Nuclear Astrophysics with Neutrons

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Overview

1. Synthesis of heavy elements

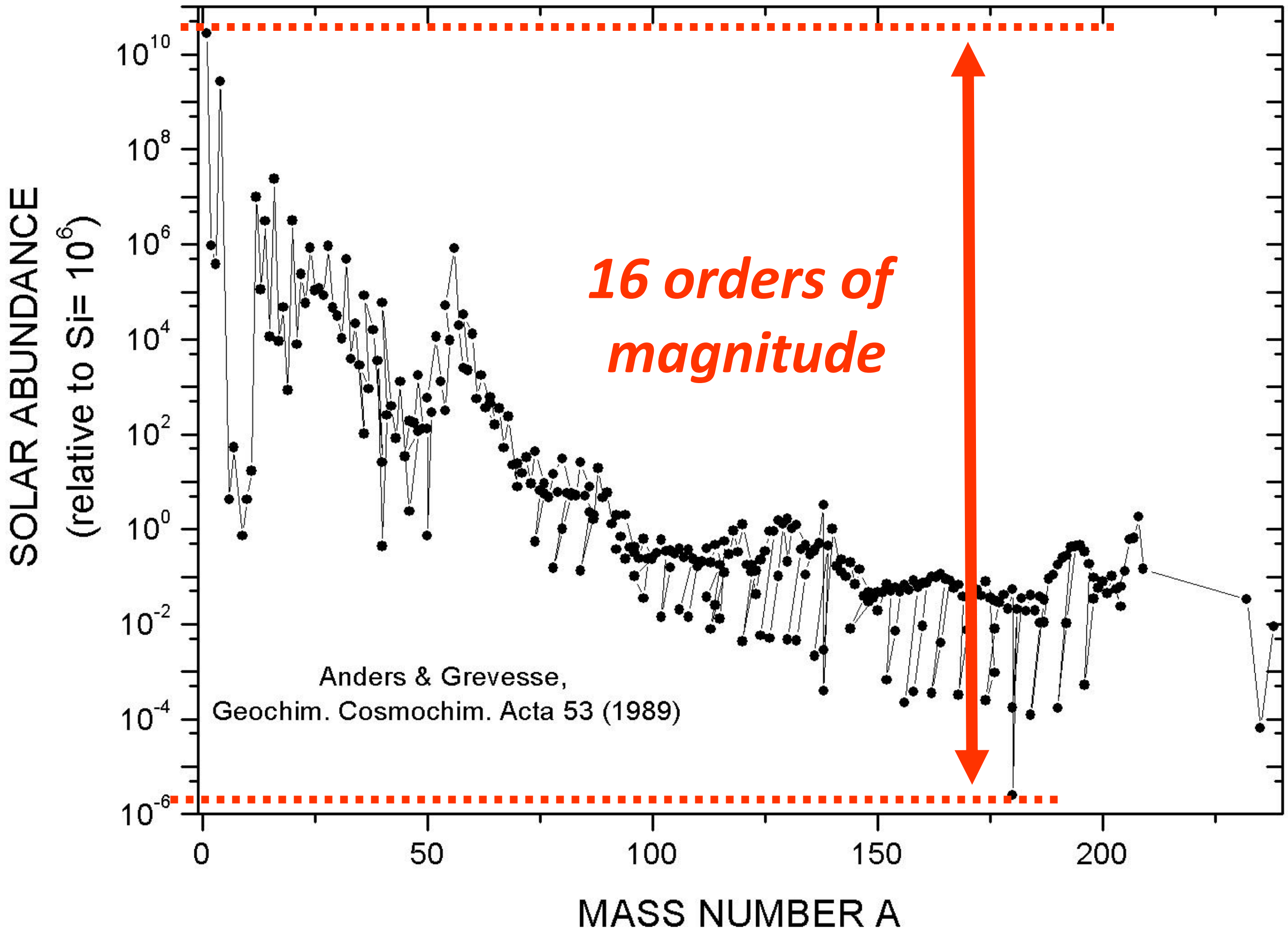
2. Measurement of very neutron-rich isotopes

3. Summary and Outlook

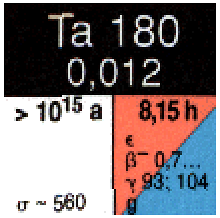
"Solar" abundances

Characteristic isotopic abundances for materials within the solar system

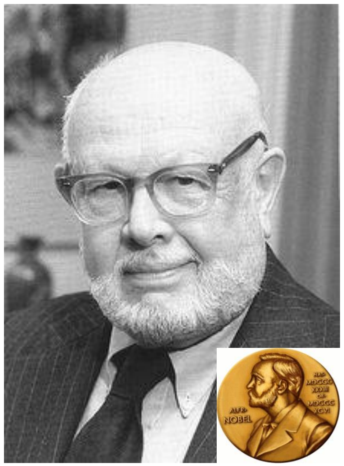
⇨ also valid outside solar system? („Galactic“ abundances?)



How are the isotopes produced?

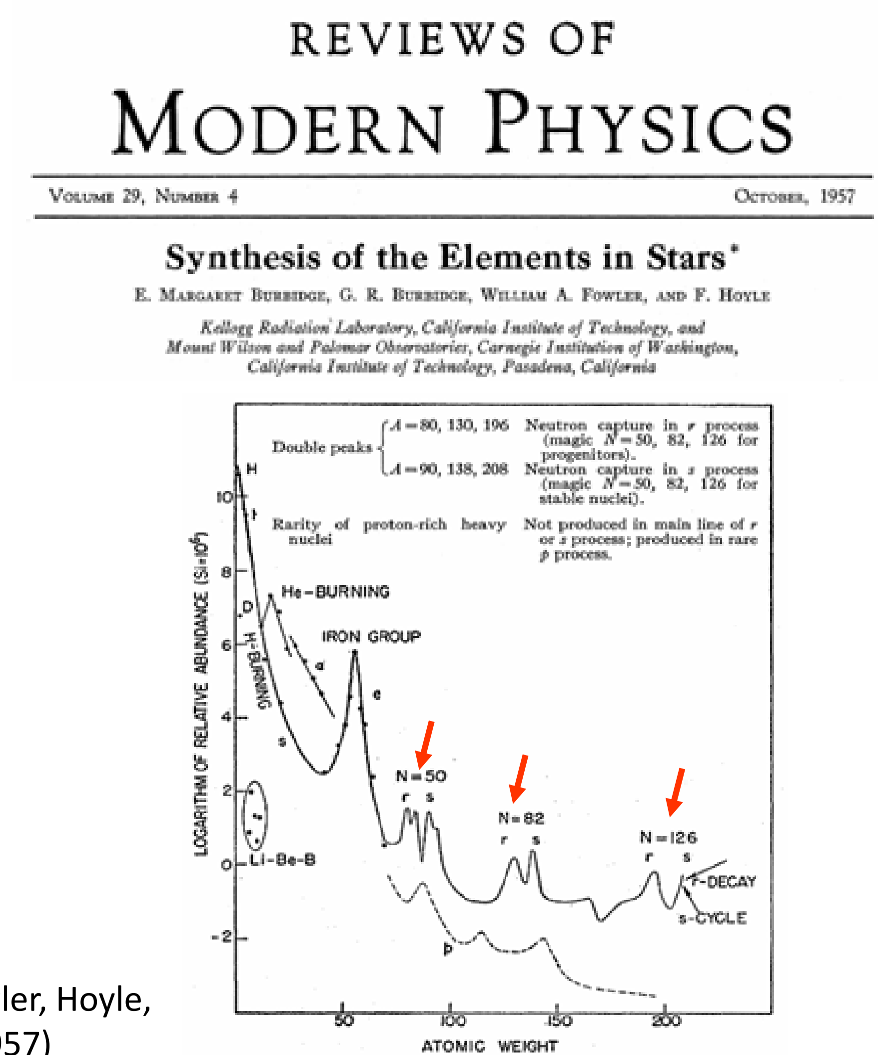


Nuclear Astrophysics =
Nuclear Physics + Astrophysics



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

"For his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe."



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

Fred Hoyle
(1915-2001)

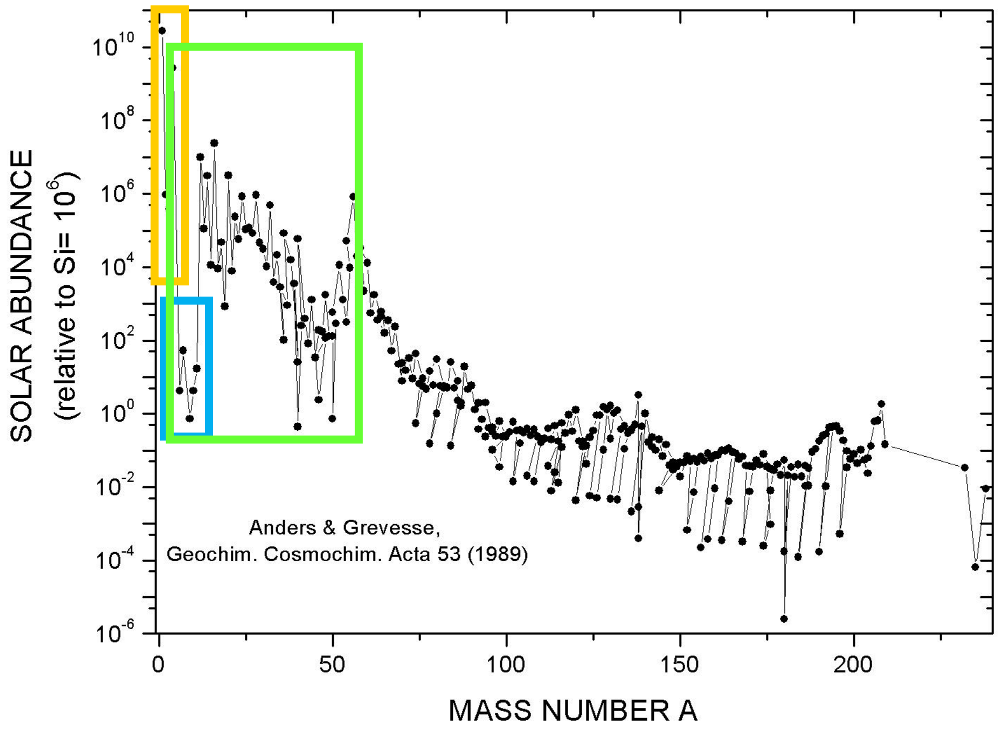
B²FH: Burbidge, Burbidge, Fowler, Hoyle, Revs. Mod. Phys. 29 (1957)

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 $M_\odot$ ⇨ + C, Ne, O, Si burning



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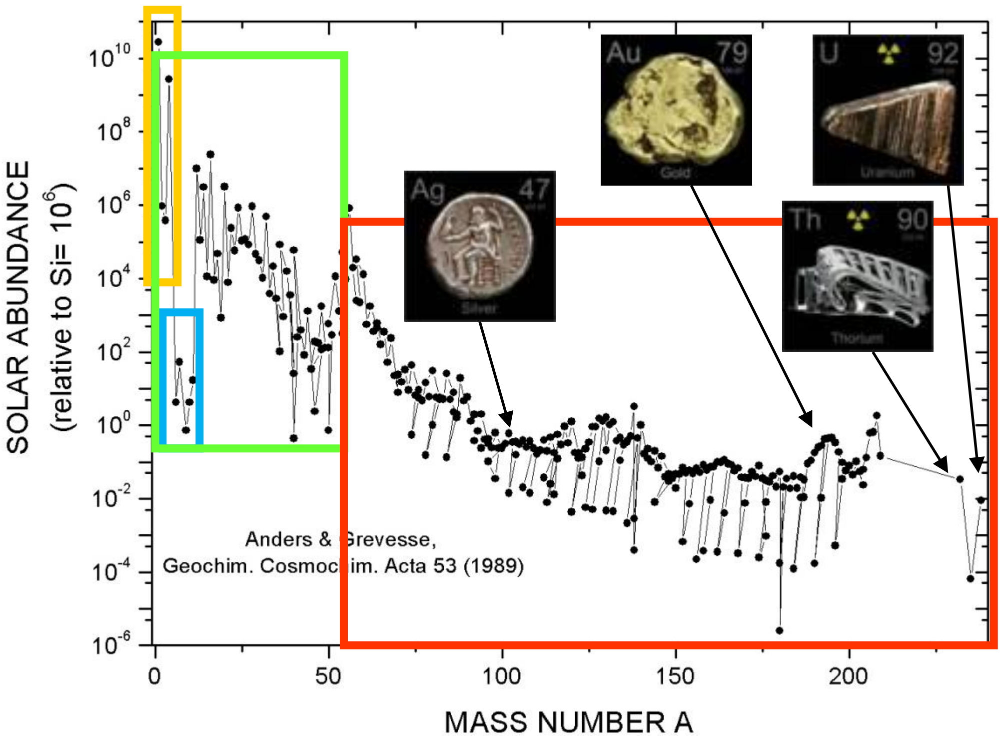
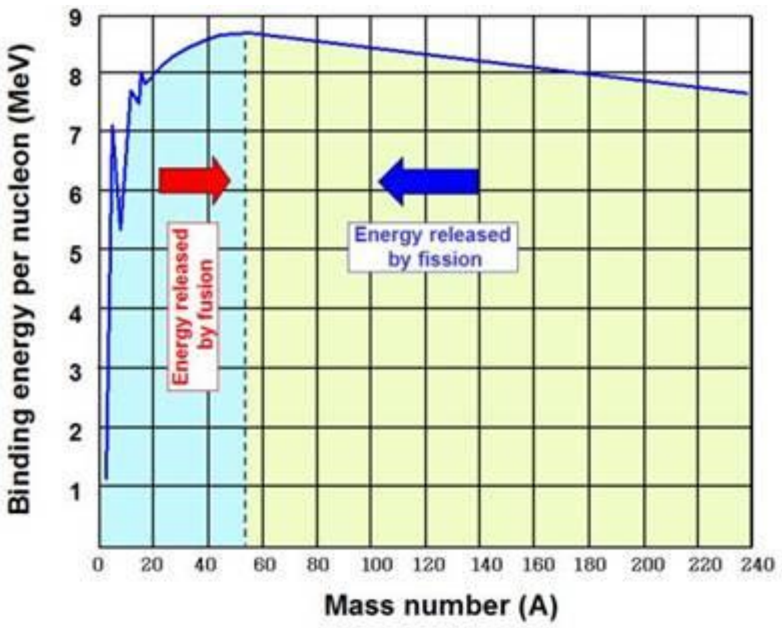
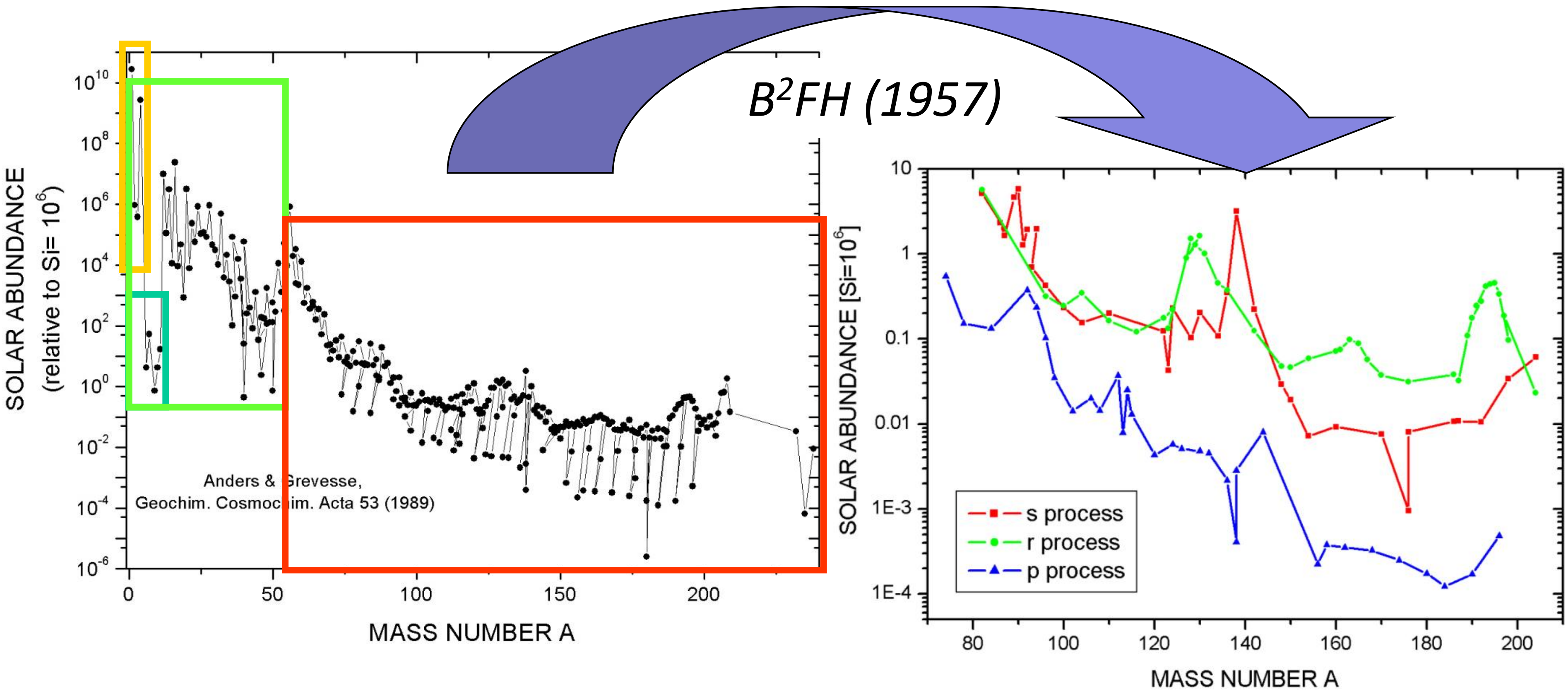
How are the heavy elements formed?





