Nuclear physics at CERN

Lecture 1: Nuclear landscape and the ISOLDE facility

Magdalena Kowalska
CERN, EP-Dept.
kowalska@cern.ch

on behalf of the CERN ISOLDE team
www.cern.ch/isolde

Outline

Aimed at both physics and non-physics students

- **This lecture**: Nuclear landscape and the ISOLDE facility
  - Nuclear physics and nuclear scale
  - Nuclear physics at CERN
  - Chart of nuclei
  - Radioactive Ion Beam facilities
  - Beam production at ISOLDE

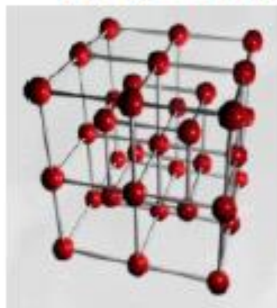
- Lecture 2: Science at ISOLDE

Nuclear physics and nuclear scale

Matter

Macroscopic

Crystal

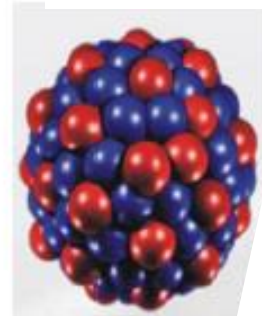


10^{-9} m

Atom

10^{-10} m

Atomic nucleus



10^{-14} m
Angstrom

Nucleon

10^{-15} m
femtometer

Quark

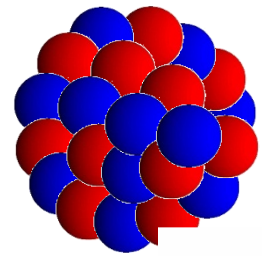
$< 10^{-18}$ m

Aim of nuclear physics:

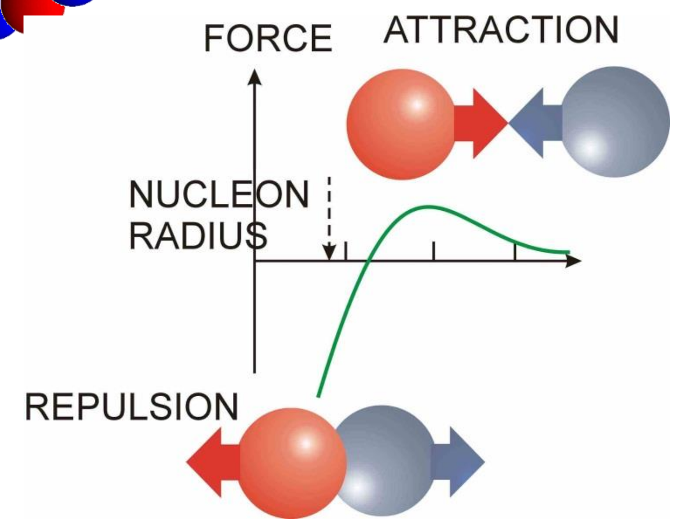
- unravel fundamental properties of nuclei from their building blocks, protons and neutrons
- determine emergent complexity in realm of strong interaction from underlying quark and gluon degrees of freedom of Quantum Chromodynamics

Forces acting in nuclei

- **Coulomb force** repels protons

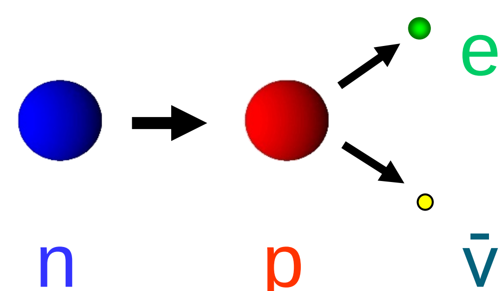


- **Strong interaction** ("nuclear force") causes binding which is stronger for proton-neutron (pn) systems than pp- or nn-systems



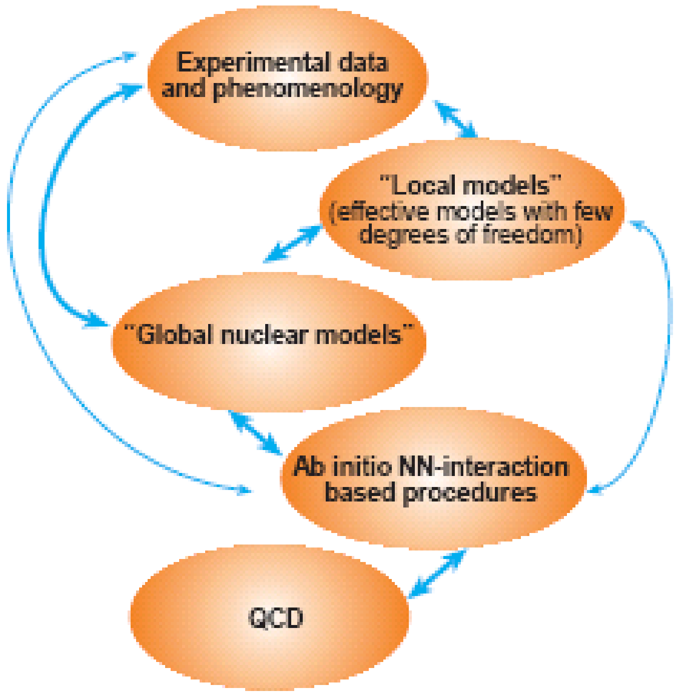
- Neutrons alone form no bound states (exception: neutron stars (**gravitation**!)

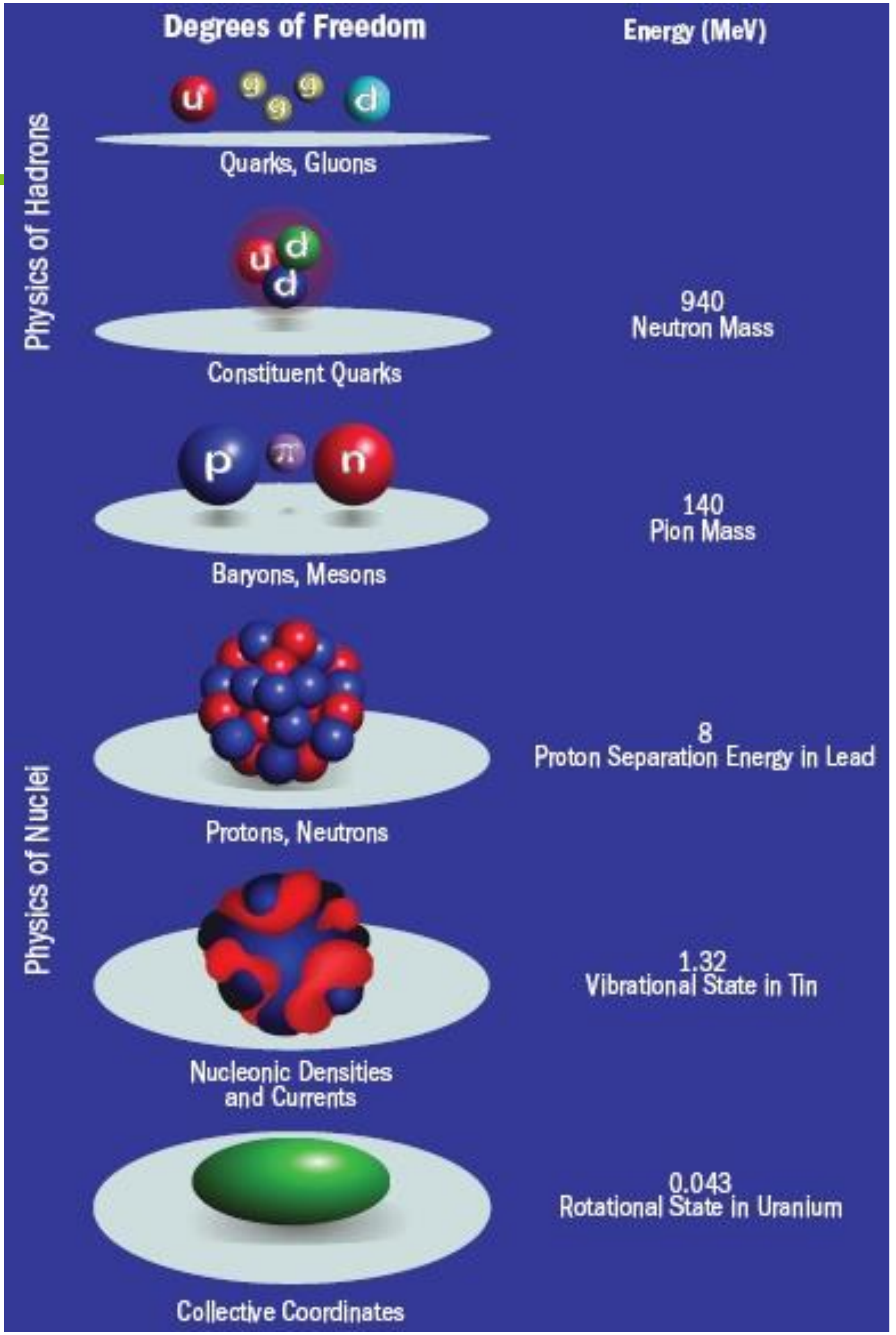
- **Weak interaction** causes β-decay



Nuclei and QCD

- Different energy scales
- In nuclei: non-perturbative QCD, so no easy way of calculating
- Have to rely on nuclear models (shell model, mean-field approaches)
- Recent progress: lattice QCD

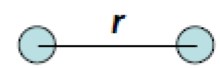


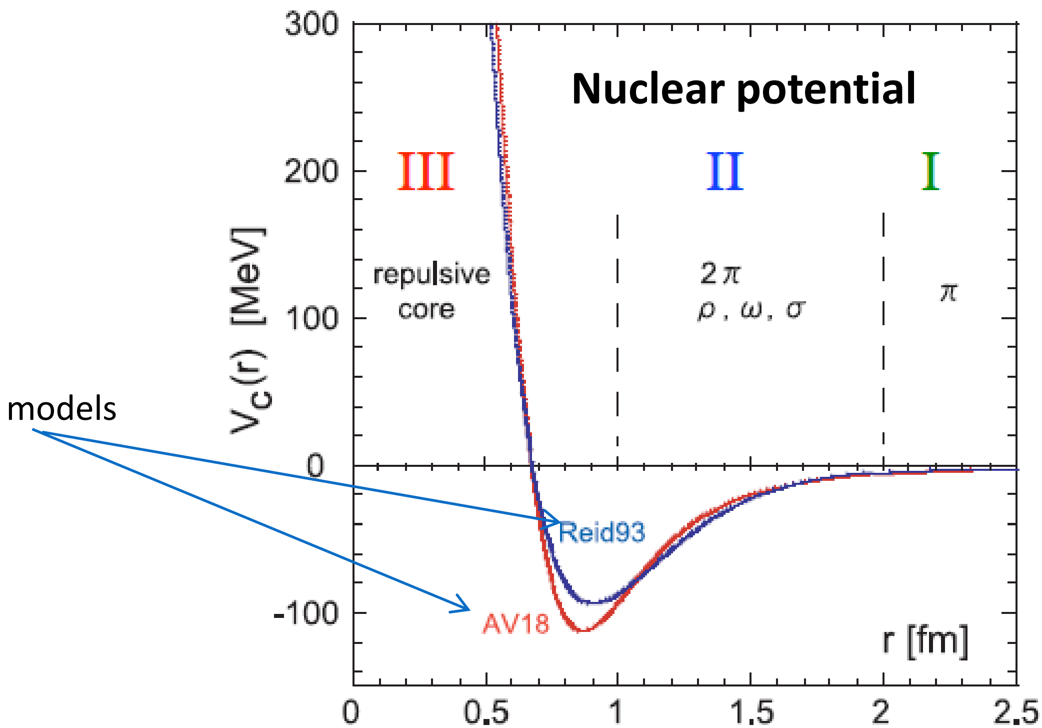


Properties of nuclear interaction

- Has a very short range
- Consists mostly of attractive central potential
- Is strongly spin-dependent
- Includes a non-central (tensor) term
- Is charge symmetric
- Is nearly charge independent
- Becomes repulsive at short distances

(residual) strong force acting in nuclei





I Long range part

one pion exchange potential

II Medium range part

$\sigma,\ \rho,\ \omega$ exchange

2π exchange

III Short range part

repulsive core (RC)

