Deutsche Physikalische Gesellschaft

Precision Experiments at Heavy-Ion Storage Rings

Yury A. Litvinov

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

GSI

IMP

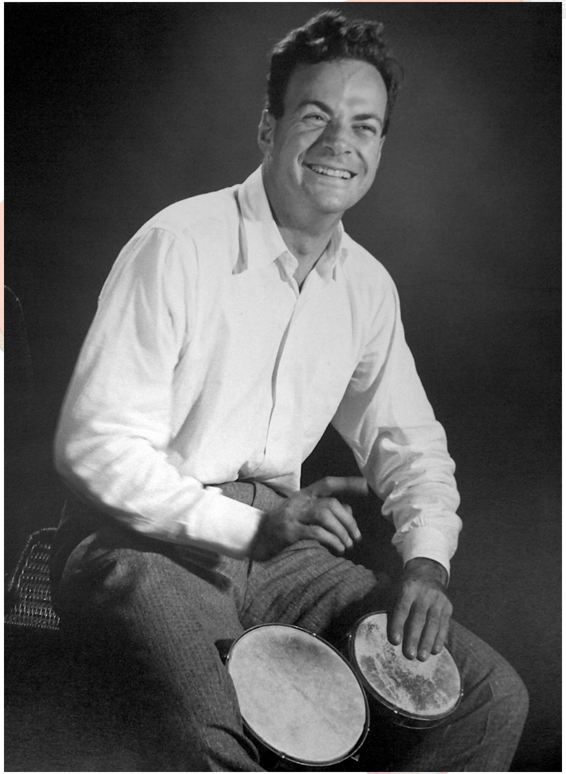
中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

erc

www.gsi.de/astrum

PhyNuBe 4

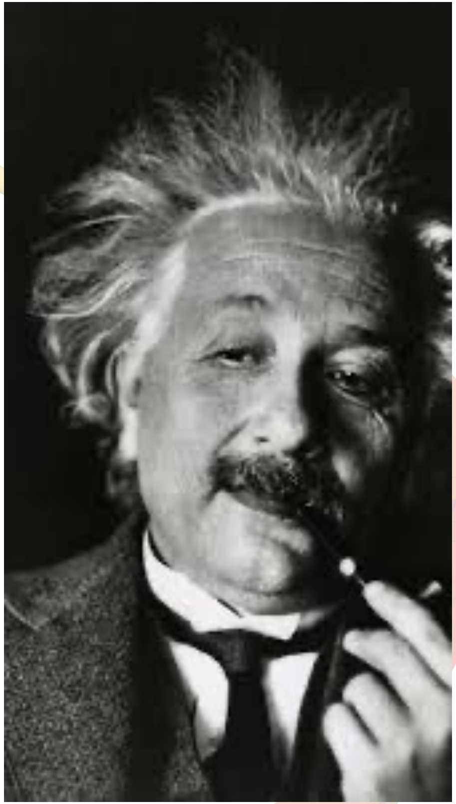
4th PhyNuBe school: Innovative Technologies, Theories, and Methodologies in Nuclear Physics
"Paul Langevin", Haute-Maurienne-Vanoise-Alpen, Aussois, France
17-22 May 2026



Richard P. Feynman
(Nobel prize1965)

nobody knows how to teach physics, or to educate people—that's a fact, and if you don't like the way it's being done, that's perfectly natural.

It is nothing short of a miracle that modern methods of instruction have not yet entirely strangled the holy curiosity of inquiry



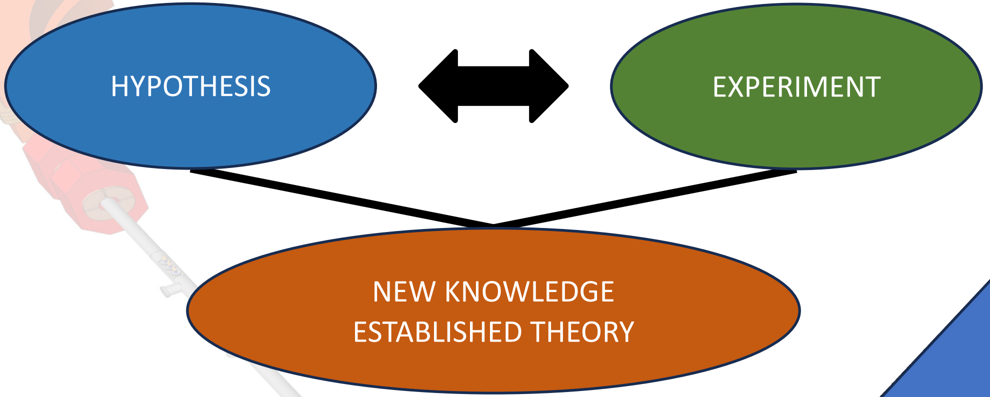
Albert Einstein
(Nobel prize1921)

Precision Experiments at Heavy-Ion Storage Rings

1. Heavy-ion storage rings: Why? Where? How?
   a) Introduction to nuclear structure and astrophysics
   b) Production and separation of radionuclides
   c) Storage, cooling, and manipulation of beams
2. Mass spectrometry of exotic nuclides
3. Radioactive decays of highly-charged ions
4. Reactions for nuclear astrophysics

How to learn something new?

Only via an experimental confirmation a hypothesis becomes a theory



Here should be a picture by M.C. Escher "Relativity" but it is copyright protected and cannot be easily displayed

M.C. Escher: „Relativity“

"The first principle is that you must not fool yourself and you are the easiest person to fool."

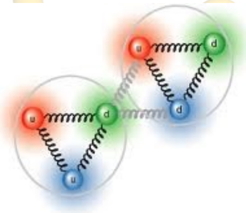
R. Feyman

Fundamental Interactions

What is so exciting about atomic nuclei?

Electromagnetic

Weak



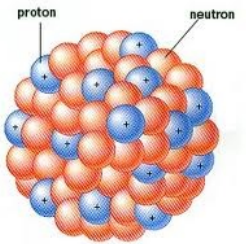
Strong

Protons

Neutrons

Nucleons

Fermions (S=1/2)

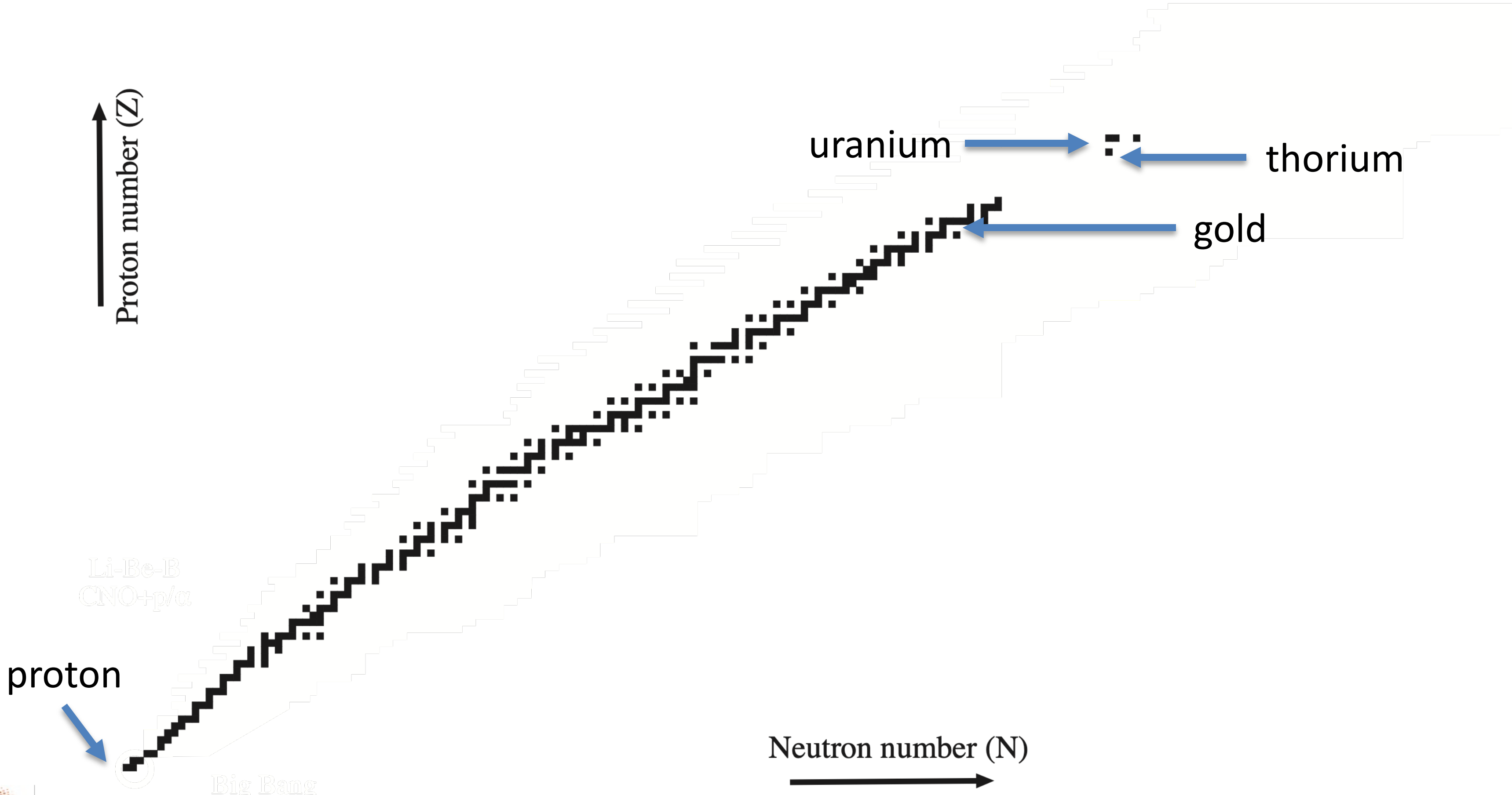


Atomic nuclei – natural results of the complex "game" of complex interactions in a complex quantum many-body system composed of two types of fermions

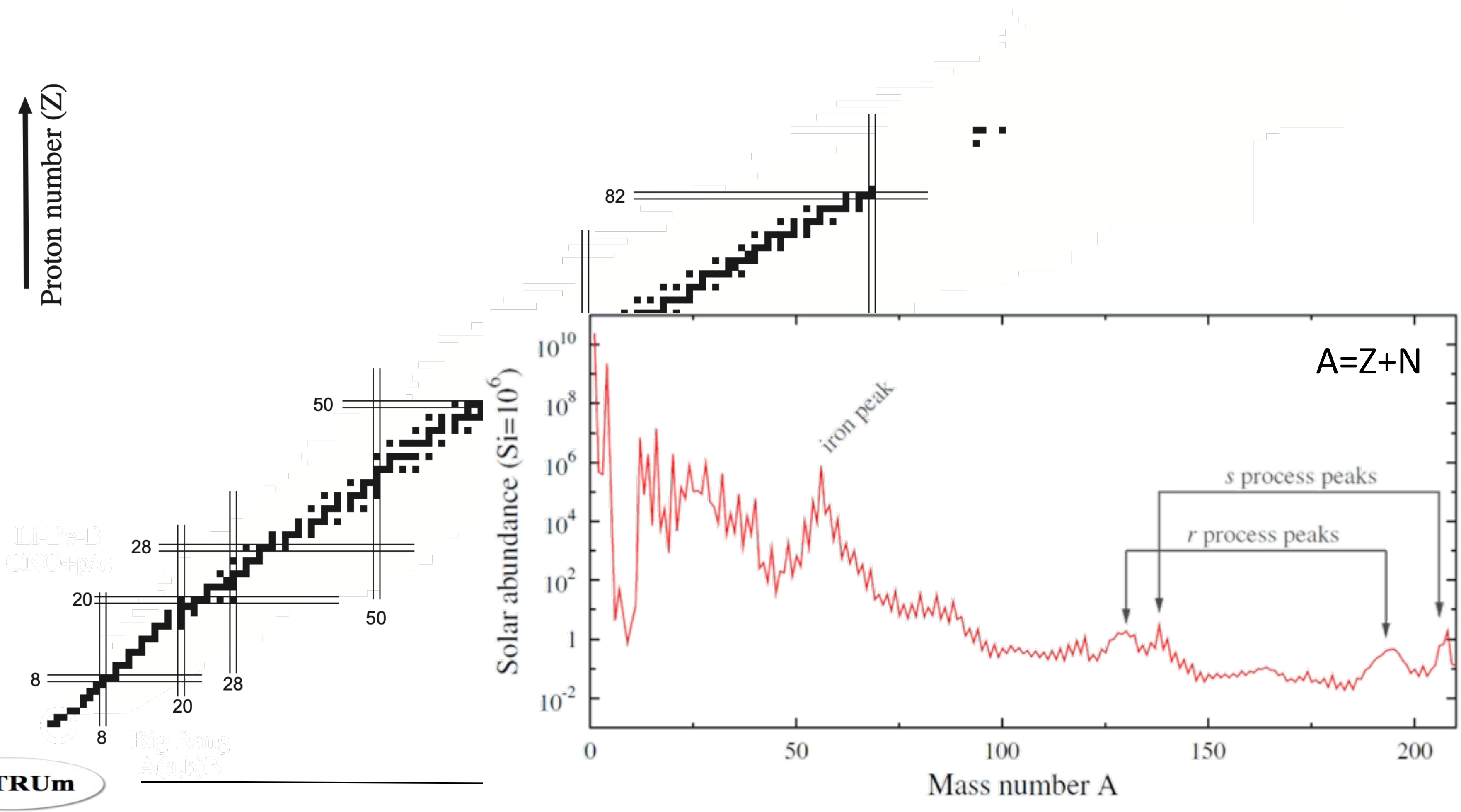
ORIGINS OF THE ELEMENTS

This periodic table depicts the primary source on Earth for each element. In cases where two sources contribute fairly equally, both appear.