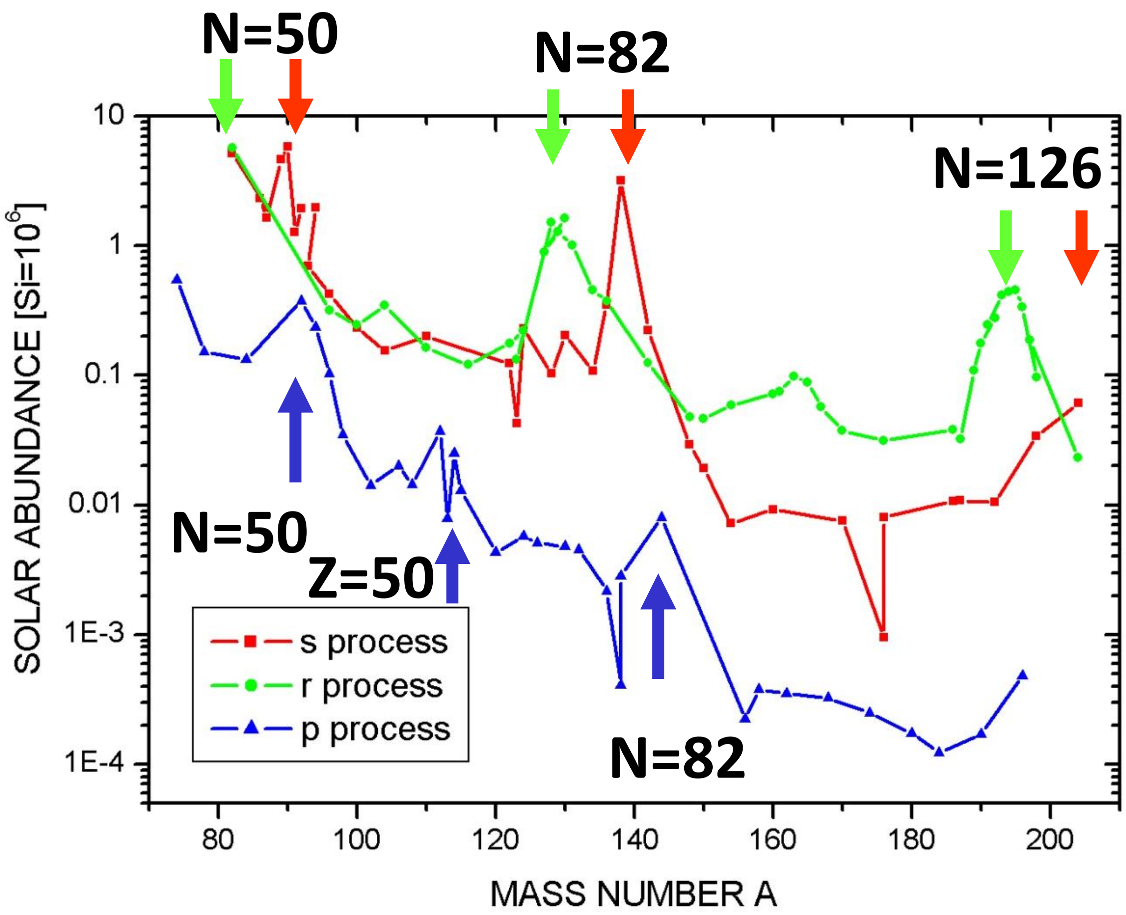
No more energy released by fusion of isotopes beyond Iron (A=56)

Solar abundances: Synthesis beyond iron



B²FH: Burbidge, Burbidge, Fowler, Hoyle, Revs. Mod. Phys. 29 (1957)

Solar abundances: Synthesis beyond iron



"slow neutron capture process"

"rapid neutron capture process"

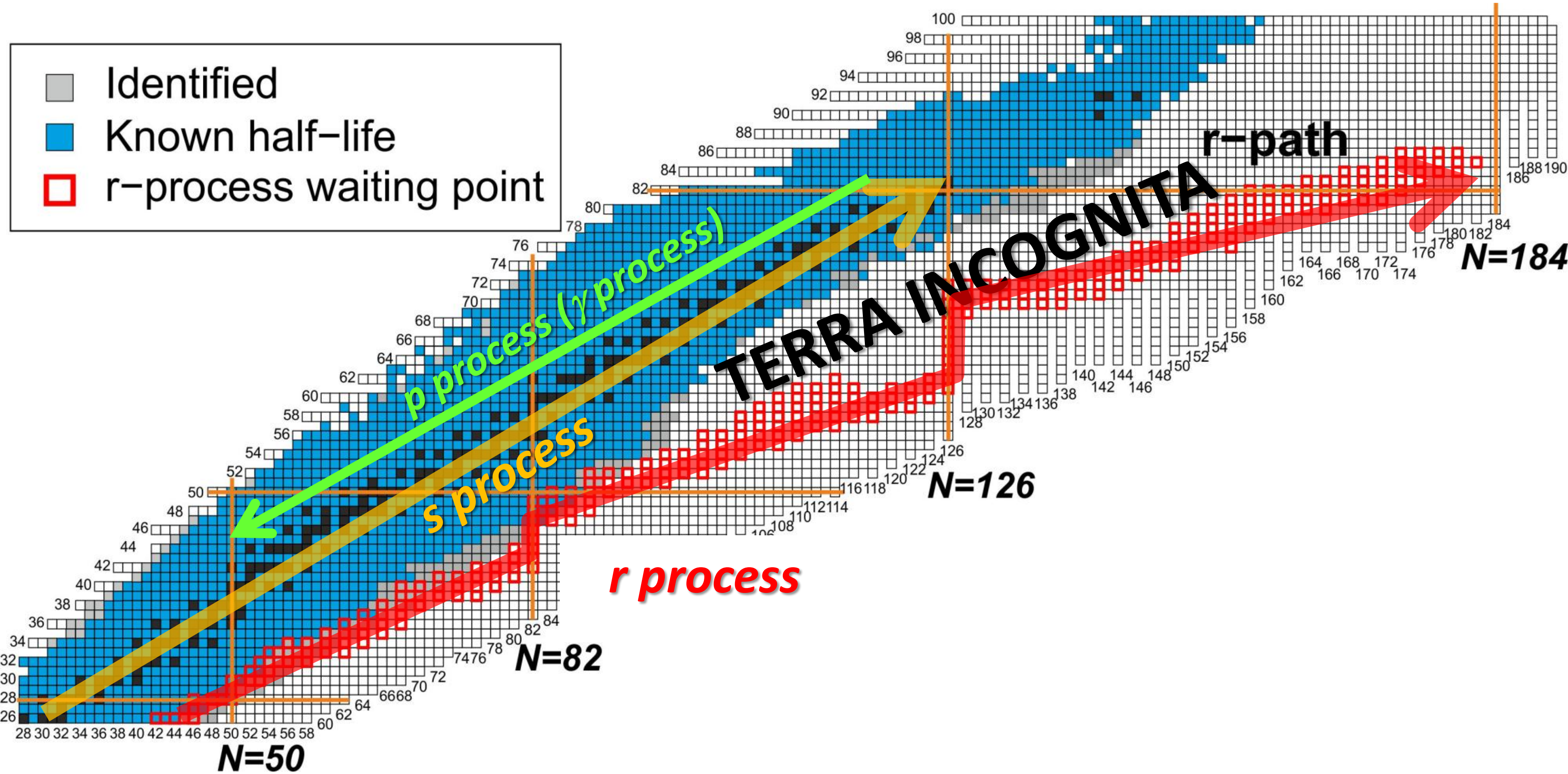
Production of p-rich isotopes

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

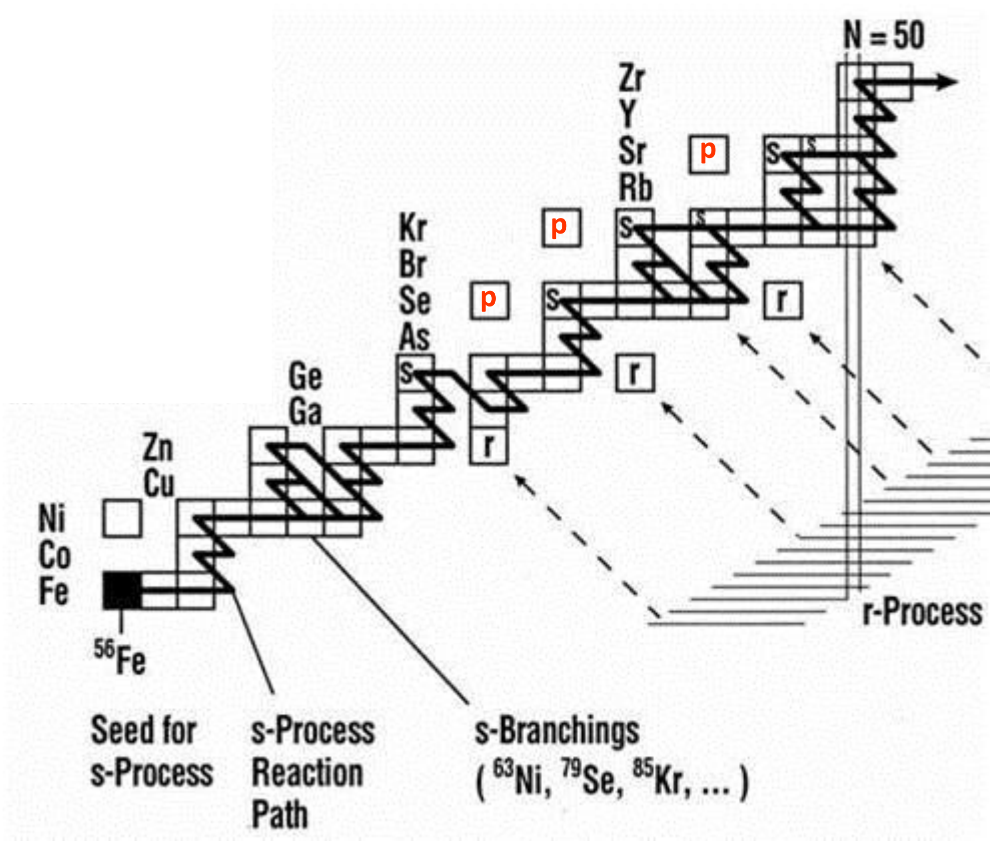
~50% ~50% ~1%

Local abundance maxima (and minima) are ***mirrors of nuclear structure***
(shell closures, pairing effects...)

Solar abundances: Synthesis beyond iron



The "slow neutron capture process"

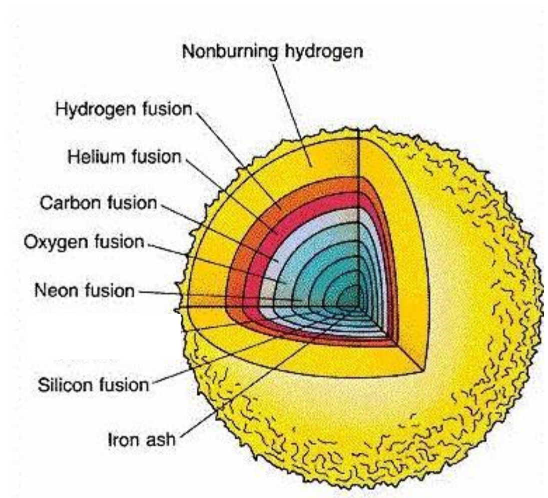


≈50% of abundances >Fe

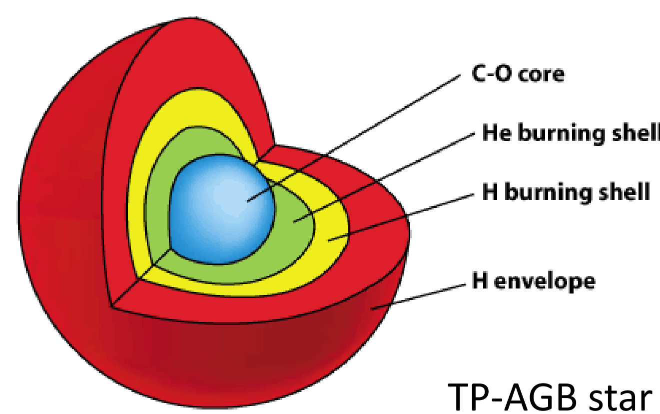
- **Neutron capture slowly** compared to β-decay (1 capture per ~1000 y)
- Well defined **path along line of stability ⇨ Well understood from astrophysical and nuclear physics side**
- End point: ^{209}Bi