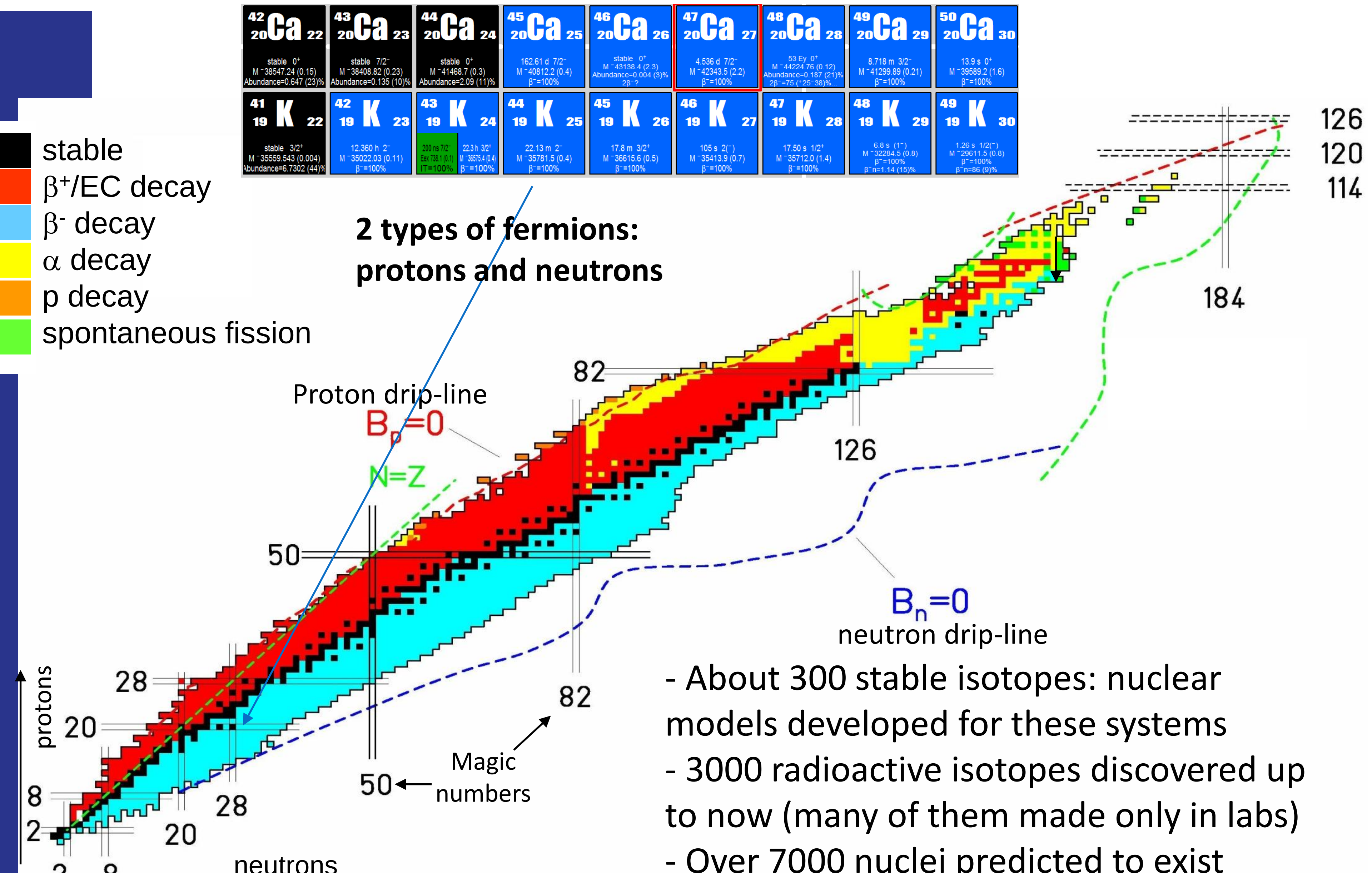
quark ?

Chart of elements

- Around 100 elements
- Ordered by proton number Z
- A few of them made only in a lab

Group	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period 1	1 H 1.008																		2 He 4.0026
2	3 Li 6.94	4 Be 9.0122												5 B 10.81	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.180
3	11 Na 22.990	12 Mg 24.305												13 Al 26.982	14 Si 28.085	15 P 30.974	16 S 32.06	17 Cl 35.45	18 Ar 39.948
4	19 K 39.098	20 Ca 40.078		21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.63	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.798
5	37 Rb 85.468	38 Sr 87.62		39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.96	43 Tc [97.91]	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90	54 Xe 131.29
6	55 Cs 132.91	56 Ba 137.33	*	71 Lu 174.97	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po [208.98]	85 At [209.99]	86 Rn [222.02]
7	87 Fr [223.02]	88 Ra [226.03]	**	103 Lr [262.11]	104 Rf [265.12]	105 Db [268.13]	106 Sg [271.13]	107 Bh [270]	108 Hs [277.15]	109 Mt [276.15]	110 Ds [281.16]	111 Rg [280.16]	112 Cn [285.17]	113 Nh [284.18]	114 Fl [289.19]	115 Mc [288.19]	116 Lv [293]	117 Ts [294]	118 Og [294]
*Lanthanoids			*	57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm [144.91]	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.05		
**Actinoids			**	89 Ac [227.03]	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np [237.05]	94 Pu [244.06]	95 Am [243.06]	96 Cm [247.07]	97 Bk [247.07]	98 Cf [251.08]	99 Es [252.08]	100 Fm [257.10]	101 Md [258.10]	102 No [259.10]		

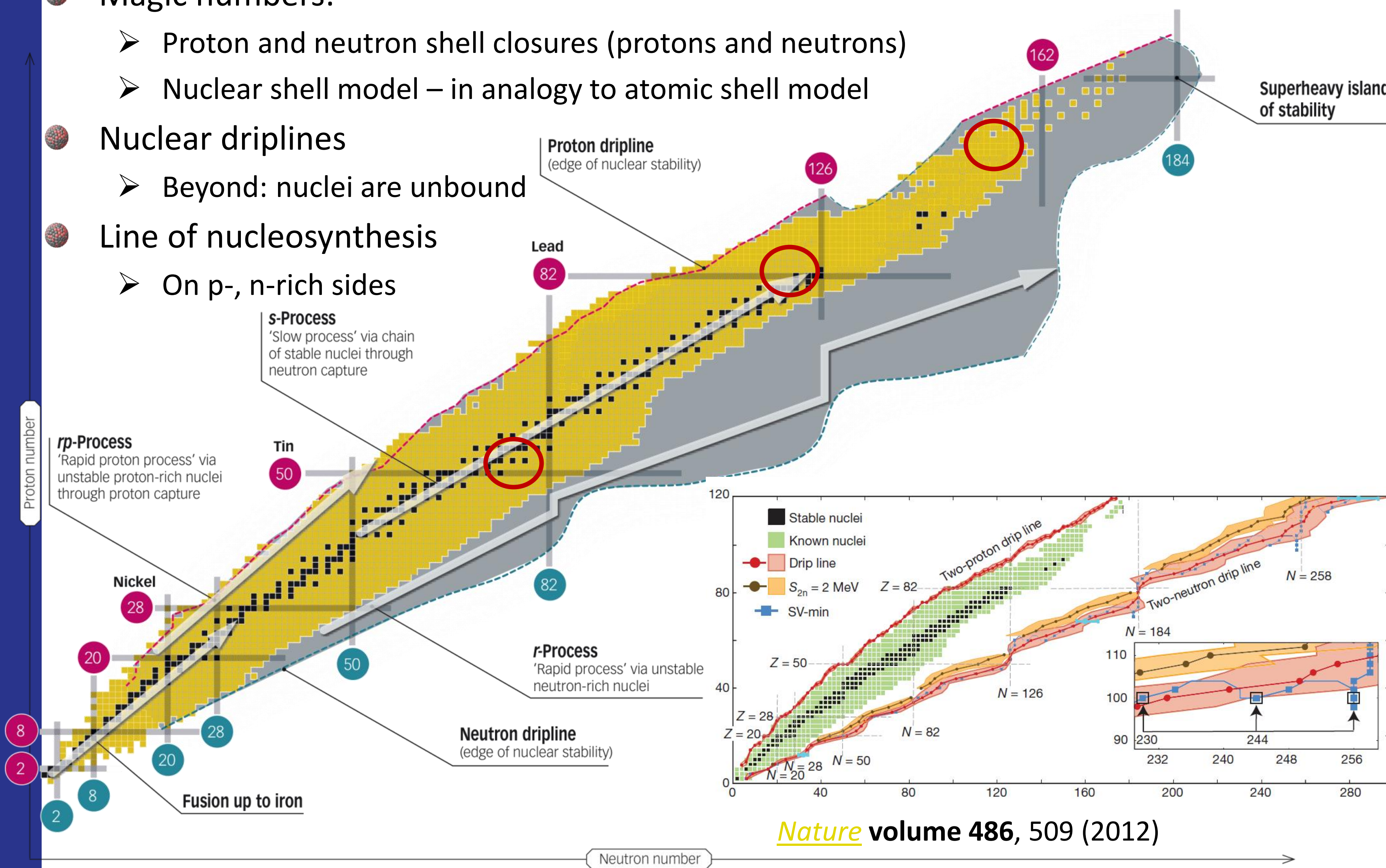
Chart of nuclei



- About 300 stable isotopes: nuclear models developed for these systems
- 3000 radioactive isotopes discovered up to now (many of them made only in labs)
- Over 7000 nuclei predicted to exist

Chart of nuclei

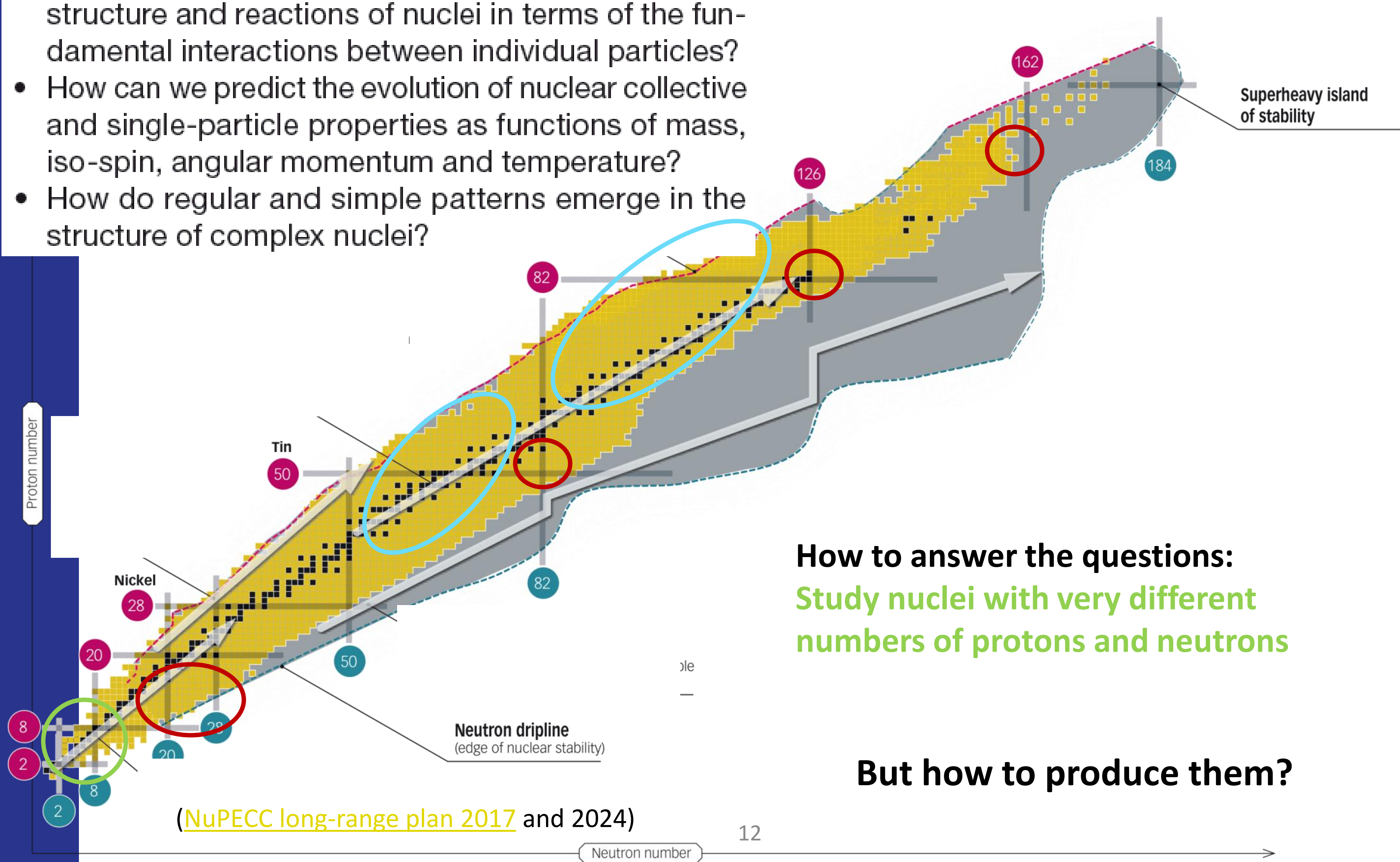
- Magic numbers:
  - Proton and neutron shell closures (protons and neutrons)
  - Nuclear shell model – in analogy to atomic shell model
- Nuclear driplines
  - Beyond: nuclei are unbound
- Line of nucleosynthesis
  - On p-, n-rich sides



[Nature](#) **volume 486**, 509 (2012)

Open questions in low-energy nuclear physics

- How can we describe the rich variety of low-energy structure and reactions of nuclei in terms of the fundamental interactions between individual particles?
- How can we predict the evolution of nuclear collective and single-particle properties as functions of mass, iso-spin, angular momentum and temperature?
- How do regular and simple patterns emerge in the structure of complex nuclei?

