Nuclear Astrophysics with Neutrons

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Germany

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RESEARCH FIELDS

- 🟨 ENERGY
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Largest science organisation in Germany

Annual budget ~ 3.3 billion €

~30.000 employees

6 Research fields

17 Research centers

~20 Young Investigator Groups/ year

5 years, budget ~1.25 Mio €

Research at Helmholtz centers

Teaching at universities

151 YIG in 9 years, ~25% working in „Structure of Matter"

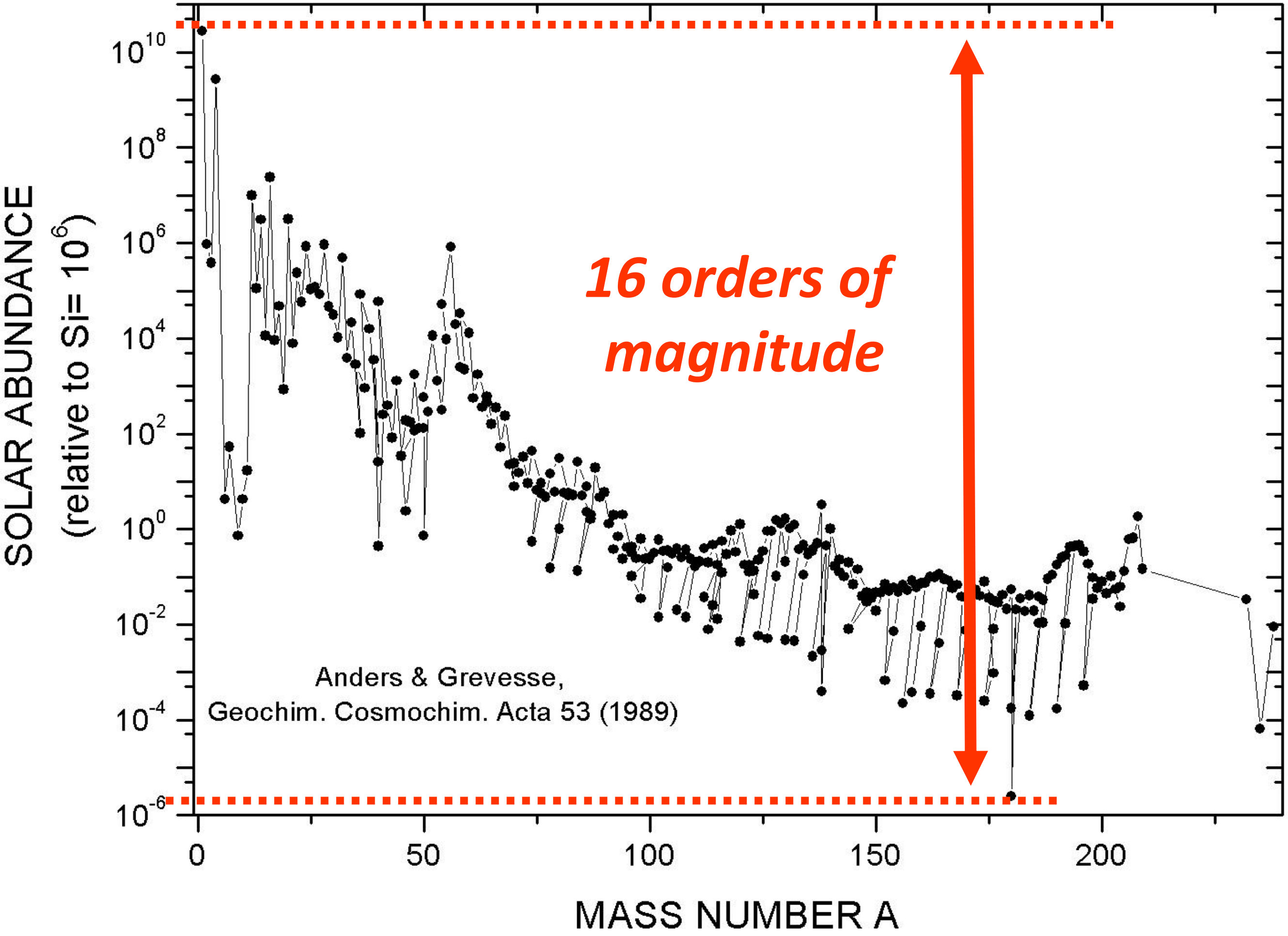
Overview

1. Astrophysical introduction
2. "slow neutron capture process"
    - Quasi-stellar neutron distributions
    - Stellar neutron capture database KADoNiS
3. "rapid neutron capture process"
    - Production of neutron-rich exotic isotopes
    - β-delayed neutrons
    - GSI experiments

"Solar" abundances

Characteristic isotopic abundances for materials within the solar system

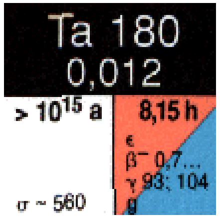
⇨ also valid outside solar system? („Galactic“ abundances?)



16 orders of magnitude

Anders & Grevesse,
Geochim. Cosmochim. Acta 53 (1989)

How are the isotopes produced?



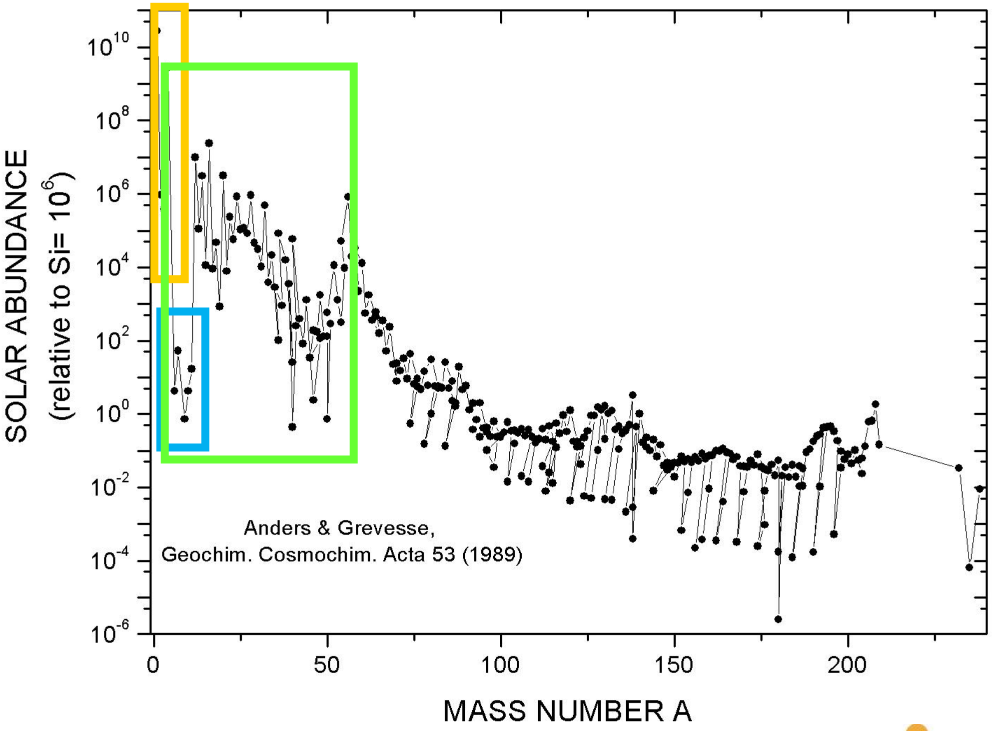
Solar abundances: Production of light isotopes

Big Bang nucleosynthesis: H, He, D, no elements heavier than Li

Galactic cosmic ray spallation: Li, Be, B by bombardment of matter by high energy cosmic "ray" particles

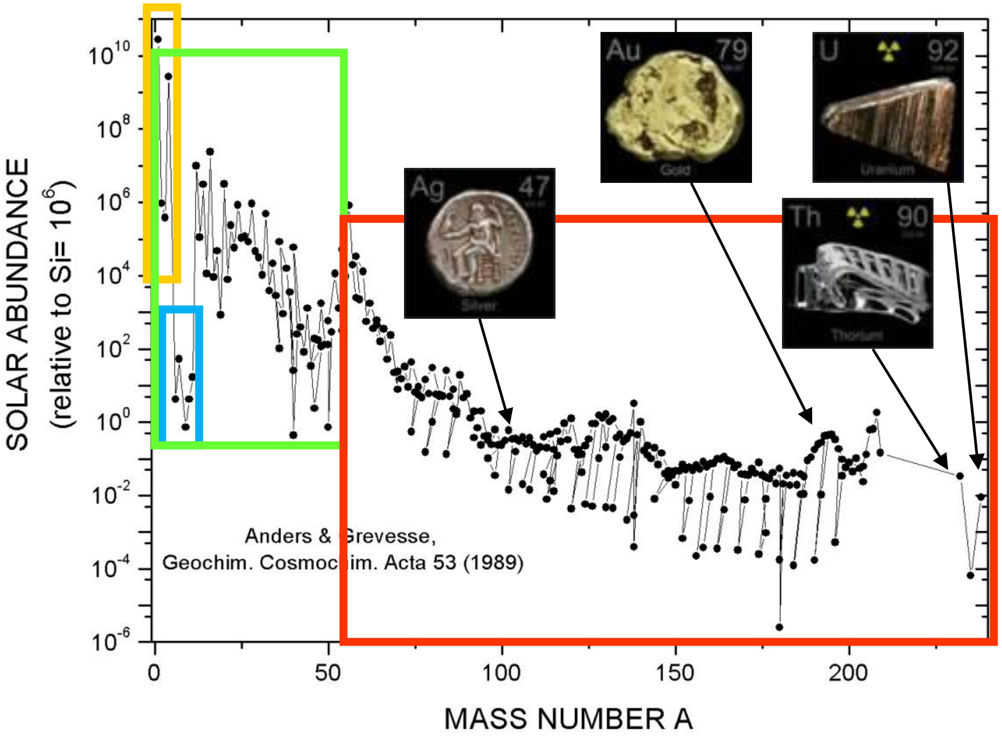
Stellar nucleosynthesis 1:
Fusion (burning processes) in stars up to Iron and Nickel (A~56)

0.08 - 0.4 $M_\odot$ ⇨ H burning
0.4 - ~8 $M_\odot$ ⇨ H, He burning
>8 $M_\odot$ ⇨ H, He, C, Ne, O, Si burning



Anders & Grevesse, Geochim. Cosmochim. Acta 53 (1989)

How are the heavy elements formed?



Anders & Grevesse,
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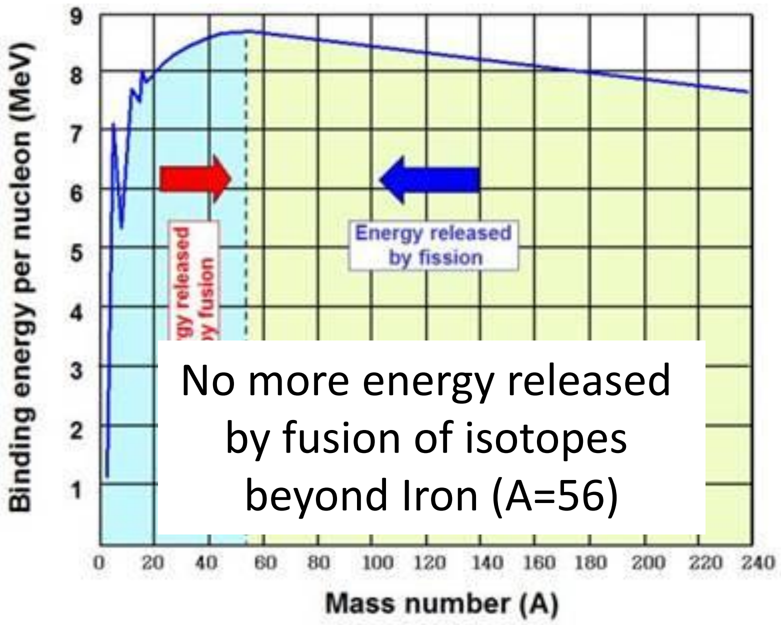
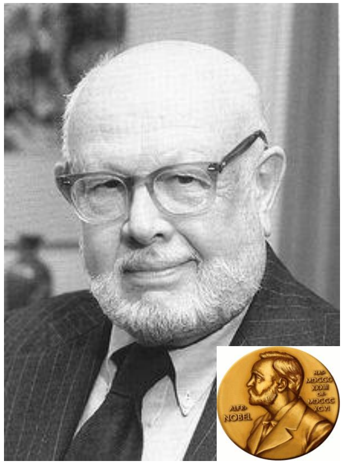


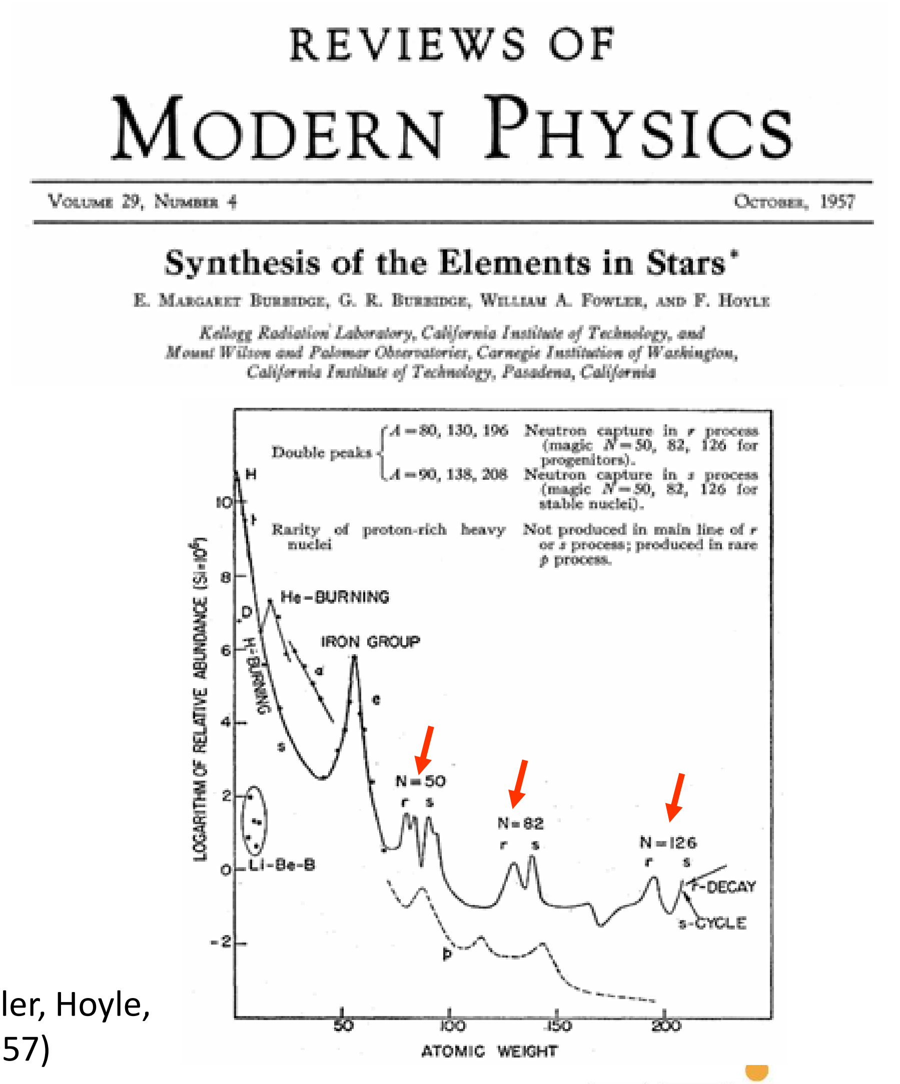
No more energy released by fusion of isotopes beyond Iron (A=56)

Nuclear Astrophysics = Nuclear Physics + Astrophysics



"Willy" Fowler (1911-1995)
1983 Nobel Prize for Physics

Fred Hoyle
(1915-2001)



REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 — OCTOBER, 1957

Synthesis of the Elements in Stars*

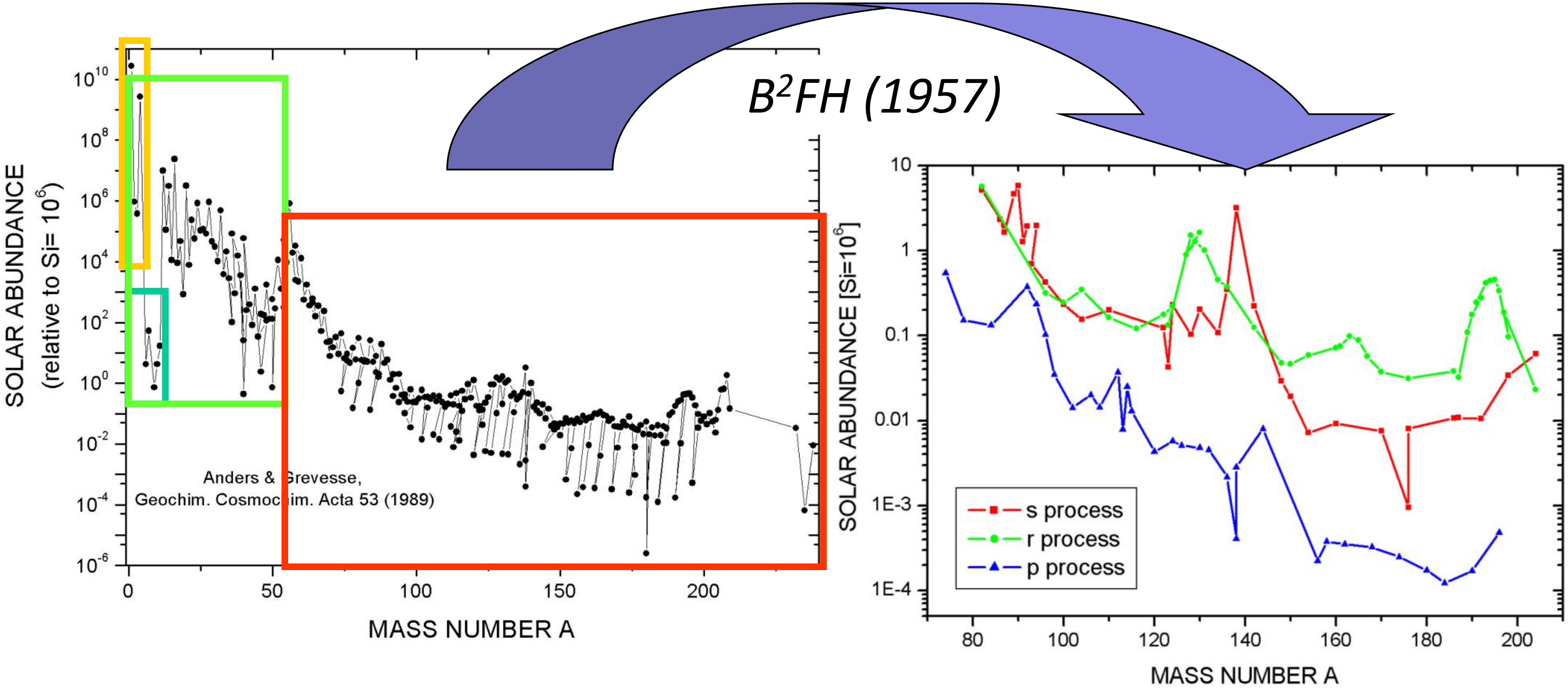
E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

Double peaks	$A = 80, 130, 196$	Neutron capture in *r* process (magic $N = 50, 82, 126$ for progenitors).
	$A = 90, 138, 208$	Neutron capture in *s* process (magic $N = 50, 82, 126$ for stable nuclei).
Rarity of proton-rich heavy nuclei		Not produced in main line of *r* or *s* process; produced in rare *p* process.