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

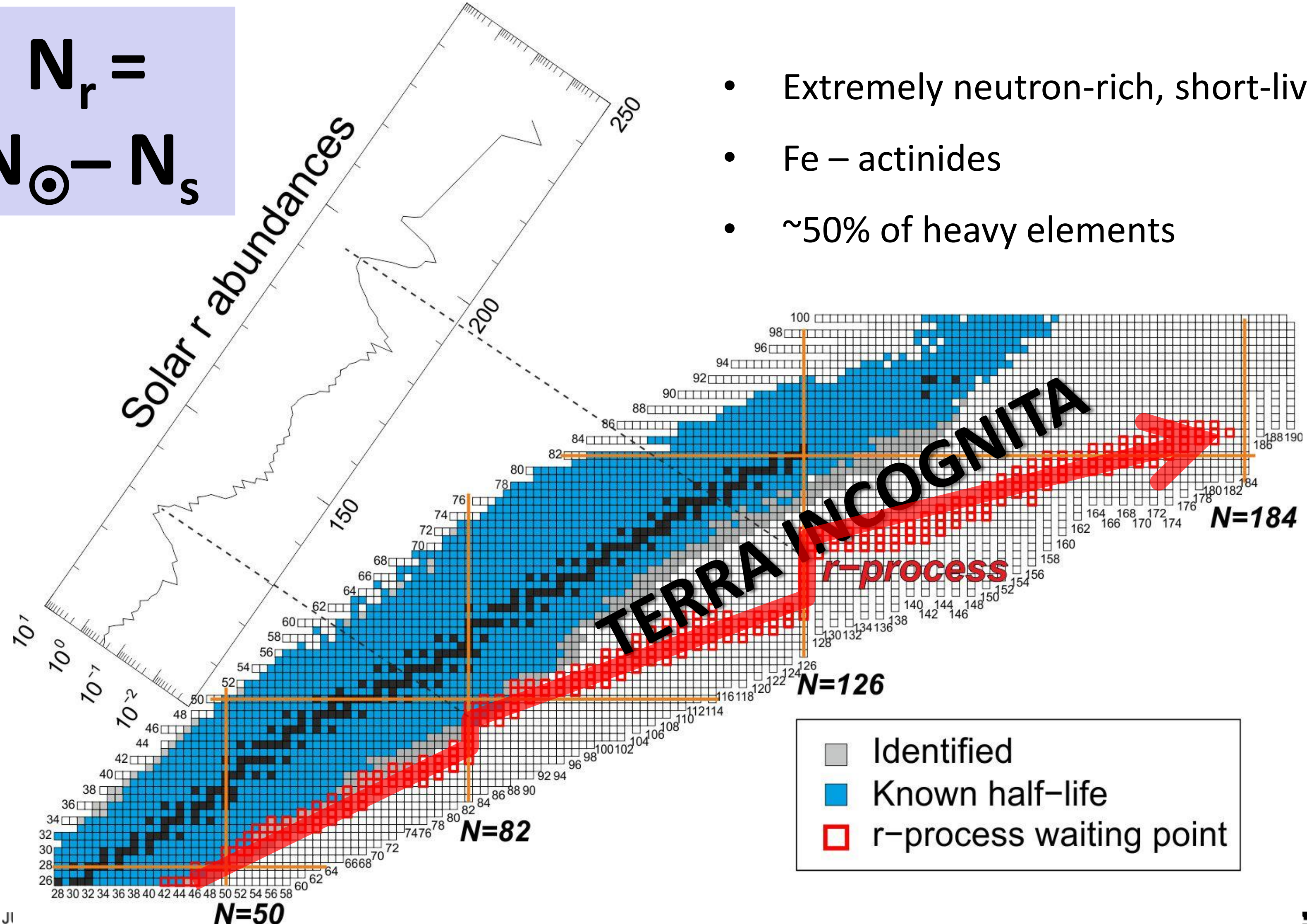


TP-AGB star
(thermally pulsing asymptotic giant branch)

The "rapid neutron capture process“

$N_r = N_{\odot} - N_s$

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

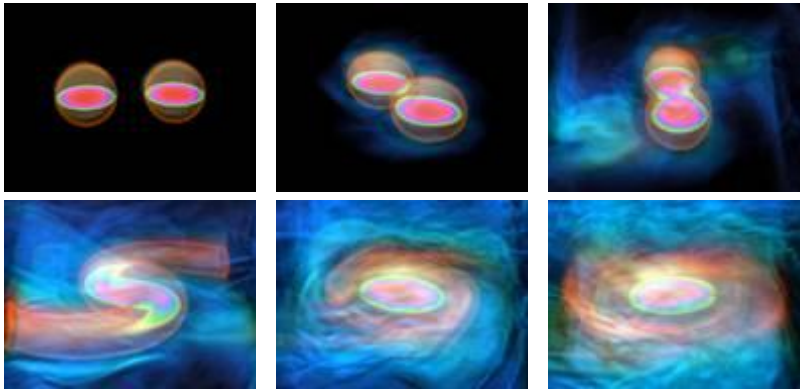


The "rapid neutron capture process“

- 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)
- Freeze-out: decay back to stability
- Astrophysical scenario: still under discussion

Core collapse supernova ?

Neutron star mergers?



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: Theory + few experimental information

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

Calculated r abundances compared to solar

Nucleosynthesis in the r-process

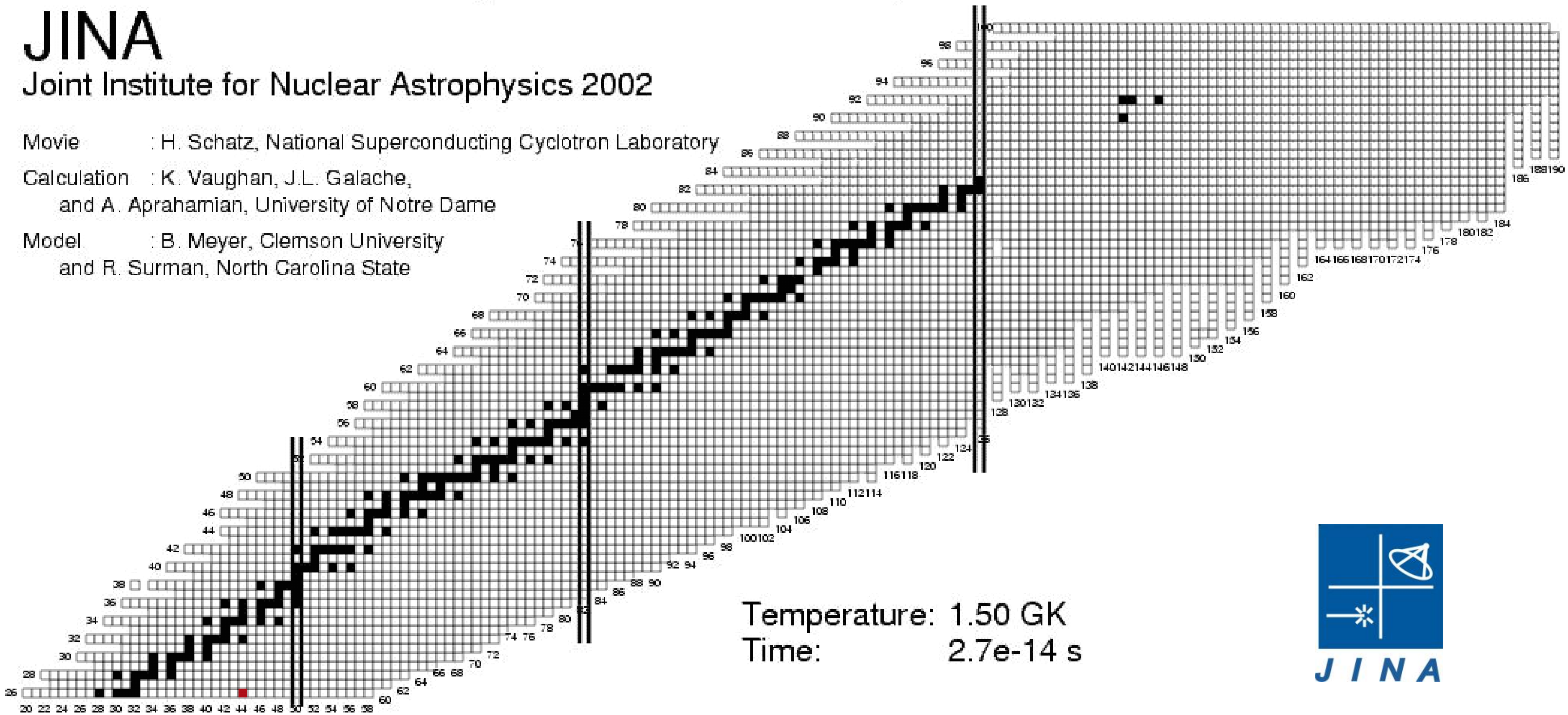
JINA

Joint Institute for Nuclear Astrophysics 2002

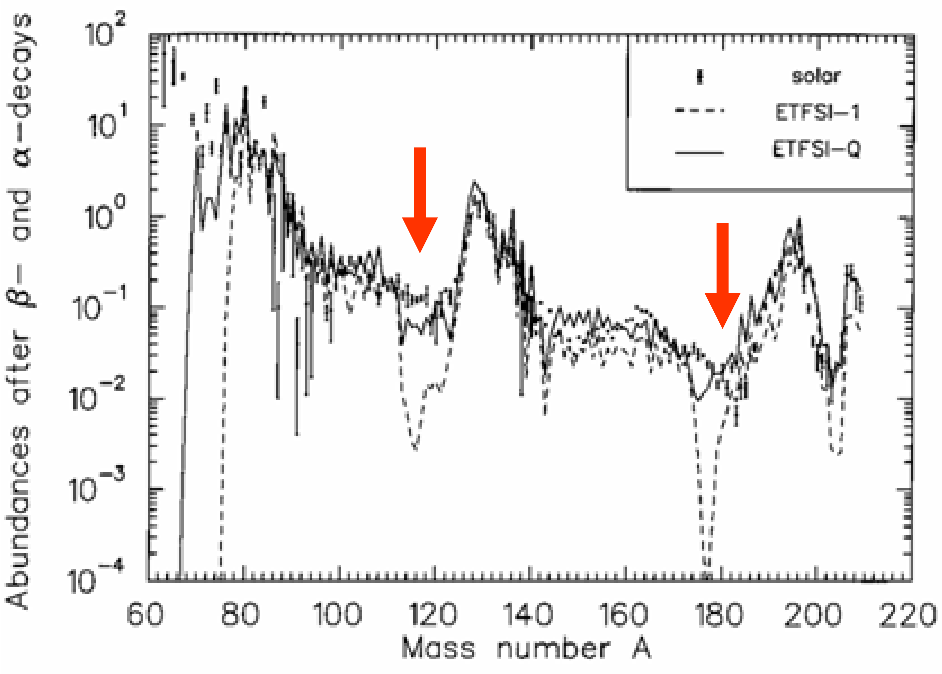
Movie : H. Schatz, National Superconducting Cyclotron Laboratory

Calculation : K. Vaughan, J.L. Galache, and A. Aprahamian, University of Notre Dame

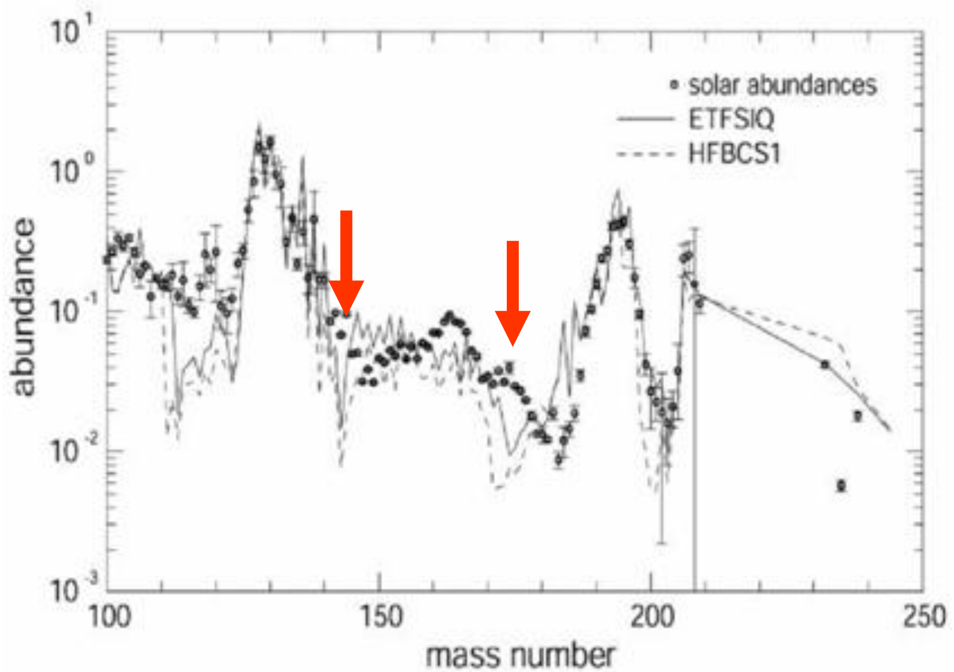
Model : B. Meyer, Clemson University and R. Surman, North Carolina State



Calculated abundances vs. solar



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

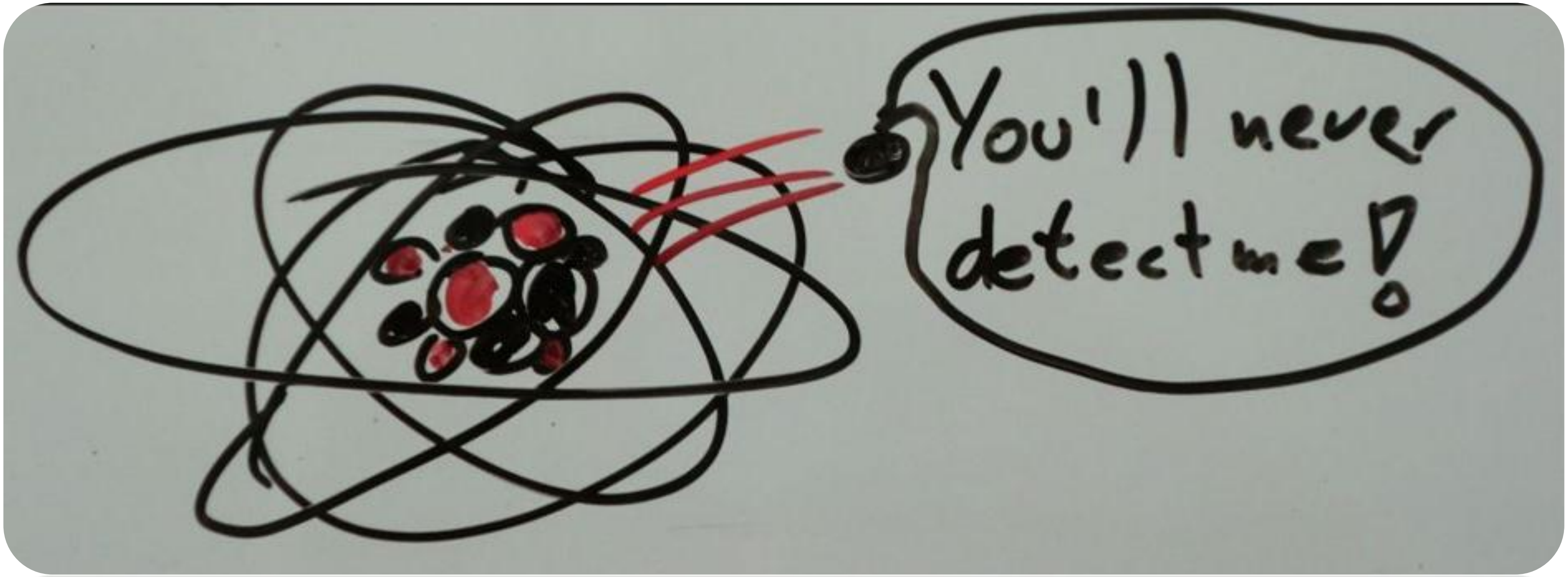


H. Schatz et al., Ap. J. 579 (2002) 626

⇨ Strongly dependent on mass models!

