NSCL

Experimental Nuclear Astrophysics: Lecture 2

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National Nuclear Physics Summer School

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NSF

MICHIGAN STATE UNIVERSITY

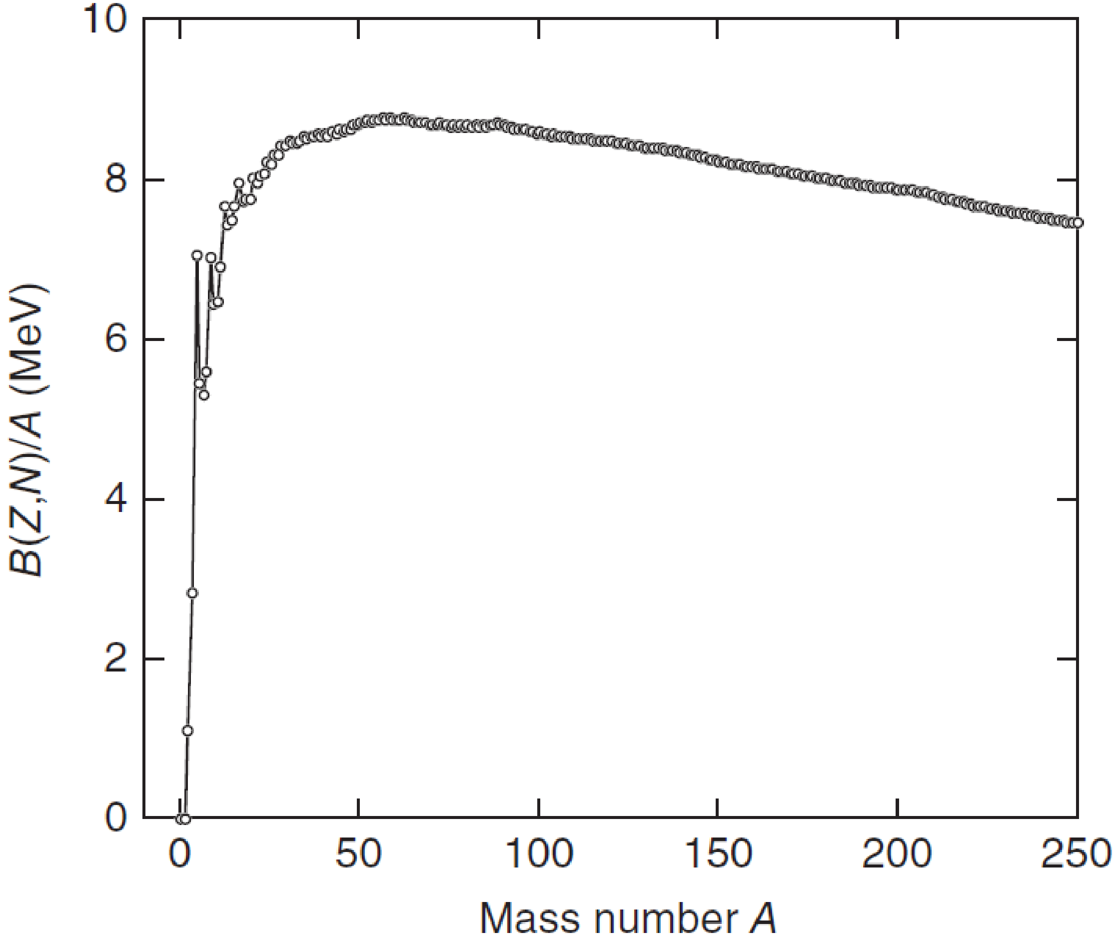
Outline

- Lecture 1: Introduction & charged-particle reactions
- **Lecture 2: Neutron-induced reactions**
- Lecture 3: What I do (indirect methods)

Today

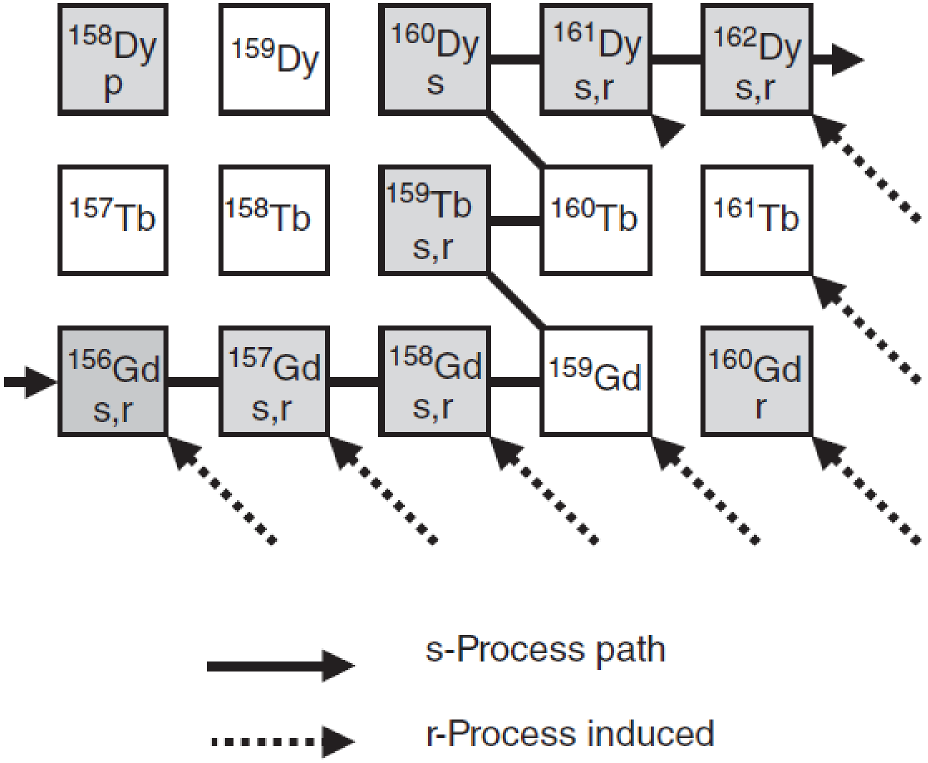
- Neutron capture
- s-process
- r-process

Binding energy per nucleon

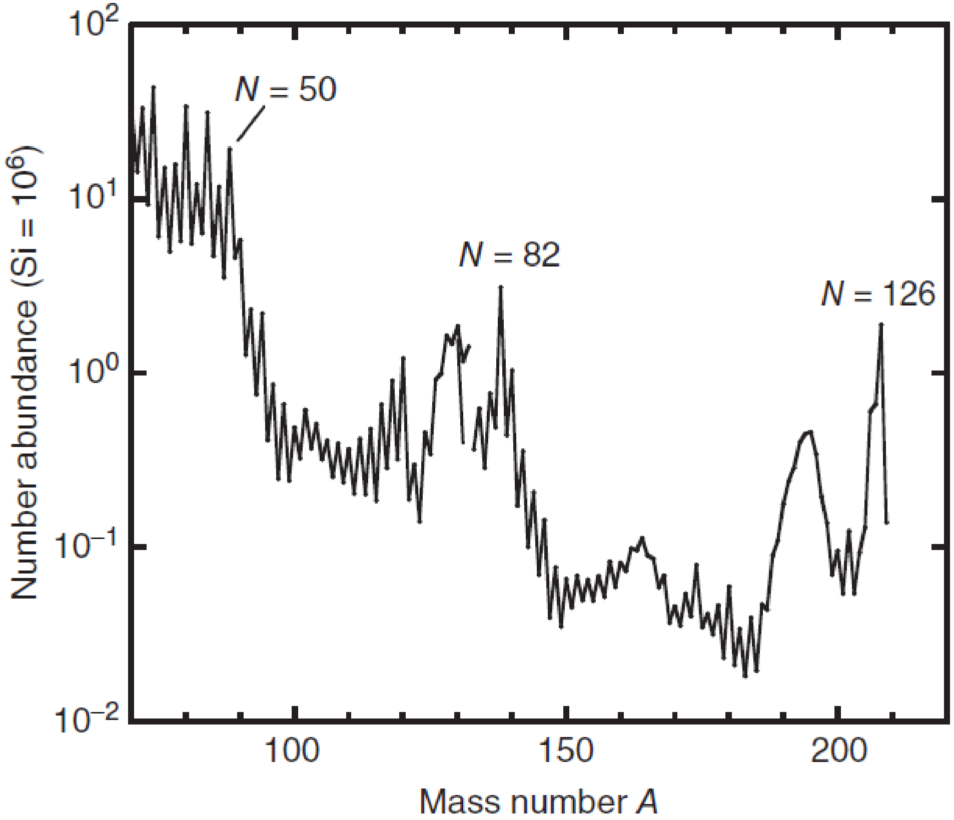


Once the Fe-peak elements are reached in a star, charged-particle fusion is no longer favorable. Need neutron capture processes to produce the heavy elements.

Production of heavy elements: (n,γ) reactions



Peaks in solar heavy element abundance pattern attributable to waiting points in s,r process paths due to nuclear structure (magic numbers)

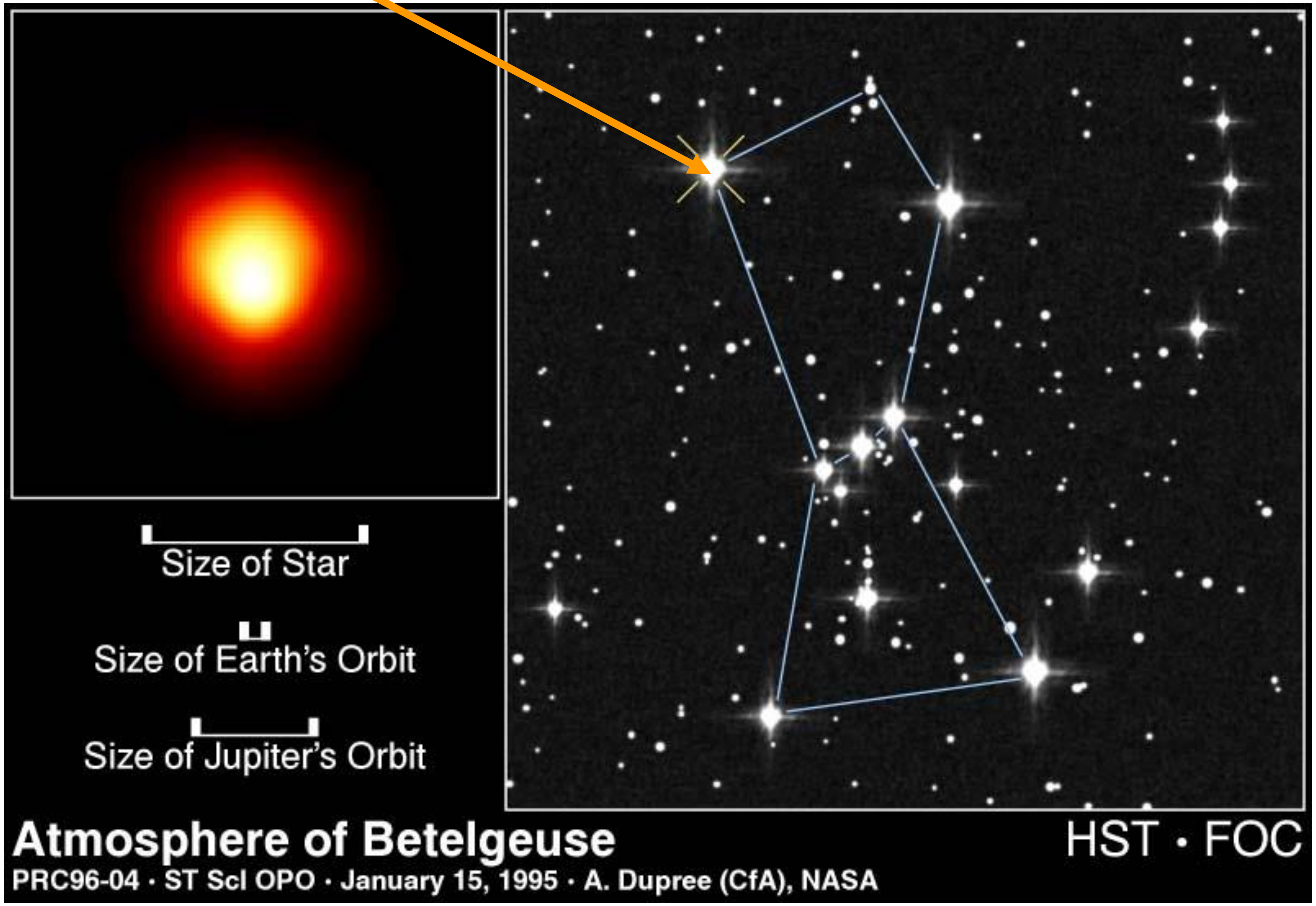


Slow neutron capture (s) process takes place at ~10^8 cm^{-3} neutron-density

Rapid neutron capture (r) process takes place at ~10^{20} cm^{-3} neutron-density

Nuclear Physics of Stars, Iliadis, 2nd Ed.

Where does the s process happen?



there !

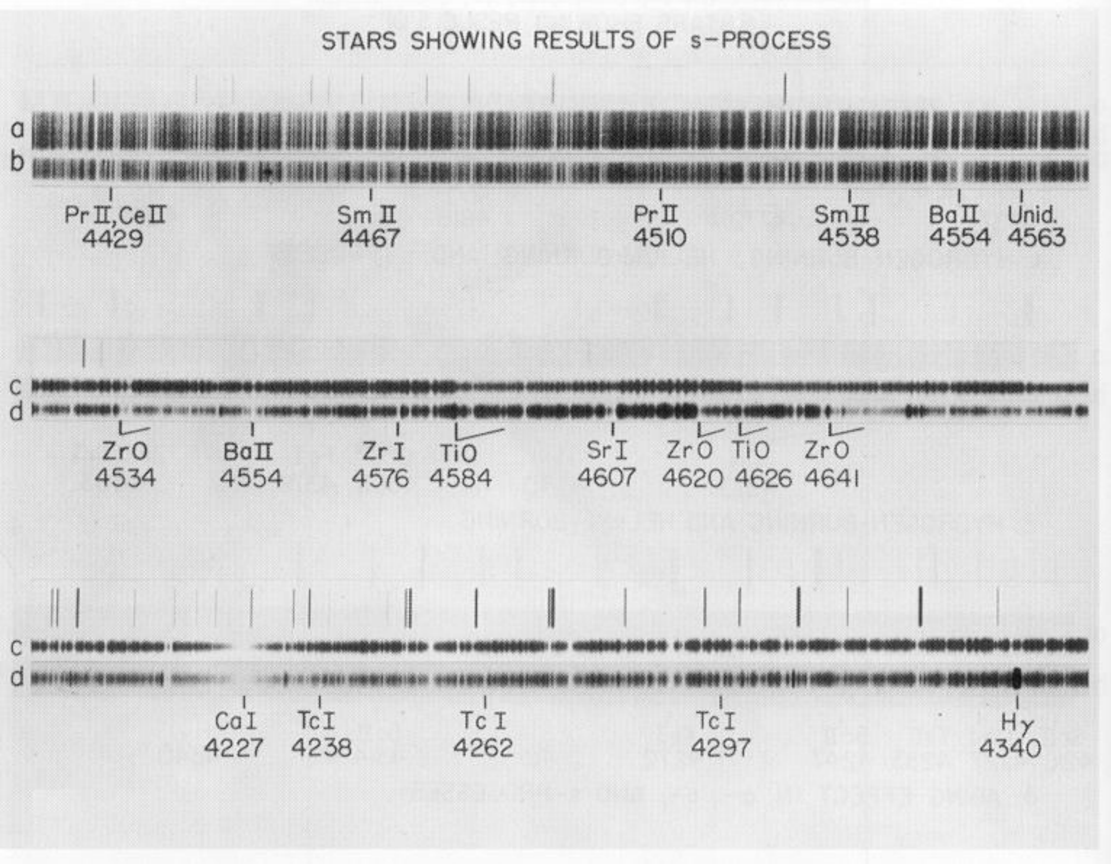
Atmosphere of Betelgeuse

PRC96-04 · ST ScI OPO · January 15, 1995 · A. Dupree (CfA), NASA

In giants and supergiants – and it takes several million years !

How can we tell?

