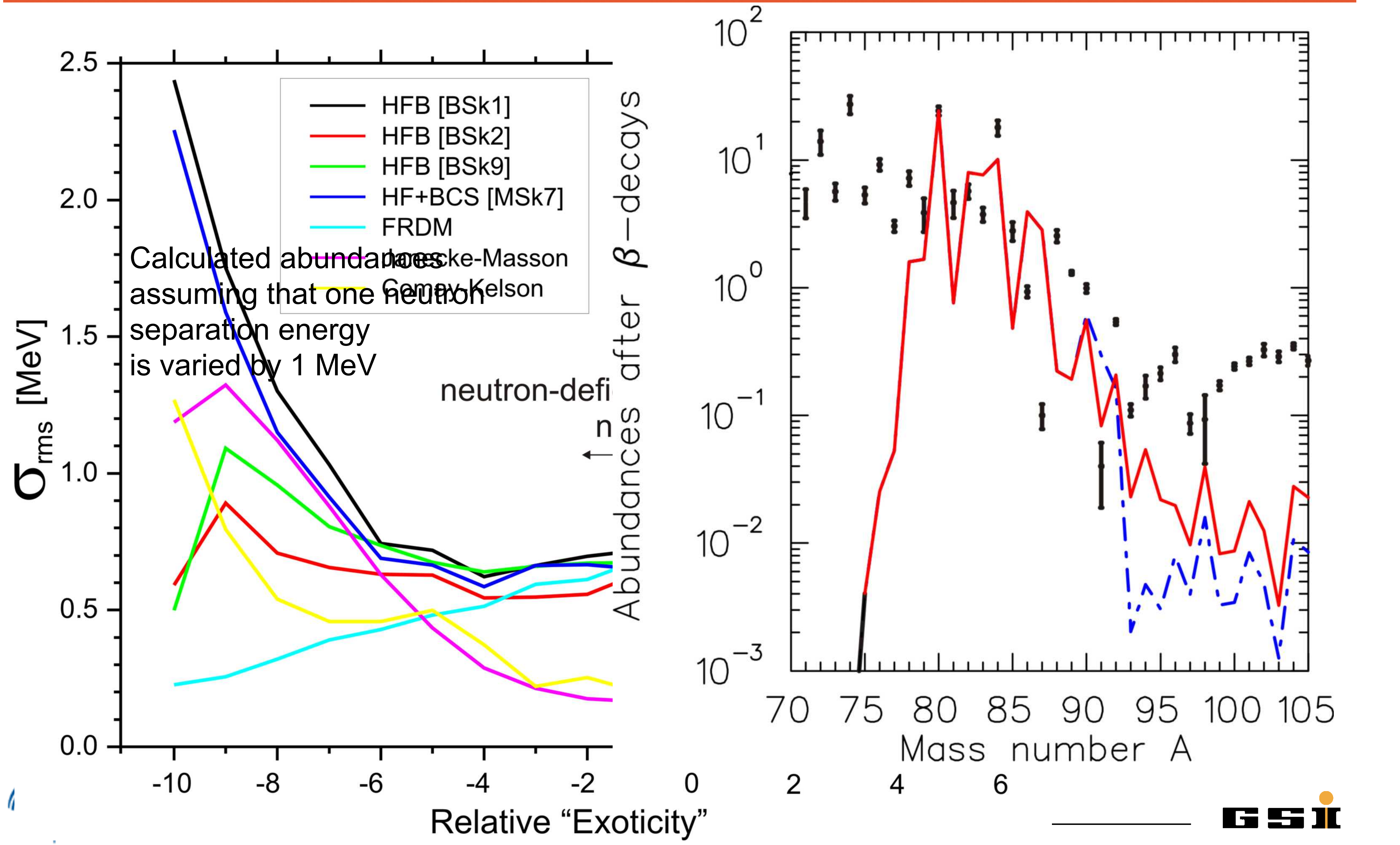


About 2200 nuclear masses were measured
3000 nuclides known
Still far away from the r-process path,
Especially for the heavy nuclides

Up to 2004!

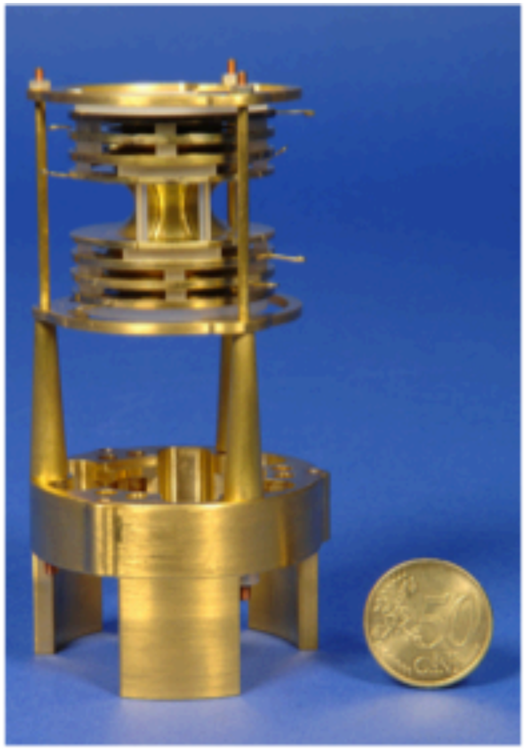
G. Audi et al., Nucl. Phys. A565, 1(1993); A 595, 409 (1995), A729.337(2003)

Predictive Powers of Mass Models



Devices for precise mass measurements

Penning trap



particles at nearly rest in space

Storage ring

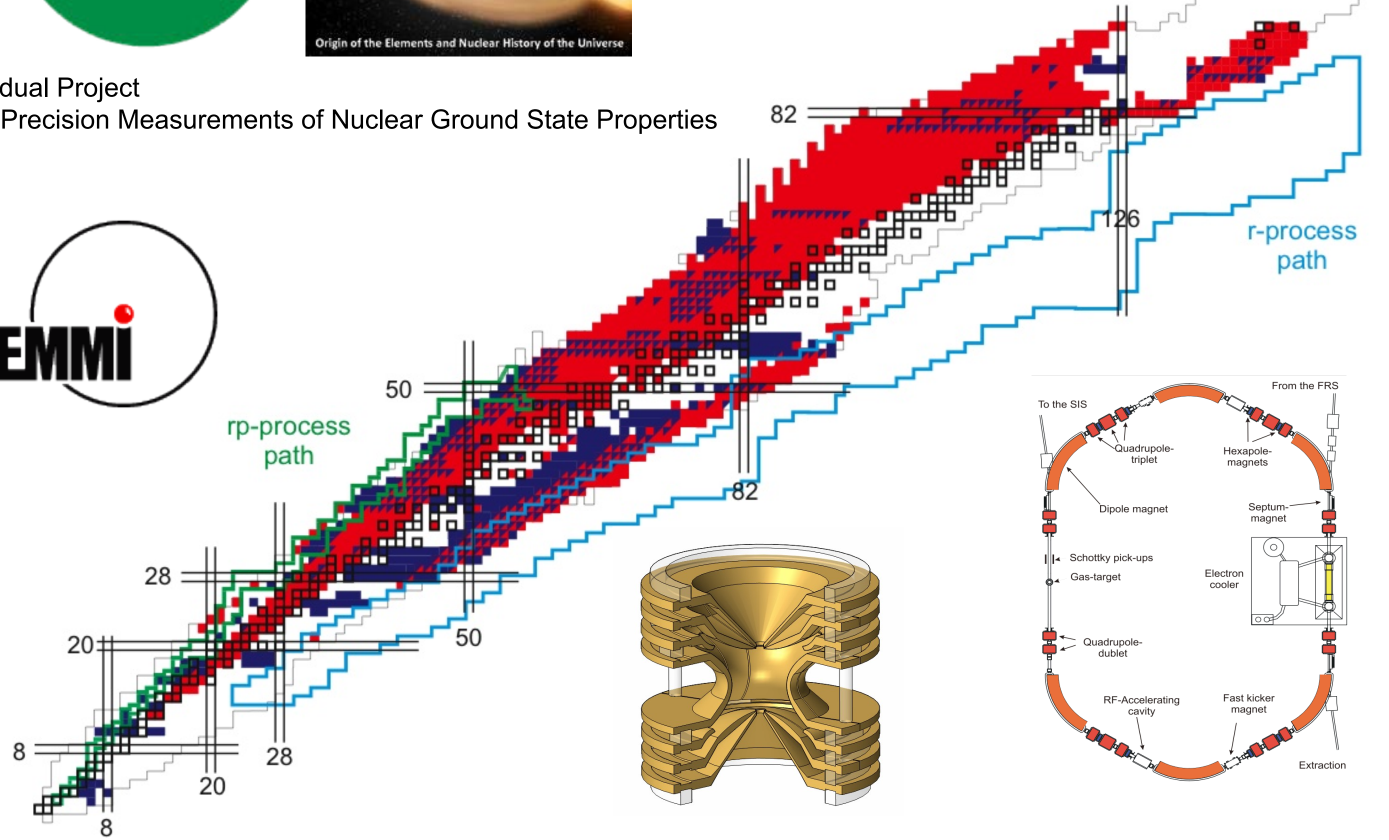
relativistic particles

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

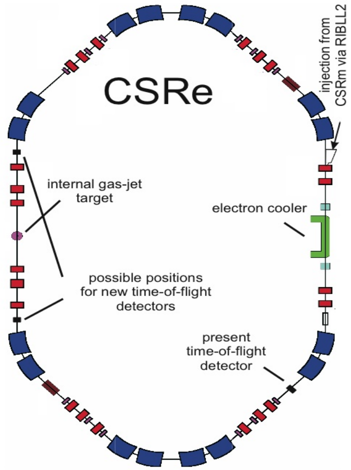
Direct Mass Measurements on the Chart of the Nuclides

EuroGENESIS
FirstStars
CoDustMas
EXNUC
MASCHE
Origin of the Elements and Nuclear History of the Universe

Individual Project
High-Precision Measurements of Nuclear Ground State Properties

