Experiments in nuclear astrophysics II (neutron-induced)

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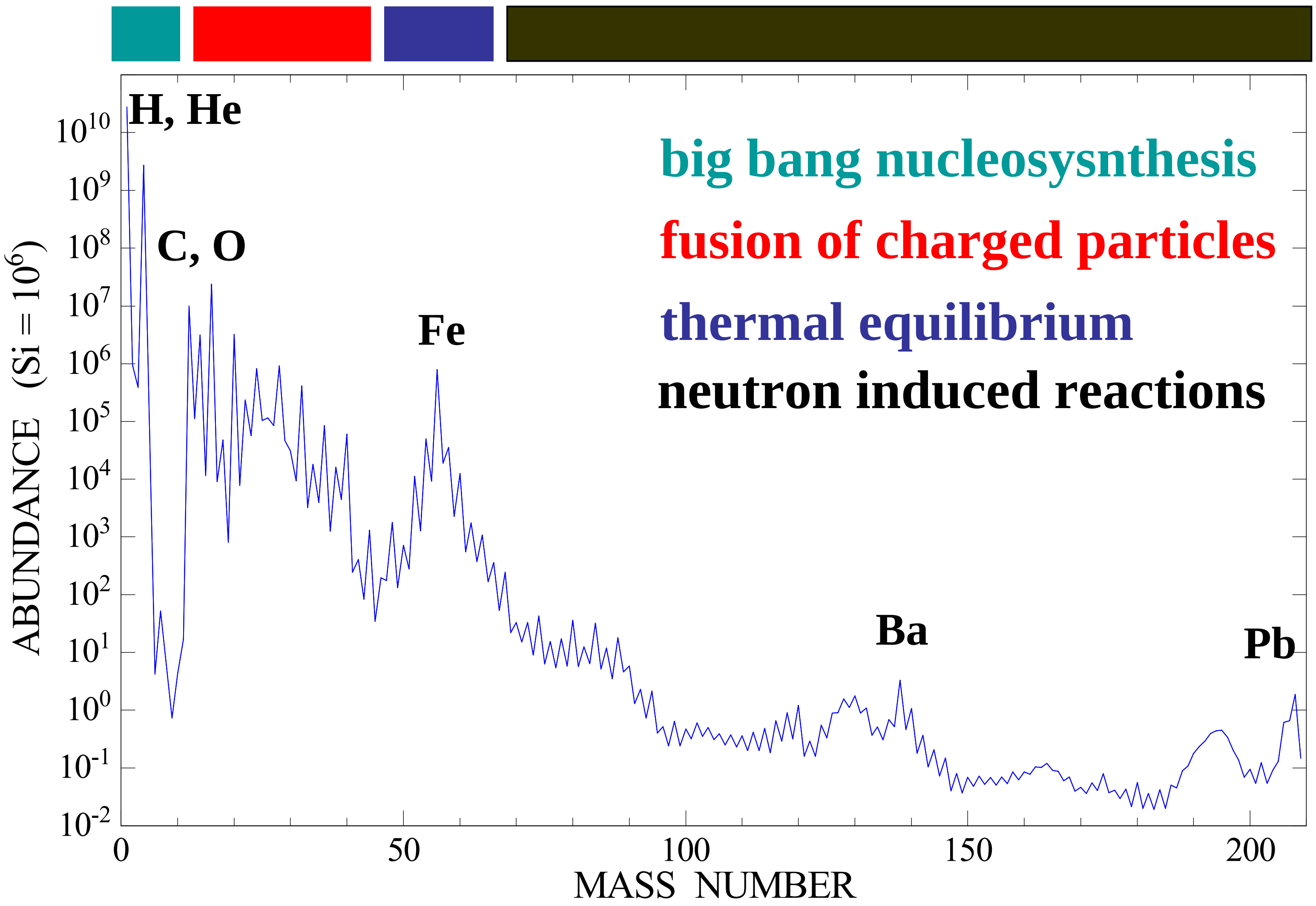
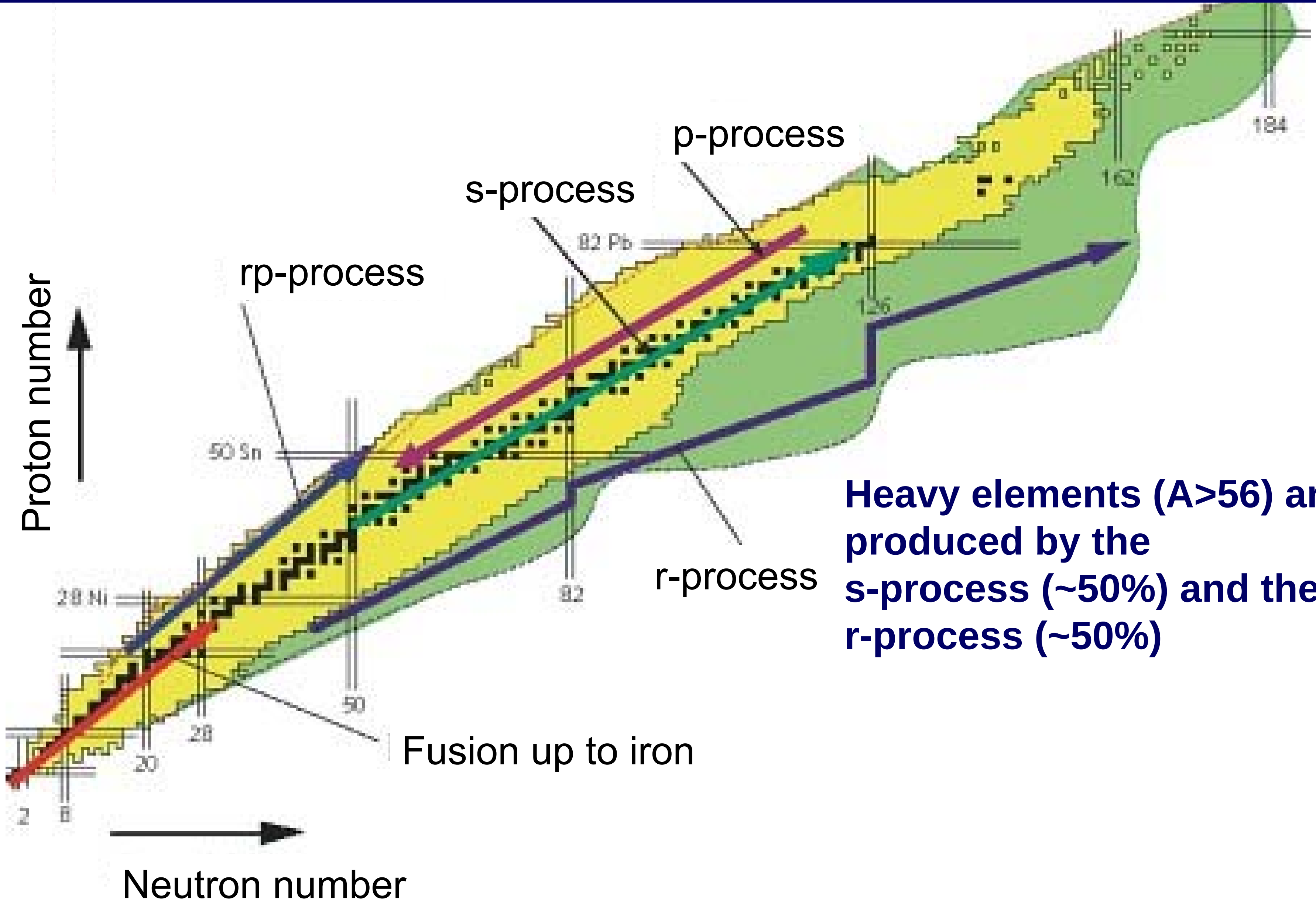
solar abundance distribution

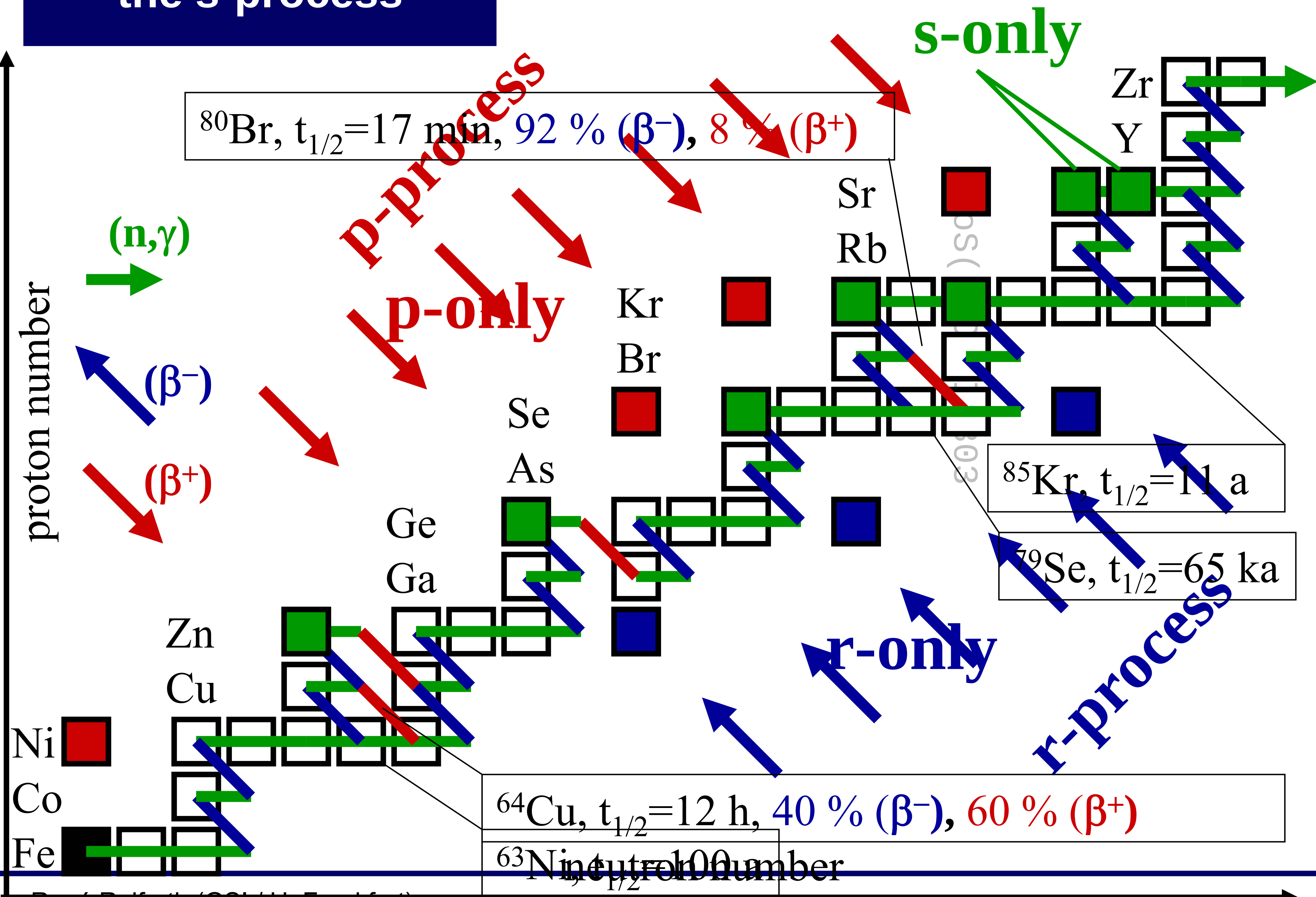


Nucleosynthesis of the elements

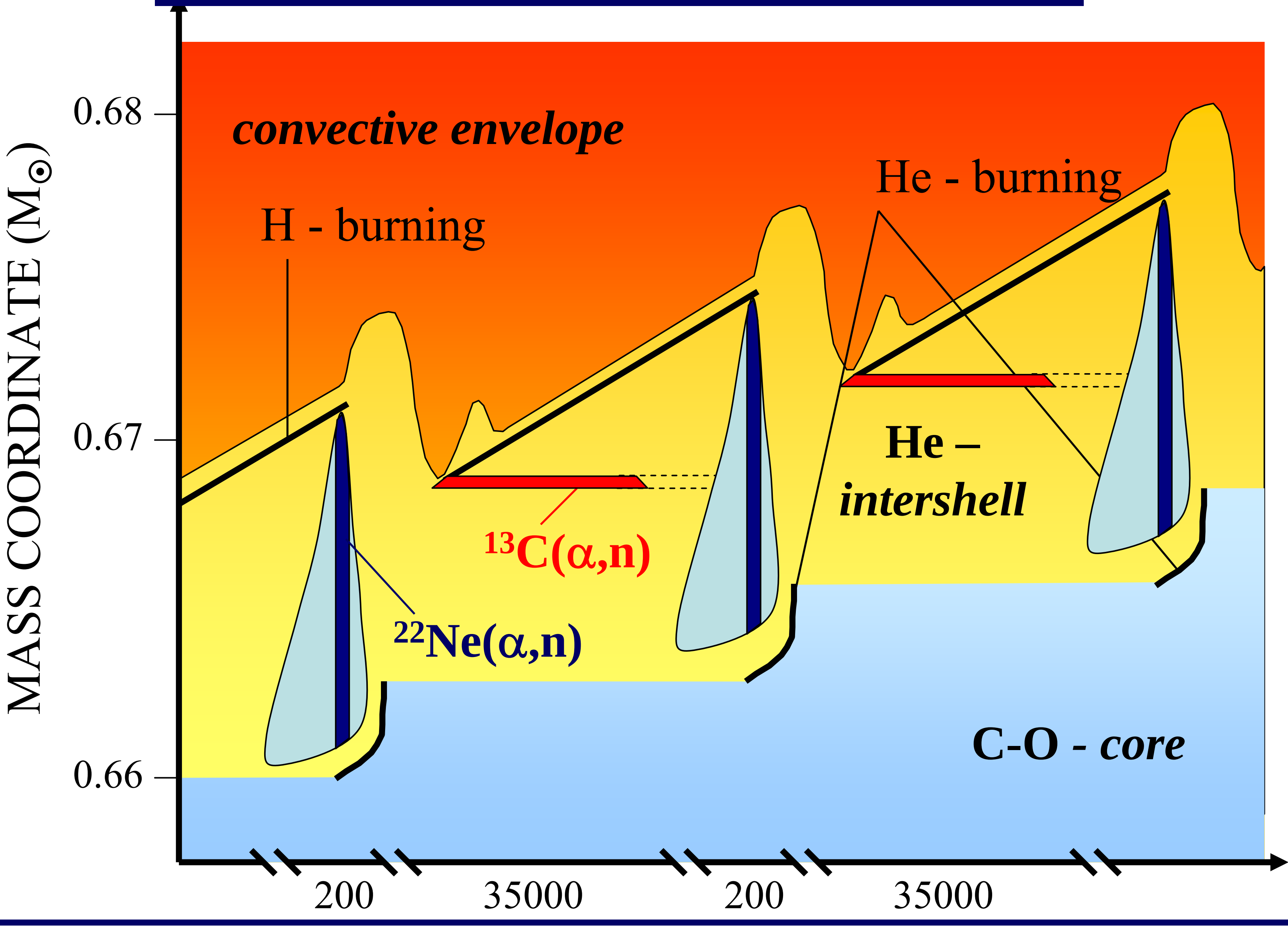


Heavy elements (A>56) are produced by the s-process (~50%) and the r-process (~50%)

the s-process



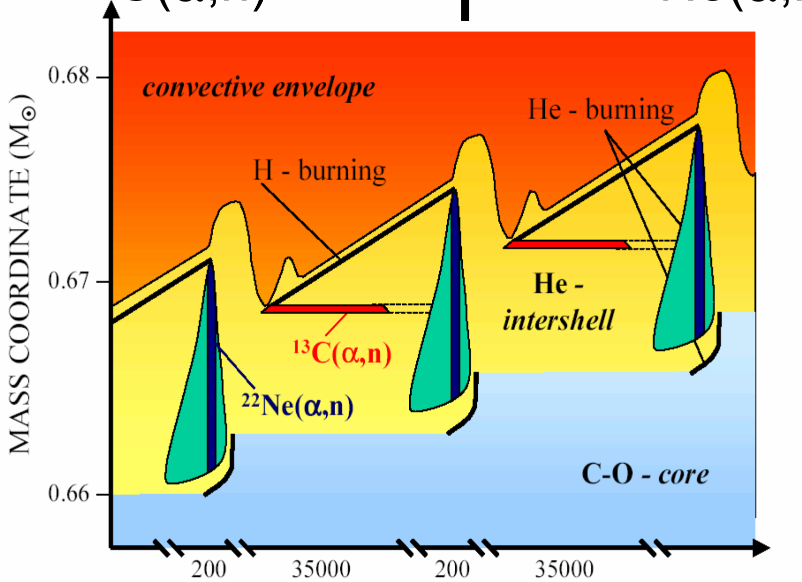
s-process in AGB stars

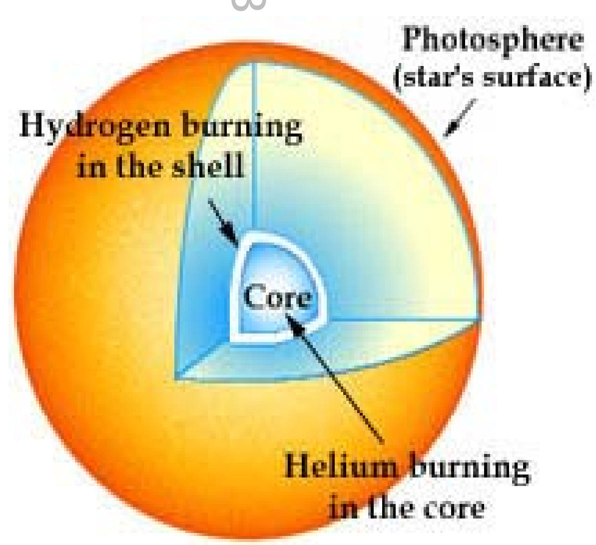


s-process nucleosynthesis

Two components were identified and connected to stellar sites:

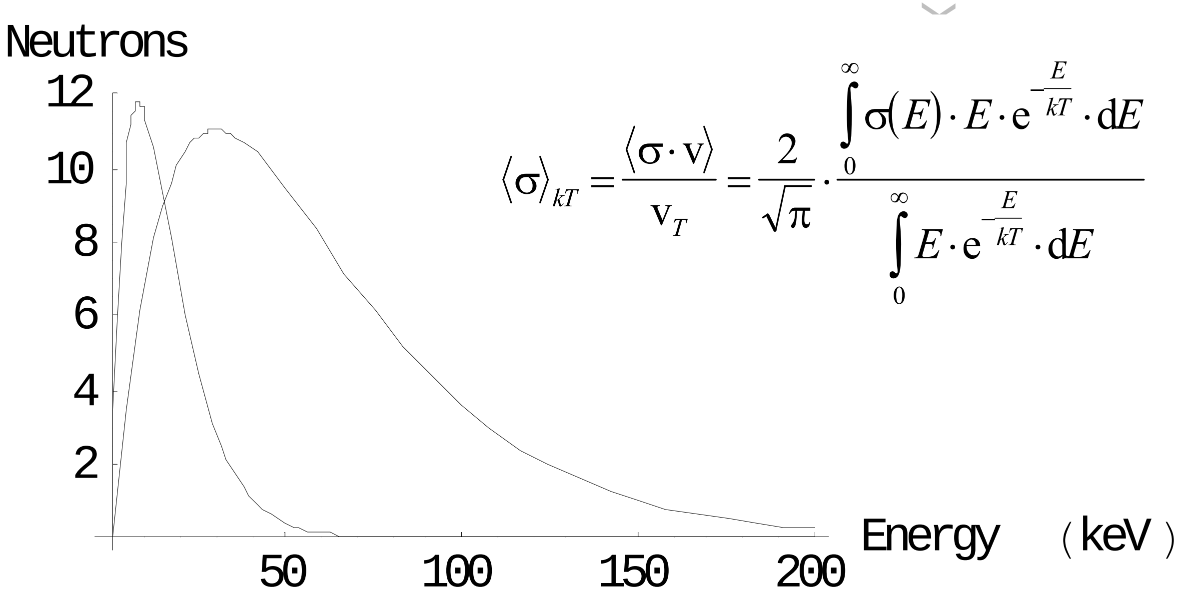
Main s-process 90<A<210		**Weak s-process A<90**	
TP-AGB stars 1-3 $M_\odot$		massive stars > 8 $M_\odot$	
shell H-burning $0.9 \cdot 10^8$ K	He-flash $3\text{-}3.5 \cdot 10^8$ K	core He-burning $3\text{-}3.5 \cdot 10^8$ K	shell C-burning $\sim 1 \cdot 10^9$ K
kT=8 keV $10^7\text{-}10^8$ cm^{-3}	kT=25 keV $10^{10}\text{-}10^{11}$ cm^{-3}	kT=25 keV 10^6 cm^{-3}	kT=90 keV $10^{11}\text{-}10^{12}$ cm^{-3}
$^{13}C(\alpha,n)$	$^{22}Ne(\alpha,n)$	$^{22}Ne(\alpha,n)$	





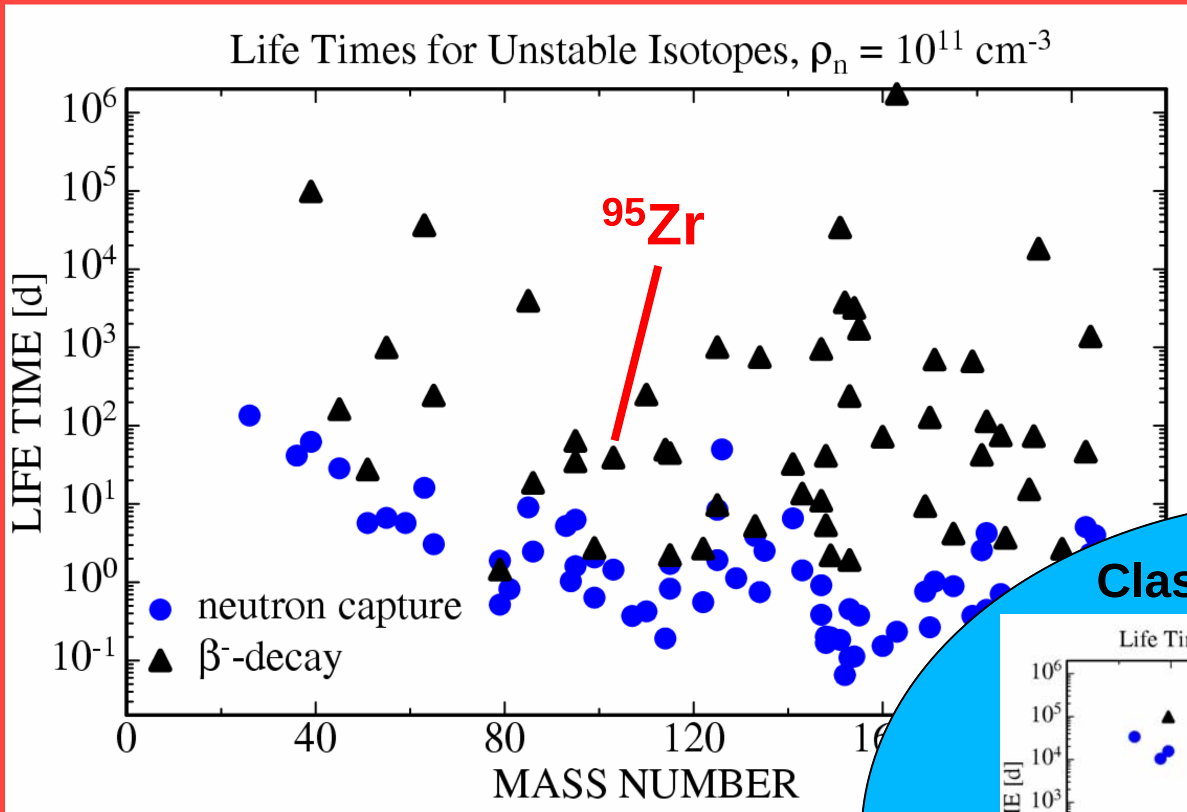
What's needed?

