Neutron data for Nuclear Astrophysics: needs and measurements

G. Tagliente

INFN Bari

Outline

Introduction

Stellar Evolution

s & r-processes

Neutrons in Lab

Measurements and Analysis Techniques

Astrphysical implications

Conclusions

Introduction: Nuclear Astrophysics

"the majority of the chemical elements in the universe is produced through nuclear reactions in the hot interiors of the stars"

REVIEWS OF

MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

Introduction: Nuclear Astrophysics

EXPERIMENTAL AND THEORETICAL NUCLEAR ASTROPHYSICS; THE QUEST FOR THE ORIGIN OF THE ELEMENTS

Nobel lecture, 8 December, 1983

by

WILLIAM A. FOWLER

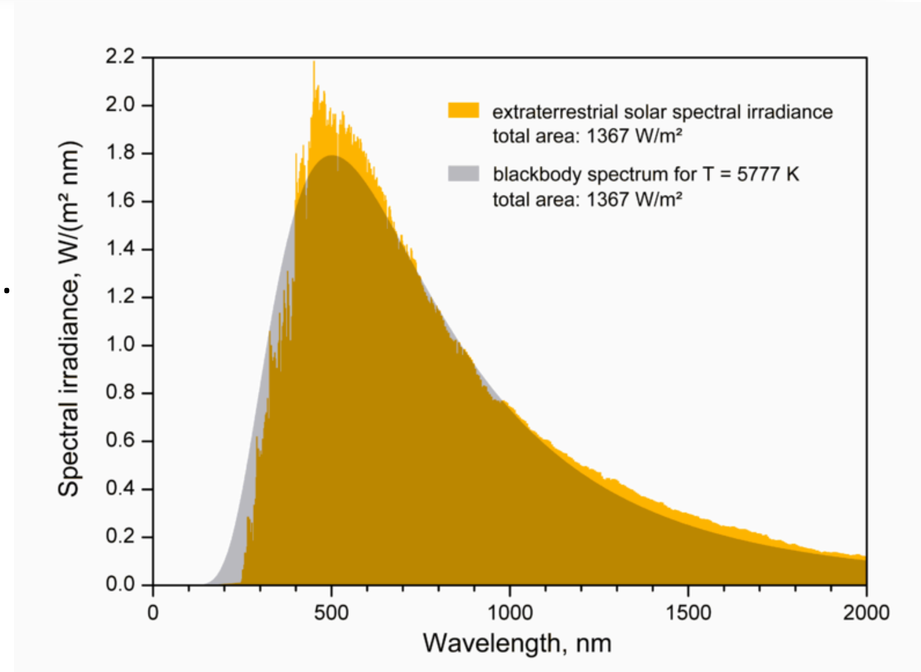
W. K. Kellogg Radiation Laboratory
California Institute of Technology, Pasadena, California 91125

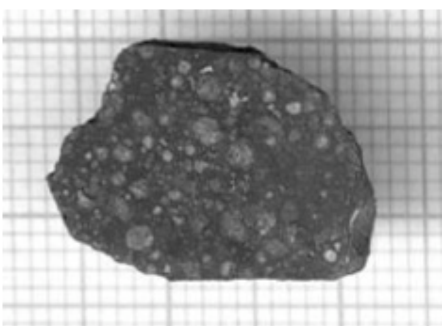
Ad astra per aspera et per ludum

SCIENCE volume 225 (1984) 922

The abundances of the elements

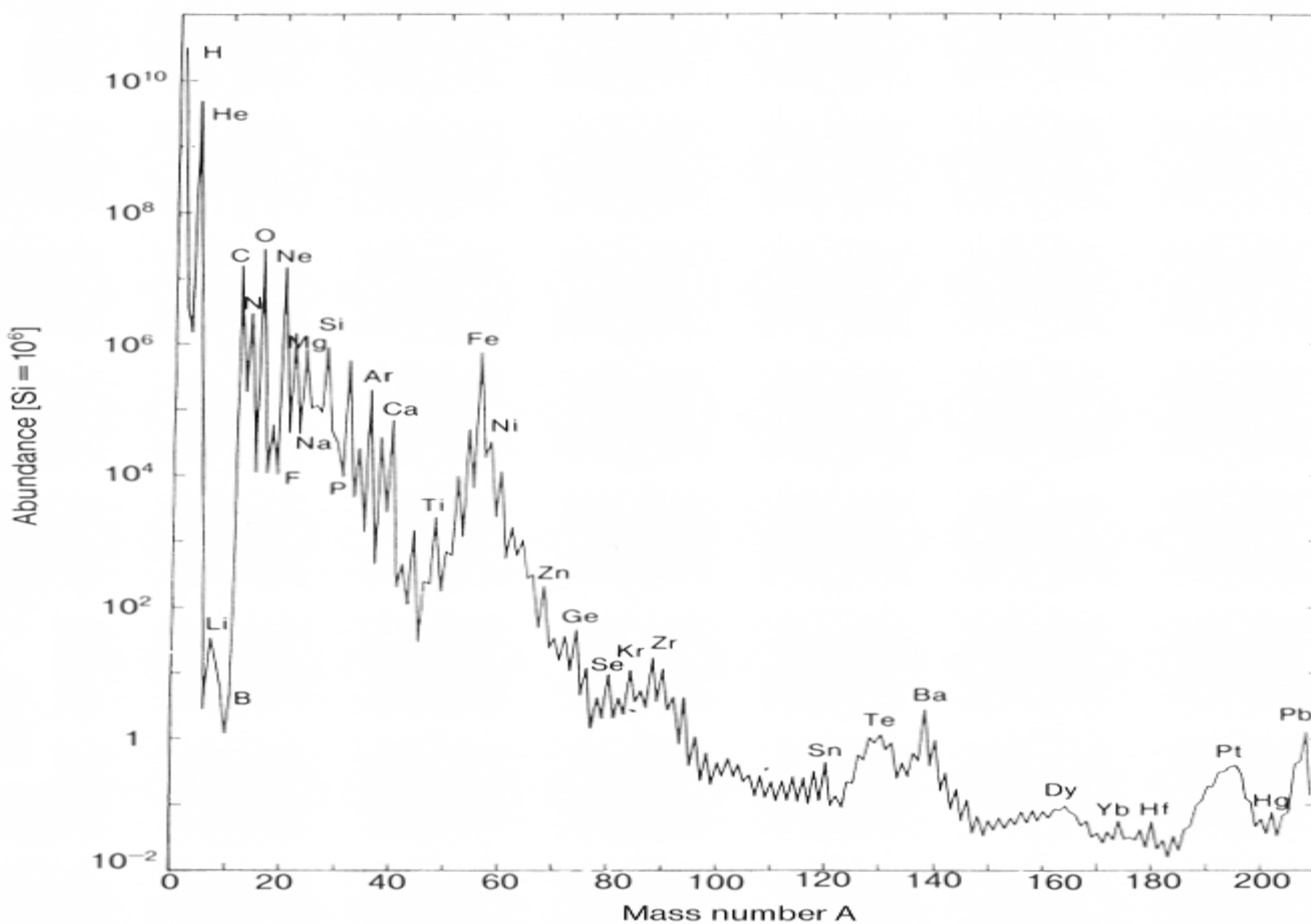
The principal source of information on the solar system abundances is the photosphere. The sun emits a black body spectra at the temperature of 5.777 K.



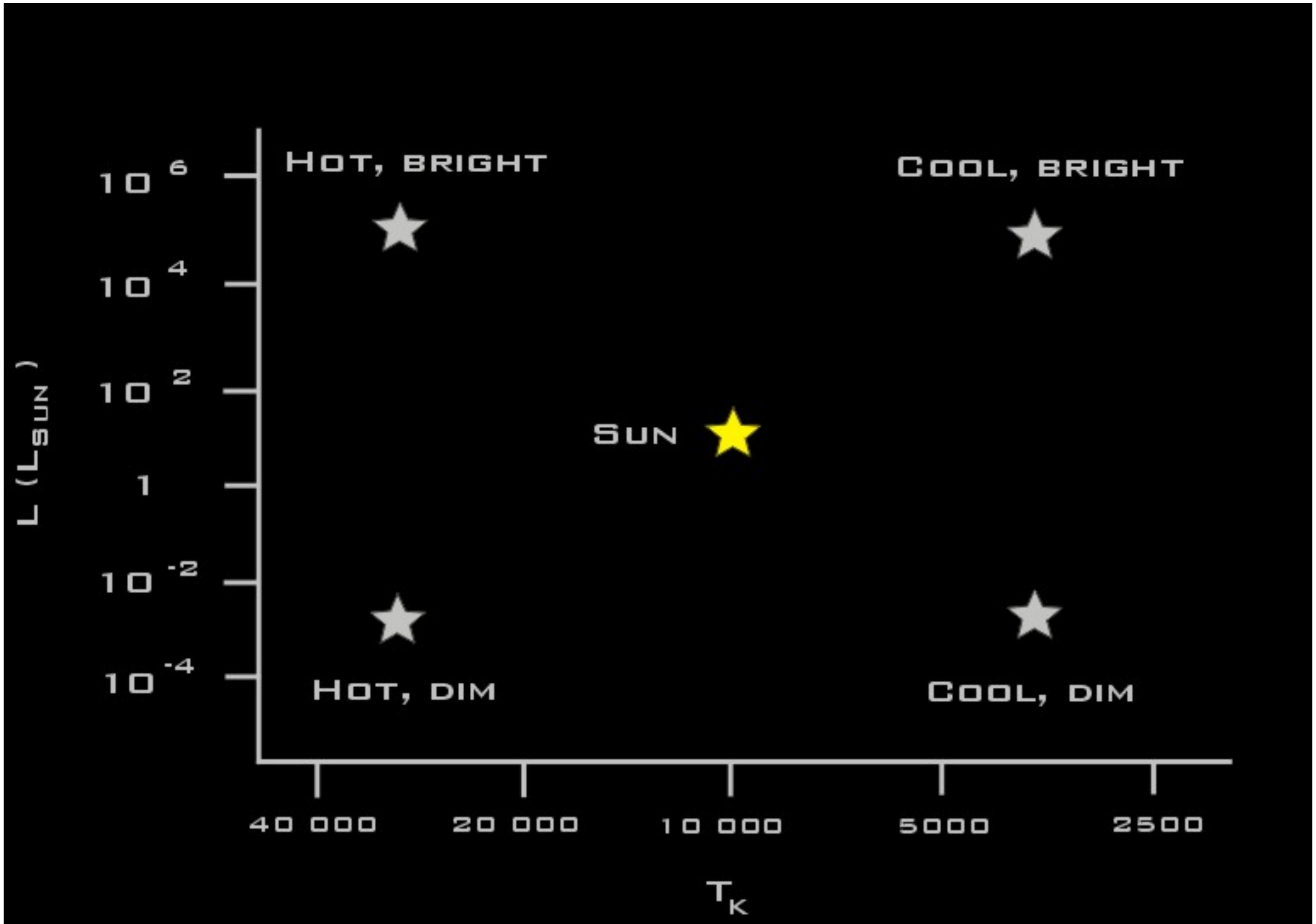


Another source of information for the abundances of elements are the meteorites.

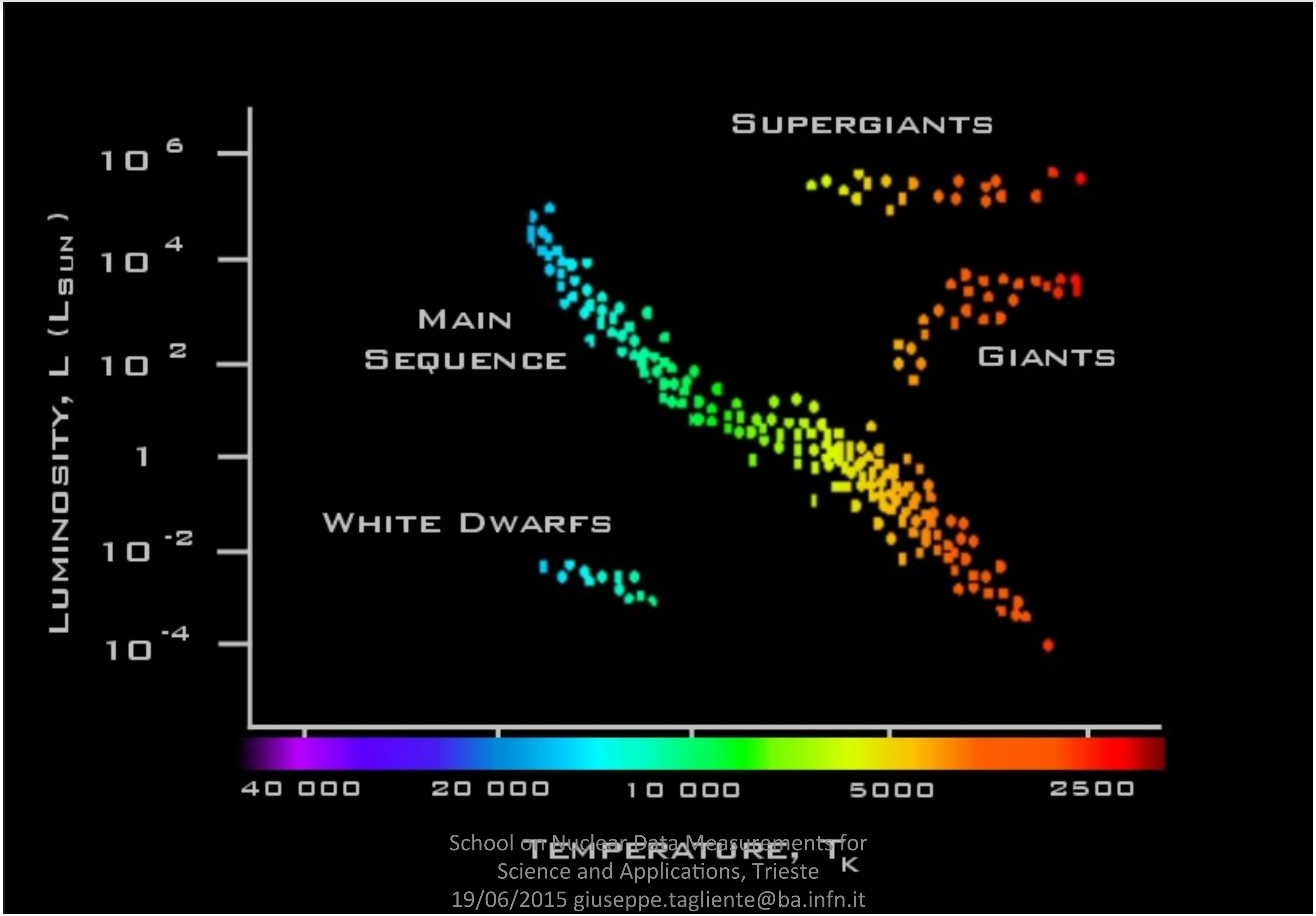
The (cosmic) abundances of the elements

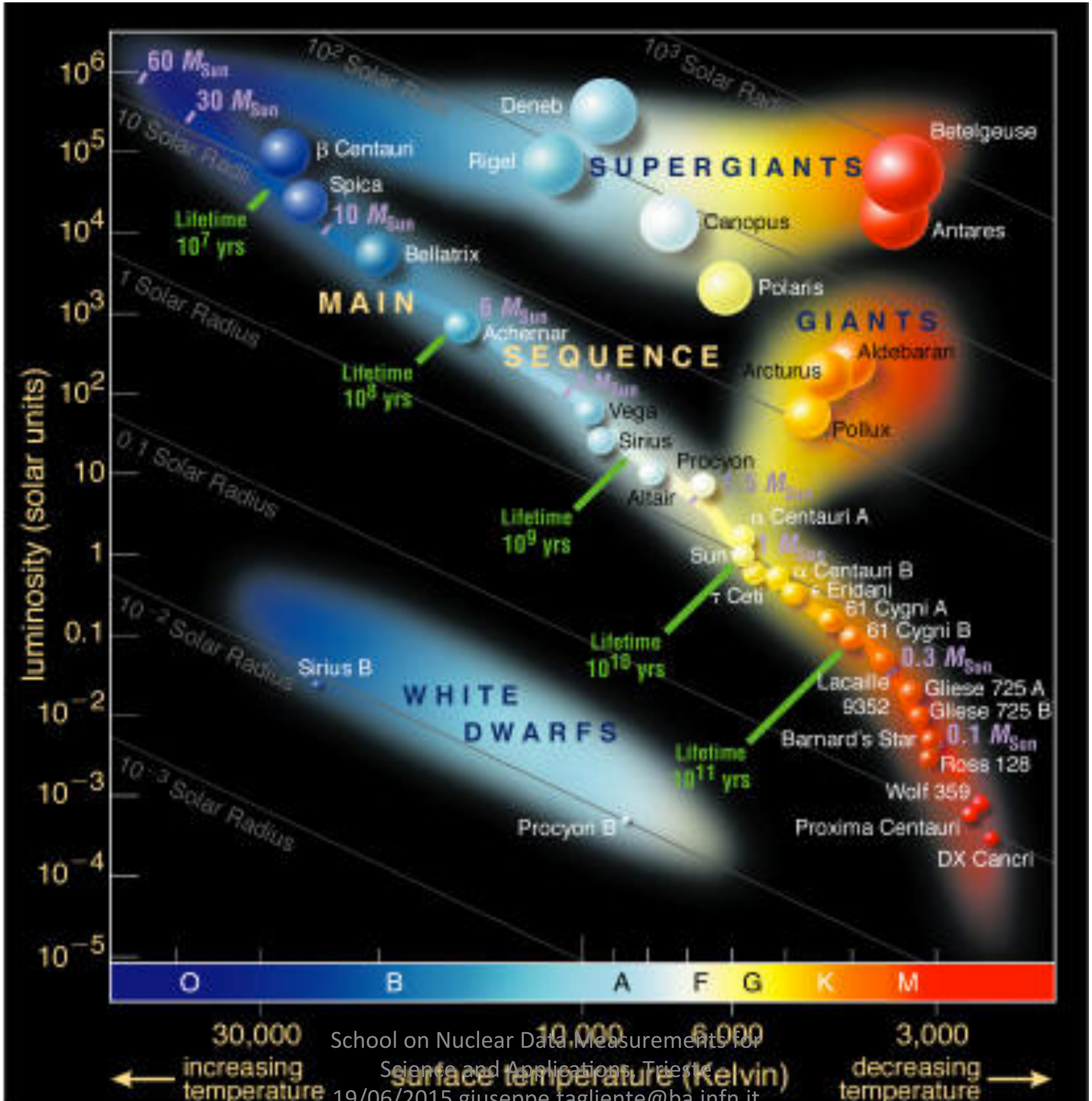


Stellar Evolution: Hertzsprung-Russell diagram



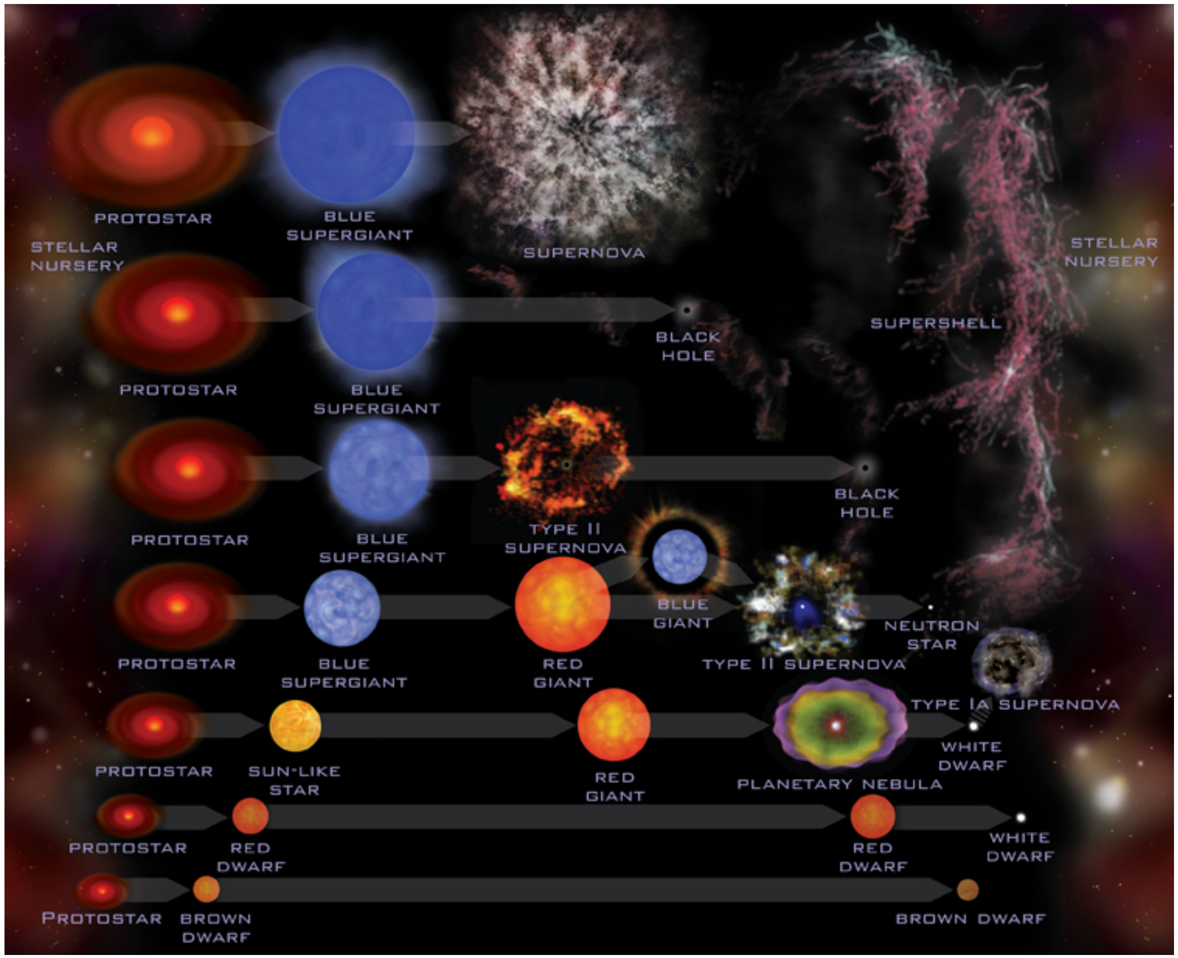
Stellar Evolution: Hertzsprung-Russell diagram





