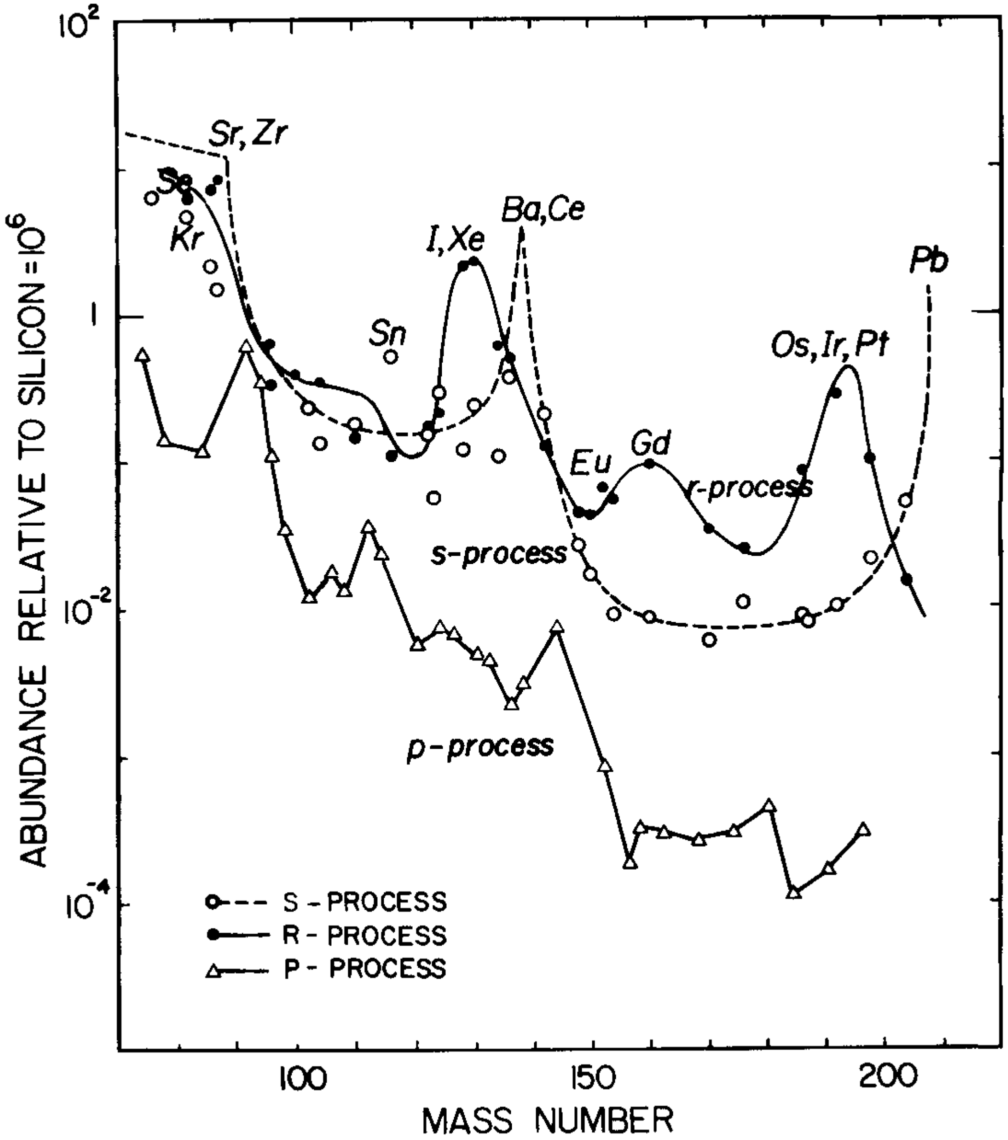
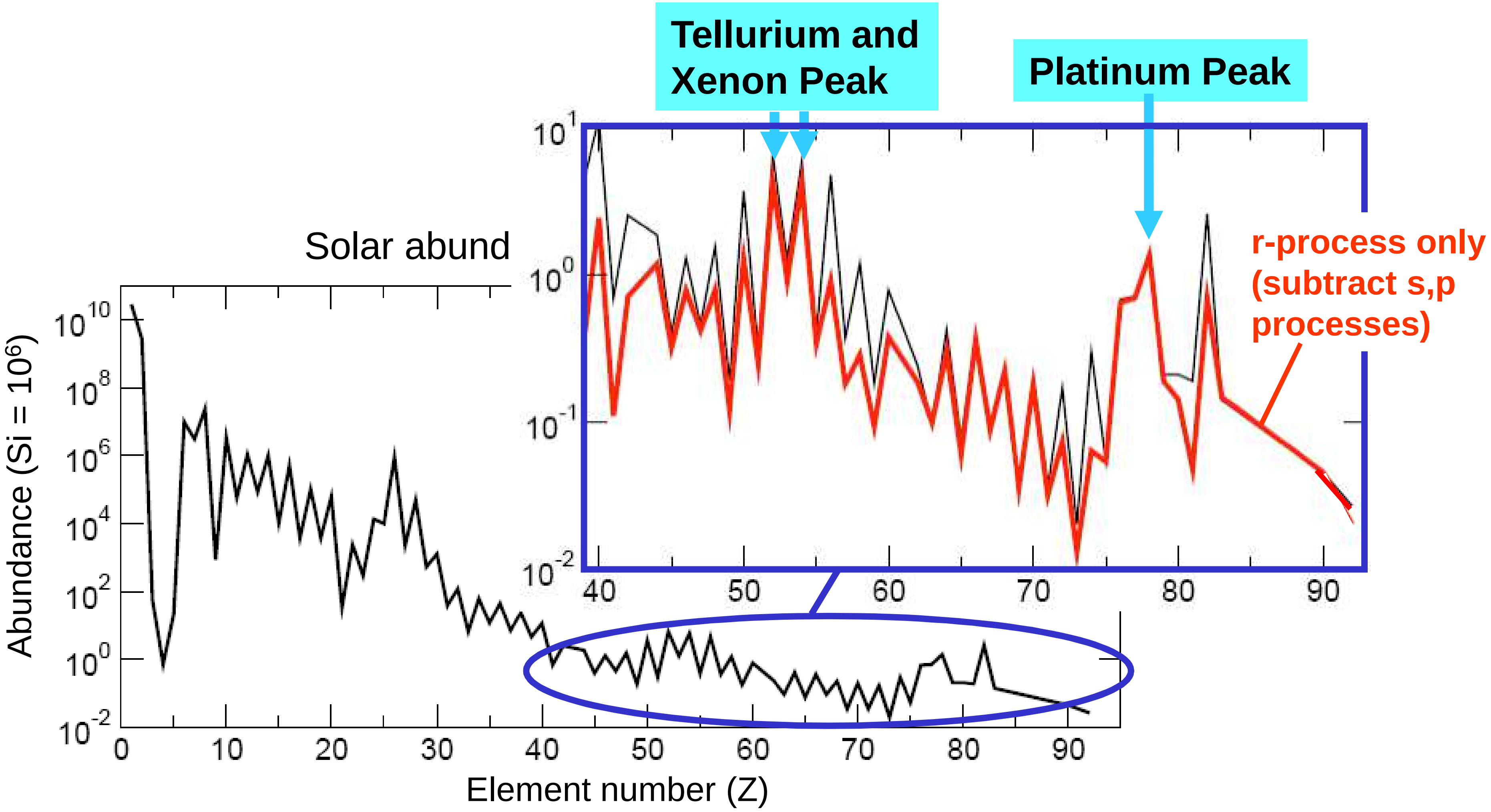
The origin of heavy elements in the solar system



(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

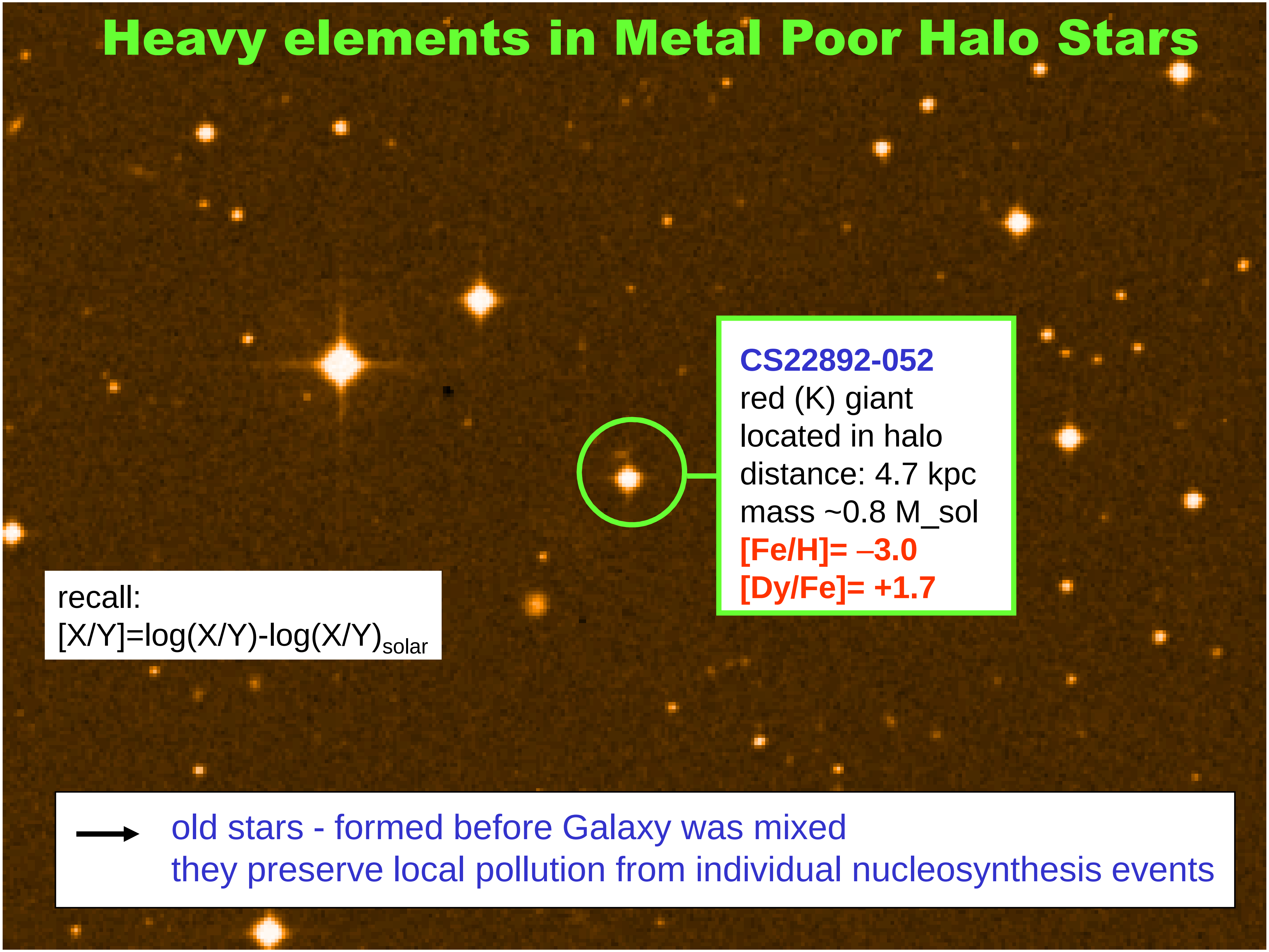
r-process only (subtract s,p processes)

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

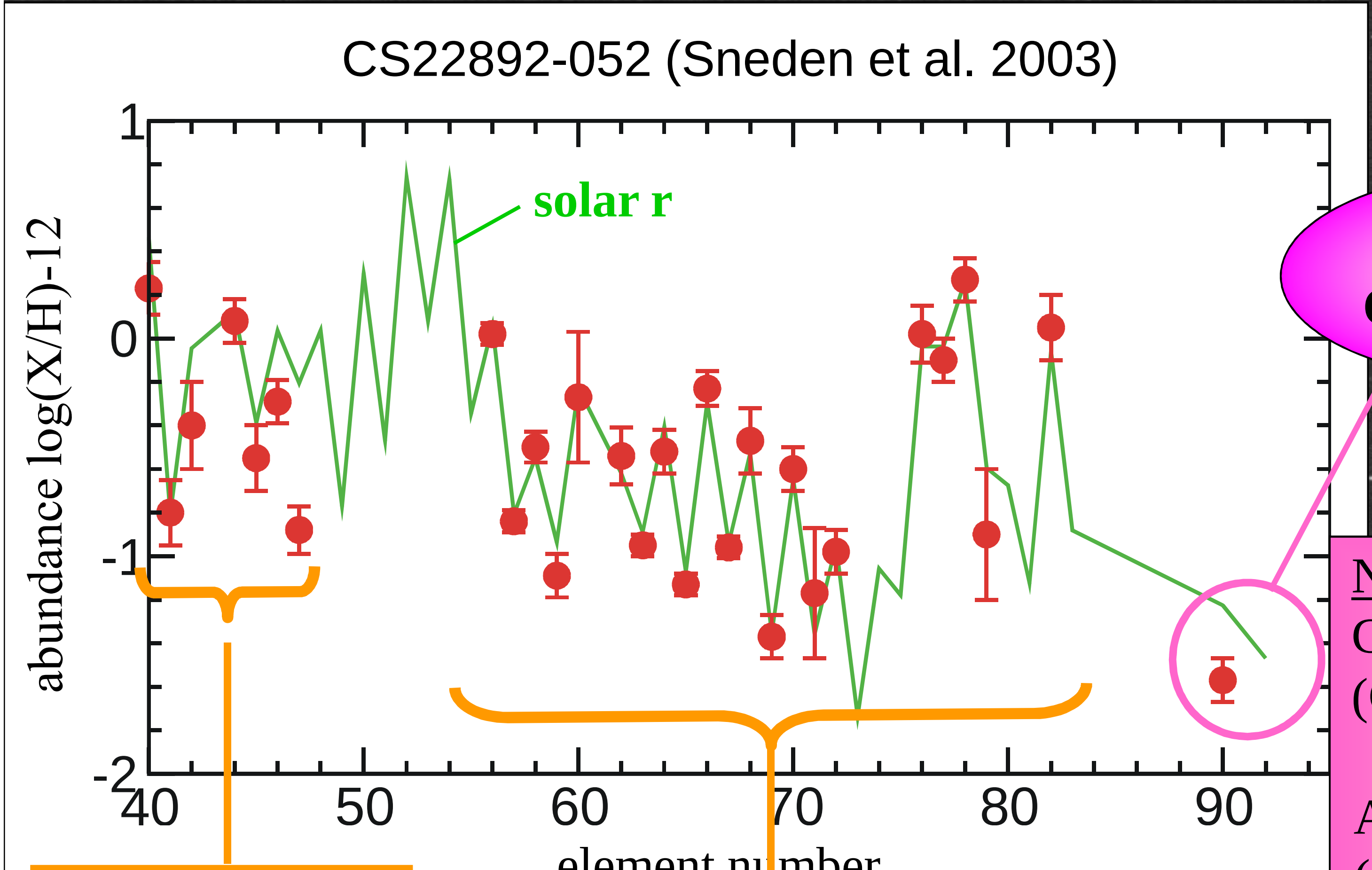


CS22892-052
red (K) giant
located in halo
distance: 4.7 kpc
mass ~0.8 M_sol
[Fe/H]= –3.0
[Dy/Fe]= +1.7

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

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

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



Cosmo Chronometer

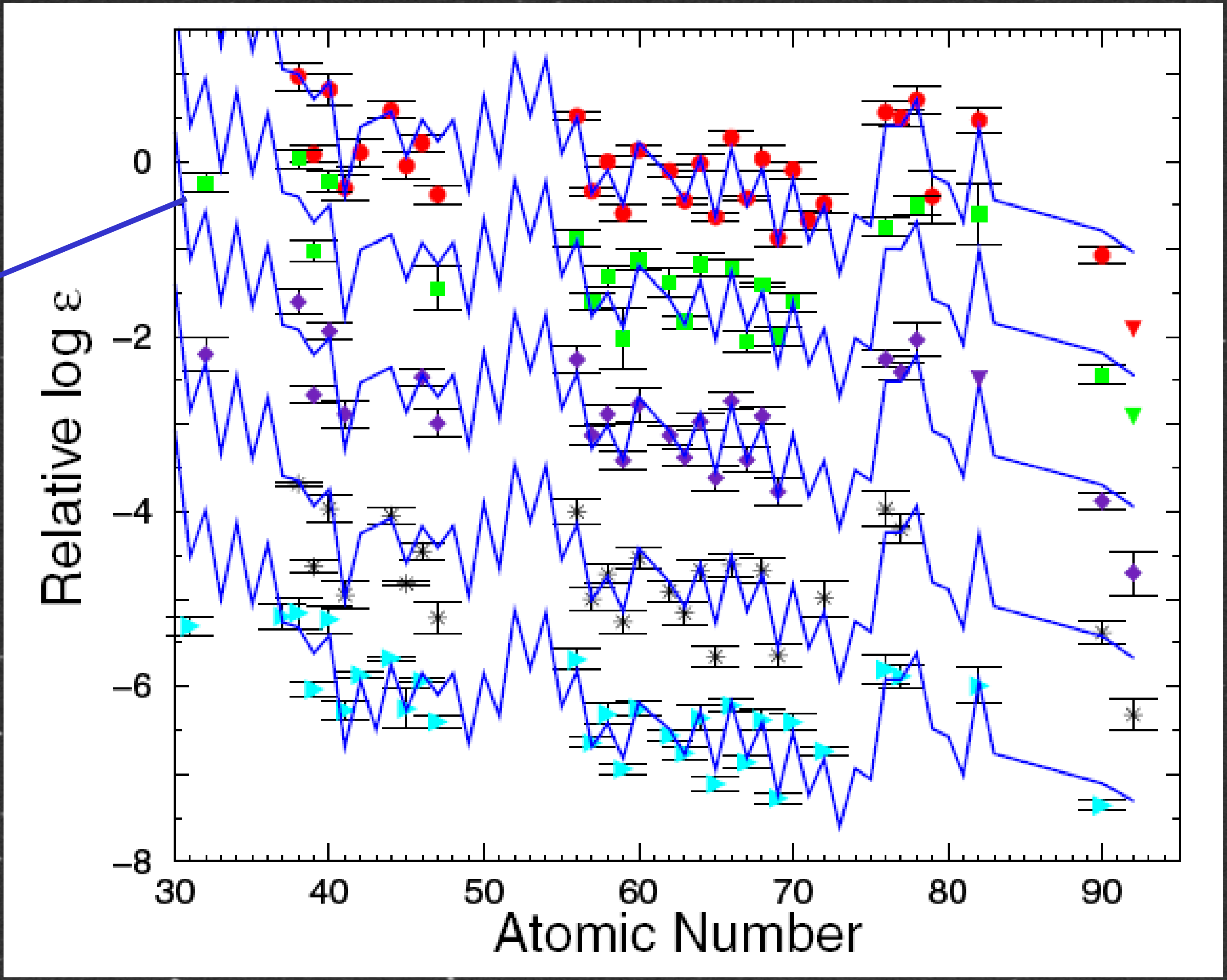
NEW:
CS31082-001 with U
(Cayrel et al. 2001)

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

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

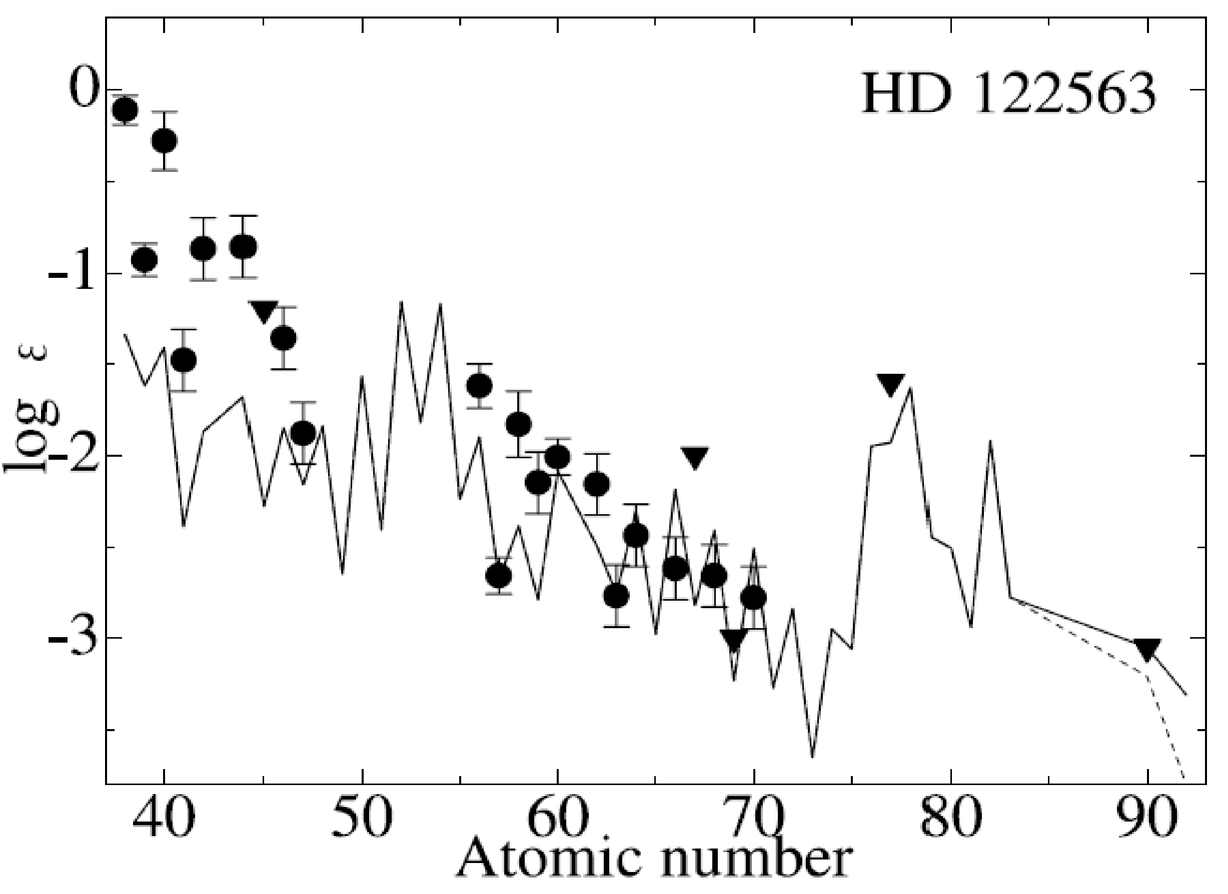
main r-process
matches exactly solar r-pattern
conclusions ?

More rII stars



Solar r-process elements from many events

A surprise



→ A new process contributing to Y, Sr, Zr (early Galaxy only? Solar?
In this case: some traditional "r-contributions" to solar are not (main) r-process)
→ Call it LEPP (Light Element Primary Process)

Overview heavy element nucleosynthesis

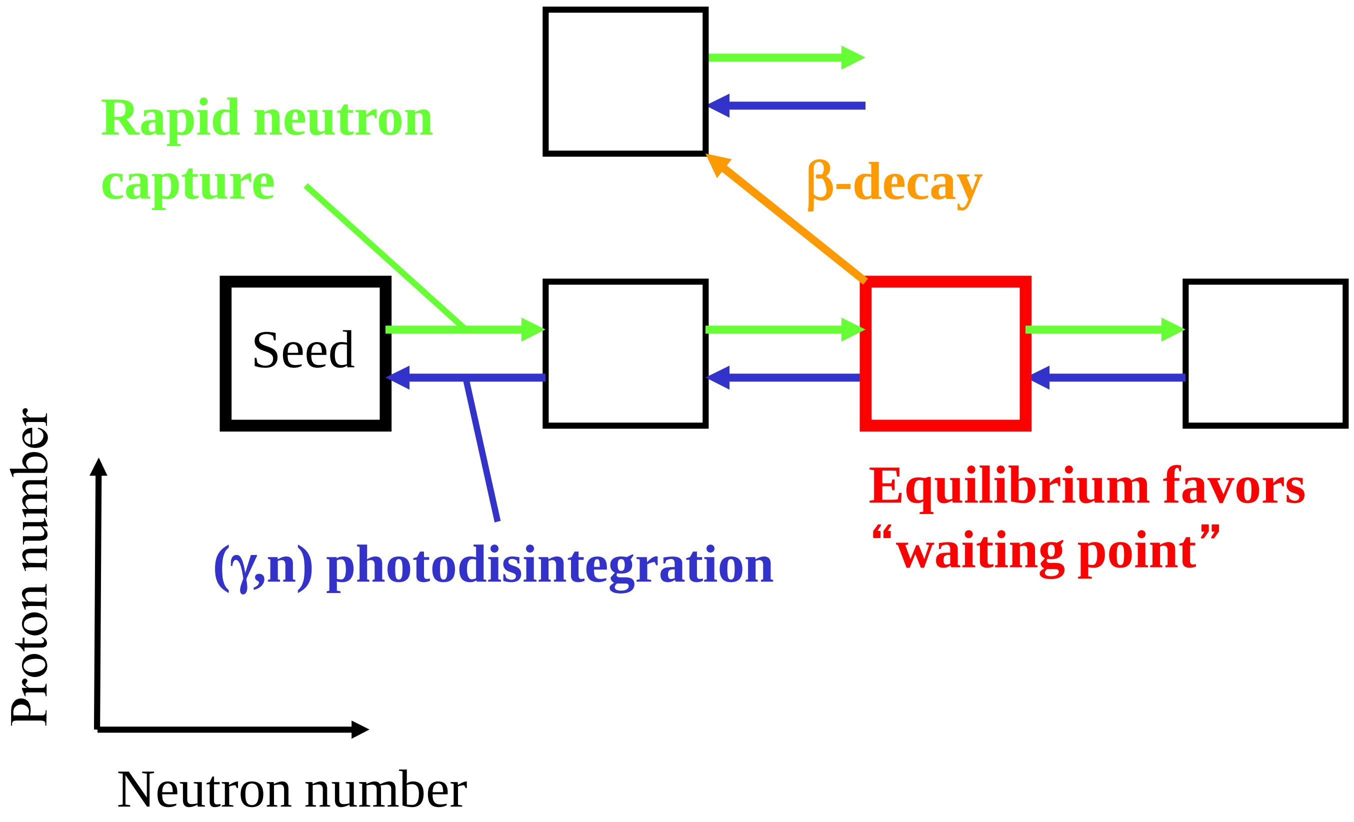
process	**conditions**	**timescale**	**site**
s-process (n-capture, ...)	T~ 0.1 GK τ_n~ 1-1000 yr, n_n~10^{7-8}/cm^3	10^2 yr and 10^{5-6} yrs	Massive stars (weak) Low mass AGB stars (main)
r-process (n-capture, ...)	T~1-2 GK τ_n ~ μs, n_n~10^{24} /cm^3	< 1s	Core collapse supernovae ? Neutron Star Mergers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

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

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 !)