- Reaction rates
  - Neutron induced (1-200 keV)
  - Charged particles
- Half-lives



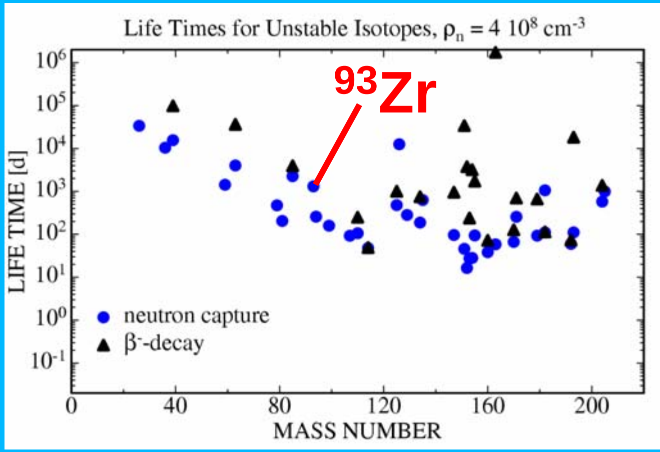
$$\langle\sigma\rangle_{kT} = \frac{\langle\sigma\cdot \mathrm{v}\rangle}{\mathrm{v}_T} = \frac{2}{\sqrt{\pi}}\cdot\frac{\int_0^\infty \sigma(E)\cdot E\cdot \mathrm{e}^{-\frac{E}{kT}}\cdot \mathrm{d}E}{\int_0^\infty E\cdot \mathrm{e}^{-\frac{E}{kT}}\cdot \mathrm{d}E}$$

Stellar model vs. experiment



Modern s-process models (AGB stars)

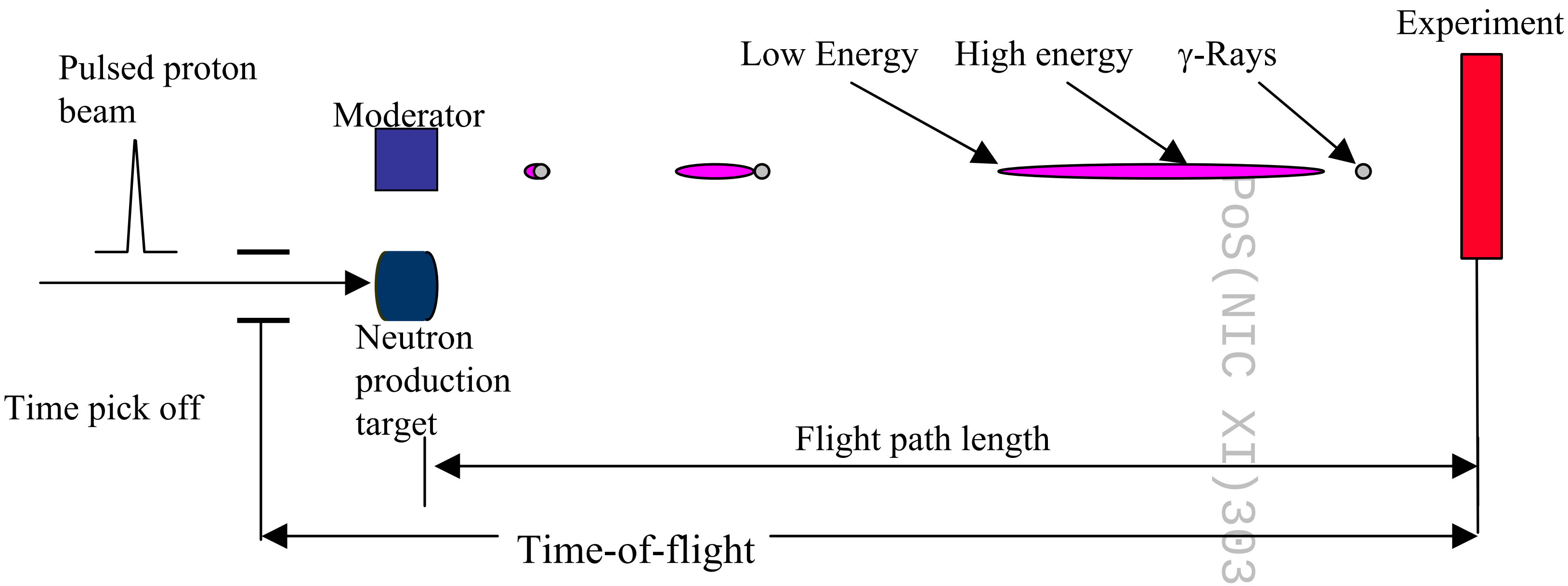
Classical s-process



DANCE, n_TOF

new n-facilities (FRANZ,SARAF)

Neutron Captures – time-of-flight technique

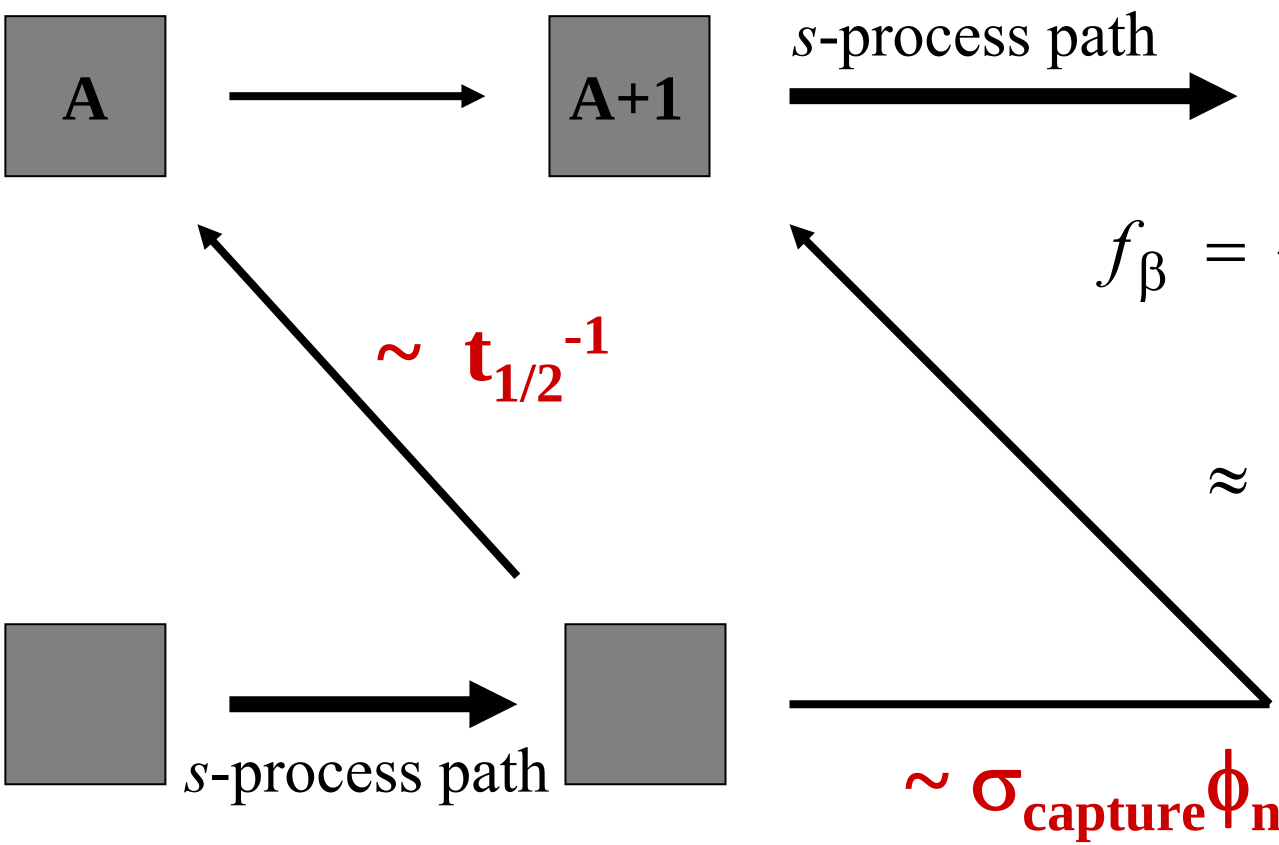


Example:

Astrophysics

L= 20m	**E_n= 1 MeV**	**E_n = 100 keV**	**E_n = 10 keV**	**E_n = 1 eV**
TOF_g = 67 ns	TOF_n= 1.5 μs	TOF_n= 4.6 μs	TOF_n= 15 μs	TOF_n= 1.5 ms
ΔTOF = 5 ns	**ΔE = 7 keV**	**ΔE = 0.2 keV**	**ΔE = 7 eV**	**ΔE = 0.01 meV**
ΔTOF = 0.7 μs	**ΔE = 1.6 MeV**	**ΔE = 32 keV**	**ΔE = 1 keV**	**ΔE = 1 meV**
ΔTOF = 1 ms	**E > 2 eV**	**E > 2 eV**	**E > 2 eV**	**ΔE = 5 eV**

branch point in the s-process path



$$f_\beta = \frac{\lambda_\beta}{\lambda_\beta + \lambda_n}$$

$$\approx \frac{<\sigma>_A N_A}{<\sigma>_{A+1} N_{A+1}}$$

(n,g) experiments with unstable isotopes and fundamental stellar physics evaluations

Branch Isotope	Half-Life	Facility	Observable	Stellar Physics	Comment
^{151}Sm	93 yr	FZK, n_TOF, DANCE	^{152}Gd in solar distribution ^{151}Eu/^{153}Eu ratio hyperfine line split	**Timescale of hot Helium-shell flash** **s-process in very old stars**	done
^{134}Cs	2 yr	DANCE, FRANZ	Ba isotope ratios from presolar grains	**Sets ^{12}C abundance of He-shell flash**	current uncertainty: ± 30%
^{135}Cs	2 Myr		Ba isotope ratios	**Amount of rotation**	± 10%
^{95}Zr	64 d	FRANZ/ FAIR	^{96}/Zr/^{94}Zr ratio presolar grains	**Temperature at bottom of He-shell flash region**	Current uncertainty: 20 - 80 mb

experimental problems

$$f_\beta = \frac{\lambda_\beta}{\lambda_\beta + \lambda_n} \approx \frac{<\sigma>_A N_A}{<\sigma>_{A+1} N_{A+1}}$$

$\lambda_n \sim \sigma_{capture} \phi_n$

unstable isotope

- sample preparation
- very small amounts
- radioactive background

⇨ activation technique

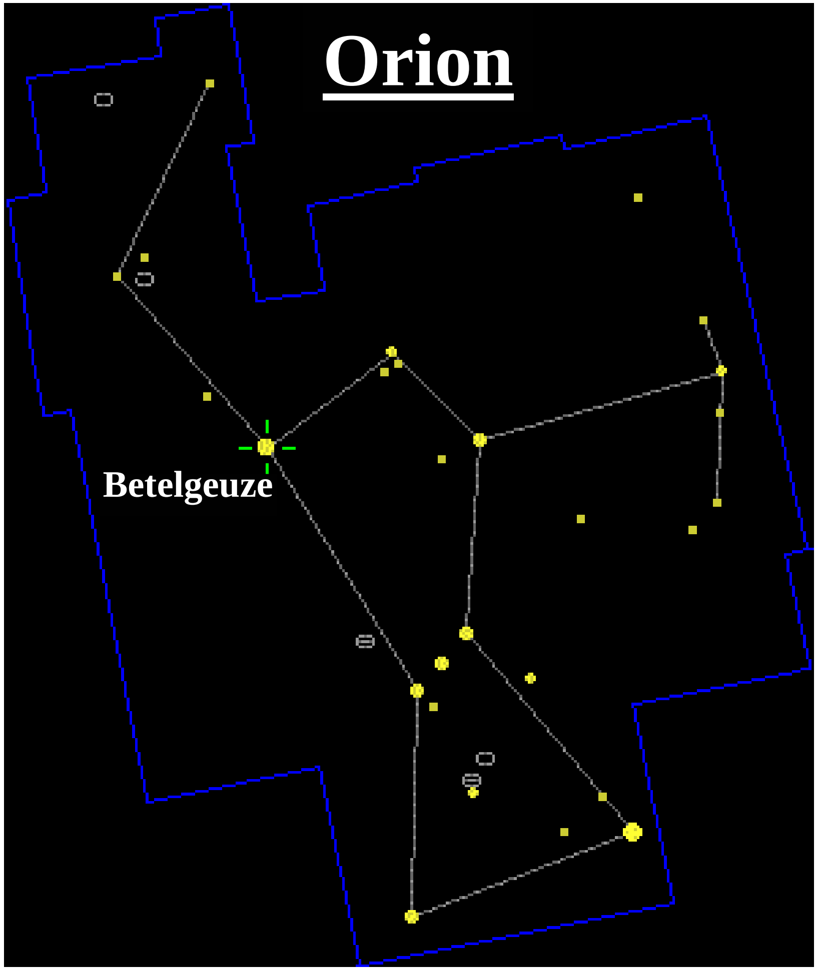
high precision

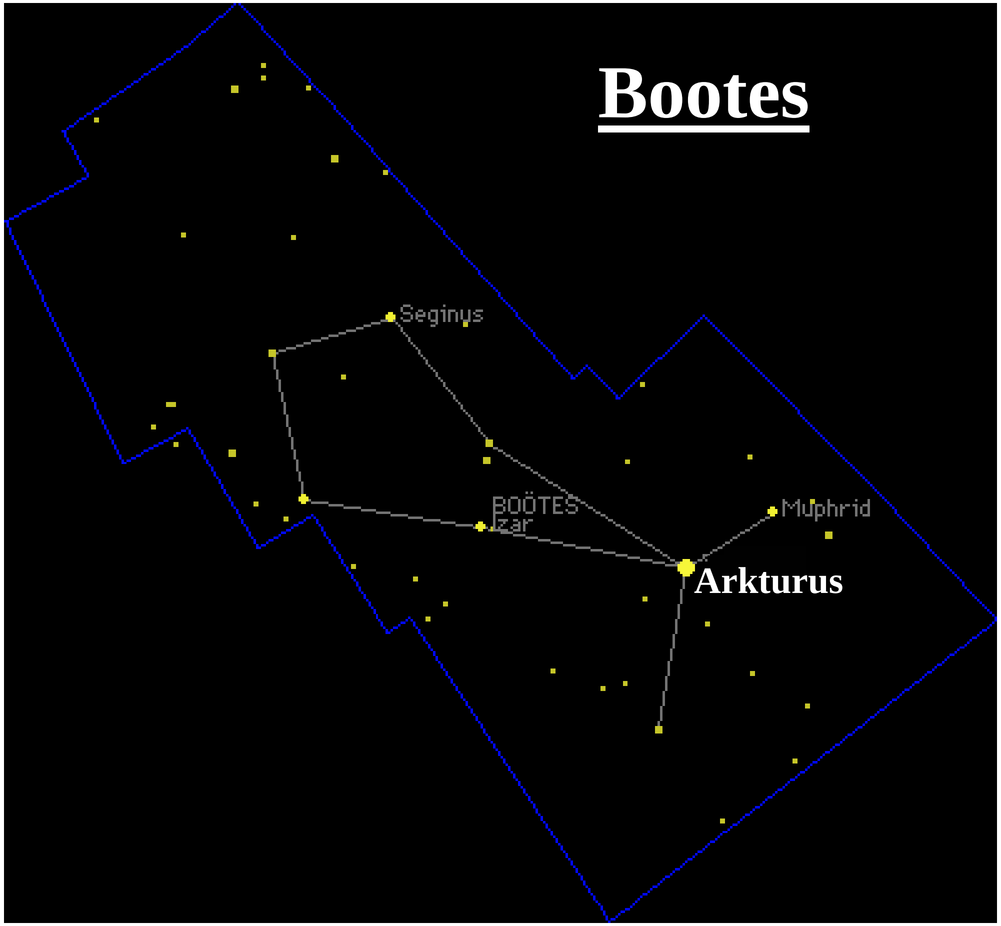
- neutron induced background
- isotopic impurities
- statistics

⇨ TOF technique,

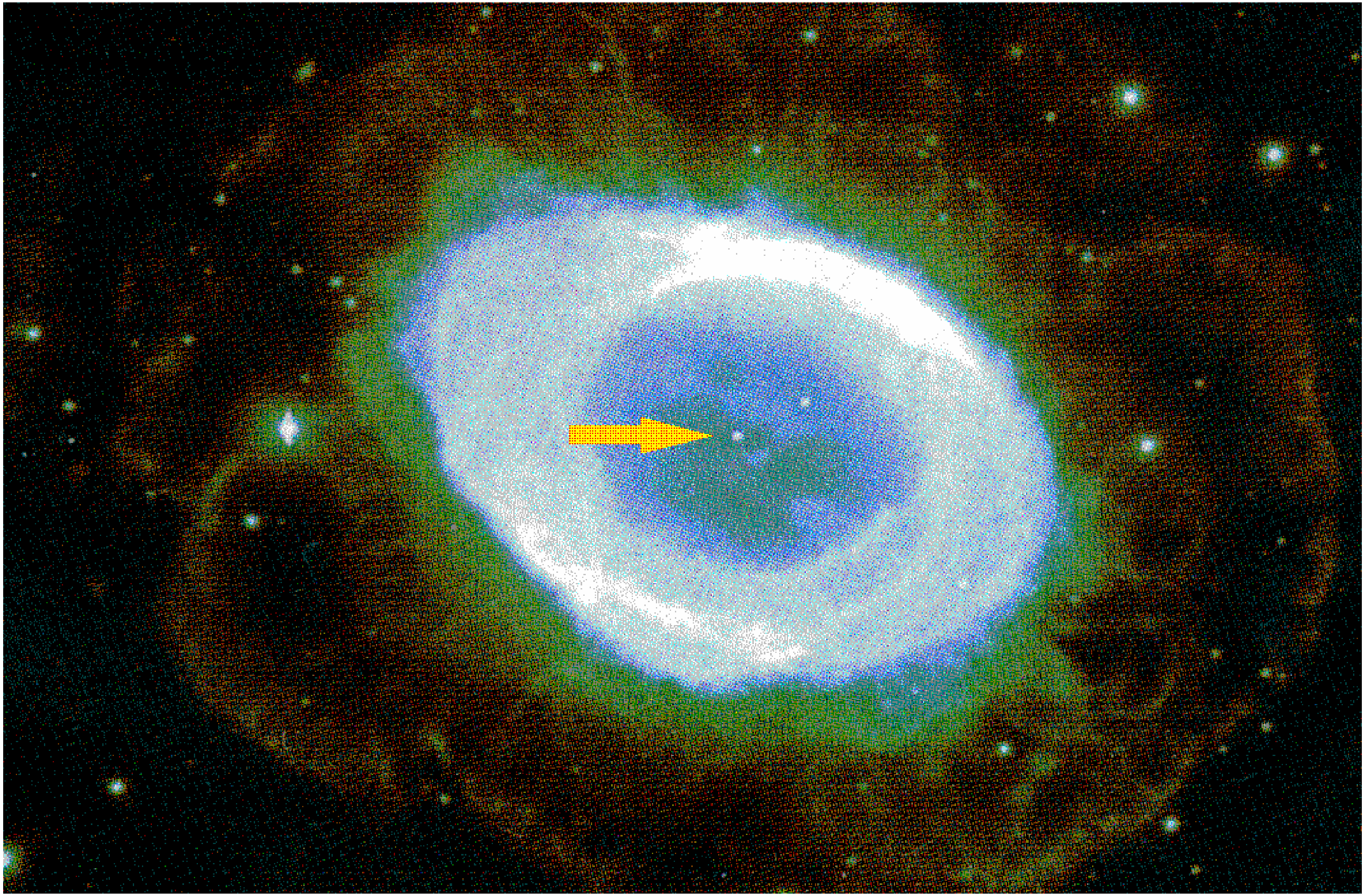
⇨ calorimetric

Red Giants – easy to spot



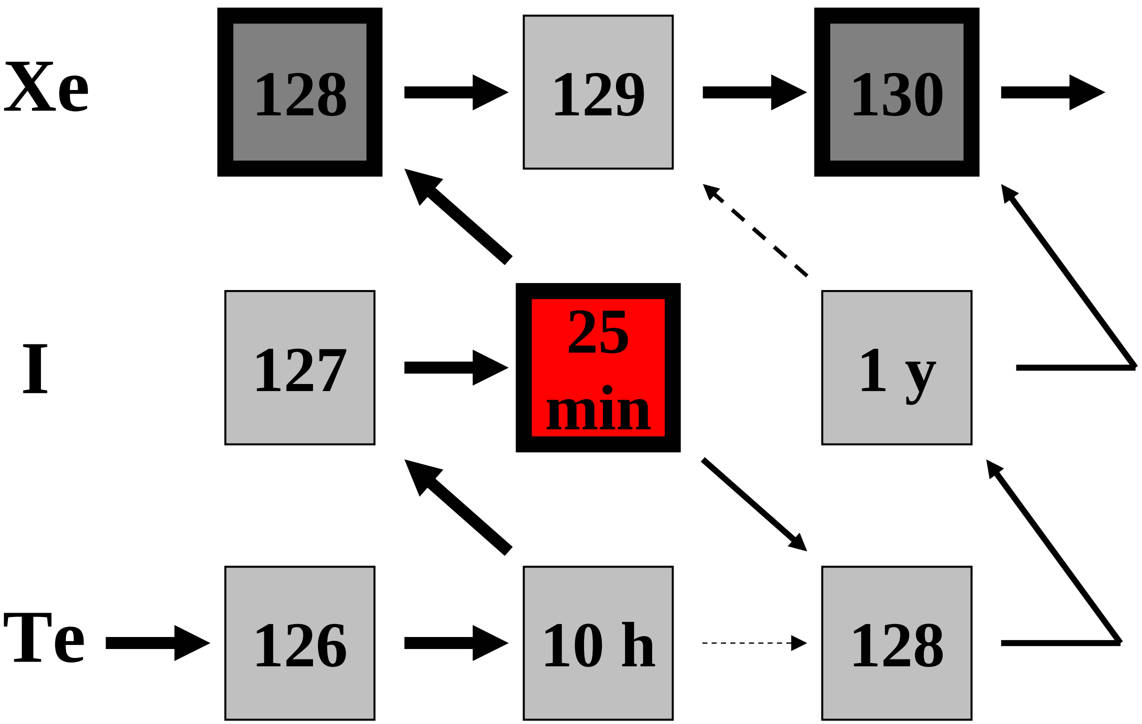


Red Giants become White Dwarfs



Ring nebula illuminated by the White Dwarf in the center.