Analyze light from a red giant:

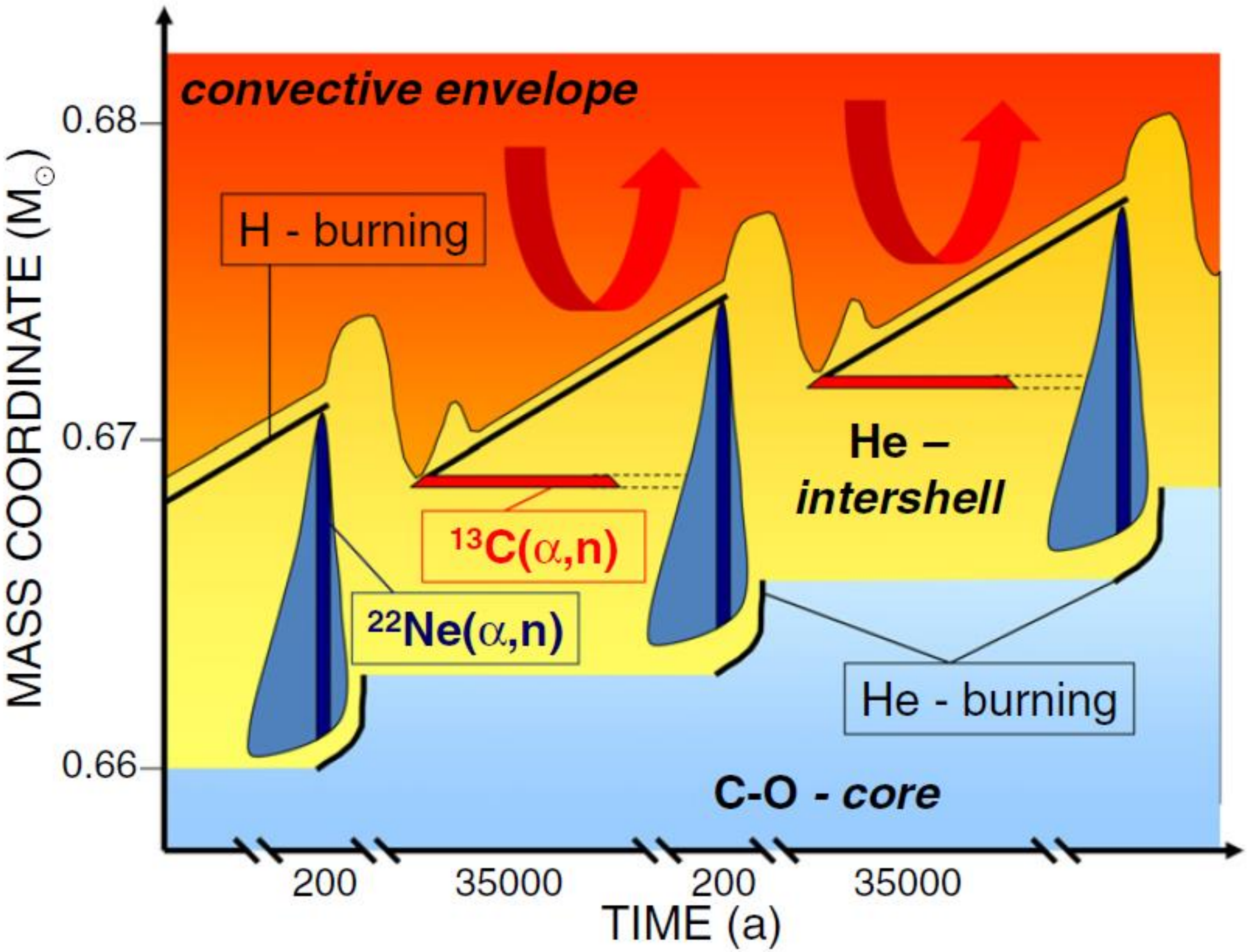


Star contains Technetium (Tc) !!!
(heavy element $Z = 43$, $T_{1/2} = 4$ million years)

Merrill, 1952

Main* s process in red giants (AGB stars)

*there are also "weak" and "strong" components



Reifarth *et al*., J. Phys. G 41, 053101 (2014)

s process inputs

- Temperature
- Seed abundance
- Neutron density
- Neutron fluence
- Half lives for β decay
- Reaction rates for $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$
- Reaction rates for (n,γ)

(n,γ) reaction rates

$$\langle \sigma v \rangle = \int \sigma(v)\phi(v) v\, dv = \int \sigma(E) \exp(-E/kT) E\, dE$$

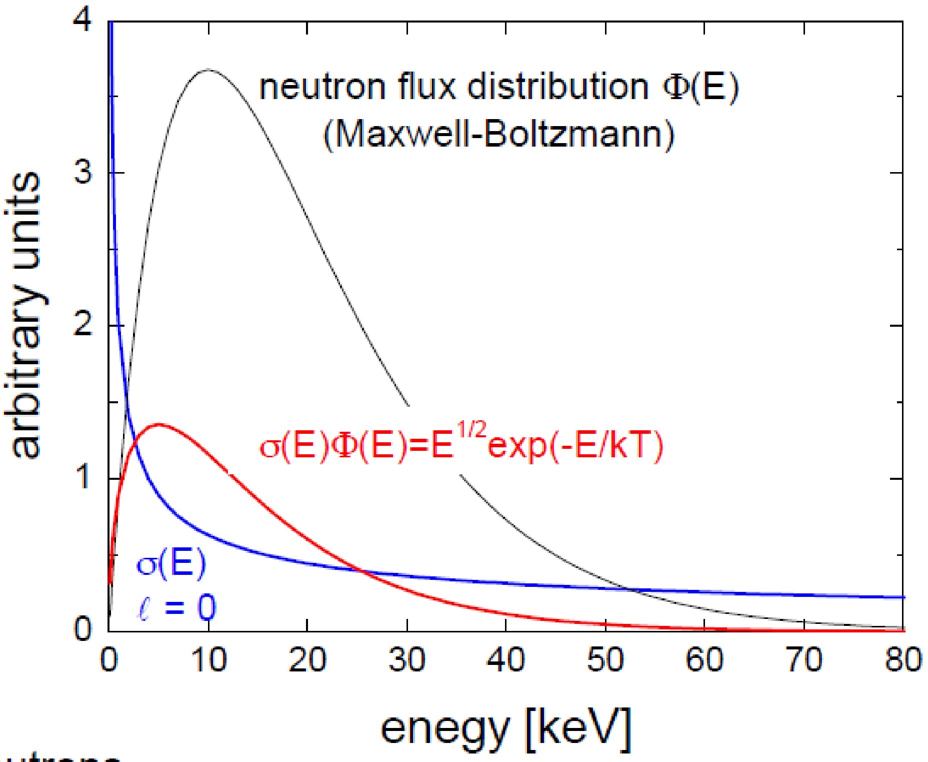
s-wave neutron capture

energy range of interest E ~ kT

$$\sigma \propto \frac{1}{v} \Rightarrow \sigma v = \text{const} = \langle \sigma v \rangle$$

stellar reaction rate

$$\langle \sigma v \rangle = v_T \sigma_{th}$$



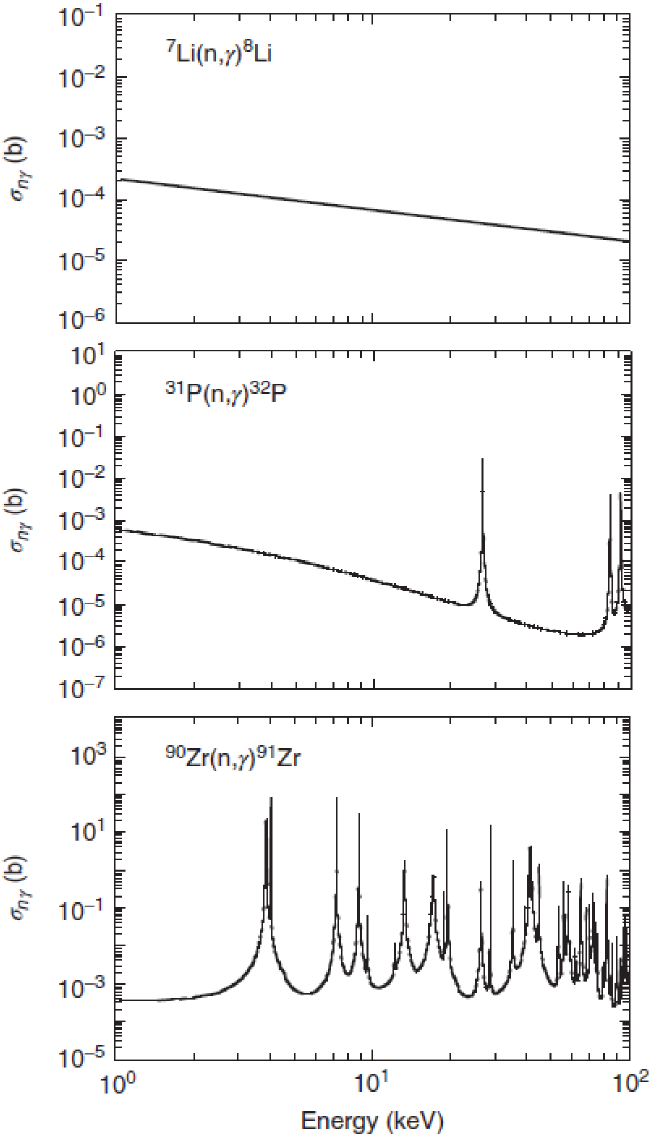
σ_{th} = measured cross section for thermal neutrons

$$v_T = \sqrt{\frac{2kT}{\mu}}$$

most probable velocity,
corresponding to E_{cm} = kT

M. Aliotta

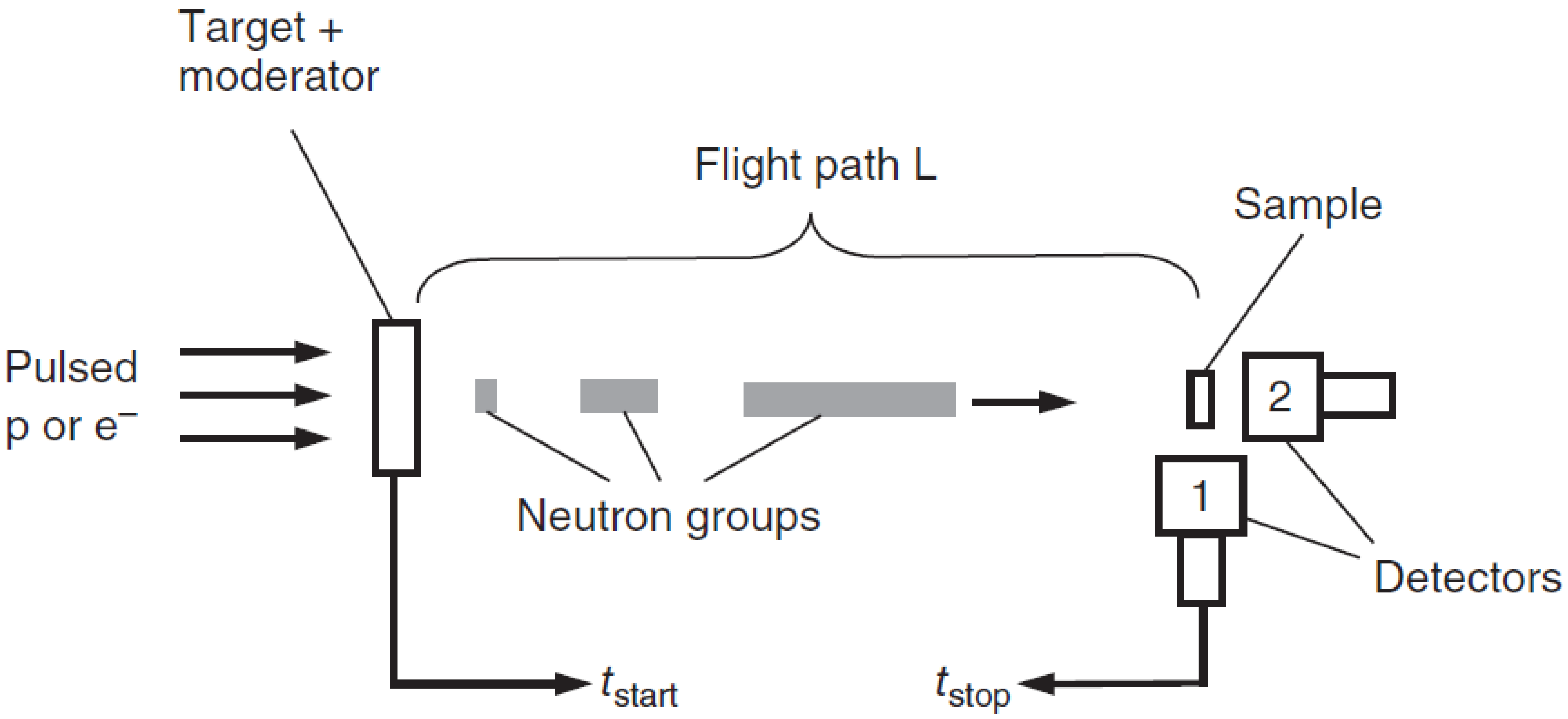
(n,γ) cross sections



- No Coulomb barrier, so cross sections are larger at low energies
- More resonances for heavier nuclei
- Need low-energy neutron beams to bombard stable targets and measure yield
- Direct s-process measurements can be done
- No realistic prospects for direct r-process measurements because beam and target are unstable

Nuclear Physics of Stars, Iliadis, 2nd Ed.

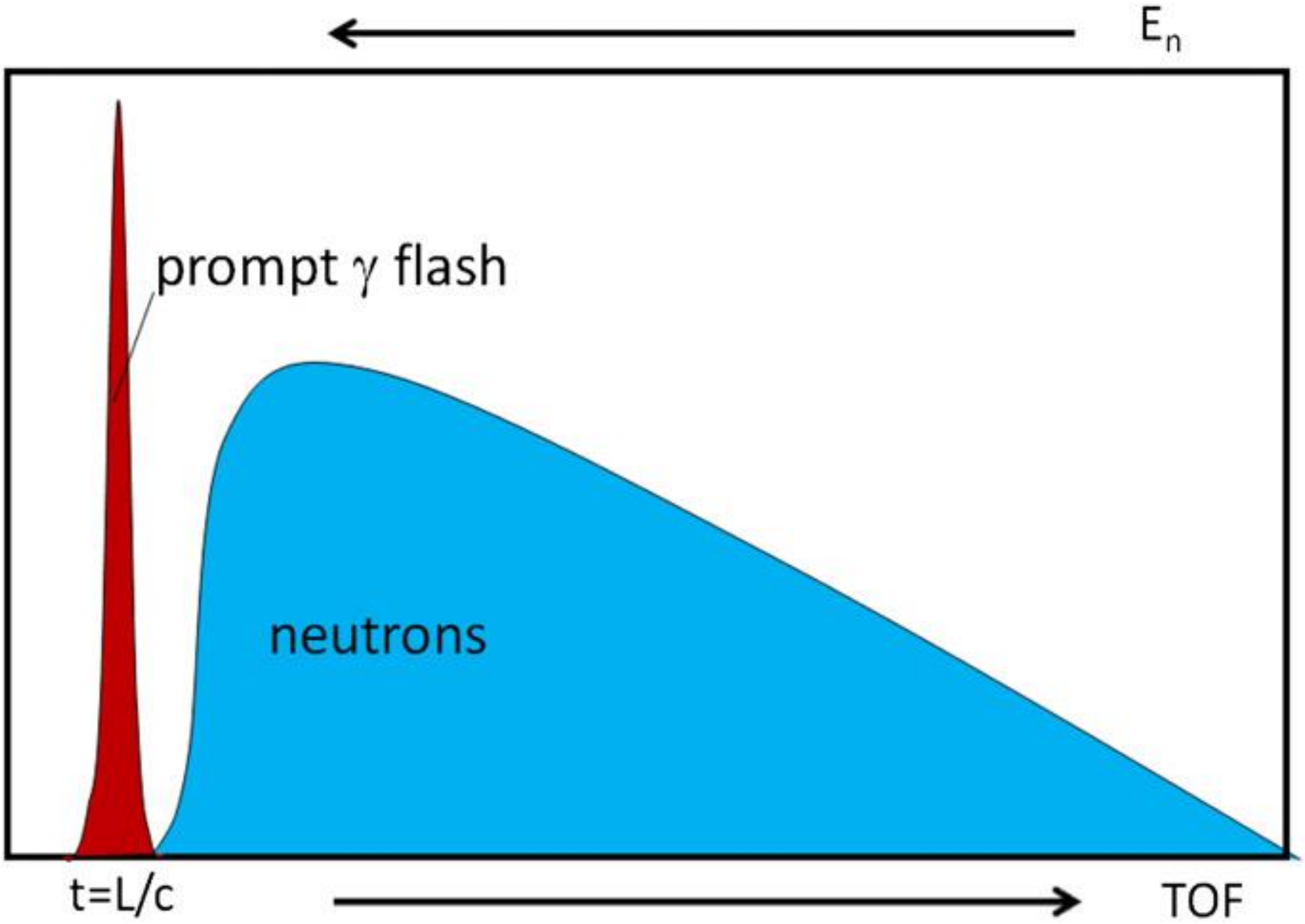
Time-of-flight technique



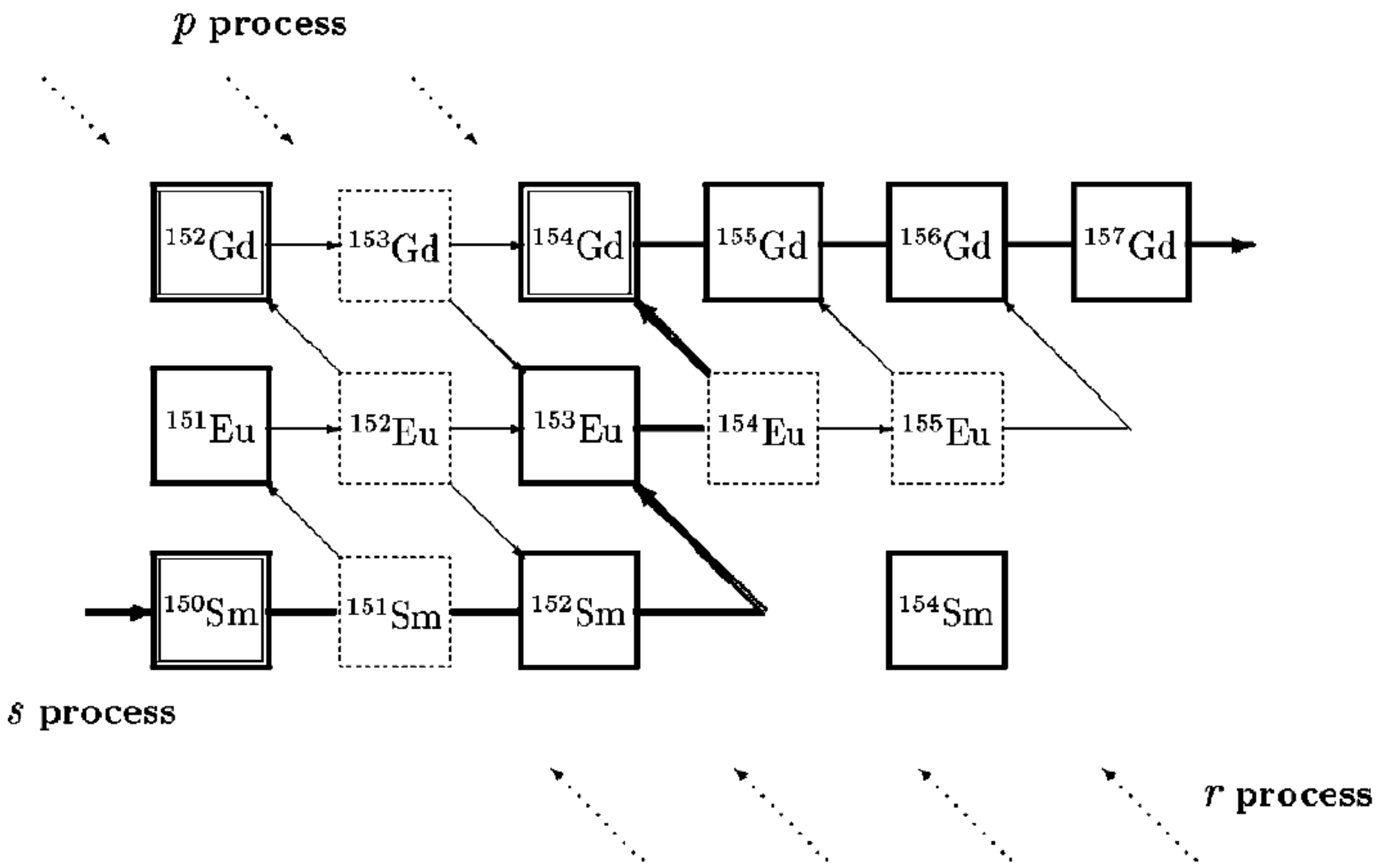
Useful to measure (n,γ) cross section at a variety of energies, all at once. Energy from neutron production target determined by time-of-flight to sample.

Nuclear Physics of Stars, Iliadis, 2nd Ed.

