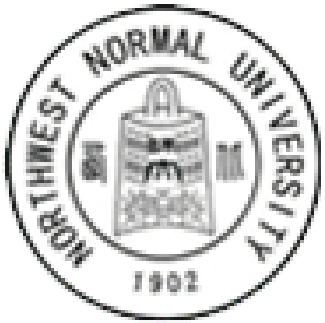
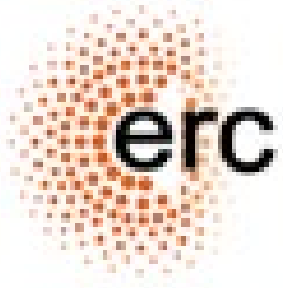
Nuclear Physics Research at Heavy Ion Accelerators: Precision experiments with stored and cooled exotic nuclei

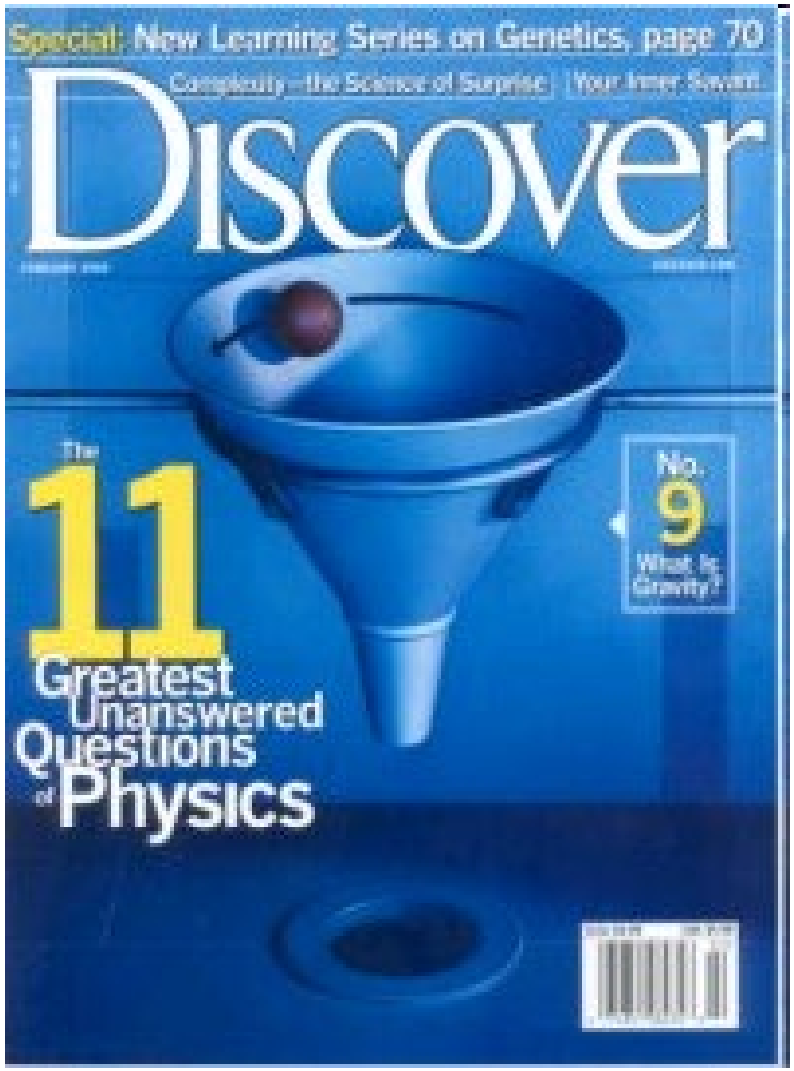
Yuri A. Litvinov





14th International Conference on Heavy Ion Accelerator Technology (HIAT'18)
22-26 October 2018, IMPCAS, Lanzhou, China

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

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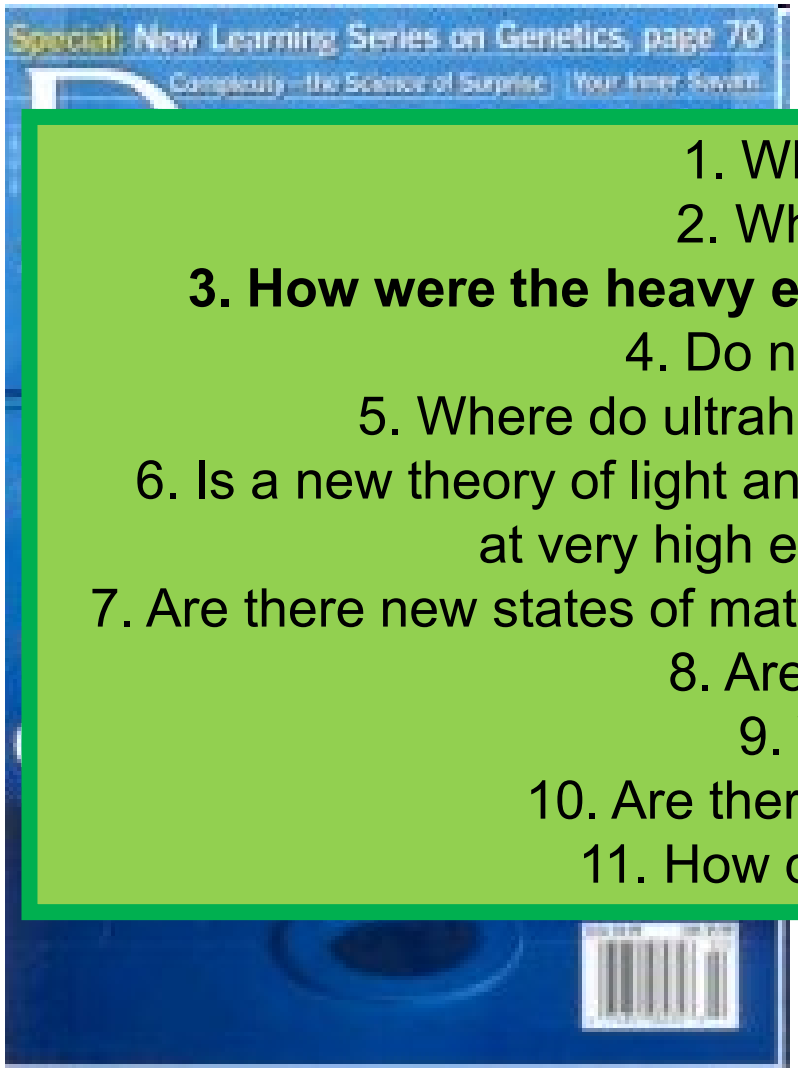
Eric Haseltine, Dan Winters & Gary Tanhauser

National Research Council's board on physics and astronomy



02.01.2002

The 11 Greatest Unanswered Questions of Physics

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?

Long Range Plans

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

NSF: The 2015
Long Range Plan for Nuclear Science
Summary and Recommendations

NuPECC: The 2017
Long Range Plan for Nuclear Physics

NuPECC: The 2017 Long Range Plan for Nuclear Physics

How is mass generated in QCD and what are the static and dynamical properties of hadrons?

How does the strong force between nucleons emerge from the underlying quark-gluon structure?

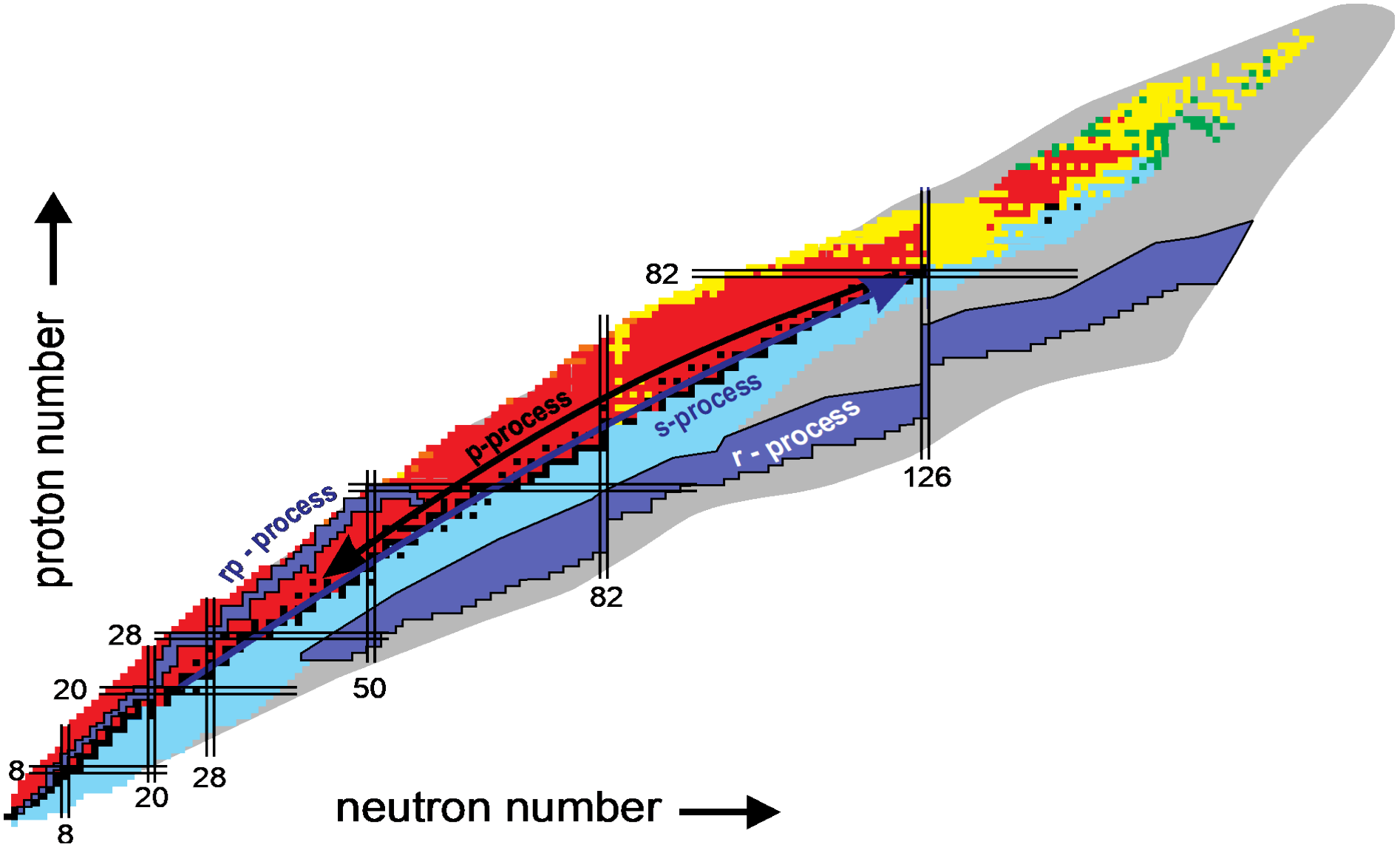
How does the complexity of nuclear structure arise from the interaction between nucleons?

What are the limits of nuclear stability?

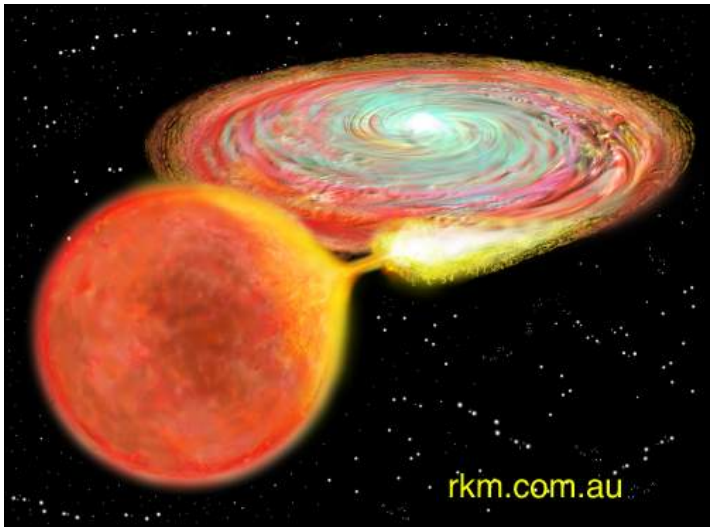
How and where in the universe are the chemical elements produced?

What are the properties of nuclei and strong-interaction matter as encountered shortly after the Big Bang, in catastrophic cosmic events, and in compact stellar objects?

Where and how was gold cooked?



Where and how was gold cooked?



