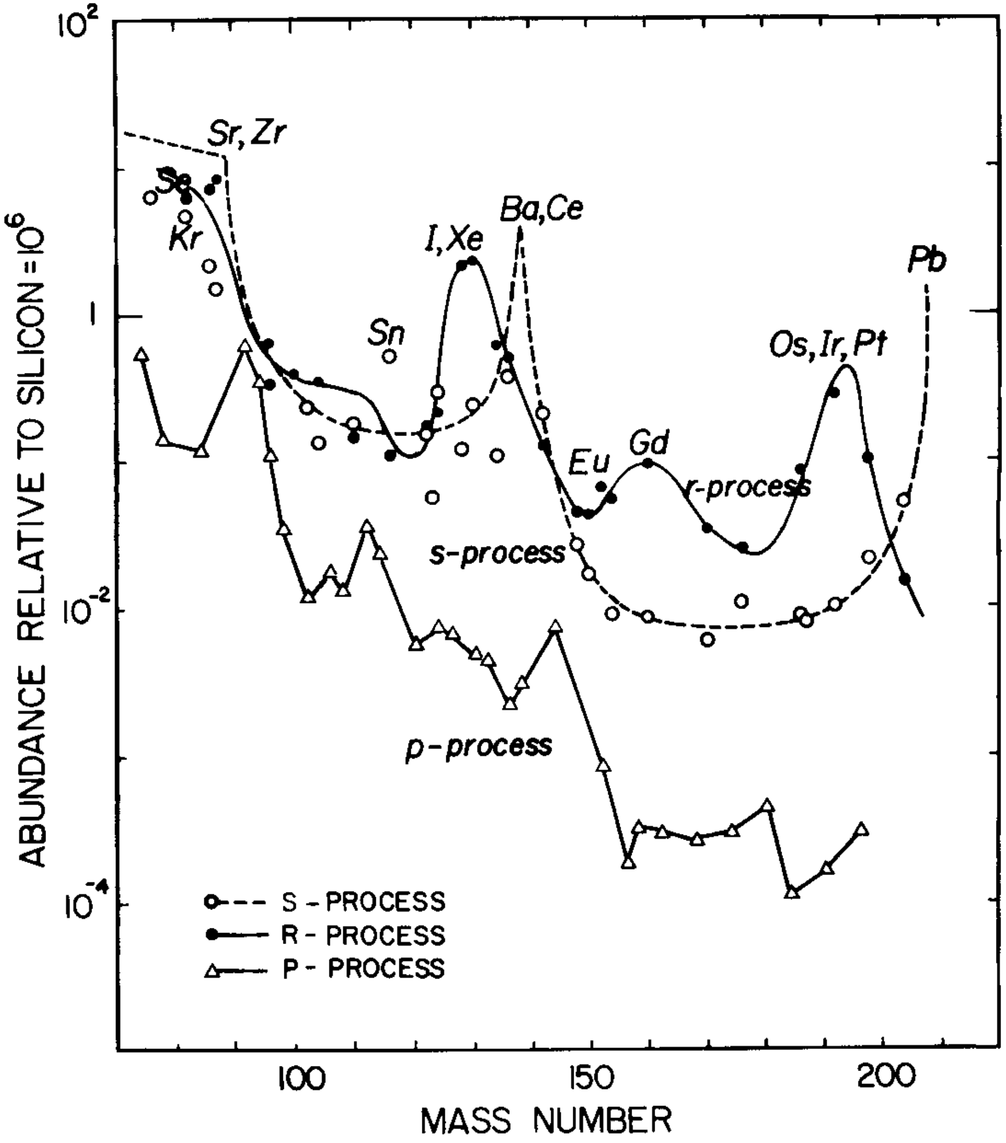
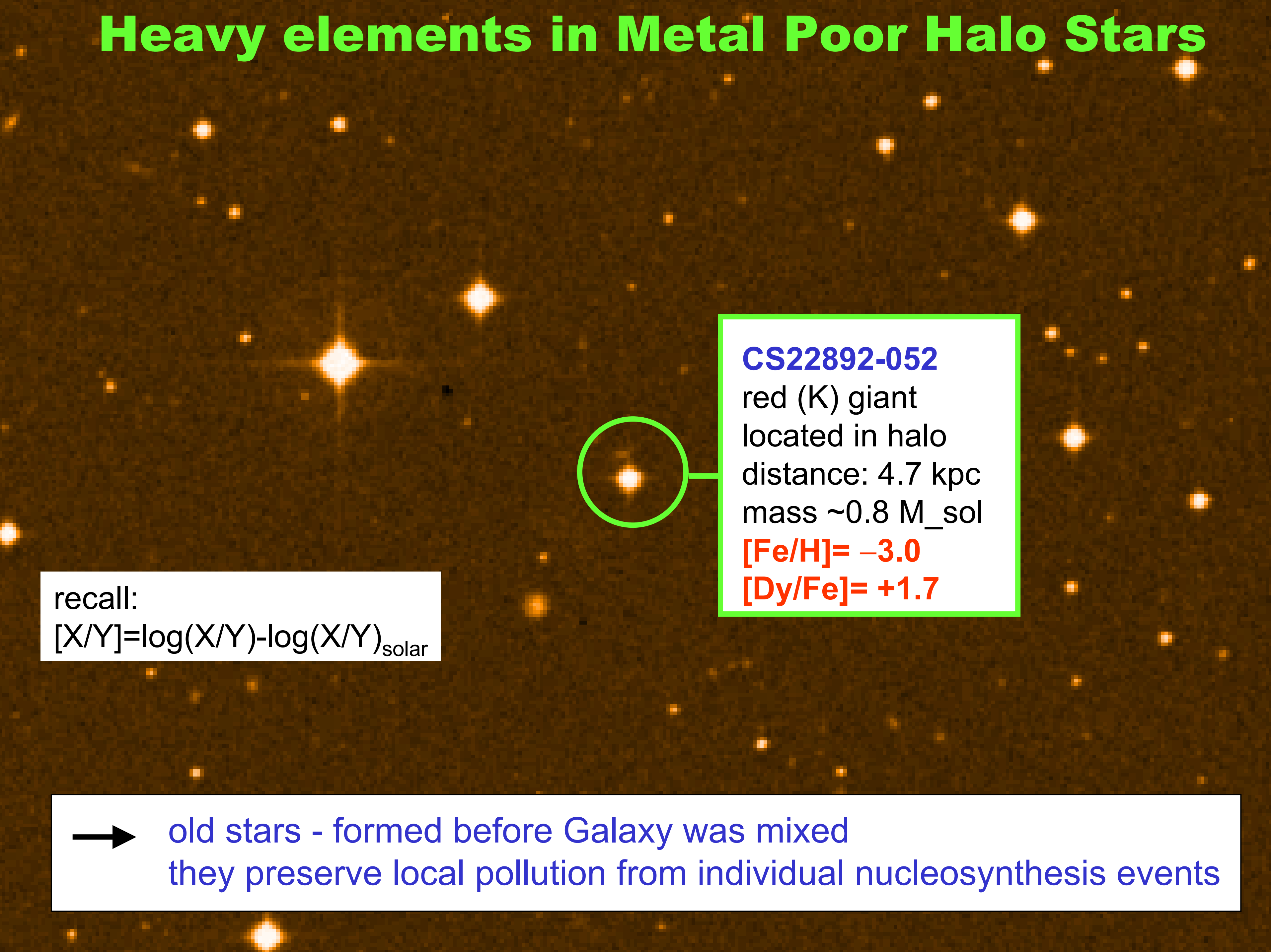
The origin of heavy elements in the solar system



(Pagel, Fig 6.8)

each process contribution is a mix of many events !