Nuclear Chart: Stable nuclei



Nuclear Chart: Magic numbers



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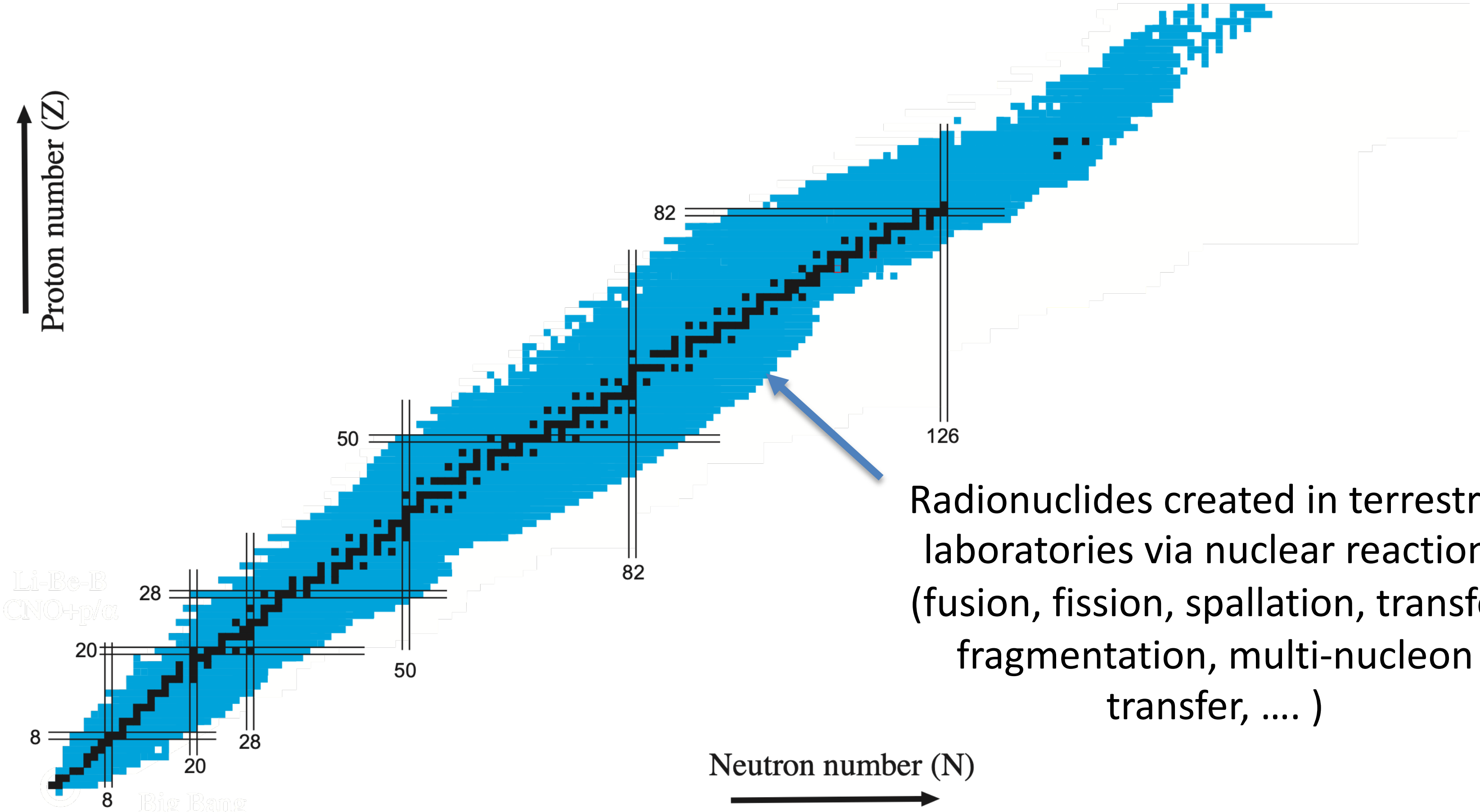
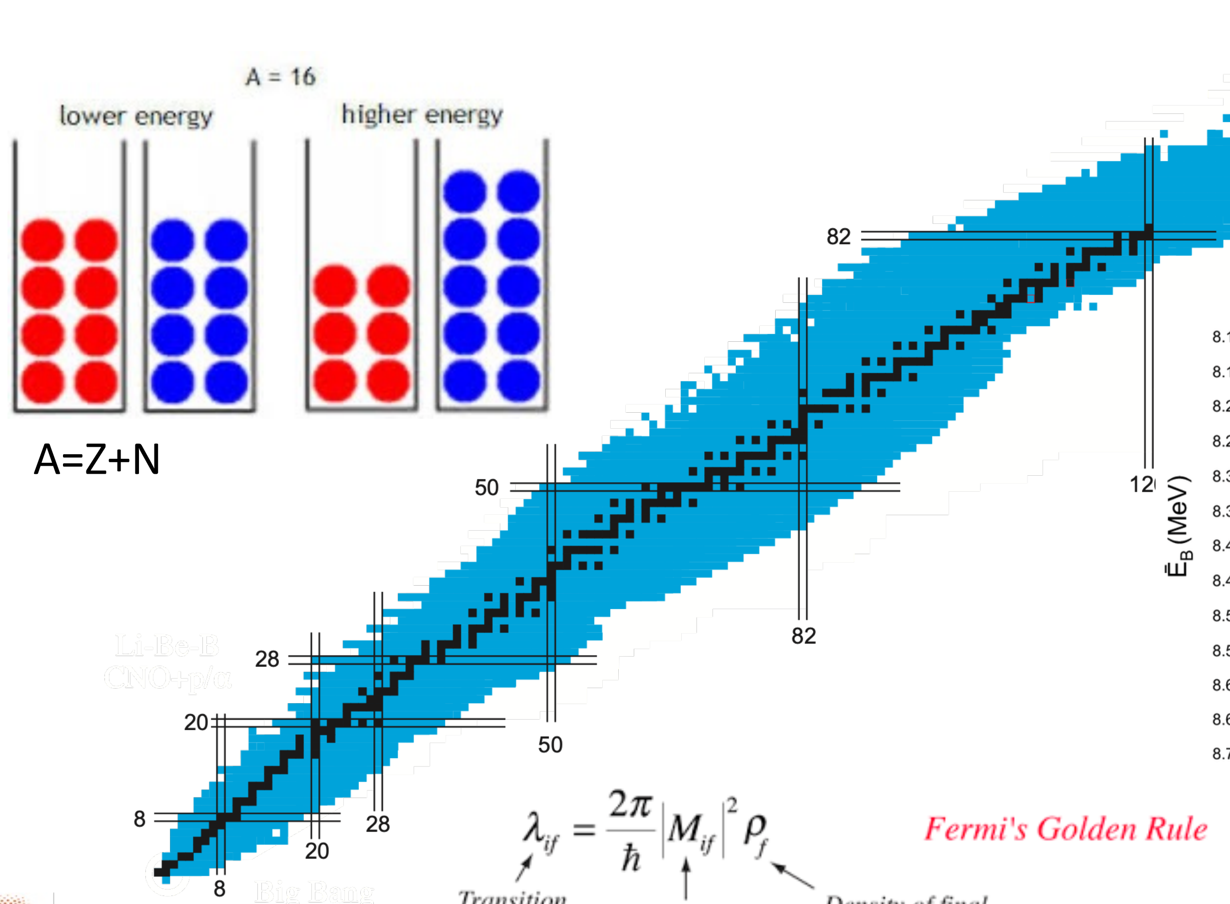
Nuclear Chart: Known nuclides



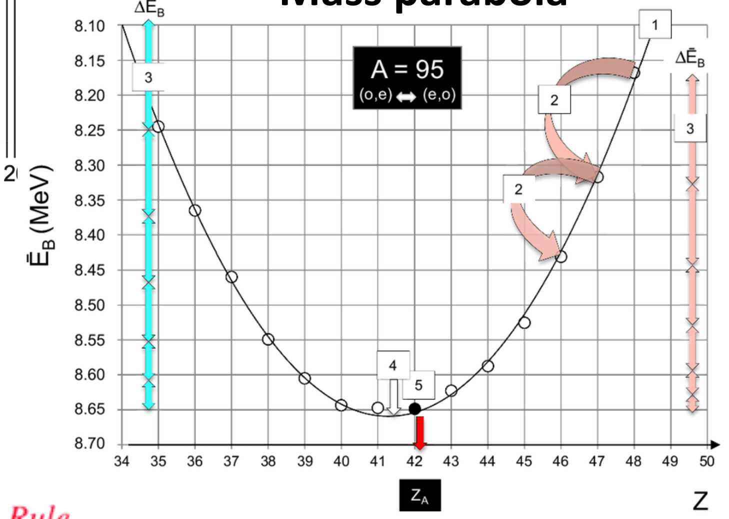
Radionuclides created in terrestrial laboratories via nuclear reactions (fusion, fission, spallation, transfer, fragmentation, multi-nucleon transfer, ….)

Nuclear Chart: Known nuclides



A=Z+N

Mass parabola



$$\lambda_{if} = \frac{2\pi}{\hbar}\left|M_{if}\right|^2 \rho_f$$

Transition probability — *Matrix element for the interaction* — *Density of final states*

Fermi's Golden Rule

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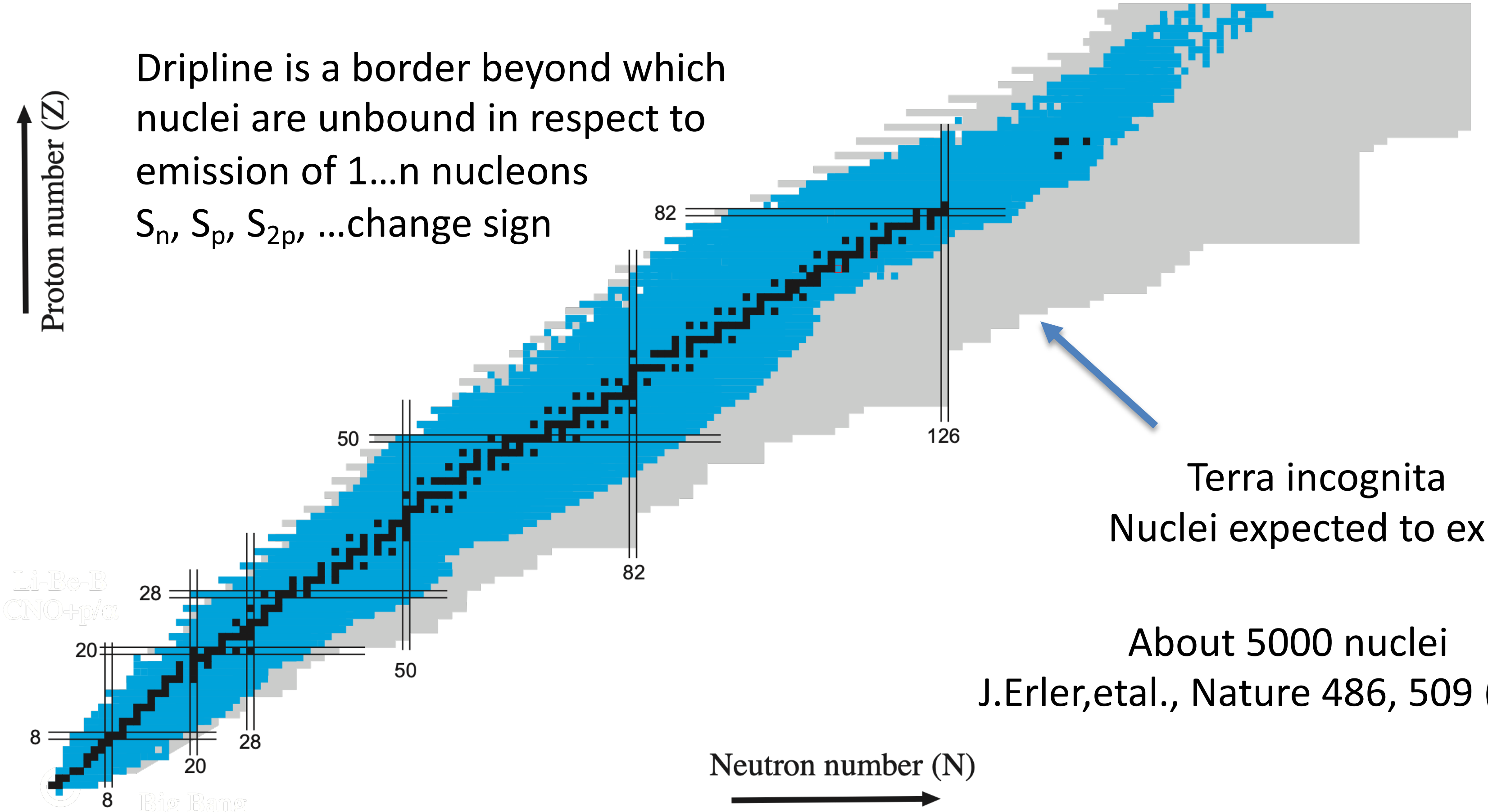
Nuclear Chart: What is not yet known?

Dripline is a border beyond which nuclei are unbound in respect to emission of 1…n nucleons

S_n, S_p, S_{2p}, …change sign



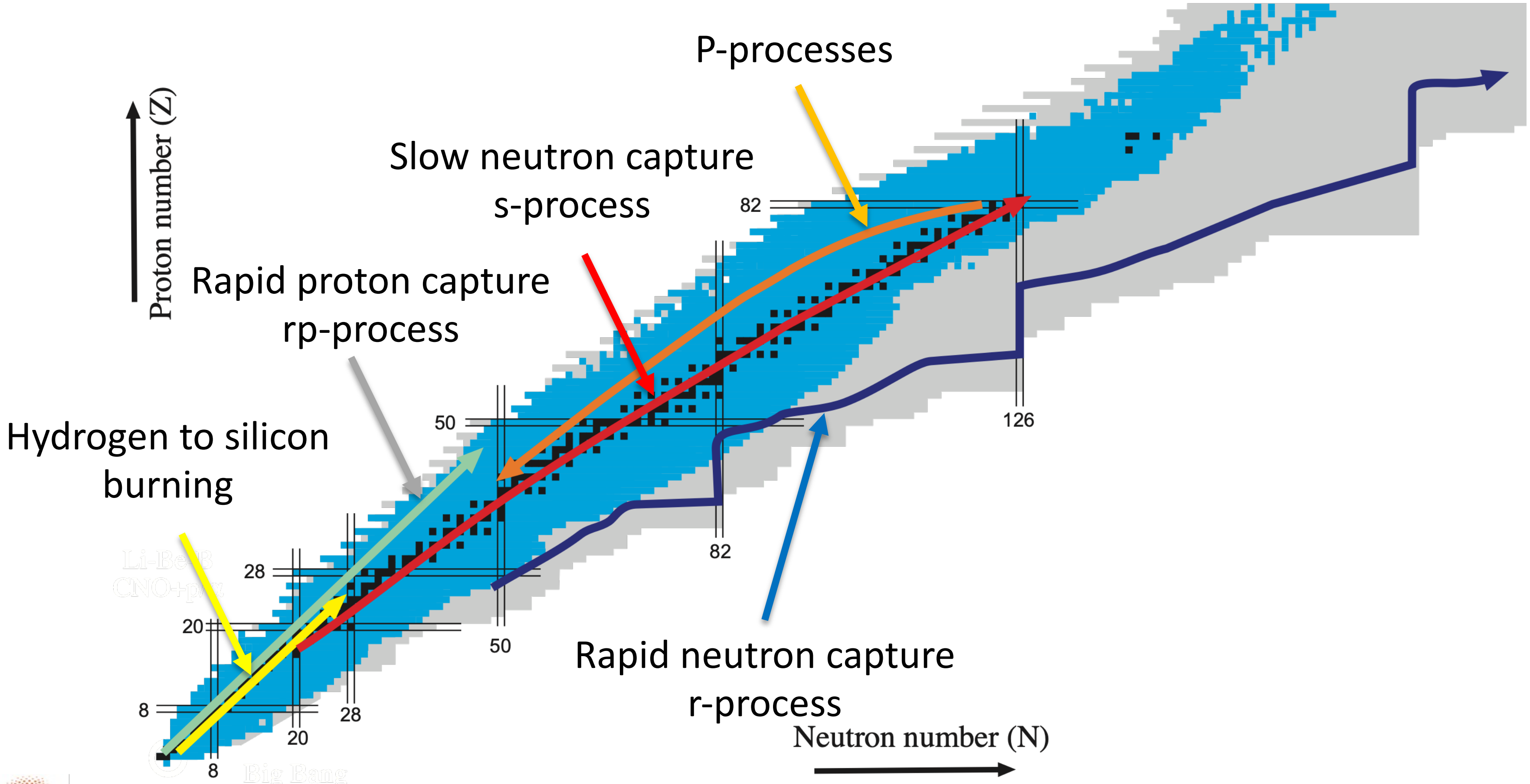
Terra incognita

Nuclei expected to exist

About 5000 nuclei

J.Erler,etal., Nature 486, 509 (2012)

Nucleosynthesis Processes



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Nucleosynthesis Processes (best known)

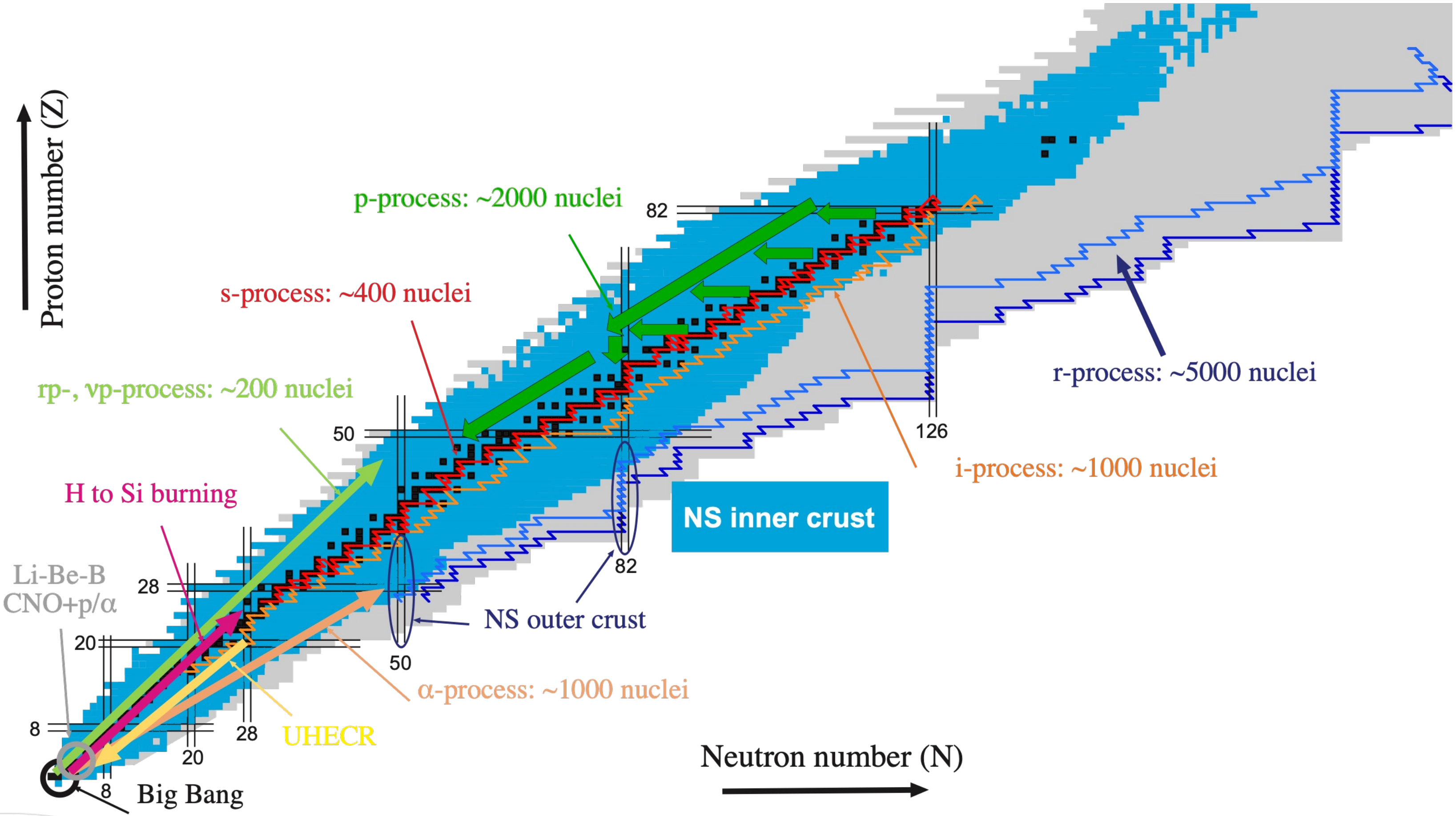

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Figure: NuPECC Long Range Plan 2024

