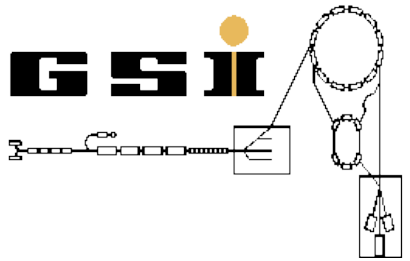
Nuclear astrophysics experiments with storage rings

Yuri A. Litvinov



10th Russbach School on Nuclear Astrophysics
Russbach, Austria, 10-16 March 2013

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]

Experiments with polarized beams

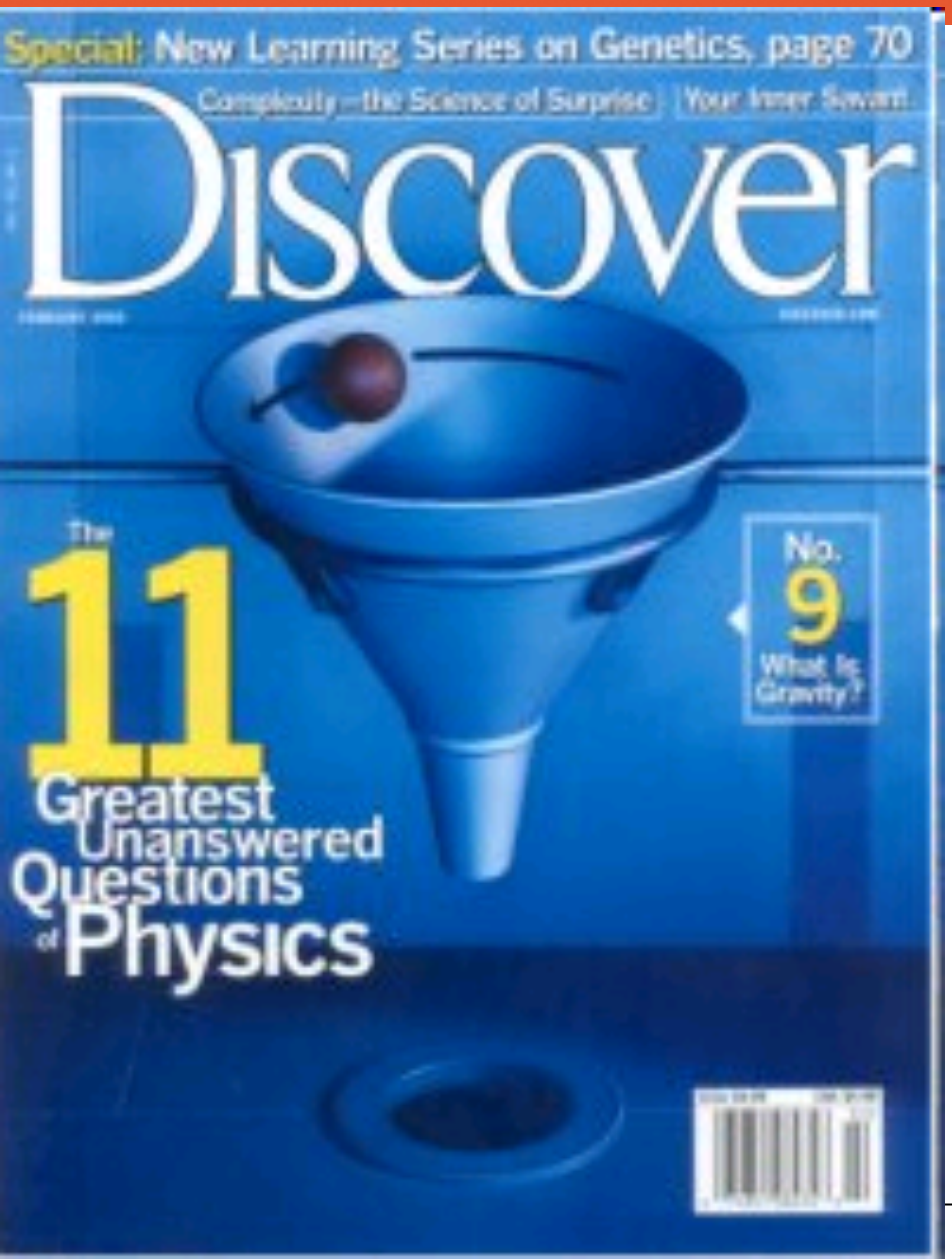
Experiments with isomeric beams [DR, reactions]

Nuclear magnetic moments [DR]

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

In-ring nuclear reactions

National Research Council's board on physics and astronomy

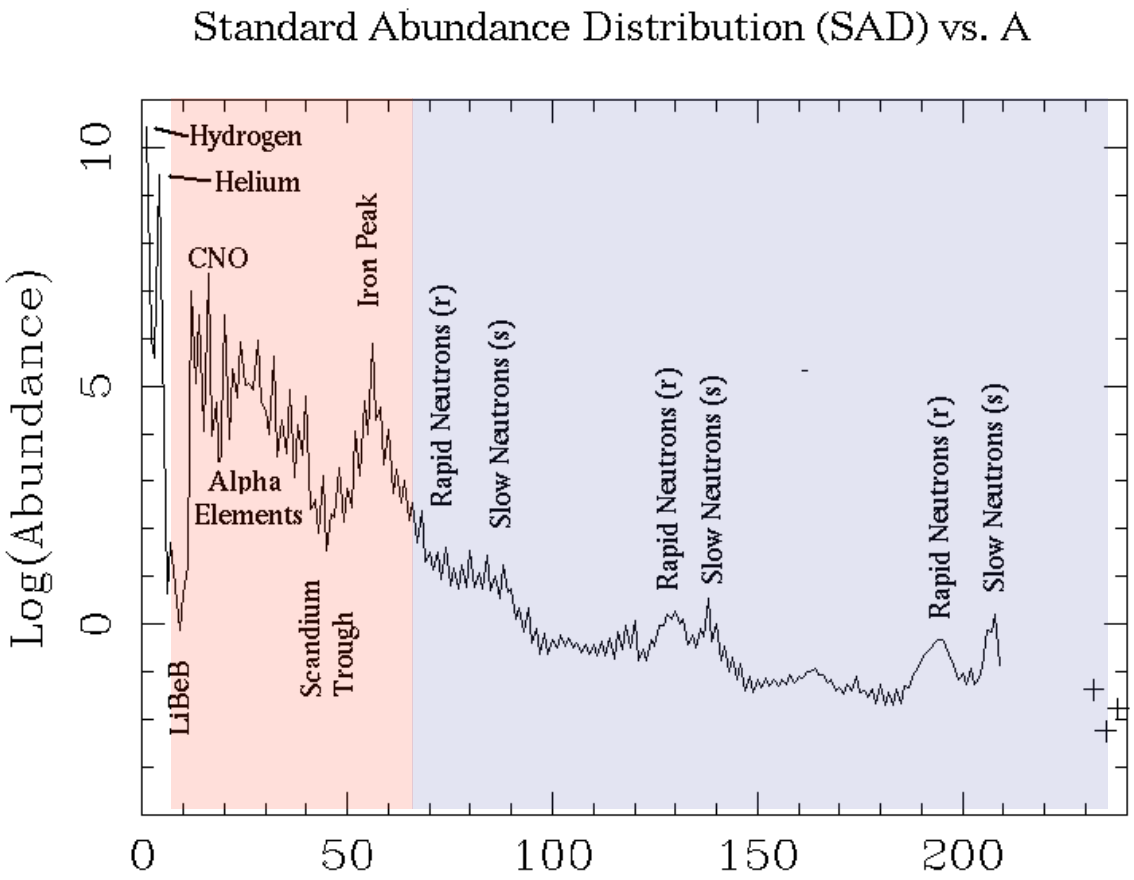


02.01.2002
The 11 Greatest Unanswered Questions of Physics

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?

Nuclear processes in astrophysics



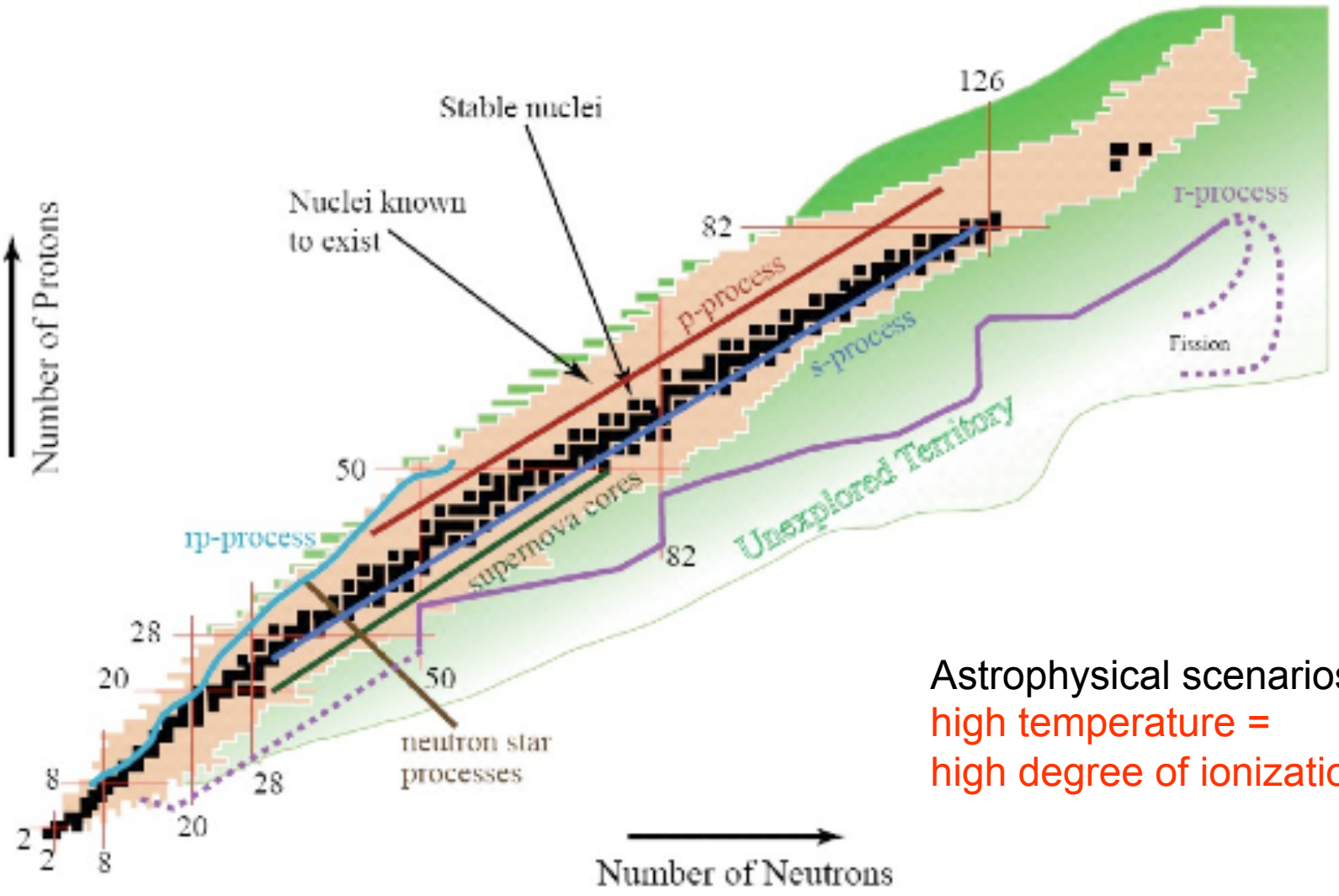
charged-particle induced reaction

mainly neutron capture reaction

involve mainly STABLE NUCLEI

involve mainly UNSTABLE NUCLEI

Nucleosynthesis on the Chart of the Nuclides



Astrophysical scenarios:
high temperature =
high degree of ionization

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

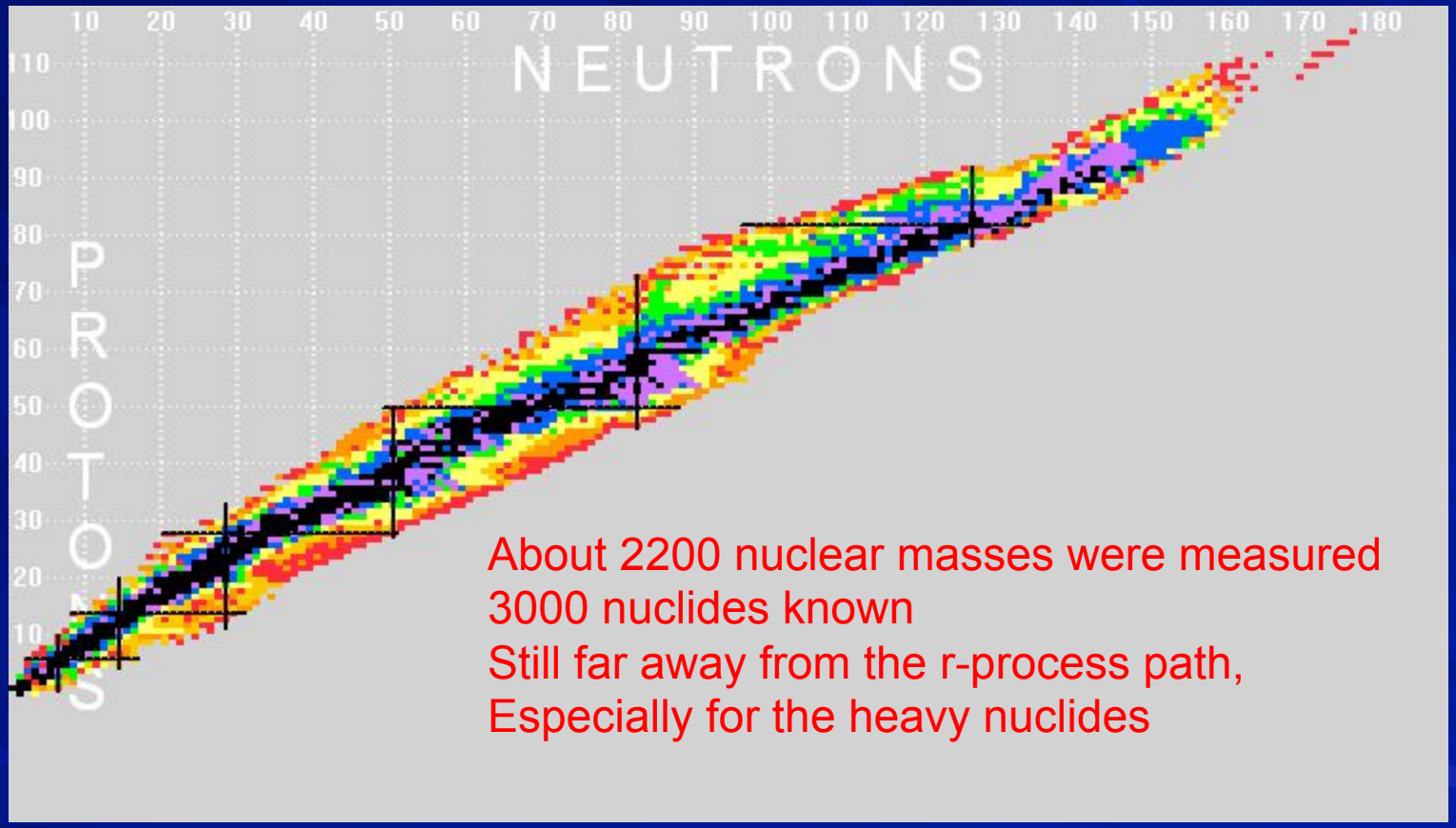
To measure: Ground state properties of exotic nuclei:

masses and β decay half-lives

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

β half-lives the accumulated abundances

Current status of experimental nuclear masses

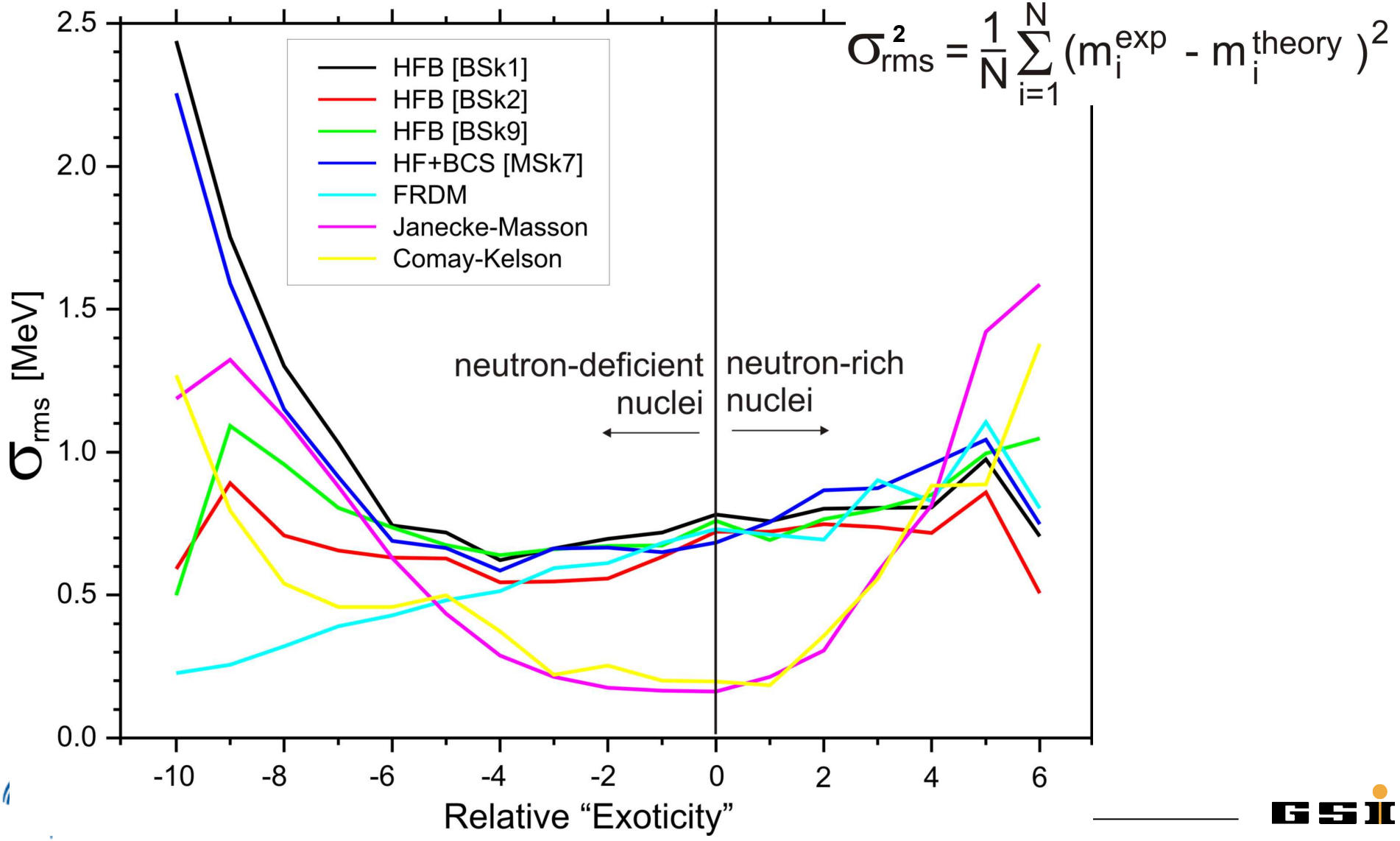


About 2200 nuclear masses were measured
3000 nuclides known
Still far away from the r-process path,
Especially for the heavy nuclides

Up to 2004!