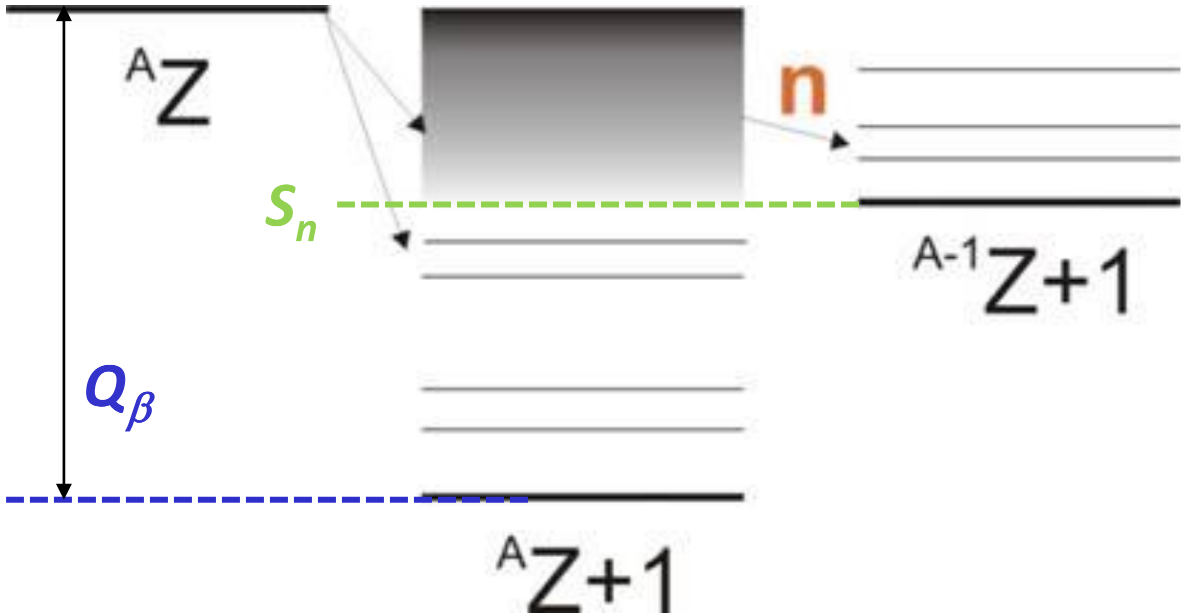
Experiments needed to constrain and tune theoretical models

Measurement of very neutron-rich isotopes



β-delayed neutron emission

$S_n < Q_\beta$

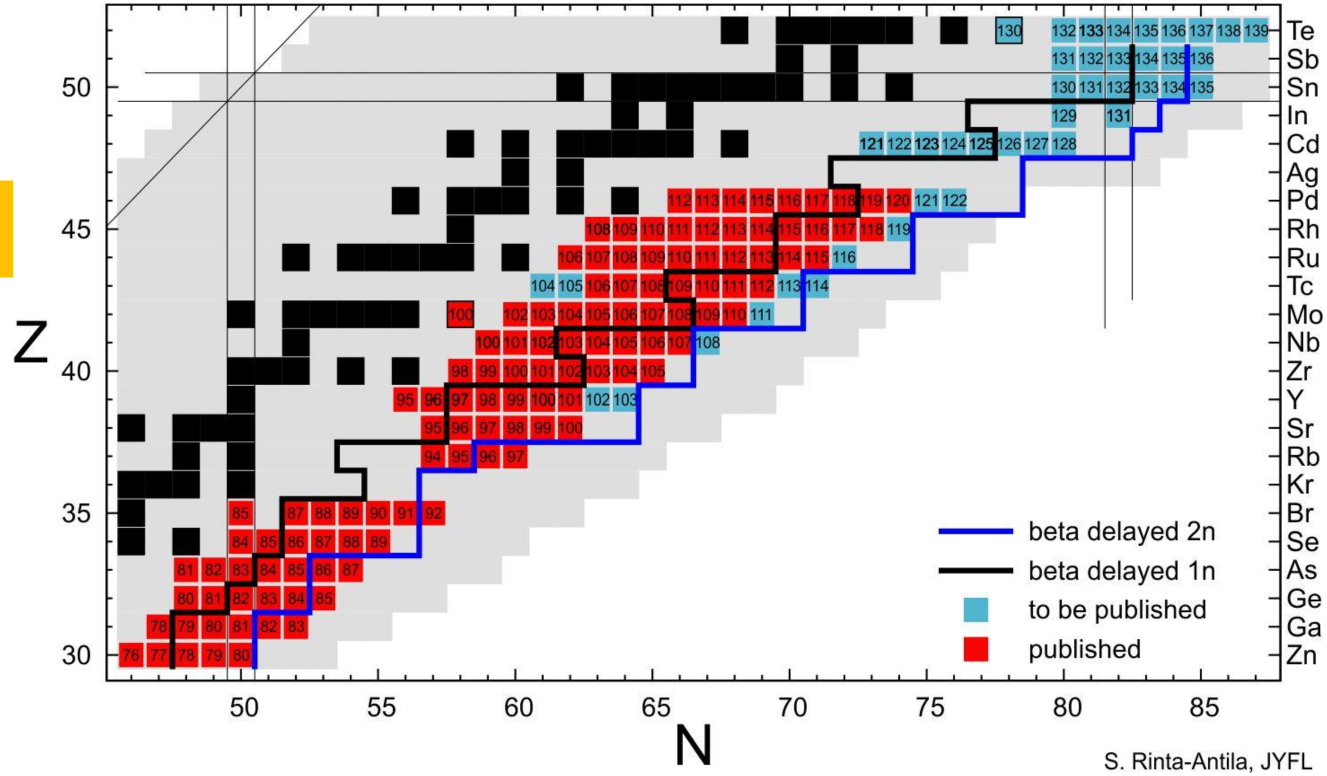


- Discovered in 1939 by Roberts et al.
- "Delayed": emission with β-decay half-life of the precursor ^{A}Z
- $t_{1/2}$≈ few ms – 55.65 s (^{87}Br)
- Important for kinetic control of fission reactors, e.g. ^{235}U: 2.47 prompt & 0.0065 delayed neutrons per fission

R.B. Roberts, R.C. Meyer, P. Wang, Phys. Rev. **55**, 510 (1939).

β-delayed neutron emission

$S_n < Q_\beta$



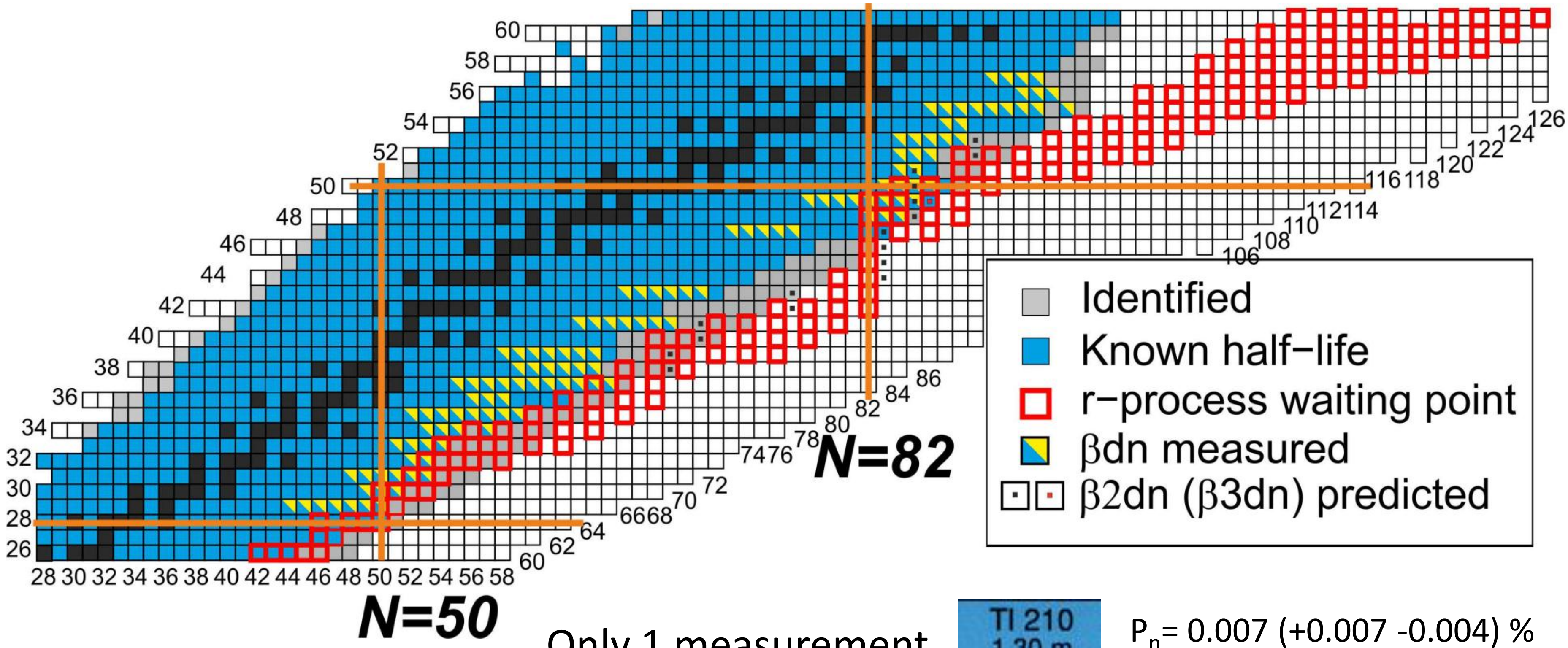
- Important nuclear structure information:

  Time-dependence of n-emission ⇨ $t_{1/2}(^{A}Z)$

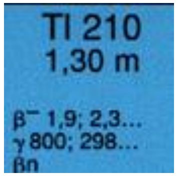
  P_n : β-strength above S_n

- Accurate mass measurements needed for predictions!

Status βn-emitters



Only 1 measurement for A>150:



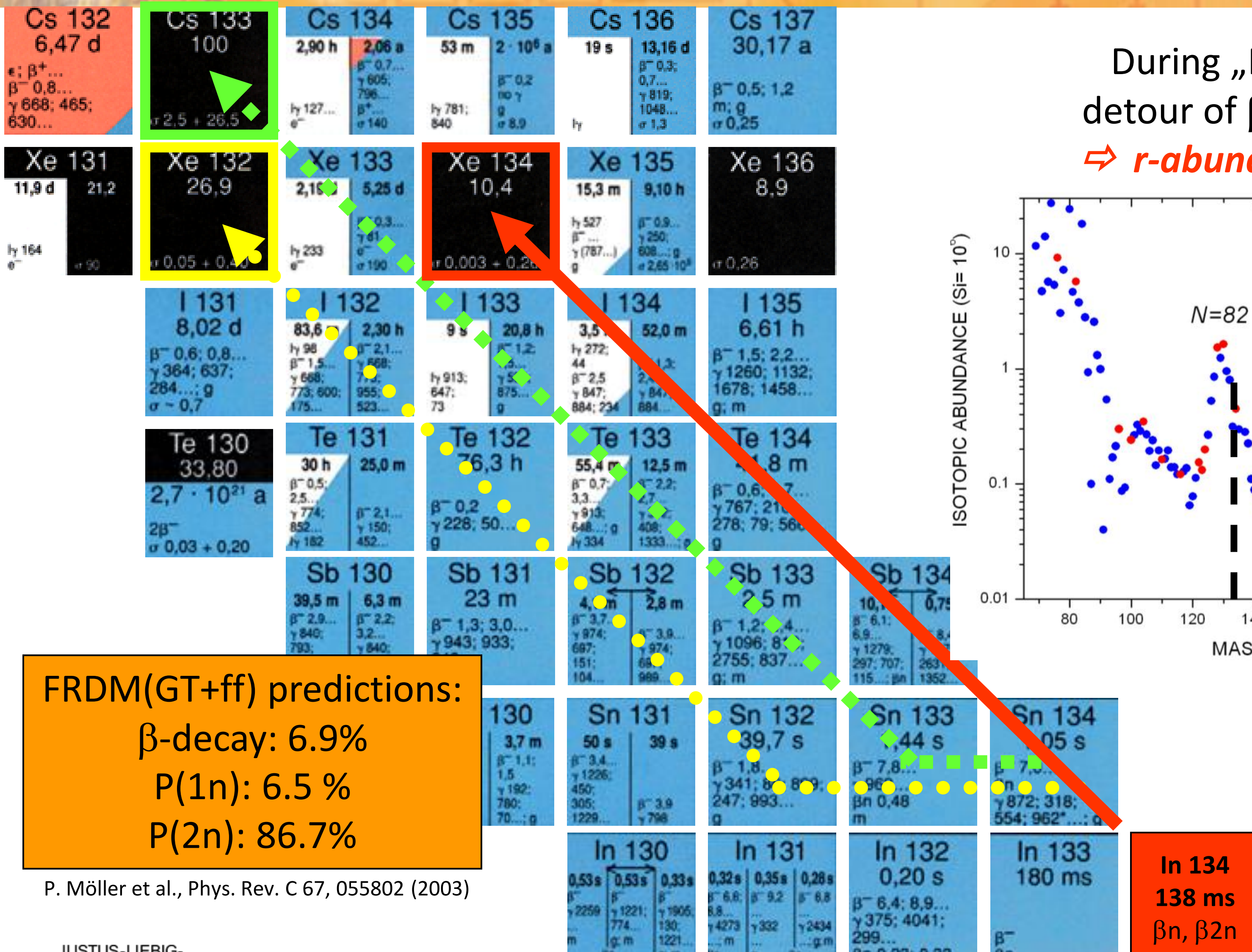
P_n= 0.007 (+0.007 -0.004) %

Validation missing

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

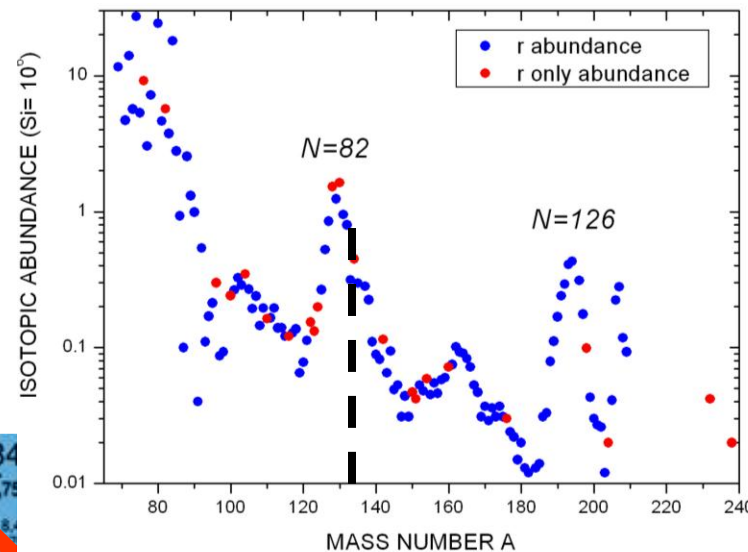
- ^{8}He- ^{150}La: ≈200 datasets available, ≈ 75 in non-fission region (A<70)
- New AME2011: 80 more βdn emitters identified, but no measurement