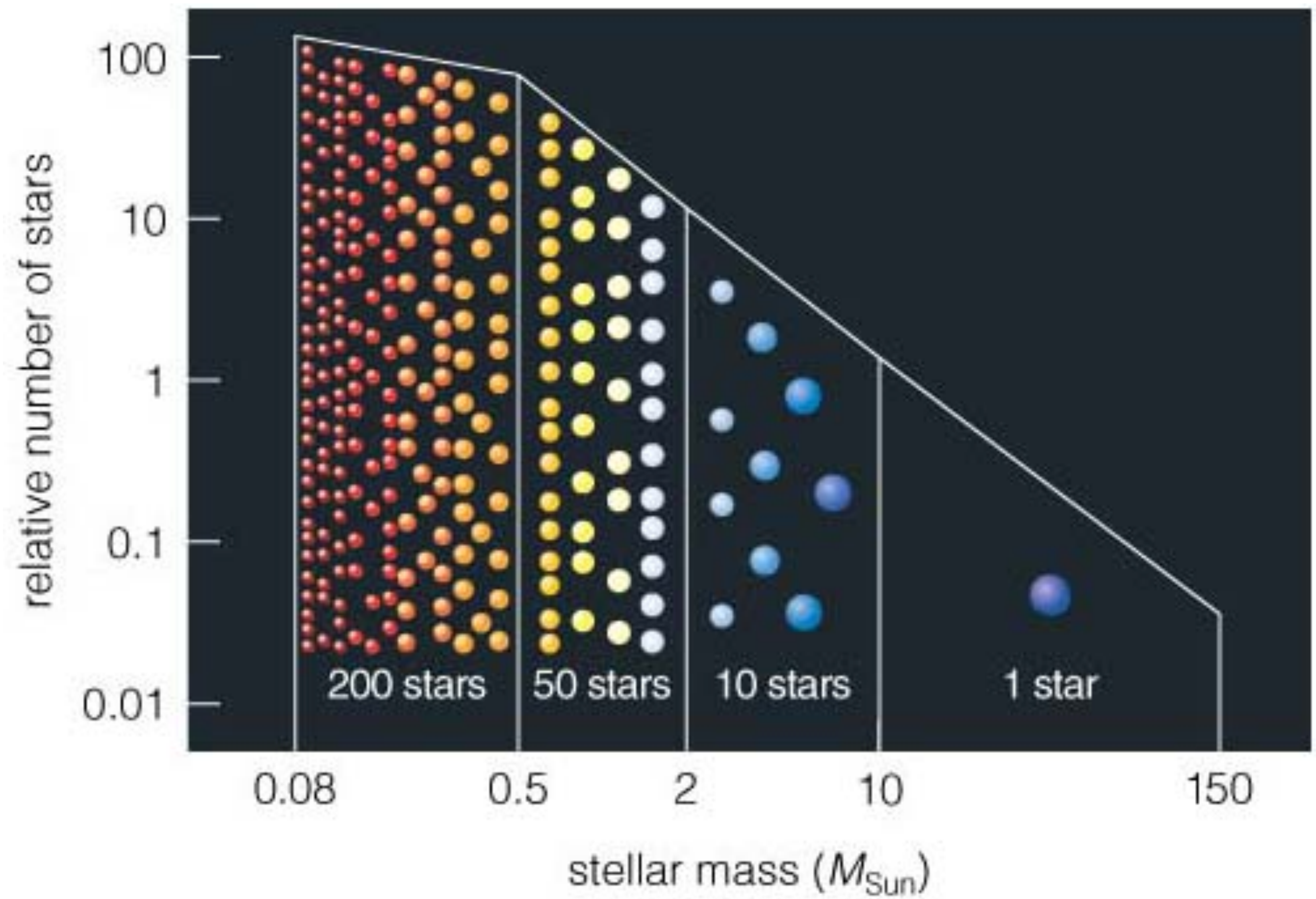
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
10^-5
60 M_Sun
30 M_Sun
10 M_Sun
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^-2 Solar Radius
10^-3 Solar Radius
Deneb
Rigel
β Centauri
Spica
Bellatrix
Achernar
Vega
Sirius
Procyon
Altair
Canopus
Polaris
Betelgeuse
Antares
Aldebaran
Arcturus
Pollux
SUPERGIANTS
GIANTS
MAIN
SEQUENCE
WHITE
DWARFS
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^10 yrs
Lifetime 10^11 yrs
α Centauri A
1 M_Sun
Sun
α Centauri B
ε Eridani
τ Ceti
61 Cygni A
61 Cygni B
0.3 M_Sun
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
0.1 M_Sun
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

Stellar Evolution



$$t_{MS} \propto M^{-\frac{5}{2}}$$

Stellar Evolution



Stellar Evolution

$M_\odot \approx 2 \times 10^{30}$ Kg

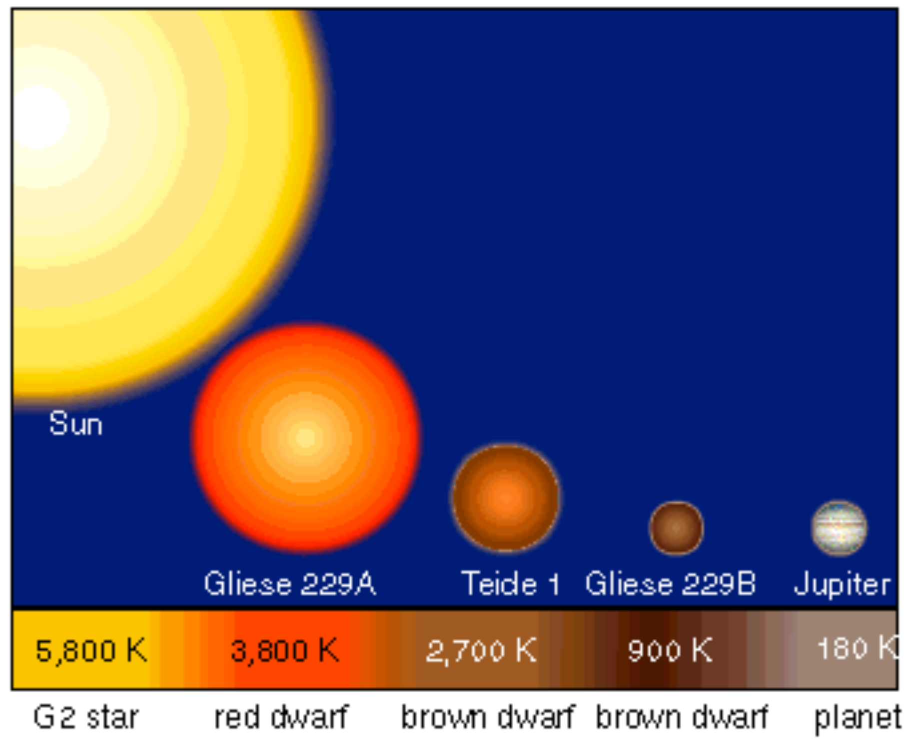
$0.013\ M_\odot \leq$ M $\leq 0.08\ M_\odot$

$0.08\ M_\odot <$ M $\leq 0.5\ M_\odot$

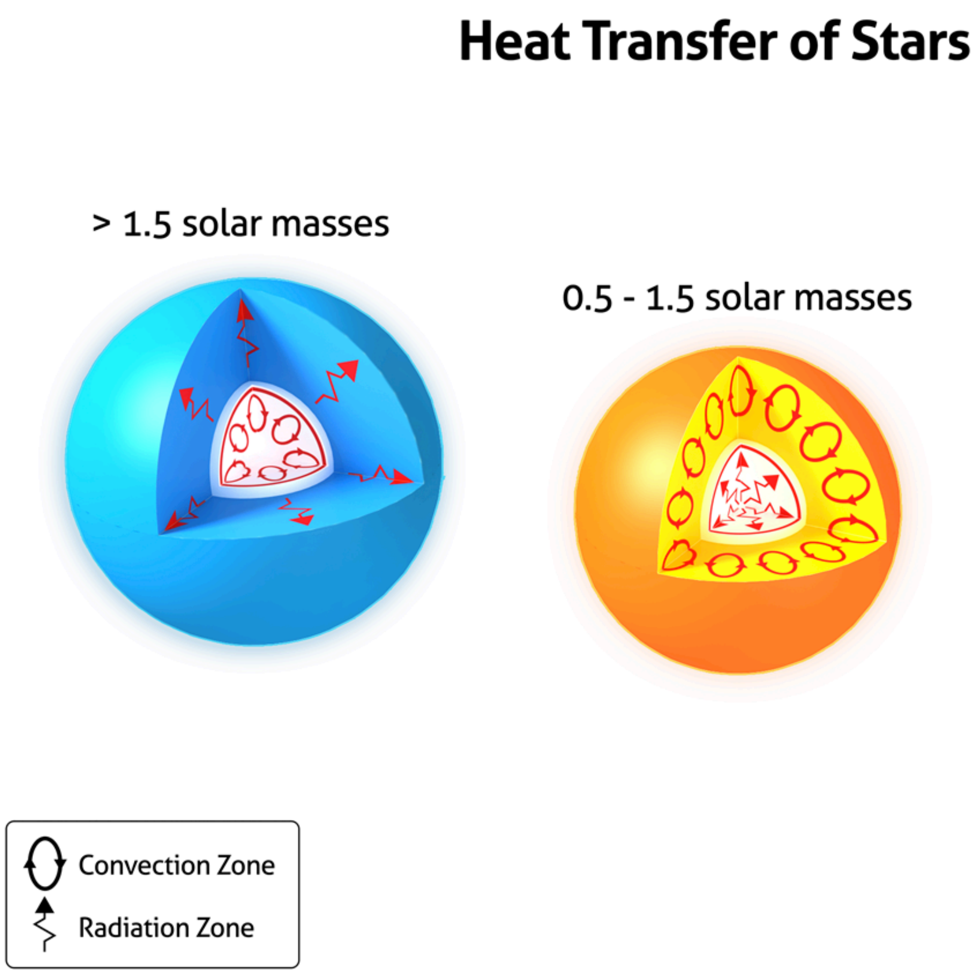
$0.5\ M_\odot <$ M $\leq 3\ M_\odot$

$3\ M_\odot <$ M $\leq 11\ M_\odot$

M $> 11\ M_\odot$



Stellar Evolution: $0.5\ M_{\odot} \leq M \leq 3\ M_{\odot}$



$M \leq 1.5\ M_{\odot}$ pp chain

$M > 1.5\ M_{\odot}$ CNO cycles

Stellar Evolution: $3 M_{\odot} \leq M \leq 11 M_{\odot}$

AGB

The evolution is similar to the stars with initial mass $1.5 M_{\odot} \leq M \leq 3 M_{\odot,}$ without the He flash in the RGB phase.

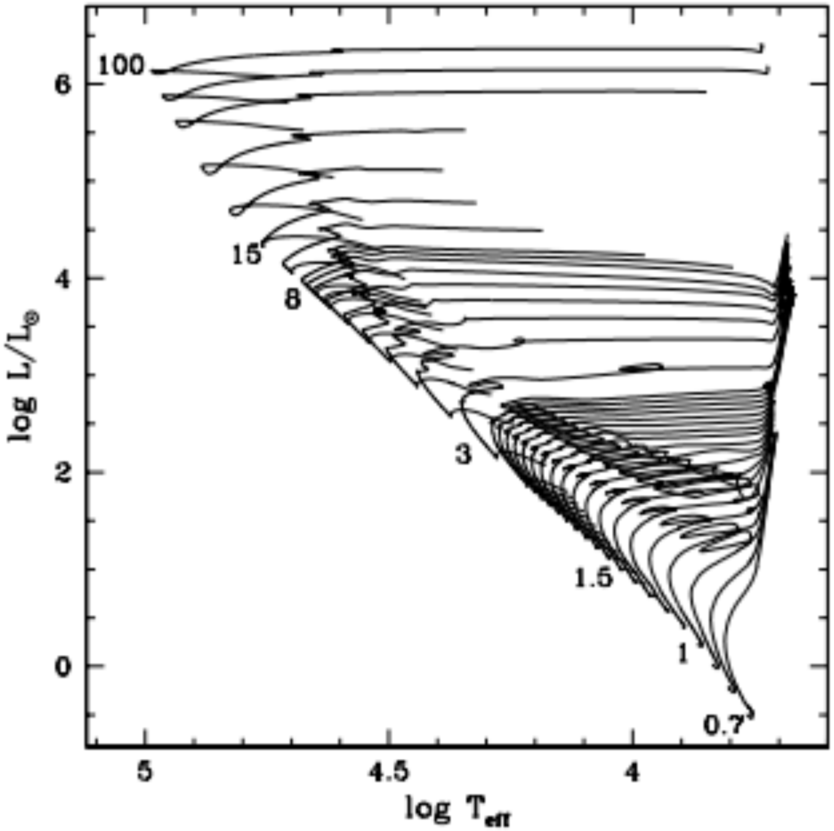
$3 M_{\odot} \leq M \leq 4 M_{\odot}$

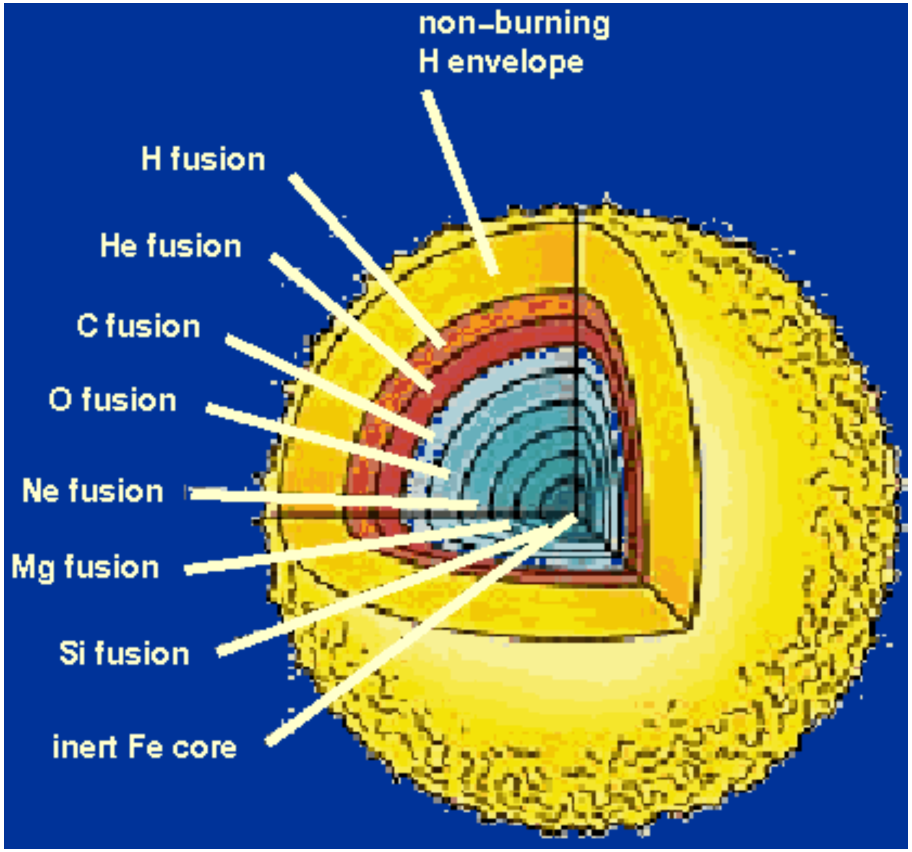
$4 M_{\odot} \leq M \leq 9$

SAGB

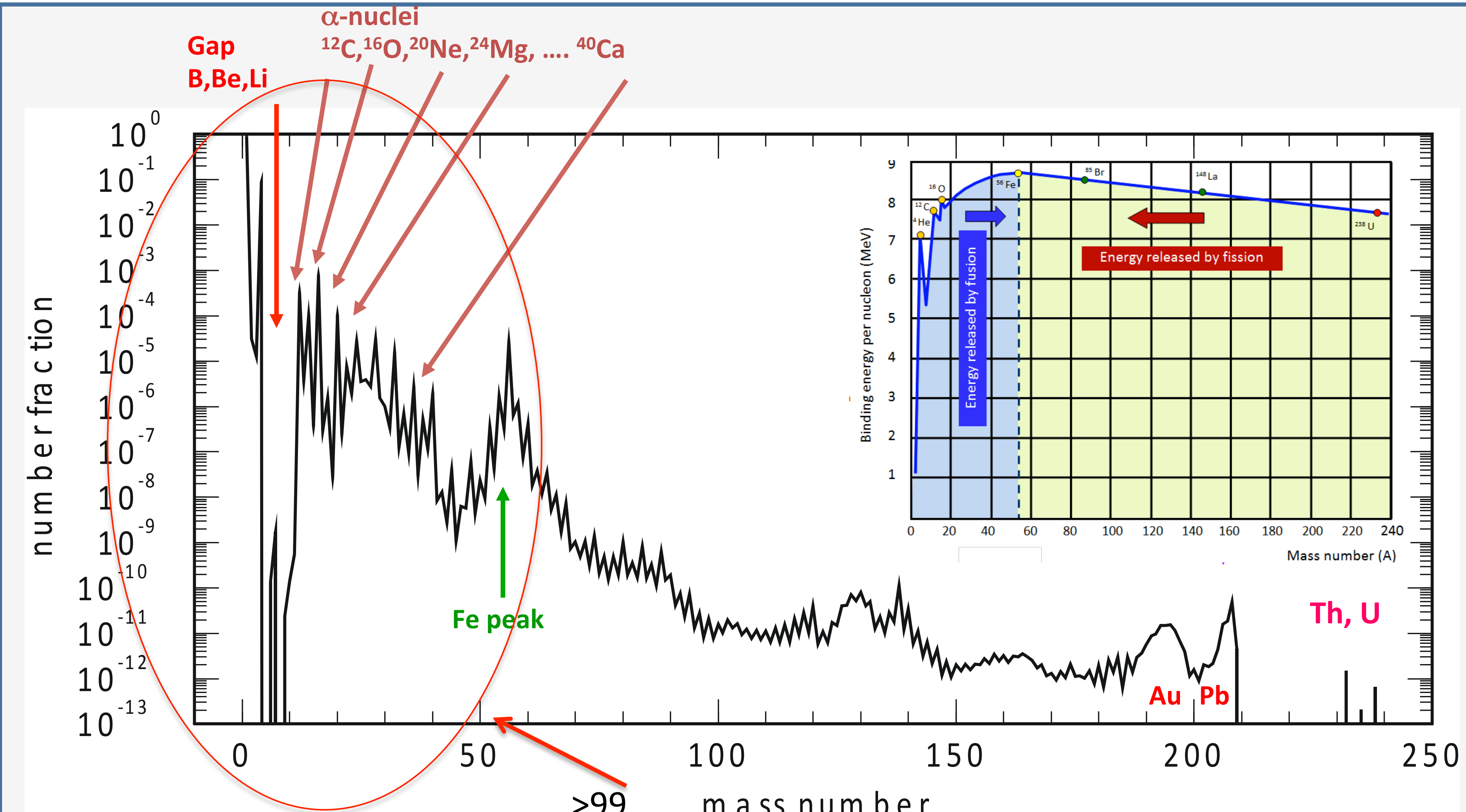
Initial Mass: $9 M_{\odot} \leq M \leq 11 M_{\odot}$ They are more complicate of the AGB, their evolution is not yet well defined. They can start burning C