branch point at ^{128}I

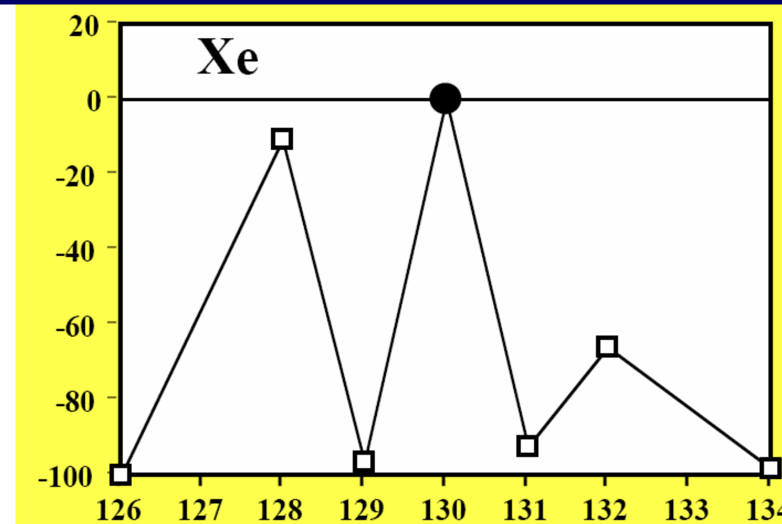


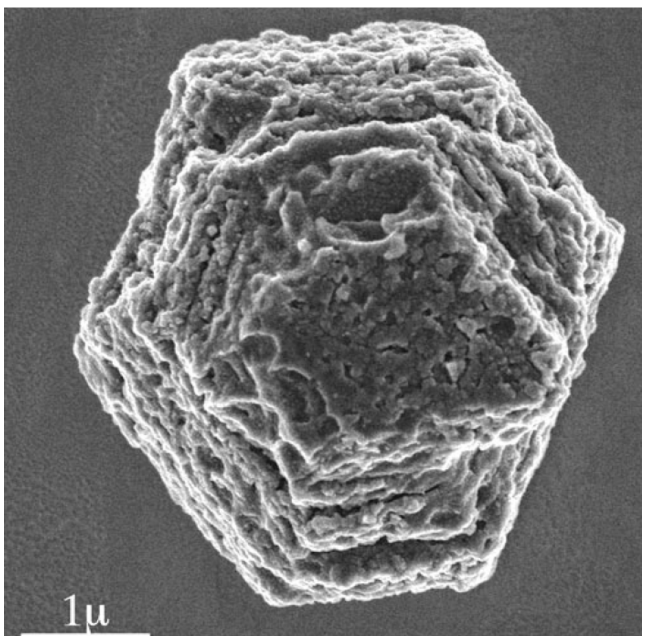
- 2 ***s-only*** isotopes
- temperature and electron density dependent
- no dependency on neutron flux

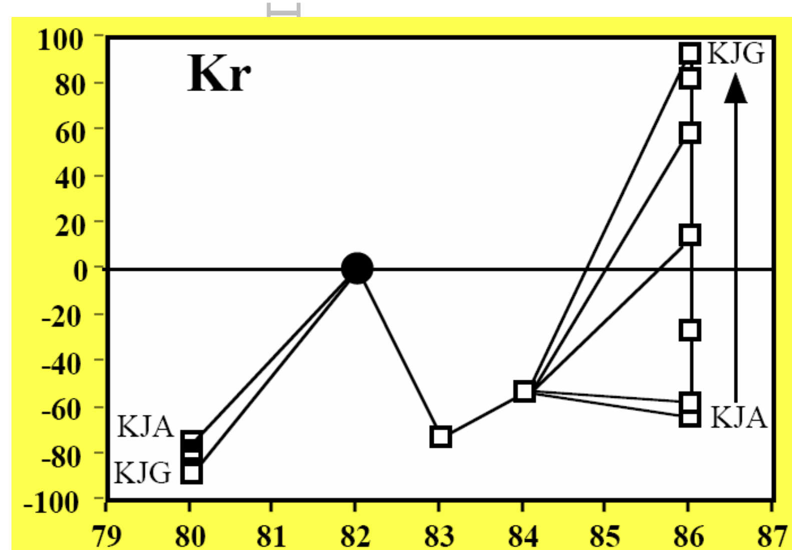
⇨ *stellar thermometer*

Meteorites – hints from the sky

Meteorites contain presolar grains!







See lecture by Ernst Zinner!

evidence for neutron capture: *DIRECT*

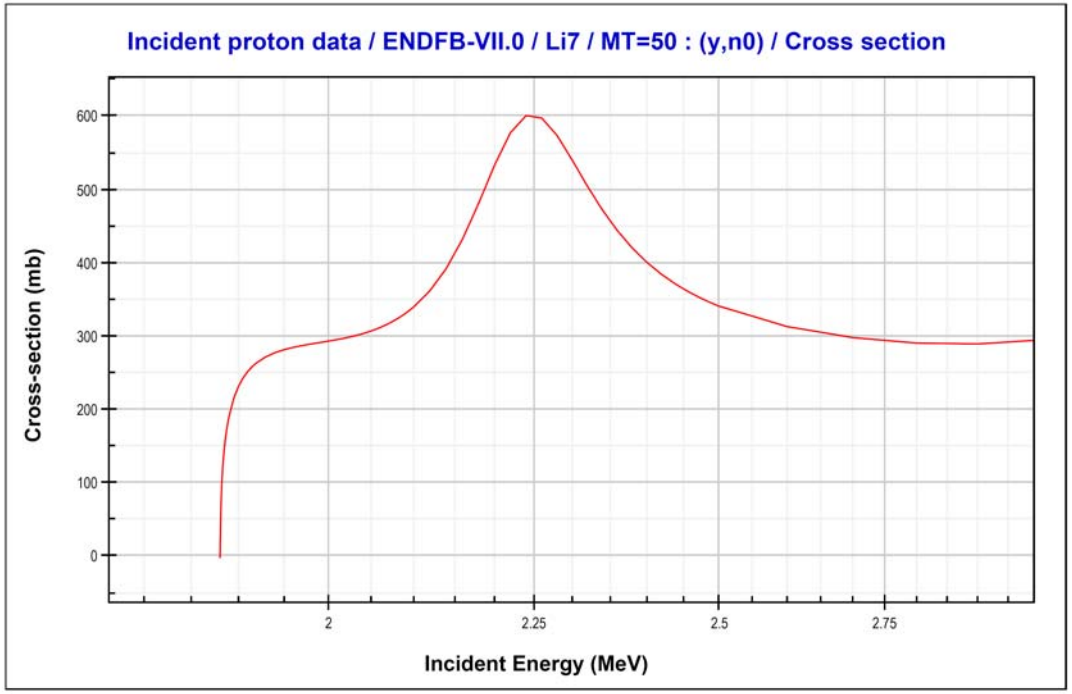
$$^{A}X + n \Rightarrow {}^{A+1}X + \mathbf{Q}$$

$$Q = \sum \gamma_i$$

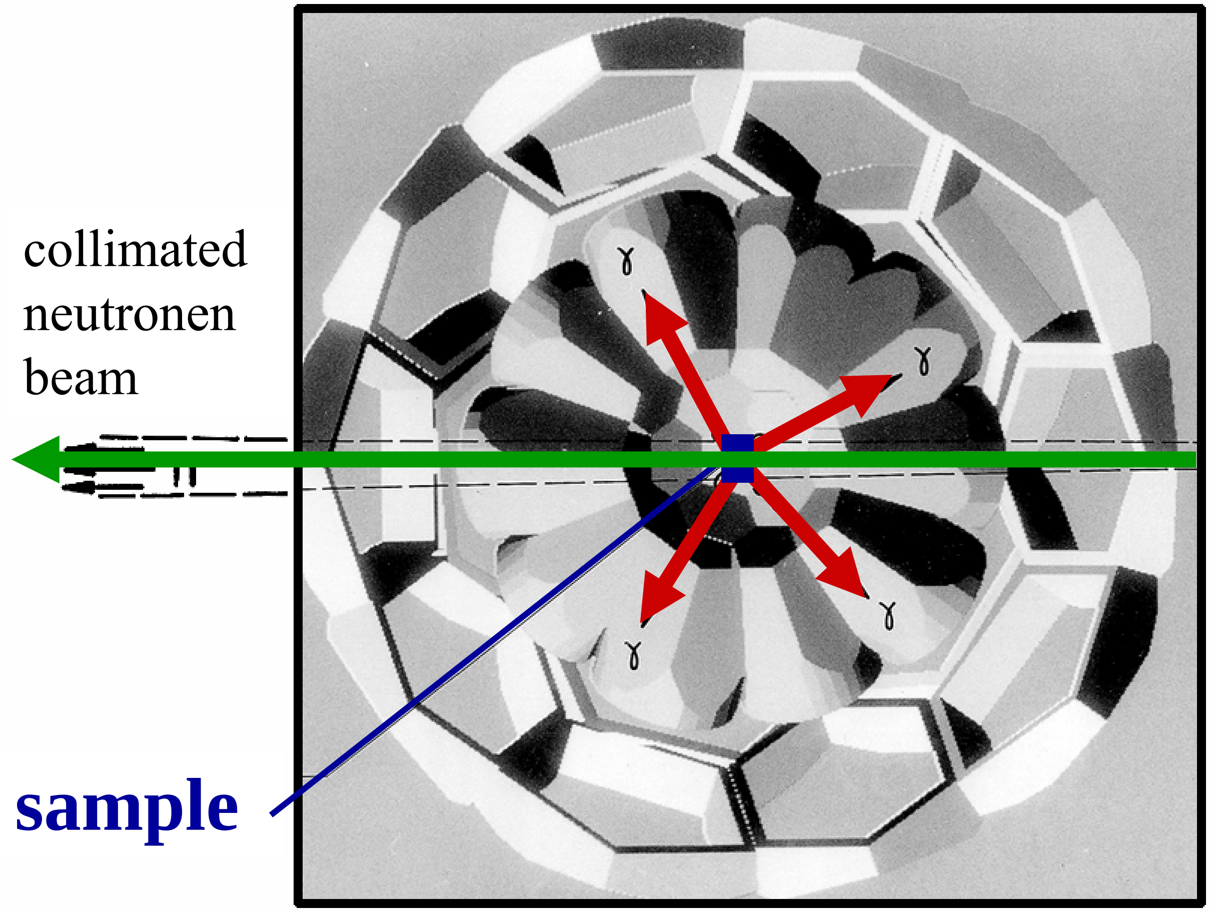
⇨ **“monoenergetic” if 100 % efficiency**

The $^7Li(p,n)$ reaction

- Negative Q-value (-1.644 MeV)
  - Neutron spectrum close to threshold depends strongly on proton energy
  - Q-value in reach for small accelerators
- Huge cross section close to threshold



experimental setup



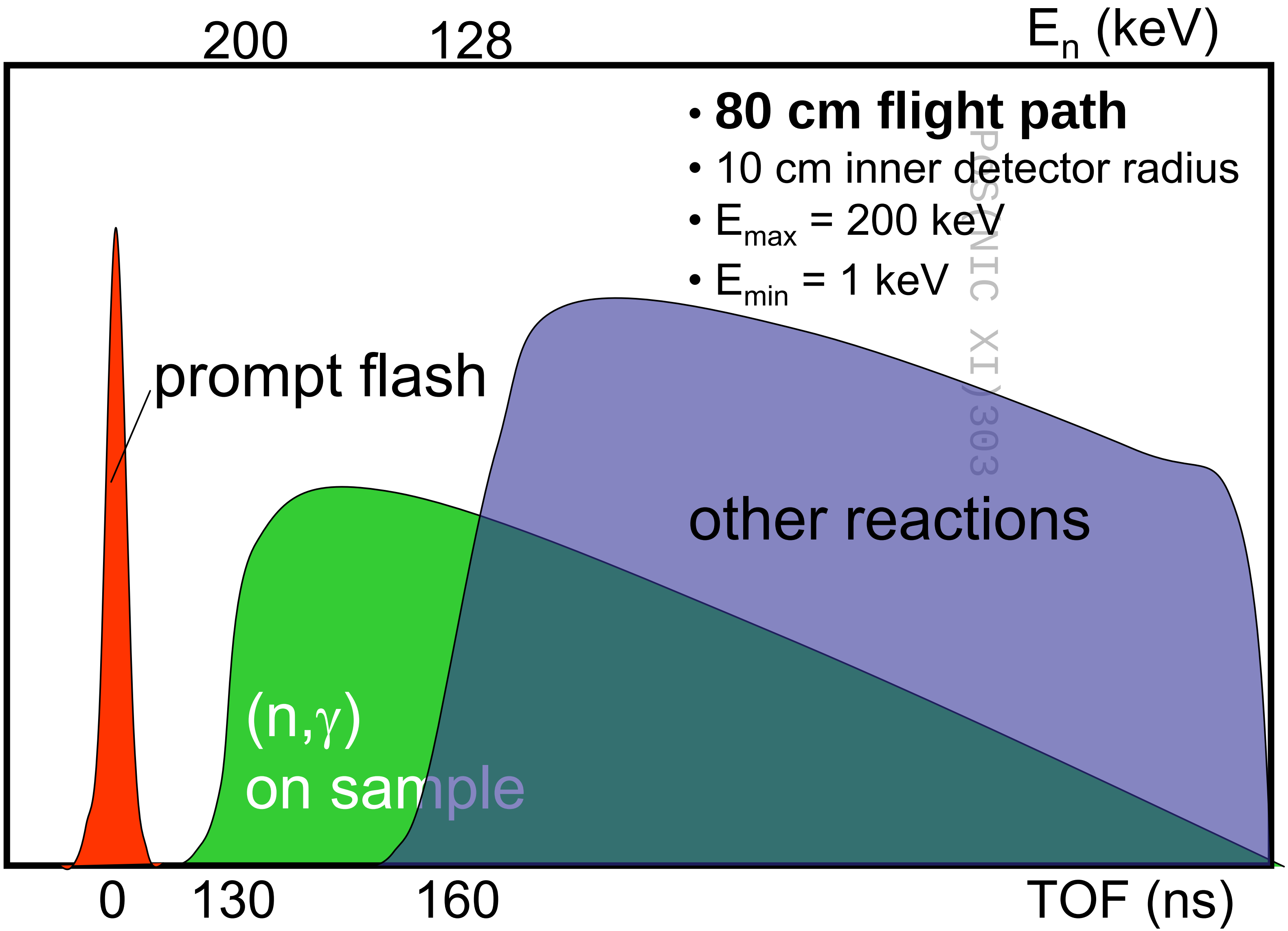
neutrons:

- ^{7}Li (p, n)
- 1 .. 200 keV
- 10^4 n / s cm^2
- 80 cm flight path

γ-Detector:

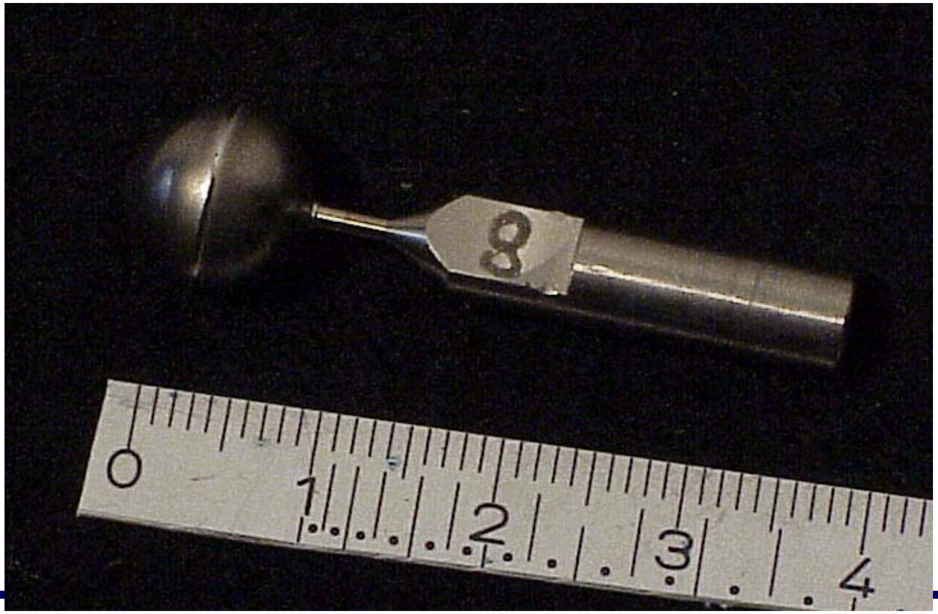
- 41 BaF_2 crystals
- 15 cm length
- $\varepsilon_\gamma \approx$ 90 %
- $\varepsilon_{casc} \approx$ 98 %

Schematic TOF spectrum



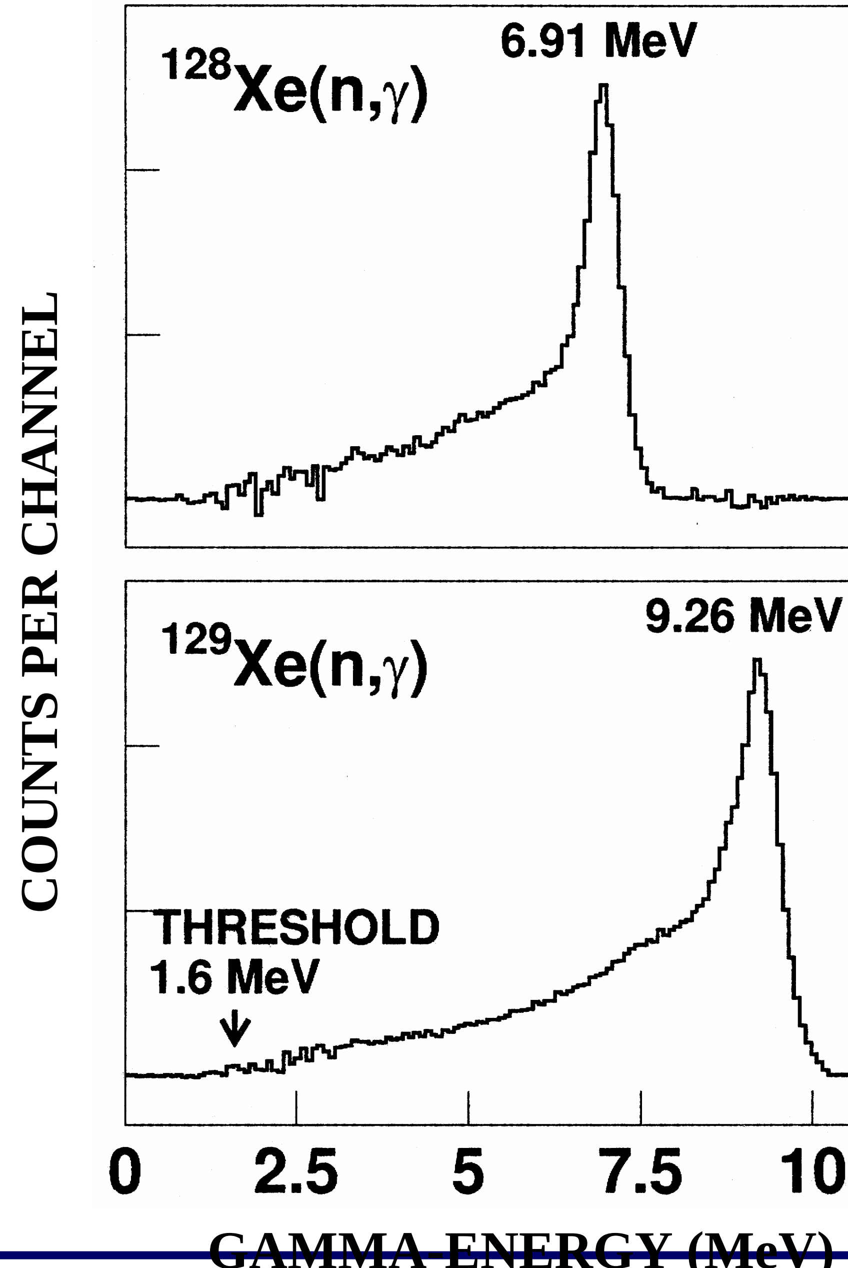
samples

- isotopically enriched $^{128,\,129,\,130}Xe$
- 0.5 .. 1 g per sample
- filled in Ti-spheres (R_{in} = 4.8 mm, R_{out} = 5 mm)
- p = 60 bar



sum spectra

- Peak at neutron-binding energy
- ε_{casc} = 96 .. 98 %
- energy threshold: 1.6 MeV
- relative to ^{197}Au(n,γ)



multiplicity

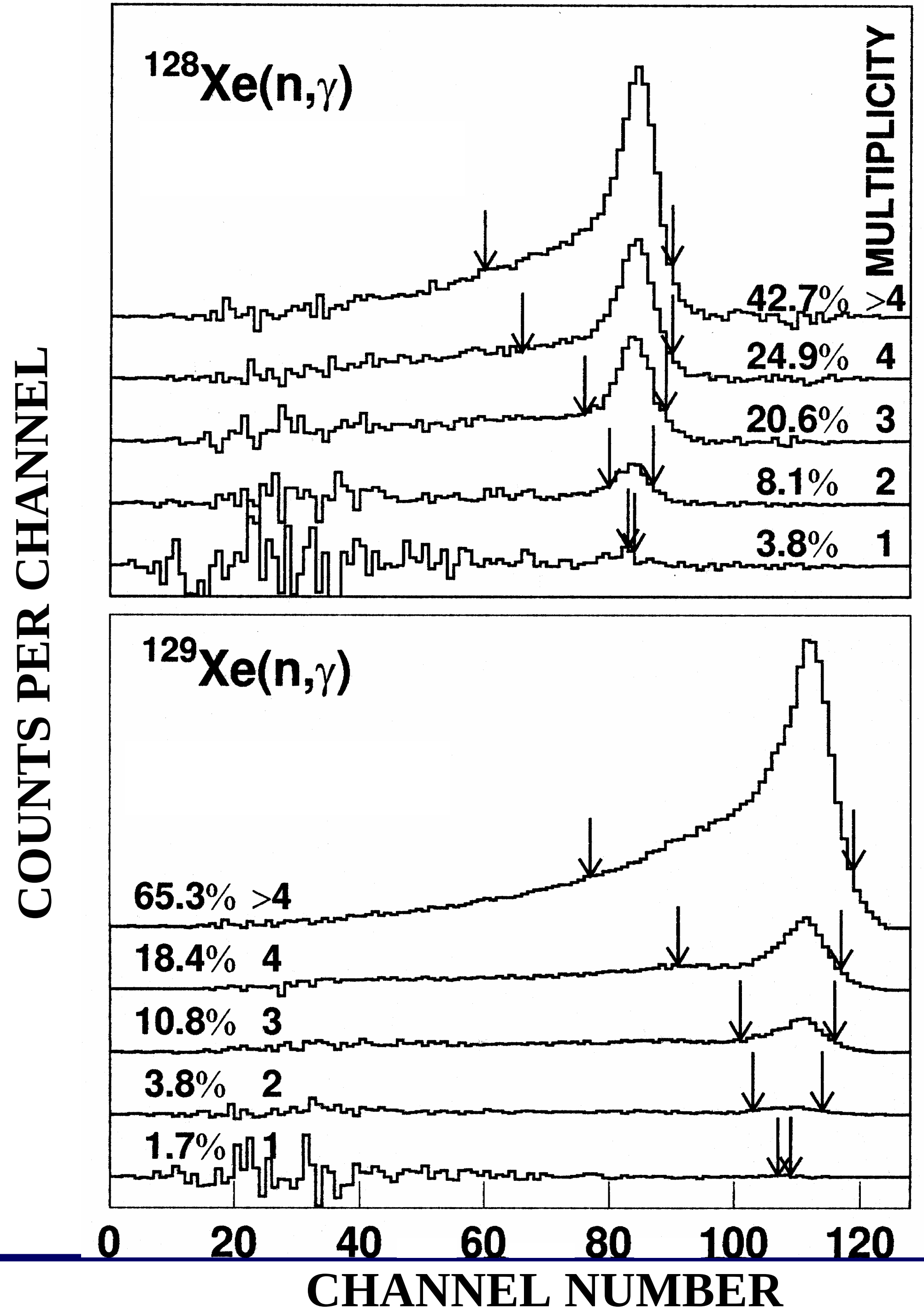
discrimination of natural background

(n,γ):