B^{2}FH: Burbidge, Burbidge, Fowler, Hoyle,
Revs. Mod. Phys. 29 (1957)

Solar abundances: Synthesis beyond iron

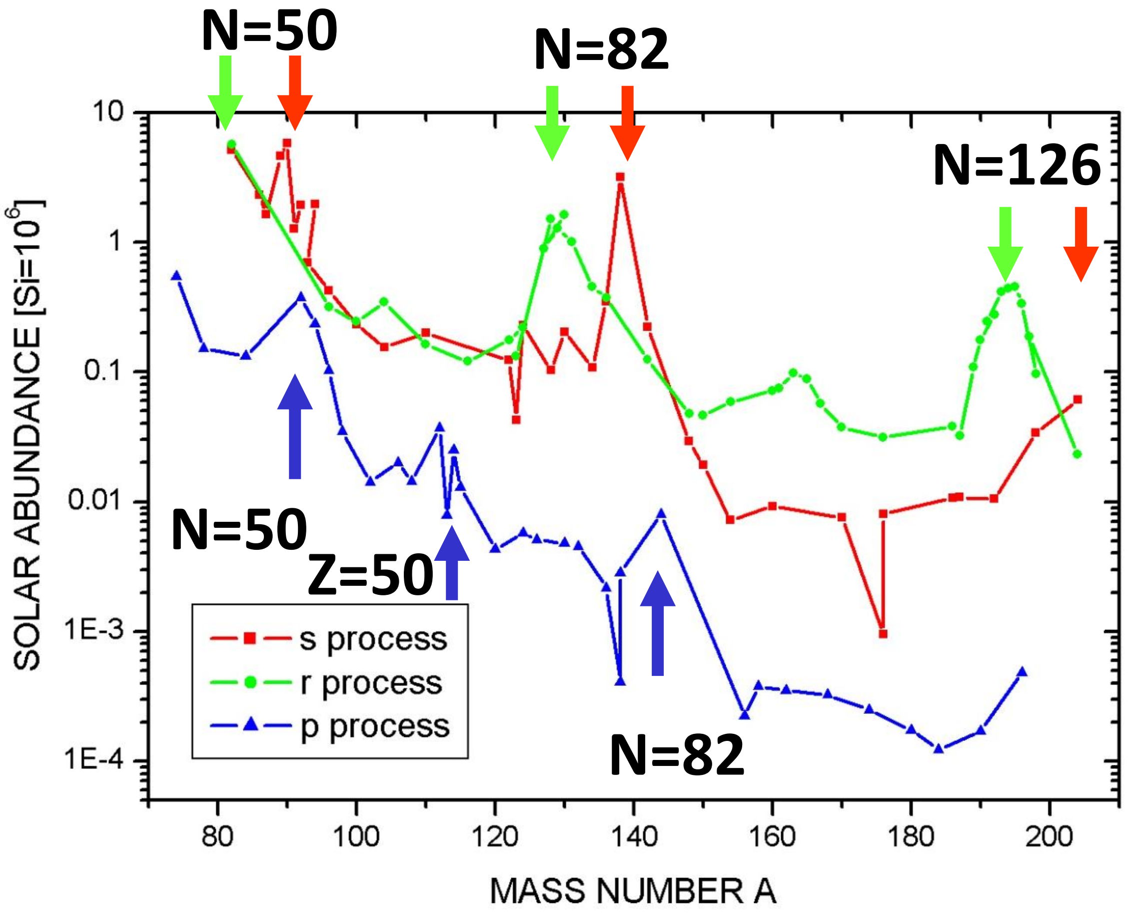


B²FH (1957)

Anders & Grevesse, Geochim. Cosmochim. Acta 53 (1989)

B^{2}FH: Burbidge, Burbidge, Fowler, Hoyle, Revs. Mod. Phys. 29 (1957)

Solar abundances: Synthesis beyond iron



"slow neutron capture process"

"rapid neutron capture process"

Production of p-rich isotopes

$$N_{\odot} = N_s + N_r + N_p$$

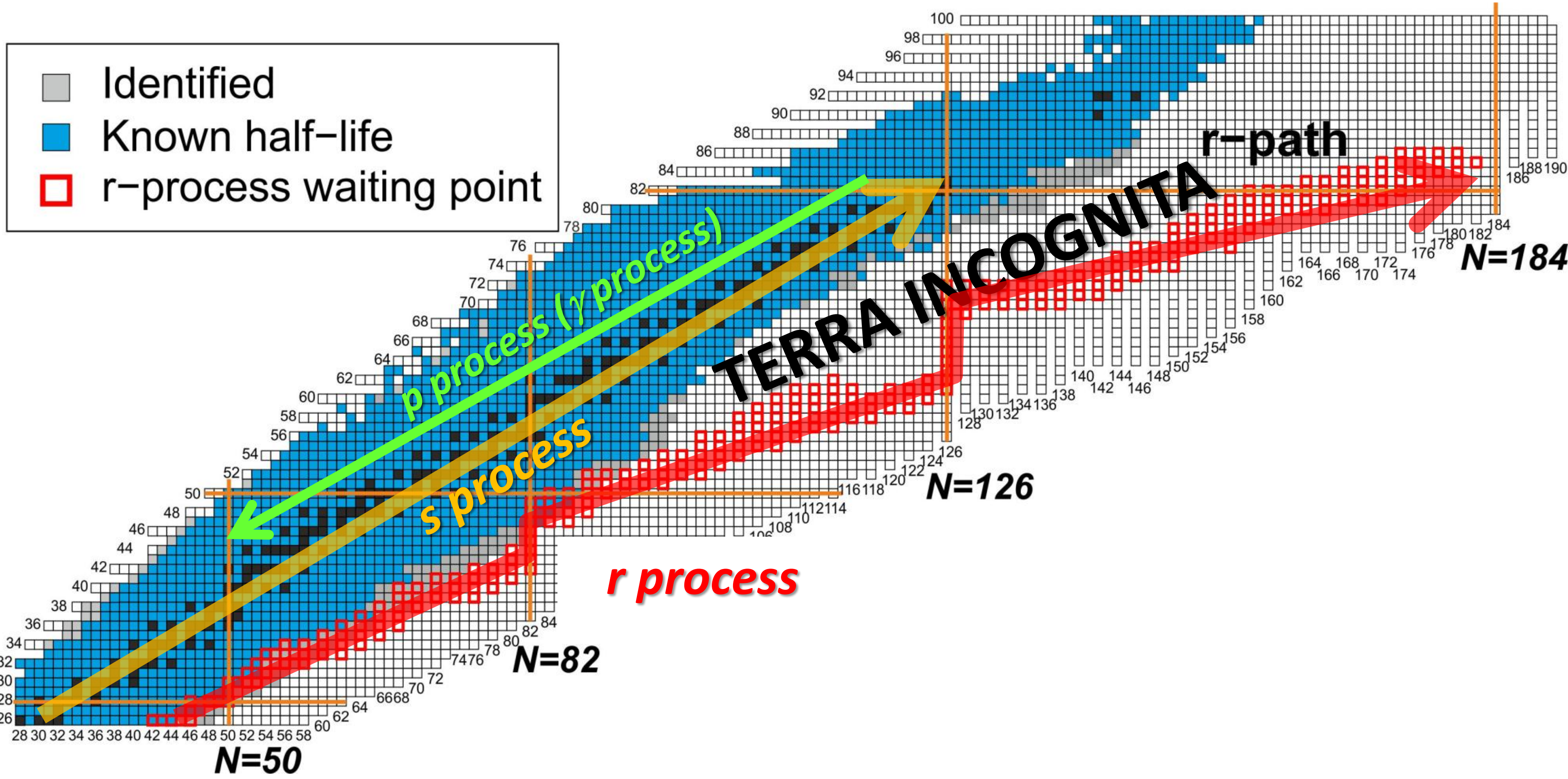
~50% ~50% ~1%

Local abundance maxima (and minima) are ***mirrors of nuclear structure***

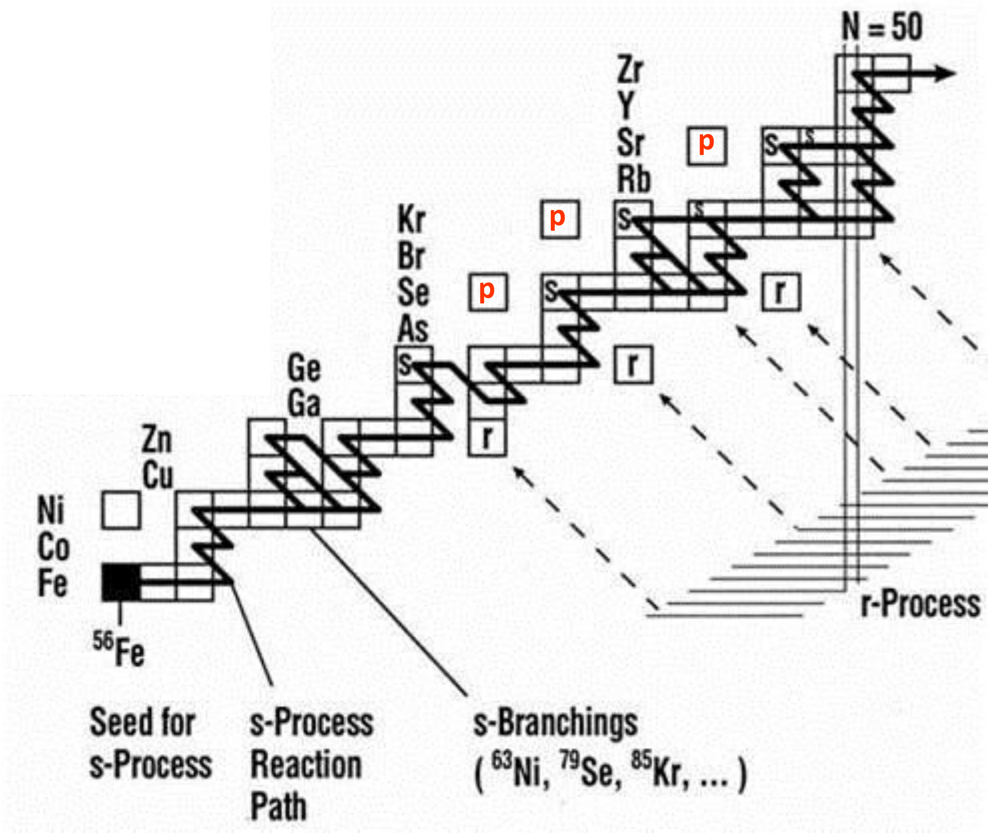
(shell closures, pairing effects...)

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Solar abundances: Synthesis beyond iron

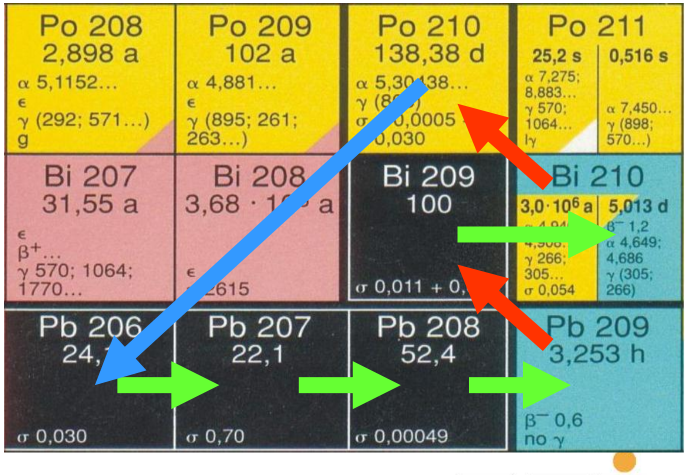


The "slow neutron capture process“



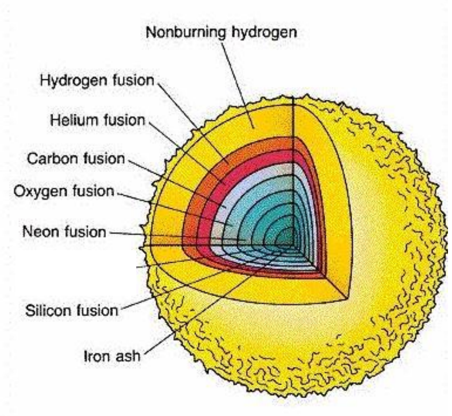
~50% of abundances >Fe

- **Neutron capture slowly** compared to β-decay (1 capture per ~1000 y)
- Well defined **path along line of stability**
- **Almost completely understood from astrophysical and nuclear physics side**
- End point: ^{209}Bi

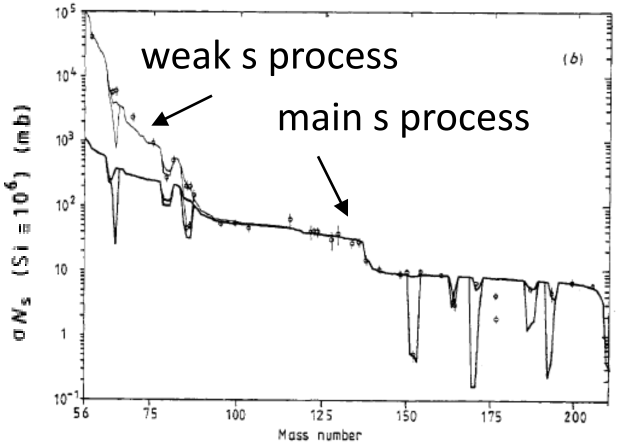


The "slow neutron capture process"

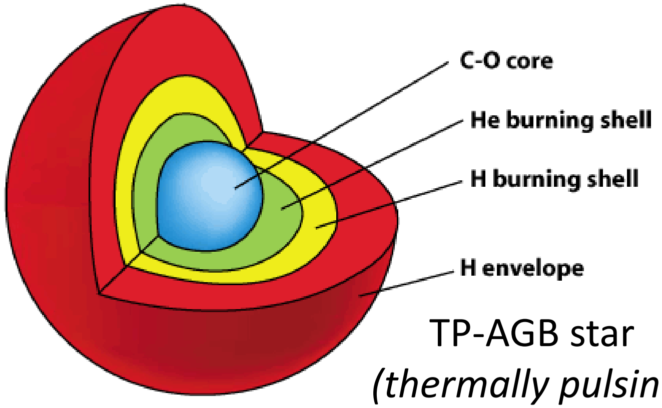
	Weak	component	Main	component
Mass region	A<90	(Fe - Zr)	A>(56) 90	(Zr - Bi)
Stellar site	massive stars	(>8 M_{sun})	TP AGB stars	(1-3 M_{sun})
Stellar burning phase	core He	shell C	H burning	He shell flashes
Temperature [MK]	300 (kT= 26 keV)	1000 (kT= 91 keV)	90 (kT= 8 keV)	250 (kT= 23 keV)
Neutron source	**Ne-22(α,n)Mg-25**	**Ne-22(α,n)Mg-25**	**C-13(α,n)O-16**	**Ne-22(α,n)Mg-25**
Av. neutron density [cm^{-3}]	10^6	10^{11}	10^7	10^{11}
Duration [y]	10^6	1-20	10^4	10



Massive star


weak s process

main s process

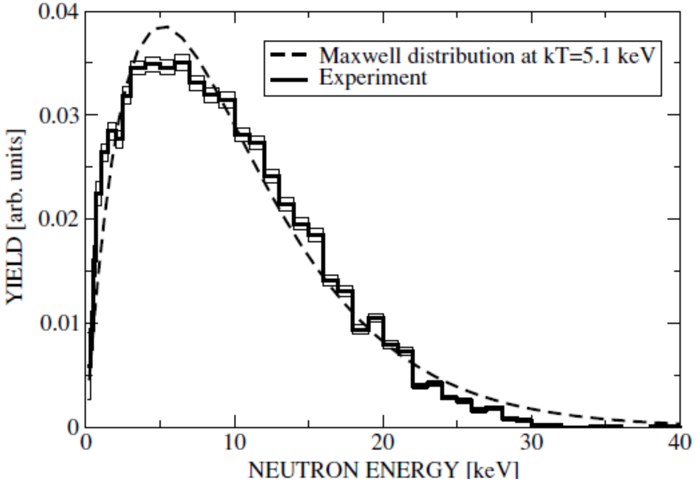


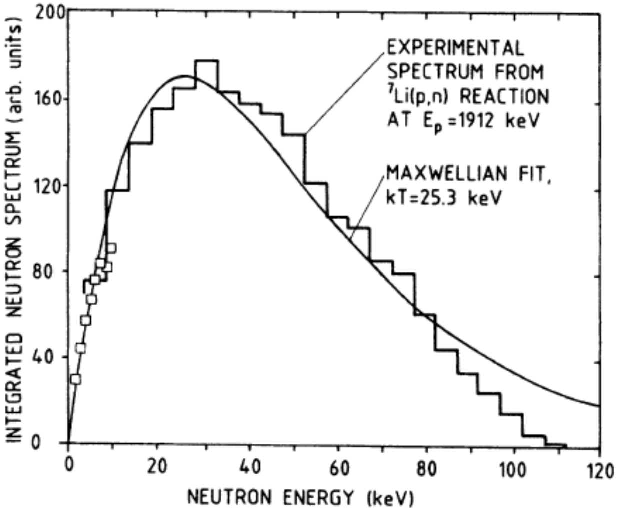
TP-AGB star

(thermally pulsing asymptotic giant branch)

