

GNU-Radio based SDRs for isotopic and isomeric mass and lifetime measurements in heavy ion storage rings

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GNU Radio Days 2024

GSI / FAIR Darmstadt



Reaching to the stars using...

... GNURadio!

Elements

- Isotopic abundance
 - Key to stellar evolution

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	* 71 Lu	* 72 Hf	* 73 Ta	* 74 W	* 75 Re	* 76 Os	* 77 Ir	* 78 Pt	* 79 Au	* 80 Hg	* 81 Tl	* 82 Pb	* 83 Bi	* 84 Po	* 85 At	* 86 Rn
7	87 Fr	88 Ra	* 103 Lr	* 104 Rf	* 105 Db	* 106 Sg	* 107 Bh	* 108 Hs	* 109 Mt	* 110 Ds	* 111 Rg	* 112 Cn	* 113 Nh	* 114 Fl	* 115 Mc	* 116 Lv	* 117 Ts	* 118 Og
			* 57 La	* 58 Ce	* 59 Pr	* 60 Nd	* 61 Pm	* 62 Sm	* 63 Eu	* 64 Gd	* 65 Tb	* 66 Dy	* 67 Ho	* 68 Er	* 69 Tm	* 70 Yb		
			* 89 Ac	* 90 Th	* 91 Pa	* 92 U	* 93 Np	* 94 Pu	* 95 Am	* 96 Cm	* 97 Bk	* 98 Cf	* 99 Es	* 100 Fm	* 101 Md	* 102 No		

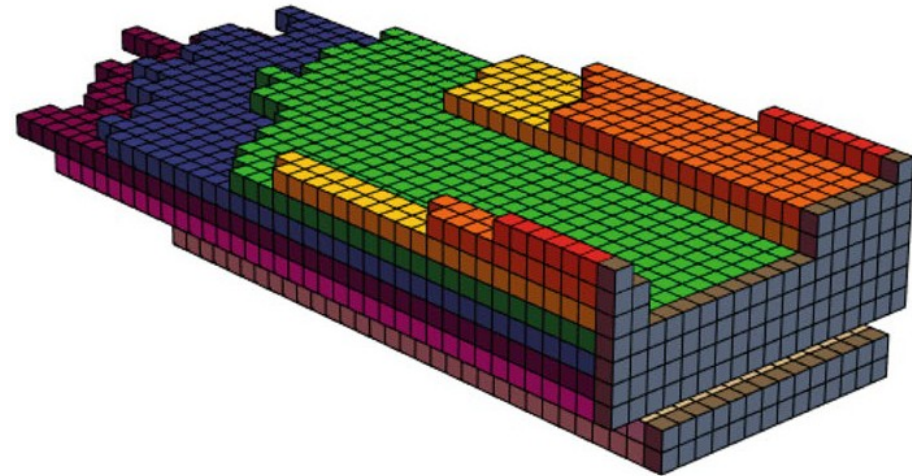
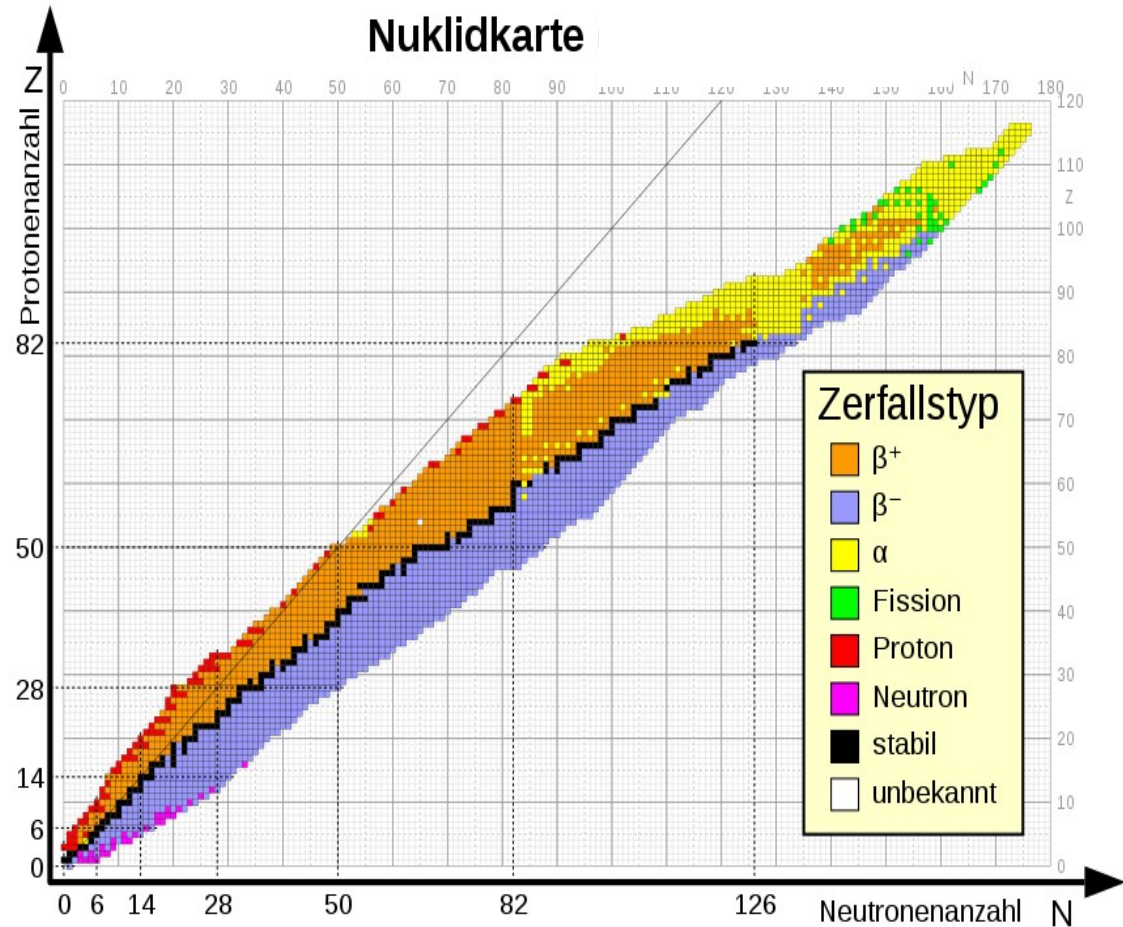


Image: Francl, M. Isotopic enrichment. Nature Chem 11, 101–102 (2019)