The rp (rapid proton capture) -process

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

→ **Novae**

mass accretion of a **neutron star** leads to

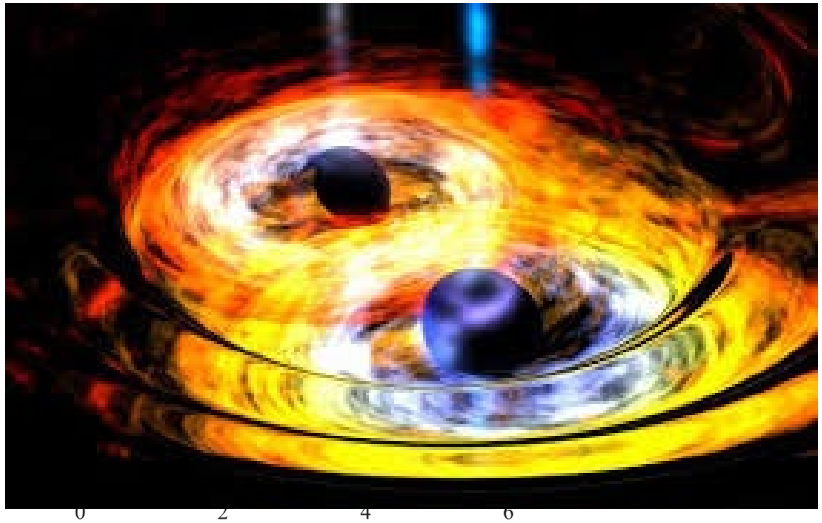
→ **X ray bursts**

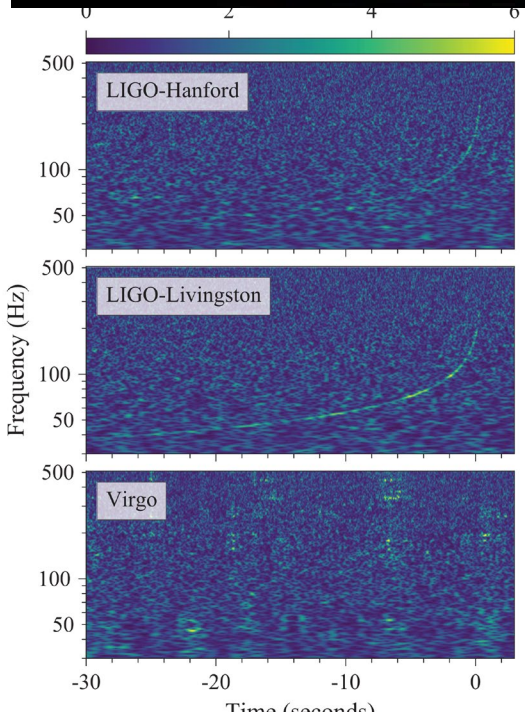
Are Supernovae IIa the sites of the r-process??

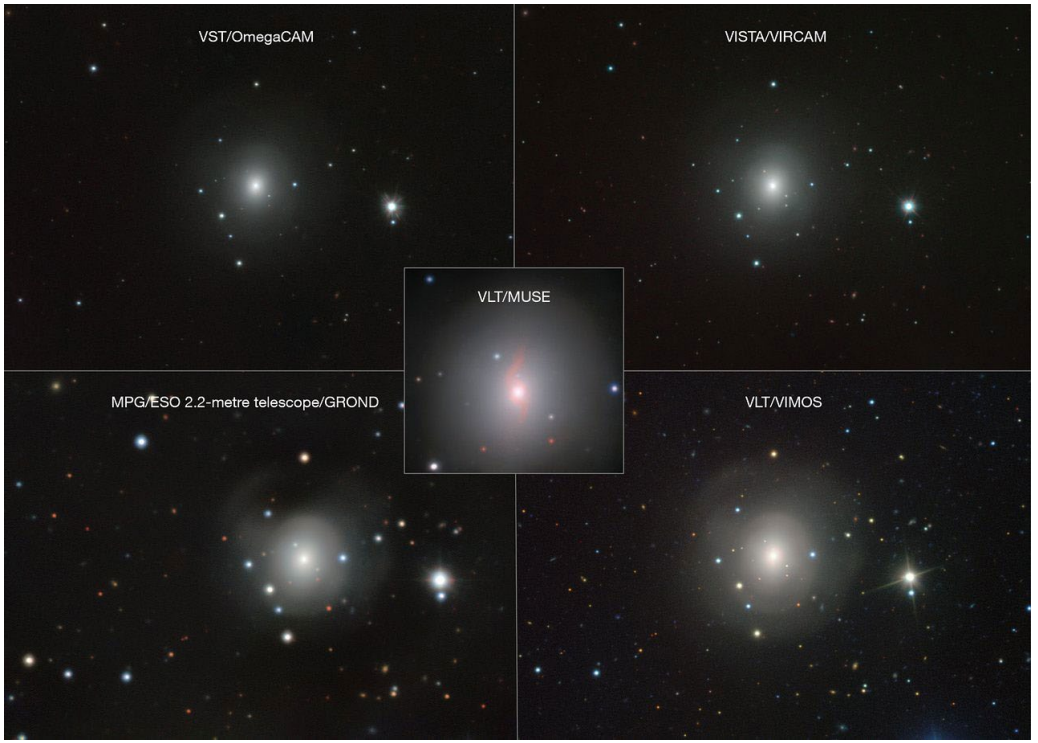
Not excluded:

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

Multi-Messenger Astronomy





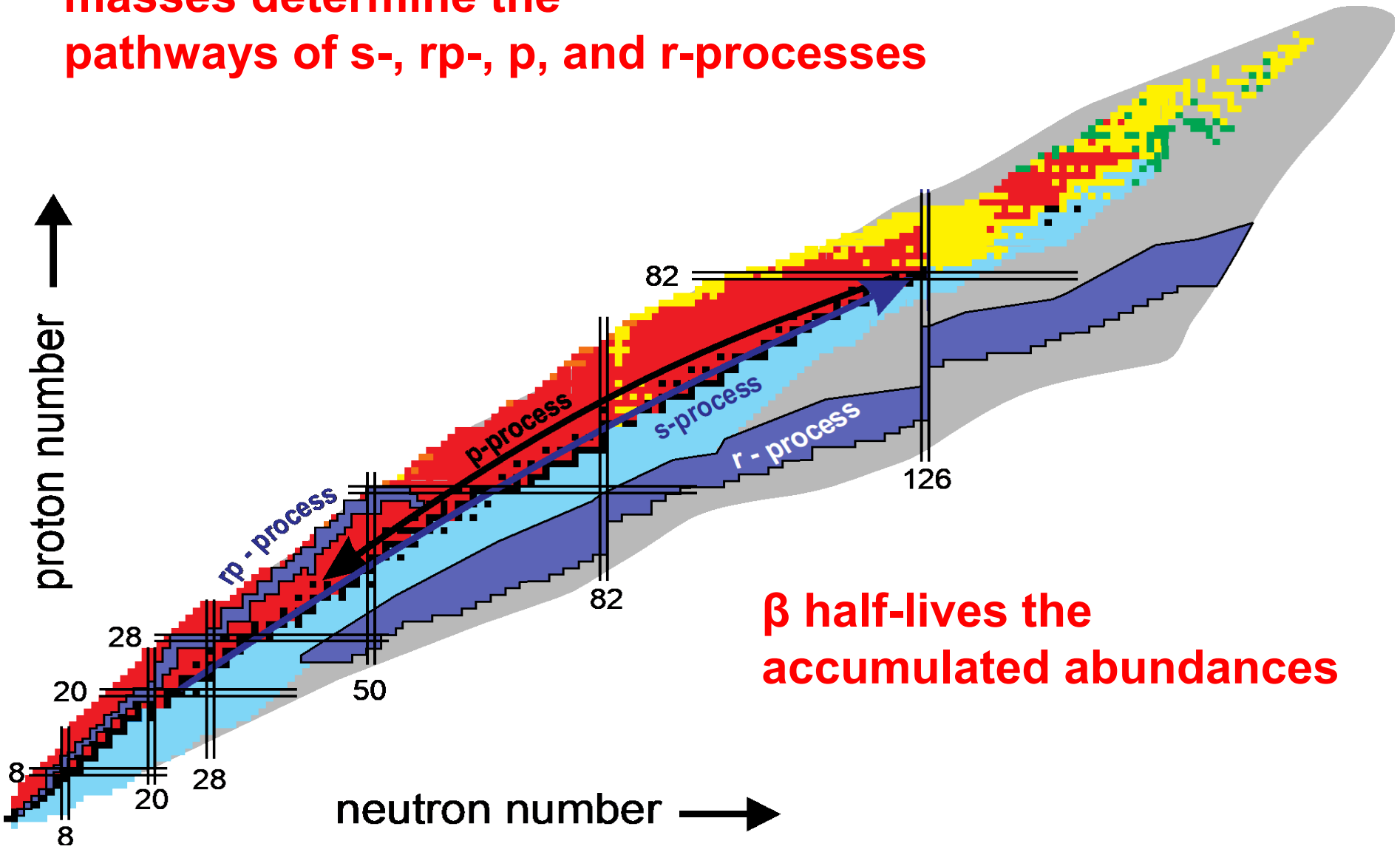


More than 50 other instruments

GW170817

Where and how was gold cooked?