Time of flight technique



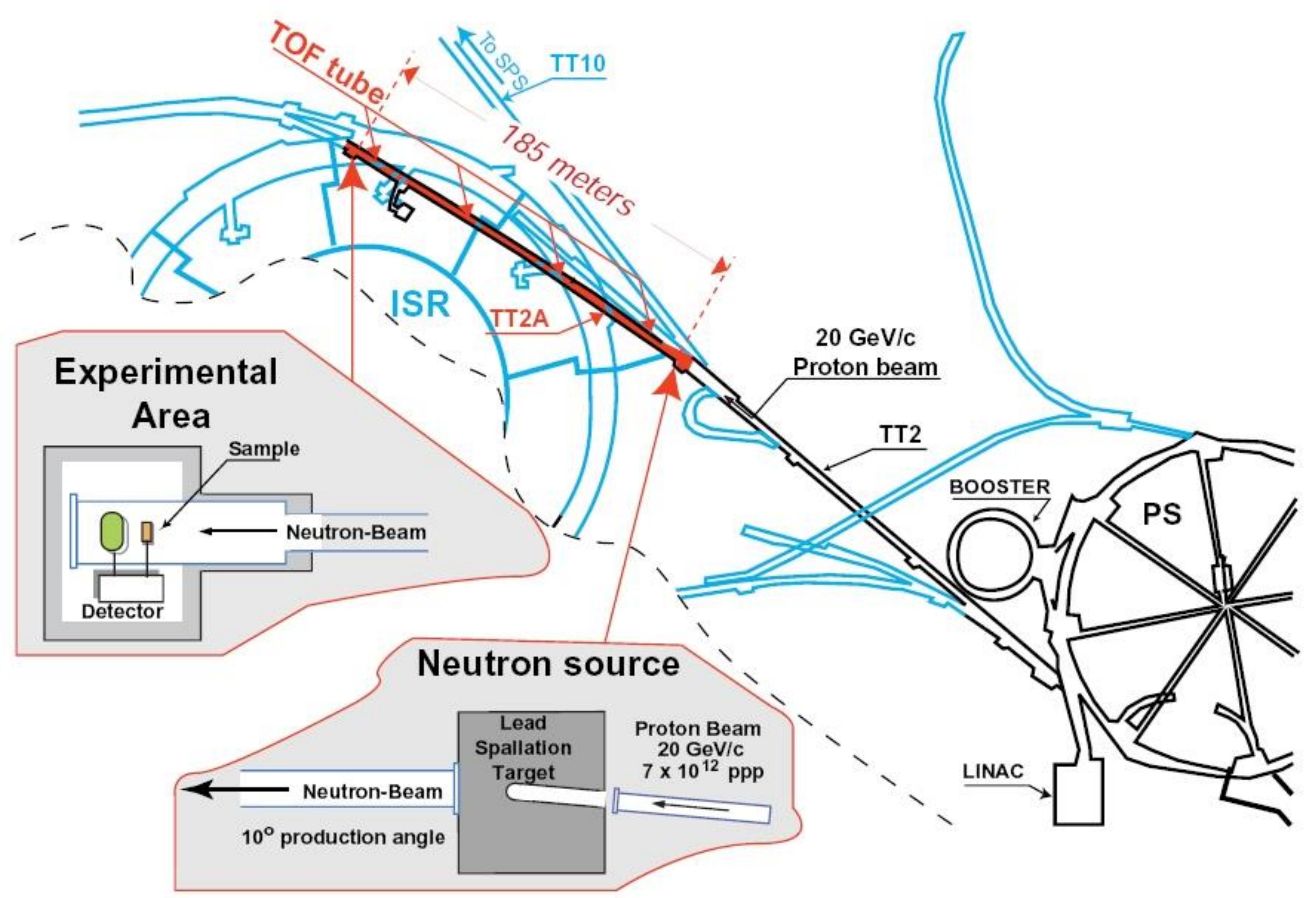
Example: ^{151}Sm(n,γ)^{152}Sm reaction



^{151}Sm is unstable with half life of 90 years, so it is a crucial branch point for the s process

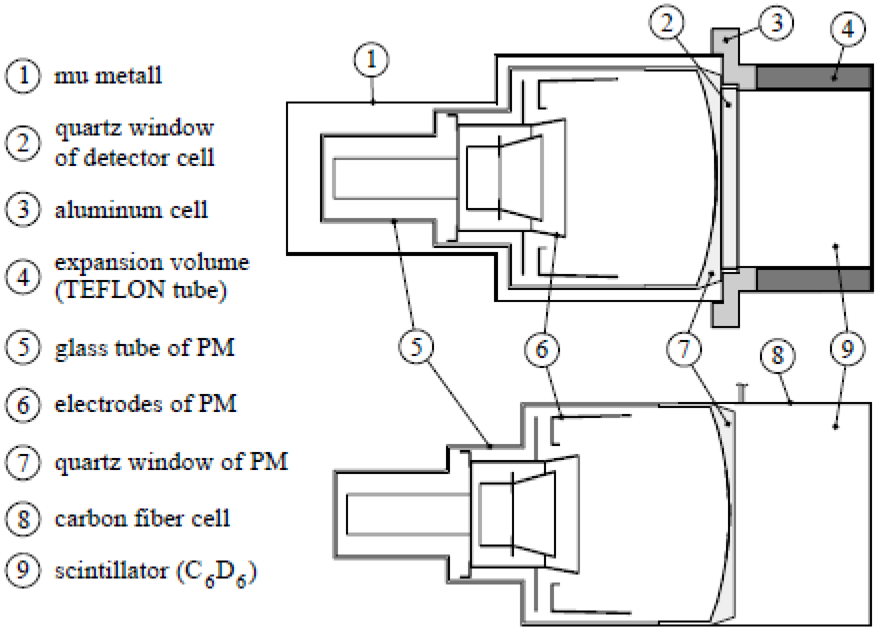
U. Abbondanno *et al*., Phys. Rev. Lett. 93,161103 (2004)

CERN nTOF facility in Geneva, Switzerland

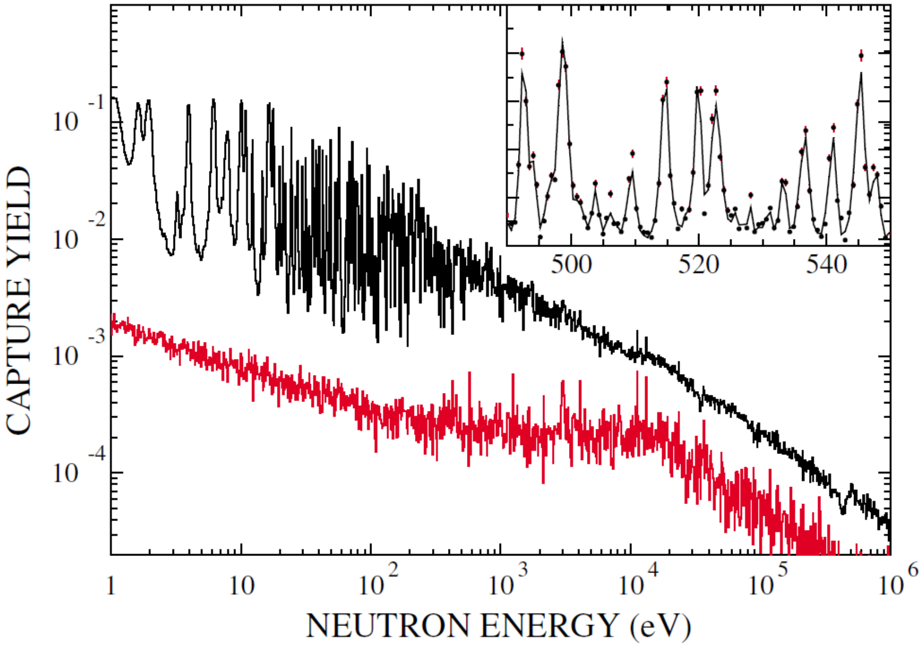


Example: ^{151}Sm(n,γ)^{152}Sm reaction

C_6D_6 scintillators used to detect γ rays in nToF experimental area

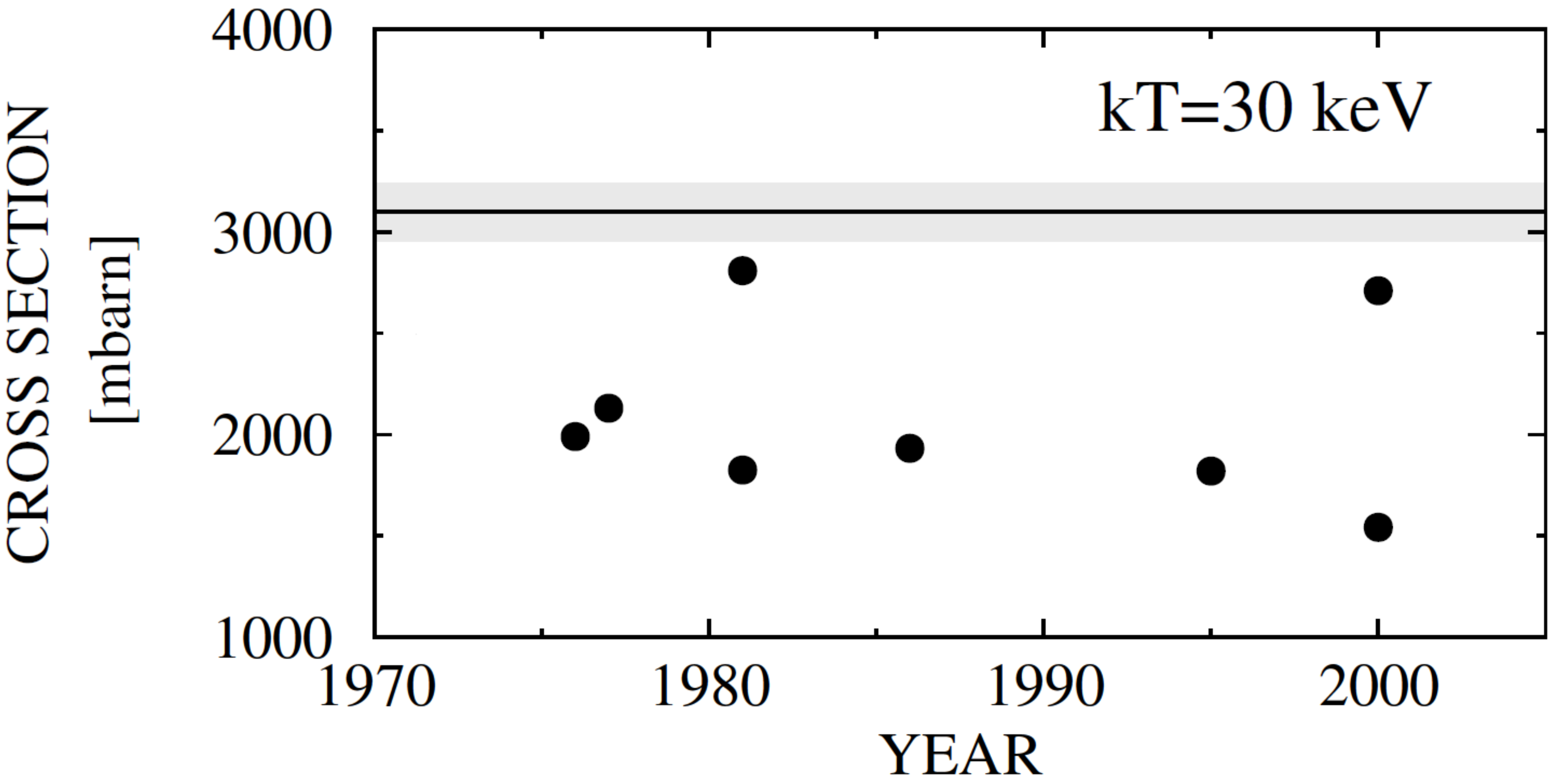


Measured ^{151}Sm(n,γ)^{152}Sm yield



U. Abbondanno *et al*., Phys. Rev. Lett. 93,161103 (2004)

^{151}Sm(n,γ)^{152}Sm results

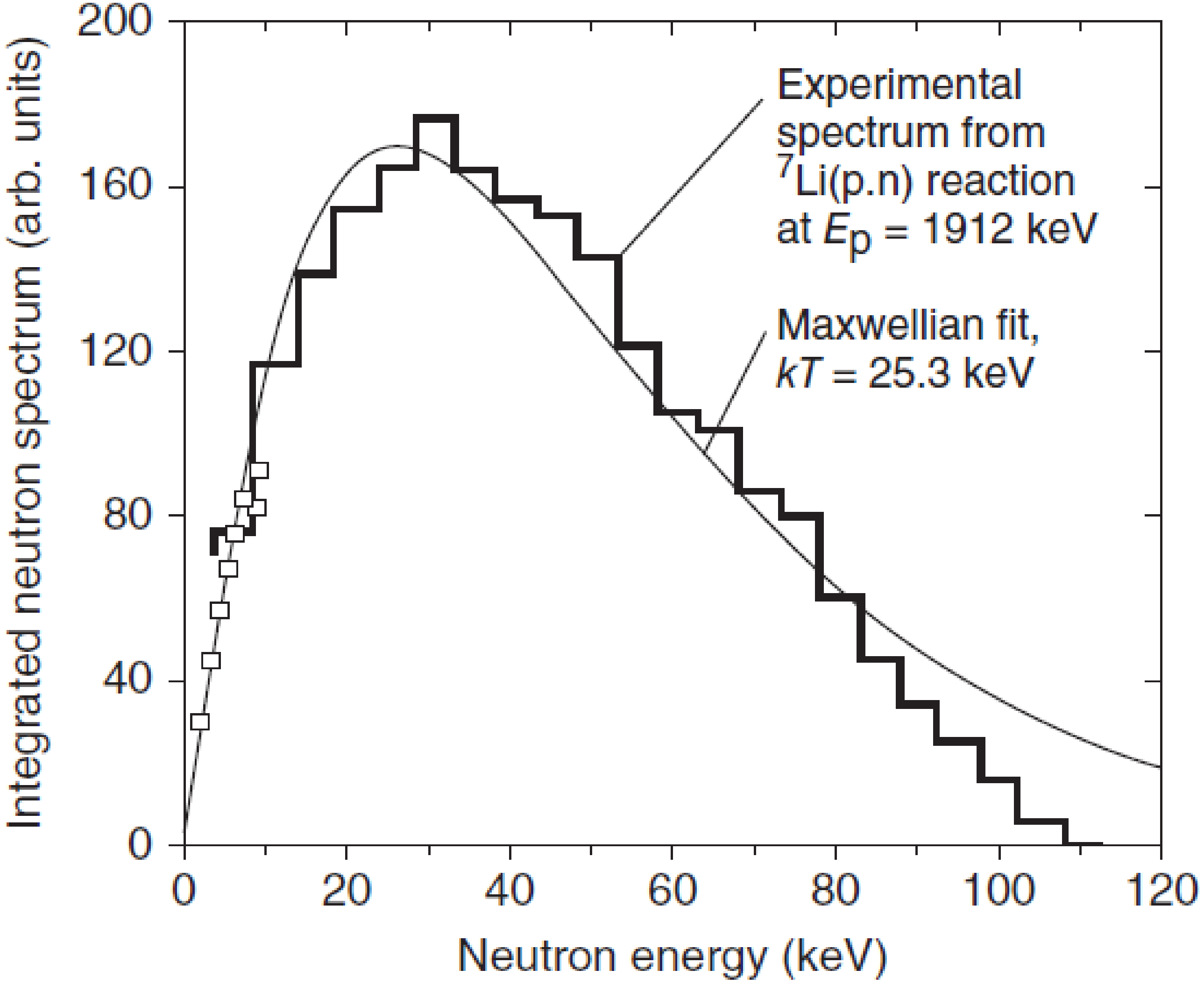


Grey band: measurement

Black dots: theoretical statistical model calculations over the years

U. Abbondanno *et al*., Phys. Rev. Lett. 93,161103 (2004)

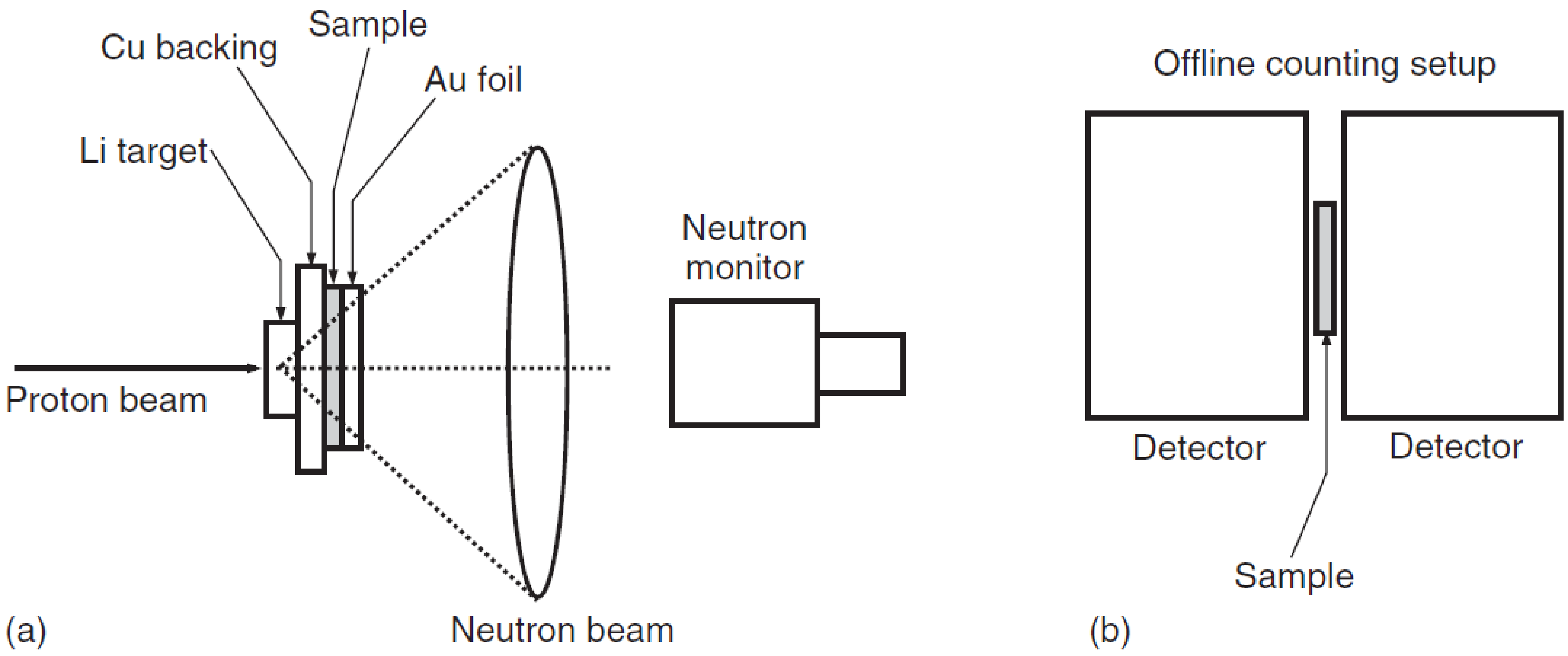
Quasi-Maxwellian neutron beams for (n,γ) measurements