Stellar evolution: M > 11 $M_{\odot}$

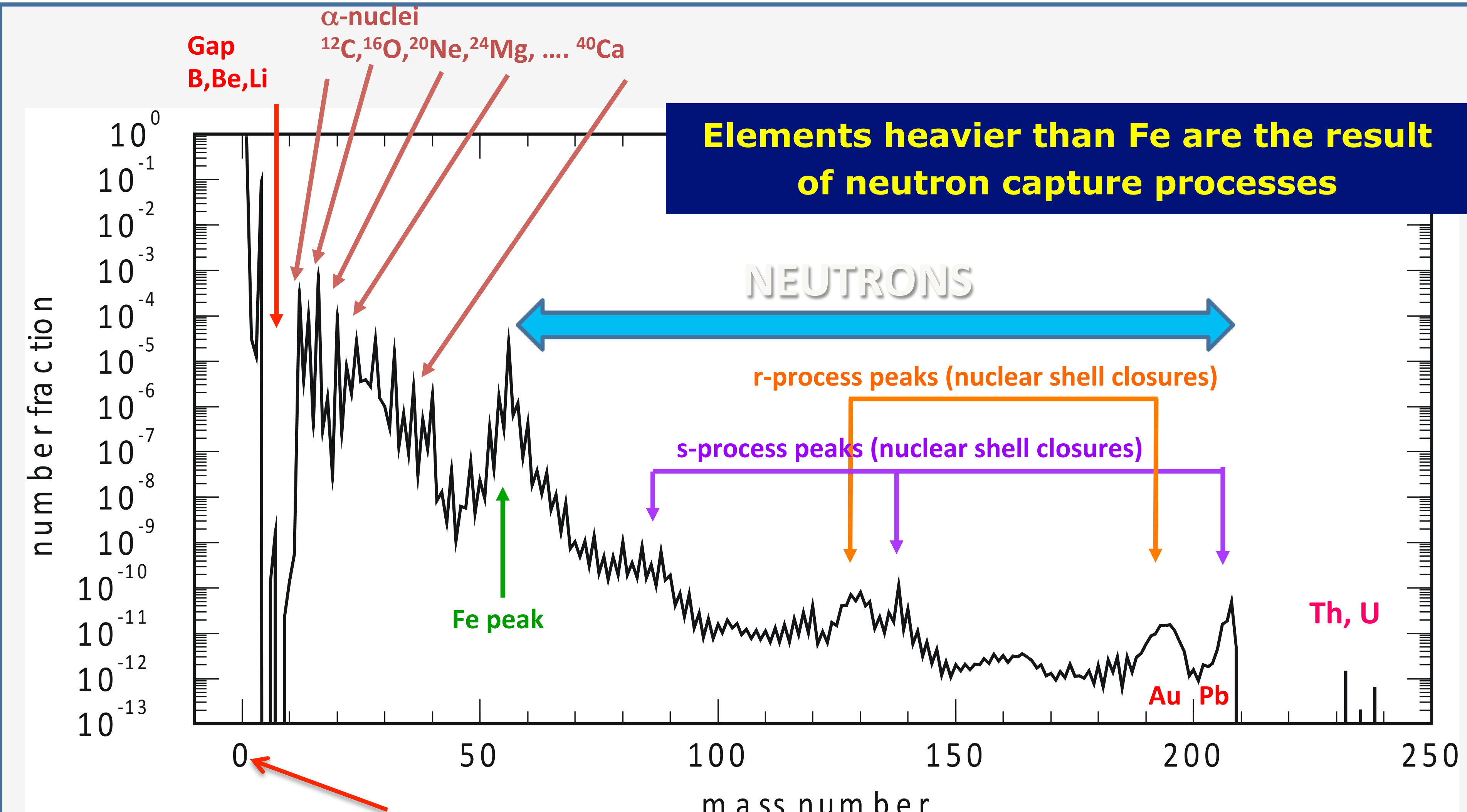




Abundances beyond Fe–ashes of stellar burning



Abundances beyond Fe–ashes of stellar burning



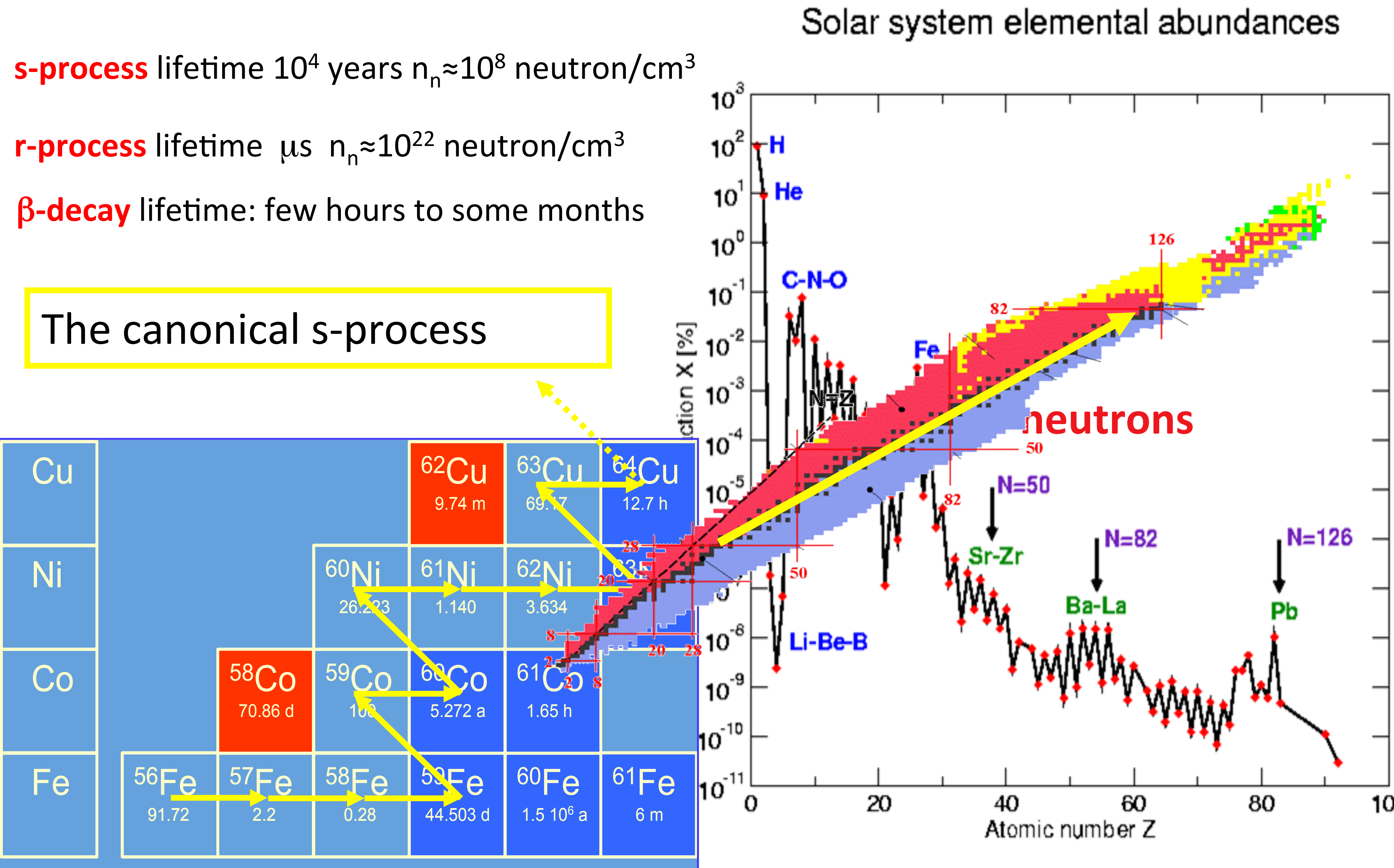
Neutron capture processes

s-process lifetime 10^4 years $n_n \approx 10^8$ neutron/cm^3

r-process lifetime μs $n_n \approx 10^{22}$ neutron/cm^3

β-decay lifetime: few hours to some months

The canonical s-process



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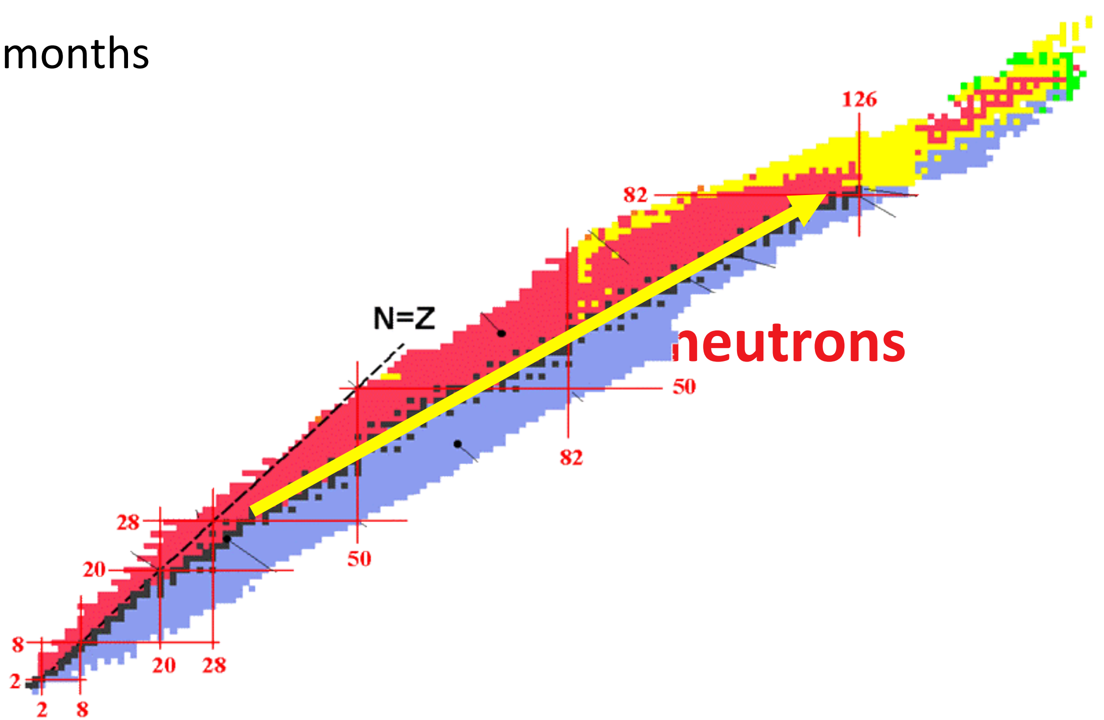
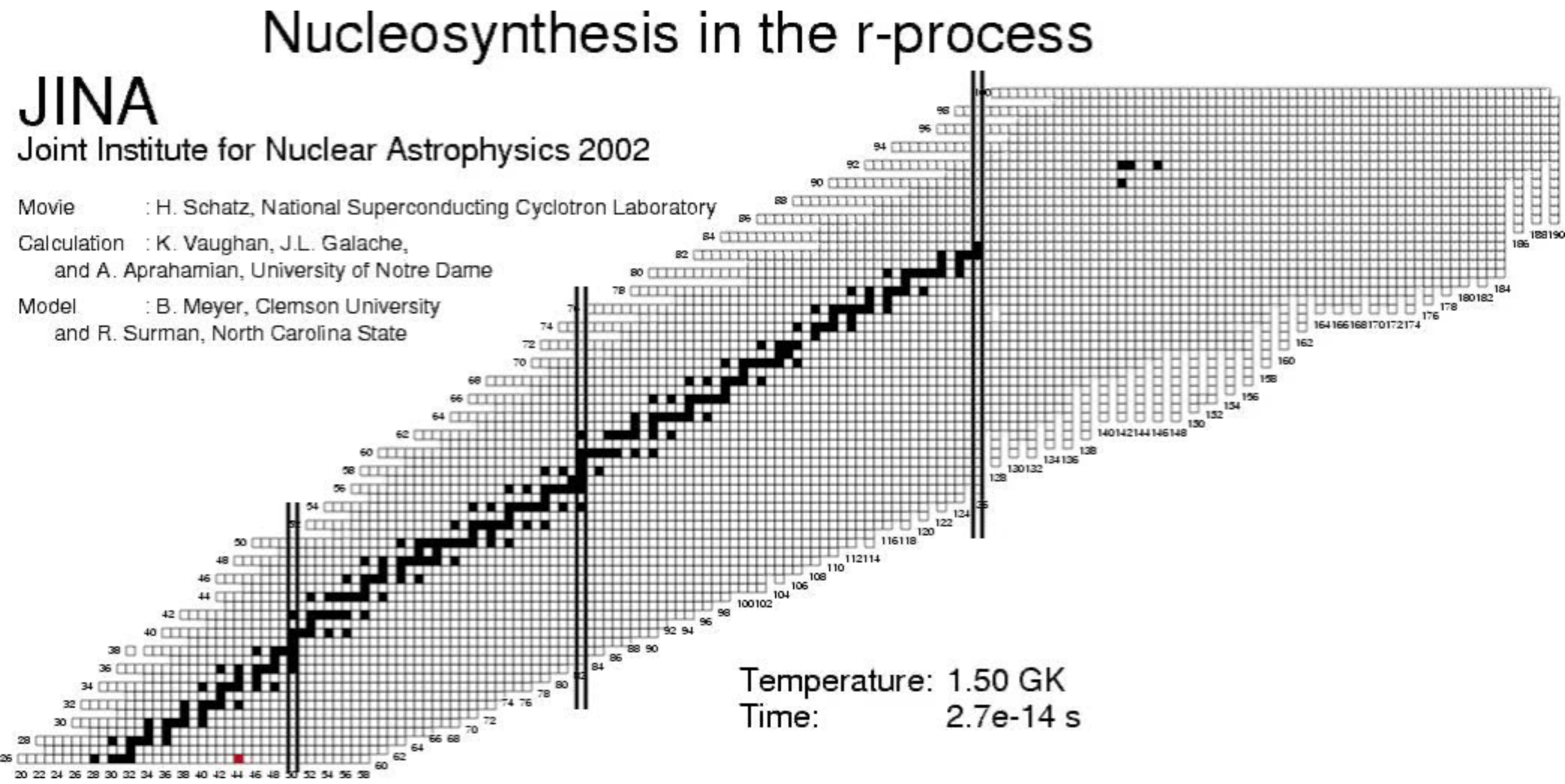
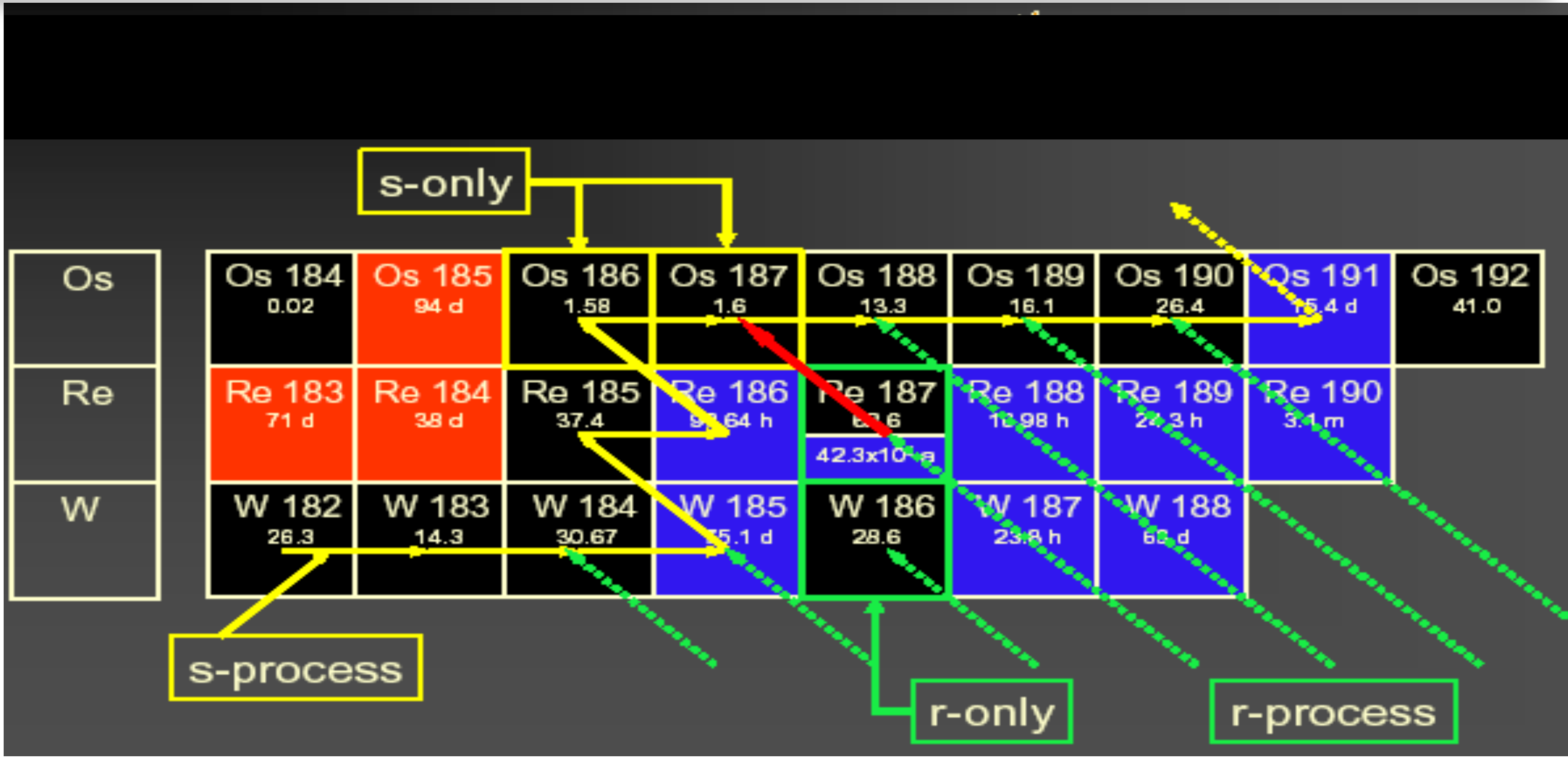


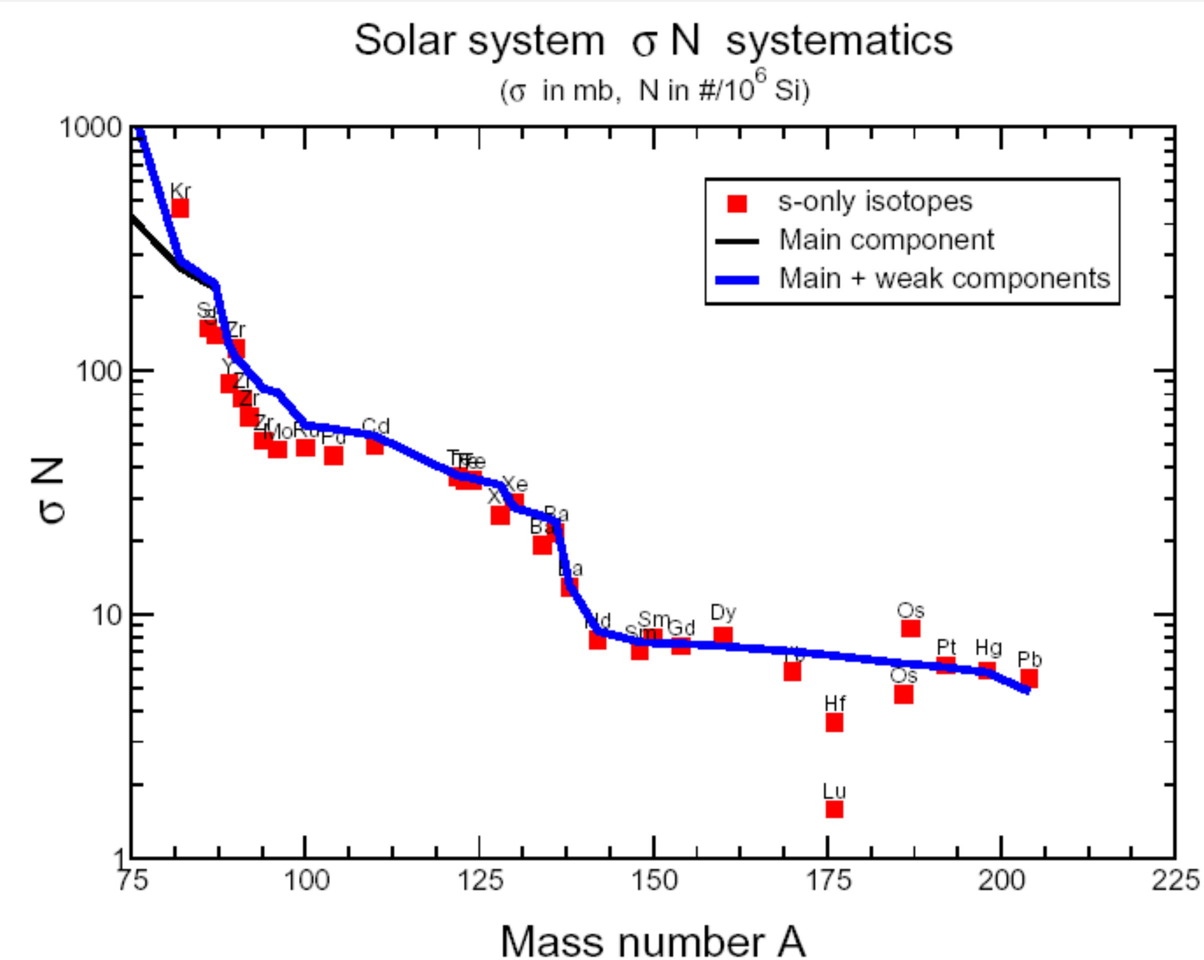
r-process


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
Temperature: 1.50 GK
Time: 2.7e-14 s

s-only & r-only istopes



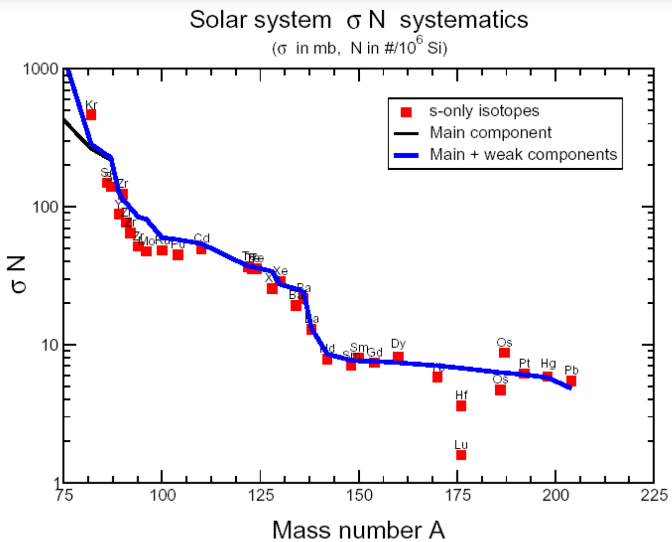
Stellar Models: local equilibrium approximation



$$\sigma_A N_A = \cos t$$

$$\langle\sigma\rangle_A N_s(A) = \frac{f N_s^{seed}}{\tau_0} \prod_{i=56}^{A} \frac{1}{\left[1 + \frac{1}{\tau_0 \langle\sigma\rangle_i}\right]}$$

Stellar Models: Standard stellar model



$$\langle\sigma\rangle_A N_s(A) = \frac{f N_s^{seed}}{\tau_0} \prod_{i=56}^{A} \frac{1}{\left[1 + \frac{1}{\tau_0 \langle\sigma\rangle_i}\right]}$$

f the fraction of ^{56}Fe seed nuclei that are subjected to an exposure of neutron

τ neutron exposure proportional to the time-integrated neutron flux

The Astrophysical Journal, 354:630–643, 1990 May 10

s-PROCESS NUCLEOSYNTHESIS: CLASSICAL APPROACH AND ASYMPTOTIC GIANT BRANCH MODELS FOR LOW-MASS STARS

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Kernforschungszentrum Karlsruhe, Institut für Kernphysik
R. Gallino
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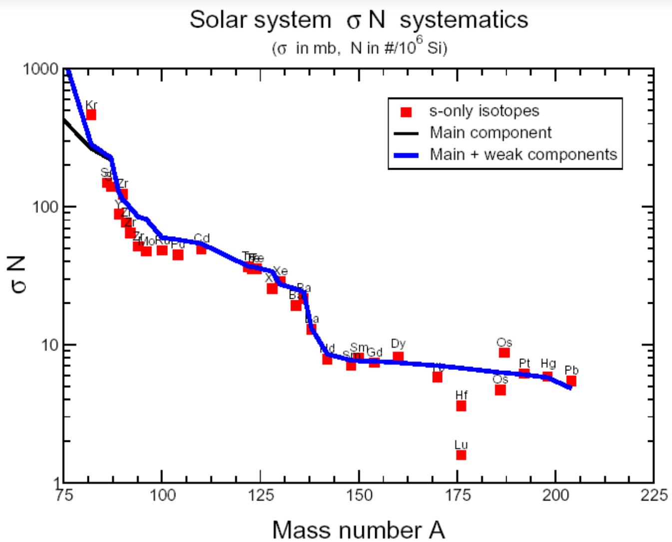
M. Busso and G. Picchio
Osservatorio Astronomico di Torino
and
C. M. Raiteri
International School for Advanced Studies, Trieste

Received 1989 August 9; accepted 1989 November 15

Stellar Models: Standard stellar model



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f the fraction of ^{56}Fe seed nuclei that are subjected to an exposure of neutron

τ neutron exposure proportional to the time-integrated neutron flux

Main com

Weak cor

PERGAMON

Progress in Particle and Nuclear Physics

Progress in Particle and Nuclear Physics 43 (1999) 419–483

http://www.elsevier.nl/locate/ppartnuclphys

The Origin of the Heavy Elements: The *s* Process

F. KÄPPELER

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Stellar Models: Standard stellar model

Annu. Rev. Astron. Astrophys. 1999. 37:239–309

NUCLEOSYNTHESIS IN ASYMPTOTIC GIANT BRANCH STARS: Relevance for Galactic Enrichment and Solar System Formation

M. Busso,[1] R. Gallino,[2] and G. J. Wasserburg[3]
[1]Osservatorio Astronomico di Torino, 10025 Pino Torinese, Italy, e-mail: busso@to.astro.it; [2]Dipartimento di Fisica Generale, Universita' di Torino, Via P. Giuria 1, 10125 Torino, Italy, e-mail: gallino@ph.unito.it; [3]Lunatic Asylum, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena California 91125, e-mail: isotopes@gps.caltech.edu

The Origin of the Heavy Elements: The *s* Process

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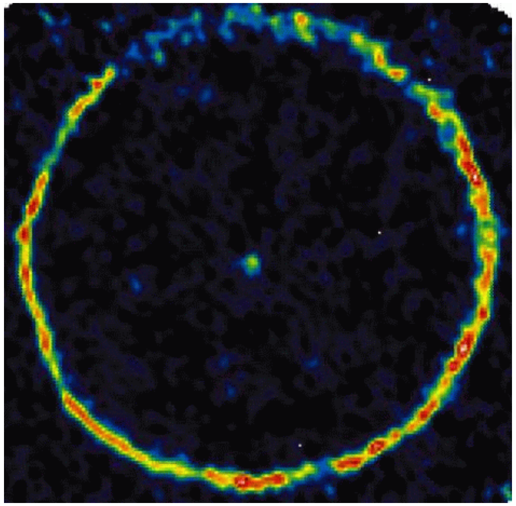
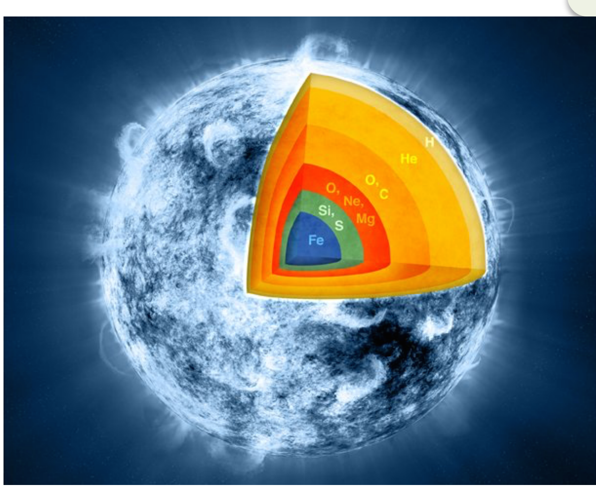
s-process stellar sites



Low mass Asympotic Giant Branch (AGB) M≈1.5 - 3 $M_\odot$

- $^{13}C(\alpha,n)^{16}O$ T ~ 8 keV $N_n < 10^7$ n/cm^3
- $^{22}Ne(\alpha,n)^{25}Mg$ T ~ 23 keV $N_n \sim 10^{10}$-10^{12} n/cm^3

Massive stars M≈15 - 25 $M_\odot$



$^{22}Ne(\alpha,n)^{25}Mg$

In core He-burning T ~ 26 keV $N_n \sim 10^6$ n/cm^3

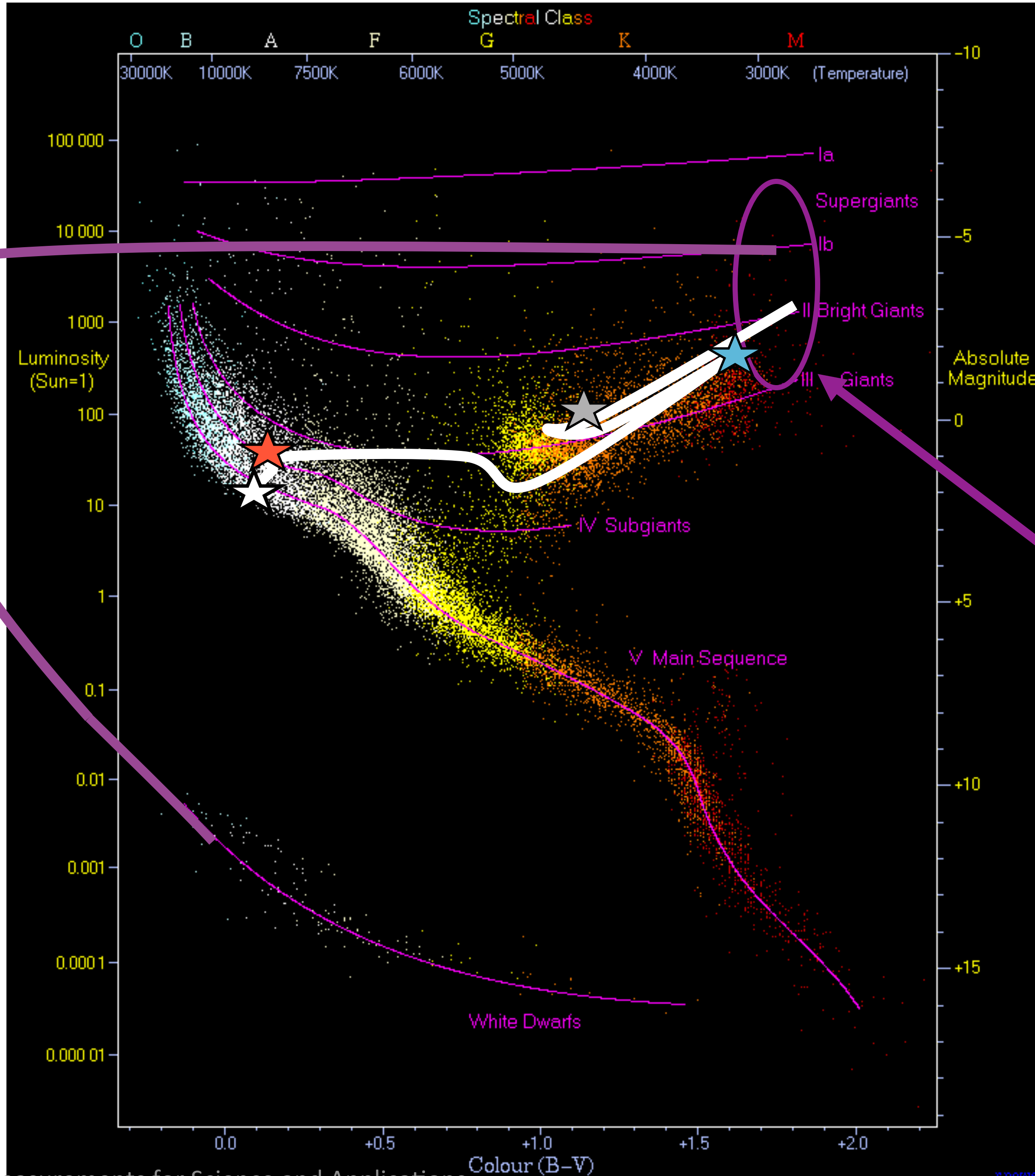
In shell C-burnig T ~ 90 keV $N_n \sim 10^{11}$ n/cm^3

The *s* process occurs in AGB stars.