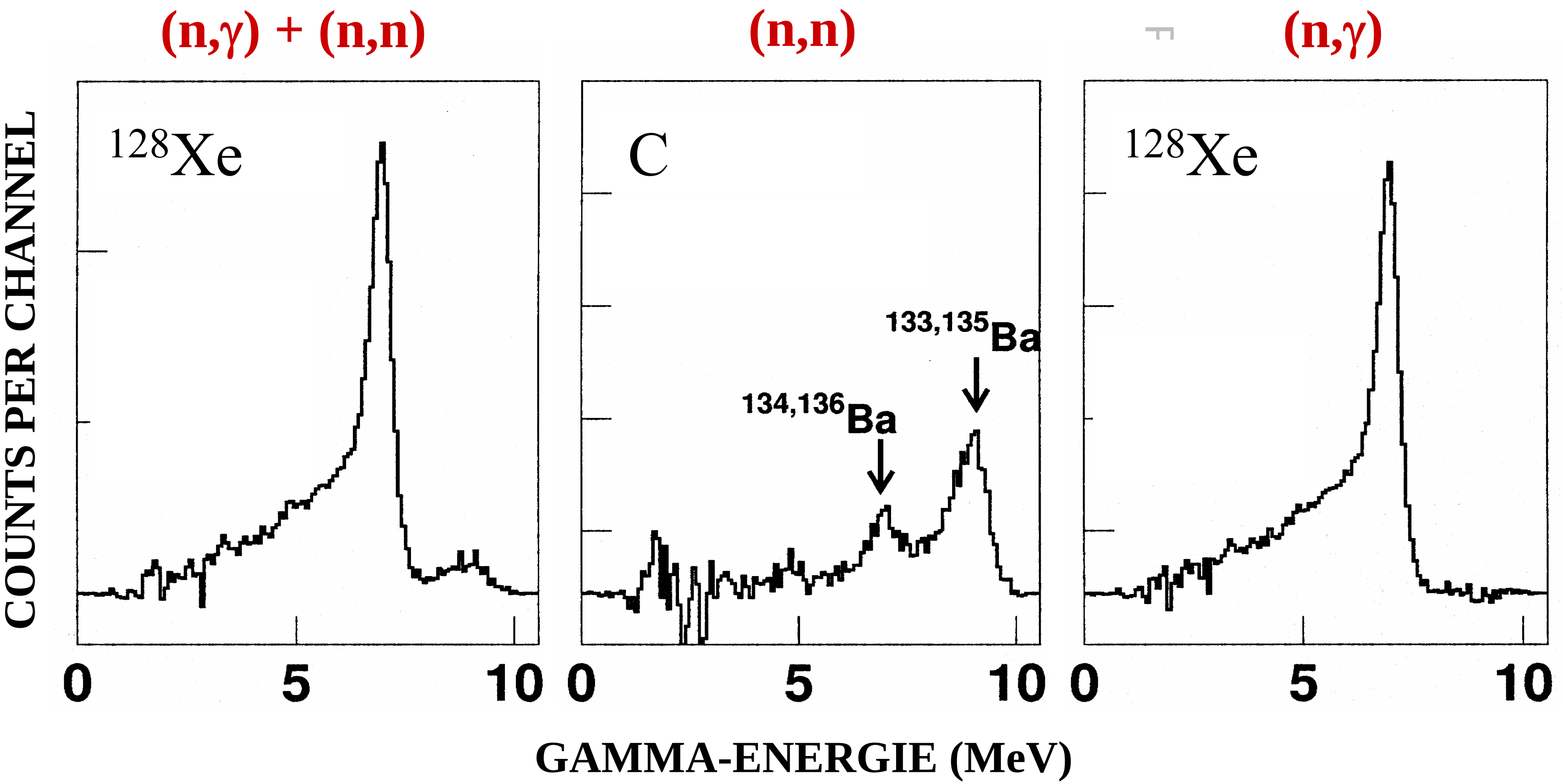
90% multiplicity ≥ 3

natural background:

multiplicity ≤ 2.

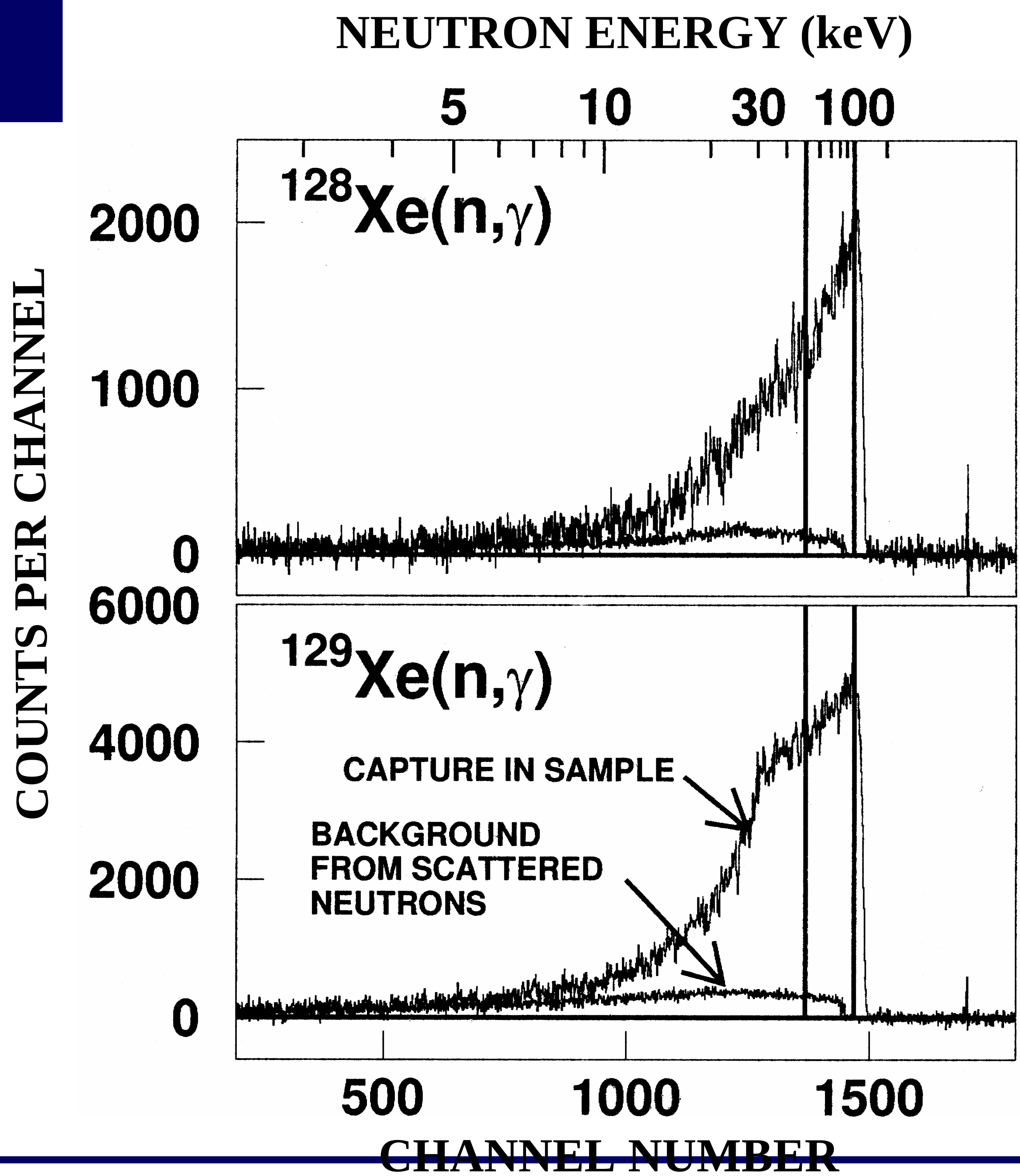


sample dependent background

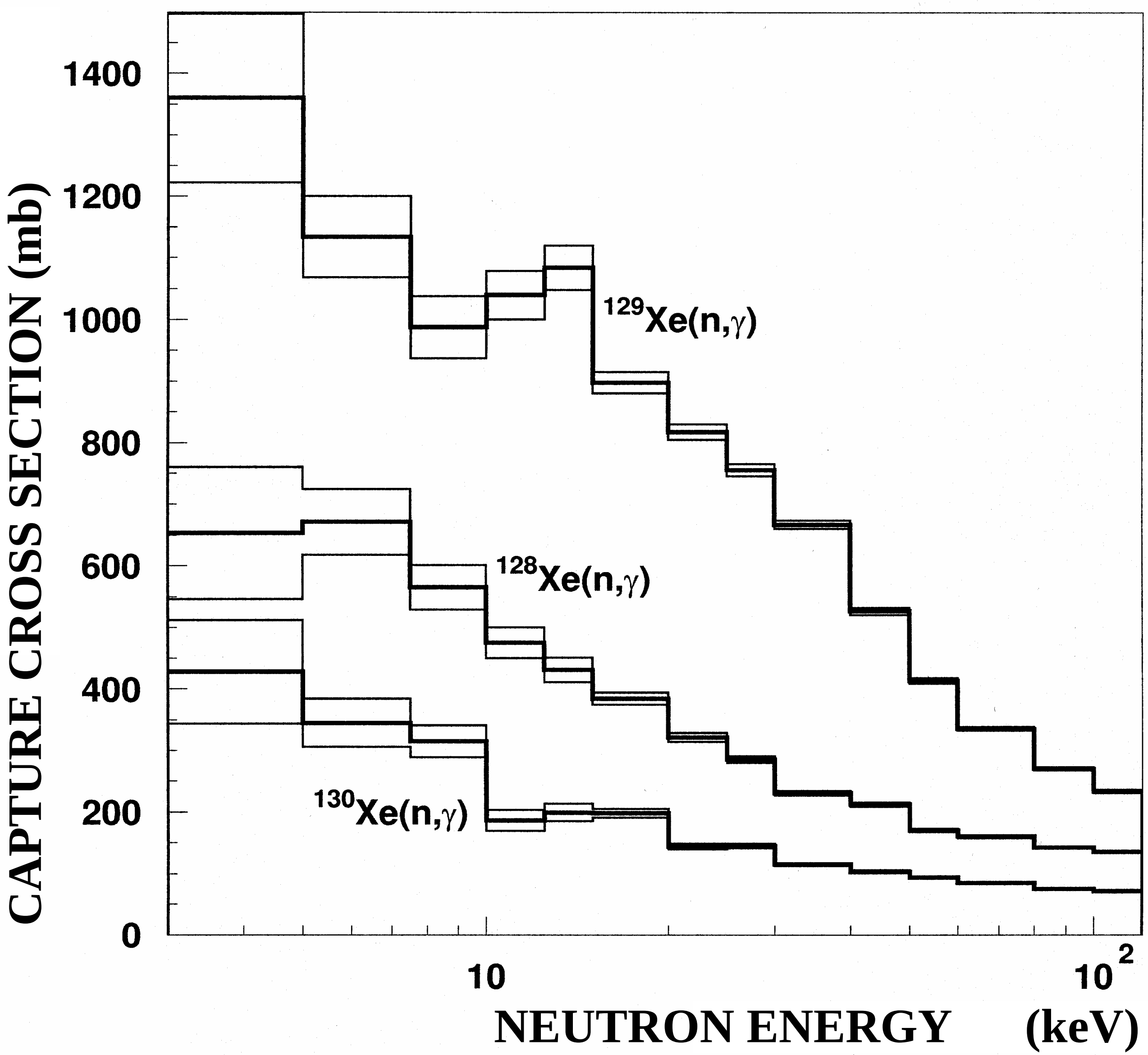


time of flight

- background due to scattered neutrons delayed
- **$\sigma_{tot}/\sigma_\gamma(^{128}Xe) = 25.$**



$^{128, 129, 130}Xe(n,\gamma)$-cross sections

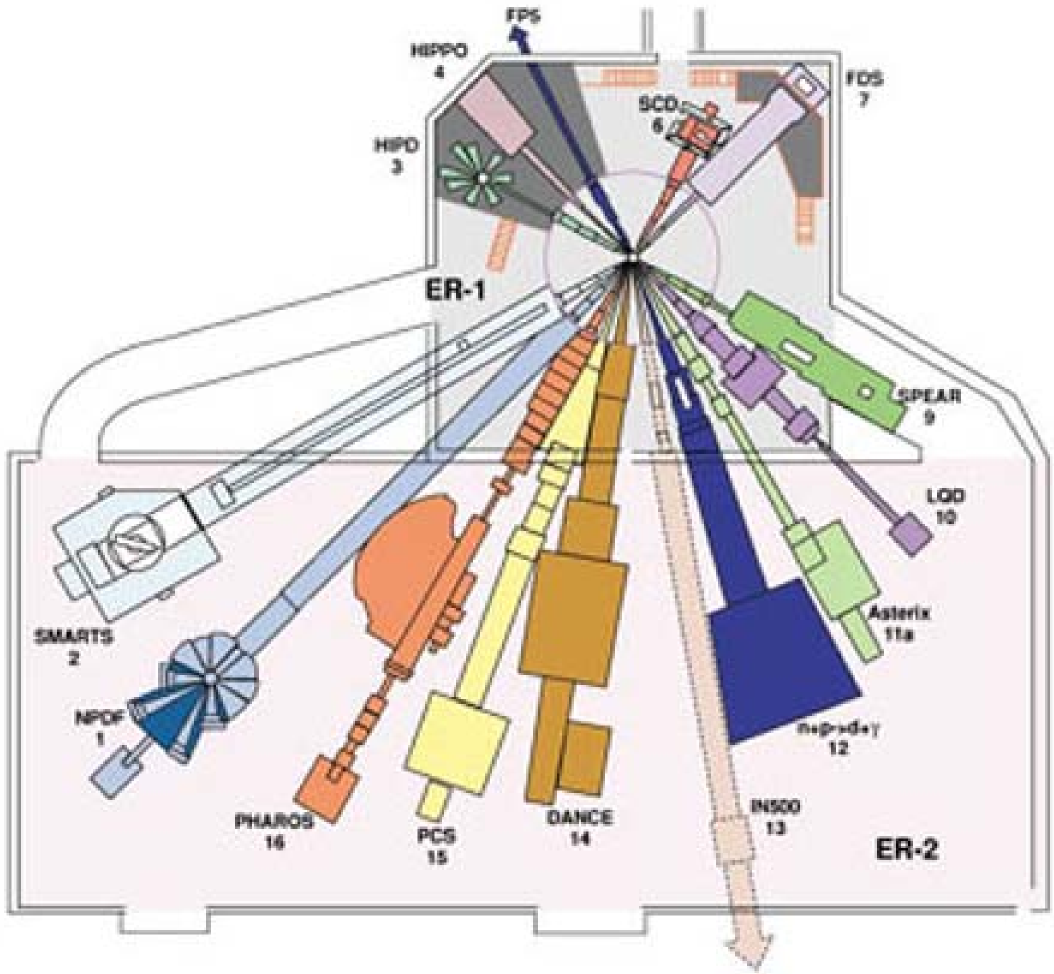


Spallation neutron sources

- Need to increase neutrons/proton
- $n/p=10^{-6}$ for $^{7}Li(p,n)$
- Idea: high energy protons use most of their energy to knock out neutrons from a heavy nucleus - spallation
- Now n/p between 20 (LANSCE,SNS) and 250 (n_TOF)

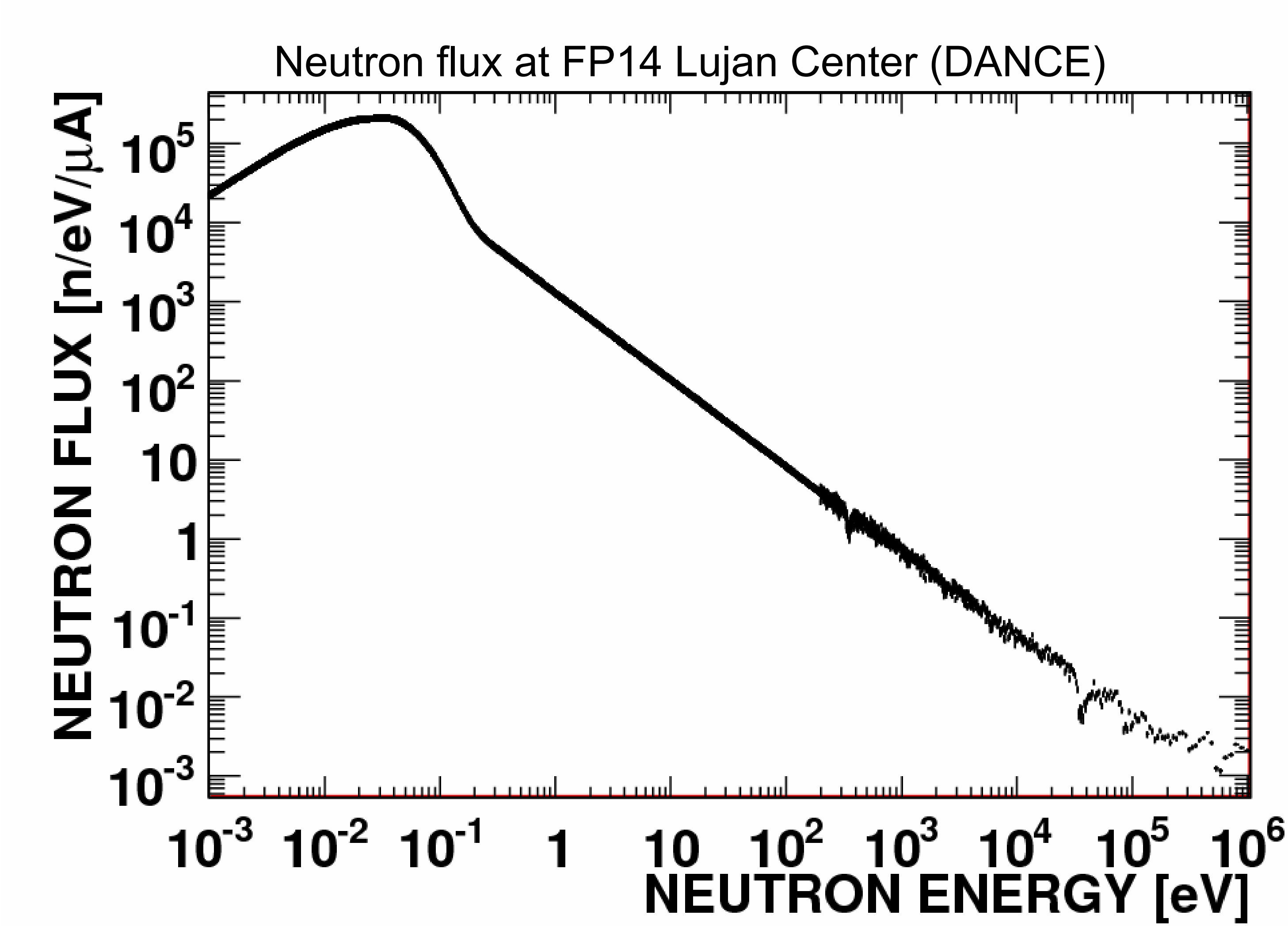
LANSCE @ LANL

Manuel Lujan Jr. Center



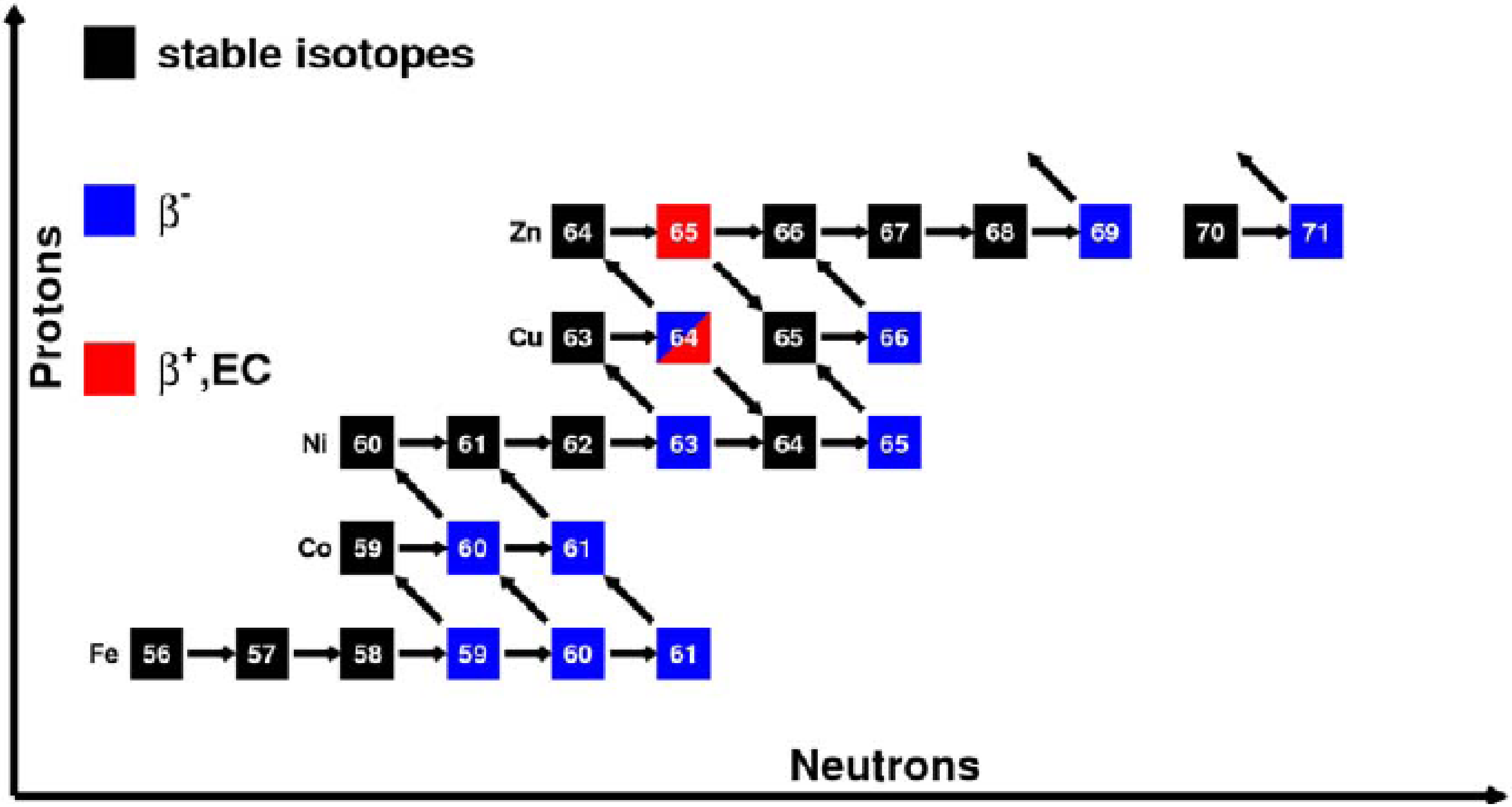
FP 14 views the second-tier coupled water moderator.