Heavy elements in Metal Poor Halo Stars



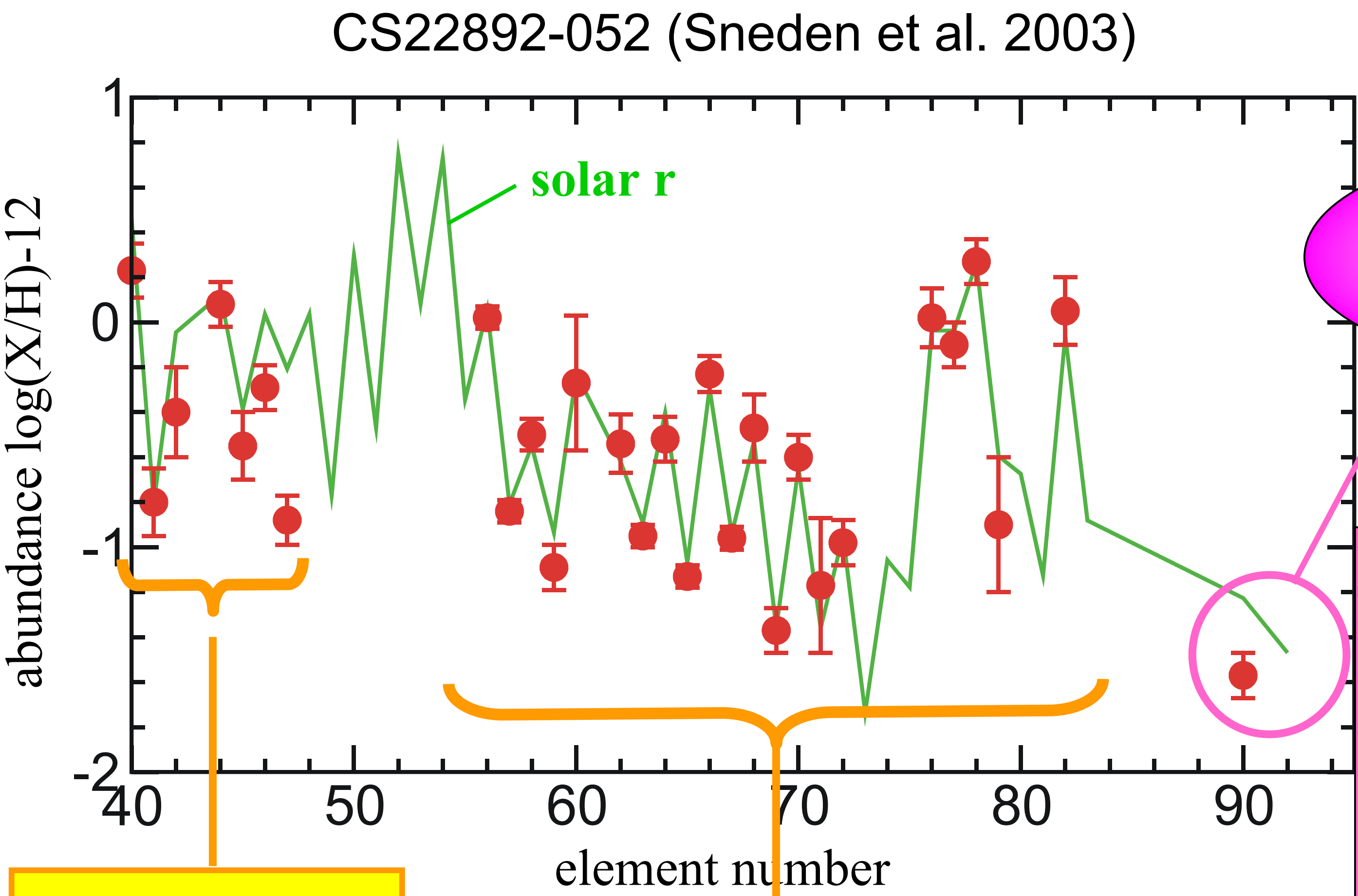
CS22892-052
red (K) giant
located in halo
distance: 4.7 kpc
mass ~0.8 M_sol
[Fe/H]= –3.0
[Dy/Fe]= +1.7

recall:
$[X/Y]=\log(X/Y)-\log(X/Y)_{solar}$

→ old stars - formed before Galaxy was mixed
they preserve local pollution from individual nucleosynthesis events

A single (or a few) r-process event(s)

CS22892-052 (Sneden et al. 2003)



Cosmo Chronometer

NEW:
CS31082-001 with U
(Cayrel et al. 2001)

Age: 16±3 Gyr
(Schatz et al. 2002
ApJ 579, 626)

other, second
r-process to fill
this up ?
(weak r-process)

main r-process
matches exactly solar r-pattern
conclusions ?

Overview heavy element nucleosynthesis

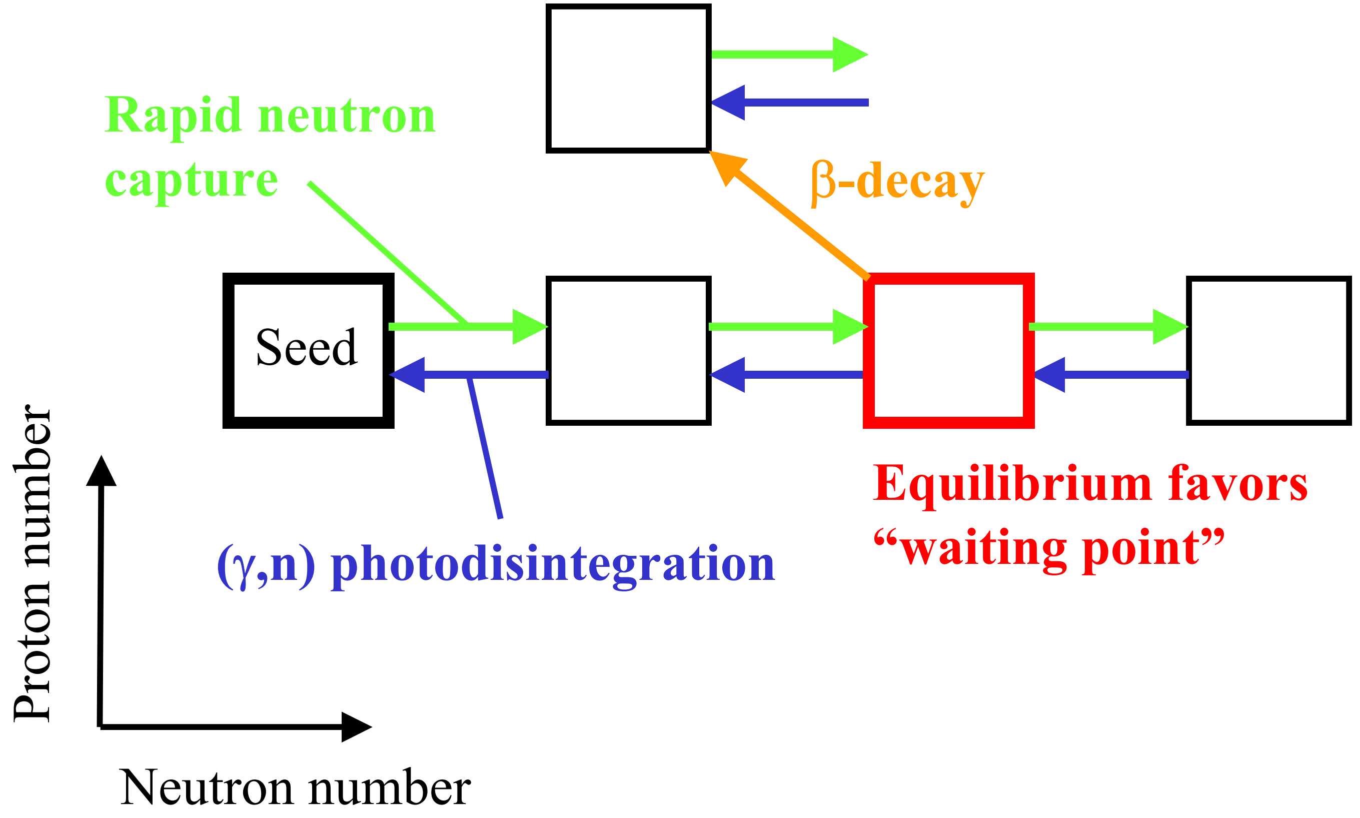
process	**conditions**	**timescale**	**site**
s-process (n-capture, ...)	T~ 0.1 GK τ_n~ 1-1000 yr, $n_n \sim 10^{7-8}/cm^3$	10^2 yr and 10^{5-6} yrs	Massive stars (weak) Low mass AGB stars (main)
r-process (n-capture, ...)	T~1-2 GK $\tau_n \sim \mu s$, $n_n \sim 10^{24}\ /cm^3$	< 1s	Type II Supernovae ? Neutron Star Mergers ?
p-process ((γ,n), ...)	T~2-3 GK	~1s	Type II Supernovae

The r-process

Temperature: ~1-2 GK

Density: 300 g/cm3 (~60% neutrons !)

neutron capture timescale: ~ 0.2 μs



Rapid neutron capture

β-decay

Seed

Equilibrium favors “waiting point”

(γ,n) photodisintegration

Proton number

Neutron number

show movie

Waiting point approximation

Definition: **ASSUME** (n,γ)-(γ,n) equilibrium within isotopic chain

How good is the approximation ?