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

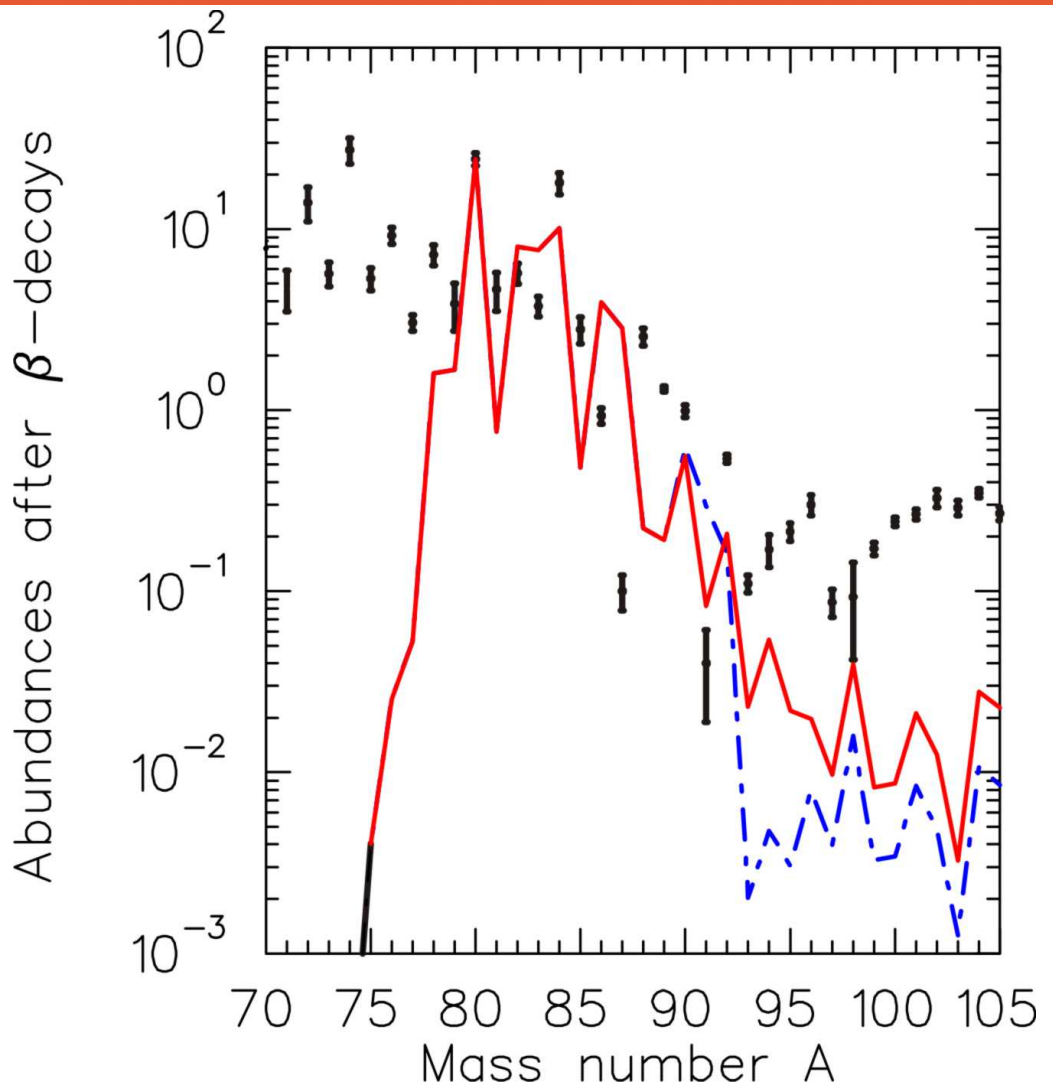
Predictive Powers of Mass Models



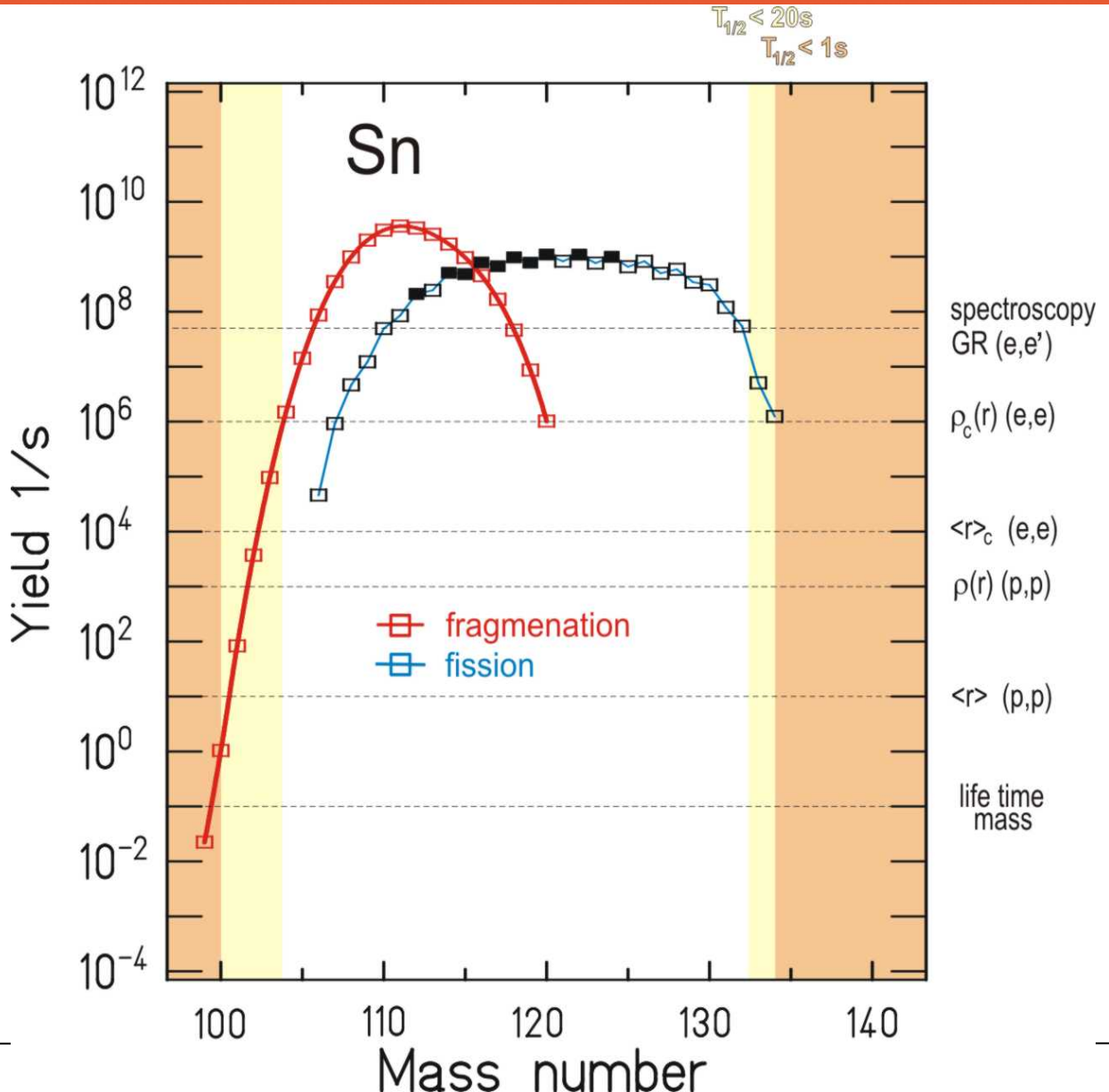
Predictive Powers of Mass Models

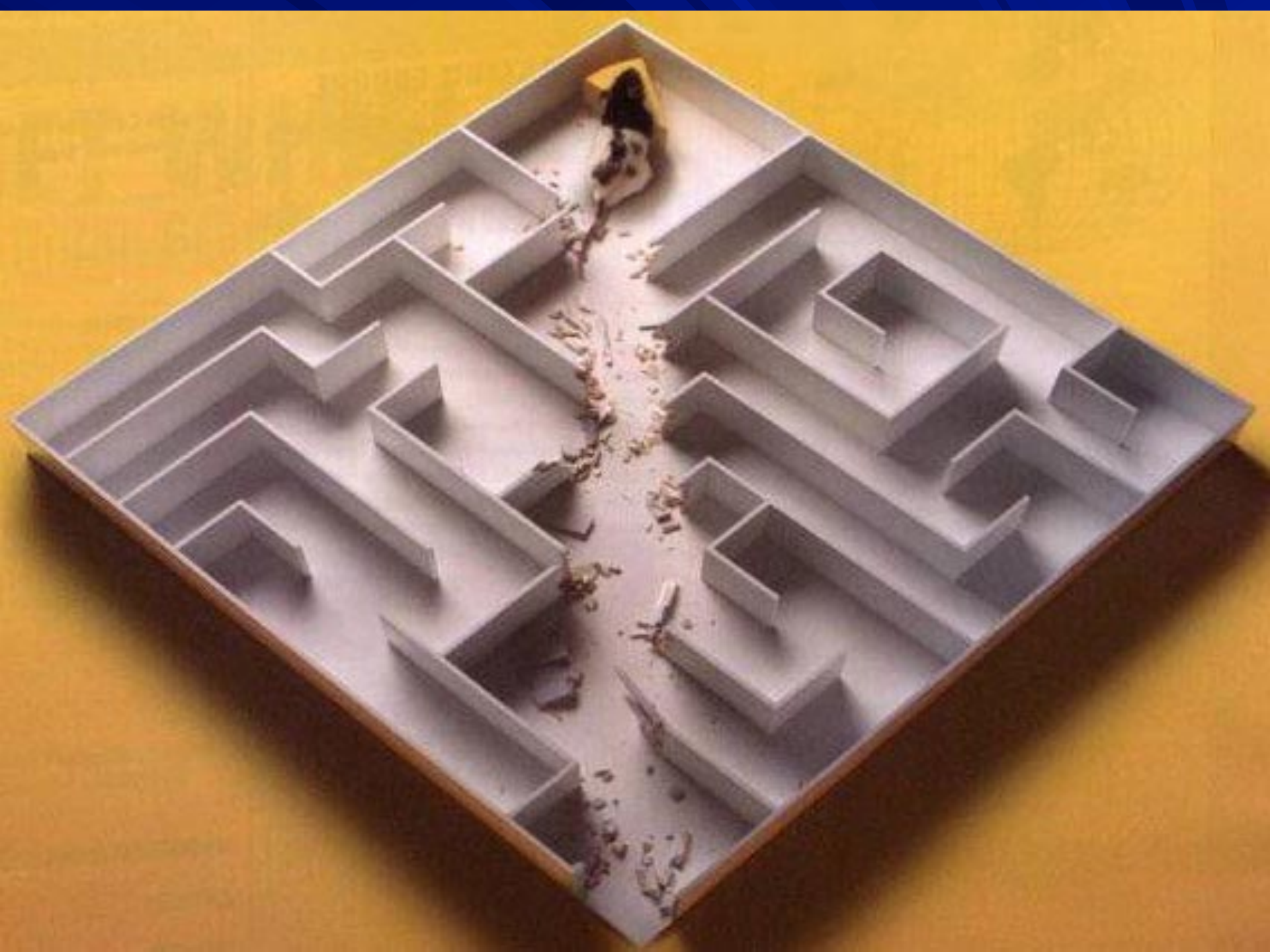
Calculated abundances assuming that one neutron separation energy is varied by 1 MeV

B. Pfeiffer et al.



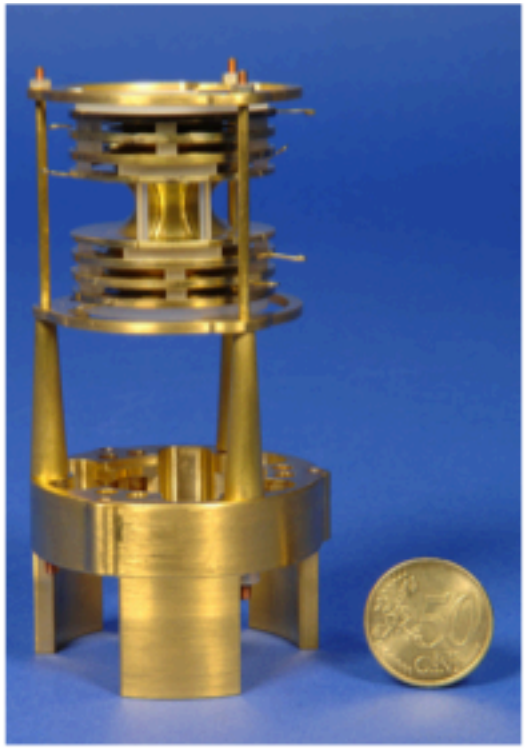
Production Cross-Sections for Tin-Isotopes





Devices for precise mass measurements

Penning trap



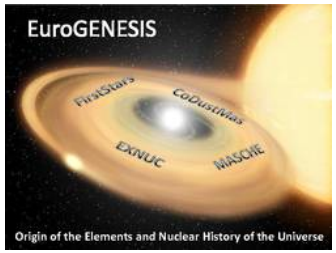
Storage ring

particles at nearly rest in space

relativistic particles

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

Direct Mass Measurements on the Chart of the Nuclides

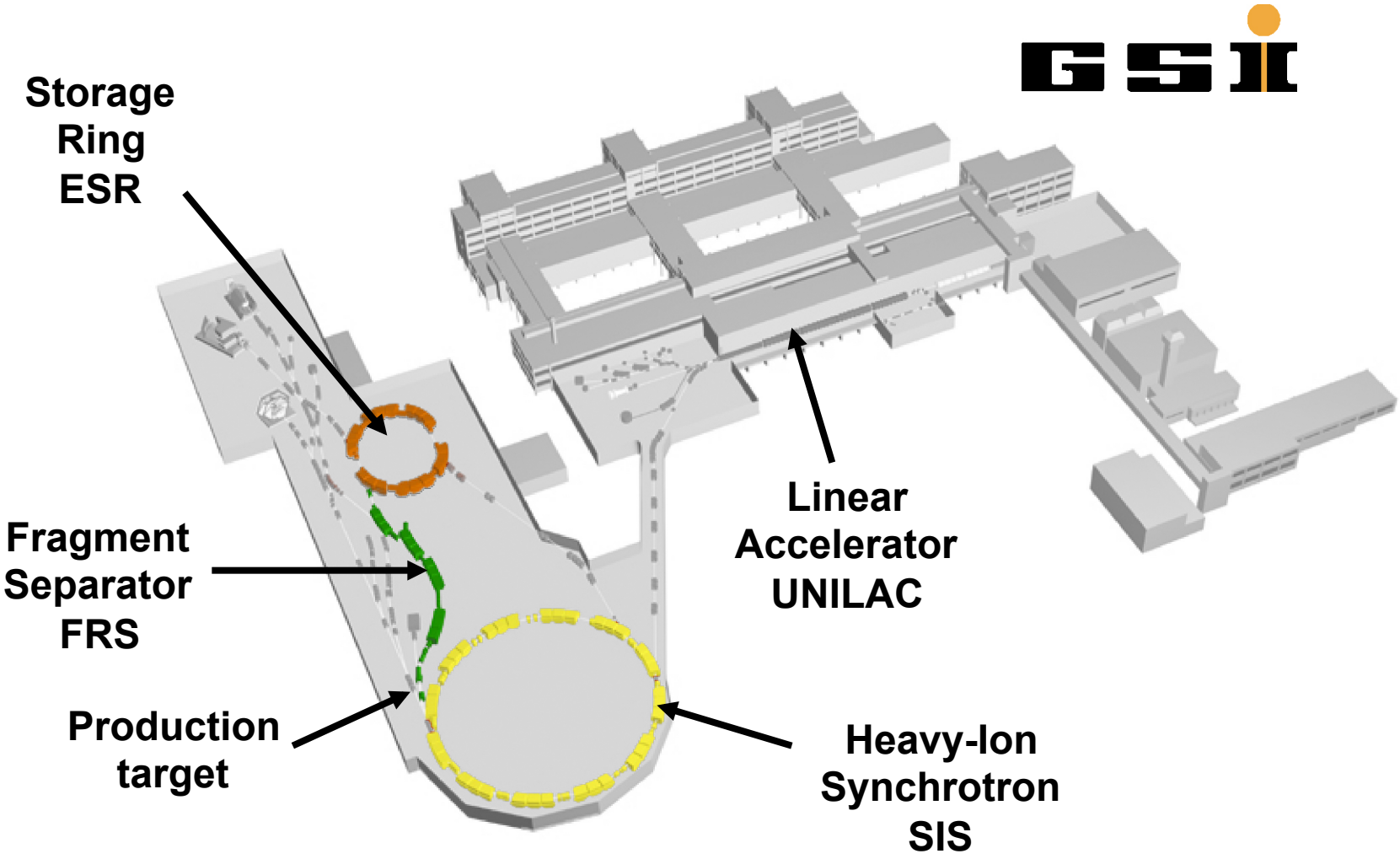


Individual Project
High-Precision Measurements of Nuclear Ground State Properties