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



β half-lives the accumulated abundances

Masses: Fundamental Properties of Atomic Nuclei

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

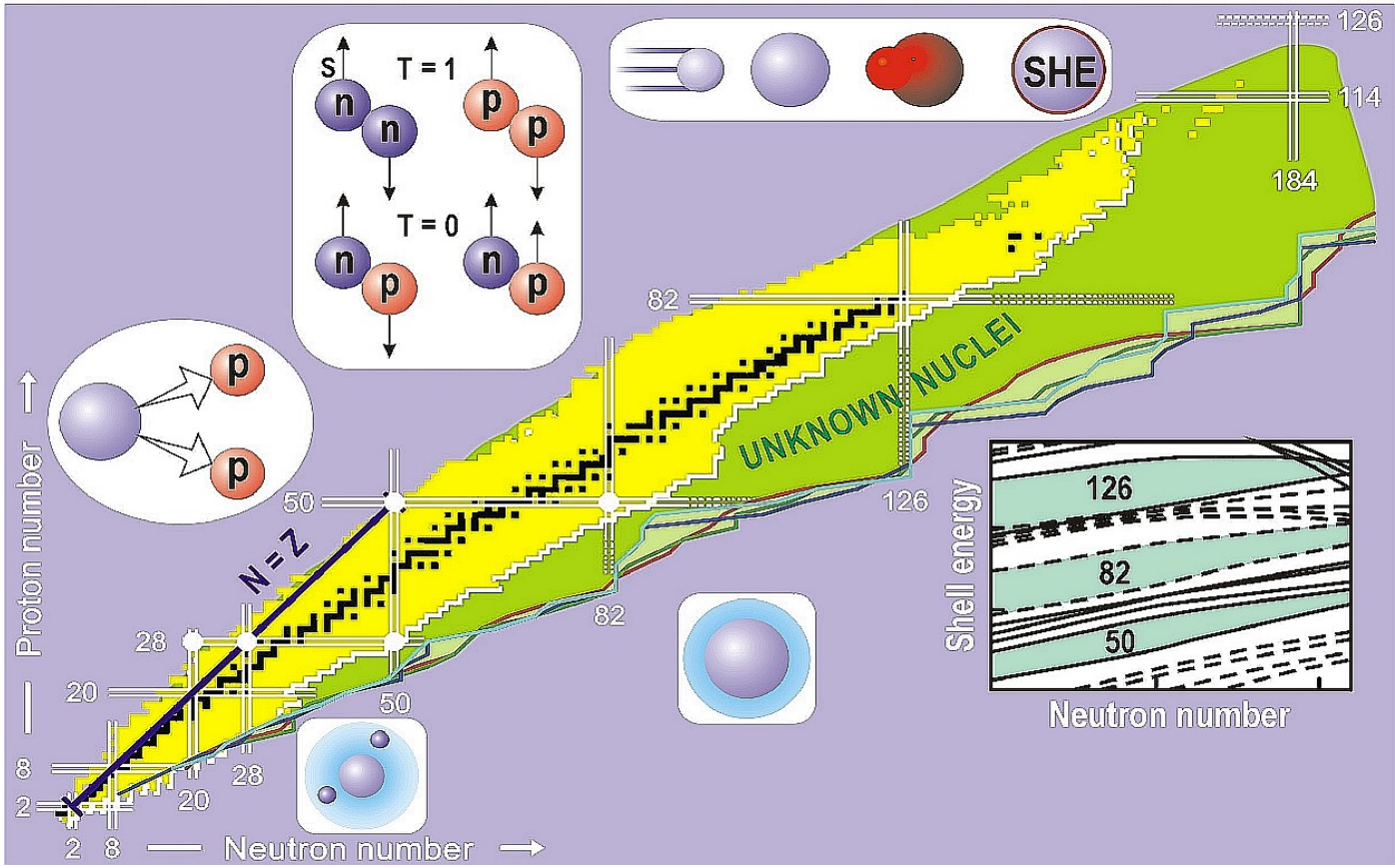
- ➢ **Correlations**
- • **pairing**

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

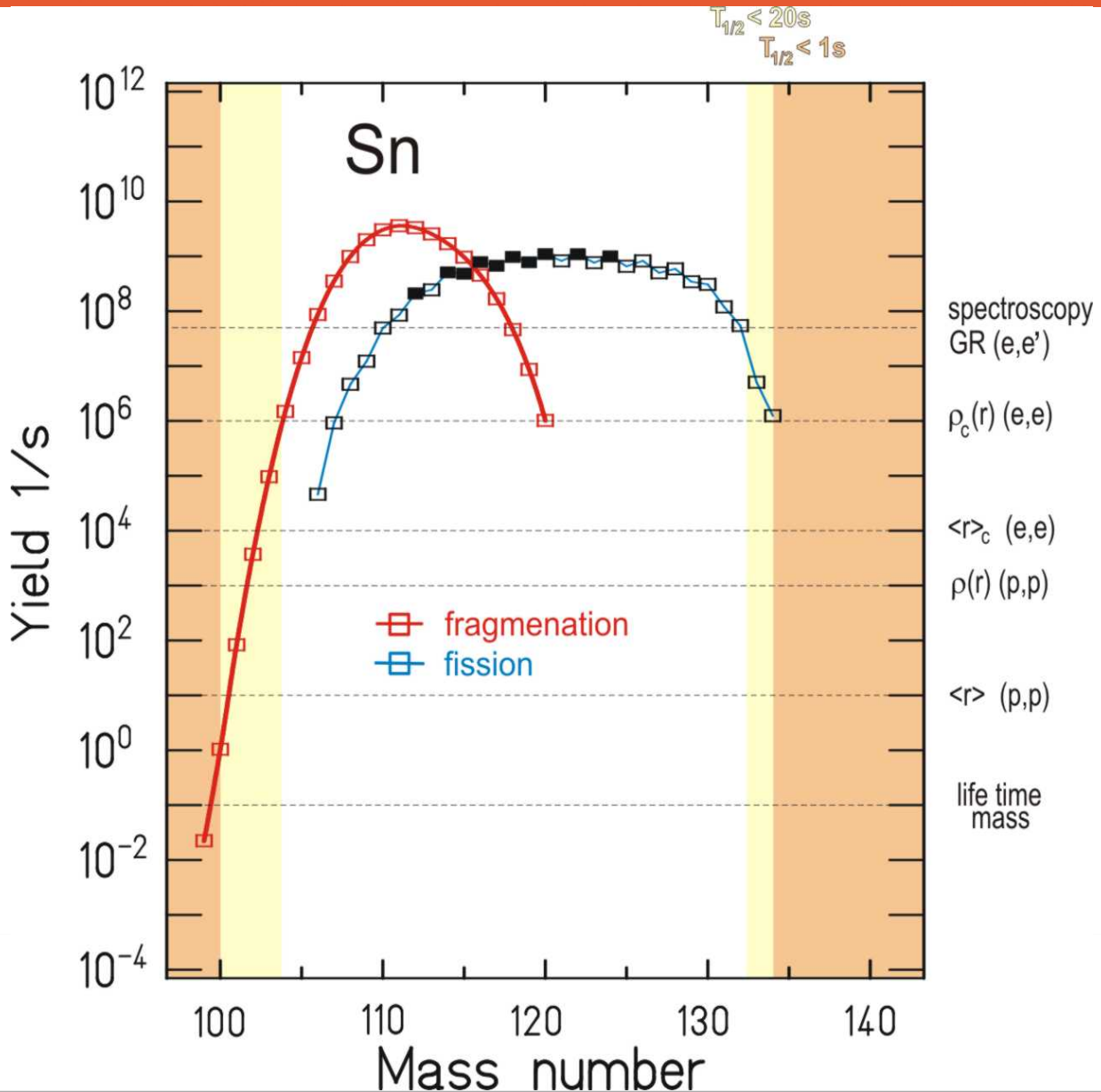
- ➢ **The reach of nuclei**
- • **Drip lines**
- • **Specific configurations and topologies**

- ➢ **Nuclear astrophysics**
- • **Paths of nucleosynthesis**

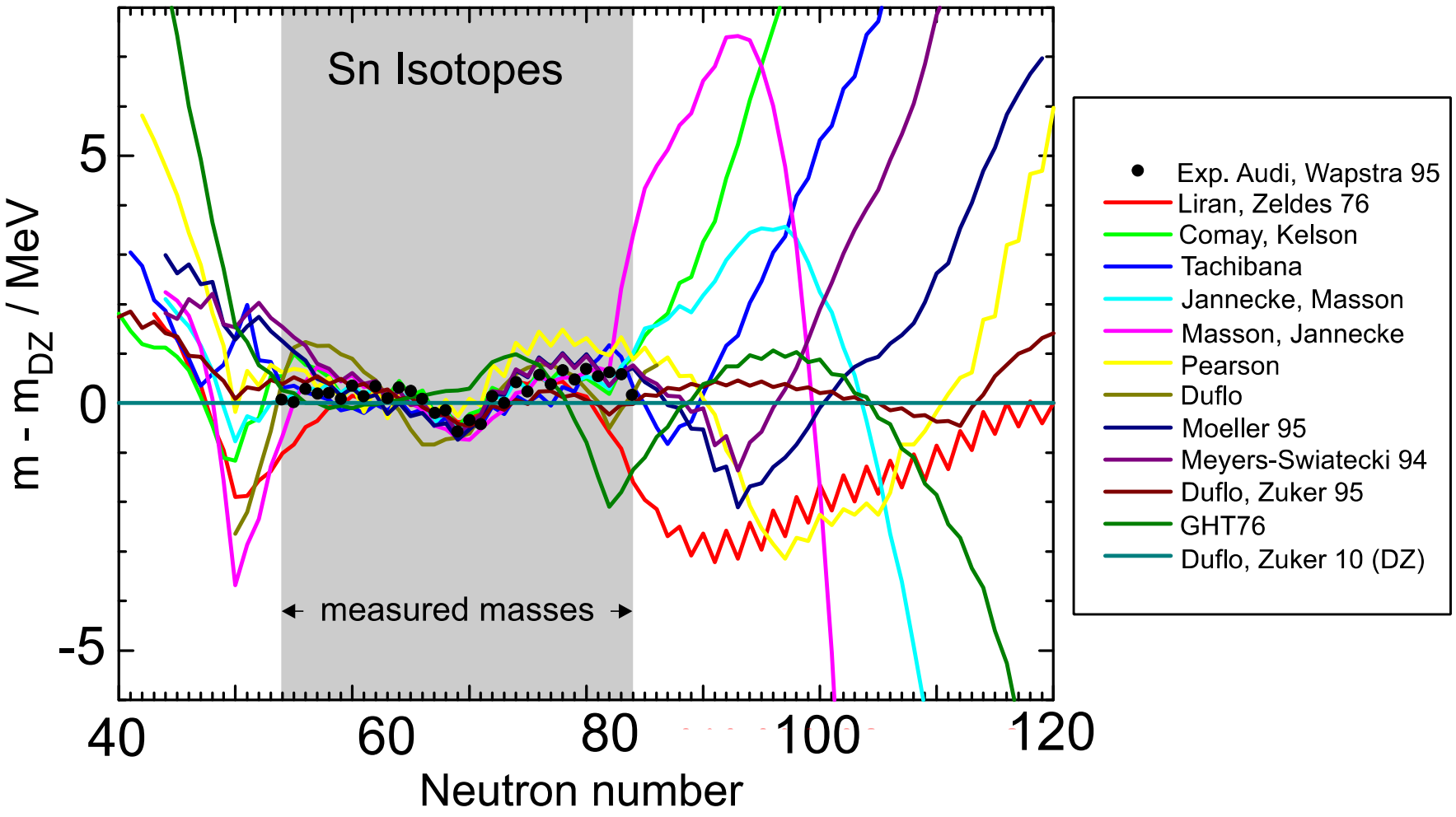
- ➢ **Fundamental symmetries**
- ➢ **Metrology**
- ➢ **…..**



Production Cross-Sections for Tin-Isotopes



Description of Nuclear Binding Energies



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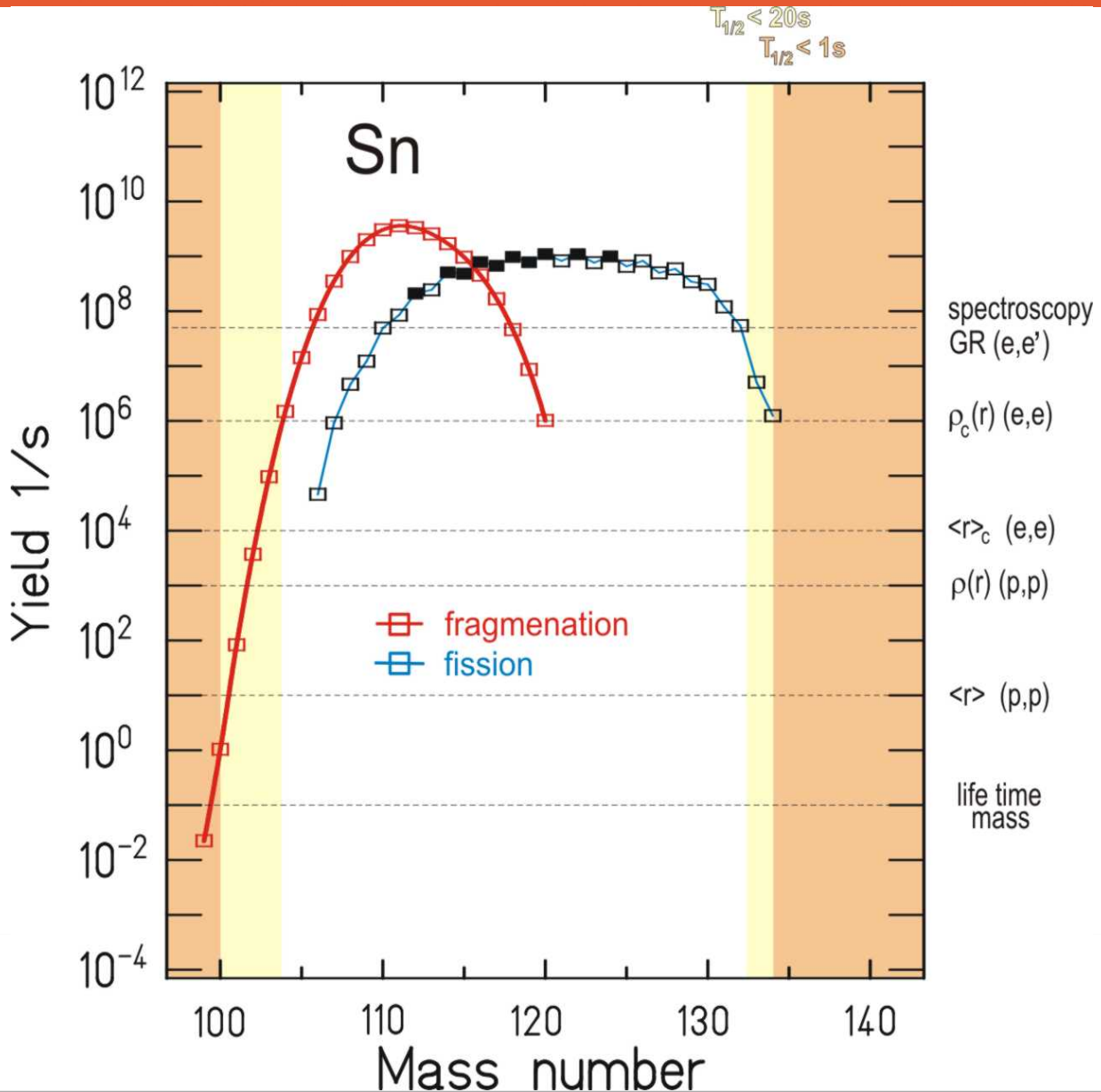
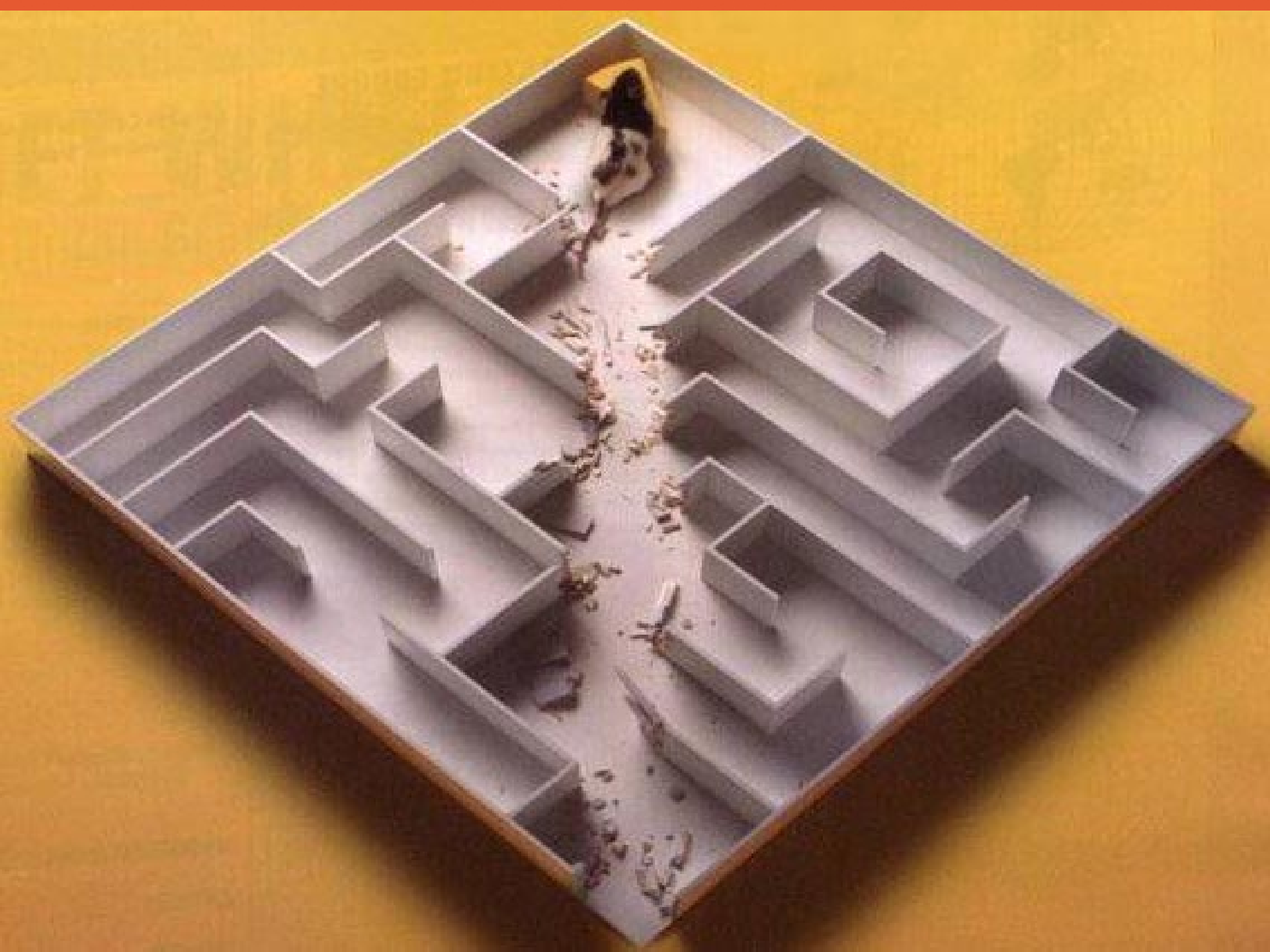