This is a valid assumption during most of the r-process

BUT: freezeout is neglected

Freiburghaus et al. ApJ 516 (2999) 381 showed agreement with dynamical models

Consequences

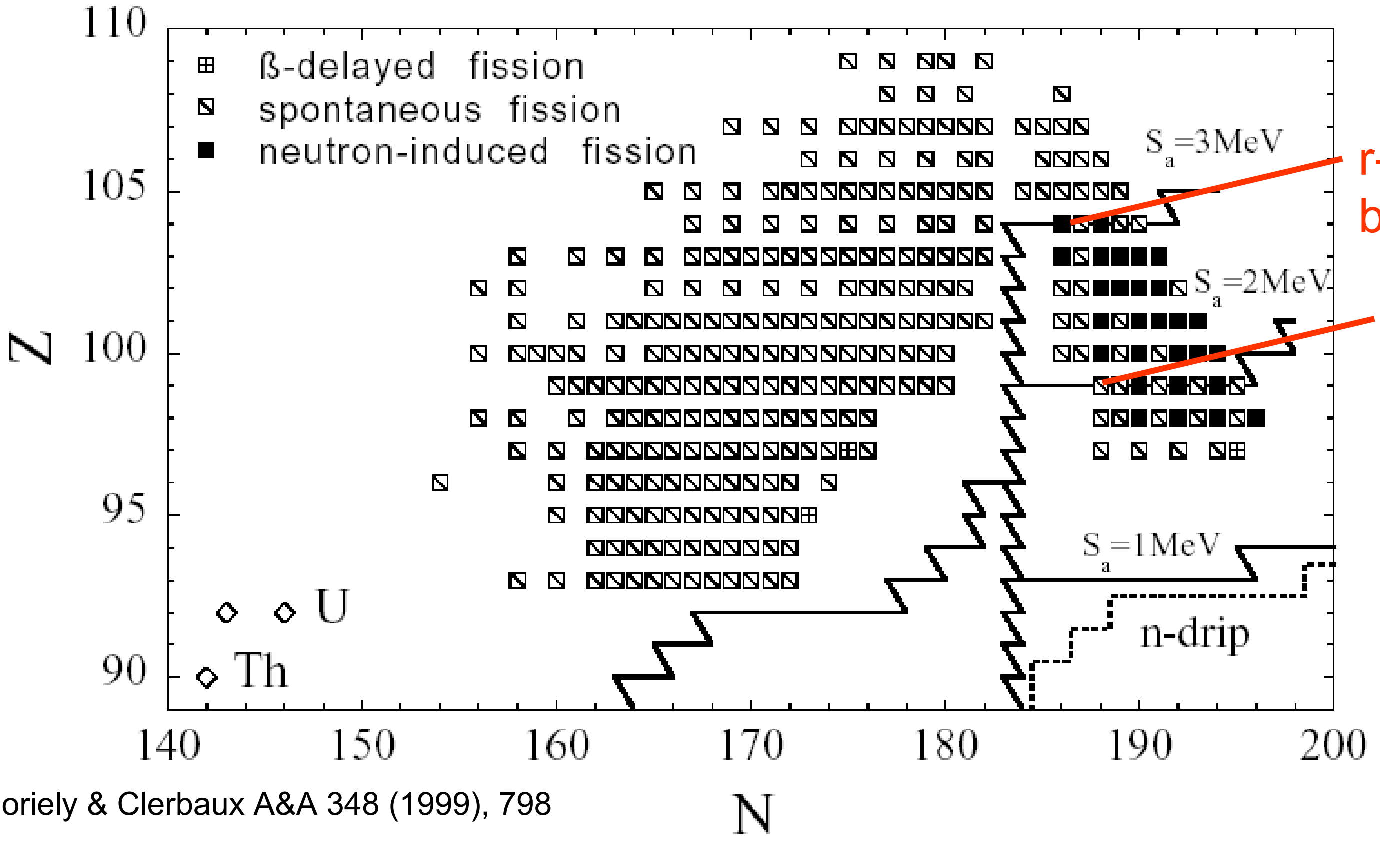
During (n,γ)-(γ,n) equilibrium abundances within an isotopic chain are given by:

$$\frac{Y(Z,A+1)}{Y(Z,A)} = n_n \frac{G(Z,A+1)}{2G(Z,A)} \left[\frac{A+1}{A} \frac{2\pi\hbar^2}{m_u kT} \right]^{3/2} \exp(S_n / kT)$$

- **time independent**
  - can treat whole chain as a single nucleus in network
  - only slow beta decays need to be calculated dynamically
- **neutron capture rate independent**

(therefore: during most of the r-process n-capture rates do not matter !)

Endpoint of the r-process

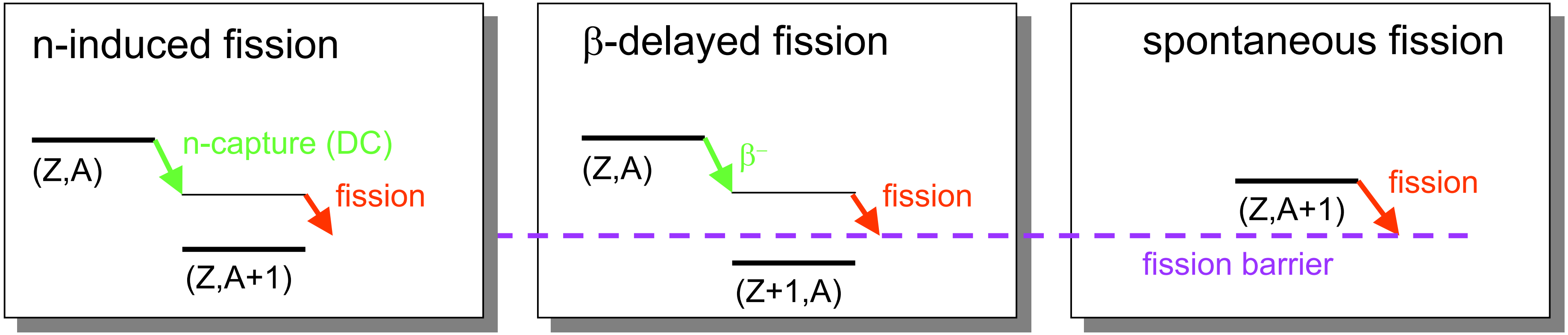


r-process ended by n-induced fission

or spontaneous fission

(different paths for different conditions)