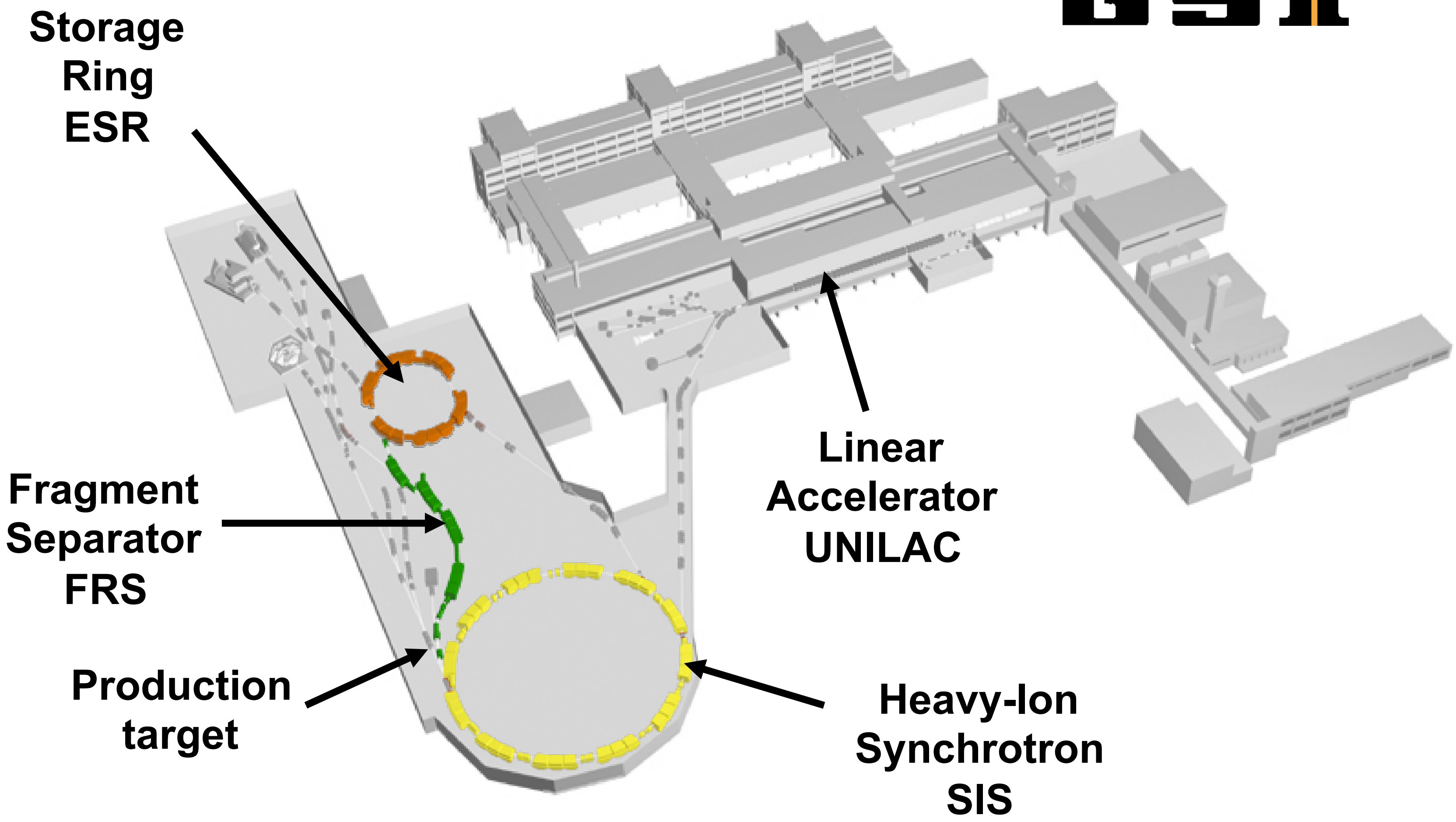


Penning Traps

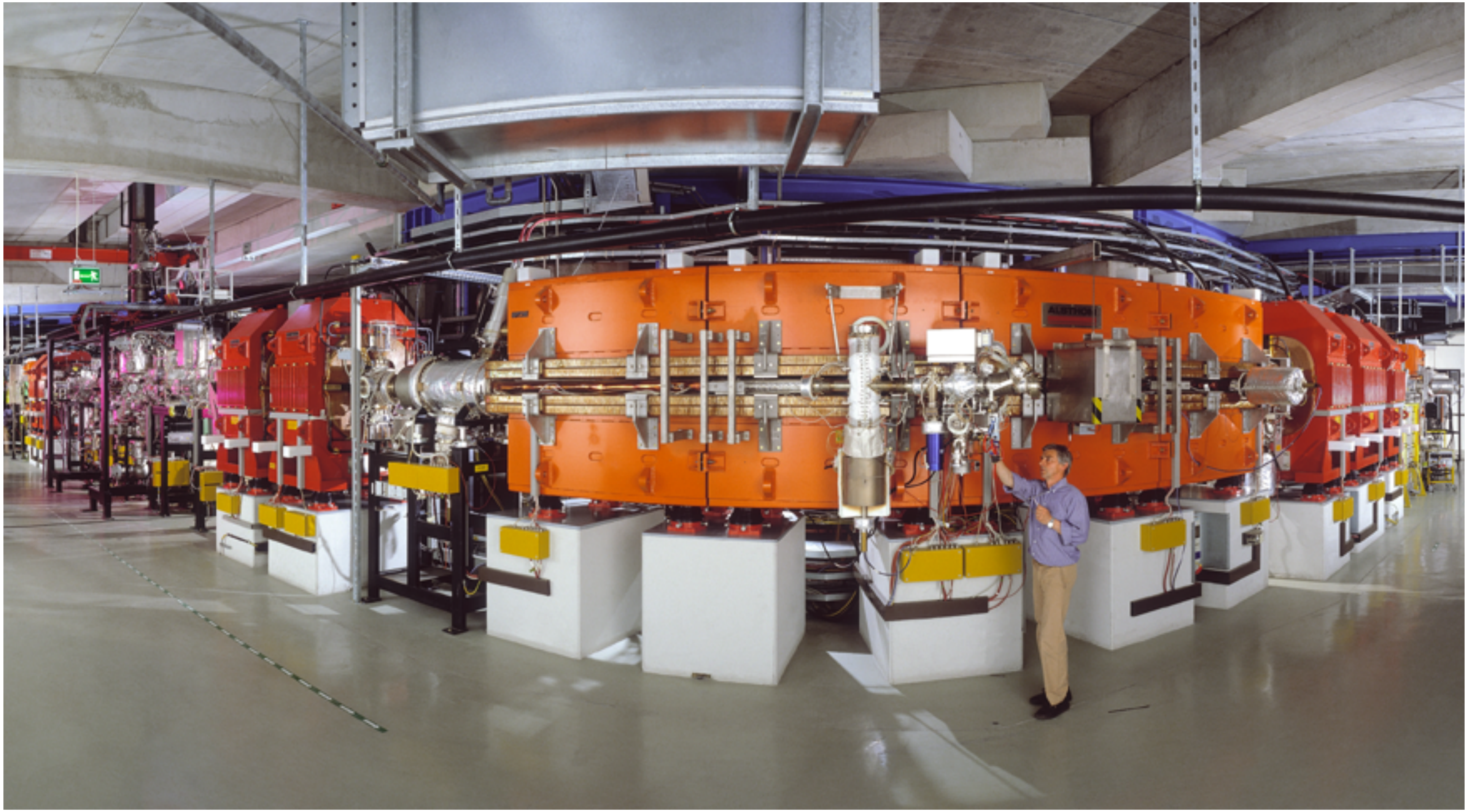


Storage Rings

Secondary Beams of Short-Lived Nuclei



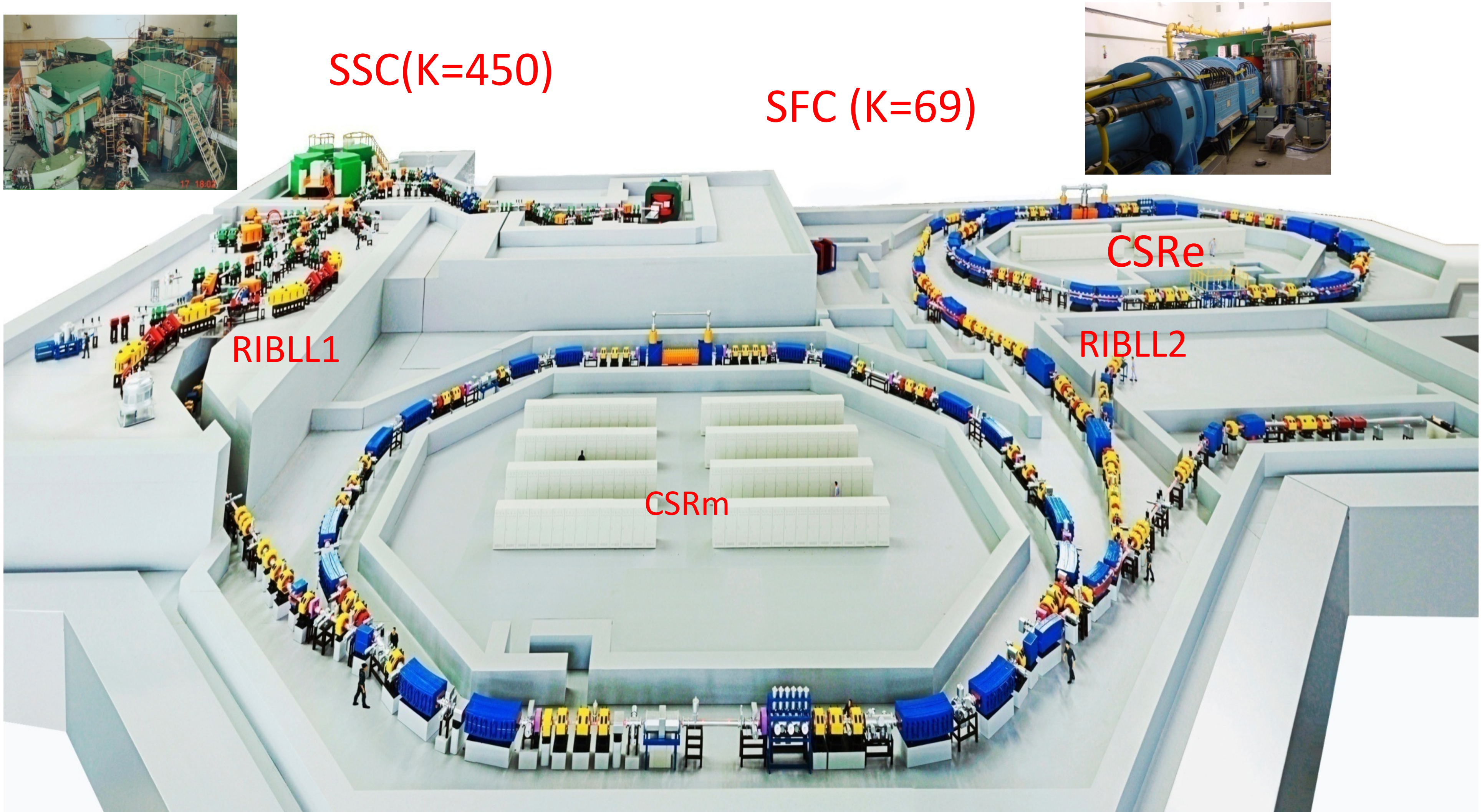
Experimental Storage Ring ESR



ESR: B. Franzke, NIM B 24/25 (1987) 18

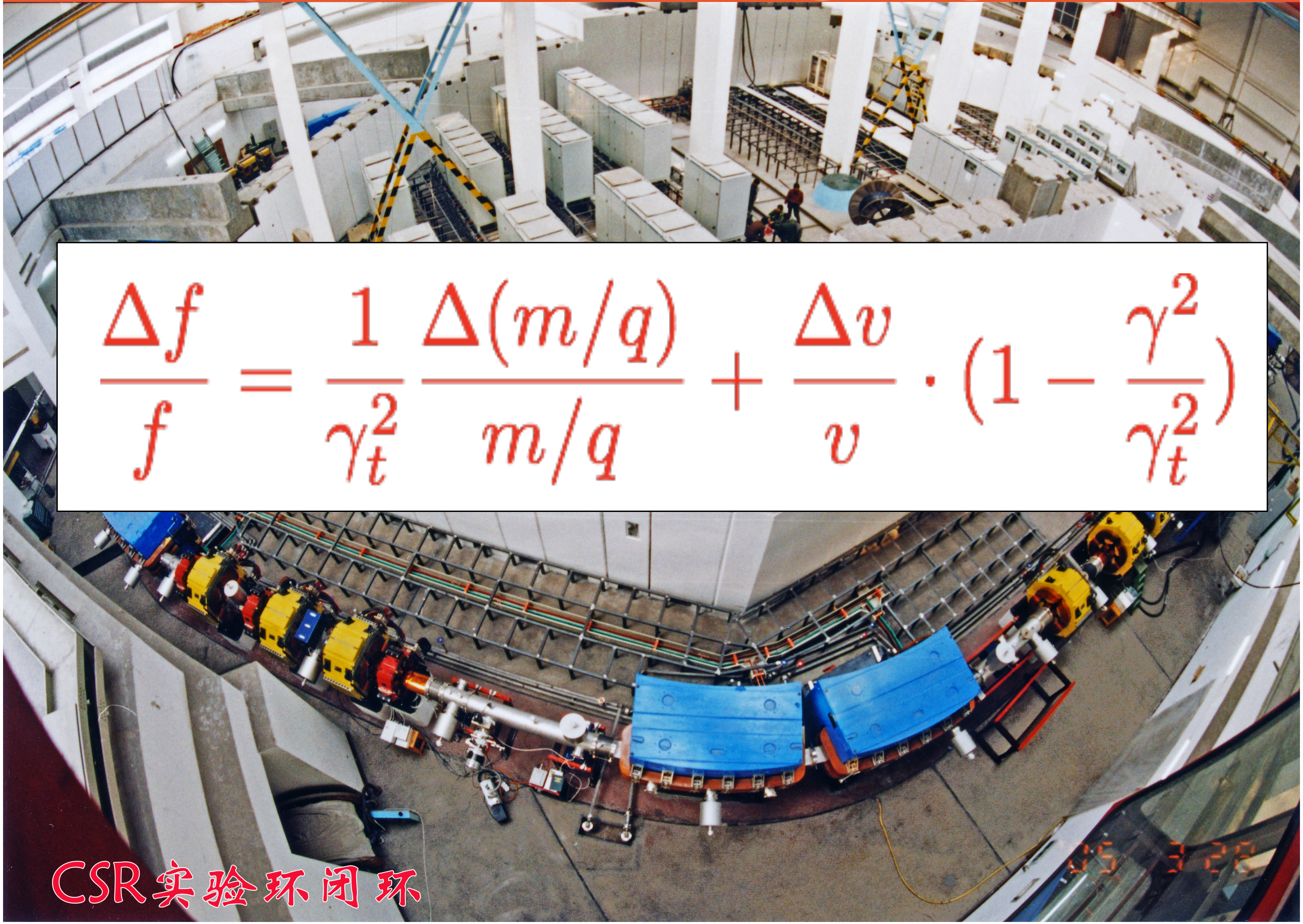
Stochastic cooling: F. Nolden et al., NIM B 532 (2004) 329
Electron cooling: M. Steck et al., NIM B 532 (2004) 357

Heavy Ion Research Facility in Lanzhou (HIRFL)



Experimental Cooler Storage Ring CSRe

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



Isochronous Mass Spectrometry

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

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

$$\gamma_t \rightarrow \gamma$$

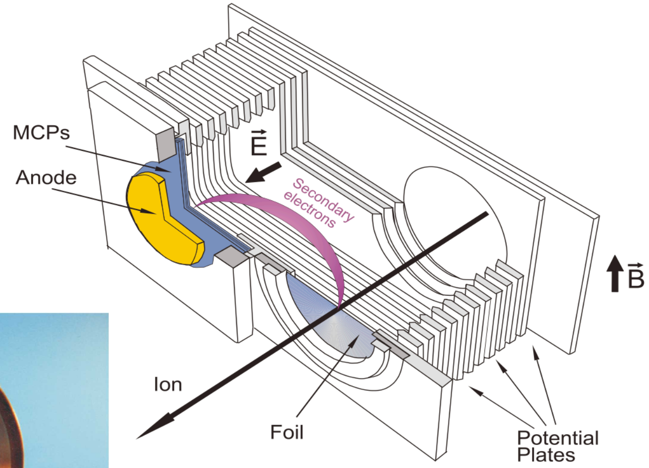
ims_basic2.swf

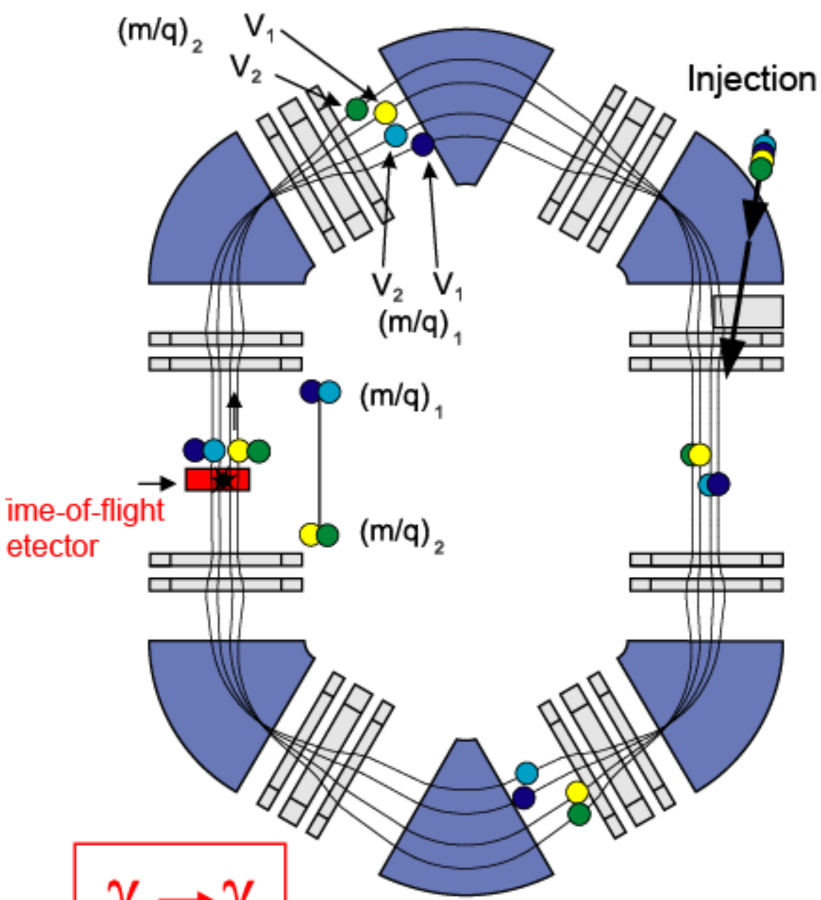
Isochronous Mass Spectrometry

1985 - H. Wollnik, et al.

