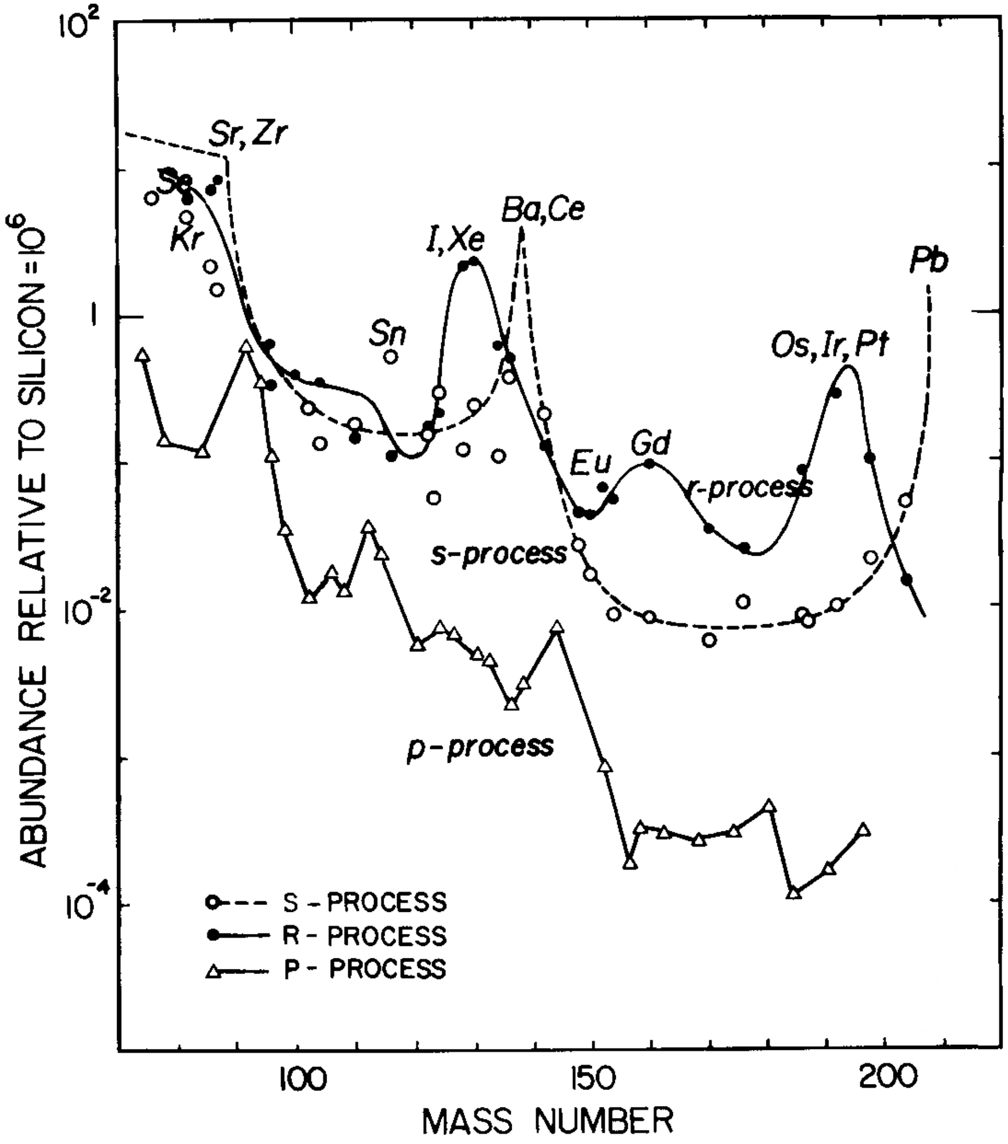
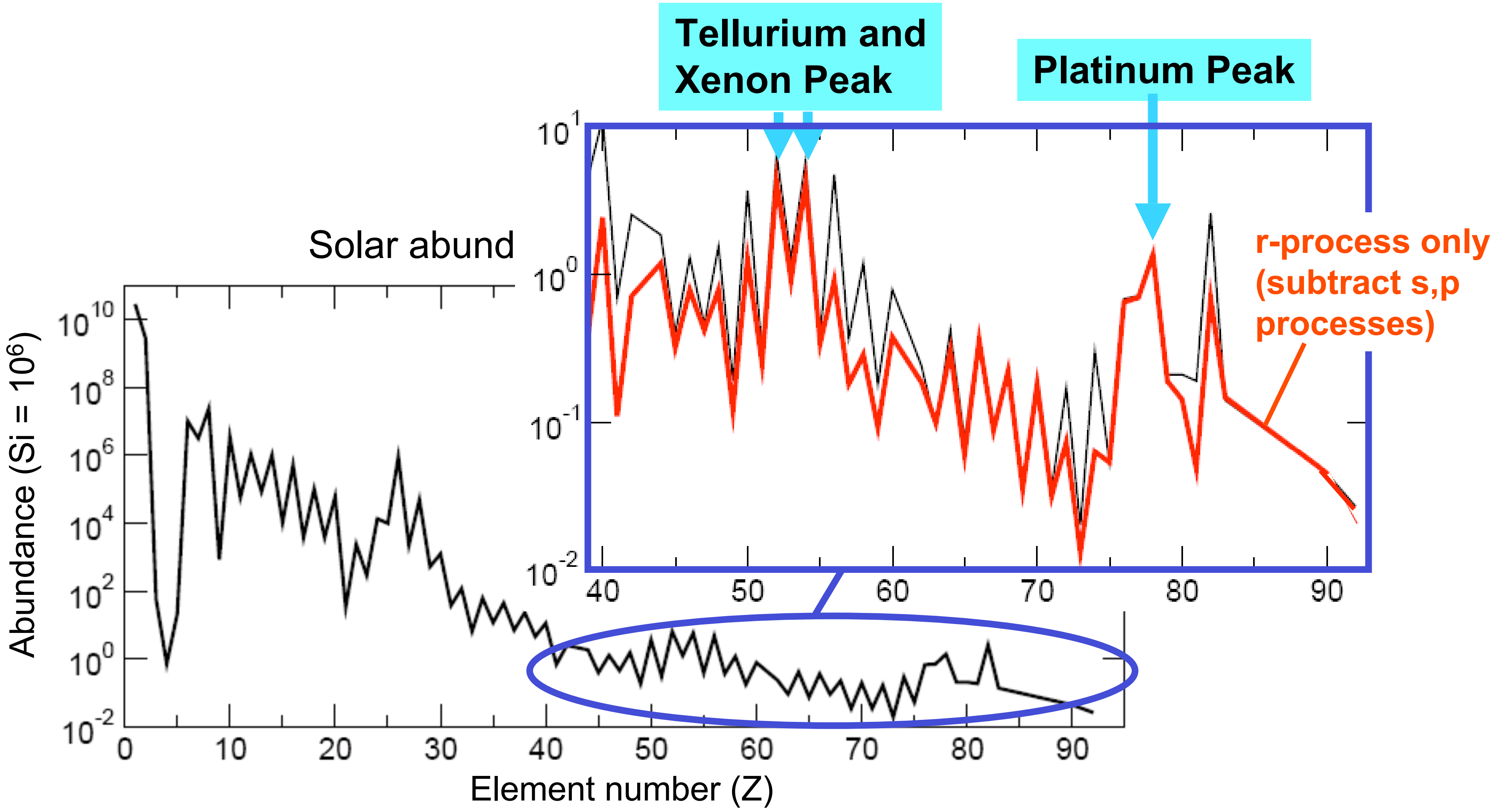
The origin of heavy elements in the solar system



(Pagel, Fig 6.8)

each process contribution is a mix of many events !

Abundance pattern: “Finger print” of the r-process ?


Tellurium and Xenon Peak

Platinum Peak

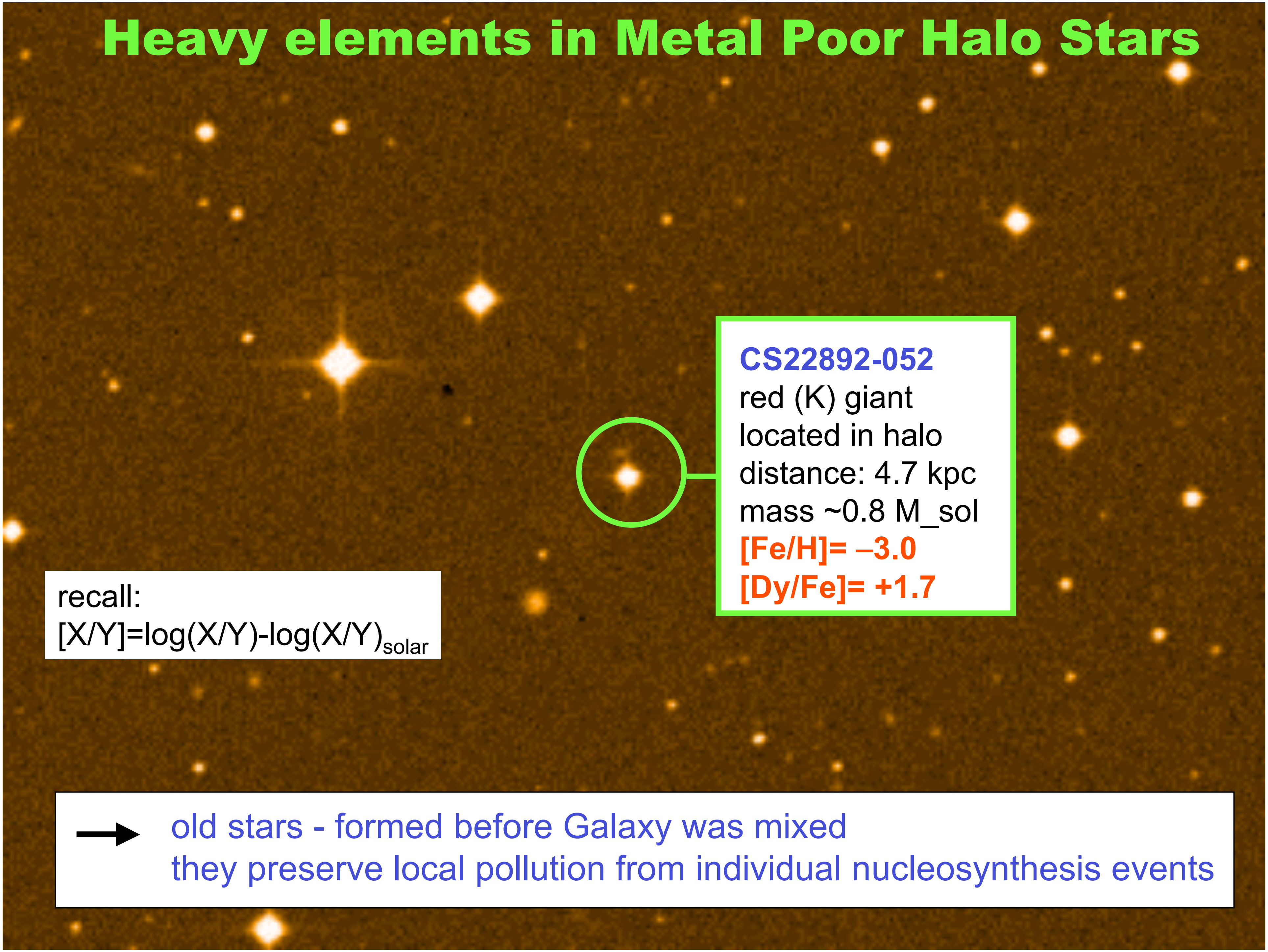
r-process only (subtract s,p processes)

But: sun formed ~10 billion years after big bang: many stars contributed to elements

→ This could be an accidental combination of many different “fingerprints” ?

→ Find a star that is much older than the sun to find “fingerprint” of single event

Heavy elements in Metal Poor Halo Stars

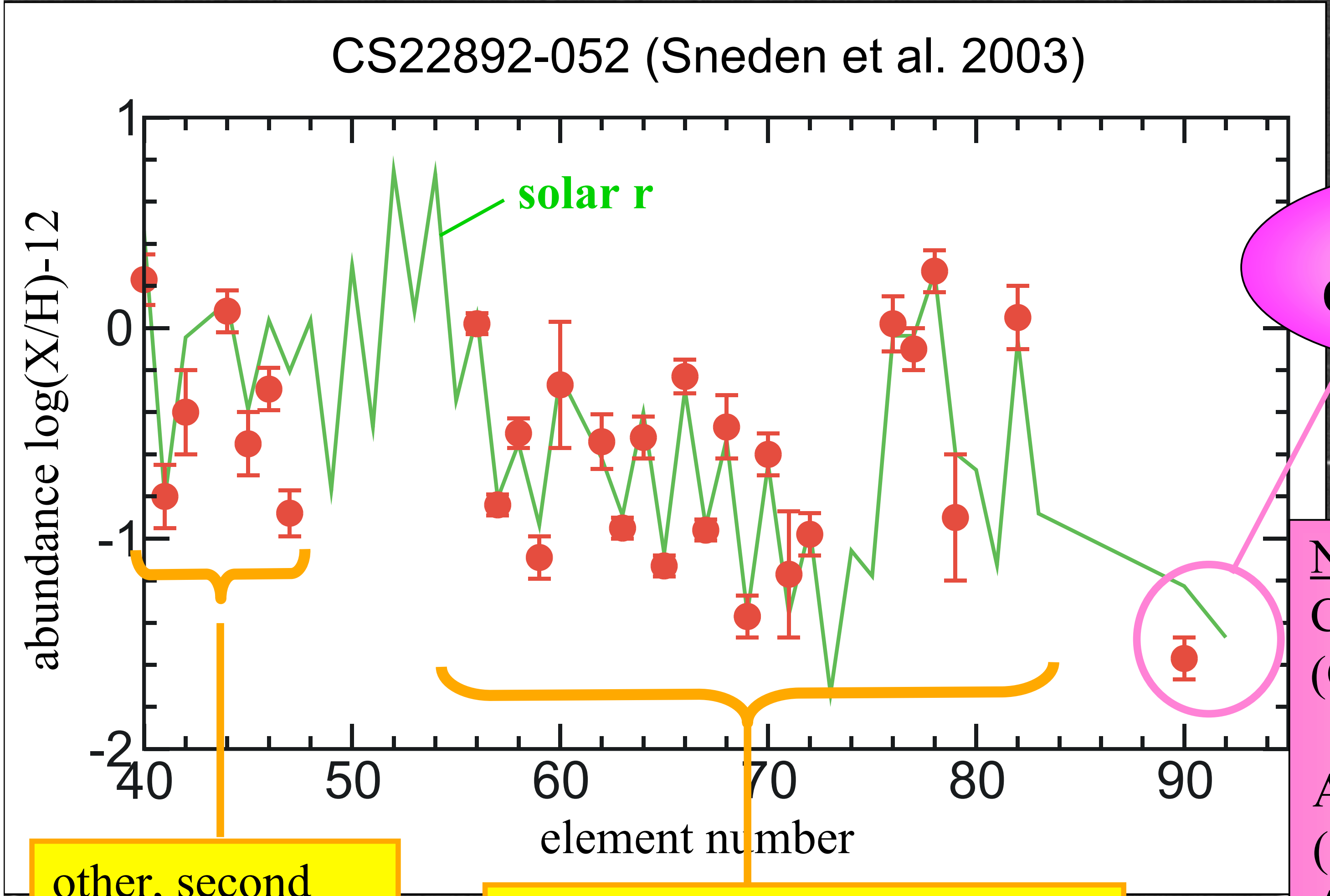


CS22892-052
red (K) giant
located in halo
distance: 4.7 kpc
mass ~0.8 M_sol
[Fe/H]= –3.0
[Dy/Fe]= +1.7

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

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

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

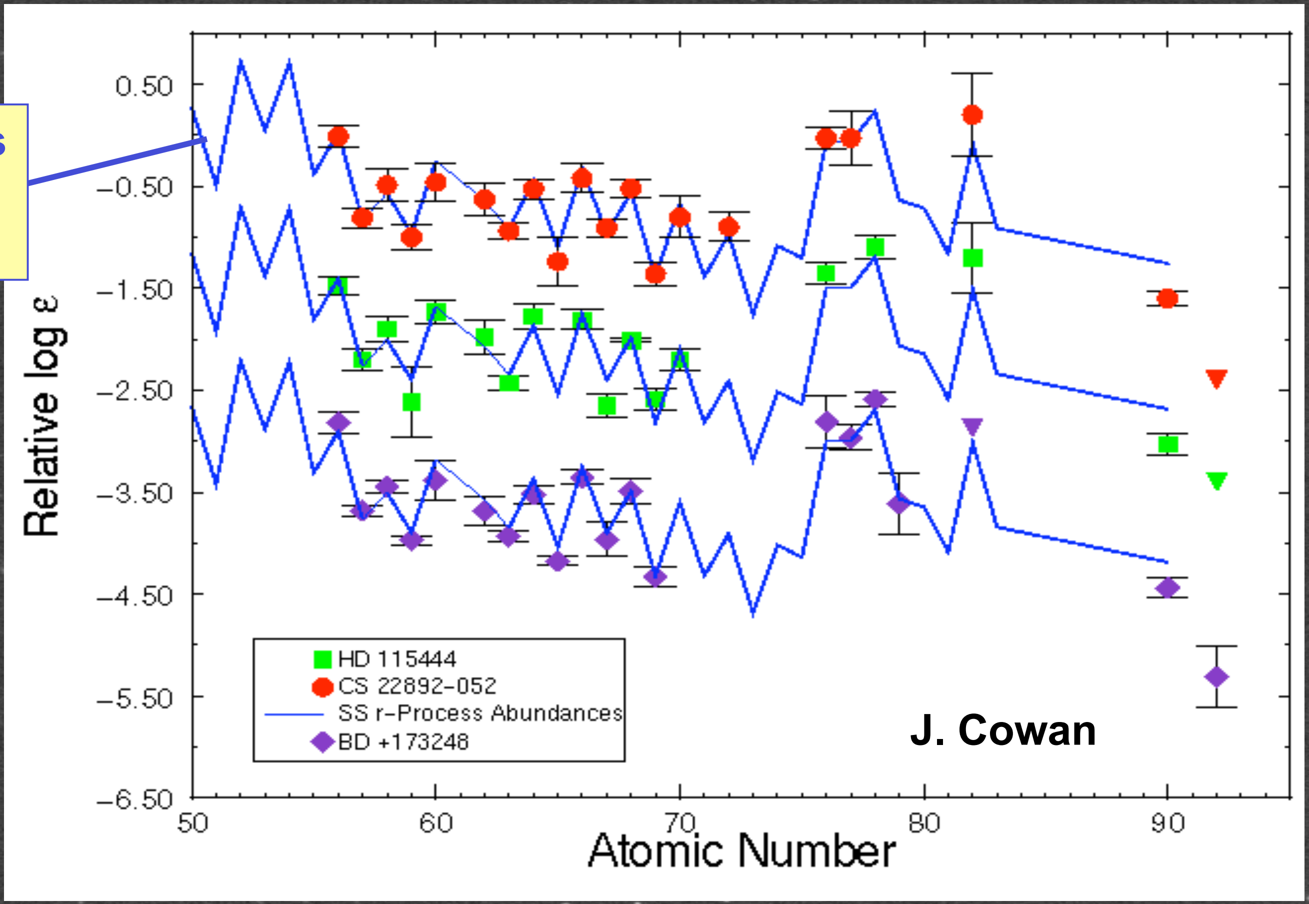
<u>NEW:</u>
CS31082-001 with U
(Cayrel et al. 2001)

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

New Observations

r-process elements from single r-process events in 3 very metal poor stars

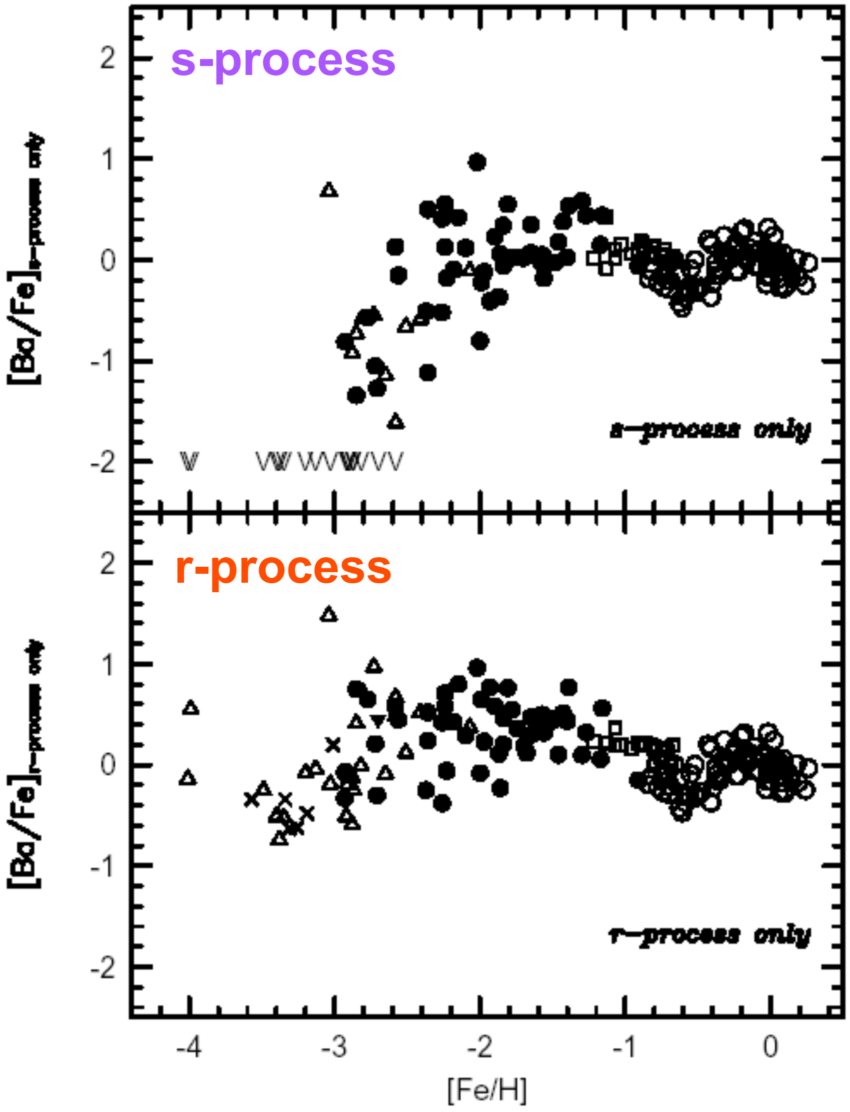
Solar r-process elements from many events