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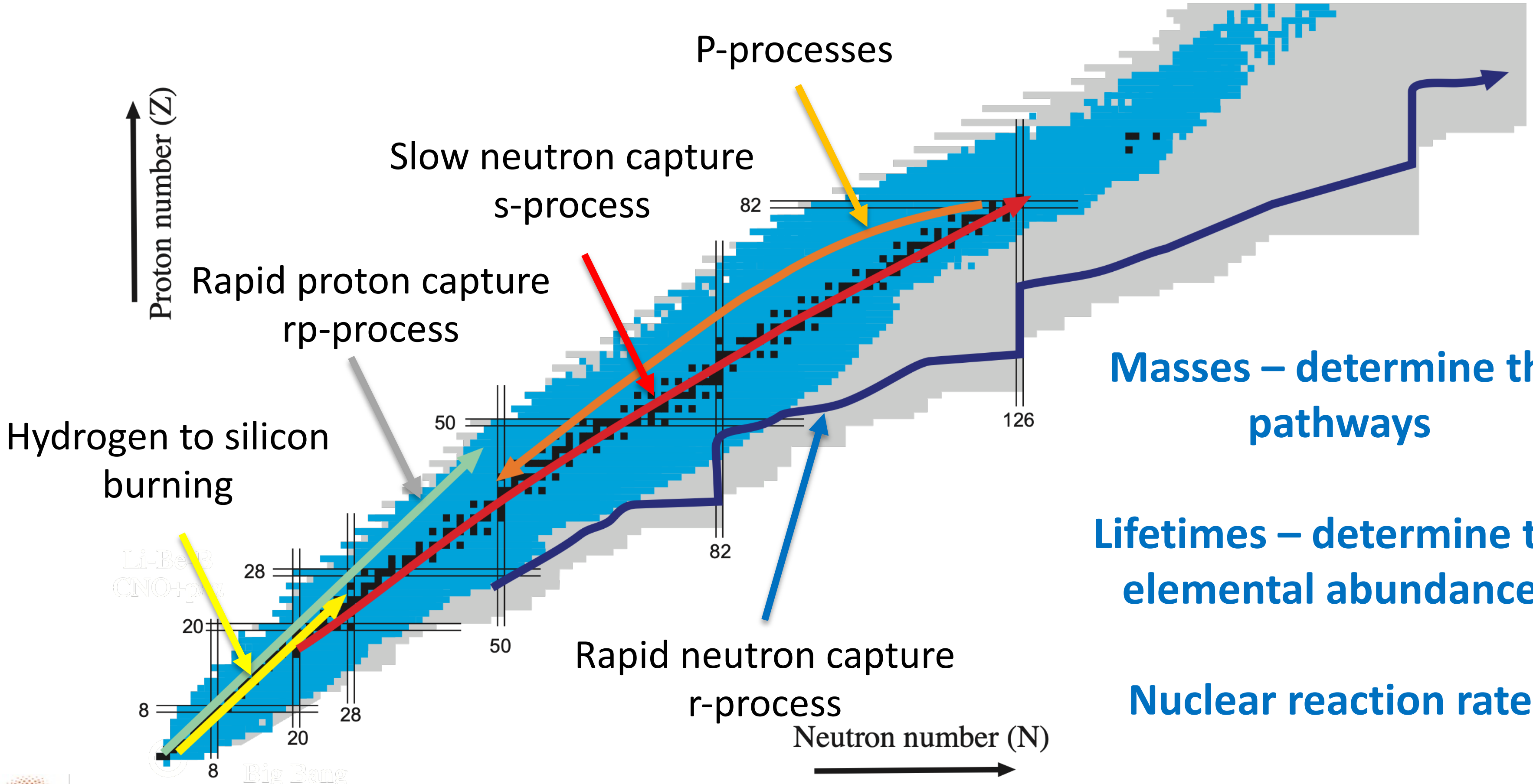
Nucleosynthesis Processes

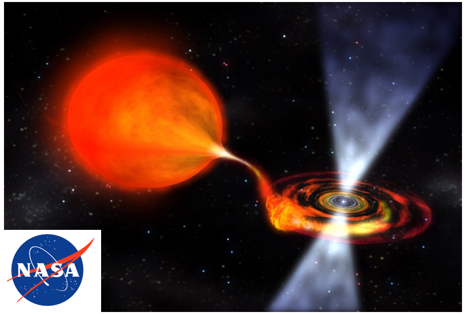


Masses – determine the pathways

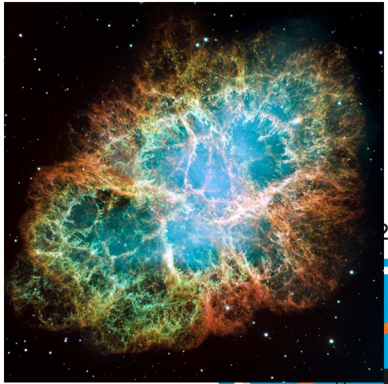
Lifetimes – determine the elemental abundances

Nuclear reaction rates

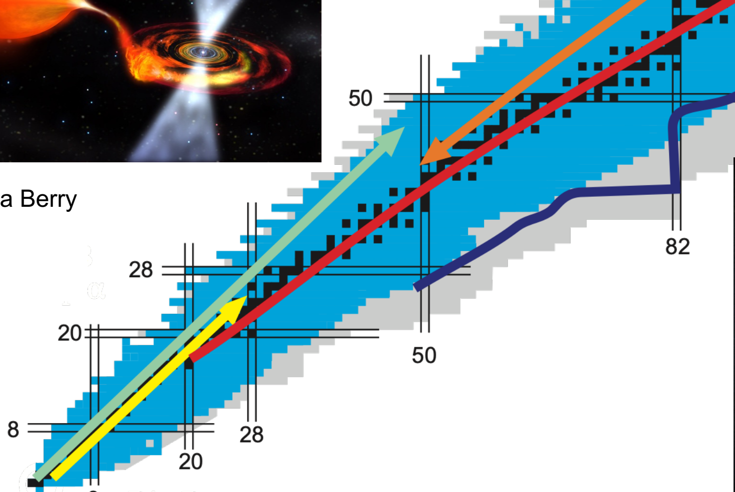
Nucleosynthesis Processes

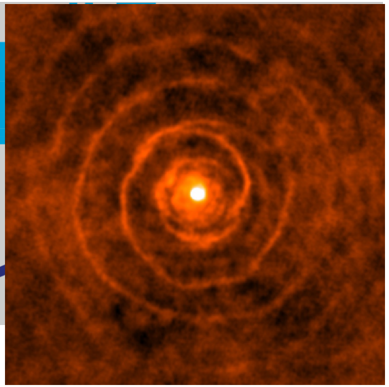


NASA/Dana Berry



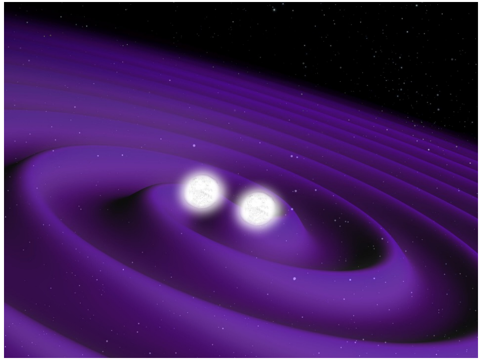
Hubble Gallery
NASA, ESA,
J. Hester, A. Loll





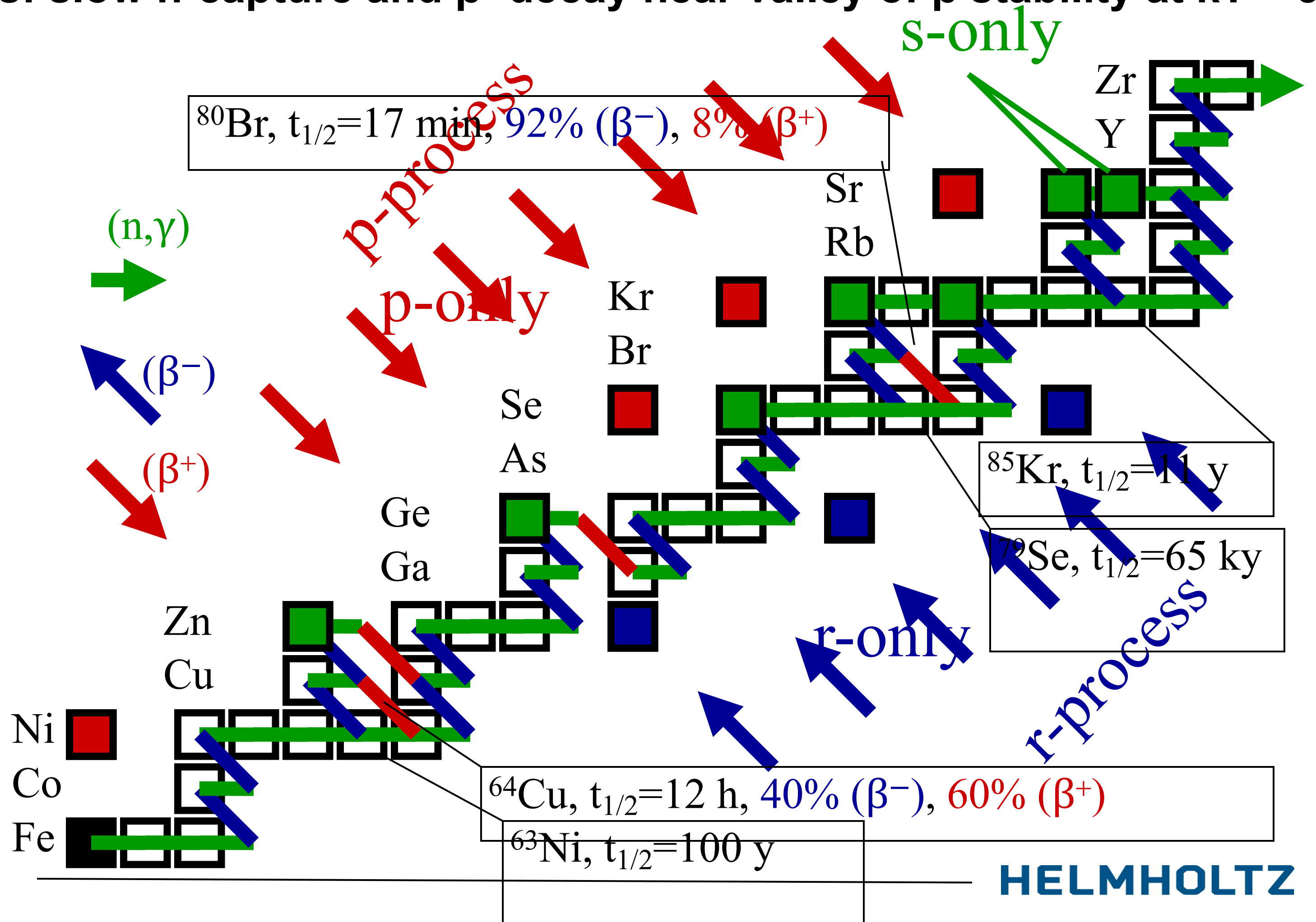
ALMA
(ESO/NAOJ/NRAO)
Hyosun Kim et al.

Hubble Gallery, NASA, ESA

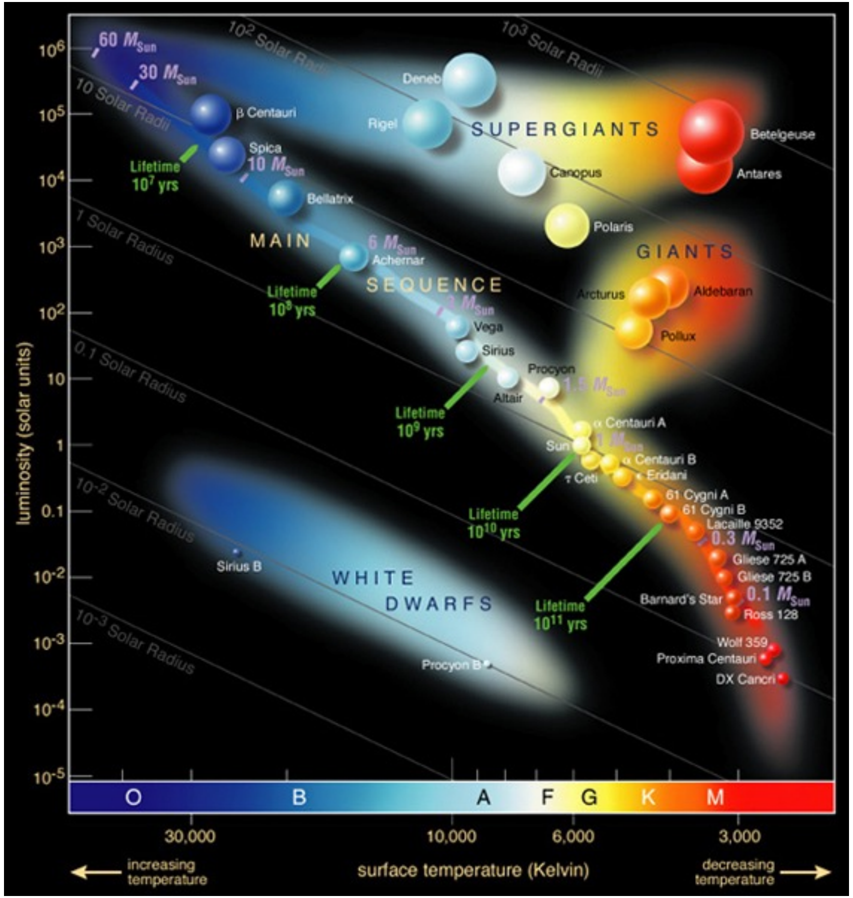


ESA, CC BY-SA 3.0 IGO

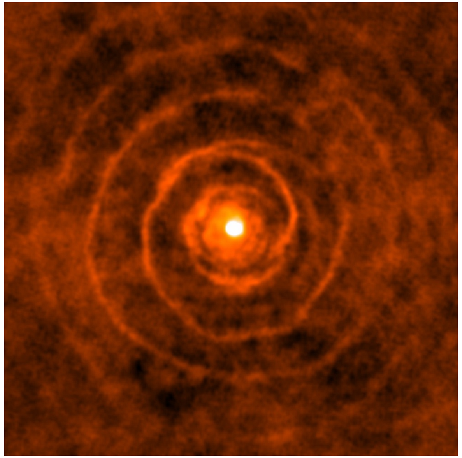
s process: slow n-capture and β- decay near valley of β stability at kT = 30 keV