Core H exhaustion

Core He burning starts

Core He exhaustion

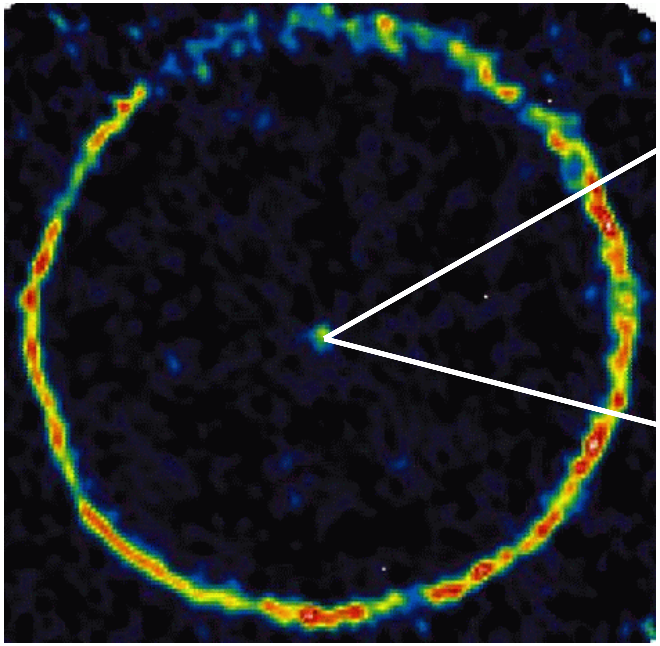


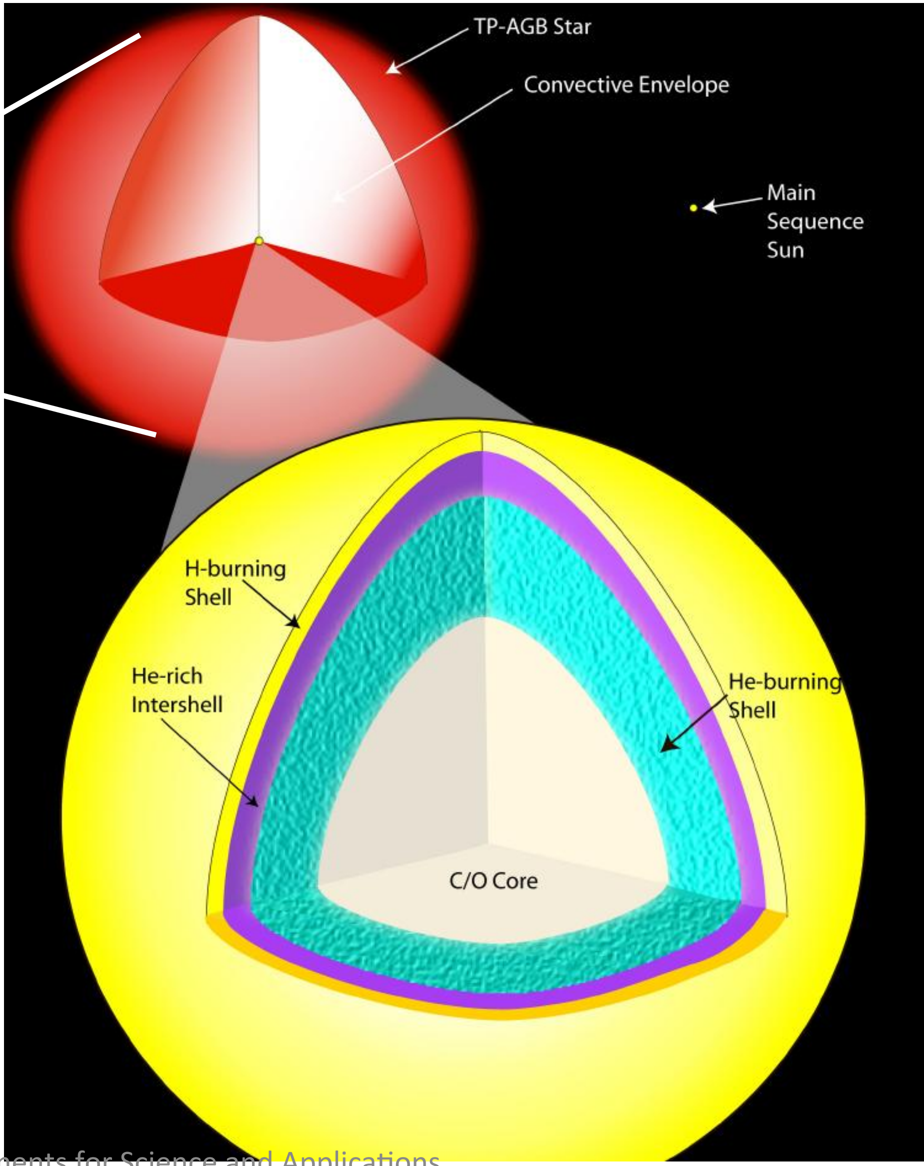
AGB stars

Theoretical evolutionary track of a star of 2 $M_\odot$

The *s* process occurs in AGB stars: cool and luminous red giant stars with winds

False-color picture of CO molecules tracing material around the AGB star TT-Cygni

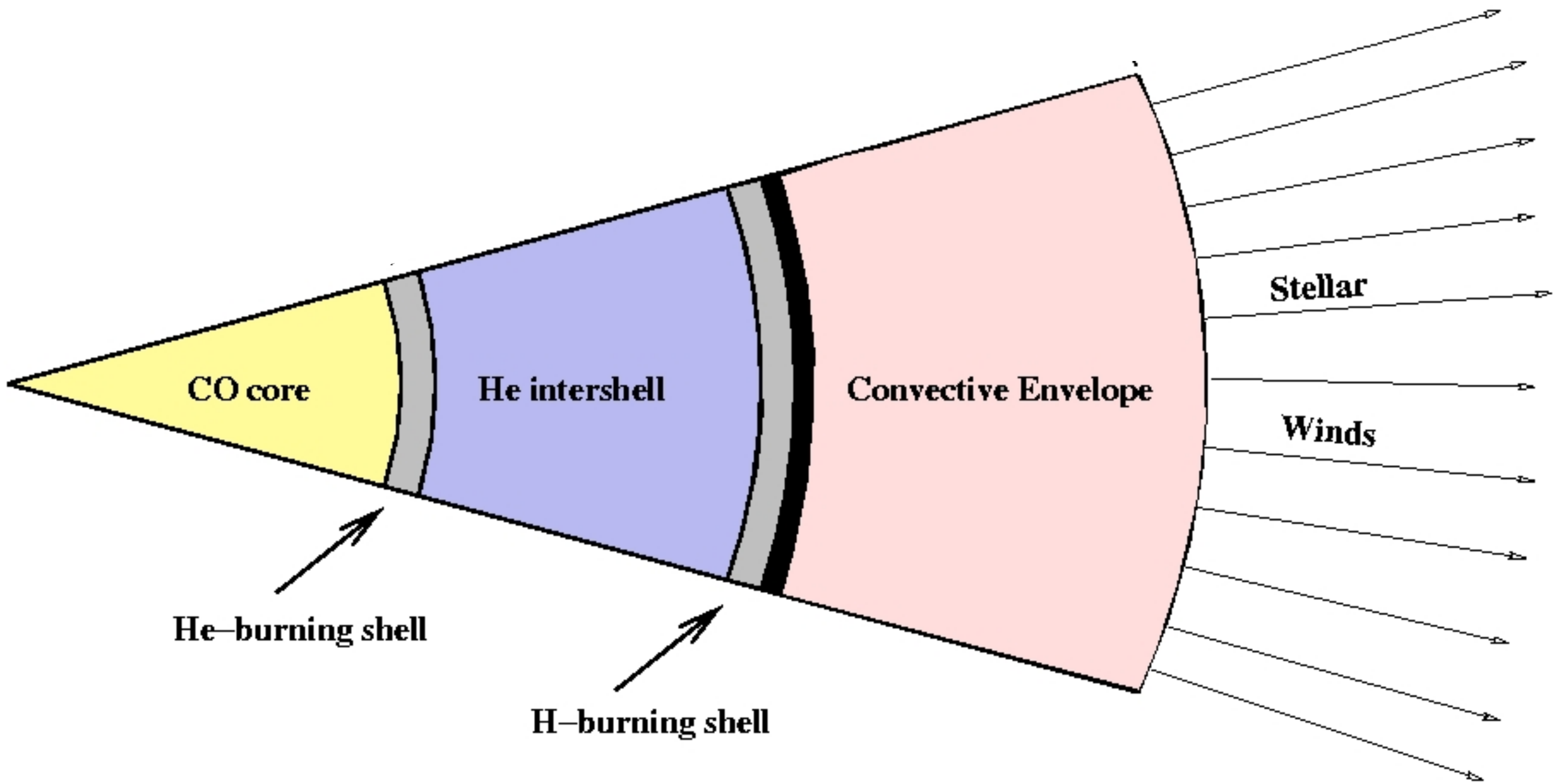


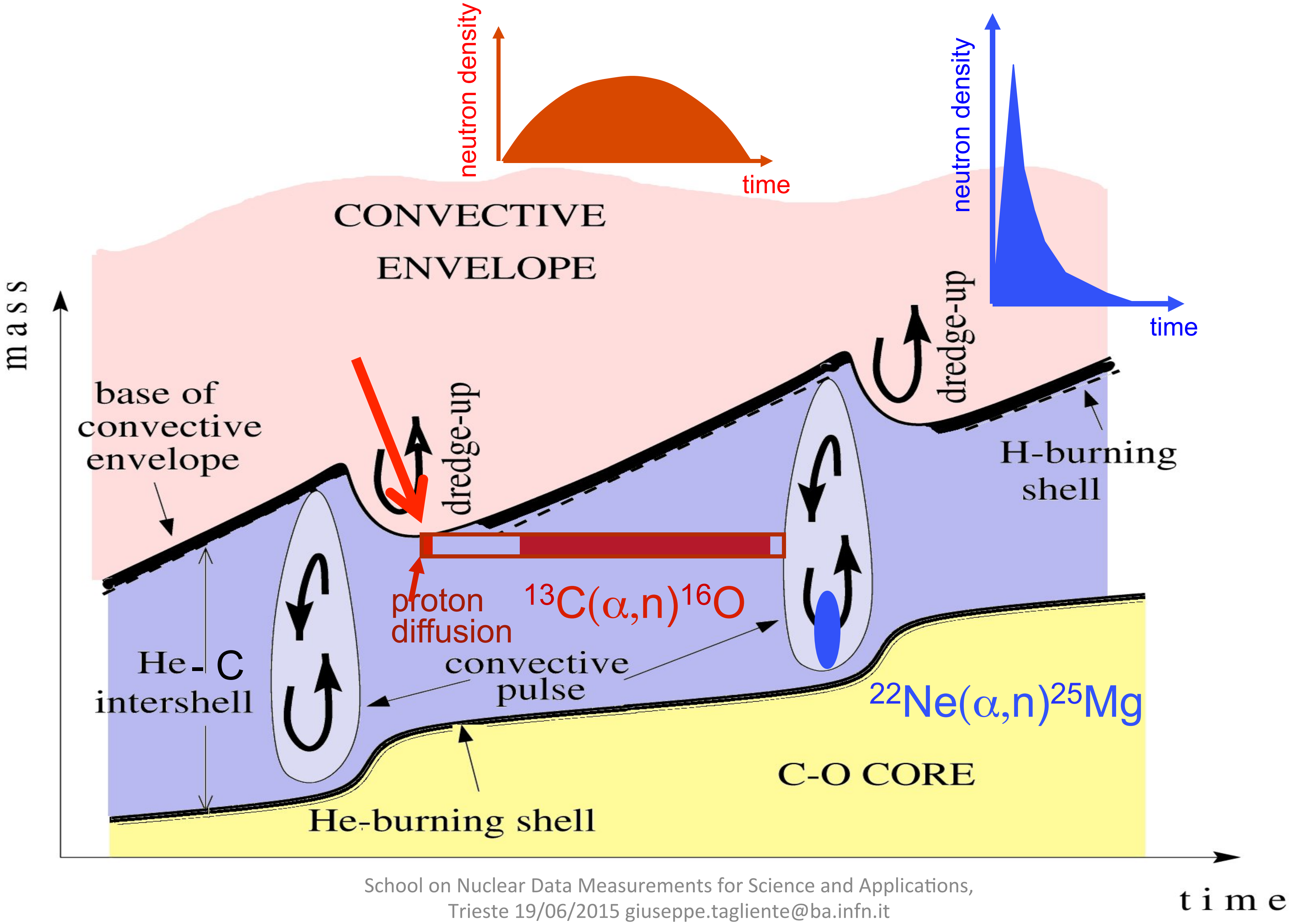


Strong mass loss driven by stellar pulsations and radiation pressure on dust.

Newly synthetised elements and dust grains are shed into the surrounding interstellar medium

Schematic **out-of-scale** picture of the structure of AGB stars.




neutron density
time
neutron density
time
CONVECTIVE
ENVELOPE
mass
base of convective envelope
dredge-up
dredge-up
H-burning shell
proton diffusion
$^{13}C(\alpha,n)^{16}O$
He - C intershell
convective pulse
$^{22}Ne(\alpha,n)^{25}Mg$
C-O CORE
He-burning shell
time

Neutrons in Laboratory

Neutrons in Laboratory

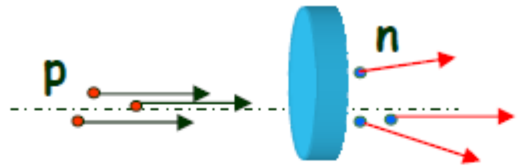
Thermal reactors

almost monoenergetic neutron, very high flux

Monoenergetic neutron

Based on reaction (p,n) or (d,n)

d(d,n), t(p,n), ^{7}Li(p,n), ^{9}Be(p,n)



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

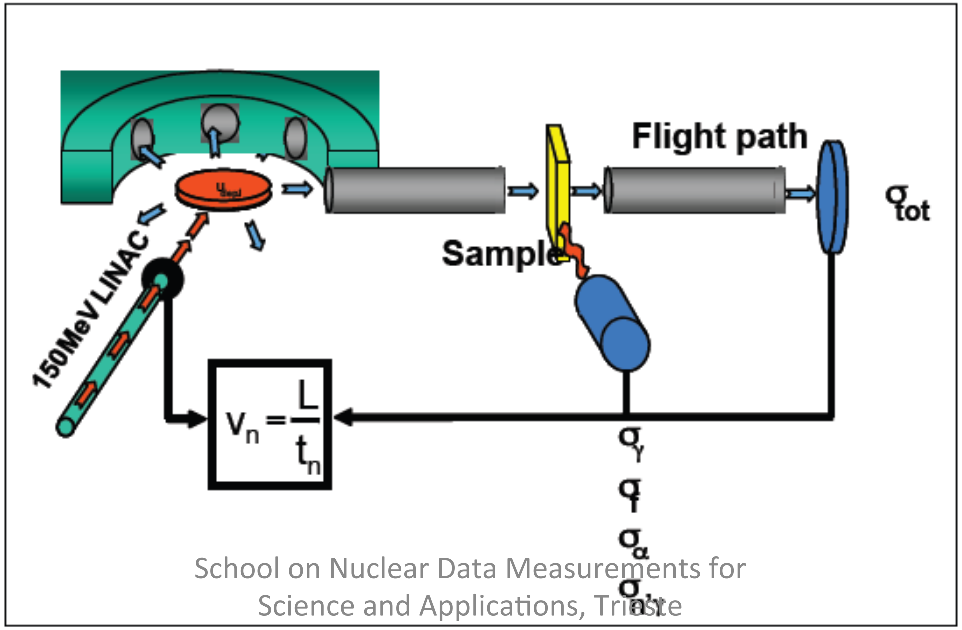
Time of Flight facilities

wide neutron energy spectrum

High energy resolution

Time of Flight facilities

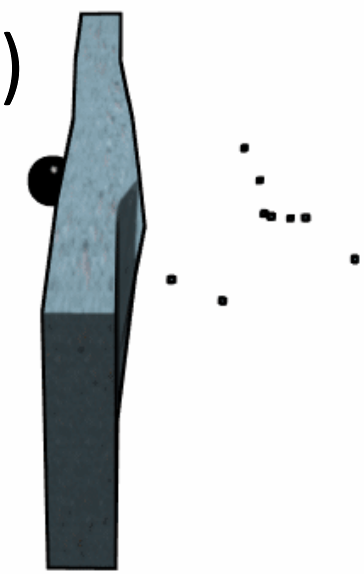
Photoproduction (γ,n): Heavy metal targets are bombarded by electron beams of typical 20 -150 MeV. The resulting neutron spectra contains all energies from thermal to near the initial γ energy. ORELA (USA), GELINA (EU) and RPI (GB)



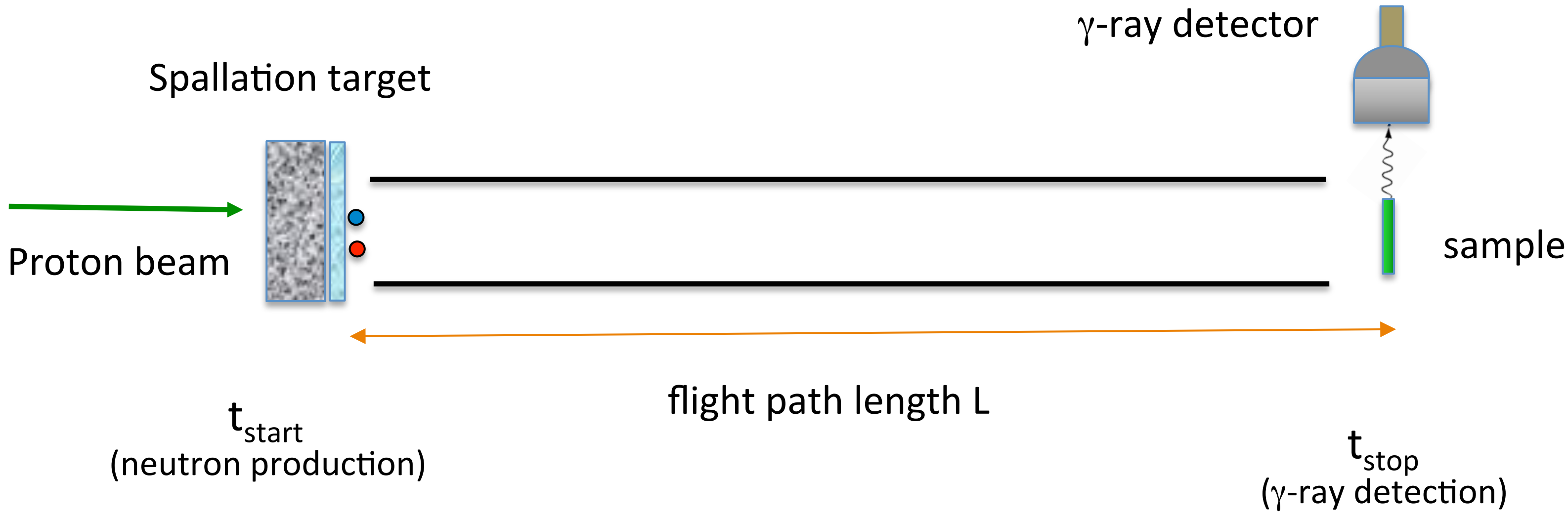
Time of Flight facilities

Spallation: neutron are ejected from a heavy target due to the impact of charged particles as protons. It provides the most prolific source of fast neutrons.

n_TOF(CERN), LANCSE(USA), ISIS(GB)



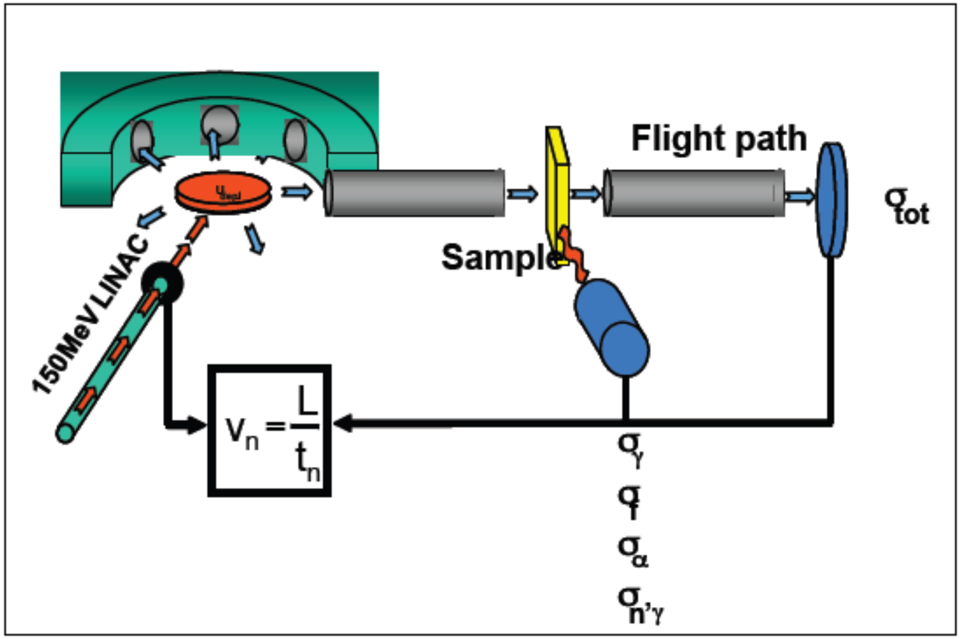
Time of Flight Technique



$$tof = t_{stop} - t_{star}$$

$$E_n = \left(\frac{72{,}2977 \cdot L}{tof} \right)^2 \qquad E_n = m_n c^2 \left(\frac{1}{\sqrt{1 - \frac{L^2}{tof^2 \cdot c^2}}} - 1 \right)$$