(Goriely & Clerbaux A&A 348 (1999), 798



n-induced fission

β-delayed fission

spontaneous fission

Consequences of fission

Fission produces $A \sim A_{end}/2 \sim 125$ nuclei

→ **modification of abundances around A=130 peak**

→ **fission products can serve as seed for the r-process**

- are processed again into A~250 region via r-process
- fission again

→ **fission cycling !**

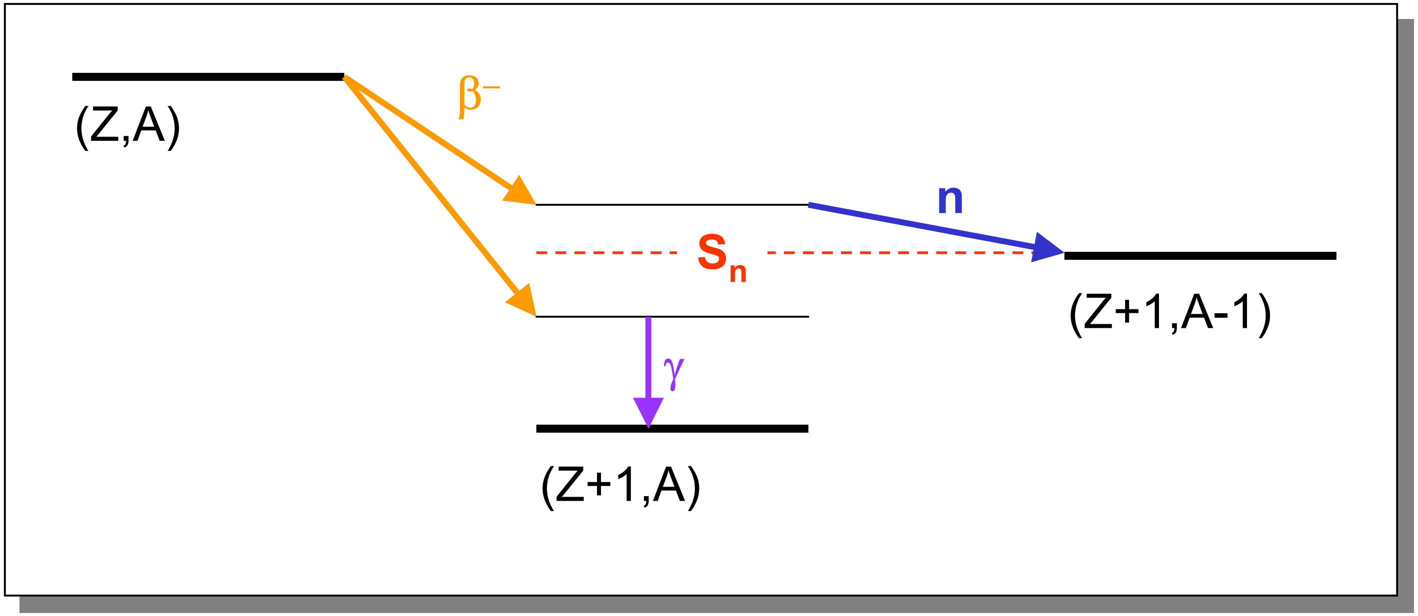
Note: the exact endpoint of the r-process and the degree and impact of fission are unknown because:

- Site conditions not known – is n/seed ratio large enough to reach fission ?
  (or even large enough for fission cycling ?)
- Fission barriers highly uncertain
- Fission fragment distributions not reliably calculated so far (for fission from excited states !)

Role of beta delayed neutron emission

Neutron rich nuclei can emit one or more neutrons during β-decay if **$S_n<Q_\beta$**

(the more neutron rich, the lower S_n and the higher Q_β)



If some fraction of decay goes above S_n in daughter nucleus then some fraction P_n of the decays will emit a neutron (in addition to e^- and ν)

(generally, neutron emission competes favorably with γ-decay - strong interaction !)

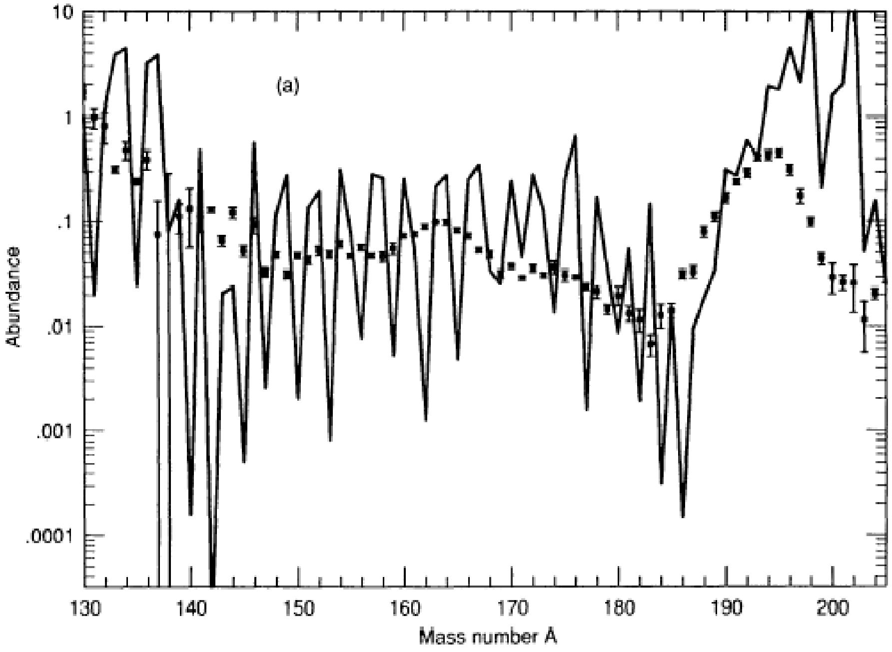
Effects: **during r-process**: **none** as neutrons get recaptured quickly

during freezeout

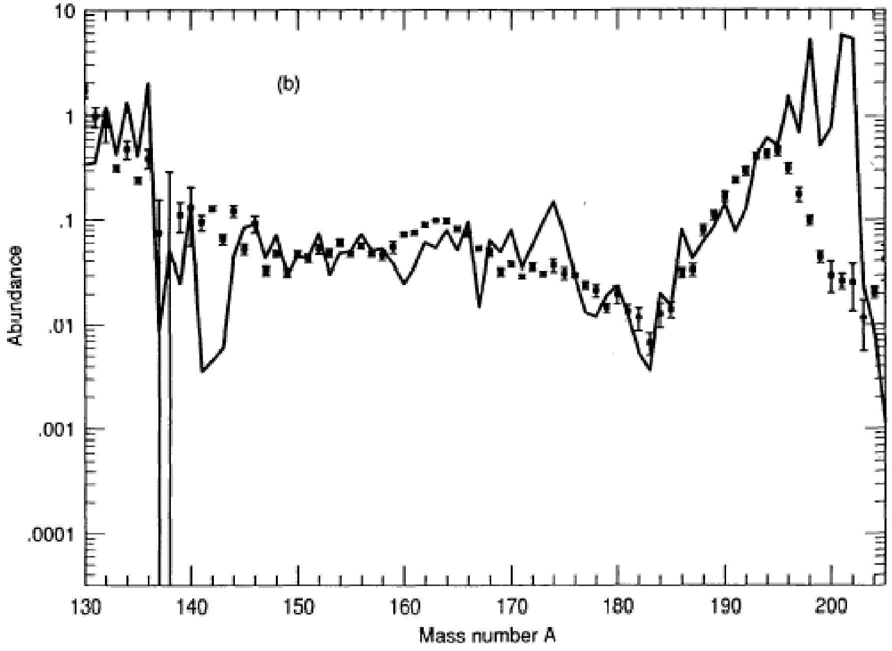
- **modification of final abundance**
- **late time neutron production (those get recaptured)**

Calculated r-process production of elements (Kratz et al. ApJ 403 (1993) 216):