Neutron spectrum at spallation sources



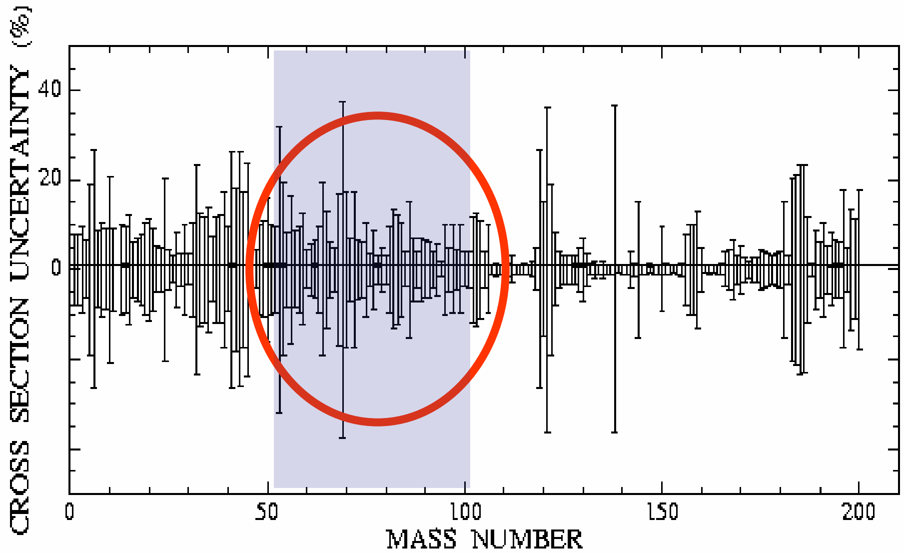
Conditions at LANSCE: Δt=0.1 μs, E_p= 800 MeV, I_P=100 μA (80 kW)

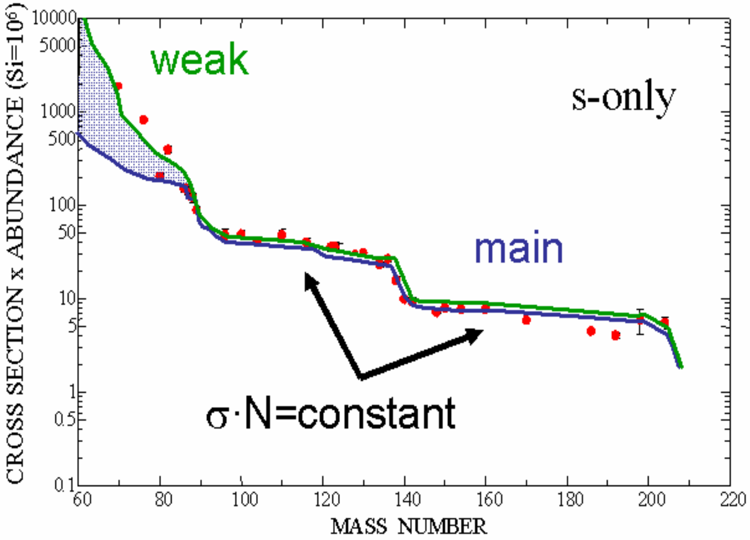
The s-process around ^{63}Ni



s-process nucleosynthesis in the region between iron and tin with the important branching at ^{63}Ni

Nuclear data needs for the weak s-process

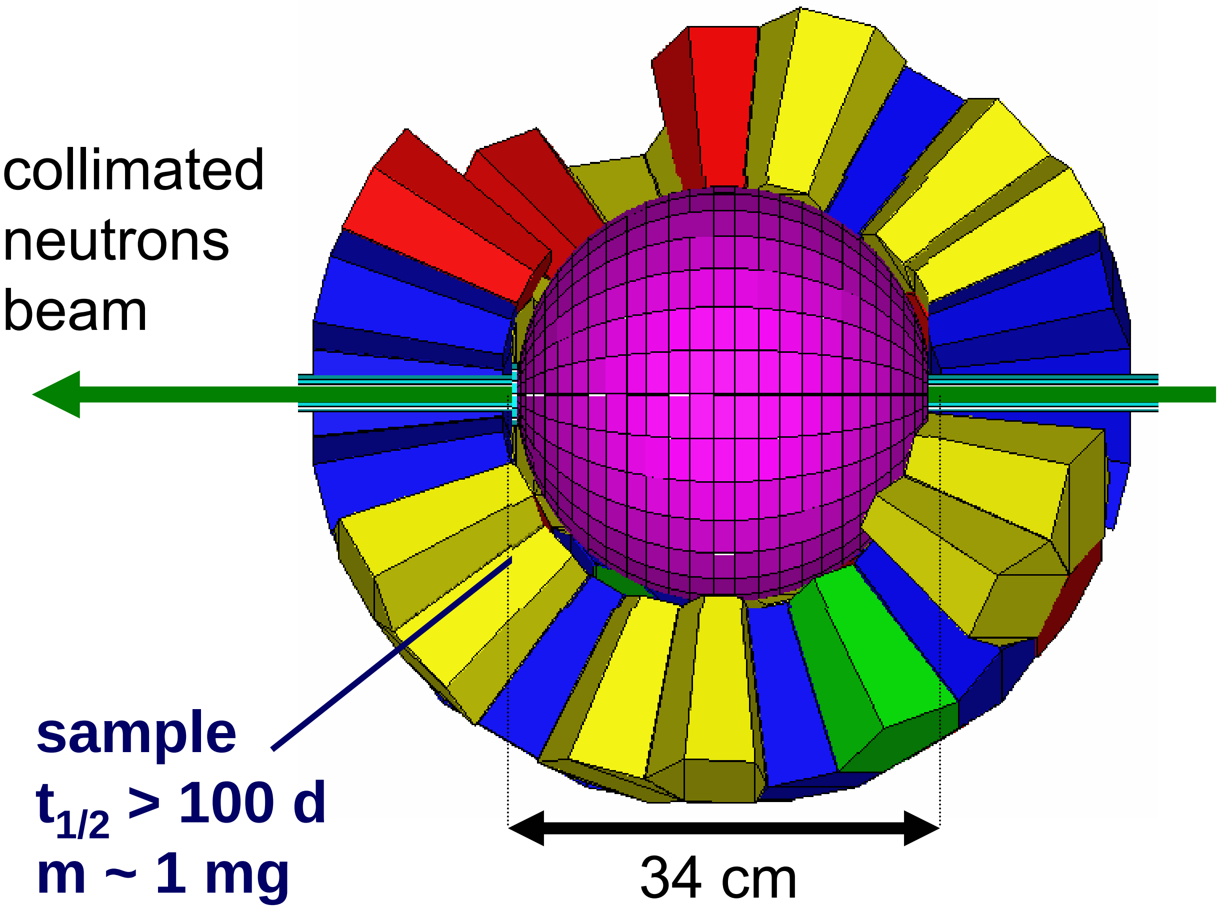




Problems:

- small cross sections
- resonance dominated
- contributions from direct capture
- propagation effects

Detector for Advanced Neutron Capture Experiments



neutrons:

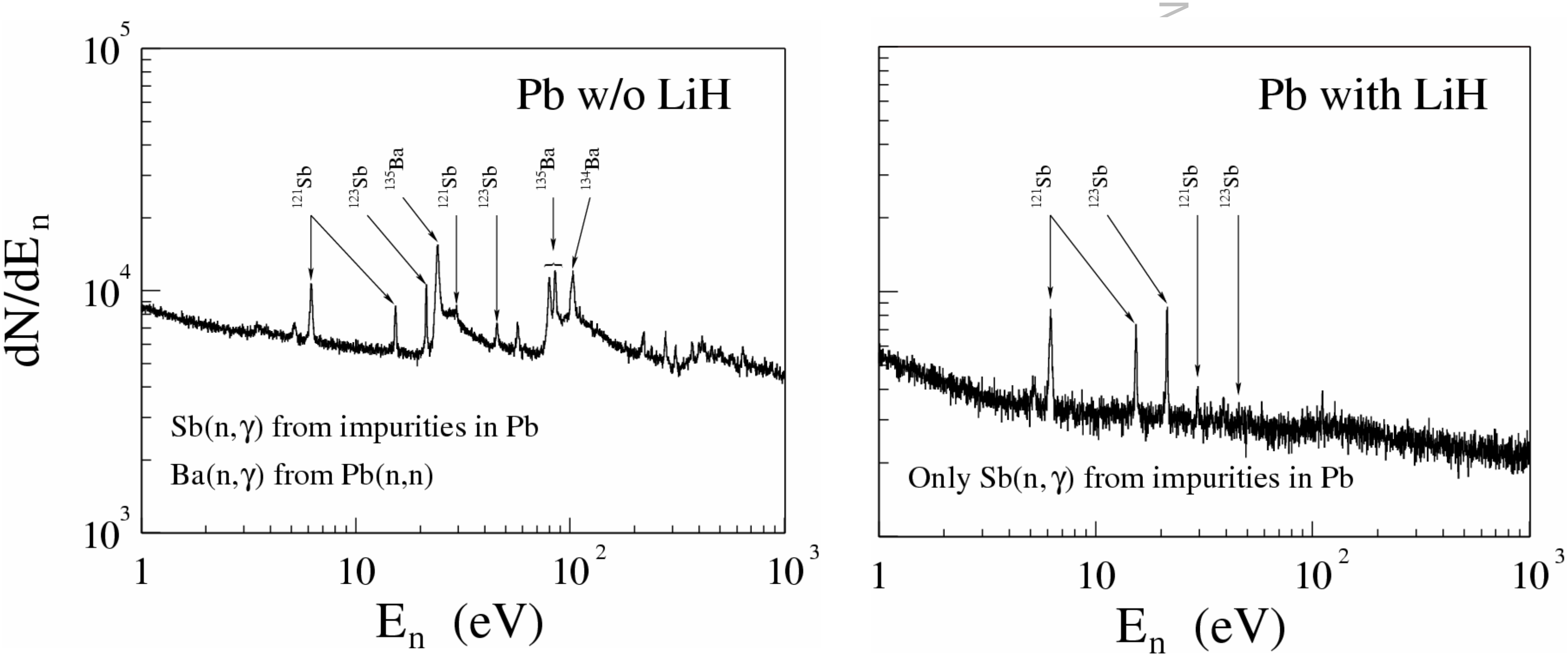
- spallation source
- thermal .. 500 keV
- 20 m flight path
- 3 10^5 n/s/cm^2/decade

γ-Detector:

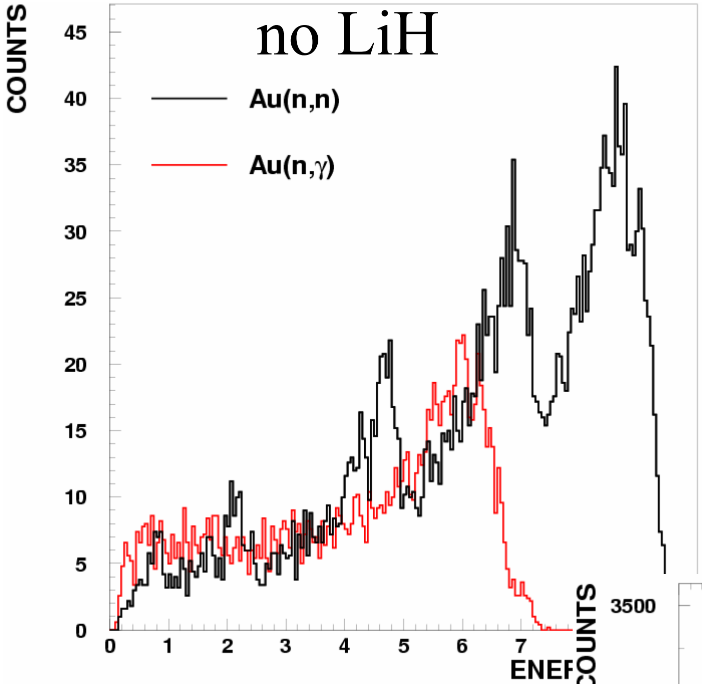
- 160 BaF_2 crystals
- 4 different shapes
- R_i=17 cm, R_a=32 cm
- 7 cm ^{6}LiH inside
- $\varepsilon_\gamma \approx$ 90 %
- $\varepsilon_{casc} \approx$ 98 %

Background due to (n,n)

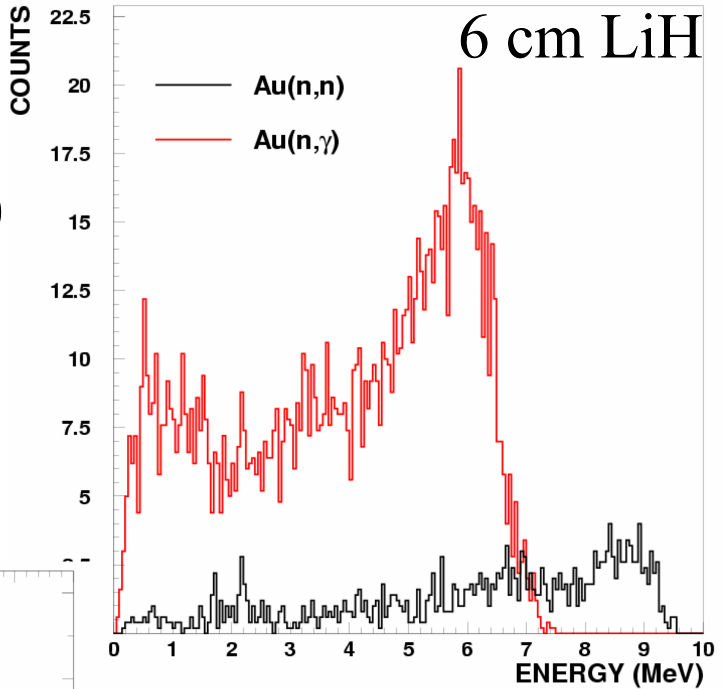
Reduction due to ^{6}LiH shell
(R_i = 10.5 cm, R_a = 16.5 cm)