ToF Technique (Flux & Energy resolution)



- **Velocity from TOF**

$$v_n = \frac{L}{t_n}$$

- **Resolution** $\Rightarrow L \nearrow$

$$\frac{\Delta v_n}{v_n} = \sqrt{\frac{\Delta t_n^2}{t_n^2} + \frac{\Delta L^2}{L^2}}$$

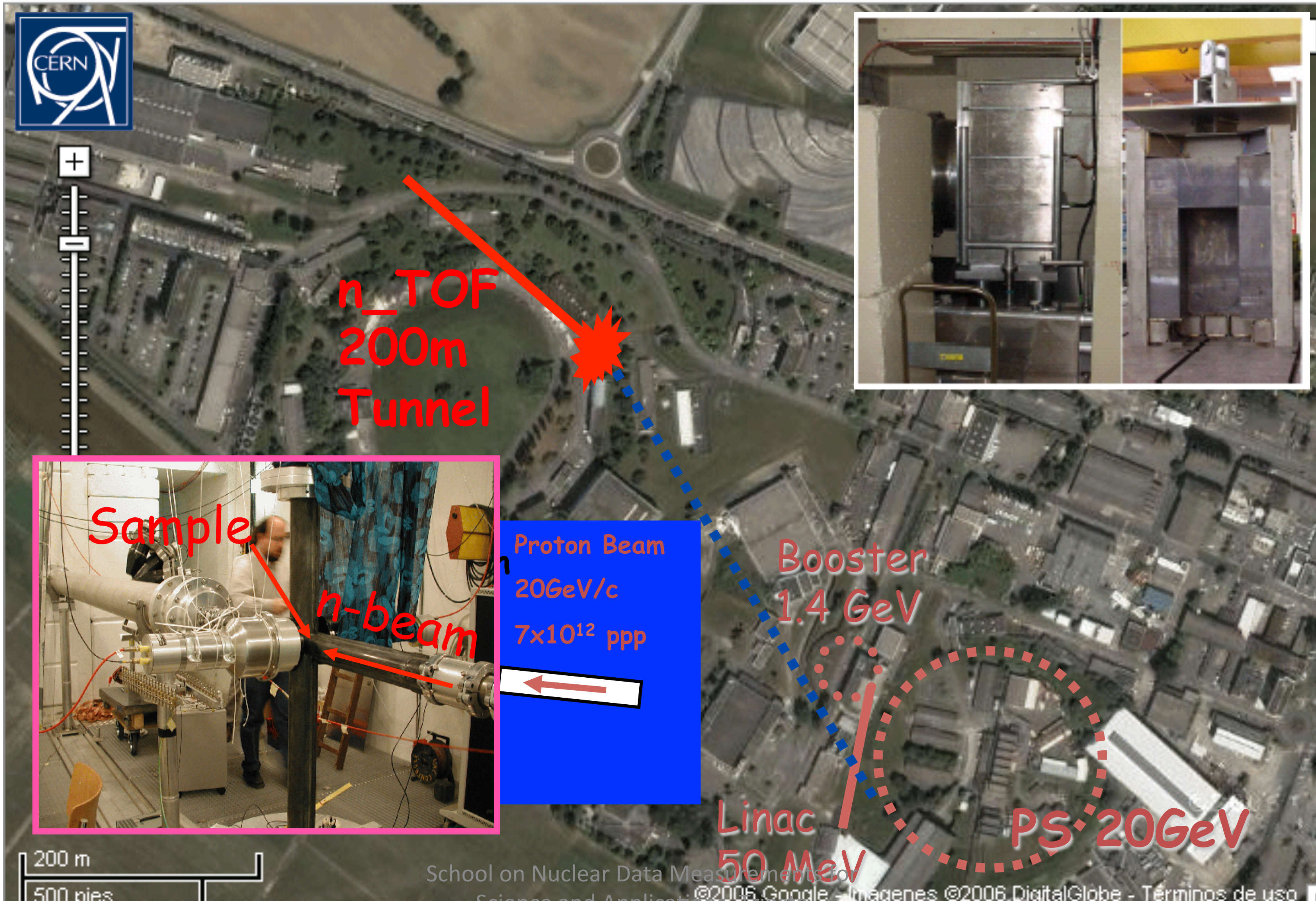
- **Neutron flux** $\Rightarrow L \searrow$

$$\varphi_n(L) \propto \frac{1}{L^2}$$

n_TOF facility at CERN

somewhere around here

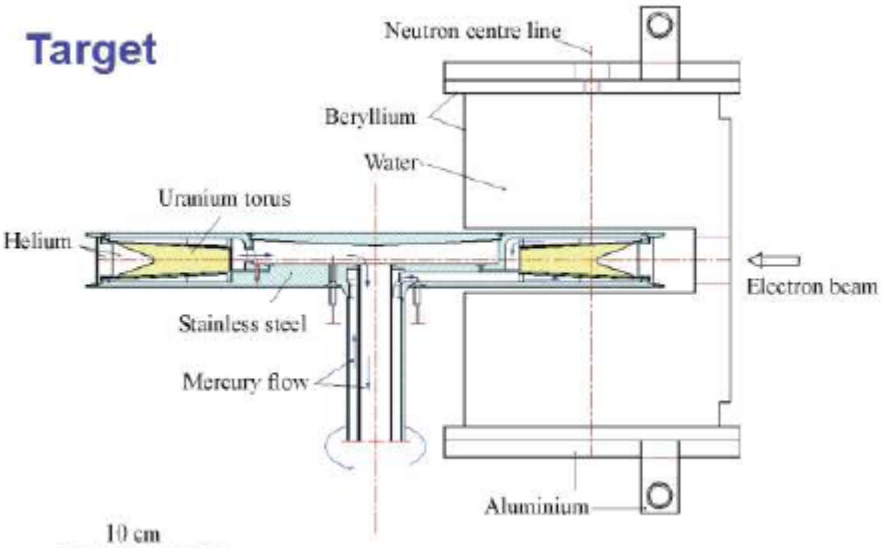
The CERN n_TOF Facility

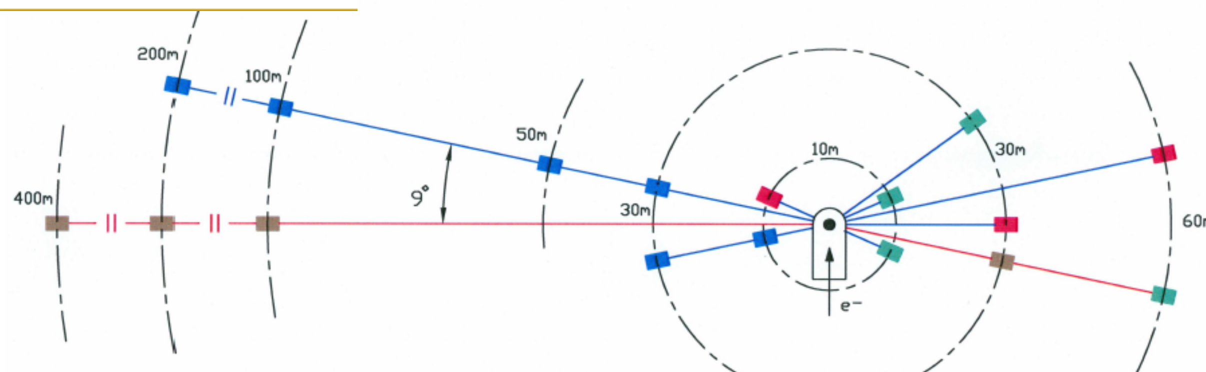


GELINA Facility

GELINA Facility

Target



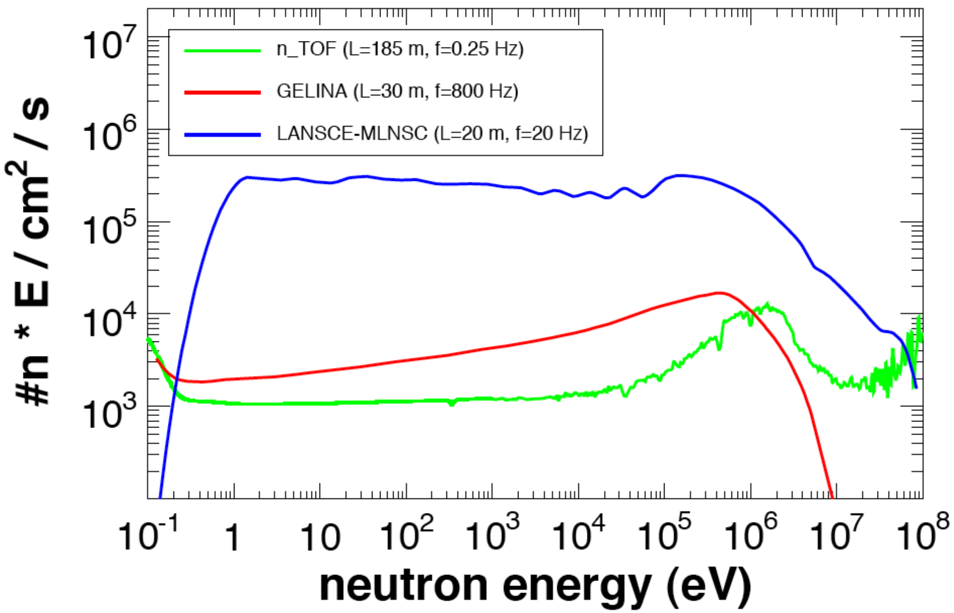


- (n,tot)
- (n,γ)
- (n,f) and (n,cp)
- (n,n'γ)

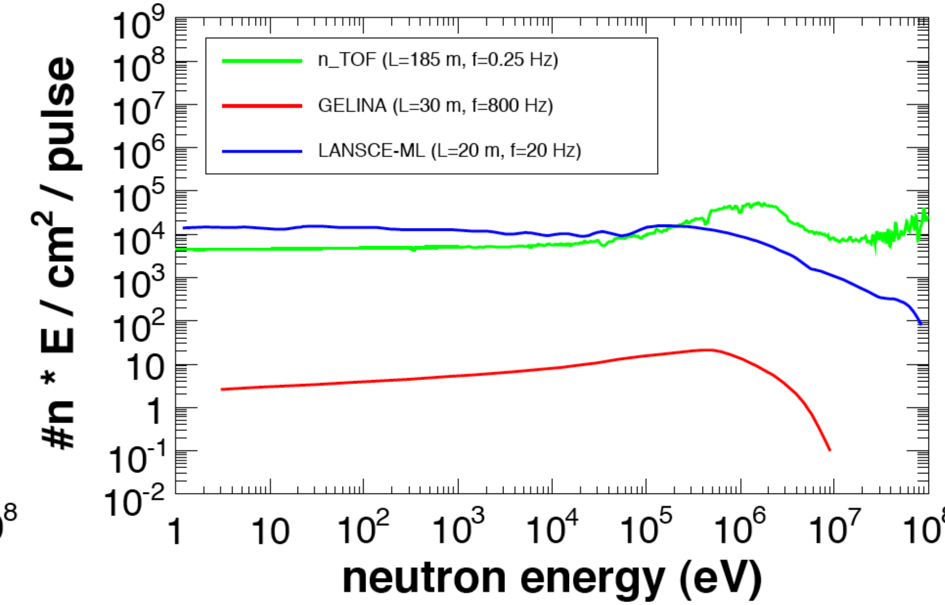
Direct spectrum
Moderated spectrum

Flux

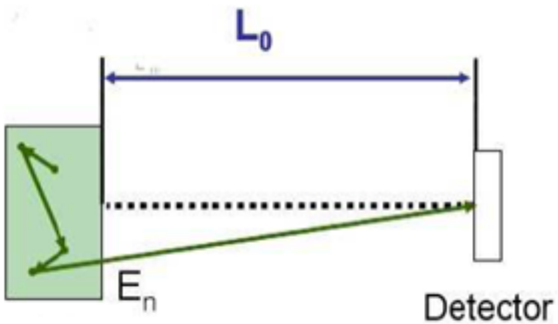
Integrated neutron flux



Istantaneous neutron fllux



Resolution



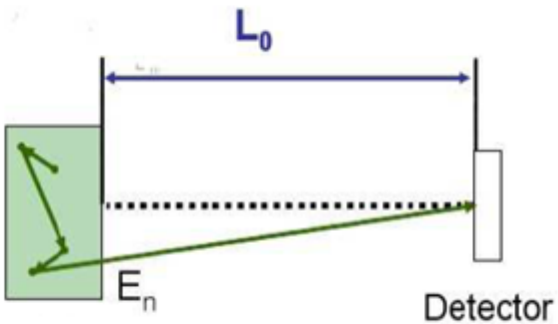
L = L0 + Lm

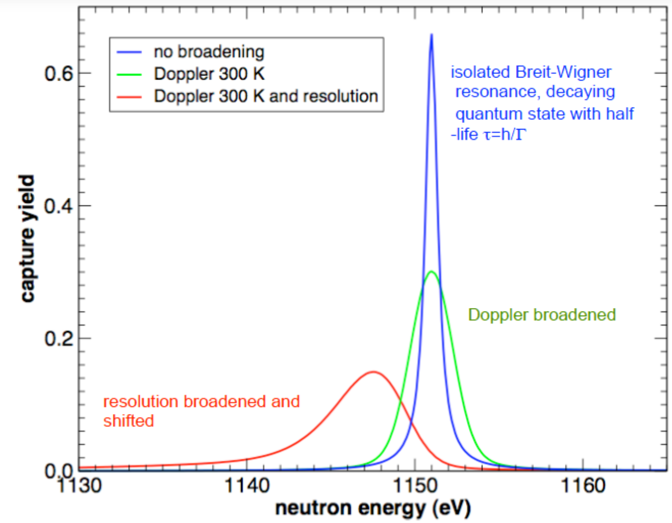
$$L = L(E_n) = L_0 + \Delta L(E_n)$$

$$E_n = \frac{1}{2} m_n v^2 = \frac{1}{2} m_n \left(\frac{L}{t}\right)^2$$

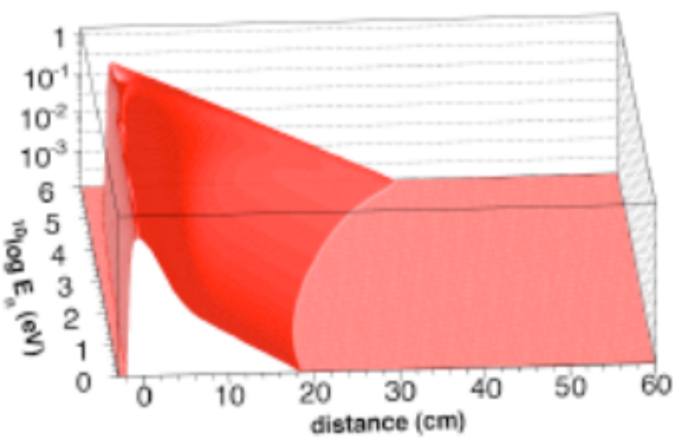
$$E_n = \frac{1}{2} m_n v^2 = \left(\frac{72.2977\, L_0}{t + t_{0ff}}\right)^2$$

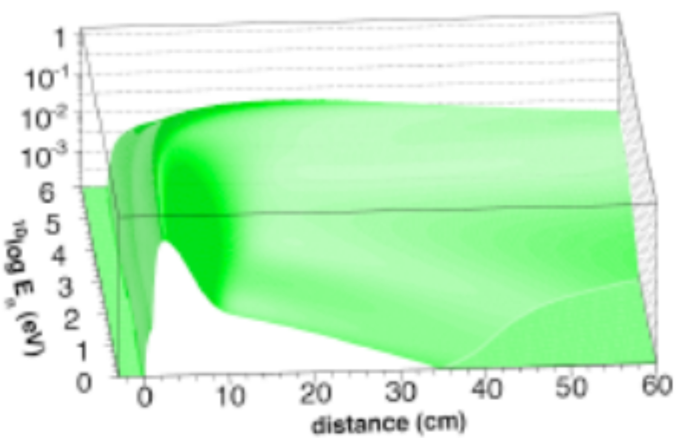
n_TOF GELINA Resolution





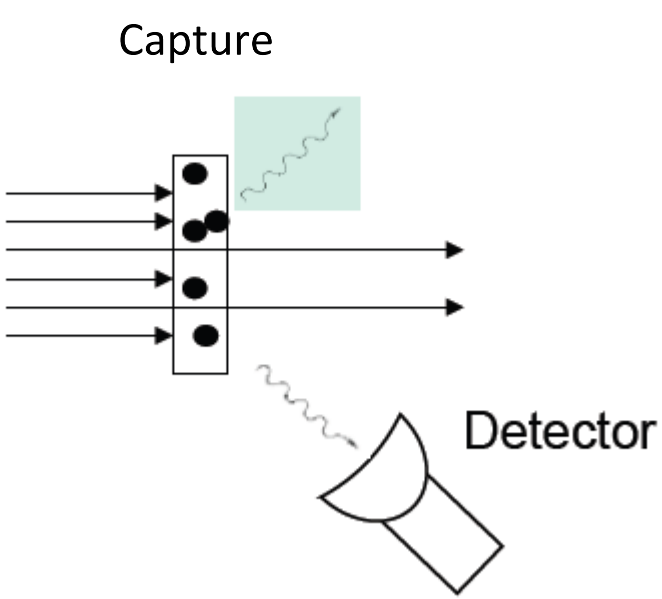
$L = L_0 + L_m$

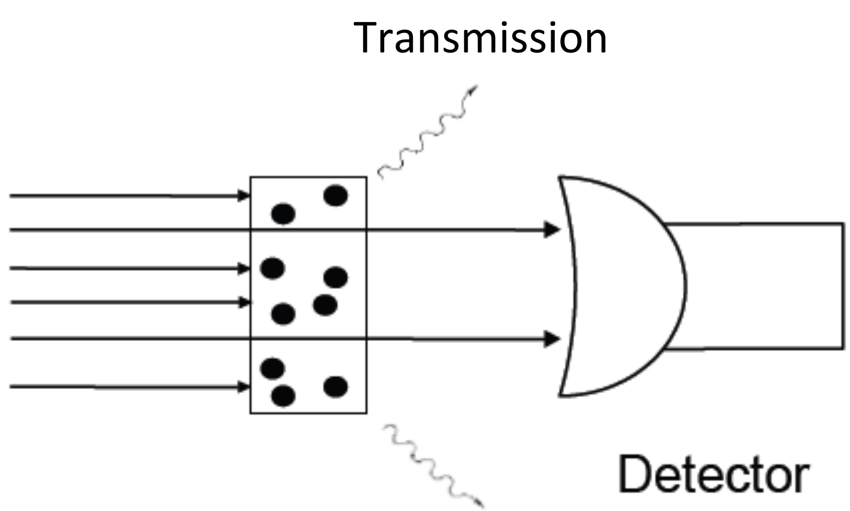




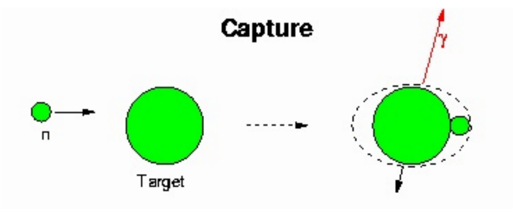
GELINA **n_TOF**

What we detect



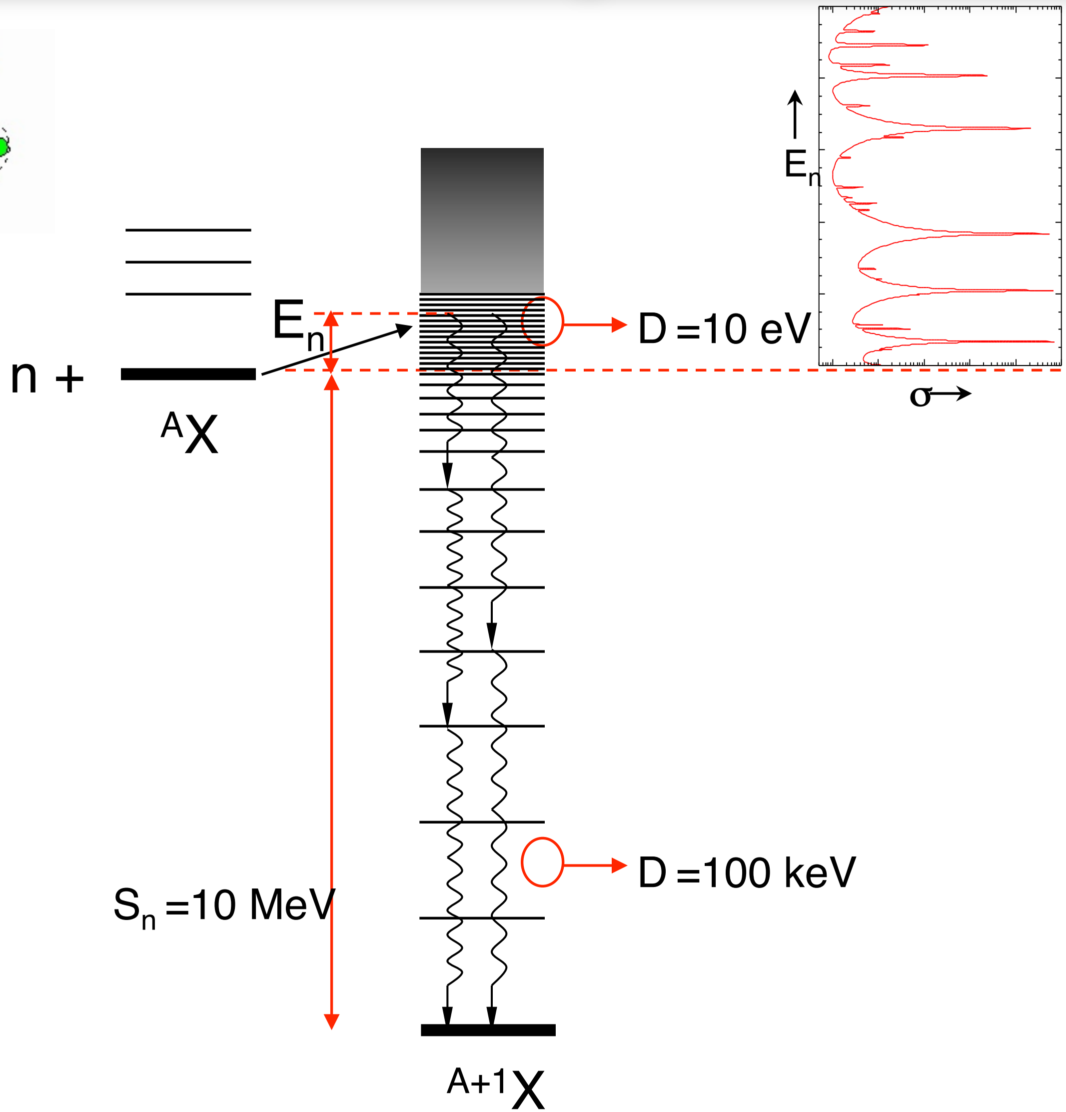


Neutron Capture

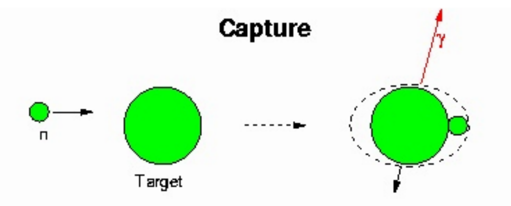


$$E^* = S_n + \frac{A}{A+1} E_n$$

$$E^* = \sum_j E_j^\gamma$$



Neutron Capture: Cross Section

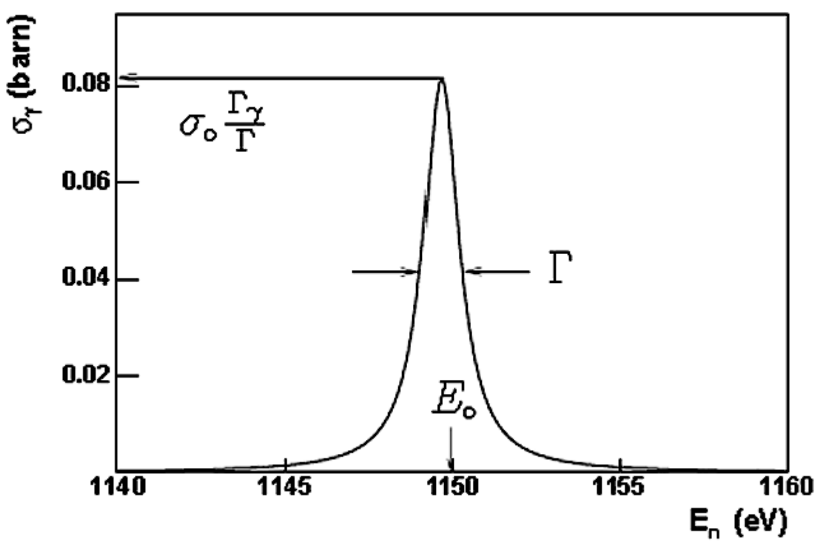


$\Gamma = \Gamma_n + \Gamma_\gamma + \Gamma_f + \ldots$

g spin factor
k_n neutron wave number
Γ total width
Γ_n neutron scattering width

$$E^* = S_n + \frac{A}{A+1} E_n$$

$$\sigma_{c^*}(E_n) = g \frac{\pi}{k_n^2} \frac{\Gamma_n \Gamma}{(E_n - E_0)^2 + \left(\frac{\Gamma}{2}\right)^2}$$