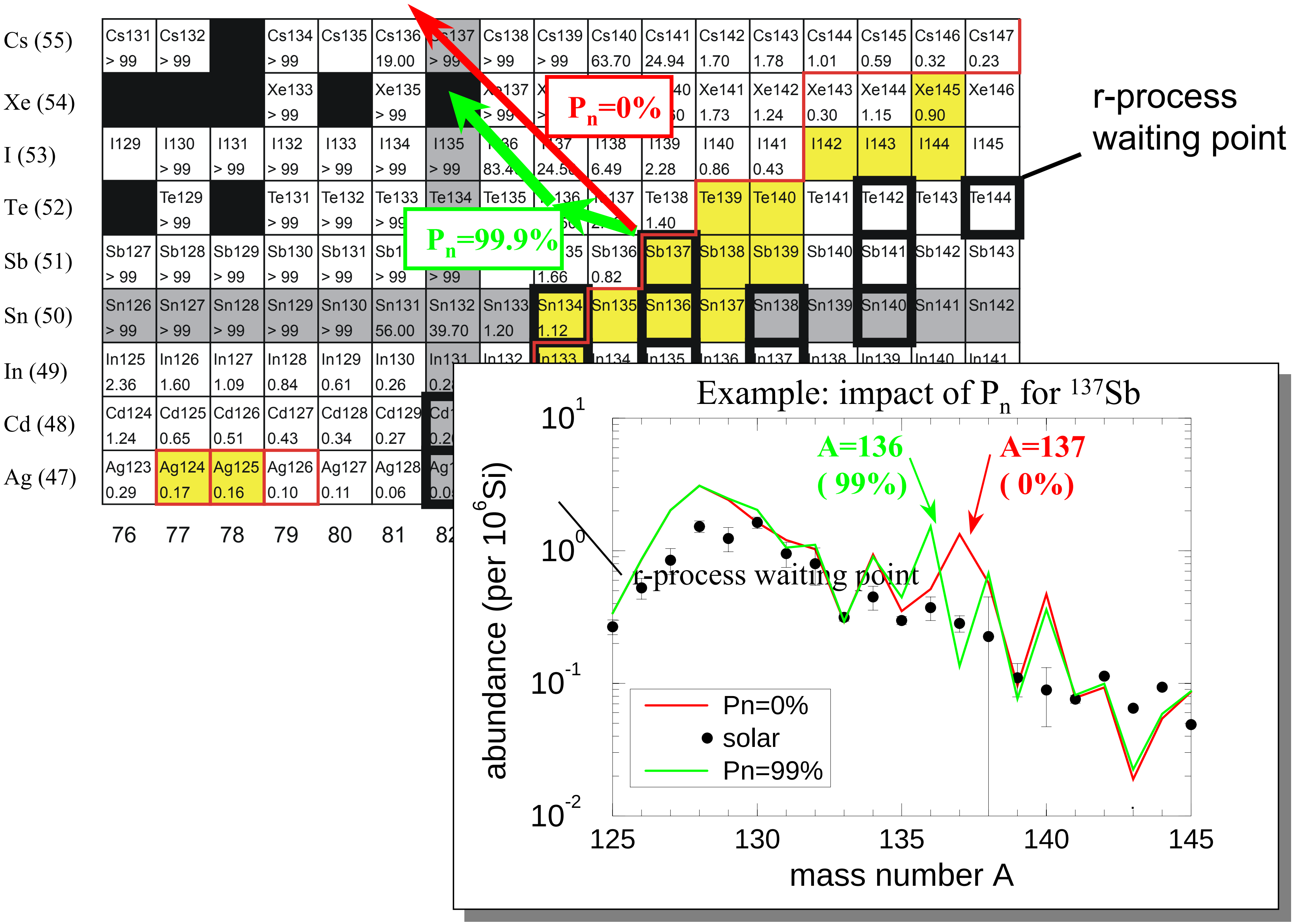
before β-decay



after β-decay



→ **smoothing effect from β-delayed n emission !**



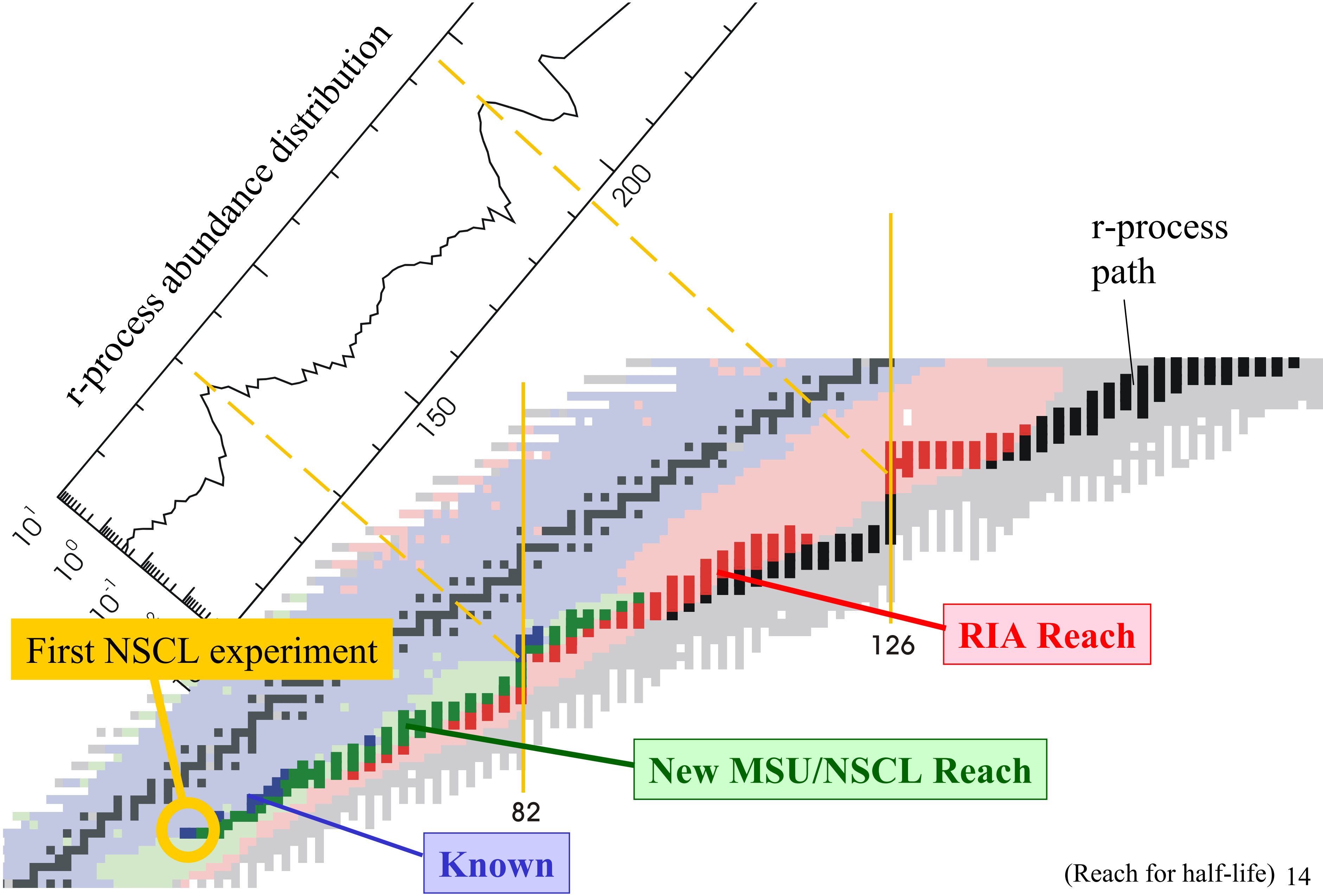
r-process waiting point

Cs (55)	Cs131 > 99	Cs132 > 99		Cs134 > 99	Cs135	Cs136 19.00	s137 > 99	Cs138 > 99	Cs139 > 99	Cs140 63.70	Cs141 24.94	Cs142 1.70	Cs143 1.78	Cs144 1.01	Cs145 0.59	Cs146 0.32	Cs147 0.23
Xe (54)				Xe133 > 99		Xe135 > 99		137 > 99	X >		40 0	Xe141 1.73	Xe142 1.24	Xe143 0.30	Xe144 1.15	Xe145 0.90	Xe146
I (53)	I129	I130 > 99	I131 > 99	I132 > 99	I133 > 99	I134 > 99	I135 > 99	36 83.4	37 24.5	I138 6.49	I139 2.28	I140 0.86	I141 0.43	I142	I143	I144	I145
Te (52)		Te129 > 99		Te131 > 99	Te132 > 99	Te133 > 99	Te134	Te135	136 50	137 2	Te138 1.40	Te139	Te140	Te141	Te142	Te143	Te144
Sb (51)	Sb127 > 99	Sb128 > 99	Sb129 > 99	Sb130 > 99	Sb131 > 99	Sb1 > 99	> 99		35 1.66	Sb136 0.82	Sb137	Sb138	Sb139	Sb140	Sb141	Sb142	Sb143
Sn (50)	Sn126 > 99	Sn127 > 99	Sn128 > 99	Sn129 > 99	Sn130 > 99	Sn131 56.00	Sn132 39.70	Sn133 1.20	Sn134 1.12	Sn135	Sn136	Sn137	Sn138	Sn139	Sn140	Sn141	Sn142
In (49)	In125 2.36	In126 1.60	In127 1.09	In128 0.84	In129 0.61	In130 0.26	In131 0.2	In132	In133	In134	In135	In136	In137	In138	In139	In140	In141
Cd (48)	Cd124 1.24	Cd125 0.65	Cd126 0.51	Cd127 0.43	Cd128 0.34	Cd129 0.27	Cd1 0.2										
Ag (47)	Ag123 0.29	Ag124 0.17	Ag125 0.16	Ag126 0.10	Ag127 0.11	Ag128 0.06	Ag1 0.0										
	76	77	78	79	80	81	82										