- Bombard 10 μm Li target with 1912 keV protons: 31 keV above (p,n) reaction threshold
- Yields forward-going neutrons with energy distribution resembling Maxwell-Boltzmann distribution for kT = 25 keV
- With 50-100 μA beam, get 10^8-10^9 neutrons/s

Nuclear Physics of Stars, Iliadis, 2nd Ed.
W. Ratynski and F. Kappeler, Phys. Rev. C 37, 575 (1988)

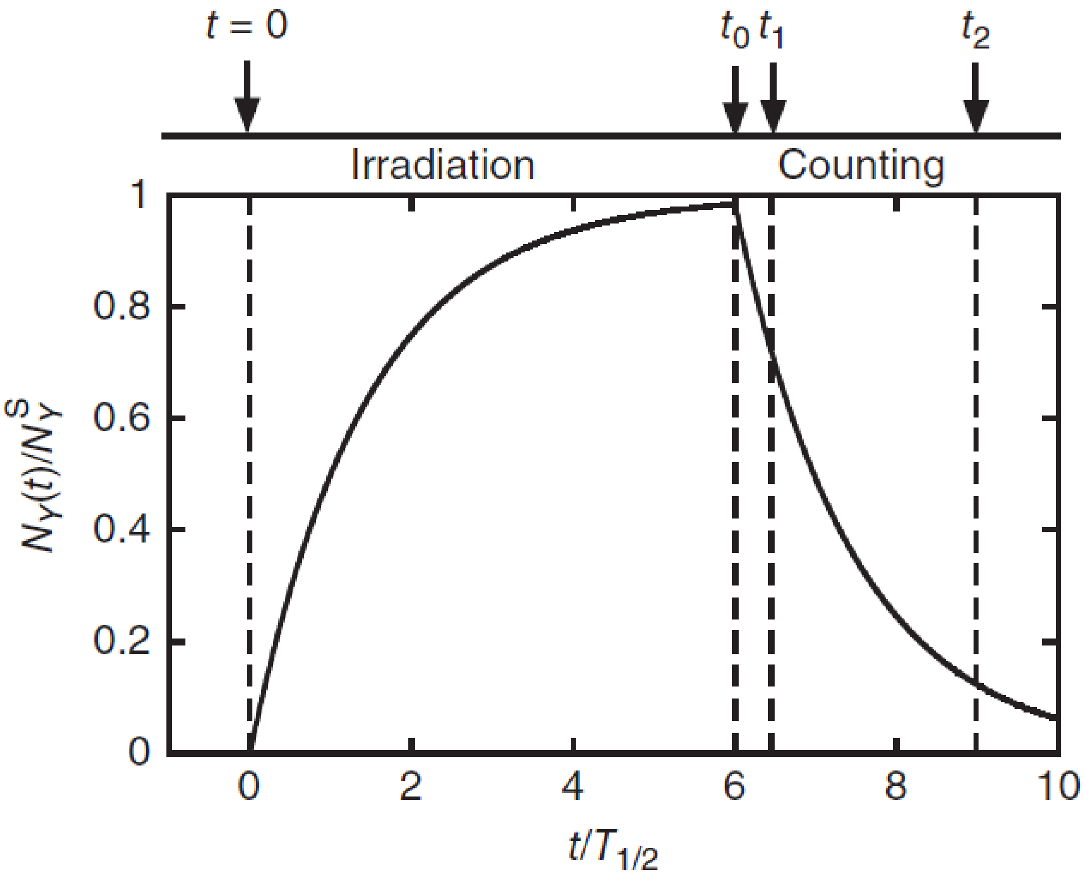
Activation method



Two-step process useful for (n,γ) reactions with radioactive products: (a) irradiate sample until saturation activity has been produced; (b) transport sample to count delayed radiation in another setup. Repeat.

Nuclear Physics of Stars, Iliadis, 2nd Ed.

Activation method

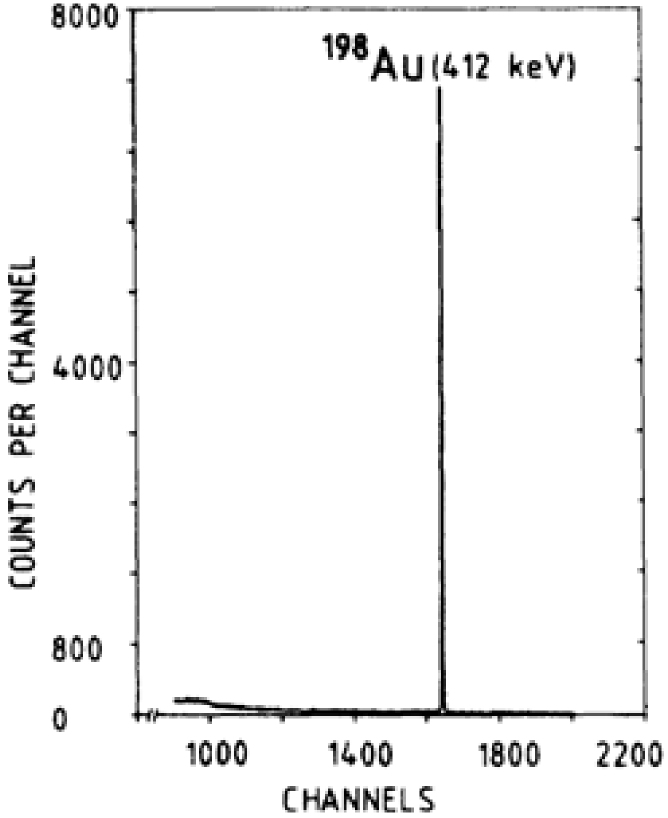


Two-step process useful for (n,γ) reactions with radioactive products: (a) irradiate sample until saturation activity has been produced; (b) transport sample to count delayed radiation in another setup. Repeat.

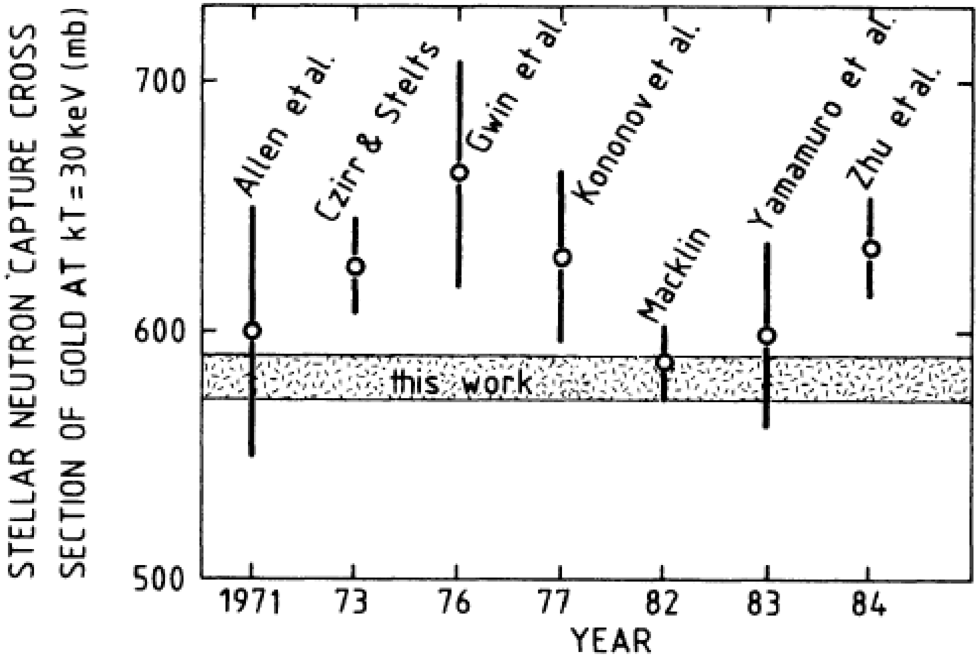
Nuclear Physics of Stars, Iliadis, 2nd Ed.

Example: $^{197}\mathrm{Au}(n,\gamma)^{198}\mathrm{Au}$

Activation spectrum:

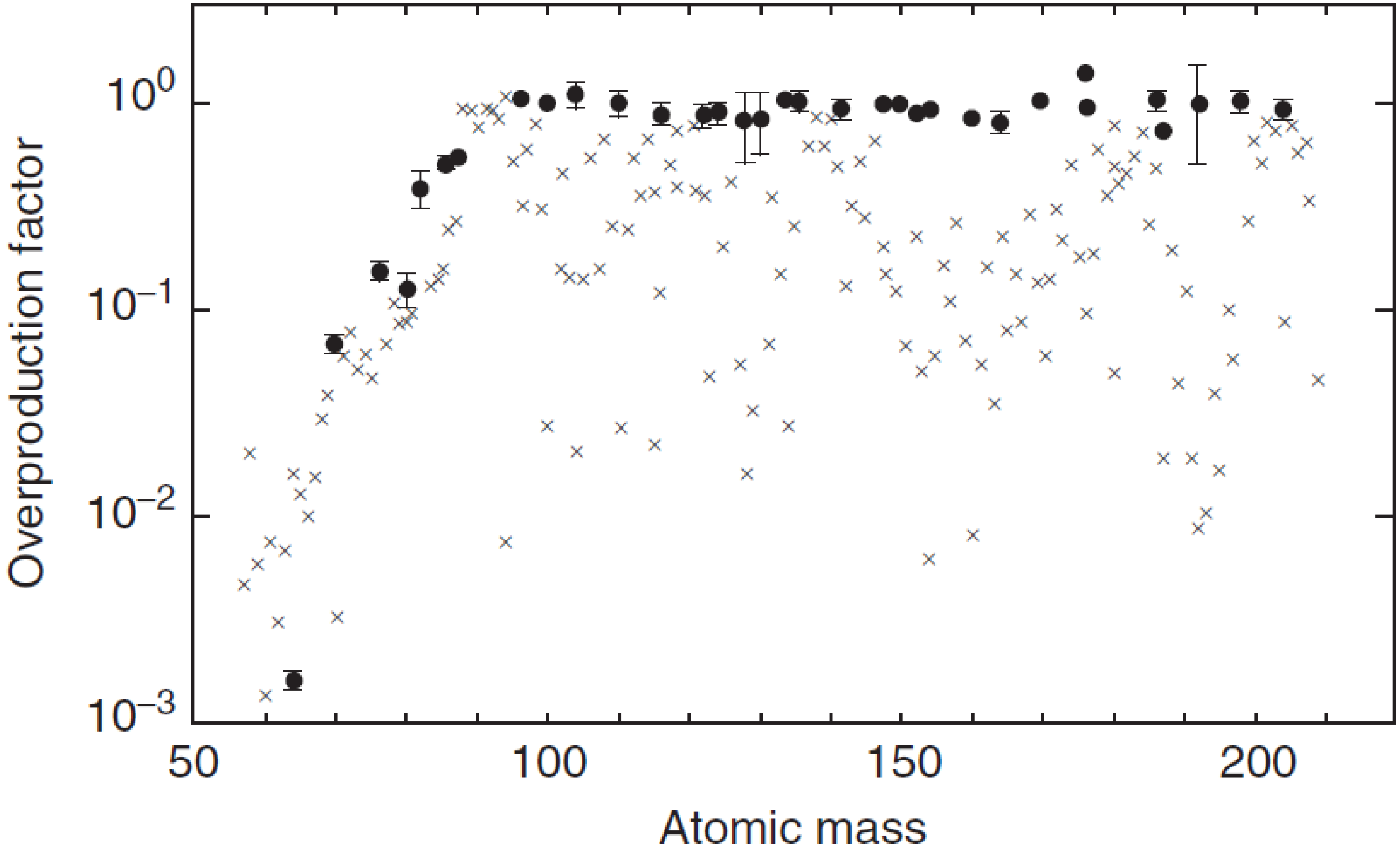


Cross section:



$^{197}\mathrm{Au}(n,\gamma)^{198}\mathrm{Au}$ cross section measured to 1.5% precision in Karlsruhe, Germany

s process works!



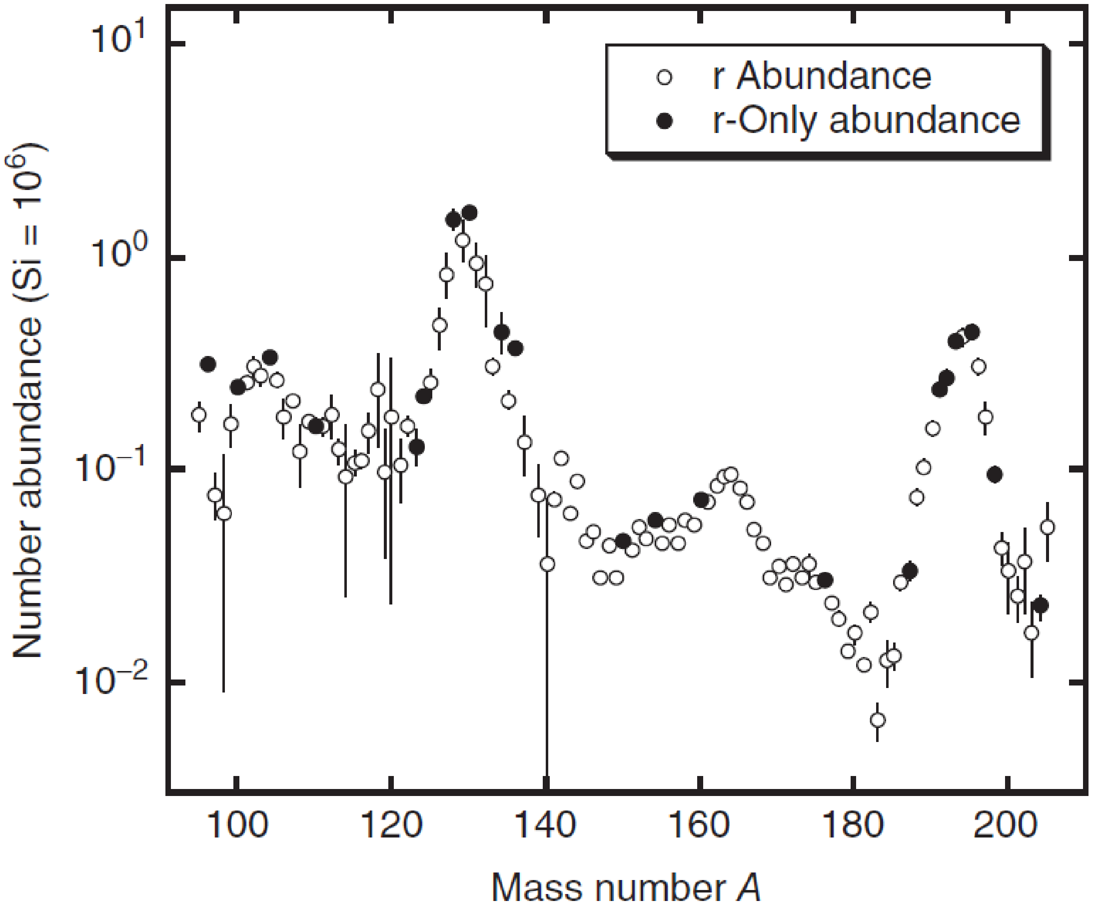
Black circles:
s-only nuclides

Grey crosses:
other nuclides

Overproduction factor: ratio of predicted abundance to Solar System abundance, normalized to ^{150}Sm

Nuclear Physics of Stars, Iliadis, 2nd Ed.

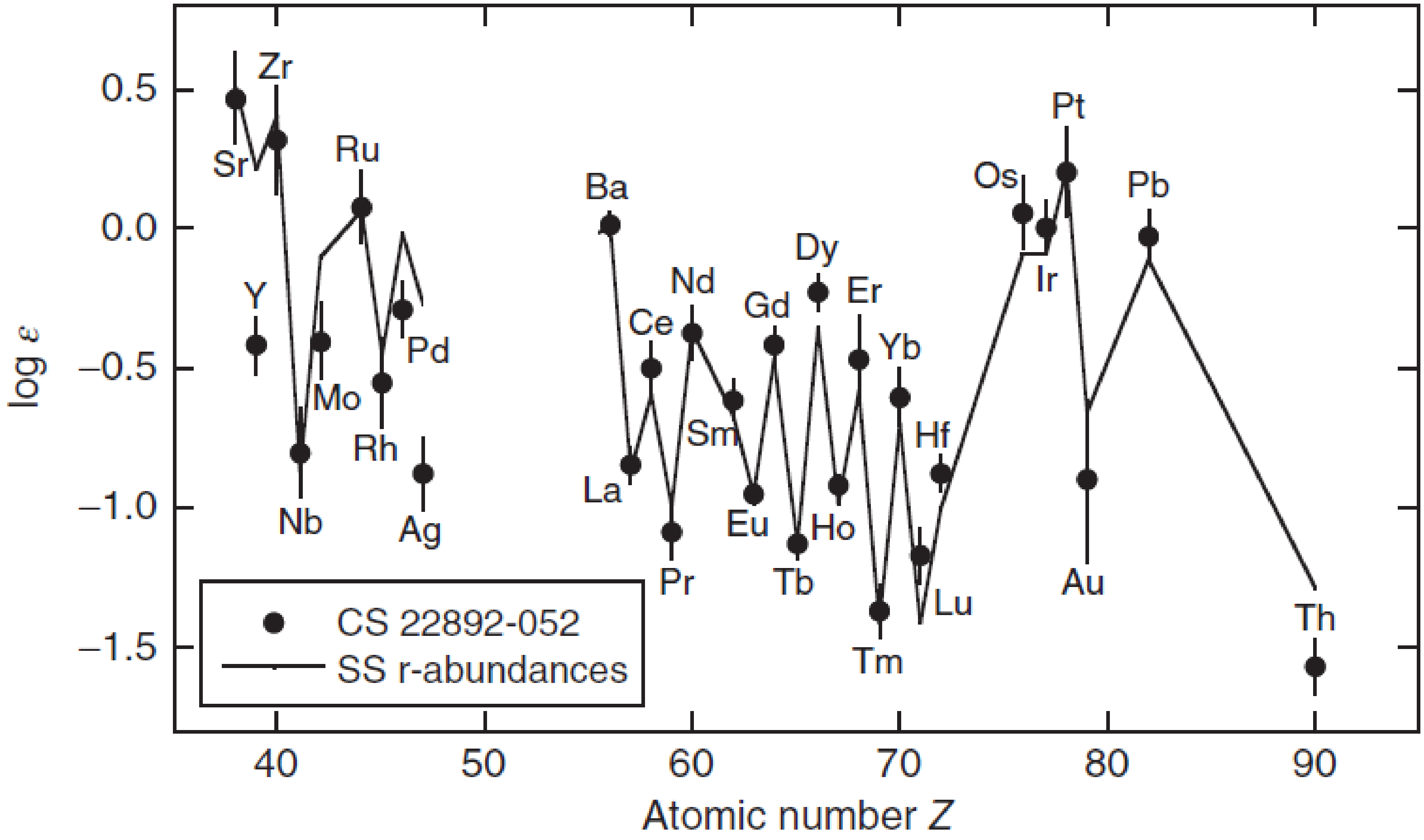
Solar System r-process abundances



Obtained by subtracting s-process abundances

Nuclear Physics of Stars, Iliadis, 2nd Ed.

r process in metal-poor stars



Main r-process pattern identical over billions of years! What is the site?