Elements

- More complete picture:
 - Nuclear chart

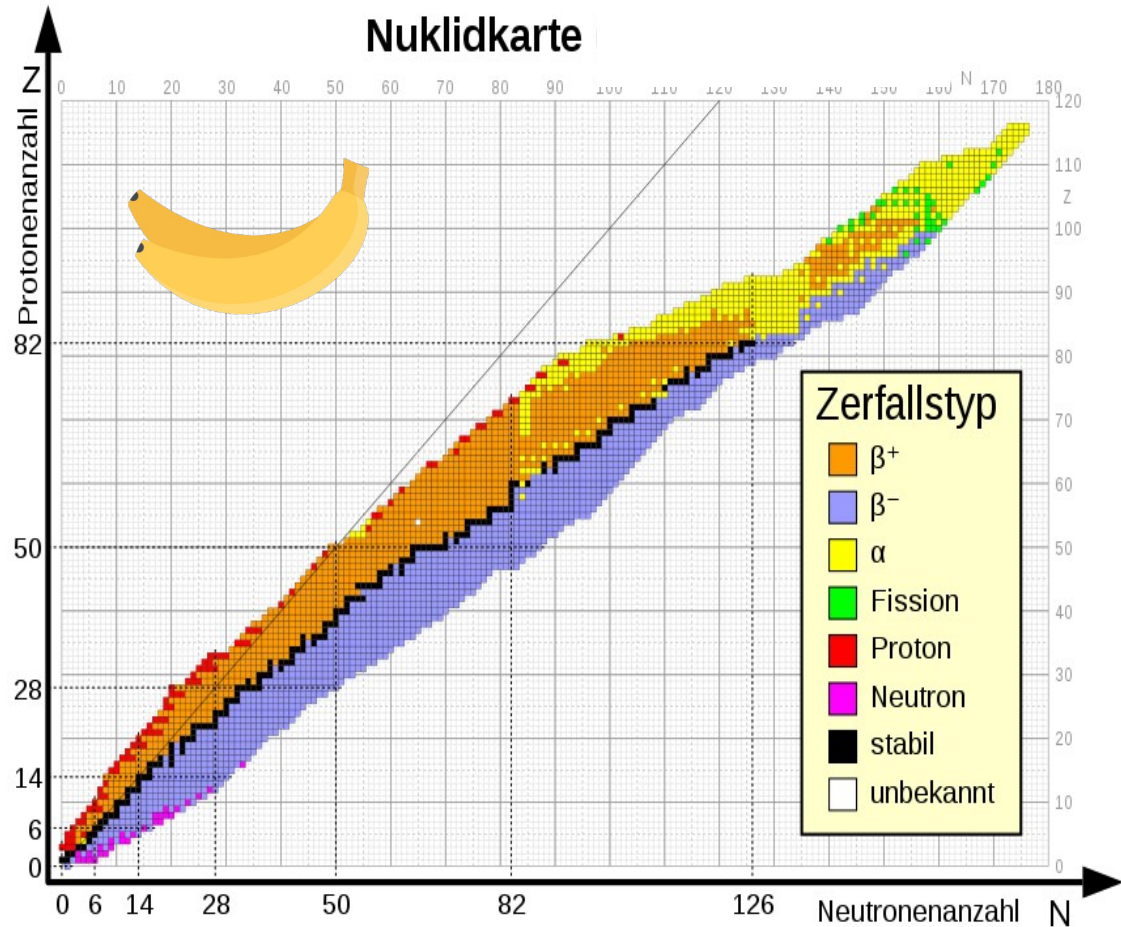


App:
Isotope
Browser



Elements

- More complete picture:
 - Nuclear chart

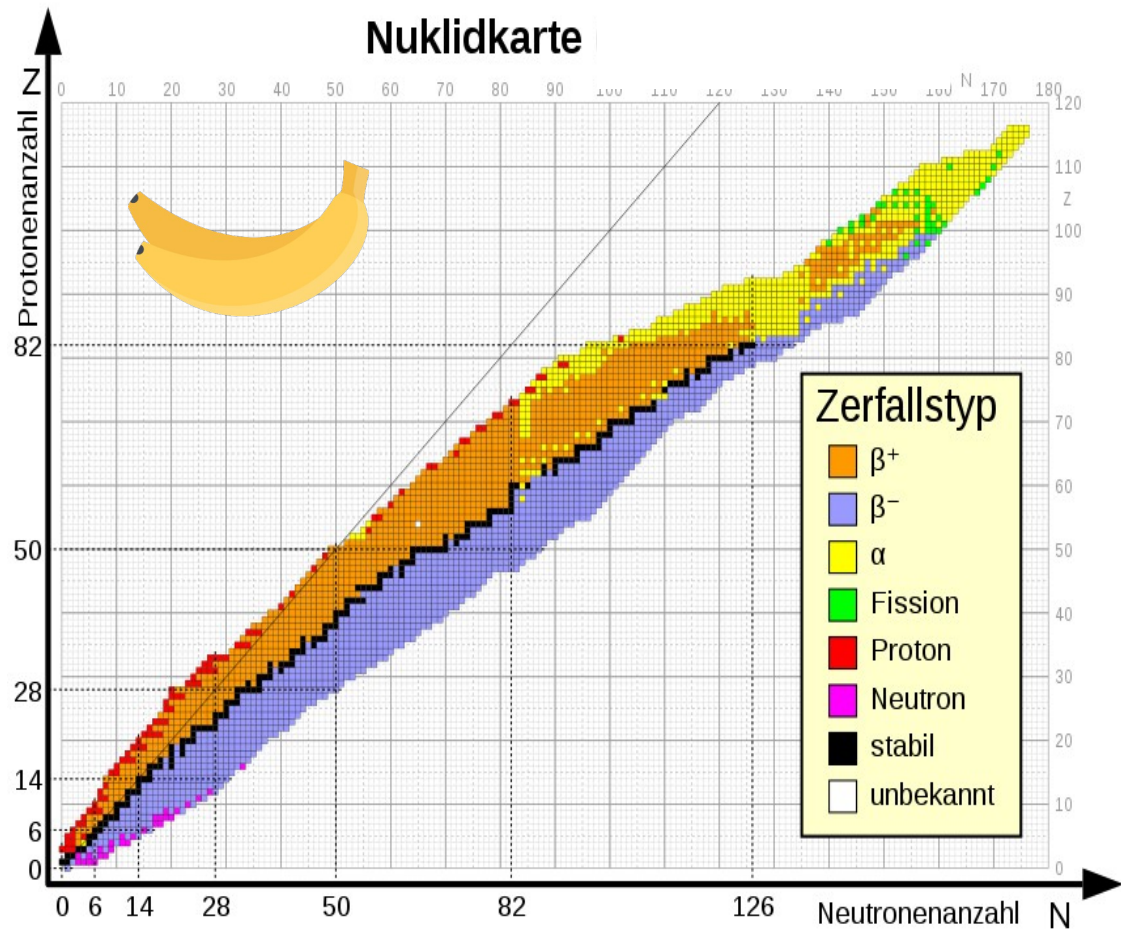


App:
Isotope
Browser



Elements

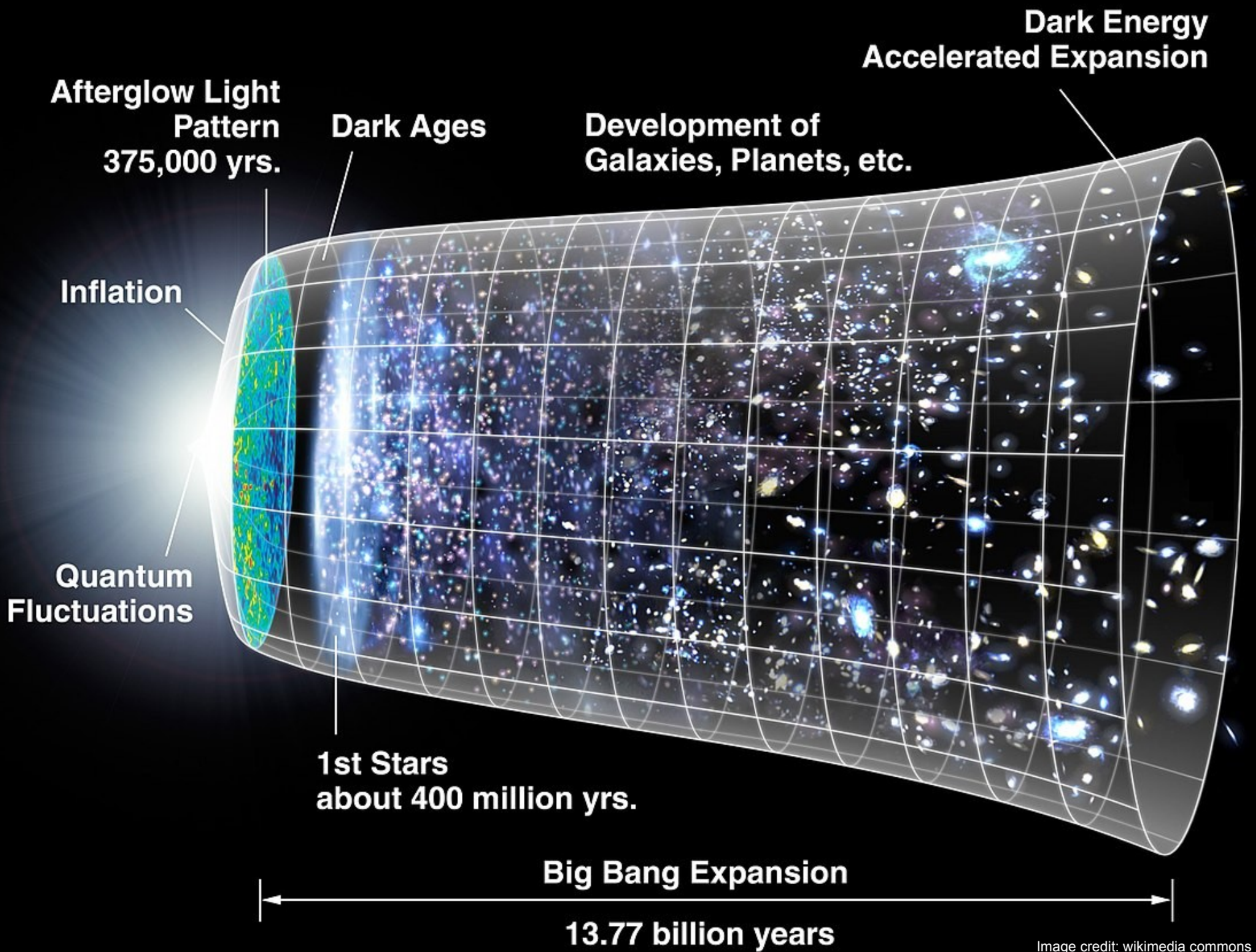
- More complete picture:
 - Nuclear chart

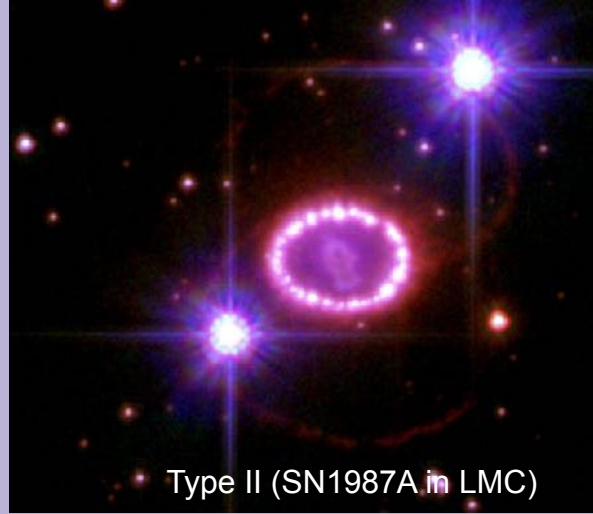
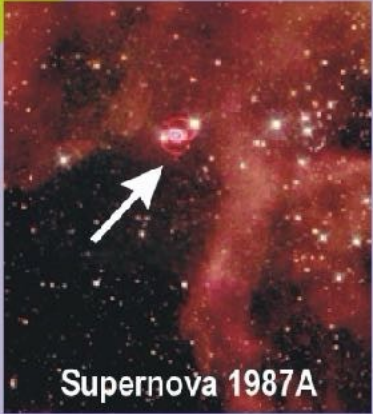
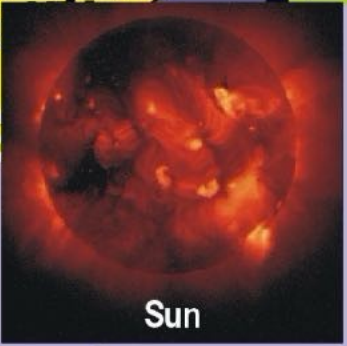
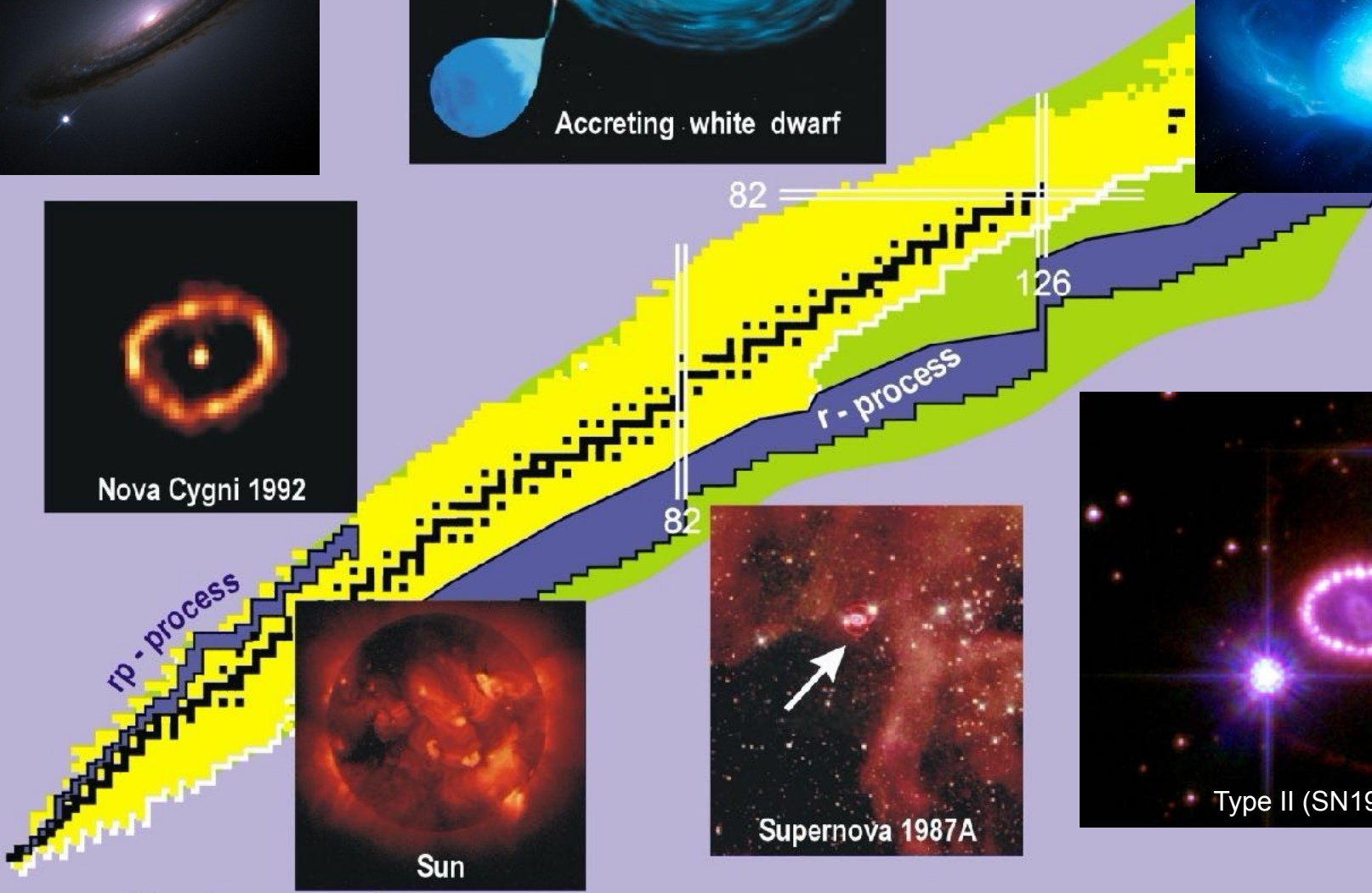
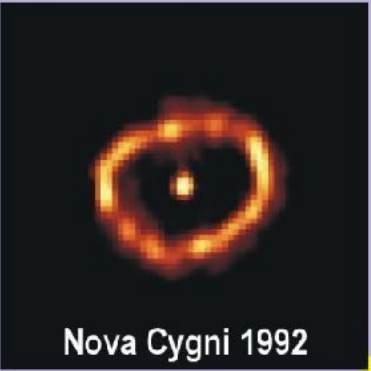
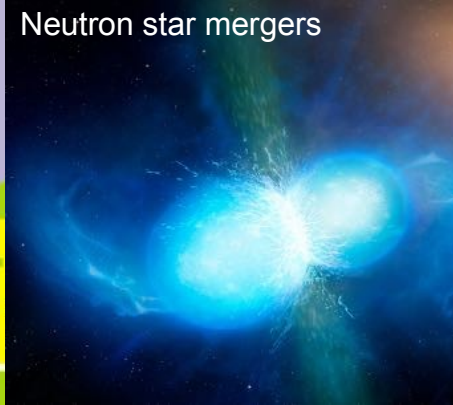
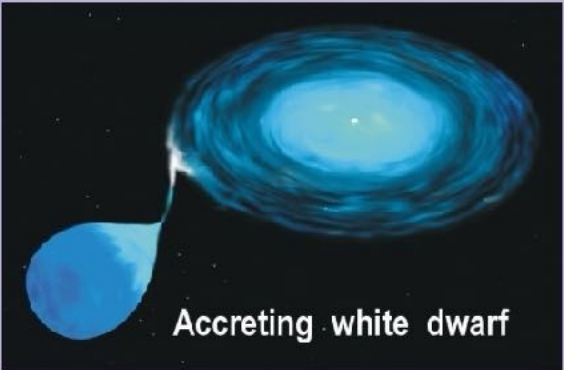
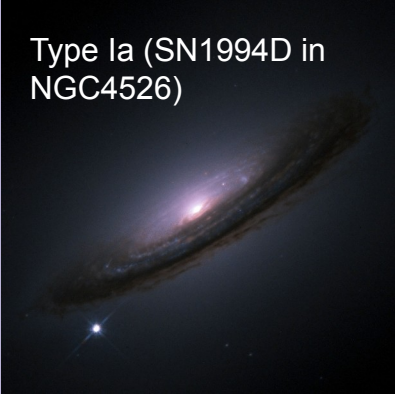