Summary: Nuclear physics in the r-process

Quantity		**Effect**
S_n	**neutron separation energy**	**path**
$T_{1/2}$	**β-decay half-lives**	**• abundance pattern** **• timescale**
P_n	**β-delayed n-emission branchings**	**final abundance pattern**
fission (branchings and products)		**• endpoint** **• abundance pattern?** **• degree of fission cycling**
G	**partition functions**	**• path (very weakly)**
$N_A\langle\sigma v\rangle$	**neutron capture rates**	**• final abundance pattern during freezeout ?** **• conditions for waiting point approximation**

The r-process path



First NSCL experiment

RIA Reach

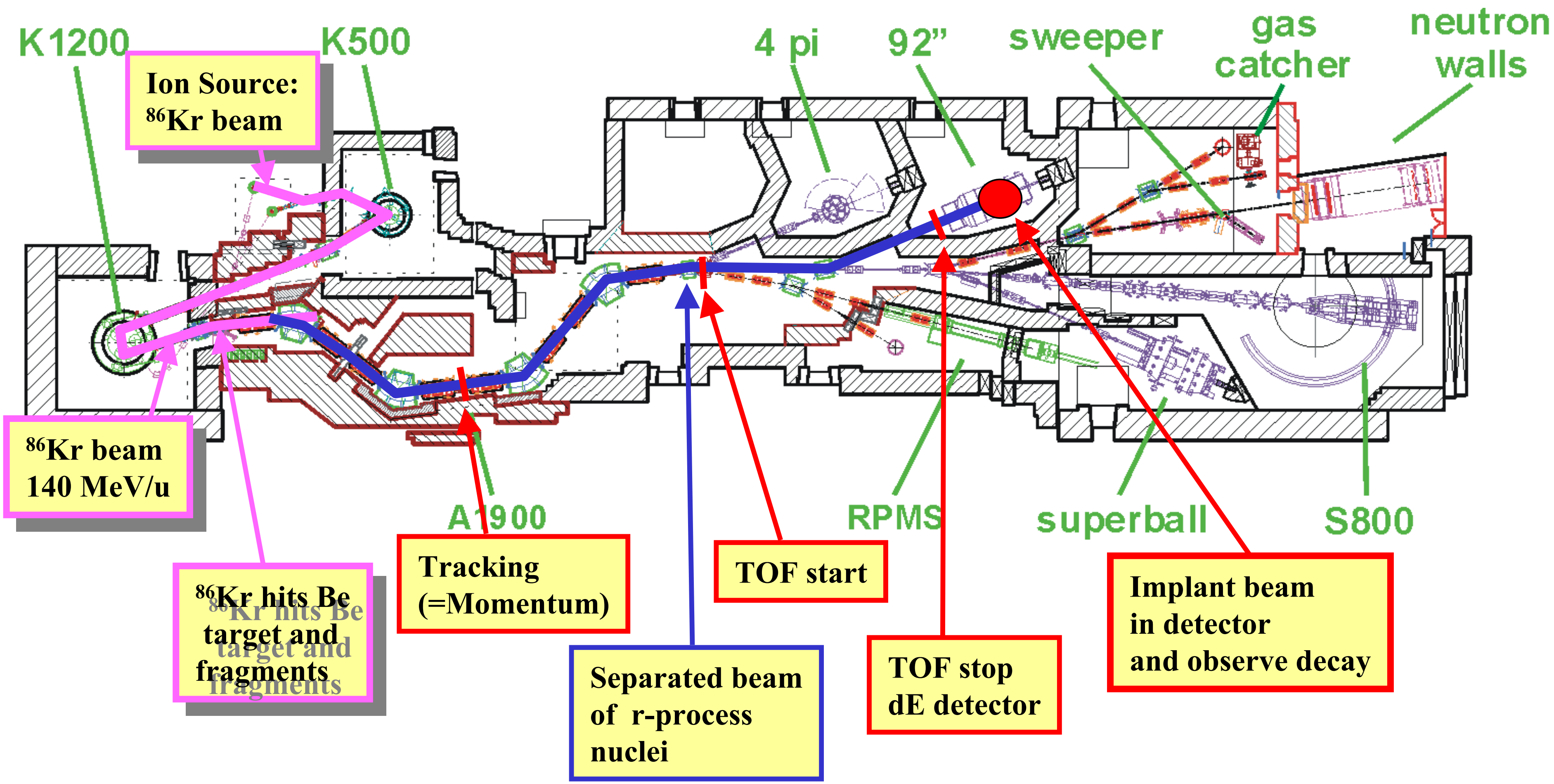
New MSU/NSCL Reach

Known

(Reach for half-life)

National Superconducting Cyclotron Laboratory at Michigan State University

New Coupled Cyclotron Facility – experiments since mid 2001



Ion Source: ^{86}Kr beam

^{86}Kr beam 140 MeV/u

^{86}Kr hits Be target and fragments

^{86}Kr hits Be target and fragments

Tracking (=Momentum)

Separated beam of r-process nuclei

TOF start

TOF stop dE detector

Implant beam in detector and observe decay

Fast beam fragmentation facility – allows event by event particle identification

Installation of D4 steel, Jul/2000

First r-process experiments at new NSCL CCF facility (June 02)

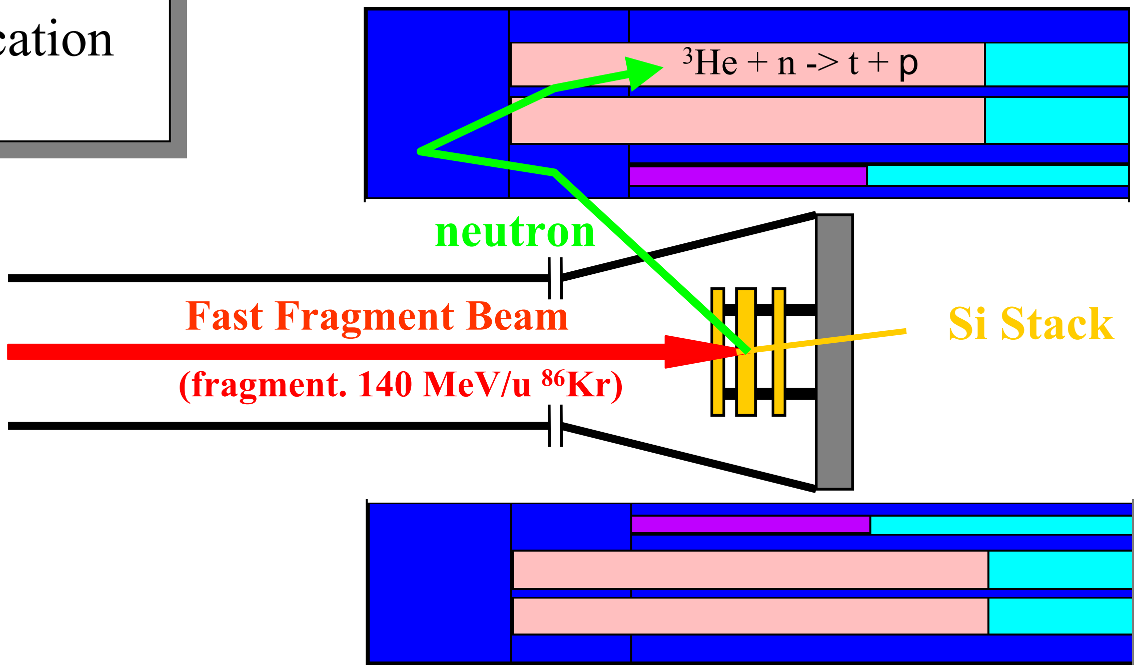
Measure:

- β-decay half-lives
- Branchings for β-delayed n-emission

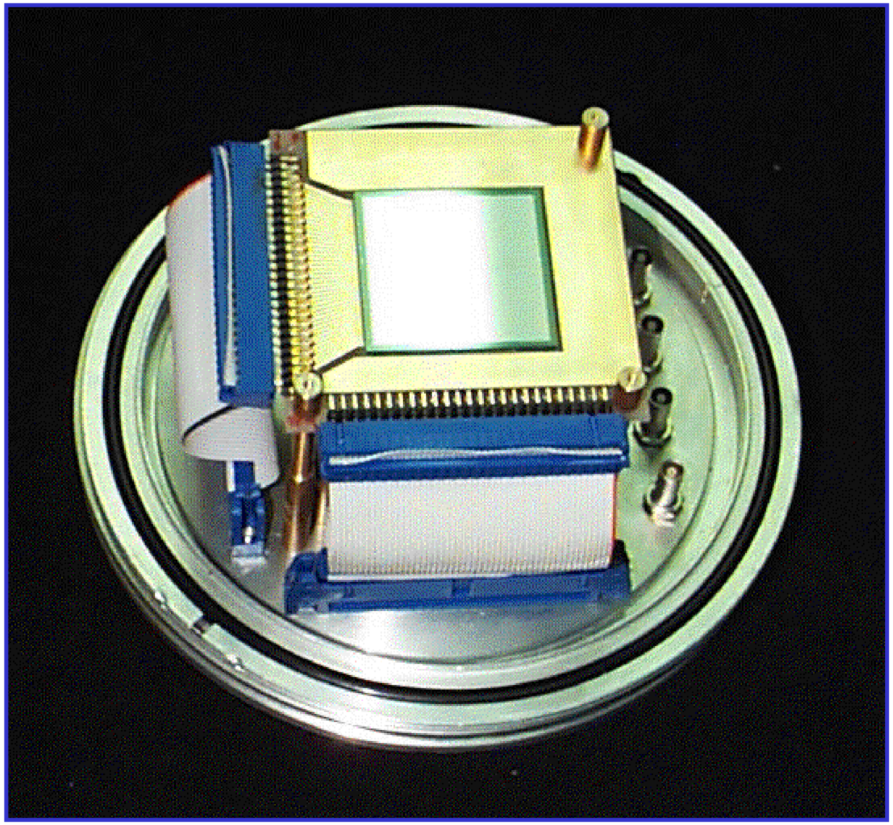
Detect:

- Particle type (TOF, dE, p)
- Implantation time and location
- β-emission time and location
- neutron-β coincidences

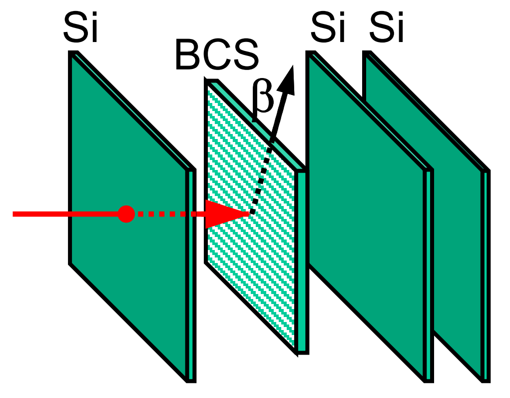
New NSCL Neutron detector NERO



NSCL BCS – Beta Counting System



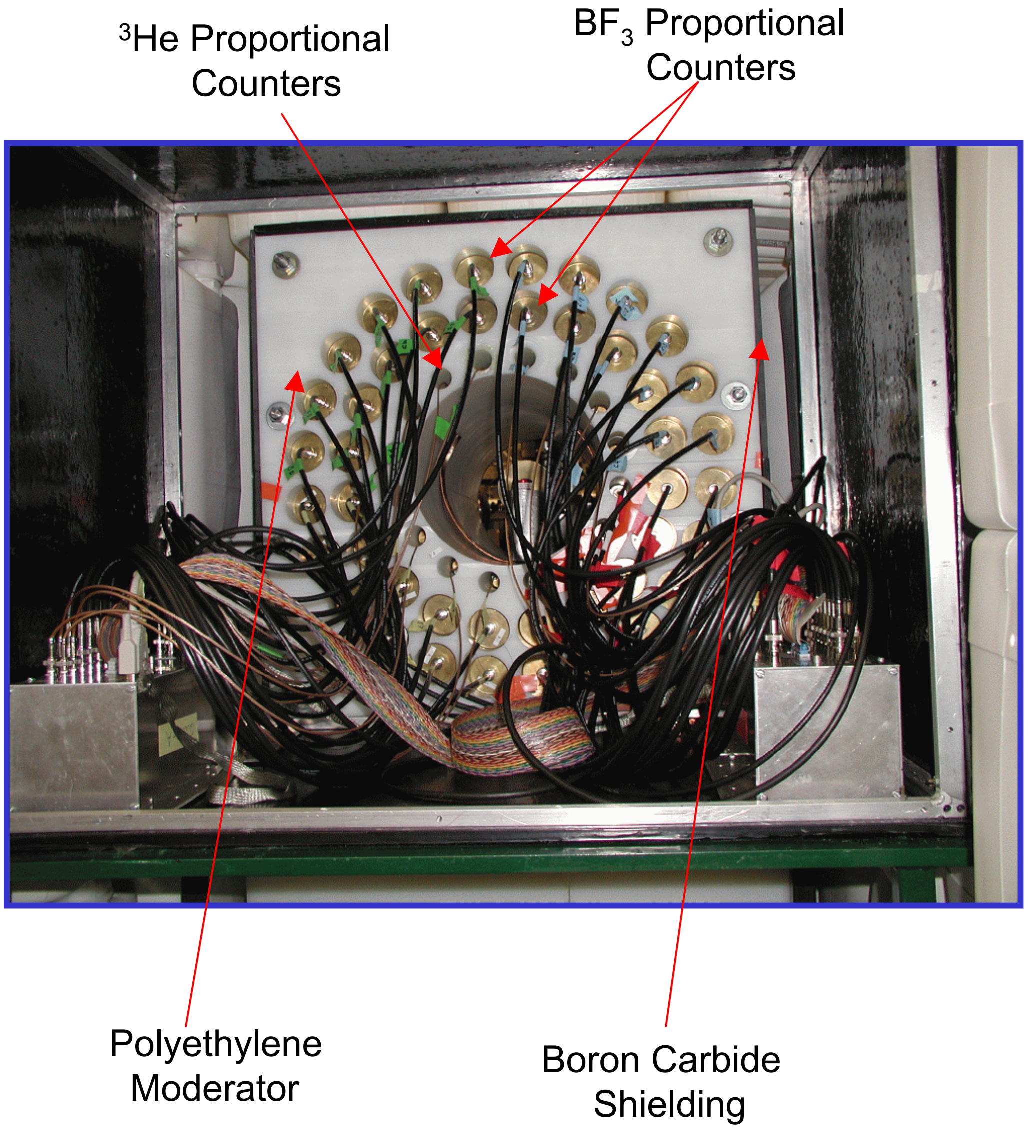
- 4 cm x 4 cm active area
- 1 mm thick
- 40-strip pitch in x and y dimensions ->1600 pixels