Astrophysical influence



During „Freeze-out“:
detour of β-decay chains

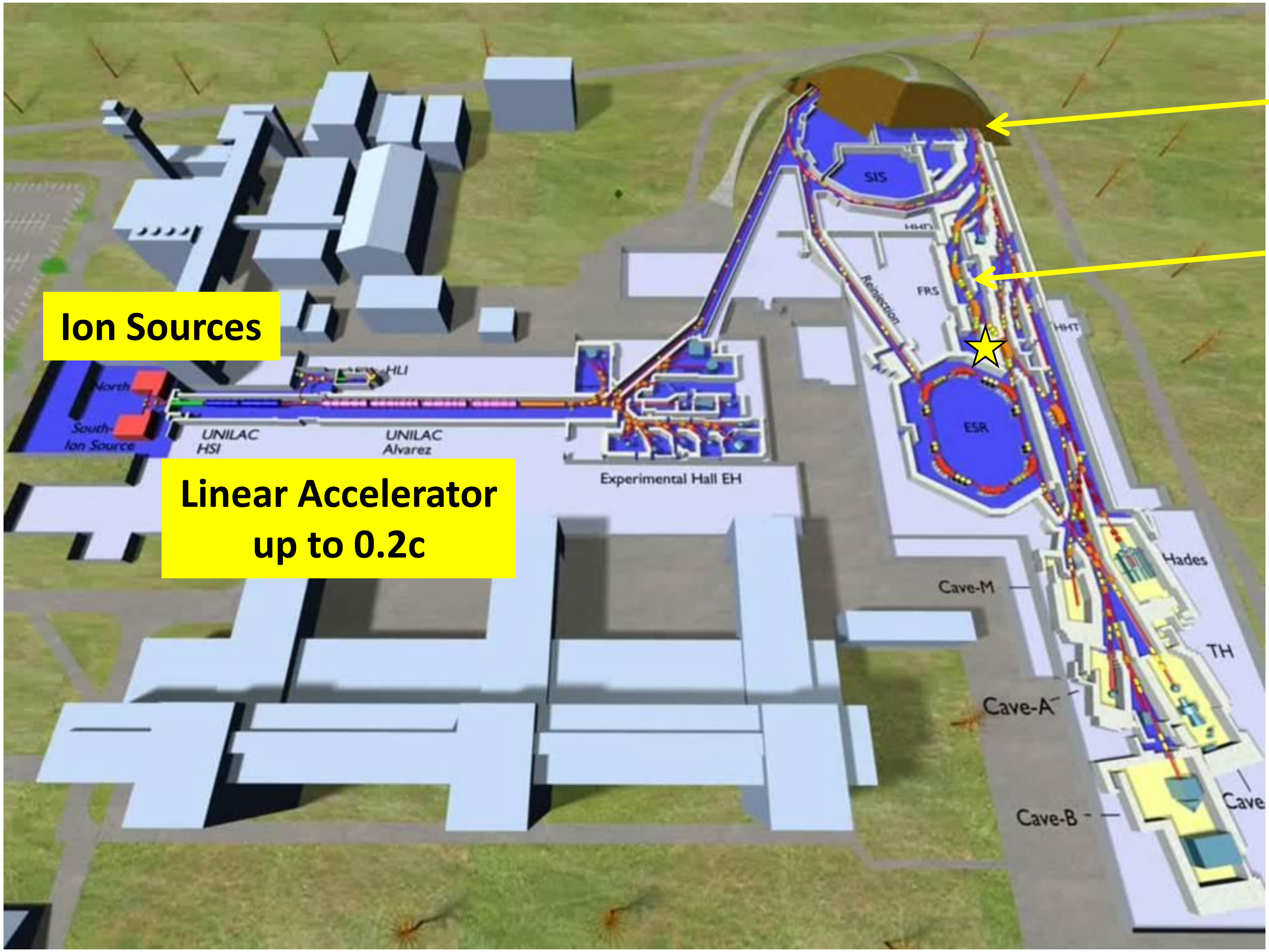
➩ ***r-abundance changes***



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)

GSI Helmholtzzentrum für Schwerionenforschung Darmstadt/Germany

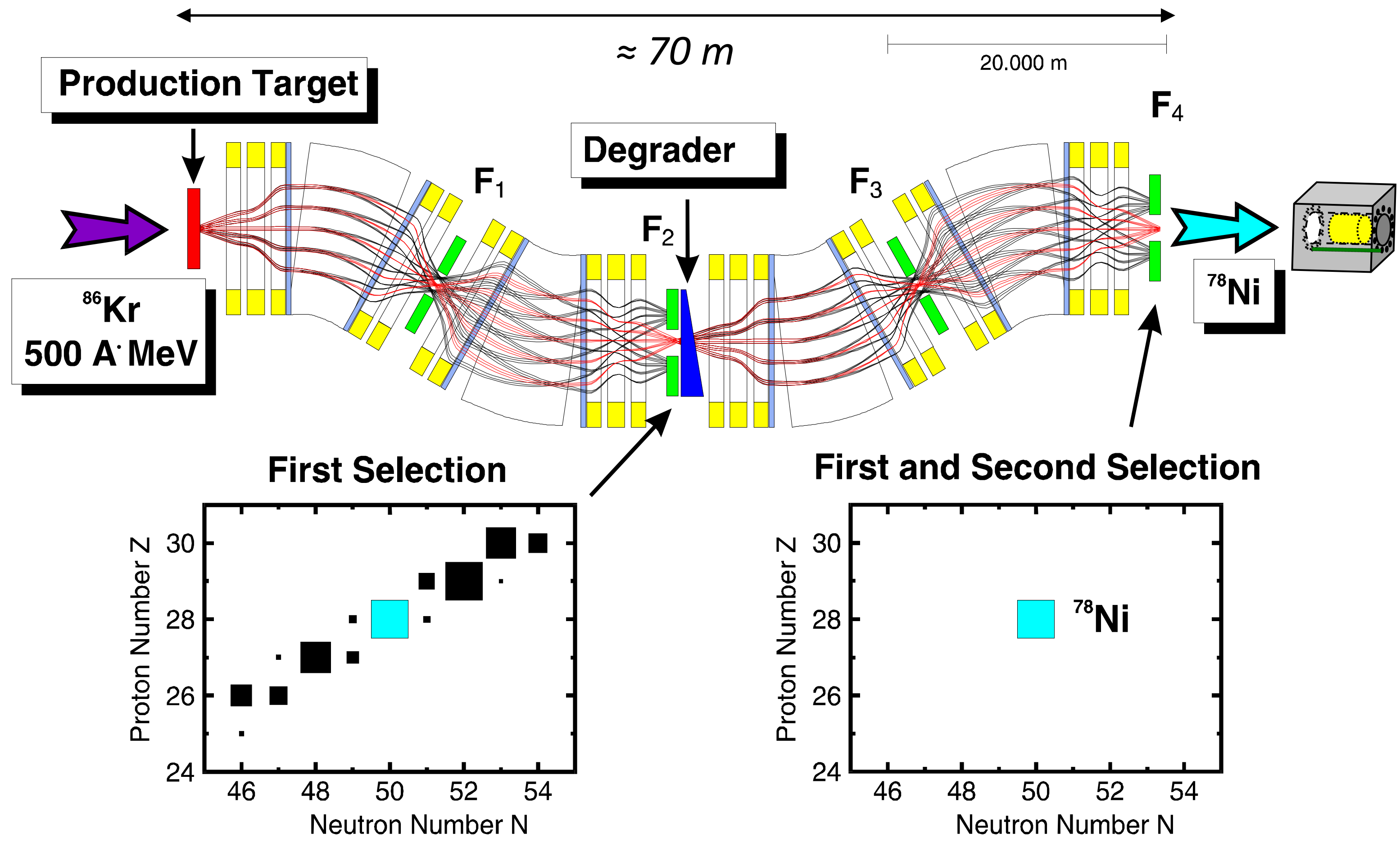


Schwer**I**onen **S**ynchrotron (up to 0.9c)

FRagment **S**eparator

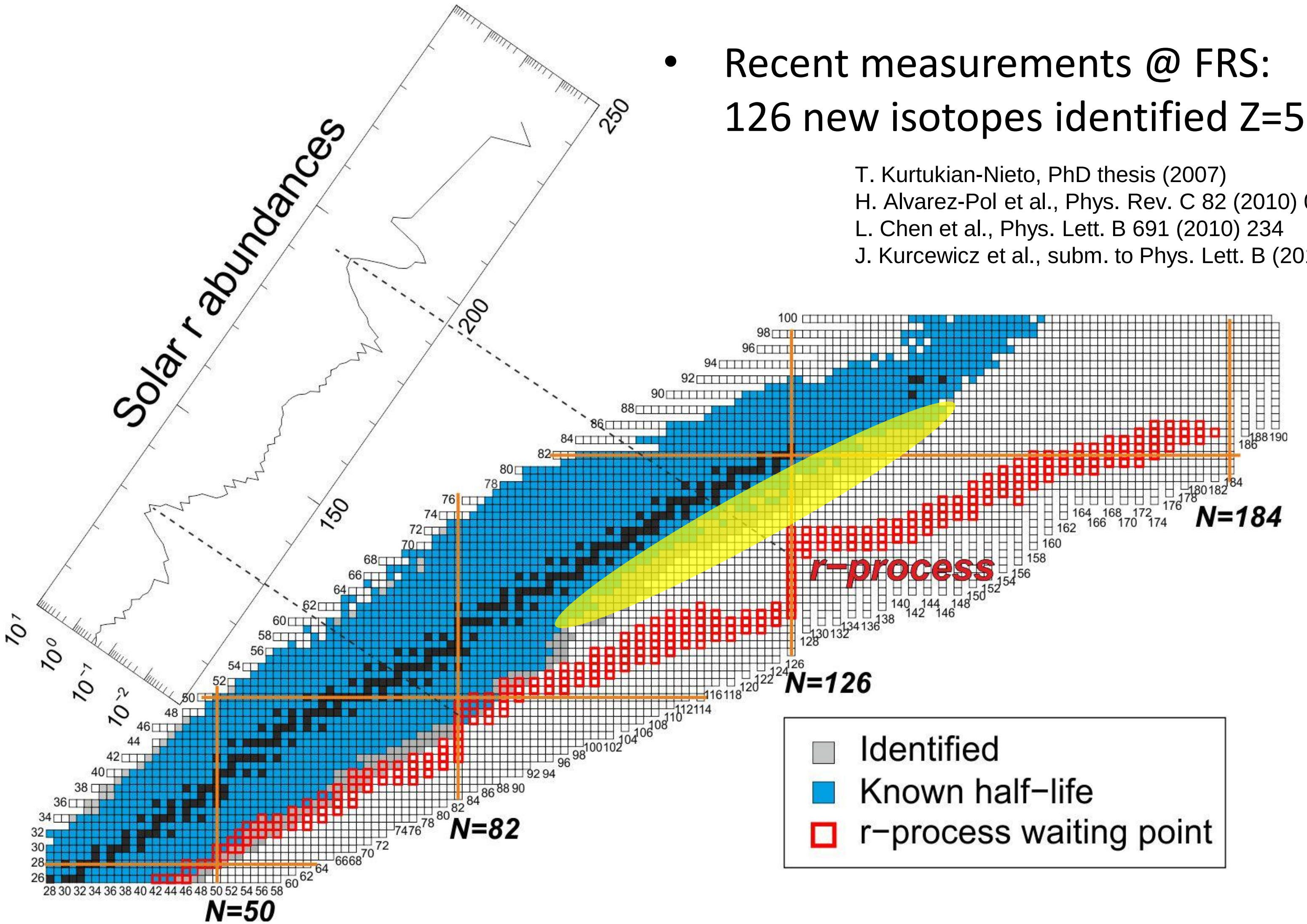
1 GeV/u ^{238}U
$1.5*10^9$ pps
^{9}Be target

FRagment Separator: Bρ-ΔE-Bρ method



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

Towards the r-process boulevard

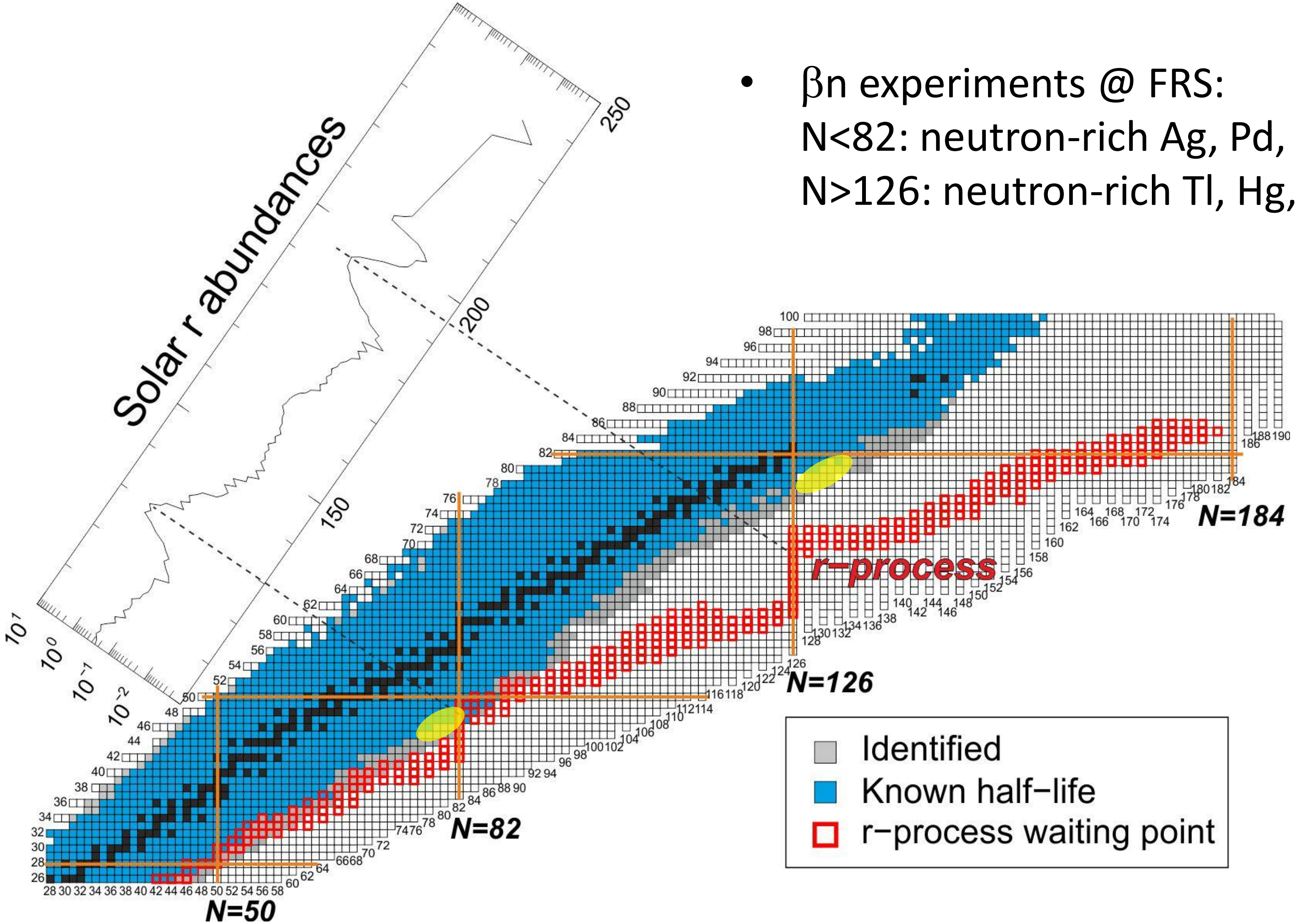


- Recent measurements @ FRS:
  126 new isotopes identified Z=59-87 (Pr-Fr)