App:
Isotope
Browser



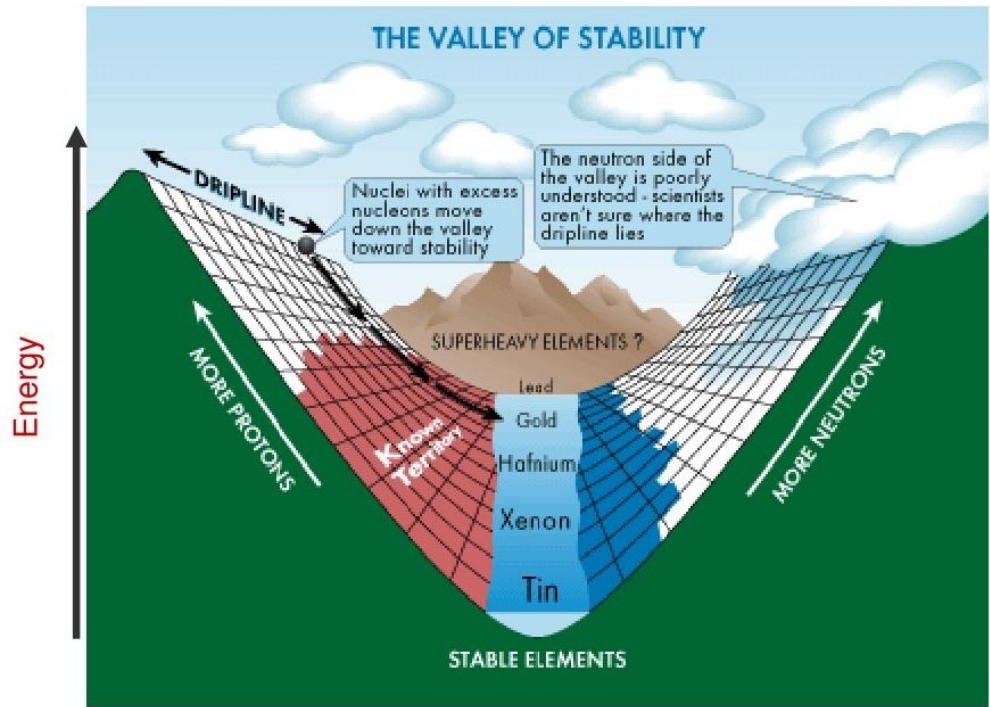
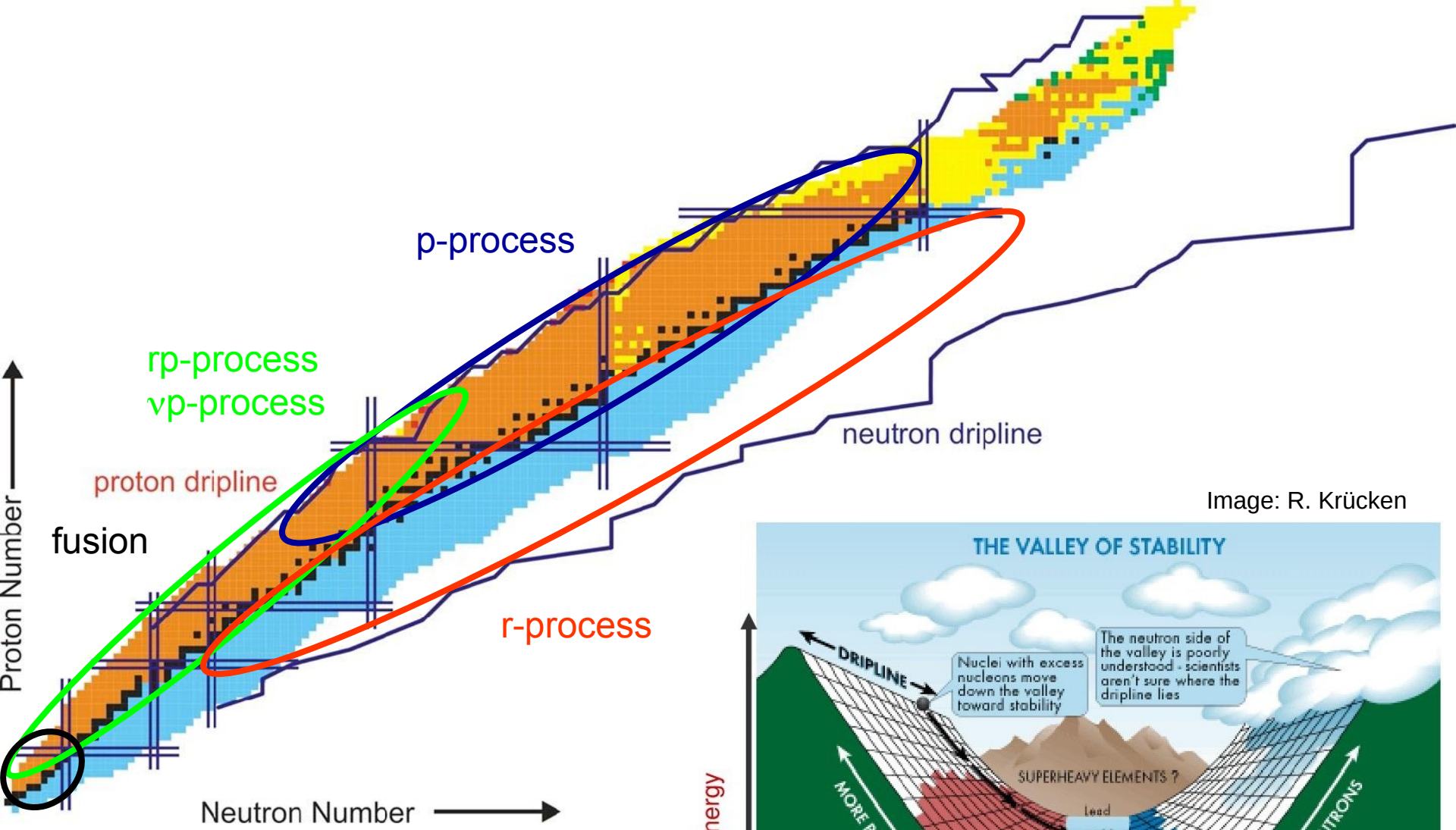
But where do elements come from?





↑ Proton number

→ Neutron number



- As if trying to climb using unstable holds!
- Among important experimental data:
 - nuclear mass
 - reaction cross sections
 - lifetime (from μs to Gy)

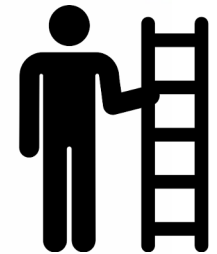
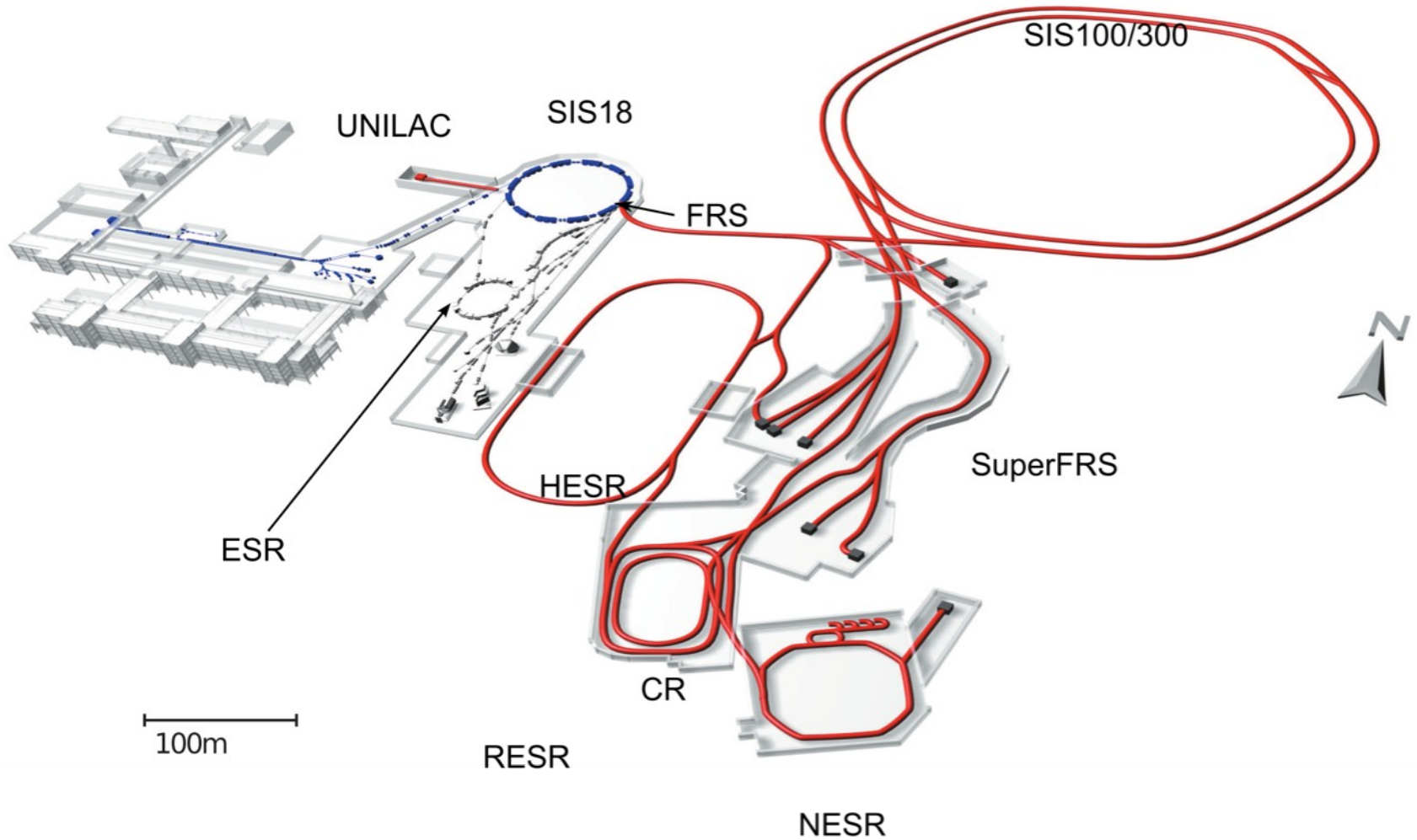


Image: wikimedia commons

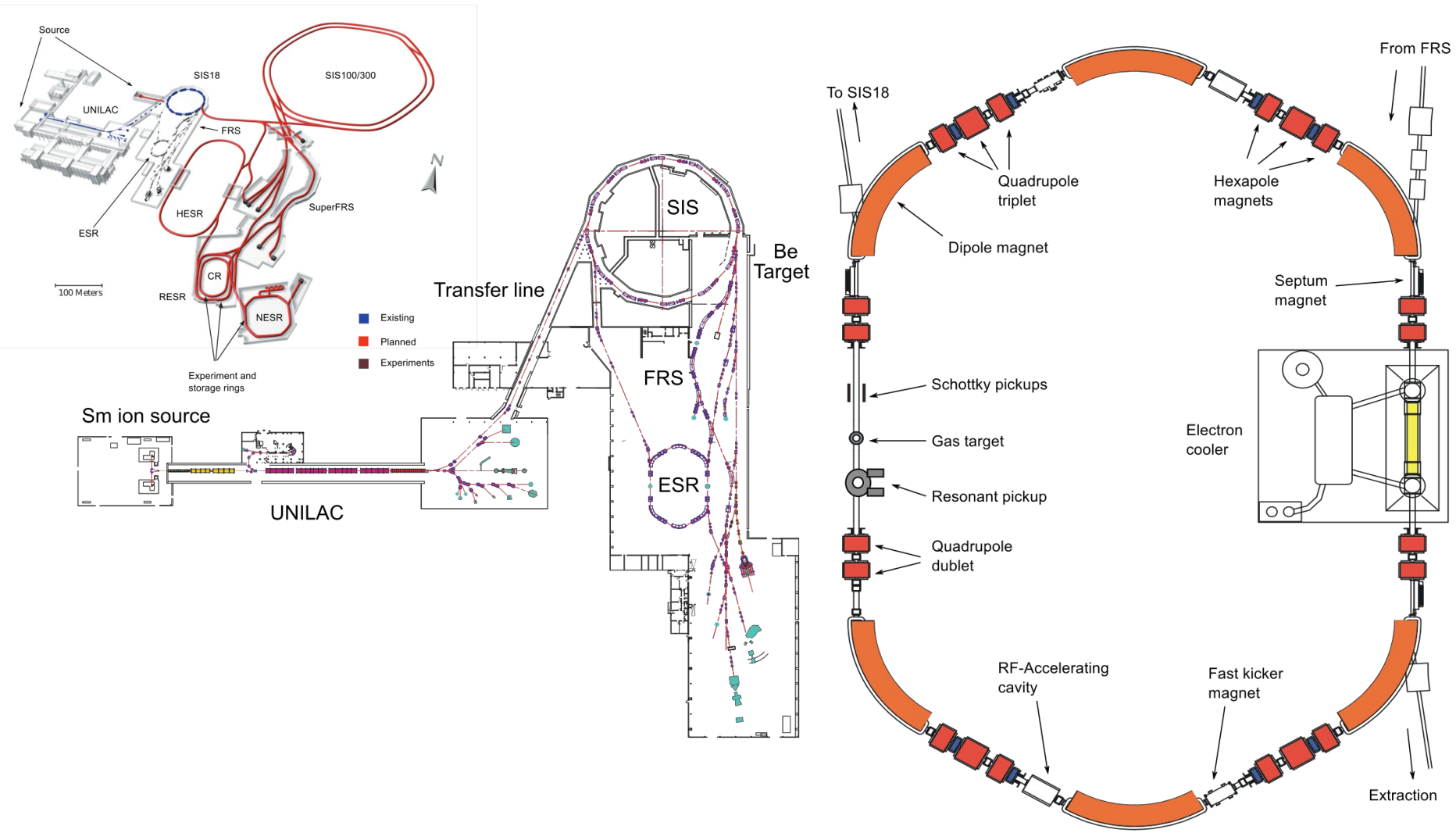




GSI and FAIR



Schottky detectors @ GSI



Schottky detectors

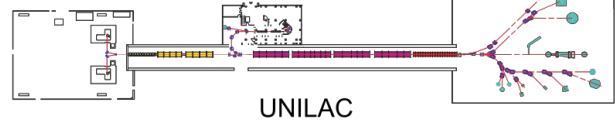
B. Schlitt, PhD Thesis 1997



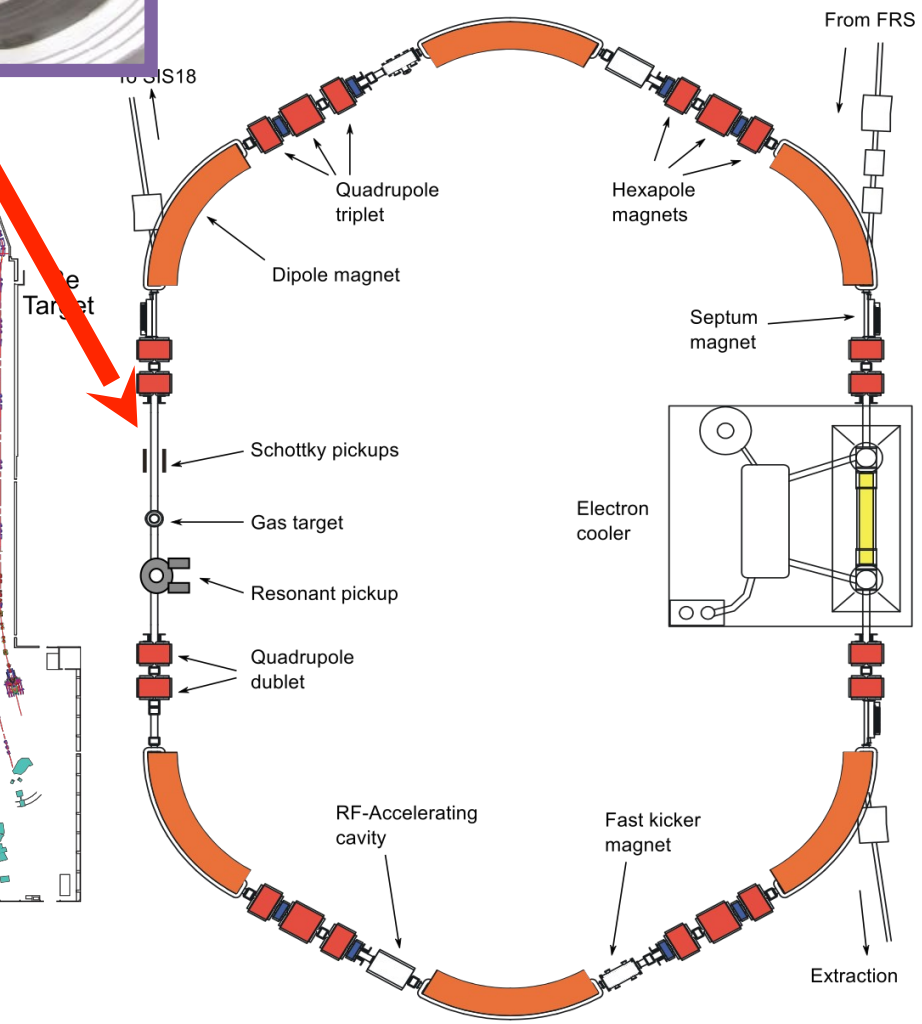
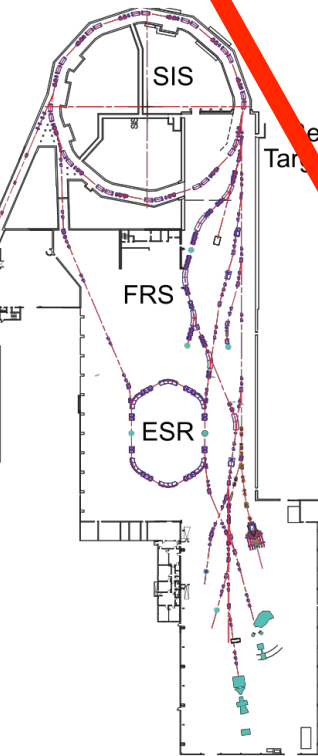
60 MHz