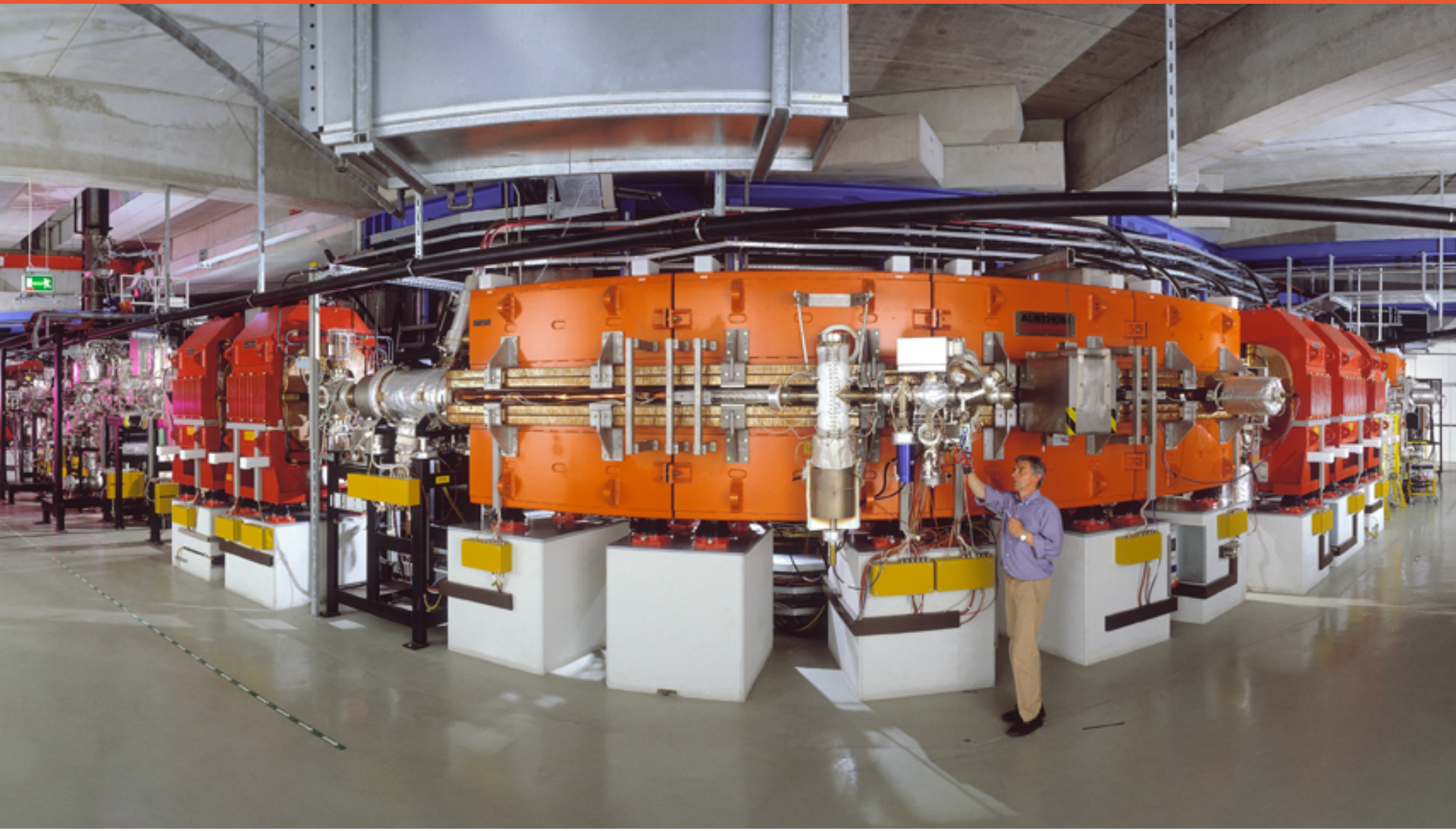
Penning Traps

Storage Rings

Secondary Beams of Short-Lived Nuclei



Experimental Storage Ring ESR



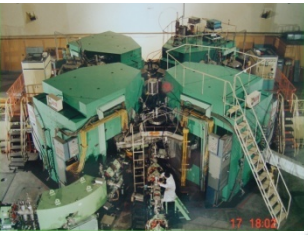
HELMHOLTZ GEMEINSCHAFT

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

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

GSI

Heavy Ion Research Facility in Lanzhou (HIRFL)



SSC(K=450)

SFC (K=69)

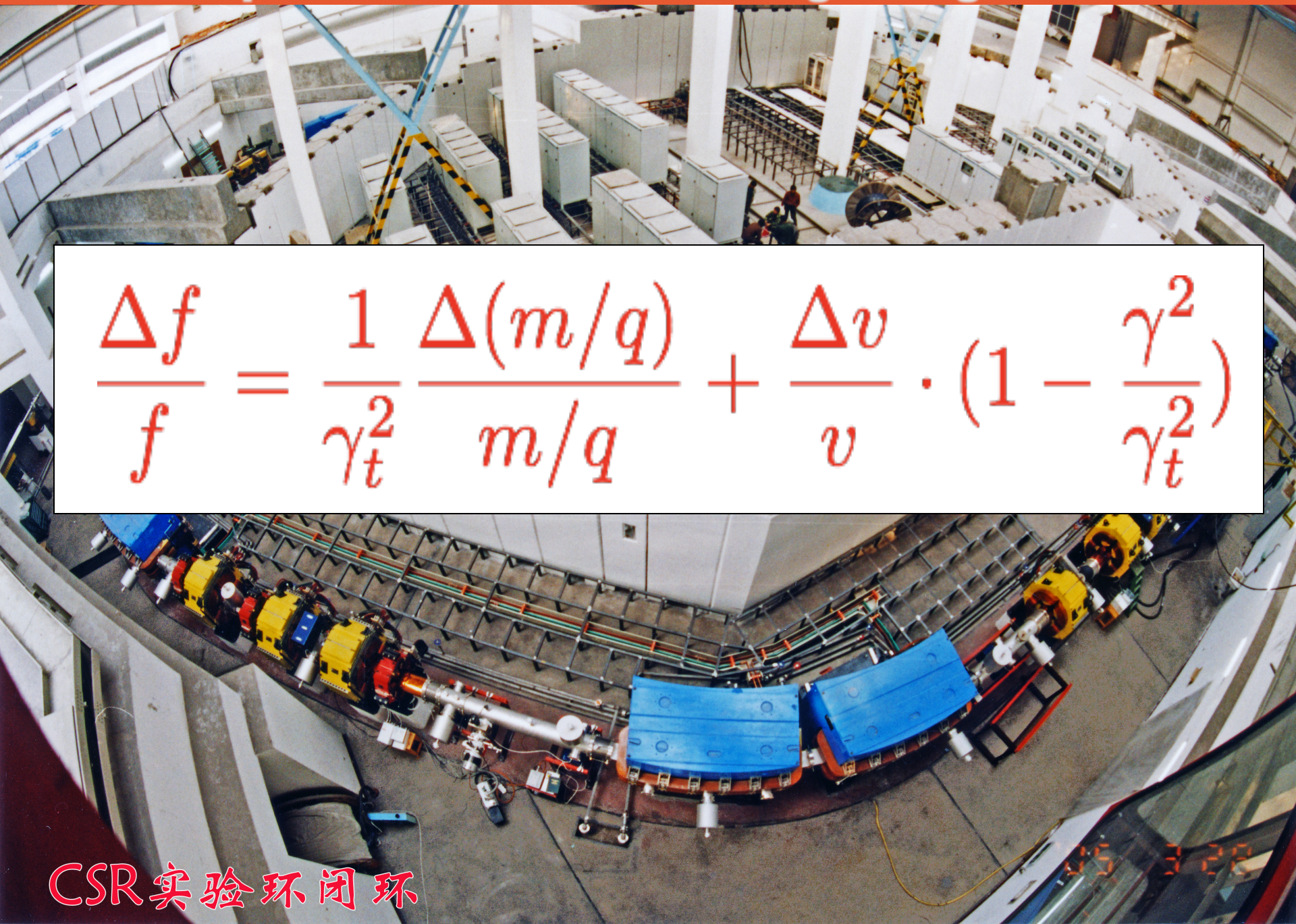
CSRe

RIBLL1

RIBLL2

CSRm

Experimental Cooler Storage Ring CSRe



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

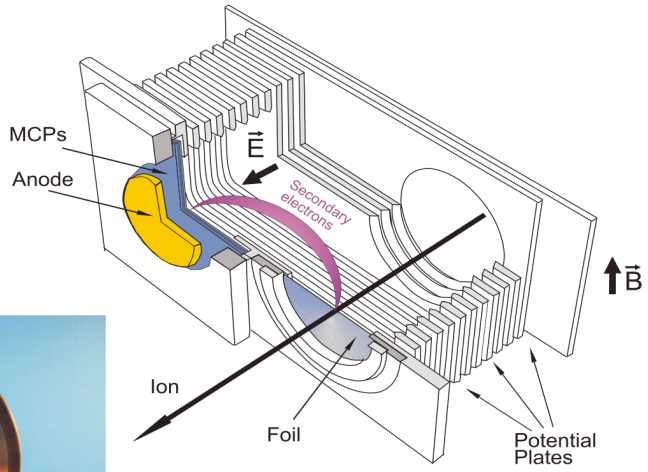
CSR实验环闭环

Isochronous Mass Spectrometry

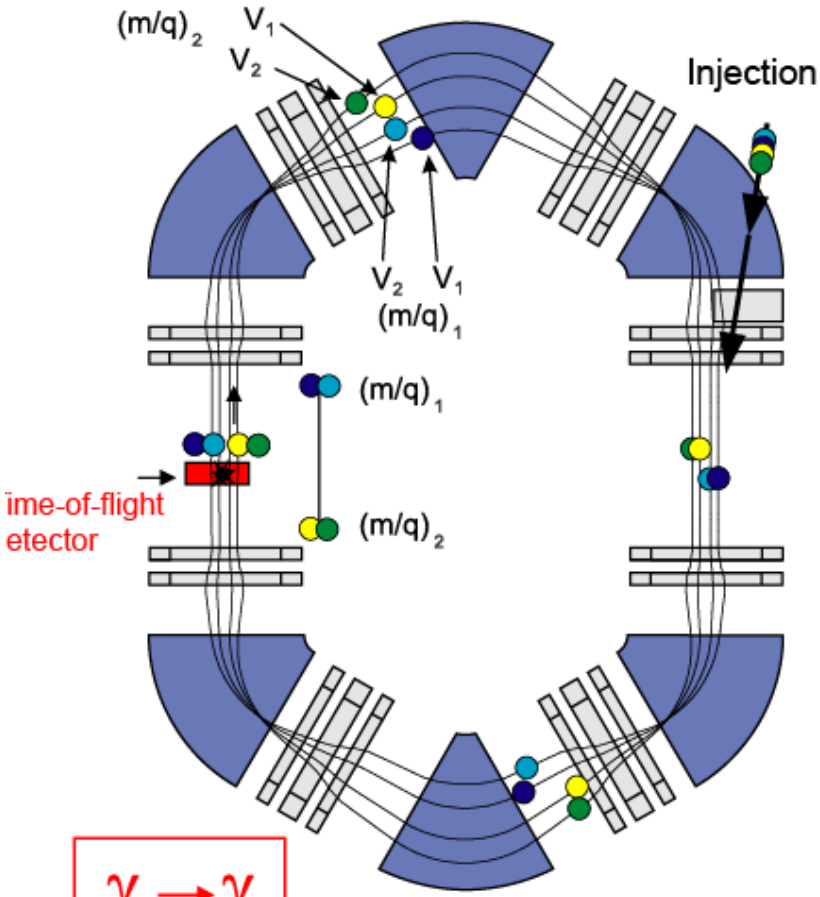
H. Wollnik et al., GSI Proposal, 1985

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

$\gamma_t \rightarrow \gamma$



Isochronus-Mass-Spectrometry



$\gamma_t \rightarrow \gamma$

Hot fragments

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.

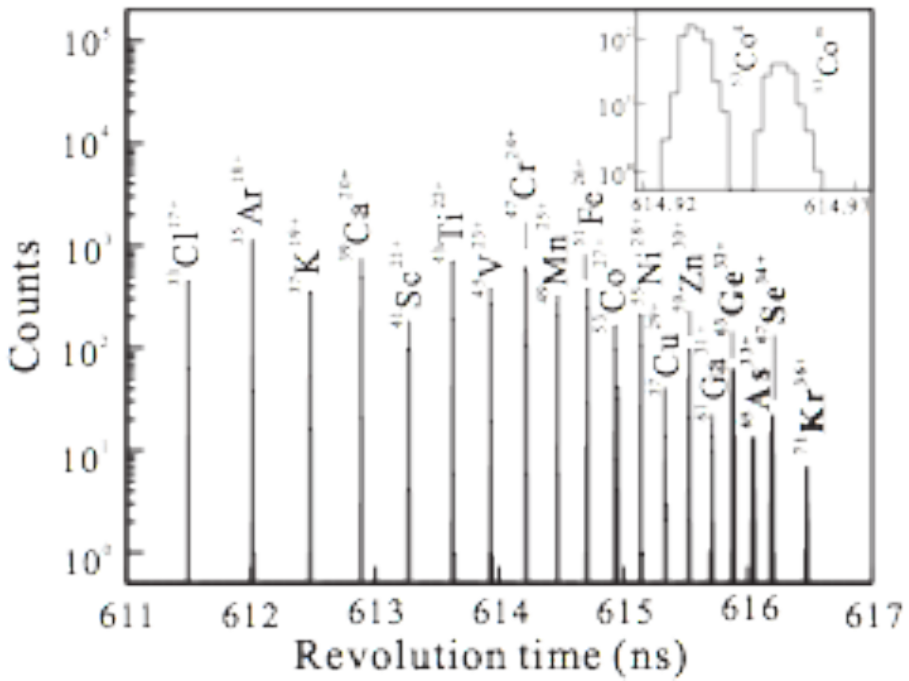
NATURE PHYSICS | VOL 7 | APRIL 2011 | www.nature.com/naturephysics

BRENNPUNKT

Kein Halten am Wartepunkt

Hochpräzise Massenmessungen erklären die Kernreaktionen bei Ausbrüchen von Röntgenstrahlung.

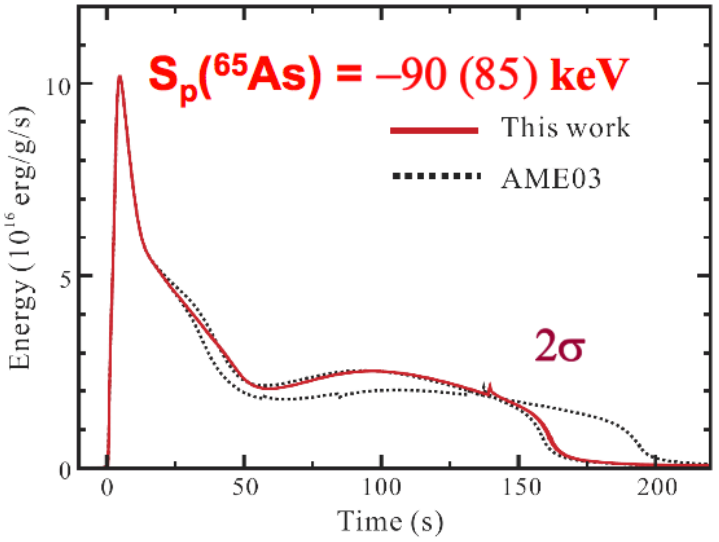
Physik Journal 10 (2011) Nr. 6



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

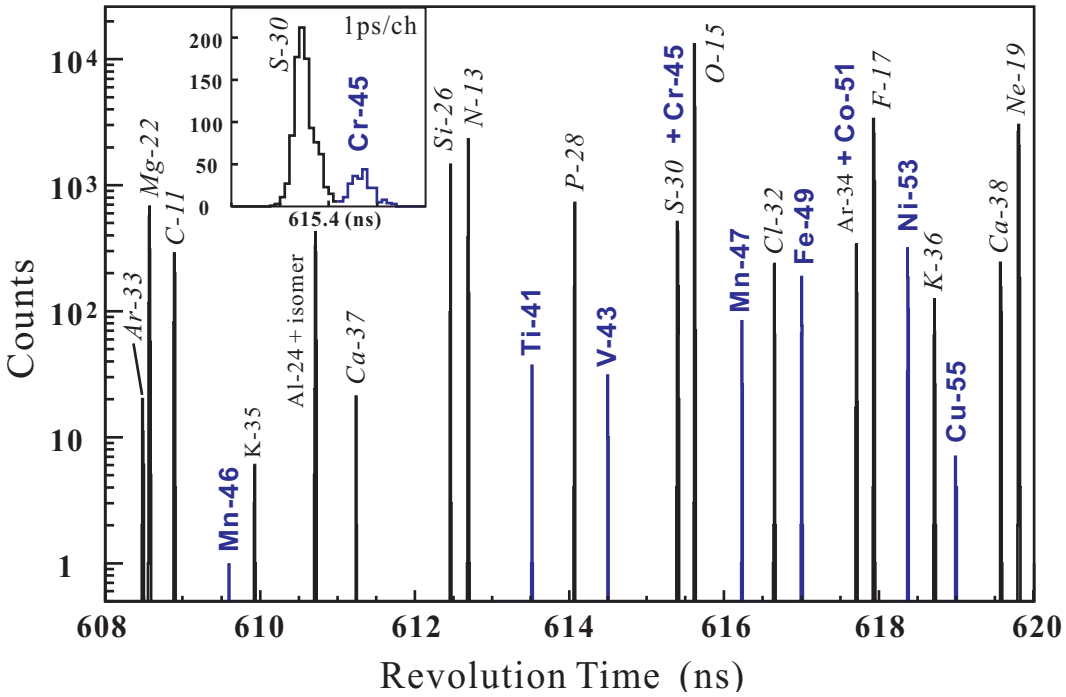
80-90% of the reaction flow passes through ^{64}Ge via proton capture reactions