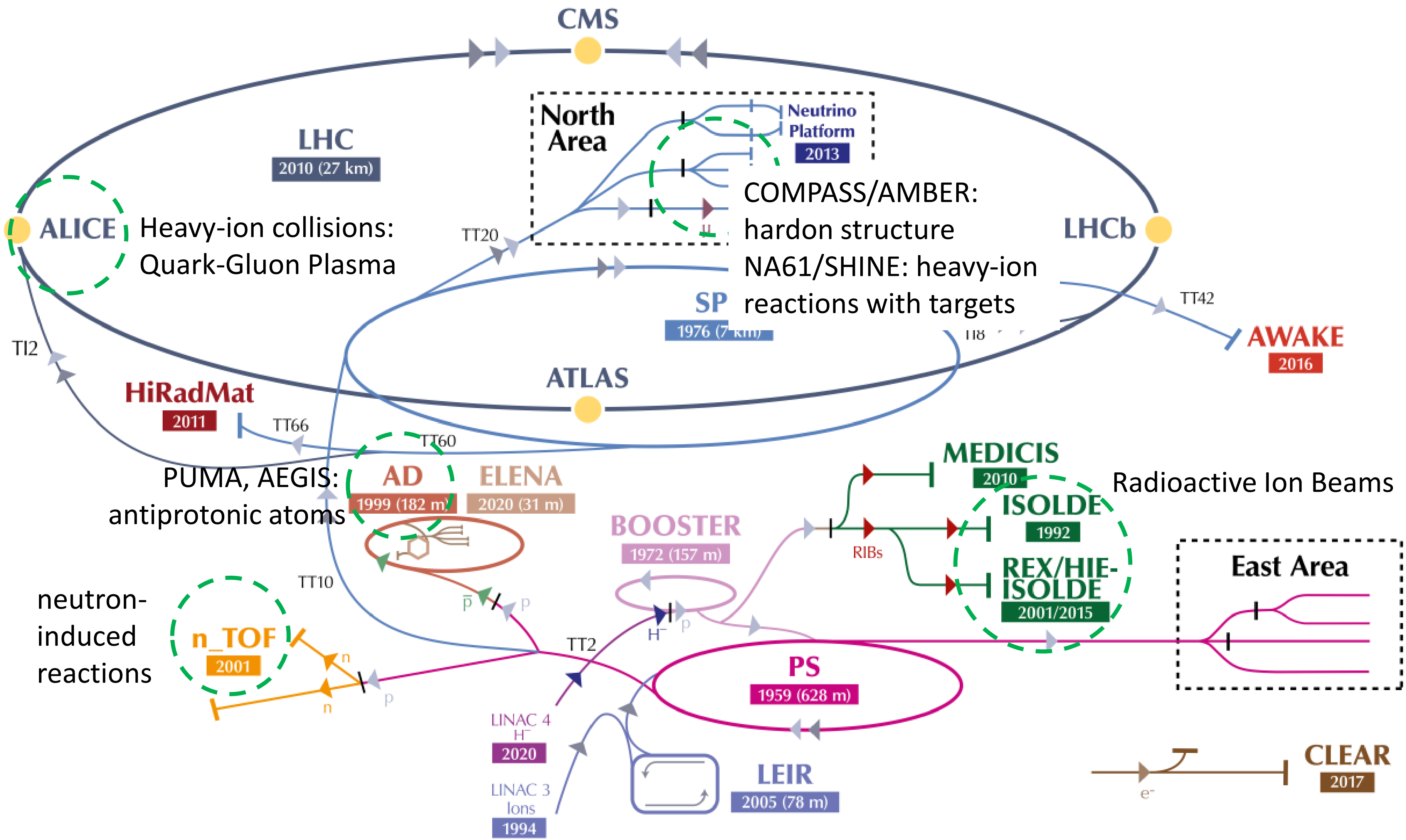


How to answer the questions:
Study nuclei with very different numbers of protons and neutrons

But how to produce them?

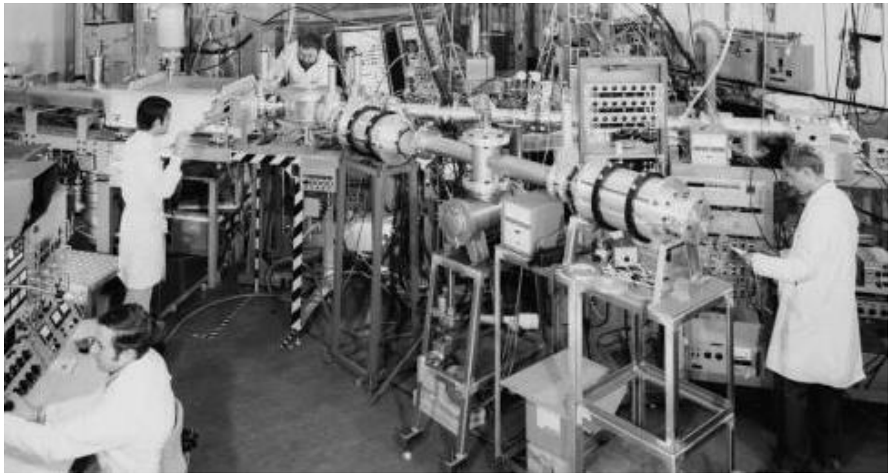
(NuPECC long-range plan 2017 and 2024)

Nuclear physics at CERN



ISOLDE facility at CERN

- Isotope Separator OnLine Device
- First ISOL facility worldwide!
- Produces Radioactive Ion Beams (RIBs)
- Approved by the CERN council in 1964
  - 1st used 600 MeV protons from SC
  - Then used 1.0 GeV (now 1.4 GeV) protons from PSB

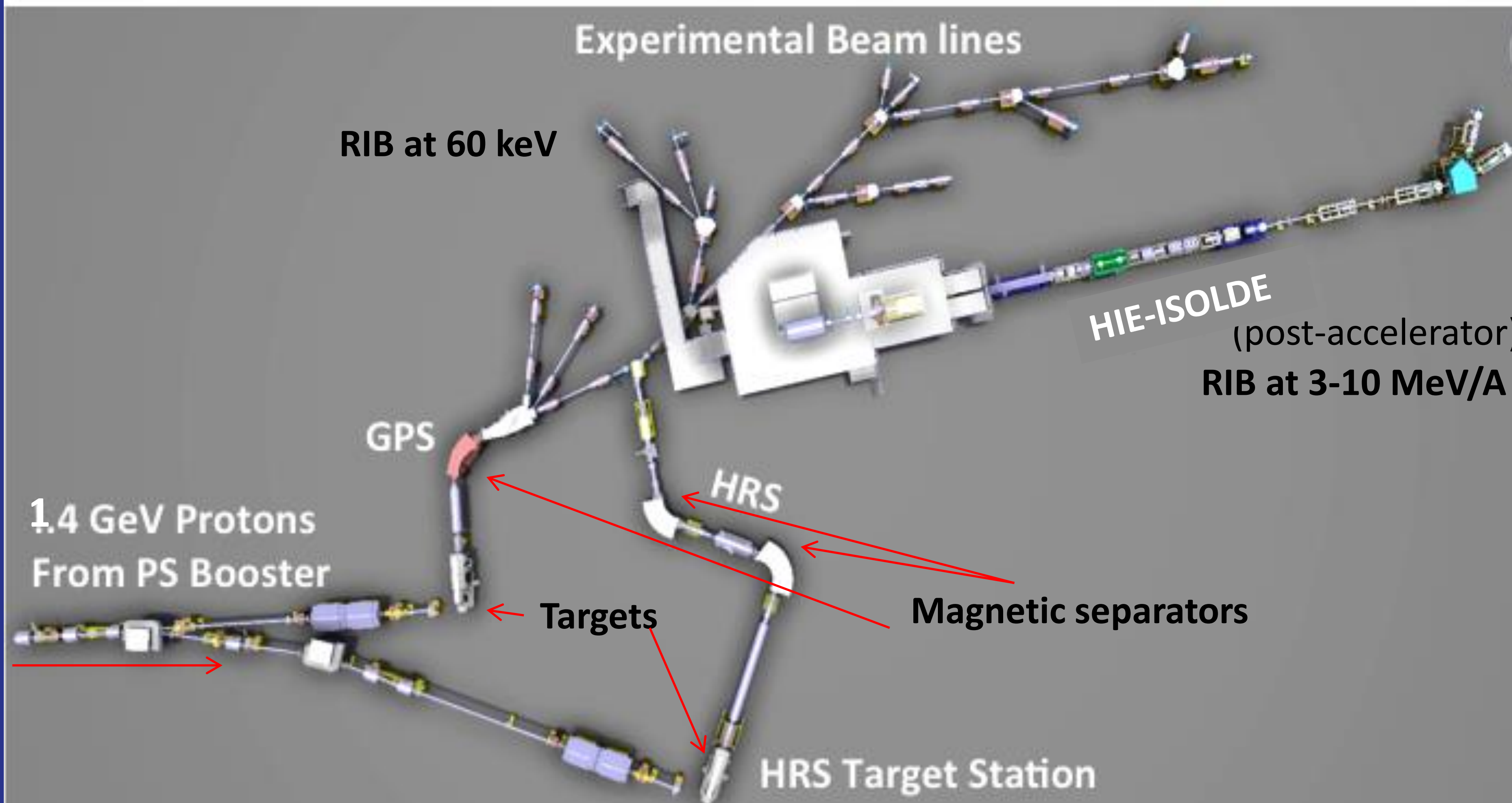


- A small facility with a big impact!
  - 0.1% of CERN budget
  - 7% of CERN scientists (> 500)
  - 50% of CERN proton pulses
  - 80% of CERN protons
  - > 50 experiments/year

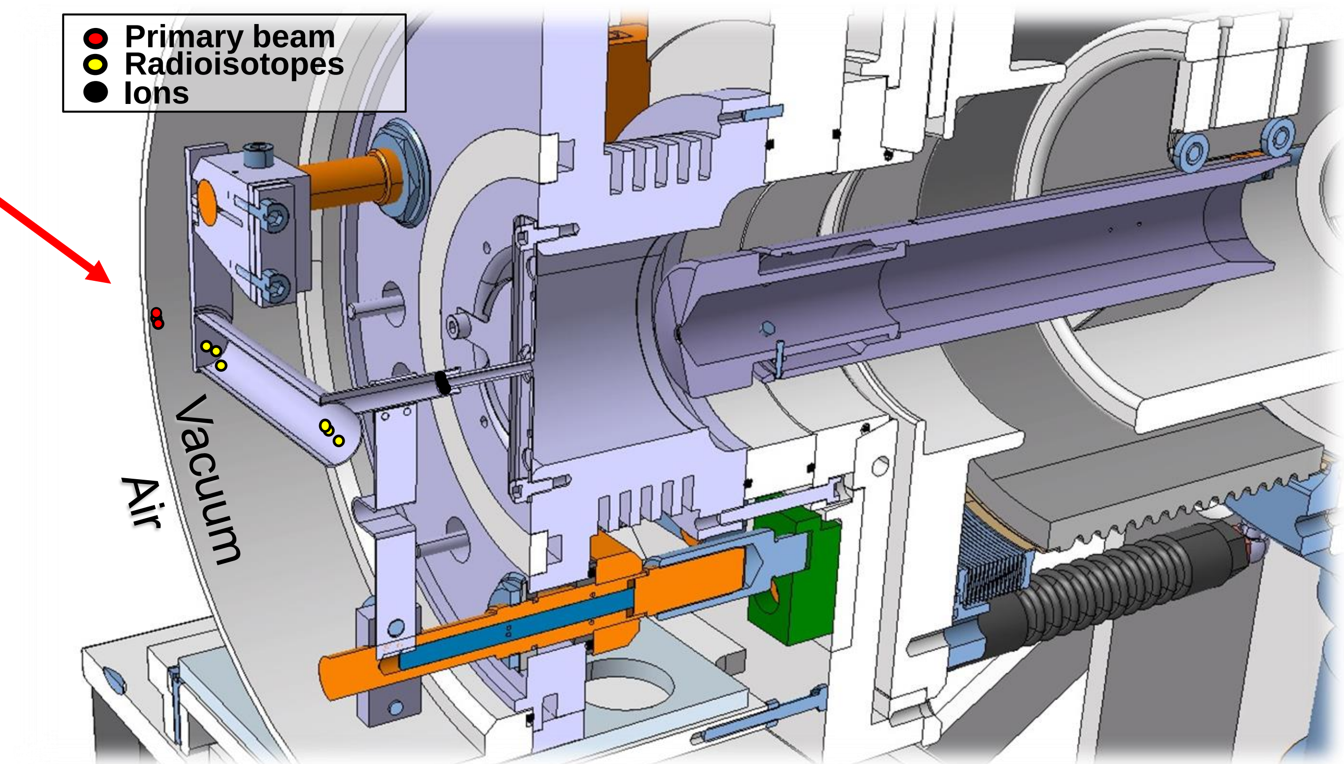
http://timeline.web.cern.ch/timelines/ISOLDE