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

$\gamma_t \rightarrow \gamma$





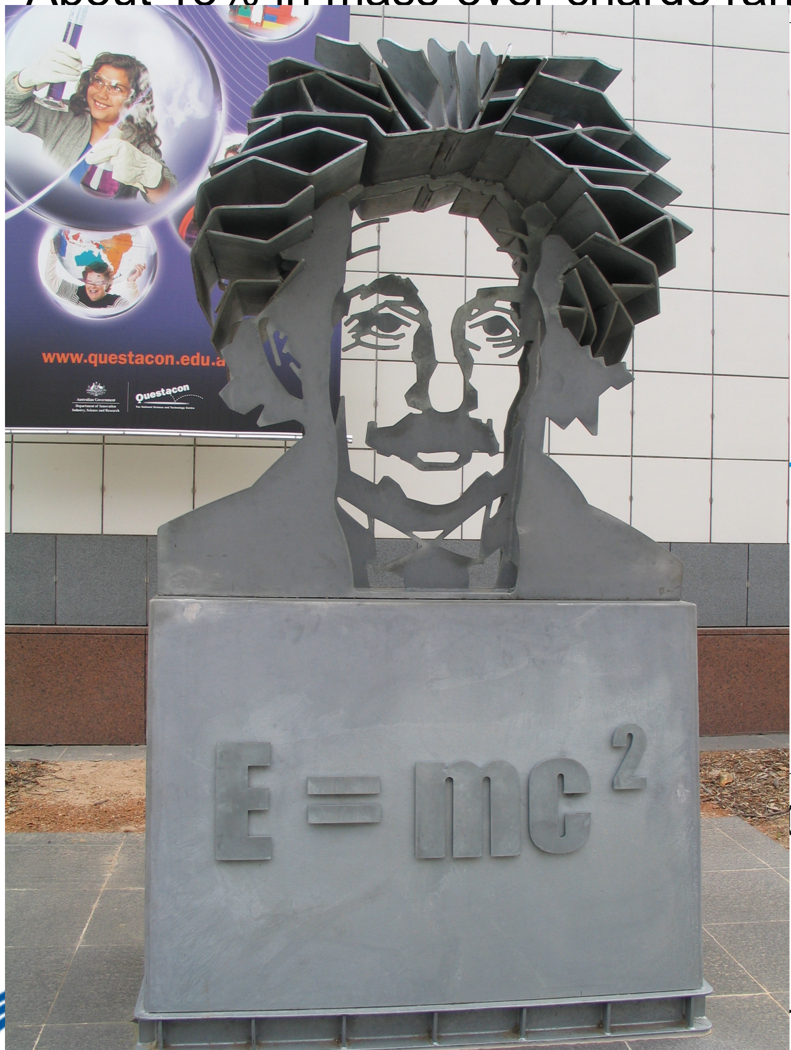
$\gamma_t \rightarrow \gamma$

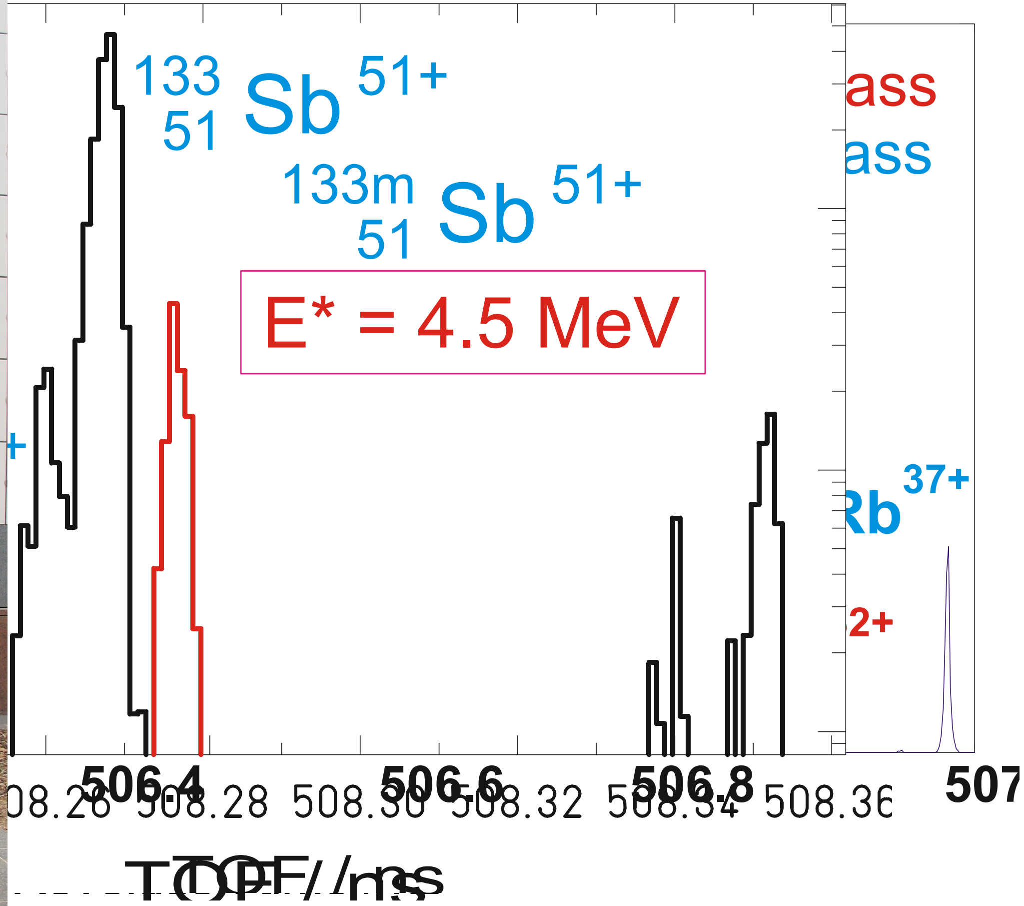
Hot fragments

IMS: Time-of-Flight Spectra

Nuclei with half-lives as short as 20 μs

About 13% in mass-over-charge range





ractions 132 (2001) 291 M. Matos et al., Proc. EXON 2004

Mass Measurements of ^{78}Kr Projectile Fragments
New masses of ^{63}Ge, ^{65}As, ^{67}Se, and ^{71}Kr

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.

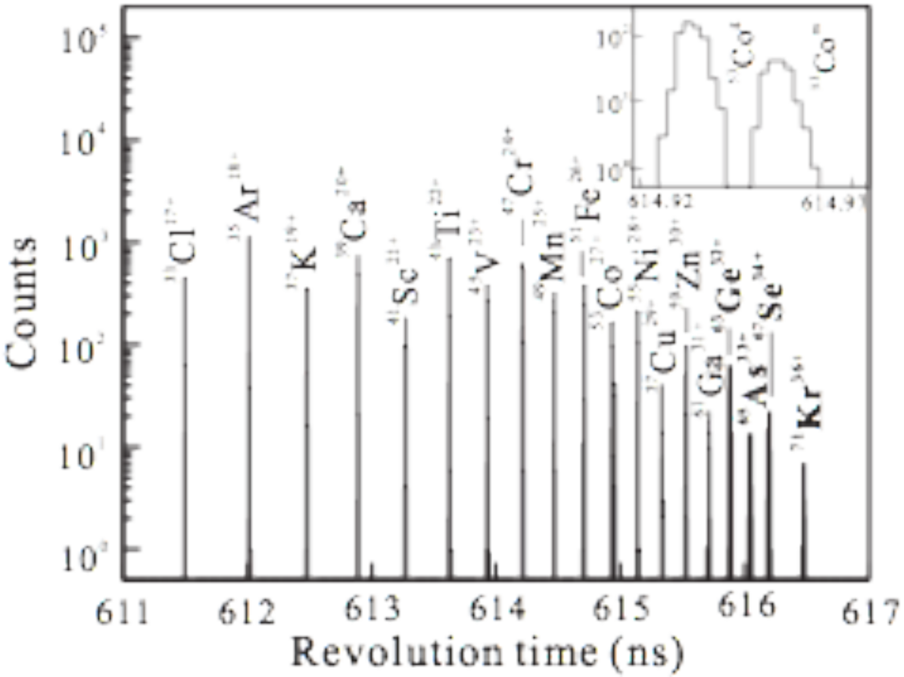
NATURE PHYSICS | VOL 7 | APRIL 2011 | www.nature.com/naturephysics

BRENNPUNKT

Kein Halten am Wartepunkt

Hochpräzise Massenmessungen erklären die Kernreaktionen bei Ausbrüchen von Röntgenstrahlung.

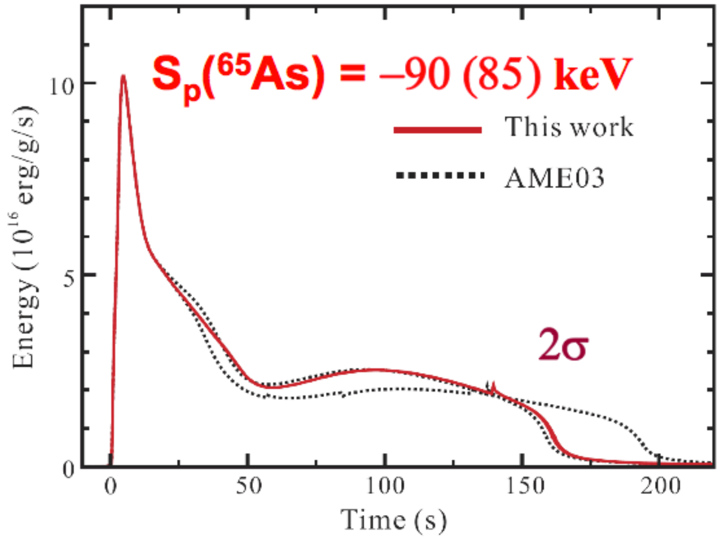
Physik Journal 10 (2011) Nr. 6



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

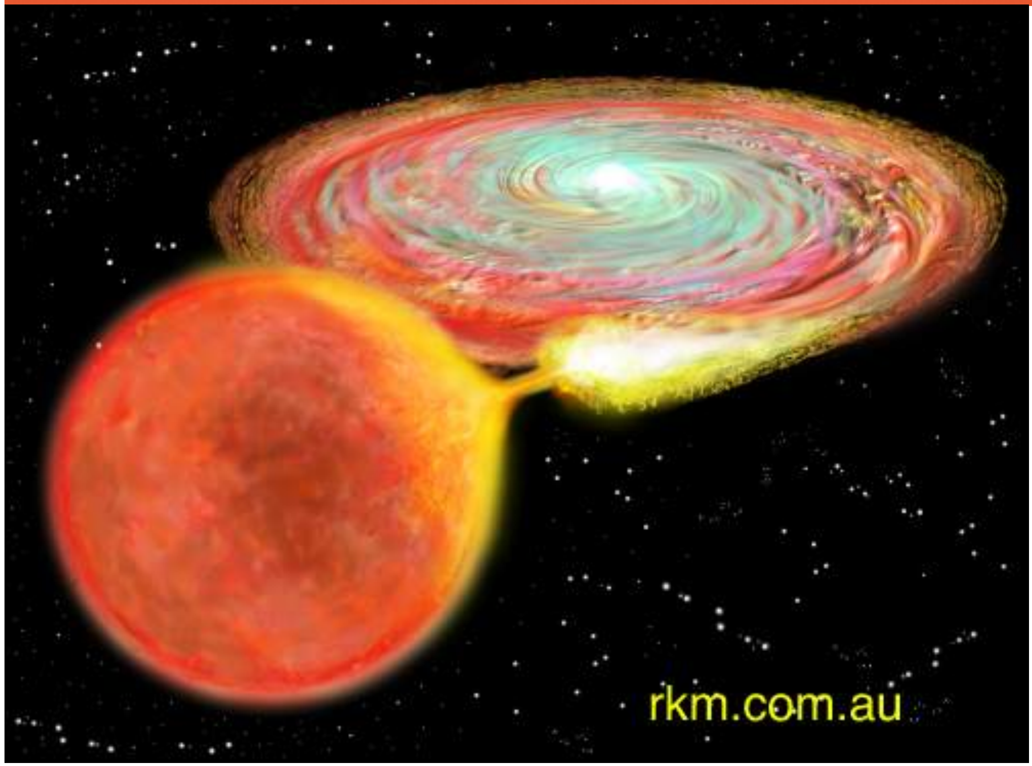
80-90% of the reaction flow passes through ^{64}Ge via proton capture reactions