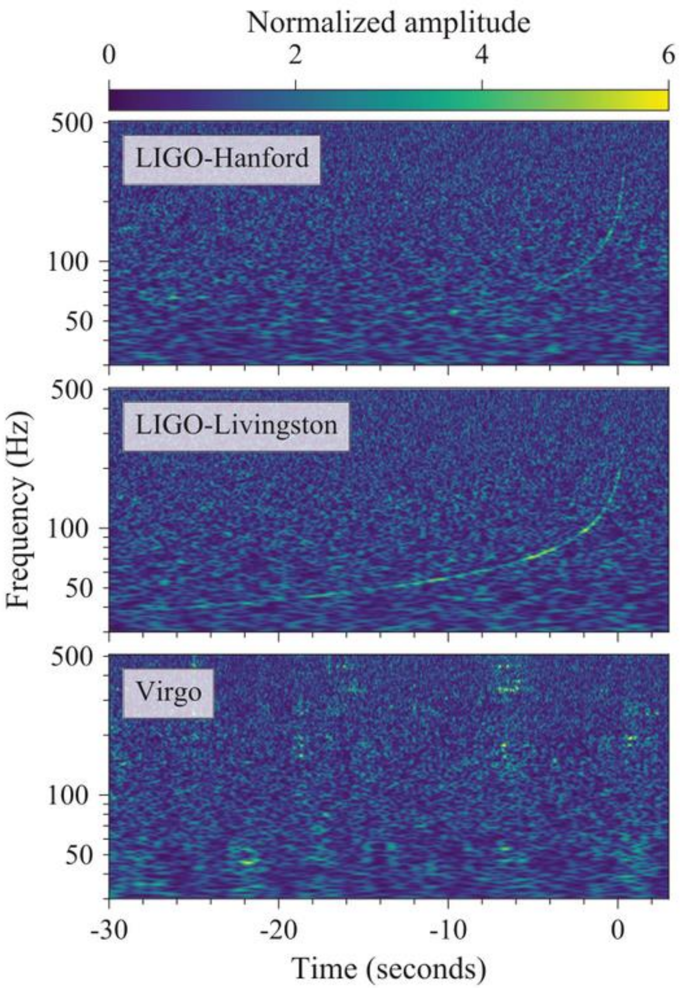
Nuclear Physics of Stars, Iliadis, 2nd Ed.

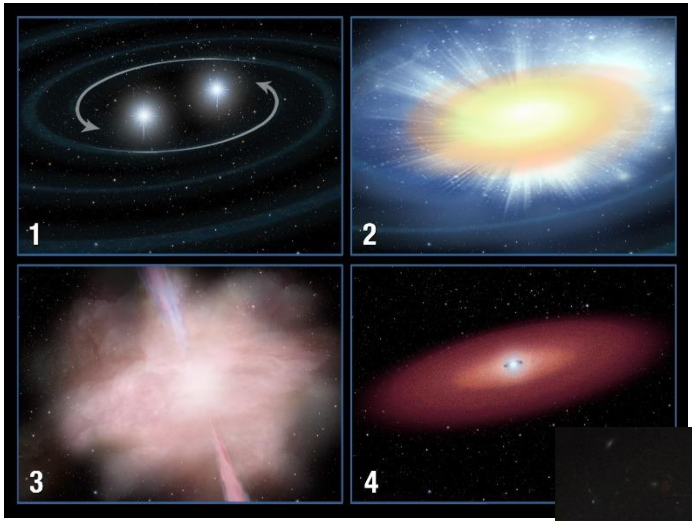
r-process site(s):

Neutron-star mergers!

Type II supernovae?

LIGO GW170817





Model: merging neutron stars

→ r-process

→ Kilonova

Kilonova observed!

https://www.aldebaran.cz/bulletin/2017_36/kilonova.jpg
Metzger, 2010
Wikipedia

r process: nuclear data needed

_Q_ values for (n,γ) reactions

β^- decay half lives

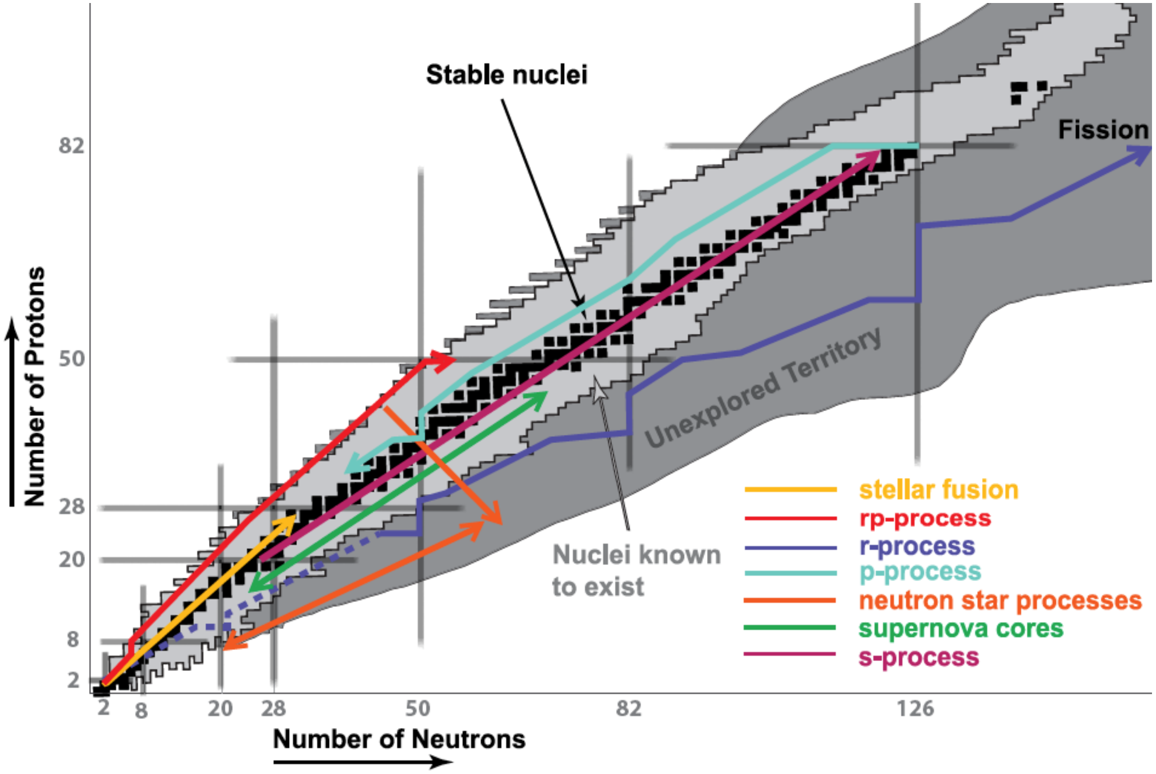
β^- delayed neutron emission

Partition functions

Fission probabilities

α-decay half lives

(n,γ) reaction rates



Generally, these properties are not known experimentally: need RIBs (eg. FRIB)

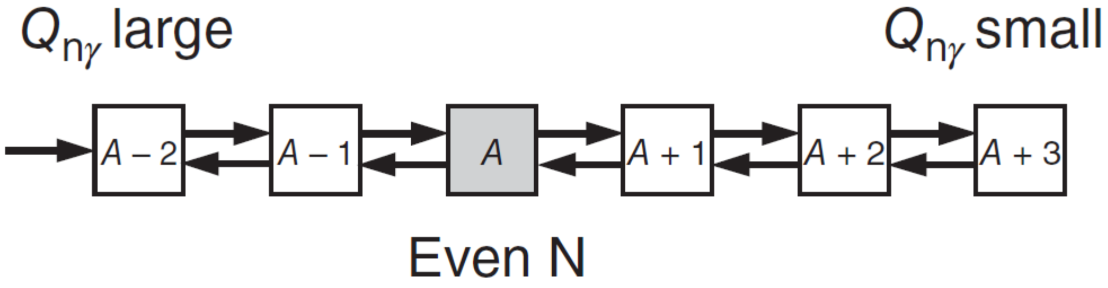
Nuclear masses: importance

Nuclear masses play a role in the determinations of most of nuclear properties needed to model the r process.

Most directly: if in (n,γ)-(γ,n) equilibrium then successive application of the Saha equation along isotopic chain yields general expression for number density of isotope x_m, which is m neutron captures away from isotope x_0:

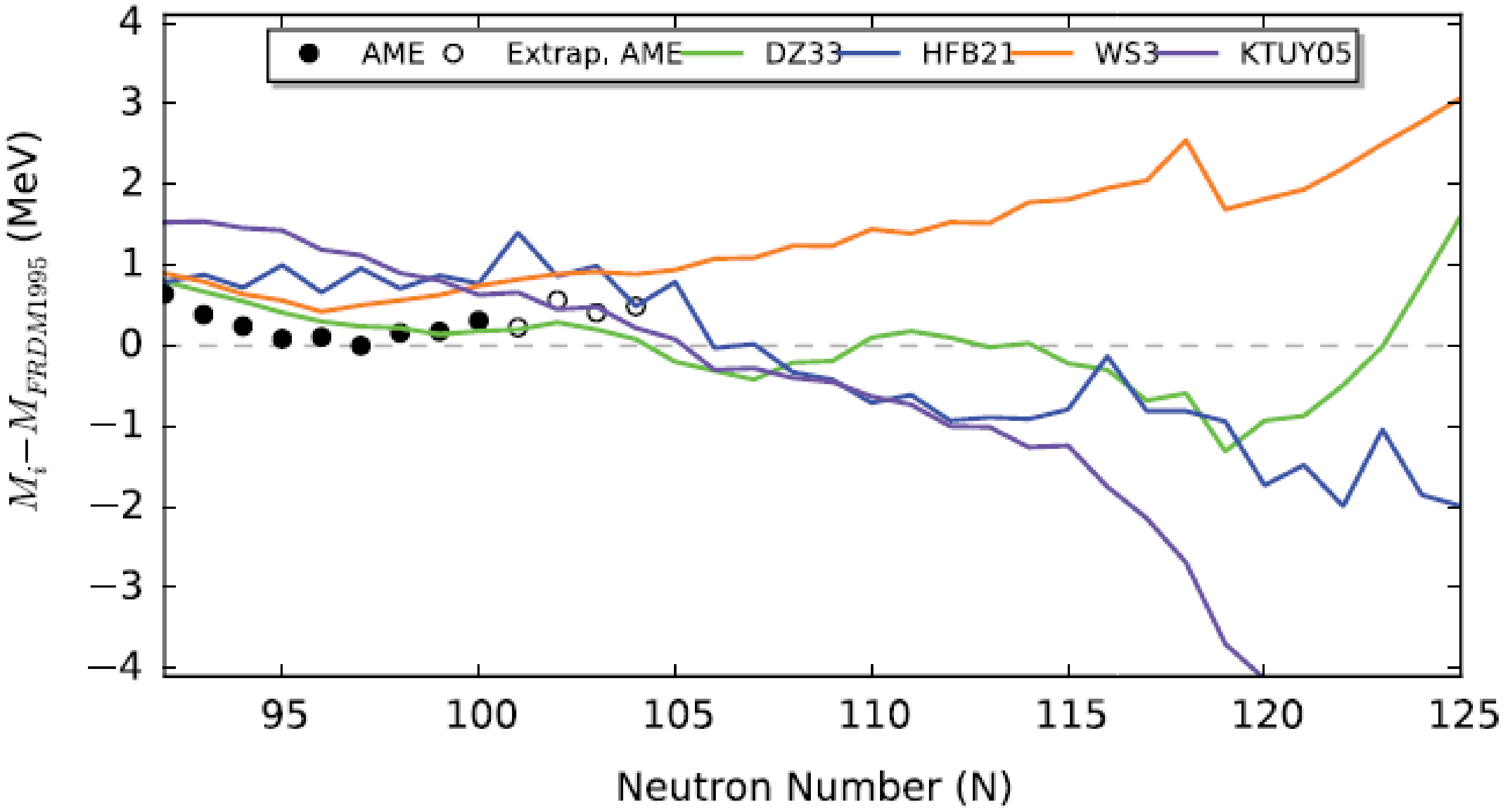
$$N_{x_m} \approx N_{x_0} \left(\frac{N_\mathrm{n}}{1.188 \times 10^{34} T_9^{3/2}} \right)^m \exp\left[\frac{11.605}{T_9} \sum_{j=0}^{m-1} Q_{x_j(\mathrm{n},\gamma)} \right]$$

Due to decrease of $Q_{n\gamma}$ as neutron drip line is approached and odd-even-N staggering, maximum abundance occurs at a particular even-N isotope with optimal $Q_{n\gamma}$ (given T, N_n).



Nuclear Physics of Stars, Iliadis, 2nd Ed.

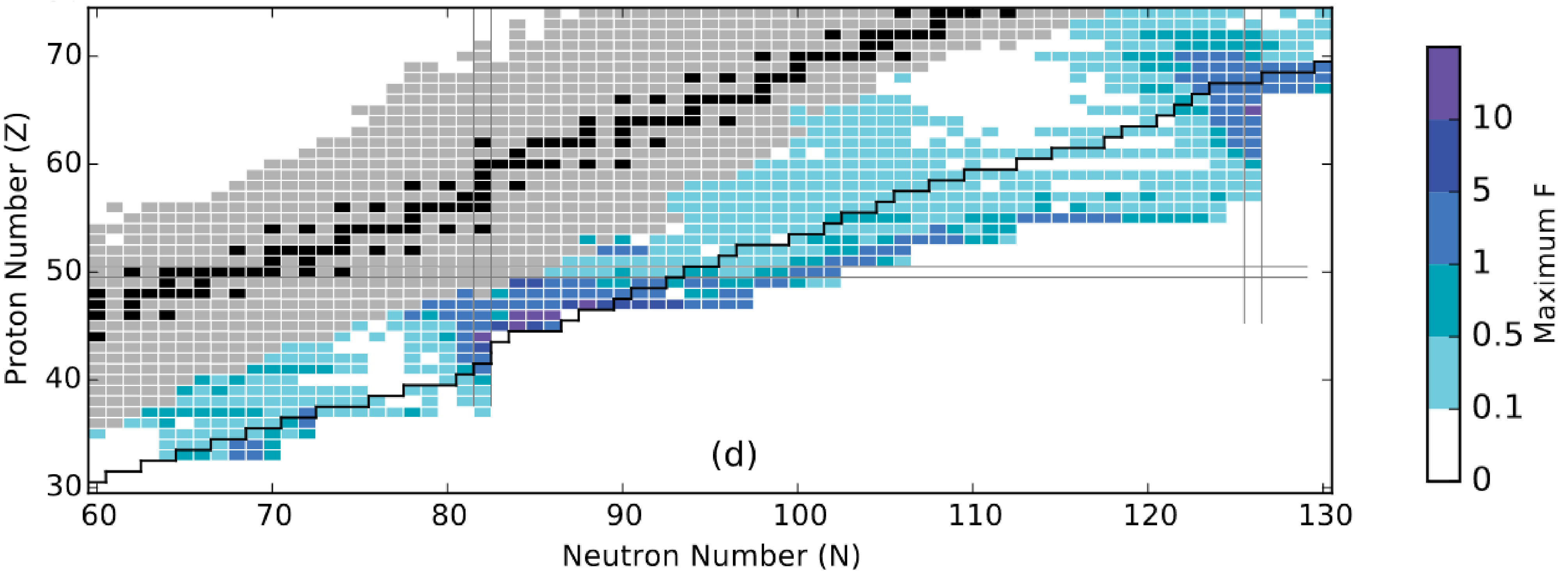
Europium isotope masses



Nuclear theory don't predict consistent masses: need to measure them!