Sm ion source



Transfer line

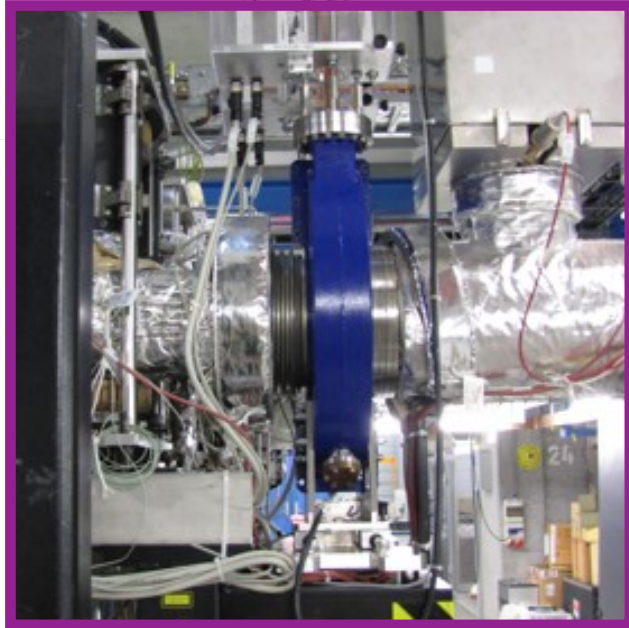
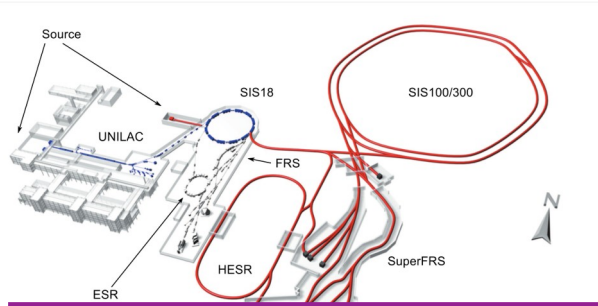


Schottky detectors

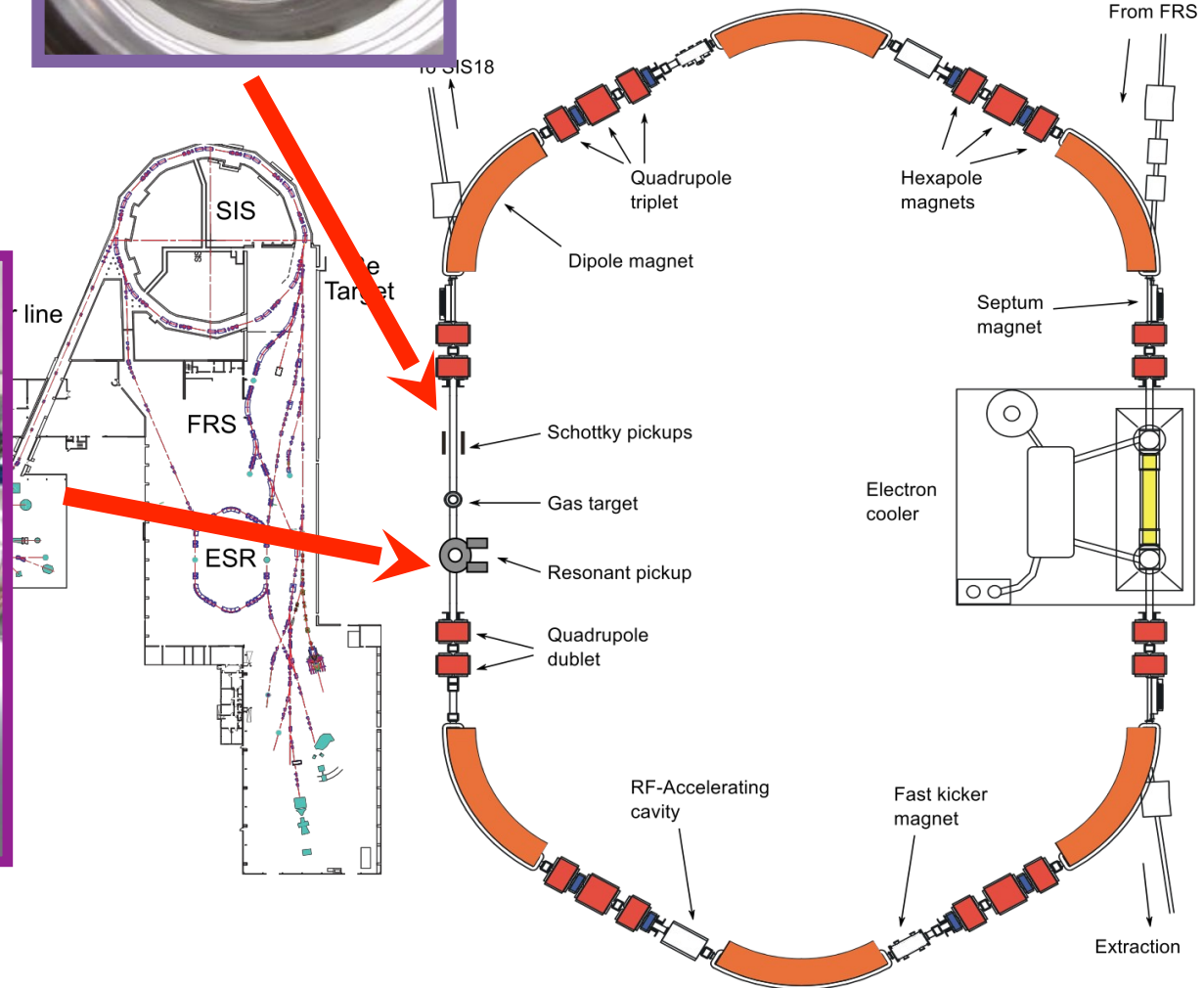
B. Schlitt, PhD Thesis 1997



60 MHz



245 MHz



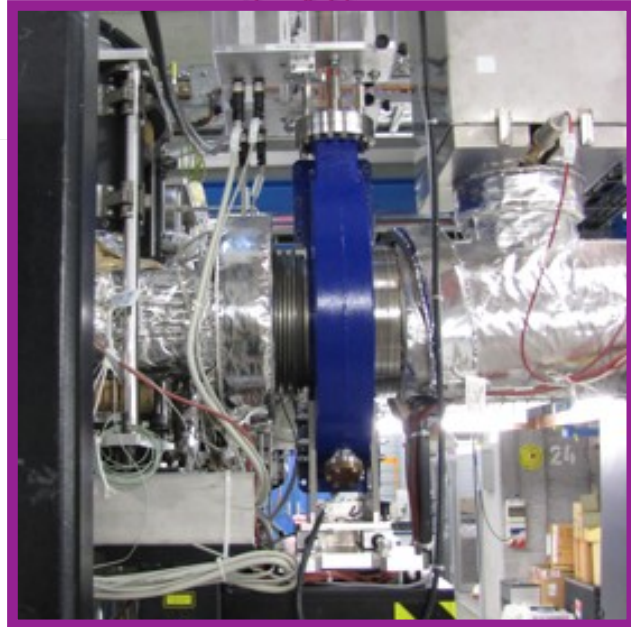
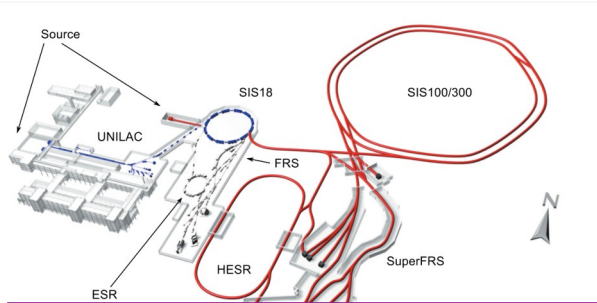
Sanjari et. al. Phys. Scr. 014088 (2013)

Schottky detectors

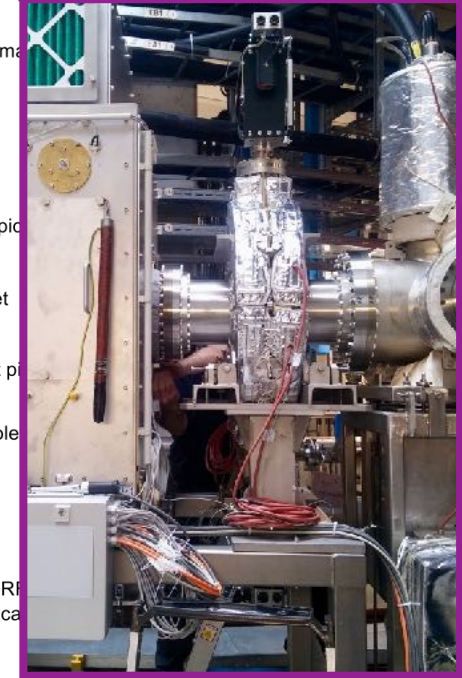
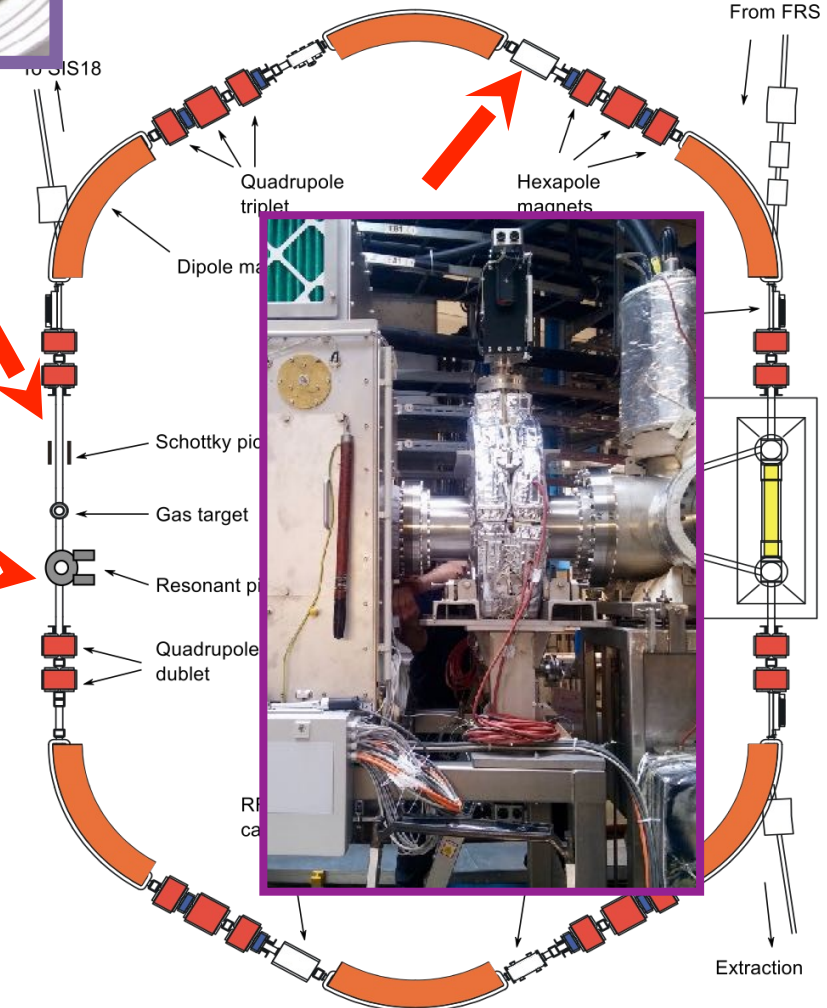
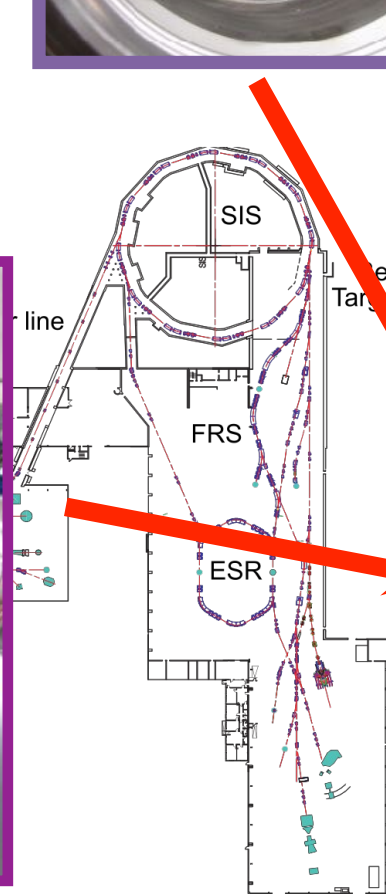
B. Schlitt, PhD Thesis 1997