Light curve shape of Type I x-ray burst

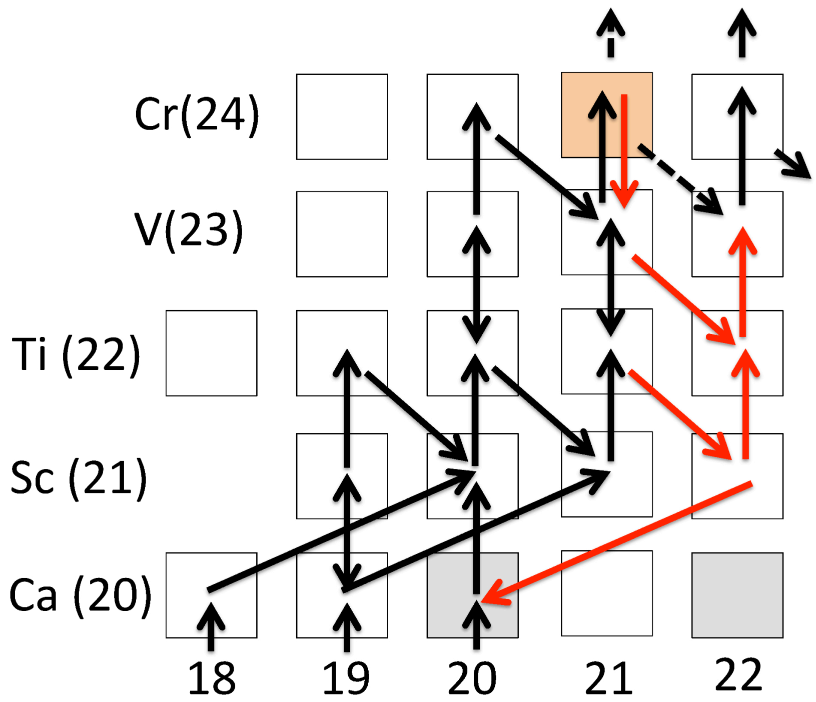


X.Tu, et al., Phys. Rev. Lett. 106 (2011) 112501

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]

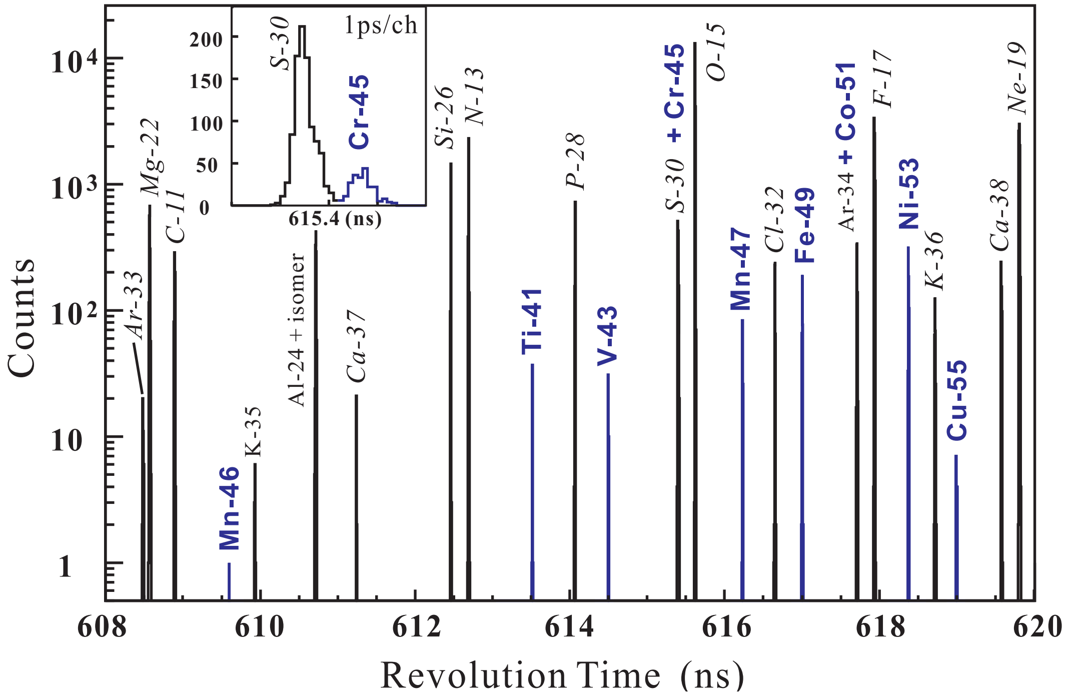


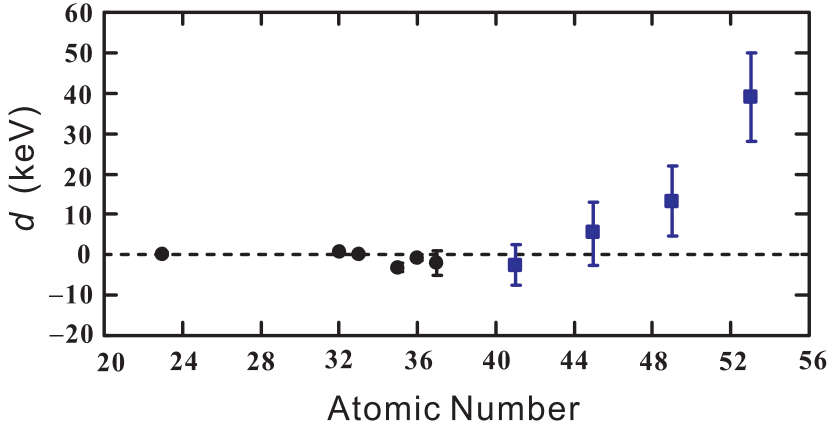
$S_p(^{45}Cr)$= 2.1(5) MeV [AME03]

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

X.L. Yan et al., in preparation (2012)