Life of a radioactive isotope at ISOLDE

- Production -> shaping into pure beam -> use at experiments -> impact
- ISOLDE elements:



Production: Targets + ionisers

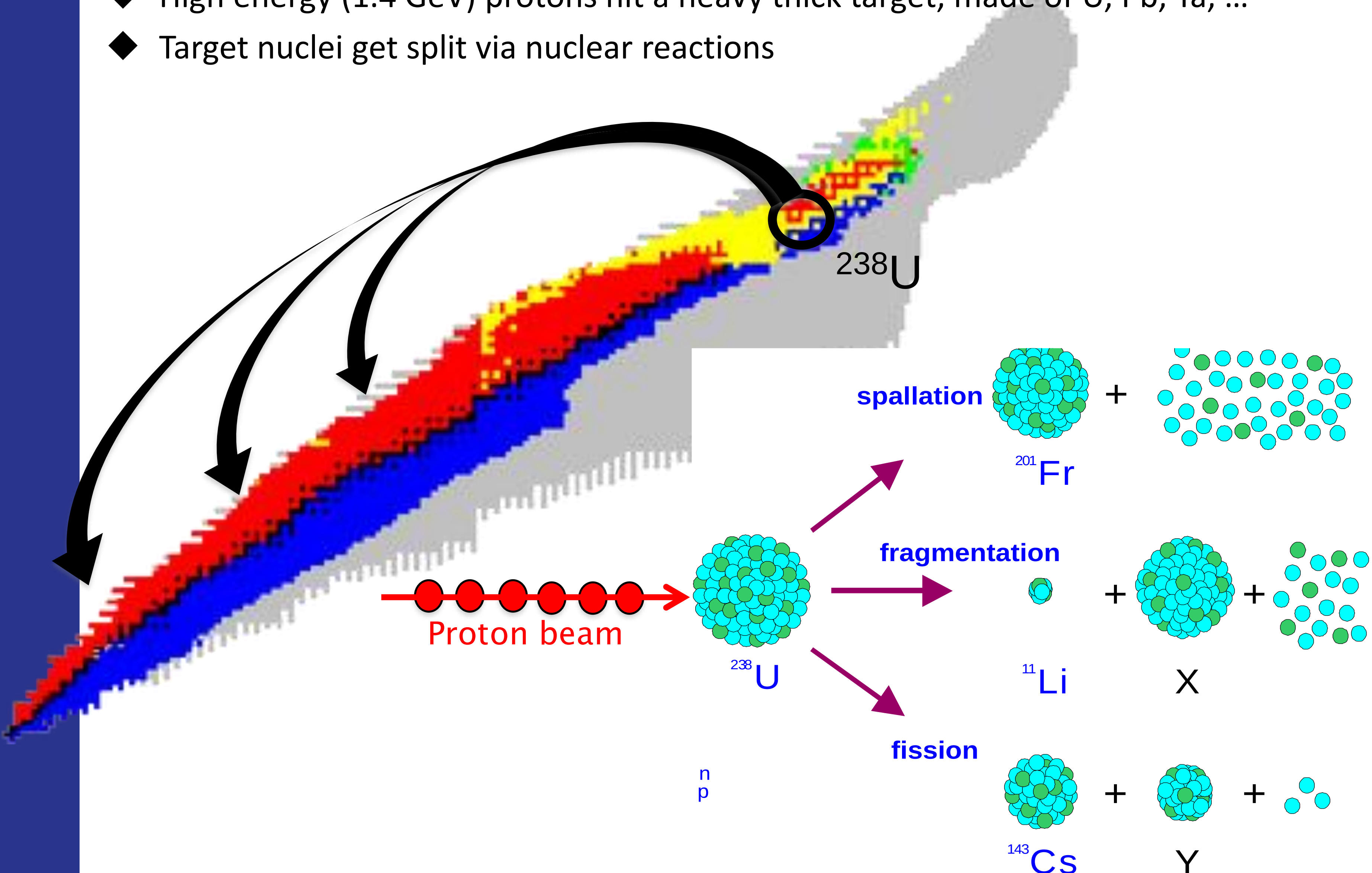


*picture and animation courtesy of M. Delonca

- Over 120 materials tested and/or used as ISOL targets
  - Examples: molten metals, nanomaterials
  - Choice given by RIB of interest
- Target material and transfer tube heated to 1500 – 2000 degrees
- Operated by robots due to radiation

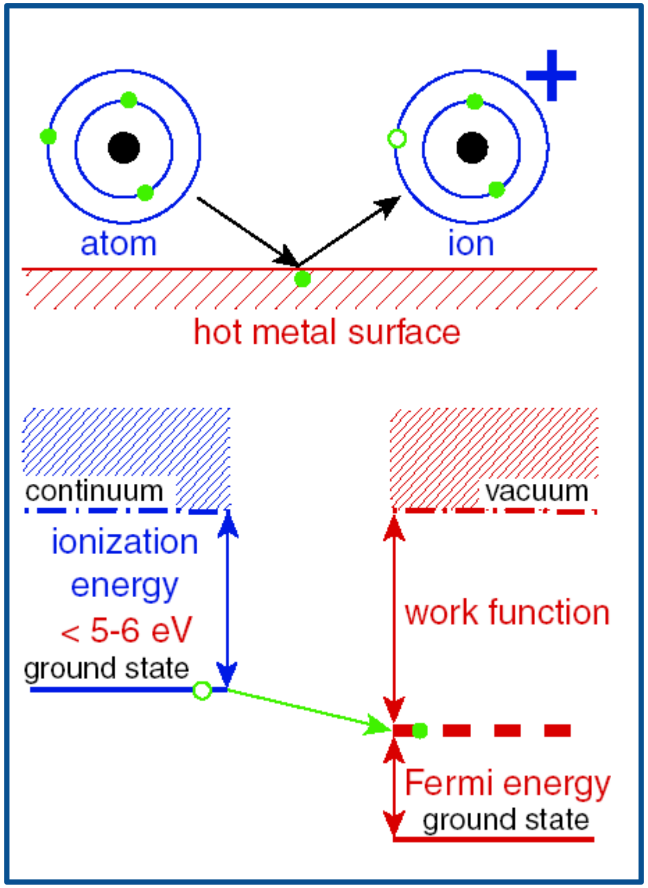
Production: Modern-day alchemy

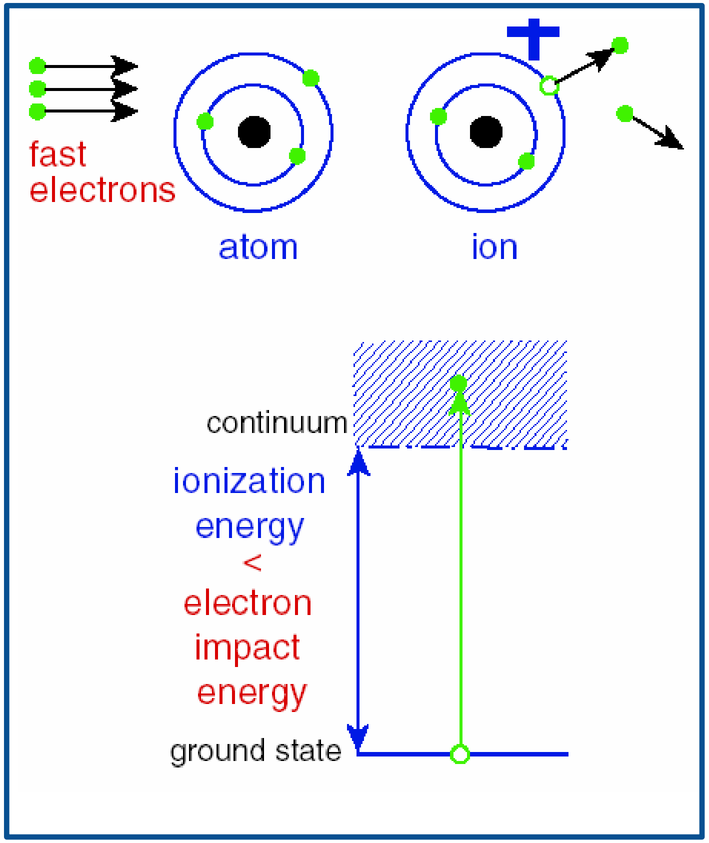
- High energy (1.4 GeV) protons hit a heavy thick target, made of U, Pb, Ta, …
- Target nuclei get split via nuclear reactions