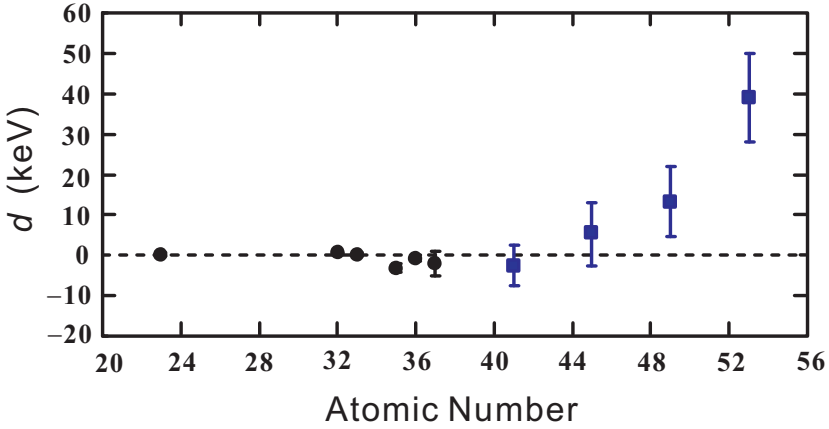
Light curve shape of Type I x-ray burst



X.L. 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





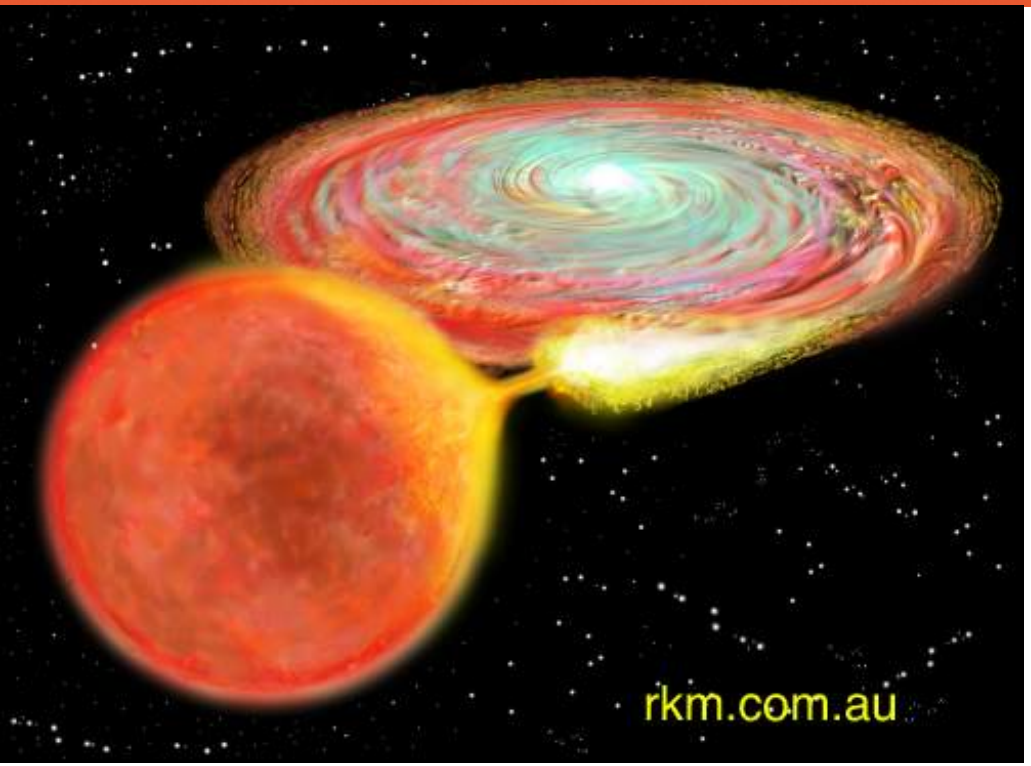
Isobaric Multiplet Mass Equation

$$ME(A,T,T_z) = a(A,T) + b(A,T)T_z + c(A,T)T_z^2$$

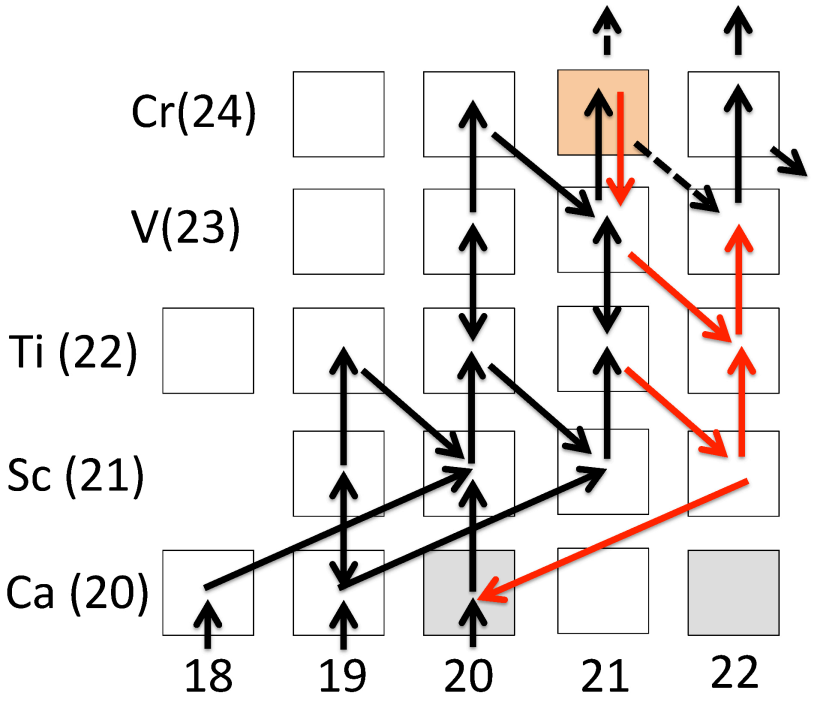
$$dT_z^3\ ?$$

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

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]

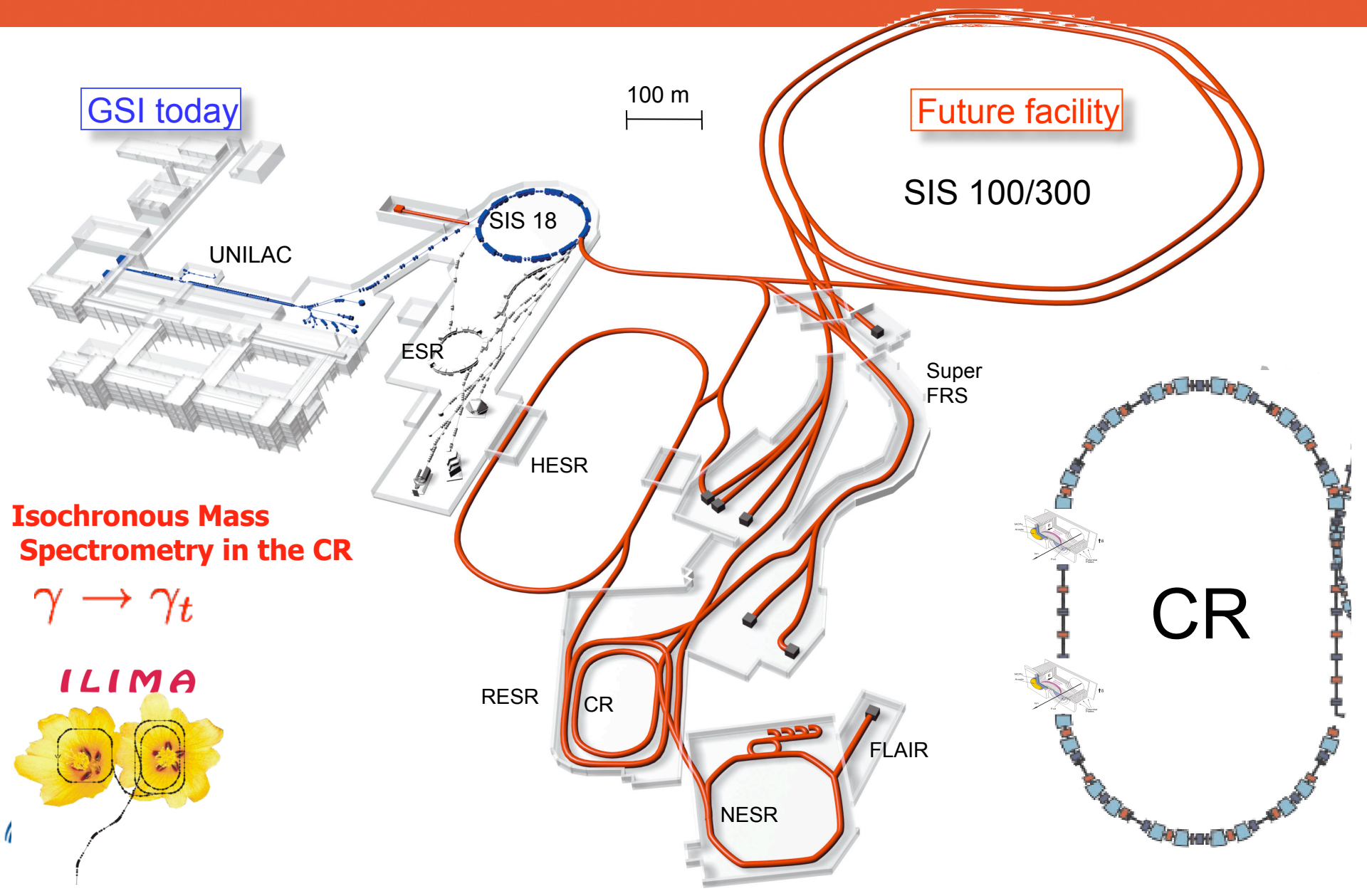


$S_p(^{45}Cr)$= 2.1(5) MeV [AME03]