Waiting point approximation continued

In the approximation of continuous S_n and abundances Y the maximum abundance in an isotopic chain occurs for

$$\frac{Y(Z,A+1)}{Y(Z,A)}=1$$

For a given temperature and neutron density one can solve for S_n (assuming A~A+1 and G=1)

$$S_n = kT\ln\left(\frac{2}{n_n}\left[\frac{m_u kT}{2\pi\hbar^2}\right]^{3/2}\right)$$

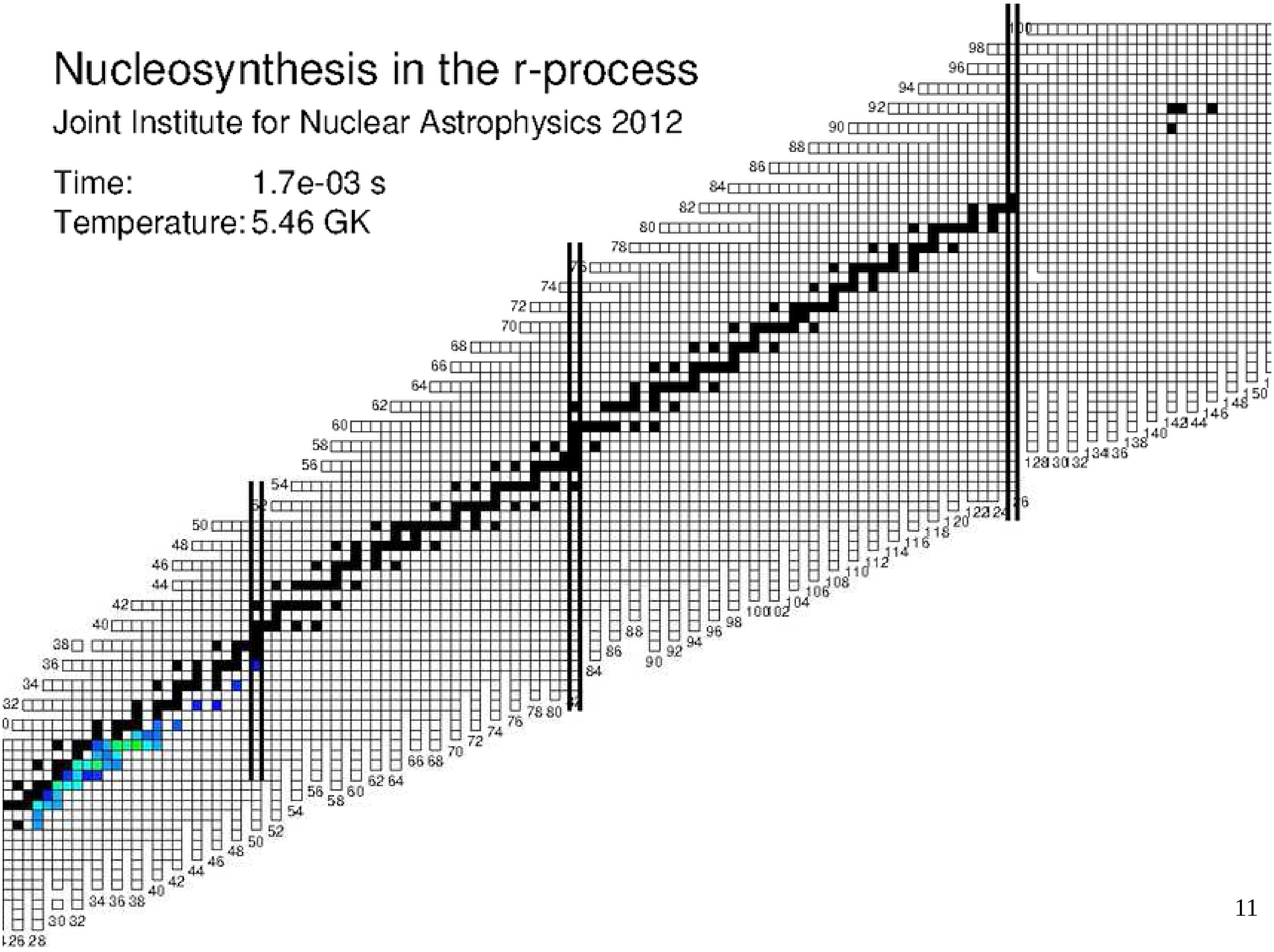
$$S_n = \frac{T_9}{11.604}\left[\frac{3}{2}\ln(T_9)-\ln(n_n)+78.460\right] \quad \text{in MeV}$$

→ r-process runs at fixed neutron separation energy (for given condition)

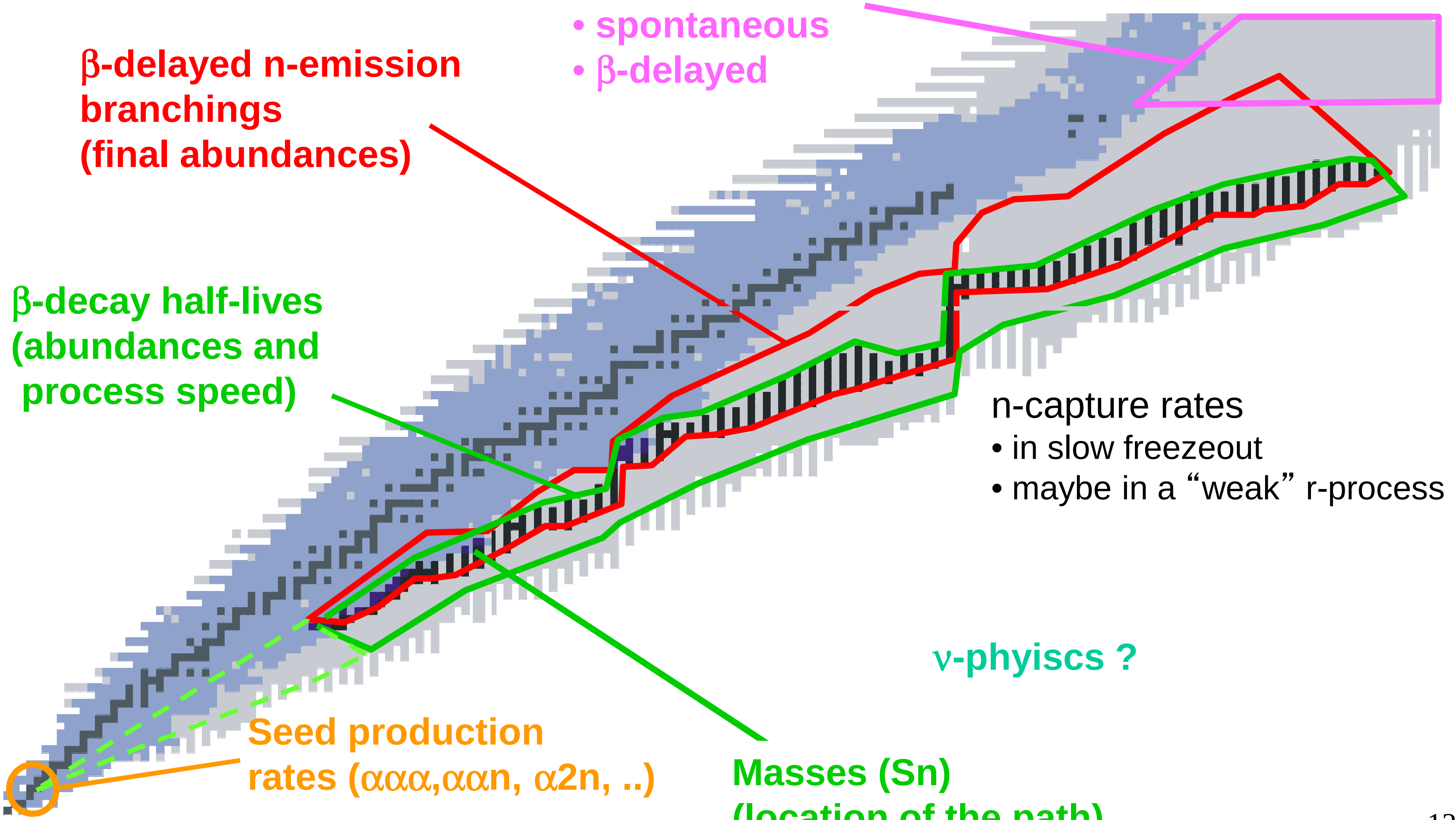
Nucleosynthesis in the r-process

Joint Institute for Nuclear Astrophysics 2012

Time: 1.7e-03 s
Temperature: 5.46 GK



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 ?

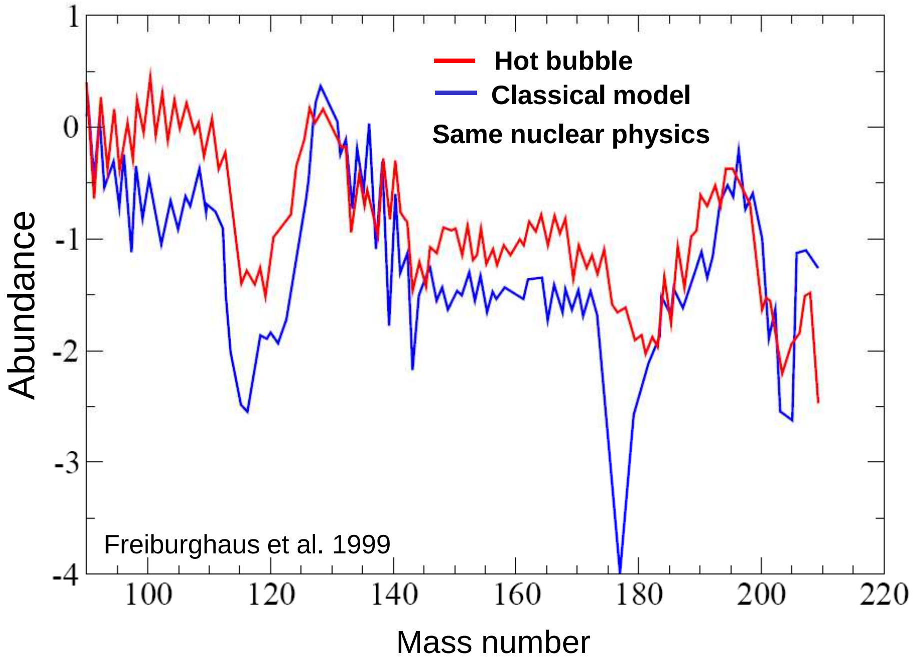
ν-phyiscs ?

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

Masses (Sn) (location of the path)

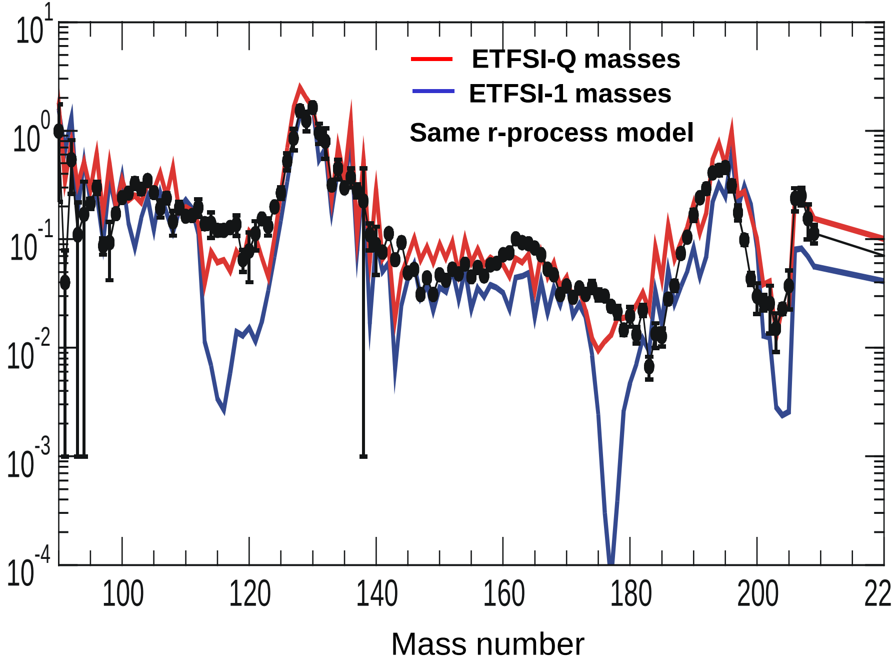
Sensitivity of r-process to astro and nuclear physics

Sensitivity to astrophysics



Freiburghaus et al. 1999

Sensitivity to nuclear physics



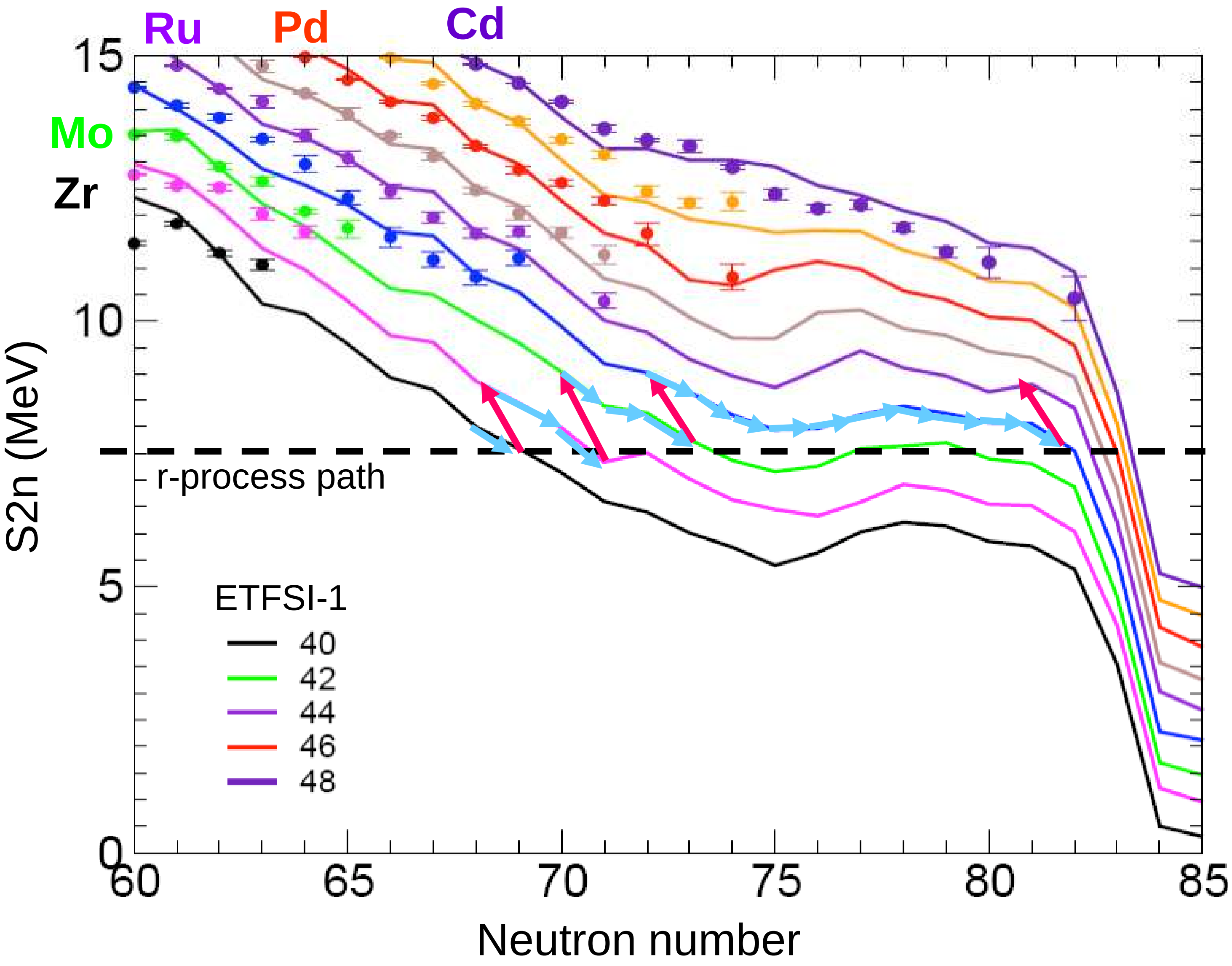
Contains information about:

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

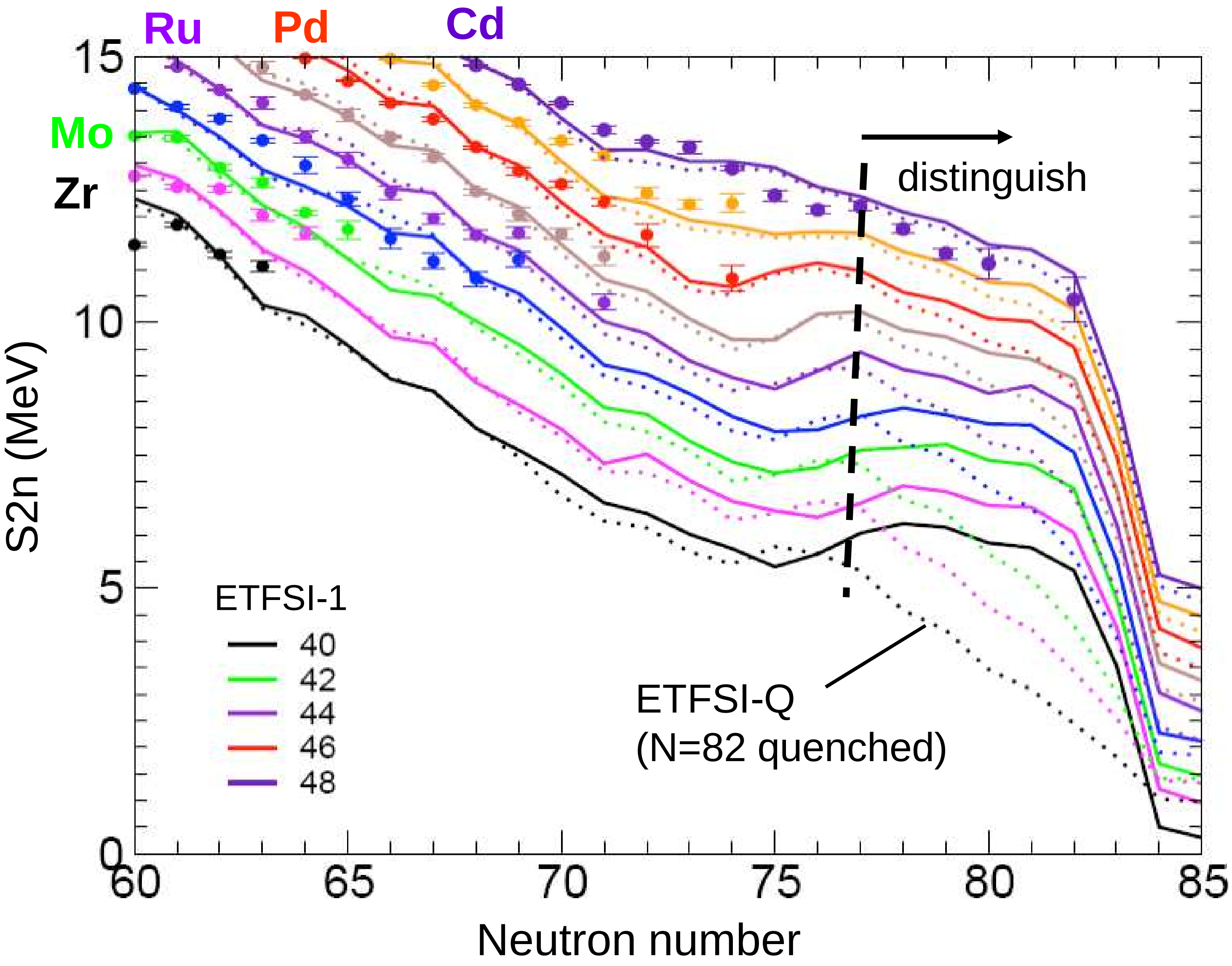
But convoluted with nuclear physics:

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

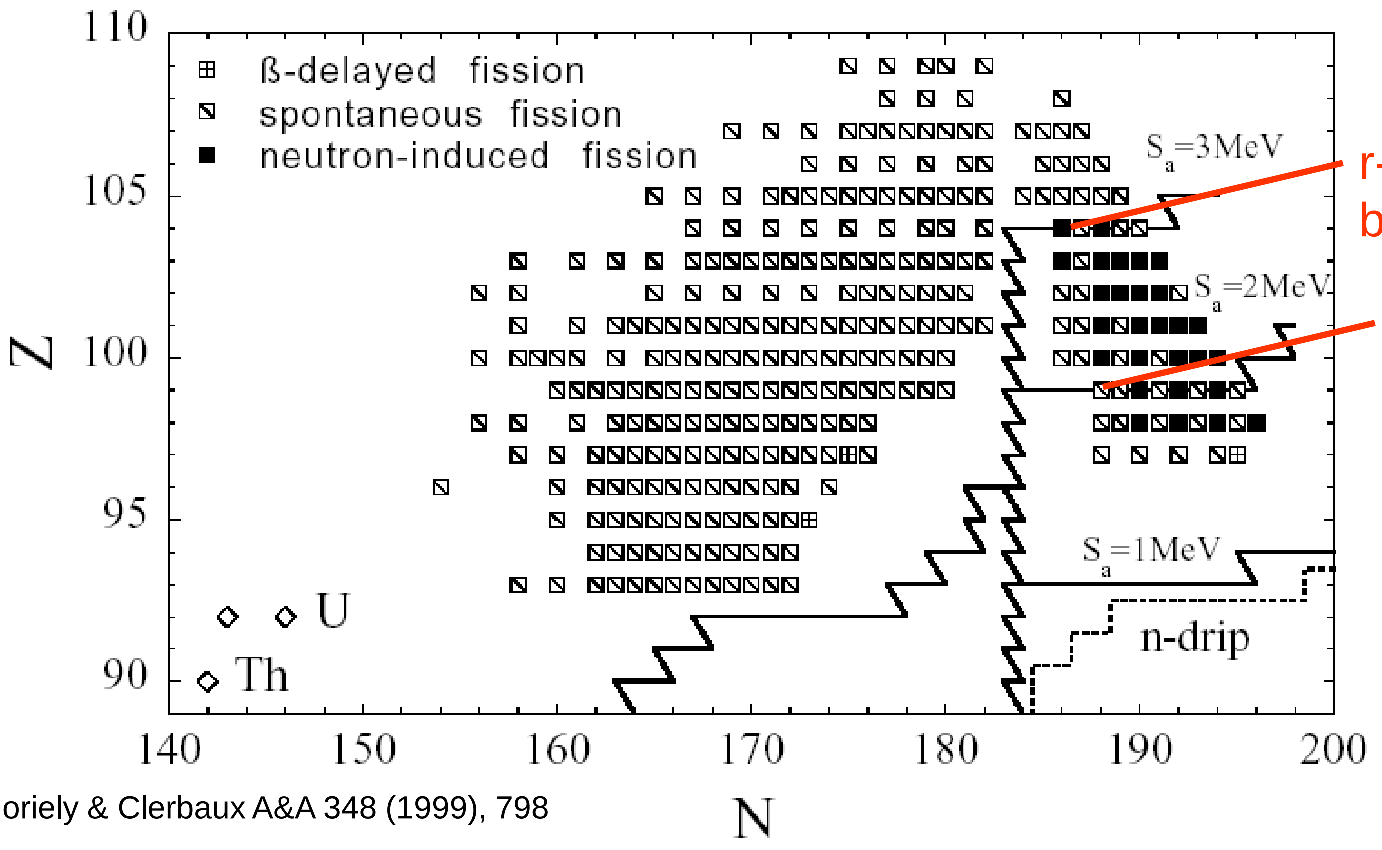
Shell quenching effect on masses/r-process