→ Many more to come from ongoing surveys and followup campaigns (e.g. VLT)

r- and s-process elements in stars with varying metallicity

(Burris et al. ApJ 544 (2000) 302)



→ ~age

s-process:
- later (lower mass stars)
- gradual onset (range of stars)

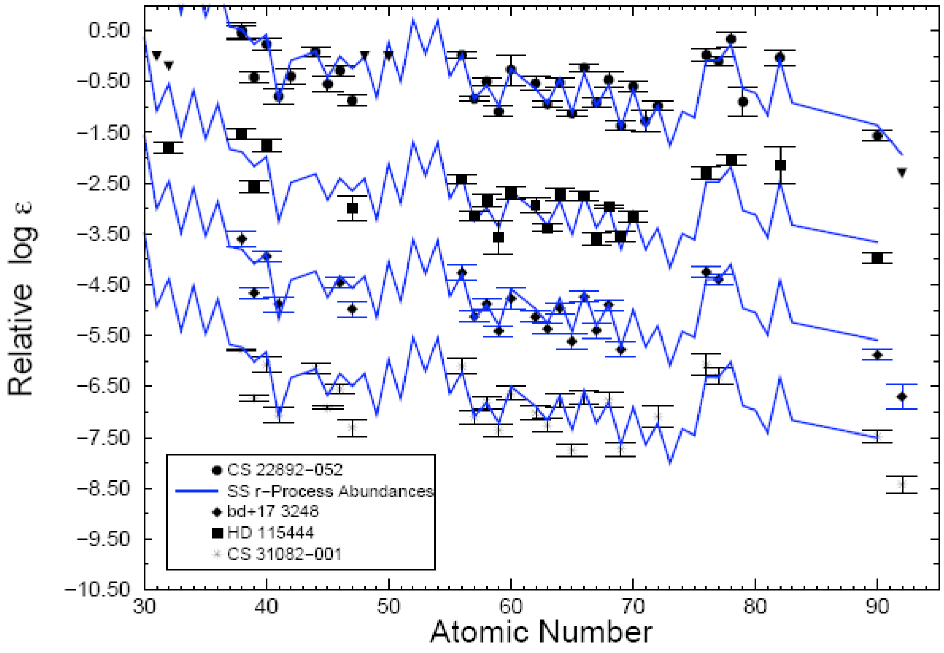
r-process:
- very early (massive stars)
- sudden onset (no low mass star contribution)

→ confirms massive stars
as r-process sites
(but includes SN and
NS-mergers)

Multiple “r-processes”

Star to star stability of all elements

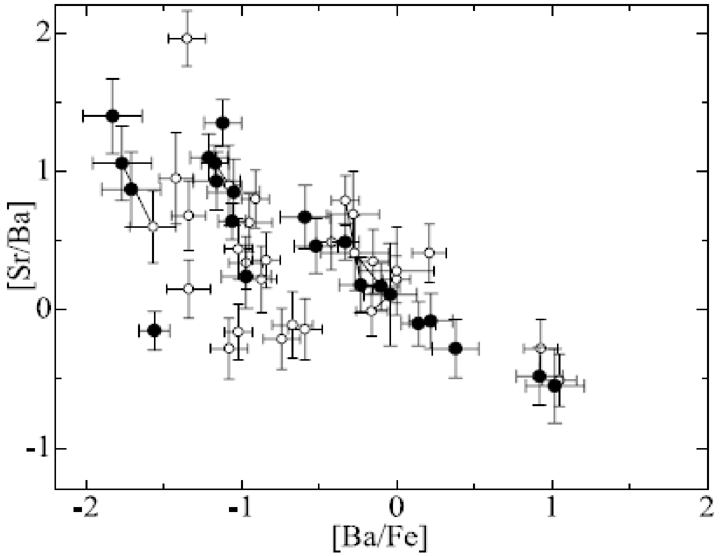
(for very r-rich stars)



(J.J. Cowan)

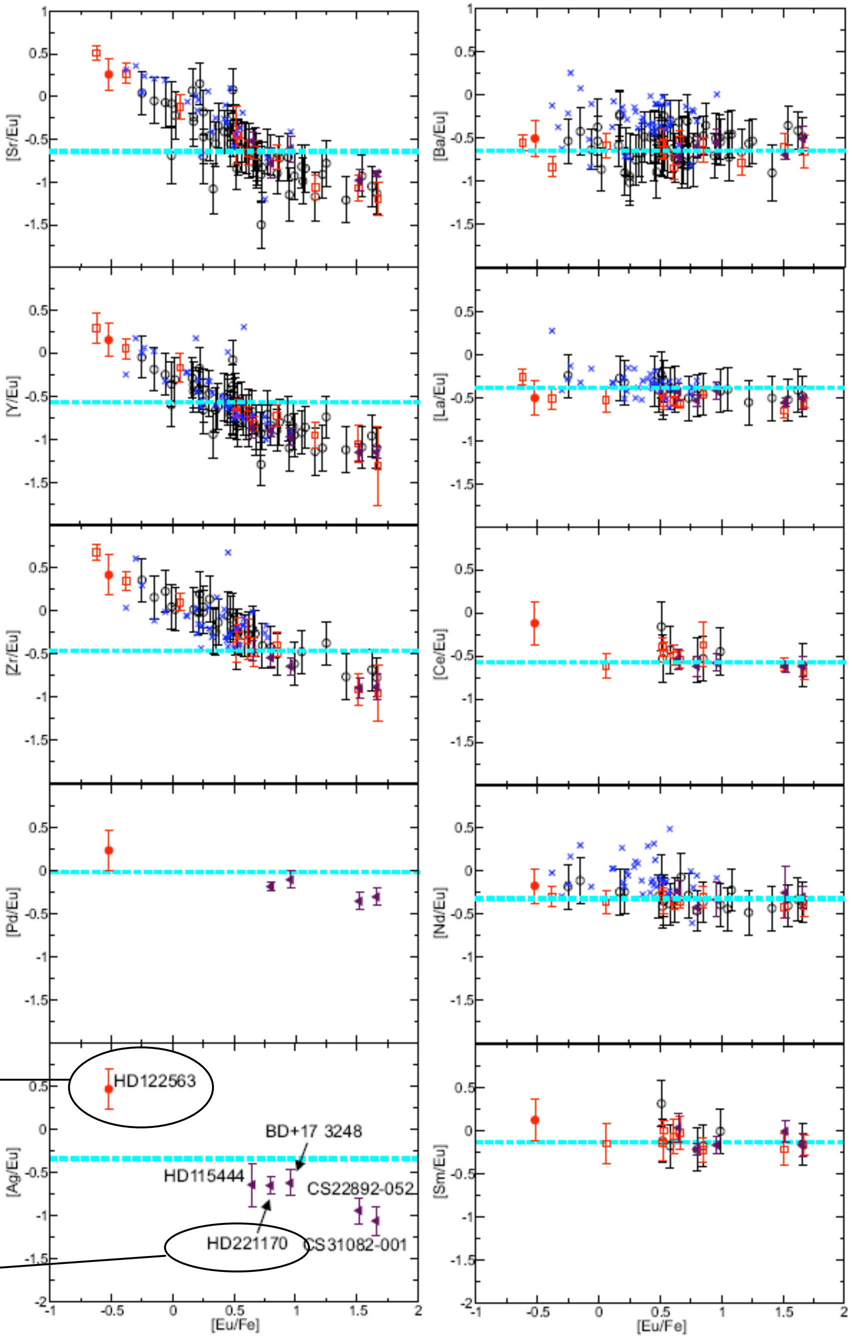
Star to star scatter of light vs heavy

for all stars [Fe/H]<-2.5, no s-process



(Honda et al. 2004)

→Additional “light” element primary process (LEPP) exists
(Travaglio et al. 2004 , Montes et al. 2006 to be published)
→ It contributes to solar r-process residual abundances



Honda et al. 2006

Ivans et al. 2006

Honda et al. 2006

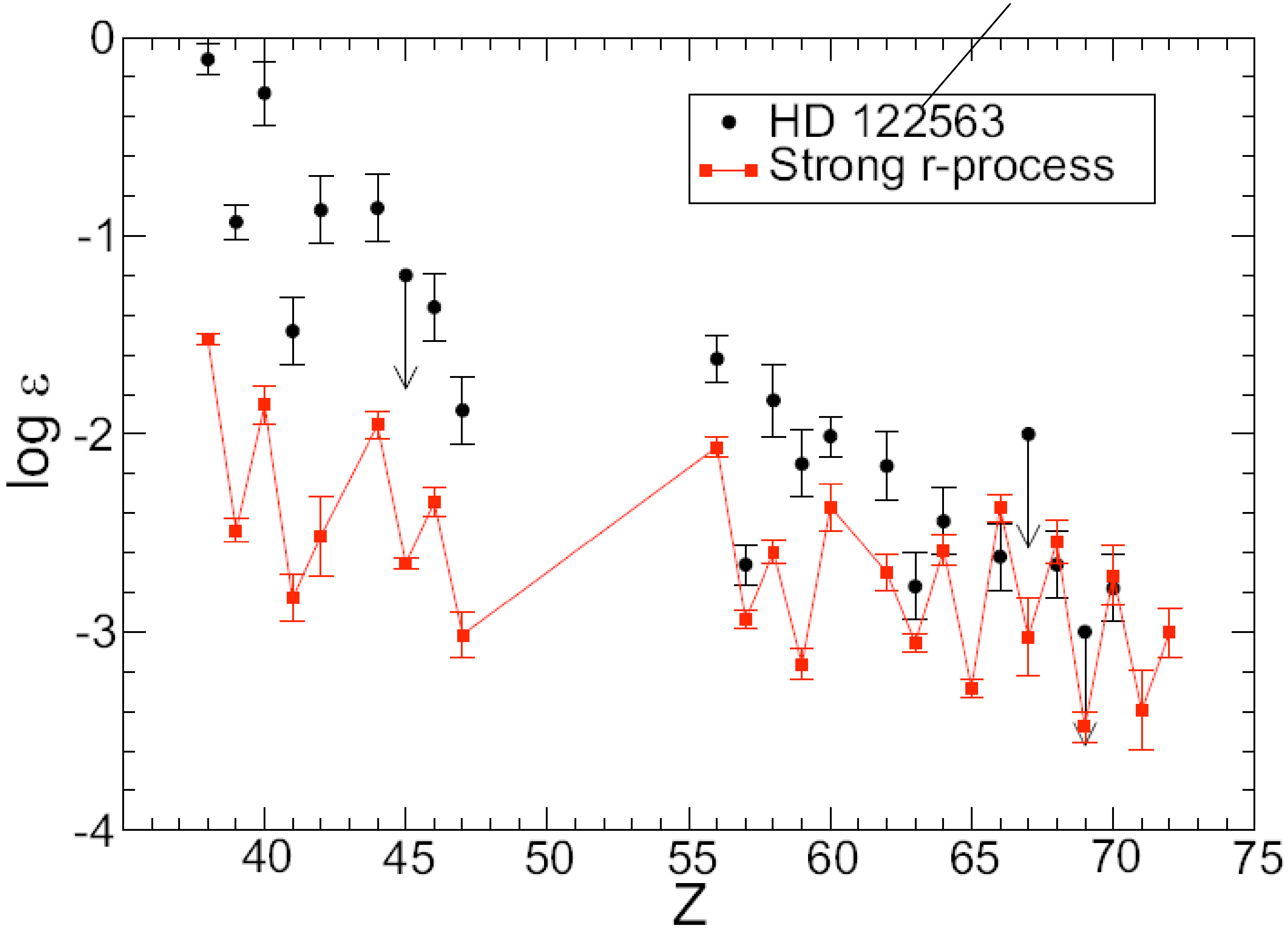


Fig. 3.— Abundance pattern of HD122563 and scaled abundance pattern obtained by averaging r-II stars CS31082-001 and CS22892-052.

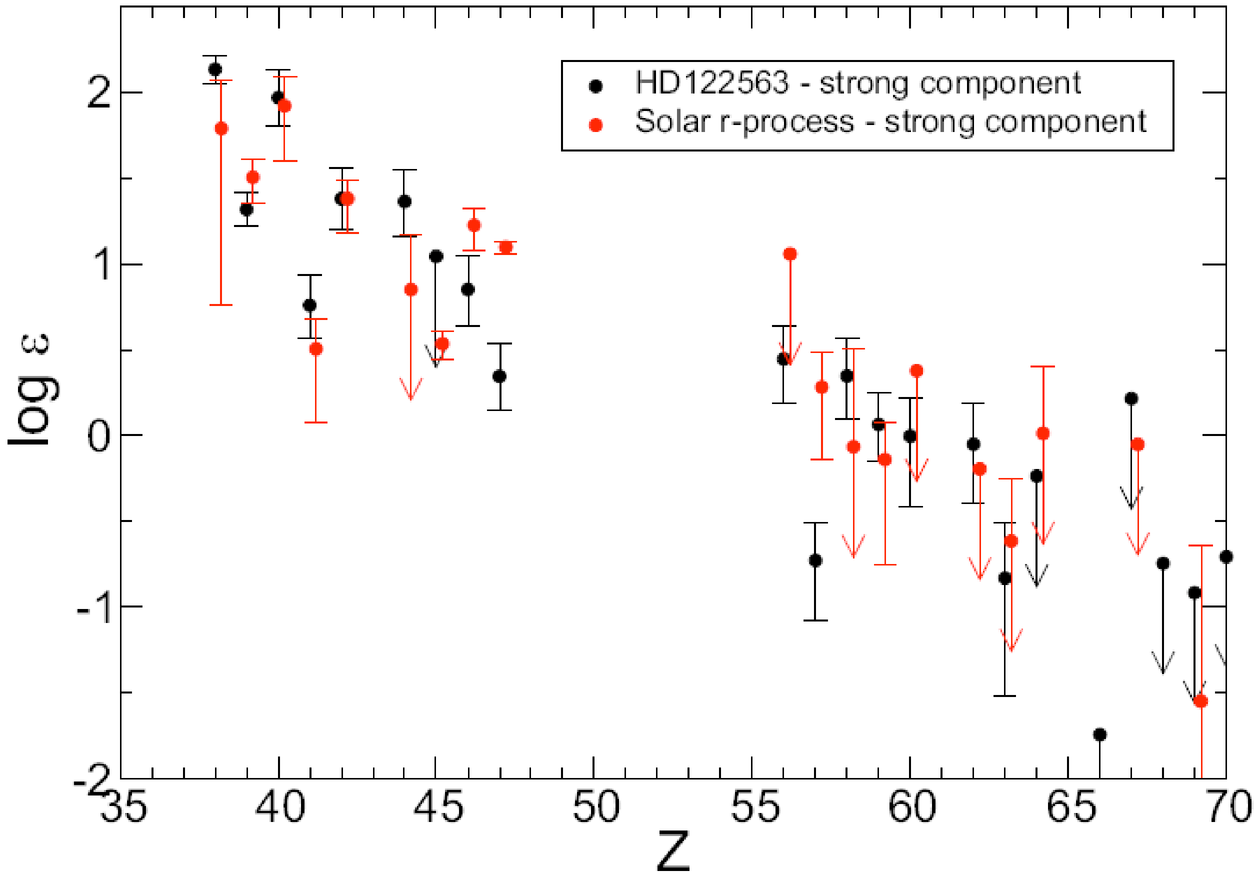
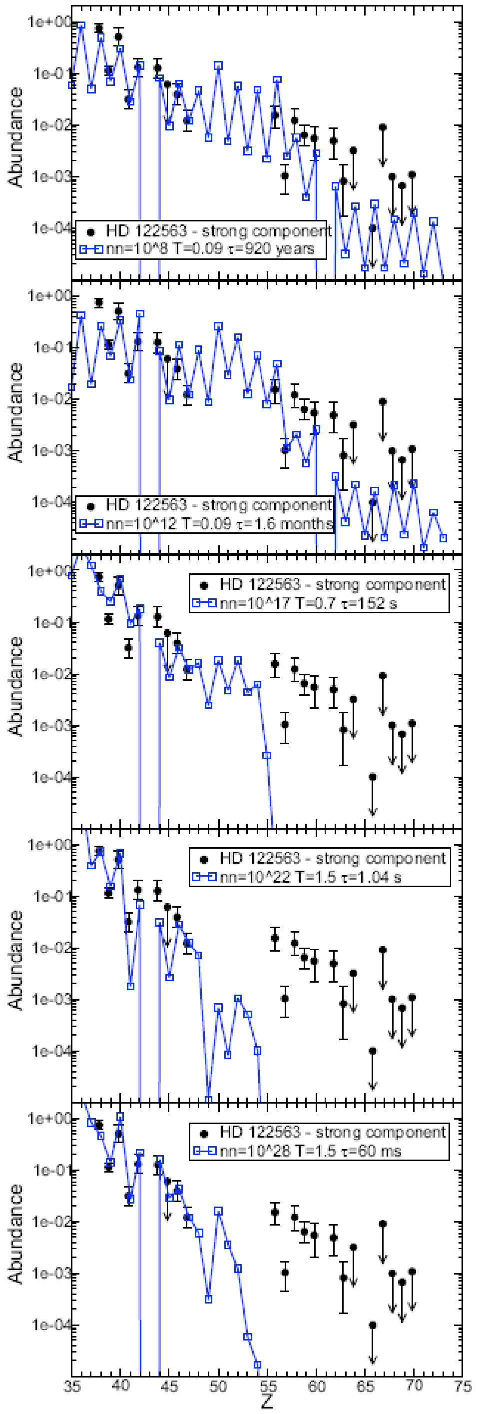


Fig. 4.— Abundance pattern created by the so-called weak r-process. a) Pattern obtained by subtracting the scaled average of CS31082-001 and CS22892-052 from HD122563. b) Pattern created by subtracting the scaled average of CS31082-001 and CS22892-052 from the solar r-process abundance. Read text for explanation.



→ Disentangling by isotope?

Multiple neutron capture processes in the early galaxy

F. Montes[1], T. Beers[2,3], J. Cowan[4], T. Elliot[2,3,5], K. Farouqi[6,7], R. Gallino[8], M. Heil[1],
K.-L. Kratz[6,7], H. Schatz[2,3,5]

Overview heavy element nucleosynthesis

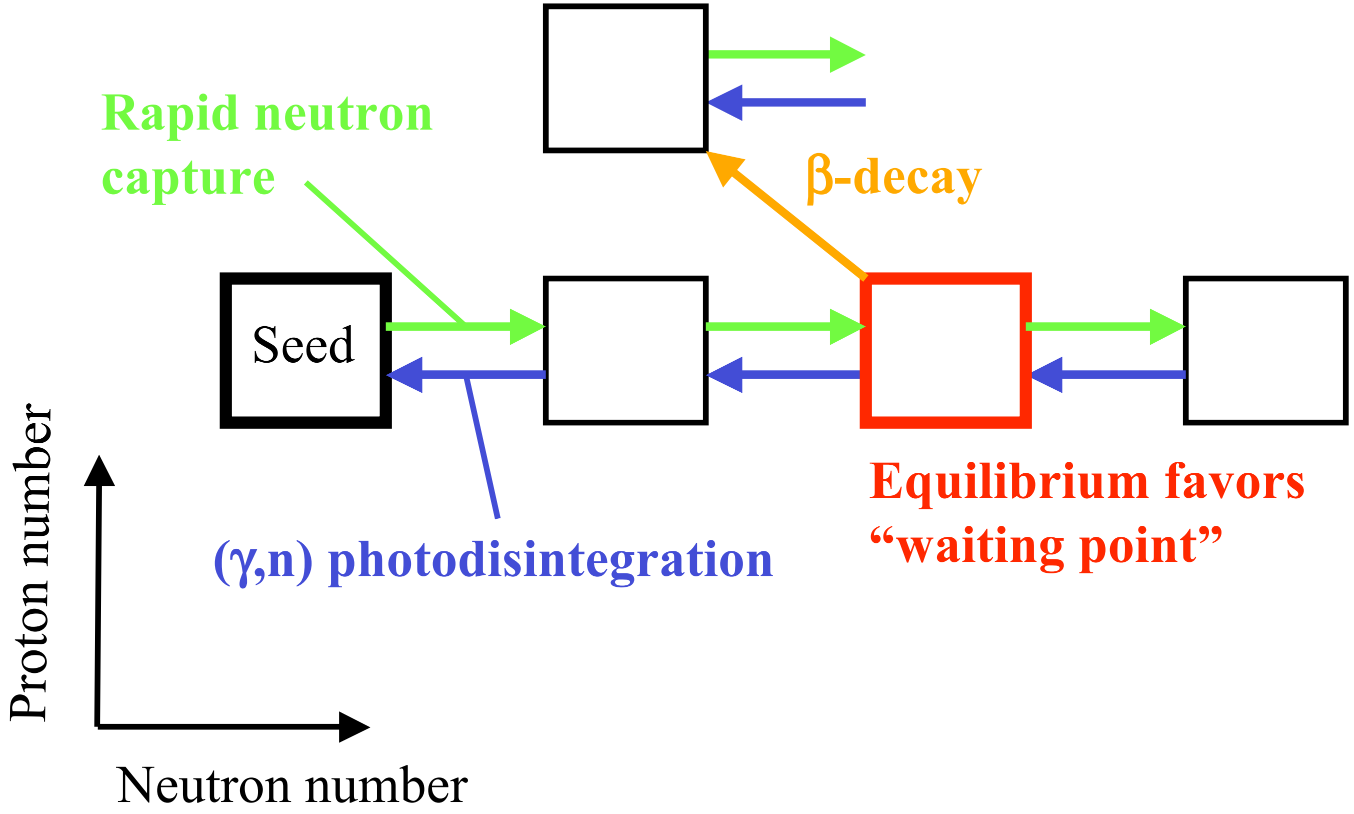
process	**conditions**	**timescale**	**site**
s-process (n-capture, ...)	T~ 0.1 GK τ_n~ 1-1000 yr, n_n~10^{7-8}/cm^3	10^2 yr and 10^{5-6} yrs	Massive stars (weak) Low mass AGB stars (main)
r-process (n-capture, ...)	T~1-2 GK τ_n ~ μs, n_n~10^{24} /cm^3	< 1s	Type II Supernovae ? Neutron Star Mergers ?
p-process ((γ,n), ...)	T~2-3 GK	~1s	Type II Supernovae
Light Element Primary Process (LEPP) ?	? (maybe s-process like?)	? (long if s-process)	?