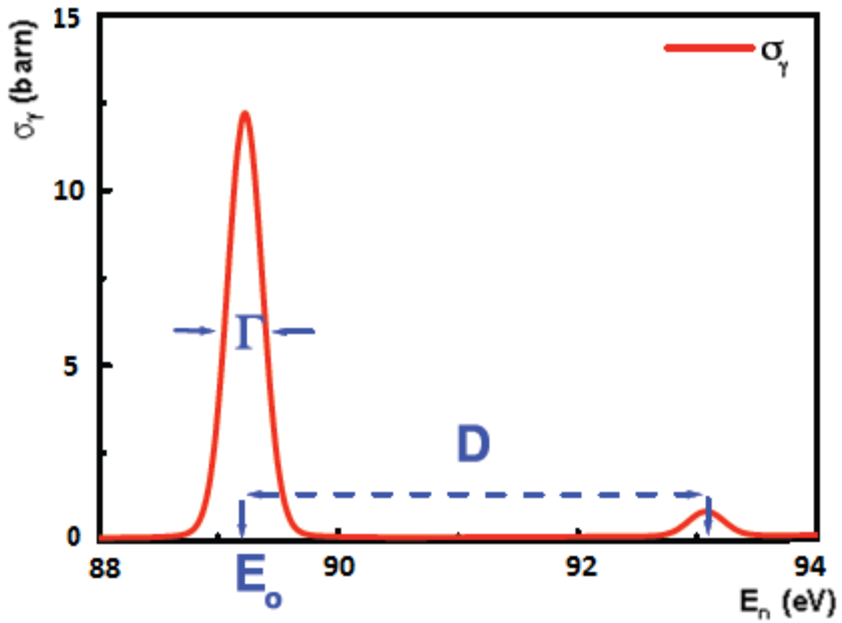


$$\sigma_0 = \frac{4\pi}{k_n^2} g \frac{\Gamma_n}{\Gamma}$$

Total radiative area:

$$A_r = \frac{2\pi^2}{k_0^2} g \frac{\Gamma_n \Gamma_\gamma}{\Gamma}$$

Neutron Capture: Resonances

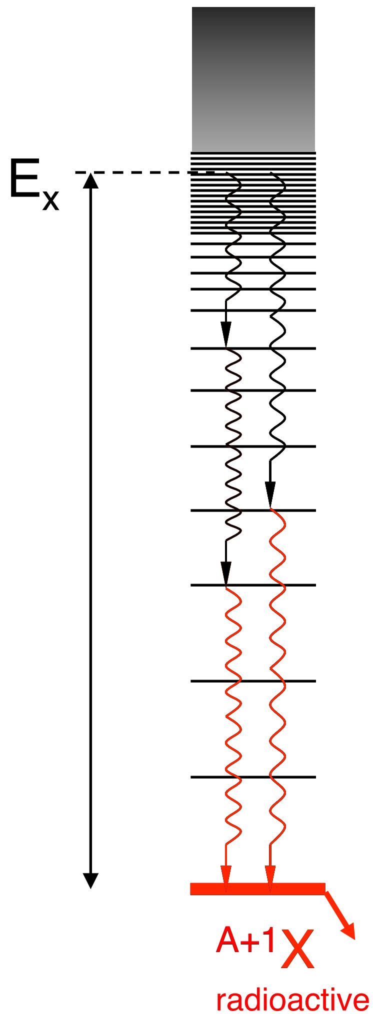


Resonance Region: $\Gamma < D$

Resolved Resonance Region (RRR): Detection resolution < D

Unresolved Resonance Region (URR): Detection resolution > D

Neutron Capture: Gamma-ray detection



- **Activation**
  - cross sections integrated over known neutron spectrum
  - applicable to some nuclei only
  - no time of flight

- **Level population spectroscopy**
  - applicable to some nuclei only
  - feasible with HPGe detectors,

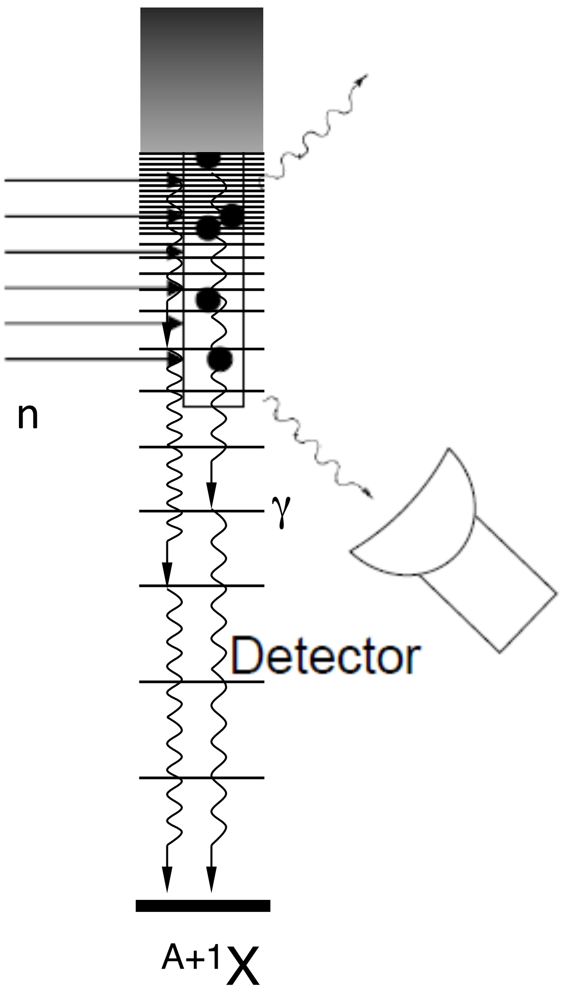
- **Total energy detection**
  - $\varepsilon_c \sim E_x$, requires weighting function
  - neutron insensitive detector

  C_6D_6 detector used at GELINA and n_TOF

- **Total absorption detection**
  - requires $\Omega = 4\pi$, efficiency 100%
  - capture/fission discrimination possible

  BaF_2 detector used at n_TOF

Experimental details: Yield



Yield: The fraction of incident neutrons undergoing a (n,γ) reaction in the sample

$$Y_{exp} = \frac{N(E_n, E_{dep})}{N_n(E_n) \times \varepsilon(E_n, E_{dep})}$$

The relation between capture Yield and cross section is given by:

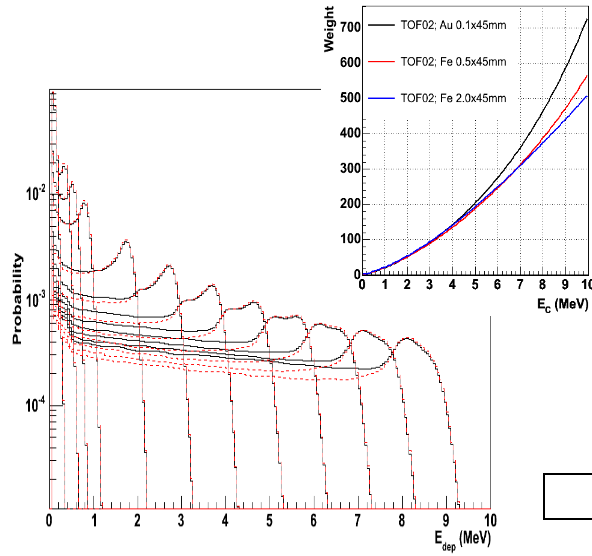
$$Y = (1 - e^{-n\sigma_{tot}}) \frac{\sigma_\gamma}{\sigma_{tot}}$$

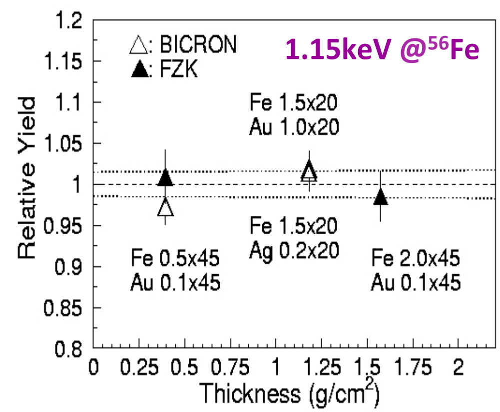
Experimental details: PHWT

Accuracy of the Pulse Height Weighting Technique? (used to count properly capture cascades)

$$\sum_i W_i R_{ij} = E_j$$

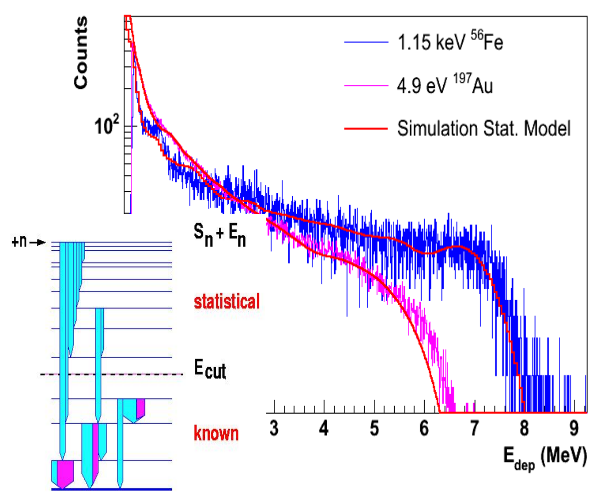
Use of detailed MC simulations of detector response with the full setup





+

Use of the nuclear statistical model to make systematic corrections

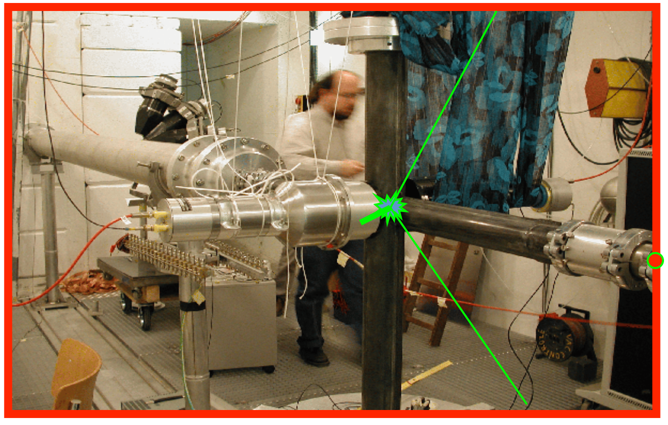


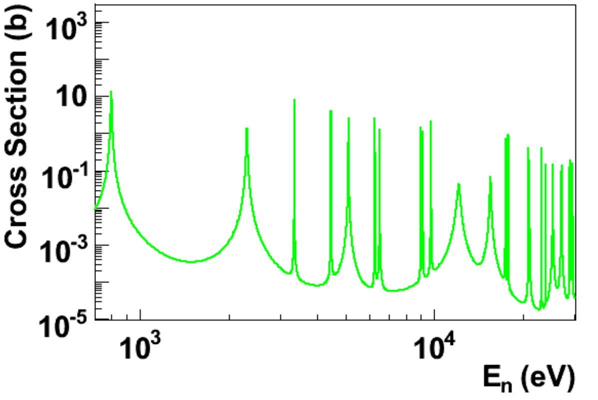
… accuracy < 2%

(n,γ) Total energy detection

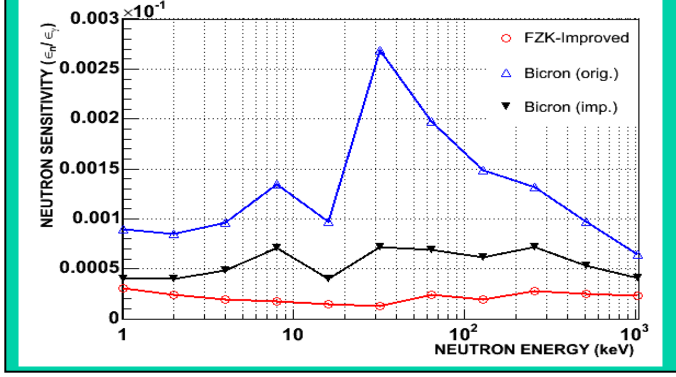
Improvements in the Experimental Setup & Data Analysis

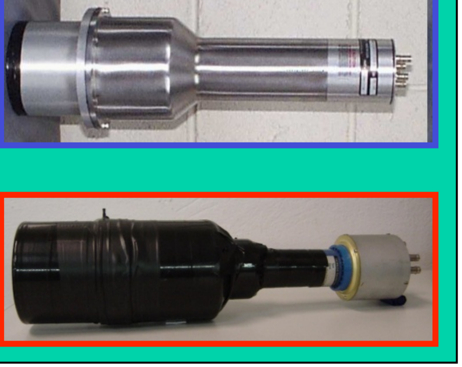
- Lowest neutron sensitivity ➡ No neutron background corrections !





(n,γ)





(n,γ) Total energy detection

Improvements in the Experimental Setup & Data Analysis

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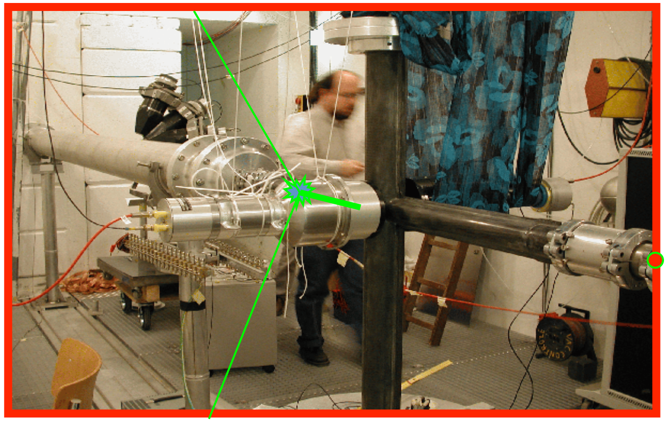
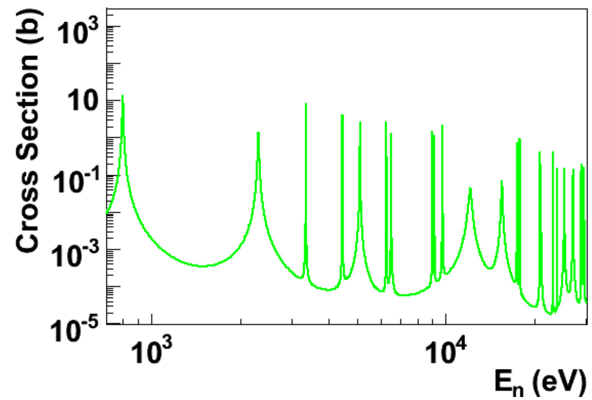
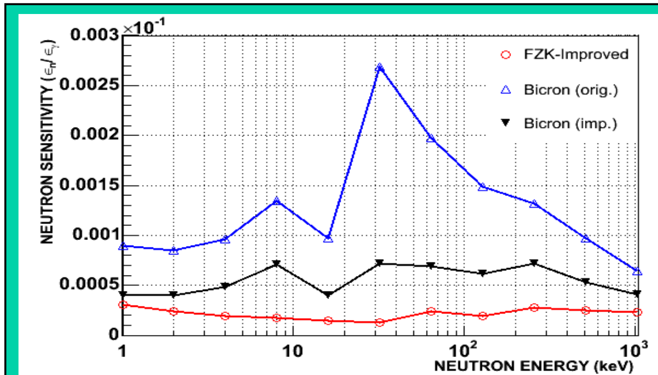
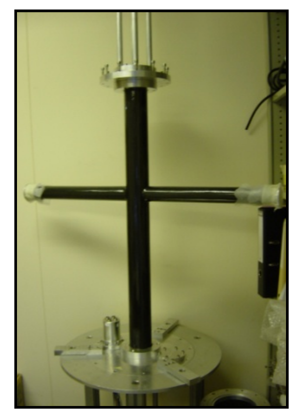




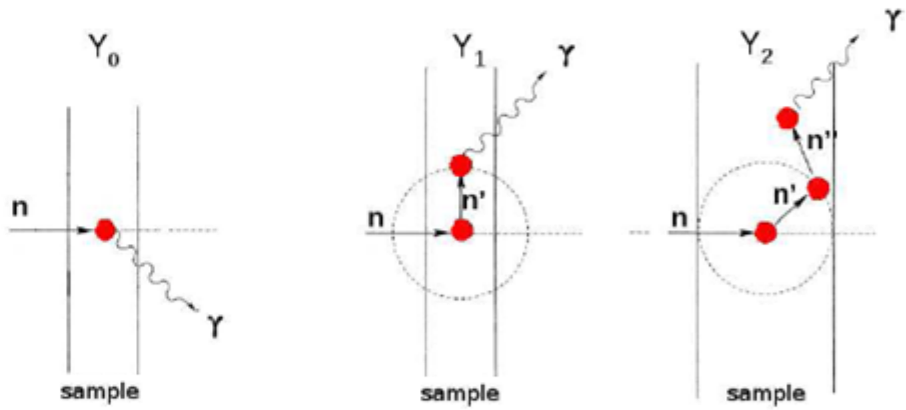
(n,n)

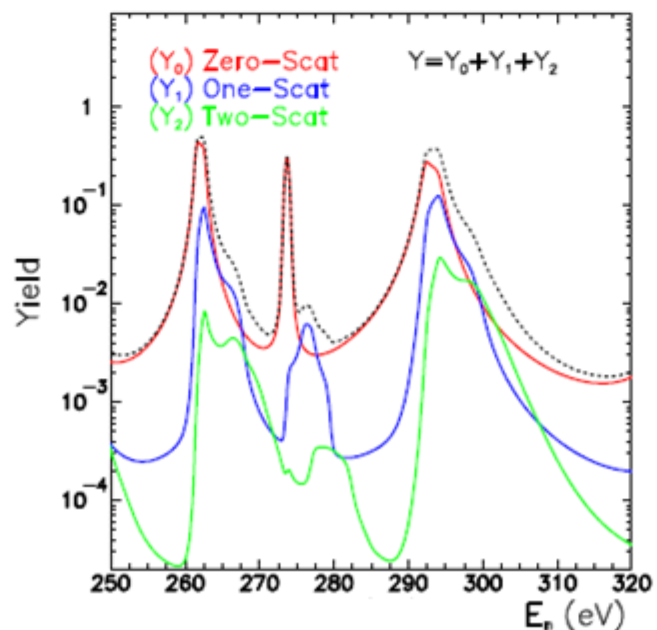
(n,γ)



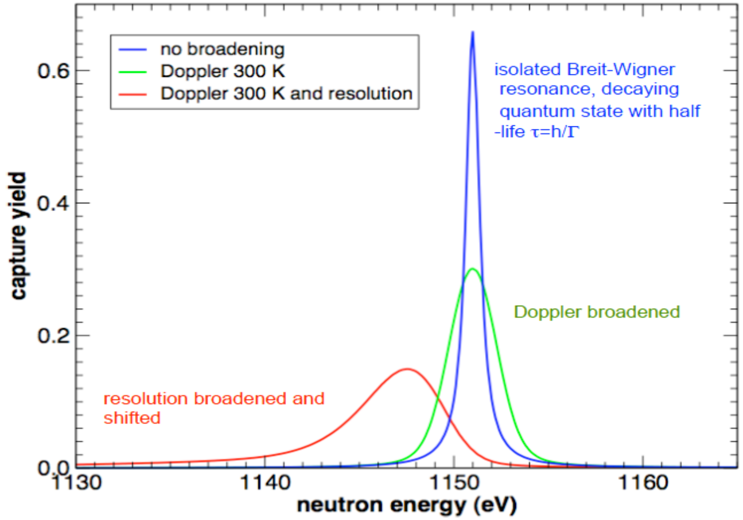


Experimental details: Sample





Experimental details: Area analysis



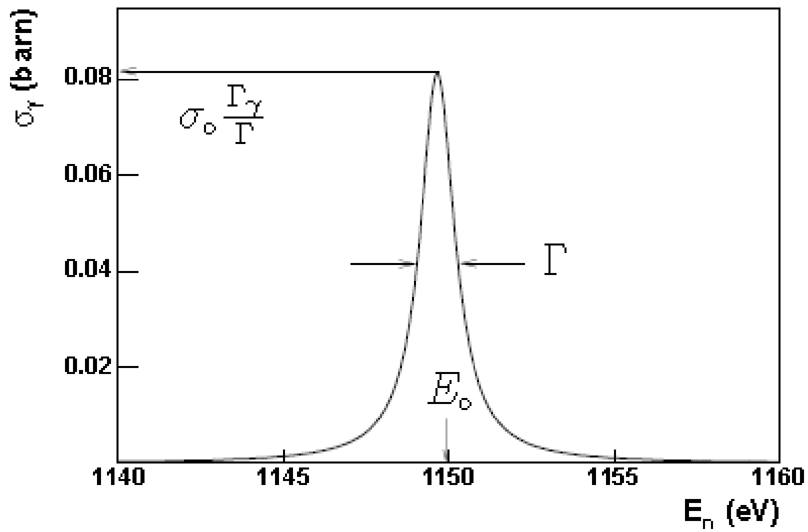
Due to the instrumental limitations and Doppler effect the effective observable is: The area of a resonance.