Shell quenching effect on masses/r-process



Endpoint of the r-process

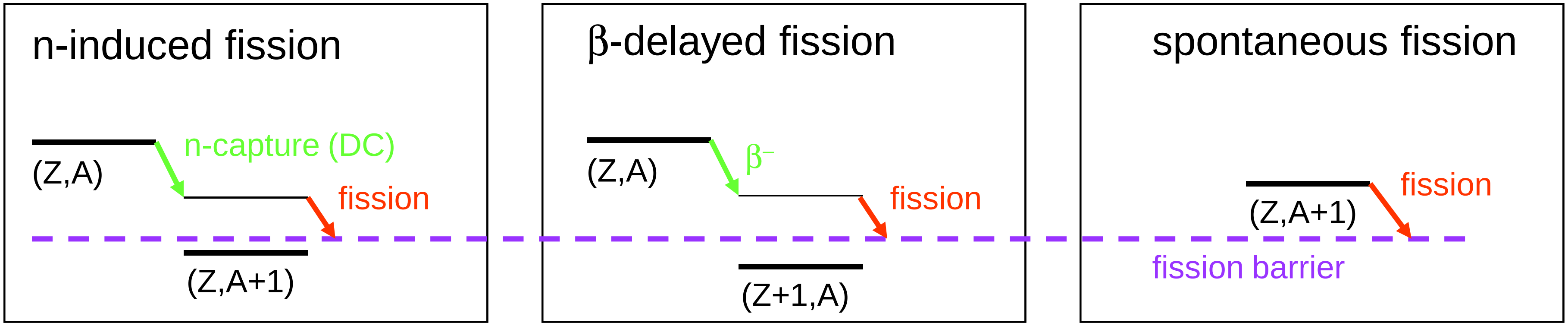


(Goriely & Clerbaux A&A 348 (1999), 798

r-process ended by n-induced fission

or spontaneous fission

(different paths for different conditions)



n-induced fission

(Z,A)

n-capture (DC)

fission

(Z,A+1)

β-delayed fission

(Z,A)

β⁻

fission

(Z+1,A)

spontaneous fission

(Z,A+1)

fission

fission barrier

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 !**

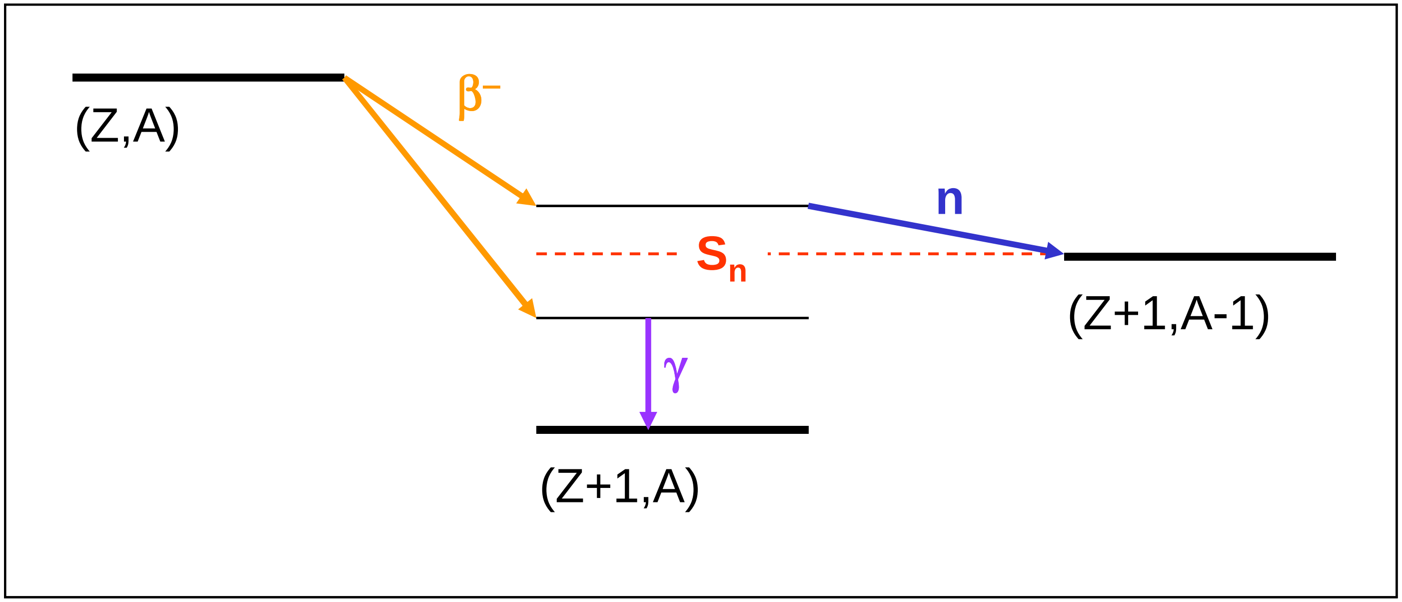
Note: the exact endpoint of the r-process and the degree and impact of fission are unknown because:

- 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 !)

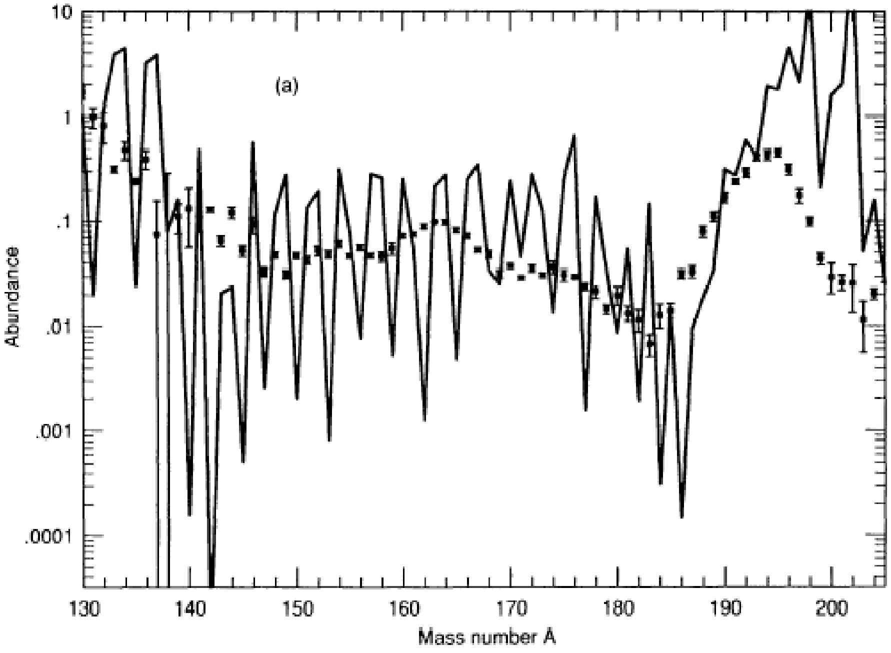
Effects: **during r-process**: **none** as neutrons get recaptured quickly

during freezeout

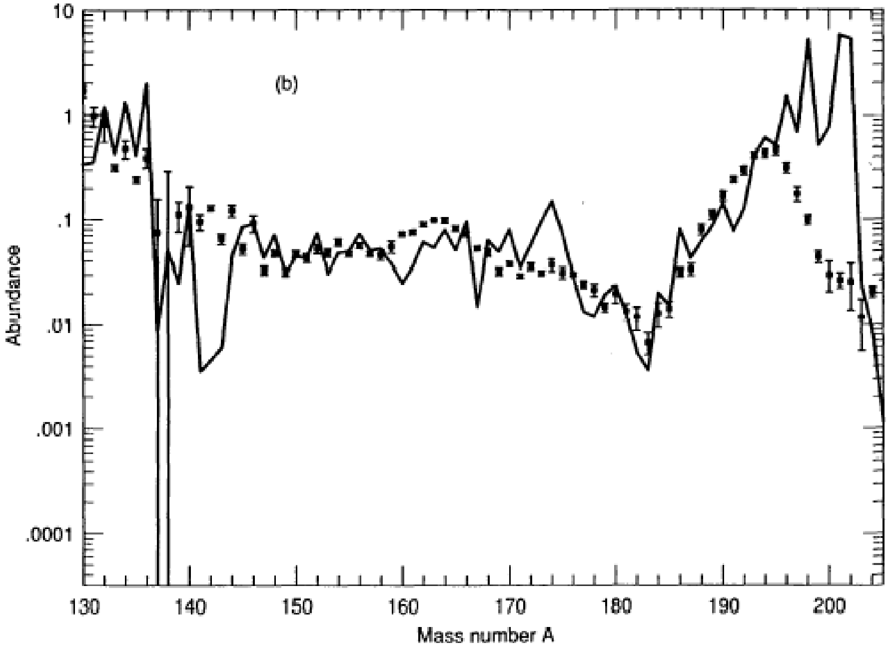
- **modification of final abundance**
- **late time neutron production (those get recaptured)**

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

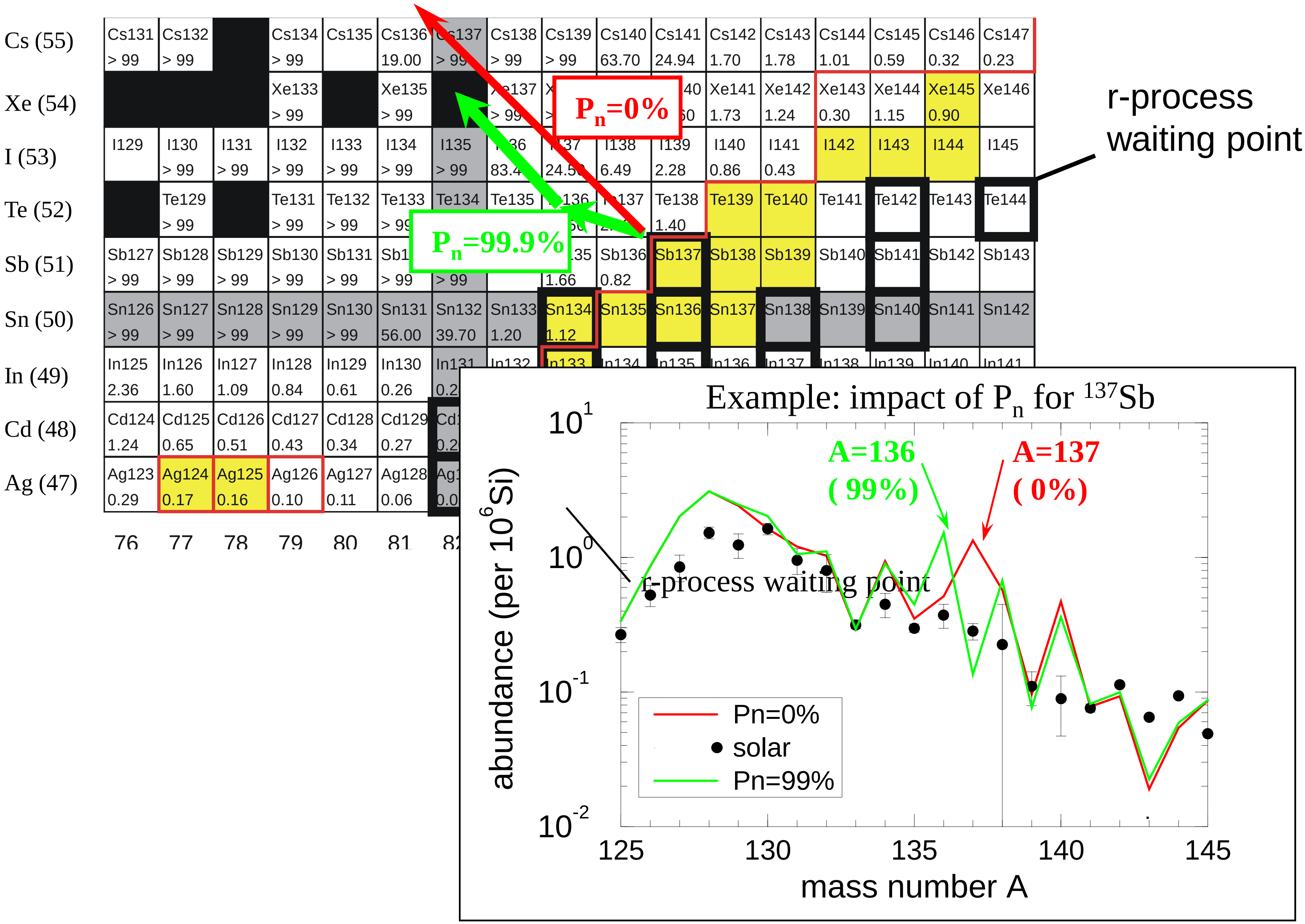
before β-decay



after β-decay



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



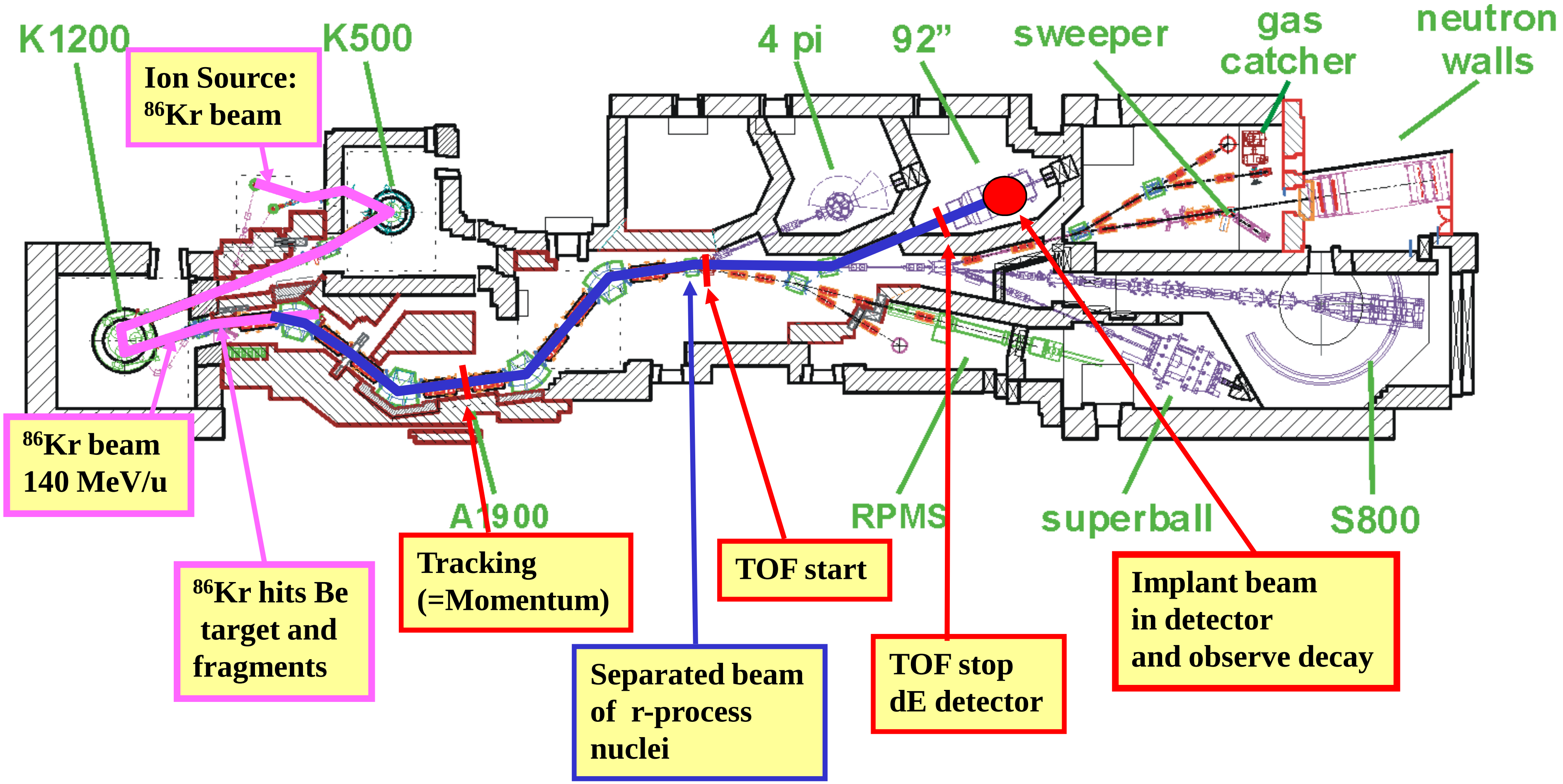
r-process waiting point

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)**
$N_A<\sigma v>$	**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

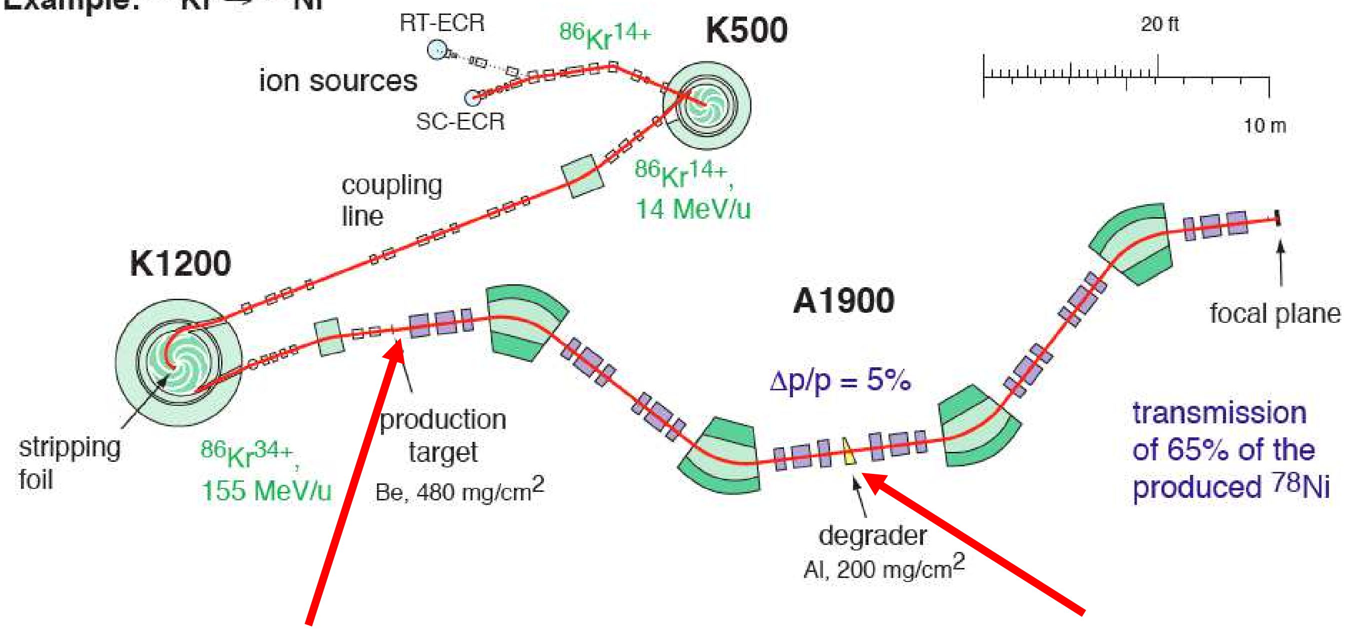
TOF start

TOF stop dE detector

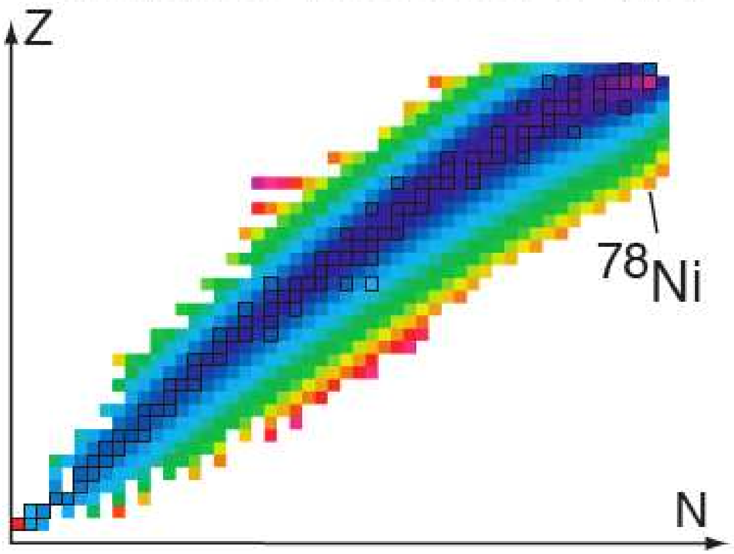
Implant beam in detector and observe decay