Devices for precision mass measurements

Penning trap

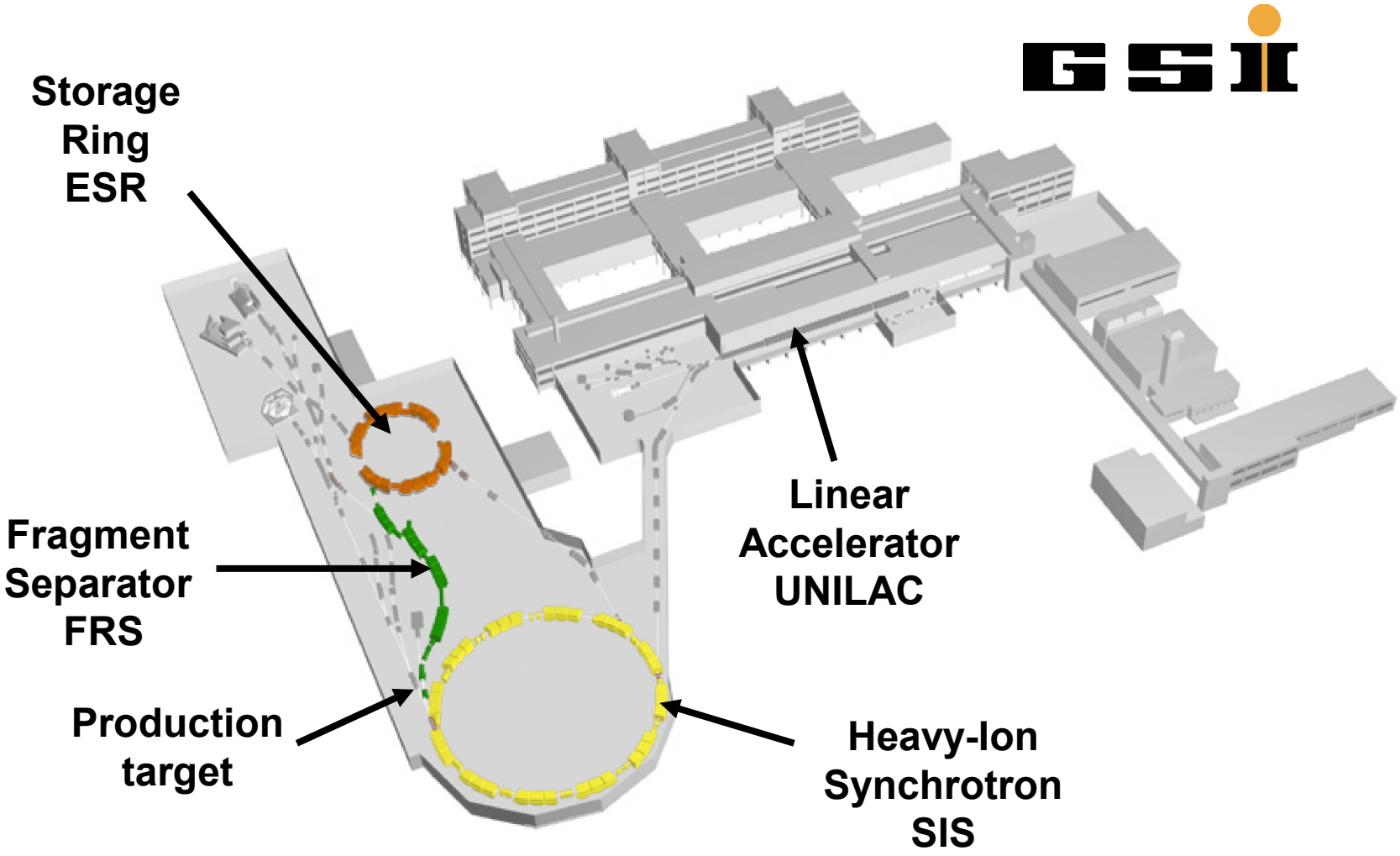
Storage ring

particles at nearly rest in space

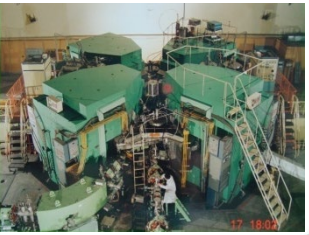
relativistic particles

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

Secondary Beams of Short-Lived Nuclei



Heavy Ion Research Facility in Lanzhou (HIRFL)



SSC(K=450)

SFC (K=69)

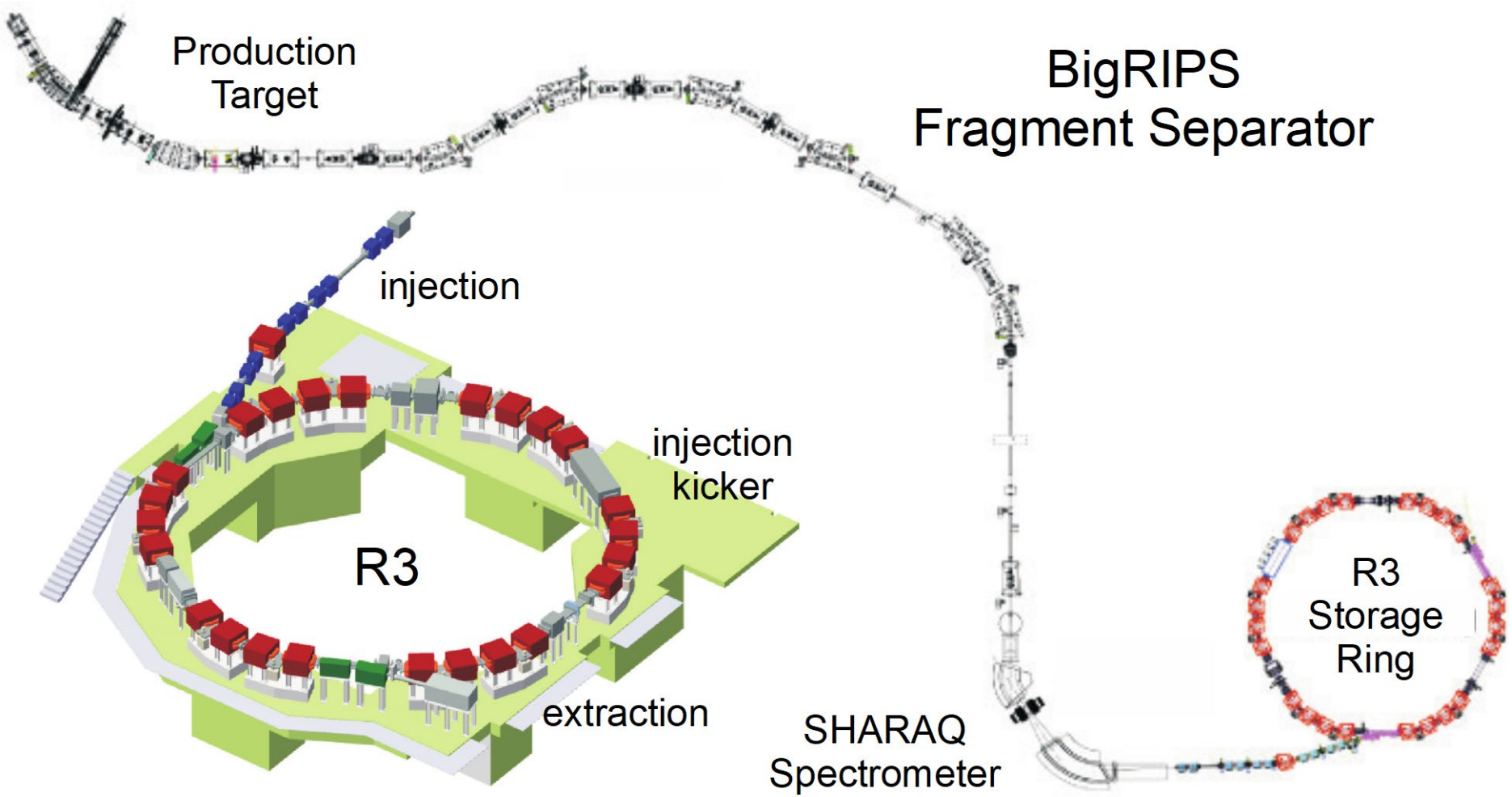
CSRe

RIBLL1

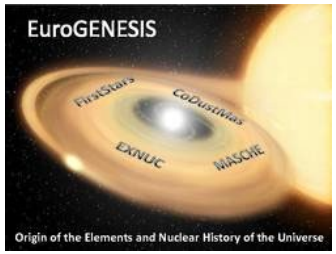
RIBLL2

CSRm

BigRIPS + R3 Setup in RIKEN



Direct Mass Measurements on the Chart of the Nuclides

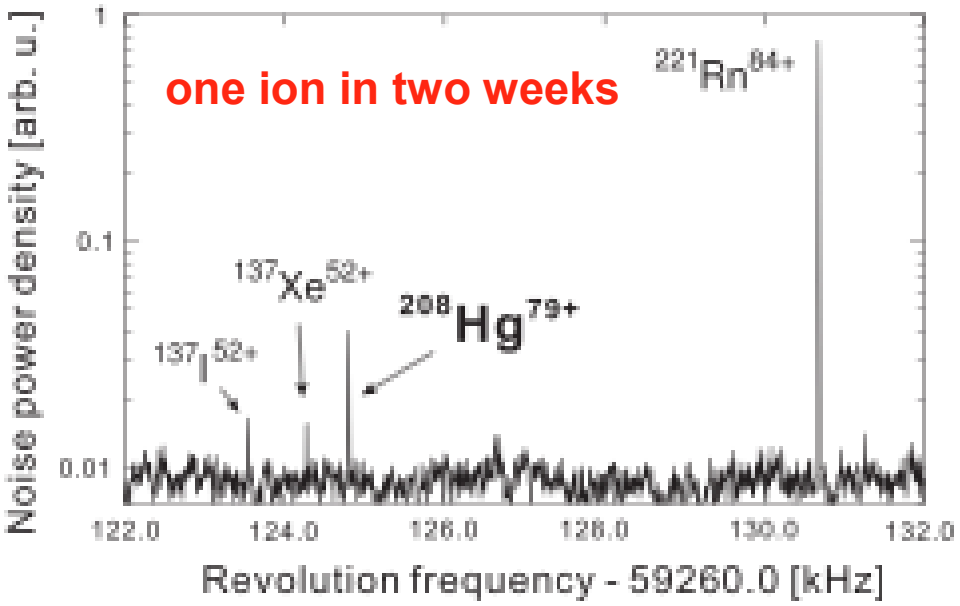


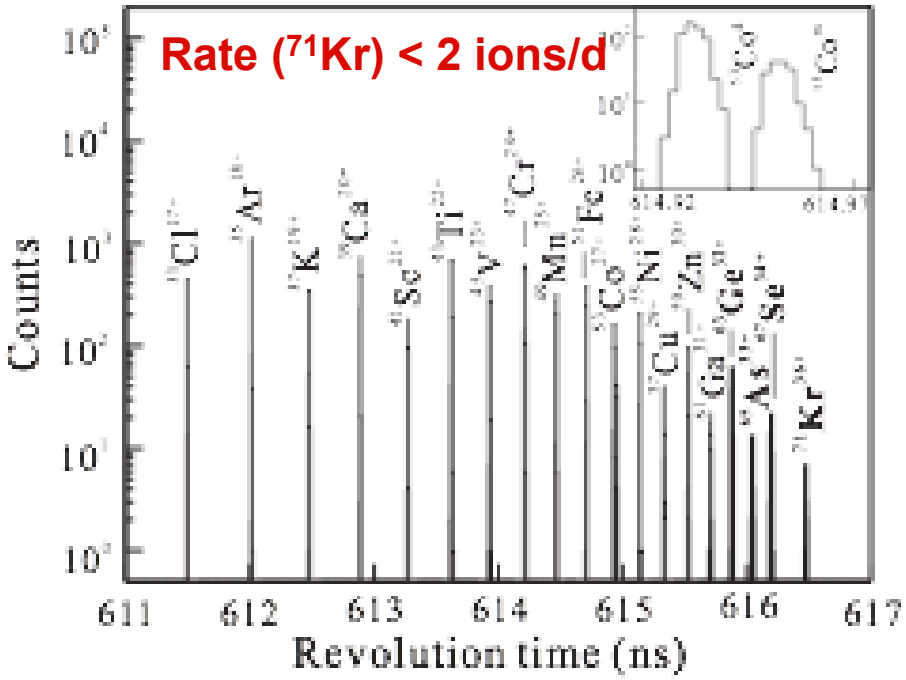
Individual Project
High-Precision Measurements of Nuclear Ground State Properties