The r-process

Temperature: ~1-2 GK

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

neutron capture timescale: ~ 0.2 µs



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

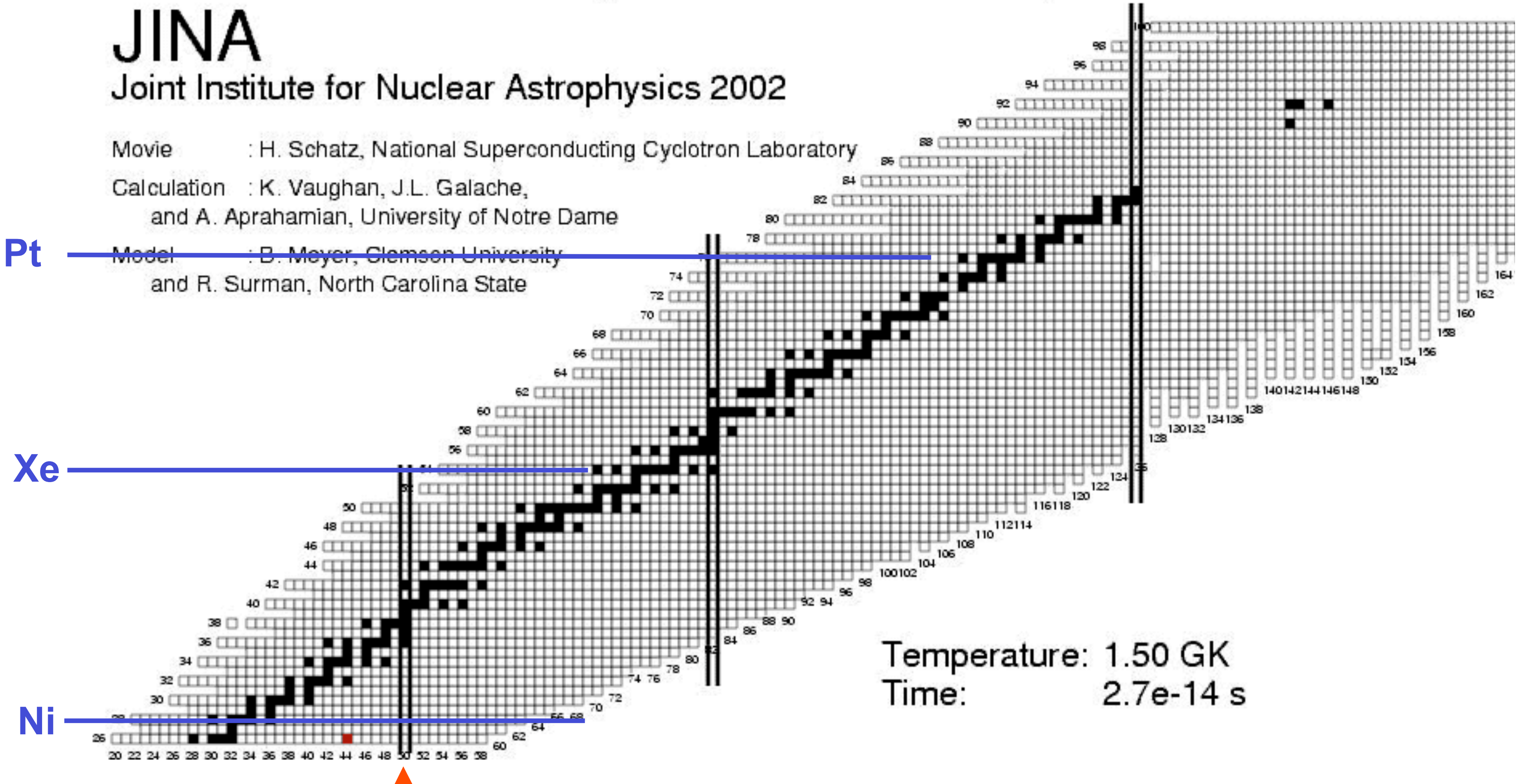
During (n,γ)-(γ,n) equilibrium abundances within an isotopic chain are given by:

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

- **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 !)

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

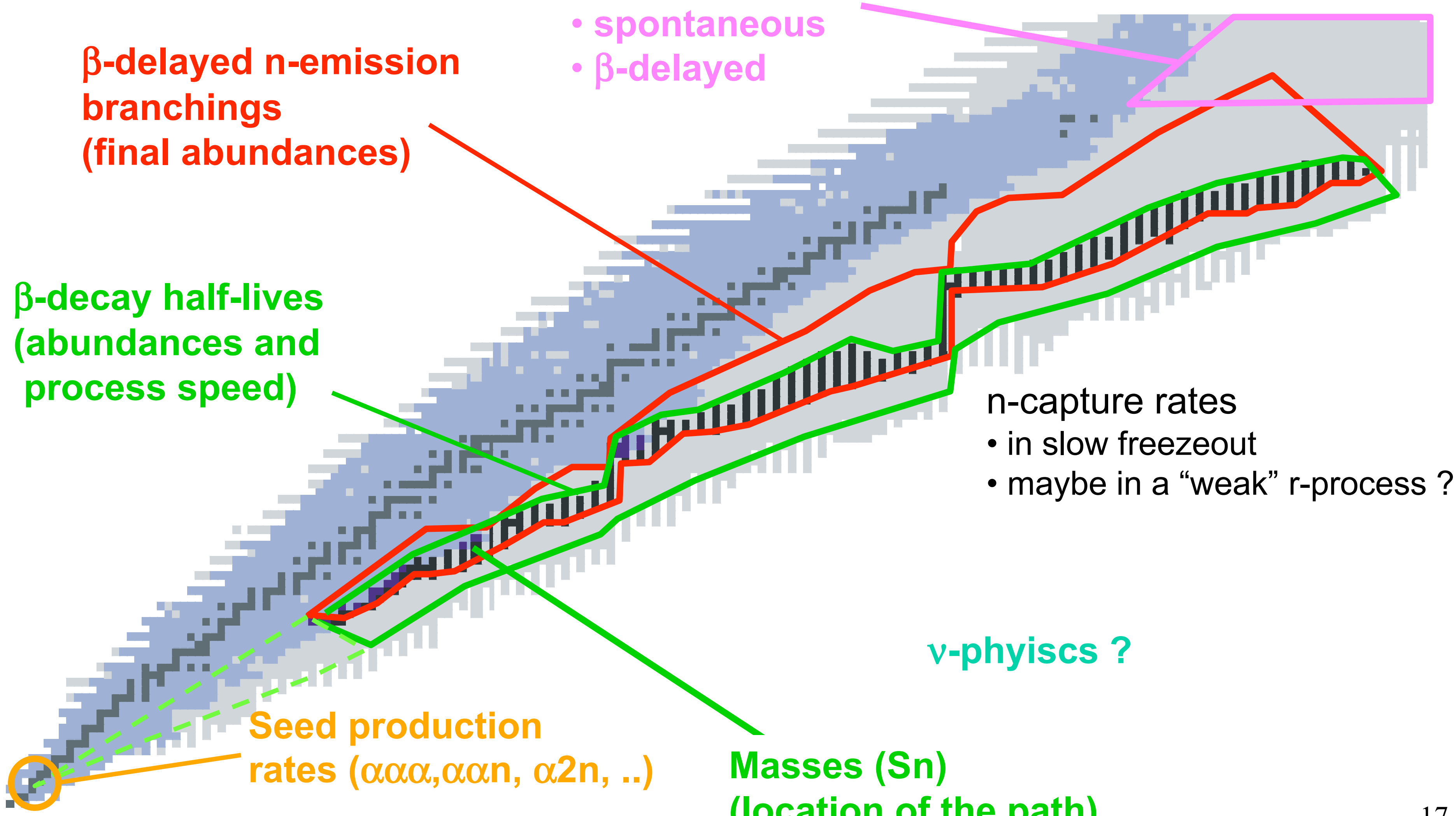
^{78}Ni, ^{79}Cu first bottle necks in n-capture flow (^{80}Zn later)

^{79}Cu: half-life measured 188 ms (Kratz et al, 1991)

^{78}Ni : half-life predicted 130 – 480 ms

2 events @ GSI (Bernas et al. 1997)

Nuclear physics in the r-process



Fission rates and distributions:
- n-induced
- spontaneous
- β-delayed

β-delayed n-emission branchings (final abundances)

β-decay half-lives (abundances and process speed)

n-capture rates
- in slow freezeout
- maybe in a “weak” r-process ?

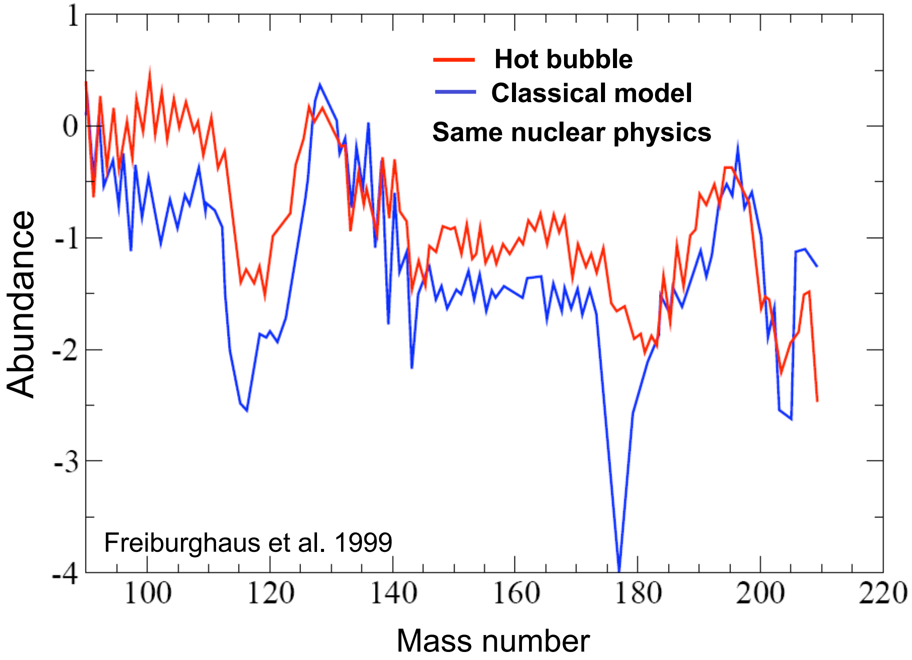
ν-phyiscs ?

Seed production rates (ααα,ααn, α2n, ..)

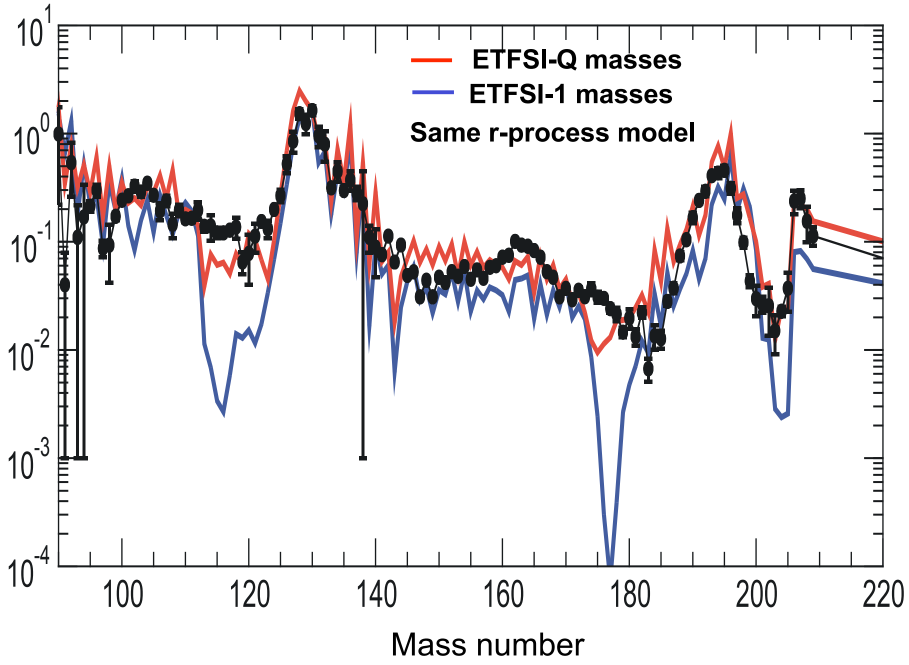
Masses (Sn) (location of the path)

Sensitivity of r-process to astro and nuclear physics

Sensitivity to astrophysics



Sensitivity to nuclear physics



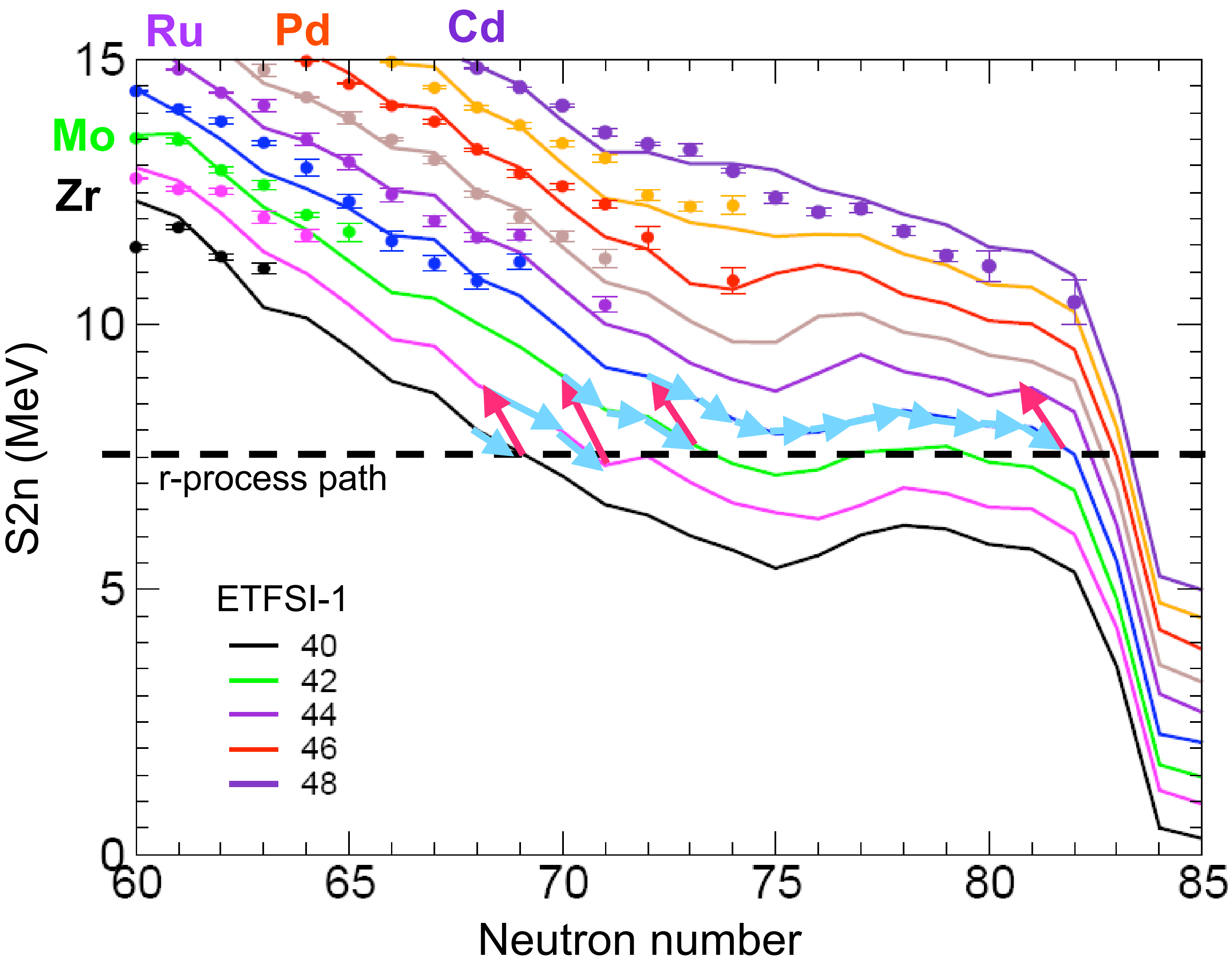
Contains information about:

- n-density, T, time (fission signatures)
- freezeout
- neutrino presence
- which model is correct

But convoluted with nuclear physics:

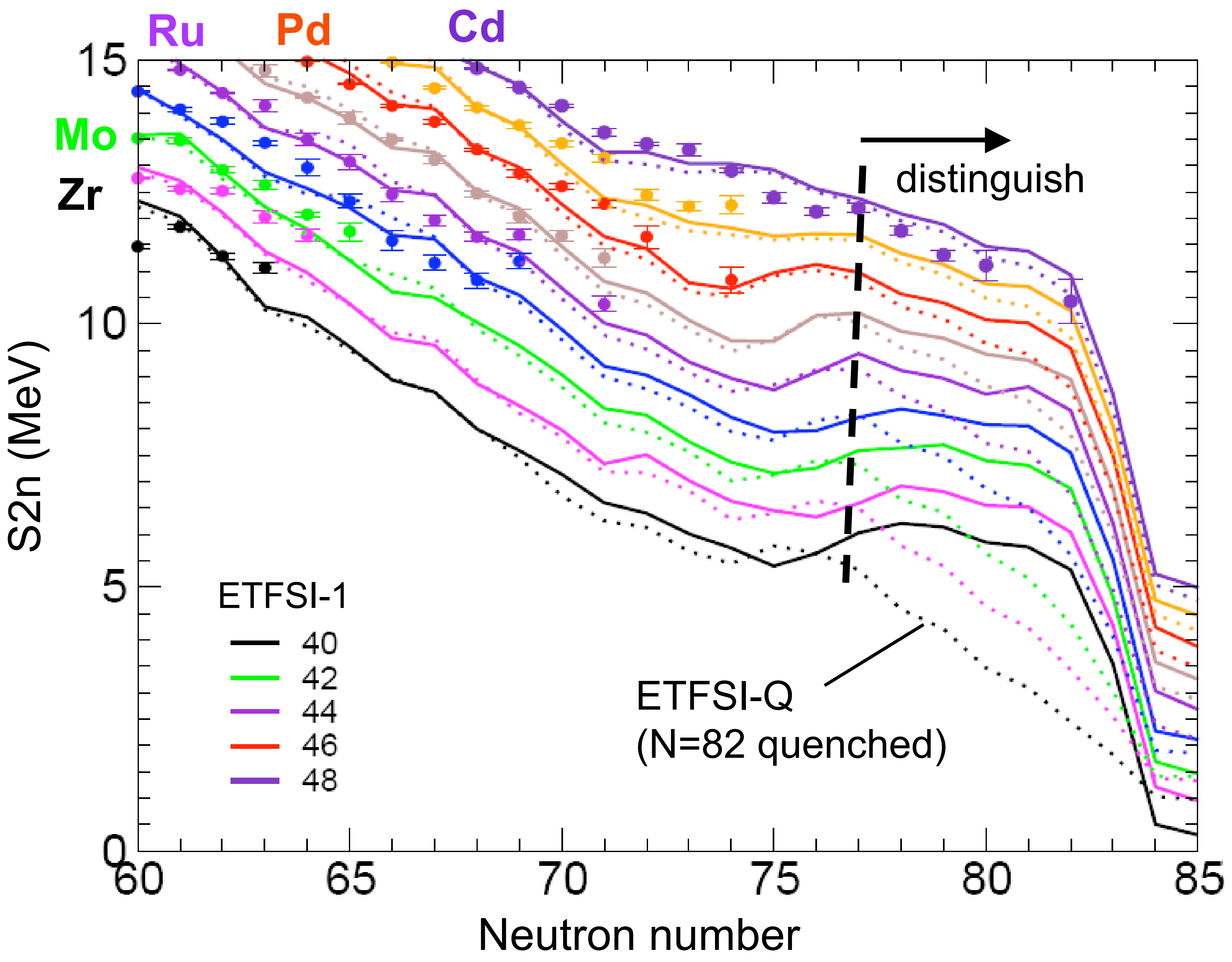
- masses (set path)
- $T_{1/2}$, Pn ($Y \sim T_{1/2(prog)}$, key waiting points set timescale)
- n-capture rates
- fission barriers and fragments