Fast beam fragmentation facility – allows event by event particle identification

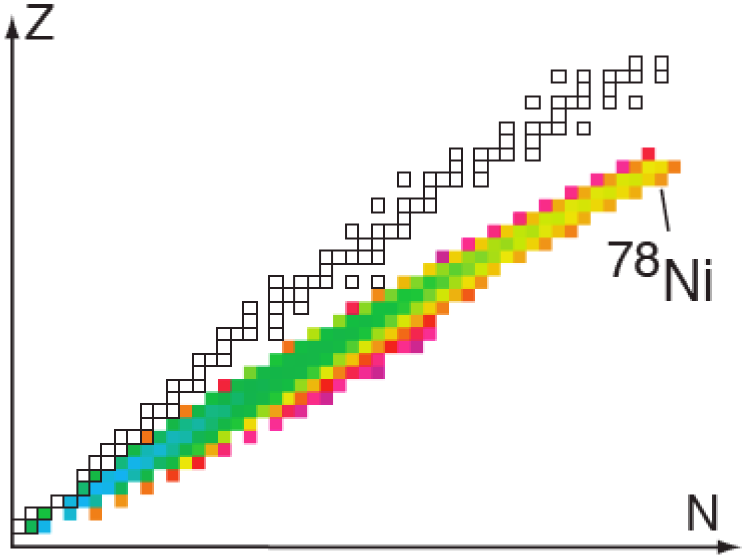
Example: ^{86}Kr → ^{78}Ni



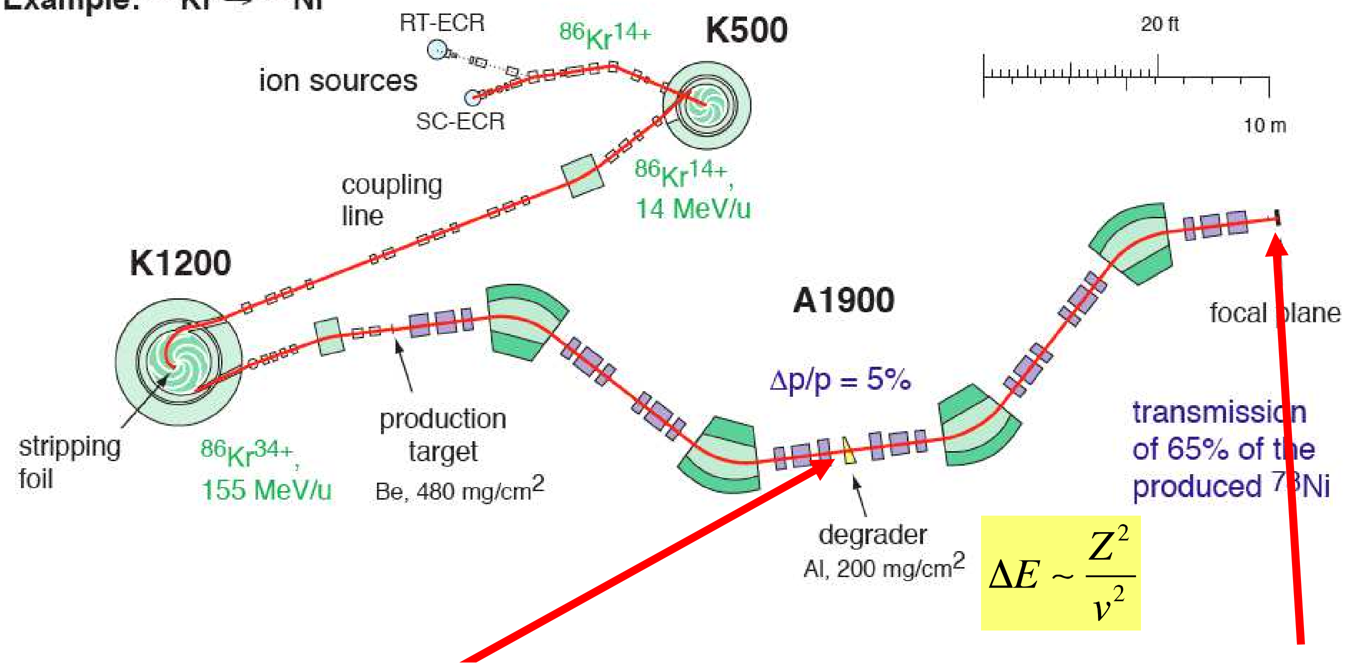
fragment yield after target



Fragment yield after Br selection



Example: ^{86}Kr → ^{78}Ni

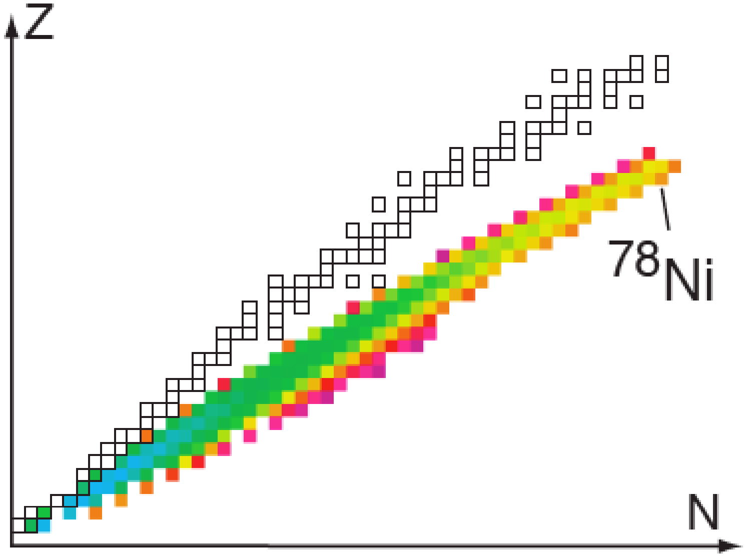


$\Delta p/p = 5\%$

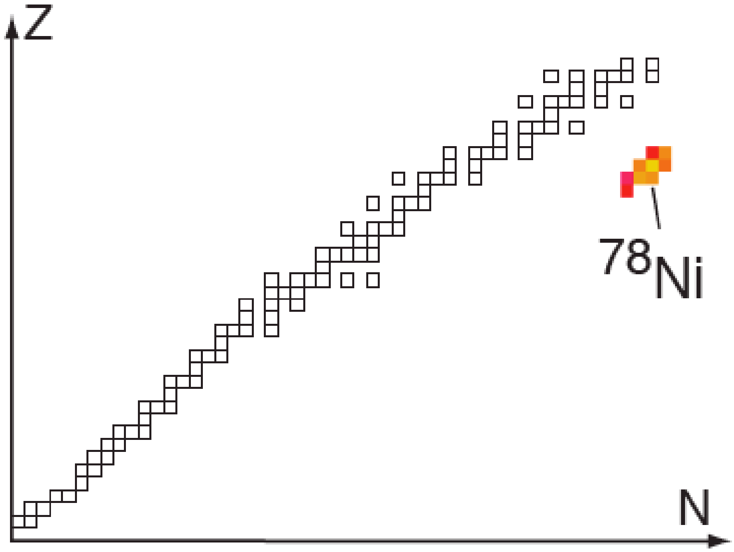
transmission of 65% of the produced ^{78}Ni

$$\Delta E \sim \frac{Z^2}{v^2}$$

Fragment yield after Br selection



fragment yield at focal plane



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

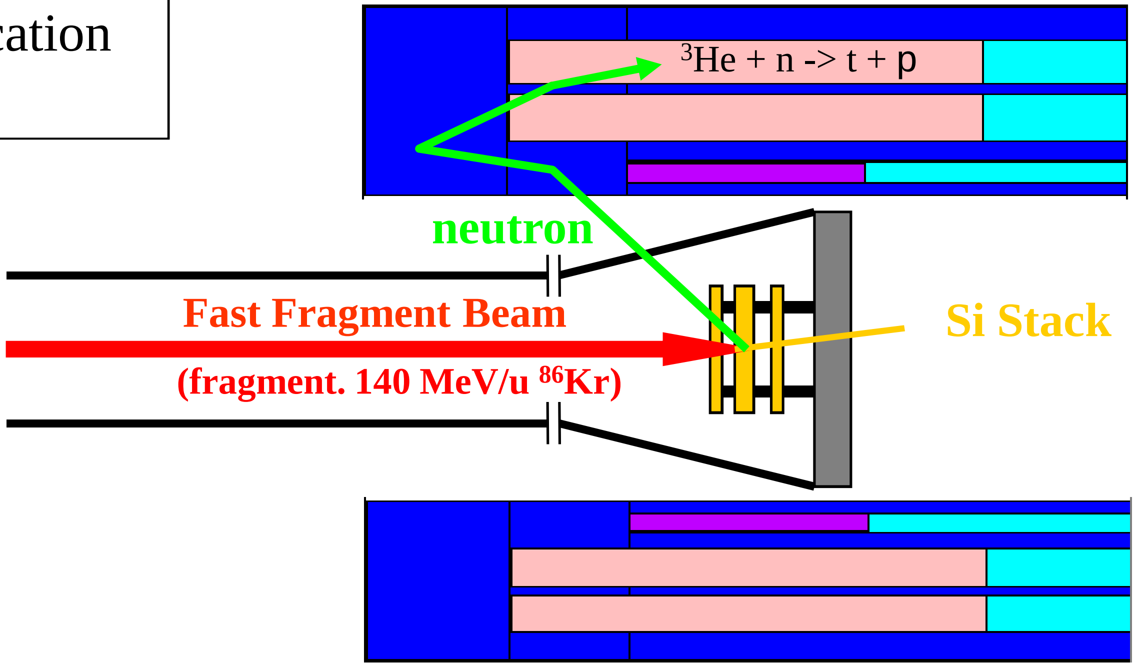
Measure:

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

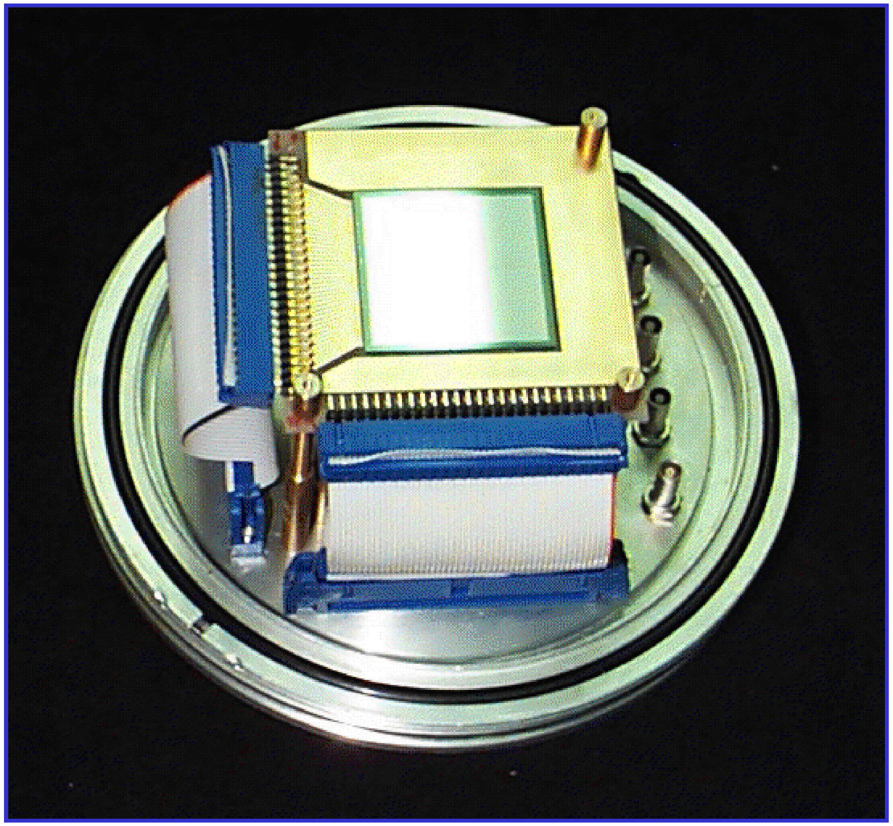
Detect:

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

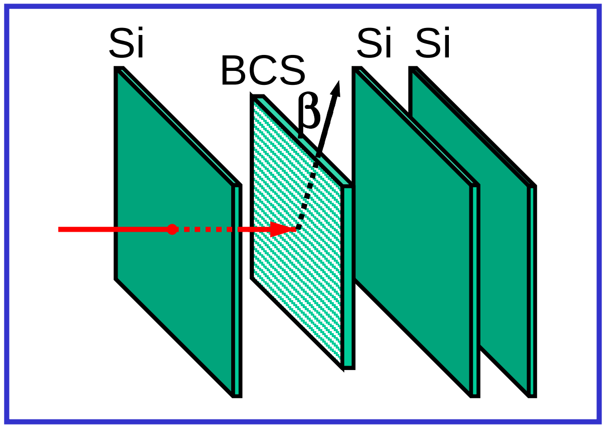
New NSCL Neutron detector NERO



NSCL BCS – Beta Counting System



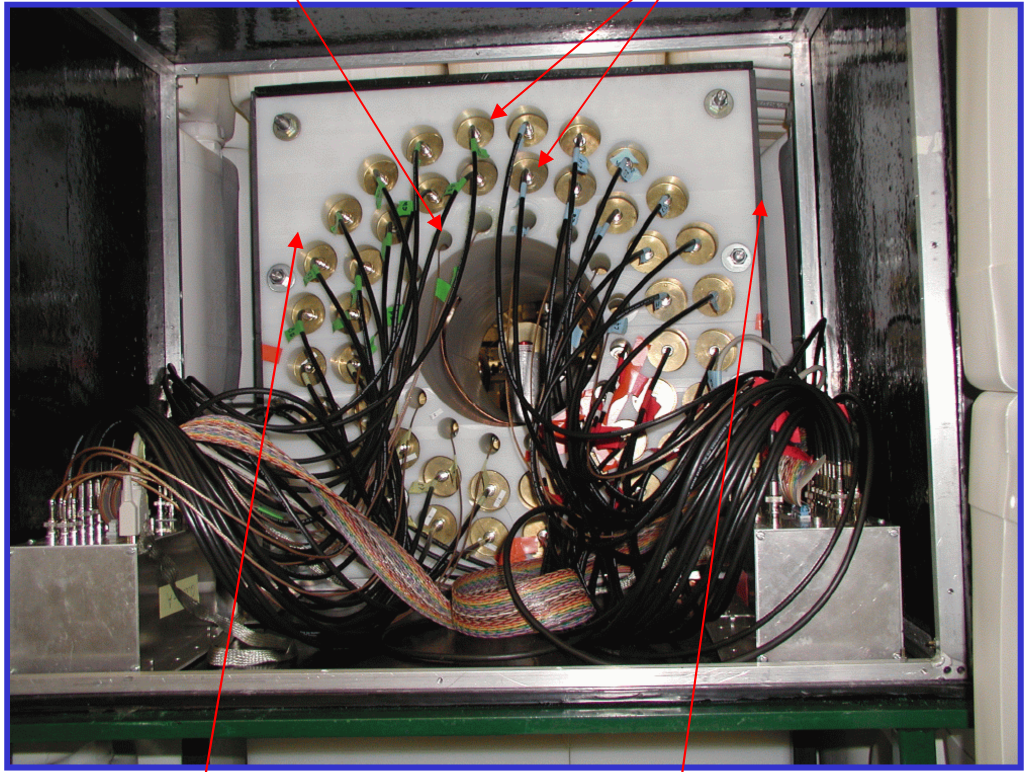
- 4 cm x 4 cm active area
- 1 mm thick
- 40-strip pitch in x and y dimensions ->1600 pixels



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)



^{3}He Proportional Counters

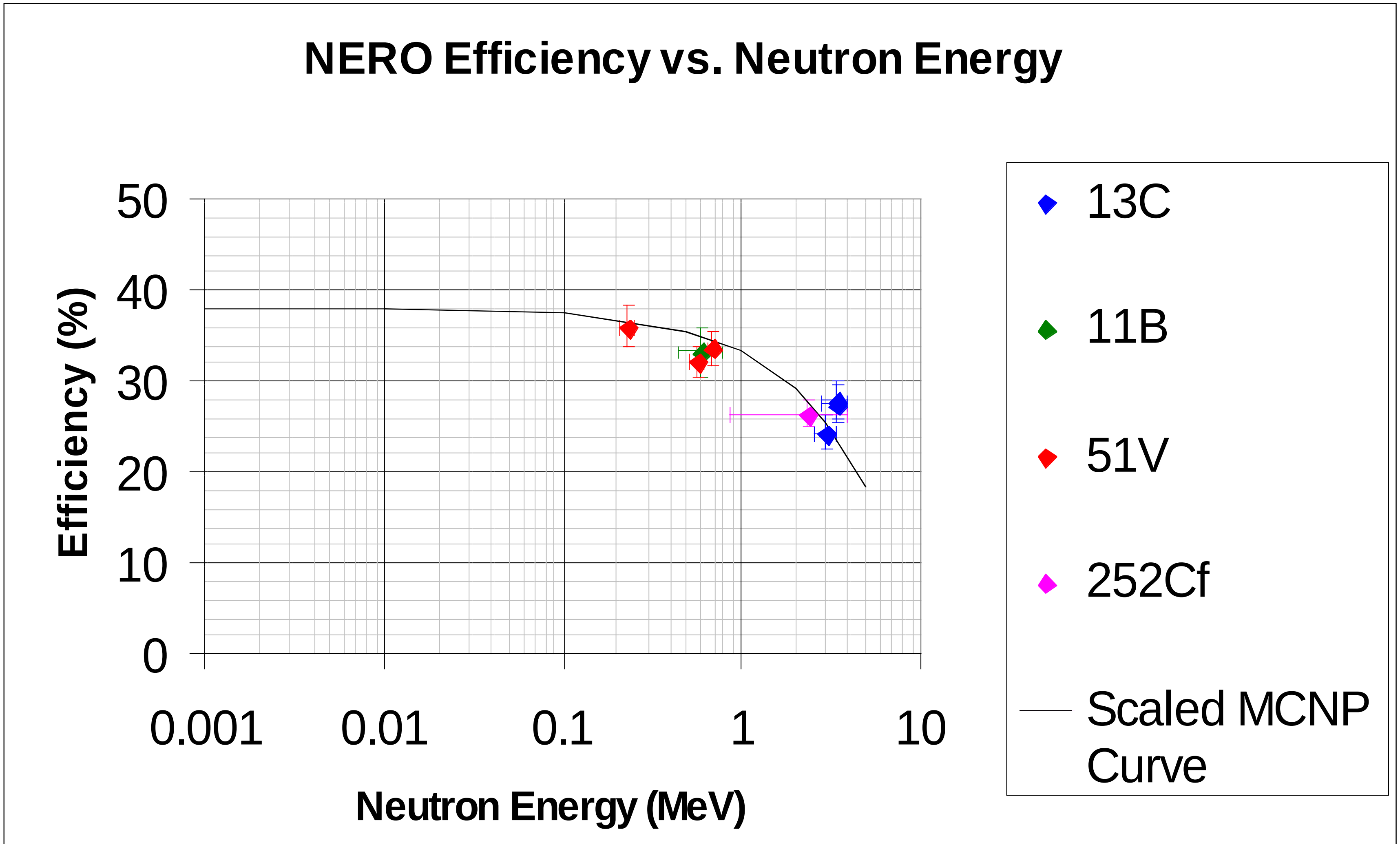
BF_3 Proportional Counters

Polyethylene Moderator

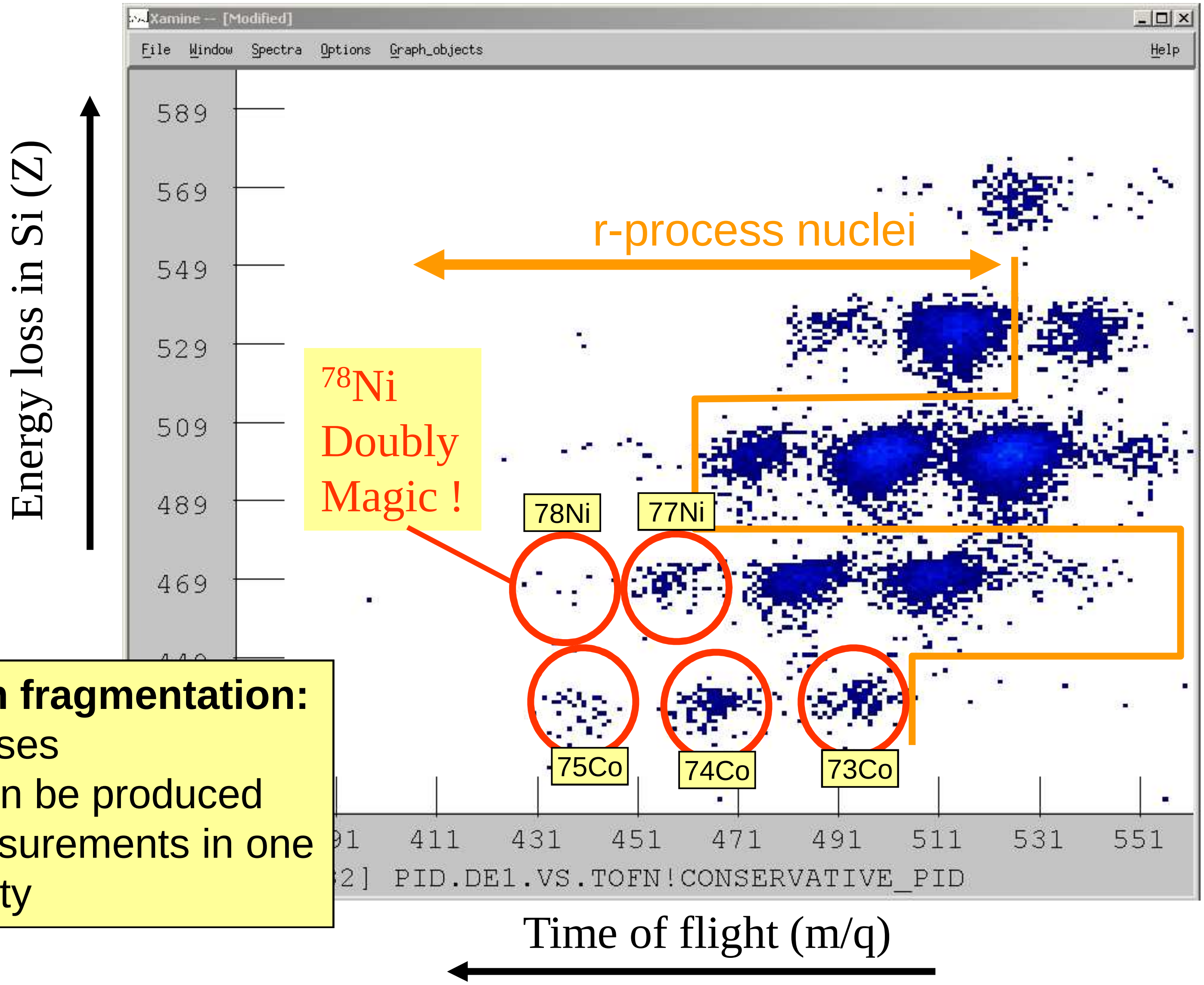
Boron Carbide Shielding

NERO Assembly

Nero efficiency



Particle Identification



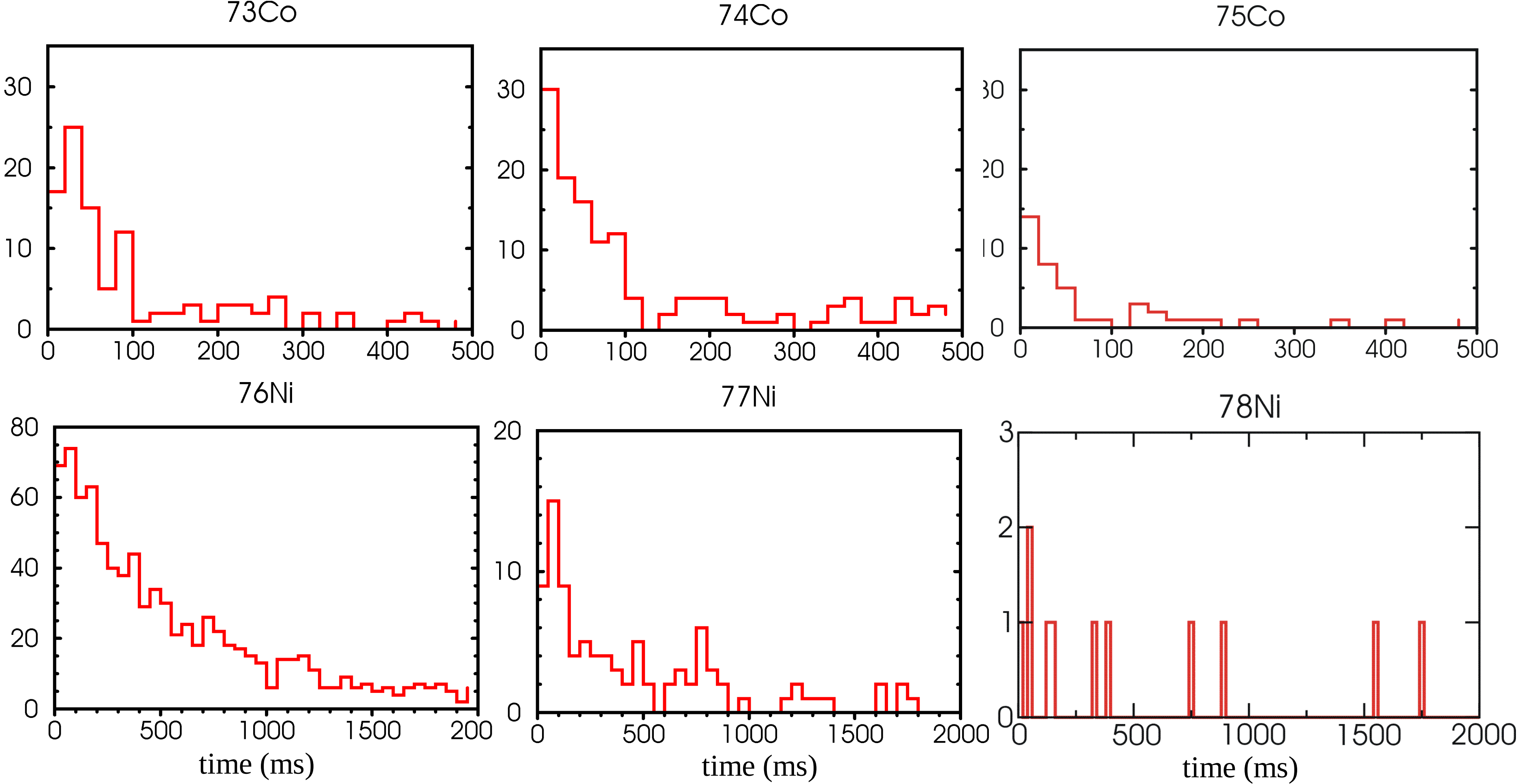
PID.DE1.VS.TOFN!CONSERVATIVE_PID

^{78}Ni
Doubly
Magic !