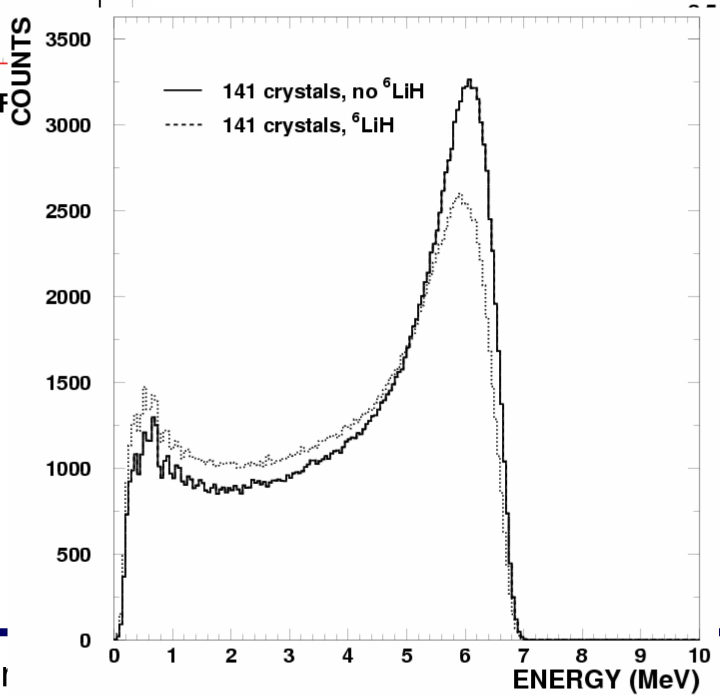


Simulated effect of the ^{6}LiH absorber

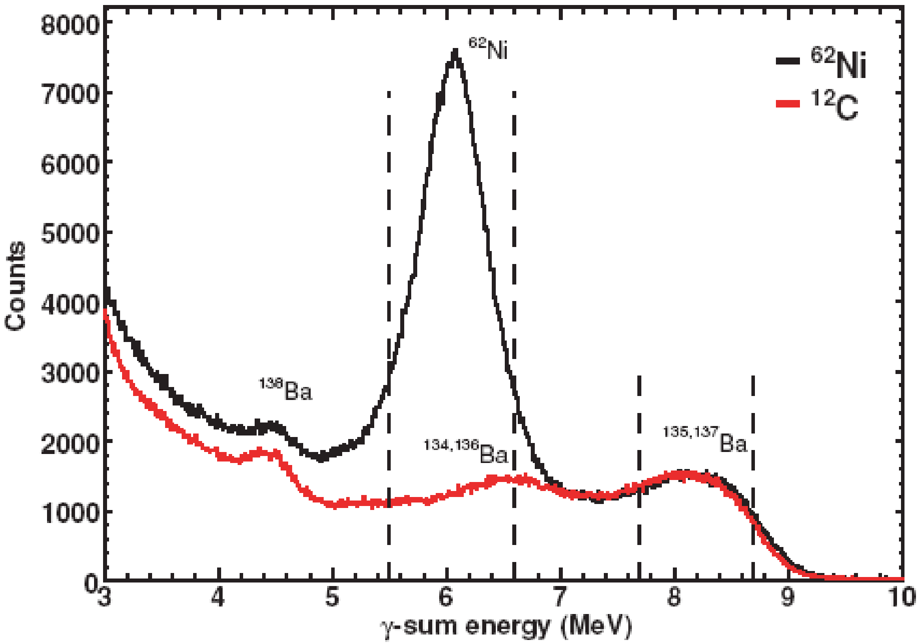


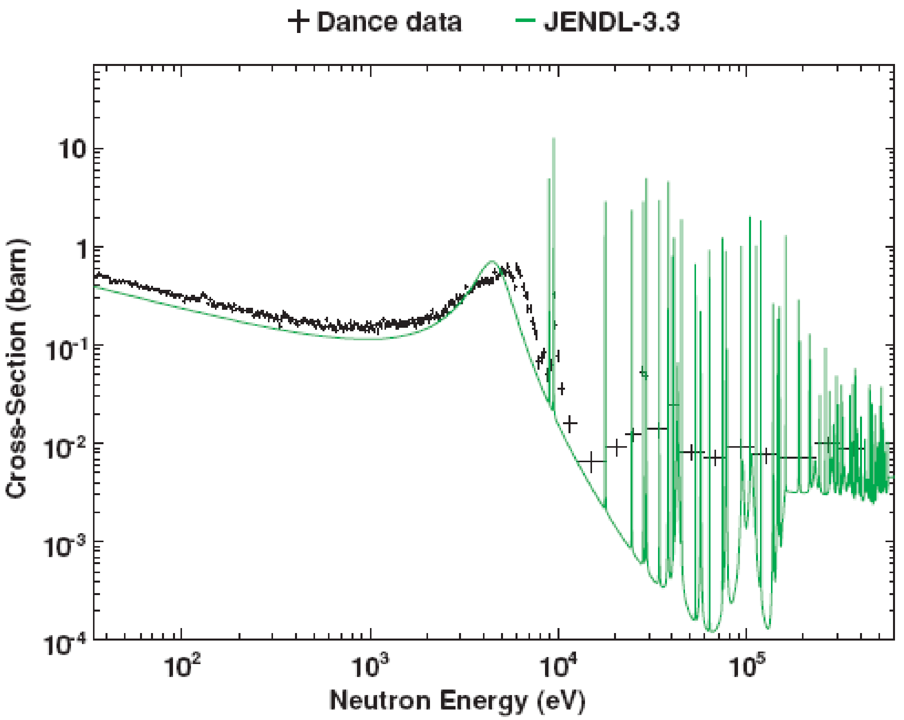
10 < E_n/keV < 100





$^{62}Ni(n,g)$ at DANCE

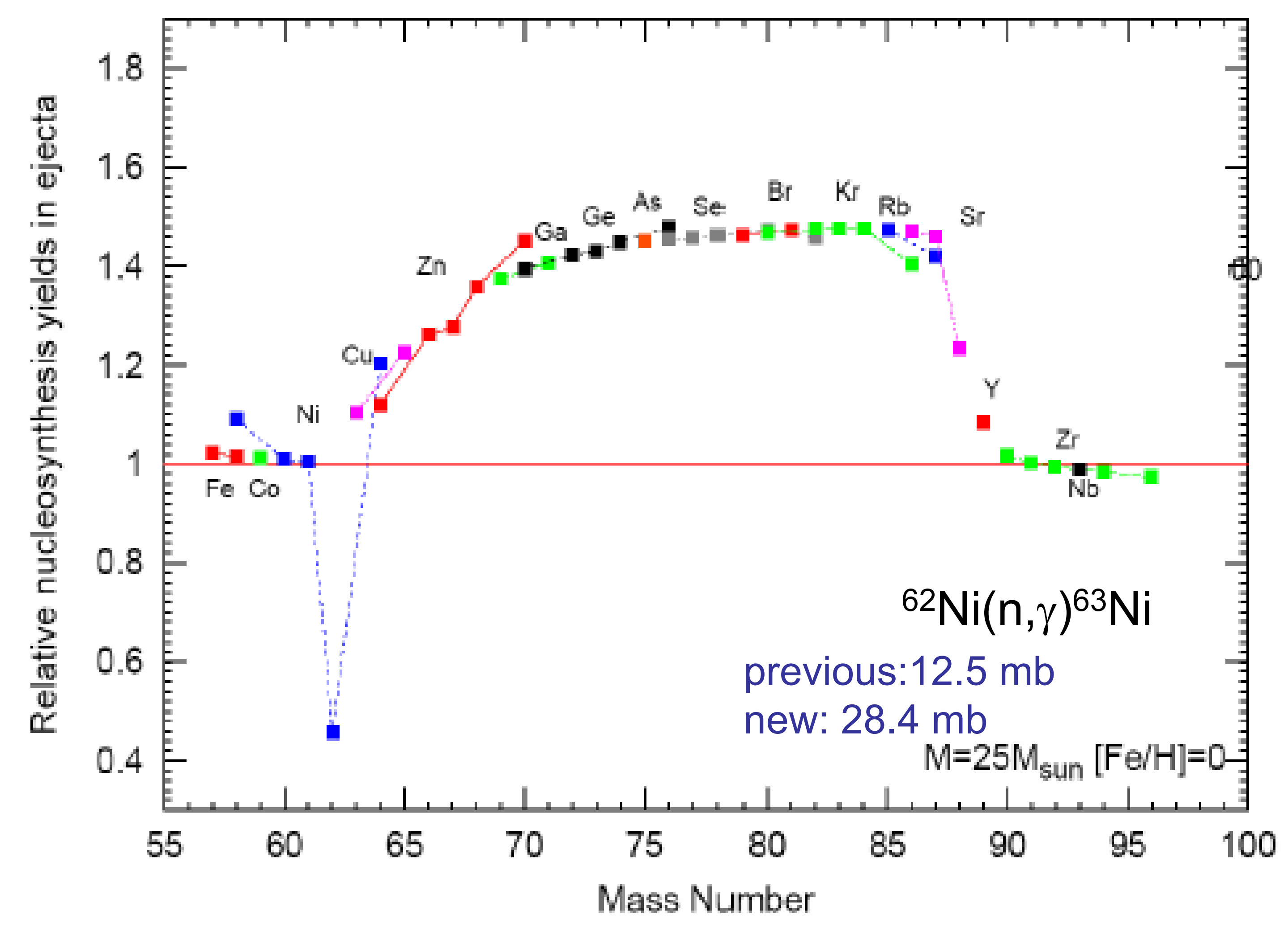




A. M. ALPIZAR-VICENTE et al., PRC **77**, 015806 (2008)

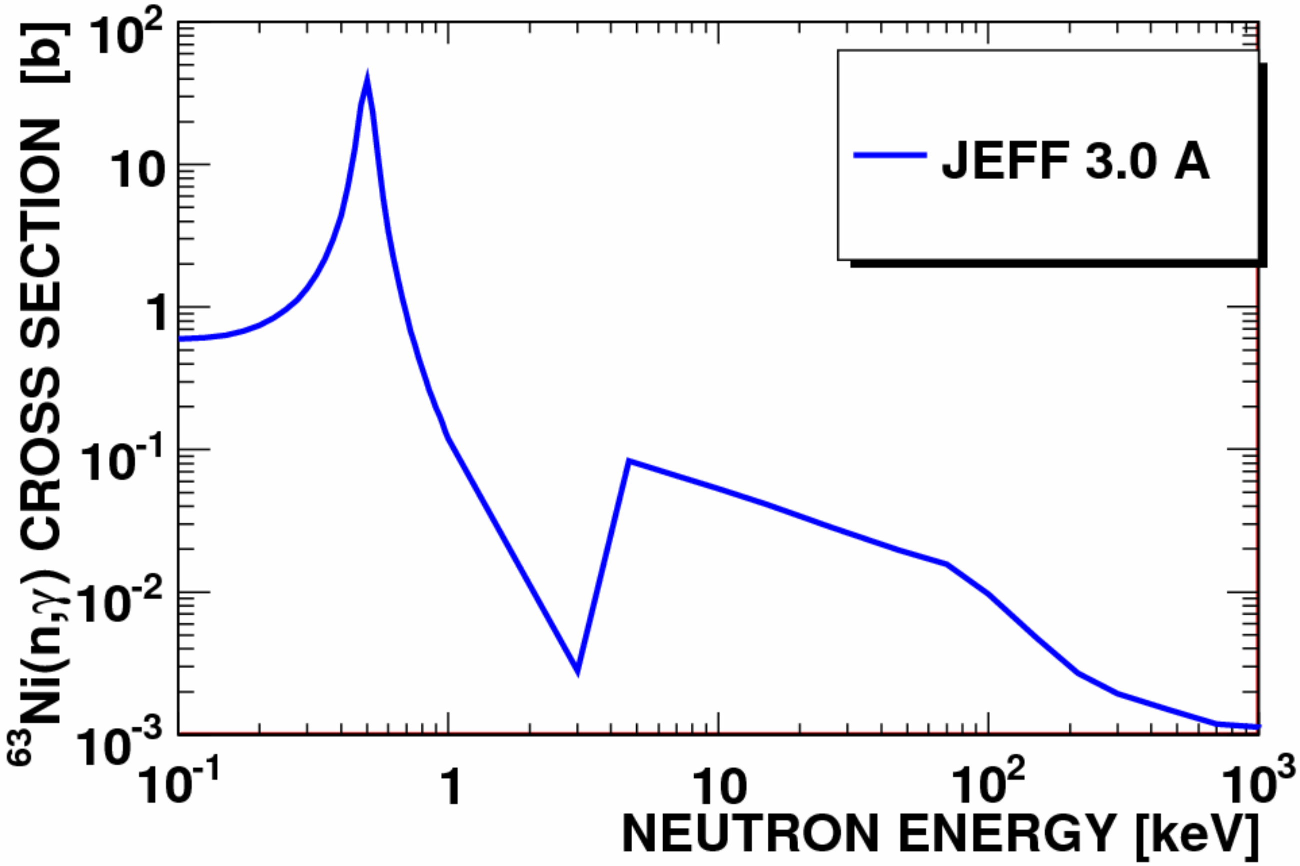
New high-resolution campaign has been performed at n_TOF

Propagation effects in the weak s-process



Nassar et al., Phys. Rev. Lett. 94, 092504 (2005)

^{63}Ni(n,g) performed at DANCE



No experimental data exist so far (only transmission measurements)

Evidence for neutron capture: *INDIRECT*

$$^{A}X + n \Rightarrow {}^{A+1}X$$

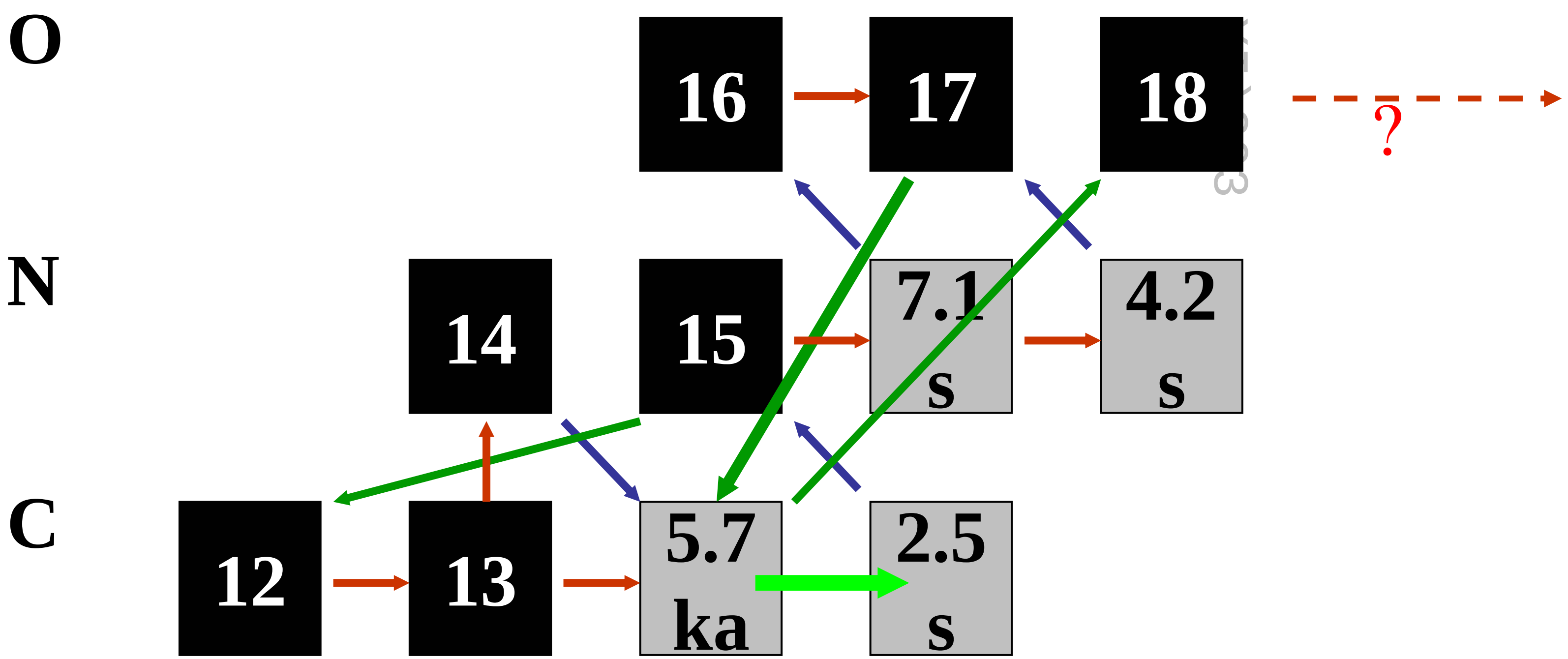
$$^{A+1}X \Rightarrow {}^{A+1}Y + \gamma + \ldots$$

Produced Activity:

$$A \propto \frac{{}^{A}N \cdot \Phi_n \cdot \sigma}{t_{1/2}} \cdot t_a$$

Neutron Capture on ^{14}C

- Verification of Coulomb Dissociation (CD) as an indirect method for determining (n,γ) rates
- Big Bang Nucleosynthesis
- Neutron-induced CNO cycles – s-process
- Neutrino-driven winds – r-process



^{14}C - sample

- 283 mg ^{14}C ($t_{1/2}$ = 5.7 ka), determined from decay heat
- carrier: ^{nat}C, activated Ni-container
- active impurities:
  - ^{44}Ti ($t_{1/2}$ = 44 y)
- 21x12 mm^2 diameter

activation only (presently) feasible method

Activation Method

$^{14}C(n,\gamma)^{15}C$ reaction detected via $^{15}C(\beta^-)^{15}N$ decay ($t_{1/2}$=2.5 s)

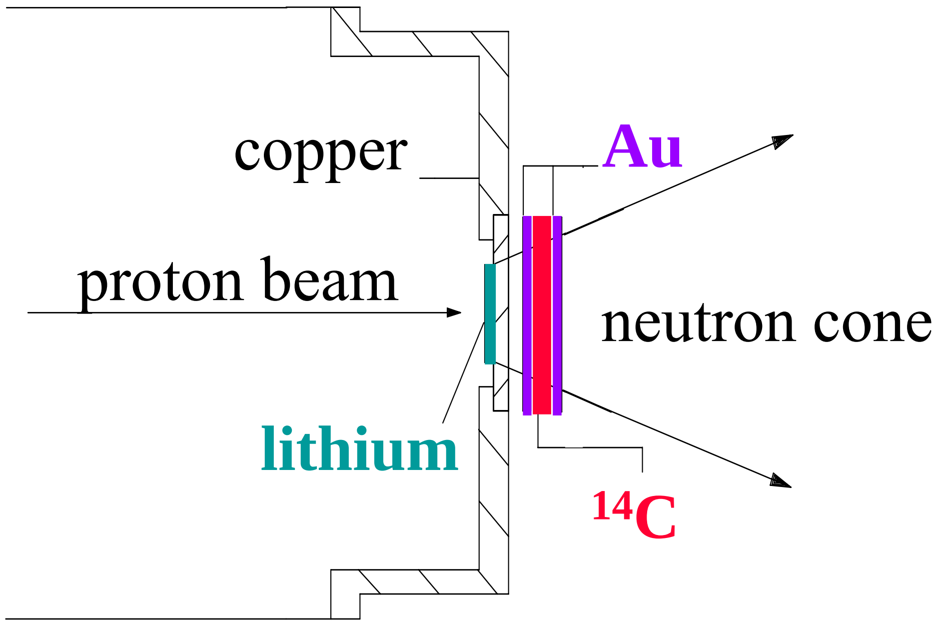
^{14}C sample irradiated for 10 s, then activity counted for 10 s („cyclic activation“)

Determination of neutron flux via

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

Neutron source:

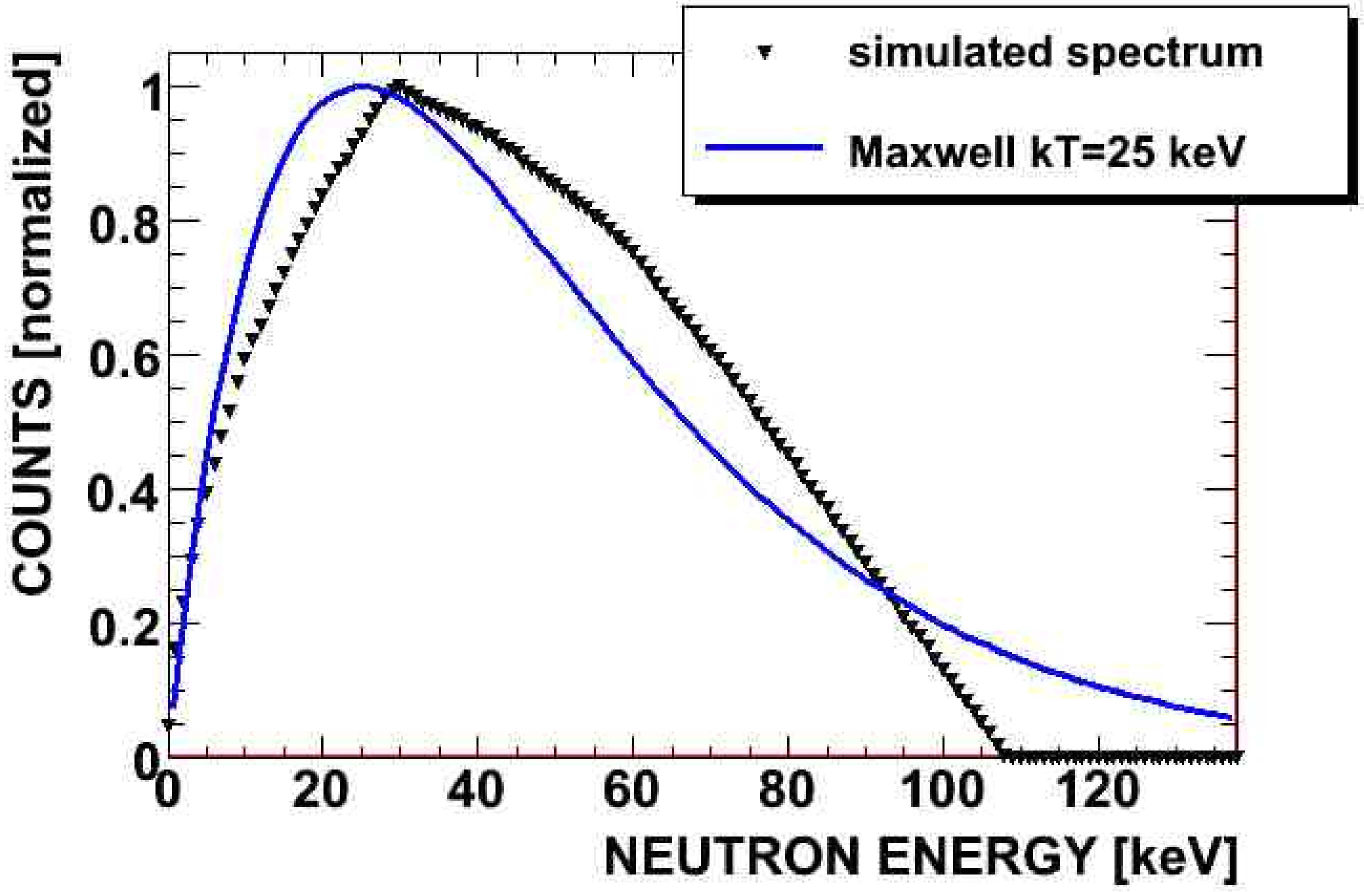
$^{7}Li(p,n)^{7}Be$



R. Reifarth et. al, PRC C 77, 015804 (2008)

A standard neutron spectrum – working horse!

E_p=1912 keV, neutron cone fully covered



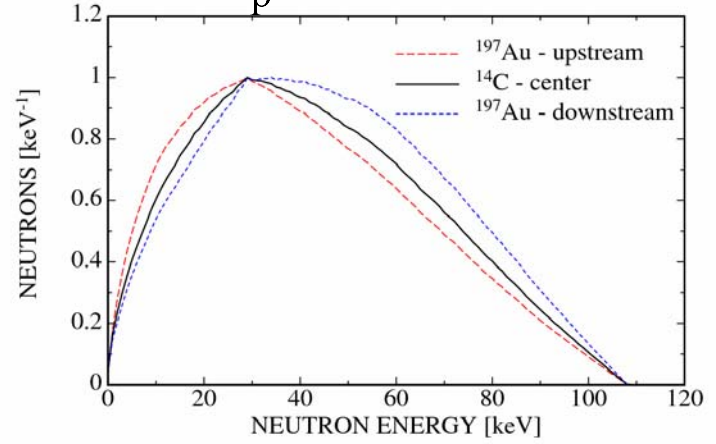
Quasi-Maxwellian averaged distribution:

kT = **25 keV**

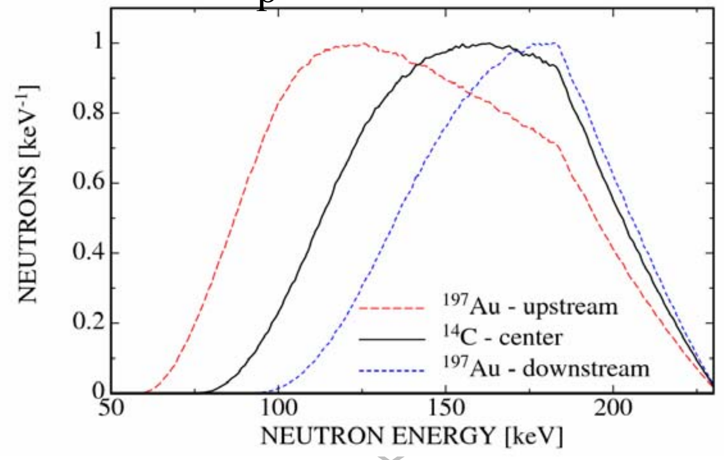
E_{max} = **110 keV**

Other neutron spectra

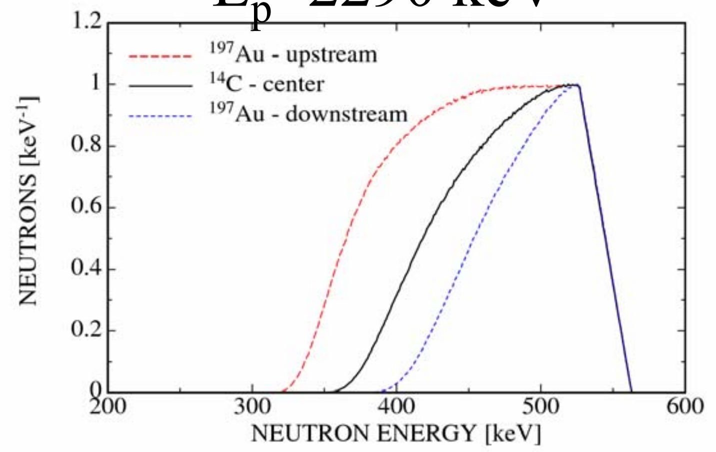
E_p=1912 keV



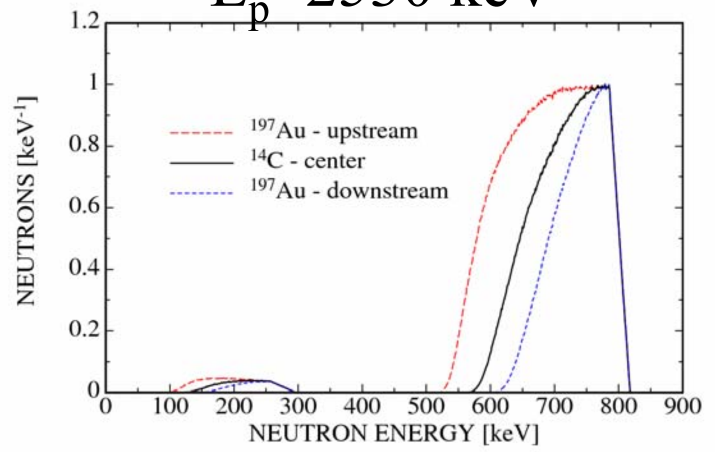
E_p=2000 keV



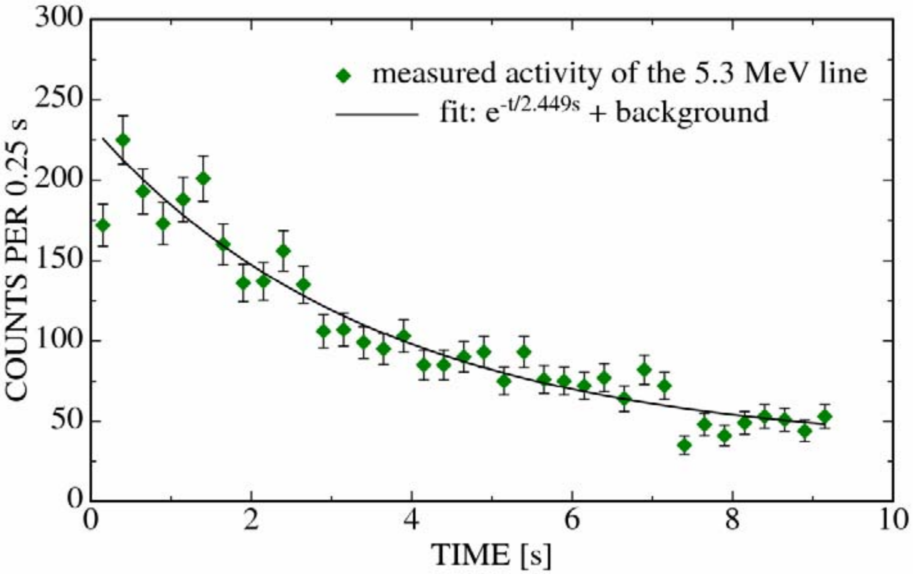
E_p=2290 keV

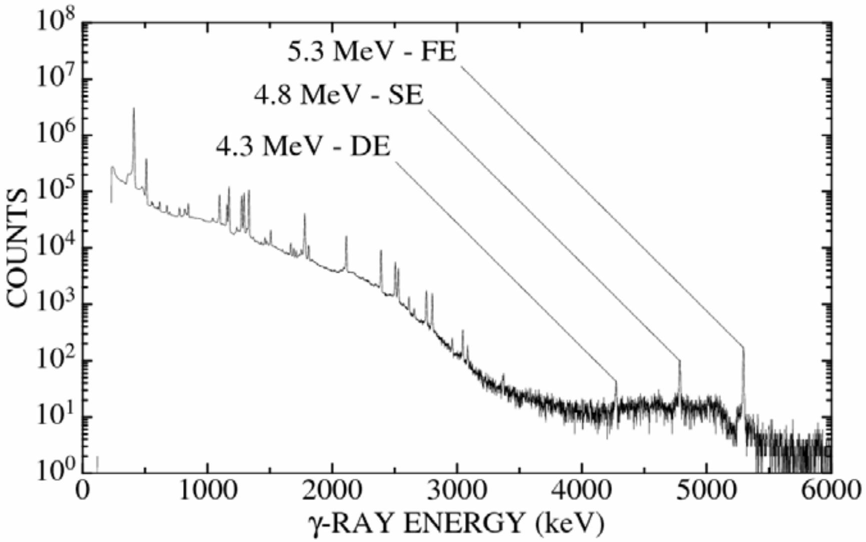


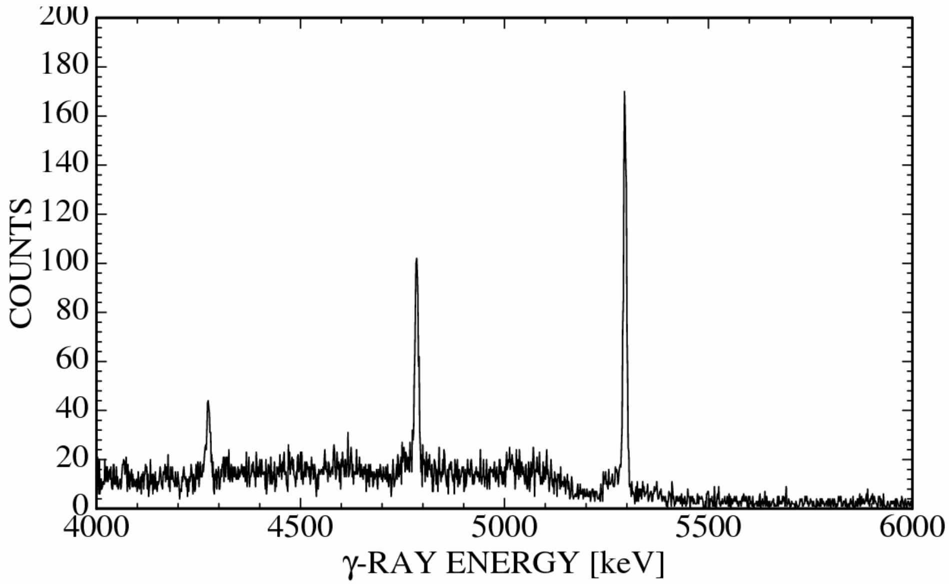
E_p=2530 keV



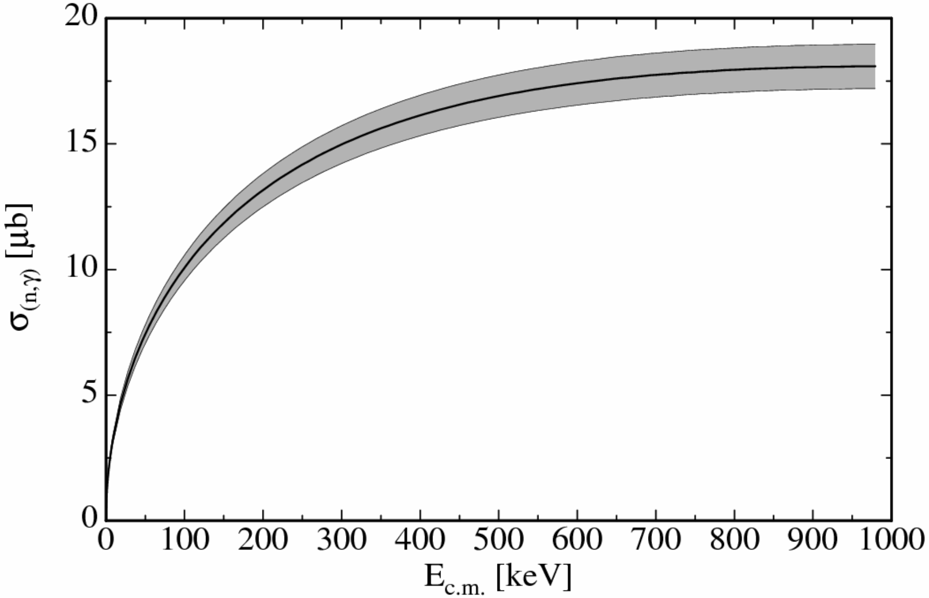
^{15}C – γ-spectra







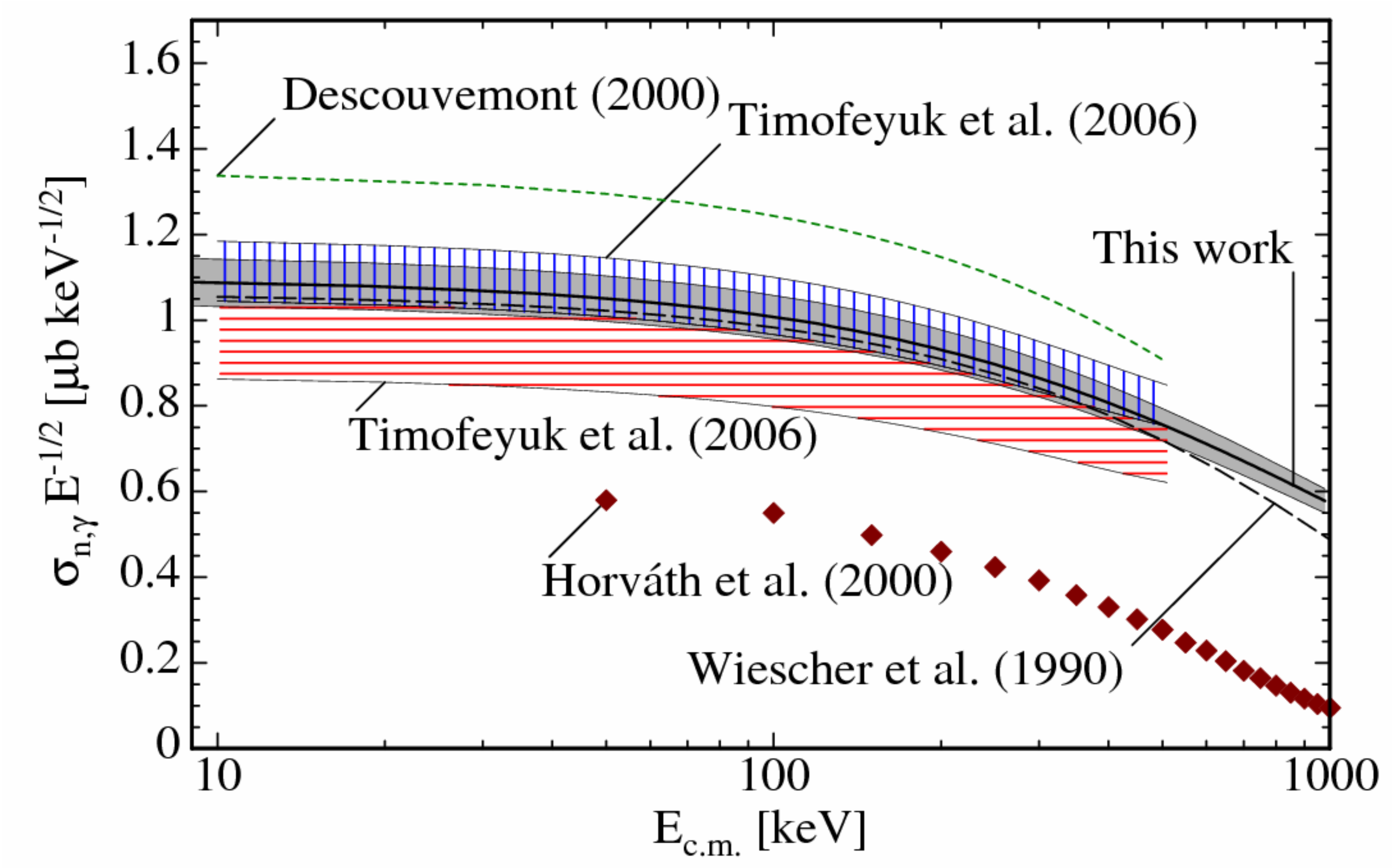
Description and Deconvolution



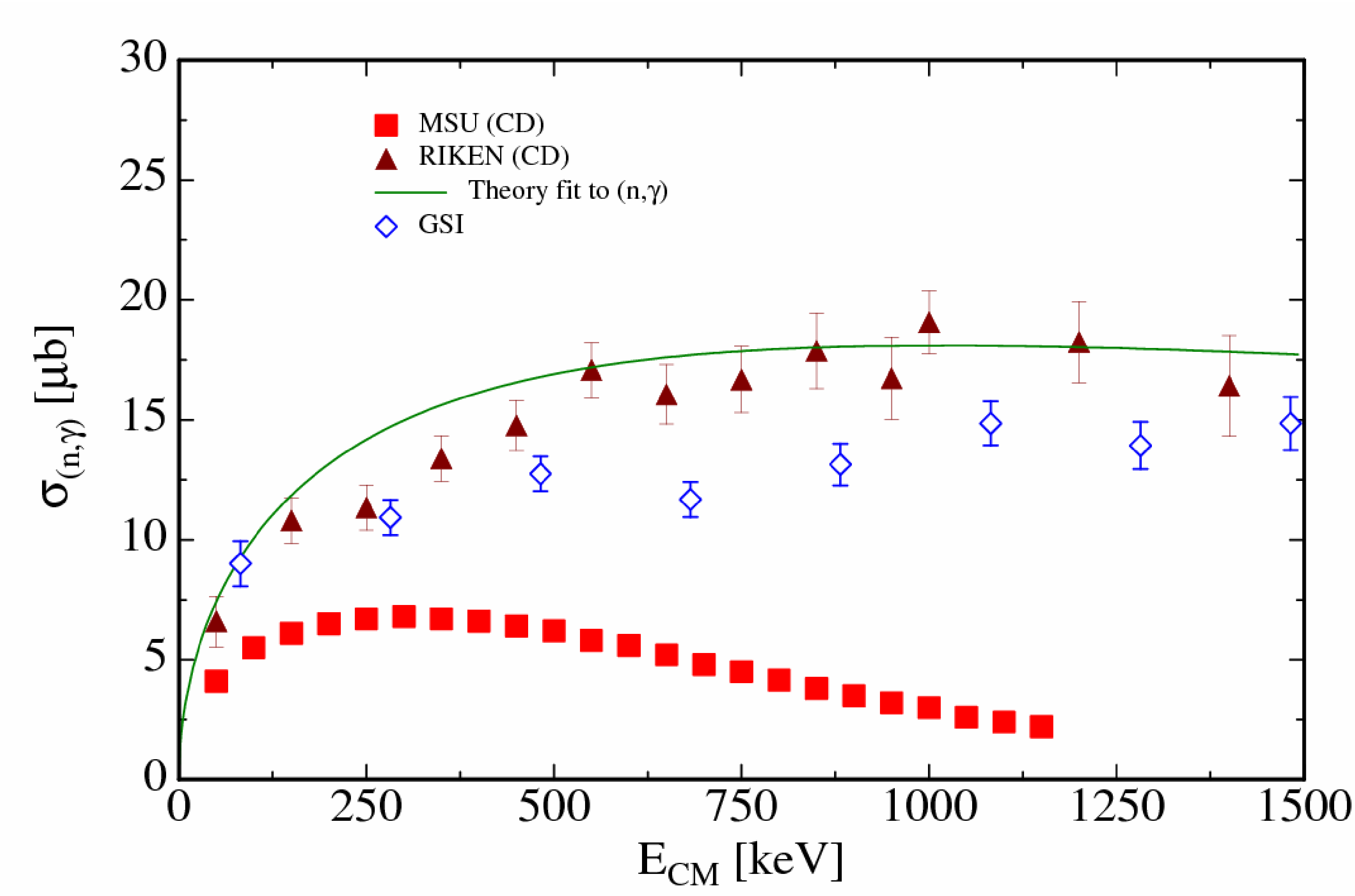
- p-wave capture
- good agreement with exp. data

keV	Exp. [μb]	Theo. [μb]	**Theo/Exp**
23	7.1 ± 5	6.5 ± 0.4	**0.92 ± 0.08**
150	10.7 ± 1.2	11.7 ± 0.6	**1.09 ± 0.12**
500	17.0 ± 1.5	16.5 ± 0.8	**0.97 ± 0.10**
800	15.8 ± 1.6	17.5 ± 0.9	**1.11 ± 0.11**

Comparison with other rate estimates



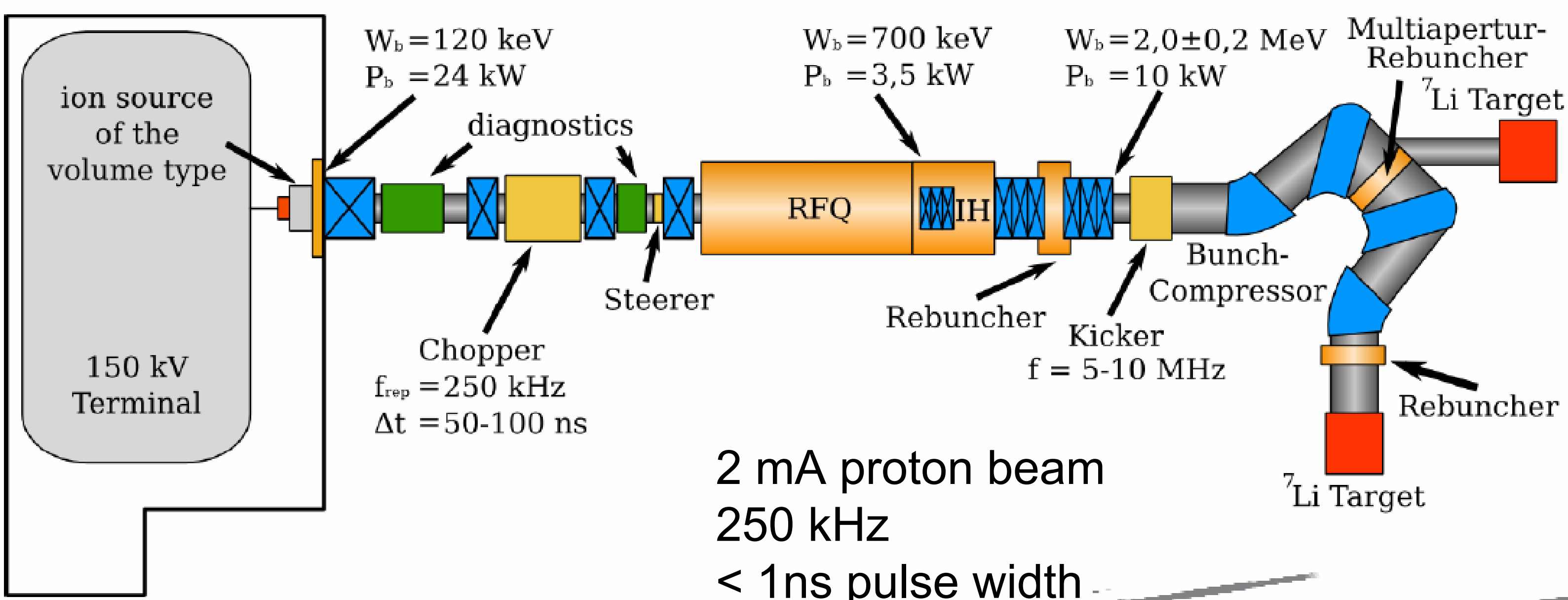
Comparison with CD



Future developments

- Ever more neutrons
- Indirect methods

The Frankfurt neutron source at the Stern-Gerlach-Zentrum (FRANZ)

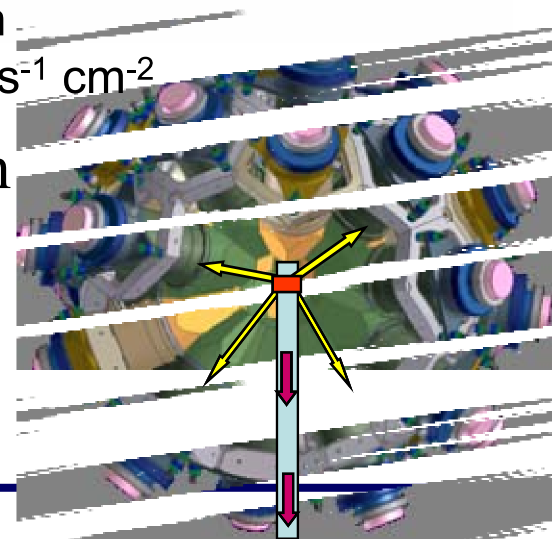


Neutron beam for activation

neutron flux: 10^{12} s^{-1}

2 mA proton beam
250 kHz
< 1ns pulse width
neutron flux: 10^7 s^{-1} cm^{-2}

Flight path: 80 cm



Possible experimental program at FRANZ and ESS

The Frankfurt neutron source will provide the highest neutron flux for a nuclear astrophysics program in relevant keV region (1 – 500 keV) worldwide.

neutron flux

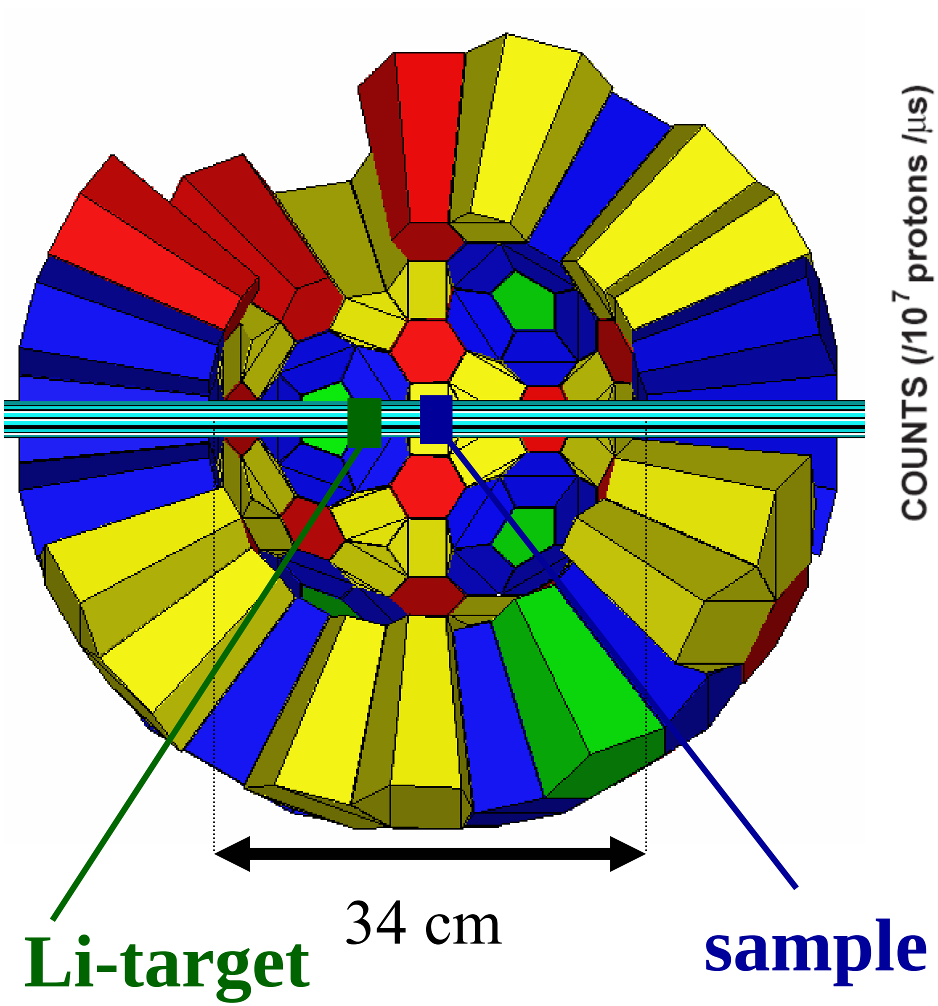
Neutron capture measurements of small cross sections:

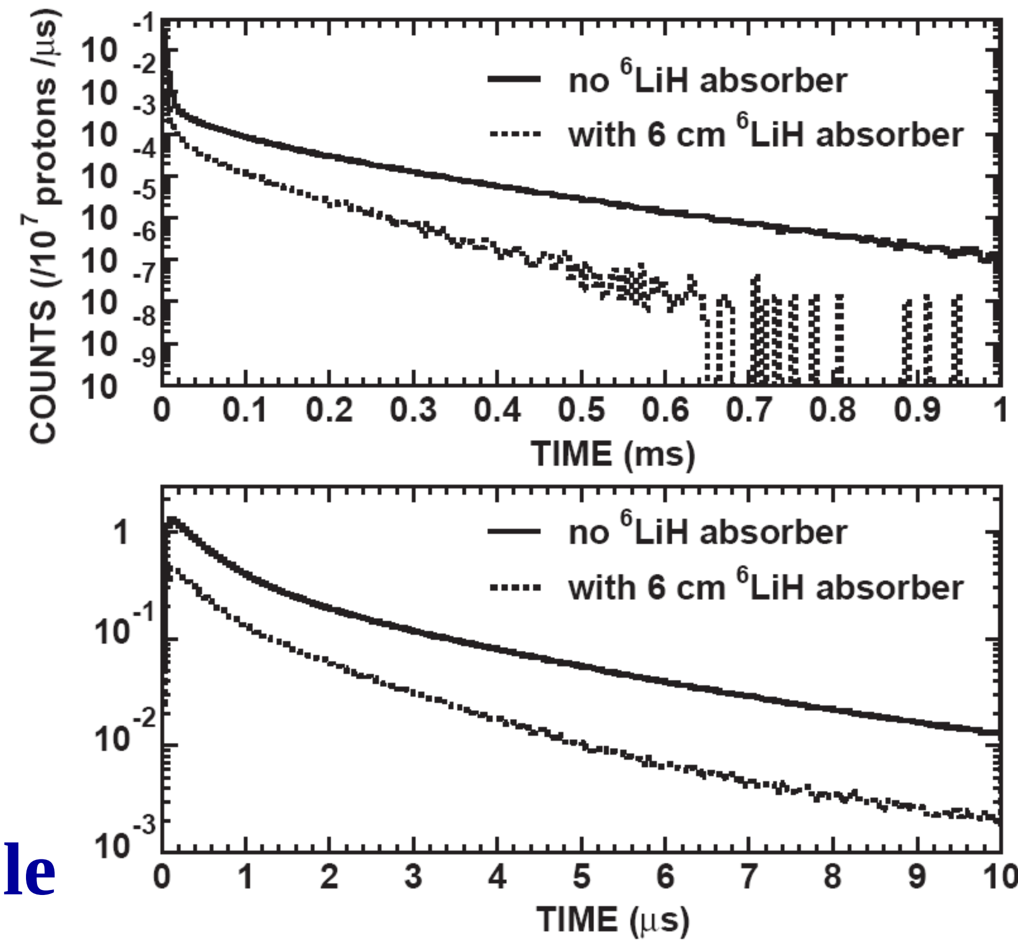
- Big Bang nucleosynthesis: ^{1}H(n,γ)
- Neutron poisons for the s-process: ^{12}C(n,γ), ^{16}O(n,γ), ^{22}Ne(n,γ).
- ToF measurements of medium mass nuclei for the weak s-process.