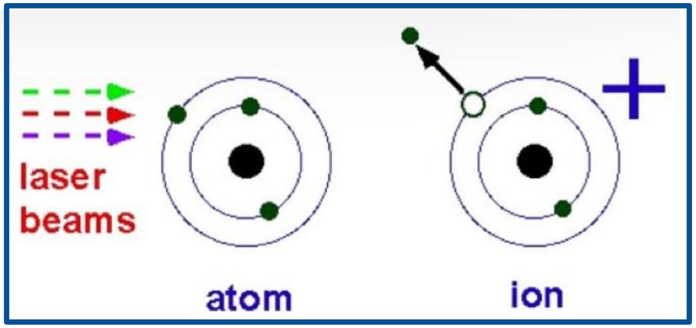


Ionization

- Surface
- Plasma
- Lasers





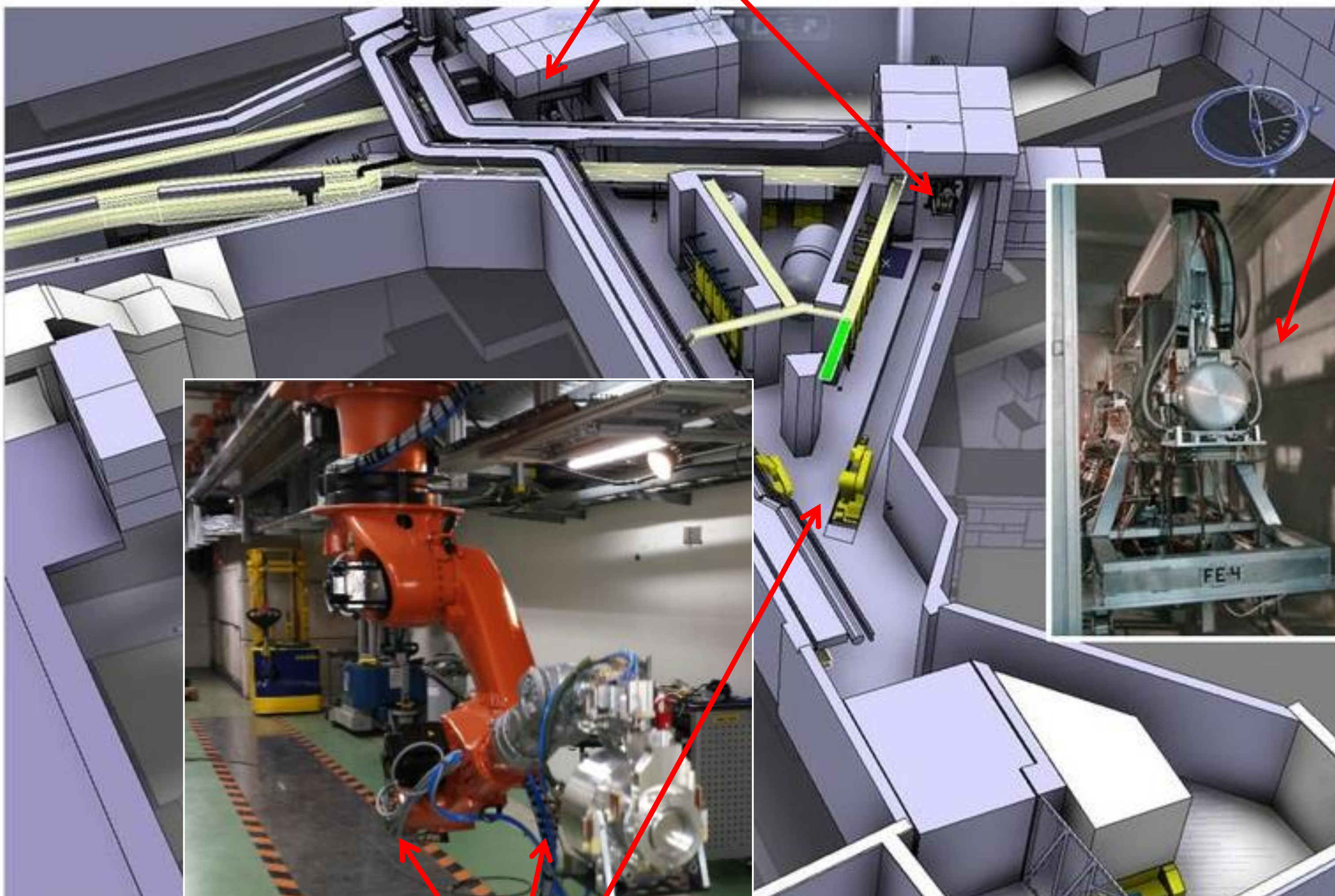


After U. Koester

Production, ionization, extraction

target

Target+ vacuum+ extraction

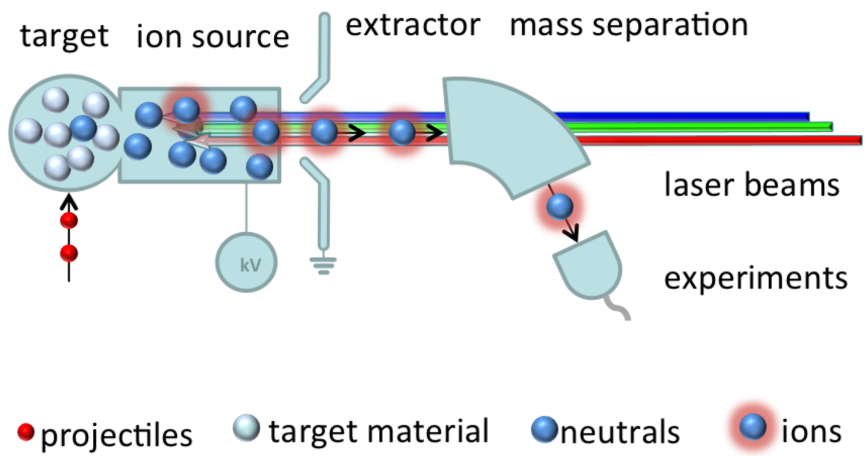


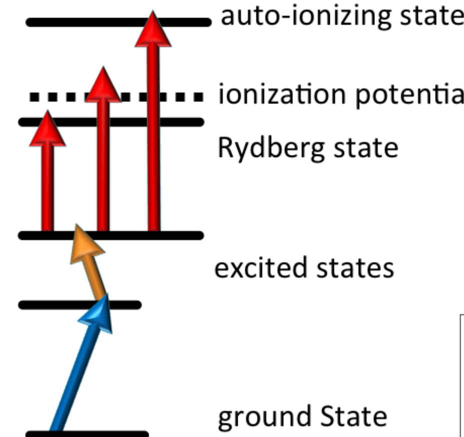
robots

Ion energy: 30-60keV

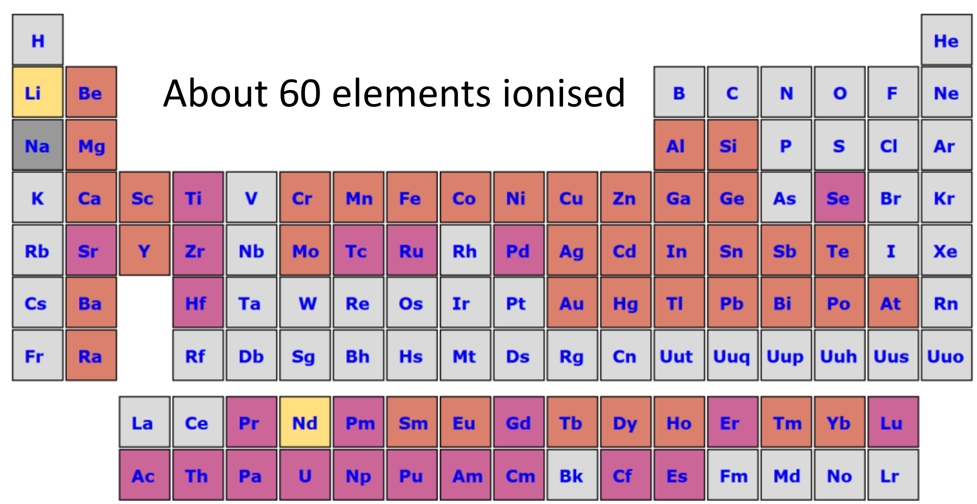
Ionization with lasers: RILIS

- Resonance Ionization Laser Ion Source
- Uses lasers to selectively ionize a particular element (isotope/isomer)



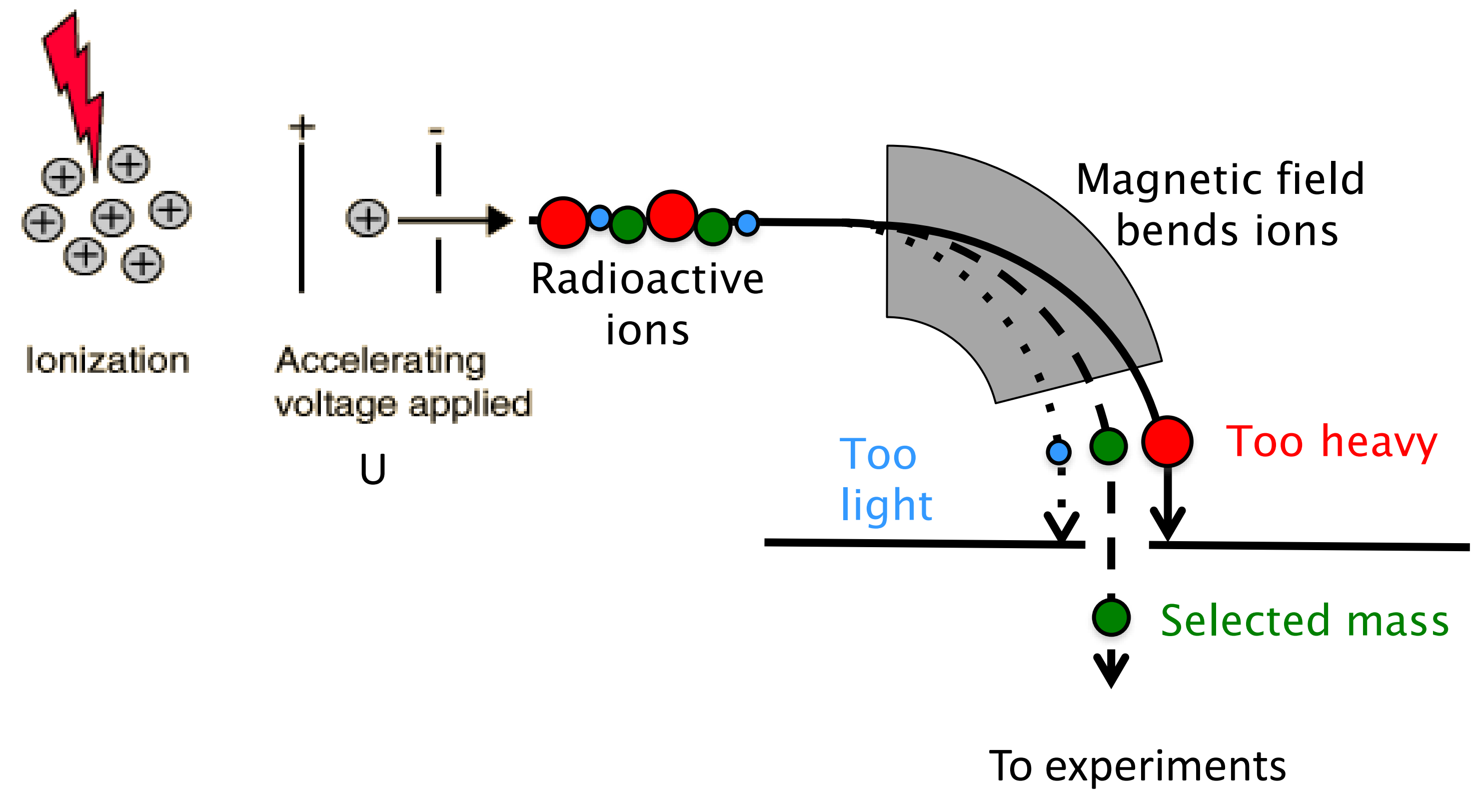


RILIS

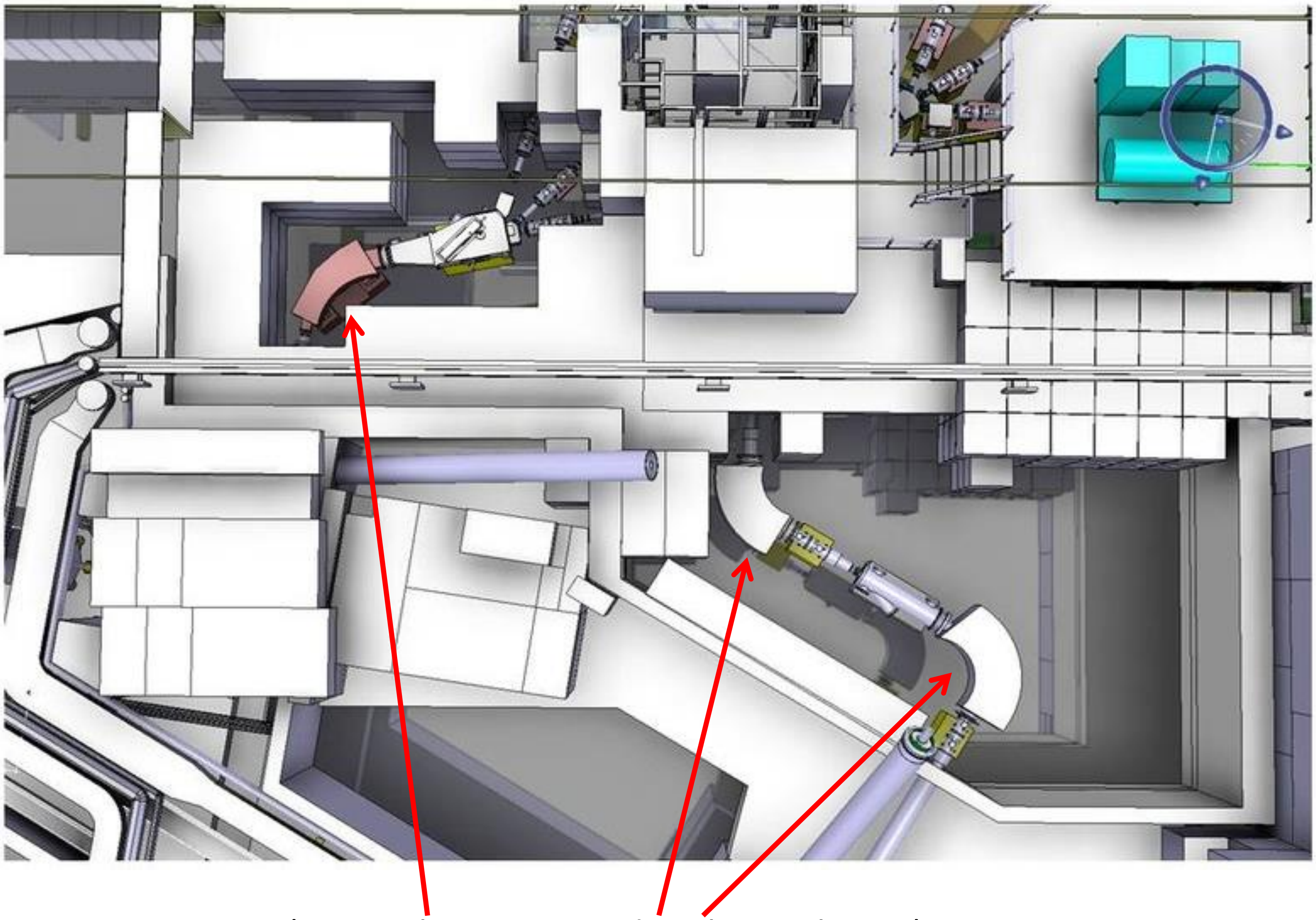


Beam extraction and separation

- All produced ions are extracted by electrostatic field (up to 60kV)
- The interesting nuclei are mass selected via magnetic field
  - Lorentz force: depends on velocity and mass
  - m/dm <5000, so many unwanted isobars also get to experiments