Fast RIB from fragmentation:

- no decay losses
- any beam can be produced
- multiple measurements in one
- high sensitivity

Decay data



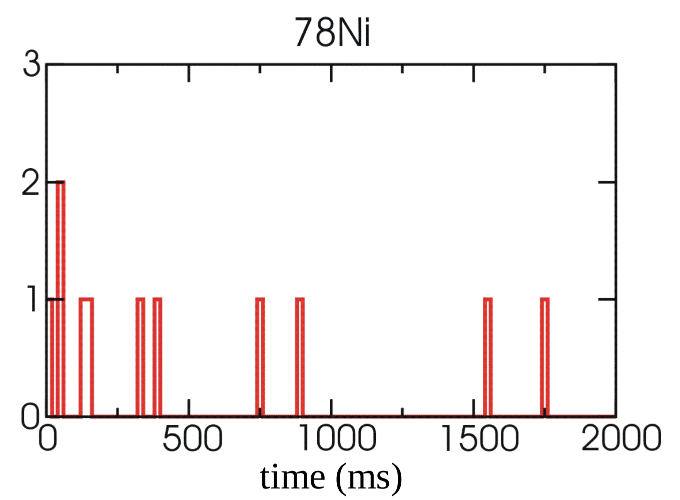
<u>Fast radioactive beams:</u>
- No decay losses
- Rates as low as 1/day useful !
- Mixed beam experiments easy

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

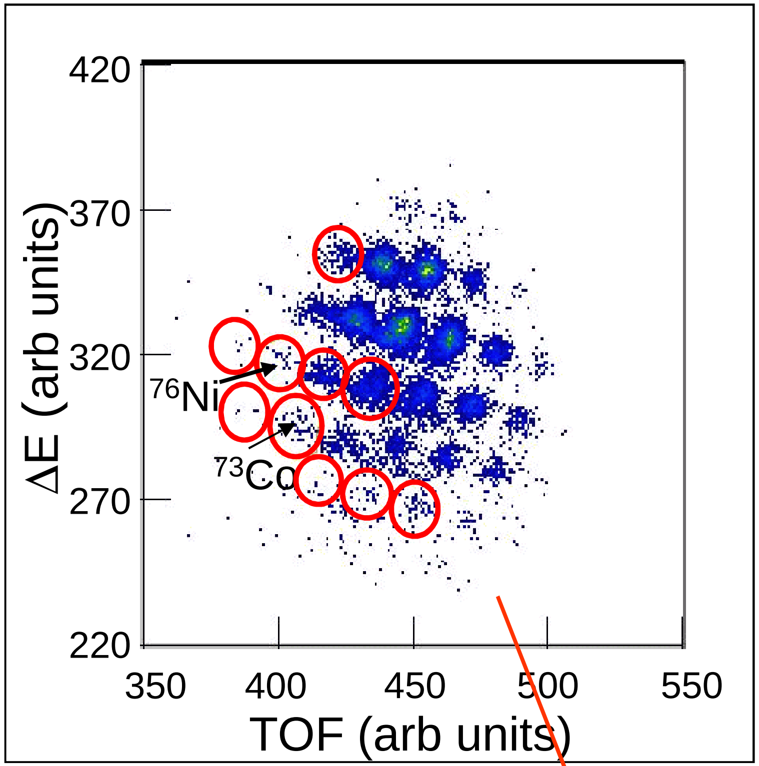
Result for half-life:
110 $^{+100}_{-60}$ ms

Compare to theoretical estimate used:470 ms

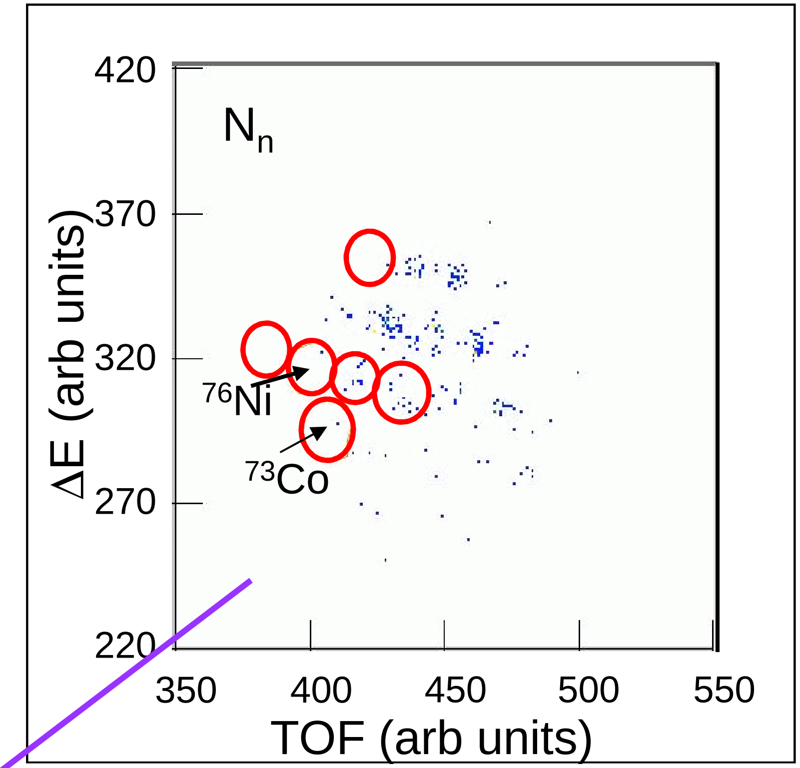
→ Acceleration of the entire r-process
→ Models need to be adjusted to explain observed abundance distribution

Neutron Data

Nuclei with decay detected



With neutron in addition



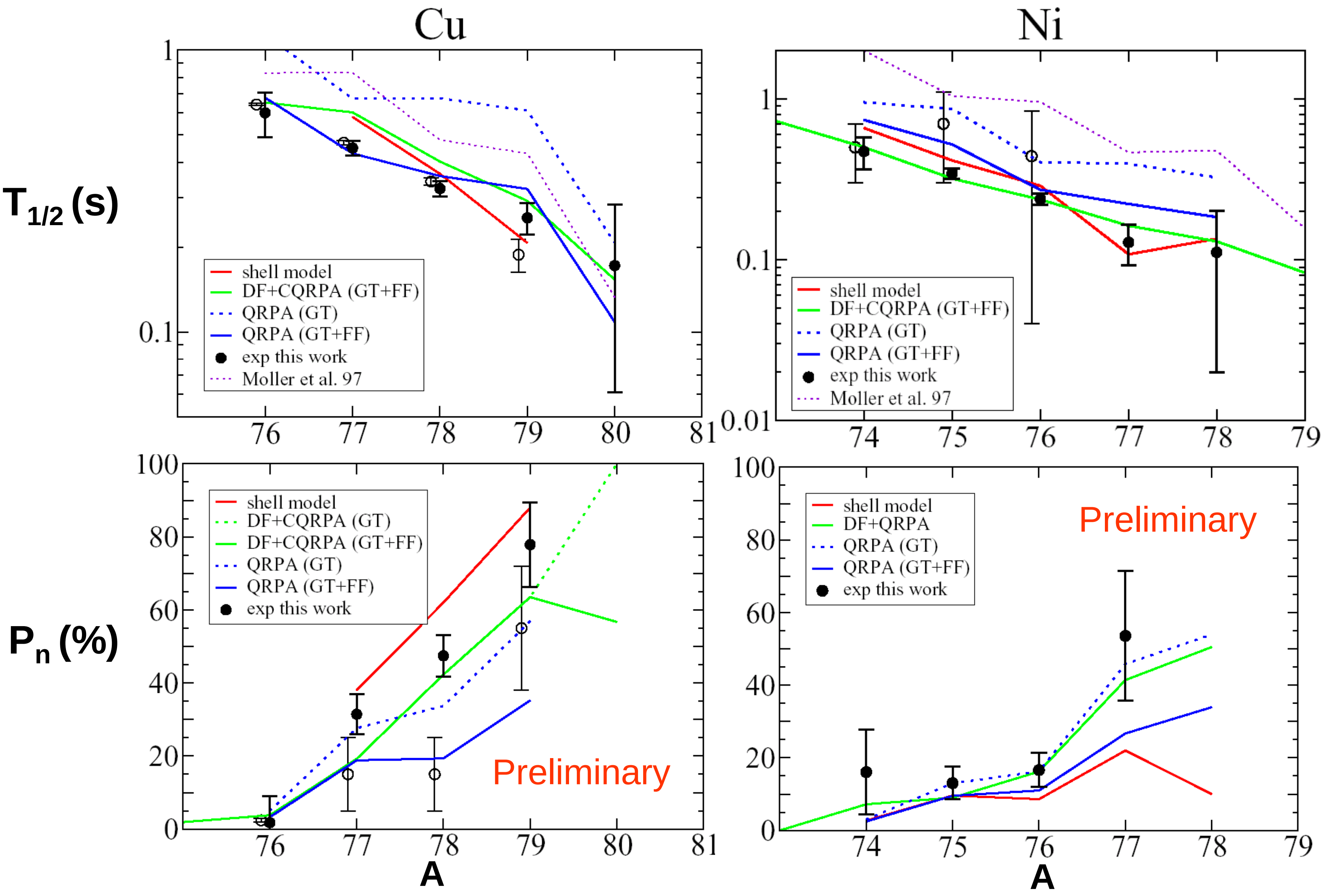
$$P_n = \frac{N_n}{N_\beta \varepsilon_n}$$

neutron detection efficiency

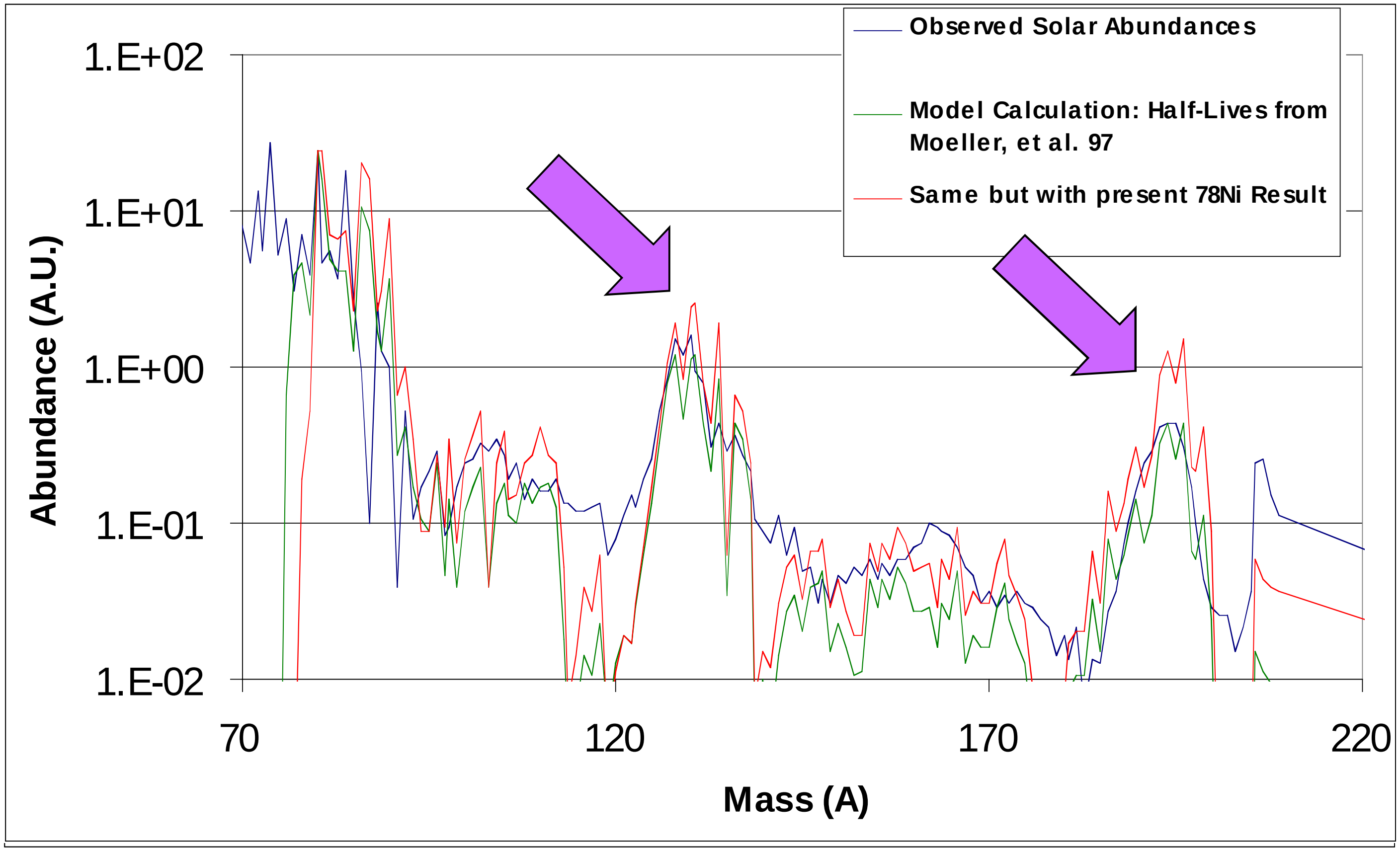
(neutrons seen/neutrons emitted)

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

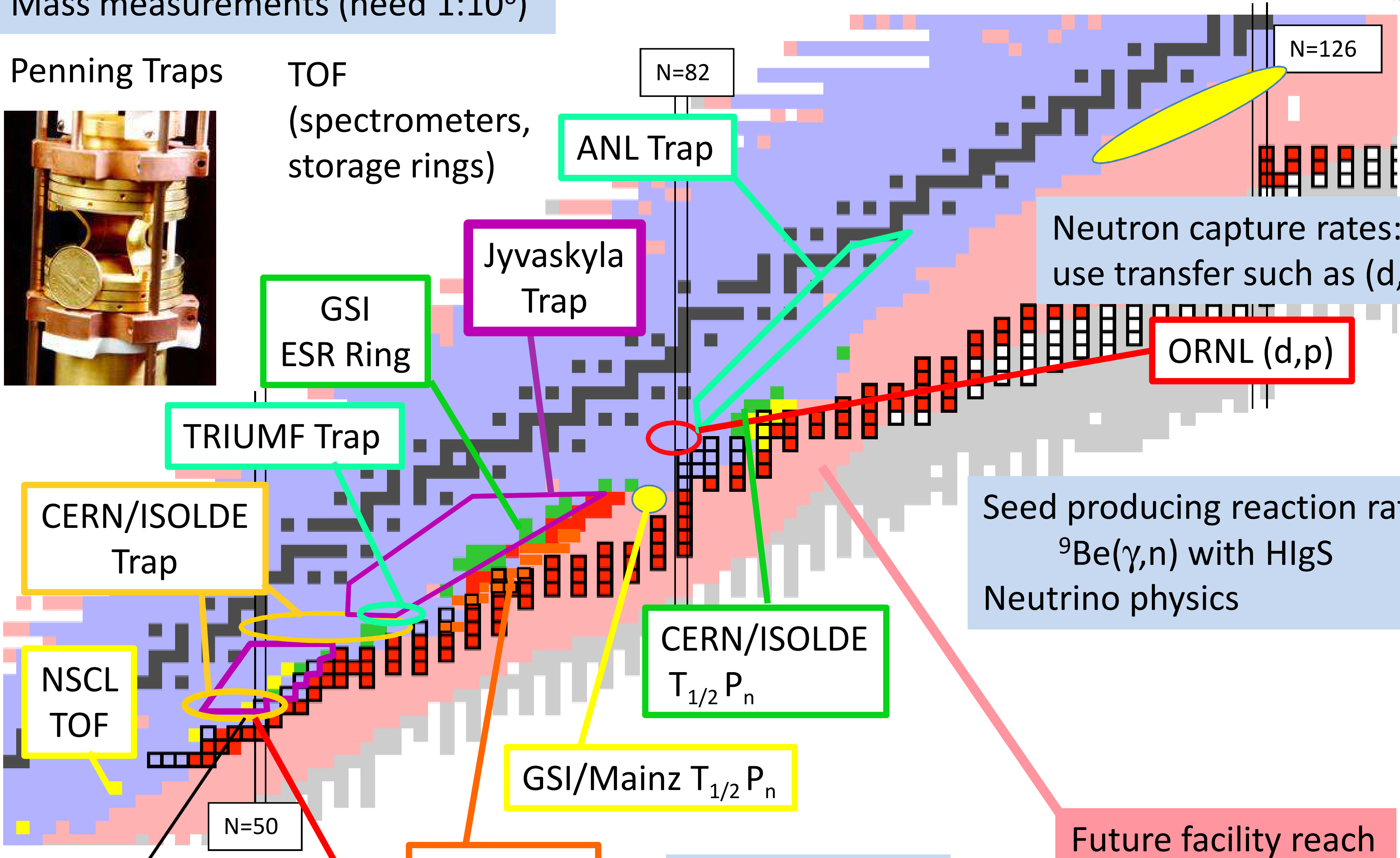
→ remainig discrepancies – nuclear physics ? Environment ? Neutrinos ? Need more data

Recent r-process related experiments

Mass measurements (need 1:10^6)

Penning Traps

TOF
(spectrometers,
storage rings)



ANL Trap

Jyvaskyla
Trap

GSI
ESR Ring

TRIUMF Trap

CERN/ISOLDE
Trap

NSCL
TOF

ORNL (d,p)

CERN/ISOLDE
$T_{1/2}$ P_n

GSI/Mainz $T_{1/2}$ P_n

RIKEN $T_{1/2}$

ORNL $T_{1/2}$ P_n

NSCL $T_{1/2}$ P_n

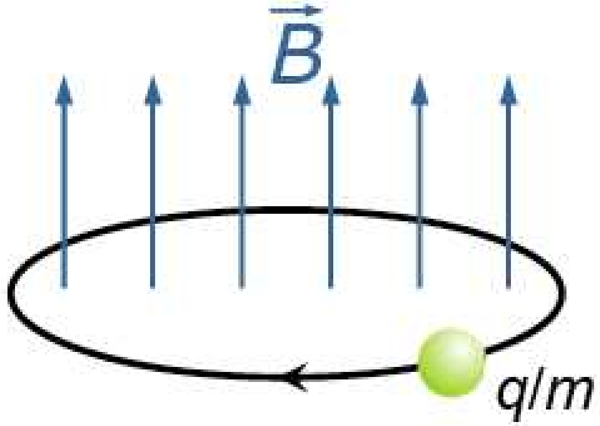
Neutron capture rates:
use transfer such as (d,p)

Seed producing reaction rates:
^{9}Be(γ,n) with HIgS
Neutrino physics

β-decay studies:
$T_{1/2}$, P_n

Future facility reach
(FRIB)

Penning Trap Mass Meausrements (stopped beams)

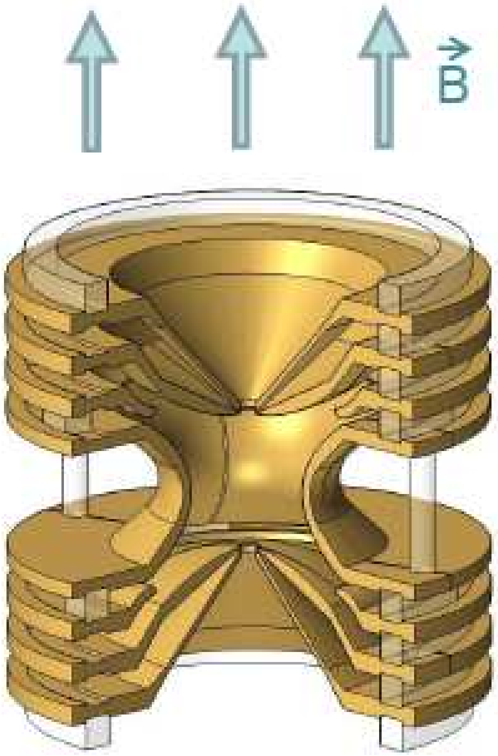


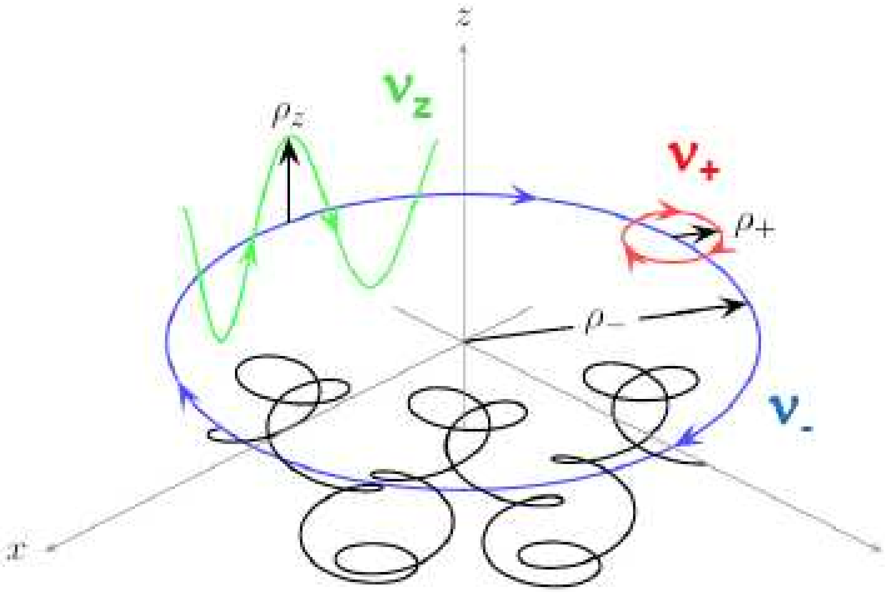
Cyclotron frequency:

$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

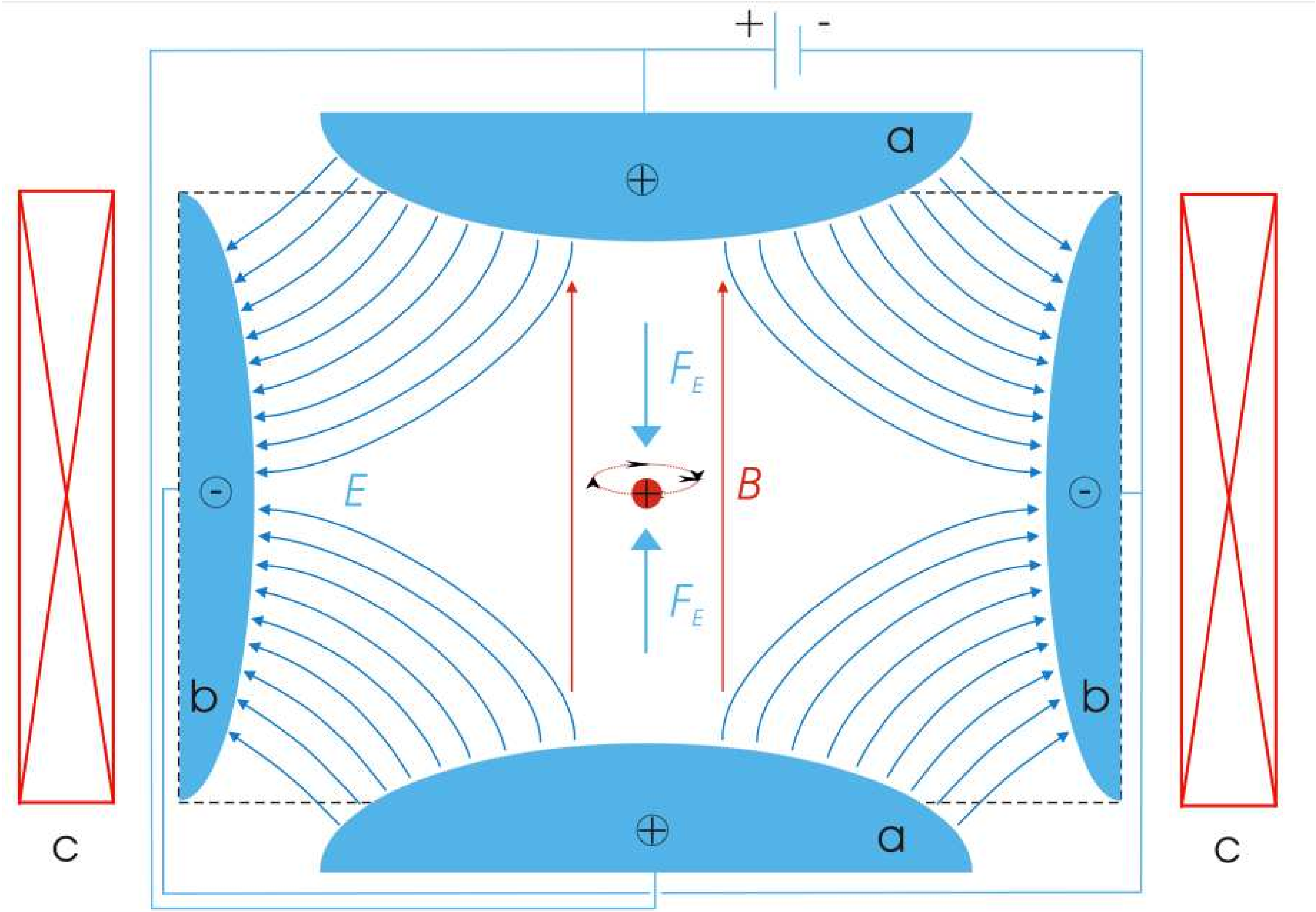
PENNING trap

- Strong homogen. magnetic field
- Weak electric 3D quadrupole field

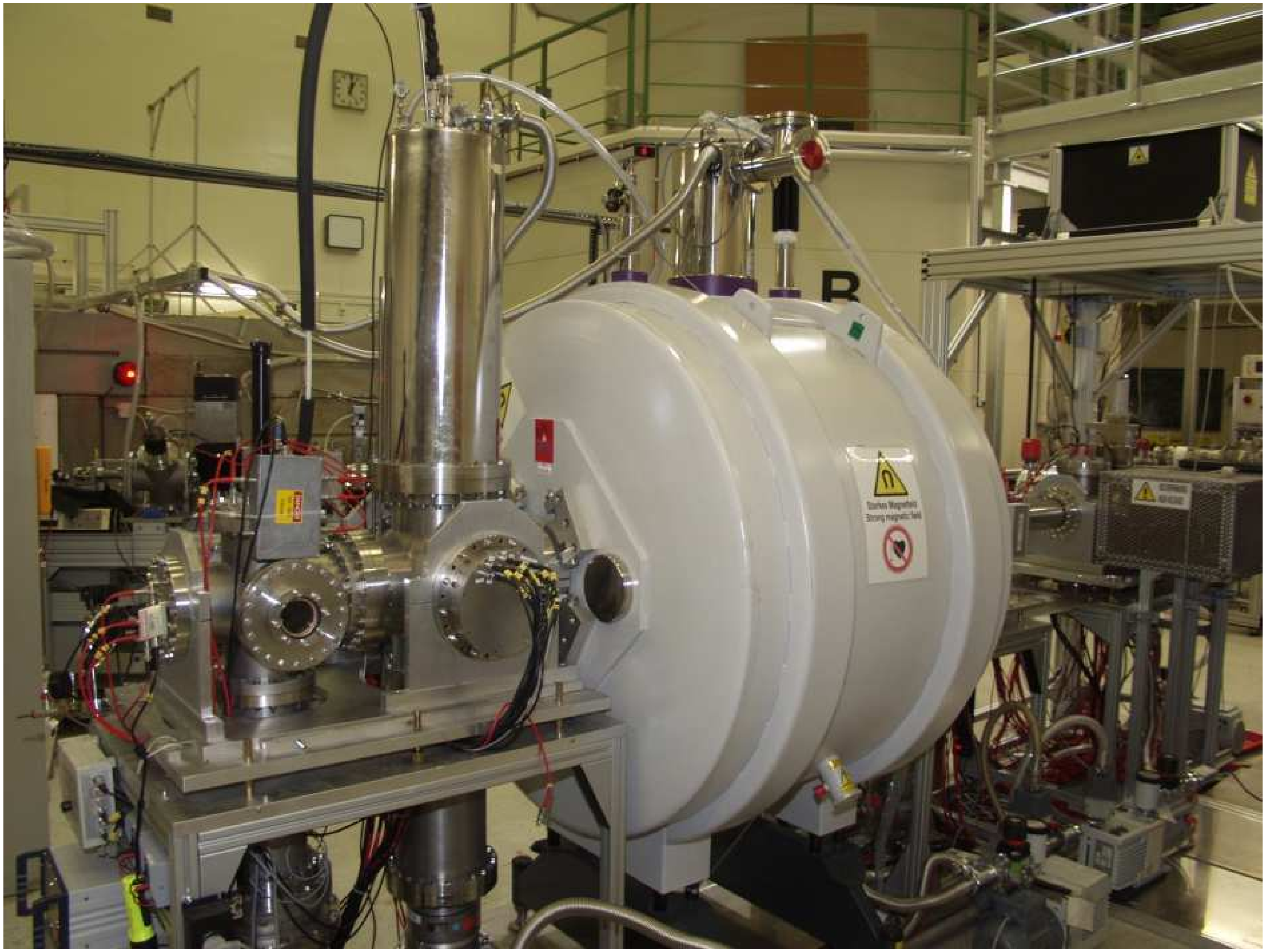




Typical freq.
q = e
m = 100 u
B = 6 T
$\Rightarrow$ $f_- \approx$ 1kHz
$f_+ \approx$ 1MHz