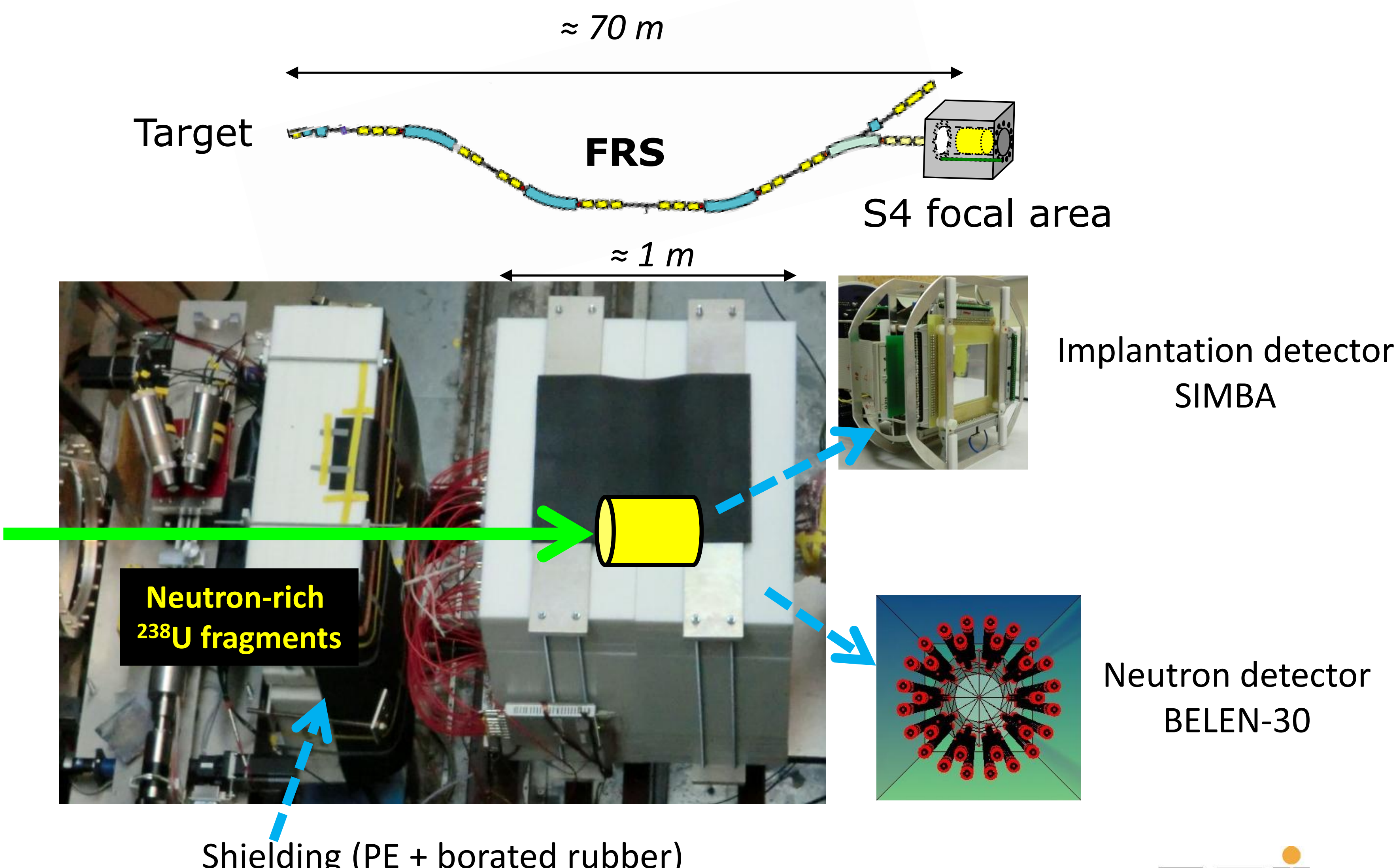
T. Kurtukian-Nieto, PhD thesis (2007)
H. Alvarez-Pol et al., Phys. Rev. C 82 (2010) 041602 (R)
L. Chen et al., Phys. Lett. B 691 (2010) 234
J. Kurcewicz et al., subm. to Phys. Lett. B (2012)

βn measurements 2011

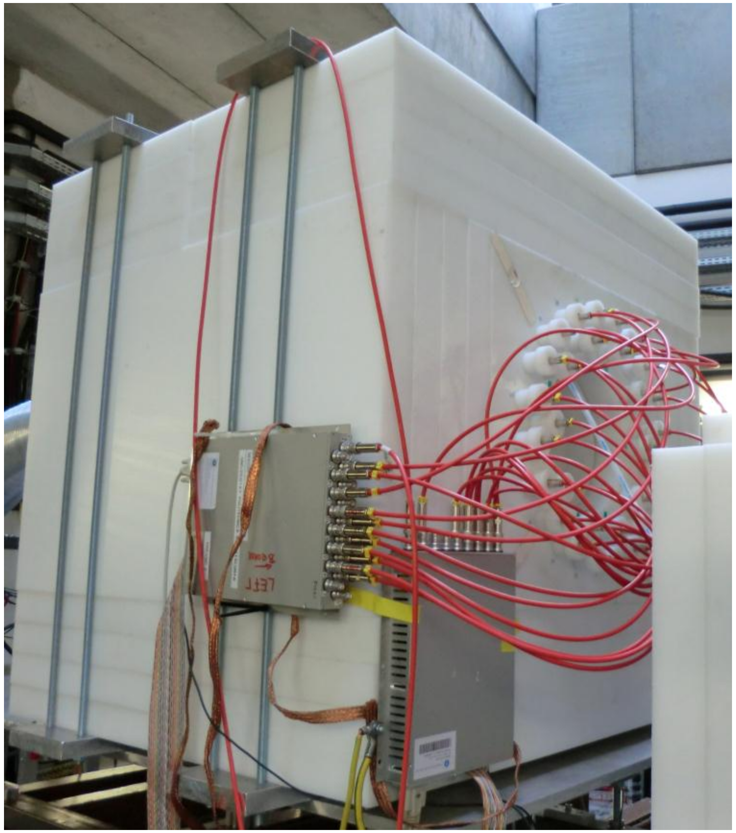
- βn experiments @ FRS:
  N<82: neutron-rich Ag, Pd, Ru
  N>126: neutron-rich Tl, Hg, Au



Setup


≈ 70 m
Target
FRS
S4 focal area
≈ 1 m
Implantation detector
SIMBA
Neutron-rich
^{238}U fragments
Neutron detector
BELEN-30
Shielding (PE + borated rubber)

BEta deLayEd Neutron detector (BELEN-30)



30 high pressure ^{3}He long counters
PE matrix, size ~ 1m^3

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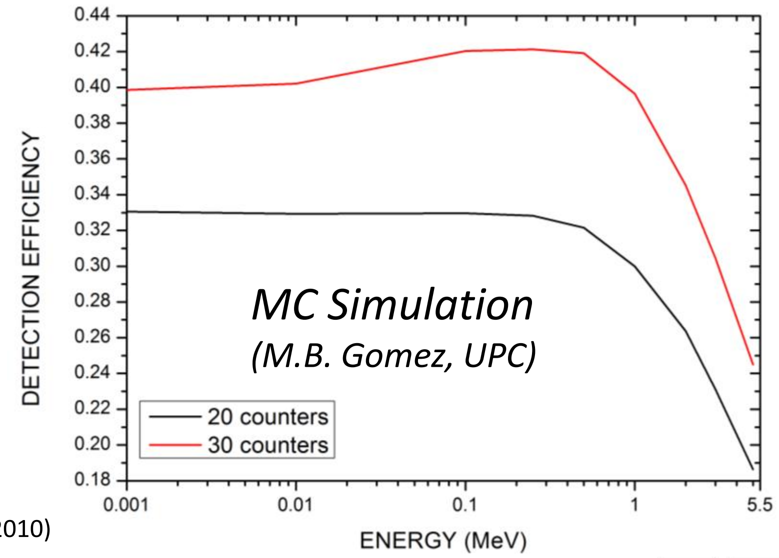
Universidad Politecnica de Cataluna, Barcelona

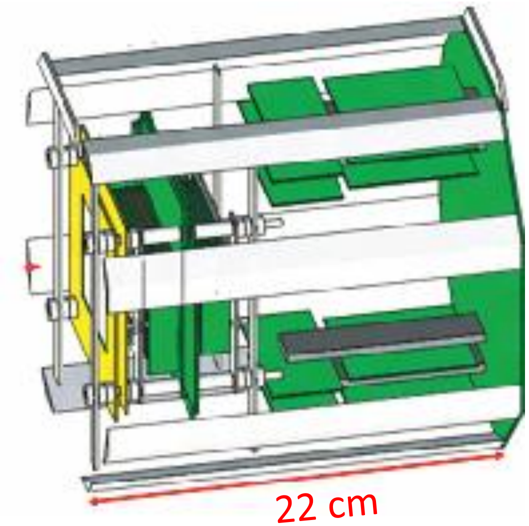
IFIC Valencia

CIEMAT Madrid



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

Silicon IMplantation detector and Beta Absorber

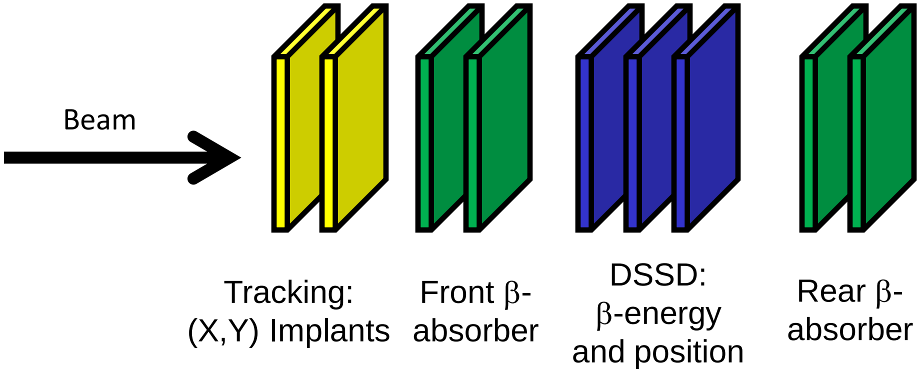


- 60x segm. X and Y-detector
- 7x segm. β-absorber (front and back)
- Implantation area: DSSD, 60x40 segm.

Constructed and developed at

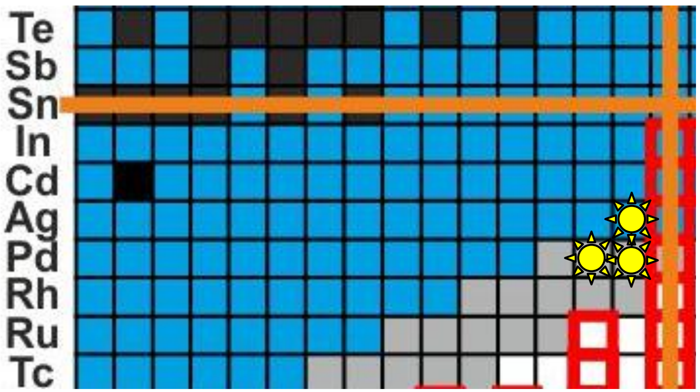
TUM Technische Universität München

Lehrstuhl E12

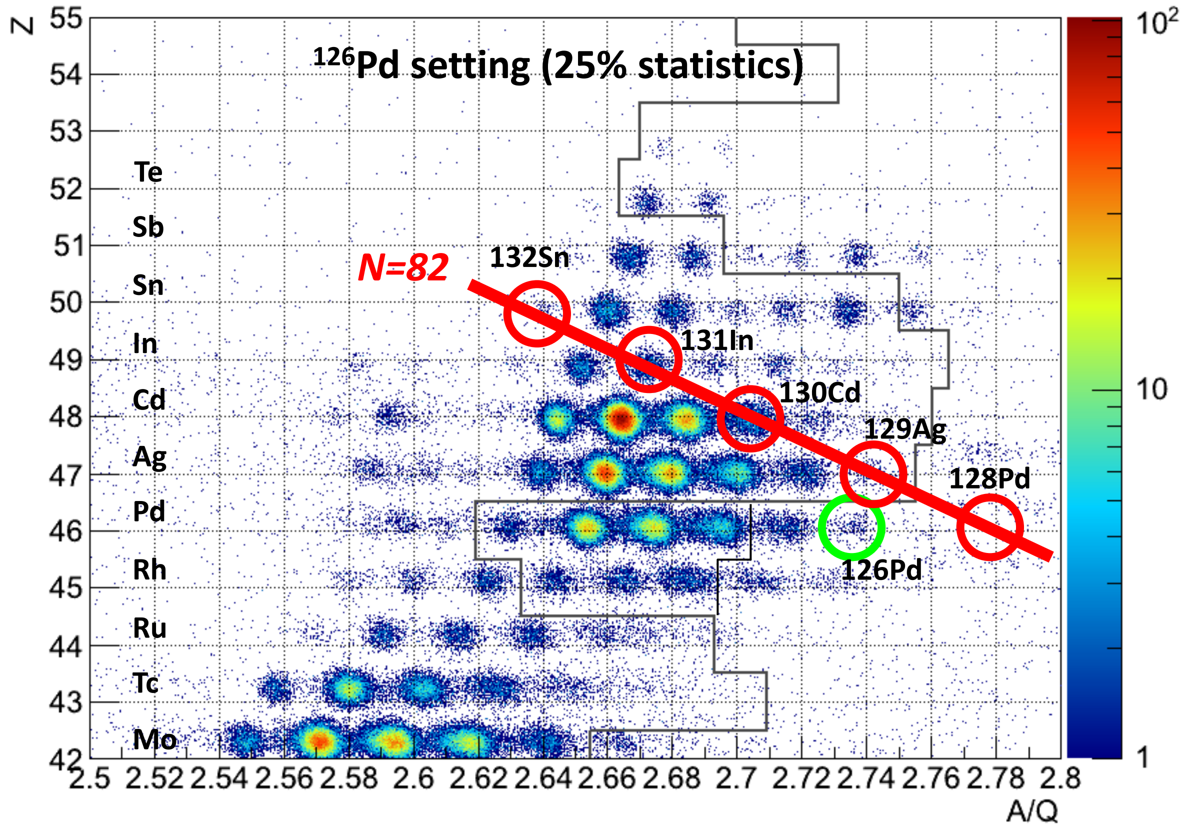


PhD thesis C. Hinke, TUM (2010)
Diploma thesis K. Steiger, TUM (2009)