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

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

FAIR - Facility for Antiproton and Ion Research

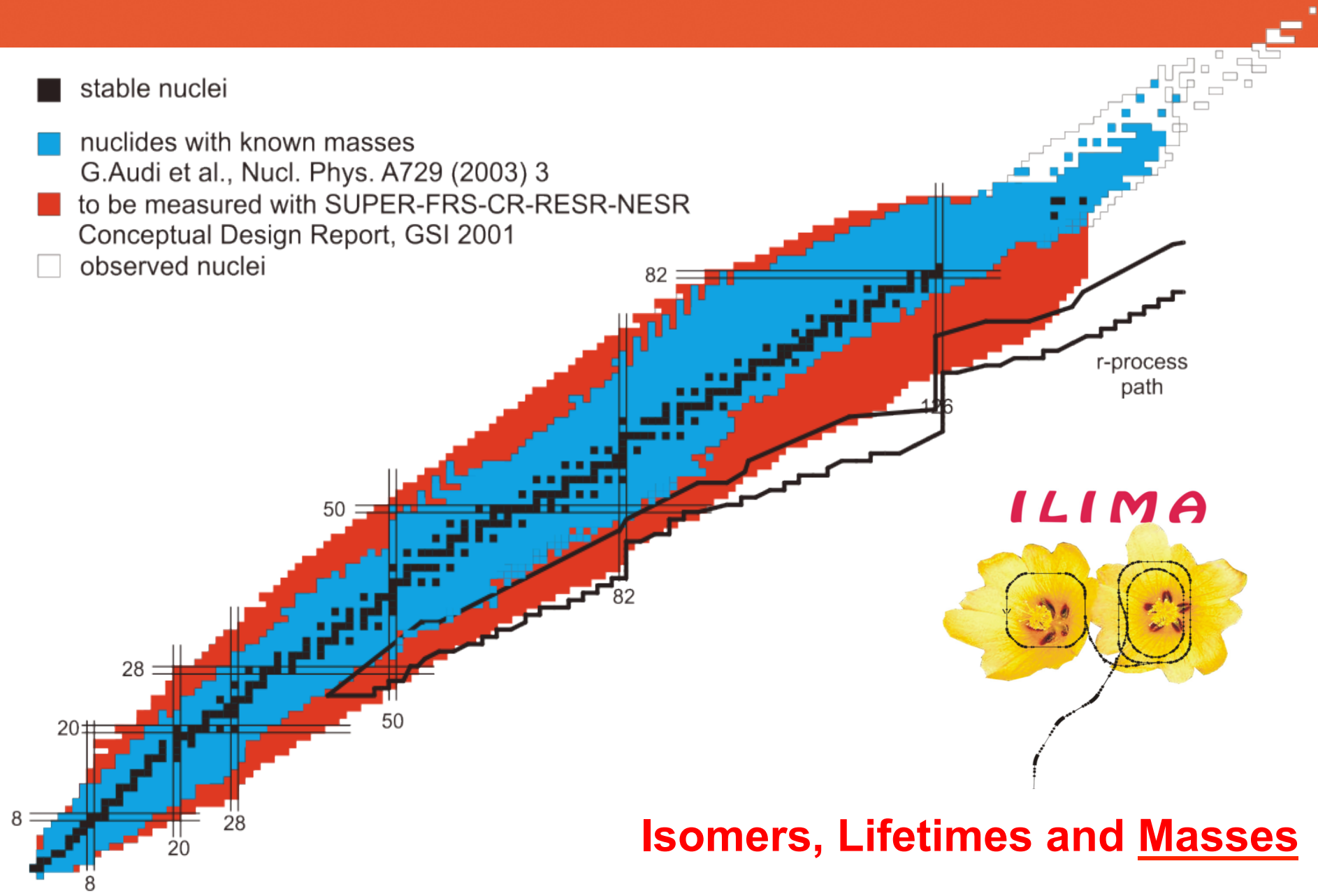


Isochronous Mass Spectrometry in the CR

$\gamma \rightarrow \gamma_t$

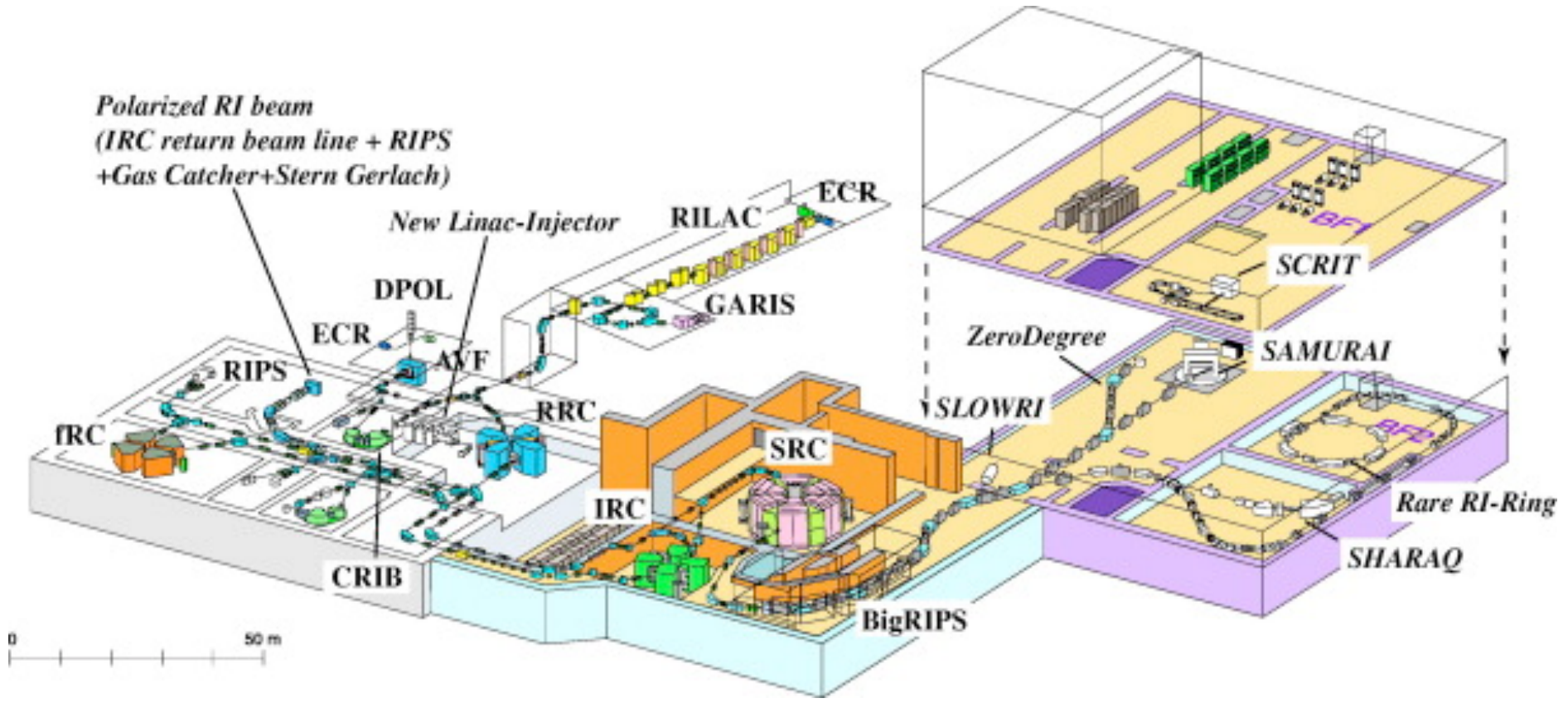
ILIMA

ILIMA: Masses and Halflives



Isomers, Lifetimes and Masses

RI-RING at RIBF



Radioactive decays of highly-charged ions

Few-electron ions
well-defined quantum-mechanical systems

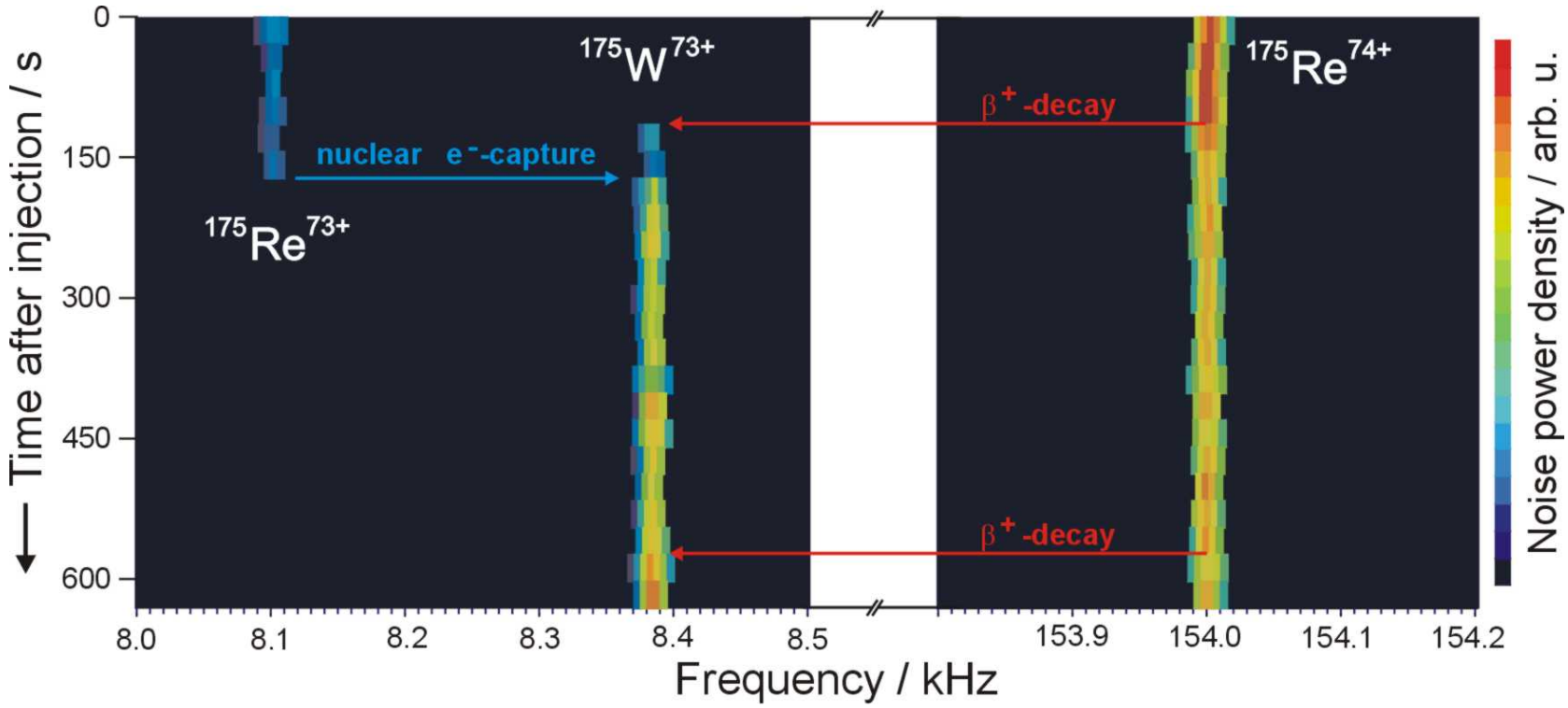
New decay modes
(bound-pair-creation, bound-state beta decay, etc.)

Influence of electrons on radioactive decay

Astrophysical scenarios:
high temperature = high degree of ionization

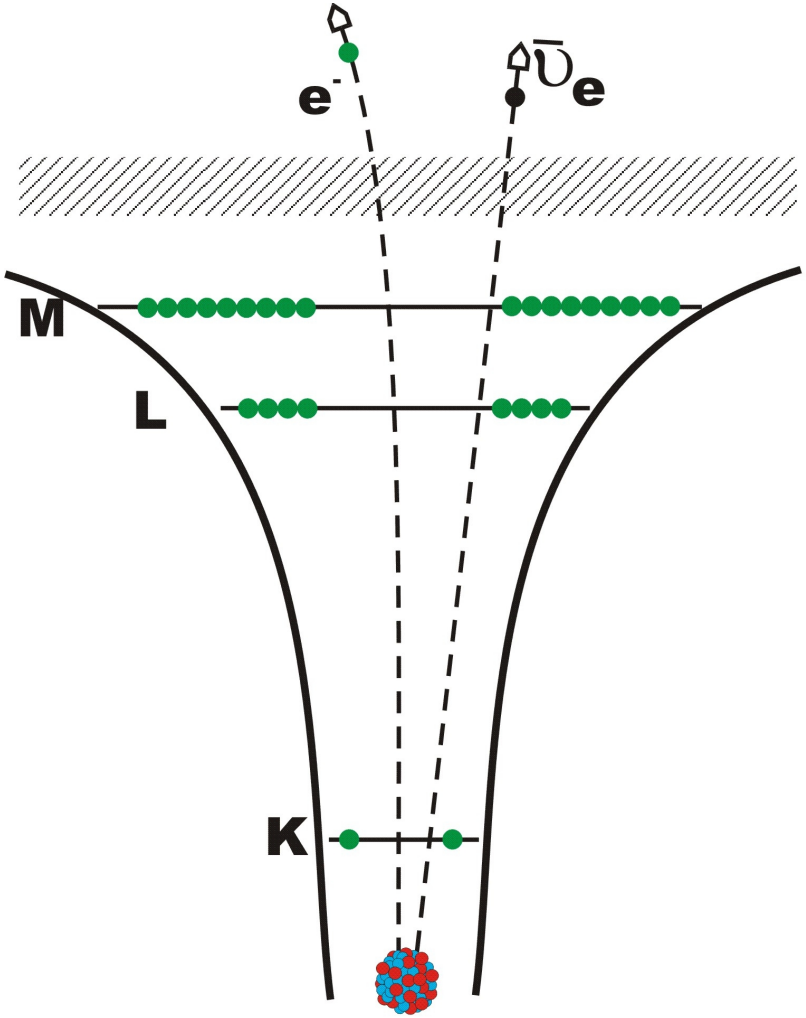
Nuclear Decays of Stored Single Ions

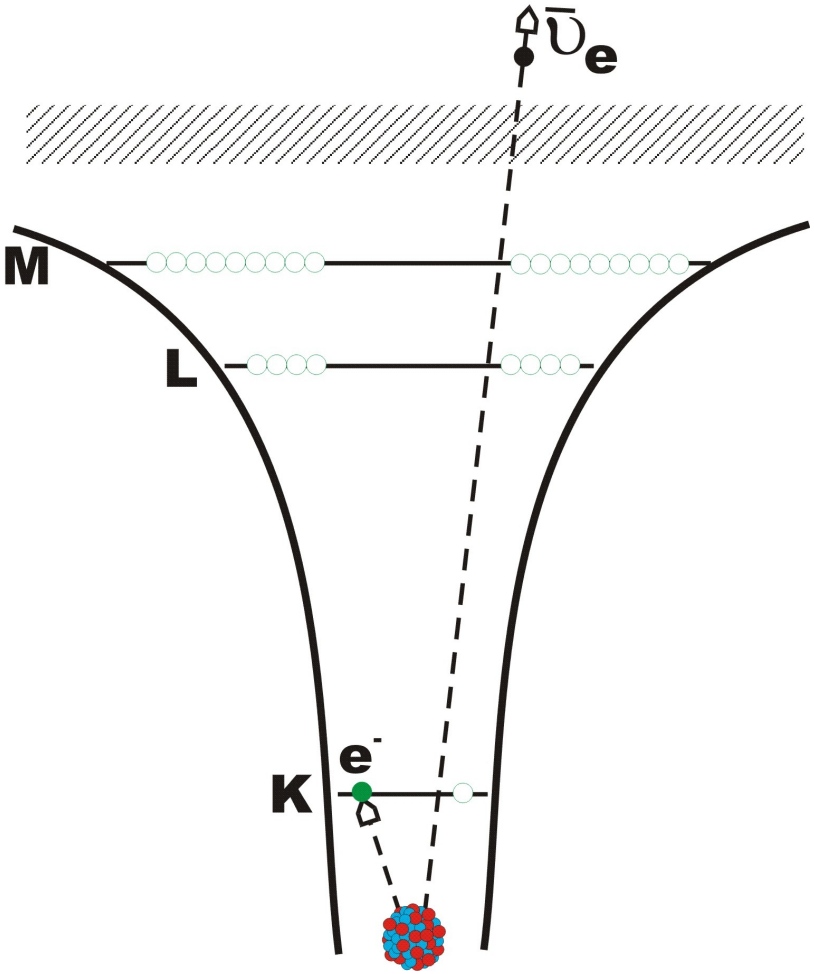
Time-resolved SMS is a perfect tool to study decays in the ESR



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

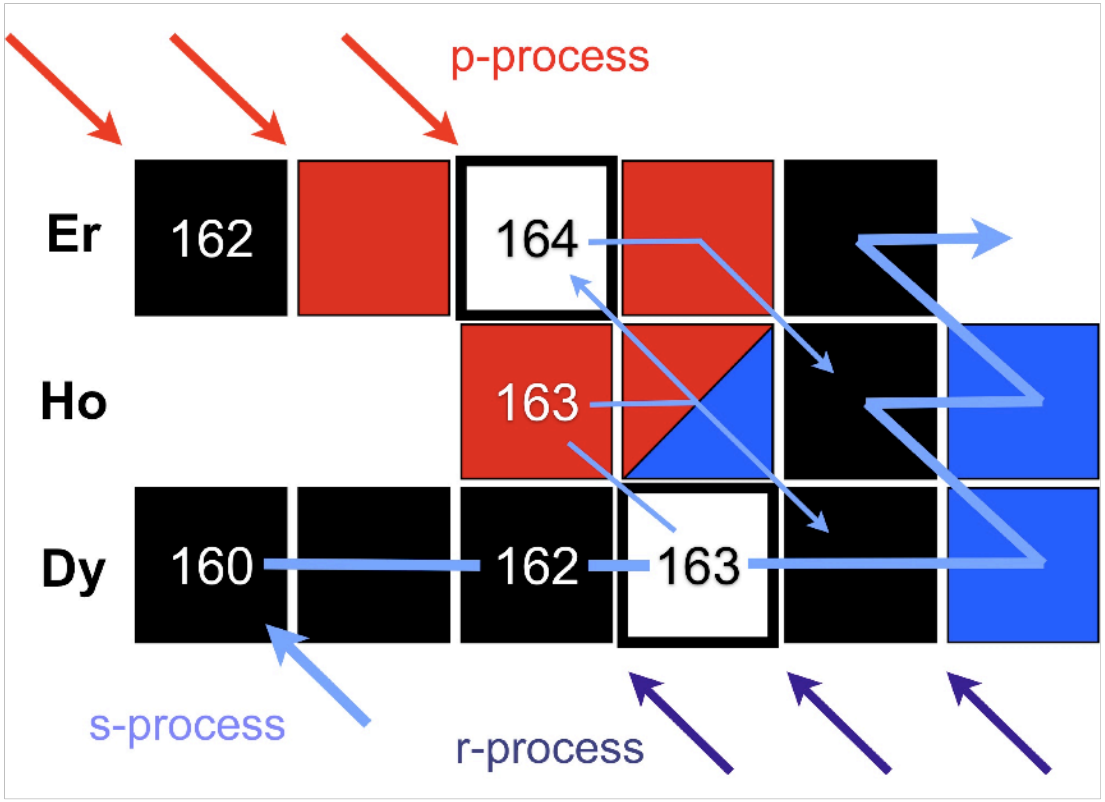
Bound-State β-decay





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

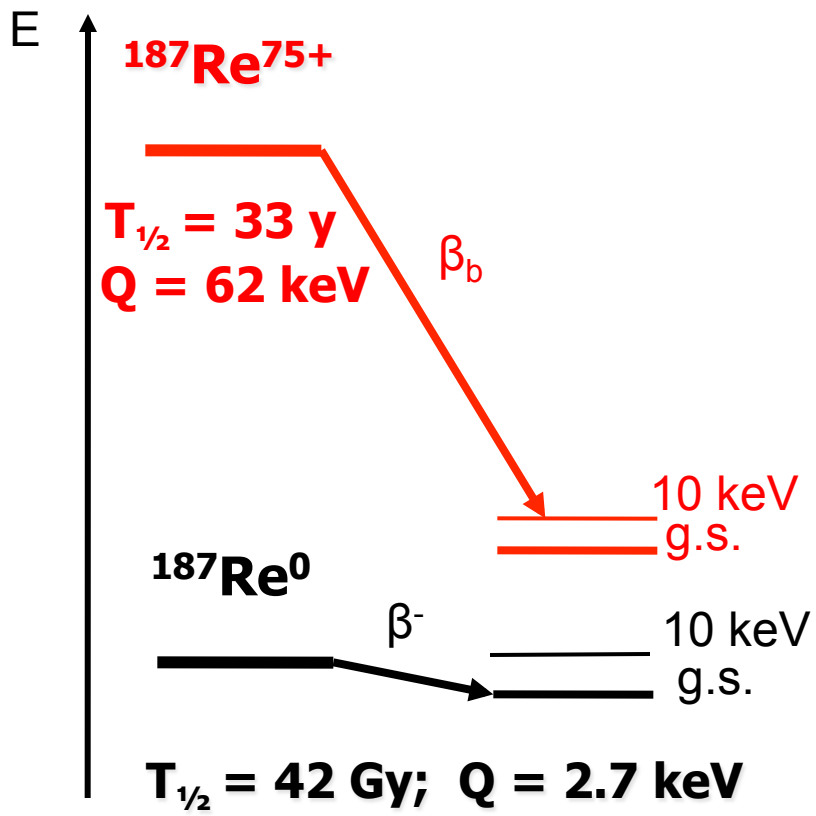


$T_{1/2}$ = 48 days

branchings caused by bound-state β decay

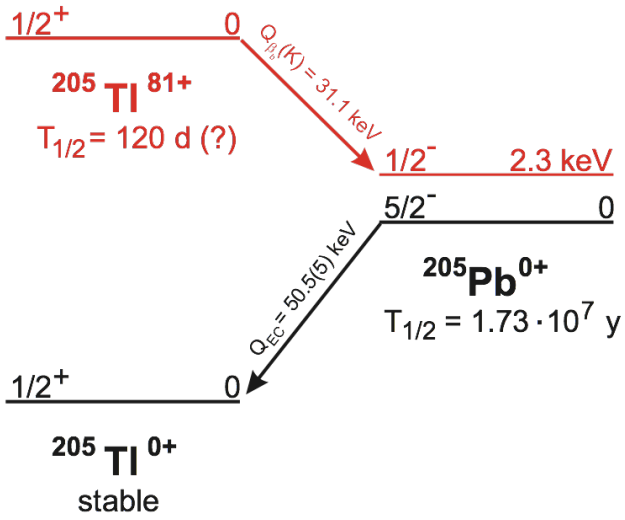
M. Jung et al., Phys. Rev. Lett. 69 (1992) 2164

Bound-State β-decay of ^{187}Re



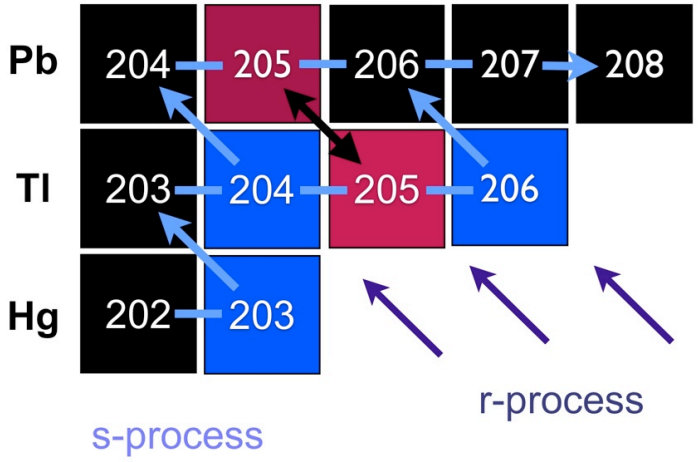
F. Bosch et al., Phys. Rev. Lett. 77 (1996) 5190

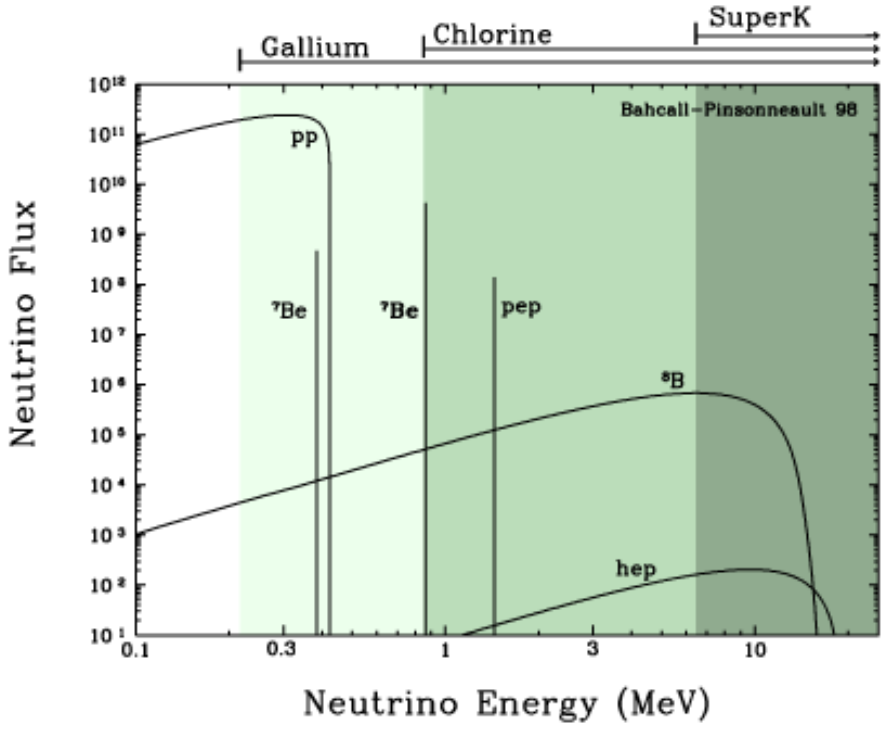
Bound-State Beta Decay of ^{205}Tl Nuclei