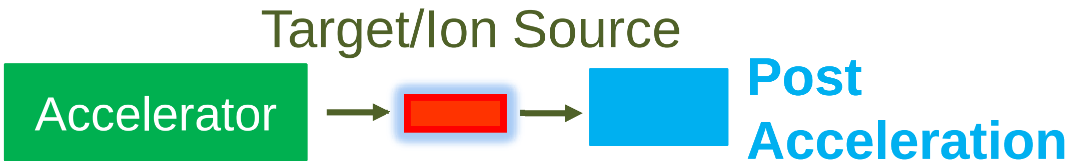

+
-
a
⊕
⊖
E
F_E
B
F_E
⊖
b
b
c
⊕
a
c

Example: TRIGA Penning Trap (Mainz)



Rare Isotope Production Techniques: Uniqueness of FRIB

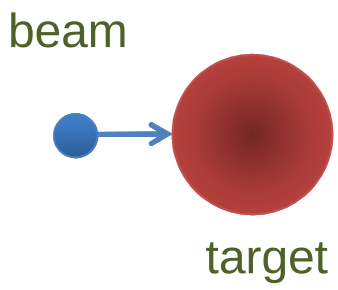
- Target spallation and fragmentation by light ions (ISOLDE/HRIBF/TRIUMF)



Target/Ion Source

Accelerator

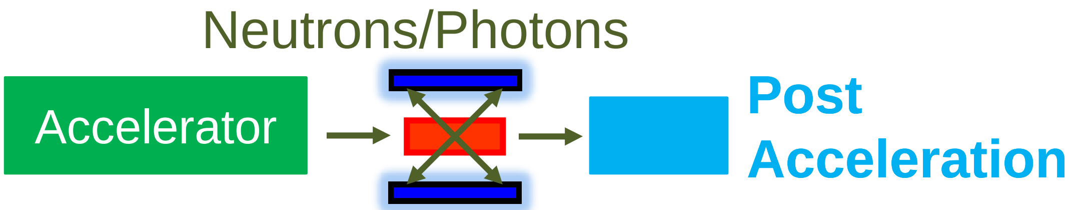
Post Acceleration



beam

target

- Neutron induced fission (2-step target) (SPIRAL2/TRIUMF)

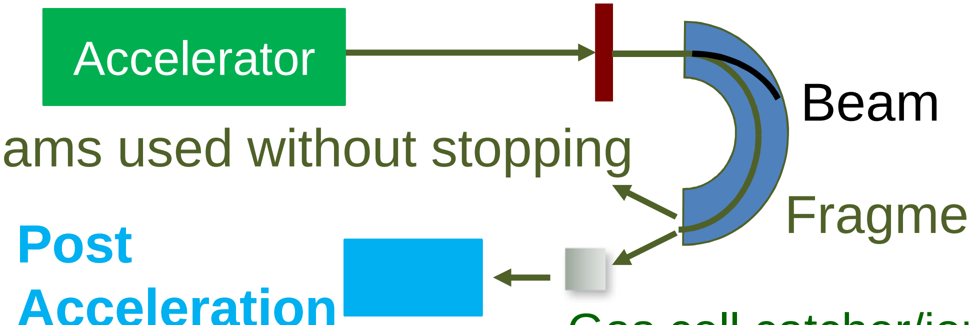


Neutrons/Photons

Accelerator

Post Acceleration

- In-flight Separation following projectile fragmentation/fission (RIKEN,FAIR,FRIB)



Accelerator

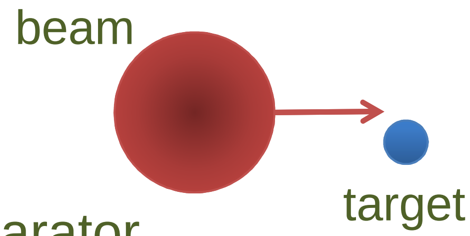
Beam

Beams used without stopping

Fragment Separator

Post Acceleration

Gas cell catcher/ion source

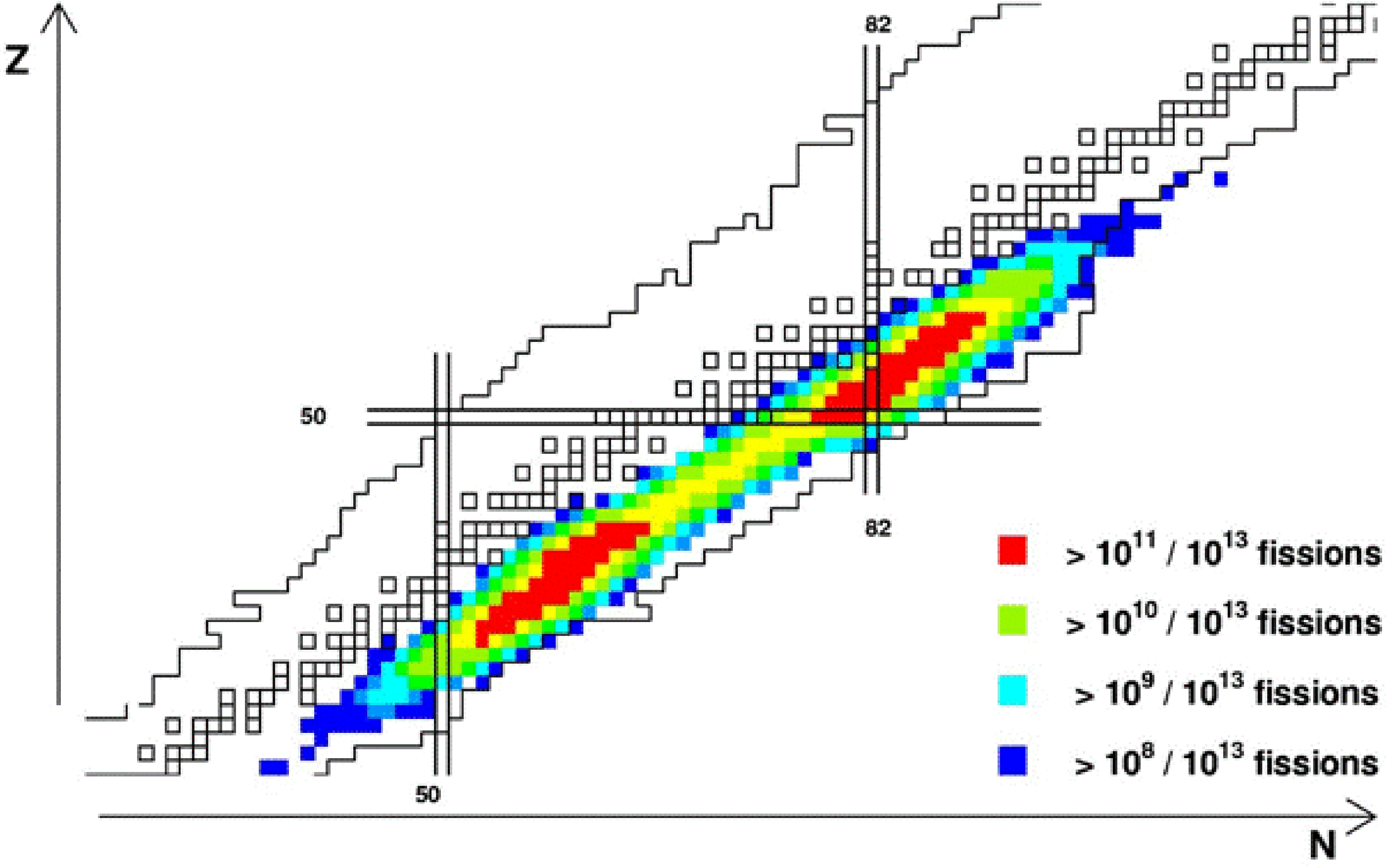


beam

target

Fission yields

SPIRAL2 projected production



NSCL and FRIB Laboratory

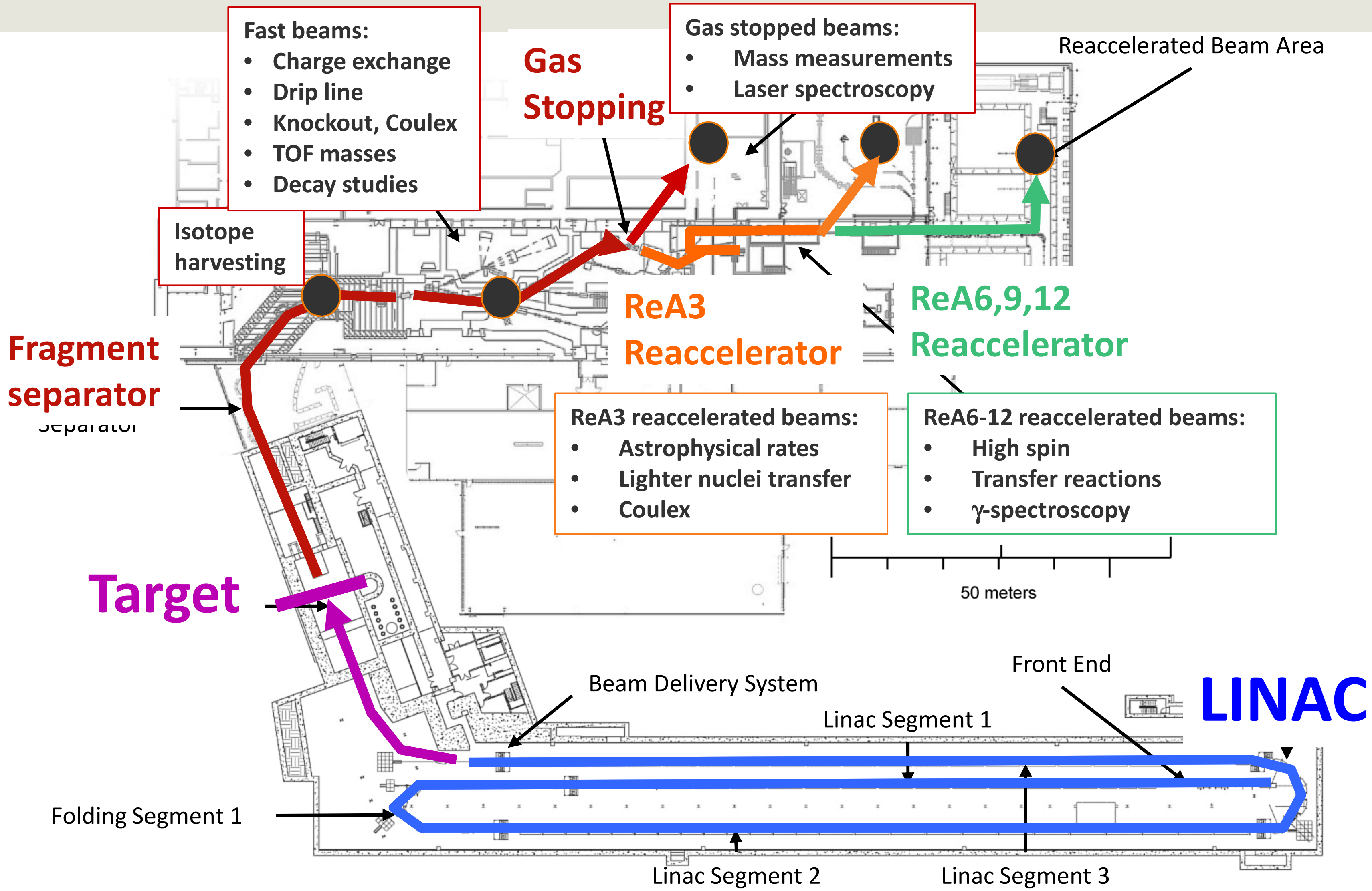
506 employees, incl. 36 faculty, 59 graduate and 71 undergraduate students (as of August 6, 2012)
NSCL user group is part of the FRIB User Organization (over 1,250 members)

- FRIB will be the world's premier rare isotope user facility, a national user facility for the U.S. Department of Energy Office of Science

Enabling over 1250 users to do world-leading rare-isotope science

FRIB Layout

example: nuclear astrophysics experiment



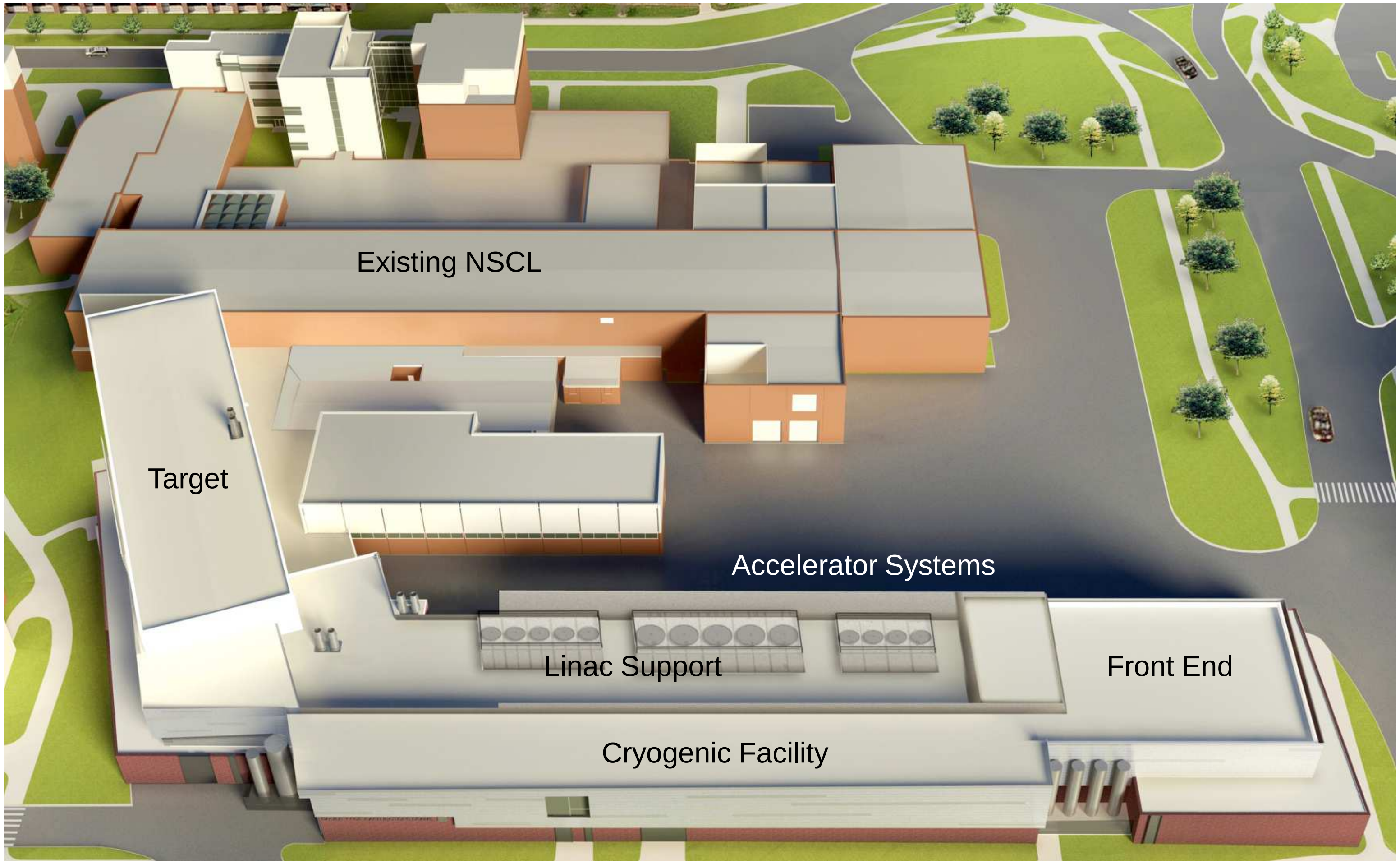
Fast beams:
- Charge exchange
- Drip line
- Knockout, Coulex
- TOF masses
- Decay studies

Gas stopped beams:
- Mass measurements
- Laser spectroscopy

ReA3 reaccelerated beams:
- Astrophysical rates
- Lighter nuclei transfer
- Coulex

ReA6-12 reaccelerated beams:
- High spin
- Transfer reactions
- γ-spectroscopy

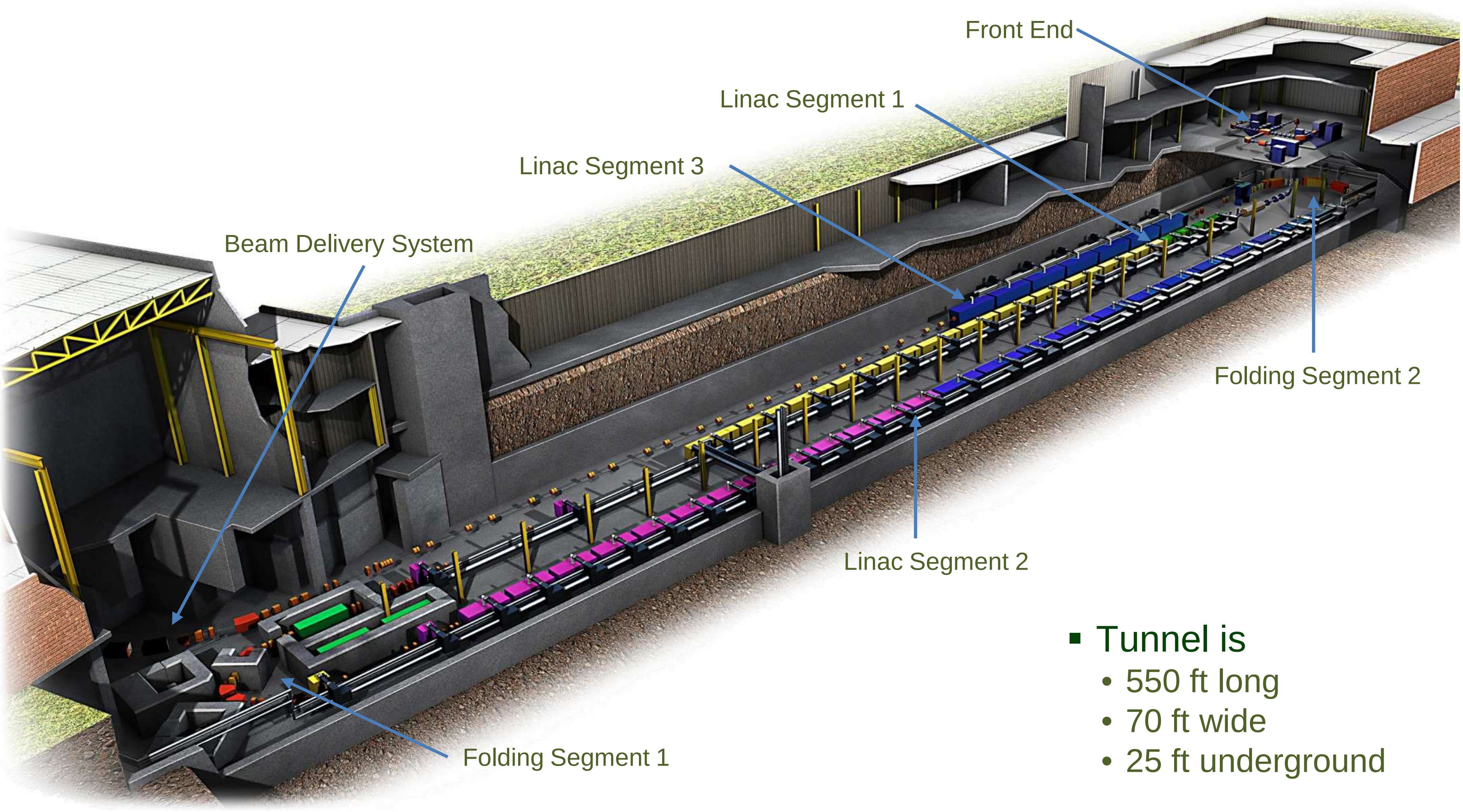
Overview of the FRIB Facility



Rendered Perspective

Southeast View

Driver Linear Accelerator

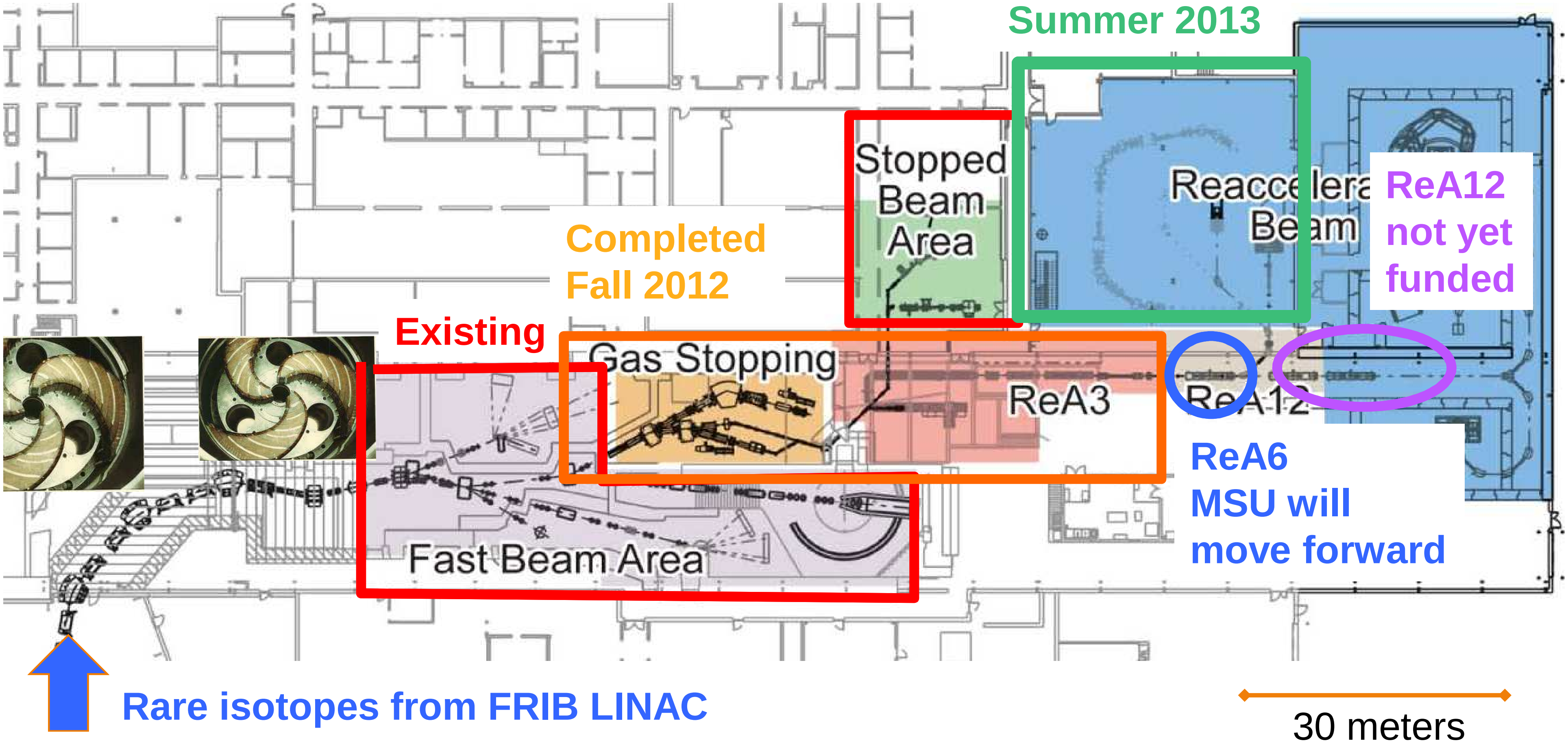


- Tunnel is
  - 550 ft long
  - 70 ft wide
  - 25 ft underground

Overview FRIB Reaccelerators, and Experimental Stations

All buildings exist

ReA3 Exp Completed Summer 2013



Completed Fall 2012

Existing

ReA12 not yet funded

ReA6 MSU will move forward

Rare isotopes from FRIB LINAC

30 meters

FRIB On Track, Moving Toward Construction

Project Start	6/2009
Conceptual design	completed 9/2010 (CD-1)
Preliminary design • CD-2/3A (civil) review in April 2012	2010-2012
Site prep • DOE approves pilings for earth ret.	2012
Civil construction begins • Pending DOE approval	2012
Final design • CD-3B (technical) review in 2013	2012-2013
Technical construction begins	2013
Early project completion	2019 (completion 2021)
Total project cost	$680M ($585 Federal)

~140M committed

NSCL/FRIB current view

Major investments have been made – construction underway

Why is it called FRIB ???