Quasi-stellar neutron spectra

Simulation of stellar Maxwell-Boltzmann energy distributions:





kT= 5.1 keV: ^{18}O (p,n) ^{18}F @

E_p=2582 keV (8 keV above TH)

Flux @FZK (100 µA): ~10^5 n/s

kT= 25 keV: ^{7}Li (p,n) ^{7}Be @

E_p=1912 keV (30 keV above TH)

Flux @FZK (100 µA): 2-3*10^9 n/s

kT= 52 keV: ^{3}H (p,n) ^{3}He @

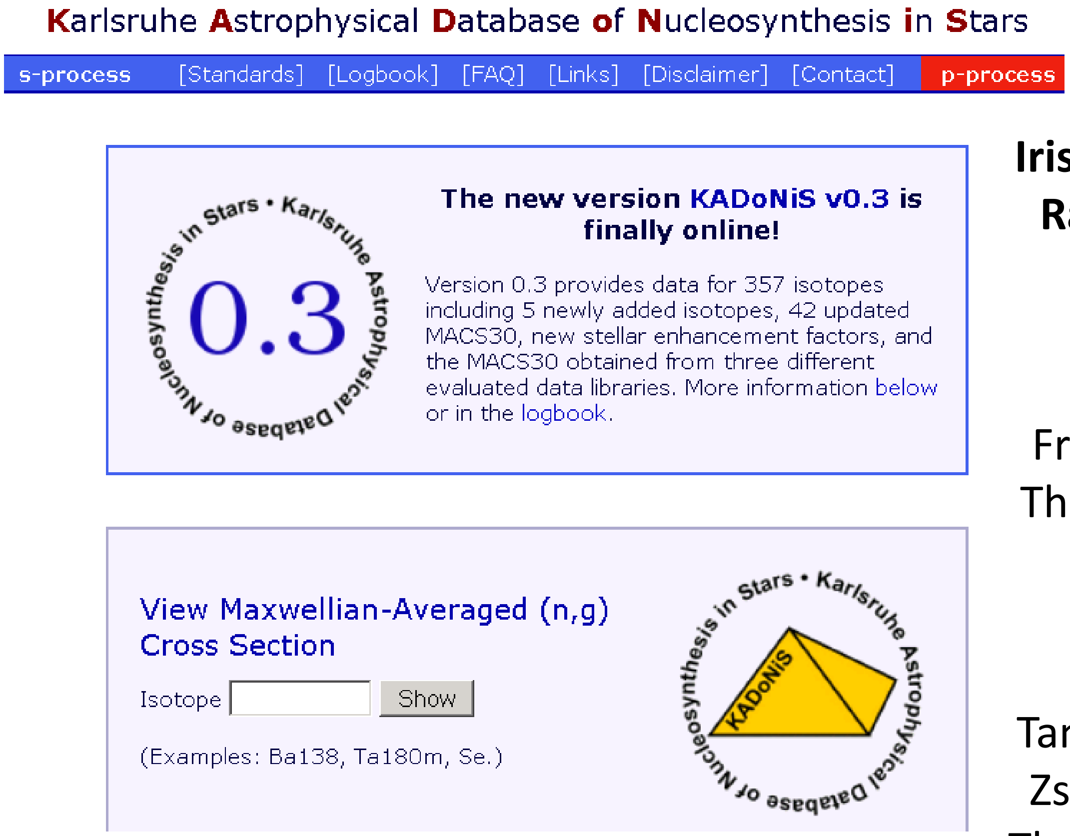
E_p=1099 keV (80 keV above TH)

Flux @FZK (100 µA): ~10^8 n/s

- *kT= 5.1 keV:* M. Heil et al., Phys. Rev. C71, 025803 (2005)
- *kT= 25 keV:* H. Beer et al., Phys. Rev. C21, 534 (1980)
- *kT= 52 keV:* F. Käppeler et al., Phys. Rev. C 35, 936 (1987)

Stellar neutron capture database

www.kadonis.org



Karlsruhe Astrophysical Database of Nucleosynthesis in Stars

The new version KADoNiS v0.3 is finally online!

Version 0.3 provides data for 357 isotopes including 5 newly added isotopes, 42 updated MACS30, new stellar enhancement factors, and the MACS30 obtained from three different evaluated data libraries. More information below or in the logbook.

View Maxwellian-Averaged (n,g) Cross Section

Isotope

(Examples: Ba138, Ta180m, Se.)

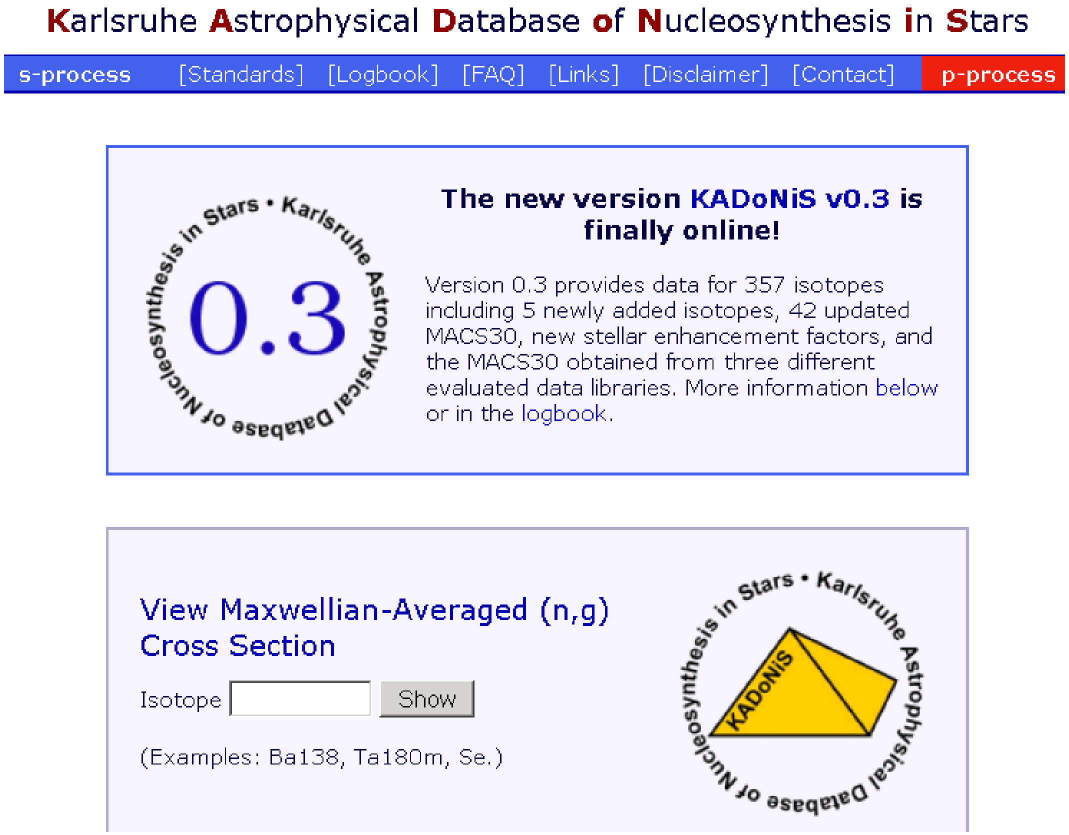
Iris Dillmann (GSI Darmstadt/ Uni Giessen)
Ralf Plag (GSI Darmstadt/ Uni Frankfurt)

s-process database:
Franz Käppeler (Karlsruhe Inst. of Techn.)
Thomas Rauscher (Uni Basel/ Switzerland)

p-process database:
Tamas Szücs (ATOMKI Debrecen/ Hungary)
Zsolt Fülöp (ATOMKI Debrecen/ Hungary)
Thomas Rauscher (Uni Basel/ Switzerland)´

Stellar neutron capture database

www.kadonis.org



Karlsruhe **A**strophysical **D**atabase **o**f **N**ucleosynthesis **i**n **S**tars

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View Maxwellian-Averaged (n,g) Cross Section

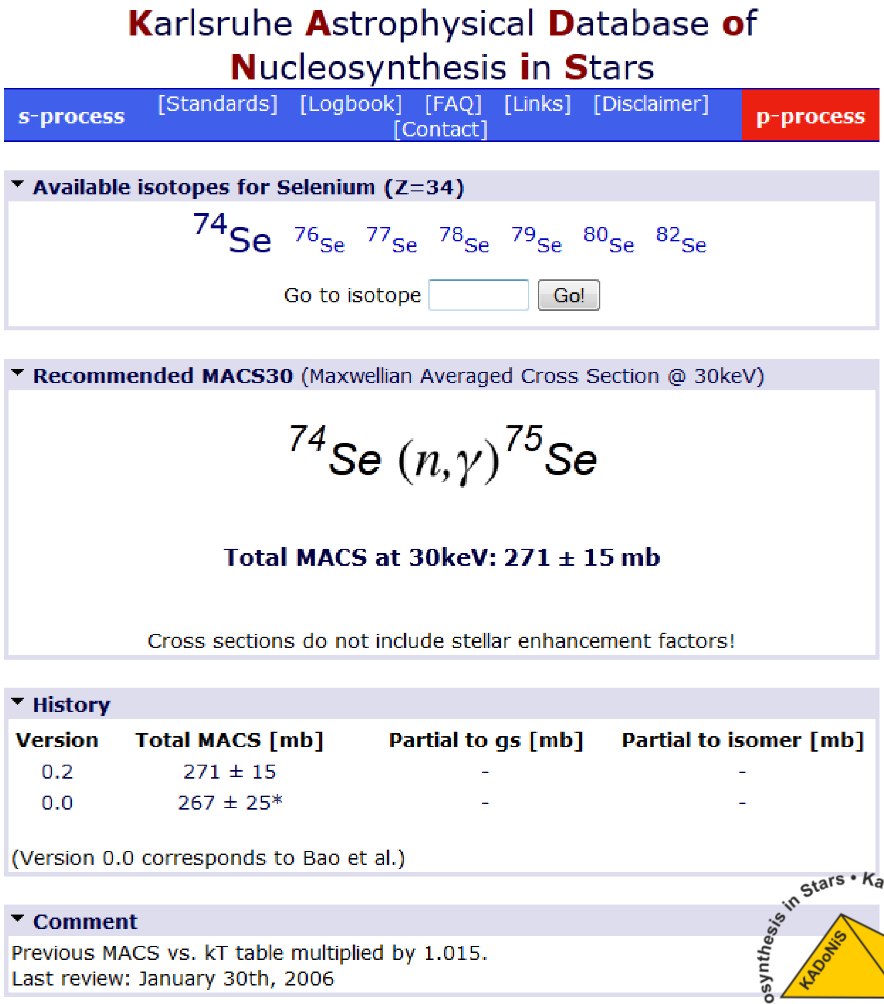
Isotope

(Examples: Ba138, Ta180m, Se.)

- Compilation, not evaluation!
- Since April 2005
- ^{1}H – ^{210}Po
- 357 isotopes: 280 stable (267 measured), 77 radioactive (13 measured)
- Maxwellian cross sections (MACS) and stellar enhancement factors for kT= 5-100 keV
- Experimental and theoretical predictions
- (n,p) and (n,α) reactions for light isotopes
- Based on previous compilations:

B.J. Allen, R.L. Macklin, J.H. Gibbons, Adv. Nucl. Phys. 4 (1971) 205
Z.Y. Bao and F. Käppeler, ADNDT 36 (1987) 411
H. Beer, F. Voss, R. Winters, Astrophys. Journ. Suppl. 80 (1992) 403
Z.Y. Bao, H. Beer, F. Käppeler, F. Voss, K. Wisshak, and T. Rauscher, ADNDT 76 (2000) 1

KADoNiS data sheets



Karlsruhe Astrophysical Database of Nucleosynthesis in Stars

s-process [Standards] [Logbook] [FAQ] [Links] [Disclaimer] [Contact] p-process

▼ Available isotopes for Selenium (Z=34)

^{74}Se ^{76}Se ^{77}Se ^{78}Se ^{79}Se ^{80}Se ^{82}Se

Go to isotope Go!

▼ Recommended MACS30 (Maxwellian Averaged Cross Section @ 30keV)

$$^{74}\mathrm{Se}\ (n,\gamma)^{75}\mathrm{Se}$$

Total MACS at 30keV: 271 ± 15 mb

Cross sections do not include stellar enhancement factors!

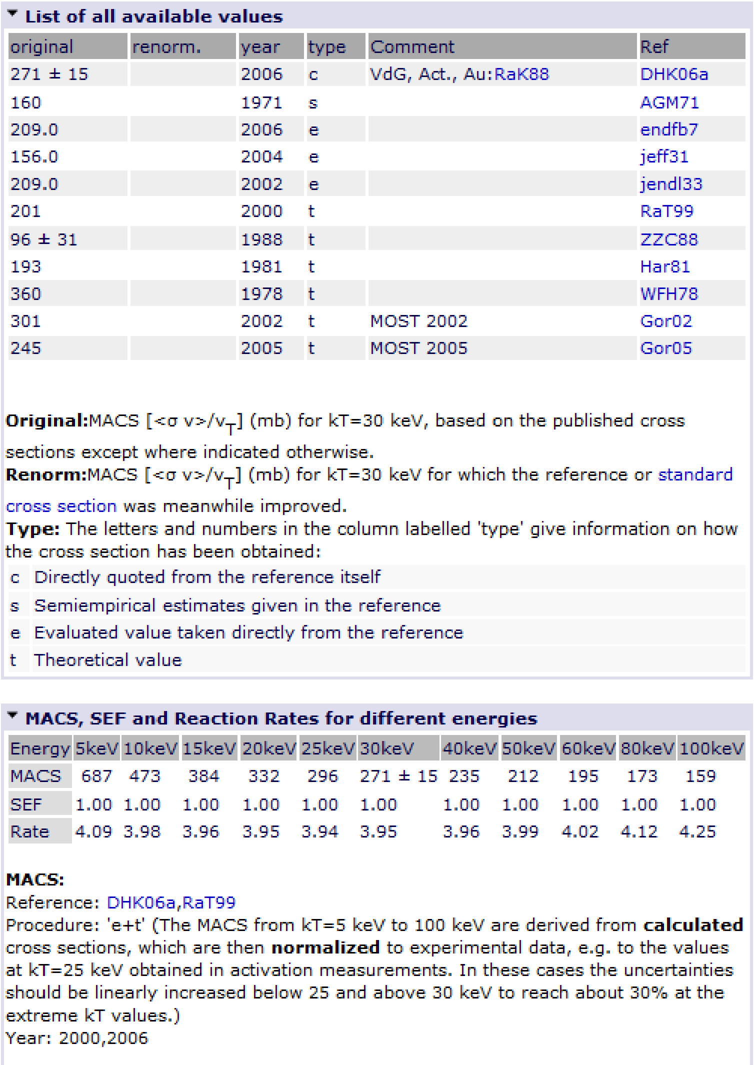
▼ History

Version	Total MACS [mb]	Partial to gs [mb]	Partial to isomer [mb]
0.2	271 ± 15	-	-
0.0	267 ± 25*	-	-

(Version 0.0 corresponds to Bao et al.)