60 MHz



245 MHz

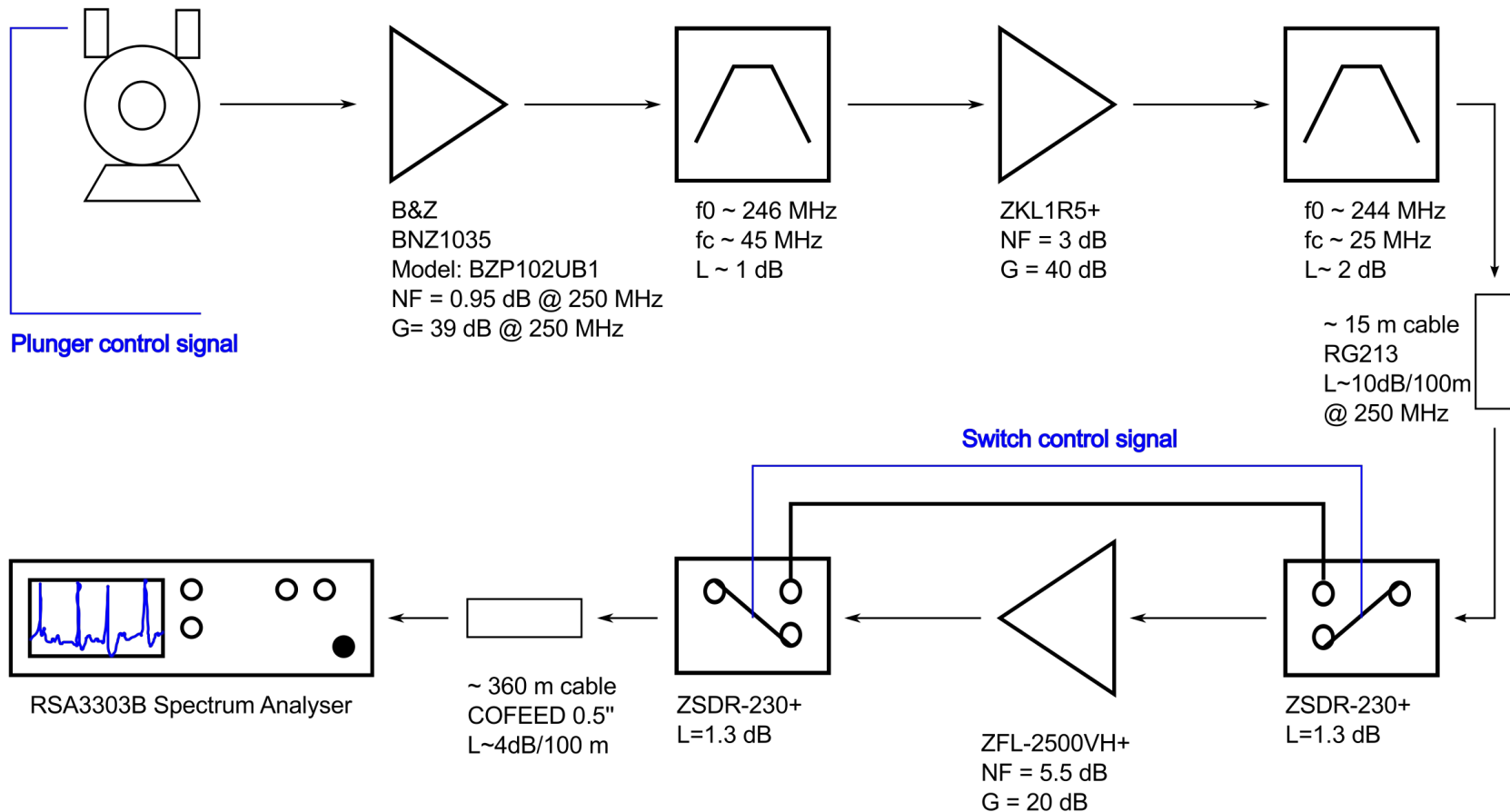


410 MHz

Sanjari et. al. Phys. Scr. 014088 (2013)

Sanjari et. al. Rev. Sci. Instr. 91(8), pp. 083303 (2020)

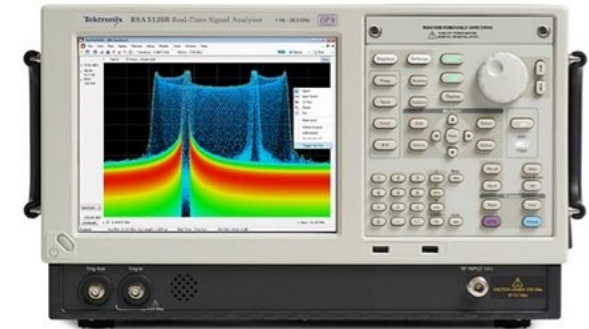
Example of RF Signal flow



Data acquisition



- Spectrum analyzer
 - Storage ring or cooler setup and configuration
 - Narrowband recording for each injection
- TCAP system: (90's - ca. 2010)
- NTCAP system:
 - broadband recording
 - Continuous
 - 2 to 70 Msp/s