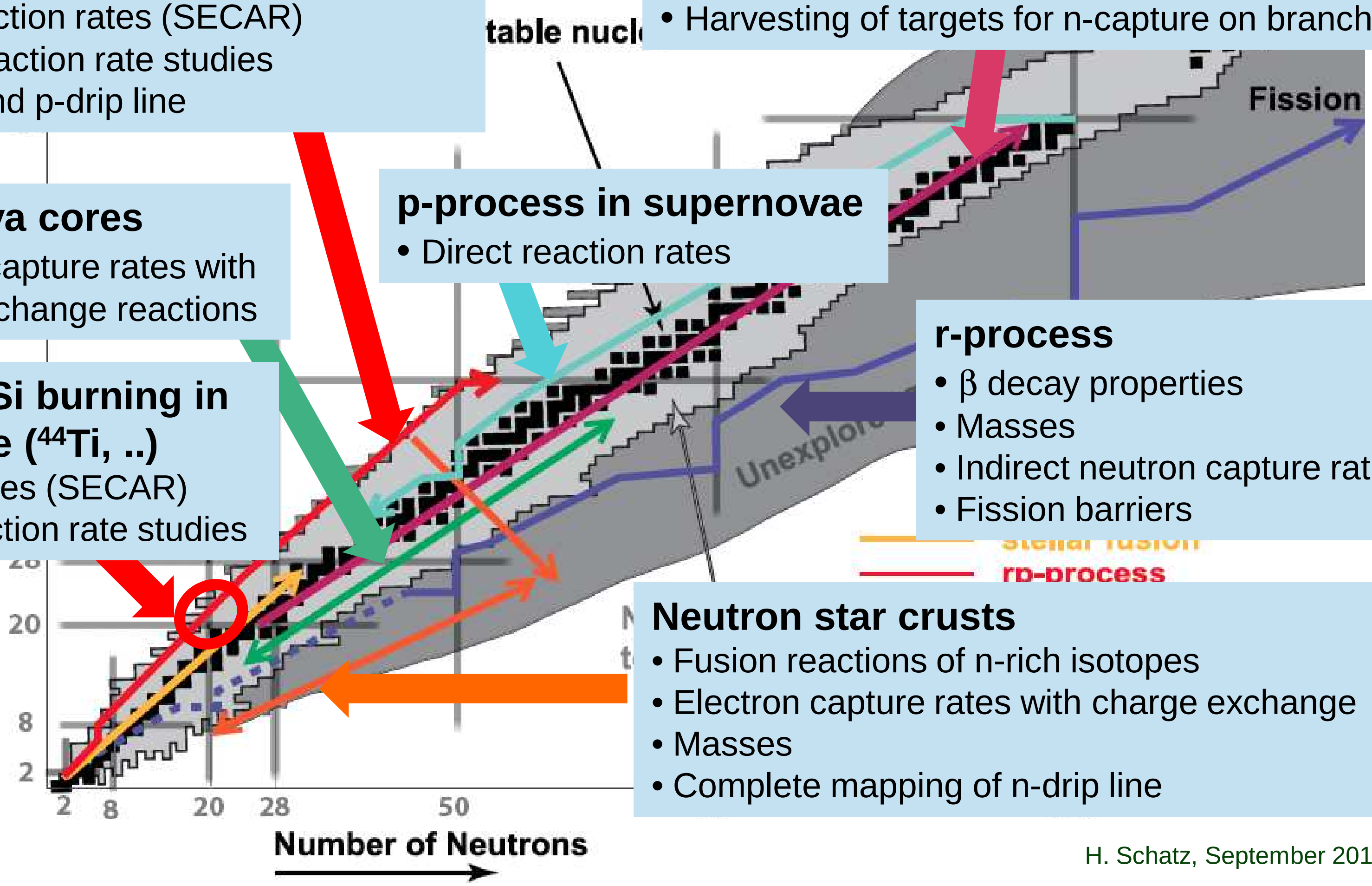
1. frib 17 up, 6 down_

birf spelled backwards

2. frib 4 up, 12 down_

A word that can be used to describe happiness, joy etc. Commonly replaces 'wow', 'cool' or 'great'.

FRIB: a key instrument for nuclear astrophysics



rp-process in X-ray bursts/Novae/Supernovae
- Direct reaction rates (SECAR)
- Indirect reaction rate studies
- Masses and p-drip line

s-process in AGB stars
- Harvesting of targets for n-capture on branchpoints

Supernova cores
- Electron capture rates with charge exchange reactions

p-process in supernovae
- Direct reaction rates

r-process
- β decay properties
- Masses
- Indirect neutron capture rate studies
- Fission barriers

Explosive Si burning in supernovae (^{44}Ti, ..)
- Reaction rates (SECAR)
- Indirect reaction rate studies

Neutron star crusts
- Fusion reactions of n-rich isotopes
- Electron capture rates with charge exchange
- Masses
- Complete mapping of n-drip line

Rare isotopes are common in many astrophysical scenarios
FRIB is critical to address a broad range of astrophysics questions

Overview of common r process models

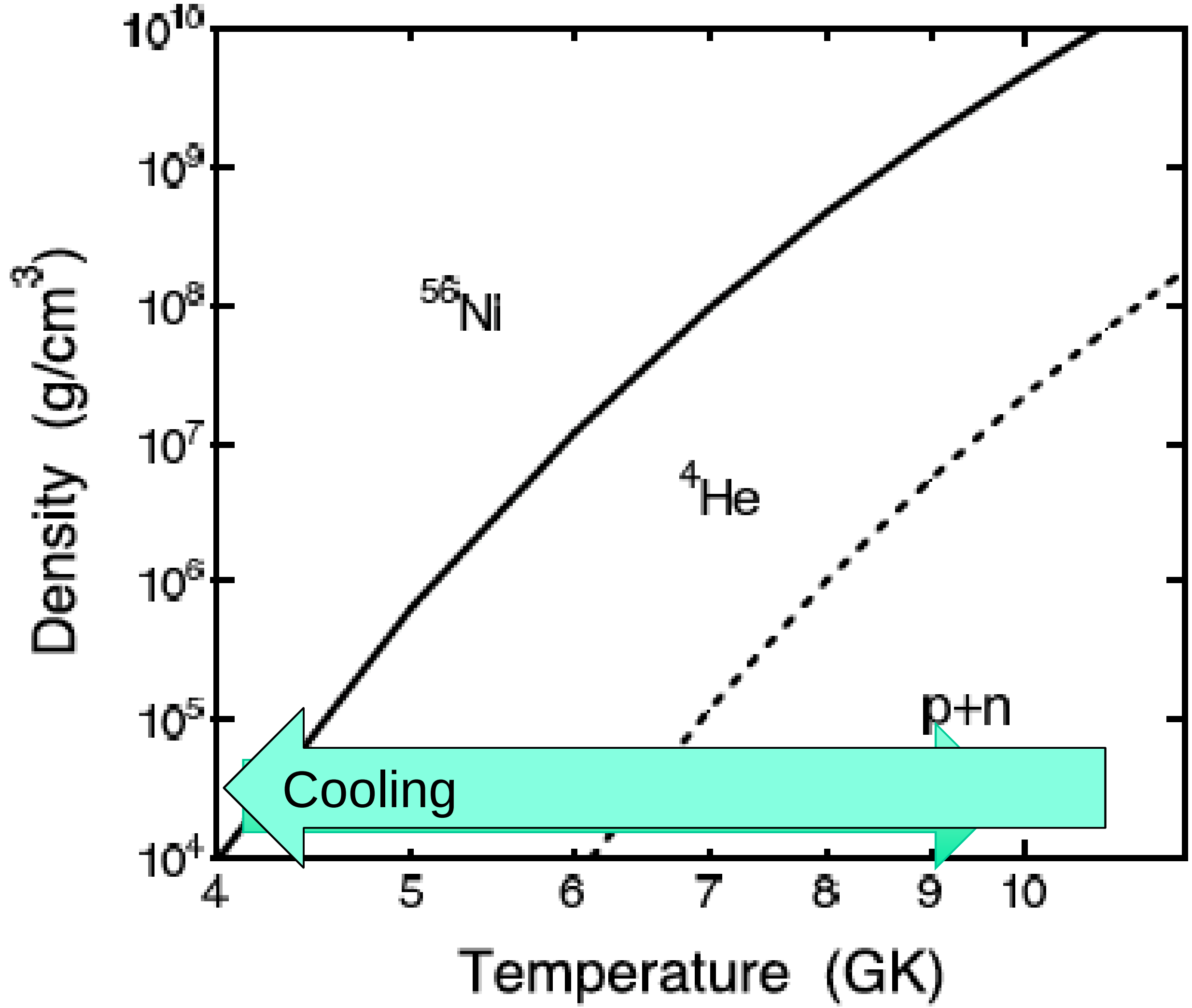
- **Site independent models:**
  - [n_n, T, t parametrization (neutron density, temperature, irradiation time)]
  - S, Y_e, t parametrization (Entropy, electron fraction, expansion timescale)
- **Core collapse supernovae**
  - Neutrino wind
  - Jets
  - Explosive helium burning
- **Neutron star mergers**

A star ready to die

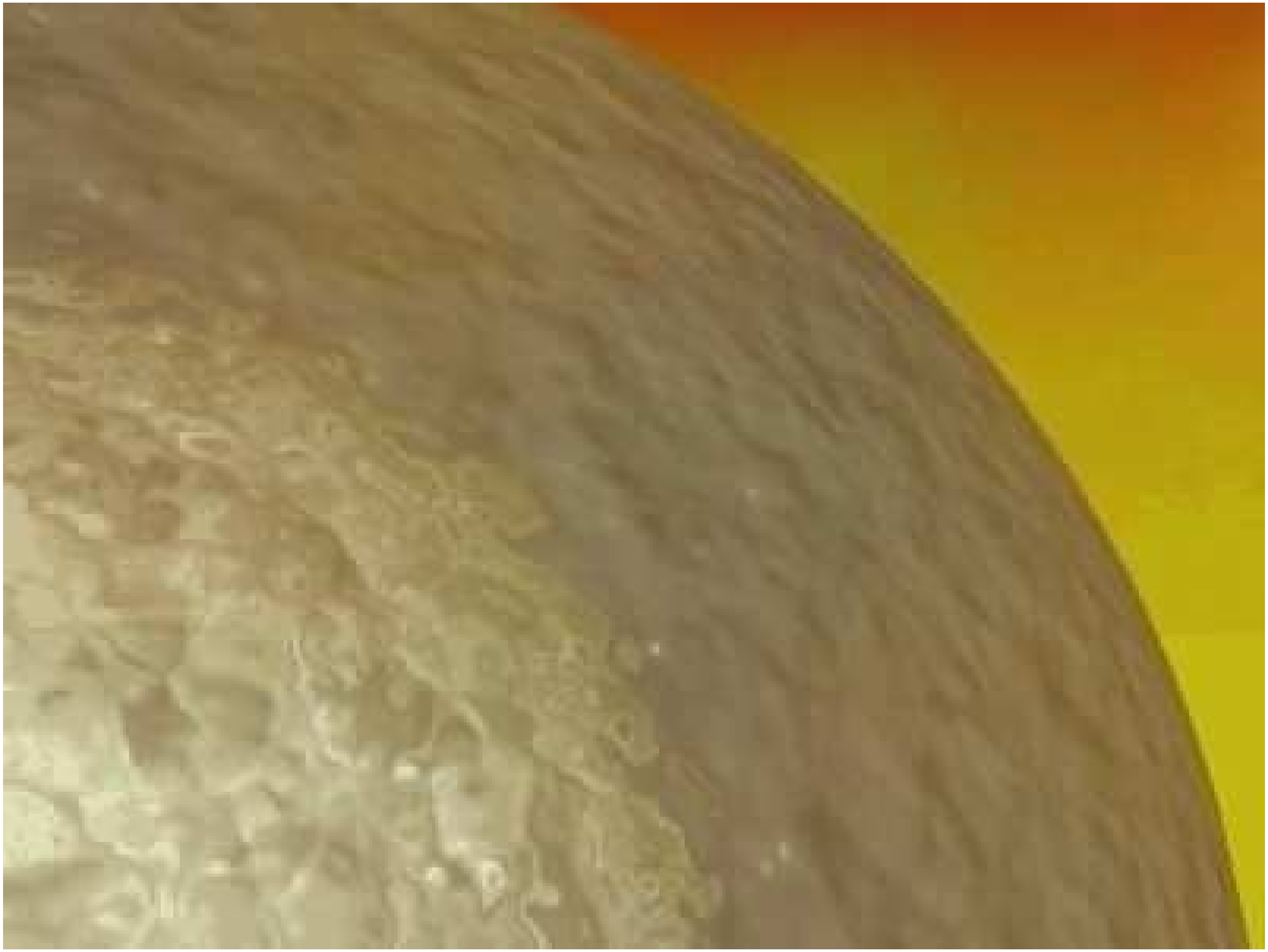
Neutron
star forms
(size ~ 10 km radius)

Matter evaporated off the hot neutron star

r-process site ?


10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
Density (g/cm^3)
4
5
6
7
8
9
10
Temperature (GK)
^{56}Ni
^{4}He
p+n
Cooling

How does the r-process work ? Neutron capture !



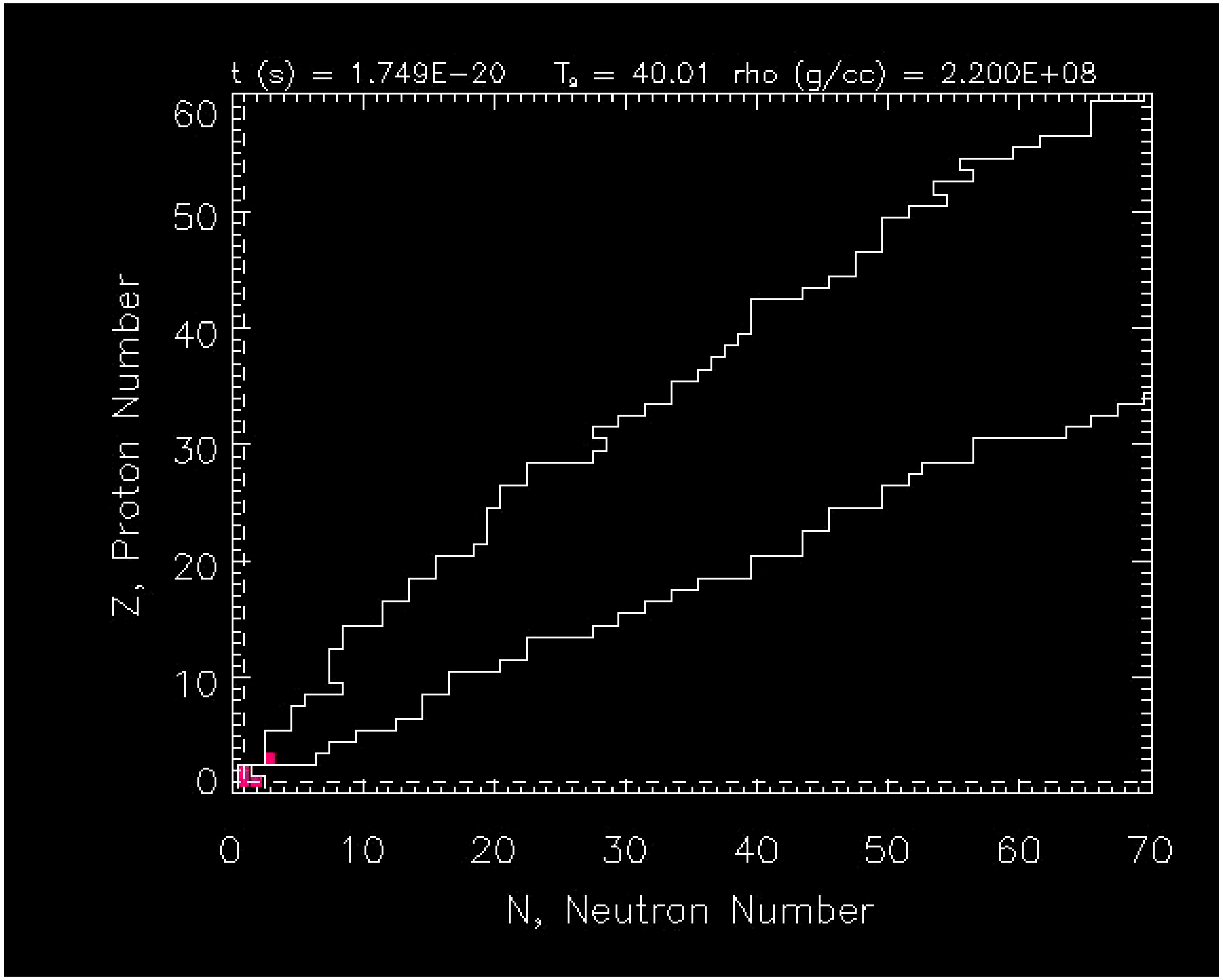
S, Y_e, τ parametrization

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:

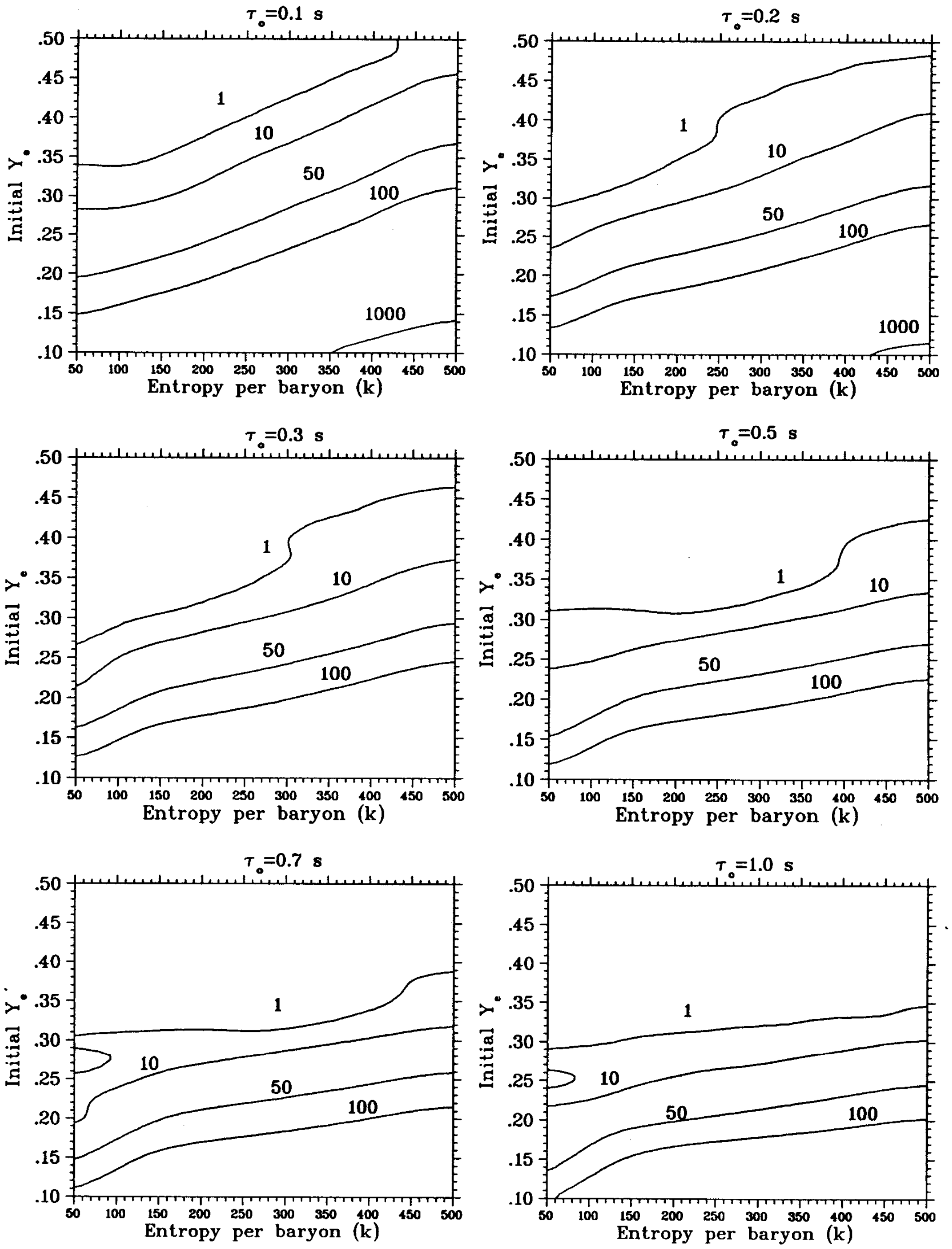
cross : most abundant nucleus
colors: degree of equilibrium with that nucleus
(difference in chemical potential)



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)

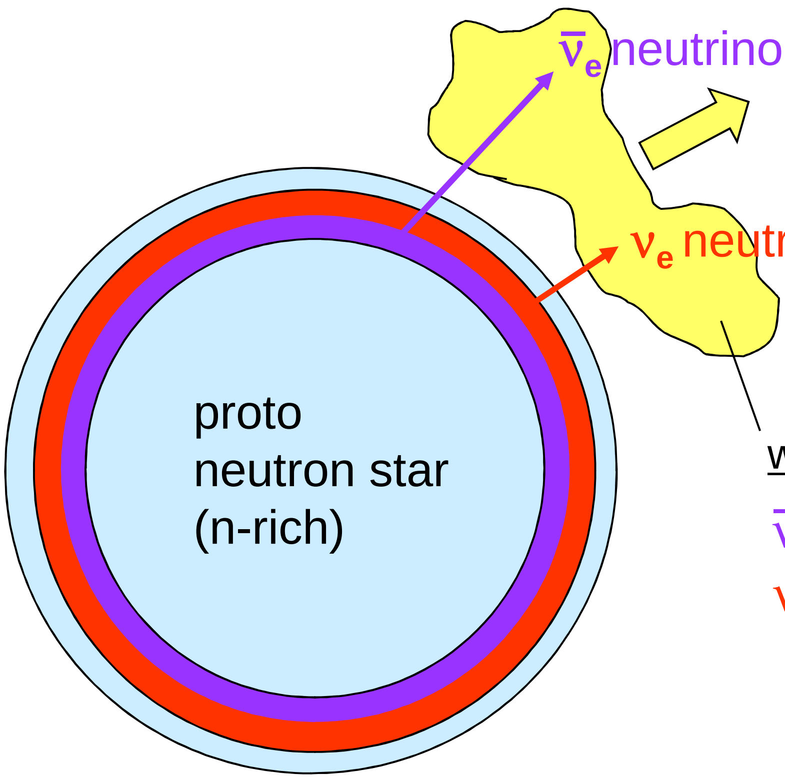
→ 2 possible scenarios:

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

r-process in Supernovae ?