The Hertzsprung–Russell diagram

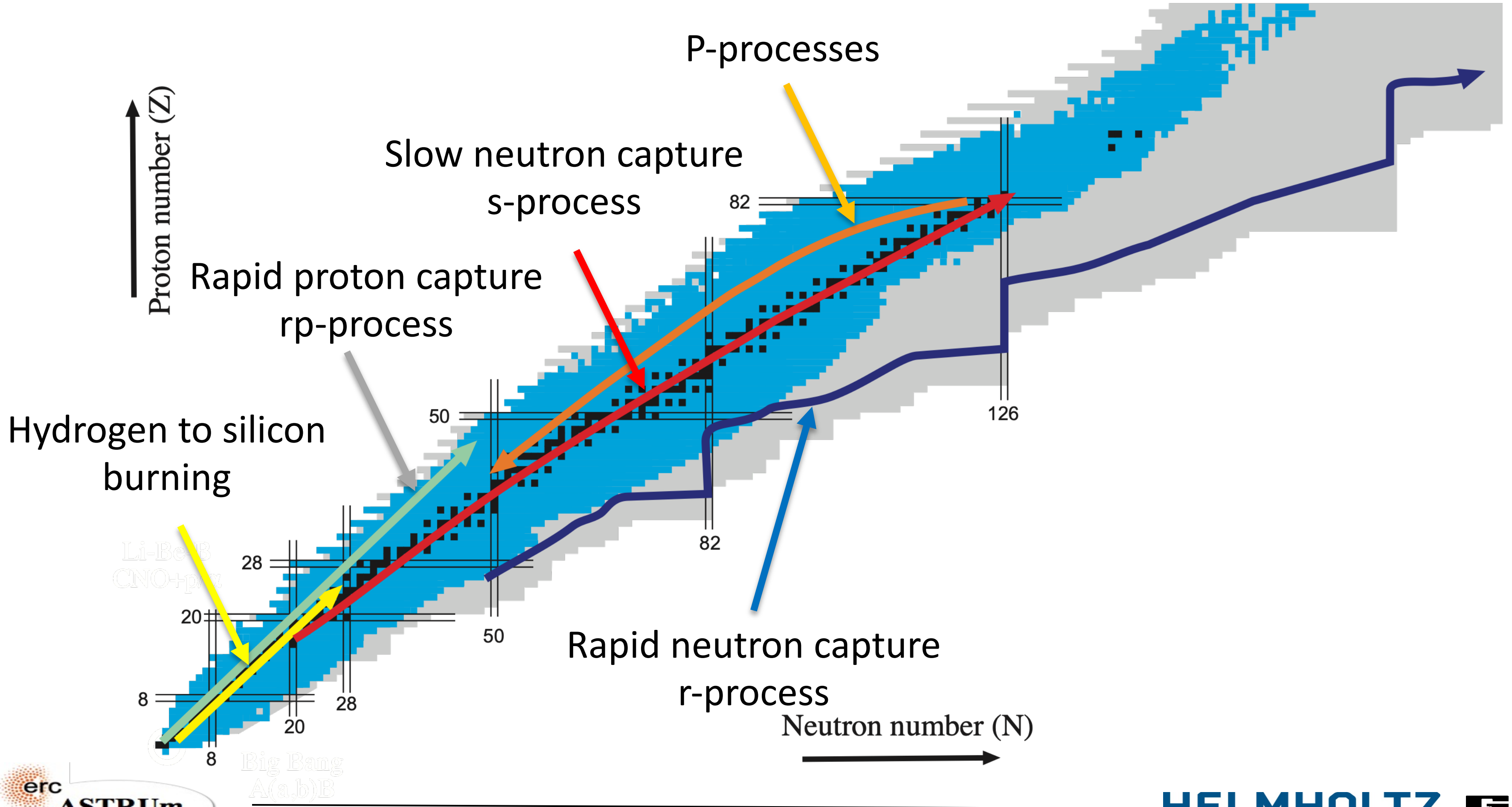


Asymptotic Giant Branch stars



ALMA
(ESO/NAOJ/NRAO)
Hyosun Kim et al.

Nucleosynthesis Processes



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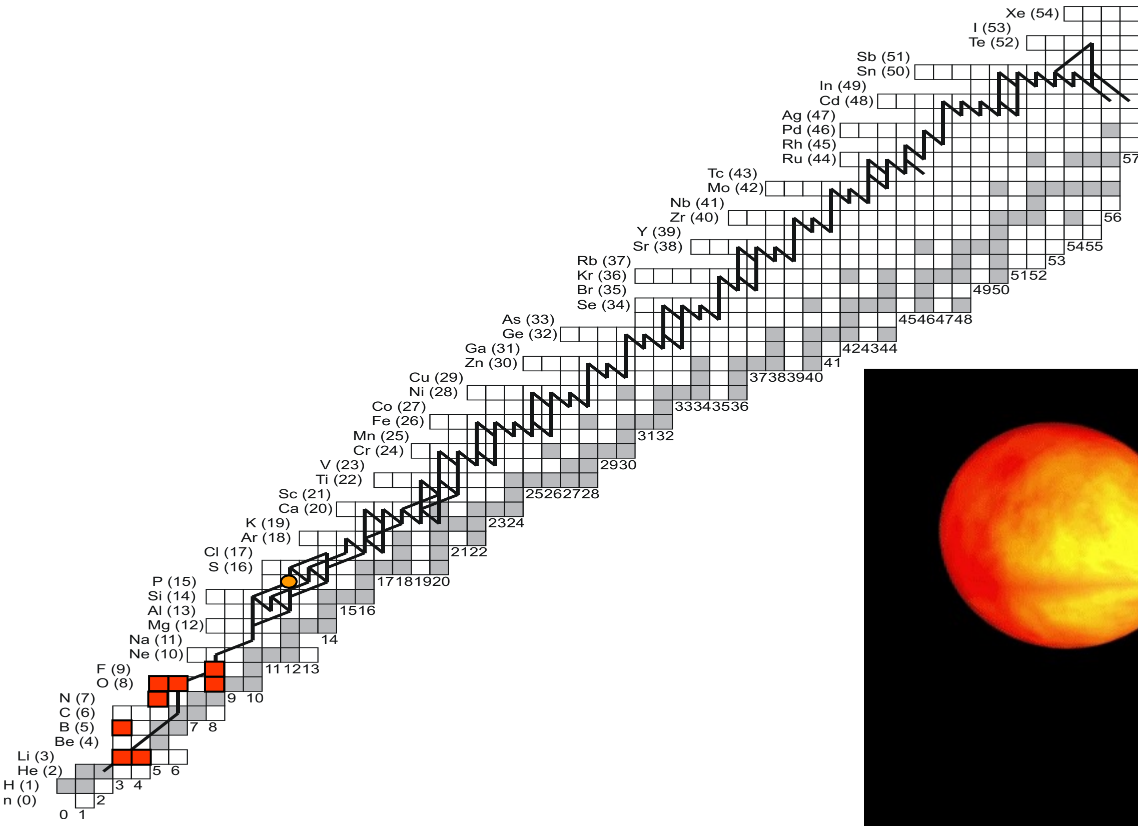
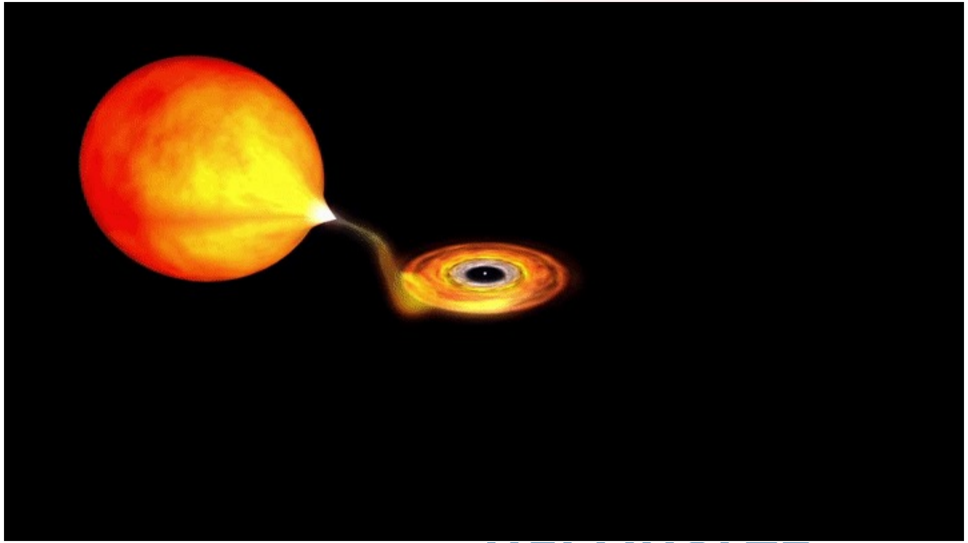
Rapid-proton capture process (rp-process)



NASA/Dana Berry



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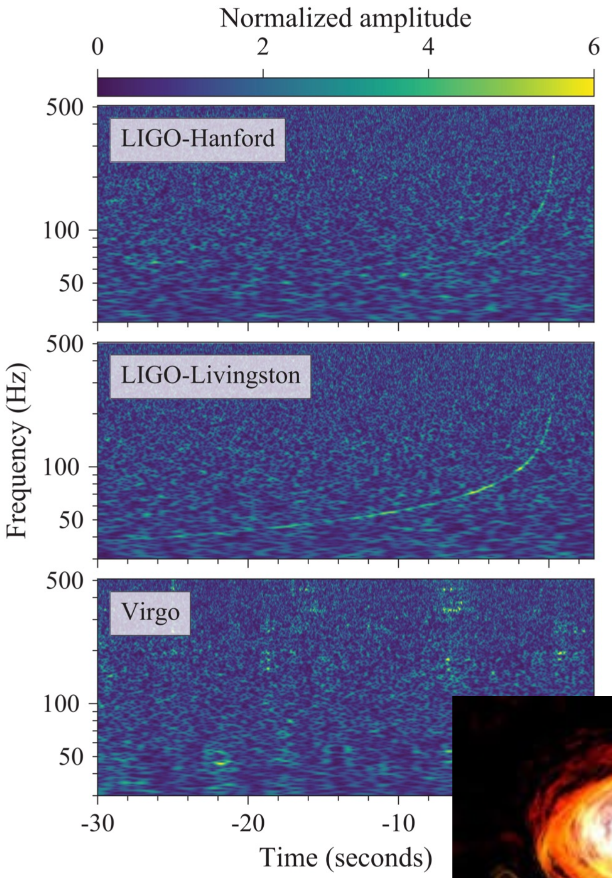
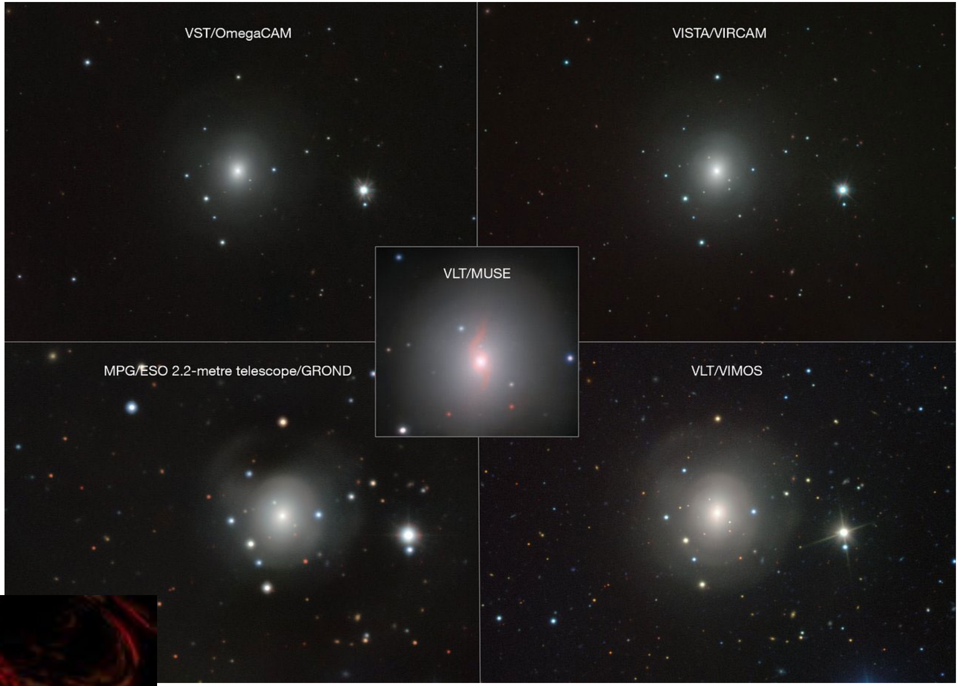
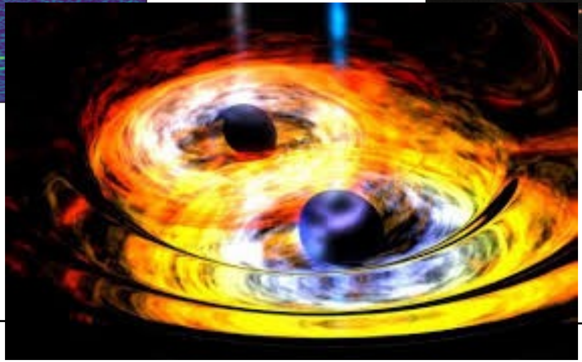
Multi-Messenger Astronomy