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

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





In-Ring Reaction Studies

Clean, basically background free detection

Inverse kinematics

Ultra-thin windowless gas targets → excellent energy, position and angular resolution

High revolution frequency compensates the loss in luminosity due to thin targets

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

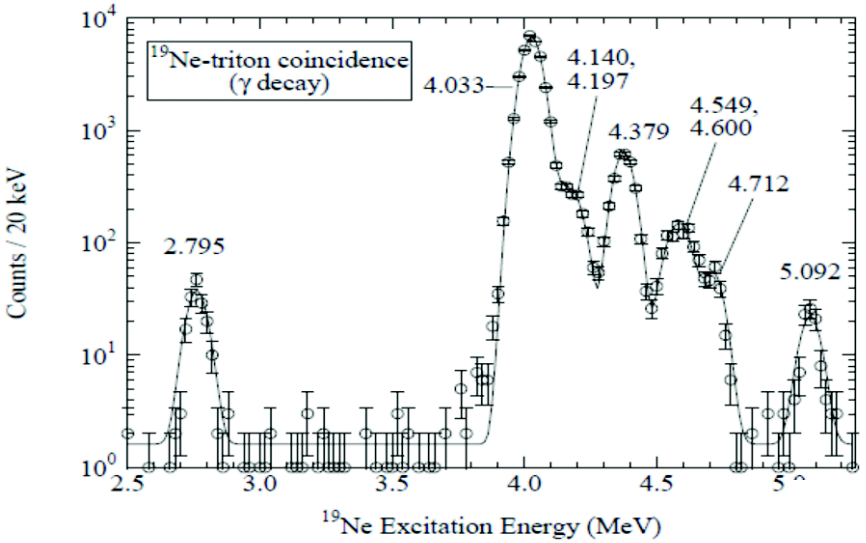
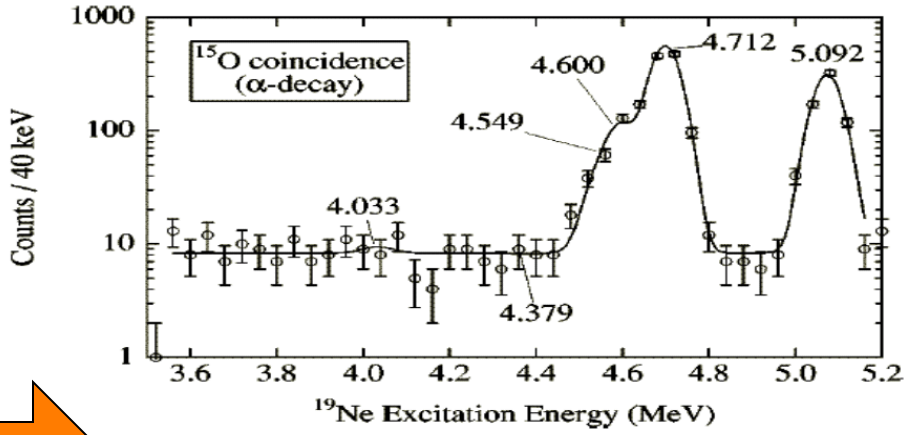


Figure 2: taken from Figure 7 in [10] wh… selective population of resonance at 4.033 MeV excitation energ… using the ^{21}Ne(p,t) reactio…

Motivation:

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

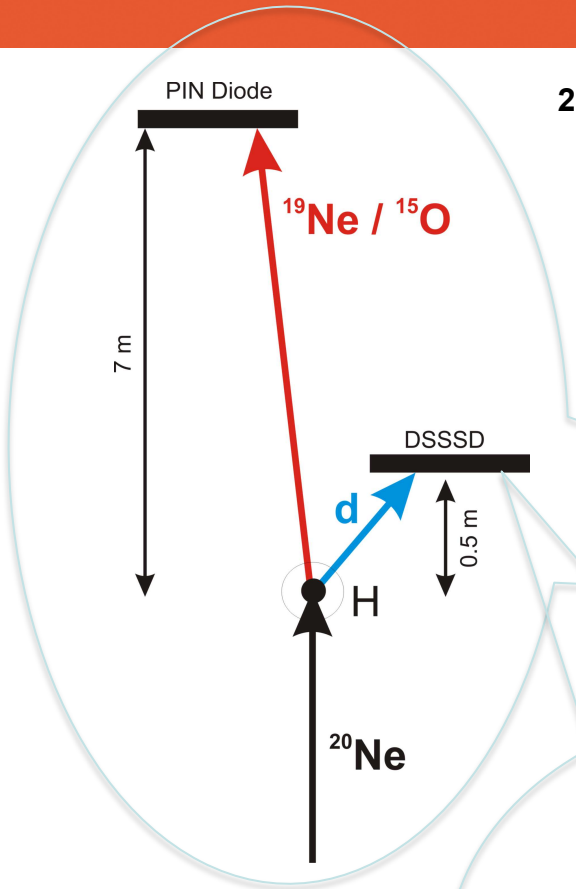


Population of 4.033 MeV level in ^{19}Ne via (p,t) reaction on ^{21}Ne

Measure g and a branching ratio

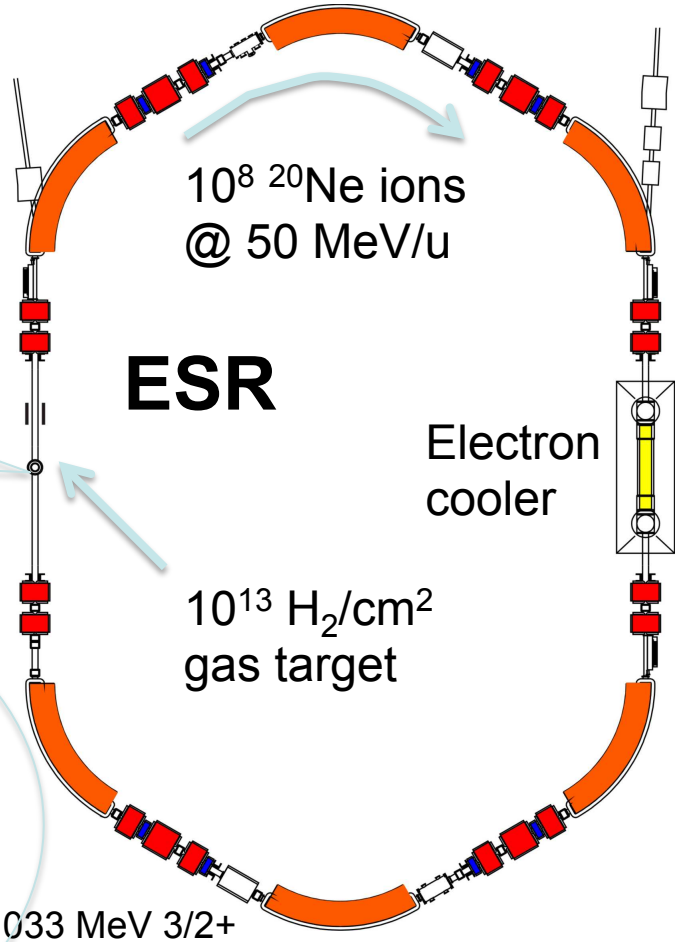
…taken from Figure 9 of [10] showing the events corresponding to α-decaying resonances in ^{19}Ne. Note the flat background associated with fragmentation reactions on C atoms in the $(CH_2)_n$ target.

First transfer reaction measurement at the ESR

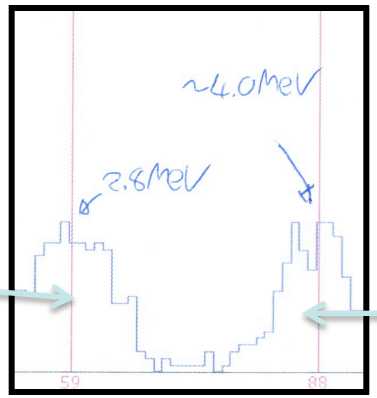


^{20}Ne(p,d)^{19}Ne reaction

Experiment: 08-14 October 2012



Online data



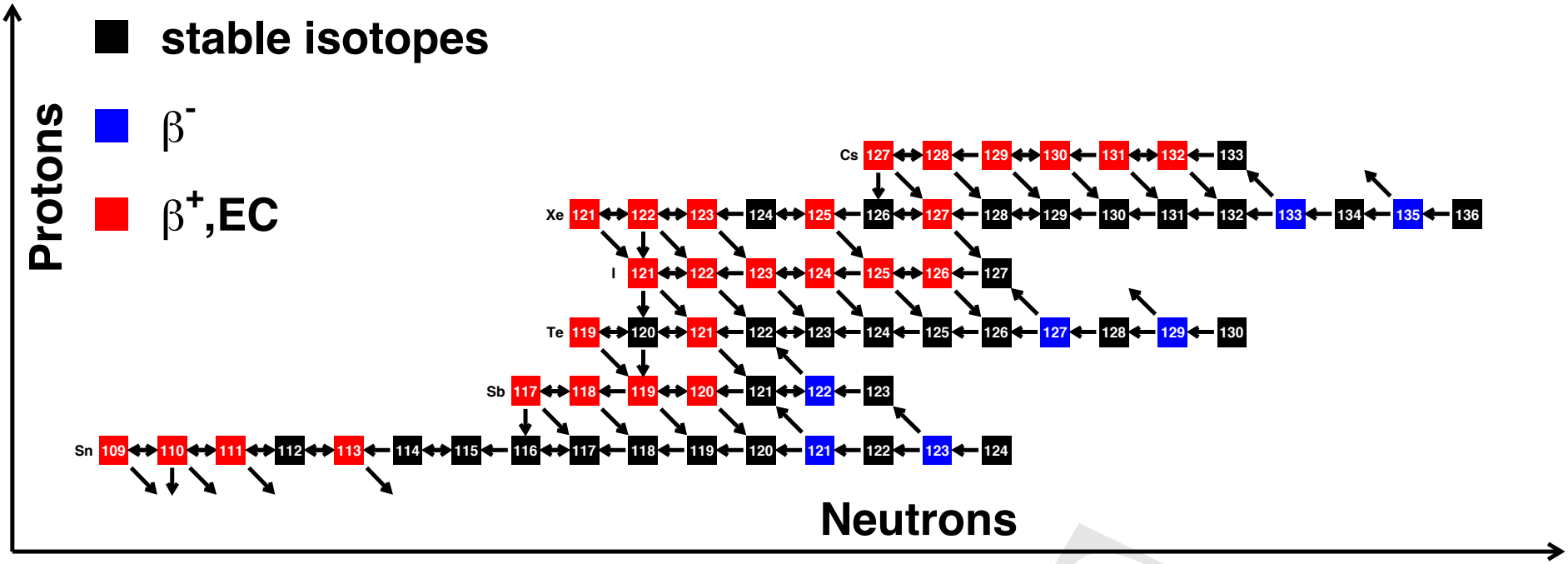
2.795 MeV 1/2- state in ^{19}Ne

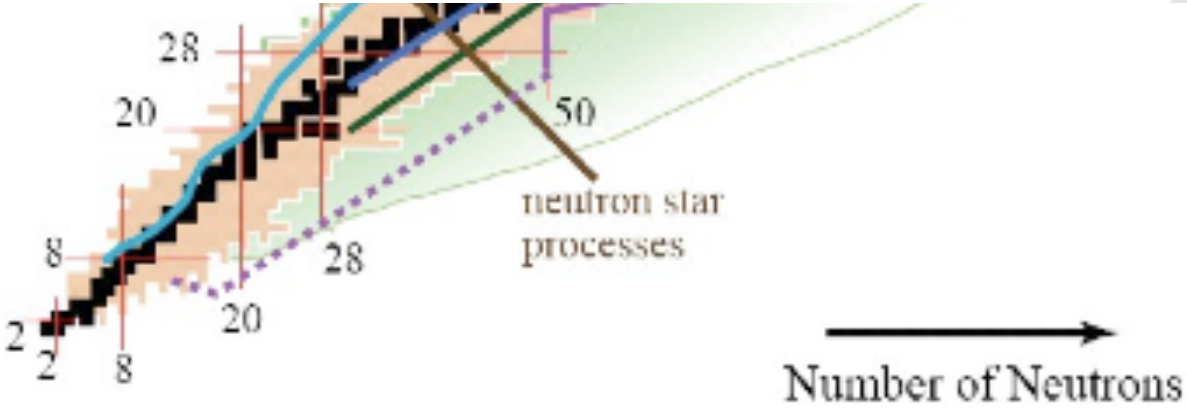
4.033 MeV 3/2+ state in ^{19}Ne

- **data evaluation under way**

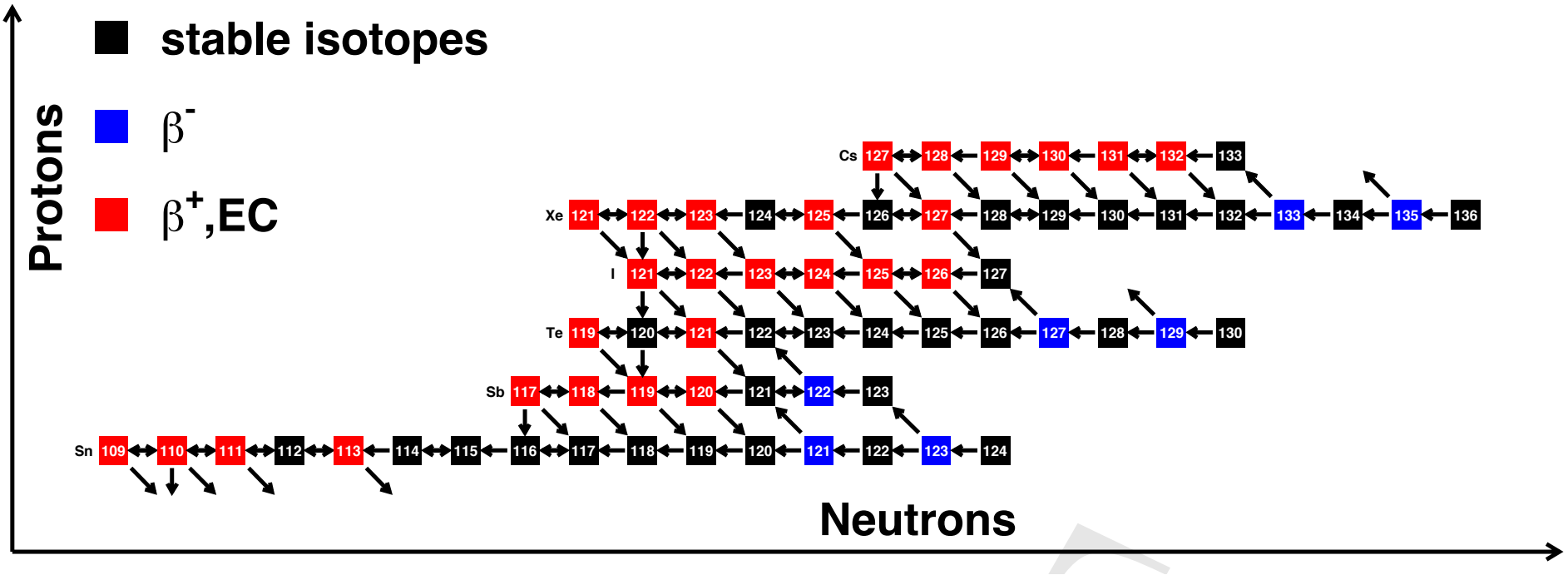
P.M. Woods, Yu. Litvinov et al.