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





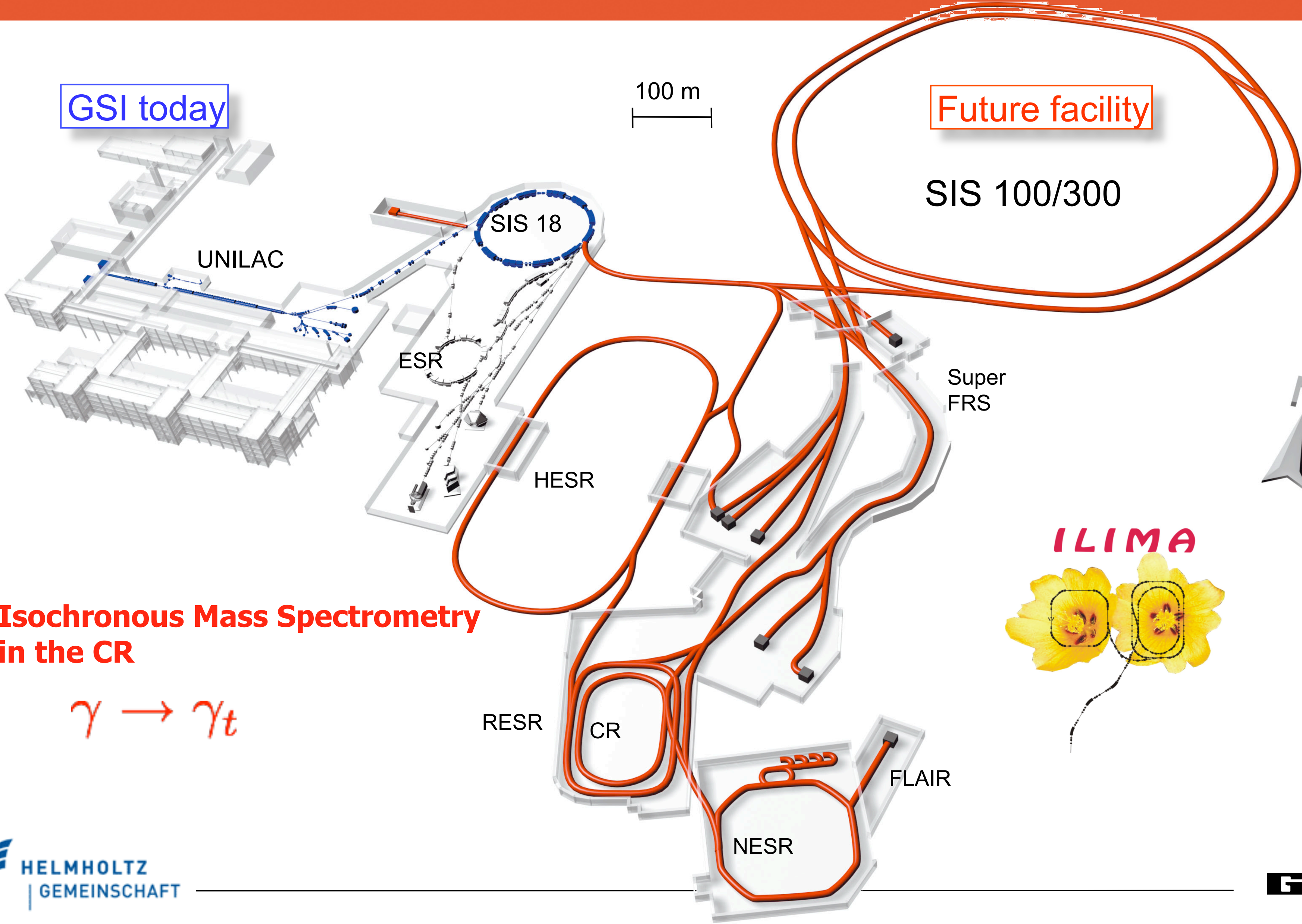
Isobaric Multiplet Mass Equation

$$ME(A,T,T_z) = a(A,T) + b(A,T)T_z + c(A,T)T_z^2 \qquad dT_z^3\,?$$

Y.H. Zhang et al., Phys. Rev. Lett. 109 (2012) 102501

HELMHOLTZ GEMEINSCHAFT — Internationales Büro des BMBF — GSI

FAIR - Facility for Antiproton and Ion Research



Isochronous Mass Spectrometry in the CR

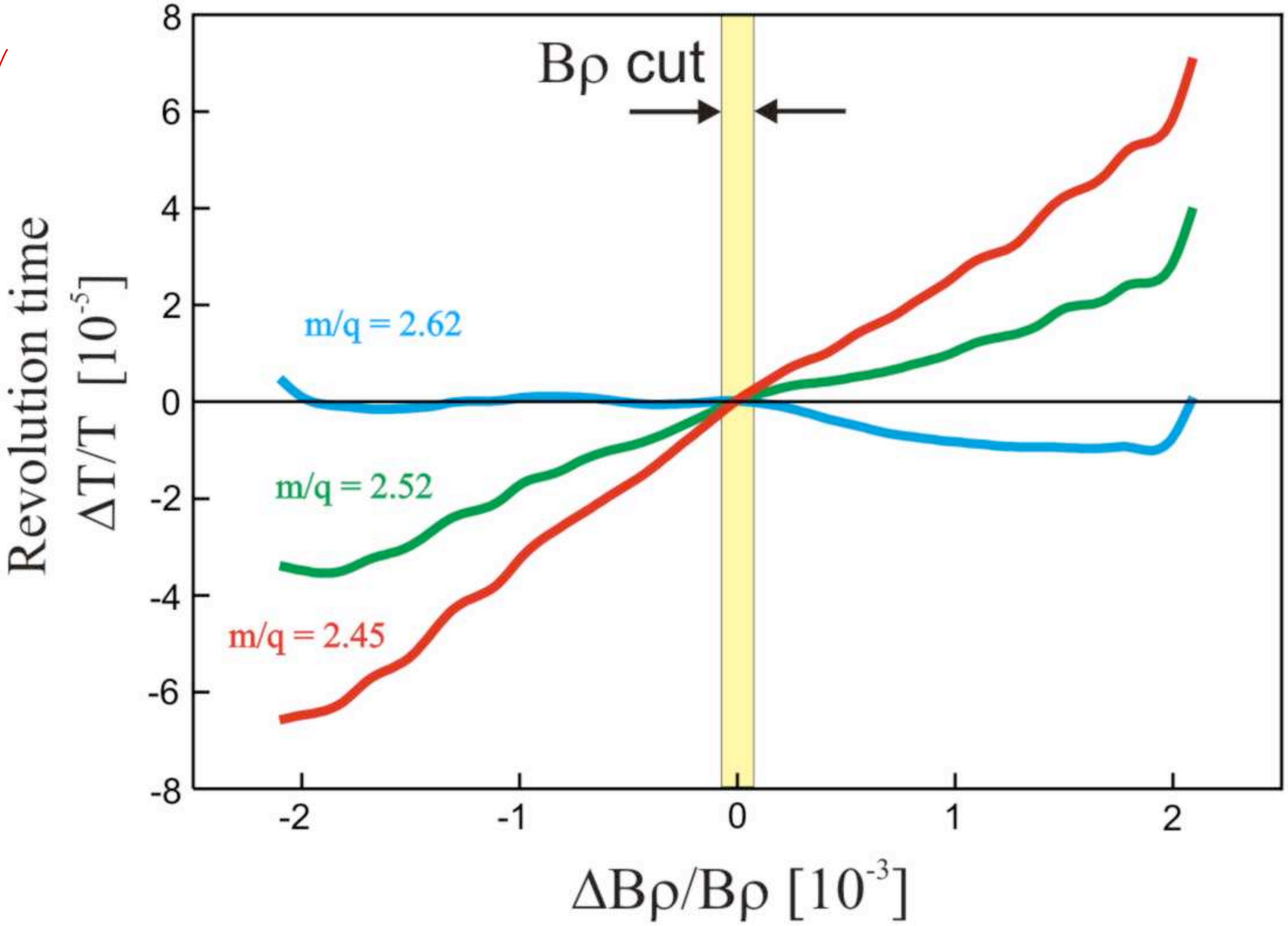
$$\gamma \rightarrow \gamma_t$$

Limitation of the Isochronicity

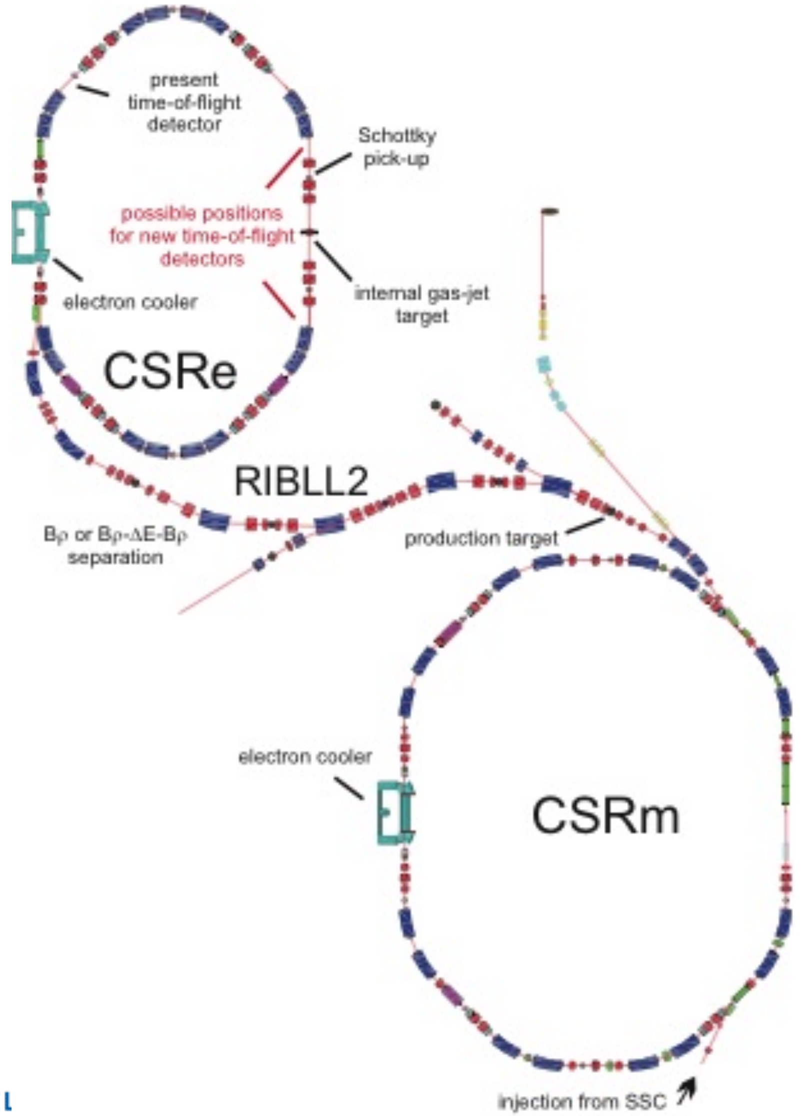
Magnetic rigidity

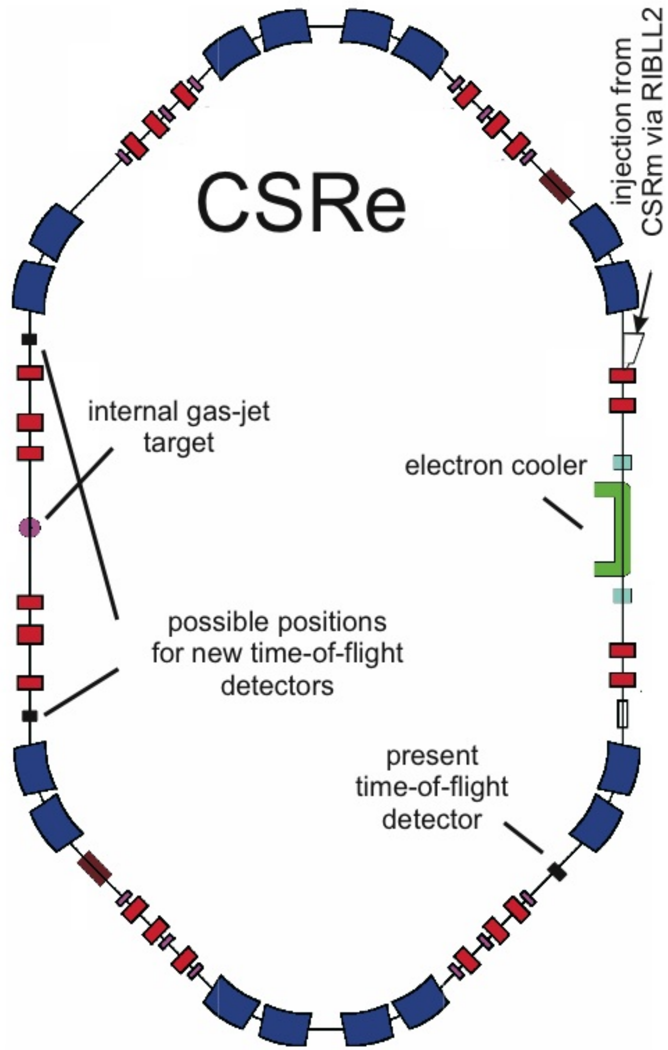
$$B\rho = \frac{m}{q} v\gamma$$

Good isochronous conditions are fulfilled only in a small range



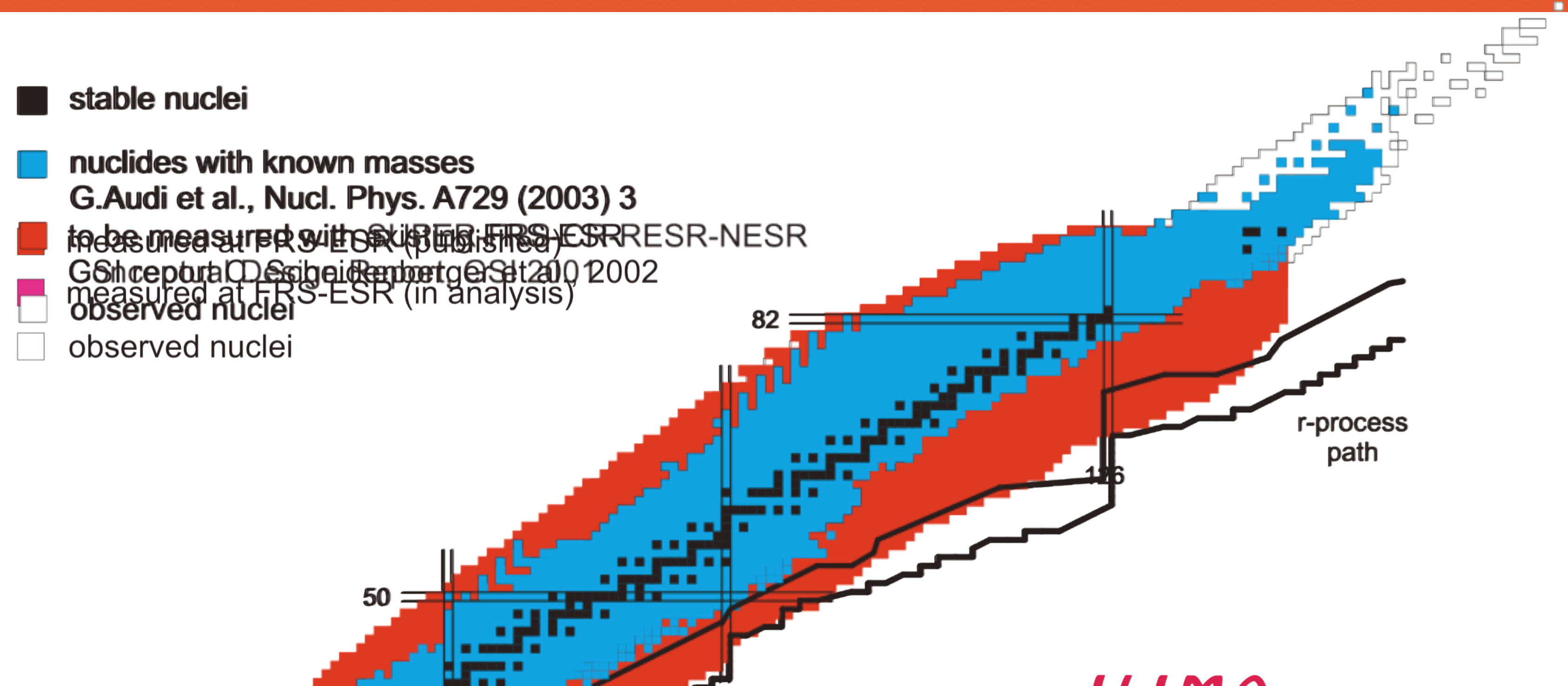
CSRm-CSRe Complex at IMP in Lanzhou



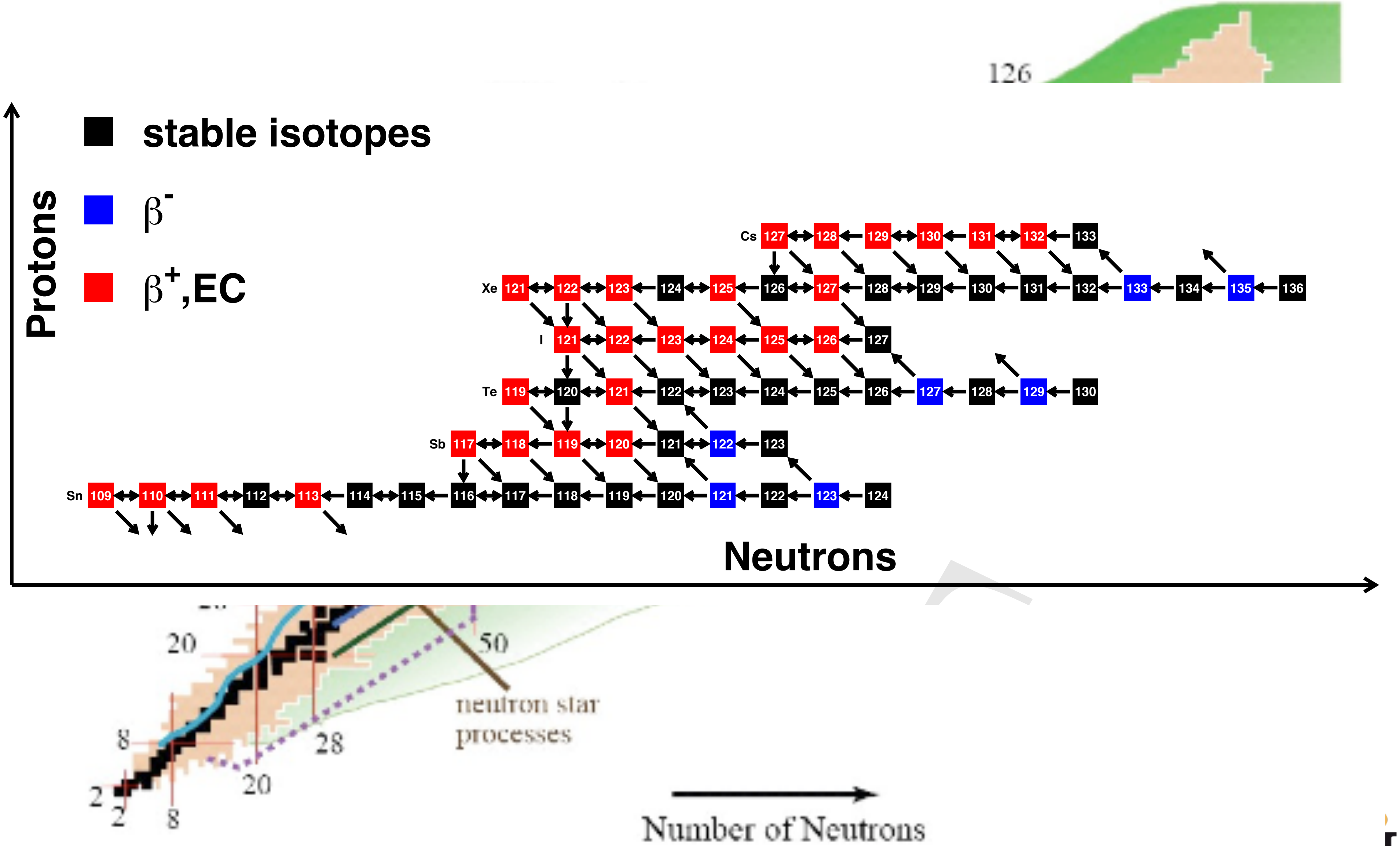


W.L. Zhan et al., Nucl. Phys. A834 (2006) 694c

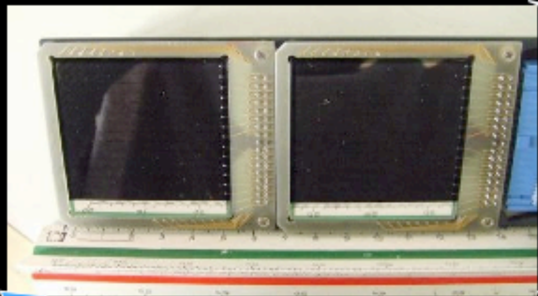
ILIMA: Masses and Halflives



2. Capture reactions for astrophysics



ESR: $^{96}Ru(p,\gamma)^{97}Rh$ at 10 MeV/u



Main Reactions:

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

$^{96}Ru(p,n)^{96}Rh$

$^{96}Ru(p,a)^{93}Tc$

$^{96}Ru^{44+} \rightarrow {}^{96}Ru^{43+}$

DSSSD:

Strips:16*16

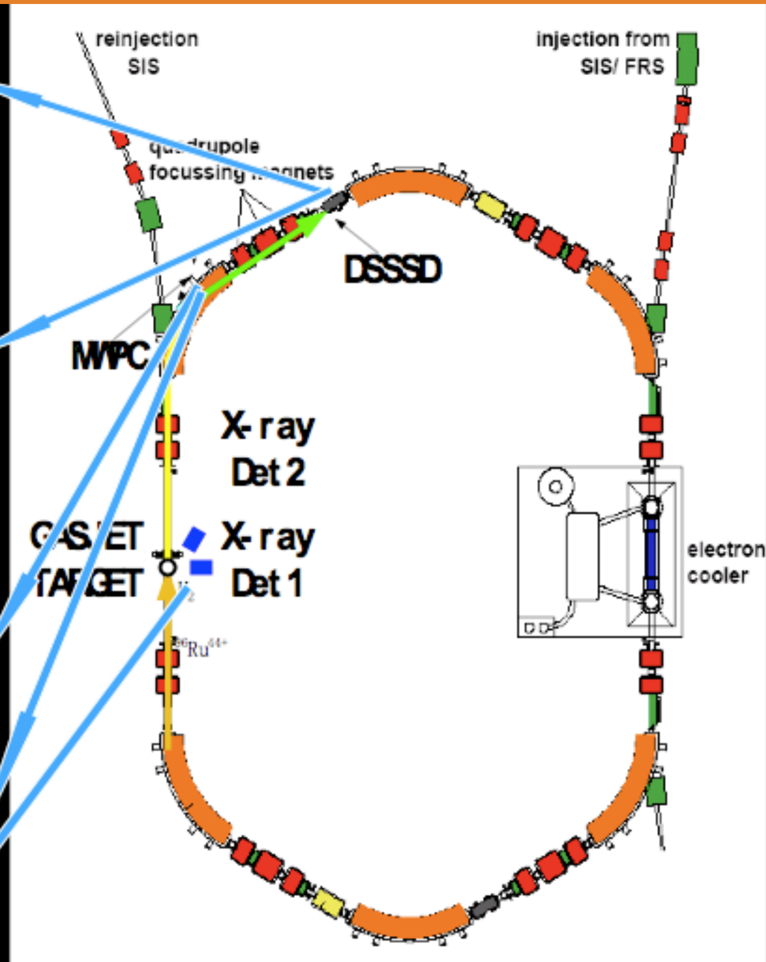
Strip width:3mm

MWPC:

Active area: ~120*20mm²

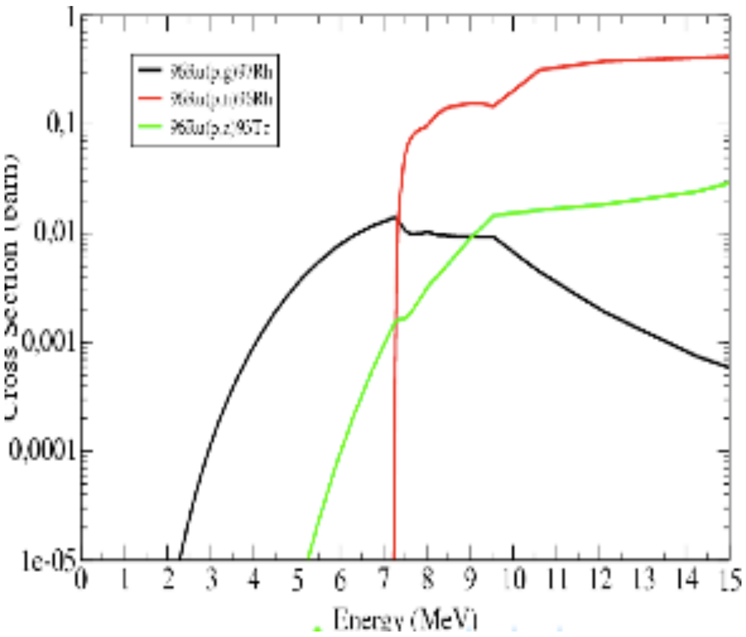
X-Ray detector:

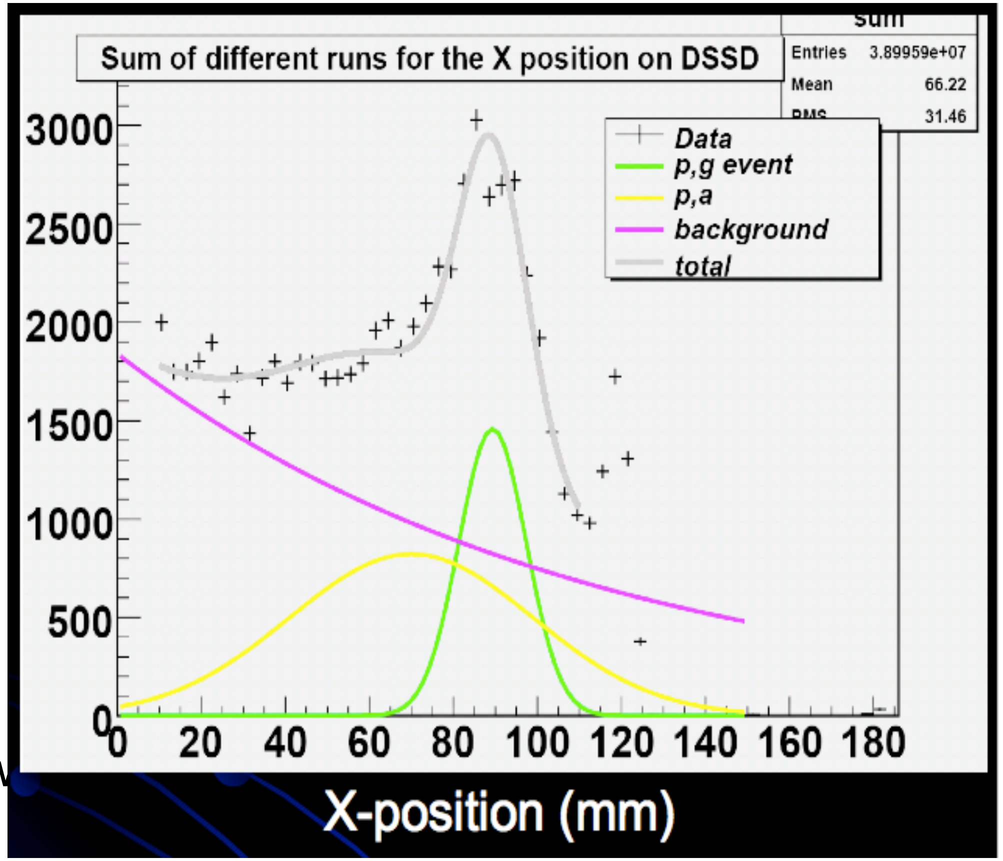
GLP Series Planar Germanium, good energy resolution in the 3~300keV range



M. Heil et al.

ESR: $^{96}Ru(p,\gamma)^{97}Rh$ at 10 MeV/u



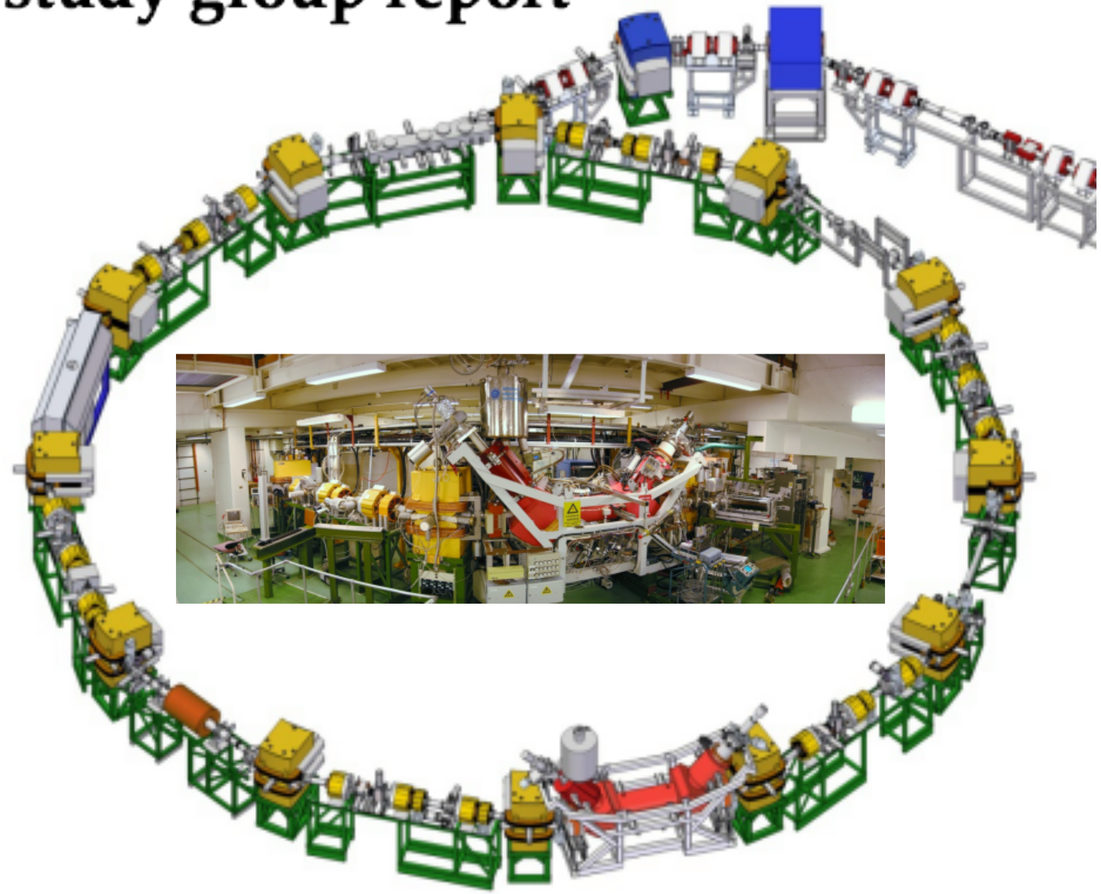


- Measurements directly in the Gamow window of the p-process
- Applicable to radioactive beams
- Clean experimental conditions

$$\sigma_{(p,\gamma)} = 3.6(5) \cdot 10^{-3} b$$

CRYRING@ESR

CRYRING@ESR:
A study group report



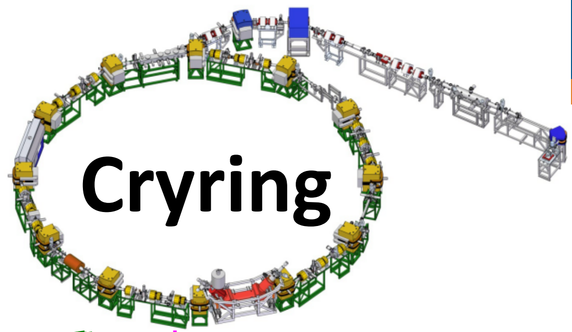
<u>Study Group</u>

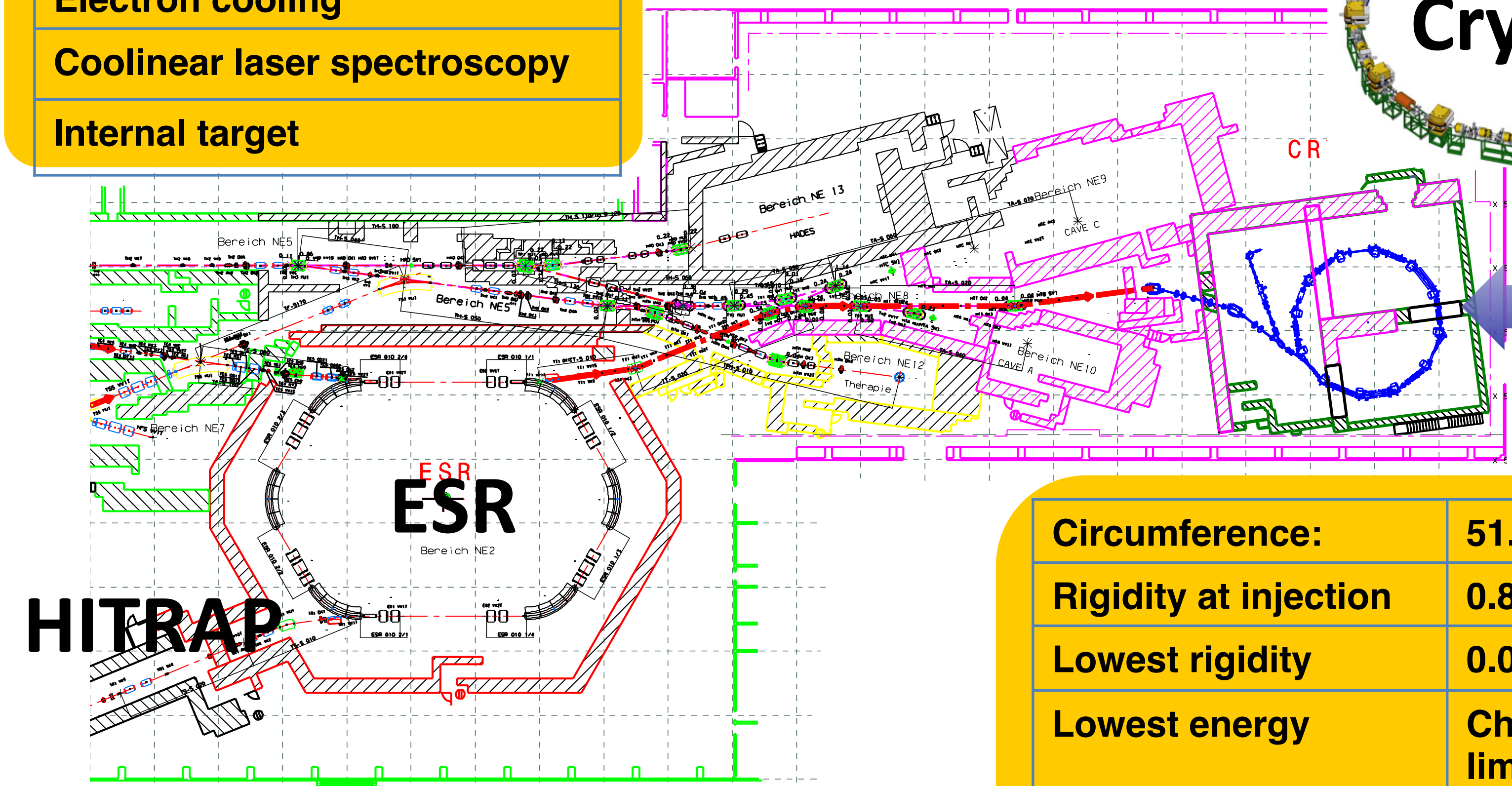
Norbert Angert
Angela Bräuning-Demian
Hakan Danared
Wolfgang Enders
Mats Engström
Bernhard Franzke
Anders Källberg
Oliver Kester
Michael Lestinsky
Yuri Litvinov
Markus Steck
Thomas Stöhlker