Penning Traps

Storage Rings

Direct Mass Measurement of ^{208}Hg Nuclide





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

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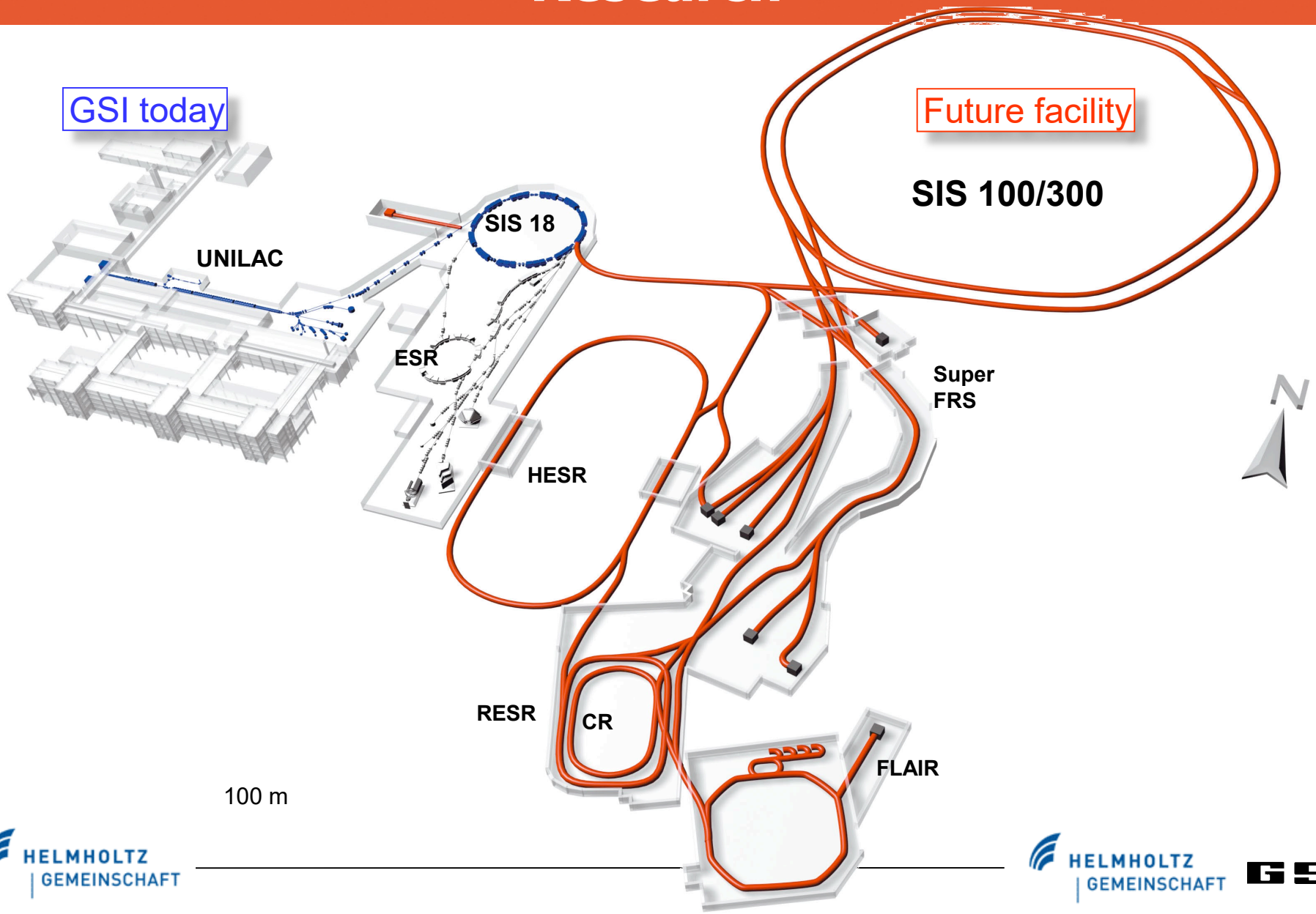
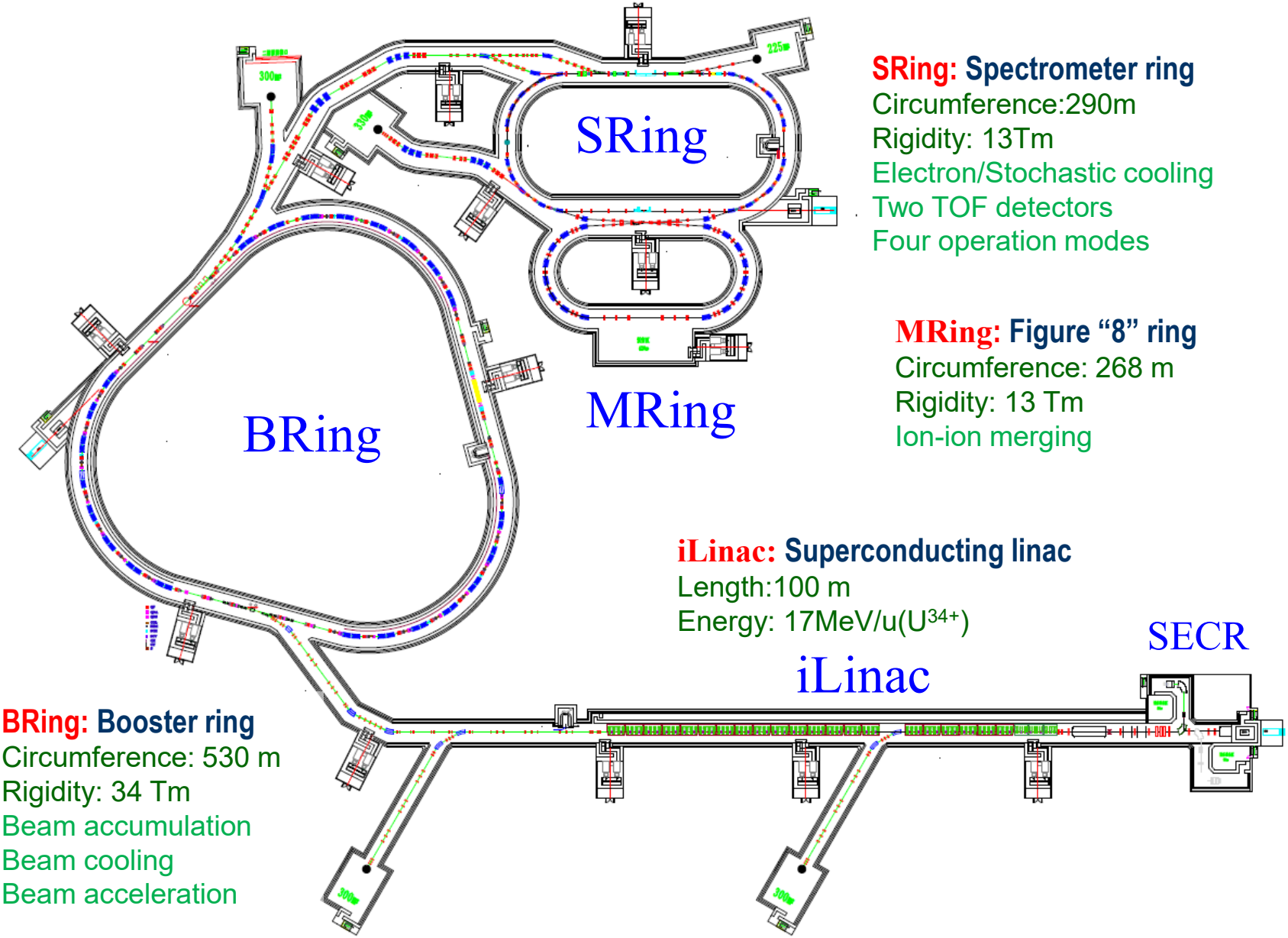
GSI

FAIR - Facility for Antiproton and Ion Research



General description – **Main components**



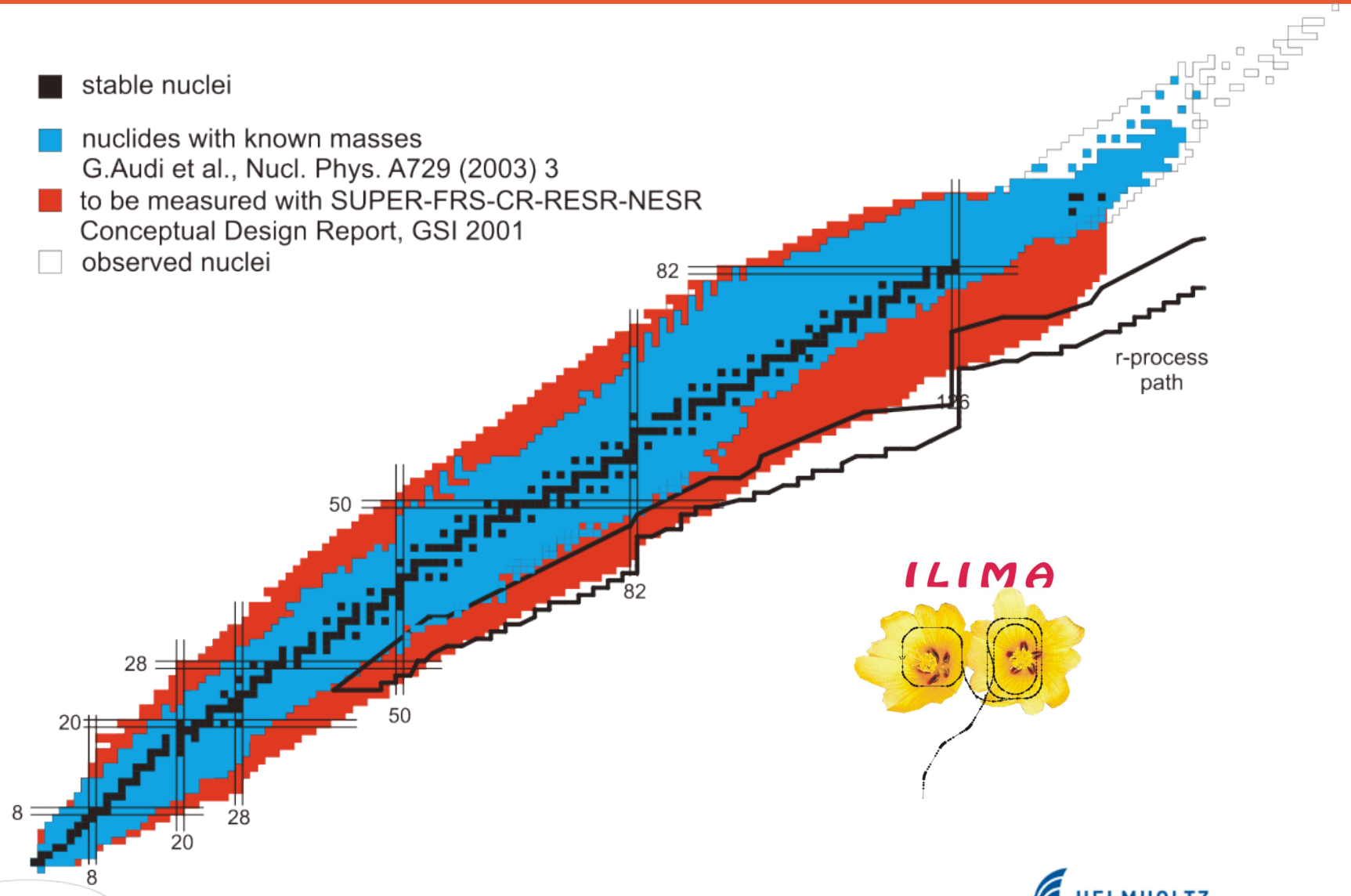
SRing: Spectrometer ring
Circumference:290m
Rigidity: 13Tm
Electron/Stochastic cooling
Two TOF detectors
Four operation modes