Shell quenching effect on masses/r-process

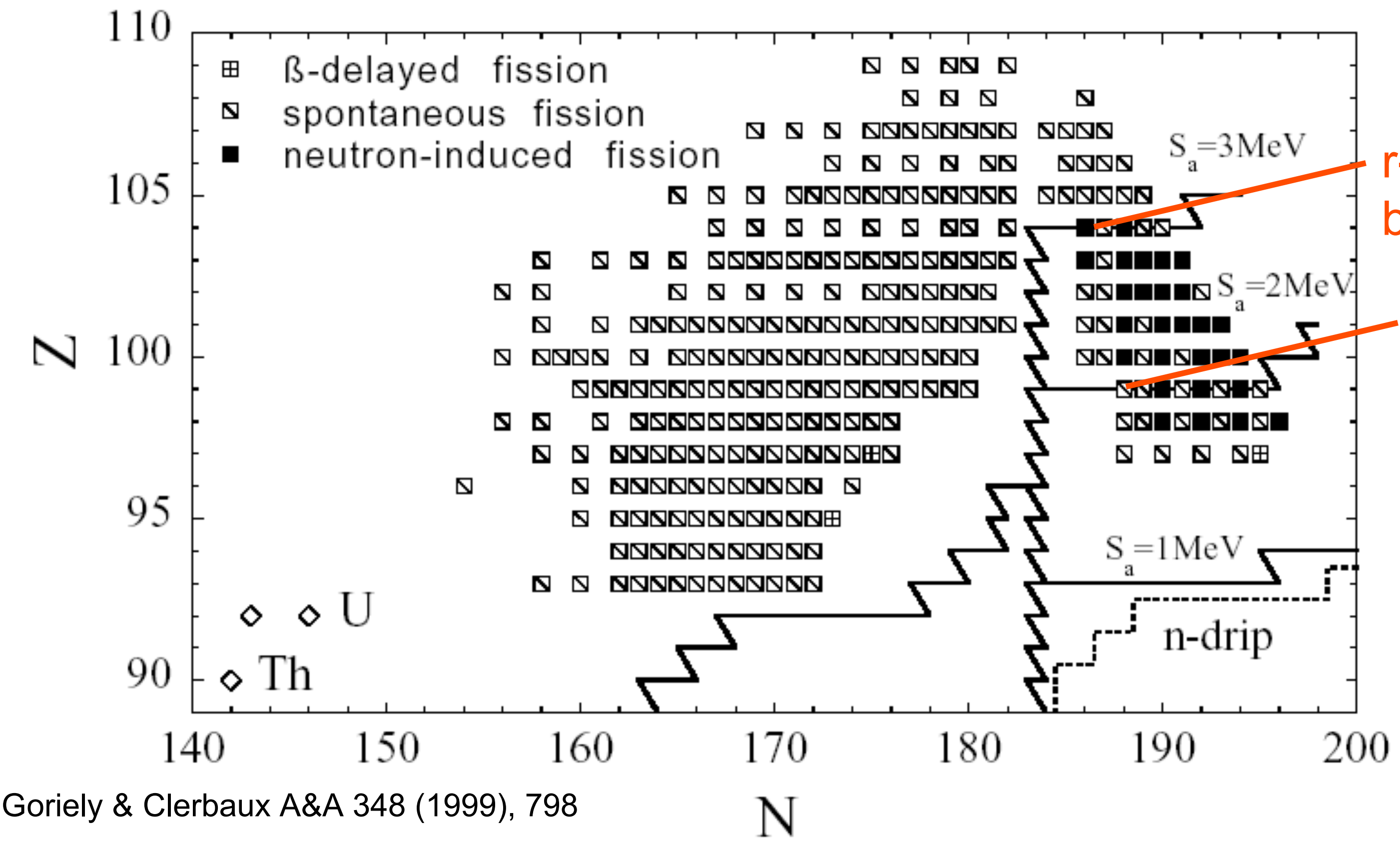


The Joint Institute for Nuclear Astrophysics

Shell quenching effect on masses/r-process



Endpoint of the r-process

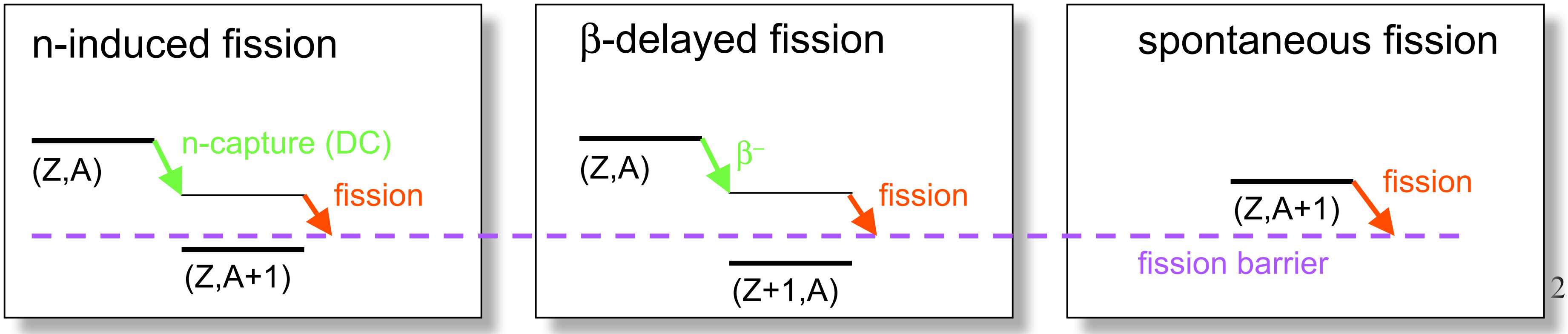


r-process ended by n-induced fission

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~A_{end}/2 ~ 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 !**

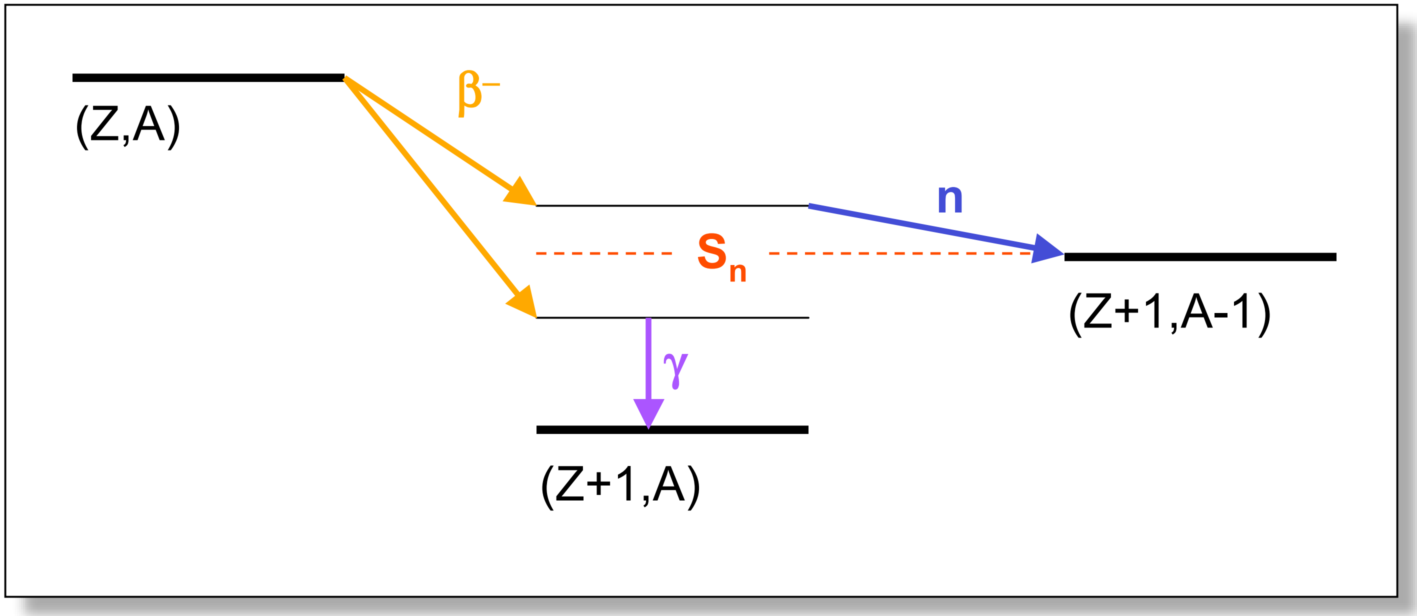
Note: the exact endpoint of the r-process and the degree and impact of fission are unknown because:

- 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)

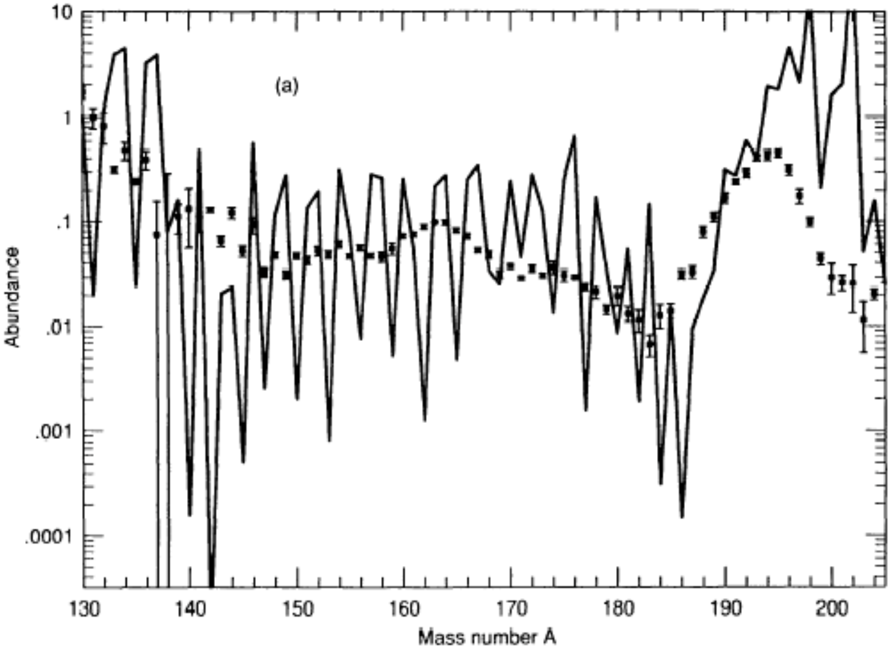
(generally, neutron emission competes favorably with γ-decay - strong interaction !)

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

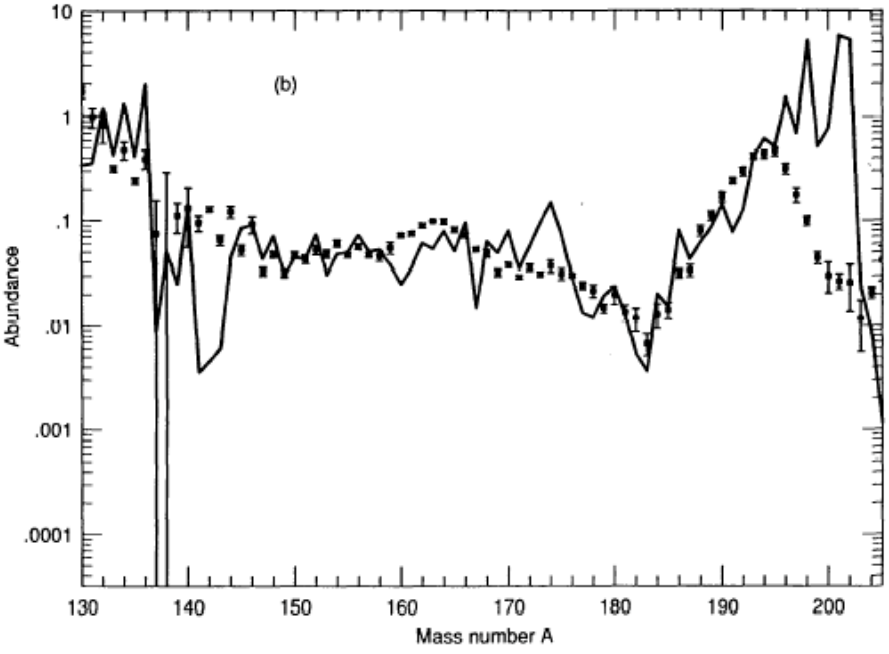
during freezeout
- **modification of final abundance**
- **late time neutron production (those get recaptured)**

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

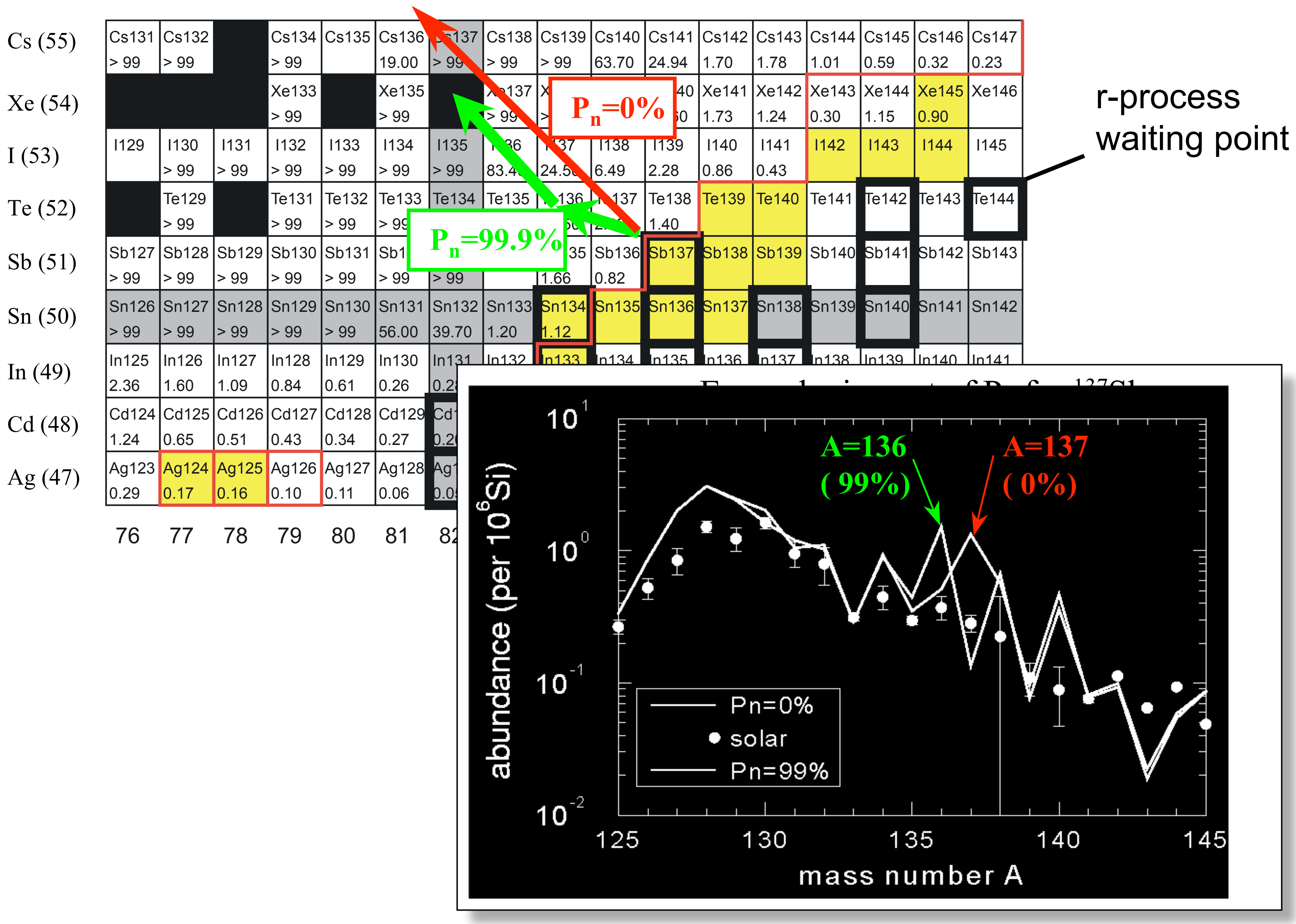
before β-decay



after β-decay



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



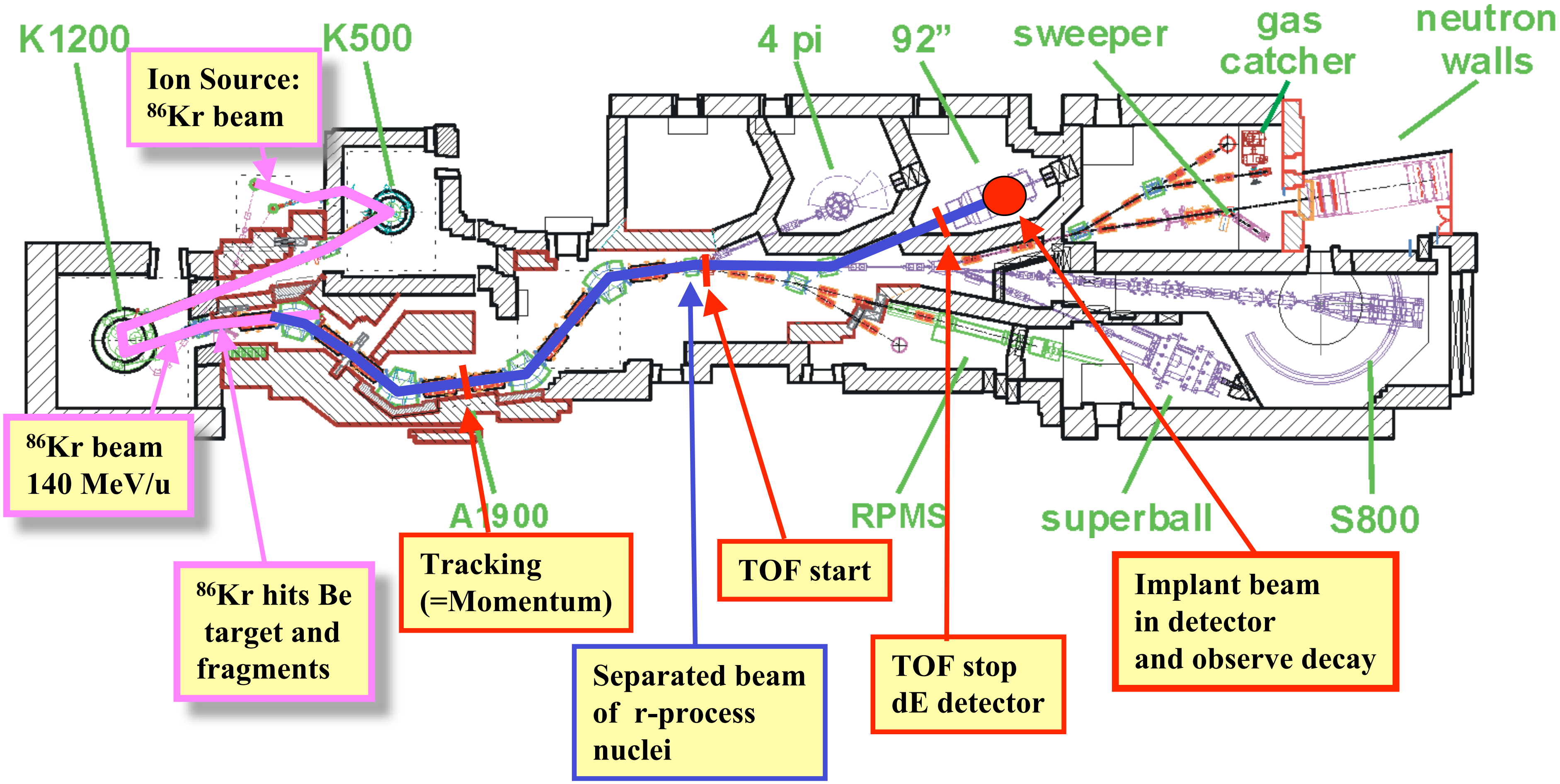
r-process waiting point

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

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

Tracking (=Momentum)