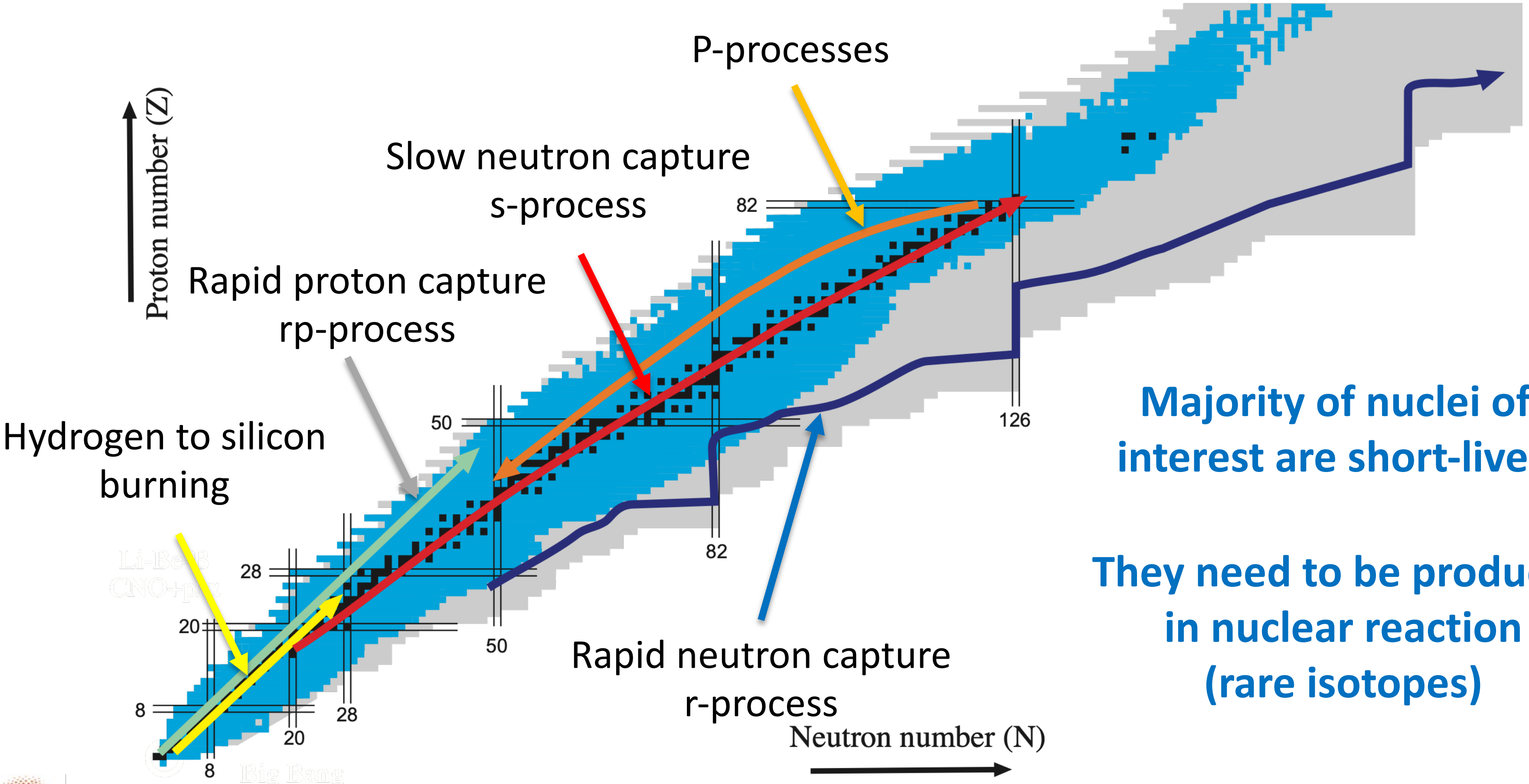




More than 50 other instruments

GW170817

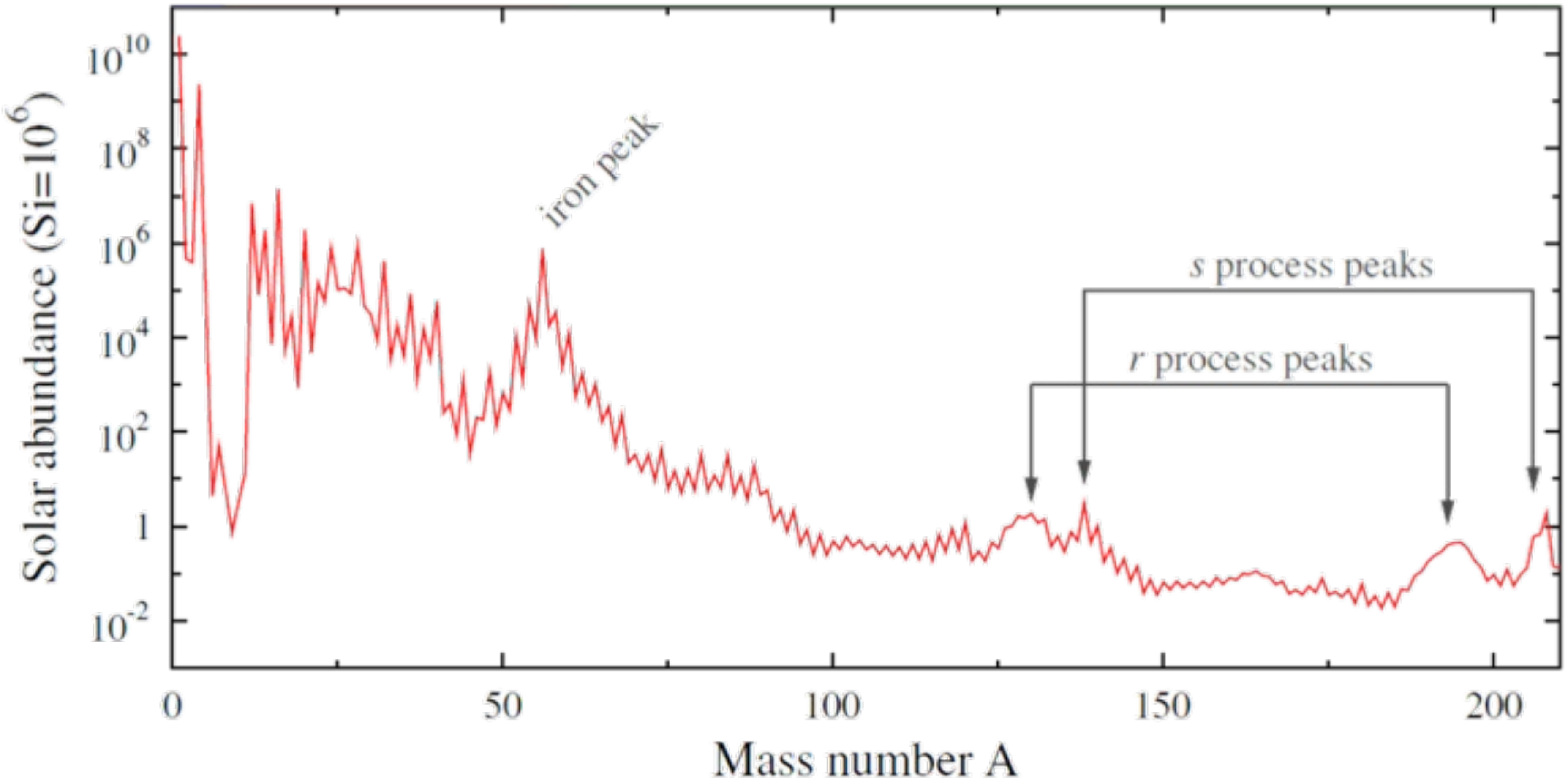
Nucleosynthesis Processes



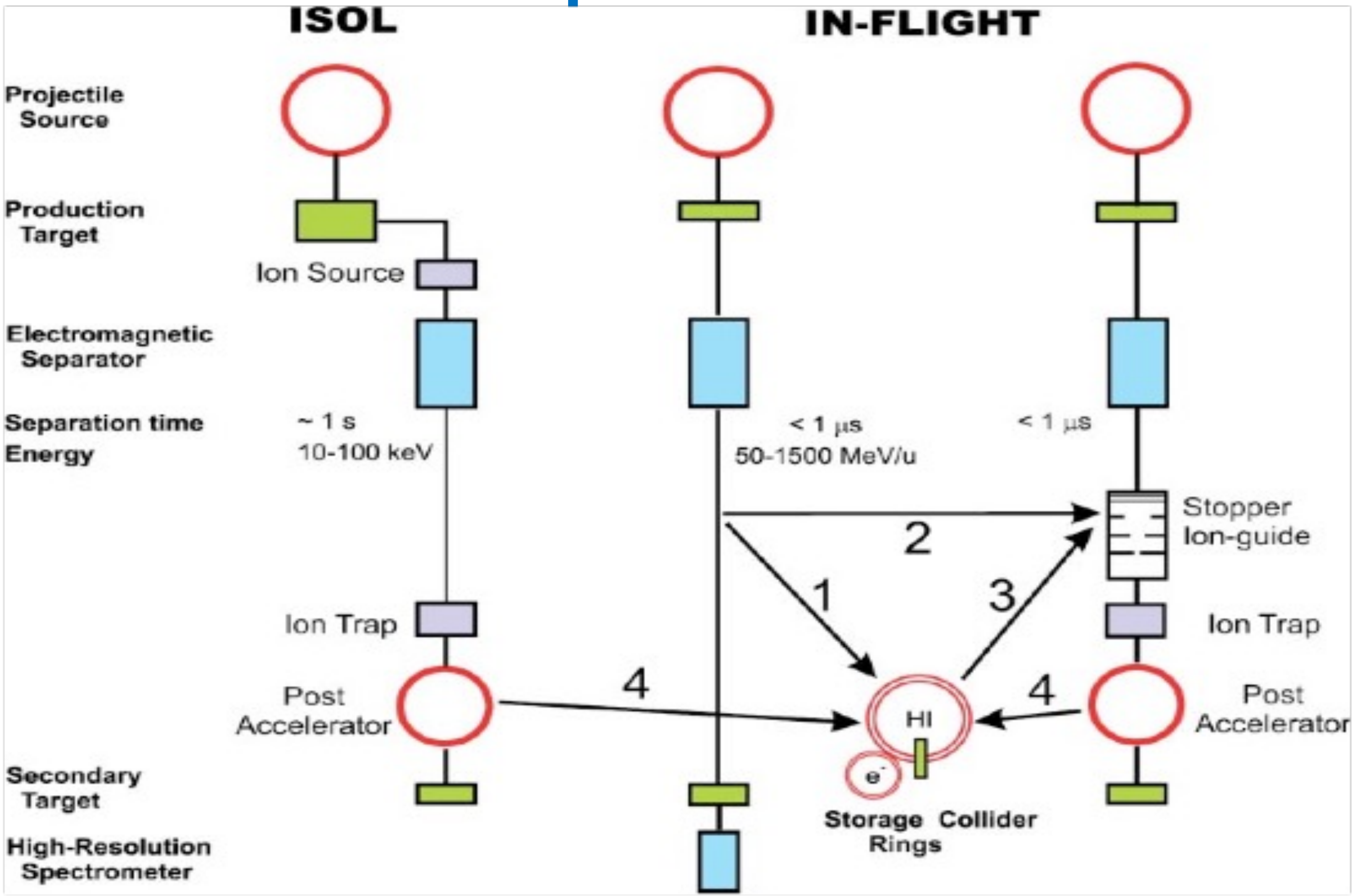
Majority of nuclei of interest are short-lived

They need to be produced in nuclear reaction (rare isotopes)