High entropy neutrino driven wind:

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 !

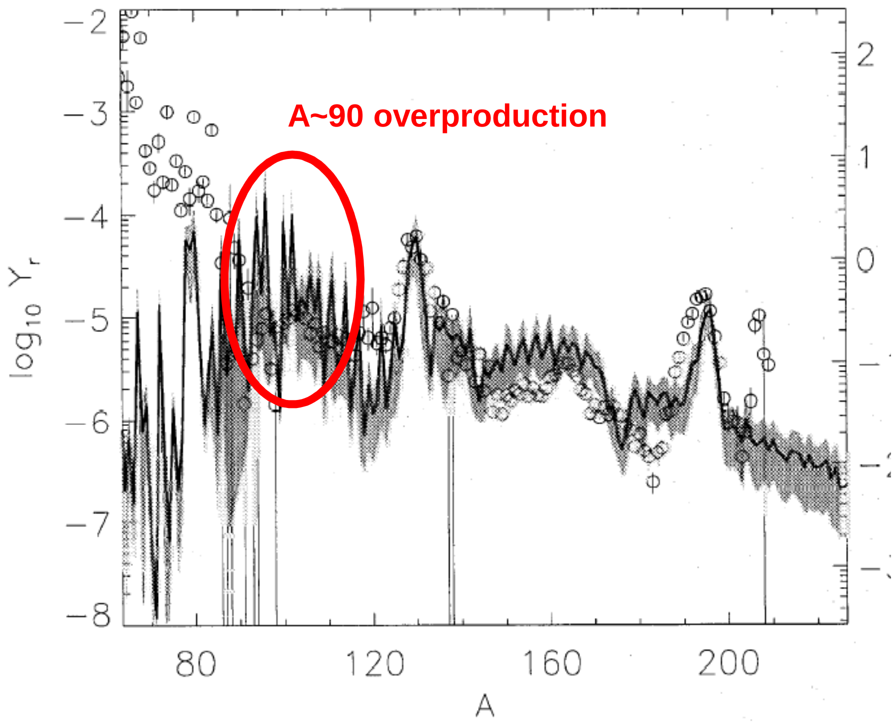
$\nu_e + n \rightarrow p + e^-$

therefore matter is driven neutron rich

Results for Supernova r-process

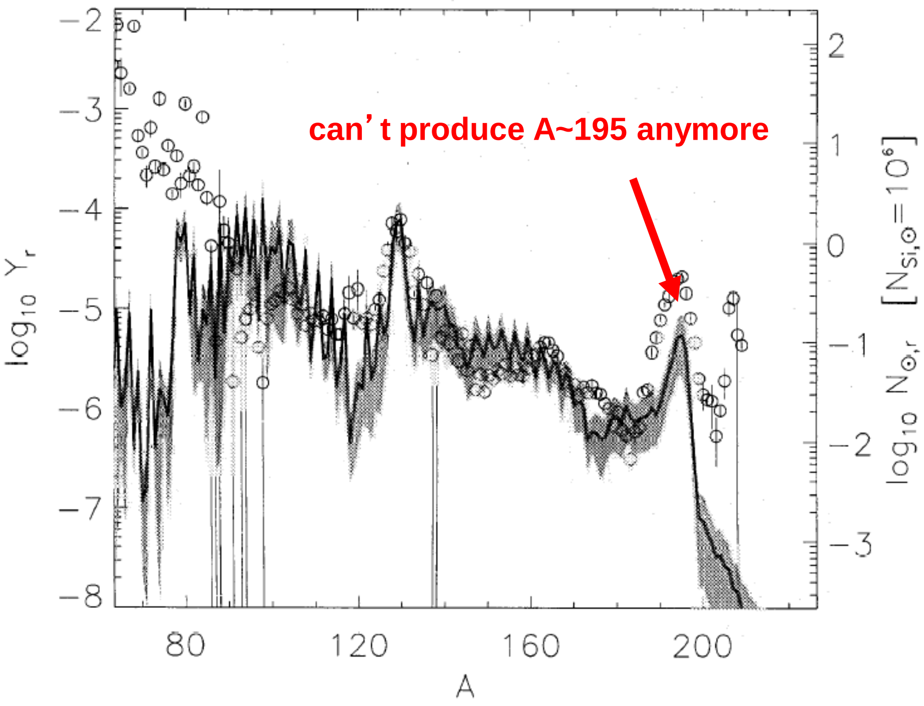
Takahashi, Witti, & Janka A&A 286(1994)857

(for latest treatment of this scenario see Thompson, Burrows, Meyer ApJ 562 (2001) 887)



A~90 overproduction

density artificially reduced by factor **5.5**



can’t produce A~195 anymore

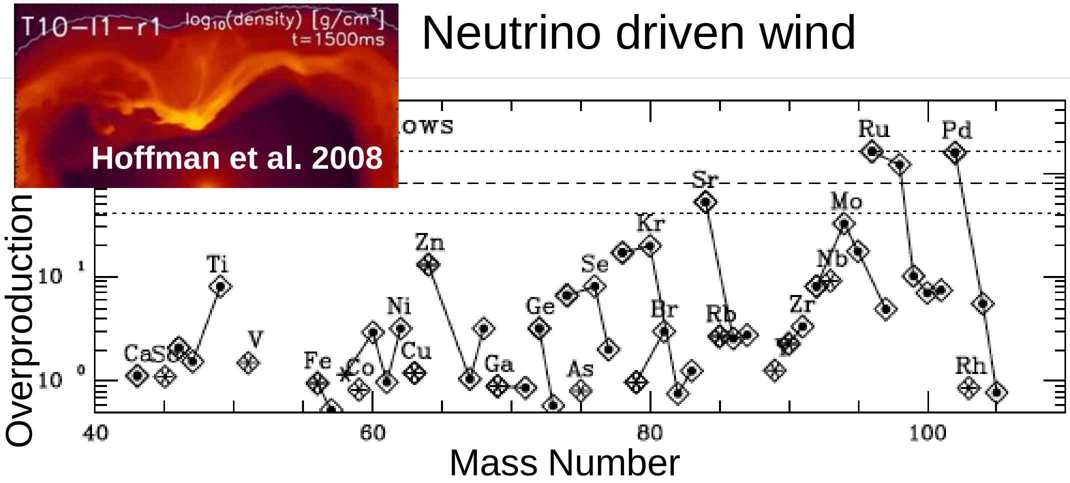
density artificially reduced by factor **5**

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

other problem: the α effect

Breakthrough in Theoretical Astrophysics

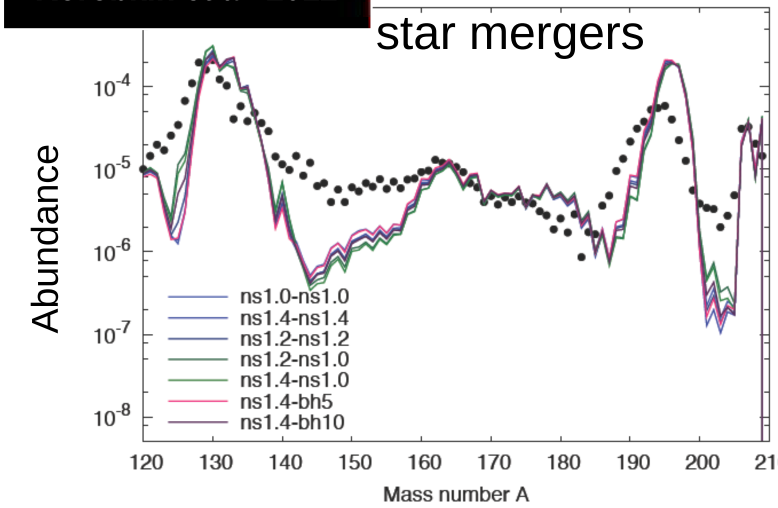
Neutrino driven wind



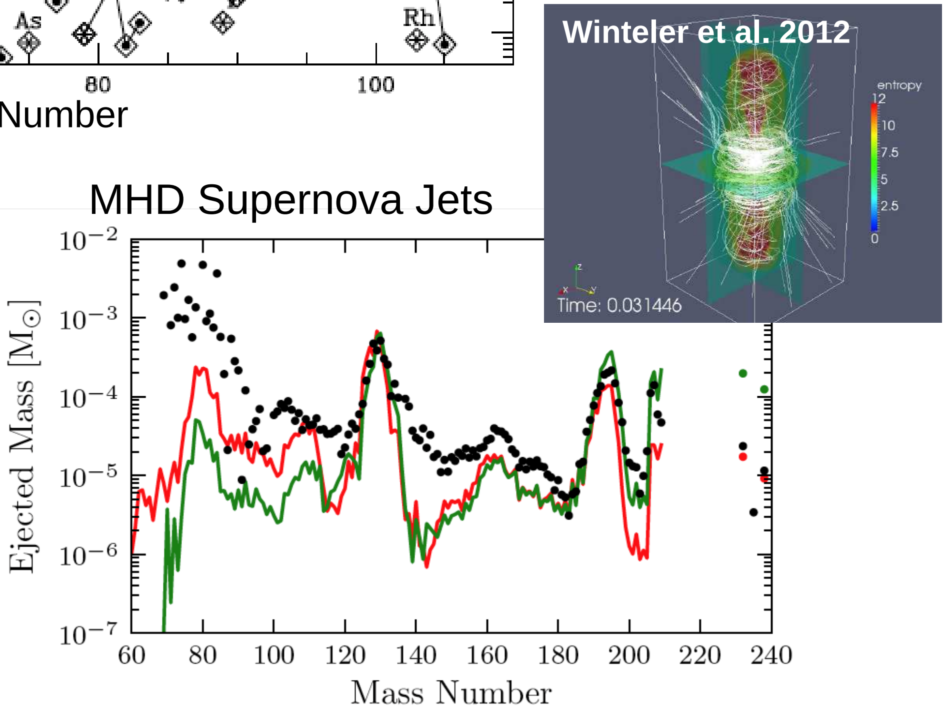
Hoffman et al. 2008

Korobkin et al. 2012

Neutron star mergers

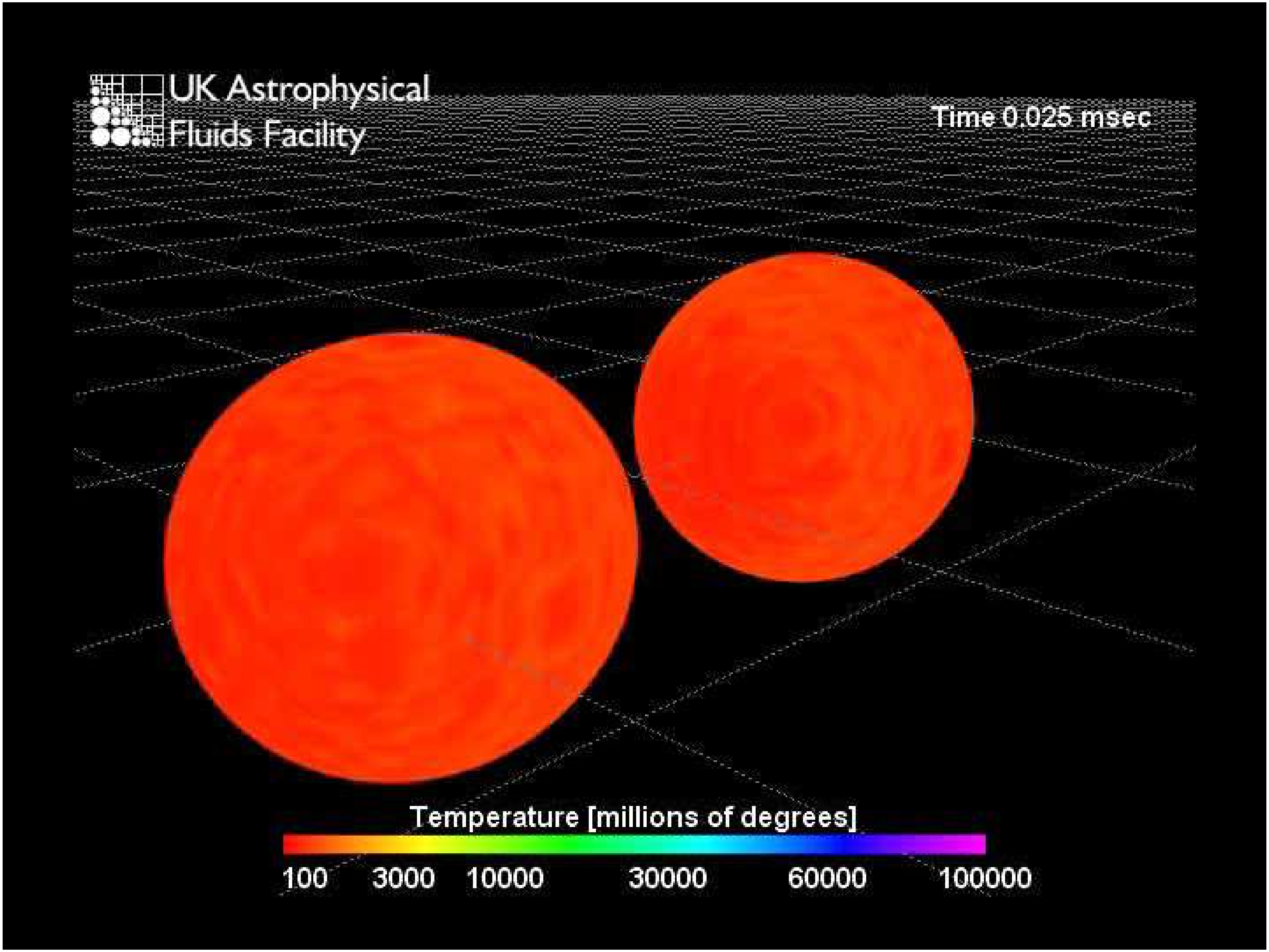


MHD Supernova Jets



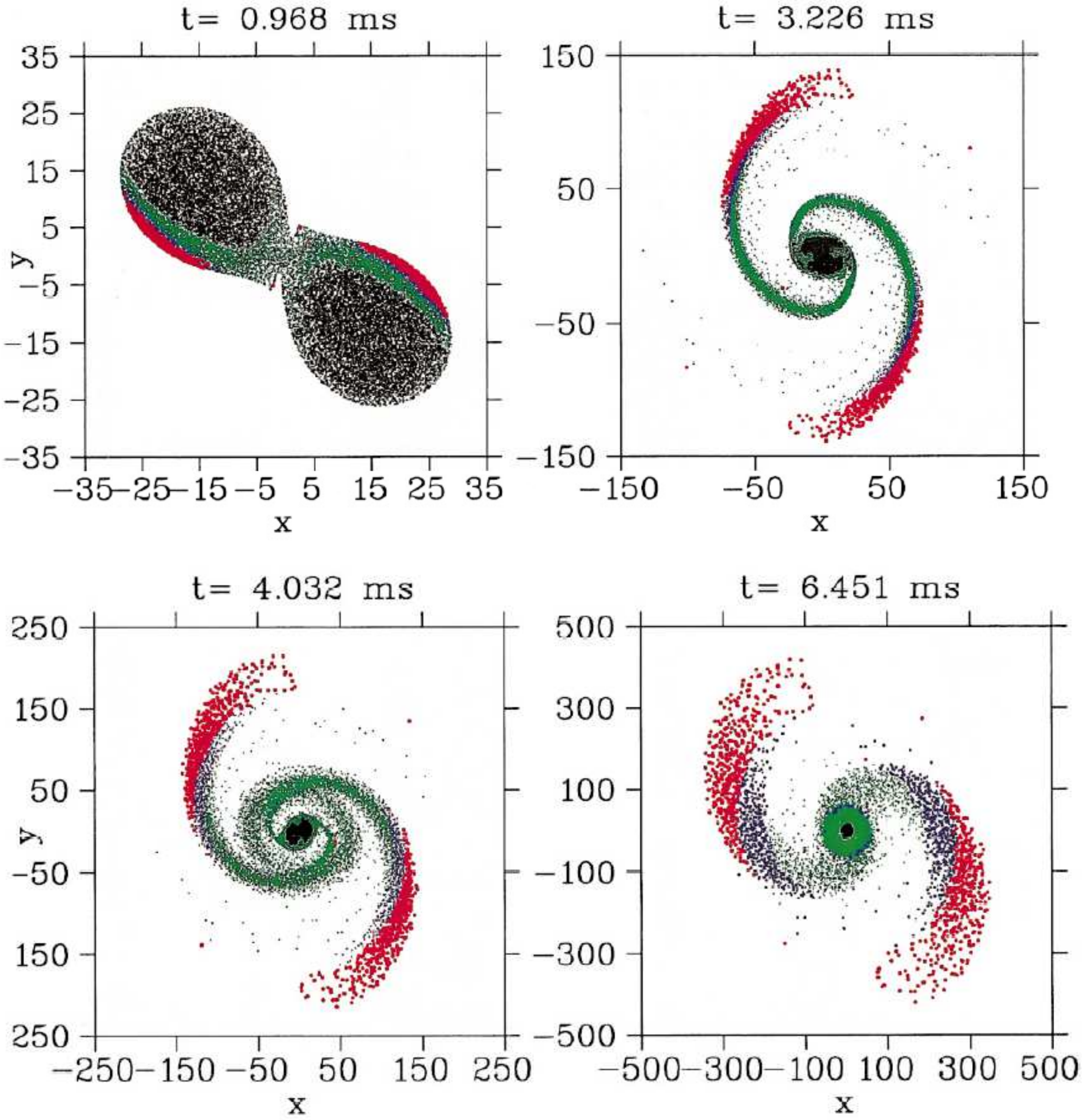
Winteler et al. 2012

- We now have several robust, rather self-consistent r-process models
- To test them against observations → Need nuclear data now!
- Goal: reveal model deficiencies and site physics signatures


UK Astrophysical Fluids Facility
Time 0.025 msec
Temperature [millions of degrees]
100
3000
10000
30000
60000
100000

Ejection of matter in NS-mergers

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



Destiny of Matter:

red: ejected

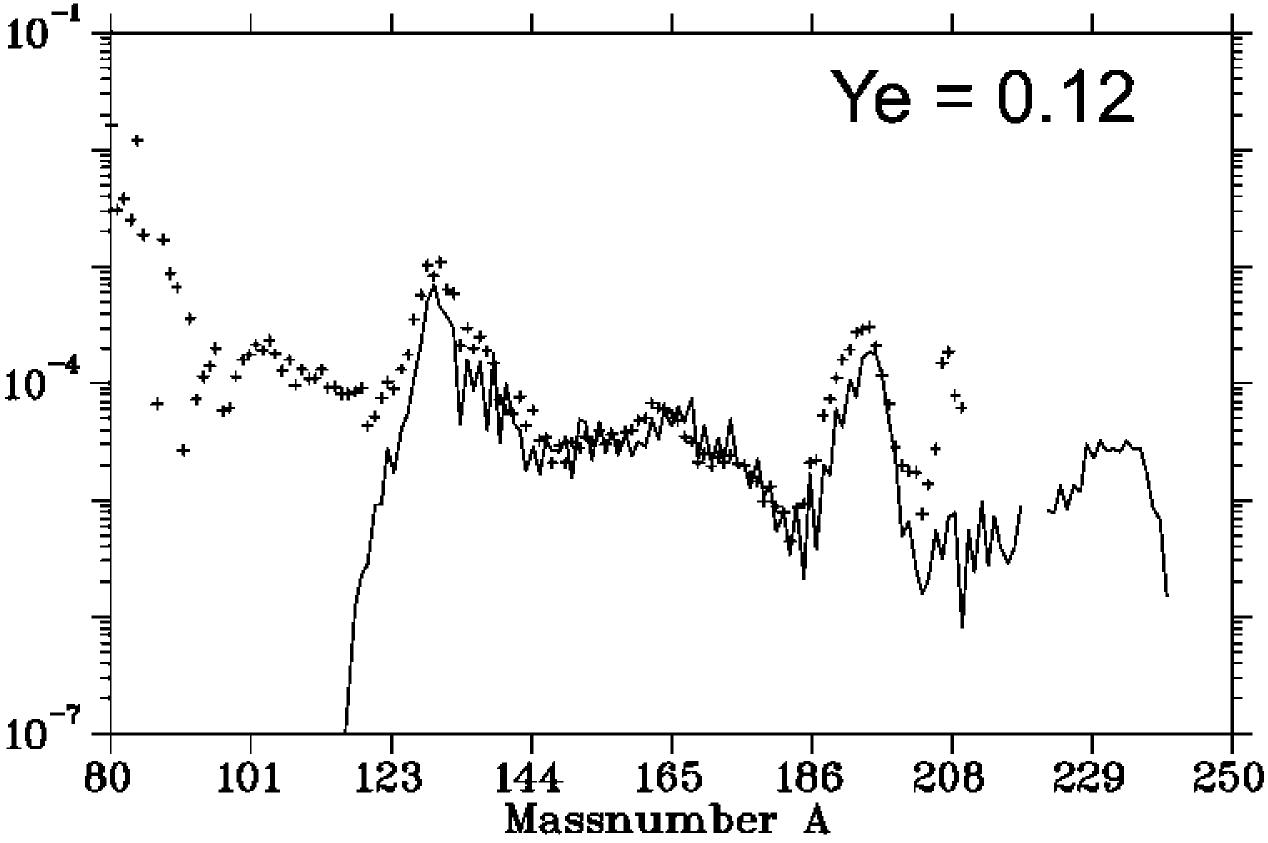
blue: tails

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 …

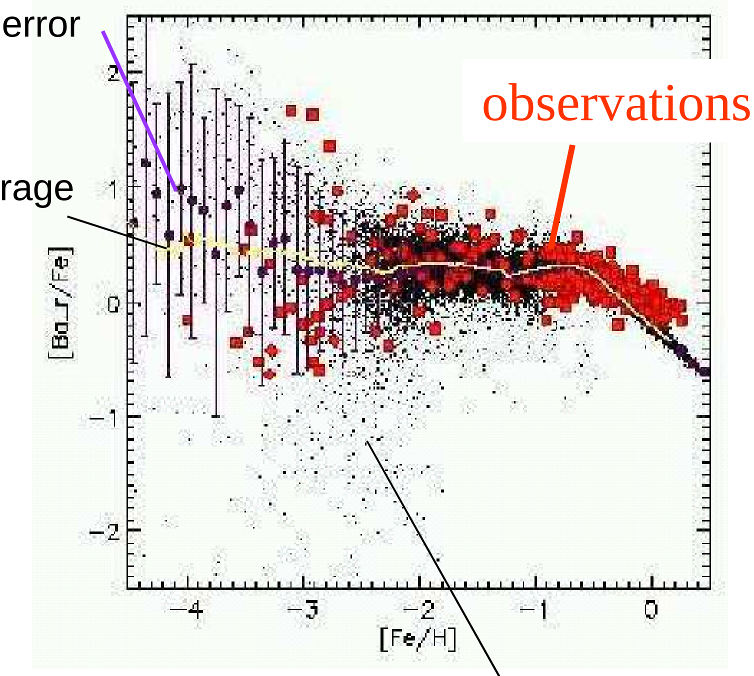
Summary theoretical scenarios

	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



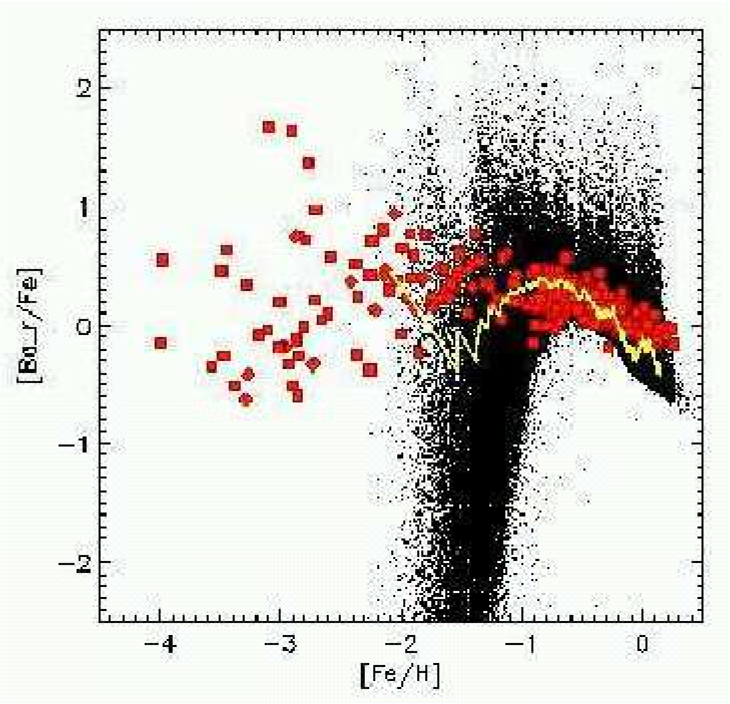
Model star average with error

Average ISM

observations

Dots: model stars

NS mergers



→ Neutron Star Mergers ruled out as major contributor