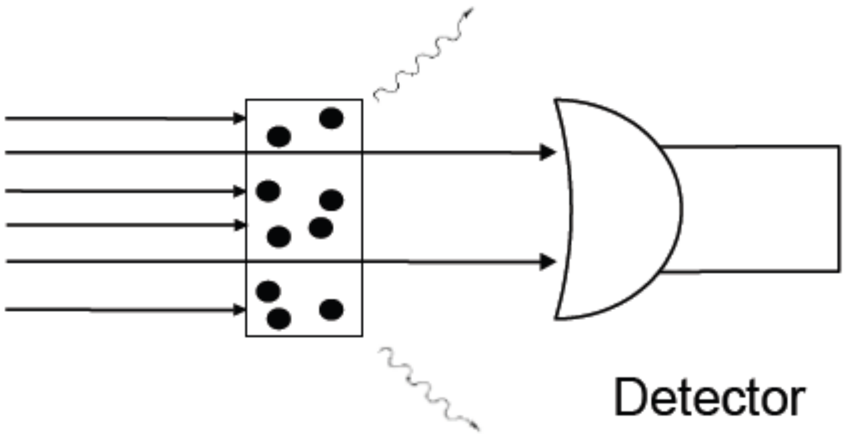
The area below a resonance is independent of the experimental resolution and Doppler effect

$$A_{tot} = \int (1 - e^{-n\sigma_{tot}}) dE$$

$$A_{\gamma} = \int (1 - e^{-n\sigma_{tot}}) \frac{\sigma_{\gamma}}{\sigma_{tot}} dE$$

Experimental details: Area analysis

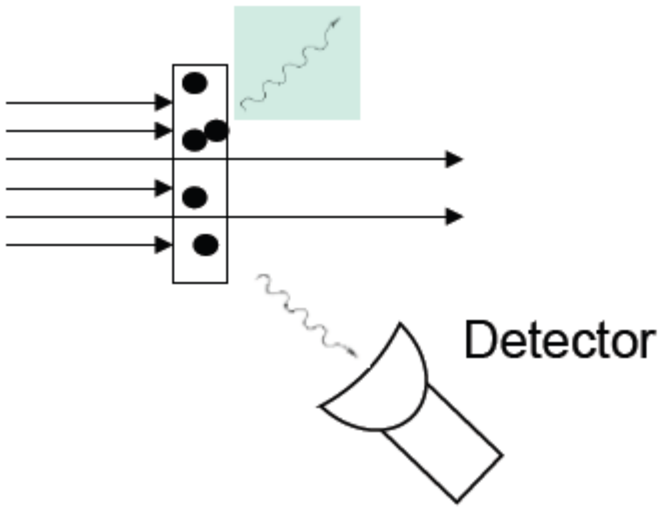


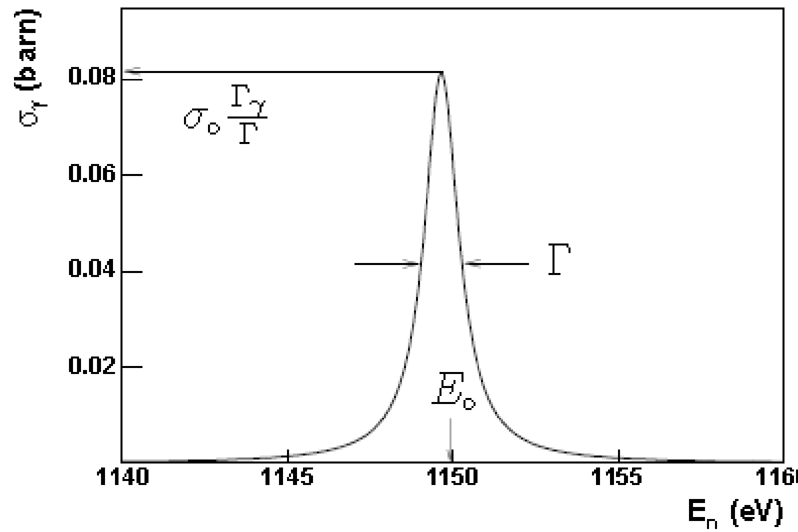


$$A_{tot}(thin) = \frac{1}{2}\pi n \sigma_0 \Gamma = 2n\pi^2 ƛ^2 g \Gamma_n$$

$$A_{tot}(thick) = \sqrt{\pi n \sigma_0 \Gamma} = 2\pi ƛ \sqrt{n g \Gamma_n \Gamma}$$

Experimental details: Area analysis





$$A_\gamma(thin) = \frac{1}{2}\pi n \sigma_0 \Gamma_n = 2n\pi^2 \lambda\!\!\!^{-2} g \frac{\Gamma_n \Gamma_\gamma}{\Gamma}$$

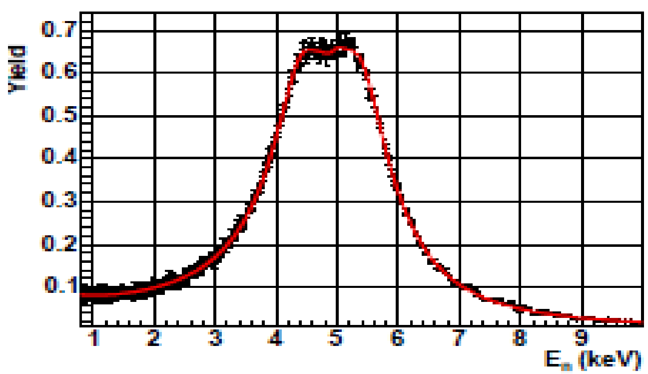
$$A_\gamma = 2n\pi^2 K \lambda\!\!\!^{-}$$

$$K = g\frac{\Gamma_n \Gamma_\gamma}{\Gamma}$$

Experimental details: Normalization

$$Y_{exp} = \frac{N(E_n, E_{dep})}{N_n(E_n) \times \varepsilon(E_n, E_{dep})}$$

^{197}Au

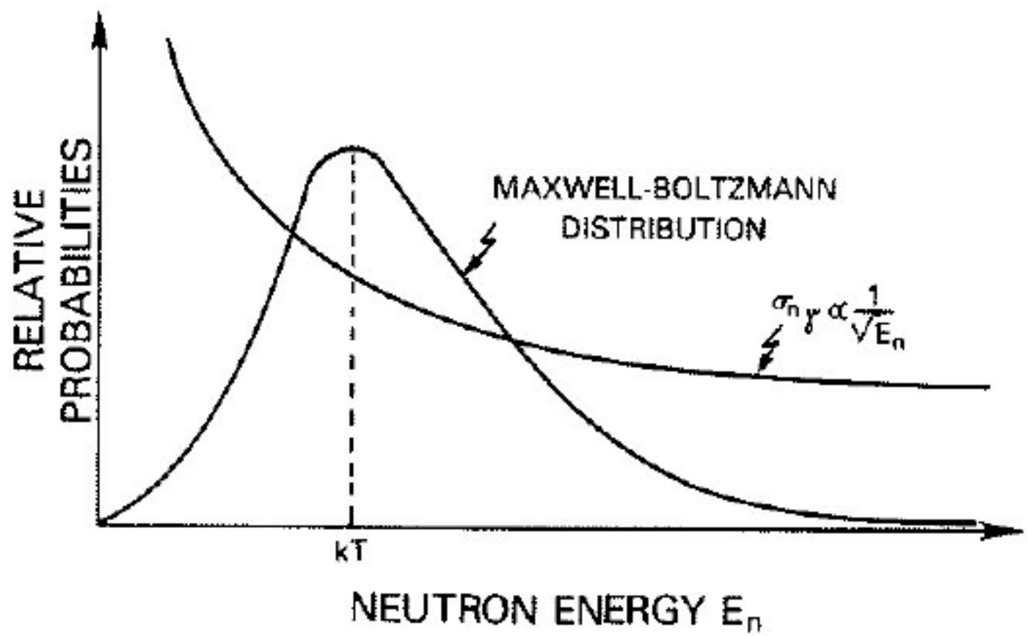


$$Y_{ref}^{exp}(E_n) = \frac{N_{ref}^{w}(E_n)}{N_n(E_n) \times (S_n^{ref} + E_n)}$$

$$Y_{ref}^{exp}(E_n) = A Y_{ref}^{th}(E_n) + B \rightarrow f^{Sat} = \frac{1}{A}$$

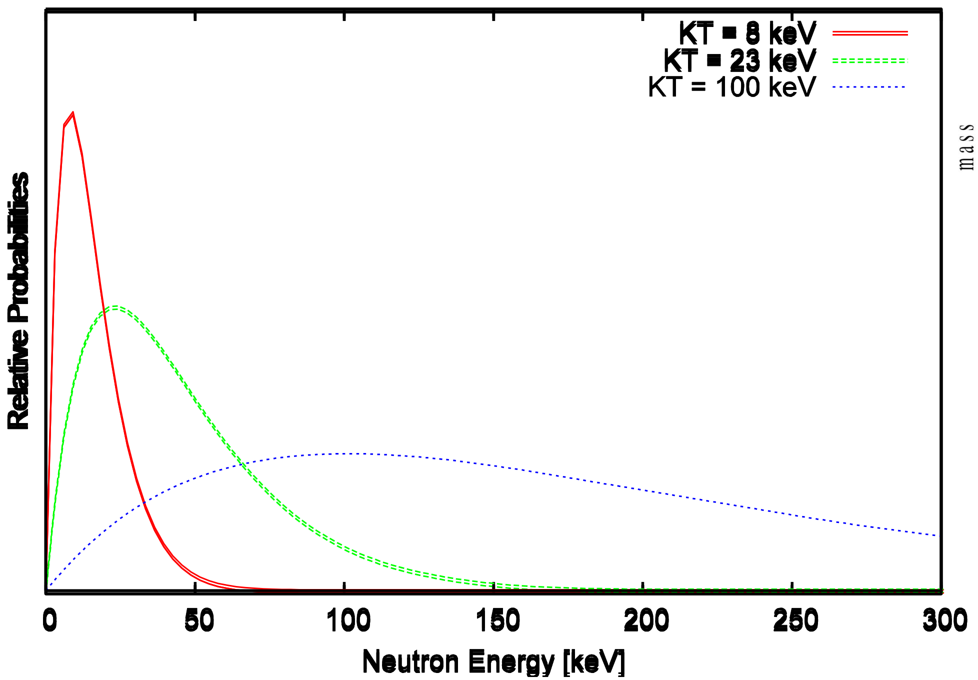
Maxwellian Averaged Cross Sections:MACS

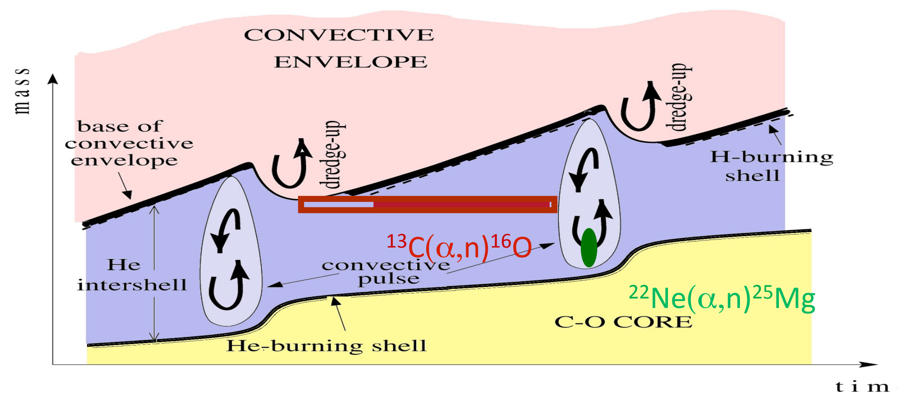
Neutrons produced in the stars are quickly thermalised ⇨ **M-B distribution**



Maxwellian Averaged Cross Sections:MACS

Neutrons produced in the stars are quickly thermalised ➡ **M-B distribution**





Reaction rate ($cm^{-3}s^{-1}$): $r = N_A N_n v\sigma(v)$ ➡ $r = N_A N_n \langle \sigma \cdot v \rangle$

$$MACS \equiv \frac{\langle \sigma \cdot v \rangle}{v_T} = \frac{2}{\sqrt{\pi}(kT)^2} \int_0^\infty \sigma(E) E e^{-E/(kT)} dE$$

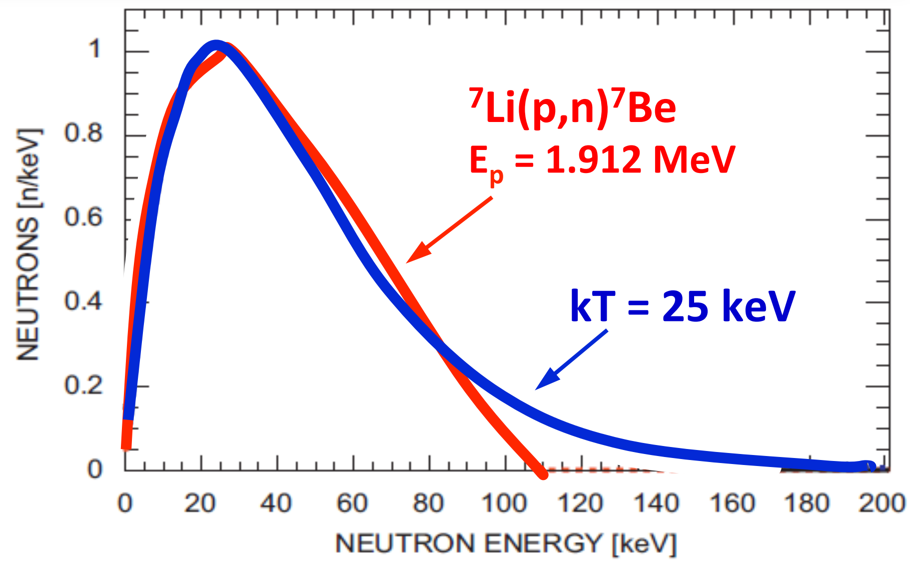
MACS: Activation

Integral measurements of MACS can be performed with neutron beams of **Maxwell-Boltzman** (MB) energy spectrum.

MB-like neutron beams typically produced by **low-energy p- or d- induced reactions** (with some moderation, if necessary).

Used for decades, at VdG accelerators.

New high-flux facilities now being built (SARAF, FRANZ, LENOS, etc…).



Two-step measurement:

- **Irradiate** sample under the neutron beam, leading to **an unstable nucleus** $^{A}X(n,\gamma)^{A+1}X$
- Determine the produced **activity** (for example, with HPGe, or using AMS technique).

Pros:

- **Selective method**, good signal-to-background ratio
- Typically **large fluxes** (close to source), does not need massive samples

Cons:

- Need **assumptions** to estrapolate results to different temperatures
- It cannot be applied if ^{A+1}X is **stable** or with **short half-life**

MACS: Time Of Flight

Time-of-flight method allows to measure directly **$\sigma(E_n)$**:

- (n,γ) events are determined by detecting the de-excitation cascade;
- Neutron energy determined from the time between production of the neutron beam and detection of the capture γ-rays.

In principle, **more powerful and accurate** than activation:

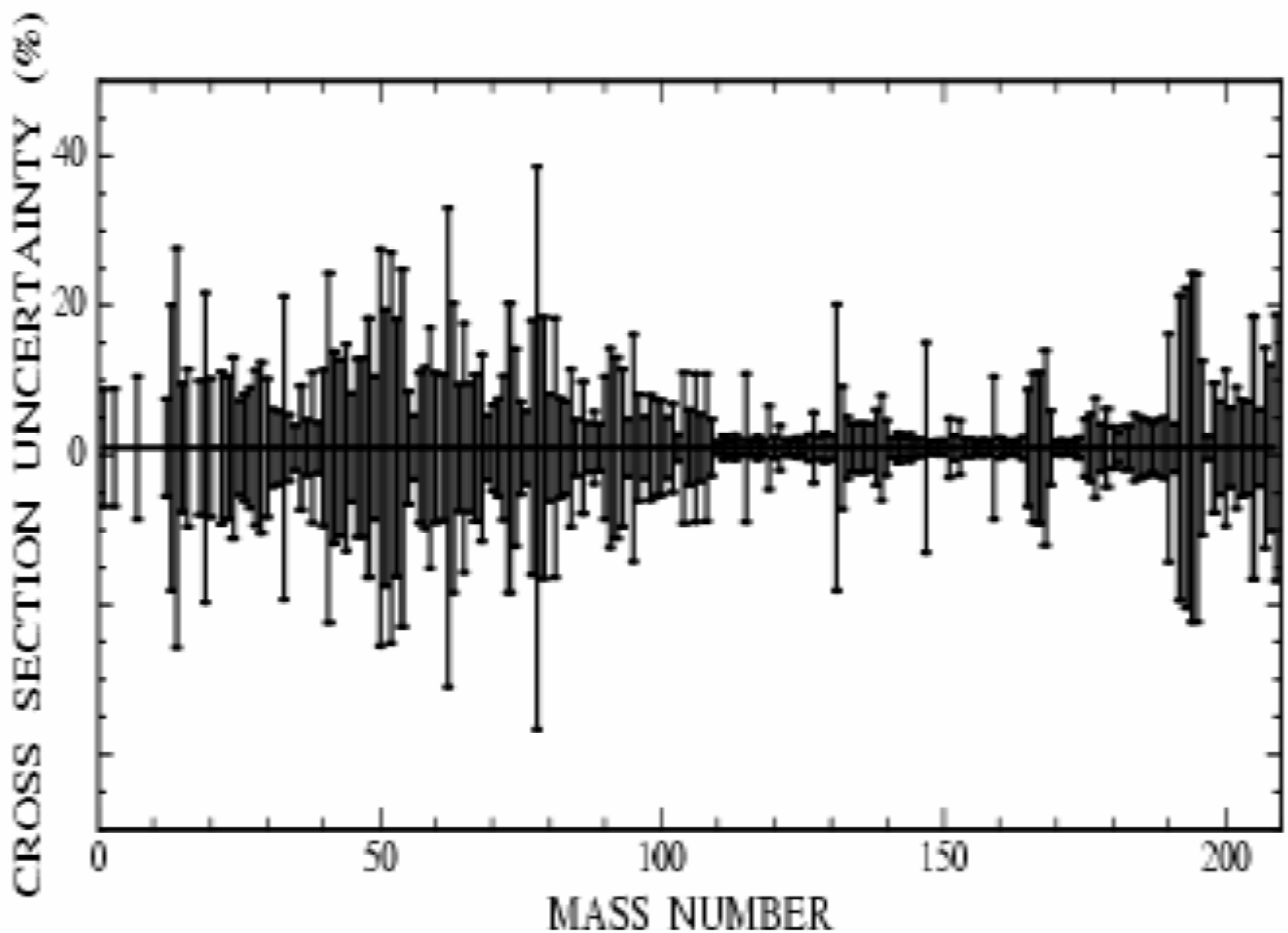
- MACS can be calculated for **ANY stellar temperature**
- **ANY isotope** can be measured.

Problems with ToF method:

- sample has to be at some **distance** from the neutron source, thus reducing the flux
- requires **pulsed neutron beams** (possibly with low repetition rate, to avoid wrap around);
- more difficult to discriminate **background** (including natural radioactivity of sample);
- requires relatively **pure samples** and in large amount.

"Difficult" measurements require high-flux facilities !!

Cross sections relevant for Nuclear Astrophysics



*** cross section uncertainties <5%

*** safe control of systematic uncertainties

Cross sections relevant for Nuclear Astrophysics

- branching point isotopes
- magic nuclei and end-point
- seeds isotopes
- isotopes of special interest

  cosmocronometer, neutron poison

Branching points

REVIEW OF MODERN PHYSICS, VOLUME 83, JANUARY–MARCH 2011

The *s* process: Nuclear physics, stellar models, and observations

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Germany

R. Gallino†

Dipartimento di Fisica Generale, Uni
INAF-Osservatorio Astronomico di T

S. Bisterzo‡

Dipartimento di Fisica Generale, Uni

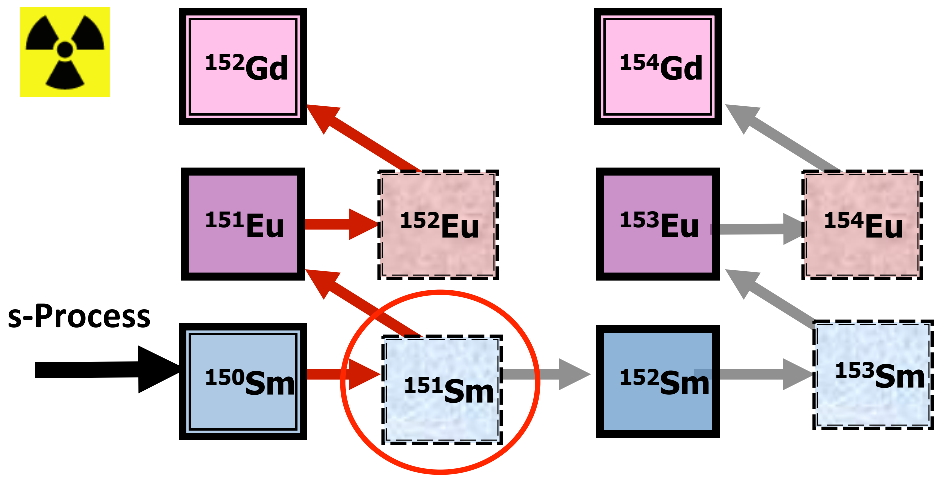
Wako Aoki§

National Astronomical Observatory,

Sample	Half-life (yr)	Q value (MeV)	Comment
^{63}Ni	100.1	β^-, 0.066	TOF work in progress (Couture, 2009), sample with low enrichment
^{79}Se	2.95×10^5	β^-, 0.159	Important branching, constrains *s*-process temperature in massive stars
^{81}Kr	2.29×10^5	EC, 0.322	Part of ^{79}Se branching
^{85}Kr	10.73	β^-, 0.687	Important branching, constrains neutron density in massive stars
^{95}Zr	64.02 d	β^-, 1.125	Not feasible in near future, but important for neutron density low-mass AGB stars
^{134}Cs	2.0652	β^-, 2.059	Important branching at $A = 134, 135$, sensitive to *s*-process temperature in low-mass AGB stars, measurement not feasible in near future
^{135}Cs	2.3×10^6	β^-, 0.269	So far only activation measurement at $kT = 25$ keV by Patronis *et al.* (2004)
^{147}Nd	10.981 d	β^-, 0.896	Important branching at $A = 147/148$, constrains neutron density in low-mass AGB stars
^{147}Pm	2.6234	β^-, 0.225	Part of branching at $A = 147/148$
^{148}Pm	5.368 d	β^-, 2.464	Not feasible in the near future
^{151}Sm	90	β^-, 0.076	Existing TOF measurements, full set of MACS data available (Abbondanno *et al.*, 2004a; Wisshak *et al.*, 2006c)
^{154}Eu	8.593	β^-, 1.978	Complex branching at $A = 154, 155$, sensitive to temperature and neutron density
^{155}Eu	4.753	β^-, 0.246	So far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1995)
^{153}Gd	0.658	EC, 0.244	Part of branching at $A = 154, 155$
^{160}Tb	0.198	β^-, 1.833	Weak temperature-sensitive branching, very challenging experiment
^{163}Ho	4570	EC, 0.0026	Branching at $A = 163$ sensitive to mass density during *s* process, so far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1996b)
^{170}Tm	0.352	β^-, 0.968	Important branching, constrains neutron density in low-mass AGB stars
^{171}Tm	1.921	β^-, 0.098	Part of branching at $A = 170, 171$
^{179}Ta	1.82	EC, 0.115	Crucial for *s*-process contribution to ^{180}Ta, nature's rarest stable isotope
^{185}W	0.206	β^-, 0.432	Important branching, sensitive to neutron density and *s*-process temperature in low-mass AGB stars
^{204}Tl	3.78	β^-, 0.763	Determines ^{205}Pb/^{205}Tl clock for dating of early Solar System

Branching points: the ^{151}Sm case

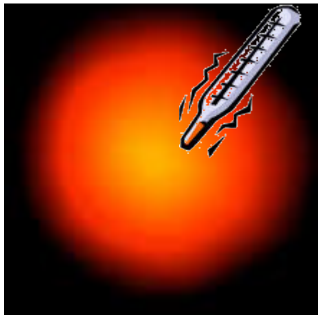
Laboratory $t_{1/2}$ = 93 yr
reduced to $t_{1/2}$ = 3 yr @ *s*-process site