Mumpower *et al.*, PNPP 86, 86 (2016)

r-process mass sensitivity



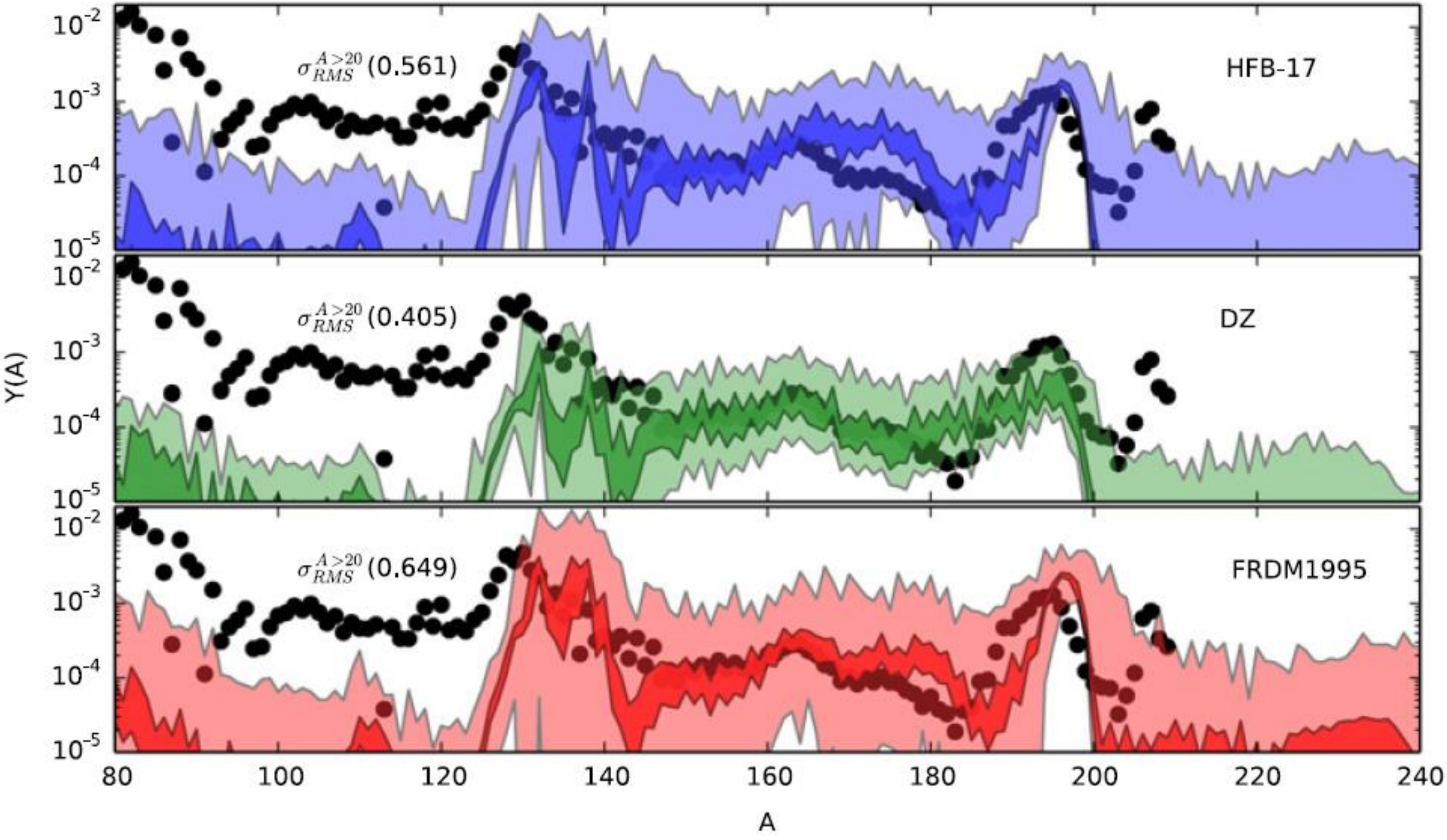
Black squares: stable nuclides

Grey squares: nuclides with measured masses in 2013 Atomic Mass Evaluation

Colored squares: nuclides with unmeasured masses affecting r-process abundances

Mumpower *et al.*, PNPP 86, 86 (2016)

r-abundances from theoretical masses



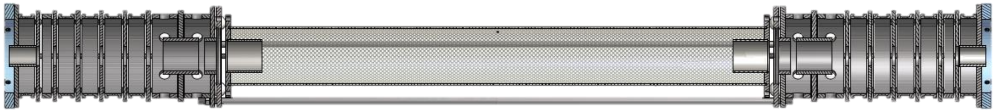
Need to measure masses to about 100 keV uncertainty (darker-shaded bands)

Mumpower *et al.*, PNPP 86, 86 (2016)

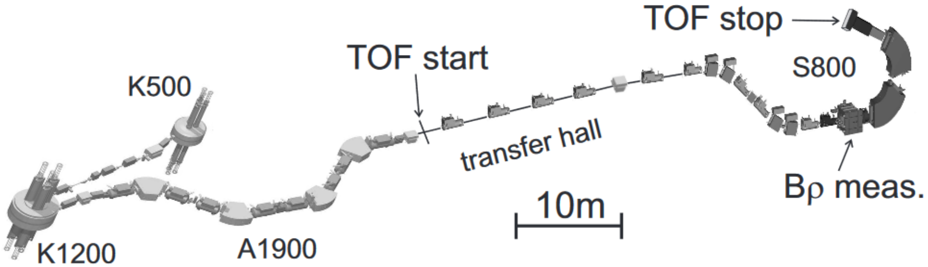
Nuclear masses: experimental approaches

Penning traps

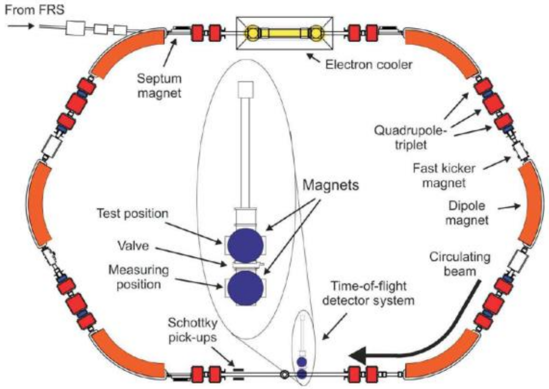
MR-ToF



ToF-Bρ

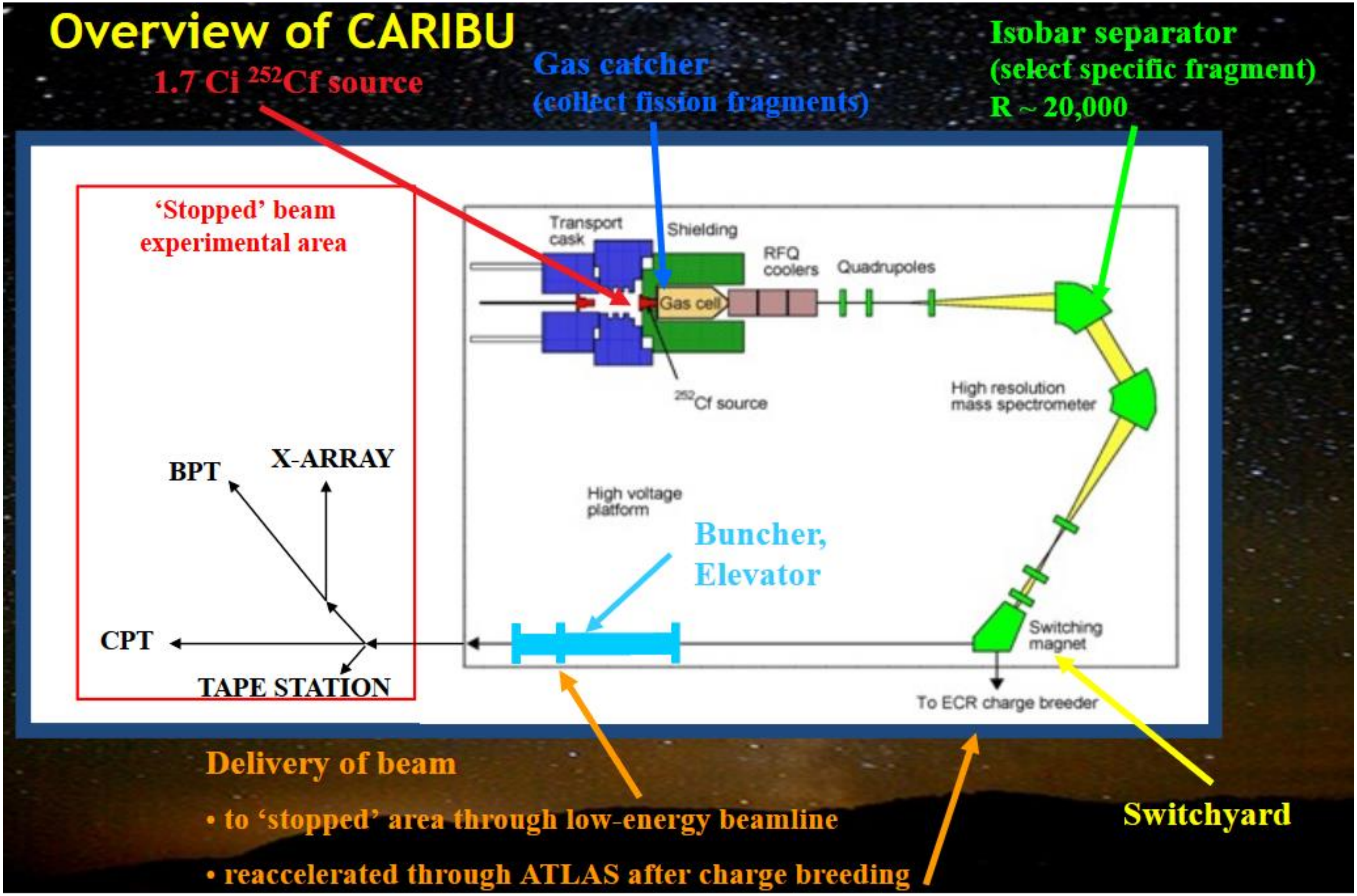


Storage ring



FRIB researchers will employ most (or all) of the approaches above

Example: CARIBU + CPT at ANL



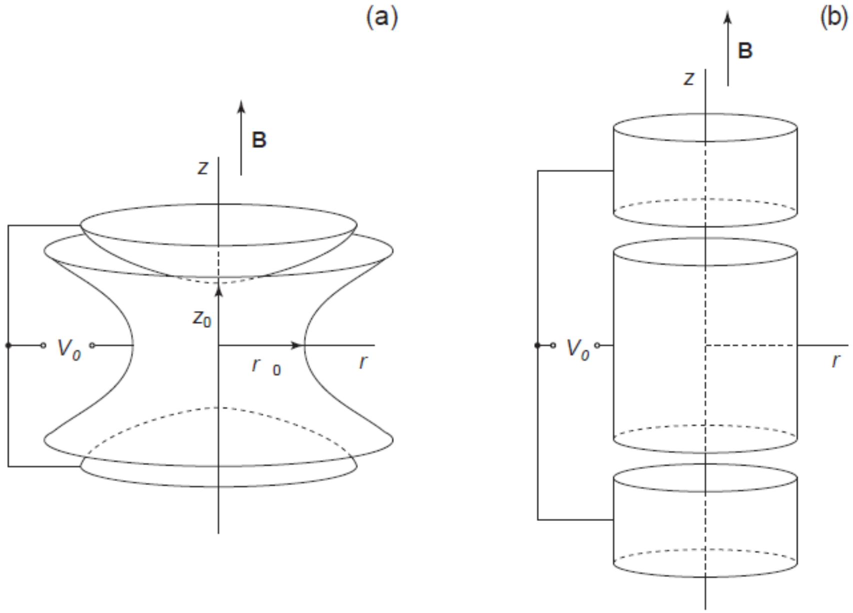
Overview of CARIBU

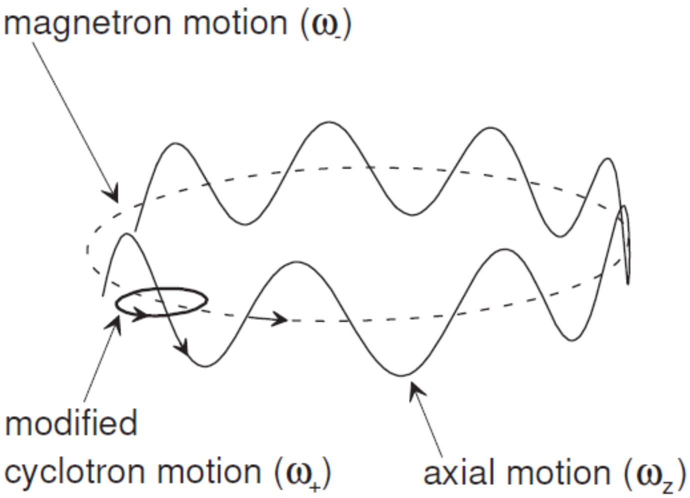
Delivery of beam

- to 'stopped' area through low-energy beamline
- reaccelerated through ATLAS after charge breeding

J. A. Clark

Example: CPT at ANL





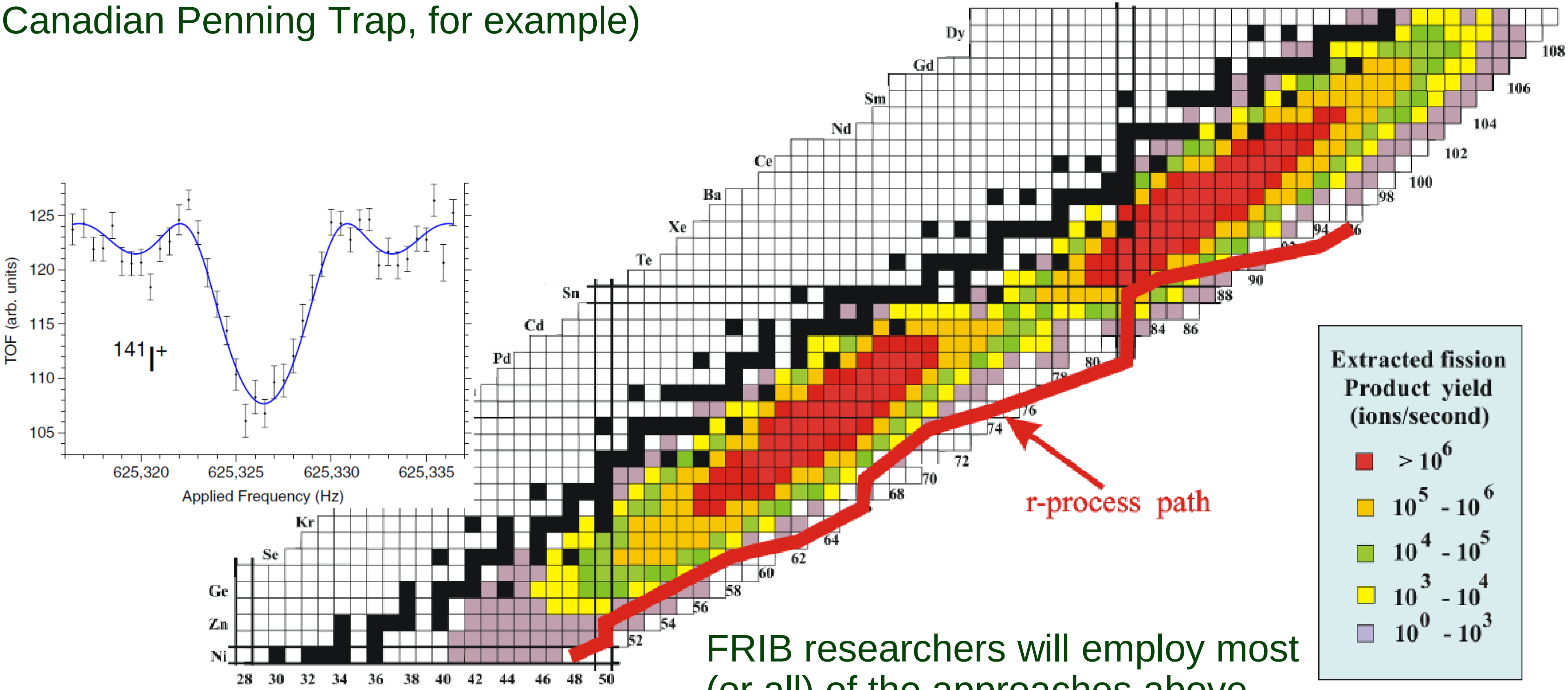
$$\omega_z = \sqrt{\frac{qV_0}{md^2}}$$

$$\omega_\pm = \frac{\omega_c}{2} \pm \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

C. Weber

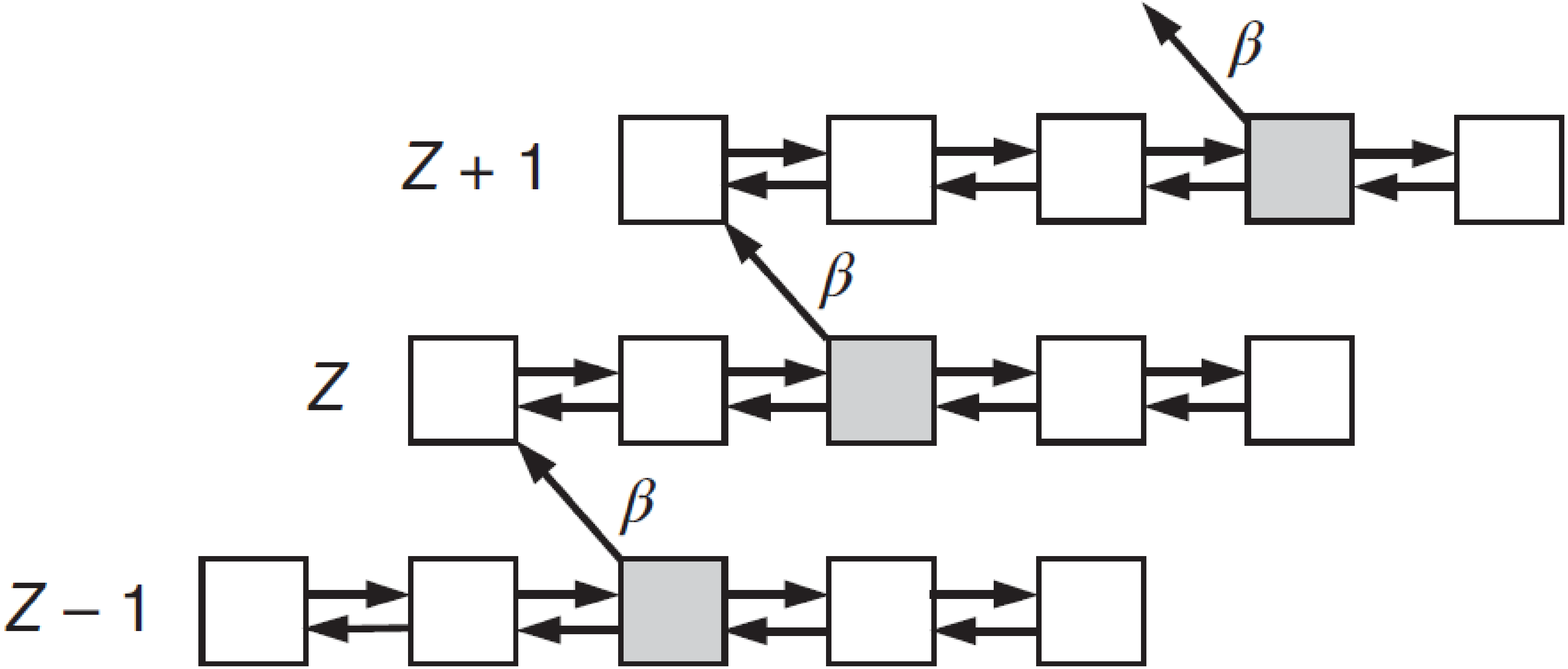
Nuclear masses: Penning trap

Example: fission of 1 Ci ^{252}Cf source at Argonne National Lab's ATLAS facility is projected to produce 500 neutron-rich species at a rate of >1/s (sufficient for mass measurements with the Canadian Penning Trap, for example)



FRIB researchers will employ most (or all) of the approaches above

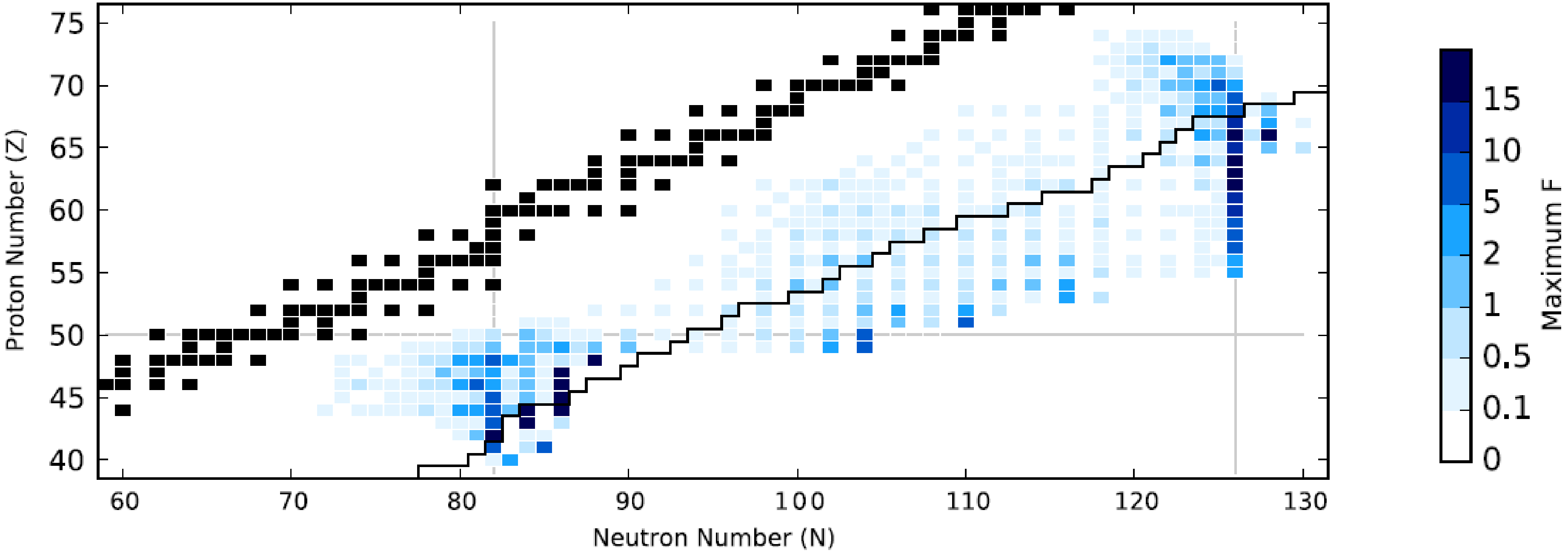
Beta decay half lives: importance



Beta decay transfers material to next isotopic chain, where equilibrium is established again. Gives rise to r process path.