▼ Comment

Previous MACS vs. kT table multiplied by 1.015.
Last review: January 30th, 2006



▼ List of all available values

original	renorm.	year	type	Comment	Ref
271 ± 15		2006	c	VdG, Act., Au:RaK88	DHK06a
160		1971	s		AGM71
209.0		2006	e		endfb7
156.0		2004	e		jeff31
209.0		2002	e		jendl33
201		2000	t		RaT99
96 ± 31		1988	t		ZZC88
193		1981	t		Har81
360		1978	t		WFH78
301		2002	t	MOST 2002	Gor02
245		2005	t	MOST 2005	Gor05

Original:MACS [<σ v>/v_T] (mb) for kT=30 keV, based on the published cross sections except where indicated otherwise.
Renorm:MACS [<σ v>/v_T] (mb) for kT=30 keV for which the reference or standard cross section was meanwhile improved.
Type: The letters and numbers in the column labelled 'type' give information on how the cross section has been obtained:

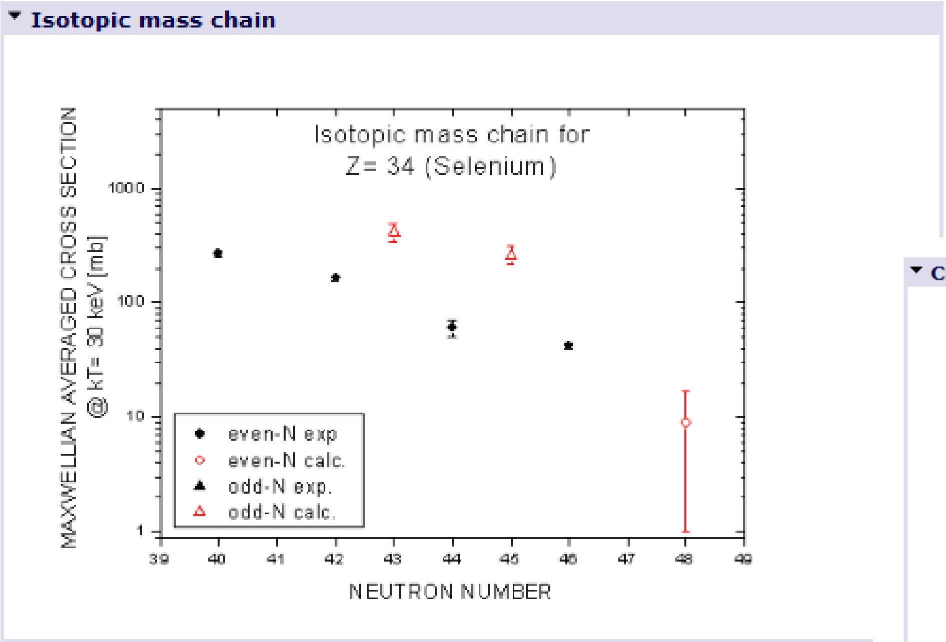
c	Directly quoted from the reference itself
s	Semiempirical estimates given in the reference
e	Evaluated value taken directly from the reference
t	Theoretical value

▼ MACS, SEF and Reaction Rates for different energies

Energy	5keV	10keV	15keV	20keV	25keV	30keV	40keV	50keV	60keV	80keV	100keV
MACS	687	473	384	332	296	271 ± 15	235	212	195	173	159
SEF	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Rate	4.09	3.98	3.96	3.95	3.94	3.95	3.96	3.99	4.02	4.12	4.25

MACS:
Reference: DHK06a,RaT99
Procedure: 'e+t' (The MACS from kT=5 keV to 100 keV are derived from **calculated** cross sections, which are then **normalized** to experimental data, e.g. to the values at kT=25 keV obtained in activation measurements. In these cases the uncertainties should be linearly increased below 25 and above 30 keV to reach about 30% at the extreme kT values.)
Year: 2000,2006

KADoNiS data sheets



Isotopic mass chain

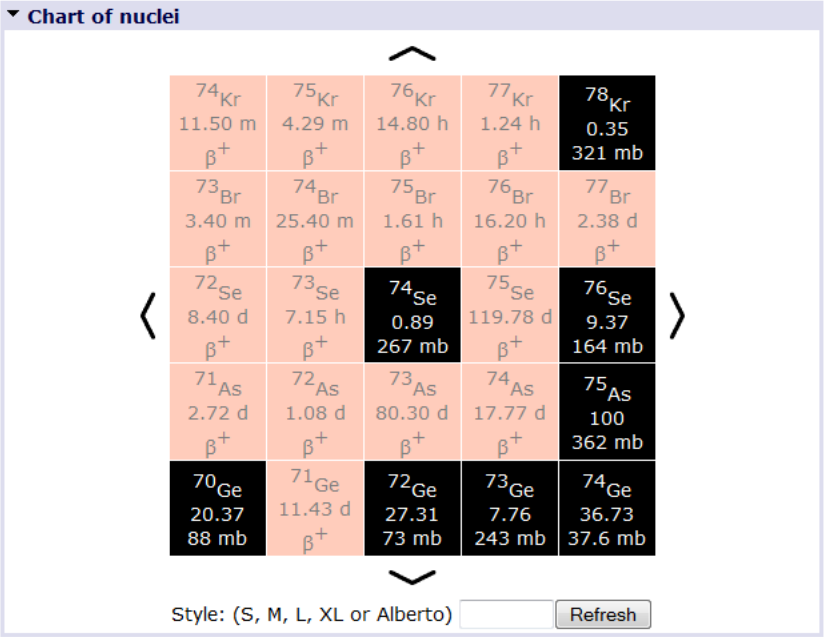


Chart of nuclei

^{74}Kr 11.50 m β^+	^{75}Kr 4.29 m β^+	^{76}Kr 14.80 h β^+	^{77}Kr 1.24 h β^+	^{78}Kr 0.35 321 mb
^{73}Br 3.40 m β^+	^{74}Br 25.40 m β^+	^{75}Br 1.61 h β^+	^{76}Br 16.20 h β^+	^{77}Br 2.38 d β^+
^{72}Se 8.40 d β^+	^{73}Se 7.15 h β^+	^{74}Se 0.89 267 mb	^{75}Se 119.78 d β^+	^{76}Se 9.37 164 mb
^{71}As 2.72 d β^+	^{72}As 1.08 d β^+	^{73}As 80.30 d β^+	^{74}As 17.77 d β^+	^{75}As 100 362 mb
^{70}Ge 20.37 88 mb	^{71}Ge 11.43 d β^+	^{72}Ge 27.31 73 mb	^{73}Ge 7.76 243 mb	^{74}Ge 36.73 37.6 mb

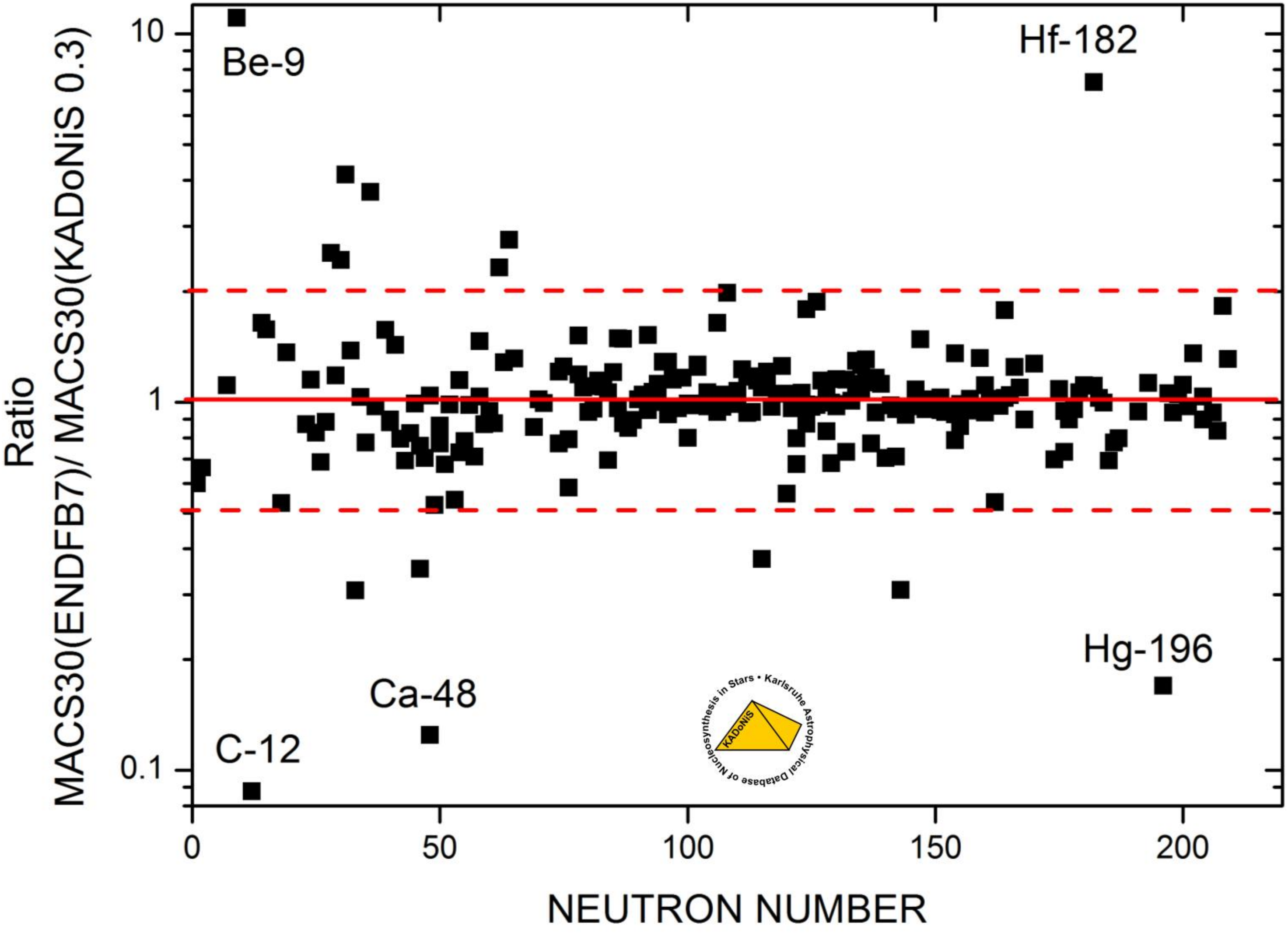
Style: (S, M, L, XL or Alberto) ☐ Refresh

Isotope: Selenium

Last modification: August, 2009 by Ralf Plag

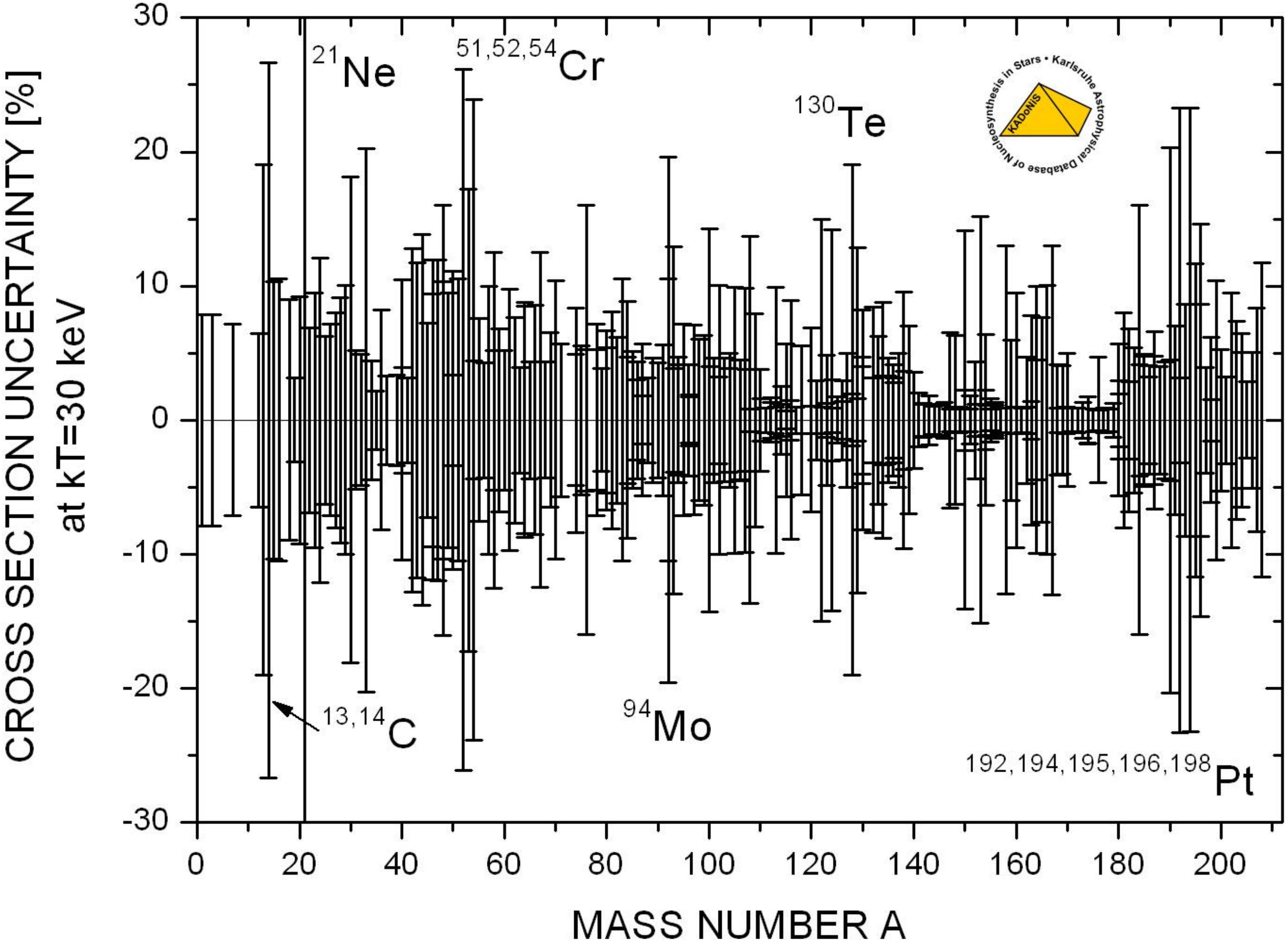
This page is **not** optimized for Microsoft Internet Explorer.

Comparison with ENDF/B-VII.0



Missing:
Ne
Zn
Yb
Ta
Os
Pt
Tl

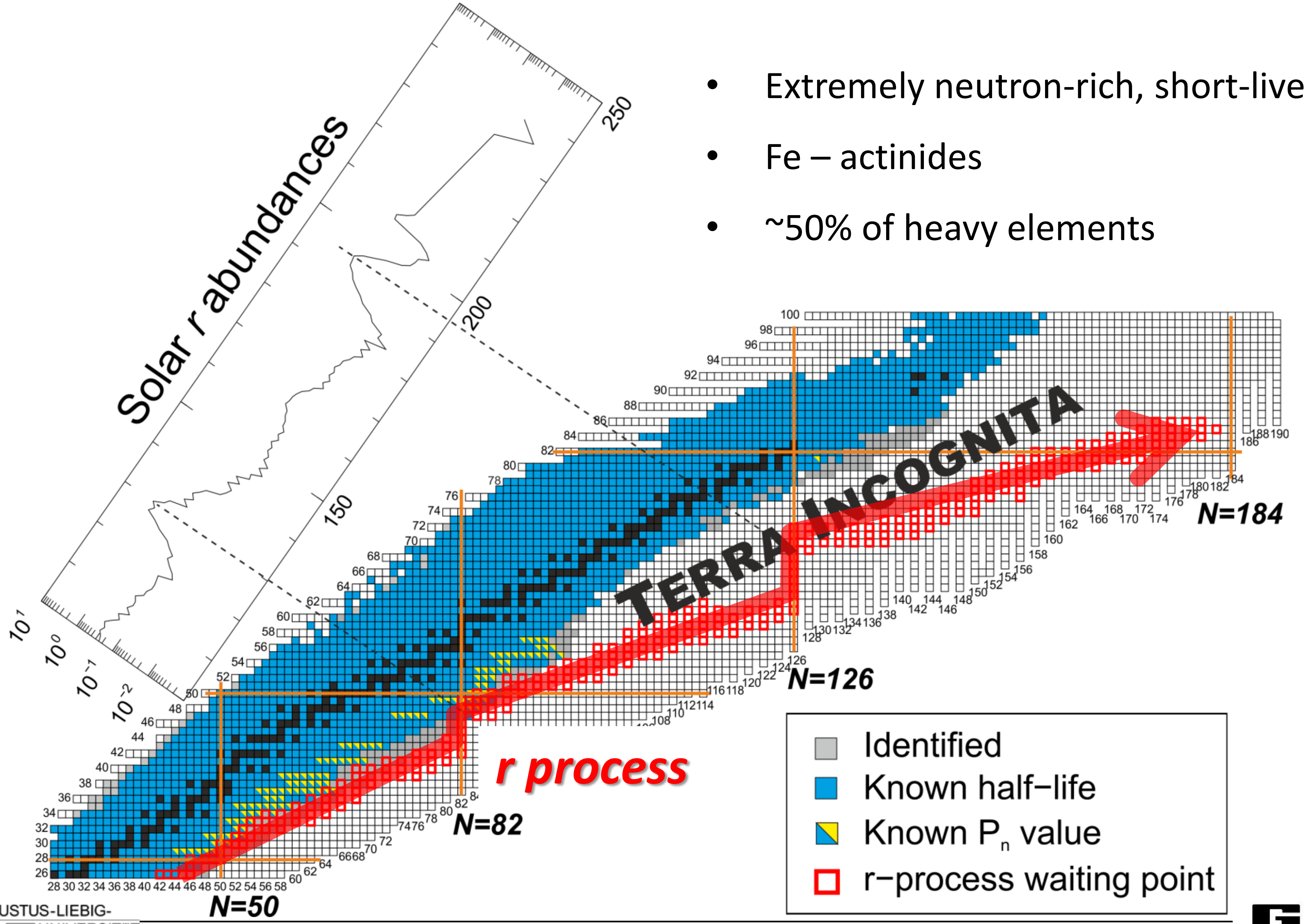
KADoNiS



Average experimental uncertainty: +/- 6.5 %

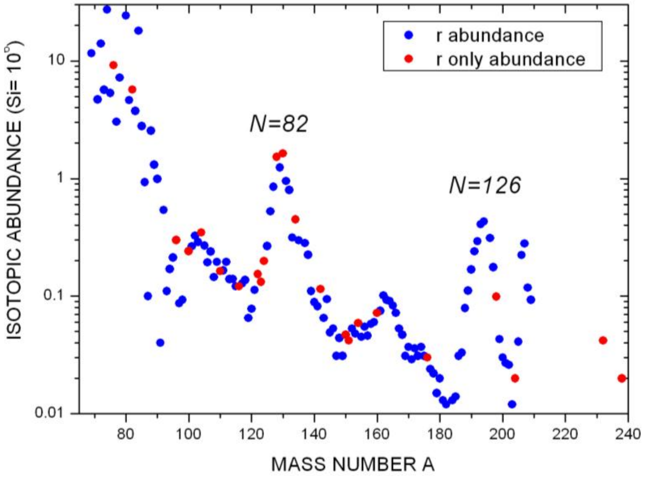
The "rapid neutron capture process“

- Extremely neutron-rich, short-lived isotopes
- Fe – actinides
- ~50% of heavy elements



The "rapid neutron capture process“

$$N_r = N_\odot - N_s$$

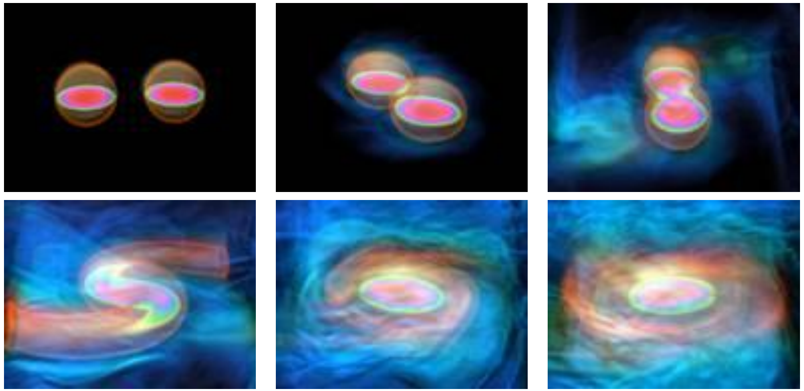


- High neutron densities (n_n>> 10^{20} cm^{-3})
  ⇨ ~1 ms per capture
- “Moderate” temperatures (T=1-2 GK)

⇨ ^{56}Fe to ~Pu (Z=94, A~260) in few seconds

- End point: fission barriers (theory!) ⇨ “fission recycling” (2x A~130)
- Astrophysical scenario: still under discussion

Neutron star mergers?