Separated beam of r-process nuclei

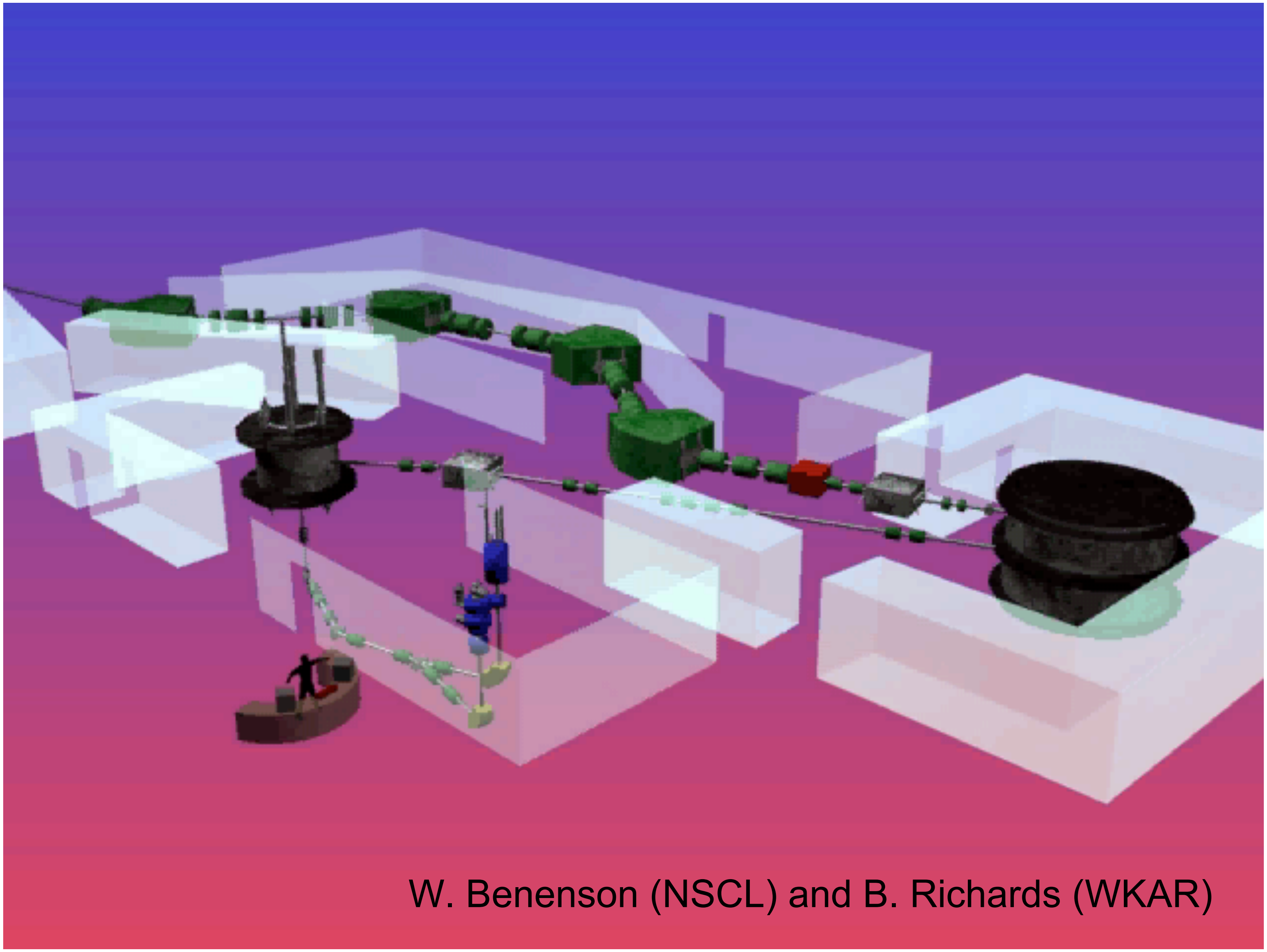
TOF start

TOF stop dE detector

Implant beam in detector and observe decay

Fast beam fragmentation facility – allows event by event particle identification

NSCL Coupled Cyclotron Facility



W. Benenson (NSCL) and B. Richards (WKAR)

Installation of D4 steel, Jul/2000

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

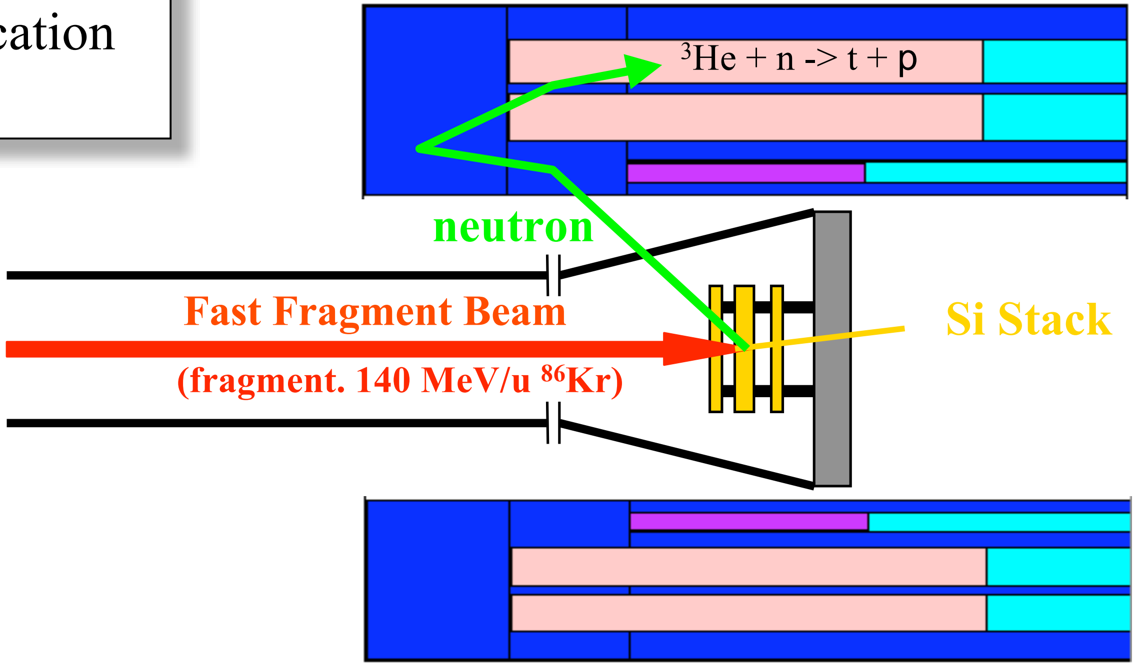
Measure:

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

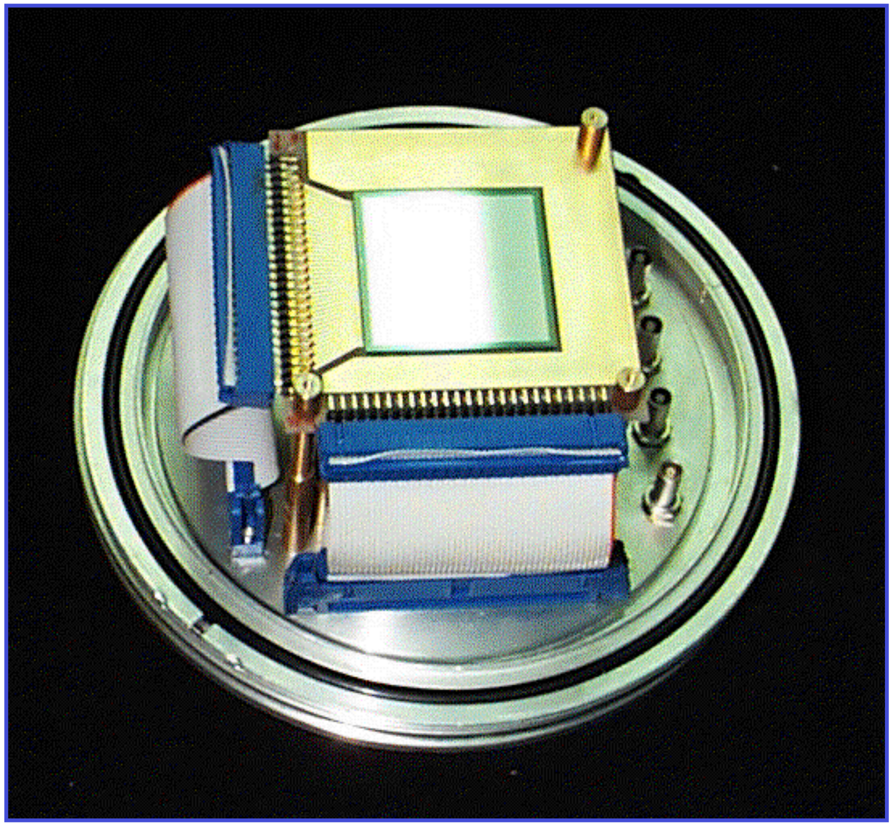
Detect:

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

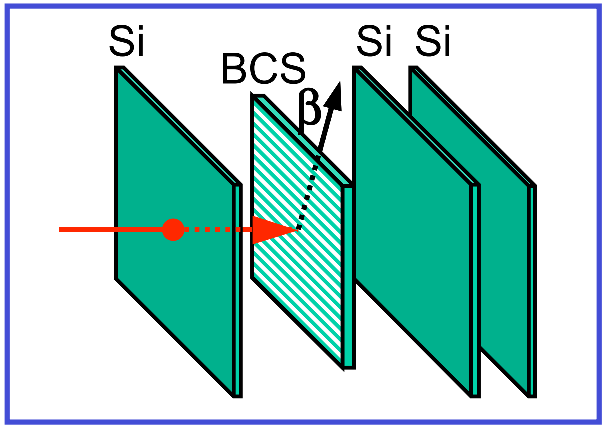
New NSCL Neutron detector NERO



NSCL BCS – Beta Counting System

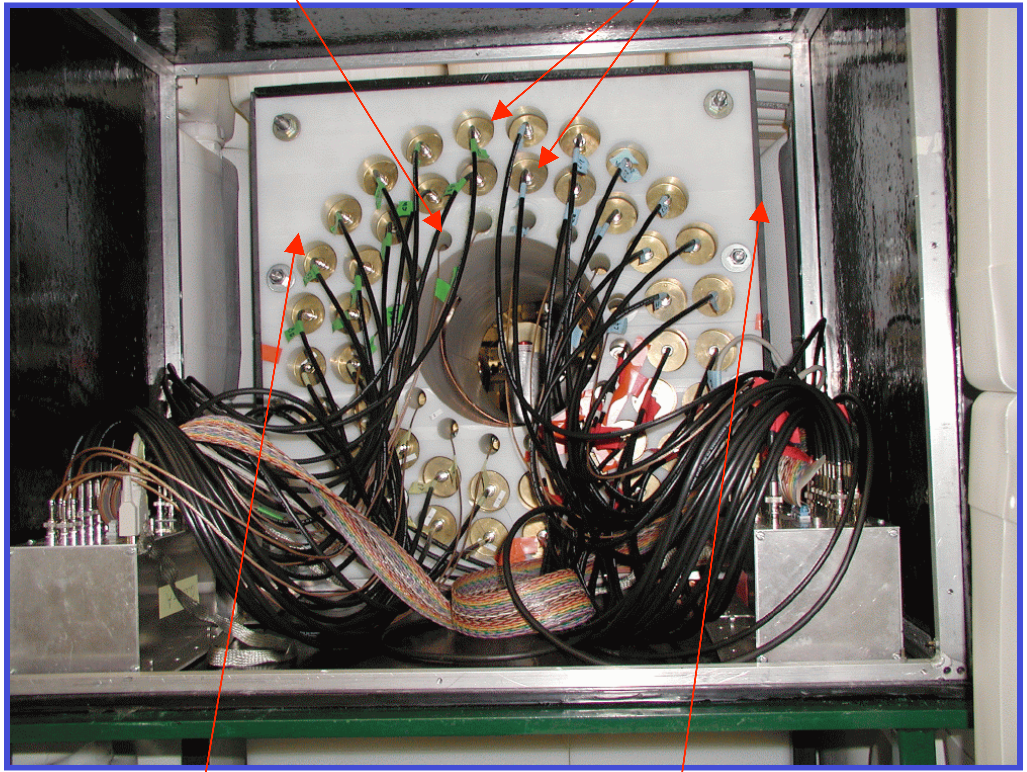


- 4 cm x 4 cm active area
- 1 mm thick
- 40-strip pitch in x and y dimensions ->1600 pixels

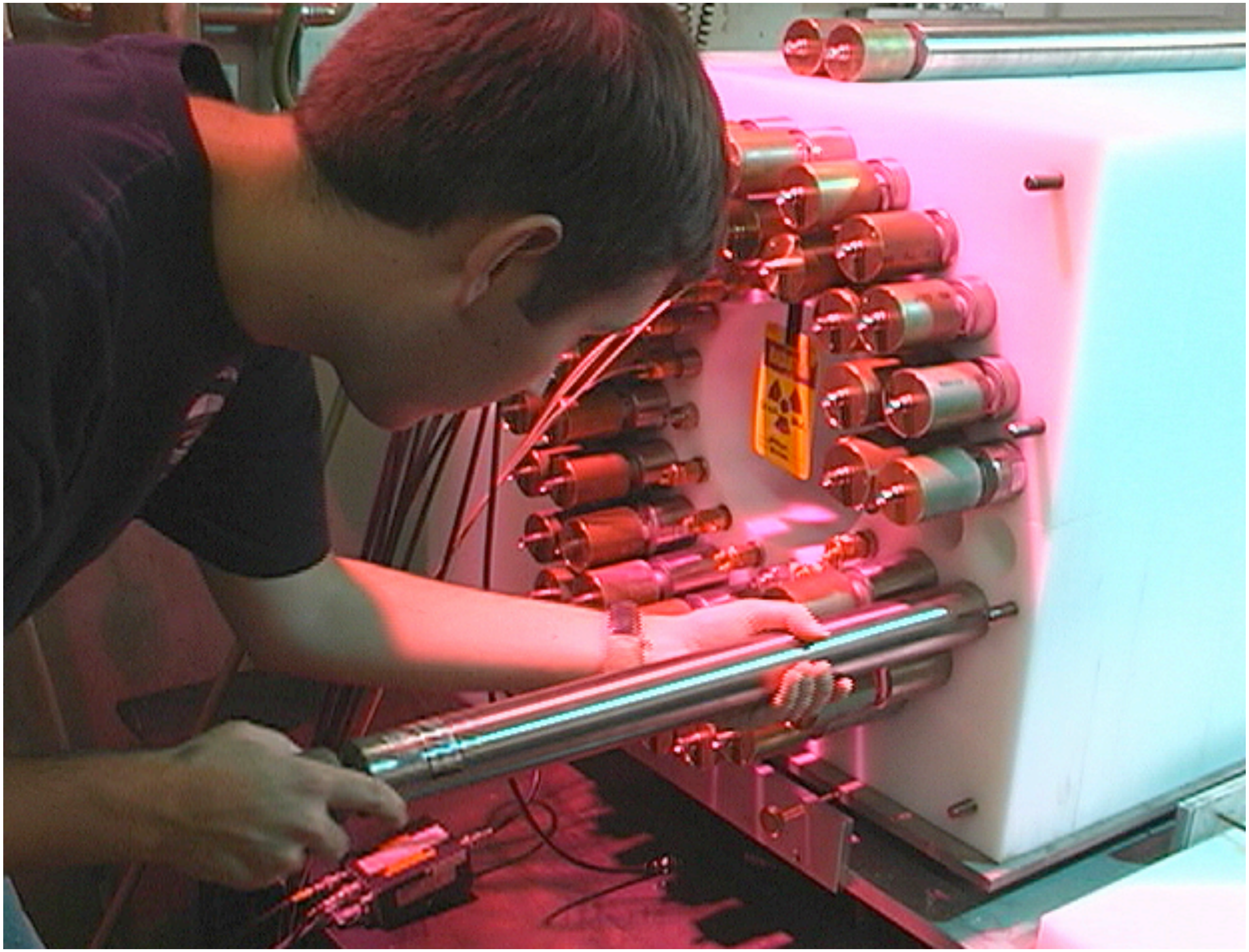


NERO – Neutron Emission Ratio Observer

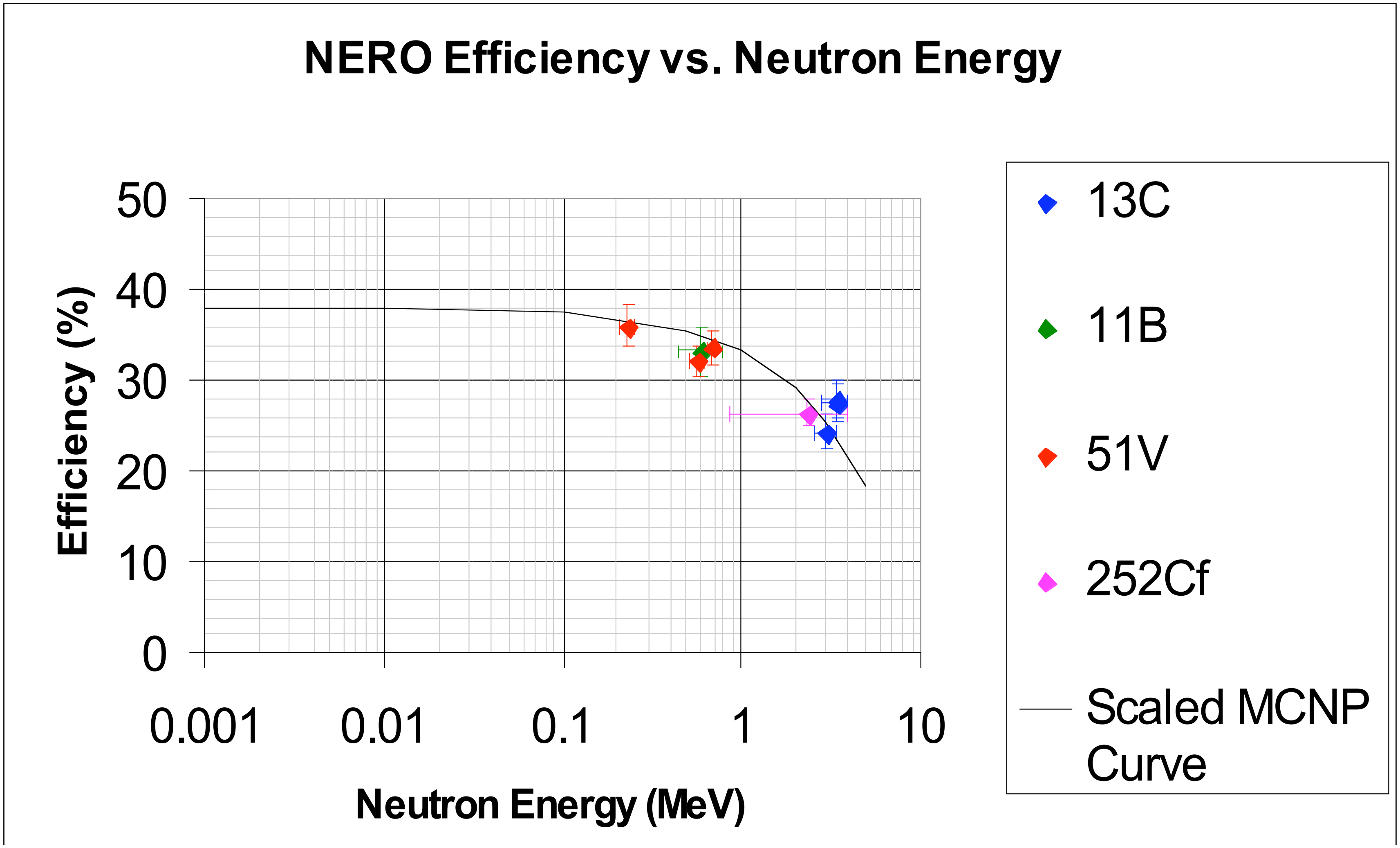
Specifications:
- 60 counters total
  ($16\ {}^{3}He$, $44\ BF_3$)
- 60 cm x 60 cm x 80 cm polyethylene block
- Extensive exterior shielding
- 43% total neutron efficiency (MCNP)