"South-west" of ^{132}Sn



N=82

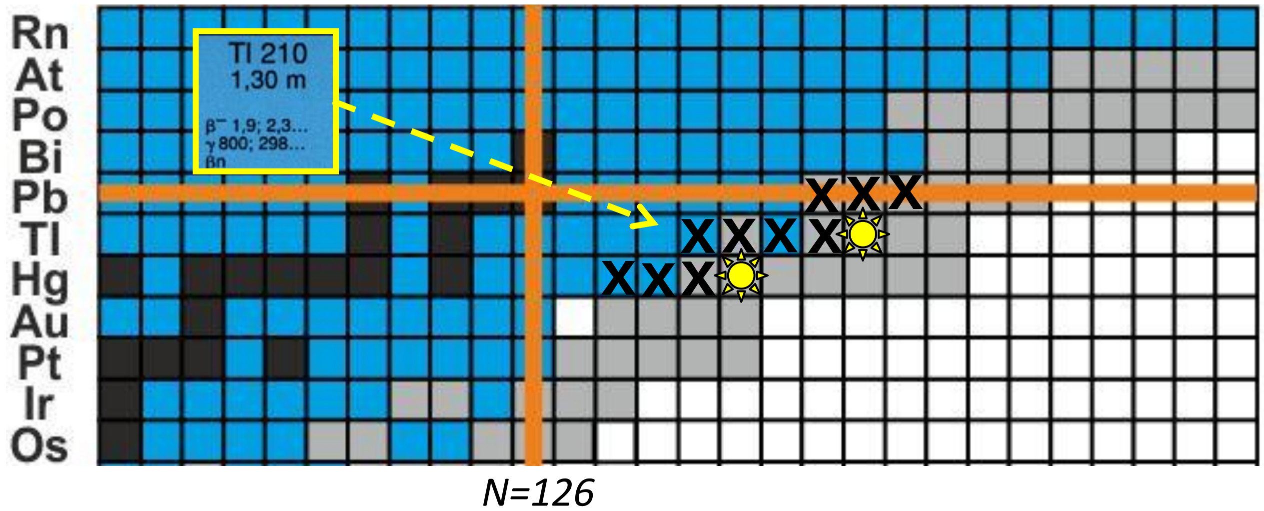


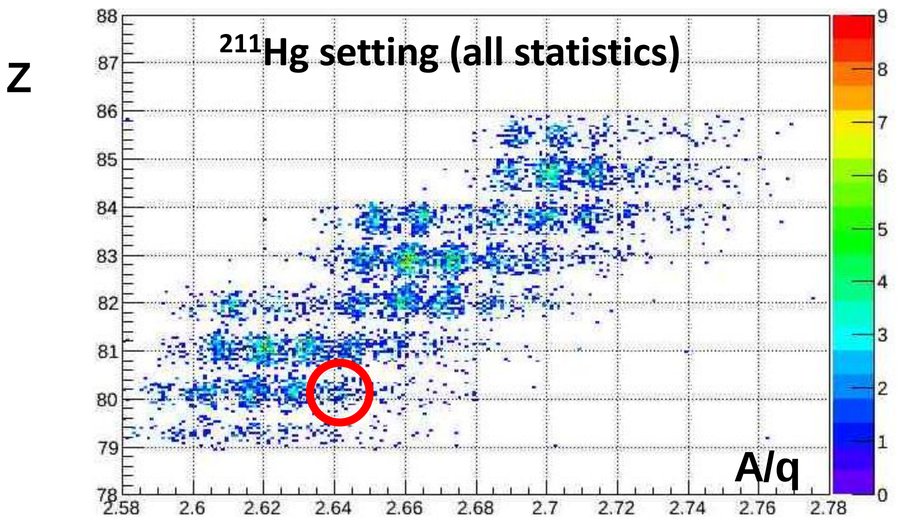
- 3 settings: central fragments ^{126}Pd (2 d), ^{127}Pd (1 d), ^{128}Ag (12 h)

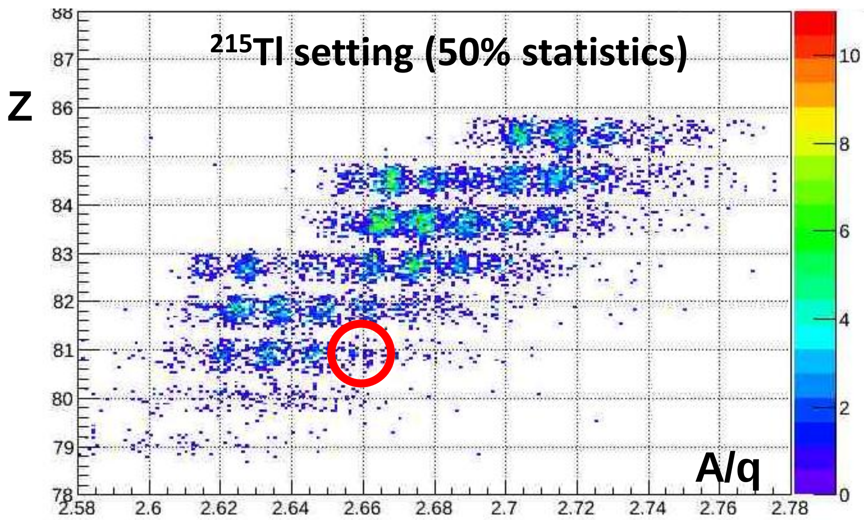
- Analysis in progress: identification of implants, β-n correlations
  - ▸ $t_{1/2}$, P_n

Courtesy of K. Smith (U Notre Dame/ MSU/ GSI)

"South-east" of ^{208}Pb



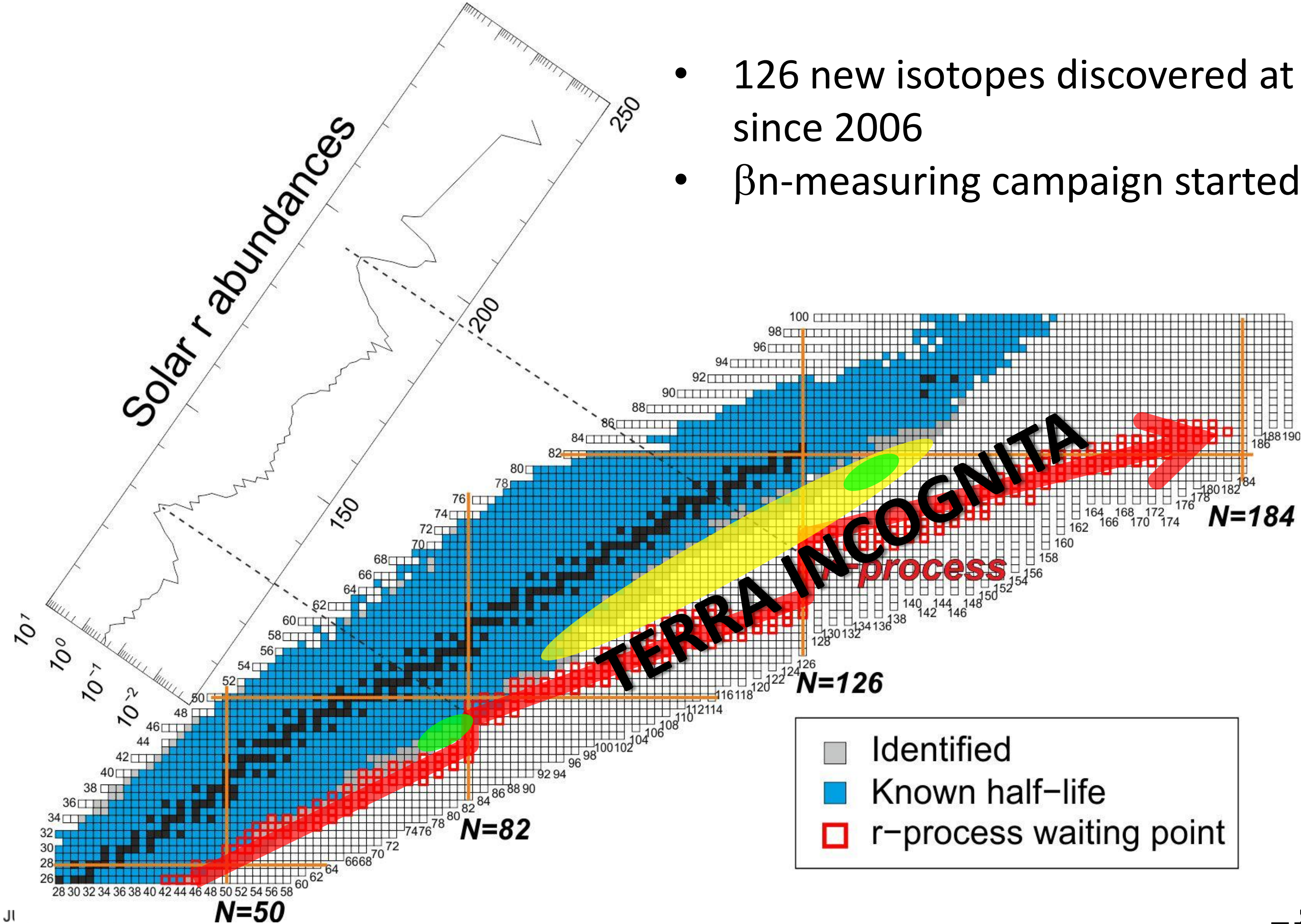




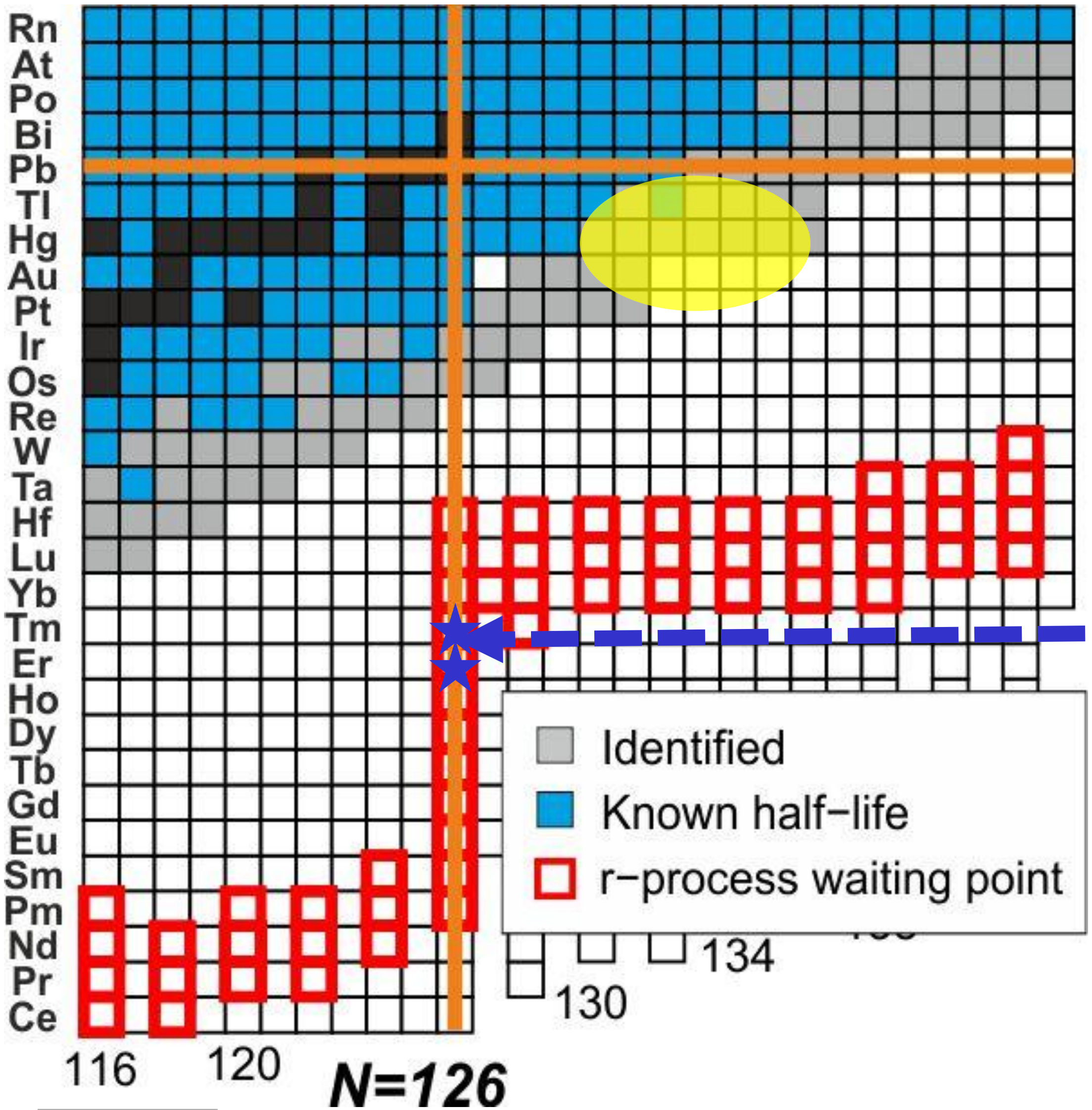
- Next step: β-n correlations ▸ $t_{1/2}$, P_n

Summary

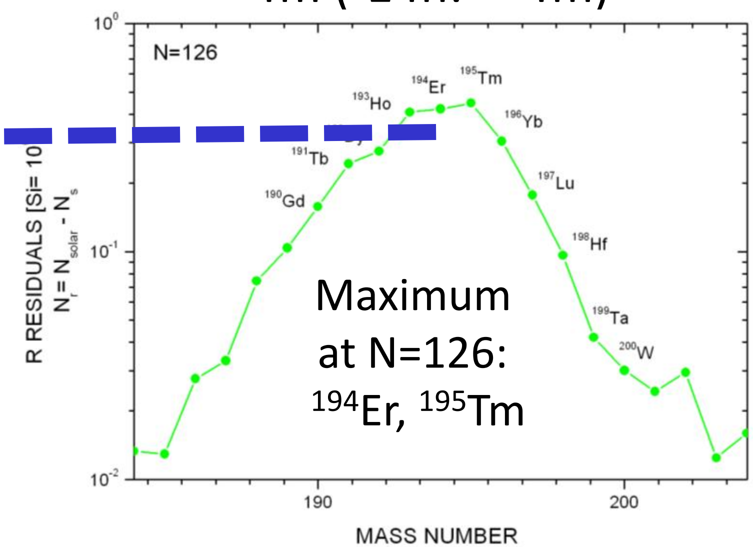
- 126 new isotopes discovered at the FRS since 2006
- βn-measuring campaign started