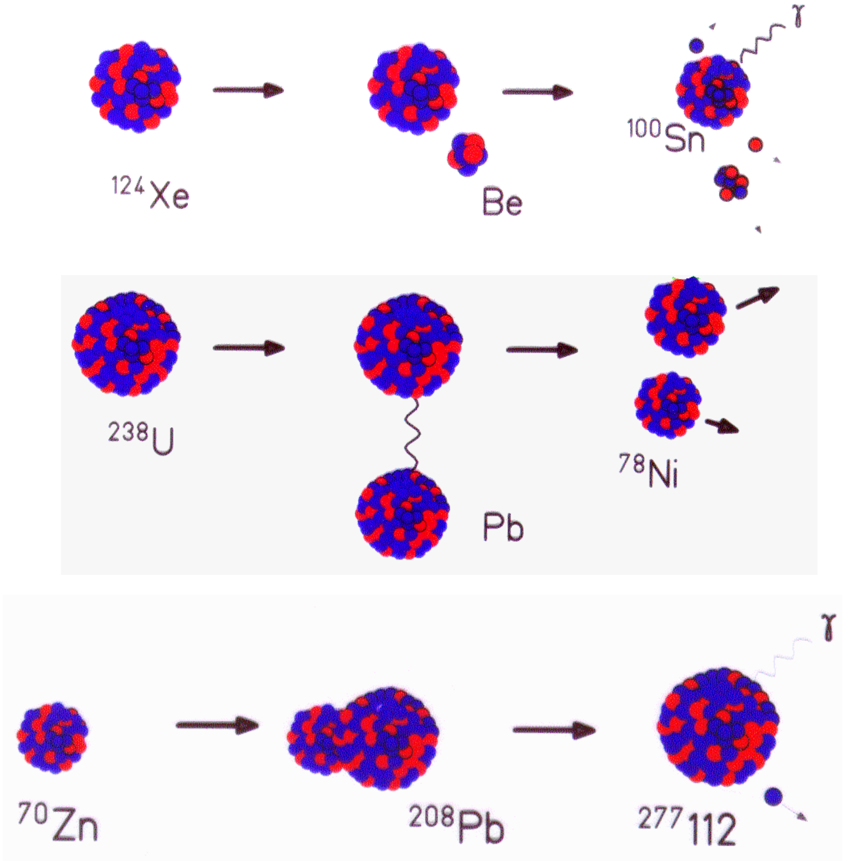
Solar Element Abundances



Production and separation of exotic nuclei



Heavy-Ion Induced Reactions

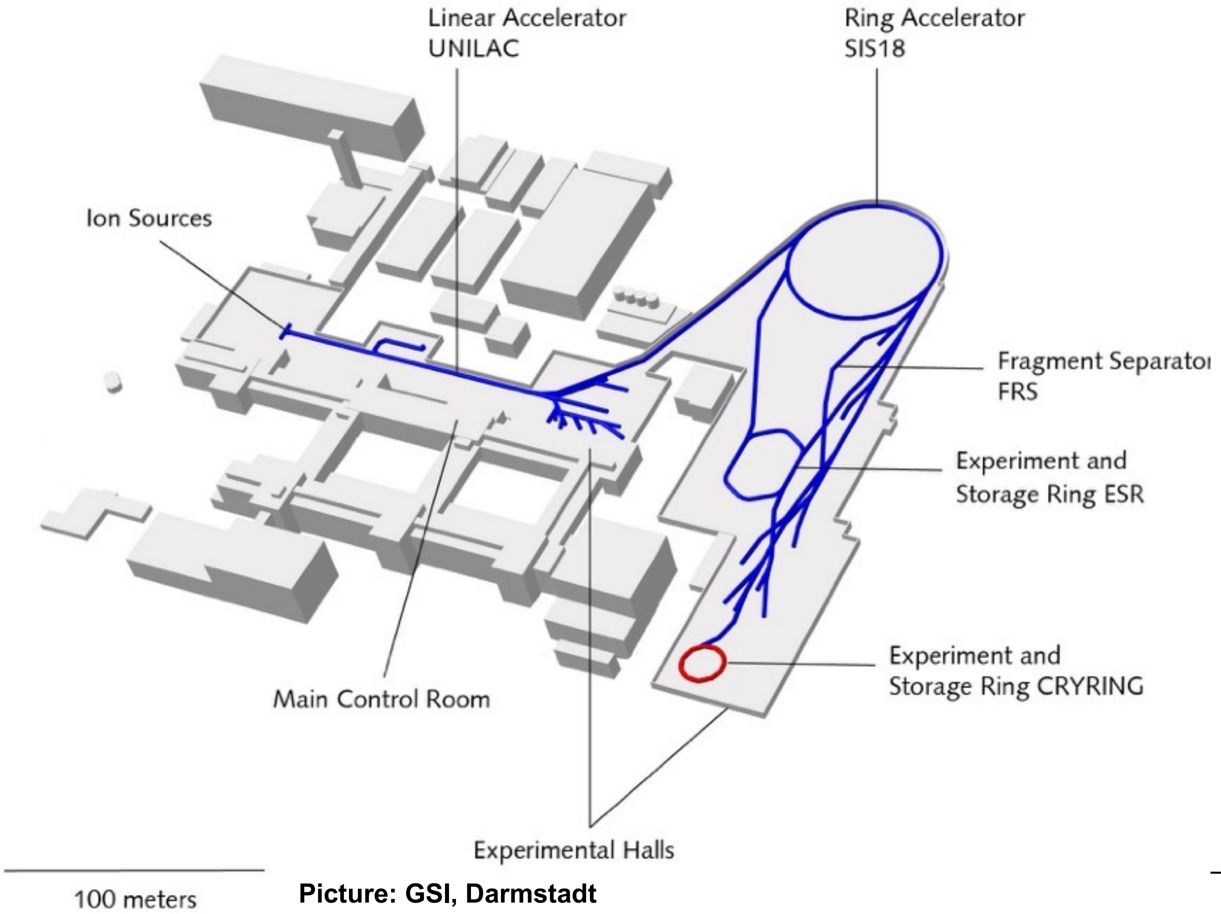


Fragmentation

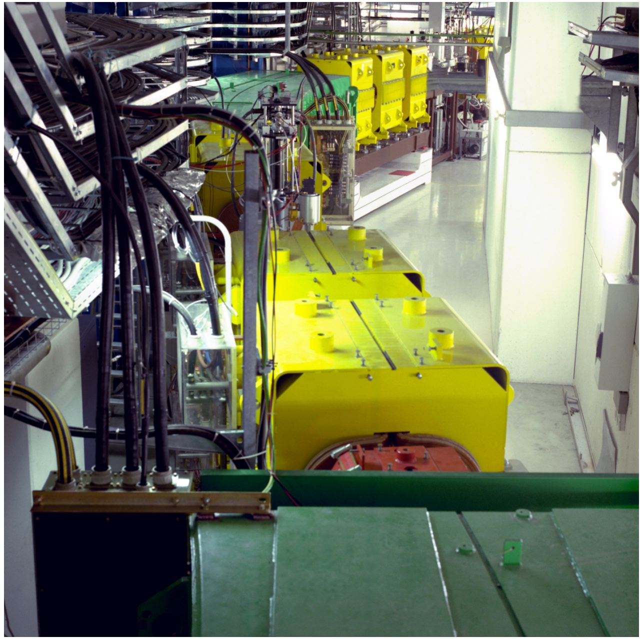
Coulomb dissociation

Fusion

Radioactive Ion Beam Facility at GSI



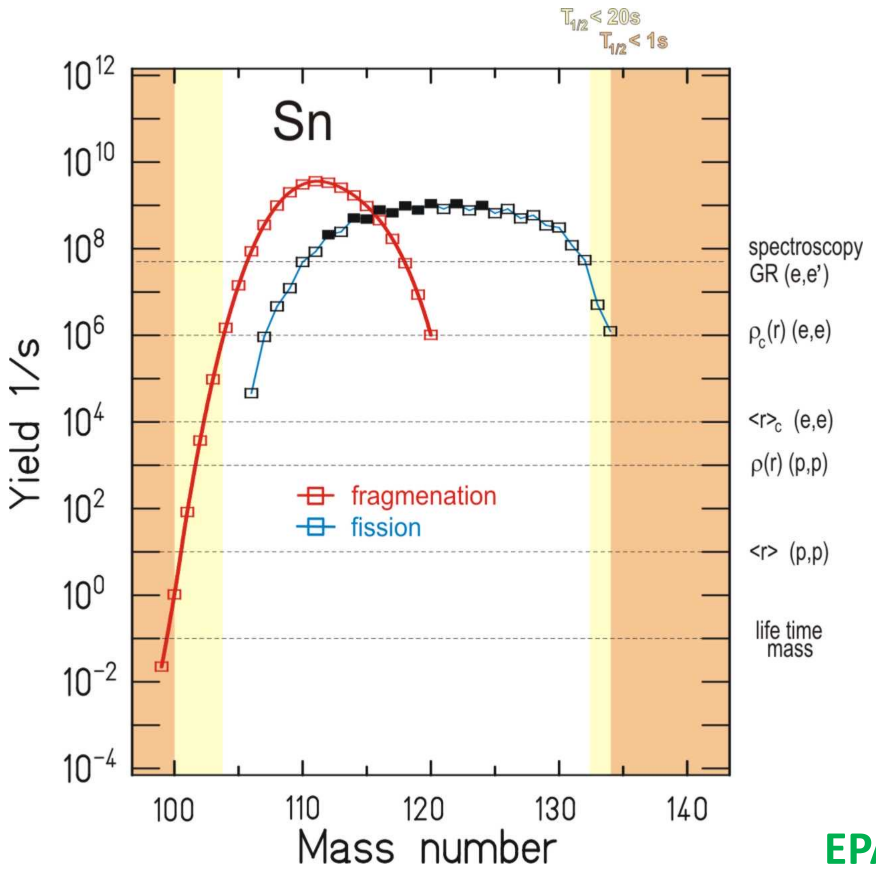
Picture: GSI, Darmstadt



Phase-0
Research Program

HELMHOLTZ

Production Cross-Sections for Tin-Isotopes



nuclides of interest today are

--as a rule--

short-lived

and

have tiny

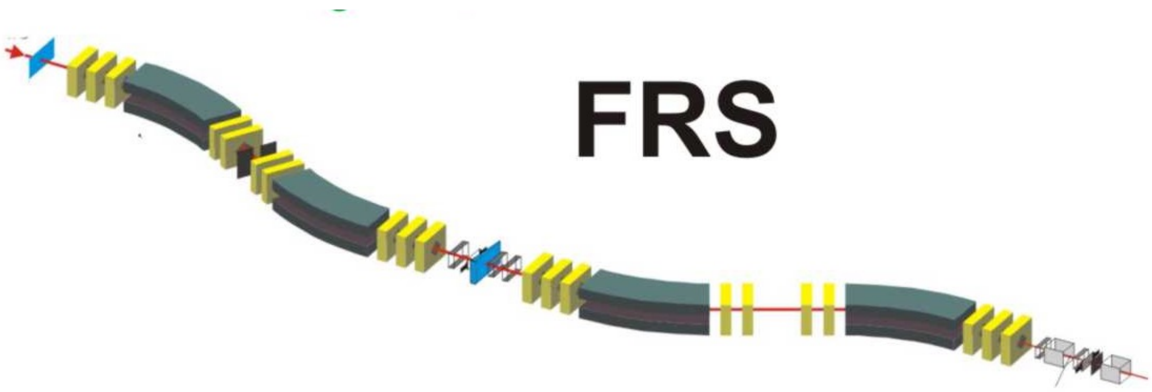
production cross-sections

EPACS, ABRABLA codes implemented in LISE++

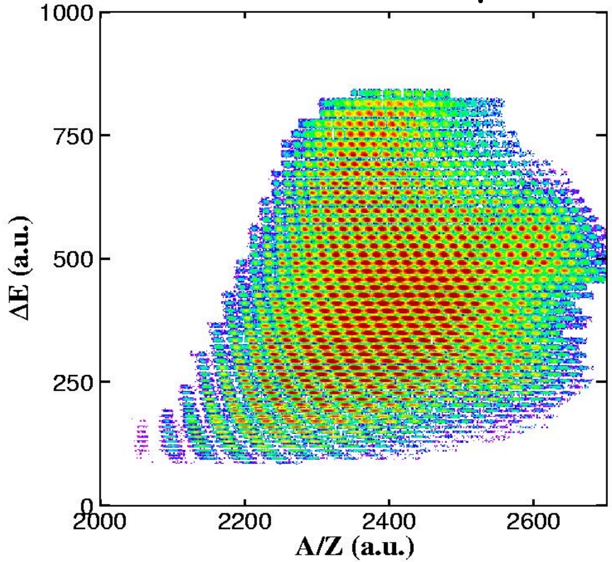
FAIR Conceptual Design Report (2002)

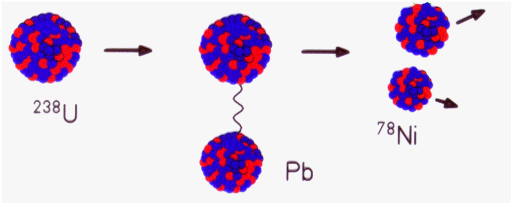
Courtesy: H. Geissel

Fragment Separator at GSI



About 1000 nuclear species





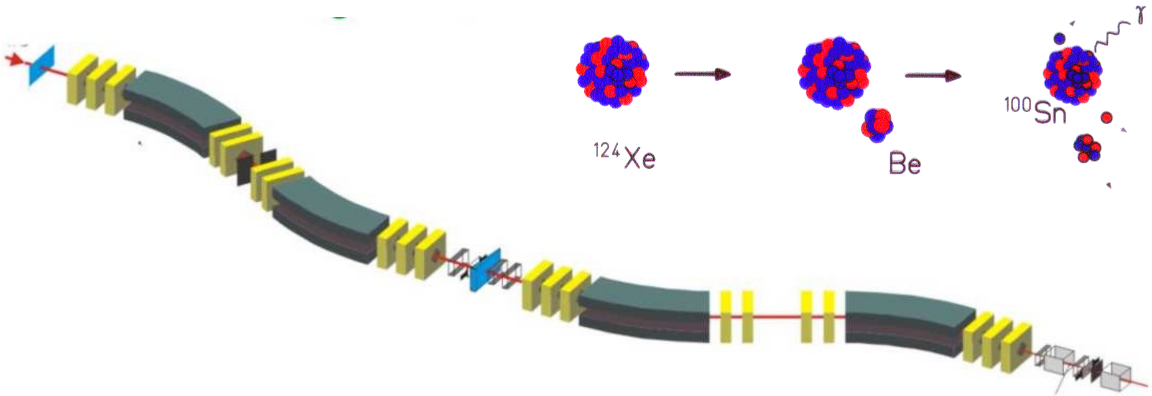
Kinetic energies – hundreds of MeV/u

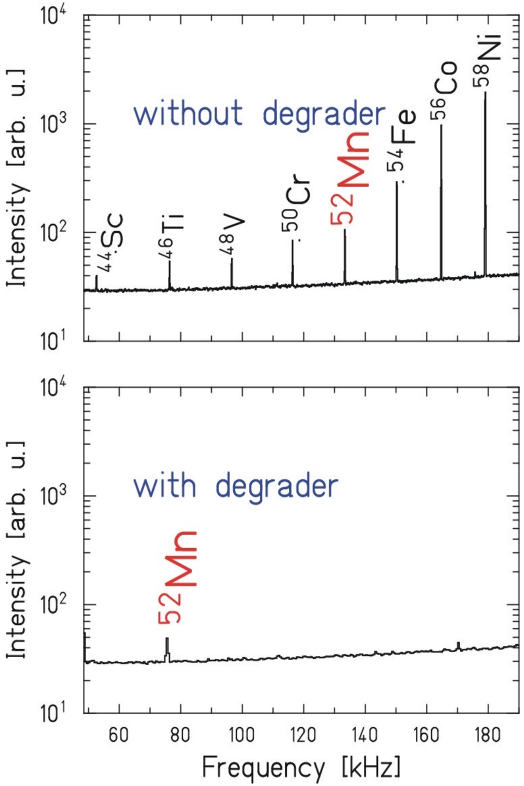
Tracking provides trajectory – flight path

Time–of–flight provides A/Q

Ionization detectors provide Z

Fragment Separator at GSI





Tracking provides trajectory – flight path
Time–of–flight provides A/Q
Ionization detectors provide Z

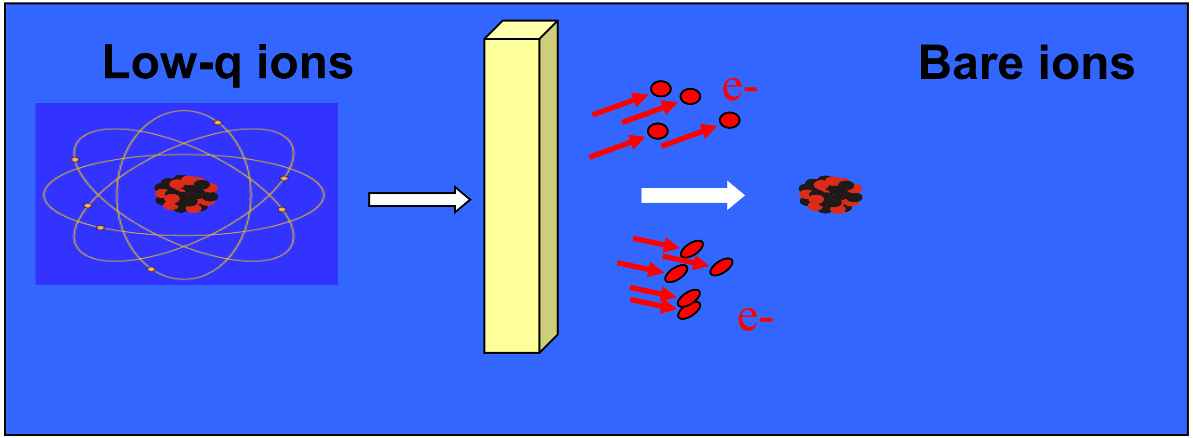
Additional separation criterion – energy loss in specially shaped energy degraders

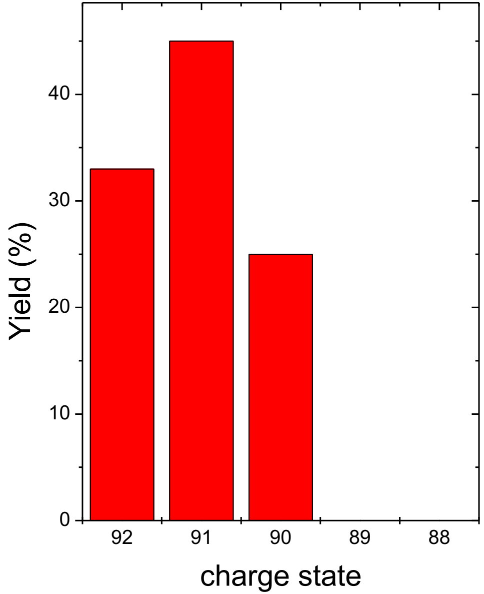
$$\Delta E \propto Z^2$$

Atomic Charge States at Relativistic Velocities

Bohr criterion: Largest ionization cross section at $v/c \approx v_K/c = \alpha Z$

Uranium $v_K/c \approx 0.67$ $E_{KIN} \approx 330$ MeV/u





GLOBAL, CHARGE codes implemented in LISE++

Issue which we have to deal with is velocity!

nuclides of interest today are

--as a rule--

short-lived

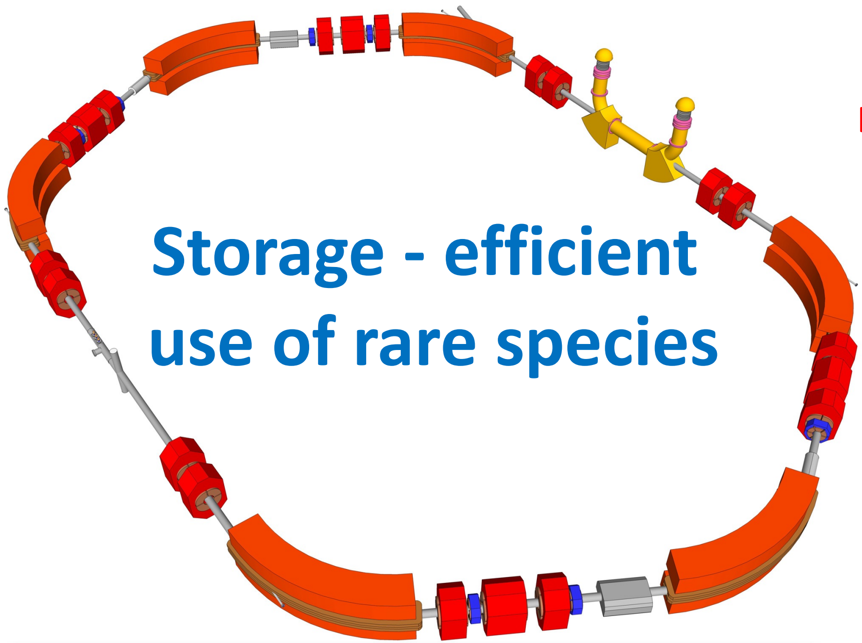
and

have tiny

production cross-sections

Heavy-Ion Storage Rings - Versatile Instruments

Dedicated beam preparation and manipulation techniques



A huge trap – more than 100 m circumference, aperture size – 25 cm

Nuclear reaction inevitably leads to large momentum spread of the secondary beam

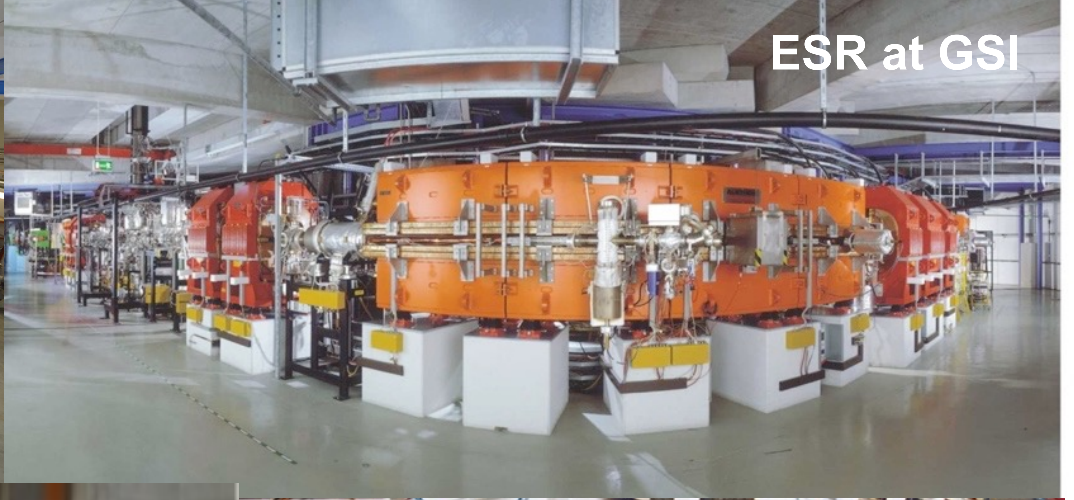
Beam cooling - high quality beams (laser, electrons, stochastic)

Small production rates of secondary beams

Accumulation techniques

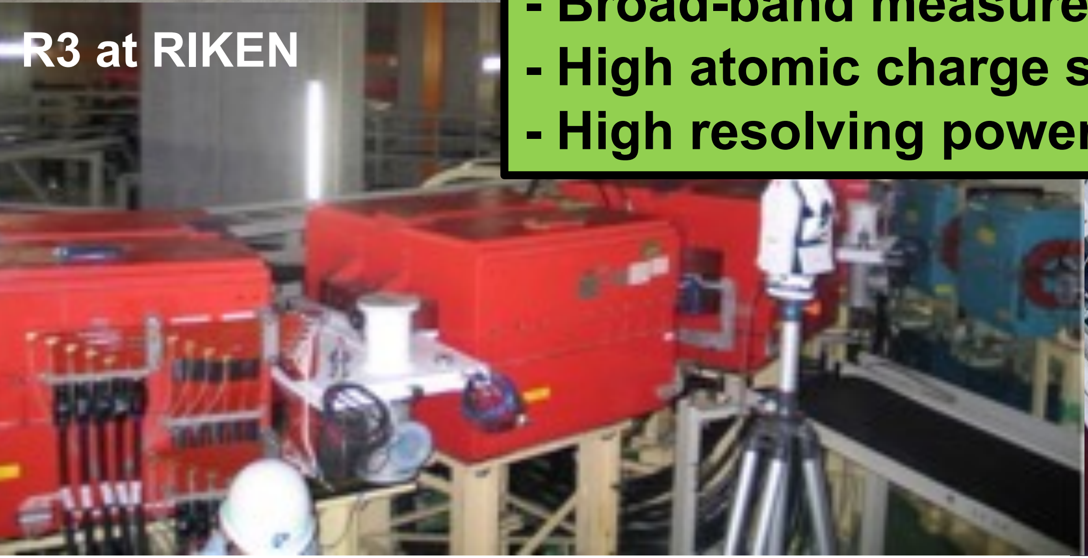
Nuclear reaction at high energy, whereas astrophysical reactions are at low energies

Adjustment of kinetic energy (acceleration or deceleration)



Photos: M. Lestinsky, A. Zschau, GSI; IMP Lanzhou; RIKEN

- Single-particle sensitivity
- High revolution frequencies
- Broad-band measurements
- High atomic charge states
- High resolving power



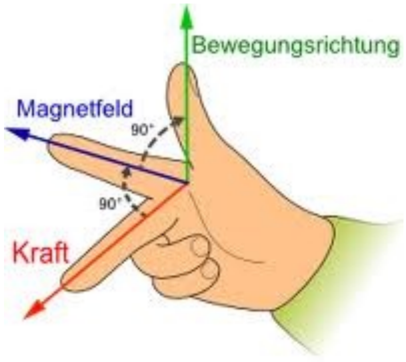
Photos: M. Lestinsky, A. Zschau, GSI; IMP Lanzhou; RIKEN

Charged Particle Motion in Magnetic Field

Centipetal Force

$$F_c = \frac{m \cdot v^2}{r}$$

$$F_L = q \cdot v \cdot B$$



Lorentz Force

$$\frac{m \cdot v}{q} = B \cdot r$$

Velocity!!!

r - Radius
q - Charge
v - Velocity
m - Mass
B – Magnetic induction

Storage ring vocabulary

Reference orbit
Sollbahn ?