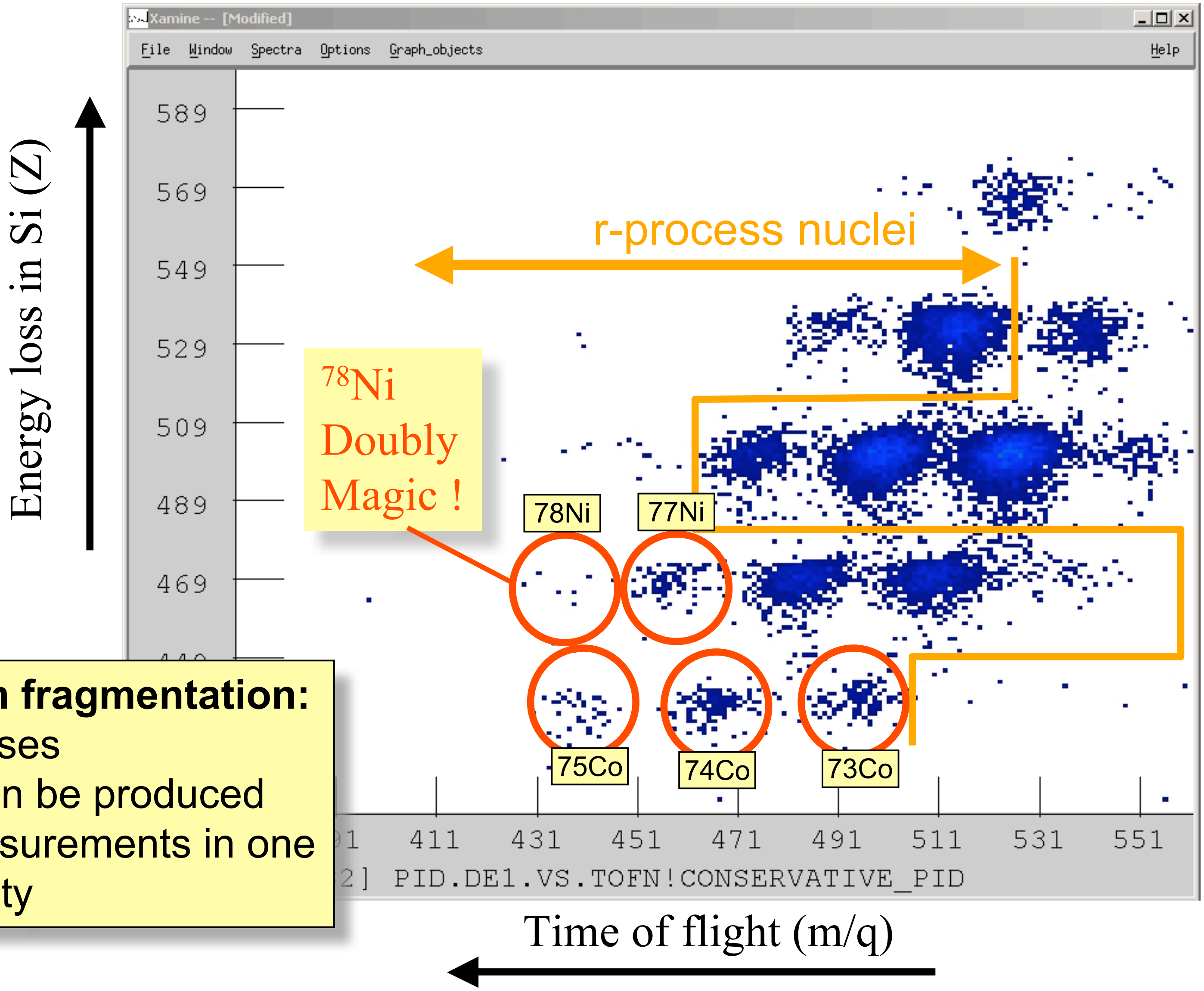
NERO Assembly



Nero efficiency



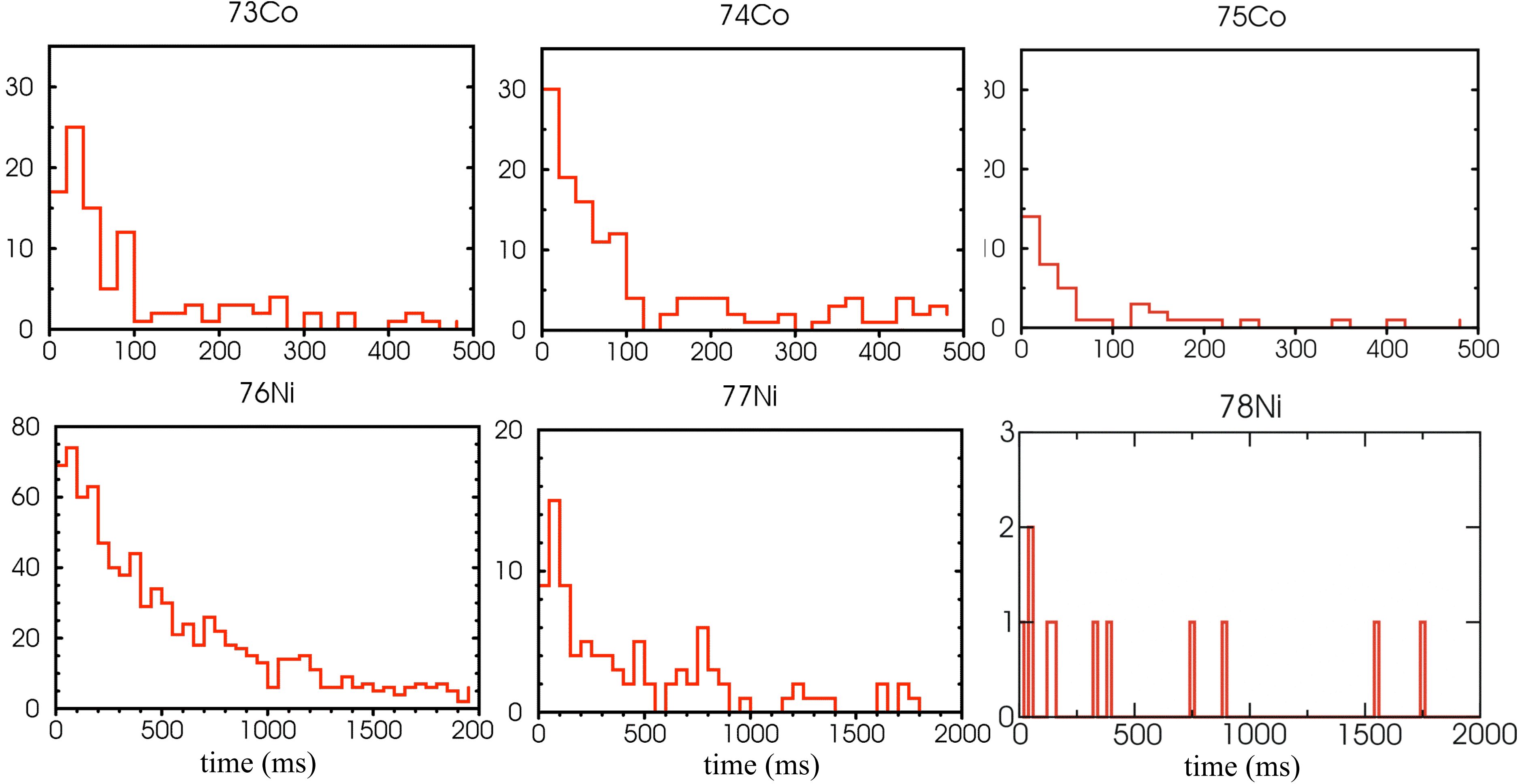
Particle Identification



Fast RIB from fragmentation:
- no decay losses
- any beam can be produced
- multiple measurements in one
- high sensitivity

H. Schatz

Decay data



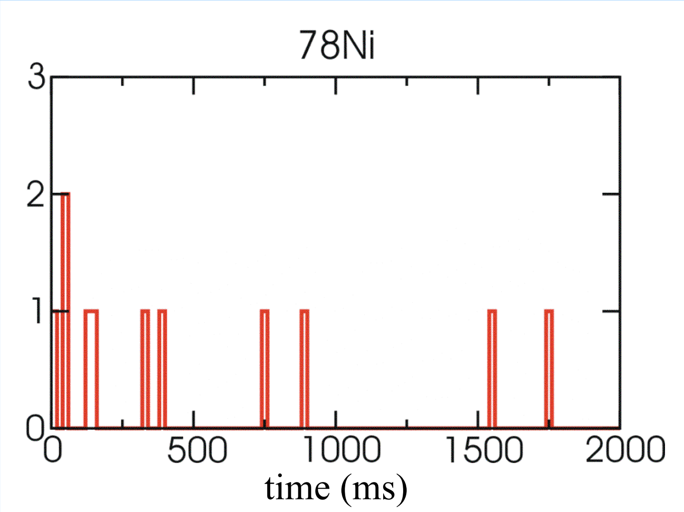
<u>Fast radioactive beams:</u>
- No decay losses
- Rates as low as 1/day useful !
- Mixed beam experiments easy

Results for the main goal: ^{78}Ni (14 neutrons added to stable Ni)

Decay of ^{78}Ni : major bottle-neck for synthesis of heavy elements in the r-process

Managed to create 11 of the doubly magic ^{78}Ni nuclei in ~ 5 days

Time between arrival and decays:



Statistical Analysis

Result for half-life:

110^{+100}_{-60} ms

Compare to theoretical estimate used:470 ms

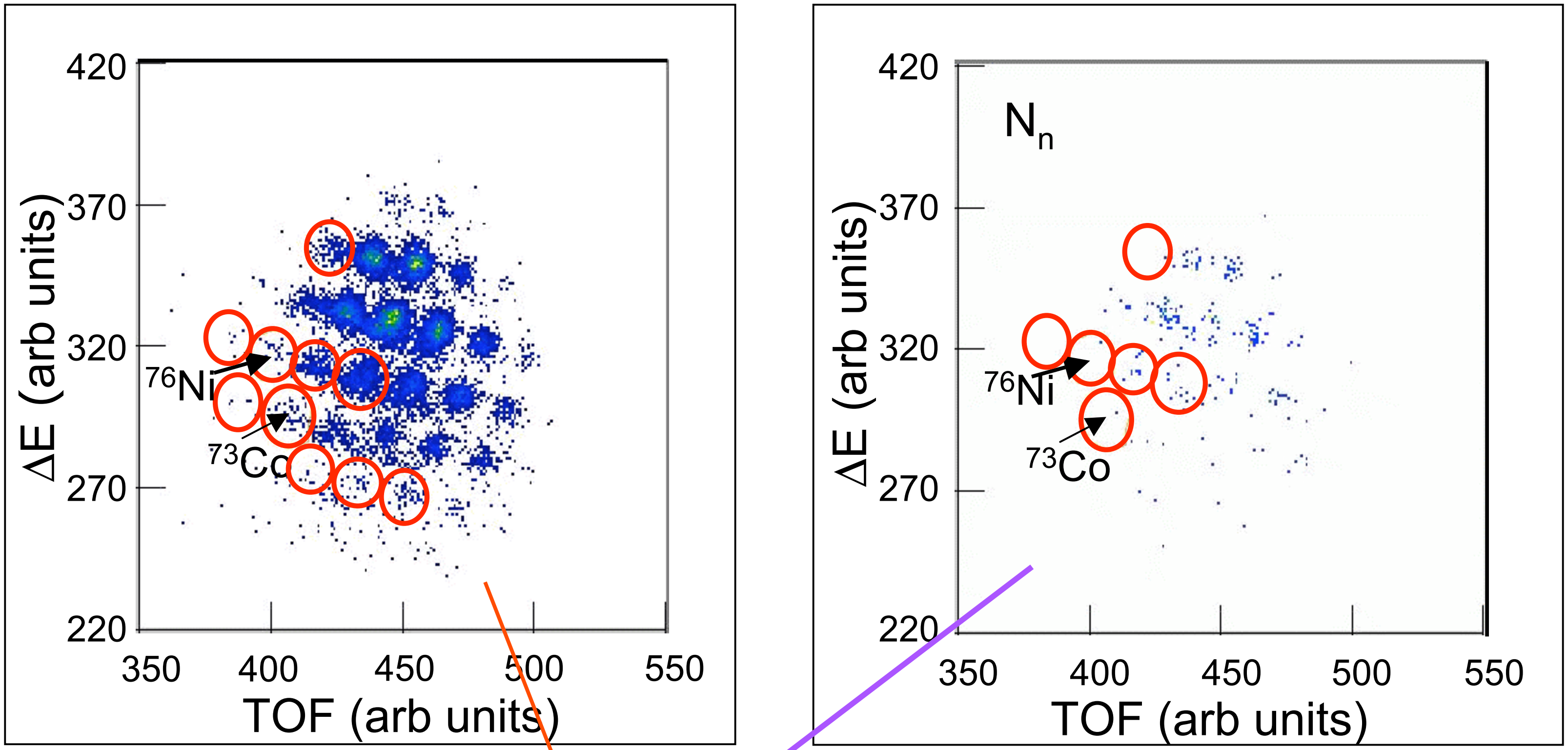
→ Acceleration of the entire r-process

→ Models need to be adjusted to explain observed abundance distribution

Neutron Data

Nuclei with decay detected

With neutron in addition



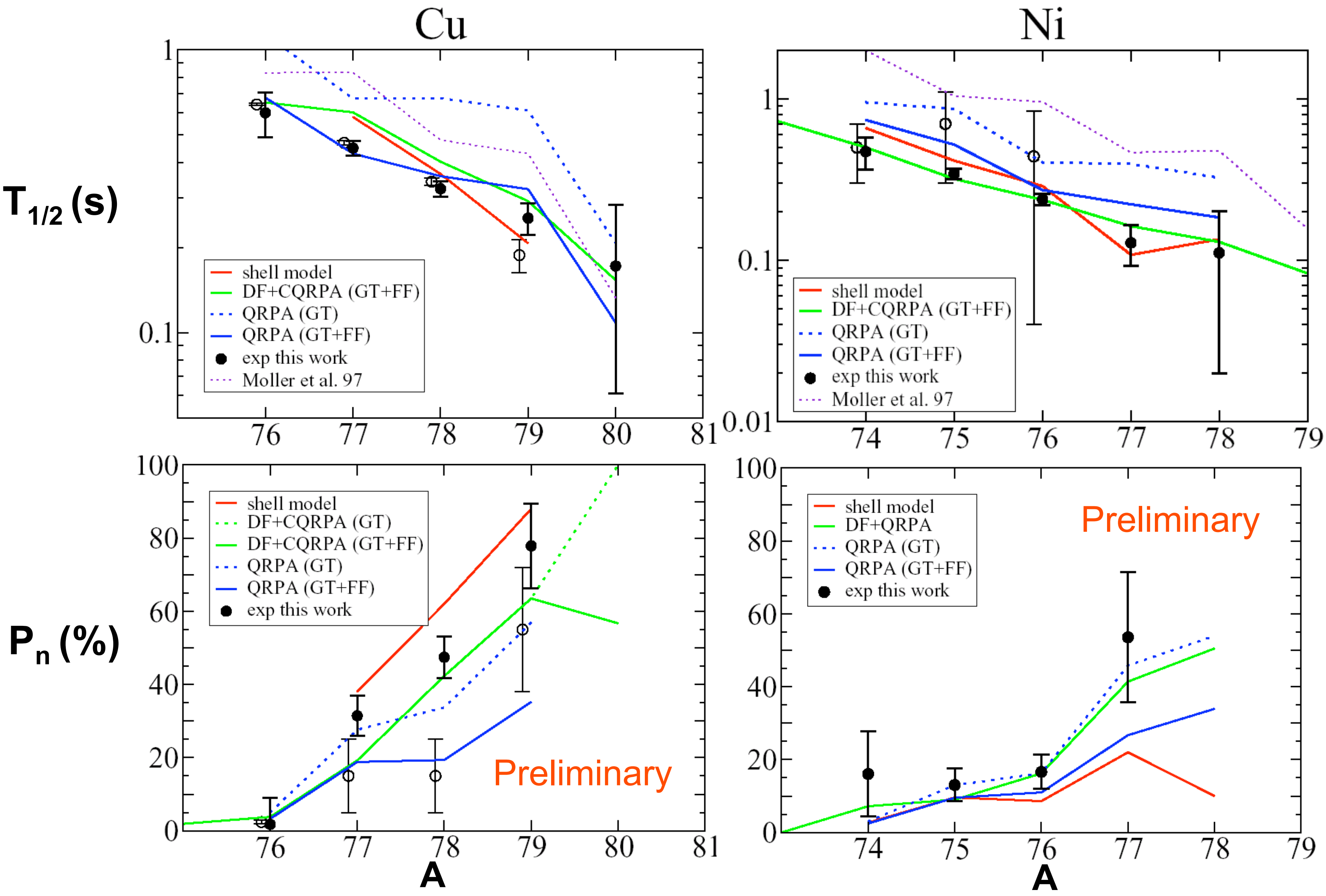
$$P_n = \frac{N_n}{N_\beta \varepsilon_n}$$

neutron detection efficiency

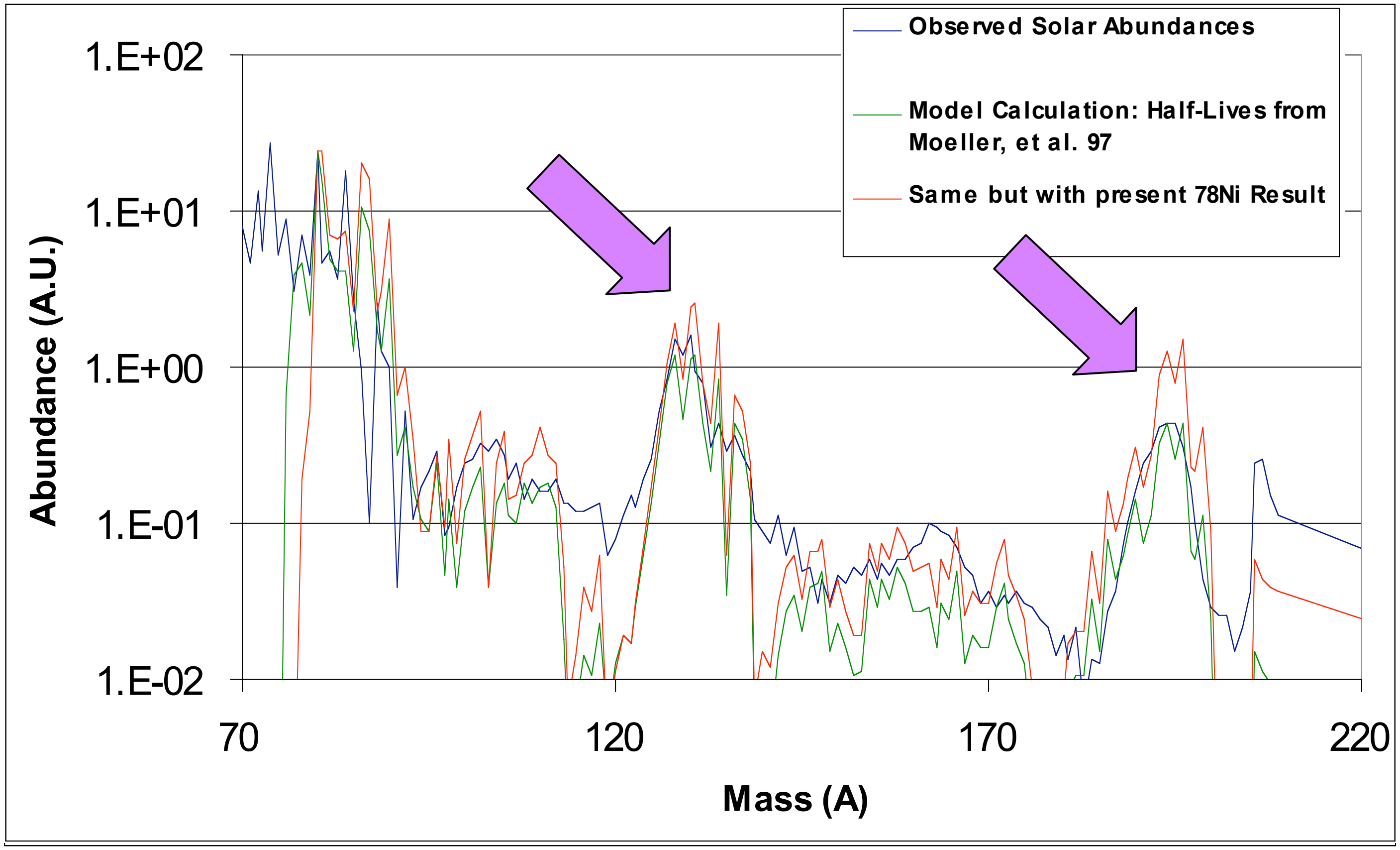
(neutrons seen/neutrons emitted)

Results (Hosmer et al.)

DF+CQRPA Borzov et al. 2005, QRPA: Moller et al. 2003, Shell model: Lisetzky & Brown 2005



Impact of ^{78}Ni half-life on r-process models



→need to readjust r-process model parameters

→Can obtain Experimental constraints for r-process models
from observations and solid nuclear physics

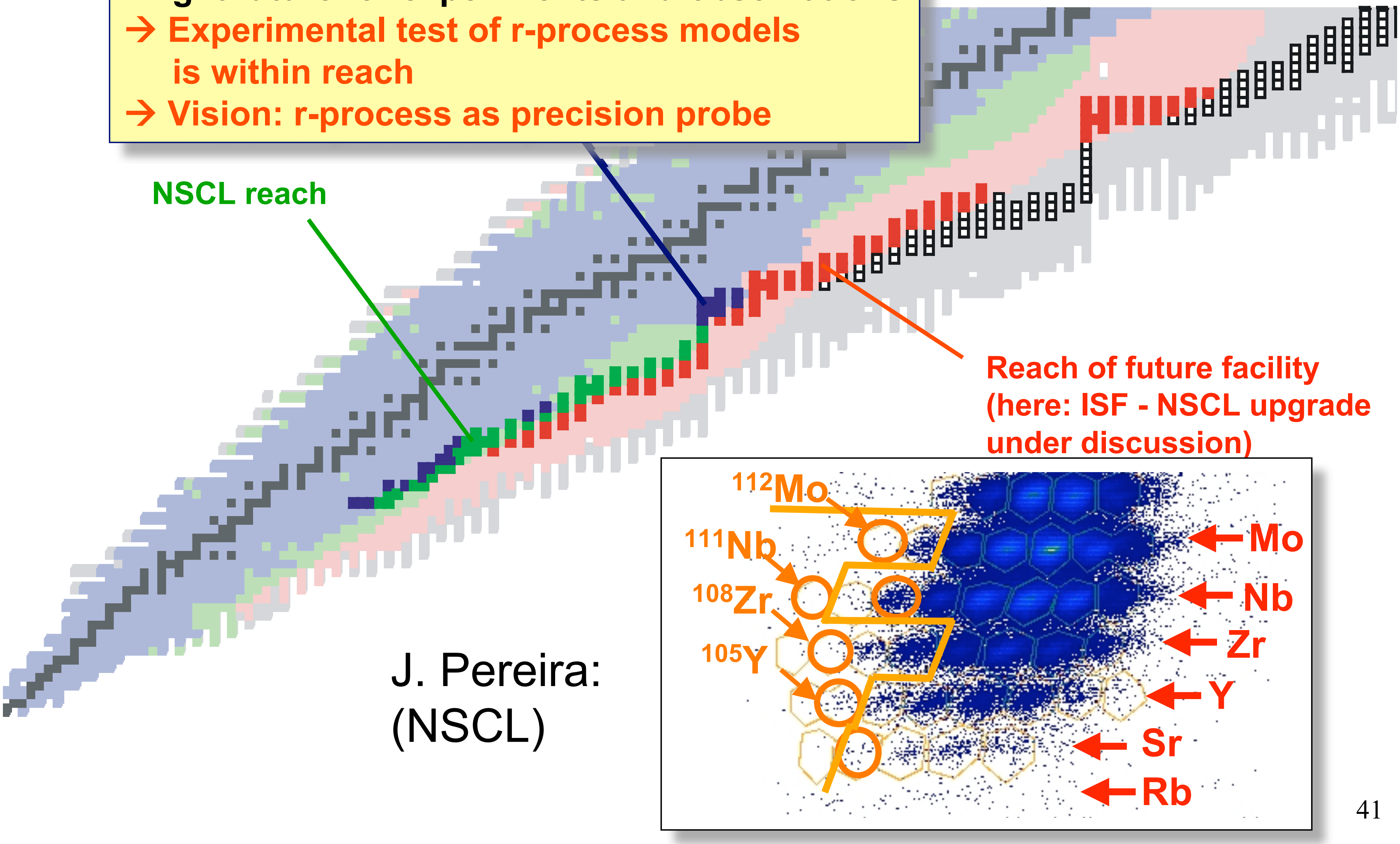
→ remainig discrepancies – nuclear physics ? Environment ? Neutrinos ?
Need more data