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

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

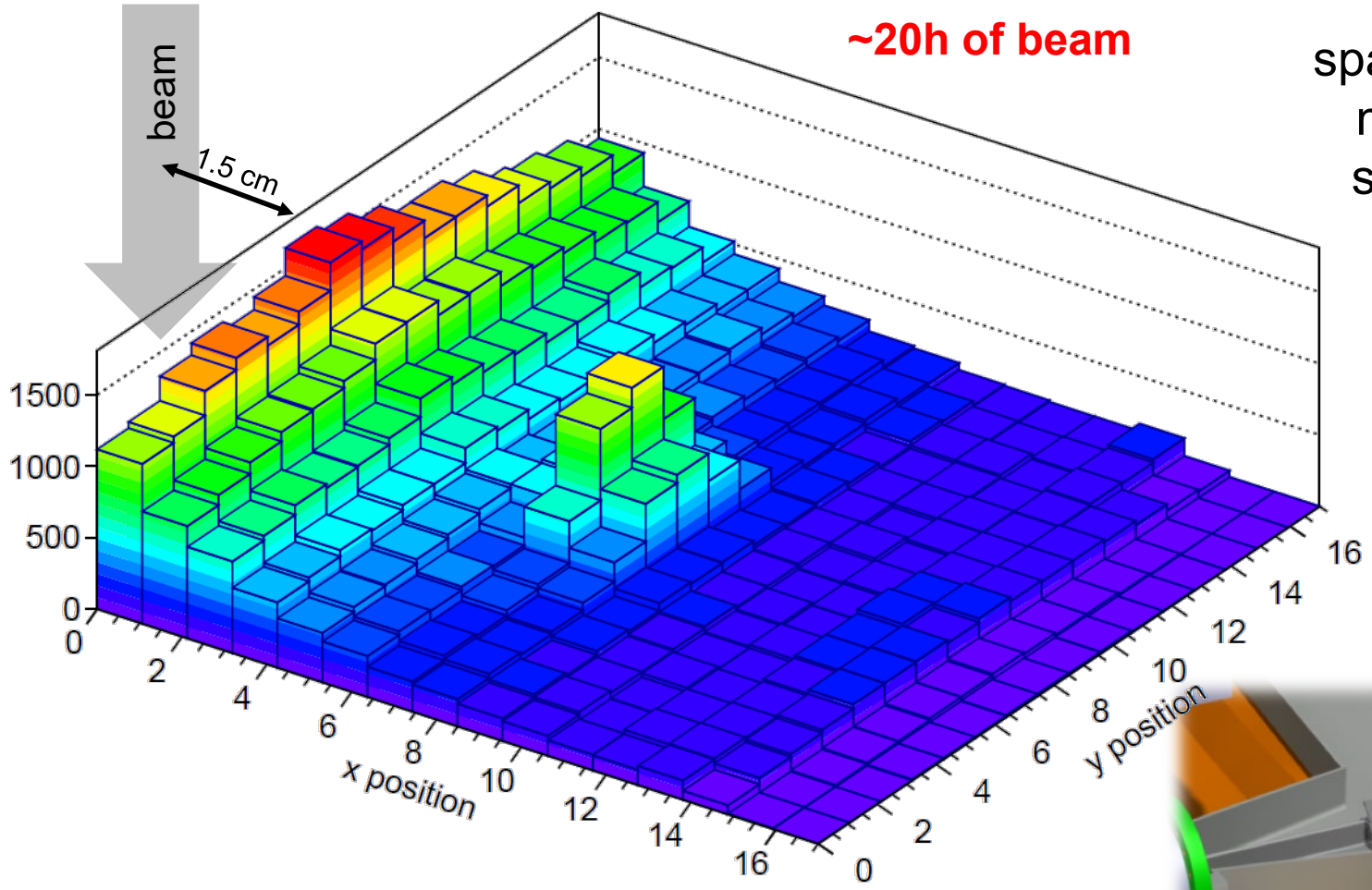
BRing: Booster ring
Circumference: 530 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration

ILIMA: Masses and Halflives

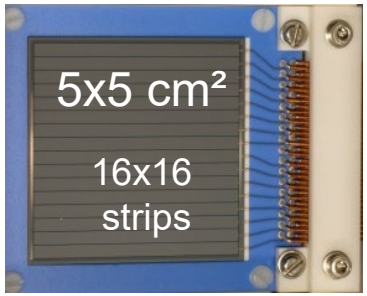


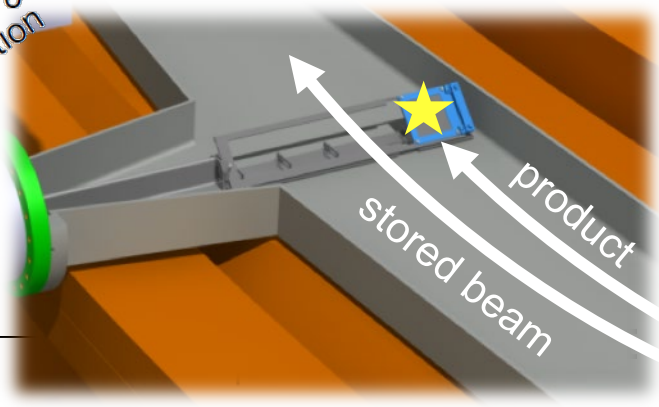
Astrophysical reactions

The first (p,g) Measurement on 124Xe



spacial distribution measured with silicon detector





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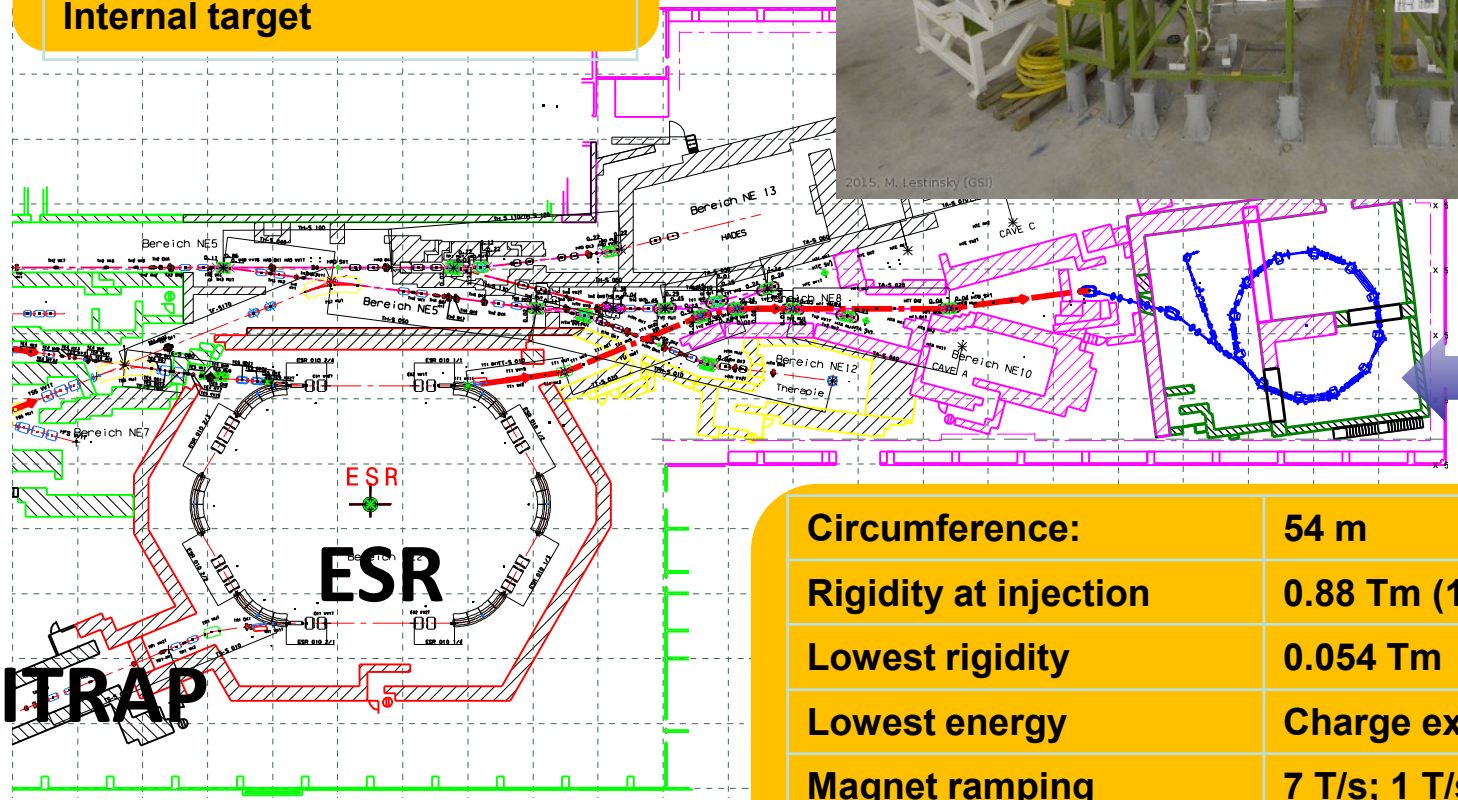
Courtesy Jan Glorius

CRYRING@ESR

- Electron cooling
- Coolinear laser spectroscopy
- Internal target

Cryring



Circumference:	54 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
Slow extraction	

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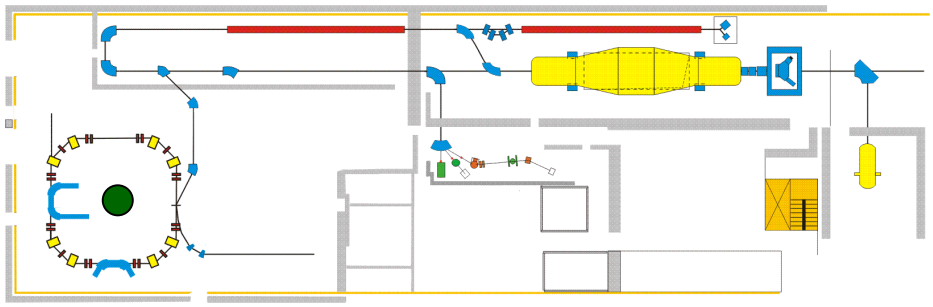
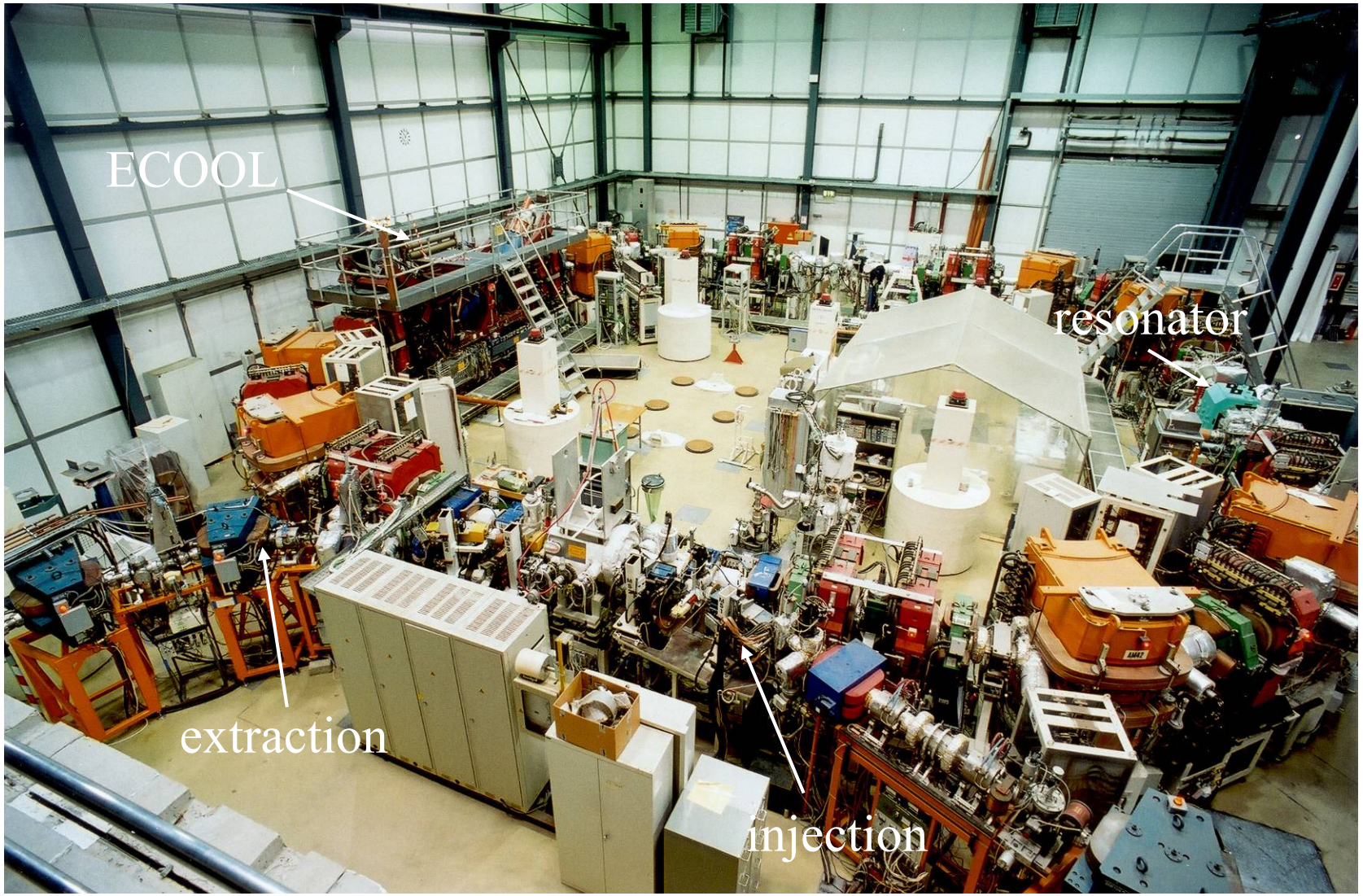