A trajectory in the machine of a **reference particle**, that is particle with

$$x = y = s = 0$$

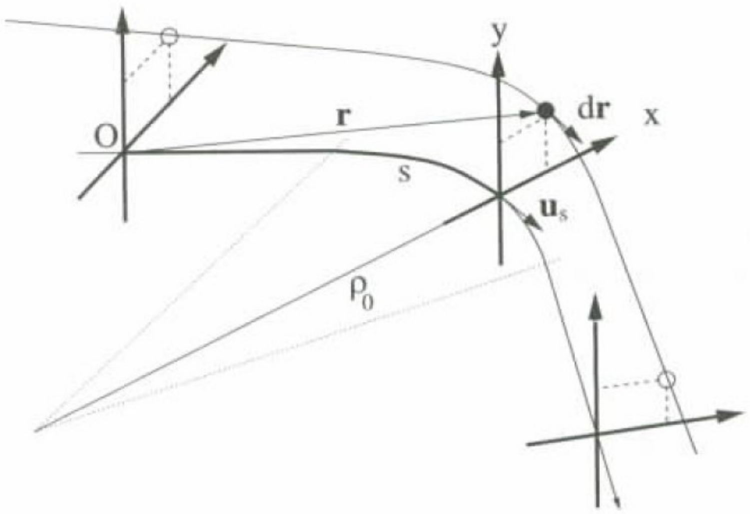


Abb. 4.1. Standardkoordinatensystem (x, y, s)

Curvilinear coordinate system

s – reference orbit / sollbahn

Trajectories of all other particles are treated relative to the reference particle

$$\delta x, \delta p_x, \delta y, \delta p_y, \delta s, \delta p_s$$

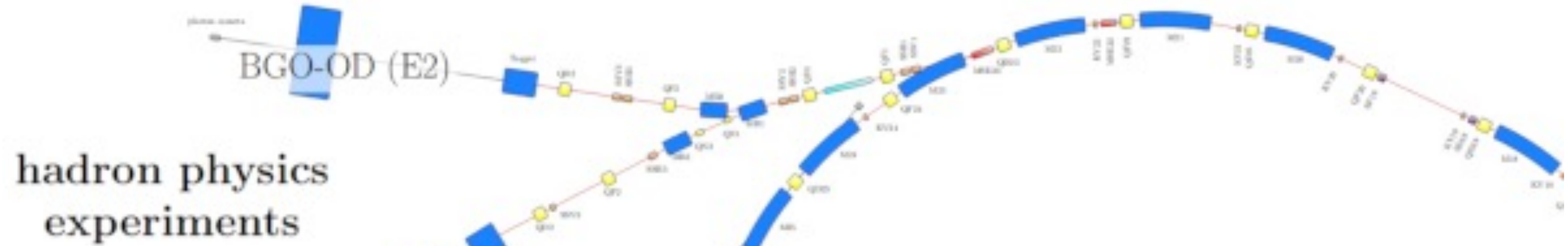
Since all deviations are small, momentum can be expressed as angle

$$p_x = x', \delta p_x = \delta x', p_y = y', \delta p_y = \delta y'$$

Storage ring vocabulary

lattice ?

To store ions, a set of magnetic elements such as dipoles, quadrupoles … is needed which form the **lattice of the ring**



Storage ring vocabulary

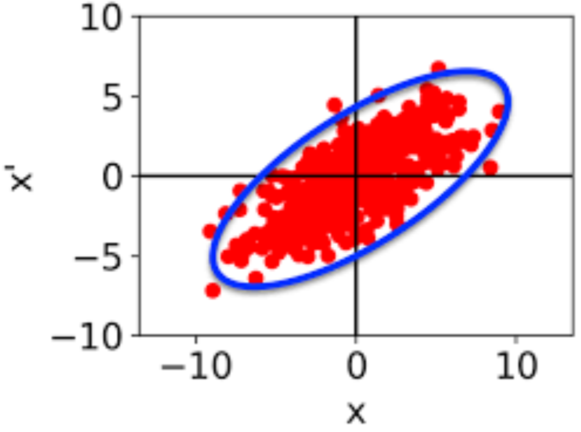
emittance ?

Storage rings have a limited acceptance which can be expressed in terms of the beam **emittance** ε and **momentum spread Δp**

$$\epsilon = \pi \cdot \delta x \cdot \delta p = \pi \cdot \delta x \cdot \delta x'$$

6.2 Hill's equations (linear approximation)

$$\left[\begin{array}{l} \dfrac{d^2x}{ds^2} + K_x(s)\,x = \dfrac{1}{\rho_0(s)}\,\dfrac{\Delta p}{p_0} \\[2ex] \dfrac{d^2y}{ds^2} + K_y(s)\,y = 0 \end{array}\right] \quad (*)$$



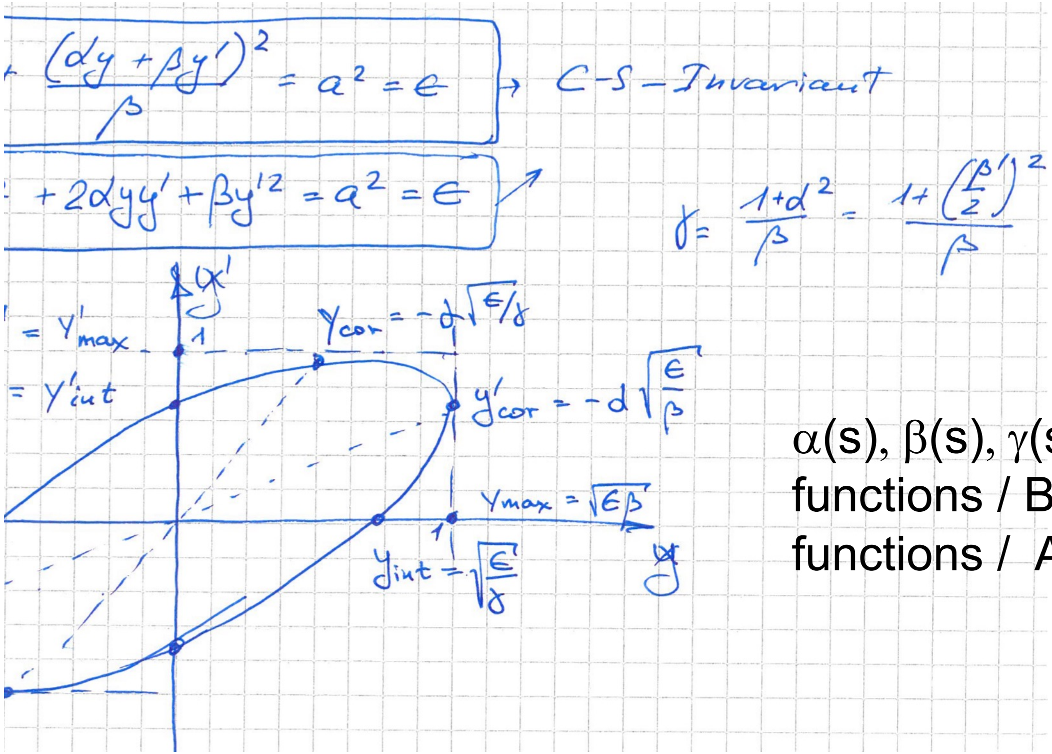
ρ_0 – bending radius of the reference orbit

$K_x(s)$ and $K_y(s)$ are focusing functions which are tabulated for dipoles, quadrupoles etc

Storage ring vocabulary

Courant-Snyder Invariant?

Liouville's law states that **emittance is strictly conserved** under the action of conservative forces.

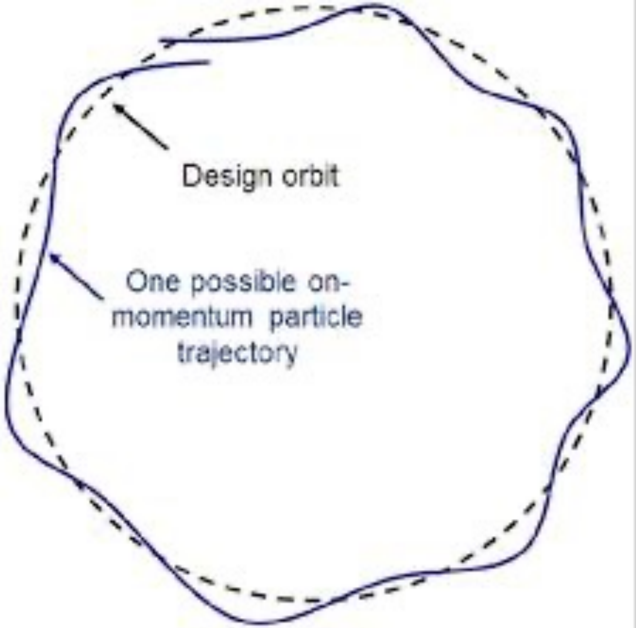


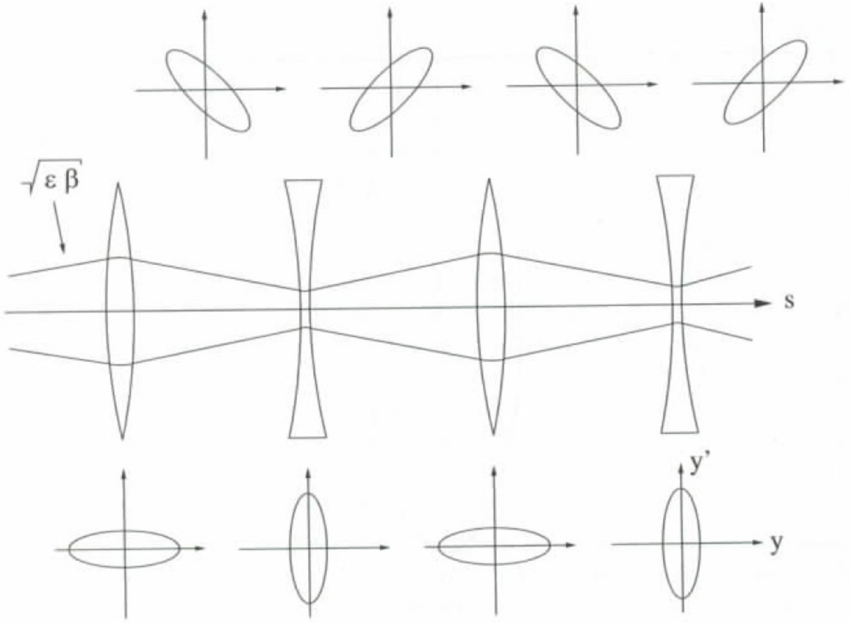
$\alpha(s), \beta(s), \gamma(s)$ – Twiss functions/ Optical functions / Betatron functions / Lattive functions / Amplitude functions

Storage ring vocabulary

Betatron oscillations and tune ?

The ions move on periodic orbits around the ideal trajectory 's' ("Sollbahn"), performing **betatron oscillations**. The number of betatron oscillations per revolution is the **tune Q**.

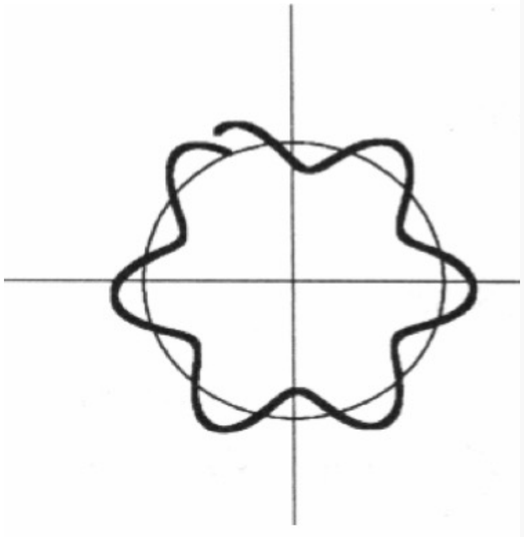


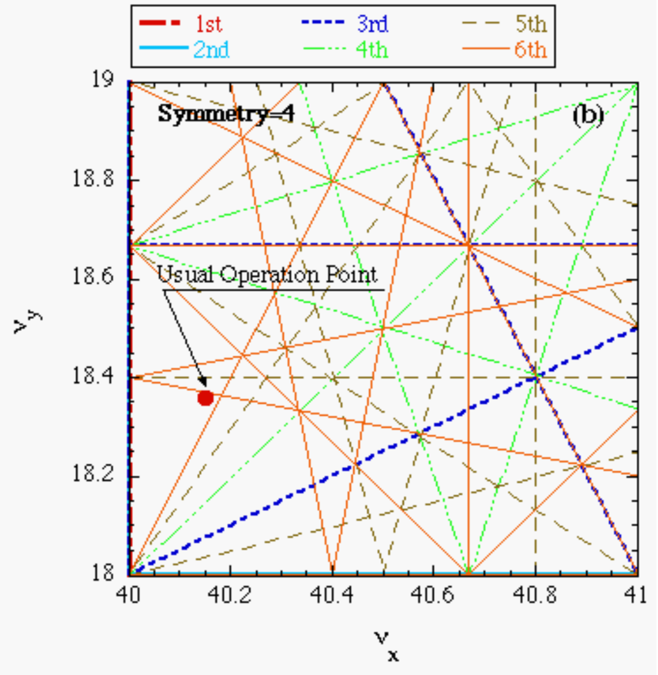


Storage ring vocabulary

resonance?

Due to imperfections of magnetic fields, misallignents etc., the particles should move on not-repeating trajectories. This implies, that tunes are highly irregular numbers. Tunes like Q=N, N/2, N/3, N/4 … - cause resonances leading to beam loss.





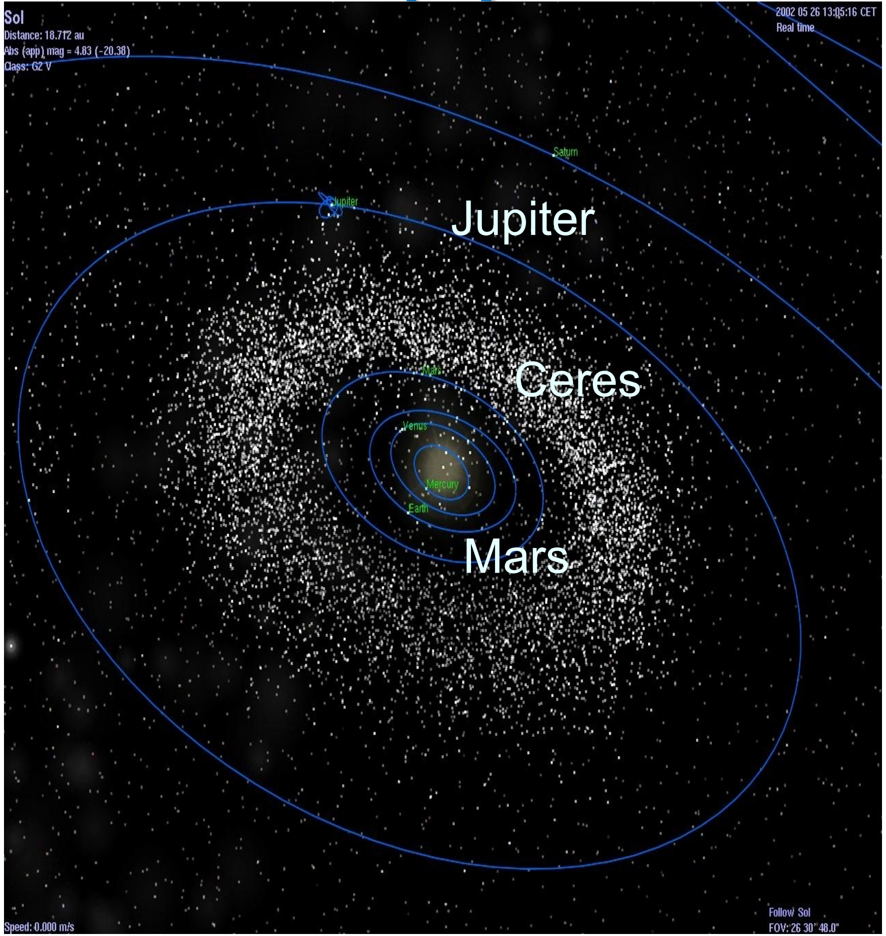
Tuning does not demand a study of "tunology", but rather the right feeling and the experience of decades

To save the beam, avoid any crossing of lines

How to do so, if the ions get acc(de)celerated ??

Lost planet or lost beam – all the same physics

Orbit of a former planet Ceres was periodically influenced by Jupiter



3rd Kepler's law: T^2/a^3 = const.

1 AU = $1.5 \cdot 10^8$ km, T_E = 1 y

a_M = 1.52, a_J = 5.20, R_{MJ} = 0.29

a_C = 2.77, " R_{CJ} = 0.53

Storage ring vocabulary

Synchrotron principle and slip factor?