Downconverter

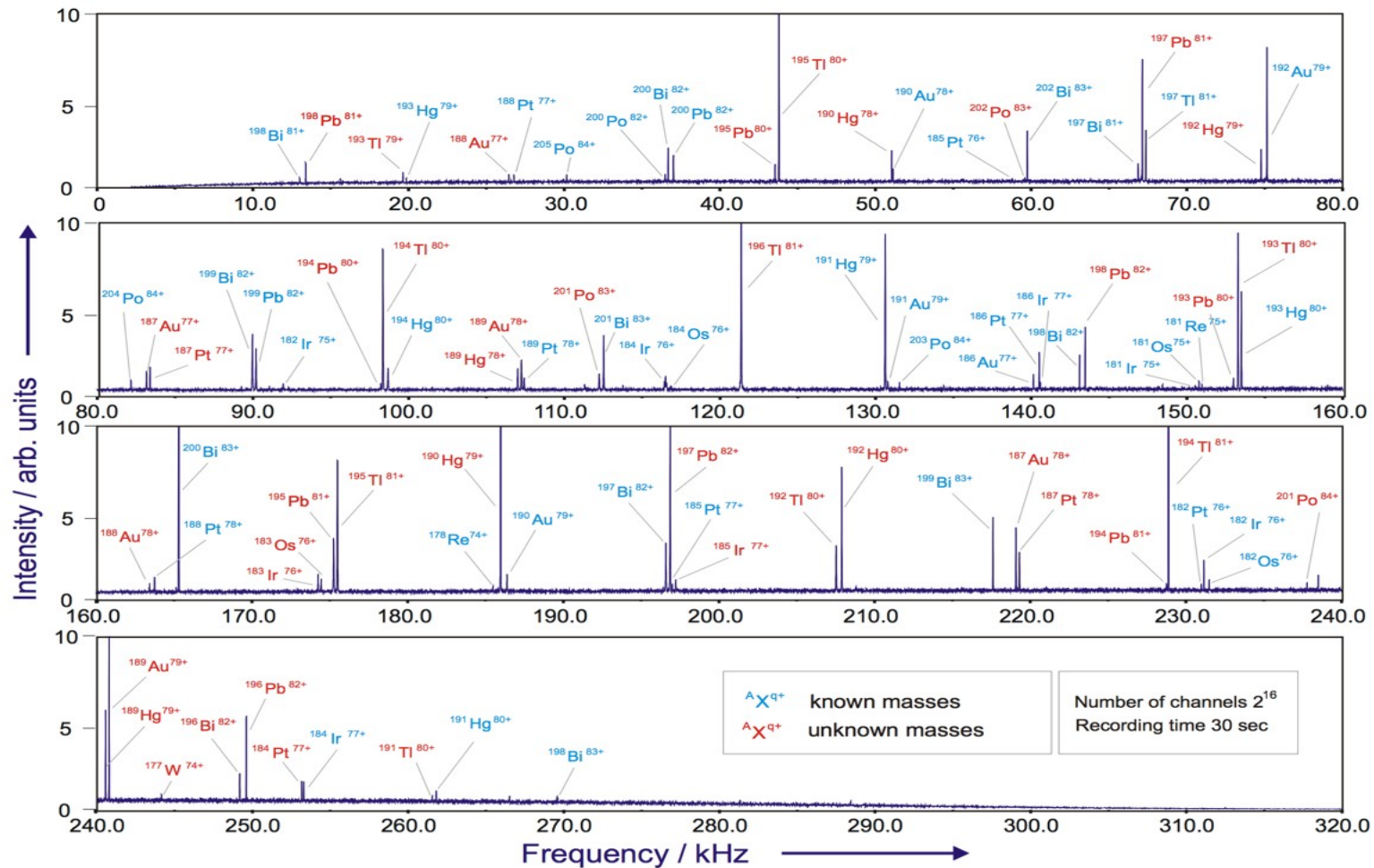
Local Oscillator

Digitizer



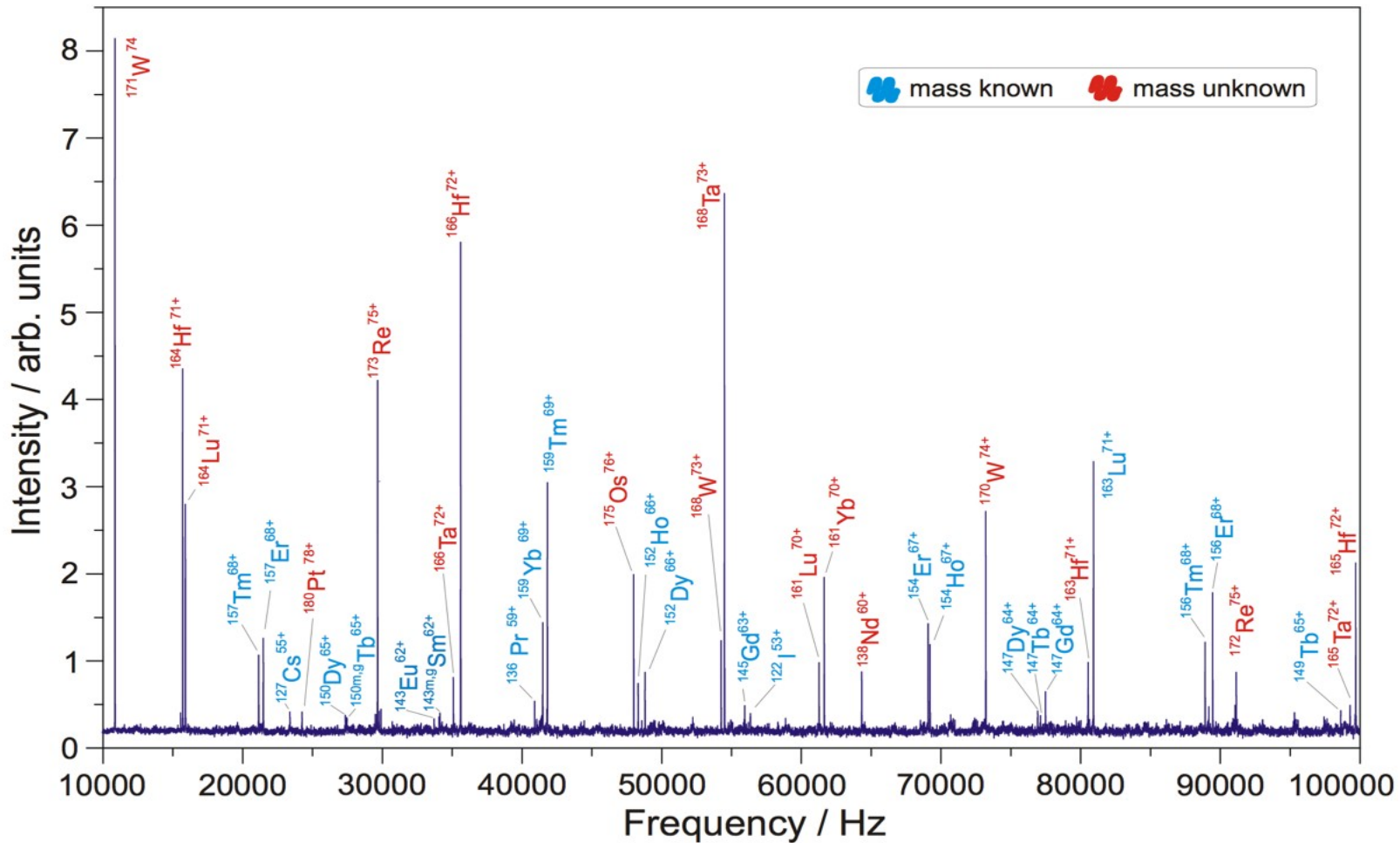
Trageser, PhD Thesis 2018

Example spectra



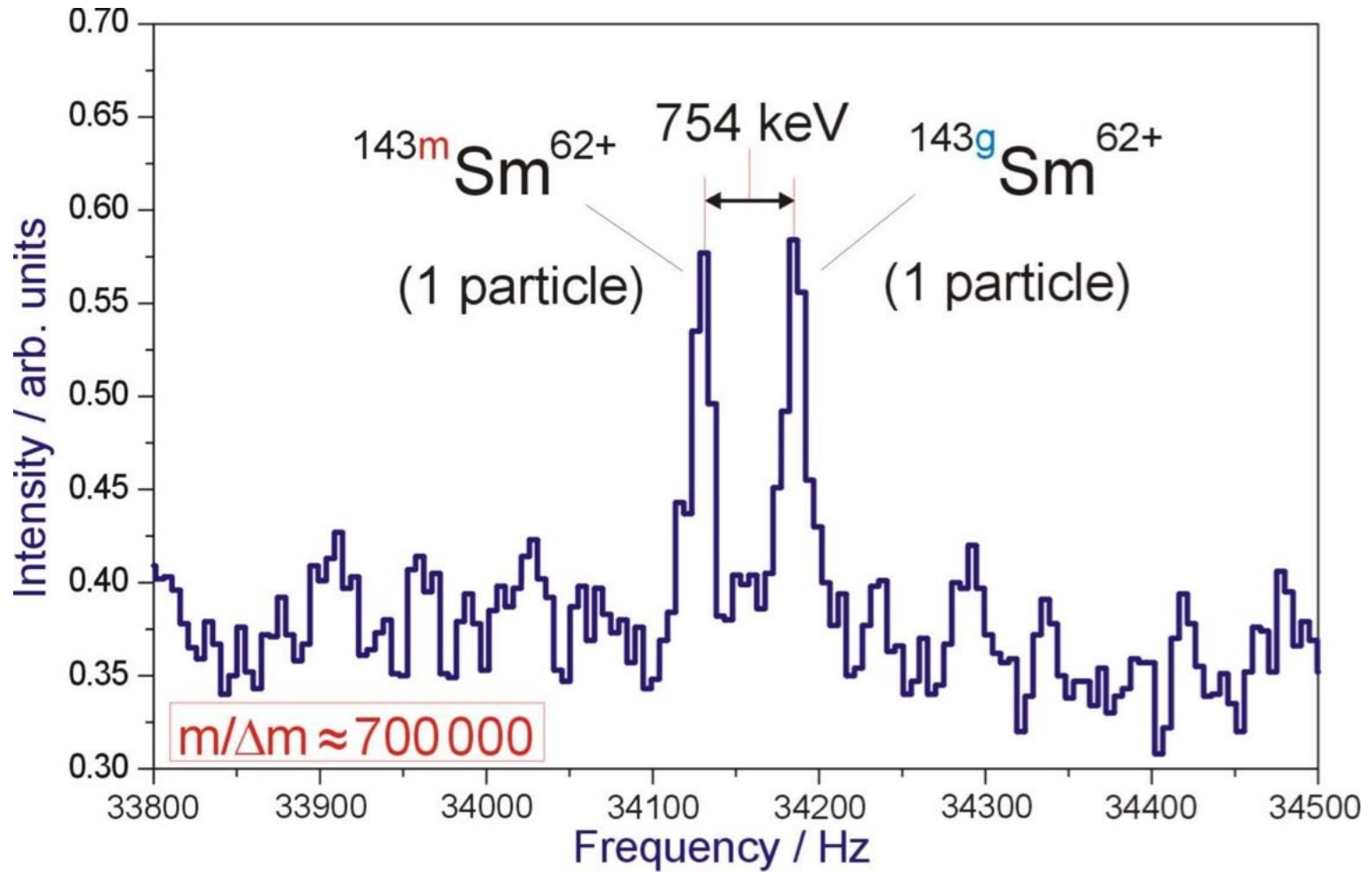
Slide courtesy of Yu. A. Litvinov

Example spectra

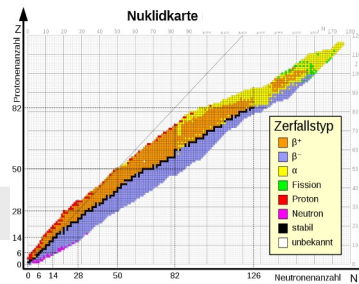


Slide courtesy of Yu. A. Litvinov

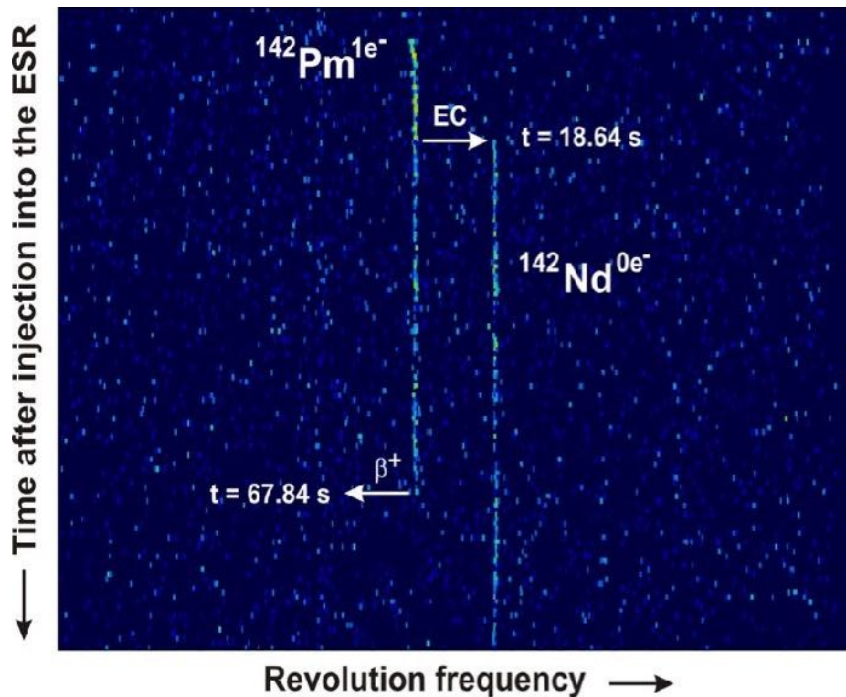
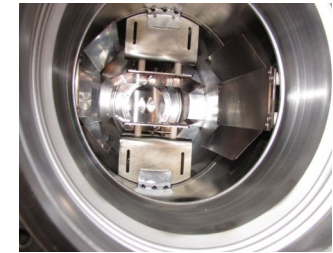
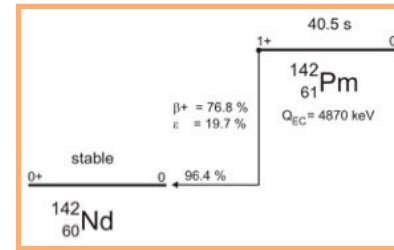
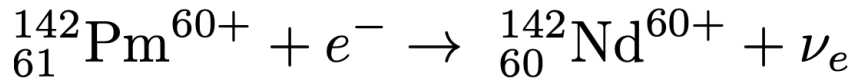
Example spectra



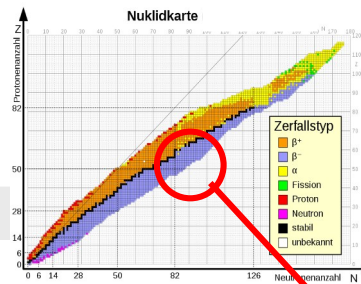
Slide courtesy of Yu. A. Litvinov



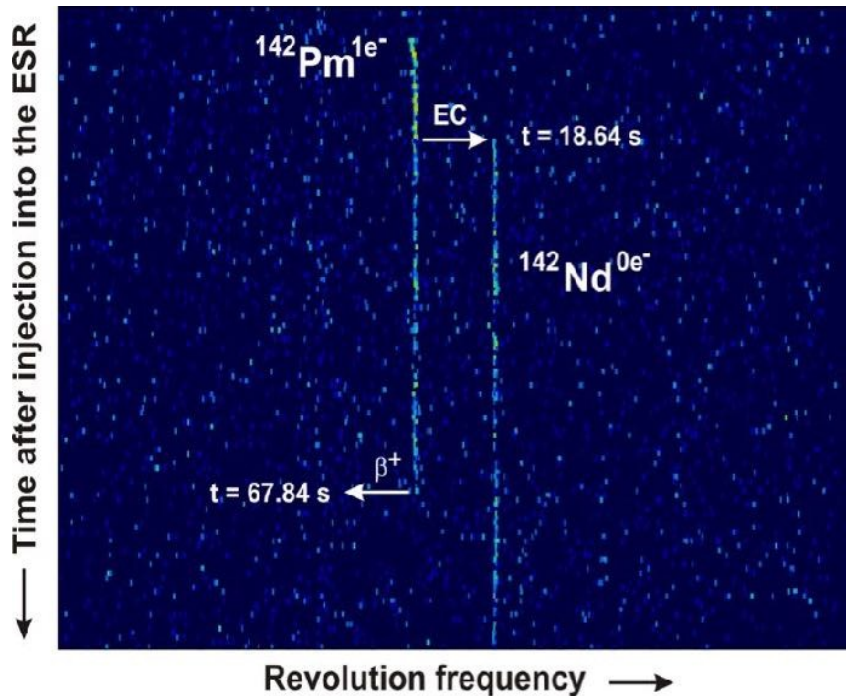
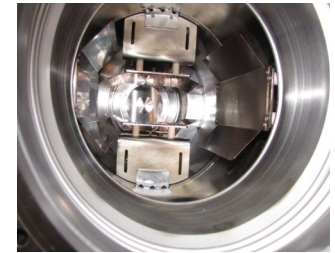
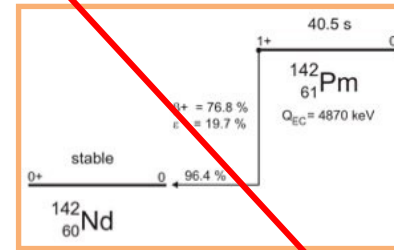
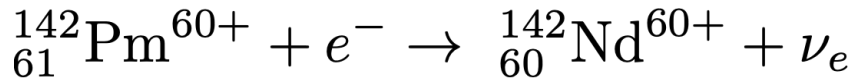
- Low sensitivity, lots of averaging



Z	140Eu 1.51 S ε: 100.00%	141Eu 40.7 S ε: 100.00%	142Eu 2.34 S ε: 100.00%	143Eu 2.59 M ε: 100.00%	144Eu 10.2 S ε: 100.00%	145Eu 5.93 D ε: 100.00%
62	139Sm 2.57 M ε: 100.00%	140Sm 14.82 M ε: 100.00%	141Sm 10.2 M ε: 100.00%	142Sm 72.49 M ε: 100.00%	143Sm 8.75 M ε: 100.00%	144Sm STABLE 3.07%
61	138Pm 10 S ε: 100.00%	139Pm 4.15 M ε: 100.00%	140Pm 9.2 S ε: 100.00%	141Pm 20.90 M ε: 100.00%	142Pm 40.5 S ε: 100.00%	143Pm 265 D ε: 100.00%
60	137Nd 38.5 M ε: 100.00%	138Nd 5.04 H ε: 100.00%	139Nd 29.7 M ε: 100.00%	140Nd 3.37 D ε: 100.00%	141Nd 2.49 H ε: 100.00%	142Nd STABLE 27.152%
59	136Pr 13.1 M ε: 100.00%	137Pr 1.28 H ε: 100.00%	138Pr 1.45 M ε: 100.00%	139Pr 4.41 H ε: 100.00%	140Pr 3.39 M ε: 100.00%	141Pr STABLE 100%
	77	78	79	80	81	82

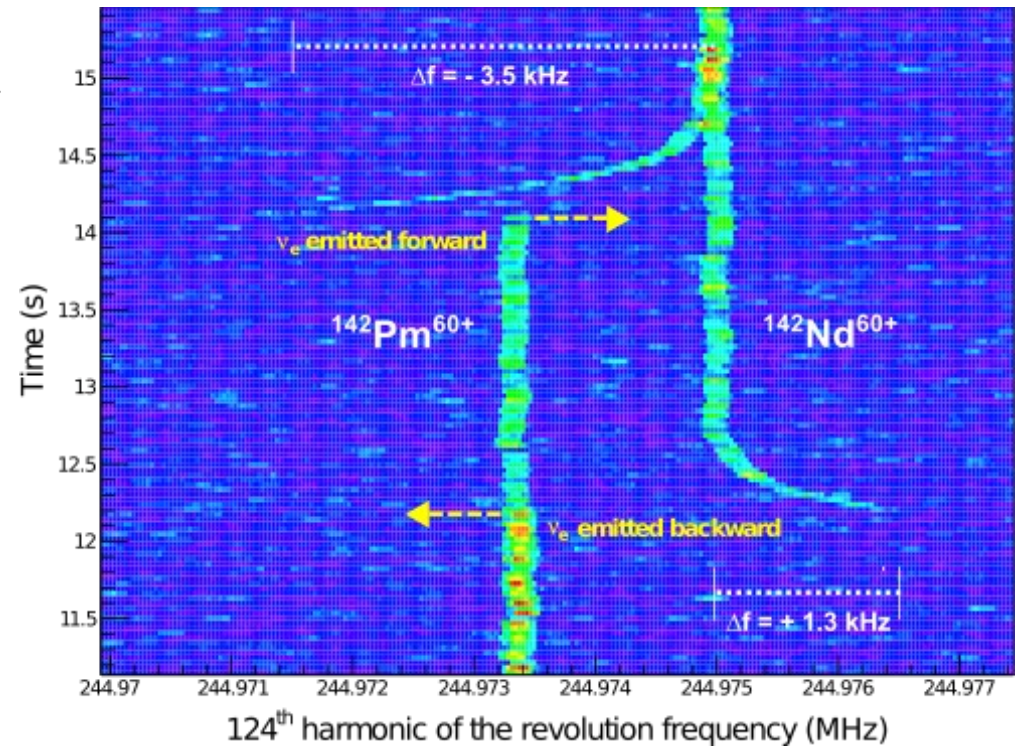
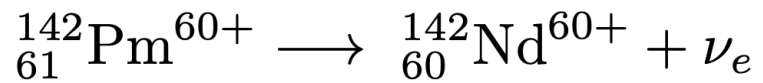
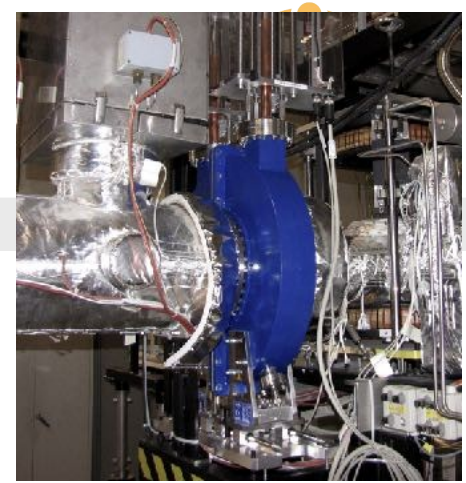


- Low sensitivity, lots of averaging

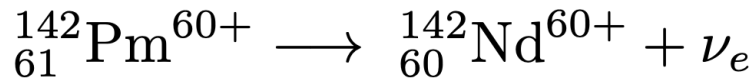
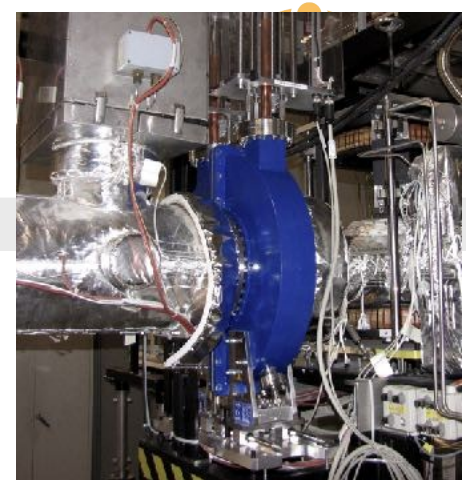