Core collapse supernova ?

Input for network calculations

During equilibrium phase:

Astrophysical parameters

Neutron density ($n_n \geq 10^{20}$ cm^{-3})
Temperature (T> 1 GK)
Duration of neutron exposure (few seconds)

Half-lives (s- ms): Shape
Masses ($S_n \approx$2-3 MeV, Q_β): Path

Calculation of progenitor abundances

Nuclear physics parameters: Experiments + Theory

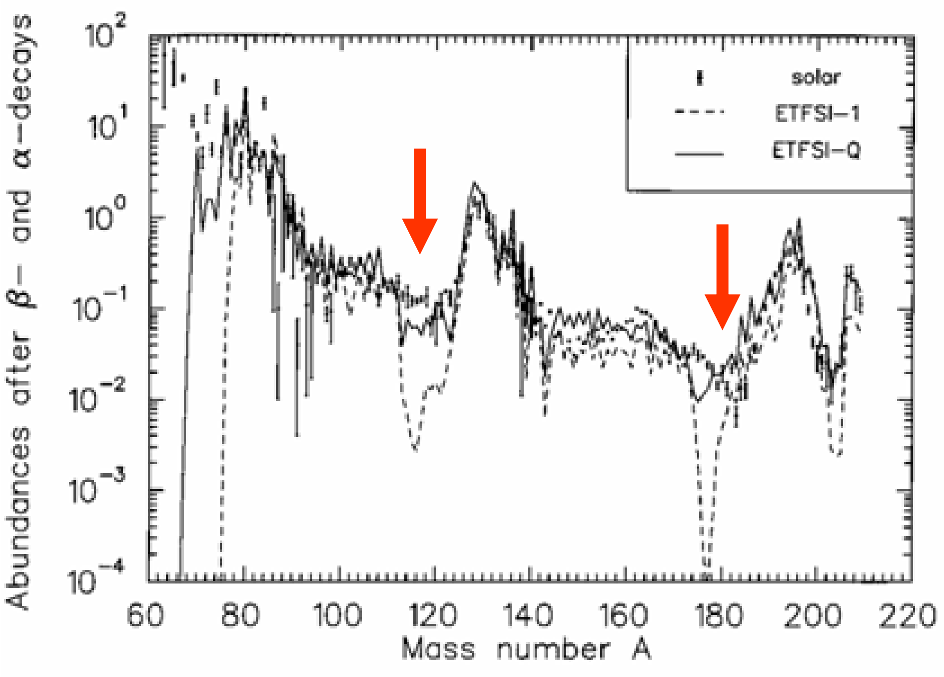
During "Freeze out" phase:

(n,γ)/ (γ,n) cross sections
β-delayed neutron emission (P_n)
Z>80: fission barriers, β-delayed fission,
(n,f)-cross sections
$t_{1/2}(\alpha)$ for A>210

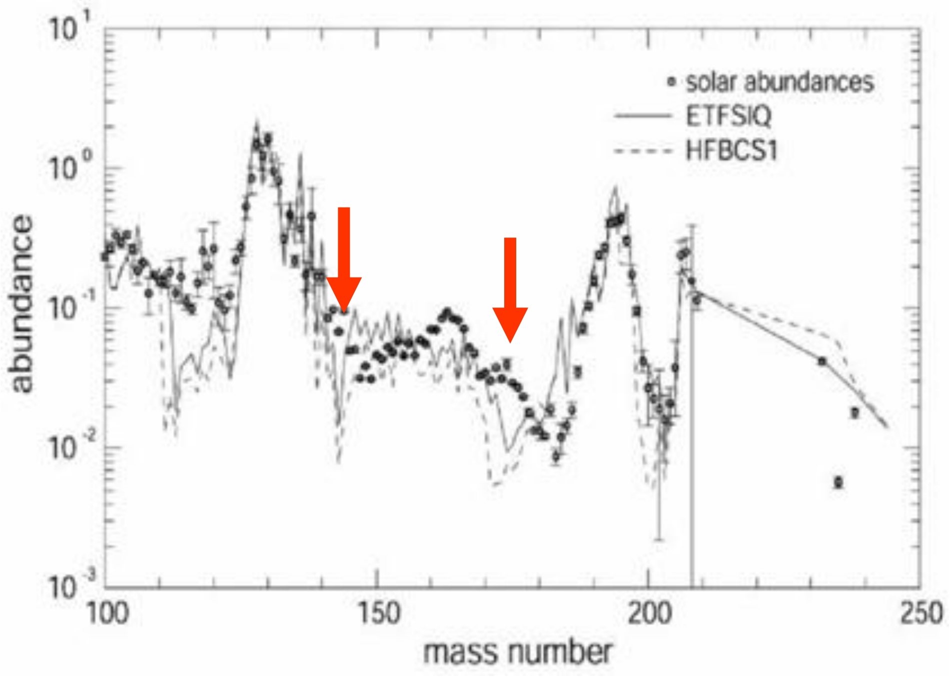
Comparison with solar r abundances

r-process calculations vs. solar

- **Strongly dependent on mass models!**



C. Freiburghaus et al., Ap. J. 516 (1999) 381



H. Schatz et al., Ap. J. 579 (2002) 626

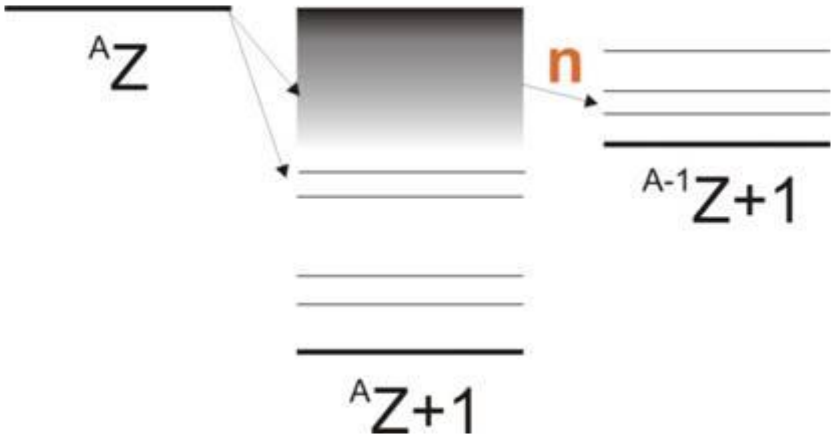
β-delayed 1 and 2 neutron emission (P_{1n}, P_{2n})

$S_n < Q_\beta$

Important nuclear structure information

P_n : β-strength above S_n

$t_{1/2}(^{A}Z+1)$: sensitive to low-lying β-strength

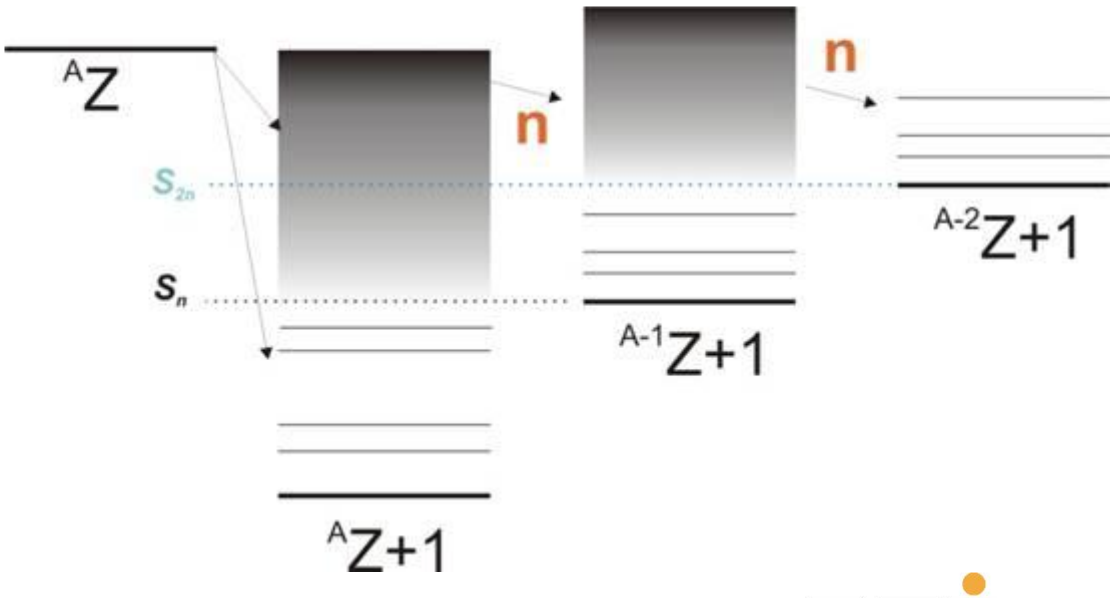


From time-dependence of n-emission: $t_{1/2}(^{A}Z)$

$S_{2n} < Q_\beta$

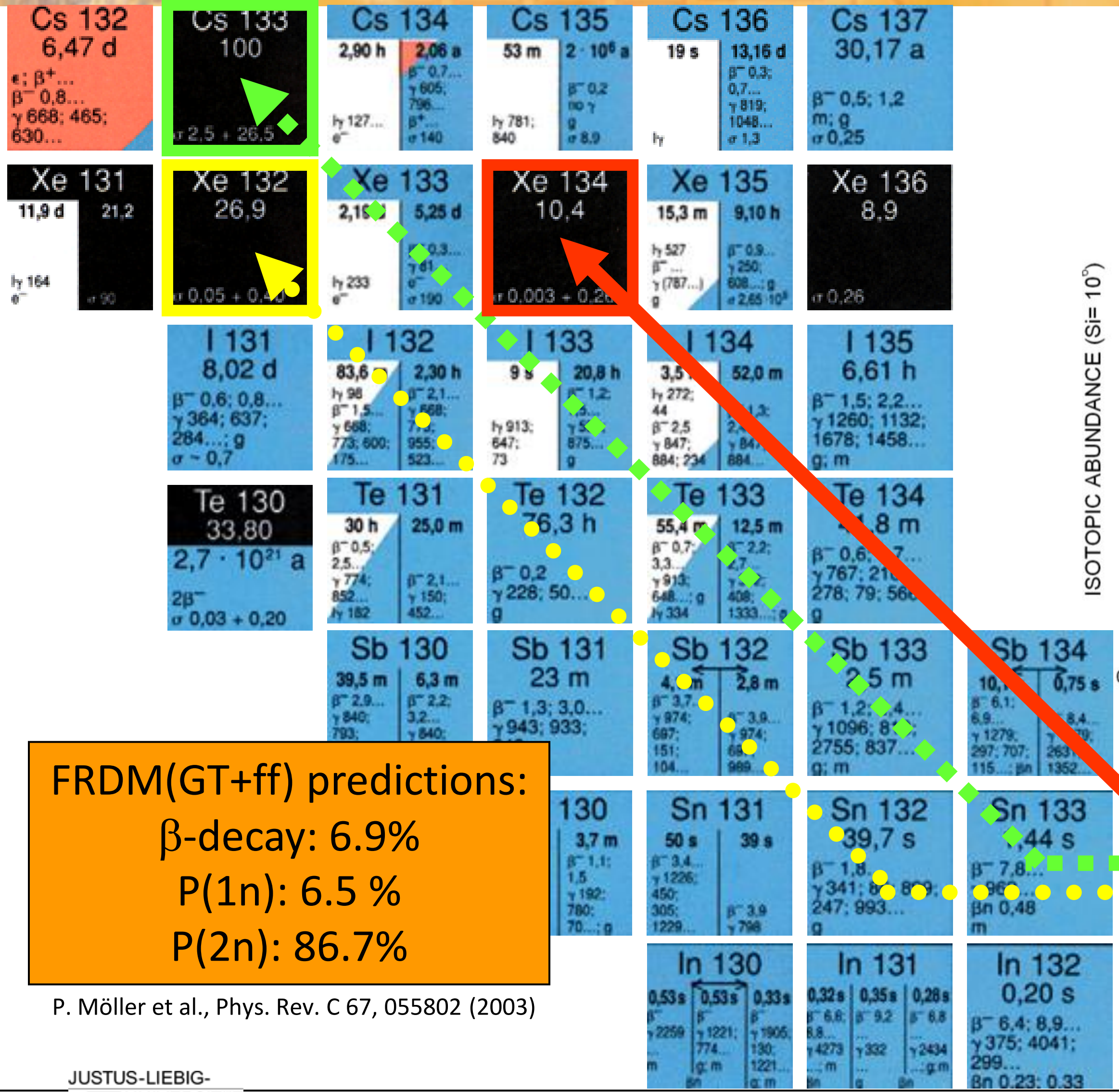
First experimental identification:

- **^{11}Li** ($t_{1/2}$= 8.6 ms) @ISOLDE:
  Azuma et al., PRL 43, 1652 (1979)
- **$^{30\text{-}32}$Na** ($t_{1/2}$= 13-48 ms) @ISOLDE:
  Detraz et al., Phys. Lett. 94B, 307 (1980)
- **^{98}Rb** ($t_{1/2}$= 114 ms) @TRISTAN:
  Reeder et al., PRL 47, 483 (1981)



▸ **Accurate mass measurements needed for predictions!**

Astrophysical influence of P_{1n} and P_{2n}

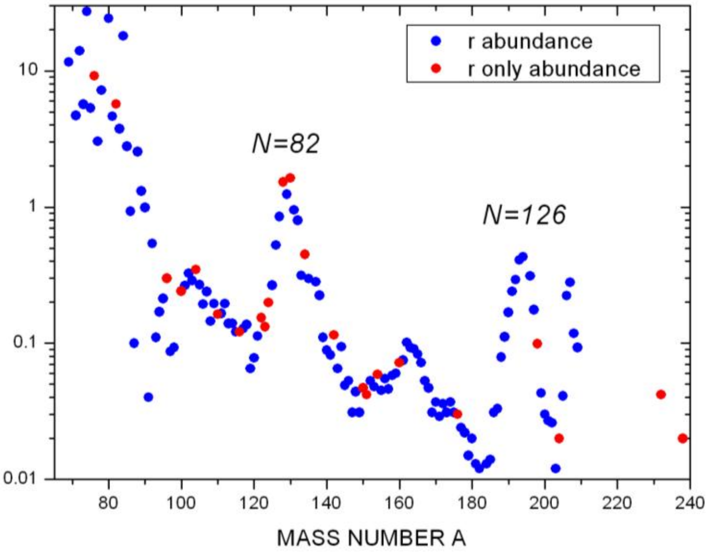


In 134
138 ms
βn, β2n

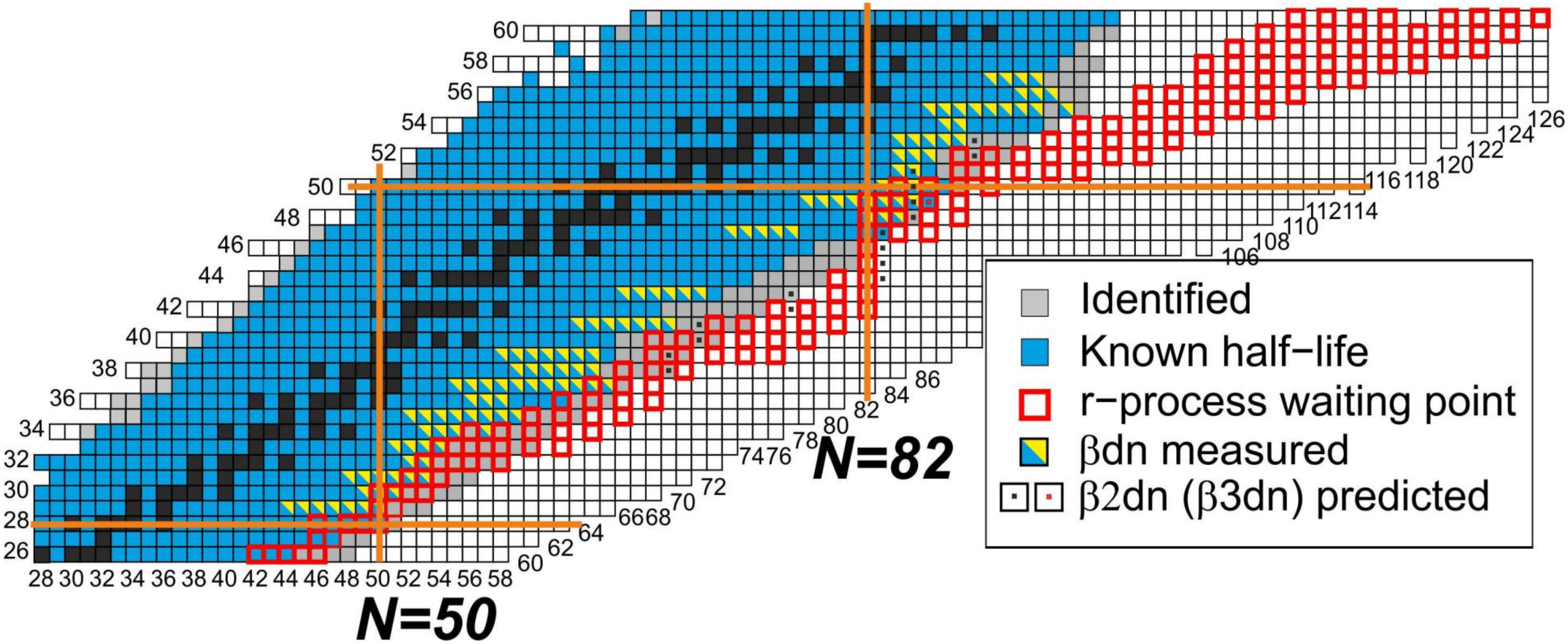
FRDM(GT+ff) predictions:
β-decay: 6.9%
P(1n): 6.5 %
P(2n): 86.7%