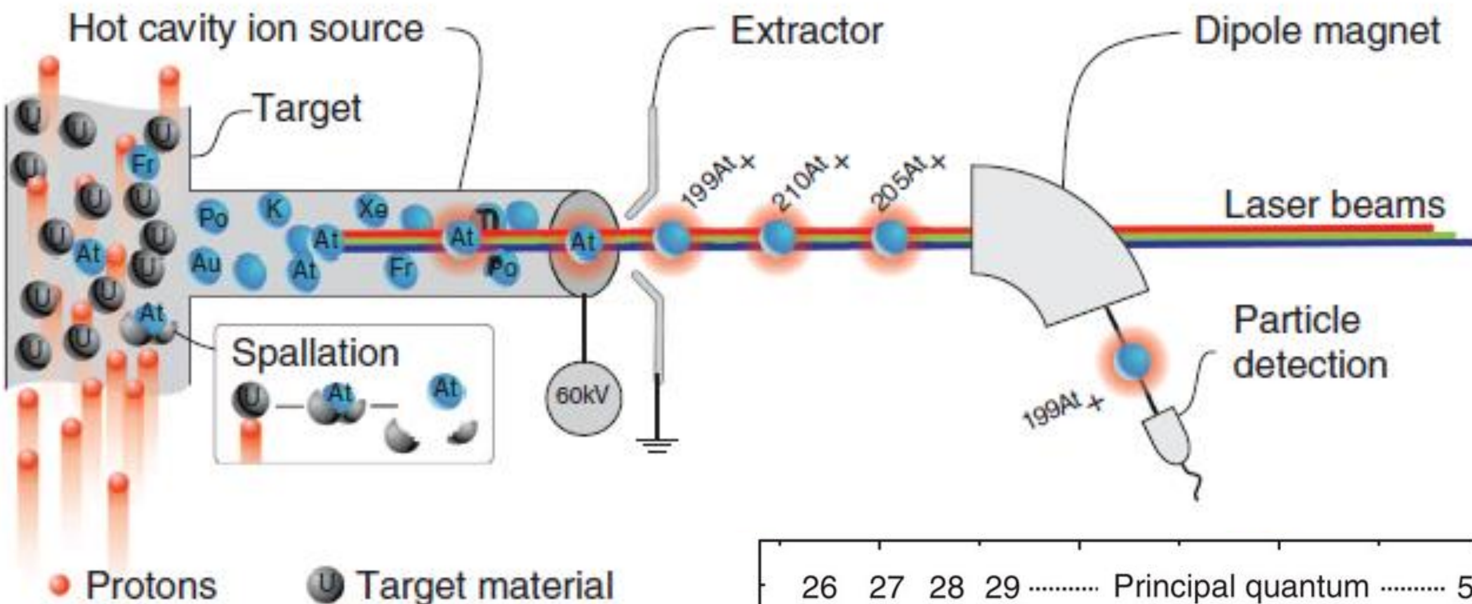
Separation



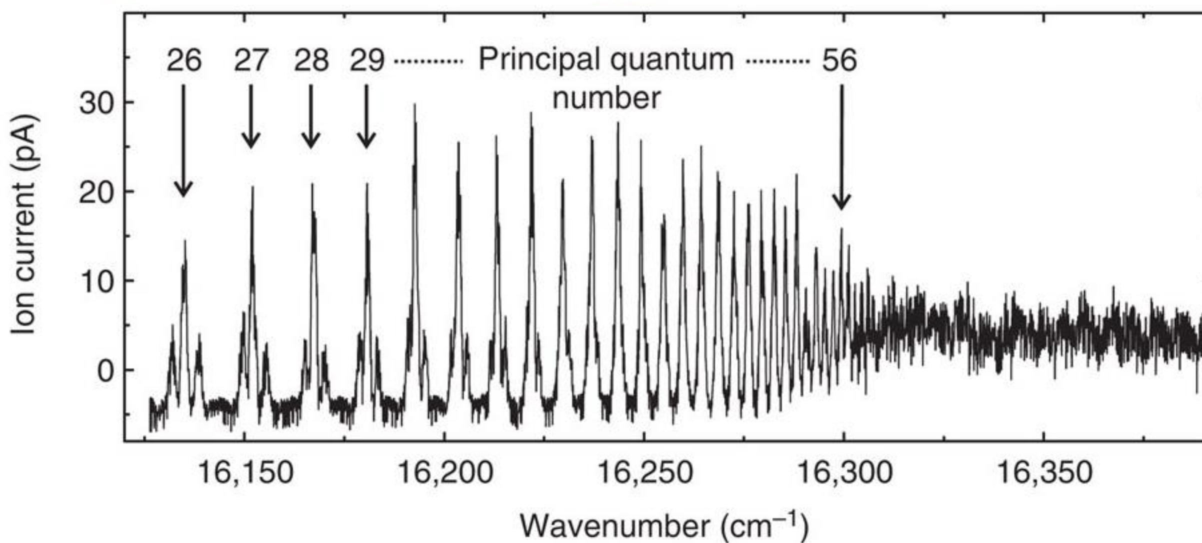
Magnet separators (General Purpose and High Resolution)

Example – astatine beams

- How to produce pure beams of astatine isotopes (all are radioactive)?
  - ➢ Use lasers to ionize them



➢ And determine
for the first time
the At ionization potential



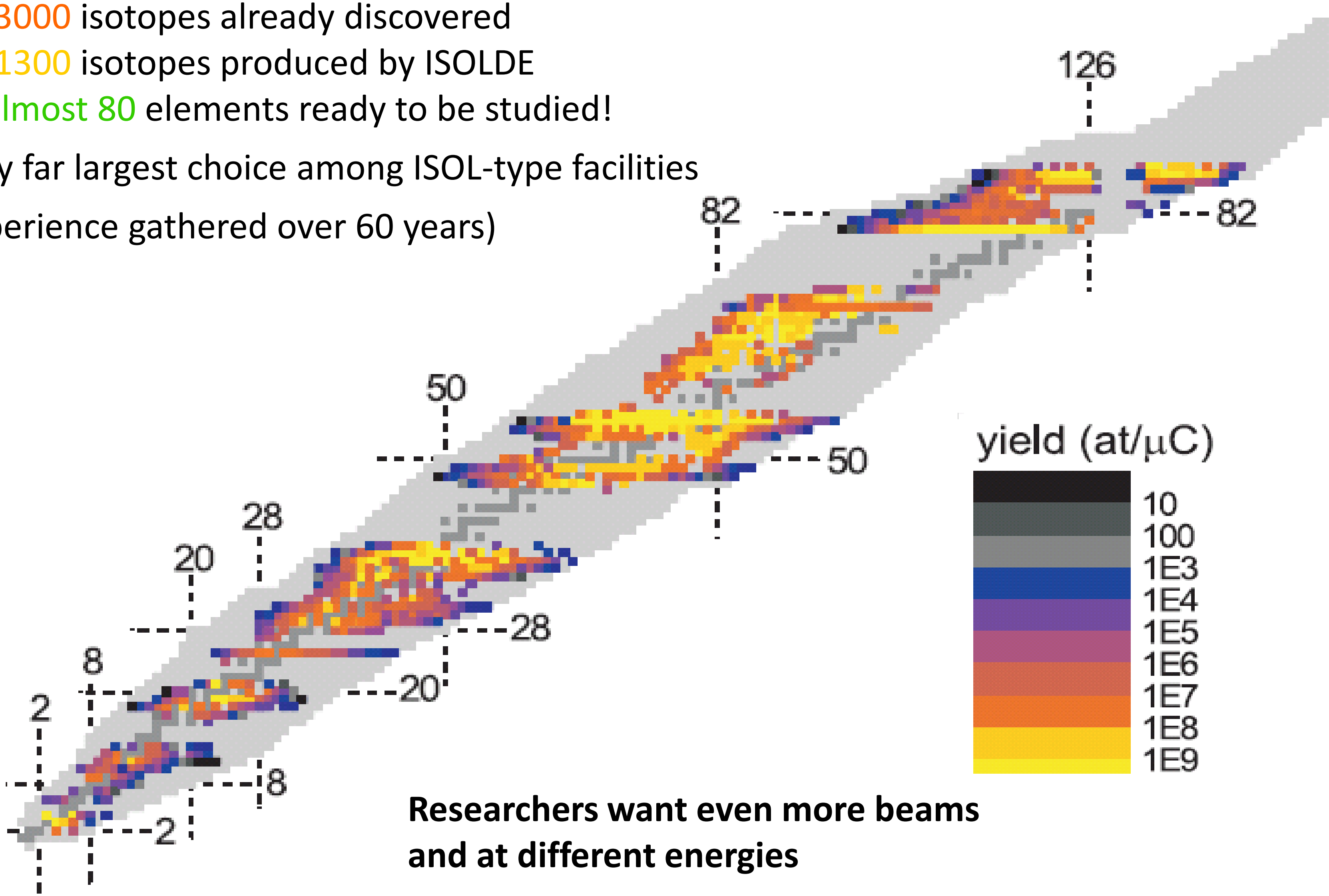
S. Rothe et al,
Nature Communications 4 (2013), 1835

Extracted nuclides

- ~6000 isotopes predicted by theory
- ~3000 isotopes already discovered
- ~1300 isotopes produced by ISOLDE
- almost 80 elements ready to be studied!

-> by far largest choice among ISOL-type facilities

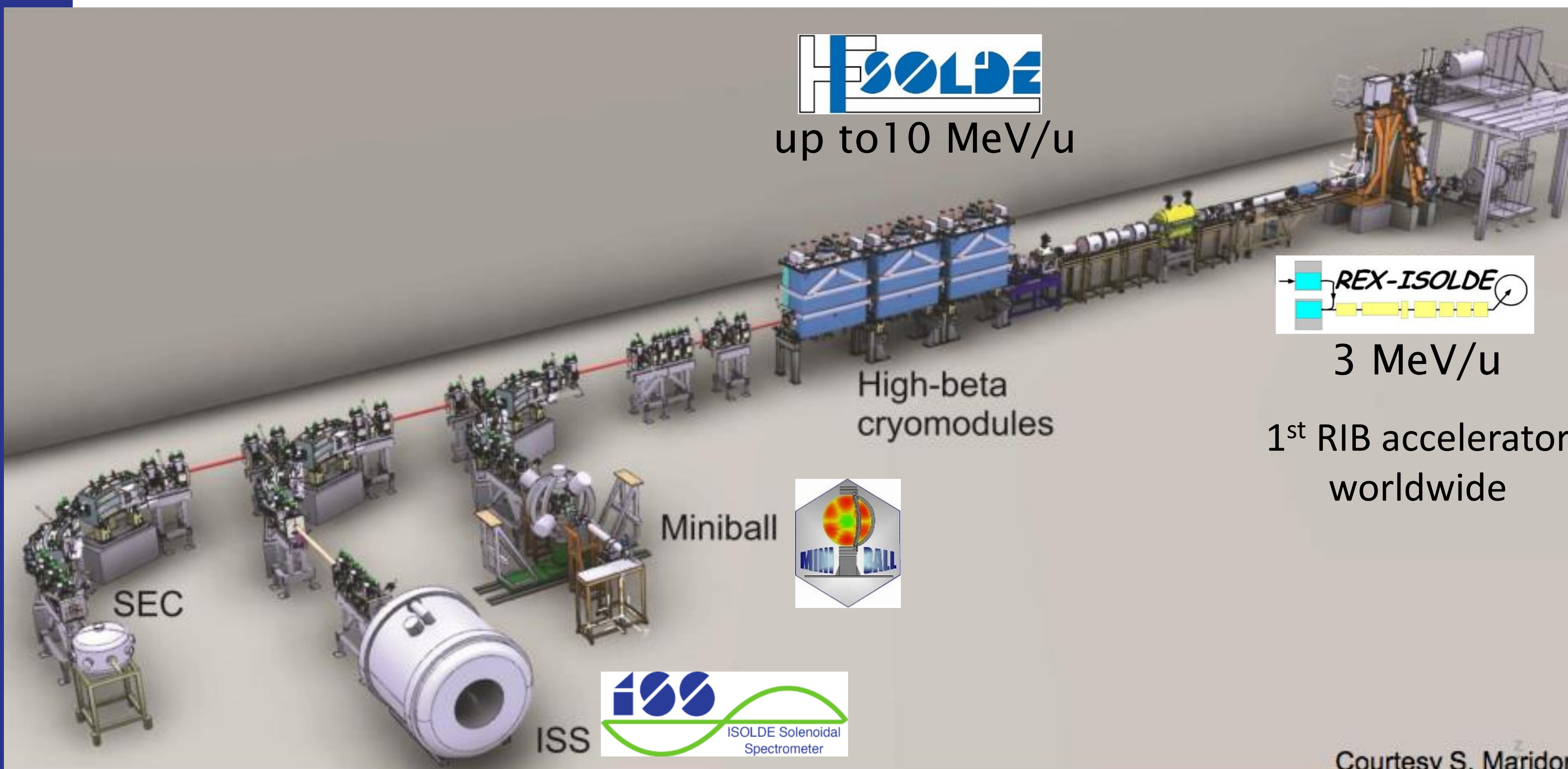
(experience gathered over 60 years)