Approaching the r-process boulevard

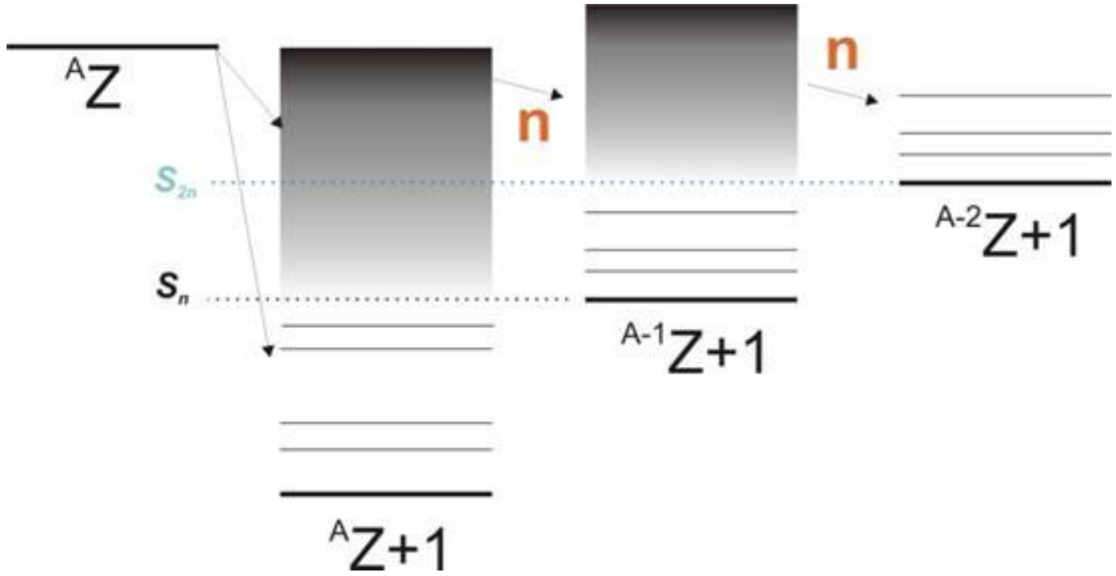


- Heaviest βn-emitters measured so far: important for theoretical predictions
- Data analysis in progress
- Gap to peak nuclei:
  - ^{194}Er (-16n: ^{178}Er)
  - ^{195}Tm (-14n: ^{181}Tm)



Outlook 1: Measure P_{xn}

$S_{2n} < Q_\beta$



First experimental identification of P_{2n}:

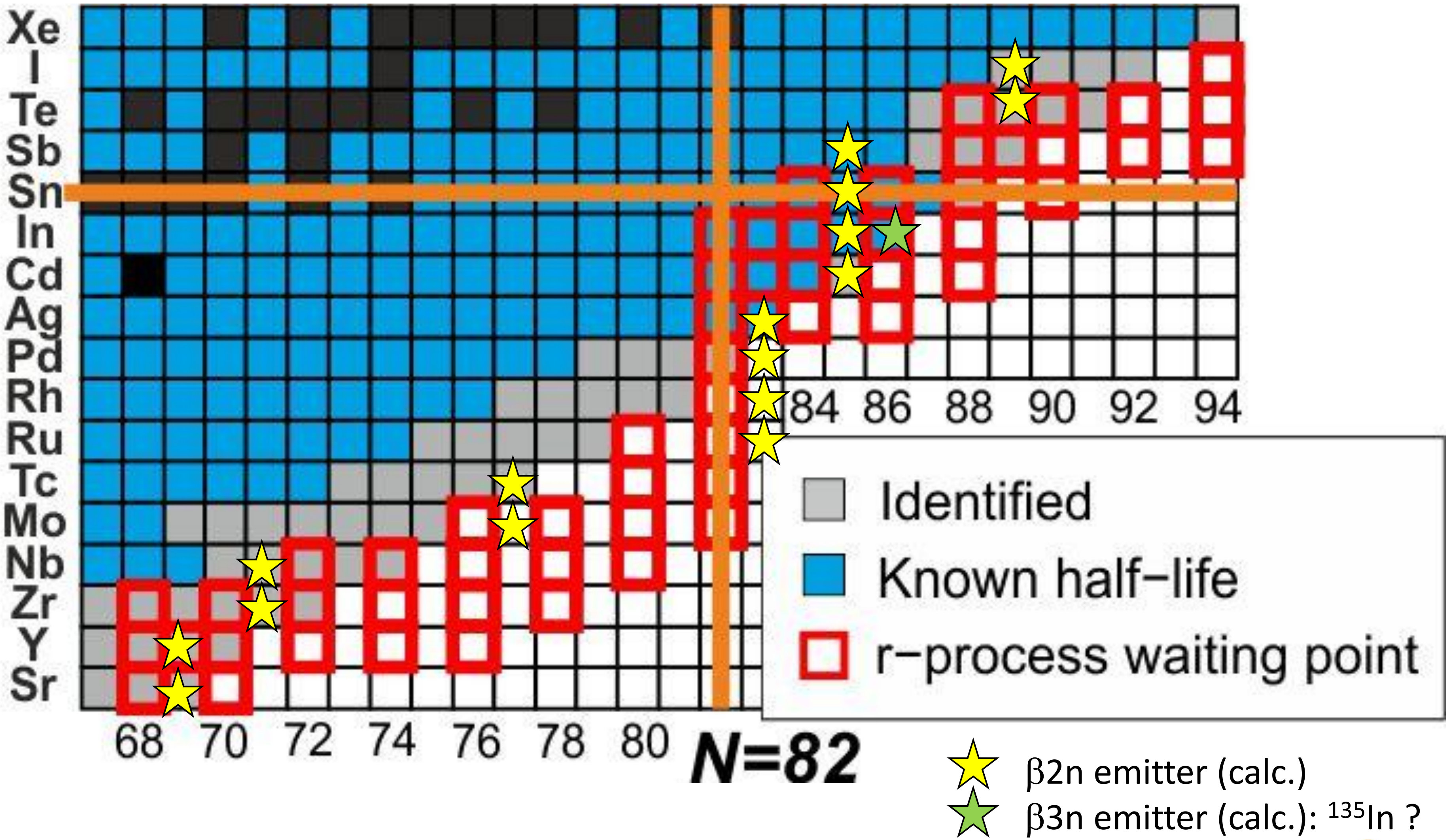
^{11}**Li** ($t_{1/2}$= 8.6 ms) @ISOLDE Azuma et al., PRL 43, 1652 (1979)

$^{30-32}$**Na** ($t_{1/2}$= 13-48 ms) @ISOLDE Detraz et al., Phys. Lett. 94B, 307 (1980)

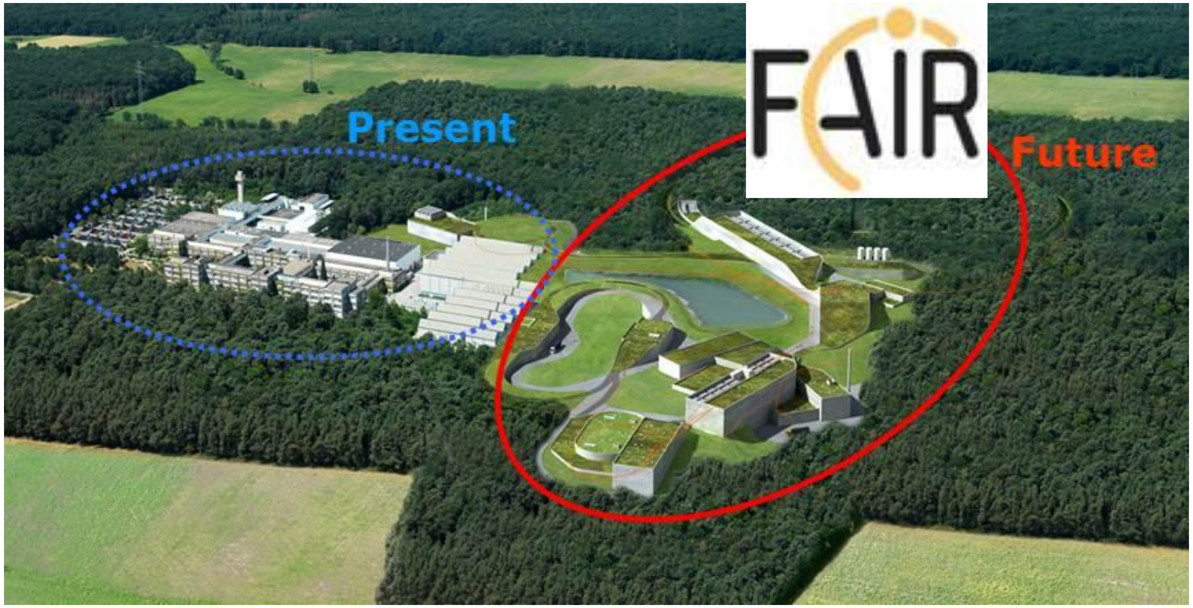
^{98}**Rb** ($t_{1/2}$= 114 ms) @TRISTAN Reeder et al., PRL 47, 483 (1981)

- 18 β2n and 4 β3n emitter (^{11}Li, ^{14}Be, ^{17}B, ^{31}Na) known

Outlook 1: Measure P_{2n} and P_{3n}

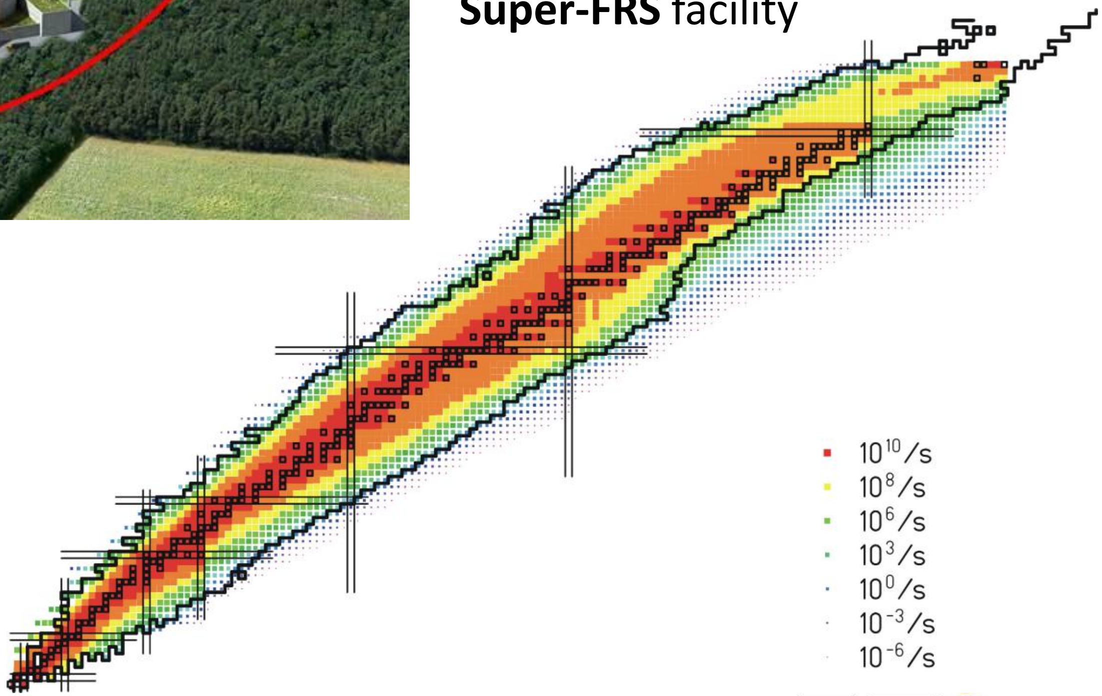


Outlook 2: Future RIB facilities



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

Super-FRS facility

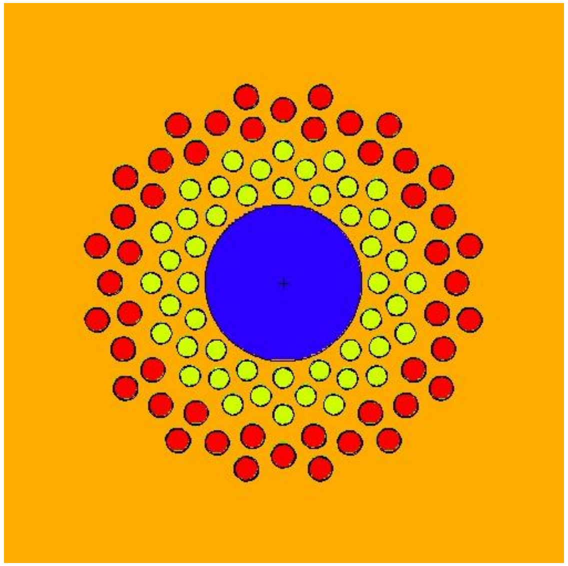


Similar RIB projects:

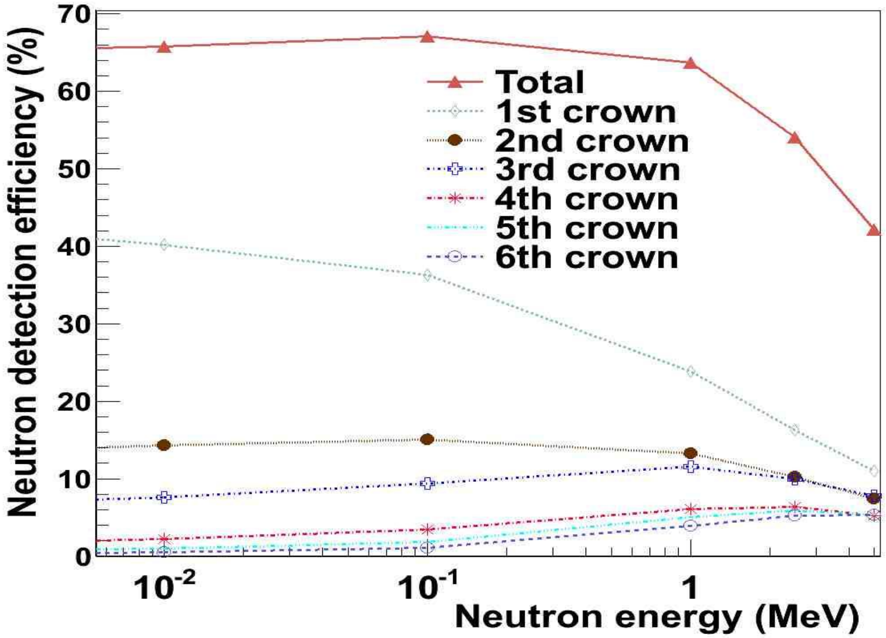
- Spiral 2 (France)
- FRIB (USA)
- RIBF (Japan, since 2007)

⇨ More βxn-emitters in reach, **priorities shifted**

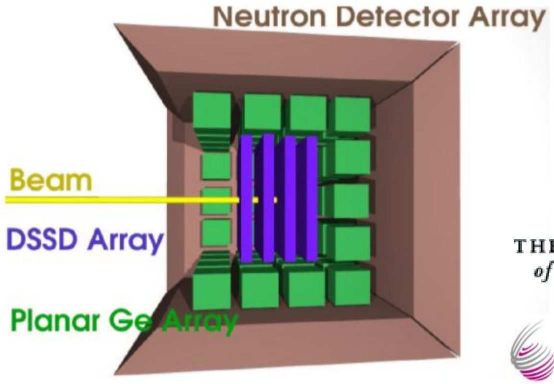
Neutron detector upgrade for DESPEC@FAIR



- Inclusion of additional counters from JINR Dubna ⇨ upgrade to 96 counters
- New implantation detector AIDA
- Efficiency: BELEN-30: ≈40% ⇨ **BELEN-96: ≈65%**



Advanced Implantation Detector Array (AIDA)



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Pictures: M.B. Gomez Hornillos and T. Davinson

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