NERO – Neutron Emission Ratio Observer

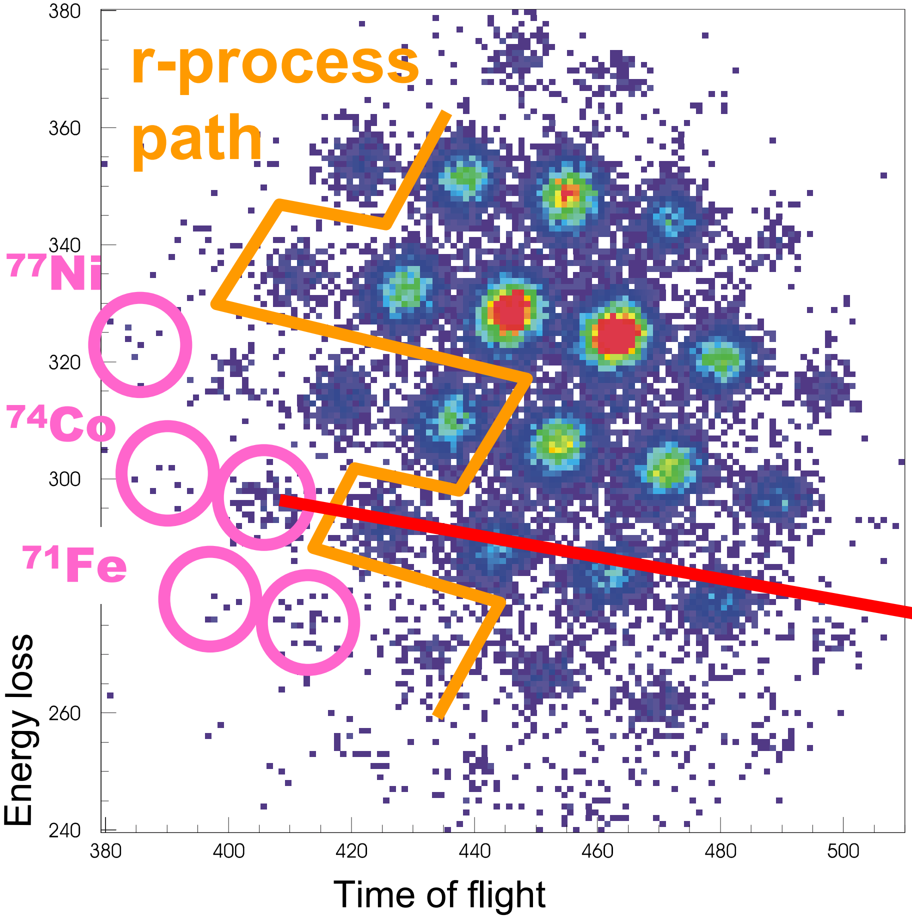
<u>Specifications</u>:

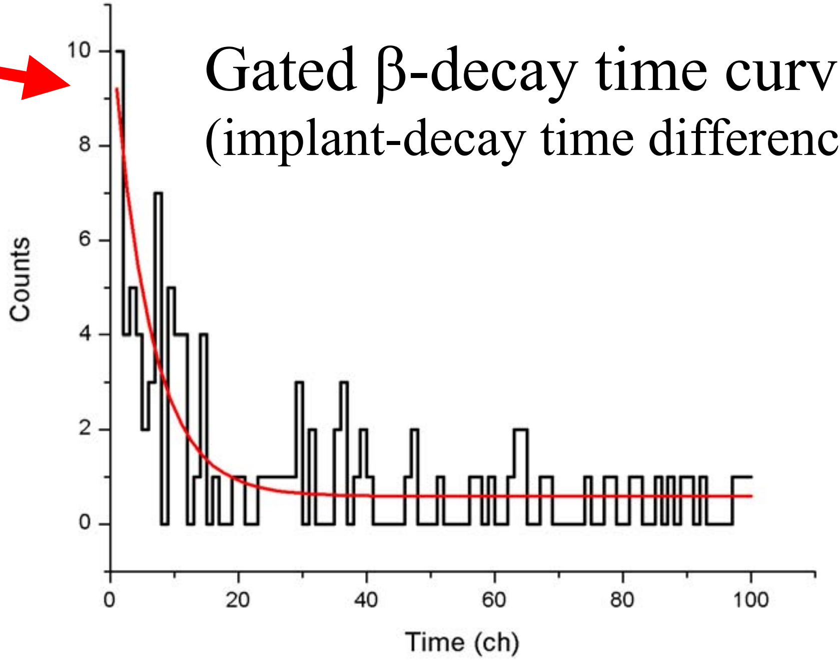
- 60 counters total
  (16 ^{3}He , 44 BF_3)
- 60 cm x 60 cm x 80 cm polyethylene block
- Extensive exterior shielding
- 43% total neutron efficiency (MCNP)



June 2002 Data – preliminary results

Mainz: K.-L. Kratz, B. Pfeiffer
PNNL: P. Reeder
Maryland/ANL: W.B. Walters, A. Woehr
Notre Dame: J. Goerres, M. Wiescher
NSCL: **P. Hosmer**, R. Clement, A. Estrade, P.F. Mantica, F. Montes, C. Morton, M. Ouellette, P. Santi, A. Stolz





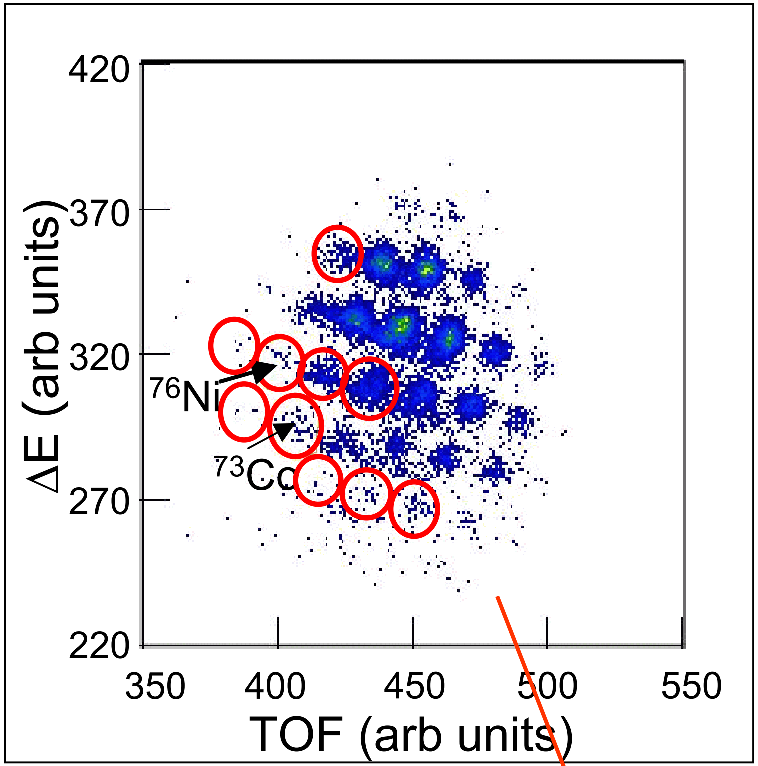
Gated β-decay time curve
(implant-decay time differences)

Fast RIBs:

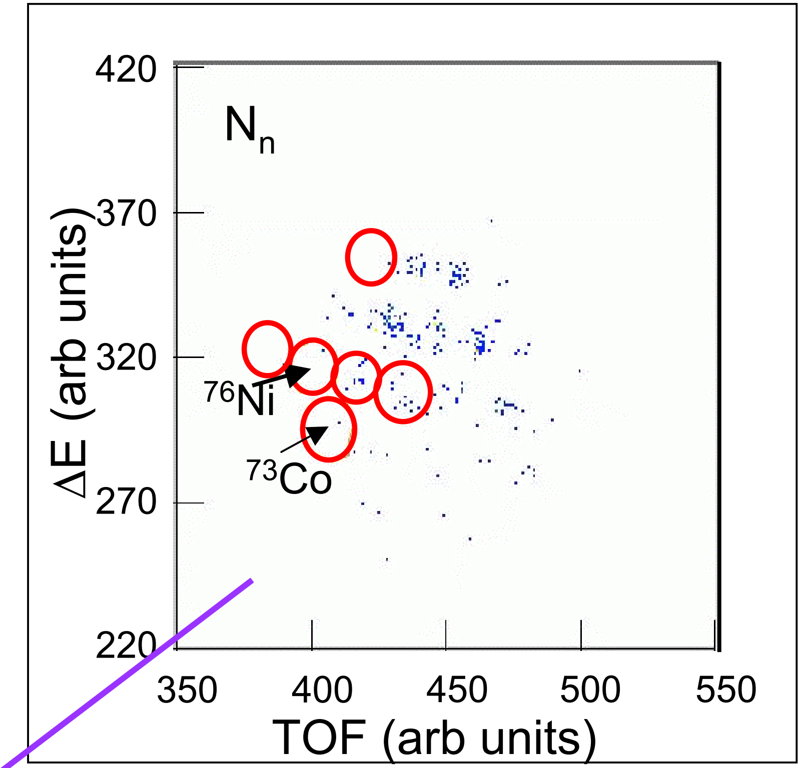
- cocktail beams
- no inflight decay losses
- measure with low rates (>1/day)

Neutron Data

Nuclei with decay detected



With neutron in addition



$$P_n = \frac{N_n}{N_\beta \varepsilon_n}$$

neutron detection efficiency

(neutrons seen/neutrons emitted)