NSCL and future facilities reach

Bright future for experiments and observations

→ Experimental test of r-process models is within reach

→ Vision: r-process as precision probe



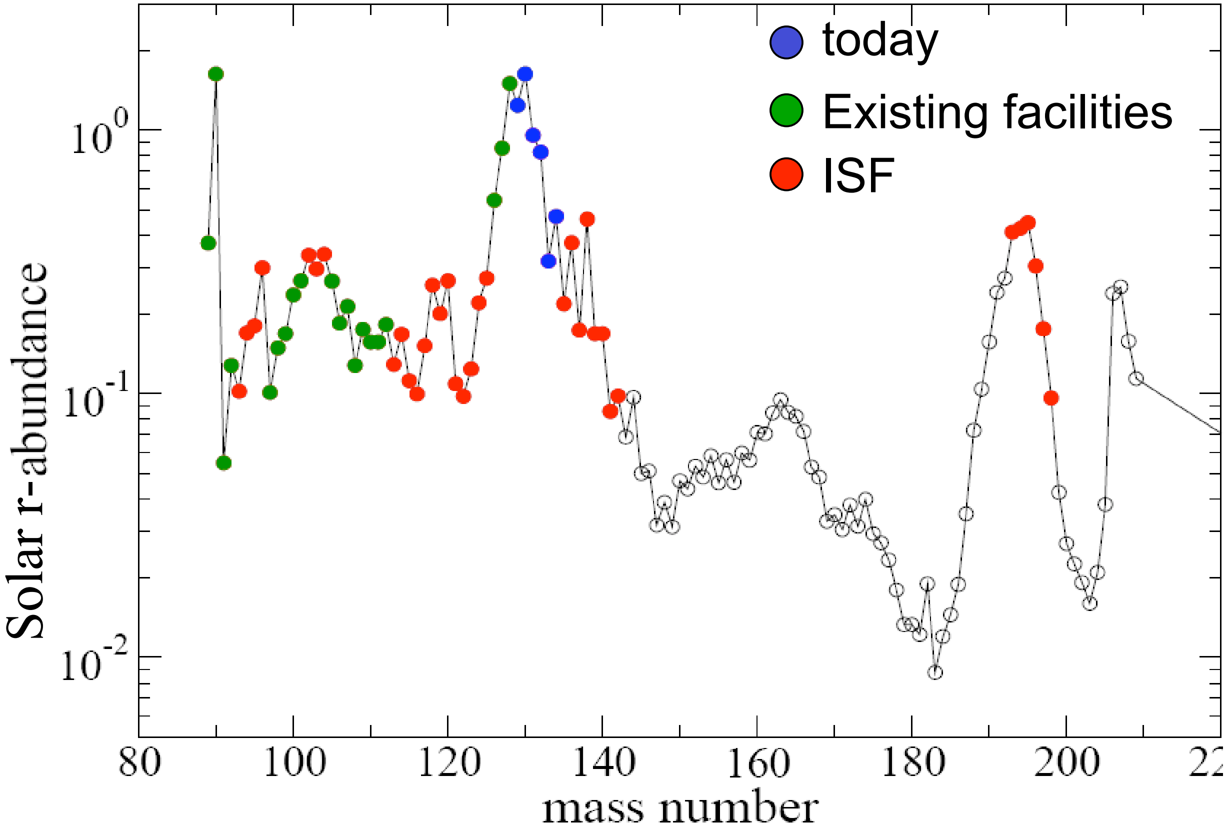
NSCL reach

Reach of future facility (here: ISF - NSCL upgrade under discussion)

J. Pereira: (NSCL)

Towards an experimental nuclear physics basis for the r-process

Final isotopes, for which >90% of progenitors in the r-process path can be reached experimentally for at least a half-life measurement



→ These abundances can be compared with observations to test r-process models

78Ni Collaboration

MSU:
P. Hosmer
R.R.C. Clement
A. Estrade
P.F. Mantica
F. Montes
C. Morton
W.F. Mueller
E. Pellegrini
P. Santi
H. Schatz
M. Steiner
A. Stolz
B.E. Tomlin
M. Ouellette

Mainz:
O. Arndt
K.-L. Kratz
B. Pfeiffer

Pacific Northwest Natl. Lab.
P. Reeder

Notre Dame:
A. Aprahamian
A. Woehr

Maryland:
W.B. Walters

Overview of common r process models

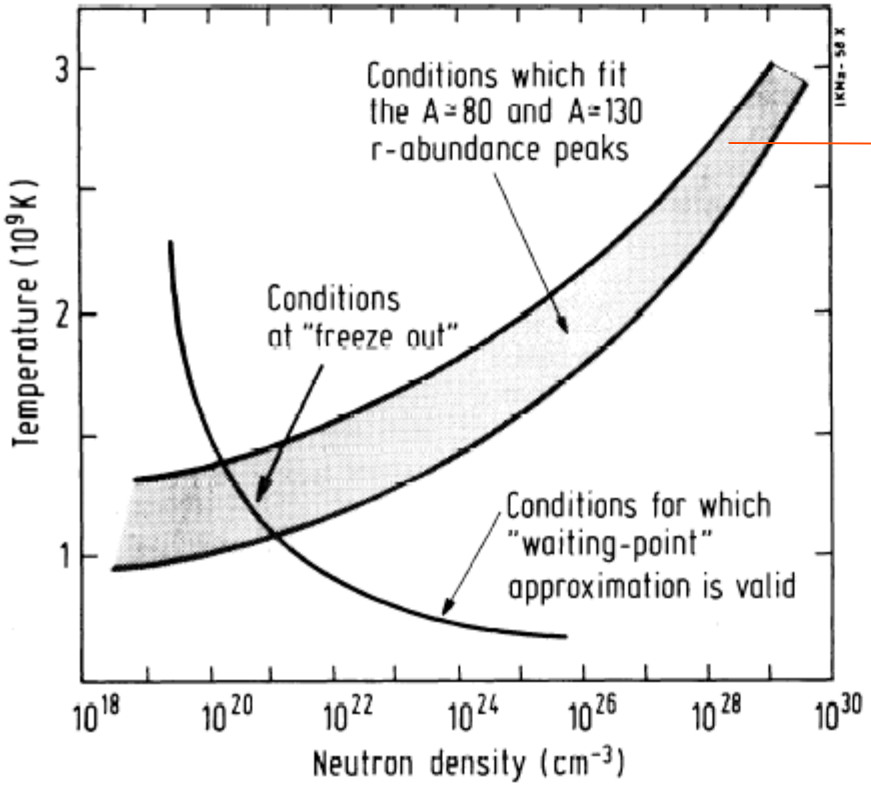
- **Site independent models:**
  - n_n, T, t parametrization (neutron density, temperature, irradiation time)
  - S, Y_e, t parametrization (Entropy, electron fraction, expansion timescale)
- **Core collapse supernovae**
  - Neutrino wind
  - Jets
  - Explosive helium burning
- **Neutron star mergers**

Site independent approach

Goal: Use abundance observations as general constraints on r-process conditions

BUT: need nuclear physics to do it

n_n, T, t parametrization (see Prof. K.-L. Kratz transparencies)



Kratz et al. ApJ403(1993)216

obtain r-process conditions needed

for which the right N=50 and N=82 isotopes are waiting points (A~80 and 130 respectively)

often in waiting point approximation

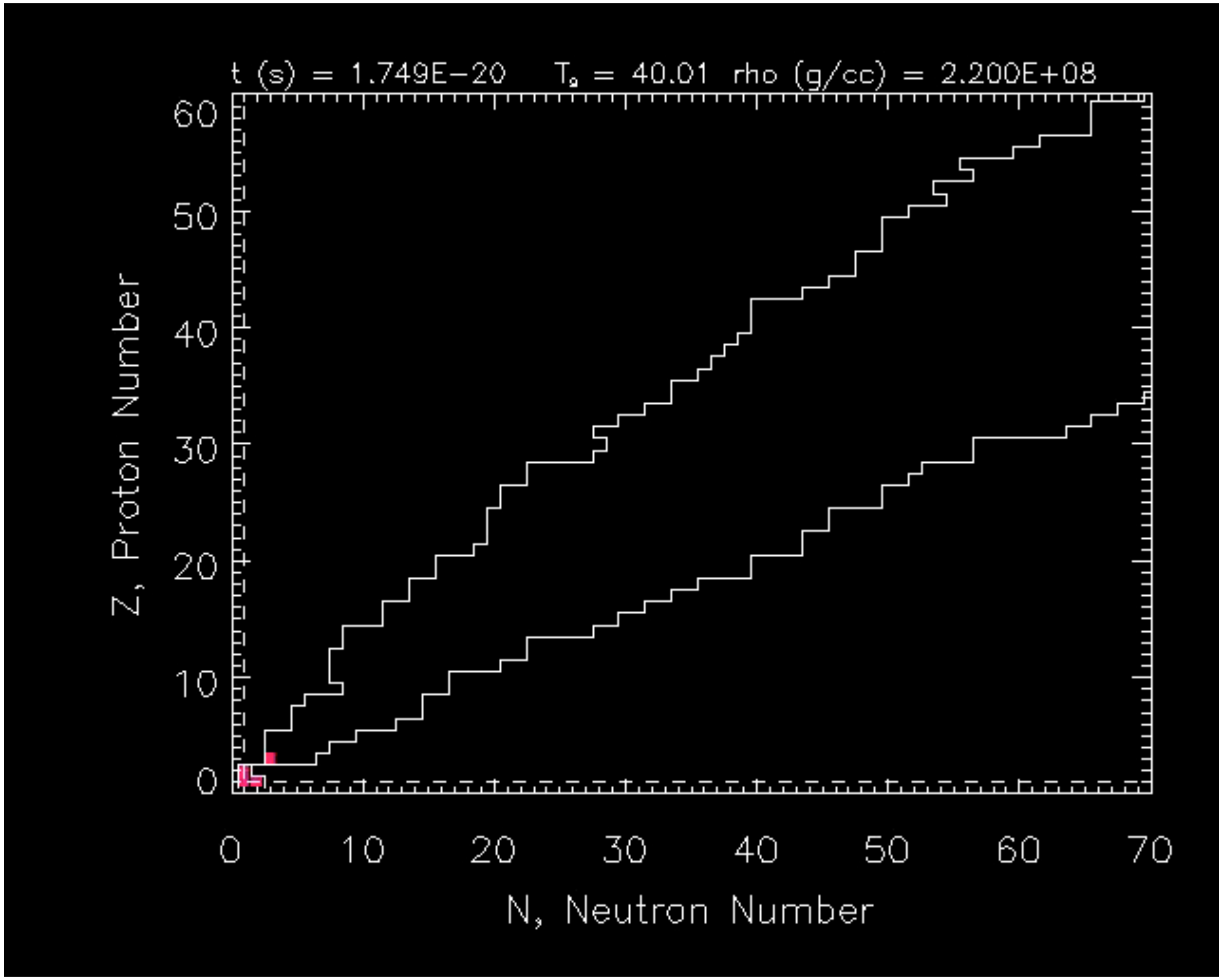
S, Y_e, τ parametrization

1. Consider a blob of matter with entropy S, electron abundance Y_e in NSE
2. Expand adiabatically with expansion timescale τ
3. Calculate abundances - what will happen:
    1. **NSE**
    2. **QSE** (2 clusters: p,n,α and heavy nuclei)
    3. **α-rich freezeout** (for higher S)
       (3a and aan reactions slowly move matter from p,n,α cluster to heavier nuclei – once a heavy nucleus is created it rapidly captures a-particles

       as a result large amounts of A~90-100 nuclei are produce which serve as seed for the r-process
    4. **r-process phase**
       initially: n,γ – γ,n equilibrium
       later: freezeout

Evolution of equilibria:

cross : most abundant nucleus
colors: degree of equilibrium with that nucleus
(difference in chemical potential)



from Brad Meyers website

Results for
neutron to seed ratios:

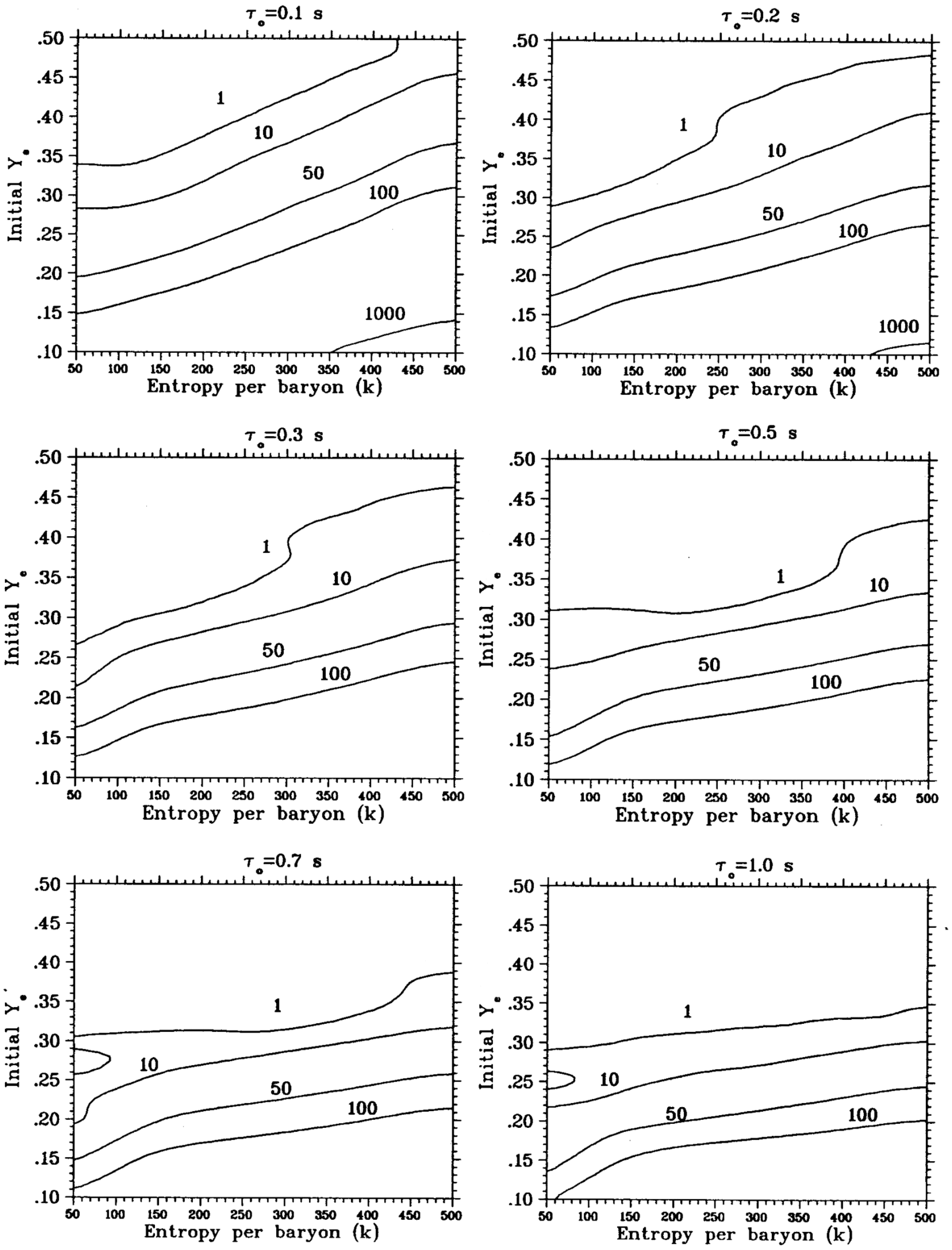
(Meyer & Brown ApJS112(1997)199)

n/seed is higher for

- lower Y_e
  (more neutrons)
- higher entropy
  (more light particles, less heavy nuclei – less seeds)
  (or: low density – low 3a rate – slow seed assembly)
- faster expansion
  (less time to assemble seeds)

→ 2 possible scenarios:

1) high S, moderate Y_e
2) low S, low Y_e

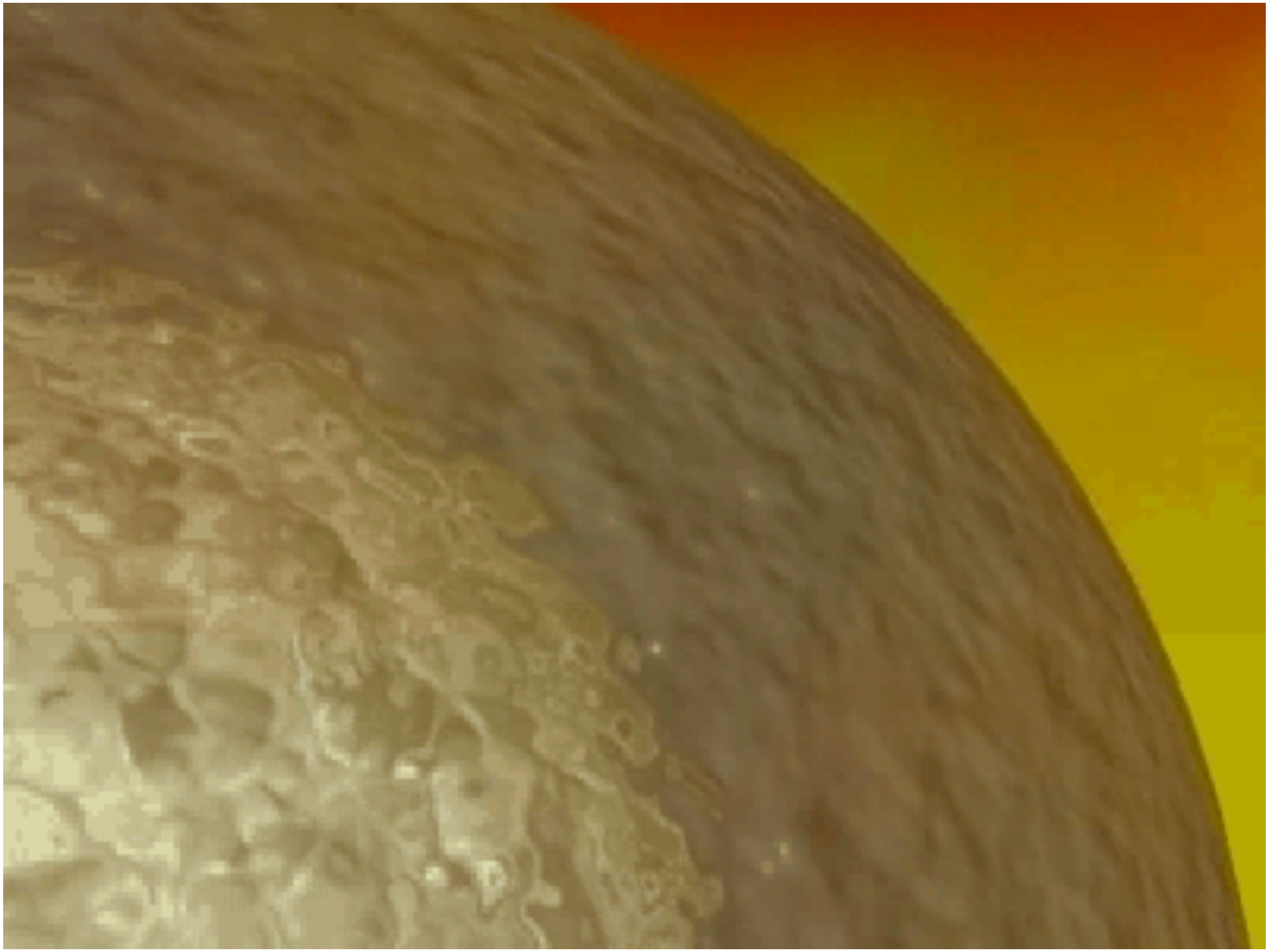


Neutron
star forms
(size ~ 10 km radius)

Matter evaporated off the hot neutron star

r-process site ?