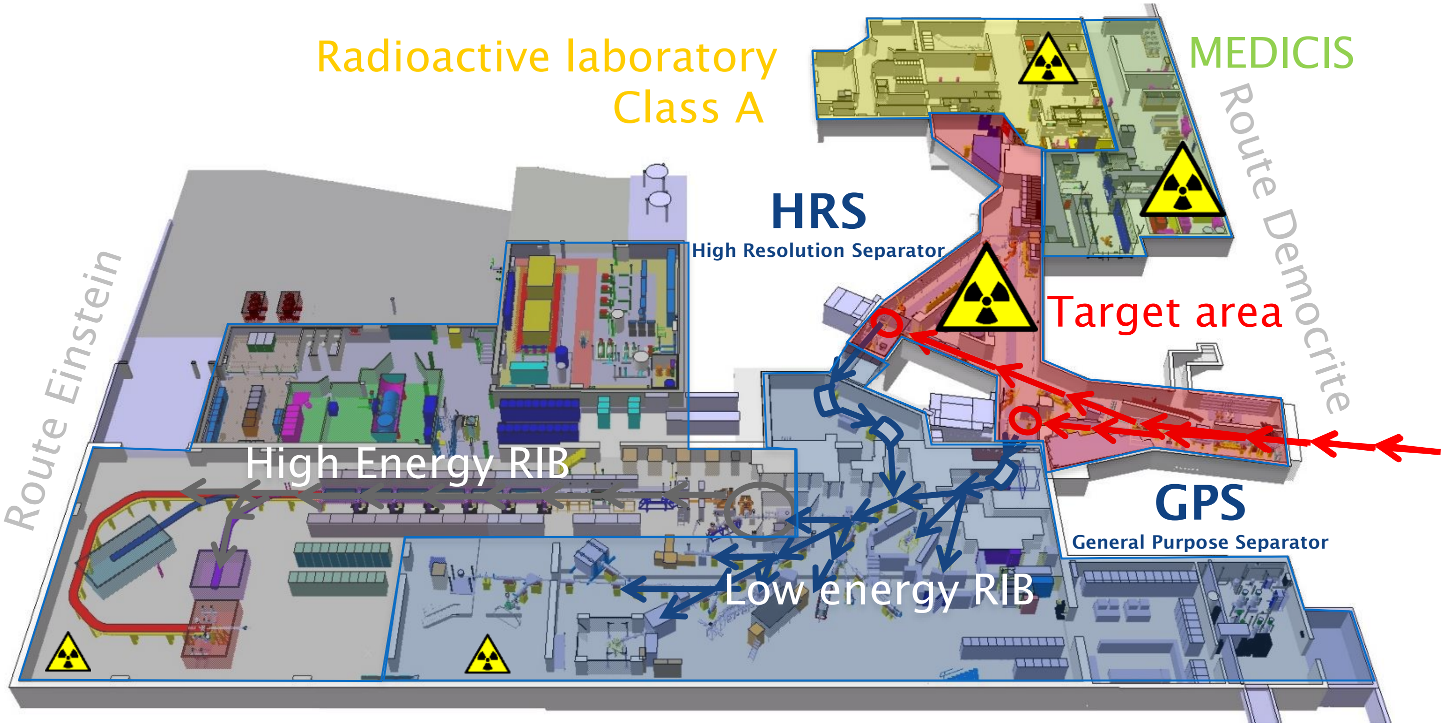
Researchers want even more beams and at different energies

Post-acceleration

- Low energy (<60 kV) beams can be accelerated up to 10 MeV / nucleon (i.e. 1.3 GeV for 132Sn or 2 GeV energy for ^{208}Pb)

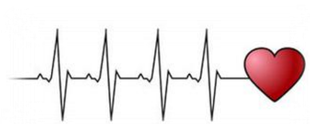


ISOLDE layout

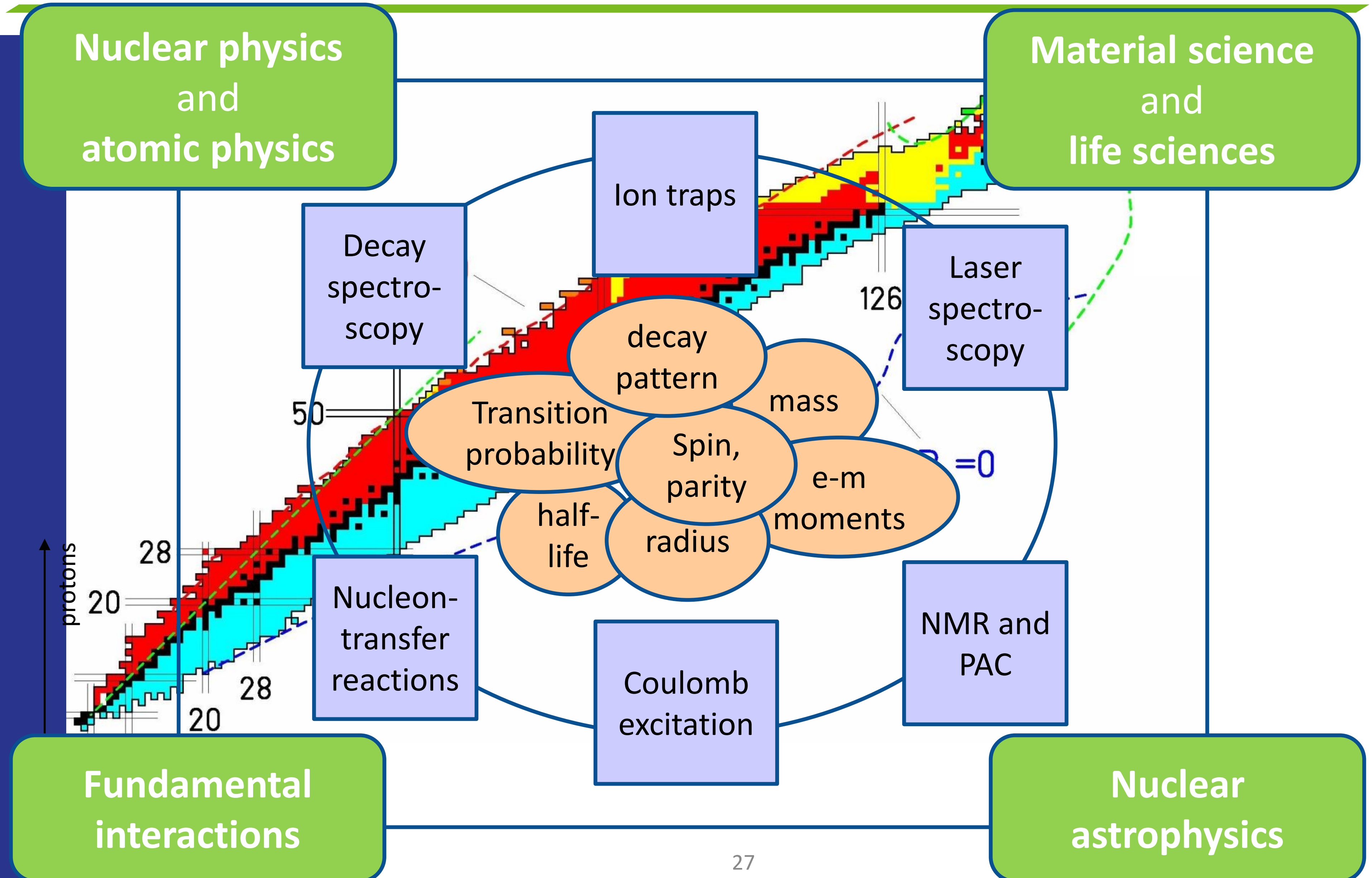


- Protons (1.4 GeV)
- Low energy RIBs (up tp 60 keV)
- High energy RIBs (up to 10 MeV/u)

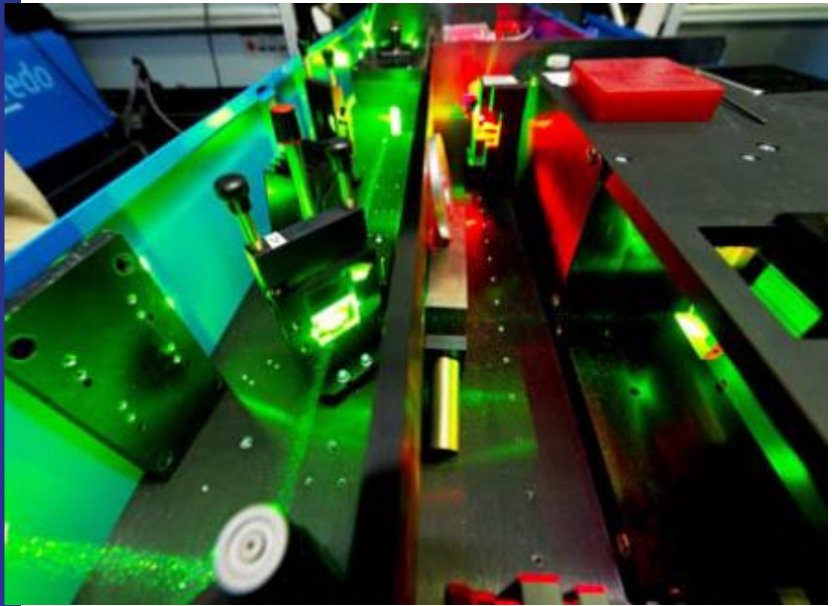
- Pulse protons (1.2 s)
- 1.4 GeV
- 3.3 x 1013 protons per pulse