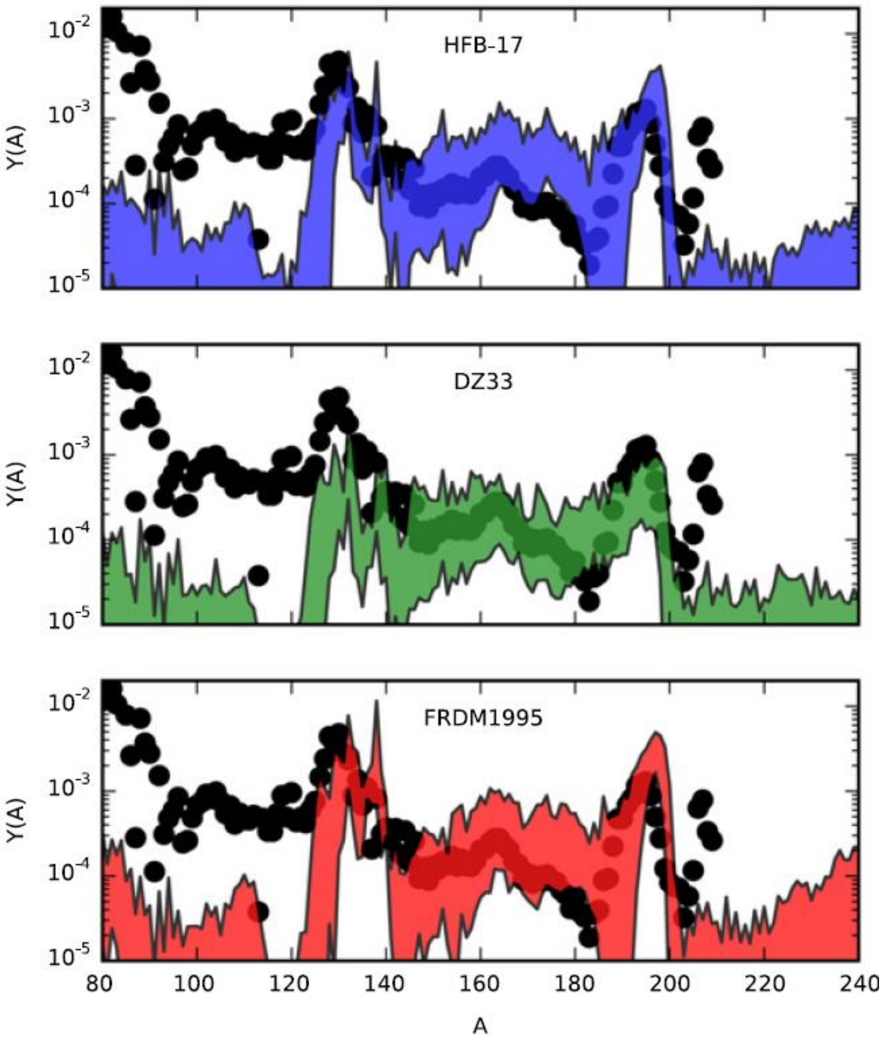
Nuclear Physics of Stars, Iliadis, 2nd Ed.

r-process $T_{1/2}$ sensitivity



Mumpower *et al.*, PNPP 86, 86 (2016)

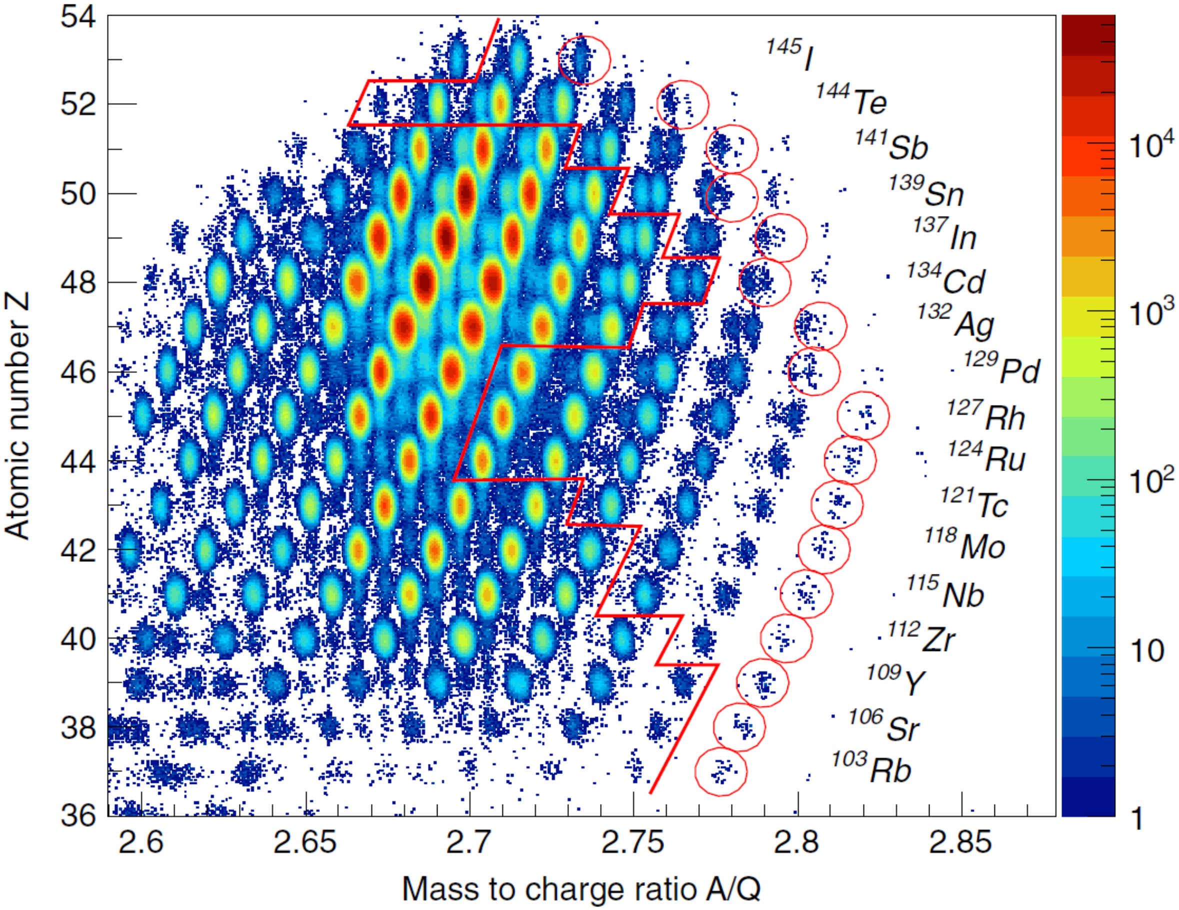
r-abundances from theoretical $T_{1/2}$



Need to measure half lives, too!

Mumpower *et al.*, PNPP 86, 86 (2016)

Beta decay half lives: experiments

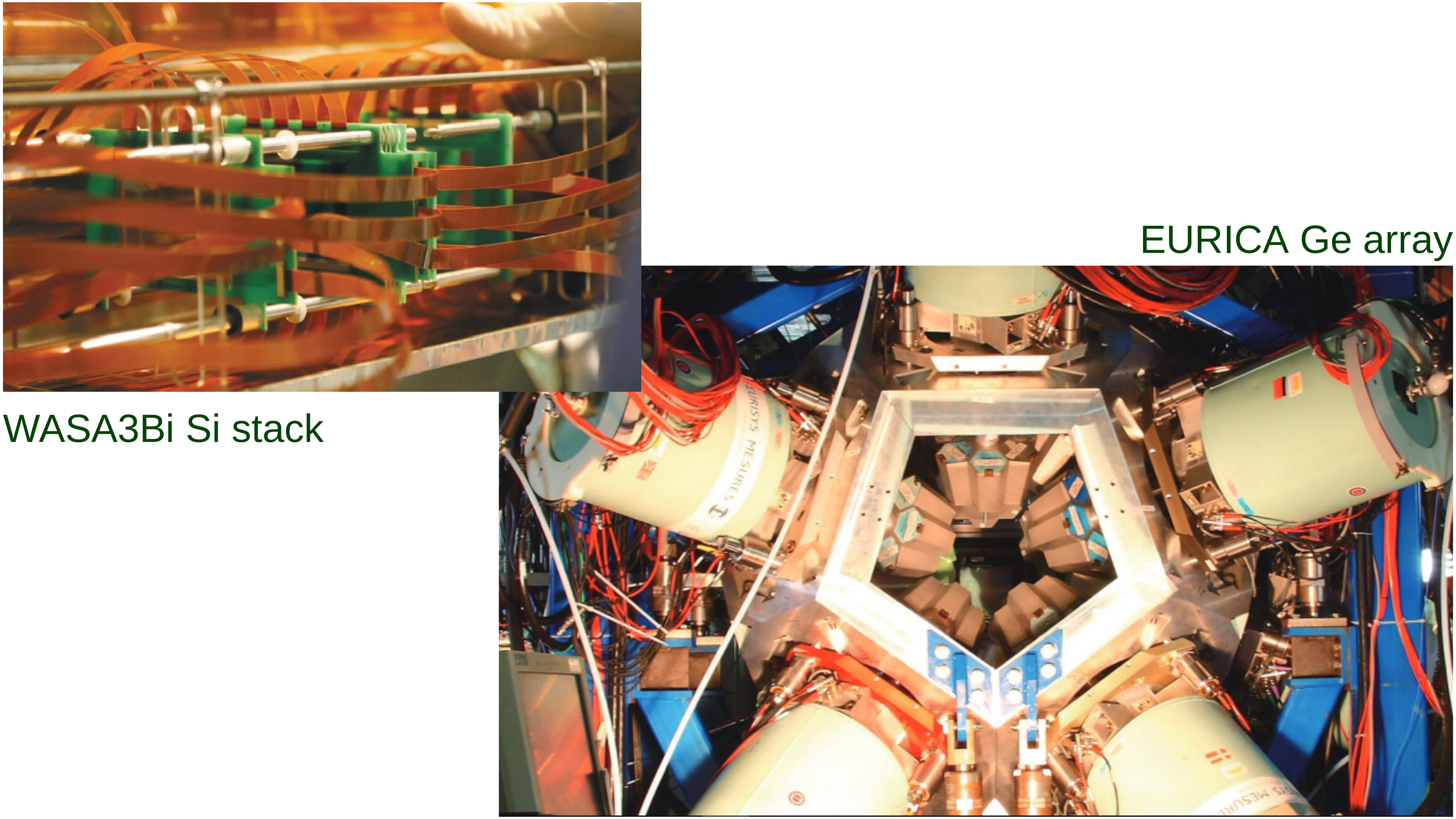


Can be measured in bulk given RIB rates of a few per day.

Example: fast beams produced by in-flight fission of ^{238}U at RIKEN.

G. Lorusso *et al.*, Phys. Rev. Lett.114, 192501 (2015)

RIKEN RIBF $T_{1/2}$ measurements

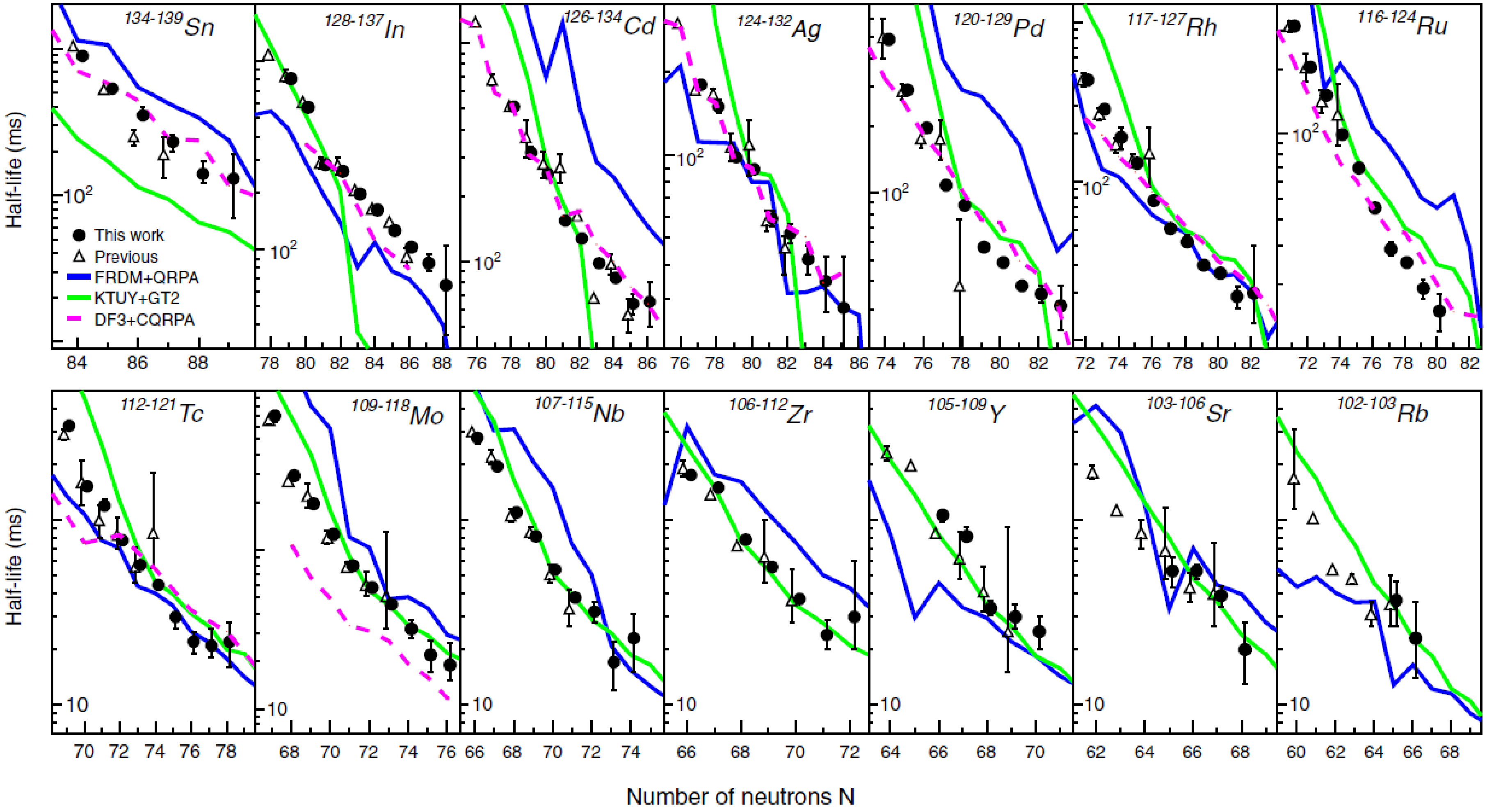


EURICA Ge array

WASA3Bi Si stack

G. Lorusso *et al.*, Phys. Rev. Lett.114, 192501 (2015)

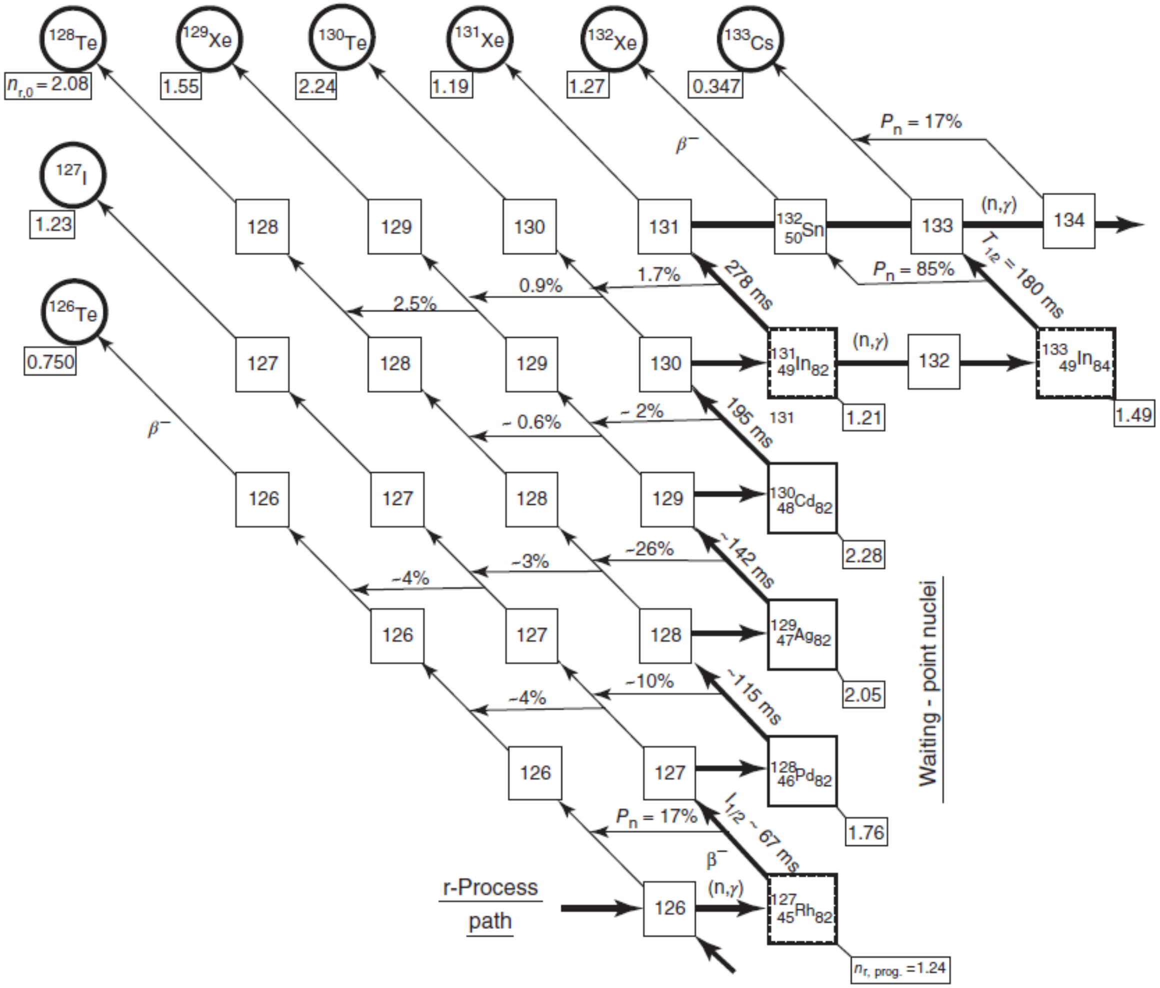
RIKEN RIBF $T_{1/2}$ measurements



$T_{1/2}$ of 110 neutron-rich nuclides were measured including 40 new ones in the vicinity of *N* = 82 r-process waiting point. Sensitivity to nuclides with $T_{1/2}$ as low as 15 ms.