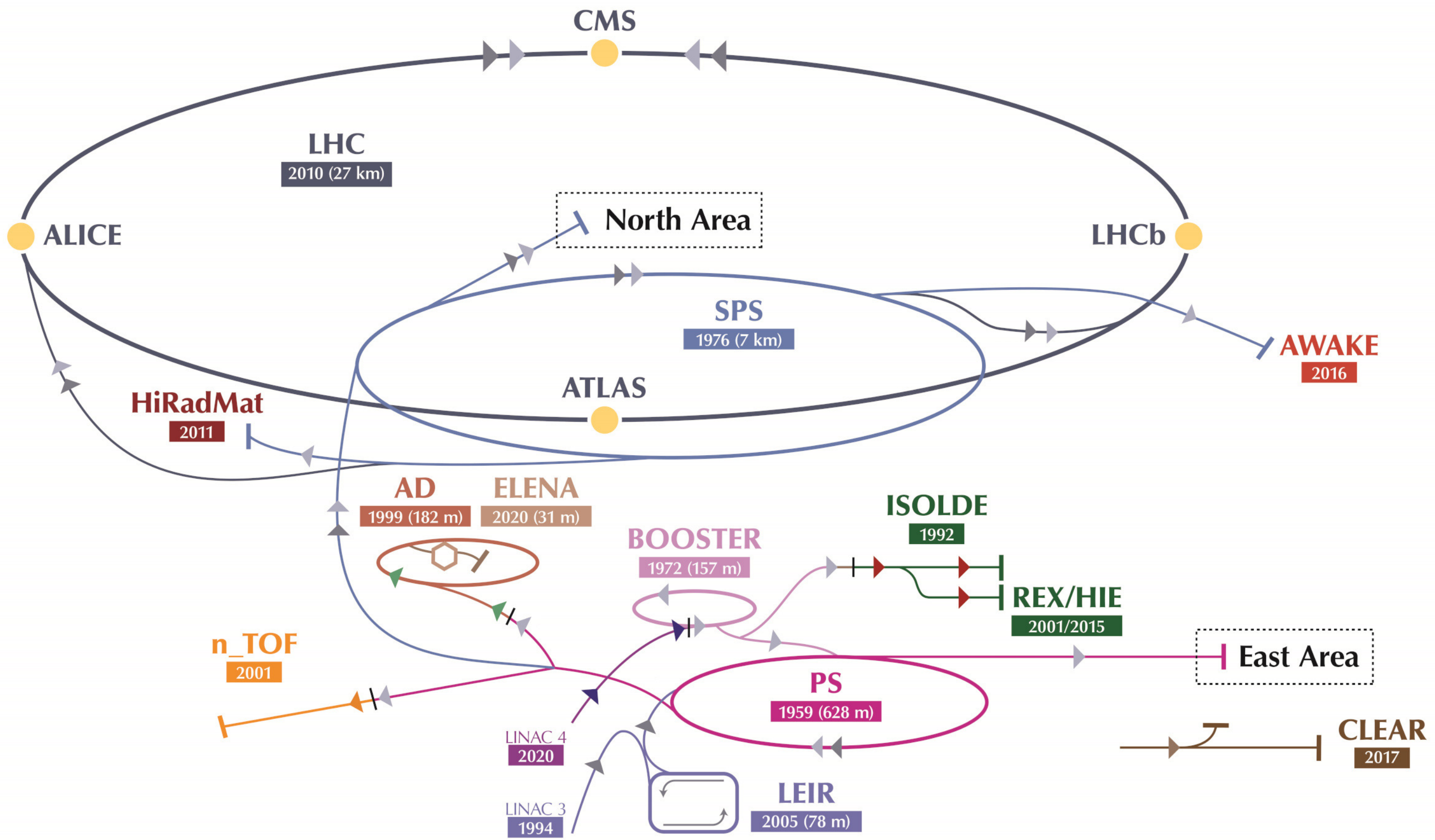
Acceleration/deceleration is only possible if a **change in momentum** transfers into a **change of frequency**. (Synchronisation)

$$\frac{\Delta\omega}{\omega} = \eta \frac{\Delta p}{p} = \left(\frac{1}{\gamma^2} - \frac{1}{\gamma_{tr}^2}\right)\frac{\Delta p}{p}$$

η – dispersion of particle frequencies

$$\alpha_p = \frac{1}{\gamma_{tr}^2}$$ – momentum compaction factor

CERN Facility



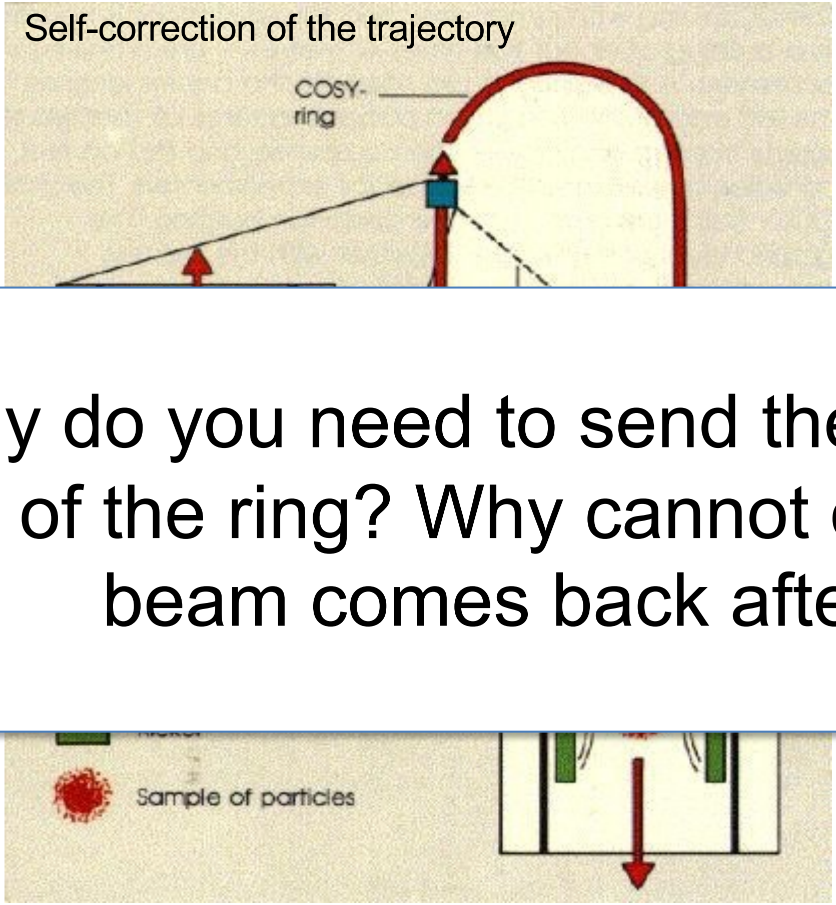
Cooling techniques applied at ion rings

- **Lasers = transfer of momentum**

- **Electrons = mixing of temperatures**

- **Stochastic = self-correction**

Stochastic Cooling of Secondary Beams



Simon van der Meer
1925 - 2011

Why do you need to send the signal to the opposite side of the ring? Why cannot one simply wait until the beam comes back after full revolution?

Nobel prize 1984: S. van der Meer and C. Rubbia

Photos from the Nobel Foundation archive.

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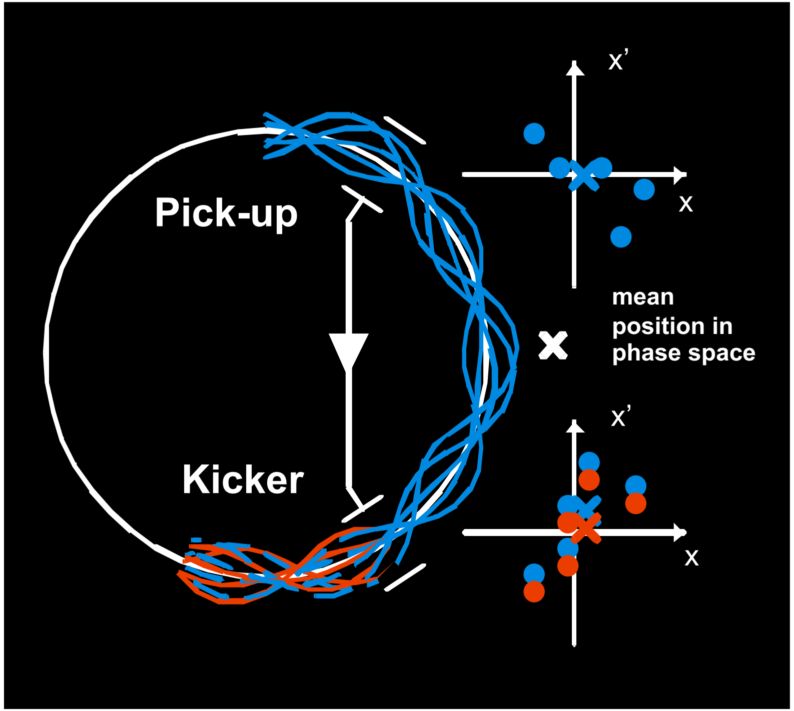
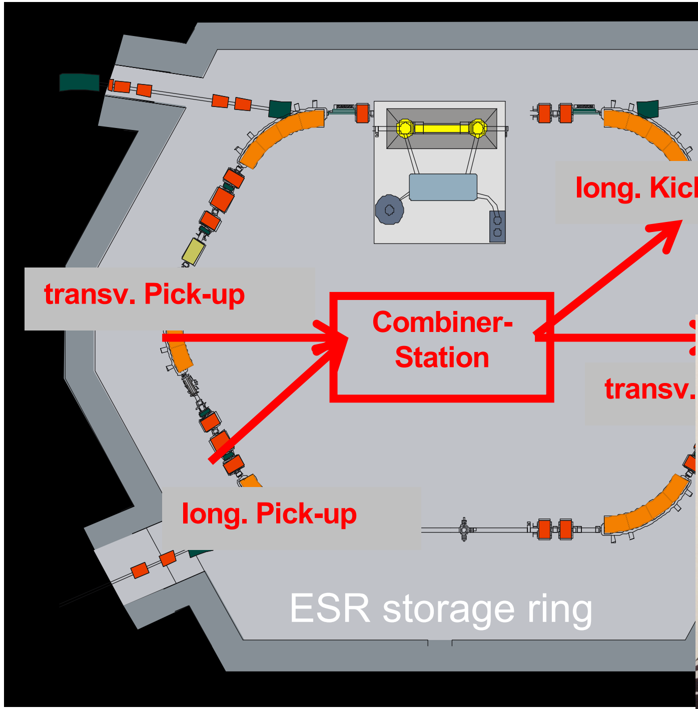
HELMHOLTZ GSI

Stochastic cooling (self-correction of trajectory)



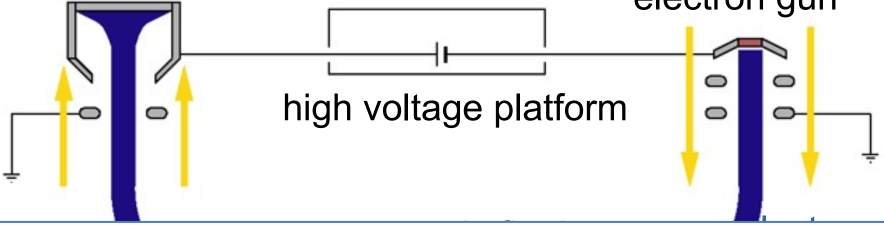


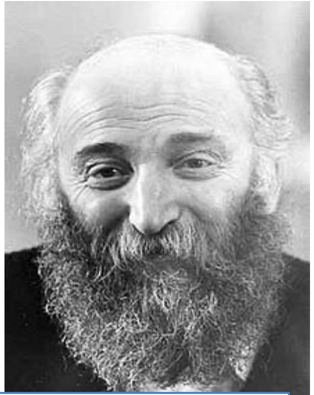
Fritz Nolden 2023+

Stochastic cooling is in particular efficient for hot ion beams

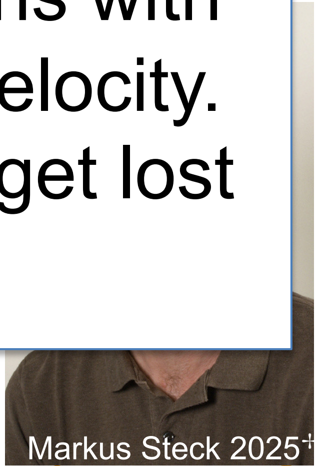
Cooling time τ scales as N_{ion} / bandwith

Electron Cooling of Secondary Beams





The cross-section for recombination of electrons with highly-charged ions diverges at zero relative velocity. Why stored ions do simply not recombine and get lost from the ring?



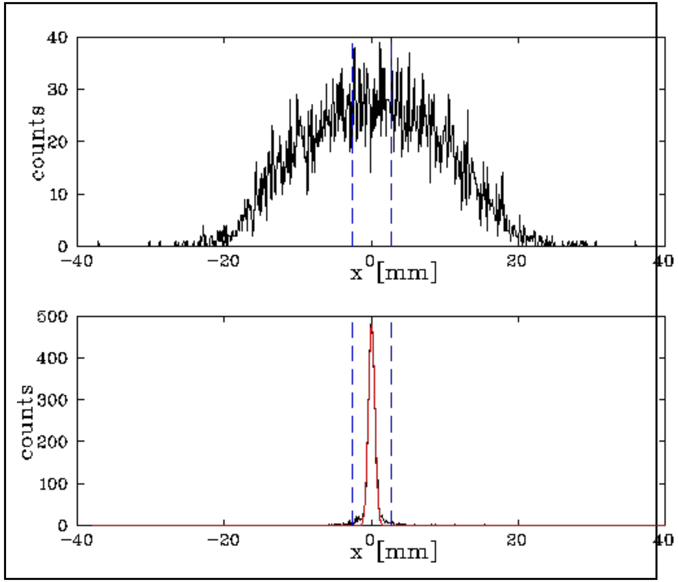
Markus Steck 2025†

Electron cooling (Coulomb cooling)

Cooling by electrons can be treated in analogy to energy loss of ions in matter

$$\frac{dE}{dx} \propto \rho \frac{Z^2}{m_e v^2}$$

What acts against cooling ?



a) ***Intra beam scattering***
Ion-ion scattering

b) ***Collisions*** (scattering) of ions with the ***residual gas atoms***

c) ***Charge exchange losses*** of the ions in collisions with the residual gas atoms or cooler electrons

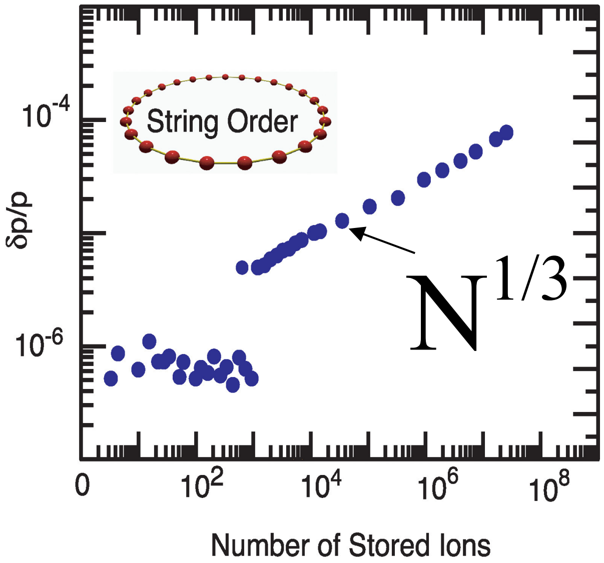
d) ***Space charge limit***

All processes (a - d) scale with $\mathbf{Z^2}$ of the ion

Electron cooling (phase transition)

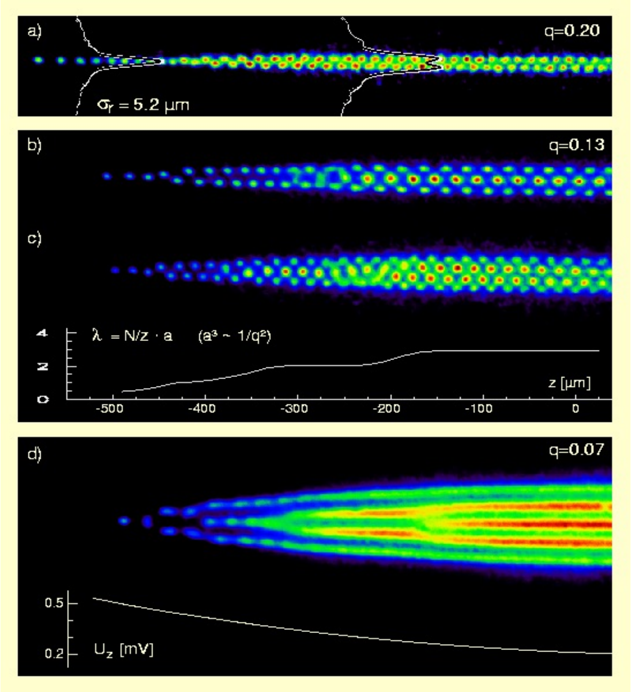
ESR: circumference ≈ 10^4 cm
For 1000 stored ions, the mean distance amounts to about 10 cm

At mean distances of about 10 cm and larger intra-beam-scattering disappeared



M. Steck et al., PRL **77** (1996) 3803

Coulomb crystalls in PALLAS ring



T. Schätz, Nature **412** (2001) 442