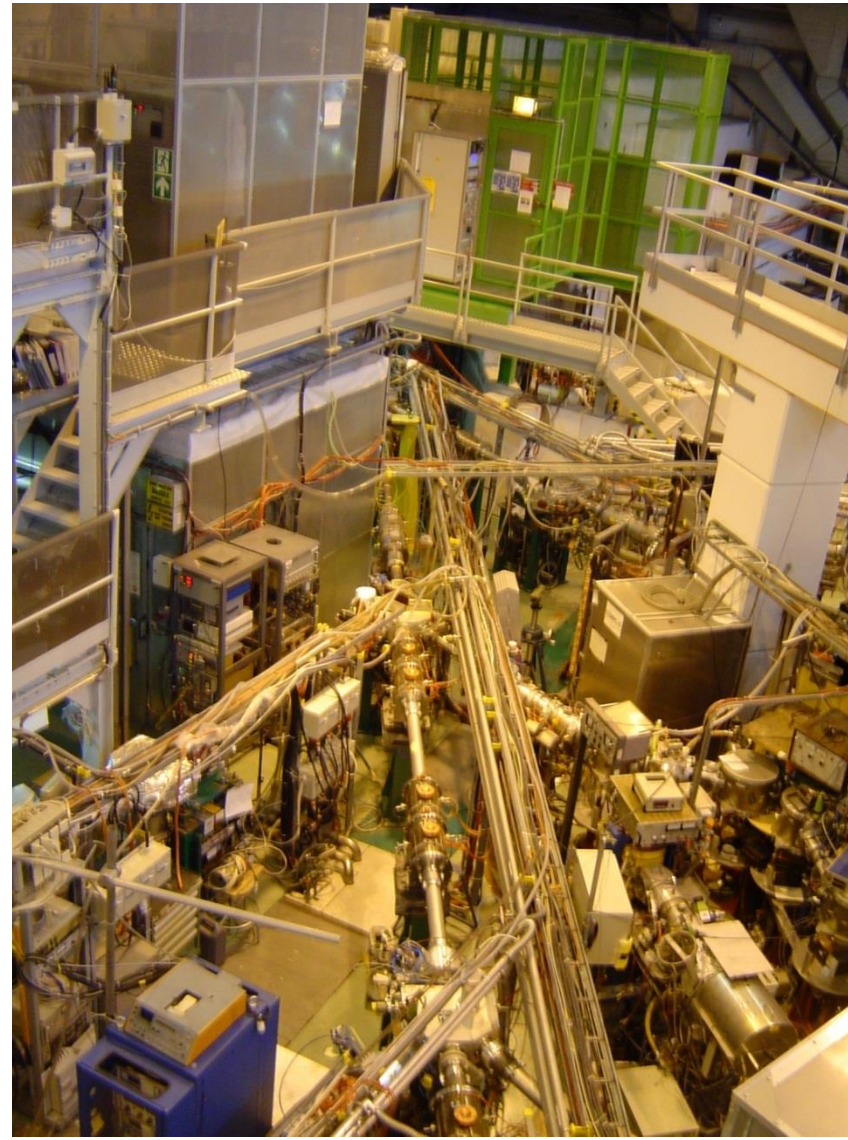
ISOLDE techniques and research topics



Facility photos



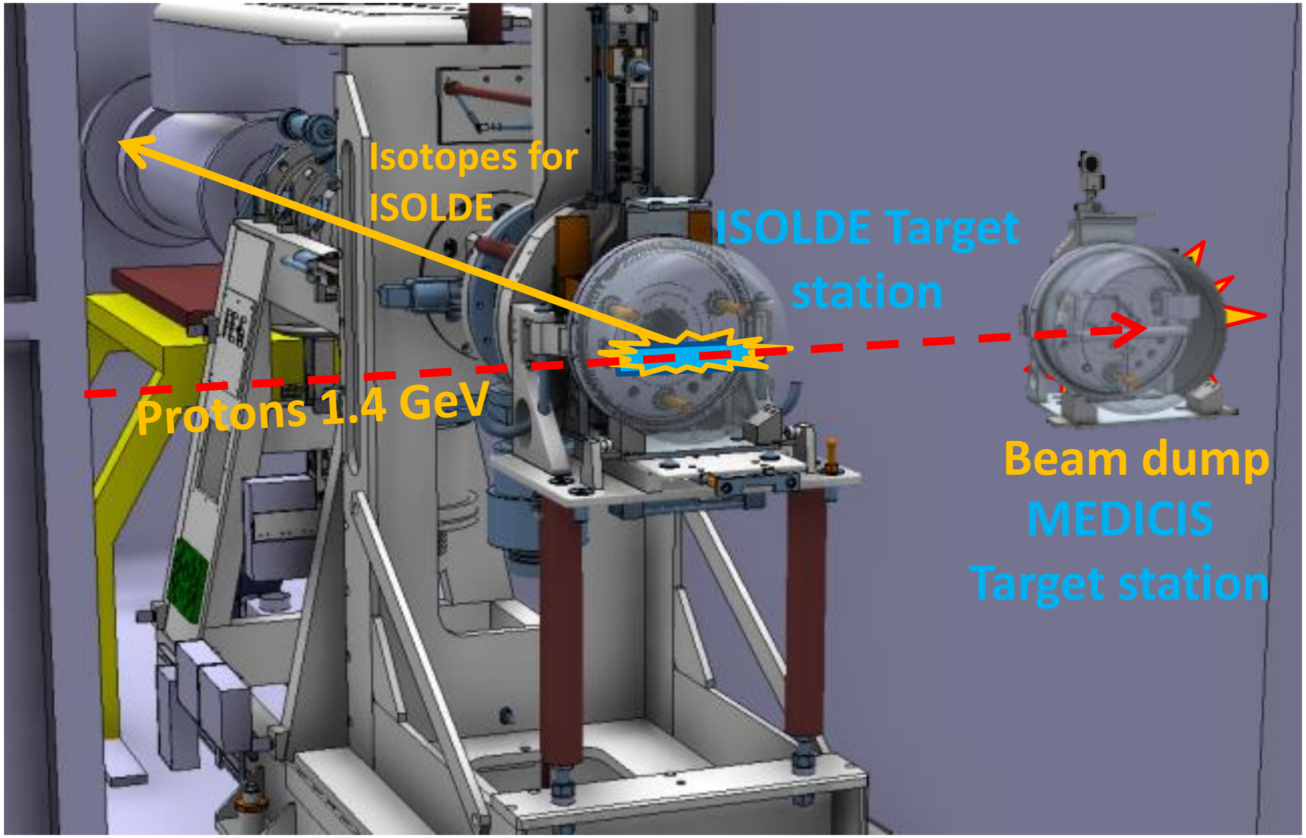
Experimental beamlines



Applications: MEDICIS at ISOLDE

Production of medical isotopes for trials (not commercial use) via ISOLDE "dump" protons

-> little ISOLDE + chemical preparation



Use protons (~90%) normally lost into the **Beam Dump**

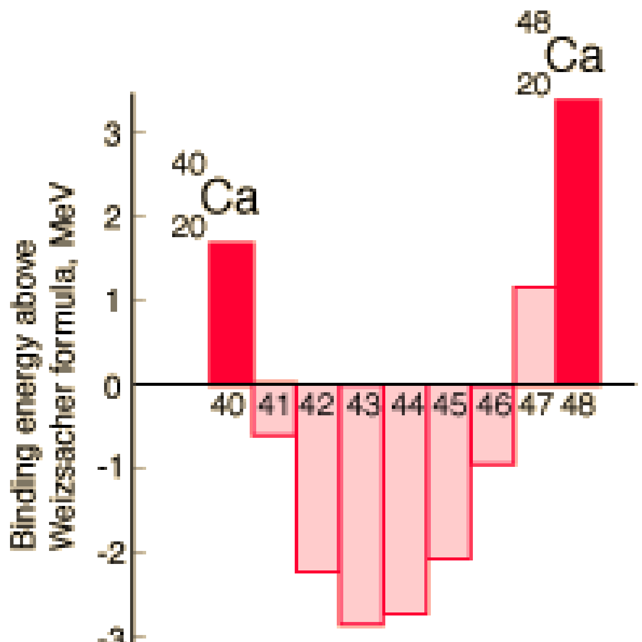
Summary

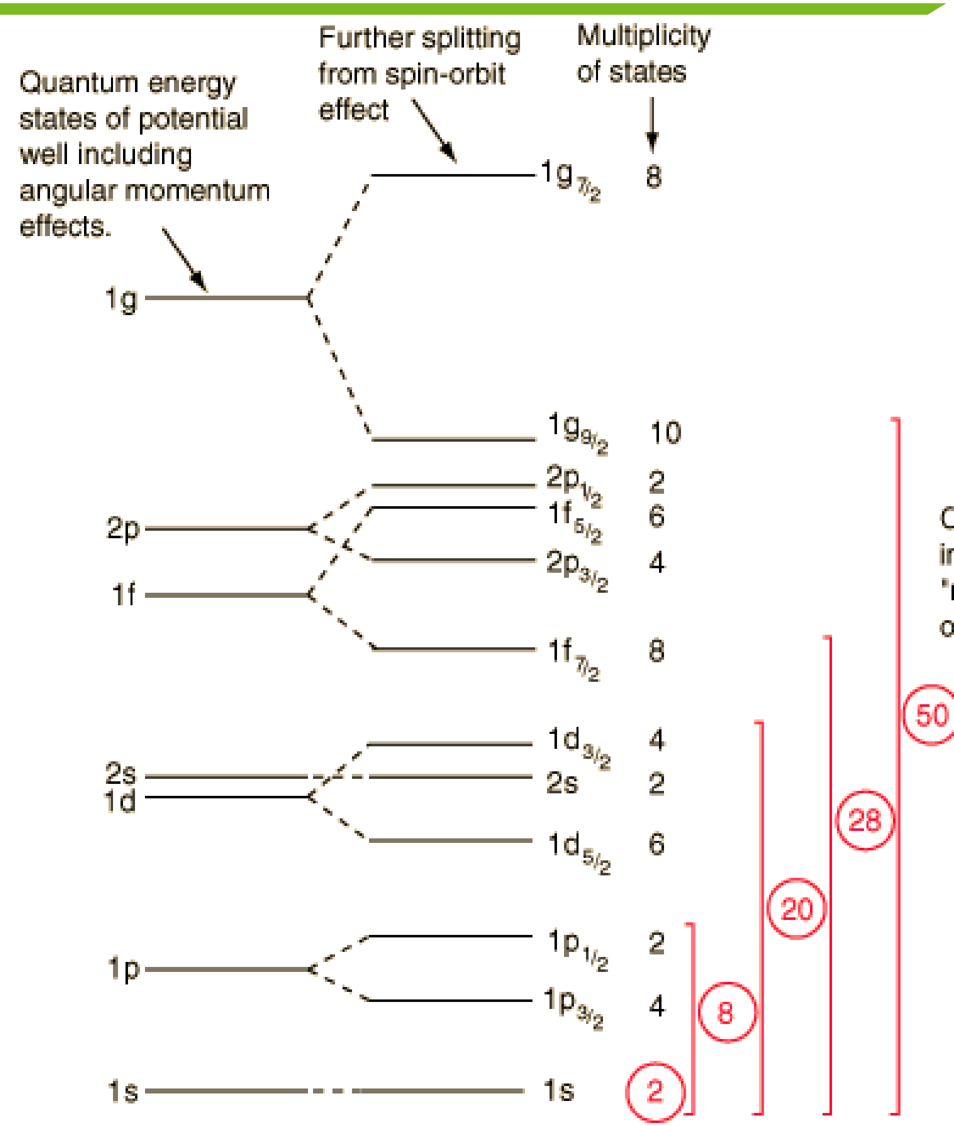
- Nuclear physics
  - deals with properties and interactions in atomic nuclei
- Addressed across CERN facilities
- ISOLDE at CERN
  - ISOL-type facility which uses protons from PSB
  - Elements: production target, ionization, extraction, separation
  - Largest variety of beams worldwide
  - Post-accelerator HIE-ISOLDE
  - Medical isotopes with MEDICIS

  - **ISOLDE research topics => Lecture 2**

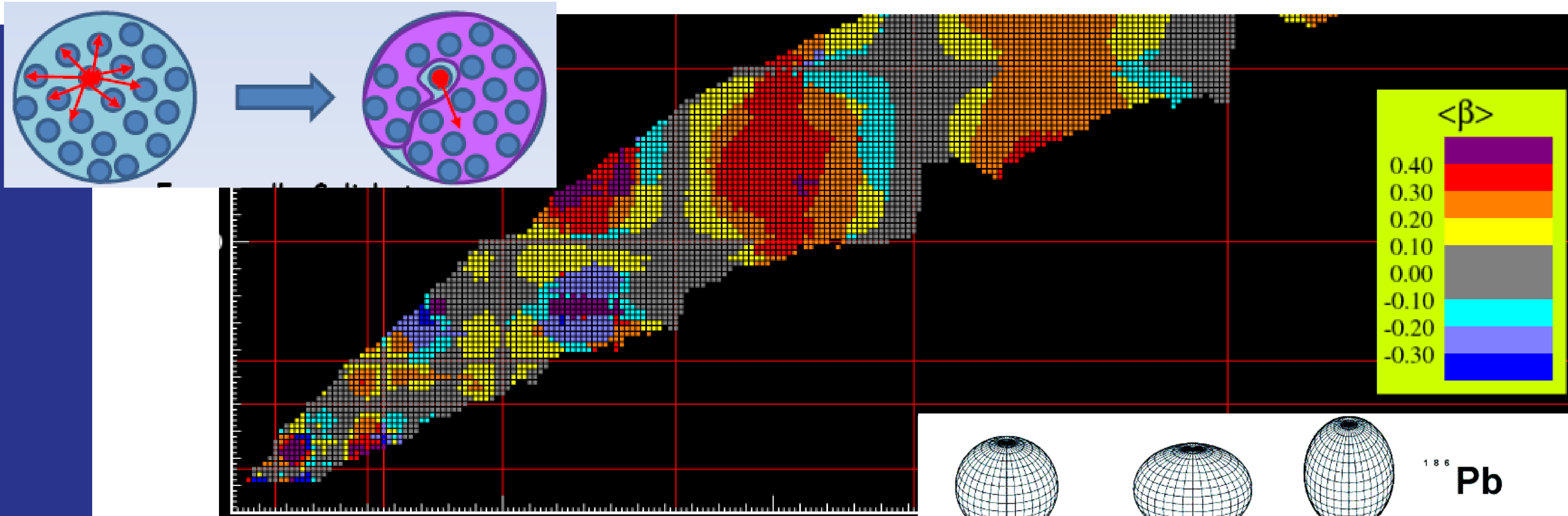
Nuclear shell model

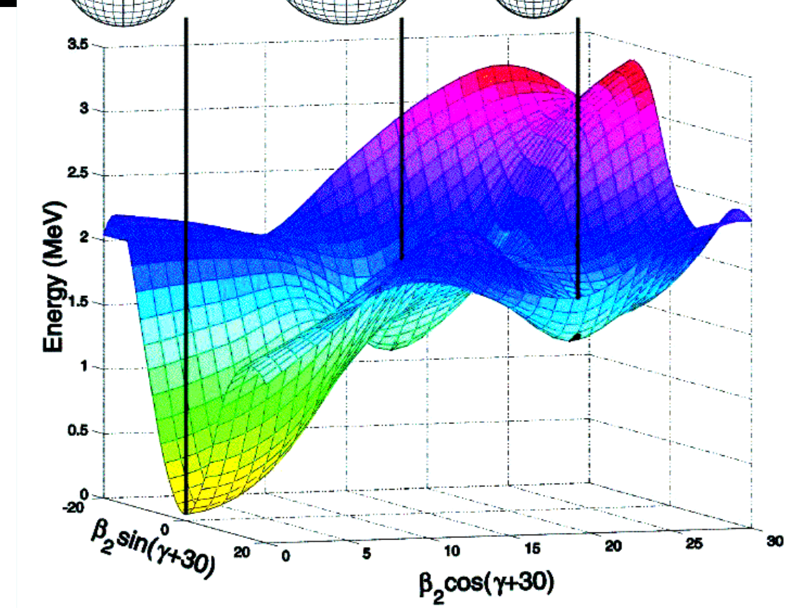
- Created in analogy to the atomic shell model (electrons orbiting a nucleus)
- Based on the observation of higher stability of certain nuclei
  - filled shell of neutrons or protons results in greater stability
  - neutron and proton numbers corresponding to a closed shell are called ‘magic‘
- Nuclei move in a self-created potential





Mean-field models





- Each particle interacts with an average field generated by all other particles: mean field
- Mean field is built from individual excitations between nucleons
- No inert core
- Very good at describing deformations
- Can predict properties of very exotic nuclei
- Not so good at closed shells