Z	140Eu 1.51 S ε: 100.00%	141Eu 40.7 S ε: 100.00%	142Eu 2.34 S ε: 100.00%	143Eu 2.59 M ε: 100.00%	144Eu 10.2 S ε: 100.00%	145Eu 5.93 D ε: 100.00%
62	139Sm 2.57 M ε: 100.00%	140Sm 14.82 M ε: 100.00%	141Sm 10.2 M ε: 100.00%	142Sm 72.49 M ε: 100.00%	143Sm 8.75 M ε: 100.00%	144Sm STABLE 3.07%
61	138Pm 10 S ε: 100.00%	139Pm 4.15 M ε: 100.00%	140Pm 9.2 S ε: 100.00%	141Pm 20.90 M ε: 100.00%	142Pm 40.5 S ε: 100.00%	143Pm 265 D ε: 100.00%
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	77	78	79	80	81	82

- High / single ion sensitivity

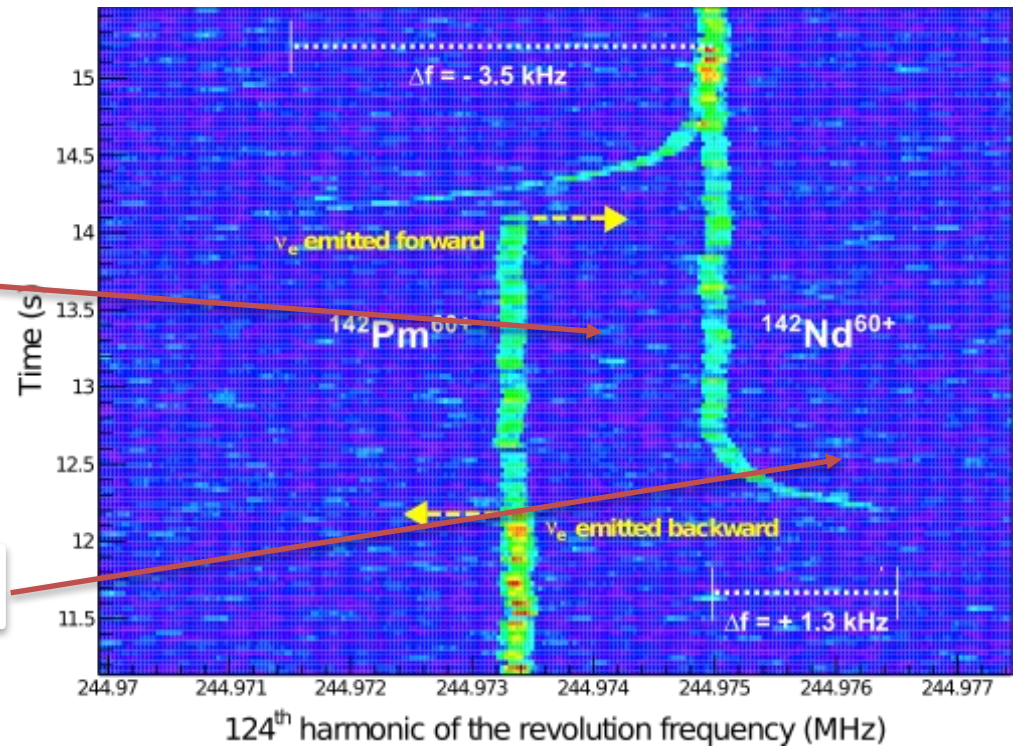


- High / single ion sensitivity



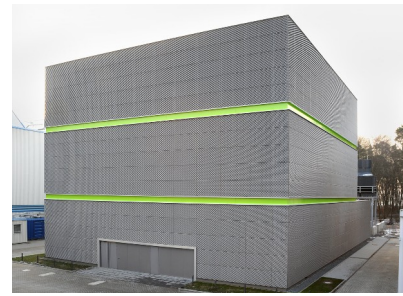
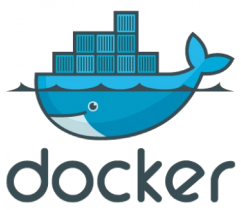
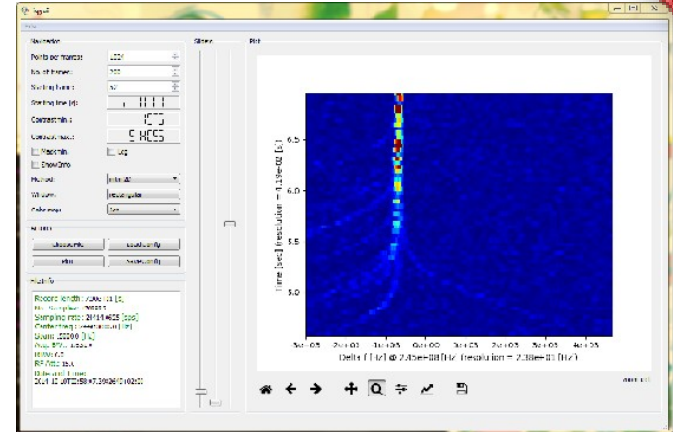
QEC = 1.6 [kHz] ~ 4.82 [MeV]
 NNDC (neutral atom) ~4.87 [MeV]

Decay time resolution 32ms



Data analysis

- Analysis code published on GitHub
- Python (+ROOT) based framework
 - IQTools / IQGUI (for different DAQs)
 - Barion (Ion calculations)
 - RionID (thanks 🙏 D. Freire-Fernandez) and other recent tools for identification / mass measurement
- HPC and some first attempts at ML (thanks 🙏 to colleagues CIT and HPC)



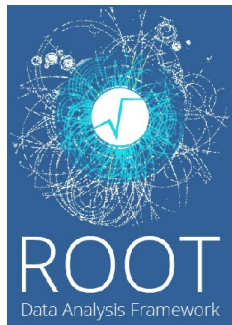
Navigation: Name: Pm, Z: 61, N: 61, Q: 00

Parameters: Energy (MeV/u): 400.0000, Analysis Freq. (MHz): 248.0000, Beam Current (µA): 1.0000, Path length (m): 100.000, Ring: ESR, Use circum.

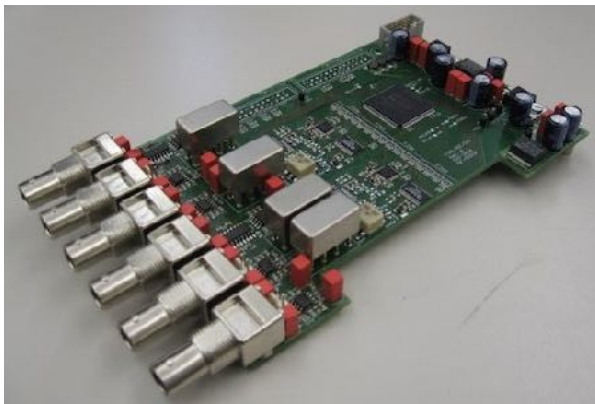
Identification: Measured Prec. [a.u.]: 244911915.1954651, Unknown particles: 144813000.8792161, Max No. Electrons: 3, P range #: 4, N range #: 4, Sensitivity radius: 0.00010

Name	Value	Unit
Nuclide:	142 Pm 60+	
Z:	61	
N:	81	
Source:	** EXX **	
Kinetic energy:	400.0	[MeV/u]
Beam current:	1.0	[µA]
Path length:	108.5	[m]
Analysis freq.:	248.0	[MHz]
Total charge:	8.61305938e-19	[C]
Atomic mass:	141.912990411	[u]
Ionic mass:	141.89021970226884	[u]
Ionic m/Q:	2.3548707763711475	[u]
Ion. kin. Energy:	88600.0	[MeV]
gamma:	1.6287602438400351	
beta:	0.7147224662006564	
beta * gamma:	1.0218983543816665	
Velocity:	214268405.31729526	[m/s]
	7713692515422657	[km/h]
Rel. mass:	188660.6653142237	[MeV/c ²]
	202.857622281636	[kg]
	5.137763636191261e-22	[kg]

Results Plane: gamma: 1.6287602438400351, alpha: 0.1788461074503987, mode: std, m/Q of the unknown particle: 2.384884918109472, Candidate size: 102-N6160+, Z: 60, N: 62



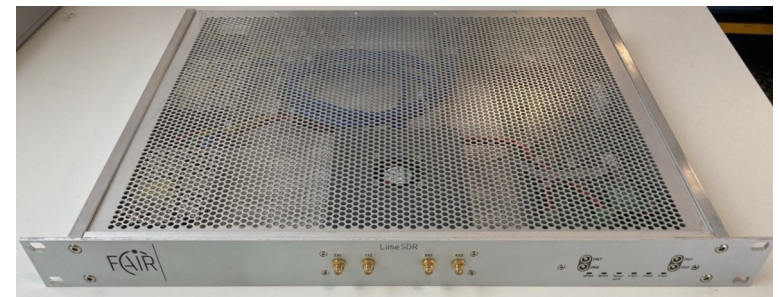
Some personal SDR history



Sanjari S. et. al. GSI Scientific Report GSI-ACCELERATORS-07 (2009)

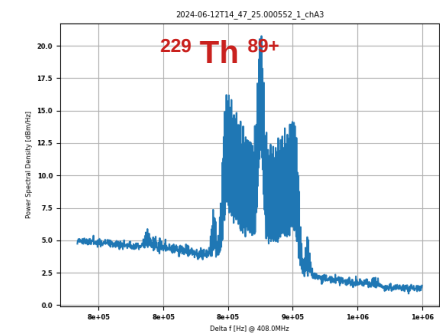
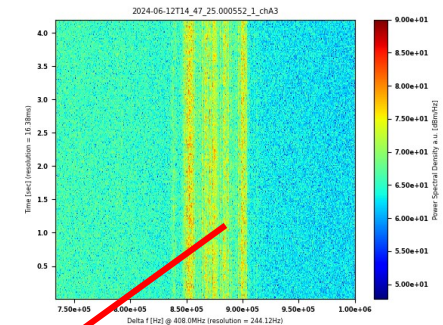
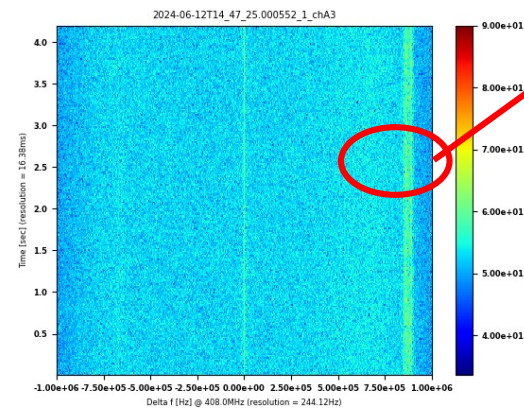
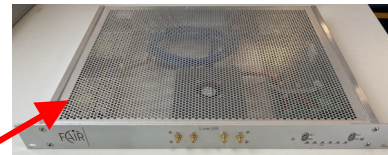
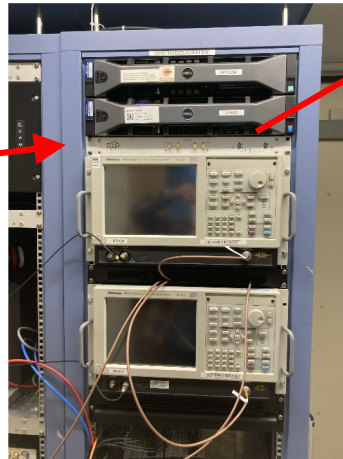
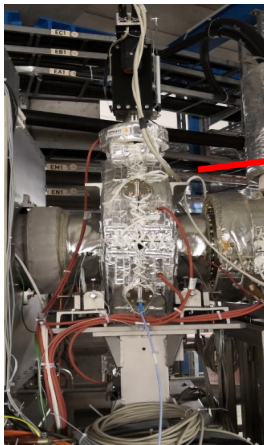
GNURadio

- Offers maximum flexibility
- Different experimental scenarios needs different DAQ configurations
- Well integrated within GSI/FAIR plans
- Unified underlying system for different classes of DAQ:
 - Time Data: (Oscilloscopes)
 - Frequency: (Spectrum Data)



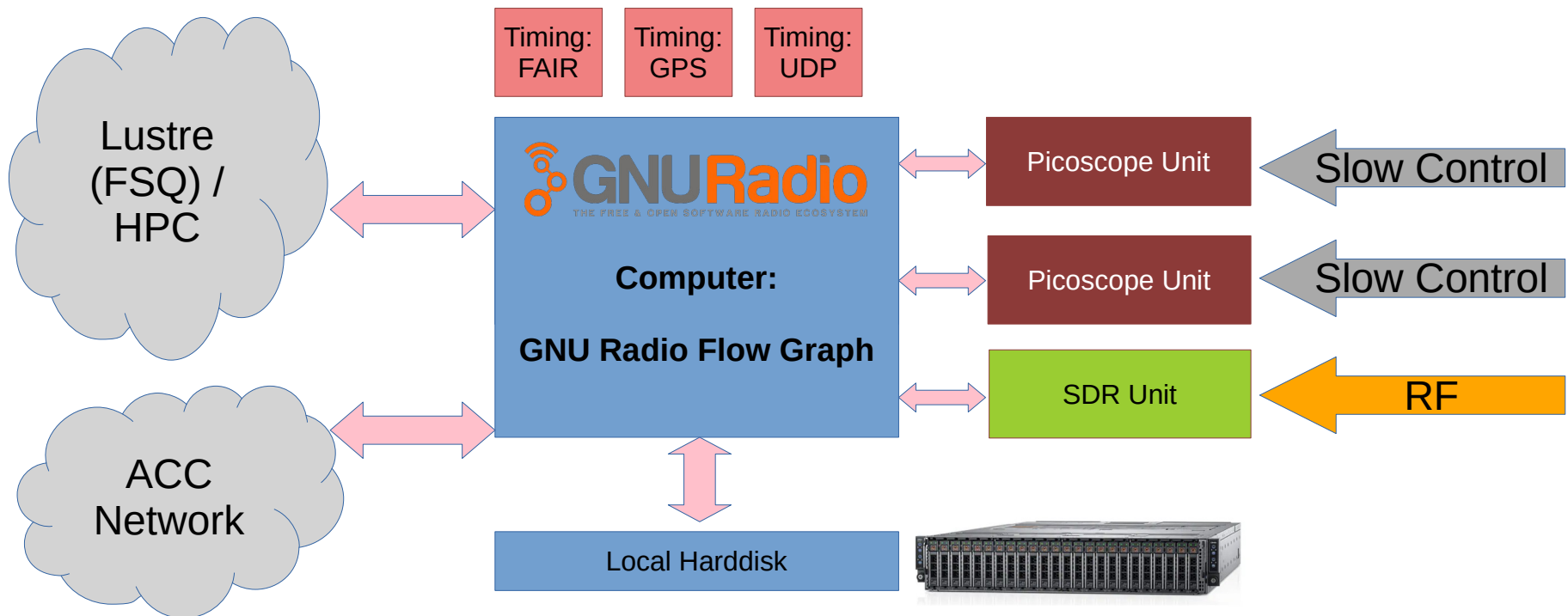
Recent measurement using GNURadio4

- First measurement using GNU-Radio LimeSDR integration (Special thanks 🙏 A. Krimm and R. Steinhagen et. al.)
- High resolution 410 MHz Schottky resonator @ ESR
- 229Th+89 Fragments (decelerated) on top of 234Pa+91, 224Ac+87 and 237U+92



Some future ideas

- One possible configuration (using FAIR+GNURadio components)
 - Control system connections (thanks 🙏 to H. Hüther, B. Peter et. al.)
 - Hardware thanks 🙏 to many other colleagues from SIS and ACO department ...
 - Lustre/HPC connection PyFSQ (thanks 🙏 to T. Stibor @ GSI)



Measurement of isomeric states

Preliminary!