Neutron capture measurements with small sample masses:

- Radio-isotopes for γ-ray astronomy ^{59}Fe(n,γ) and ^{60}Fe(n,γ)
- Branch point nuclei, e.g. ^{85}Kr(n,γ), ^{95}Zr(n,γ), ^{147}Pm(n,γ), ^{154}Eu(n,γ), ^{155}Eu(n,γ), ^{153}Gd(n,γ), ^{185}W(n,γ)

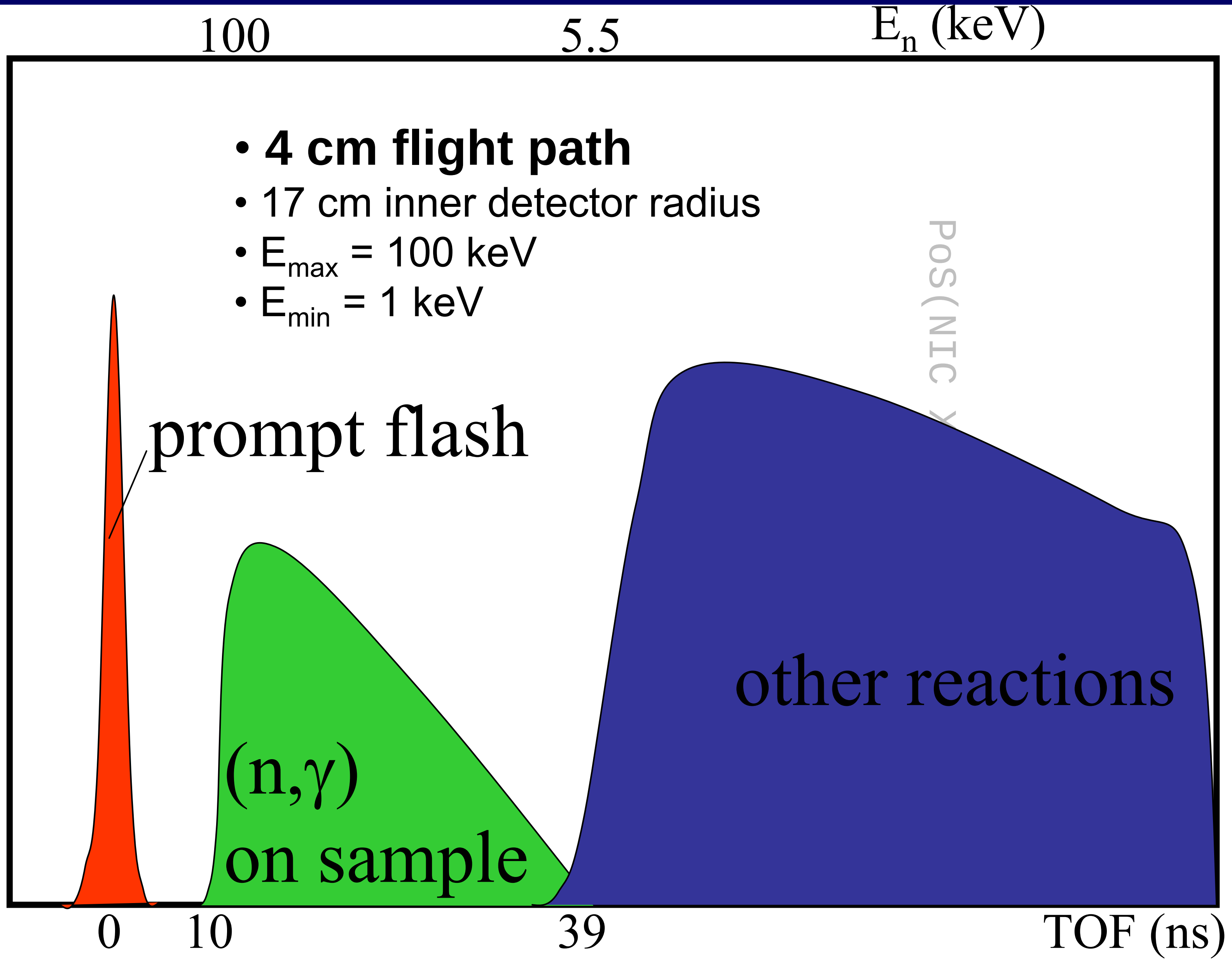
Setup with very short flight path





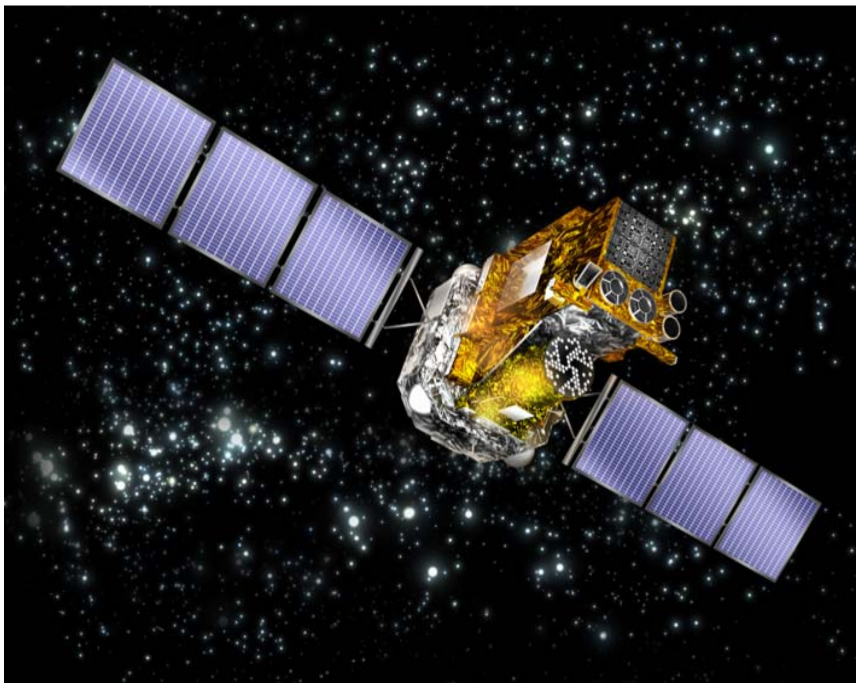
Challenge: Neutrons bouncing around in the detector

TOF spectrum - very short flight path



Motivation – ^{60}Fe in the universe

Detection of γ-ray lines from interstellar ^{60}**Fe** with SPI (INTEGRAL)



E_γ = 1173 and 1333 keV

^{60}**Fe**/^{26}Al = 0.11 ± 0.03

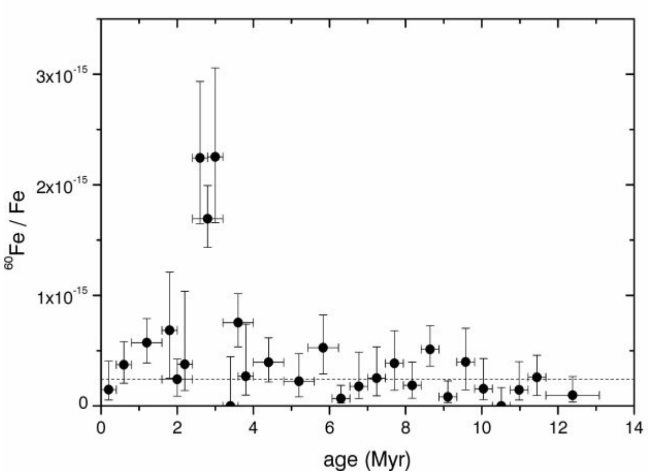
ongoing production in massive stars
and
distribution by subsequent supernovae

→ **tests stellar model and SN rate**

Harris et al, A&A **433** (2005) L49

Motivation – ^{60}Fe on earth

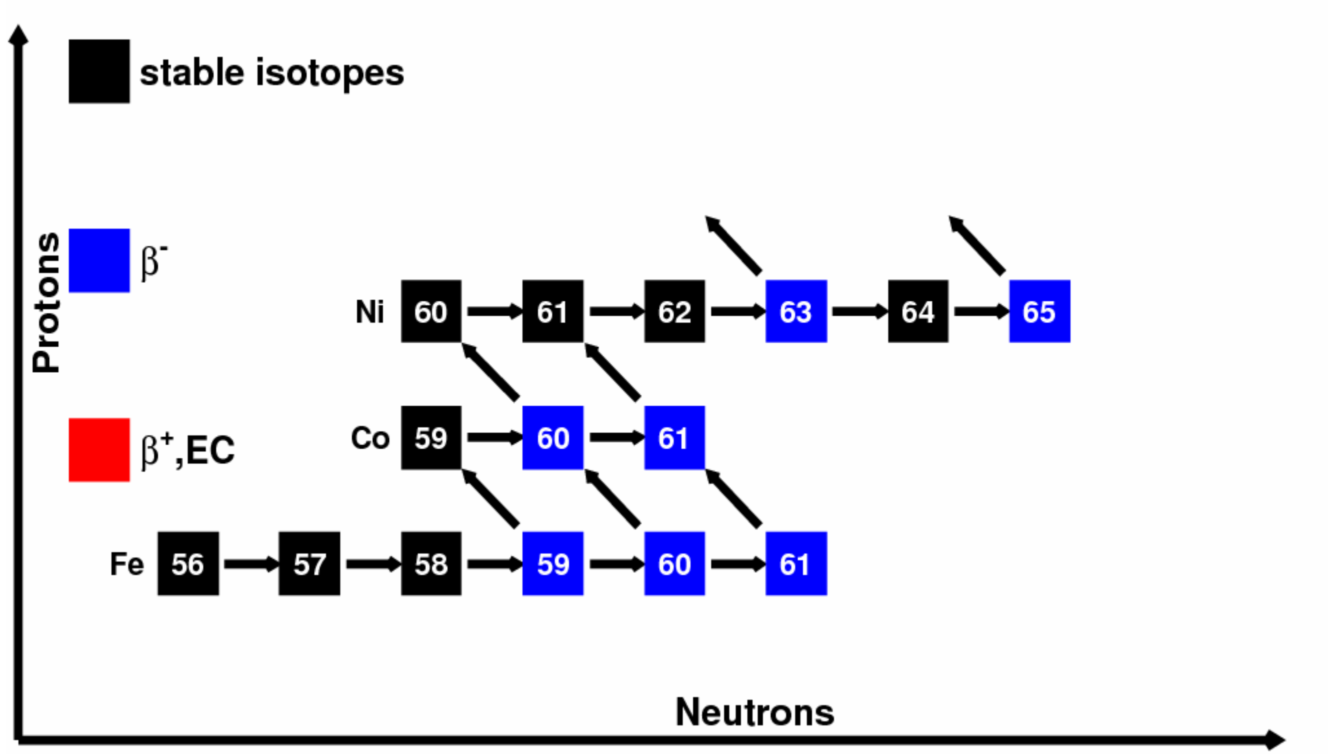
- can be found in deep sea manganese crusts
- Gives hints about a nearby supernova
- 2.8 Ma ago



Knie et al, PRL **93** (2004) 171103

^{60}Fe in stars

- Weak s-process component
- During C-shell burning in massive stars



Production and Destruction of ^{60}Fe

^{60}Fe(β^-) :
done

^{59}Fe(n,γ) :
Extremely difficult

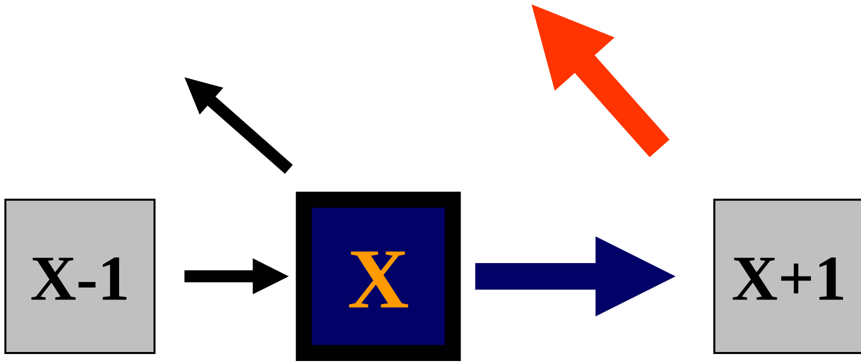
^{60}Fe

^{60}Fe(n,γ) :

Cyclic activation @ 25 keV,
Needs to be improved to meet requirements at
kT= 90 keV

^{60}Fe(γ,n) :
Coulomb dissociation,
scheduled

Double neutron capture

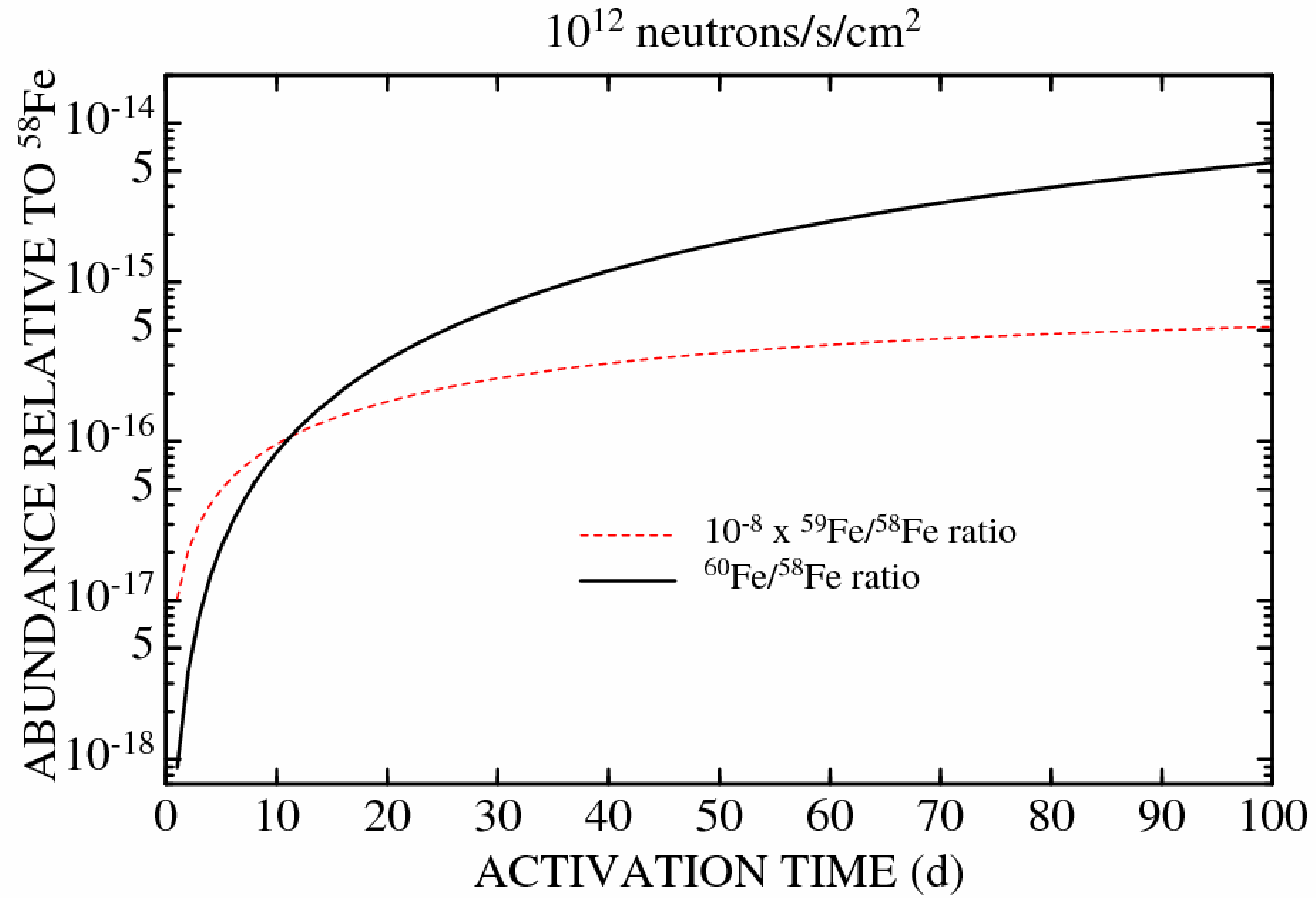


$$t_{1/2} \sim 1..100 \text{ d}$$

- produce the sample "on the fly"
- 10^{12} n/s/cm^2 @ 25 keV ~ 5 10^3 n/cm^3

$^{59}Fe(n,\gamma)$ at FRANZ ($t_{1/2}$=45 d)

- activate ^{58}Fe, wait for 2nd neutron capture
- measure $^{60}Fe/^{58}Fe$ ratio via AMS



Coulomb dissociation

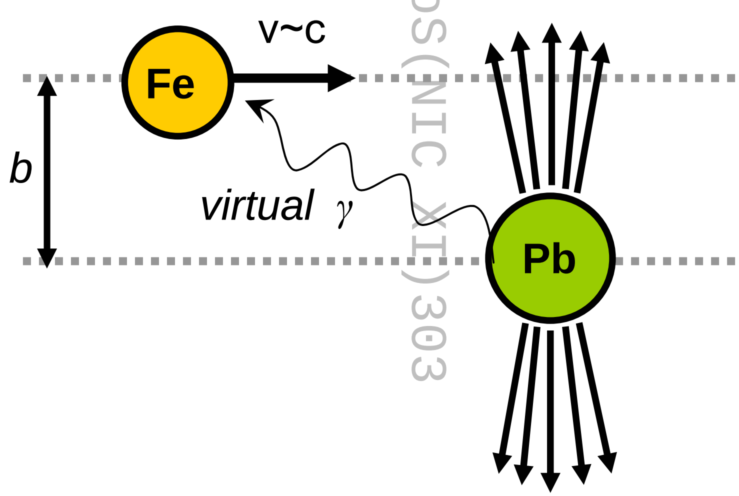
- Method for radioactive beams:
  - Inverse kinematics
  - “virtual photon field” as result of relativistic interaction with high-Z target (lead)
  - Produce beam of radioactive ions
  - In-beam experiment
  - Detect ALL prompt products
    - Gammas
    - Ions

Experimental method

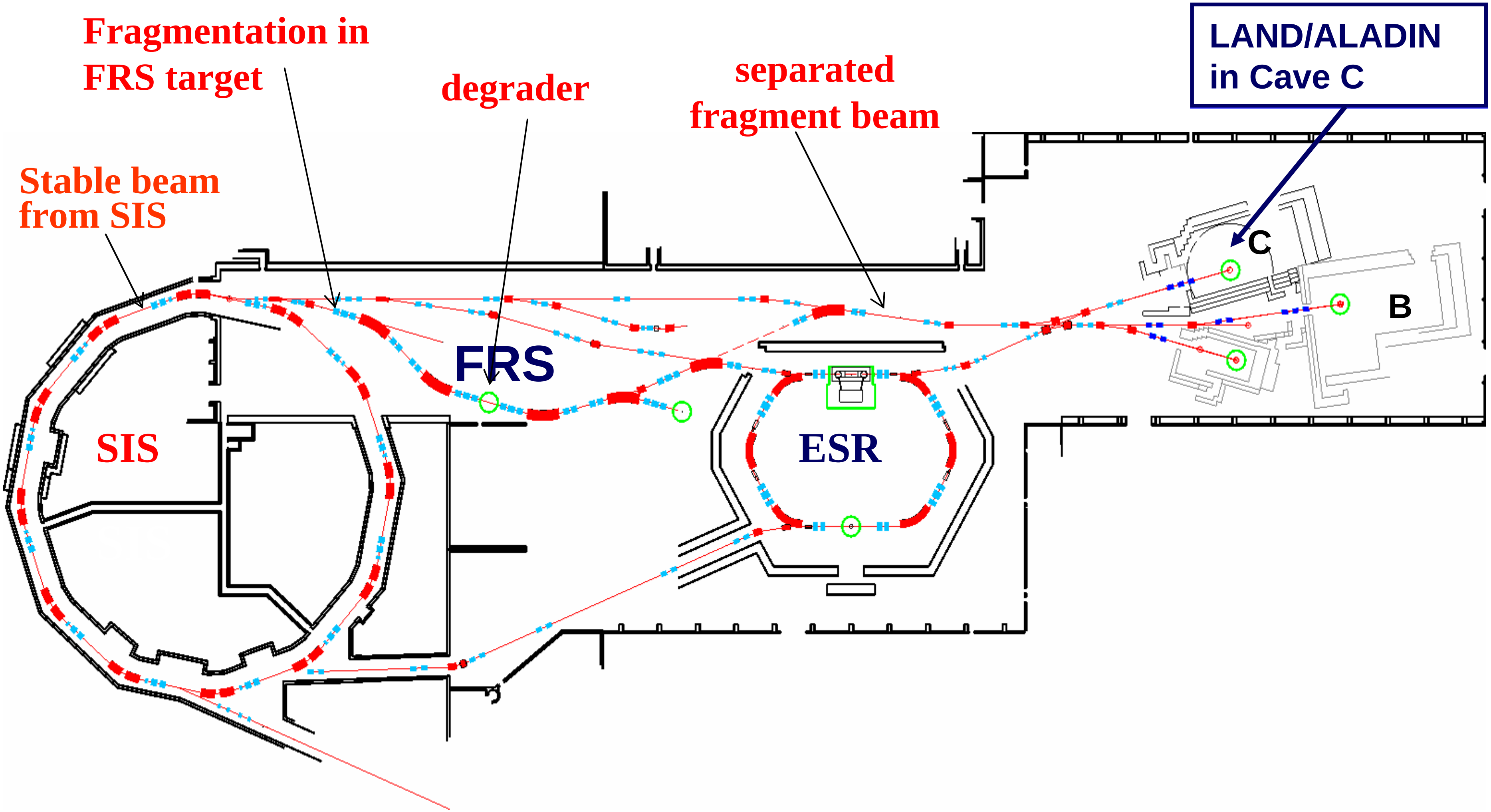
Astrophysically relevant energy window: $E_\gamma \approx S_n + kT/2$ = 8-12 MeV, width ~ 1 MeV

Coulomb dissociation in inverse kinematics:

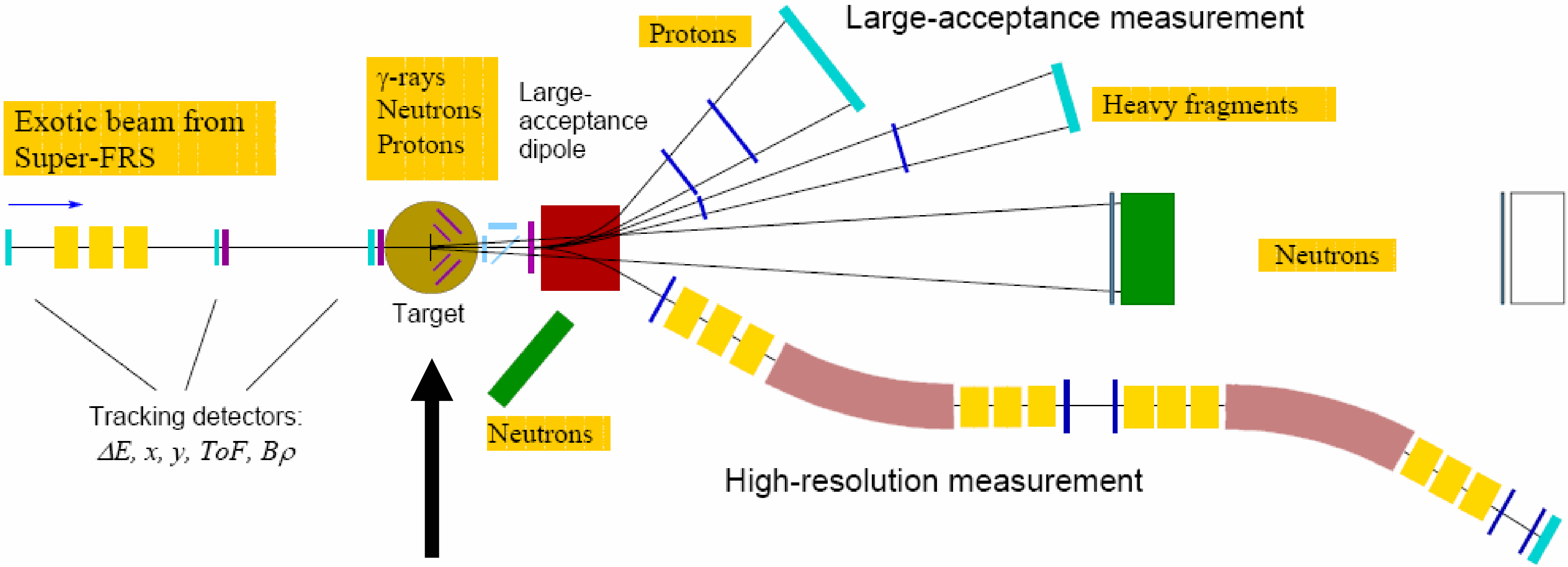
- Virtual photons produced by a high-Z target (Pb)
- Projectile at ~500 MeV/u
- Large impact parameter *b*
- E_{max} of the virtual photon spectrum ~ 20 MeV
- C and empty target measurements (to subtract nuclear contribution and background)



Layout of the experimental facilities at GSI



R³B - Reactions with Relativistic Radioactive Beams



TARGET
(CH_2, LH_2, Pb…)

~100 – ~1000 AMeV

From: R³B Technical Report

Summary

- n-induced reactions are important for nucleosynthesis beyond iron
- s-process can be used as a tool to constrain stellar parameters, if the corresponding reaction rates are known
- we are now close to measure n-induced cross section at stellar energies on radioactive nuclei on a routinely basis
- So far almost all measurements are done on stable nuclei