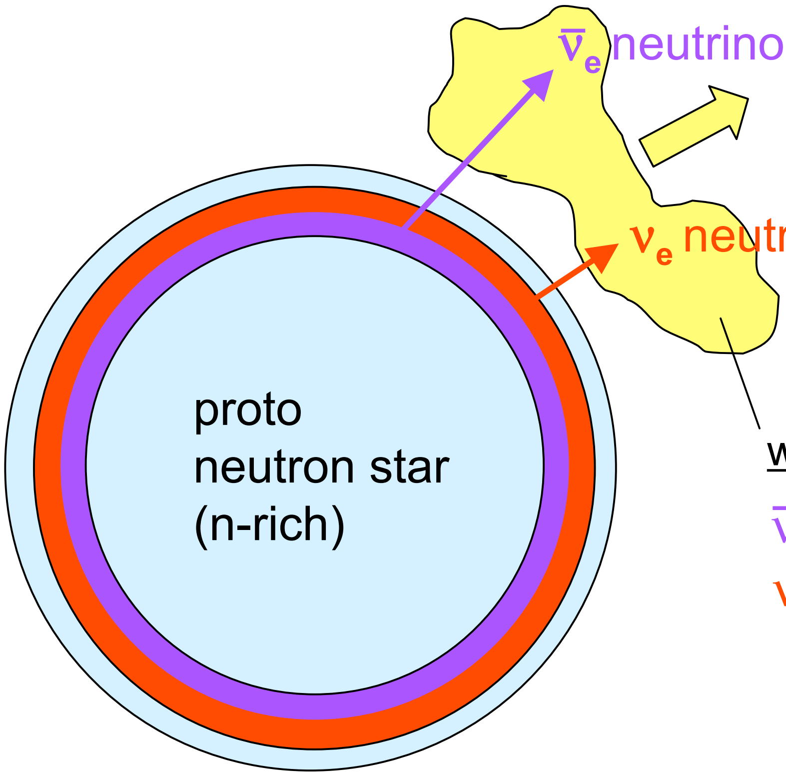
How does the r-process work ? Neutron capture !



r-process in Supernovae ?

Most favored scenario for high entropy:

Neutrino heated wind evaporating from proto neutron star in core collapse



$\bar{\nu}_e$ neutrino sphere ($\bar{\nu}_e + p \rightarrow n + e^+$ weak opacity
because only few protons present)

ν_e neutrino sphere ($\nu_e + n \rightarrow p + e^+$ strong opacity
because many neutrons present)

proto
neutron star
(n-rich)

<u>weak interactions regulate n/p ratio:</u>

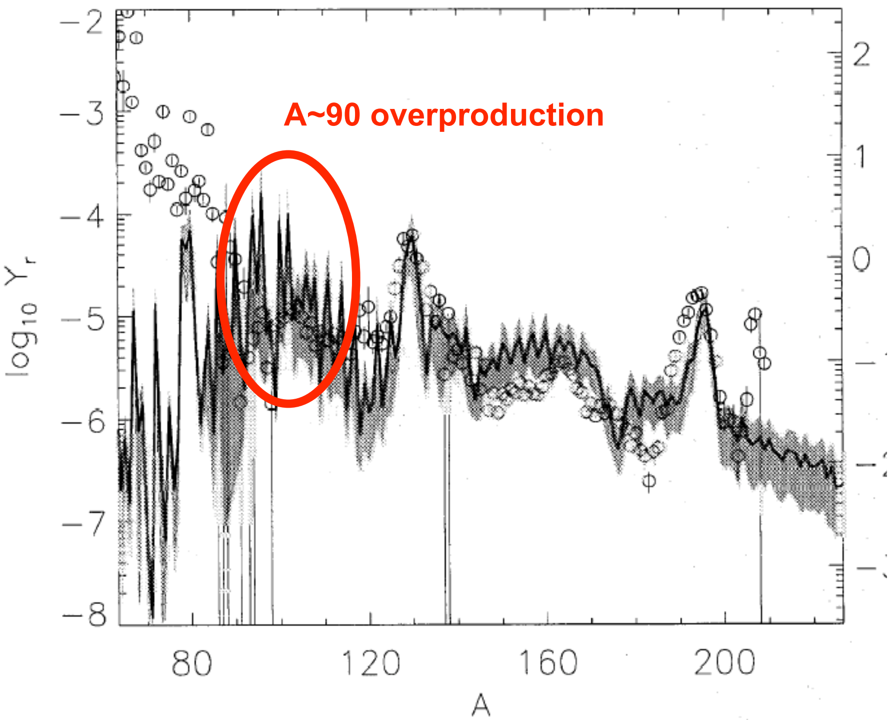
$\bar{\nu}_e + p \rightarrow n + e^+$ ← faster as $\bar{\nu}_e$ come from deeper and are therefore hotter !

$\nu_e + n \rightarrow p + e^-$

therefore matter is driven neutron rich

Results for Supernova r-process

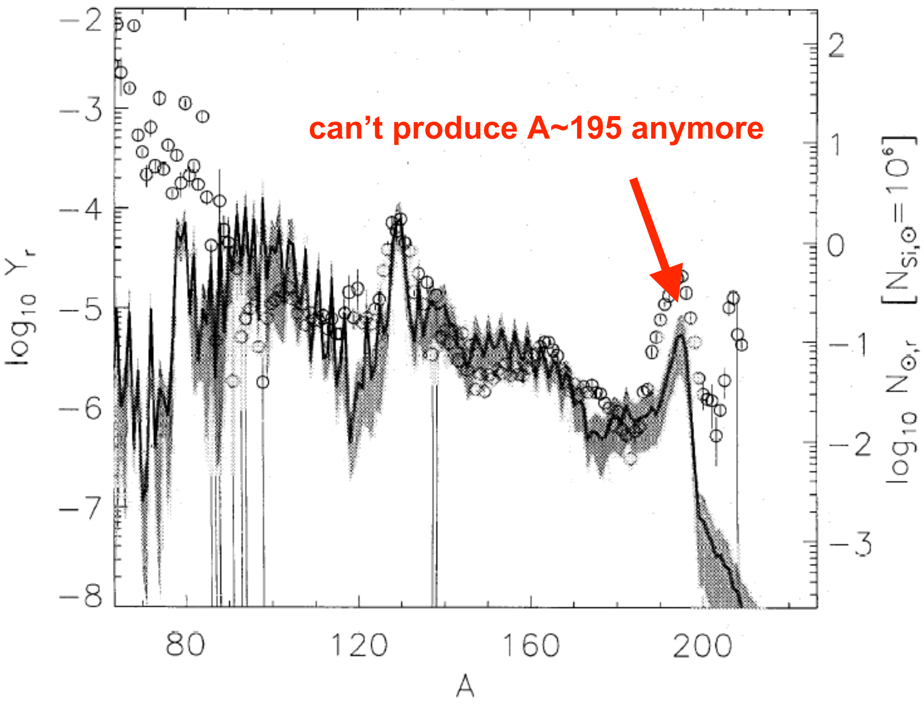
Takahashi, Witti, & Janka A&A 286(1994)857
(for latest treatment of this scenario see Thompson, Burrows, Meyer ApJ 562 (2001) 887)



A~90 overproduction

density artificially reduced by factor **5.5**

artificial parameter to get A~195 peak (need S increase)



can't produce A~195 anymore

density artificially reduced by factor **5**

other problem: the α effect

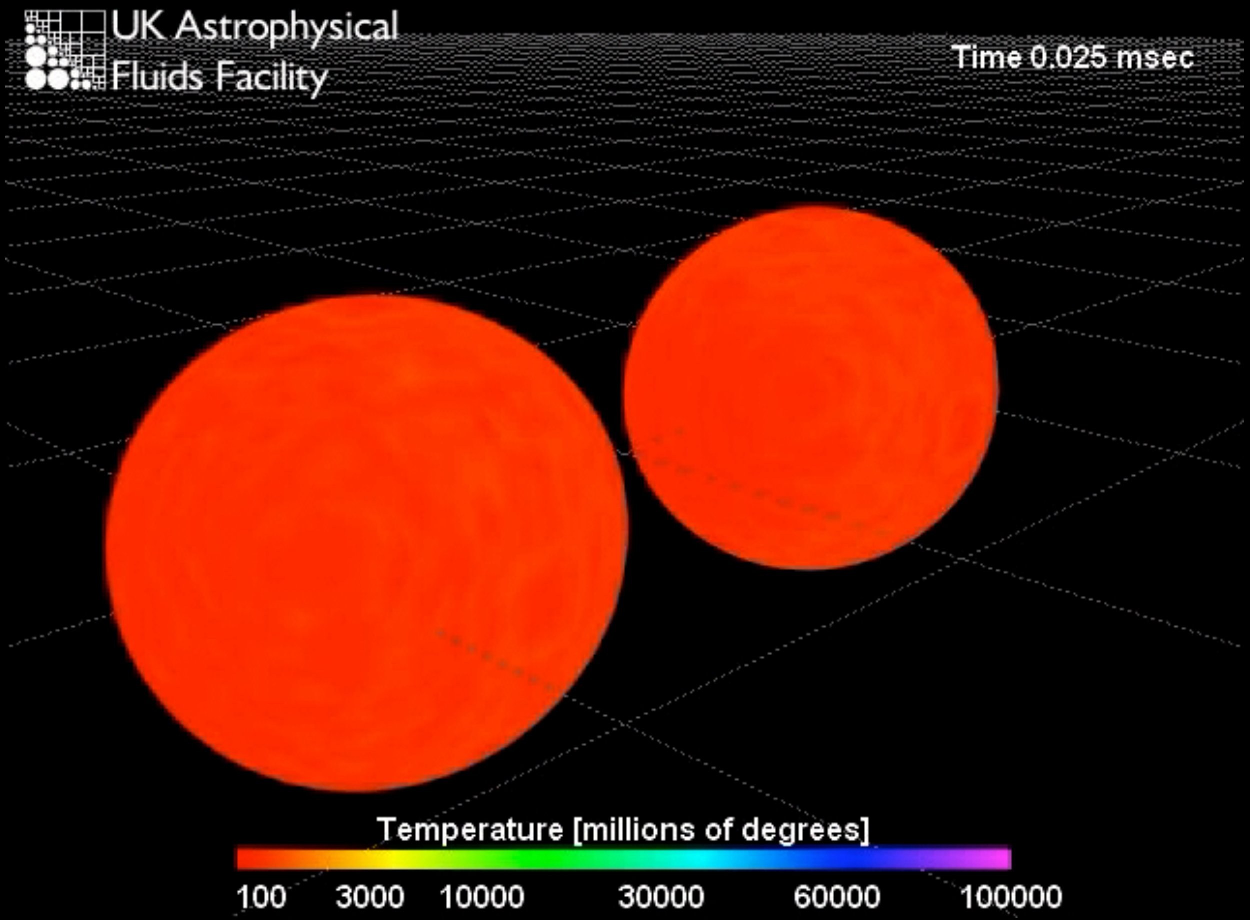
other problem: the α effect

Recall equilibrium of nucleons in neutrino wind:

$$\left.\begin{array}{l}\bar{\nu}_e + p \rightarrow n + e^+ \\ \nu_e + n \rightarrow p + e^-\end{array}\right\}$$ Maintains a slight neutron excess $$\frac{n_p}{n_p + n_n} \approx 0.4$$

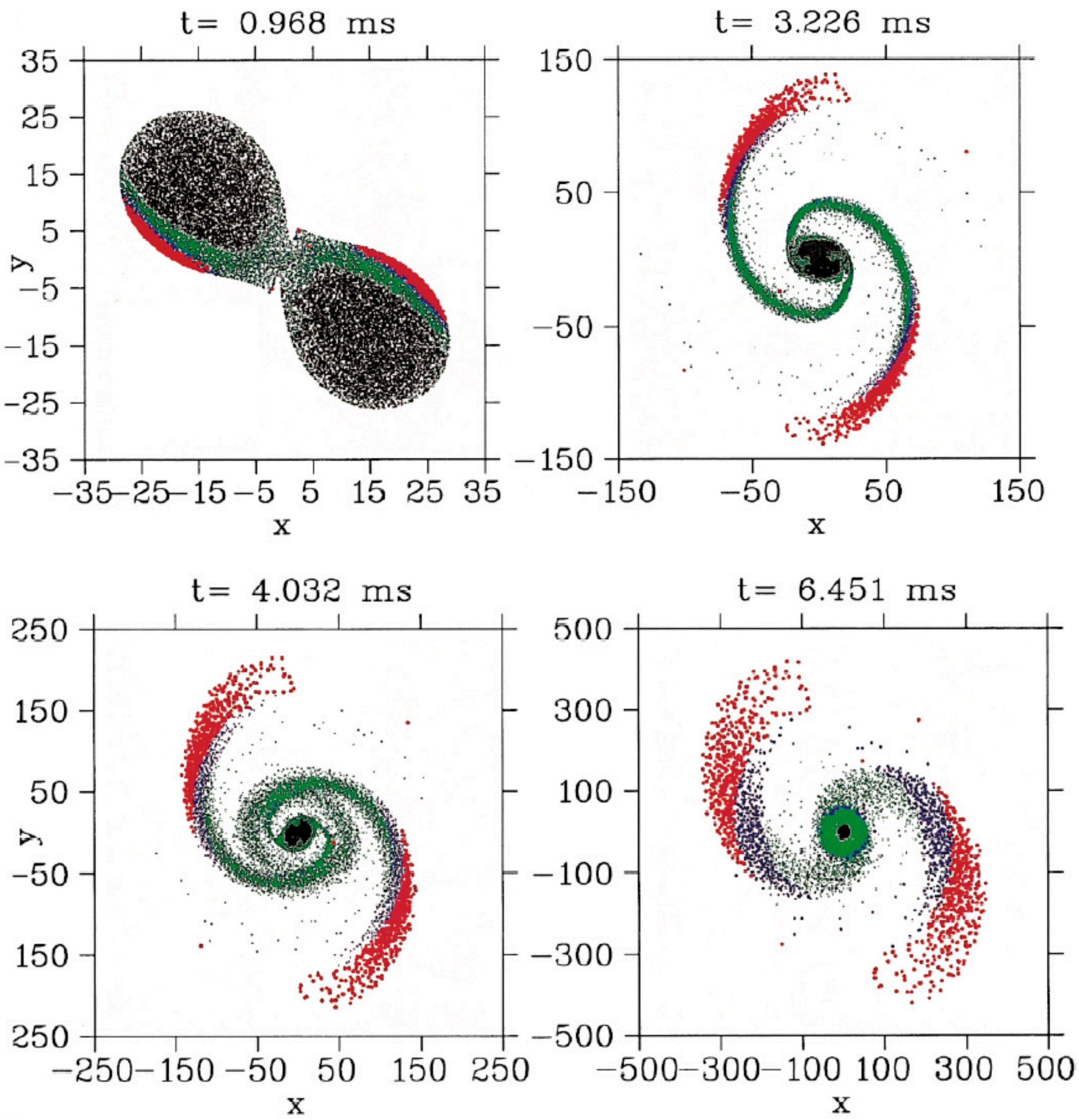
What happens when α-particles form, leaving a mix of α-particles and neutrons ?

r-process in neutron star mergers ?



Ejection of matter in NS-mergers

Rosswog et al. A&A 341 (1999) 499



<u>Destiny of Matter:</u>

red: ejected

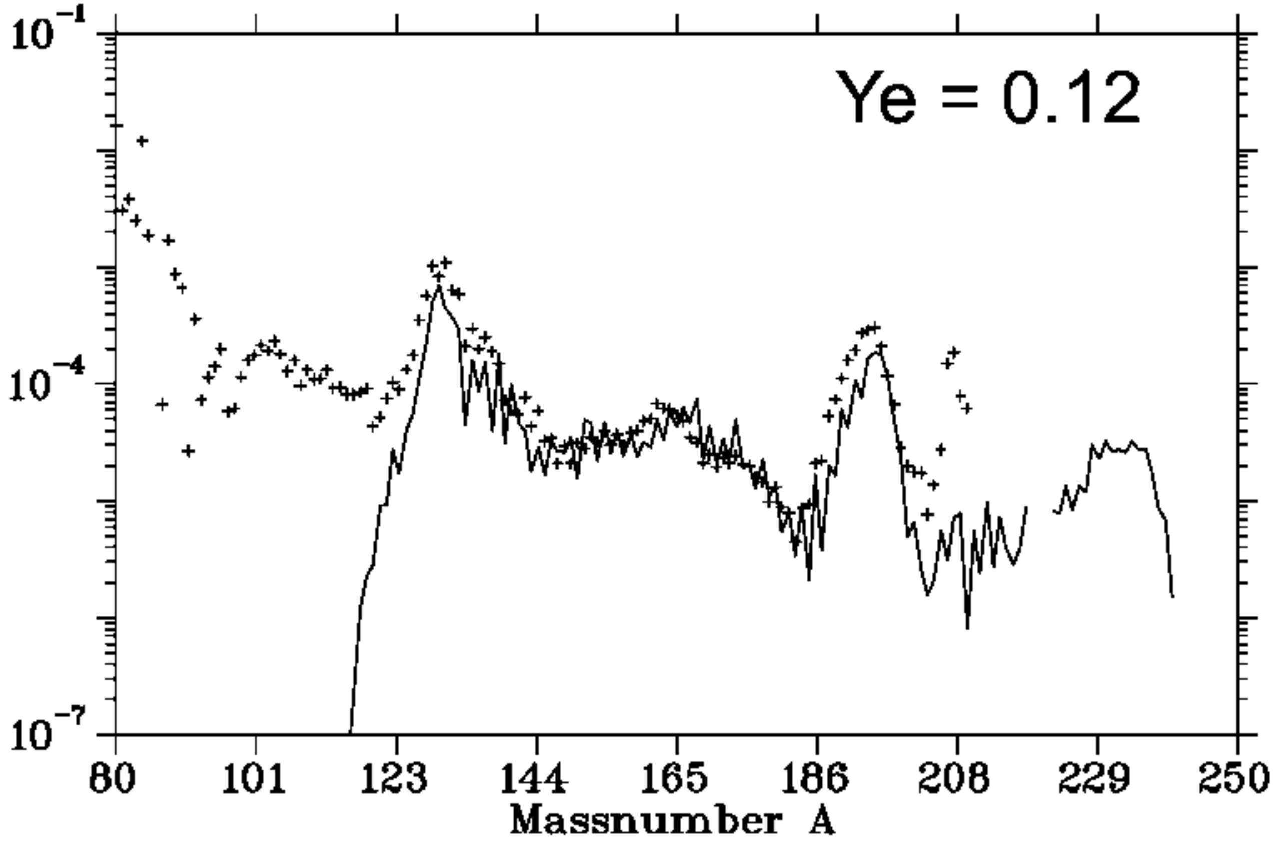
blue: tails

green: disk

black: black hole

(here, neutron stars are co-rotating – tidally locked)

r-process in NS-mergers



large neutron/seed ratios, fission cycling !

But: Y_e free parameter …

Summary theoretical scenarios

	NS-mergers	Supernovae
Frequency (per yr and Galaxy)	1e-5 - 1e-4	2.2e-2
Ejected r-process mass (solar masses)	4e-3 – 4e-2	1e-6 – 1e-5
Summary	less frequent but more ejection	more frequent and less ejection

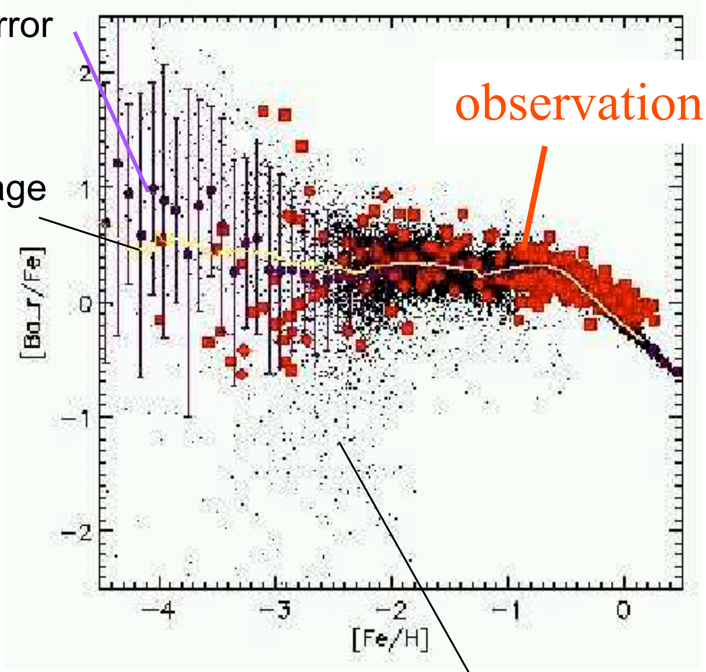
What does galactic chemical evolution observations tell us ?

Argast et al. A&A 416 (2004) 997

Supernovae

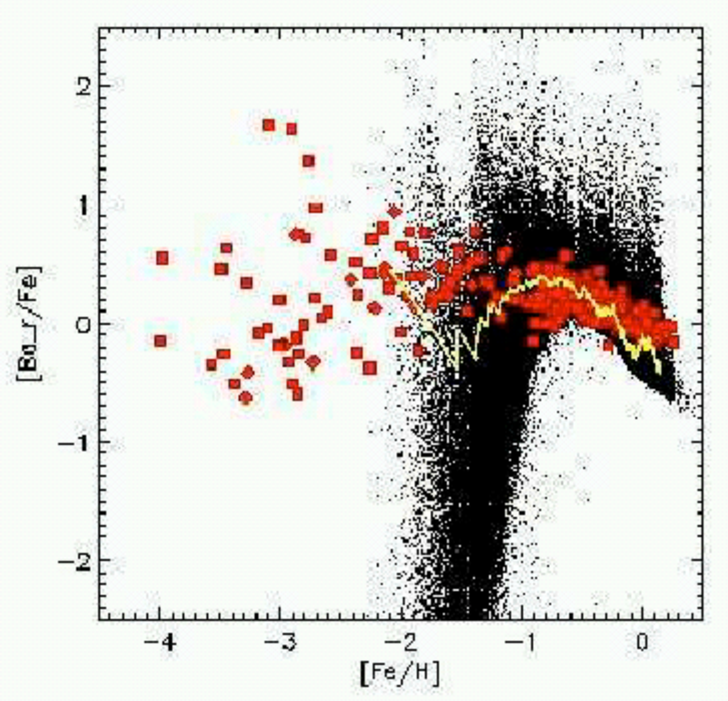
Model star average with error

Average ISM



Dots: model stars

NS mergers



→ Neutron Star Mergers ruled out as major contributor