P. Möller et al., Phys. Rev. C 67, 055802 (2003)

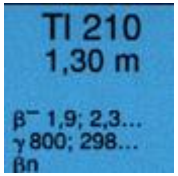
During „Freeze-out“:
detour of β-decay chains
⇨ *solar r-abundance changes*



Status P_n for astrophysics



- ^{8}He- ^{150}La: ~200 datasets available, ~75 in non-fission region (A<70)
- Only 1 measurement for A>150:



Tl 210
1,30 m

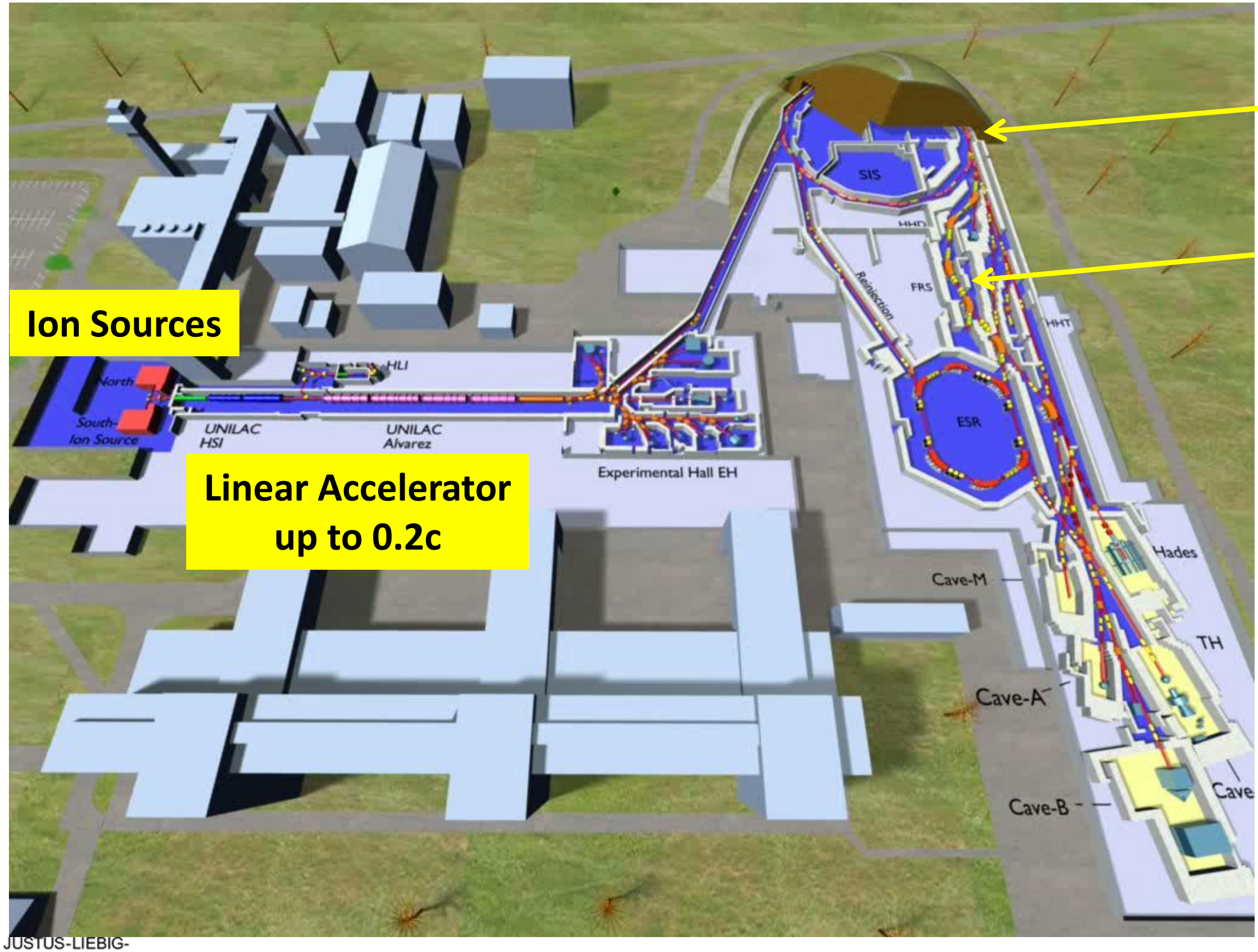
β^- 1,9; 2,3...
γ 800; 298...
βn

P_n= 0.007 (+0.007 -0.004) %

Validation missing

G. Stetter, Nucl. Sci. Abstr. 16, 1409, Abstr.10963 (1962)

GSI Heavy Ion Research Center Darmstadt/Germany



Ion Sources

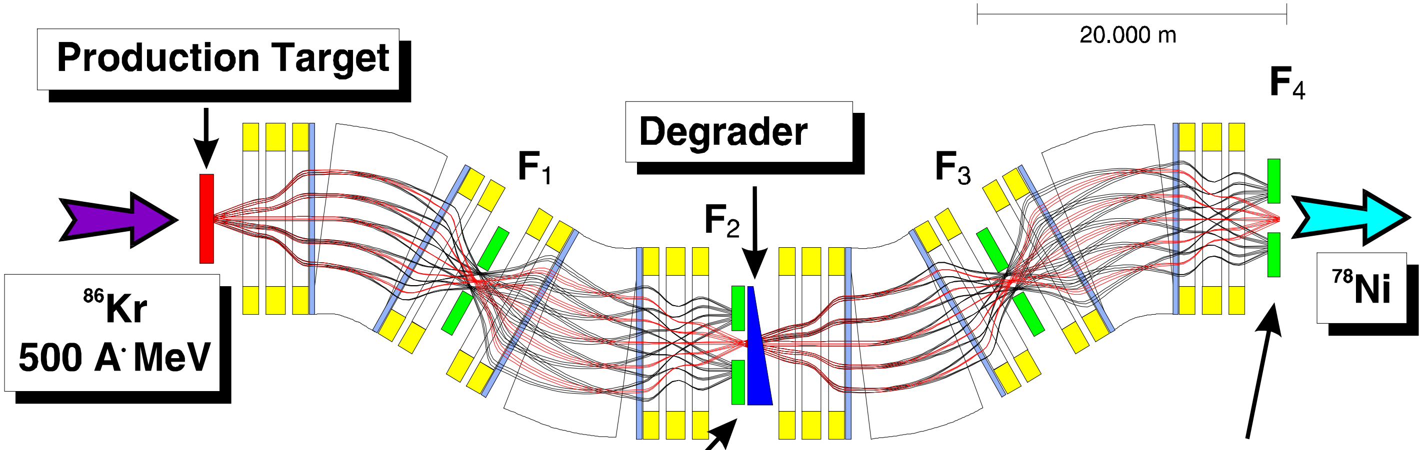
Linear Accelerator
up to 0.2c

SchwerIonen
Synchrotron
(up to 0.9c)

FRagment
Separator

1 GeV/u ^{238}U
1.5*10^9 pps
^{9}Be target

FRagment Separator: Bρ-ΔE-Bρ method


Production Target

^{86}Kr
500 A·MeV

F_1

Degrader

F_2

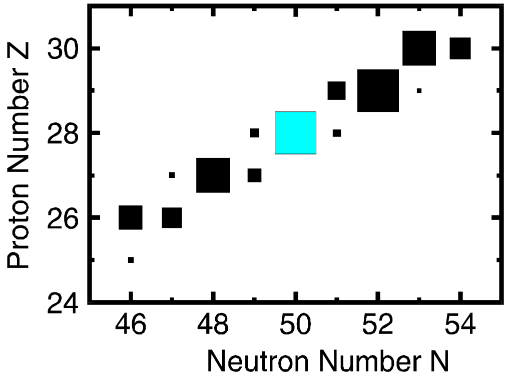
F_3

20.000 m

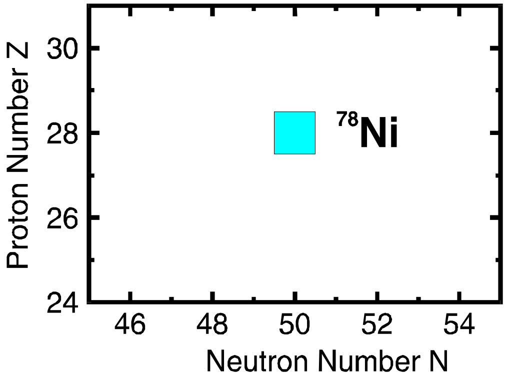
F_4

^{78}Ni

First Selection

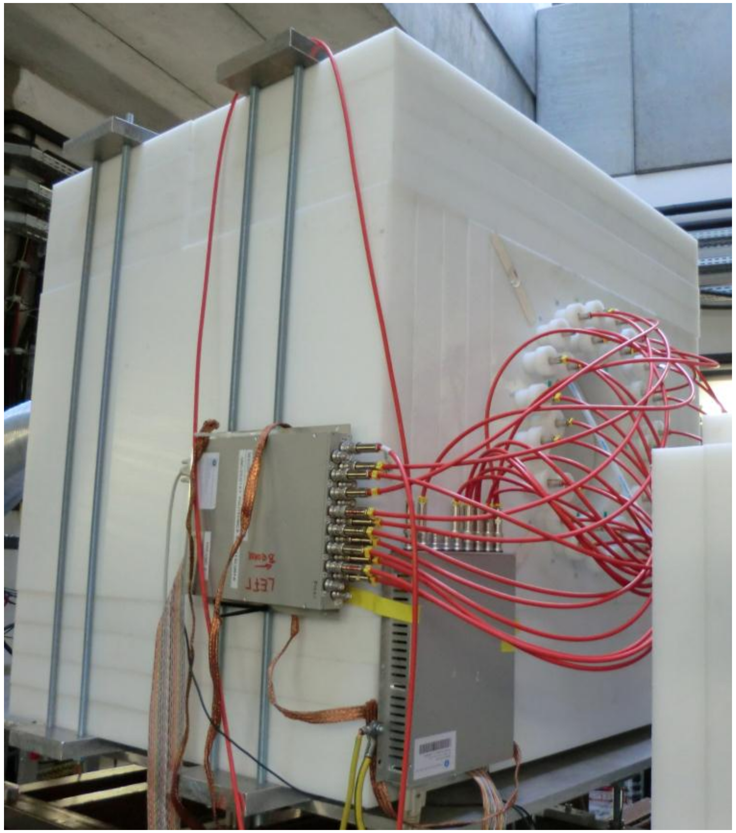


First and Second Selection



H. Geissel et al., NIM B 70, 286 (1992)

BEta deLayEd Neutron detector (BELEN-30)



30 high pressure ^{3}He long counters

PE matrix, size ~ 1m^3

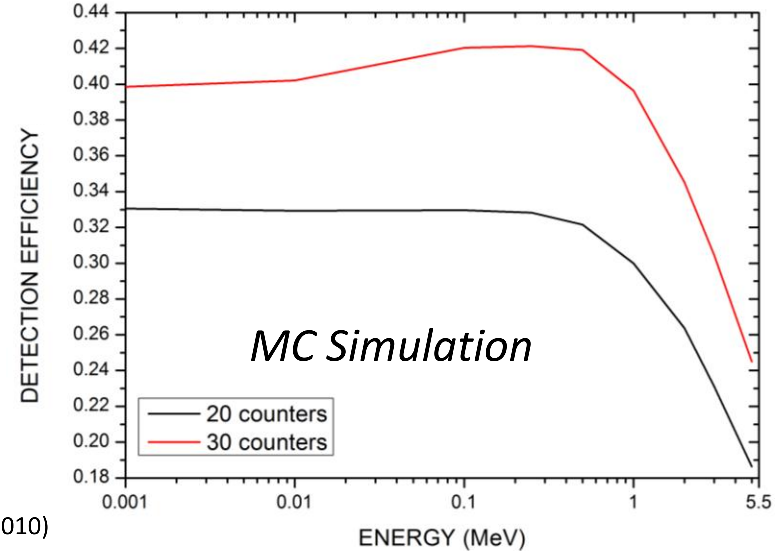
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

GSI

Universidad Politecnica de Cataluna, Barcelona

IFIC Valencia

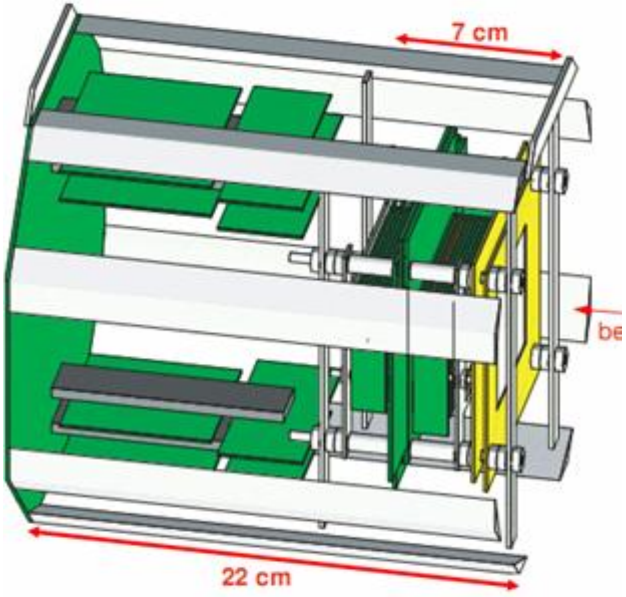
CIEMAT Madrid



MC Simulation

M.B. Gómez Hornillos et al., Proc. Int. Conf. on Nucl. Data for Science and Techn. (2010)

Silicon IMplantation detector and Beta Absorber



SIMBA
Constructed and developed at

Technische Universität München

Lehrstuhl E12

- 1 x- and 1 y-detector, 60x segmented each
- 2 SSSSD, 7x segmented in x
- 3 DSSSD (implantation area): 60x segmented in x-, 40x in y-direction
- 2 SSSSD, 7x segmented in x

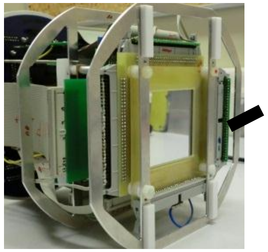
PhD thesis C. Hinke, TUM (2010)
Diploma thesis K. Steiger, TUM (2009)

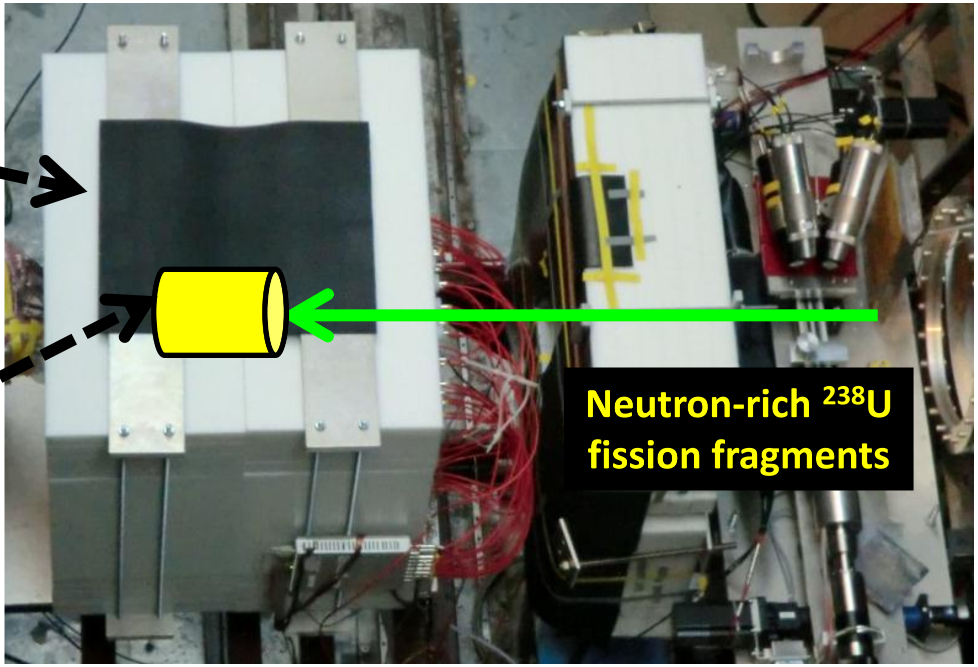
Pictures: K. Steiger

Setup at the FRS (Summer 2011)