- Experiment E143: Isomer of ^{72}Br
 - Spokesperson:
W. Korten, Yu. A. Litvinov

- Many thanks 🙏 to E143 collaboration

- First time super high resolution:
 - ~100keV resolution

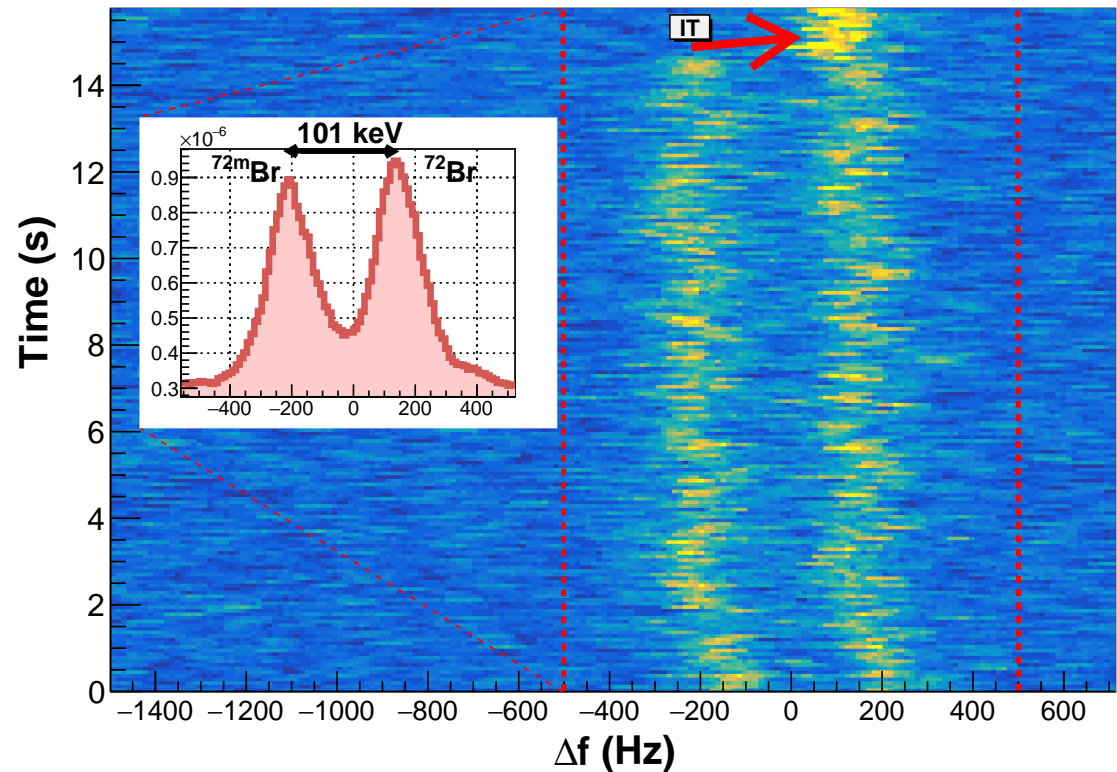


Image: Curtesy D. Freire-Fernandez

More concrete plans for 2025

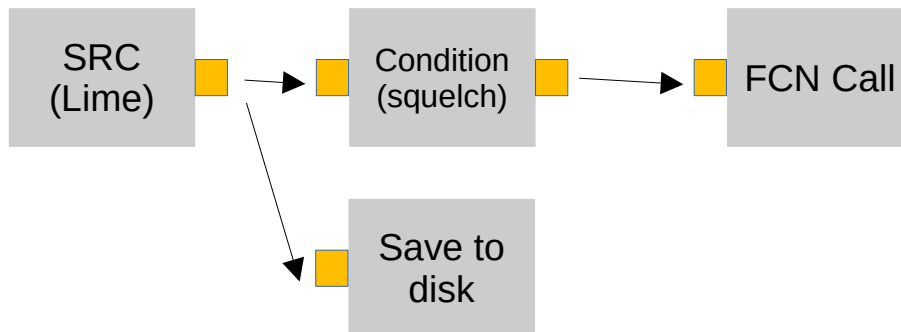
- 2025 Experiment proposal (G-22-00203):
 - Mass & half-life measurements in the neutron-rich $N \approx 116$ Hf region
 - Spokesperson: Yuri A. Litvinov
- Conditional recording:
 - Only if there is an isomer! (i.e. just pause the accelerator!)
 - Enormously increase beam time **efficiency!**
 - Explore regions **never discovered before!**
- Needs just a simple GNURadio flow graph!

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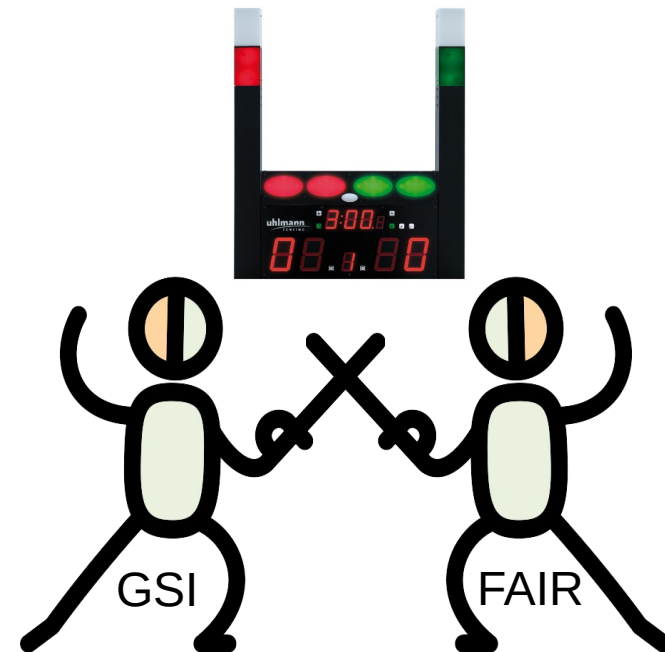
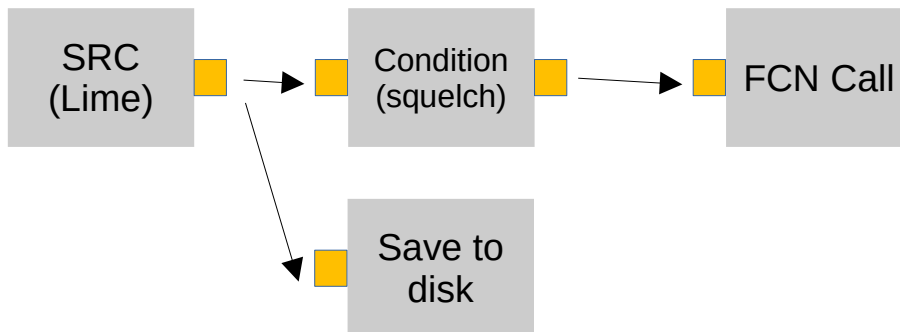
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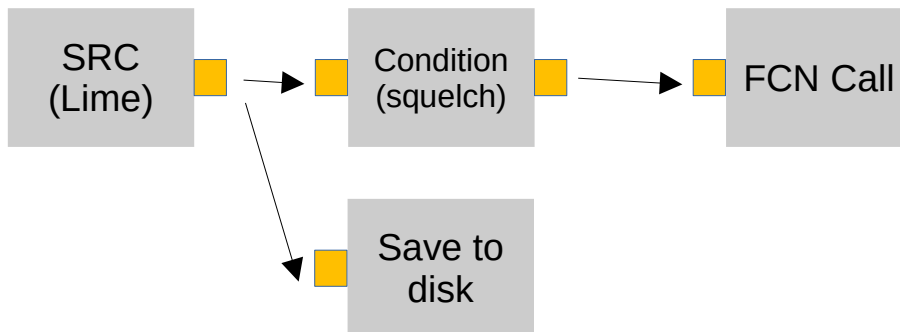
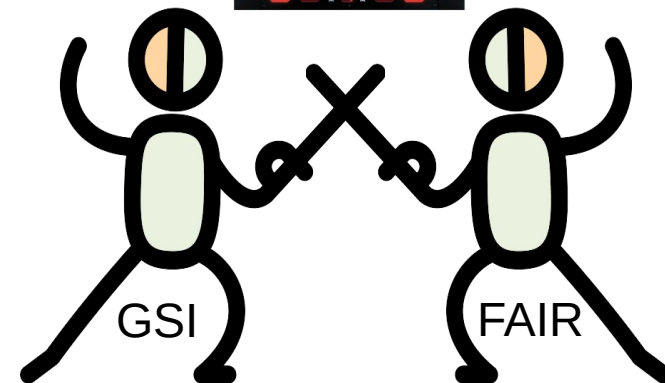
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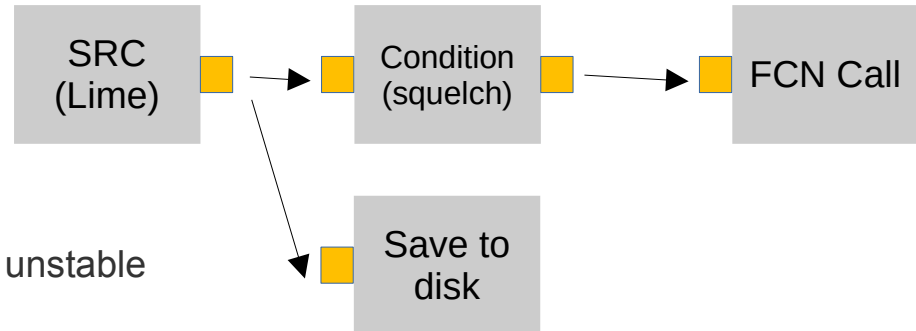
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- Optimization of beam time:

- Recording is always running
- Re-inject if there are no isomers!
- If you find one, wait until it decays

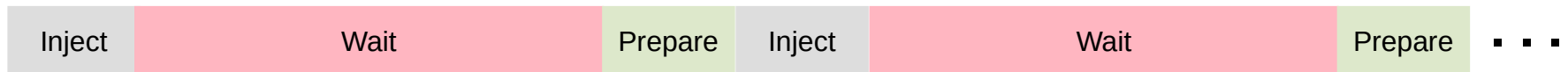


- Only way to efficiently tackle **rare** and **long lived** unstable nuclear states!

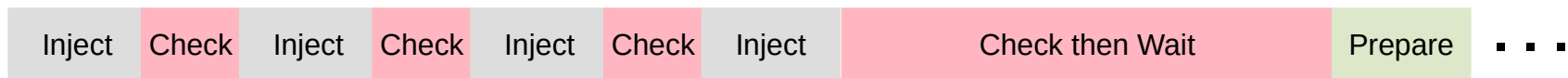
- Much easier offline processing!

- Empty injections are easily discarded → reduction of error

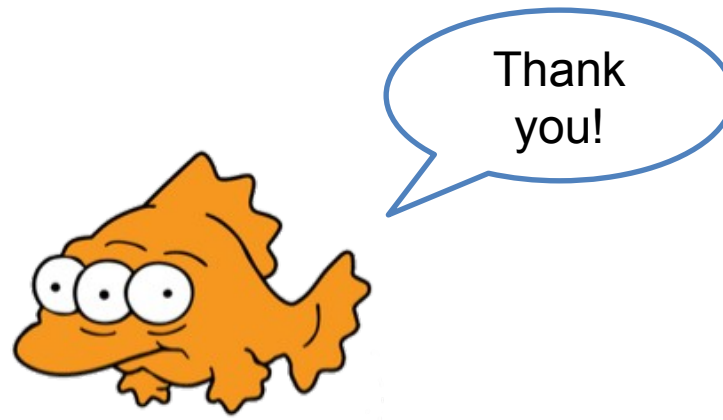
Current situation:

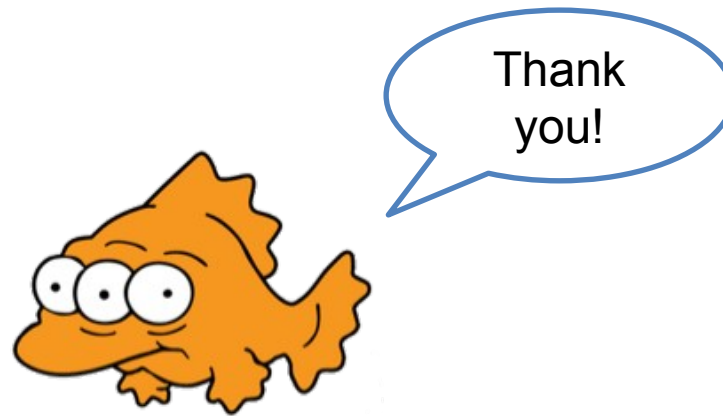


Future plan:



Time →





Long lived rare species!