Capture reactions for astrophysics

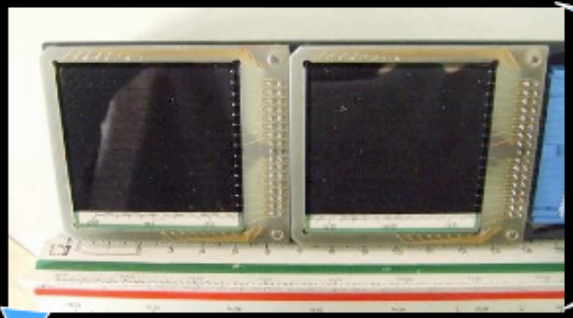




Capture reactions for astrophysics



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



Main Reactions:

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

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

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

DSSSD:

Strips:16*16

Strip width:3mm

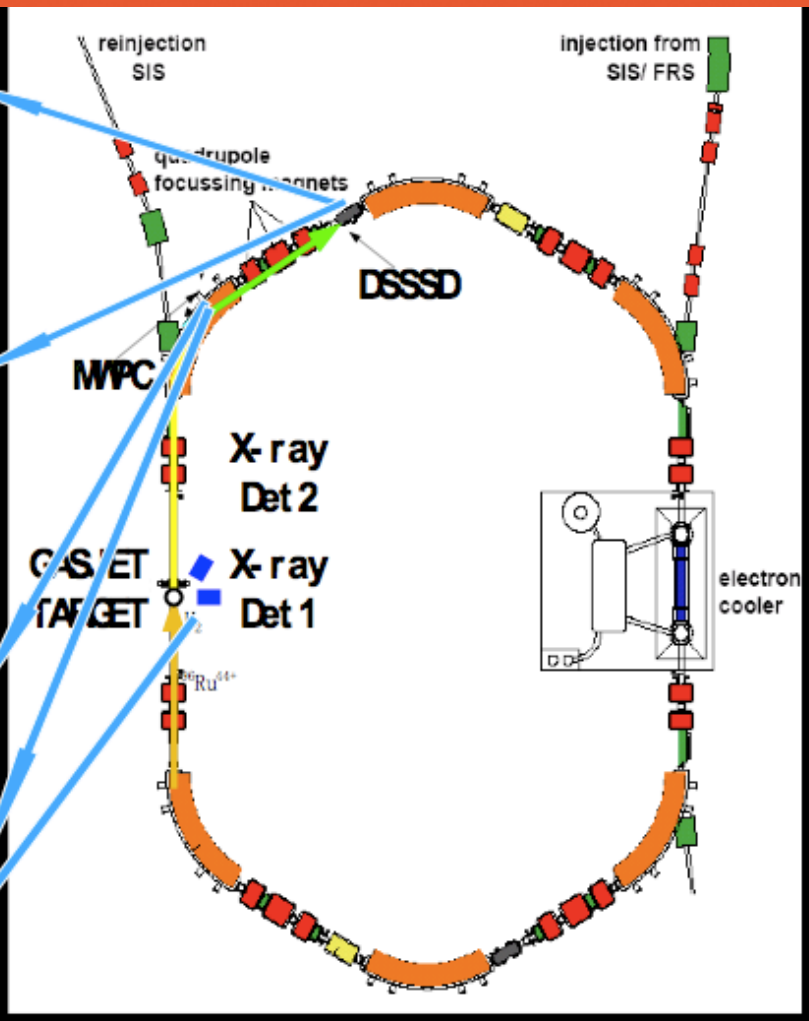
$^{96}Ru^{44+} \rightarrow {}^{96}Ru^{43+}$

MWPC:

Active area: ~120*20mm²

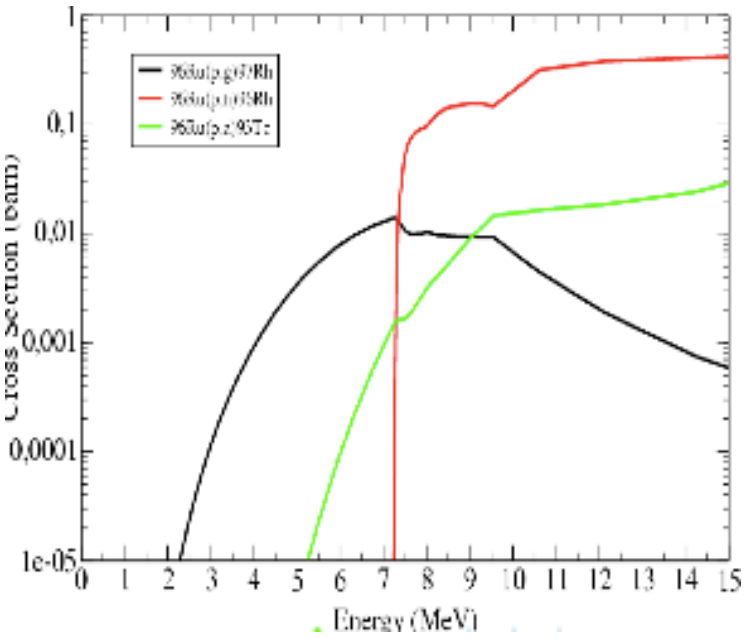
X-Ray detector:

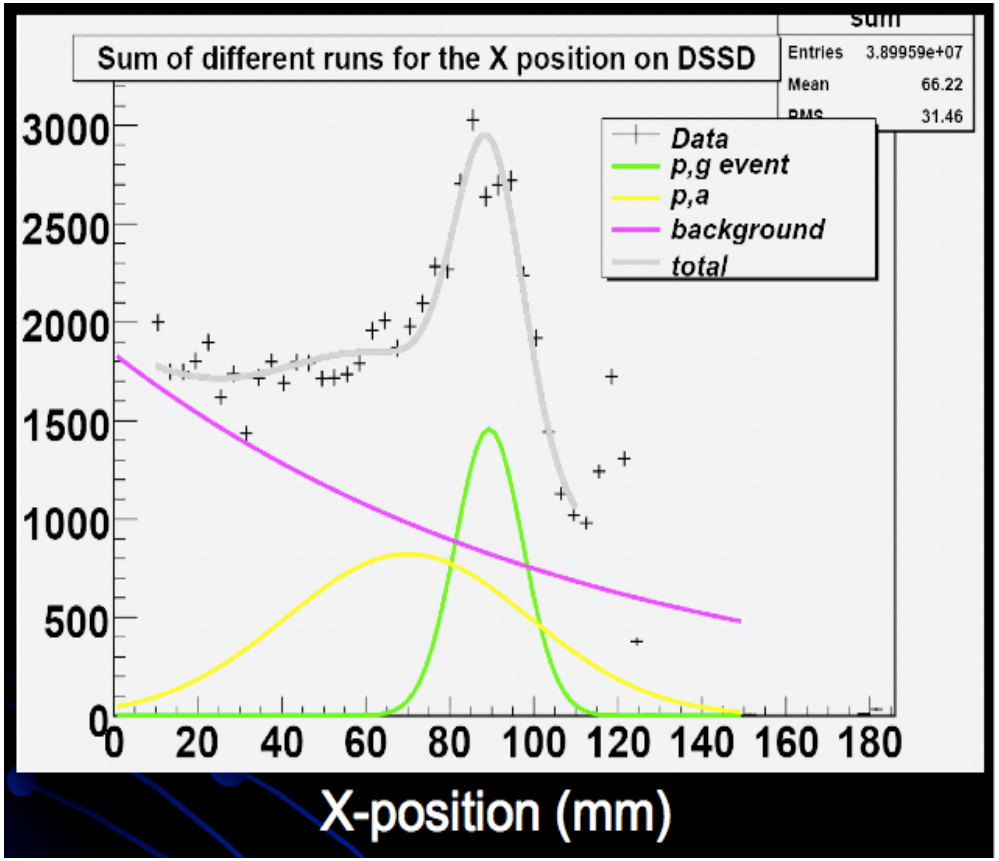
GLP Series Planar Germanium, good energy resolution in the 3~300keV range



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

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





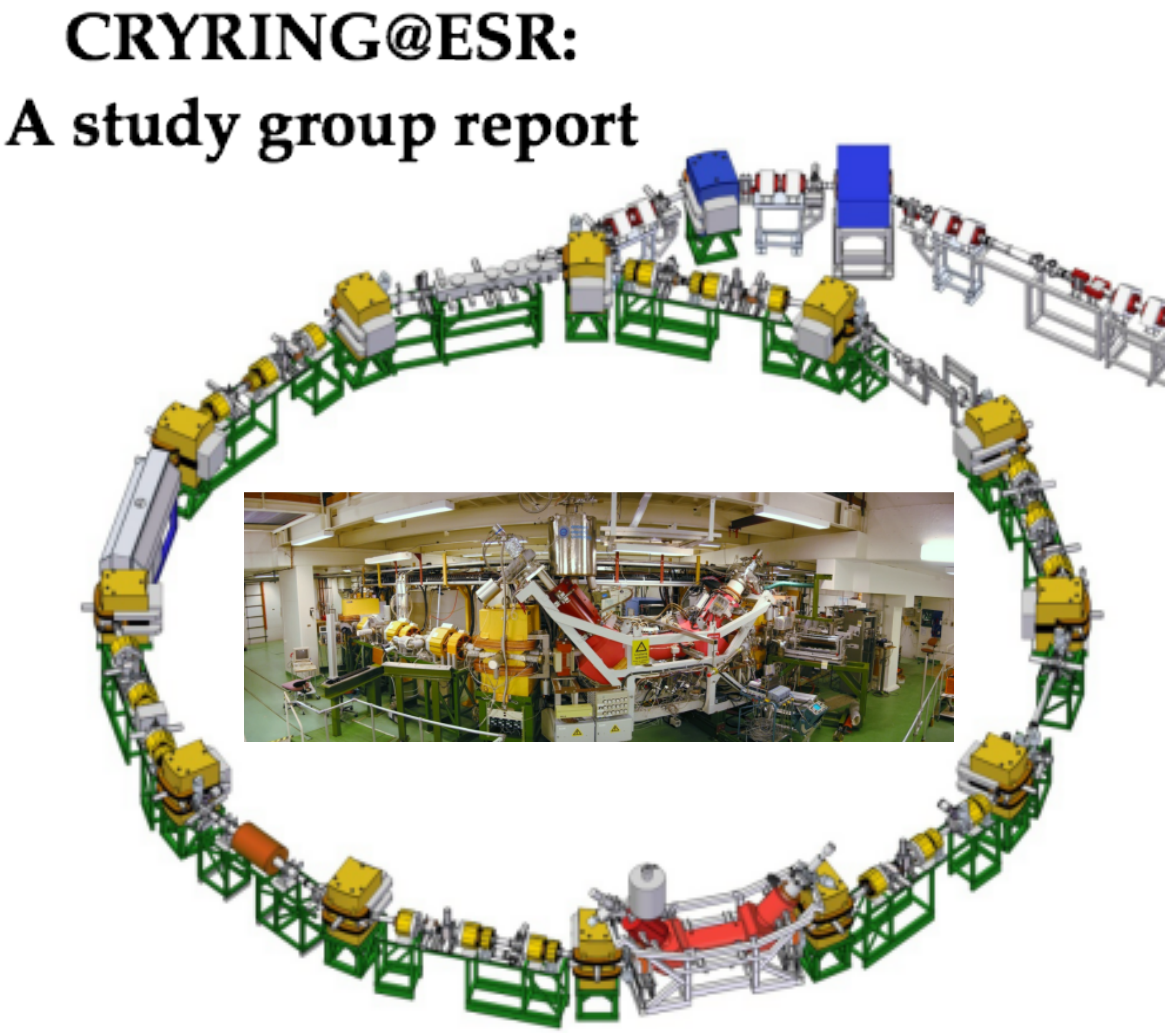
- Measurements directly in the Gamow window of the p-process
- Applicable to radioactive beams
- Clean experimental conditions

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

Q. Zhong et al., J. Phys. Conf. Series 202 (2010) 012011
R. Reifarth et al., GSI Experimental Proposal

Future Measurements

CRYRING@ESR



Study Group

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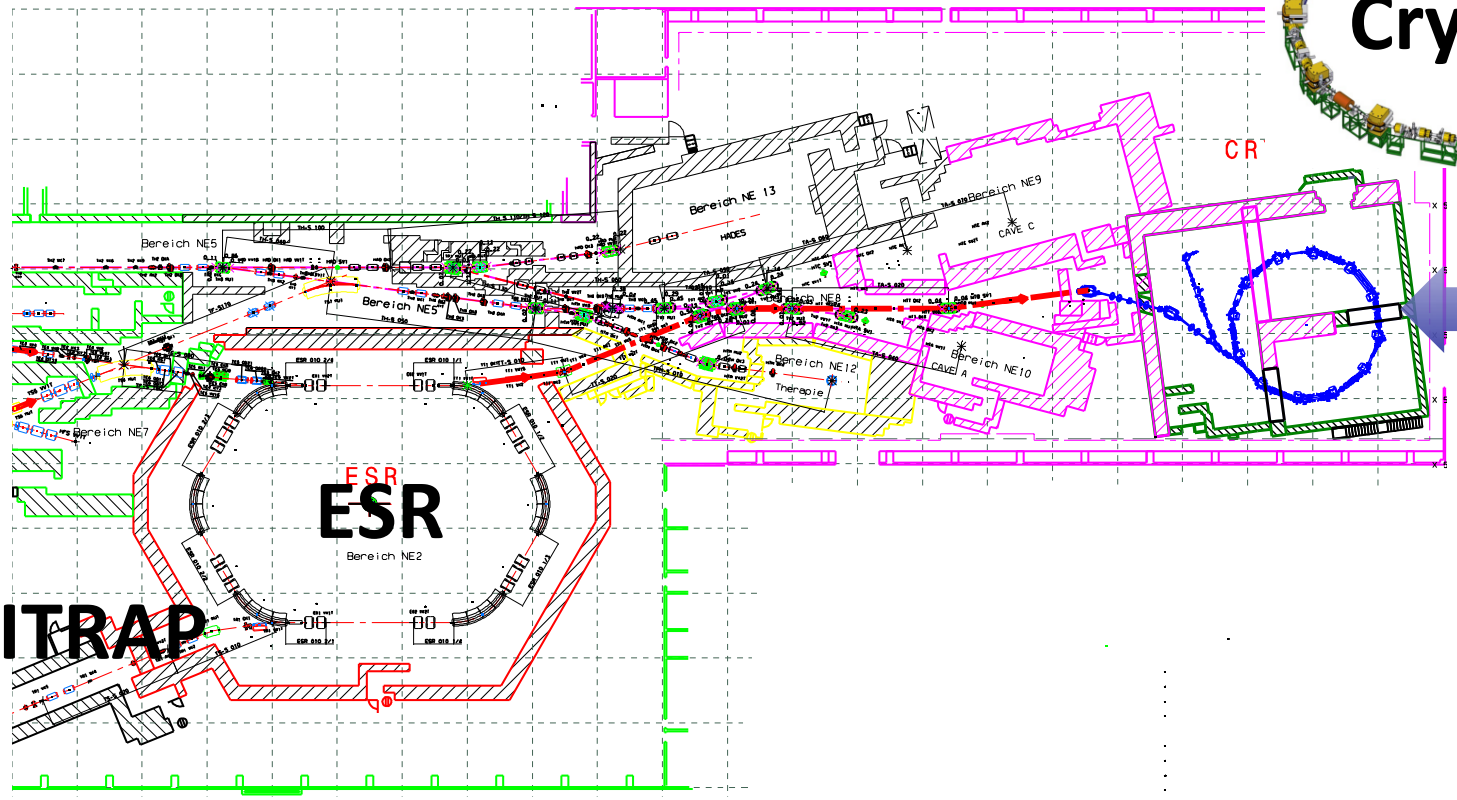
Bernhard Franzke
Anders Källberg
Oliver Kester
Michael Lestinsky
Yuri Litvinov
Markus Steck
Thomas Stöhlker

CRYRING@ESR



HITRAP

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

CRYRING@ESR

November 2012

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

→

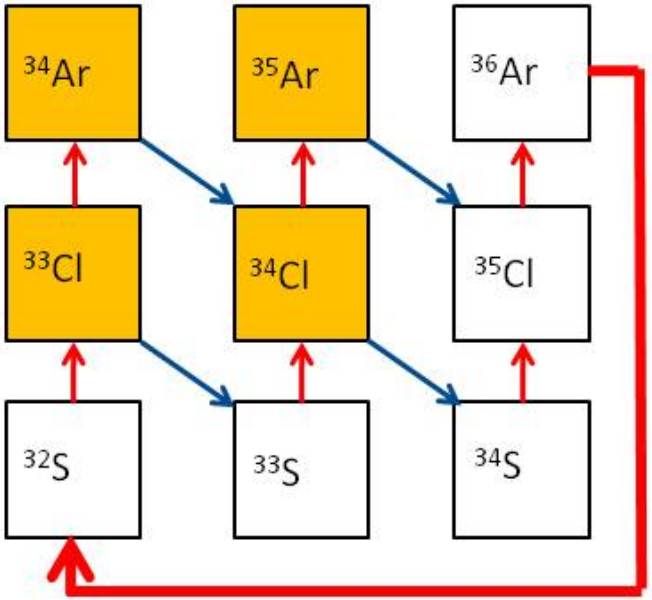
Cryring+ESR: beam energies 0.1-1.0 MeV/u
reaction rates measurements in the Gamow window of the **rp-process**

R. Reifarth et al., Cryring Physics Book

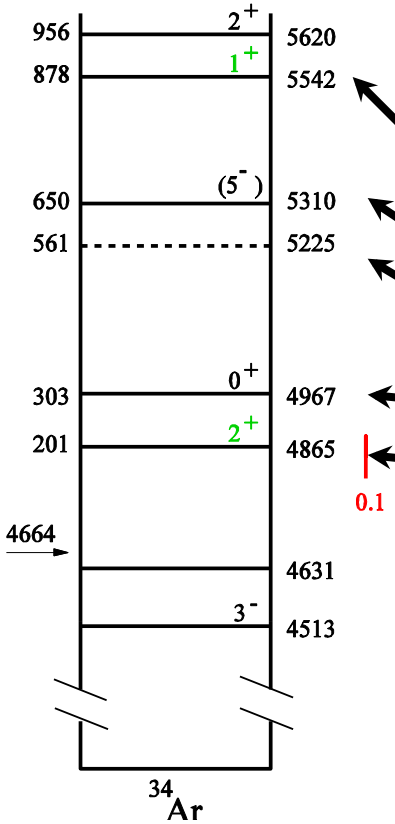
One example: ^{33}Cl(p,γ)^{34}Ar by-pass of ^{34m}Cl γ-ray emitting isomer