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

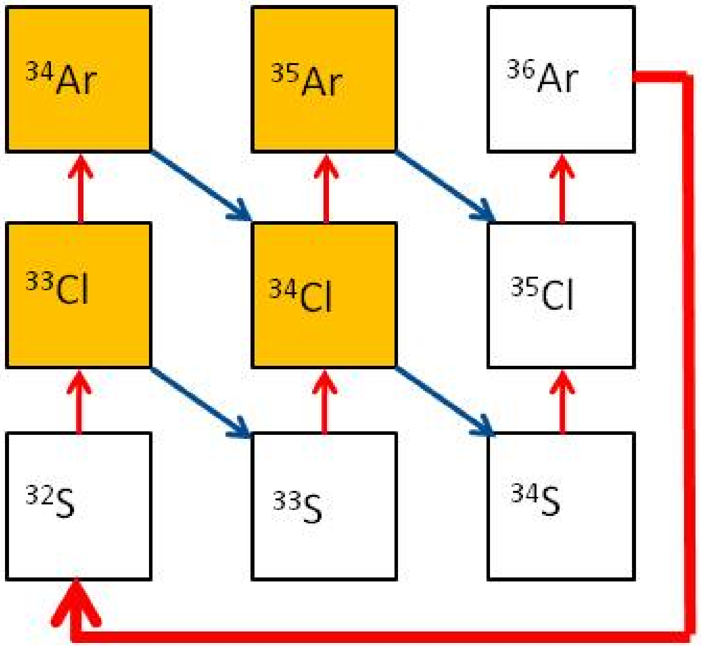
The case of CRYRING

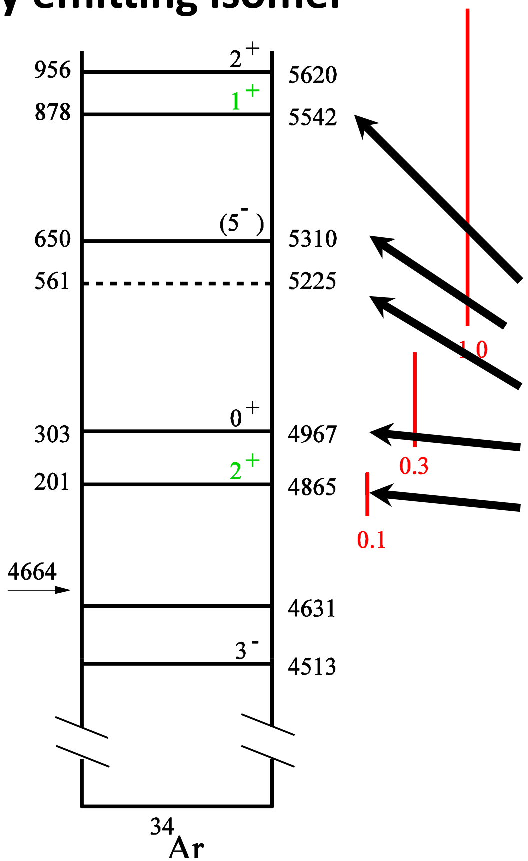
ESR: beam energies > 4.0 MeV/u
reaction rates measurements in the
Gamow window of the **p-process**
[^{96}Ru(p,g)^{97}Rh, Zhong et al., 2010]

→

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

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





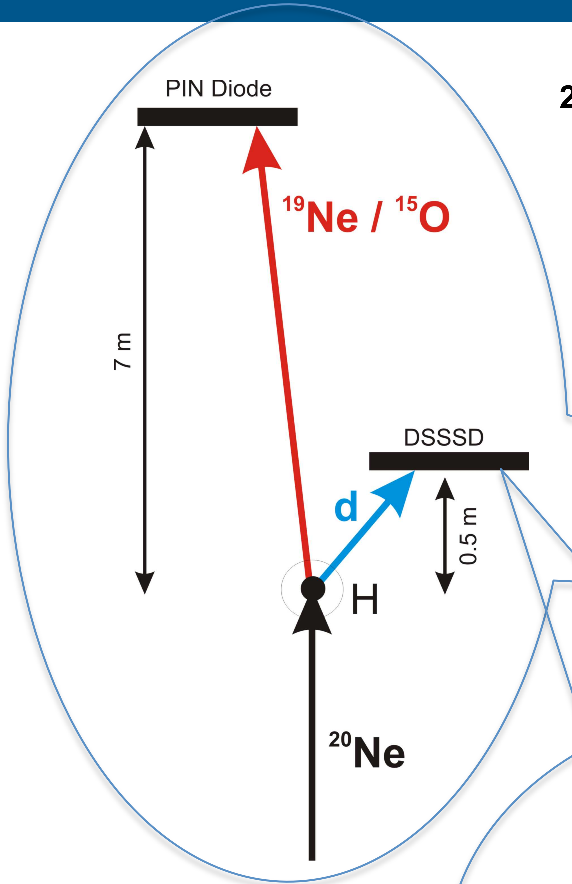
resonance strengths

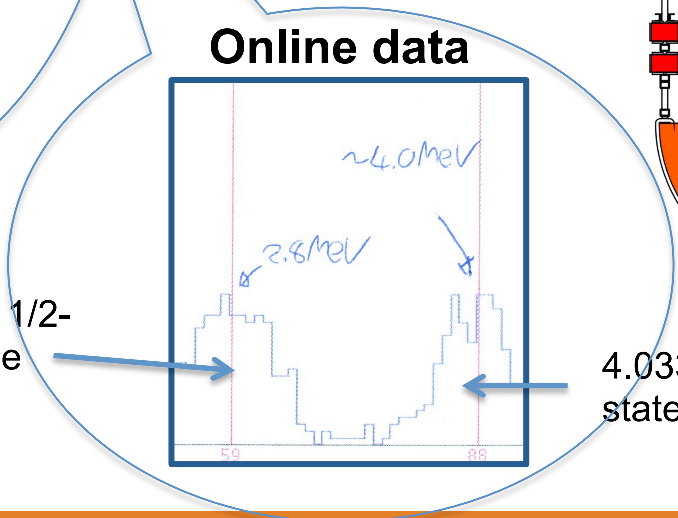
assuming 10^6
stored ^{33}Cl
we can expect:
1200 count/hr
1 count/s
2 counts/s
10 counts/day
1 count/s

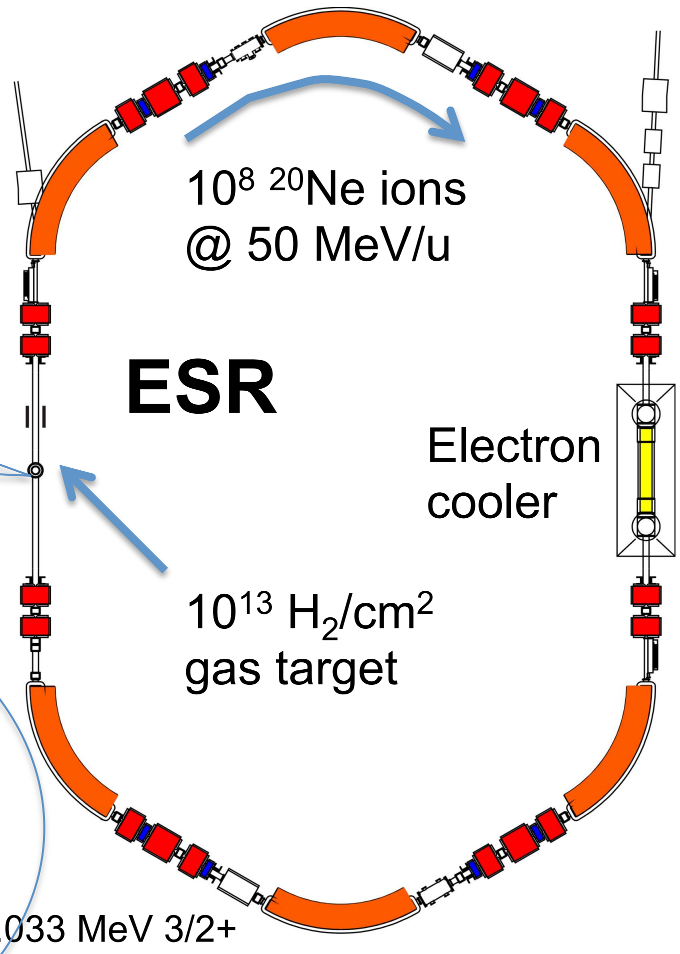
3. First transfer reaction measurement at the ESR

$^{20}Ne(p,d)^{19}Ne$ reaction

Experiment: 08-14 October 2012







P. Woods et al.

- **data evaluation under way**

^{15}O(a,g)^{19}Ne reaction for the rp-process

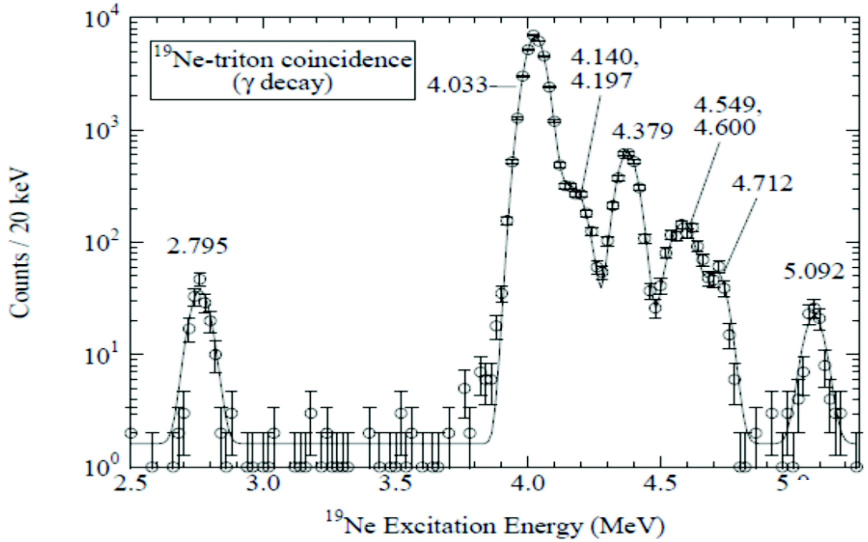
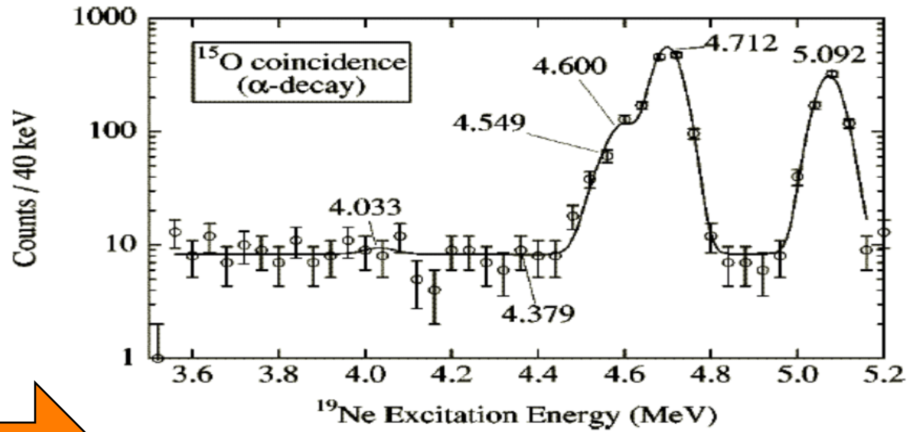


Figure 2: taken from Figure 7 in [10] wh… selective population of resonance at 4.033 MeV excitation energ… using the ^{21}Ne(p,t) reactio…

Motivation:

A reaction possibly responsible
for the break out of the hot CNO cycle



Population of 4.033 MeV level in
^{19}Ne via (p,t) reaction on ^{21}Ne

Measure g and a branching ratio

…taken from Figure 9 of [10] showing the events corresponding to α-decaying reson…ces in ^{19}Ne. Note the flat background associated with fragmentation reactions on C atoms in the $(CH_2)_n$ target.

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Physics at Storage Rings

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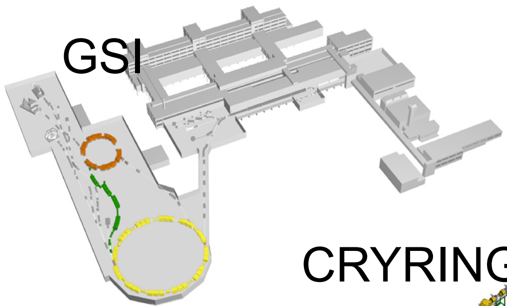
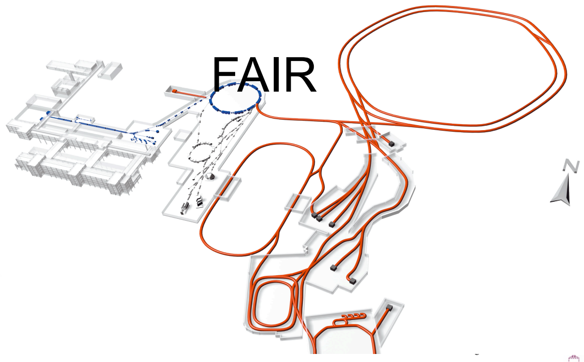
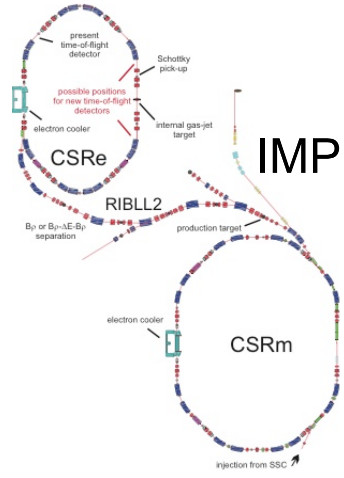