Neutron detector BELEN-30

Implantation detector SIMBA



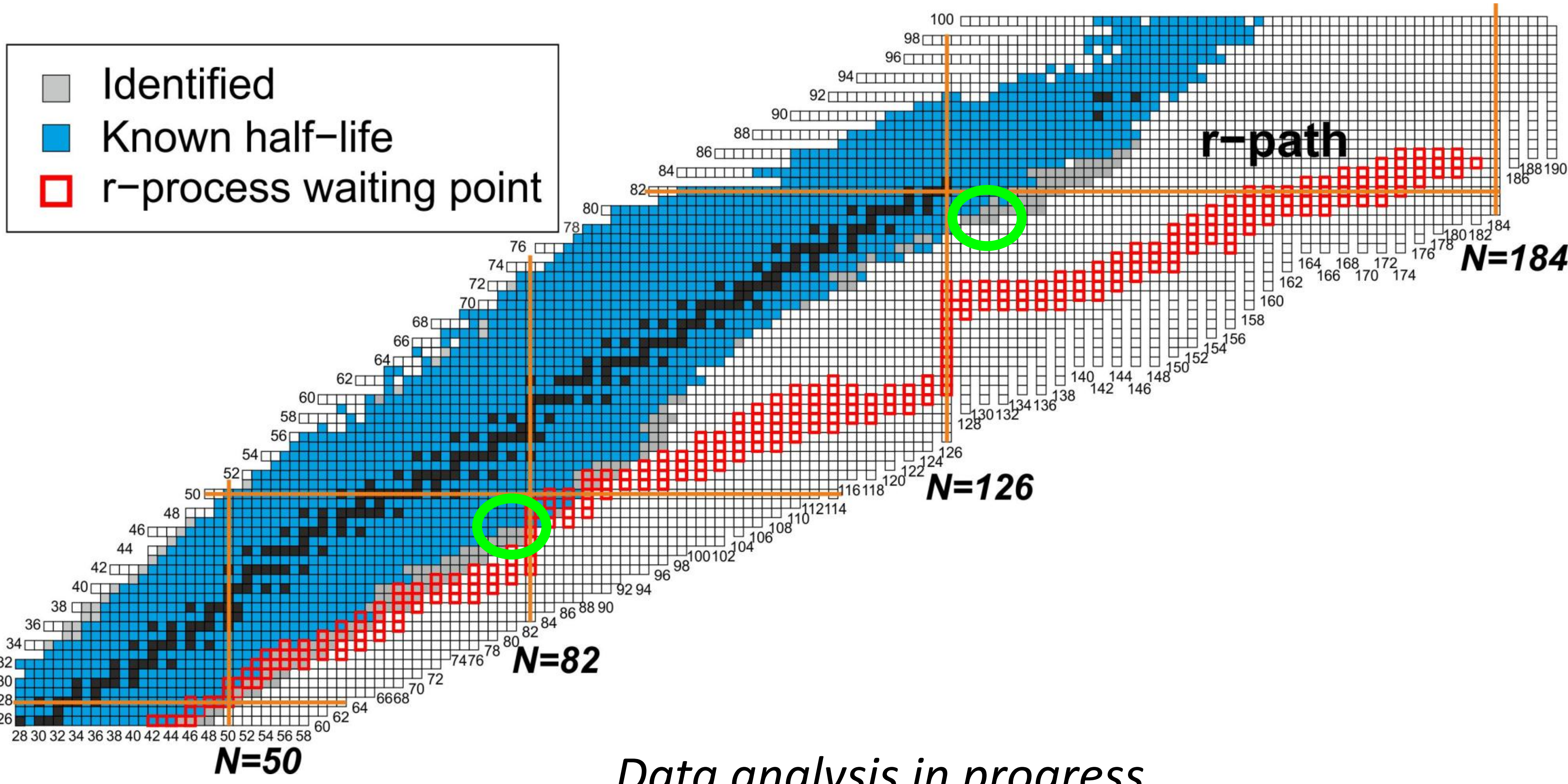


Next steps:

- Upgrade of detector: up to 90 counters (detection efficiency ~70%): collaboration with Dubna
- Measure P_{xn}
- Prepare for first experiments @FAIR/DESPEC (>2018)

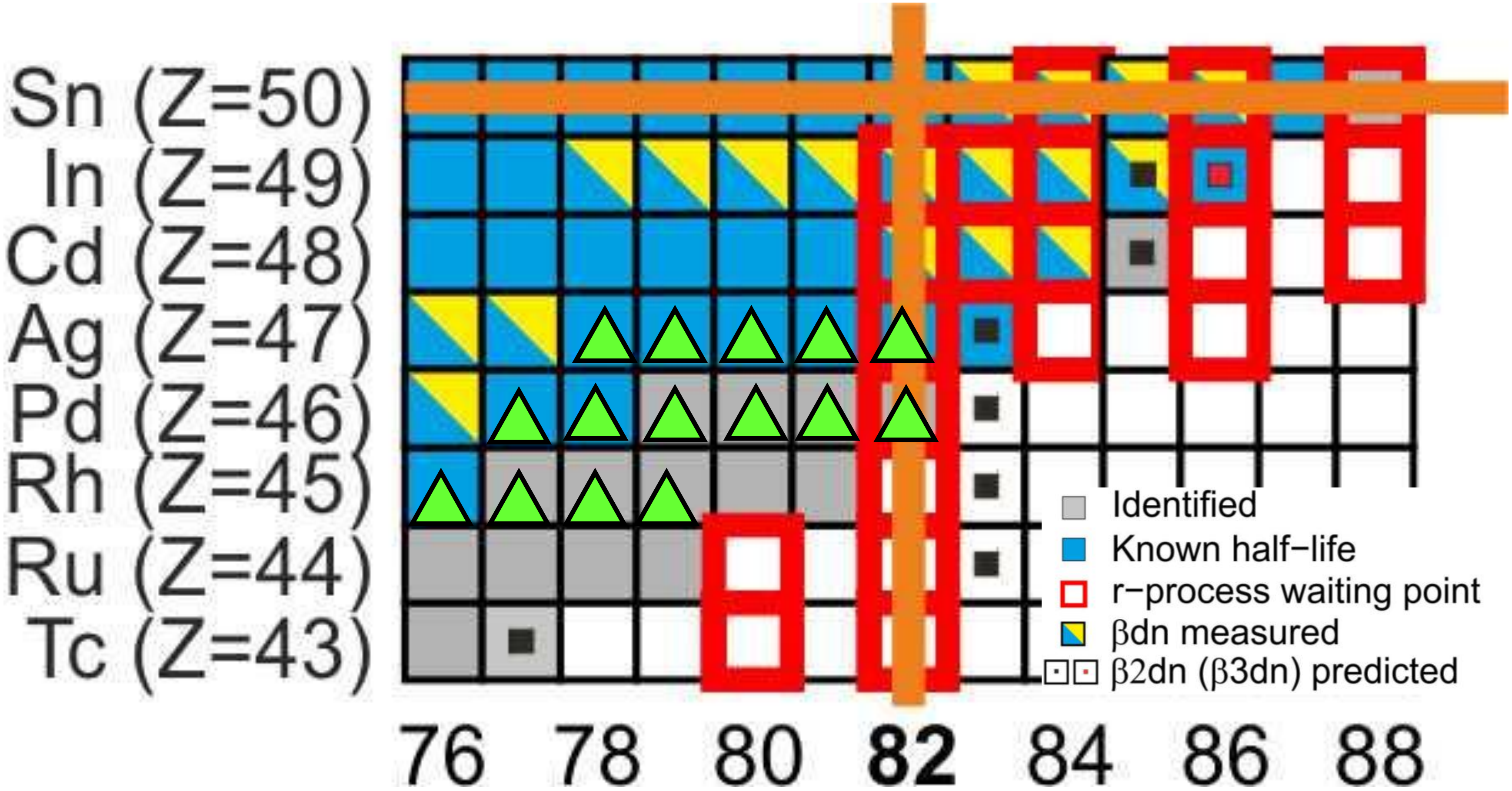
βdn measurements at GSI Darmstadt

2 weeks beamtime in September 2011



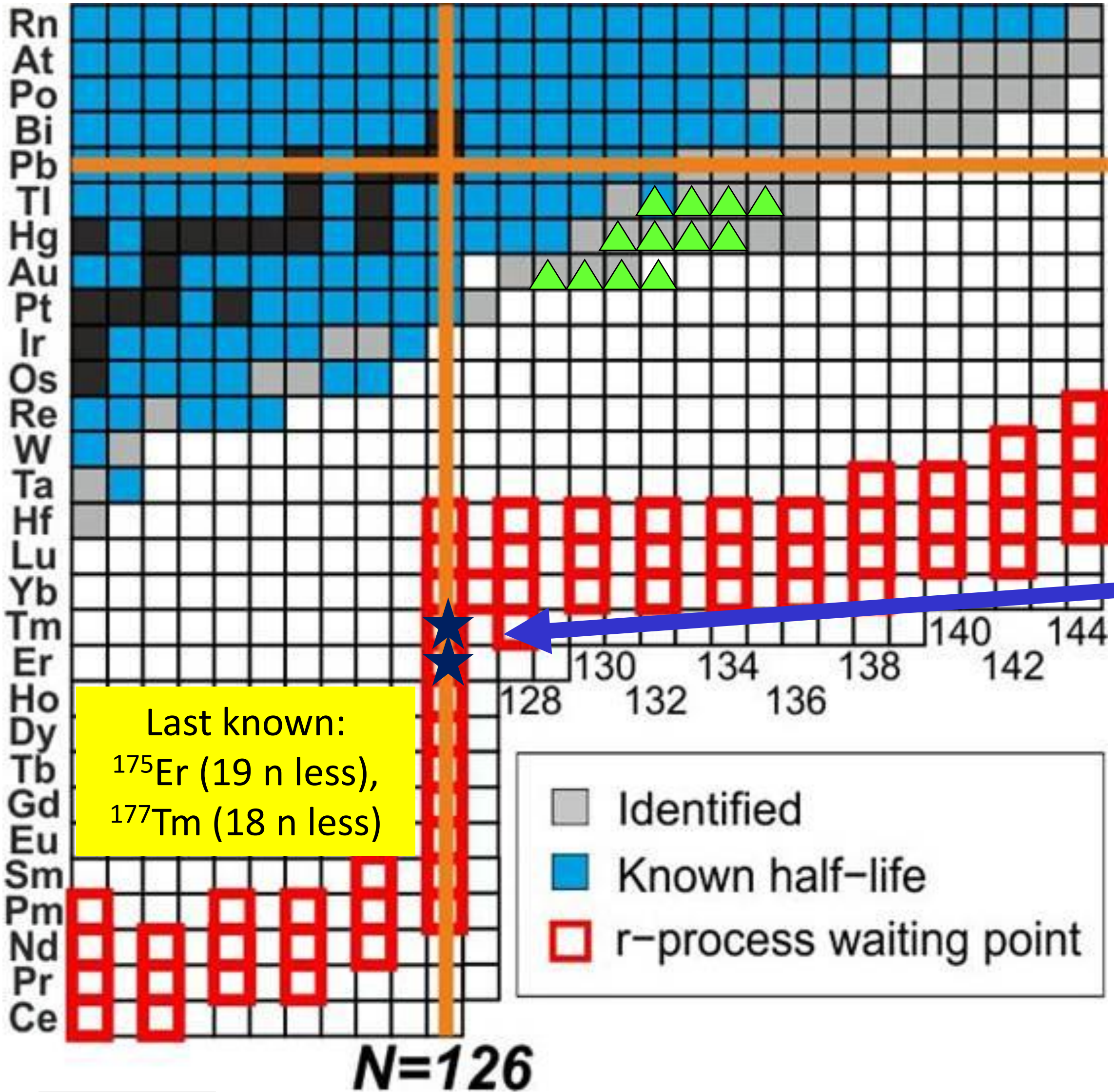
Data analysis in progress

N=82: Status and S323 proposal



△ **GSI proposal**

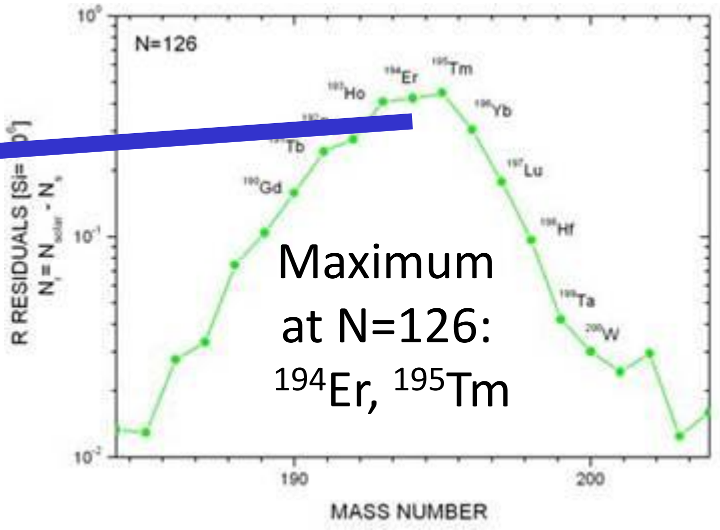
N=126: Status and S410 proposal



Last known:
^{175}Er (19 n less),
^{177}Tm (18 n less)

▲ **GSI proposal**

Will be heaviest βdn-emitters measured so far



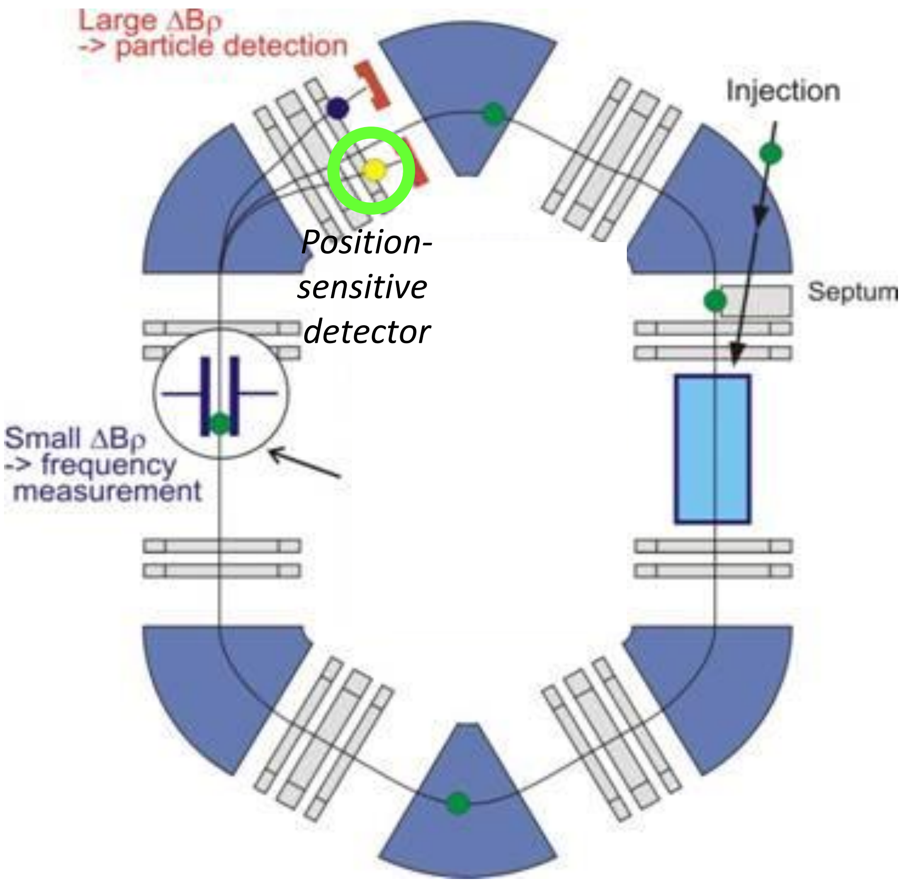
Maximum
at N=126:
^{194}Er, ^{195}Tm

…still long way to go…

Outlook 1: βdn in a storage ring?

Problems: High price of ^{3}He detectors due to shortage; Energy-dependent efficiencies

▸ alternative methods?

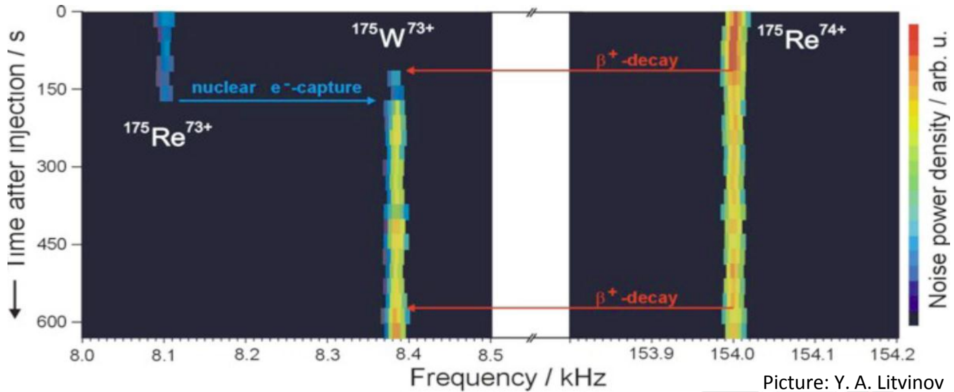


- Fully ionized βdn-mother ^{A}Z inserted into ESR
- Few (<10) ions ^{A}Z circulating (500 ns/turn): Half-lives down to ms and μs
- If decay in straight sections: deflection in next dipole

  2 possibilities:

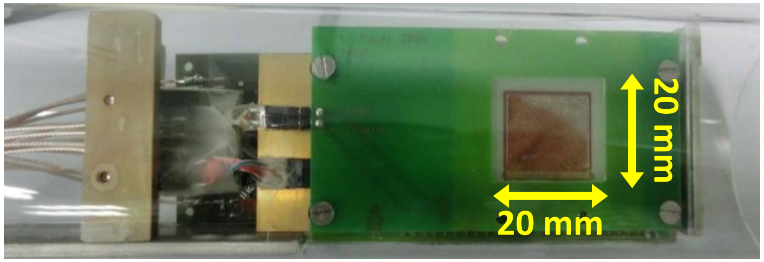
  ΔBρ< 3% ▸ β-decay and βdn: detected with Schottky pickups

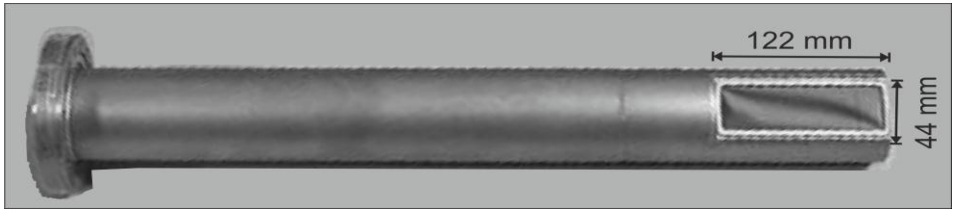
  ΔBρ> 3% ▸ detection with position sensitive detector

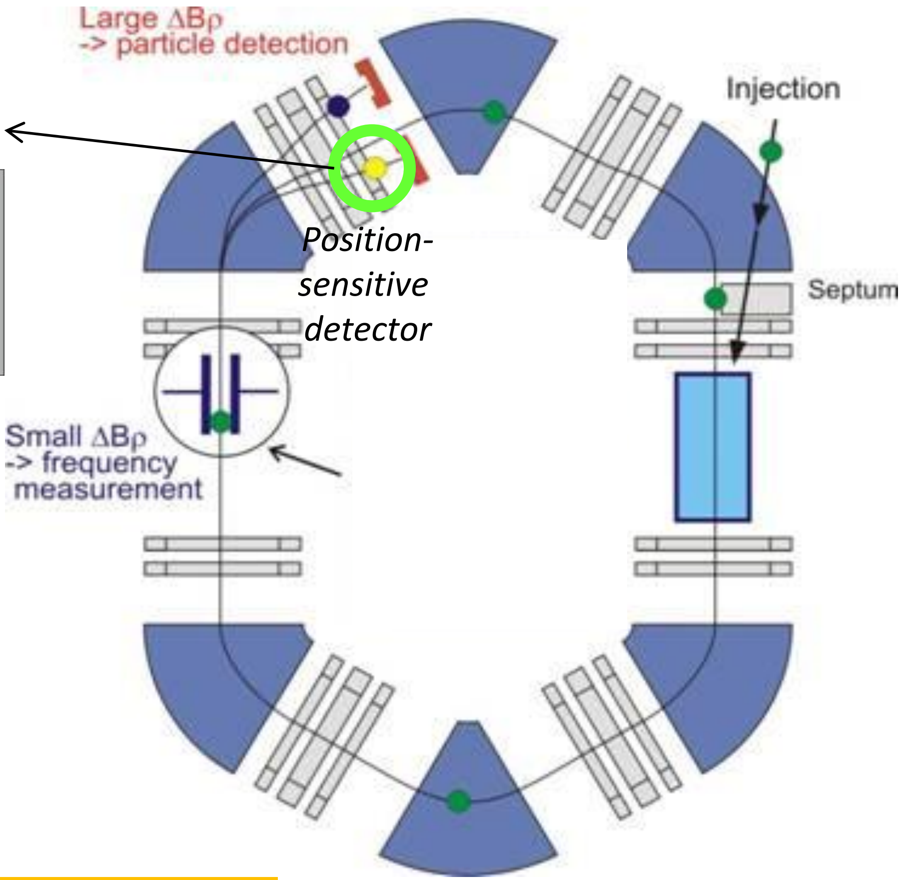


Picture: Y. A. Litvinov

Outlook 1: βdn in a storage ring?