Novae physics

Production of ^{34m,g}Cl



S. Bishop et al., Cryring Physics Book



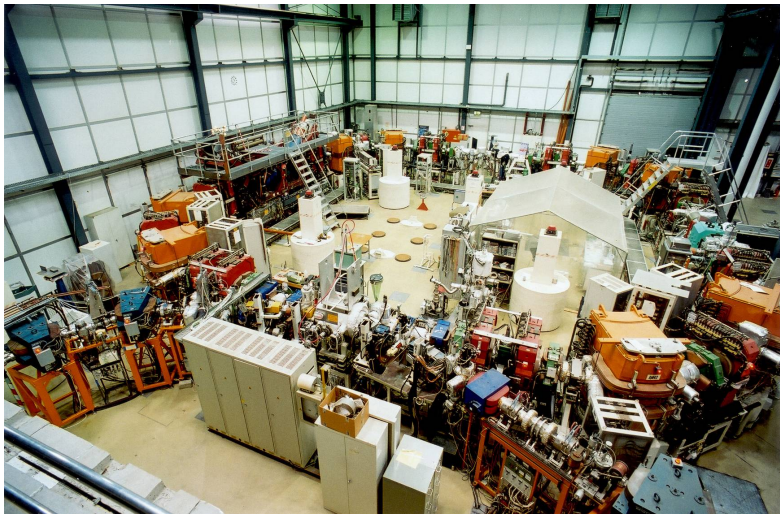
resonance strengths

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

1200 count/hr
1 count/s
2 counts/s
10 counts/day
1 count/s

1.0
0.3
0.1

TSR @ ISOLDE



Eur. Phys. J. Special Topics **207**, 1–117 (2012)
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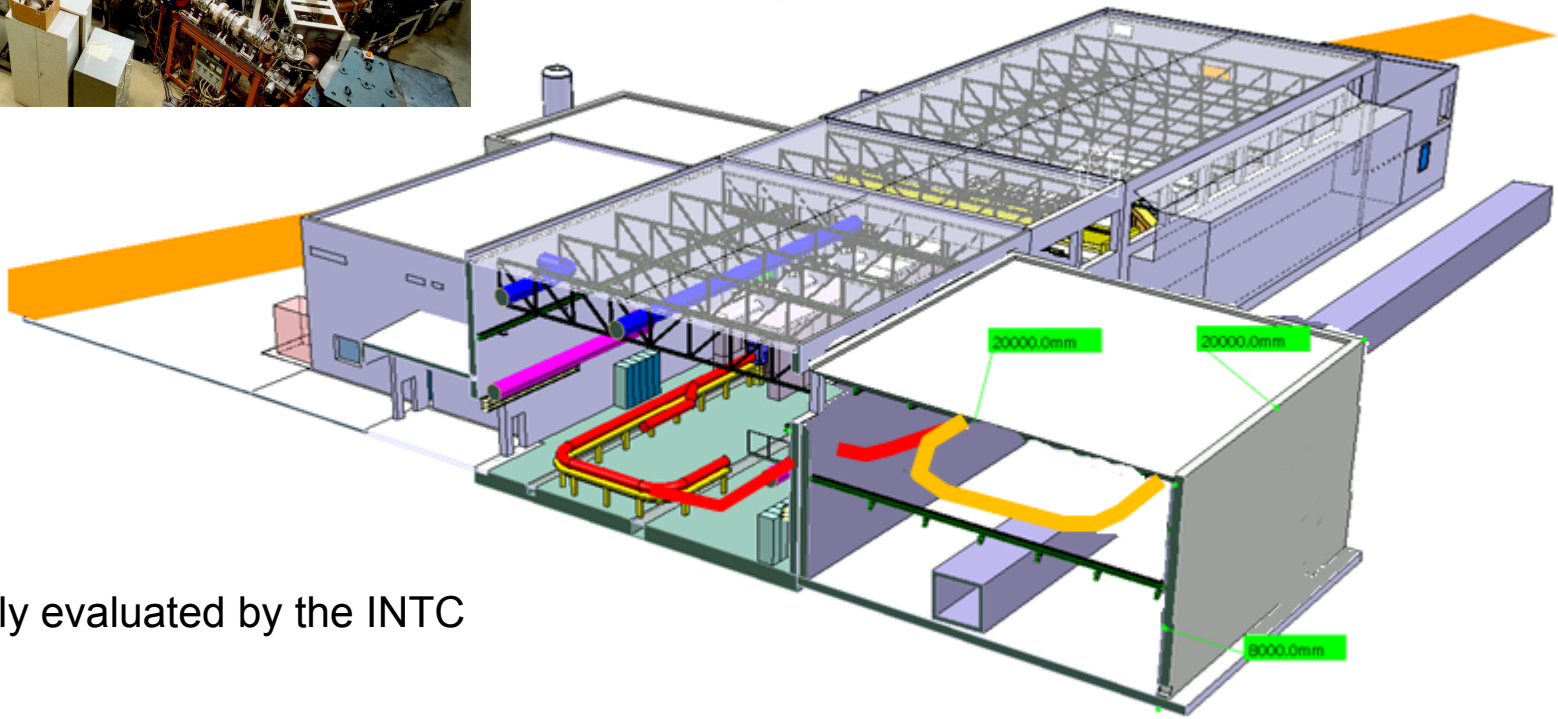
DOI: 10.1140/epjst/e2012-01599-9

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Review

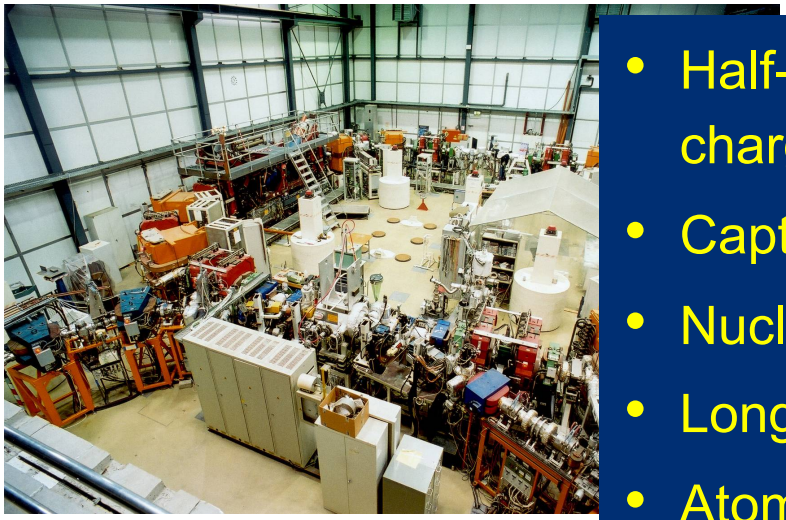
Storage ring at HIE-ISOLDE

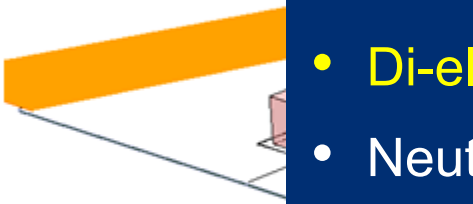
Technical design report



TDR positively evaluated by the INTC

TSR @ ISOLDE





- Half-life measurements of ^{7}Be in different atomic charge states
- Capture reactions for astrophysical p-process
- Nuclear structure through transfer reactions
- Long-lived isomeric states
- Atomic effects on nuclear half-lives
- Nuclear effects on atomic decay rates
- Di-electronic recombination on exotic nuclei
- Neutrino physics; Tests for the neutrino beam project
- Purification of secondary beams from contaminants
- .....

TDR positively evaluated by

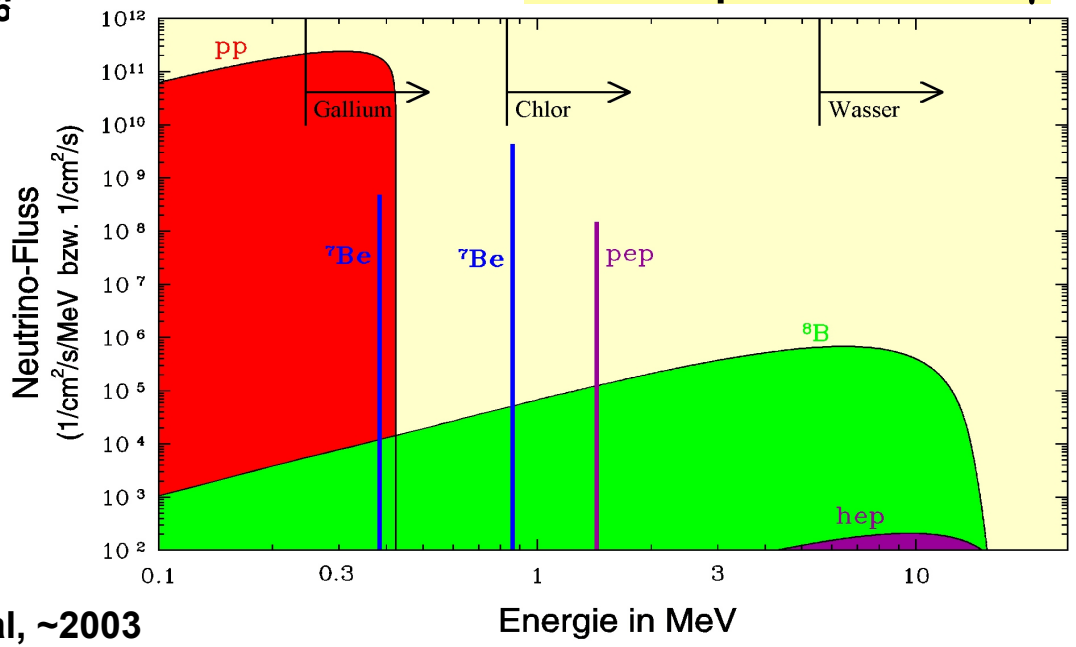
The fate of ^{7}Be in the Sun

J.N. Bahcall, Phys. Rev. C 128 (1962) 1297
I. Iben, K. Kalata, J. Schwartz, ApJ 150 (1967) 1001
J.N. bahcall, C.P. Moeller, ApJ 155 (1969) 511
C.W. Johnson, E. Kolbe, S.E. Koonin,
K. Langanke, ApJ 392 (1992) 320
A.V. Gruzinov, J.N. Bahcall, ApJ 490 (1997) 437
A.V. Gruzinov, J.N. Bahcall, ApJ 504 (1998) 996
and many others

About 20% of ^{7}Be EC decay rate in the Sun are due to bound electrons

$$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$$

$$^{7}Be + p \rightarrow {}^{8}B + \gamma$$



$T_{1/2}$ ($^{7}Be^{0+}$) ~ 53.22 days
$T_{1/2}$ ($^{7}Be^{4+}$) ~ infinity
$T_{1/2}$ ($^{7}Be^{3+}$) ~ 106 days
$T_{1/2}$ ($^{7}Be^{2+}$) ~ 53 days
$T_{1/2}$ ($^{7}Be^{1+}$) ~ 53 days

C. Rolfs et al., suggestion for an ESR proposal, ~2003
C. Rolfs, W. Rodney, Cauldrons in the Cosmos, 1988

TSR@ISOLDE will be the best place to perform such experiments!

The High Energy Storage Ring HESR

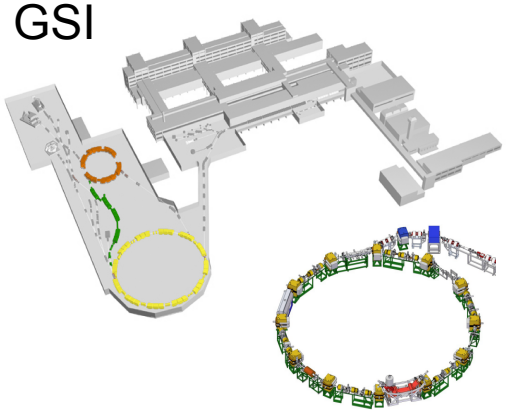
SPARC Experiments at the HESR:

A Feasibility Study

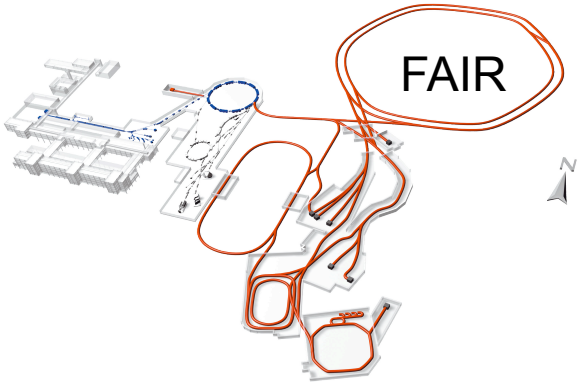
Thomas Stöhlker[1,2,3], Reinhold Schuch[4], Siegbert Hagmann[1,5], Yuri A. Litvinov[1,2]
for the SPARC Collaboration*
Christina Dimopoulou[1], Alexei Dolinskii[1], & Markus Steck[1]

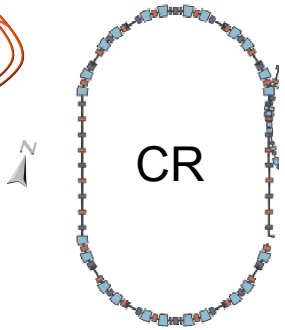
Physics at Storage Rings

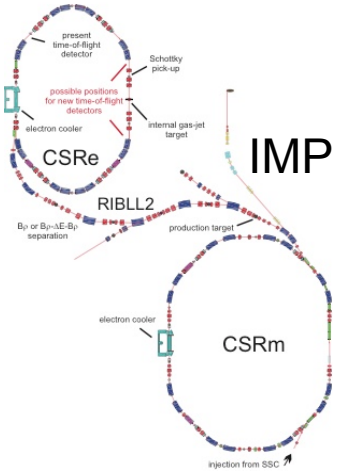
GSI

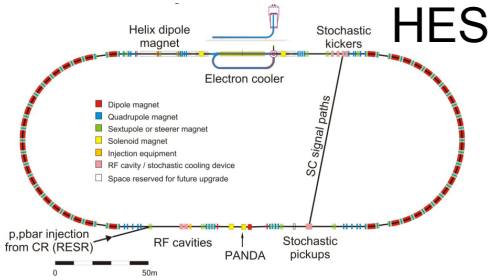


CRYRING

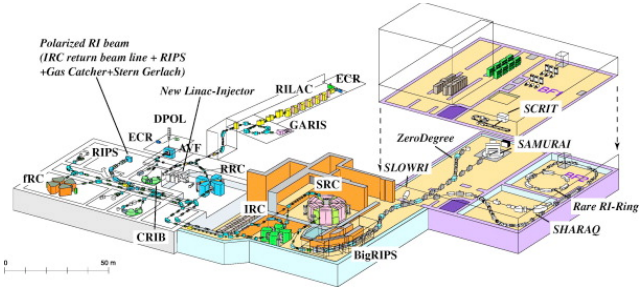






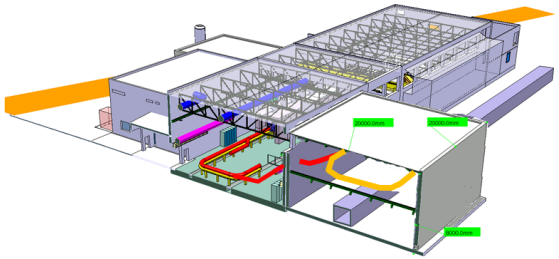


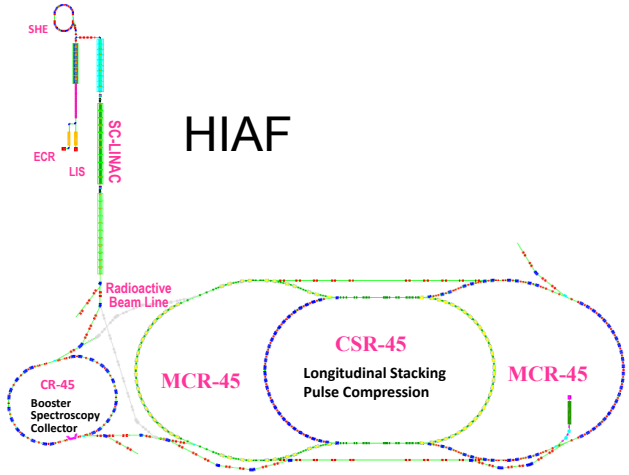
HESR



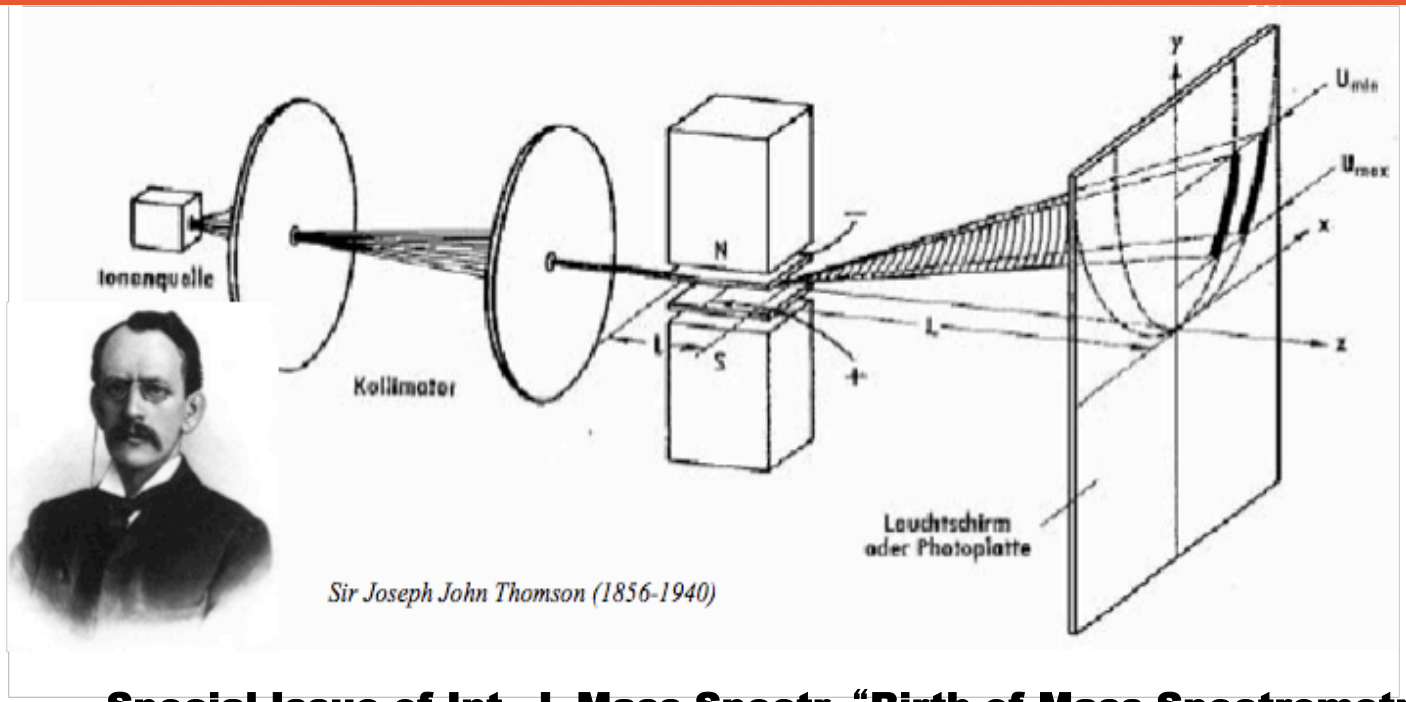
RI-RING

TSR@ISOLDE





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~~ December 2012**

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