The heavy ion storage ring TSR at MPIK Heidelberg

Circumference: 55m



Physics at Storage Rings

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

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

Direct mass measurements of exotic nuclei

Radioactive decay of highly-charged ions

Charge radii measurements [DR, scattering]

Experiments with polarized beams

Experiments with isomeric beams [DR, reactions]

Nuclear magnetic moments [DR]

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

In-ring nuclear reactions

Experimental Storage Ring ESR

Experimental Cooler-Storage Ring CSRe

Low energy ring CryRING@ESR

RI-RING at RIKEN

New Storage Ring Complex at FAIR

New Storage Ring Complex at HIAF

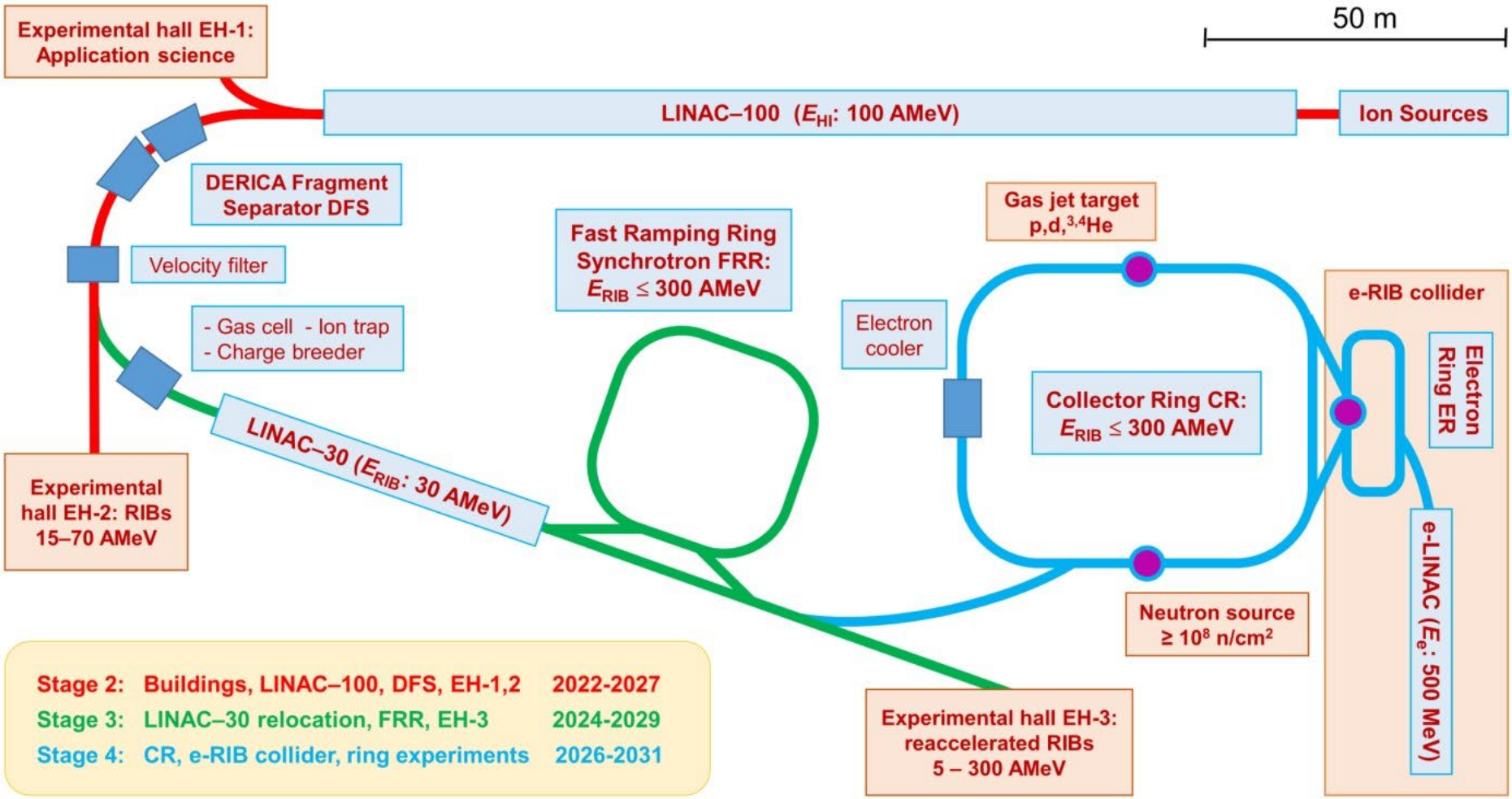
Low-Energy Storage Ring TSR at IMPCAS

Low-Energy Storage Ring at ISOLDE, CERN

DERICA at JINR, Dubna

Low-energy storage rings at TRIUMF, RIKEN …

DERICA Project



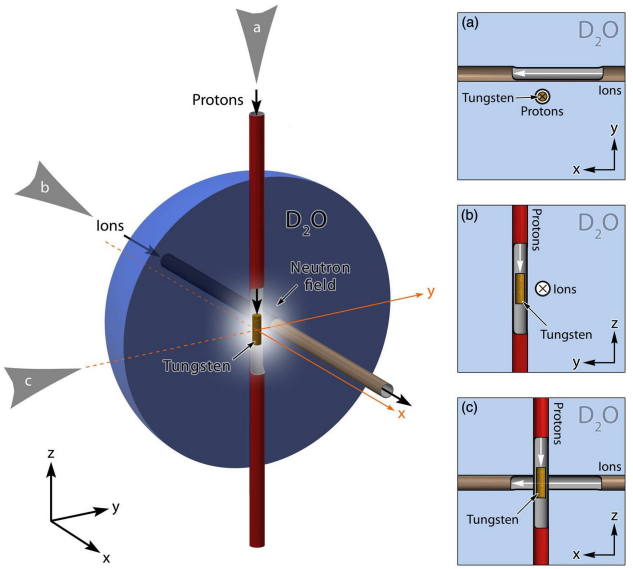
Neutron captures in inverse kinematics

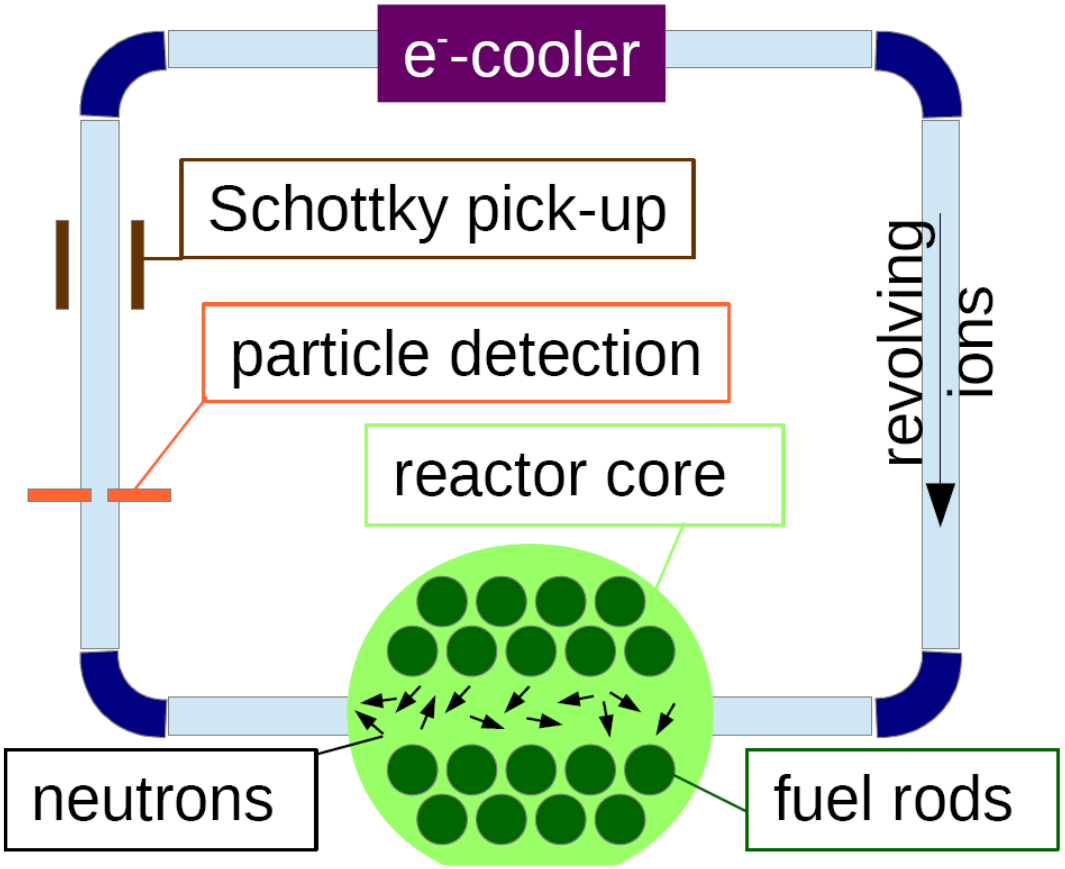
Neutron flux: 10^{14} n/cm^2/s ->

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

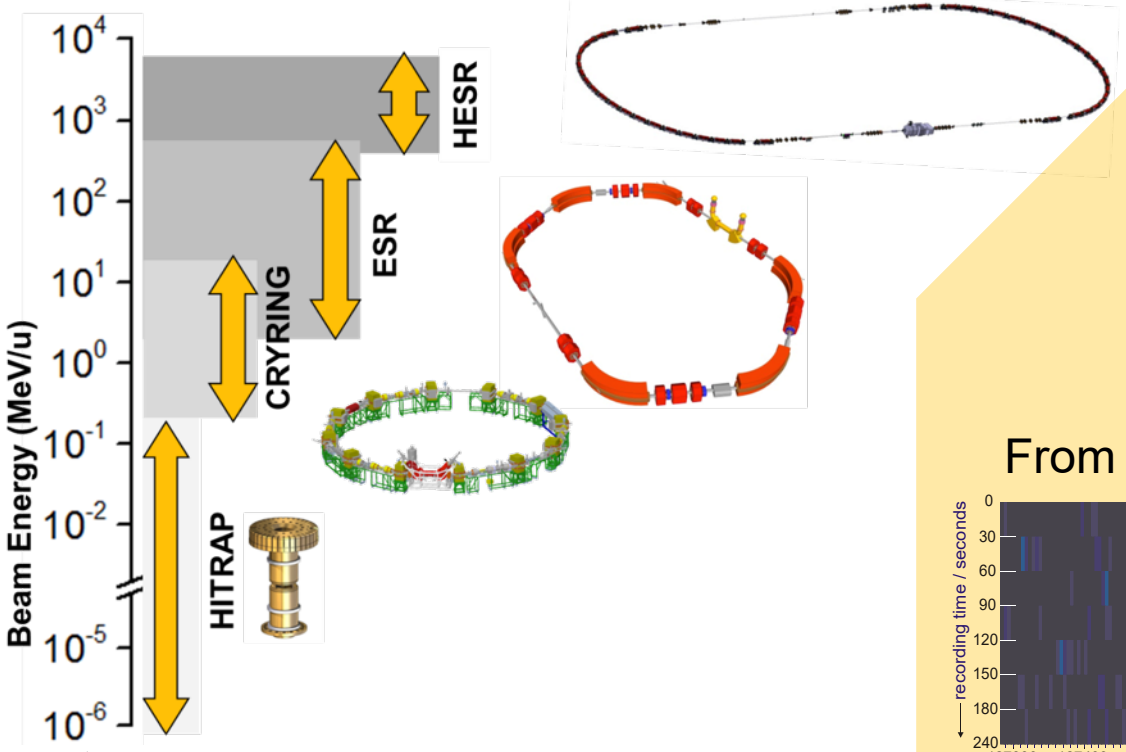
Ion Beam Facilities / Trapping & Storage

Worldwide Unique !