G. Lorusso *et al.*, Phys. Rev. Lett.114, 192501 (2015)

Beta delayed neutron emission: importance



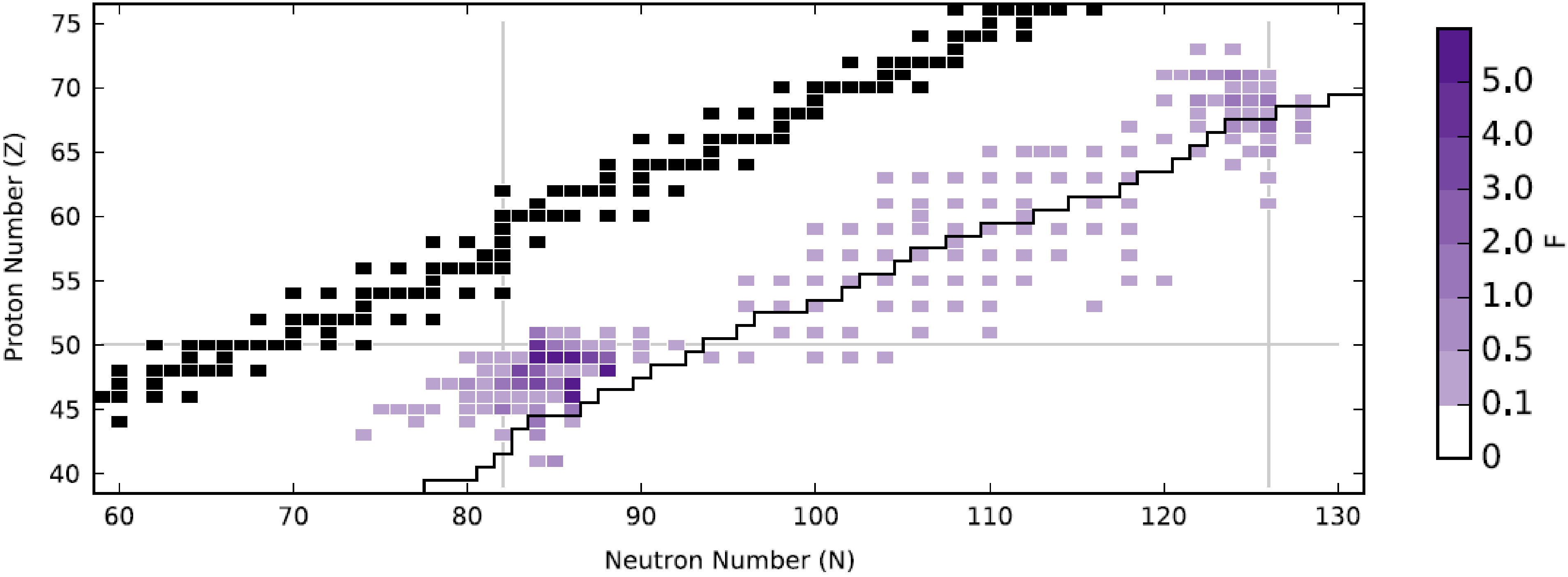
When r process ends, material beta decays back to stability to form the r-process abundance pattern.

Beta decays can’t be assumed to proceed along an isobaric chain because beta-delayed neutron emission branch can be significant.

Example: interpretation of *A* = 130 abundance peak is influenced by probabilities of beta delayed neutron emission, P_n.

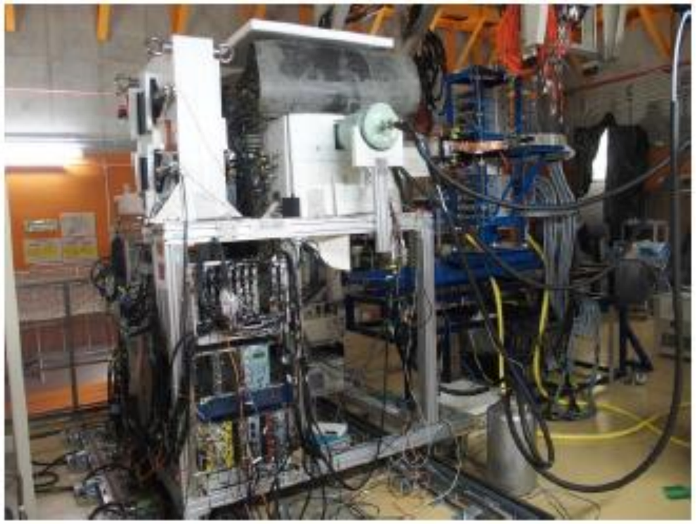
Nuclear Physics of Stars, Iliadis, 2nd Ed.

r-process P_n sensitivity



Mumpower *et al.*, PNPP 86, 86 (2016)

Beta delayed neutron emission: experiments



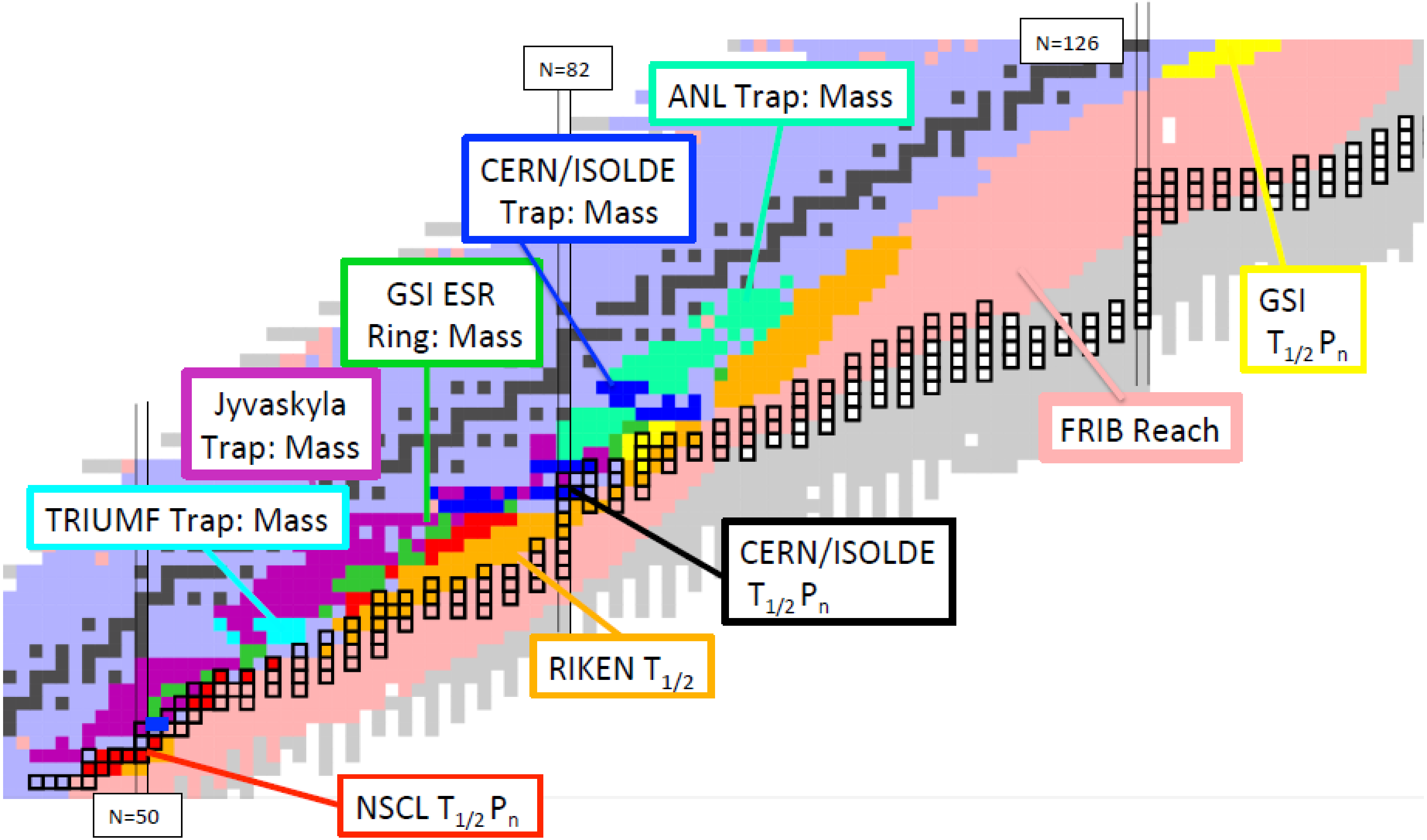
P_n can be measured directly.

Example: BRIKEN/AIDA setup at RIKEN. AIDA is Si strip array for RIB implantation and beta-particle detection. BRIKEN is a high-efficiency neutron detector.

Recent measurement by Estrade *et al*. will provide 25 new P_n values in the vicinities of ^{130}Ag and ^{149}Xe to investigate *A* =130 abundance peak.

Similar setups and measurements planned for FRIB.

Recent r-process measurements



Horowitz *et al.*, arxiv:1805.04637

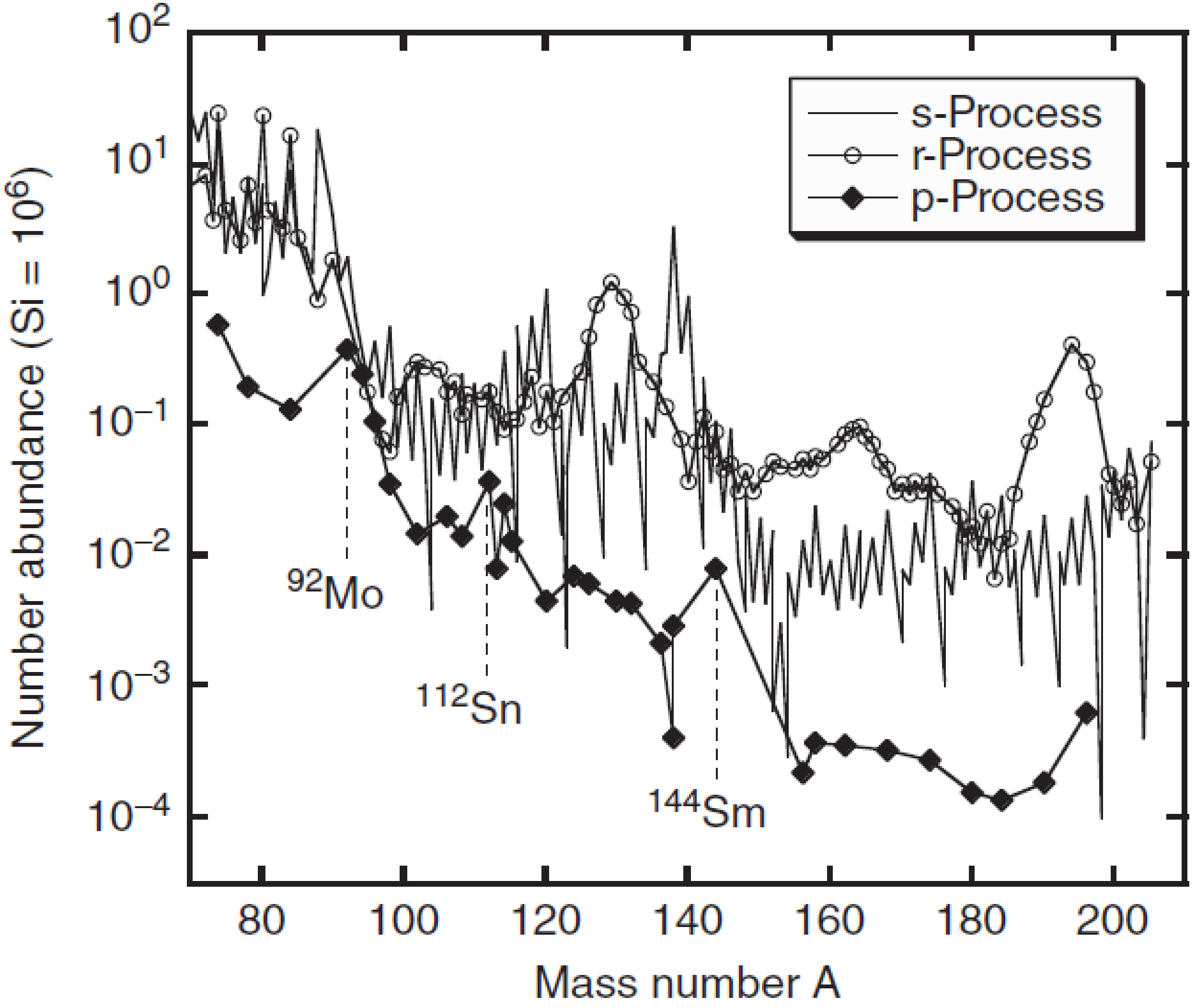
Things experimentalists won't be able to measure in detail/bulk anytime soon

Partition functions: Needed to augment ground-state decay constants with thermal excitations. Requires complete spectroscopy of the low-lying excited states of nuclides on the r-process path.

Fission probabilities: When r-process path runs close to the drip line, fission cycling becomes important. Region of interest (A~260, Z~94) is far from anything RIB facilities can produce in the near future. Instead, experimentalists will measure fission where they can and use that information to constrain theoretical models, which can then be applied to the r process.

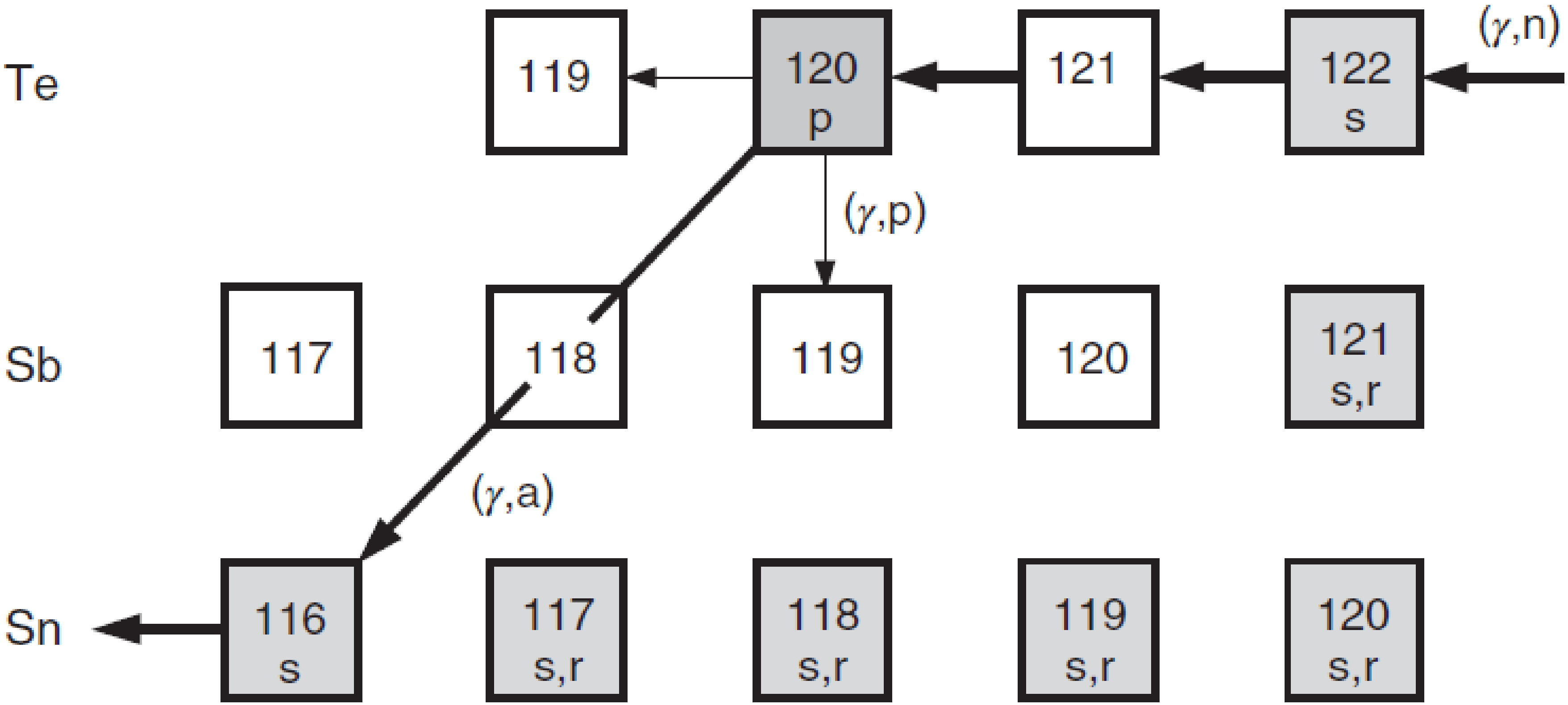
(n,γ) reaction rates: Important when there is no (n,γ)-(γ,n) equilibrium. Can't make a sufficiently dense neutron target for use with RIBs. Maybe one day our grandkids will be able to fill a bottle with Avogadro's number of ultra-cold neutrons. Until then, use indirect methods on selected reactions to constrain statistical-model calculations.

p process



Number abundance (Si = 10^6)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
s-Process
r-Process
p-Process
^{92}Mo
^{112}Sn
^{144}Sm
80
100
120
140
160
180
200
Mass number A

p process



Gamma process may produce p nuclides from s,r-process seeds in Type II supernovae

Can measure (p,γ) and (α,γ) reactions to learn about photodisintegrations

Nuclear Physics of Stars, Iliadis, 2nd Ed.

Thanks again for your attention!