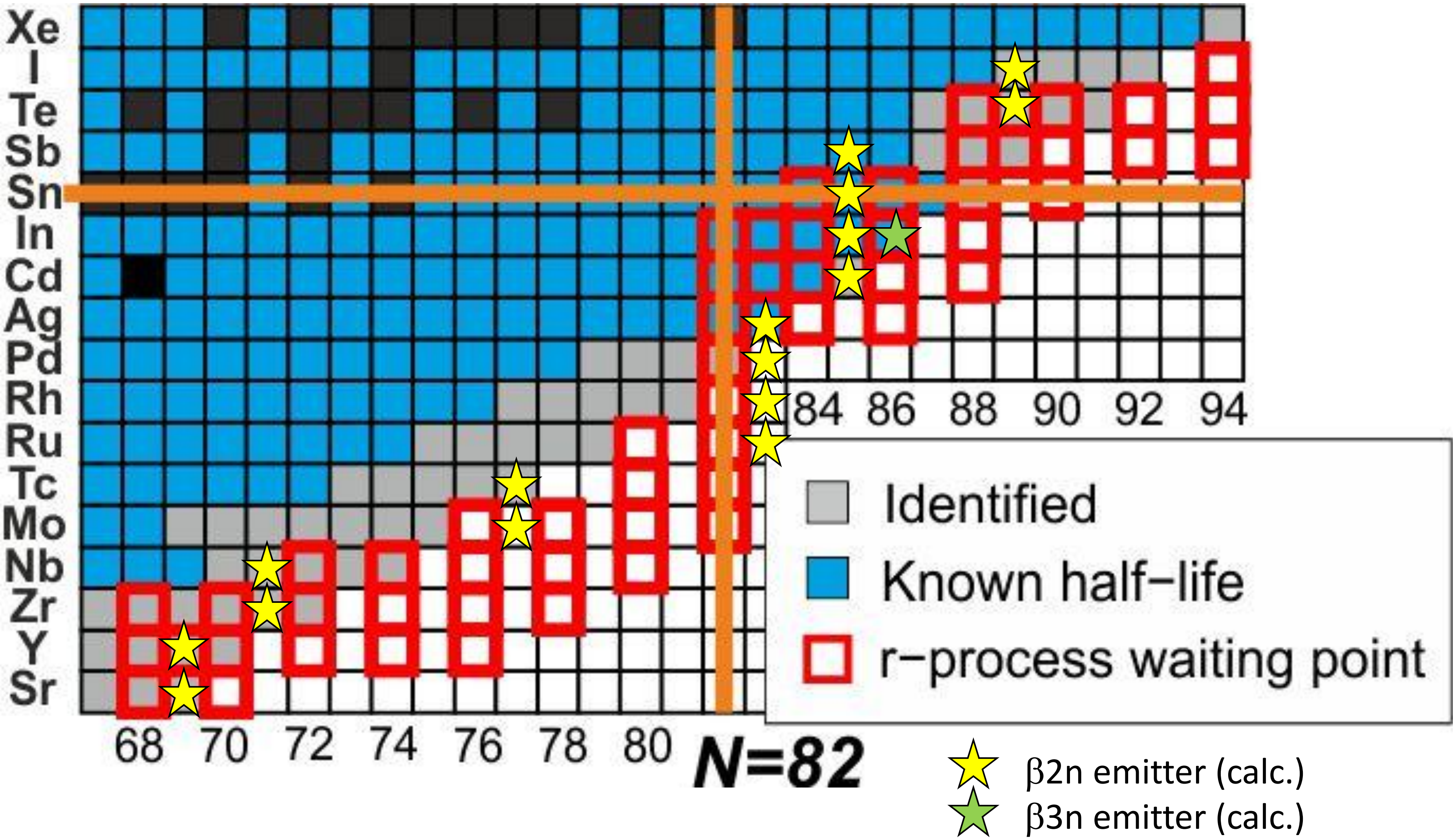


Problems

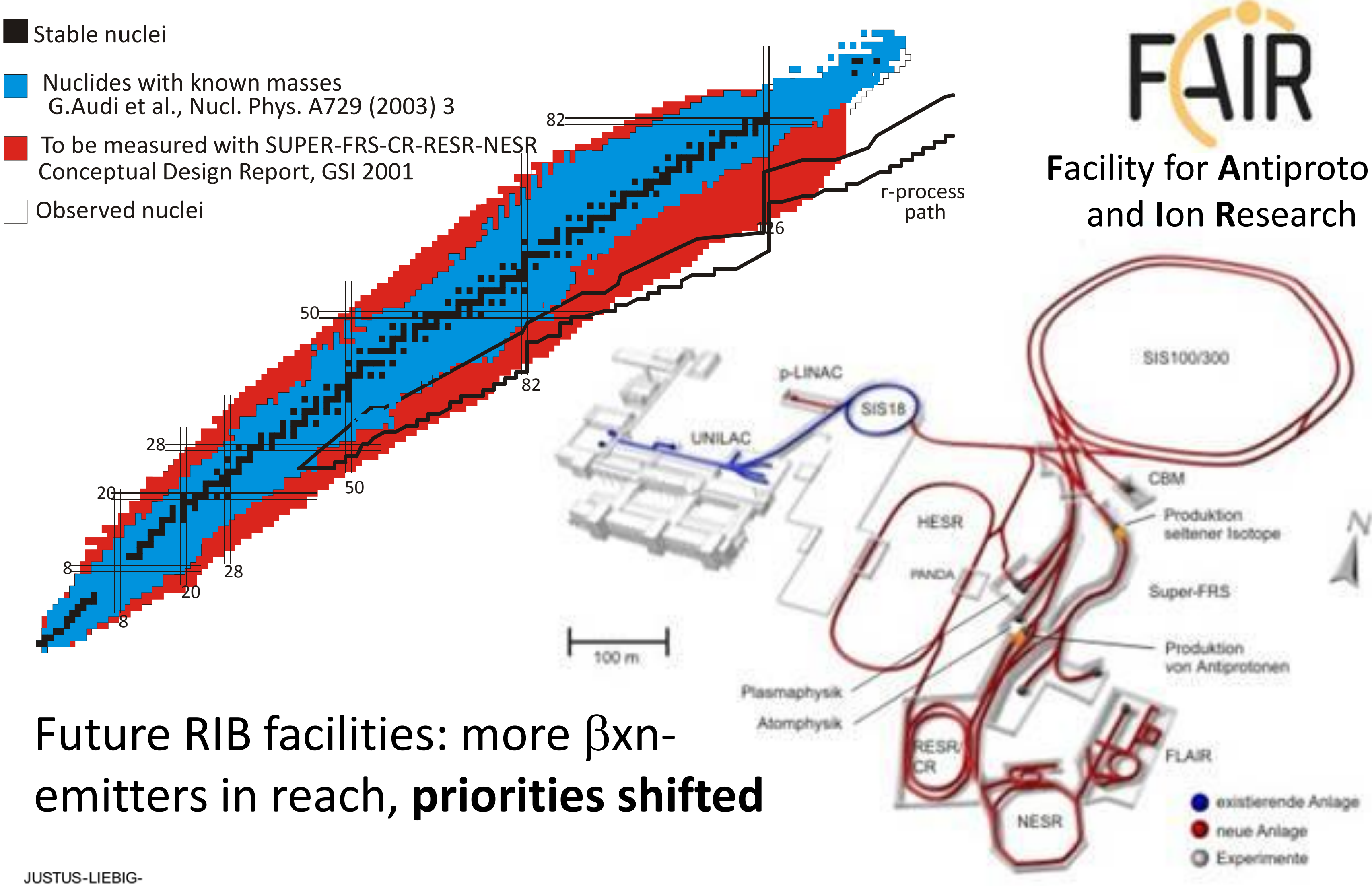
- Losses due to transfer from FRS into ESR
- Short-lived isotopes ($t_{1/2} < 1$ s): No electron cooling possible
  - ▸ Test with longer-lived βdn-emitters (A~210)
- Reconstruction and identification of mother
- Low detection efficiency (▸ 2nd detector)

Complementary method: no detection of neutron, independent of neutron energy

Outlook 2: Measure P_{2n} and P_{3n}



Outlook 3: RIB facilities

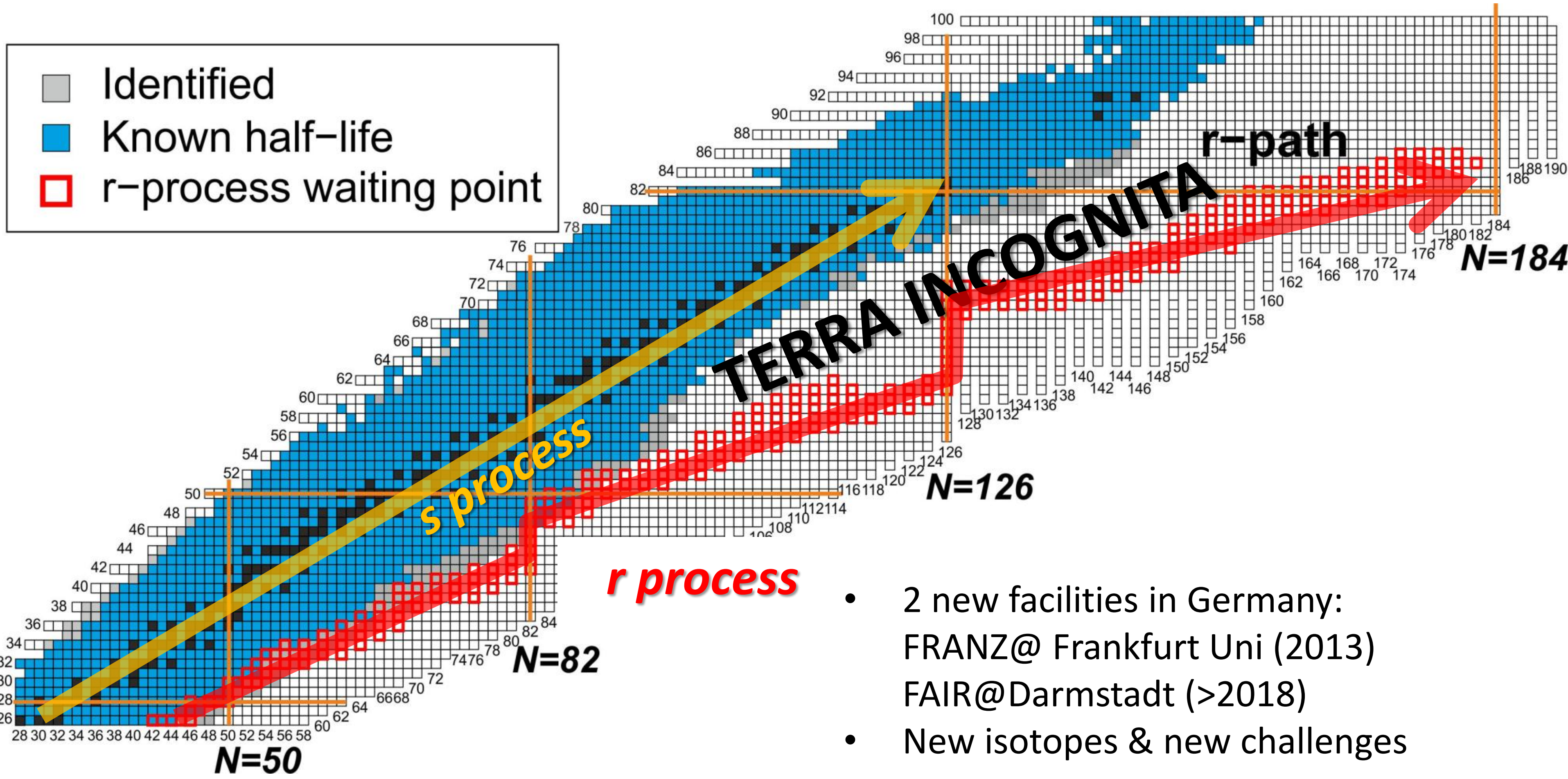


Facility for **A**ntiproton and **I**on **R**esearch

Future RIB facilities: more βxn-emitters in reach, **priorities shifted**

Summary: Nuclear Astrophysics with Neutrons

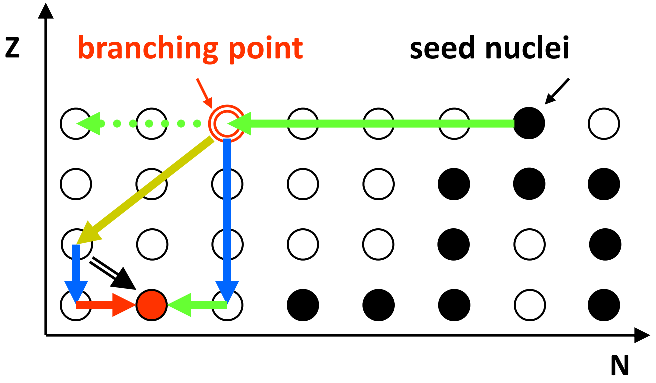
- "rapid" and "slow" neutron capture process

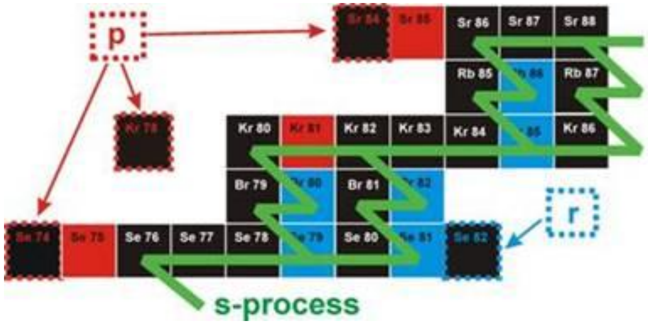


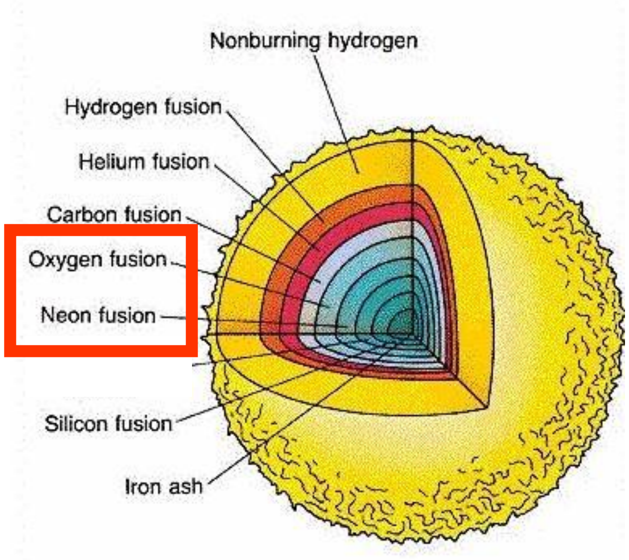
- 2 new facilities in Germany:
  FRANZ@ Frankfurt Uni (2013)
  FAIR@Darmstadt (>2018)
- New isotopes & new challenges

The „p processes“: To p or not to p

- **Superposition** of independent processes? **$p = \gamma$ (+ rp?) + νp + ν**
- **„γ process“: Expl. O/Ne burning** during **core collapse SN** in massive stars
- Shock front heats shells up to 2-3 GK ⇨ Explosive burning for 1-10 s
- **Photodisintegration** of pre-existing heavy (s or r) seed nuclei
- Formation of >30 stable isotopes between **^{74}Se and ^{196}Hg**







~1% of abundances >Fe