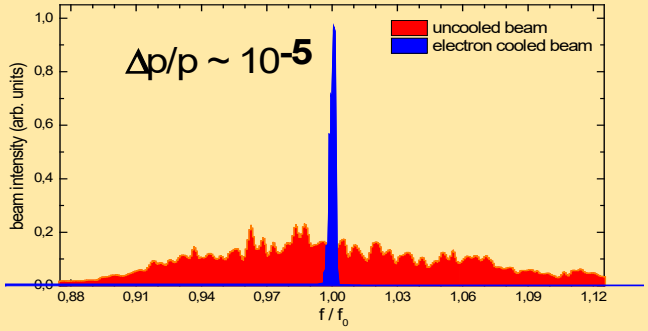
Stored and Cooled

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

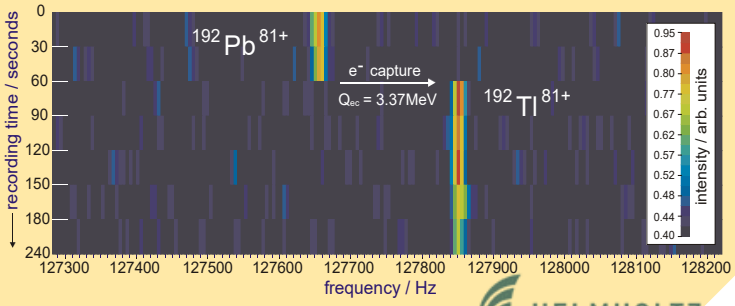
From Rest to Relativistic Energies (up to 4.9 GeV/u)



Cooling: The Key for Precision



From Single Ions to Highest Intensities



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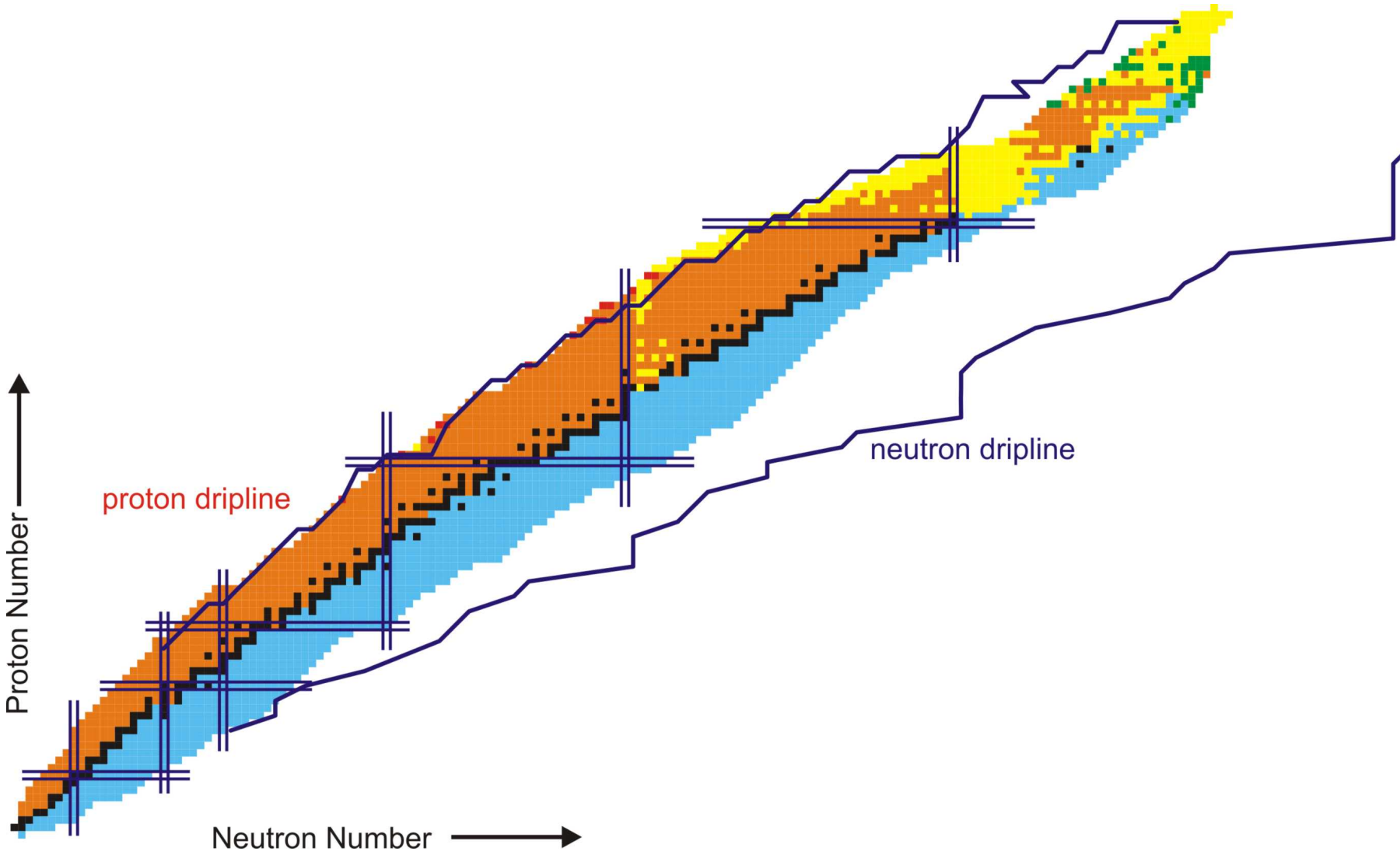
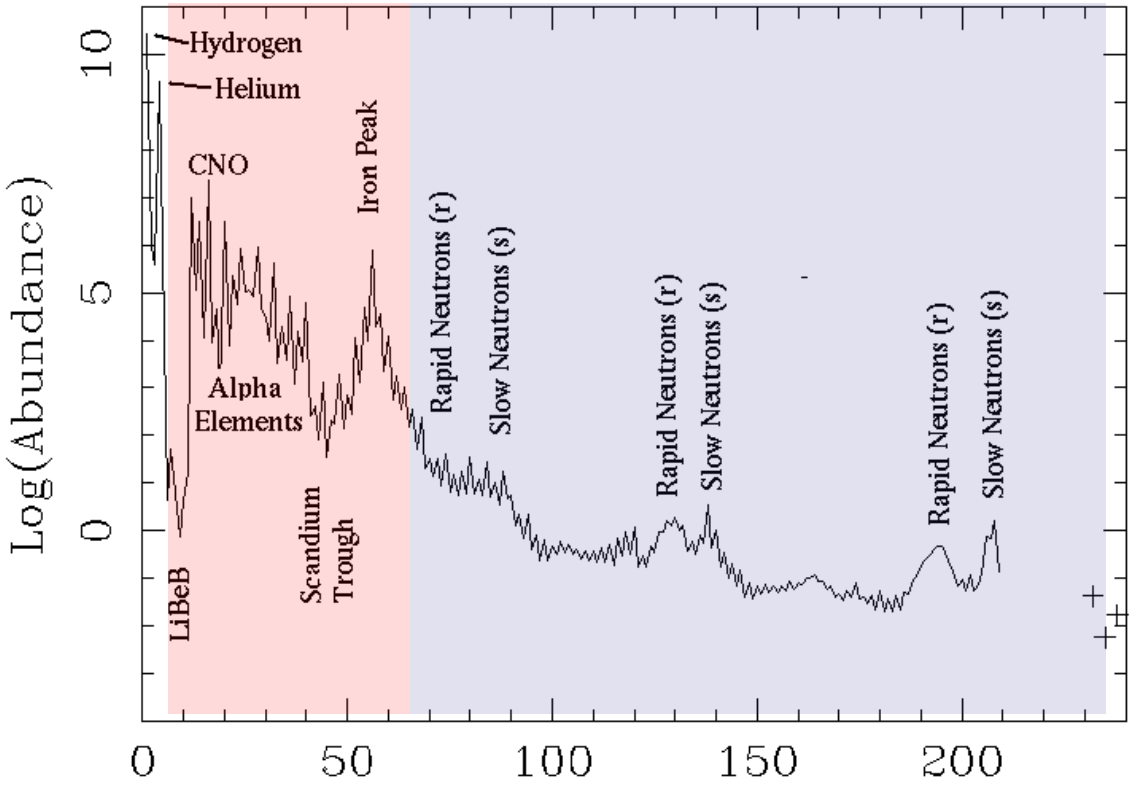
The Chart of Nuclides



Standard Abundance Distribution



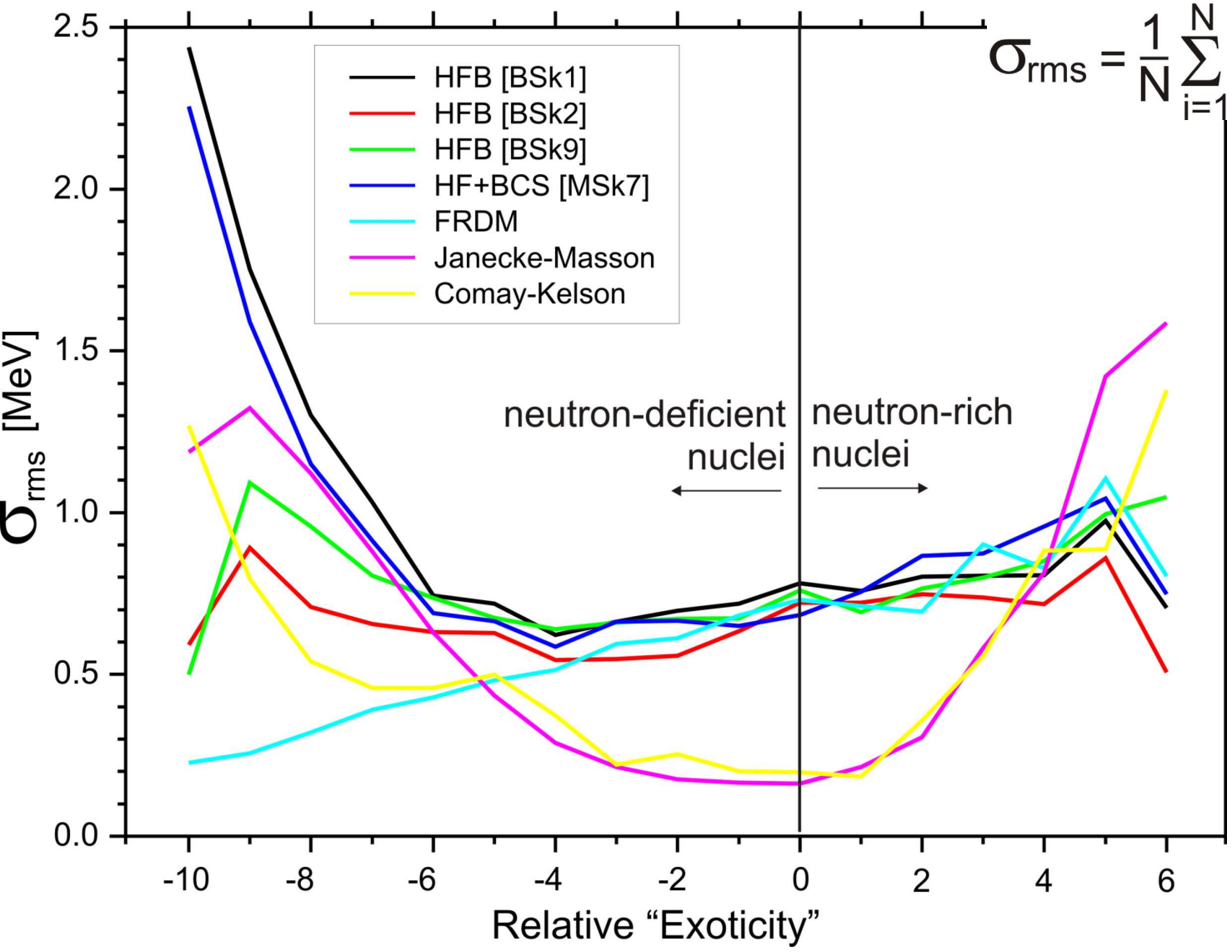
charged-particle induced reaction

mainly neutron capture reaction

involve mainly STABLE NUCLEI

involve mainly UNSTABLE NUCLEI

Predictive Powers of Mass Models



$$\sigma_{rms} = \frac{1}{N}\sum_{i=1}^{N}(m_i^{exp} - m_i^{theory})^2$$

Predictive Powers of Mass Models

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