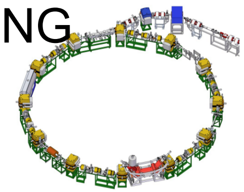
FAIR



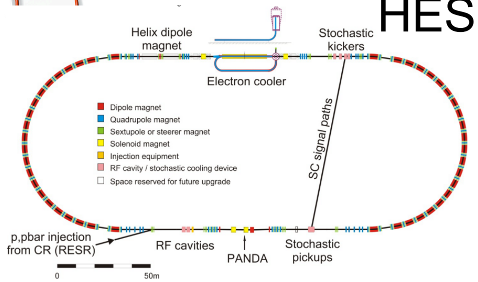
IMP

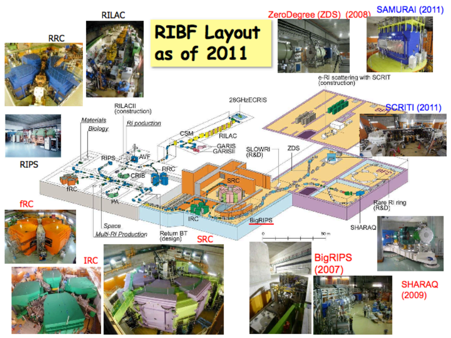


CRYRING



HESR





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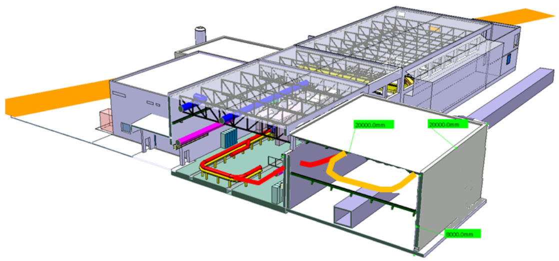
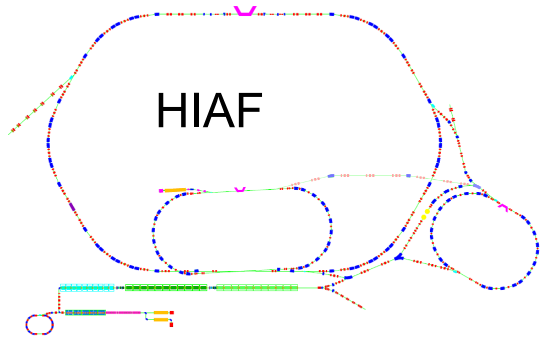
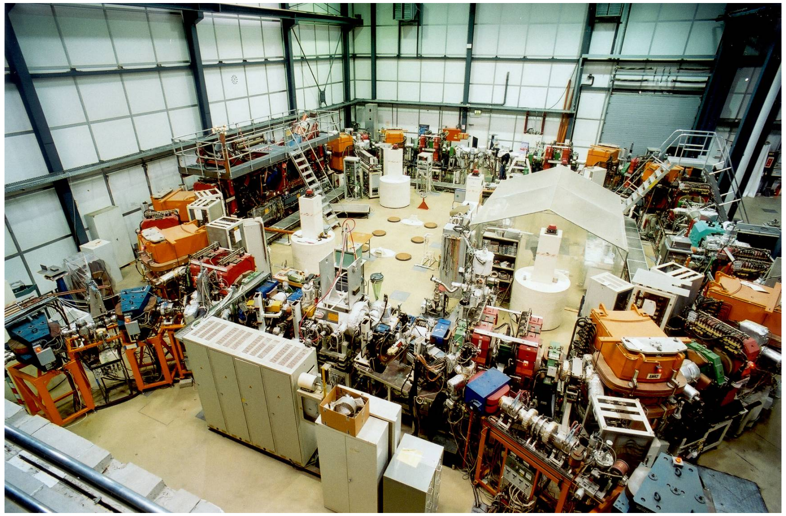
TSR@ISOLDE



HIAF



TSR @ Hie-Isolde



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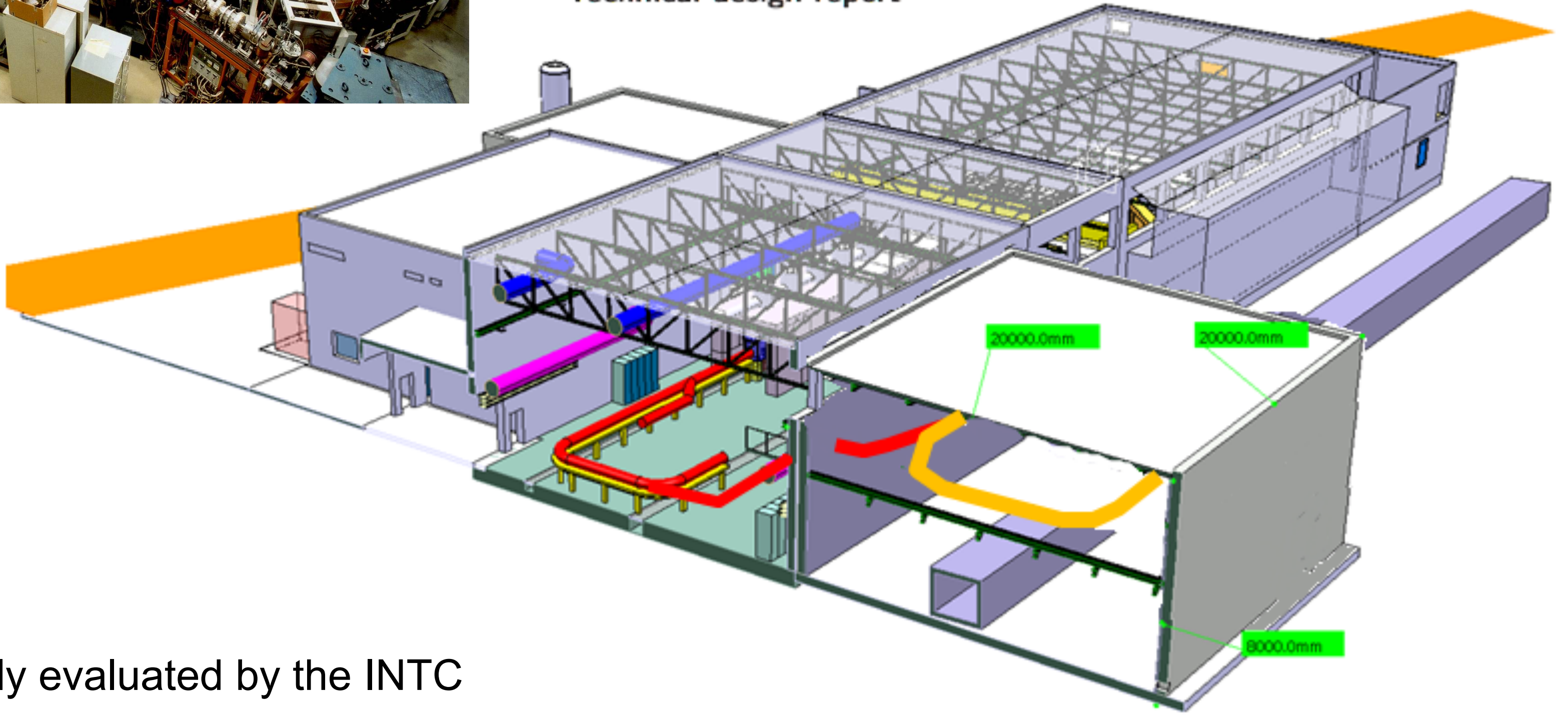
Review

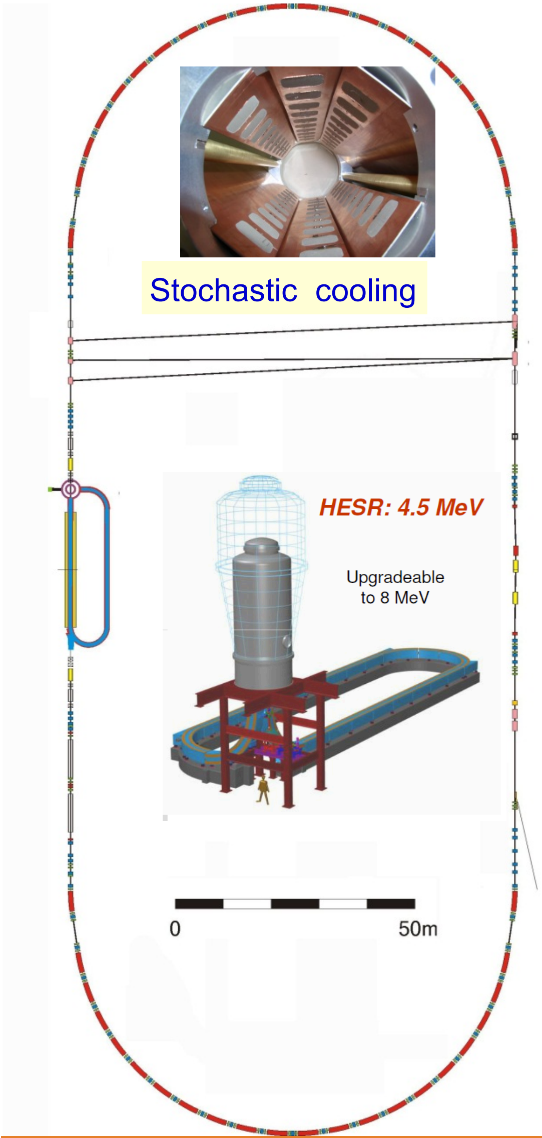
Storage ring at HIE-ISOLDE

Technical design report



TDR positively evaluated by the INTC

The High Energy Storage Ring HESR



SPARC Experiments at the HESR:

A Feasibility Study

sparc

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]

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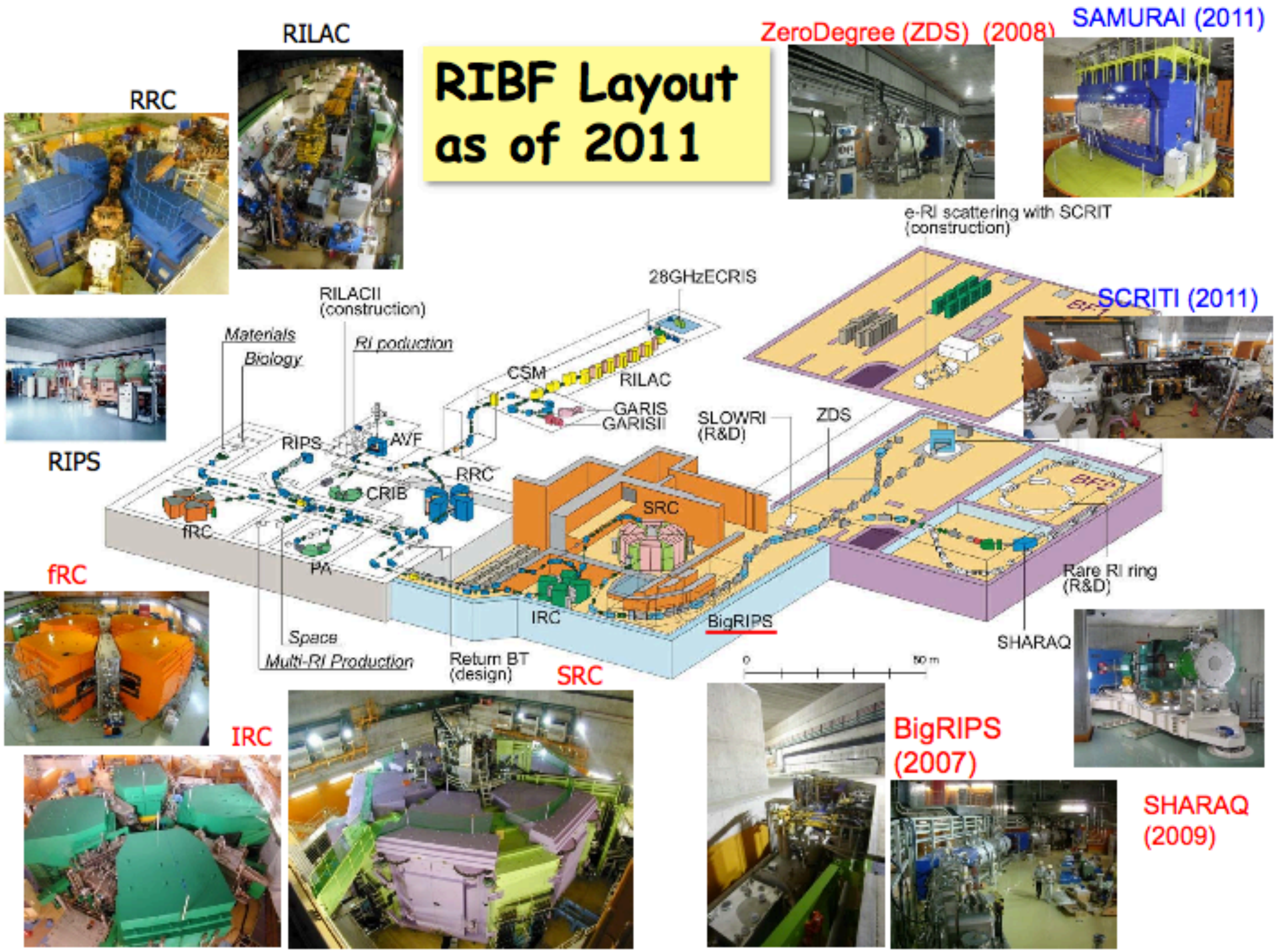
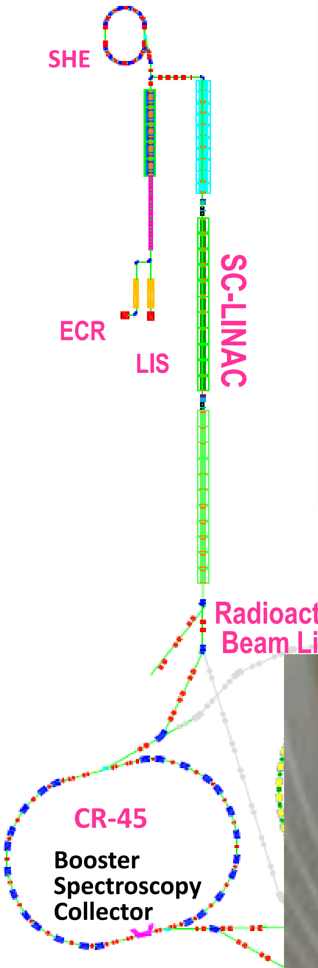
RIKEN Radioactive Ion Beam Facility



Next-Generation Heavy-Ion Beam Facility HIAF



Thank you for your attention

HELMHOLTZ
GEMEINSCHAFT

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

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