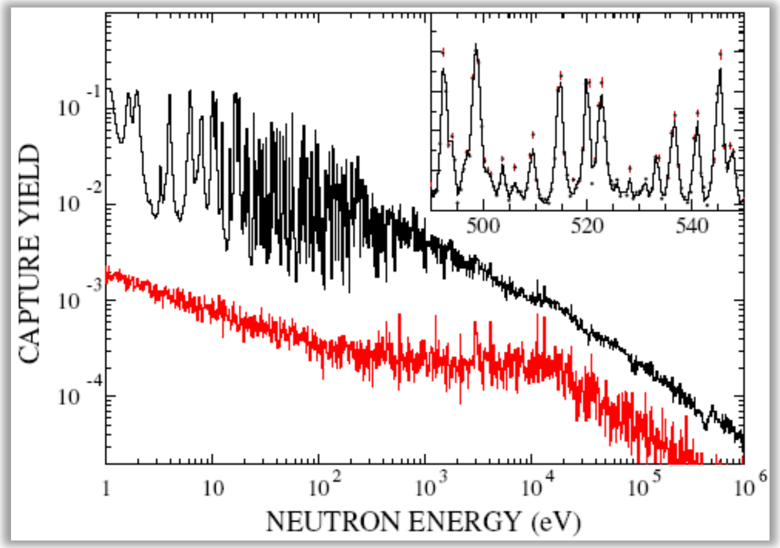
The branching ratio for **^{151}Sm** depends on:

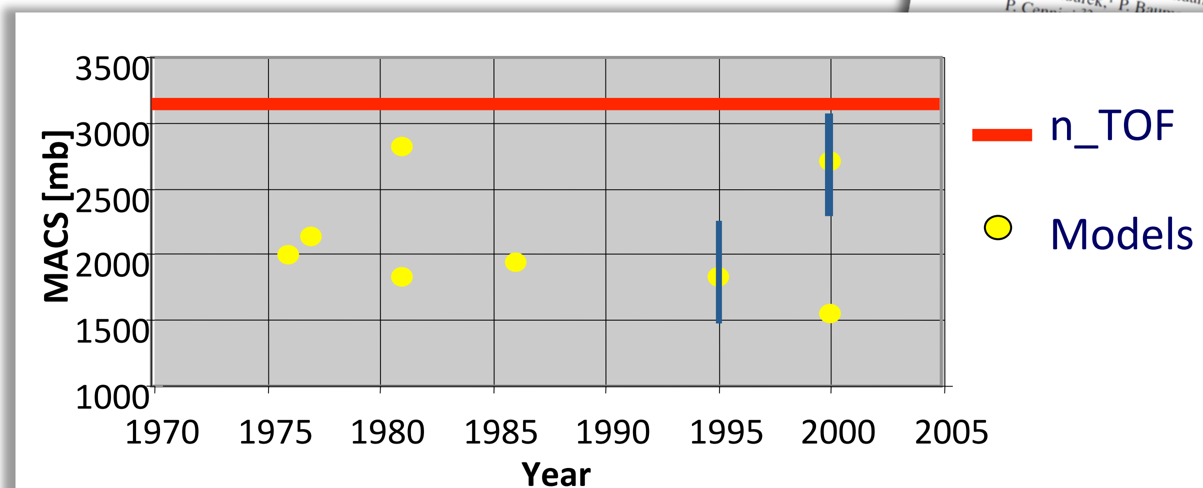
- **Termodynamical condition** of the stellar site (temperature, neutron density, etc…)
- Cross-section of **^{151}Sm(n,γ)**

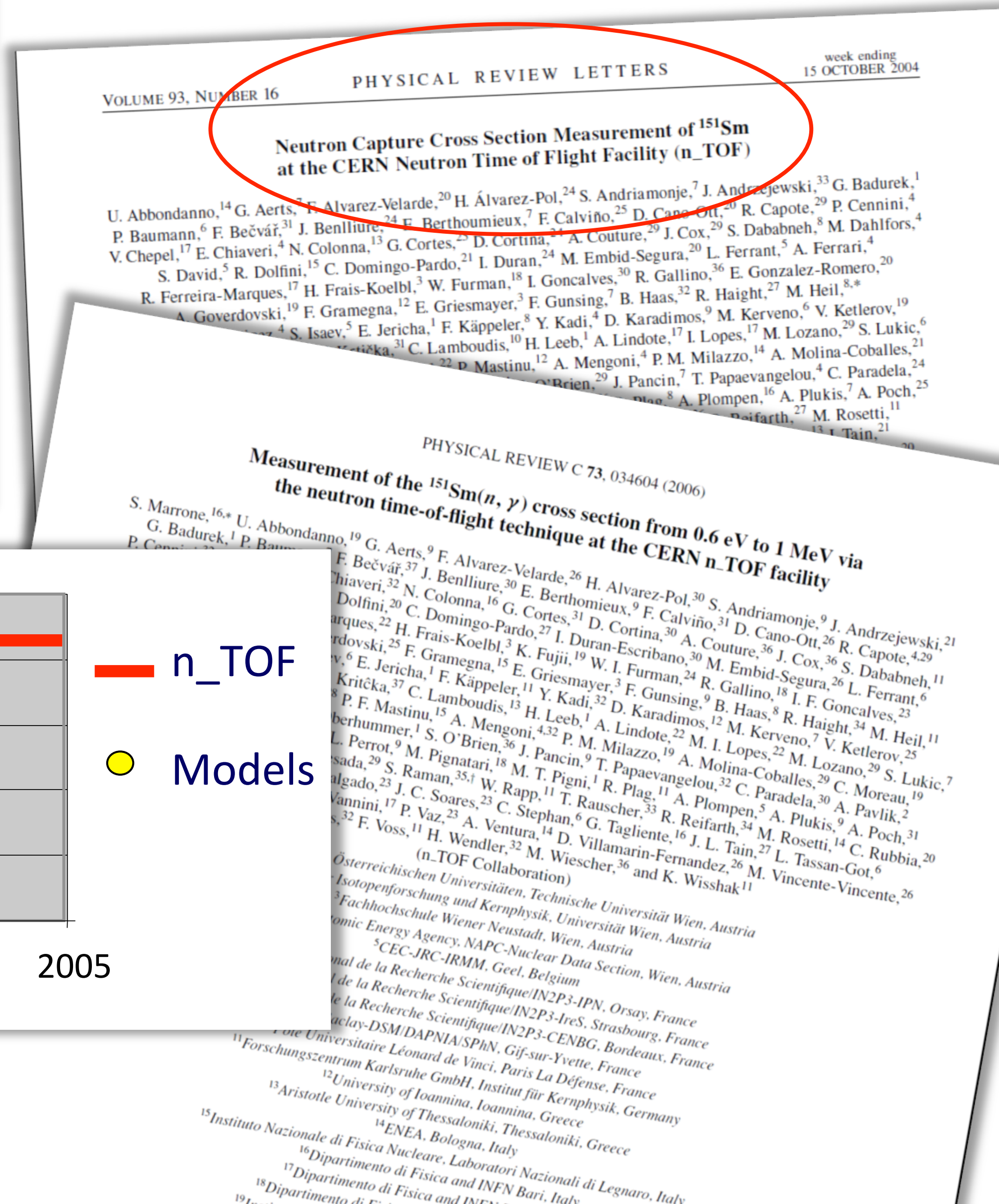
^{151}Sm used as **stellar thermometer** !!



Branching points: the ^{151}Sm case






VOLUME 93, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 15 OCTOBER 2004

Neutron Capture Cross Section Measurement of ^{151}Sm at the CERN Neutron Time of Flight Facility (n_TOF)

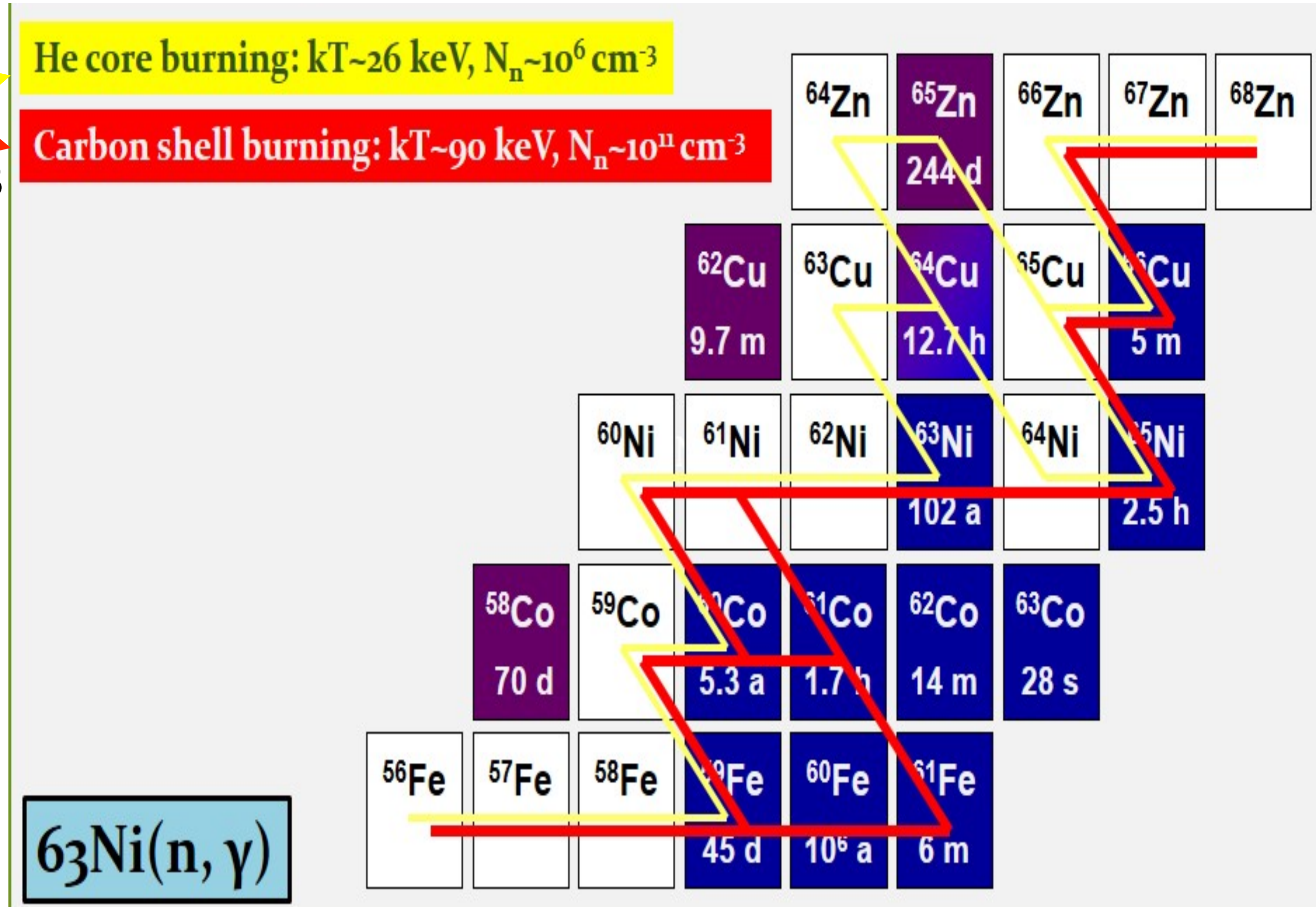
PHYSICAL REVIEW C 73, 034604 (2006)

Measurement of the ^{151}Sm(n,γ) cross section from 0.6 eV to 1 MeV via the neutron time-of-flight technique at the CERN n_TOF facility

(n_TOF Collaboration)

Branching points: the ^{63}Ni case

Scenarios
in massive stars



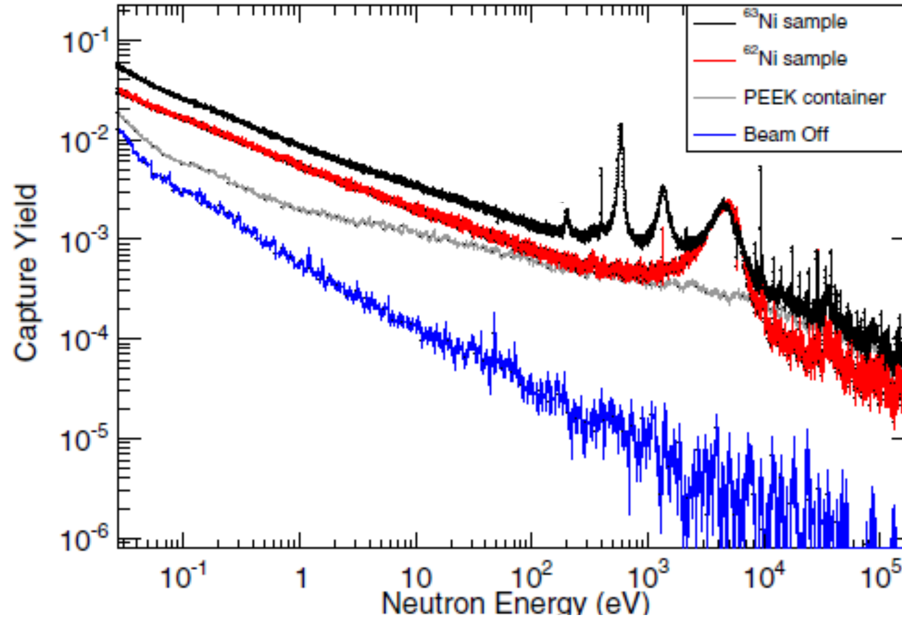
Branching points: the ^{63}Ni case

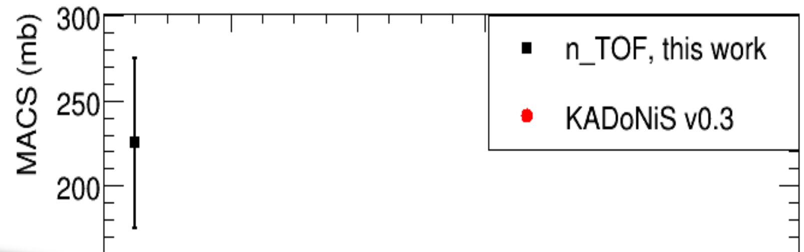
^{63}Ni ($t_{1/2}$=100 y) represents the **first branching point** in the s-process, and determines the **abundance** of **^{63,65}Cu**

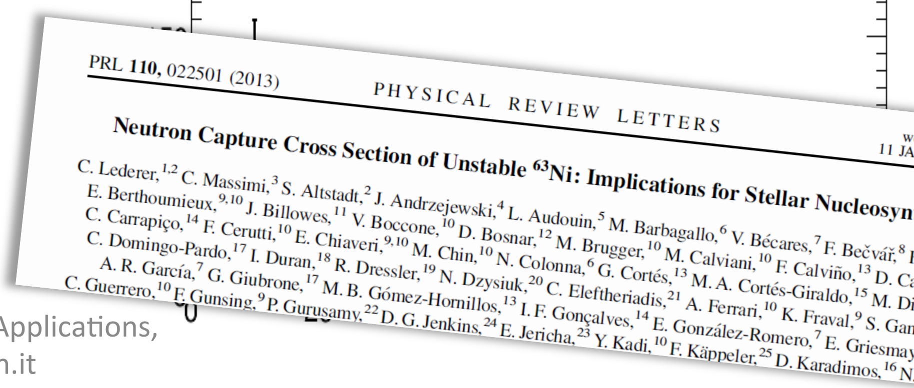
^{62}Ni sample (1g) irradiated **in thermal reactor** (1984 and 1992), leading to enrichment in **^{63}Ni** of **~13 %** (131 mg)

In 2011 ~**15.4 mg ^{63}Cu** in the sample (from ^{63}Ni decay).

After **chemical** separation at PSI, **^{63}Cu** contamination <**0.01 mg**






PRL 110, 022501 (2013) PHYSICAL REVIEW LETTERS

Neutron Capture Cross Section of Unstable ^{63}Ni: Implications for Stellar Nucleosynth

C. Lederer,[1,2] C. Massimi,[3] S. Altstadt,[2] J. Andrzejewski,[4] L. Audouin,[5] M. Barbagallo,[6] V. Bécares,[7] F. Bečvář,[8] F.
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C. Domingo-Pardo,[17] I. Duran,[18] R. Dressler,[19] N. Dzysiuk,[20] C. Eleftheriadis,[21] A. Ferrari,[10] K. Fraval,[9] S. Ganes
A. R. García,[7] G. Giubrone,[17] M. B. Gómez-Hormillos,[13] I. F. Gonçalves,[14] E. González-Romero,[7] E. Griesmayer
C. Guerrero,[10] F. Gunsing,[9] P. Gurusamy,[22] D. G. Jenkins,[24] E. Jericha,[23] Y. Kadi,[10] F. Käppeler,[25] D. Karadimos,[16] N. K

First high-resolution measurement of ^{63}Ni(n,γ) in the astrophysical energy range;

First experimental observation of resonances in the keV region.

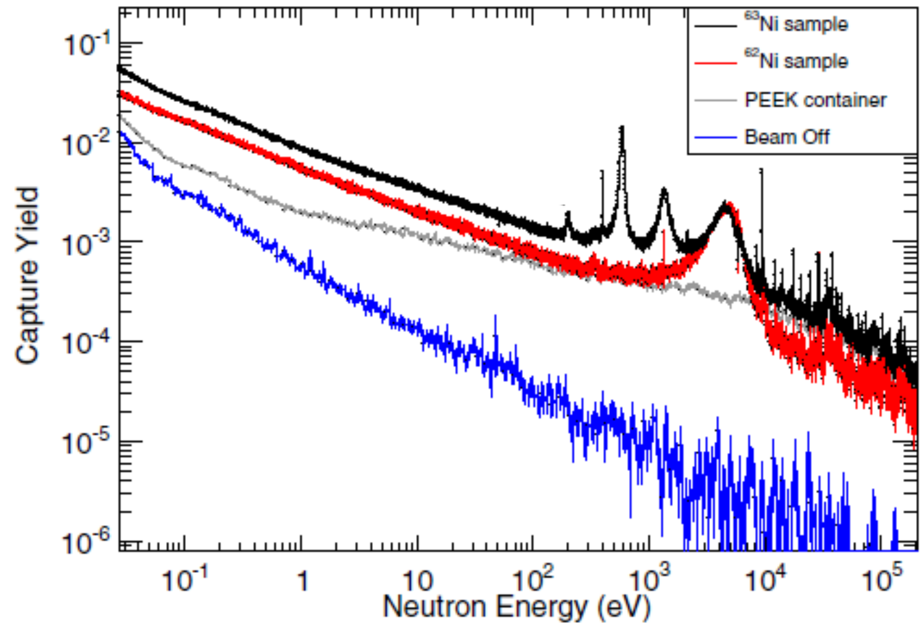
Branching points: the ^{63}Ni case

^{63}Ni ($t_{1/2}$=100 y) represents the **first branching point** in the s-process, and determines the **abundance** of **^{63,65}Cu**

^{62}Ni sample (1g) irradiated **in thermal reactor** (1984 and 1992), leading to enrichment in **^{63}Ni** of **~13 %** (131 mg)

In 2011 ~**15.4 mg ^{63}Cu** in the sample (from ^{63}Ni decay).

After **chemical** separation at PSI, **^{63}Cu** contamination <**0.01 mg**



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PRL **110,** 022501 (2013) PHYSICAL REVIEW LETTERS week endin[g] 11 JANUARY

Neutron Capture Cross Section of Unstable ^{63}Ni: Implications for Stellar Nucleosynthesis

C. Lederer,[1,2] C. Massimi,[3] S. Altstadt,[2] J. Andrzejewski,[4] L. Audouin,[5] M. Barbagallo,[6] V. Bécares,[7] F. Bečvář,[8] F. Bellon[i],
E. Berthoumieux,[9,10] J. Billowes,[11] V. Boccone,[10] D. Bosnar,[12] M. Brugger,[10] M. Calviani,[10] F. Calviño,[13] D. Cano-Ott,
C. Carrapiço,[14] F. Cerutti,[10] E. Chiaveri,[9,10] M. Chin,[10] N. Colonna,[6] G. Cortés,[13] M. A. Cortés-Giraldo,[15] M. Diakaki,[16]
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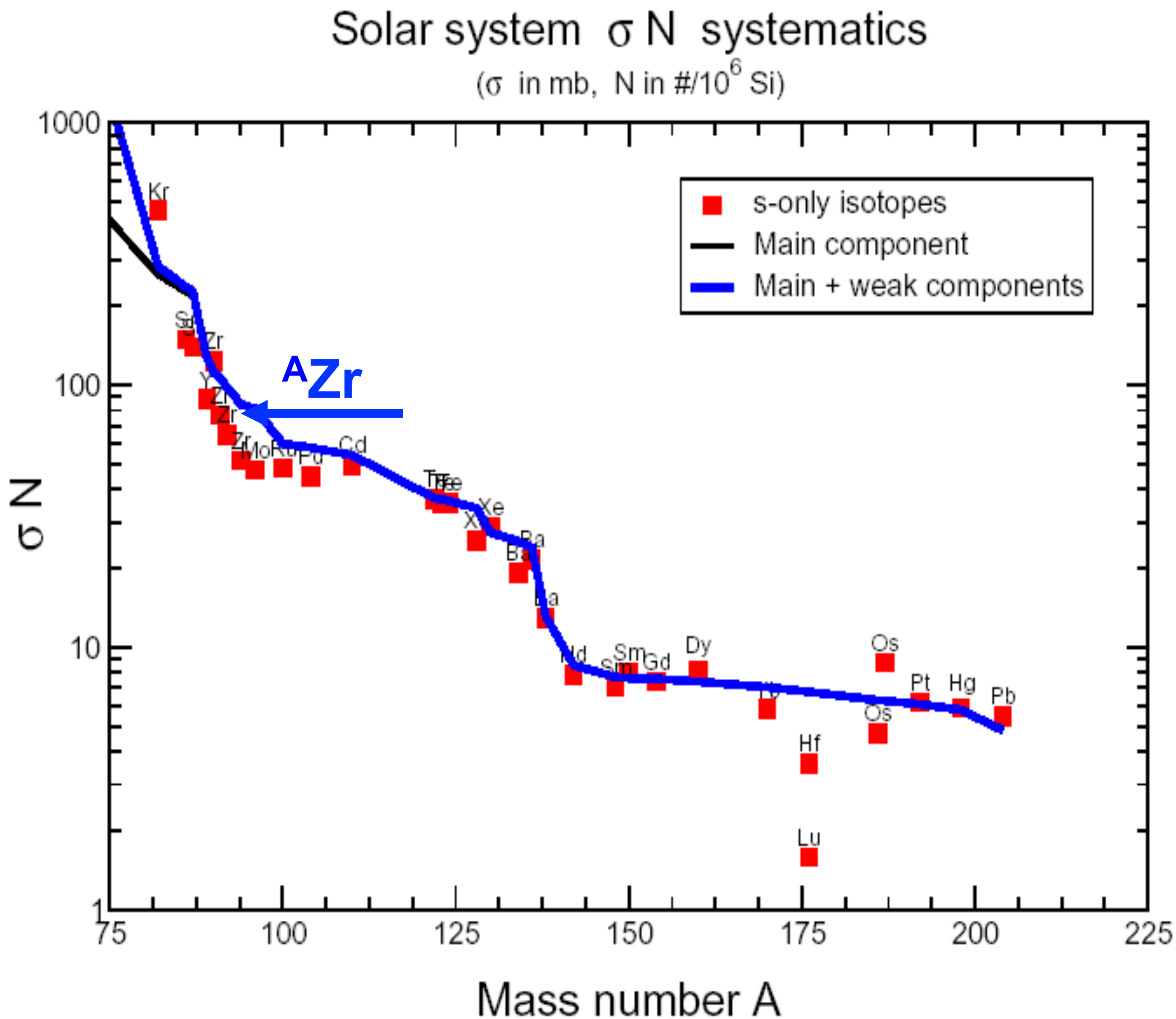
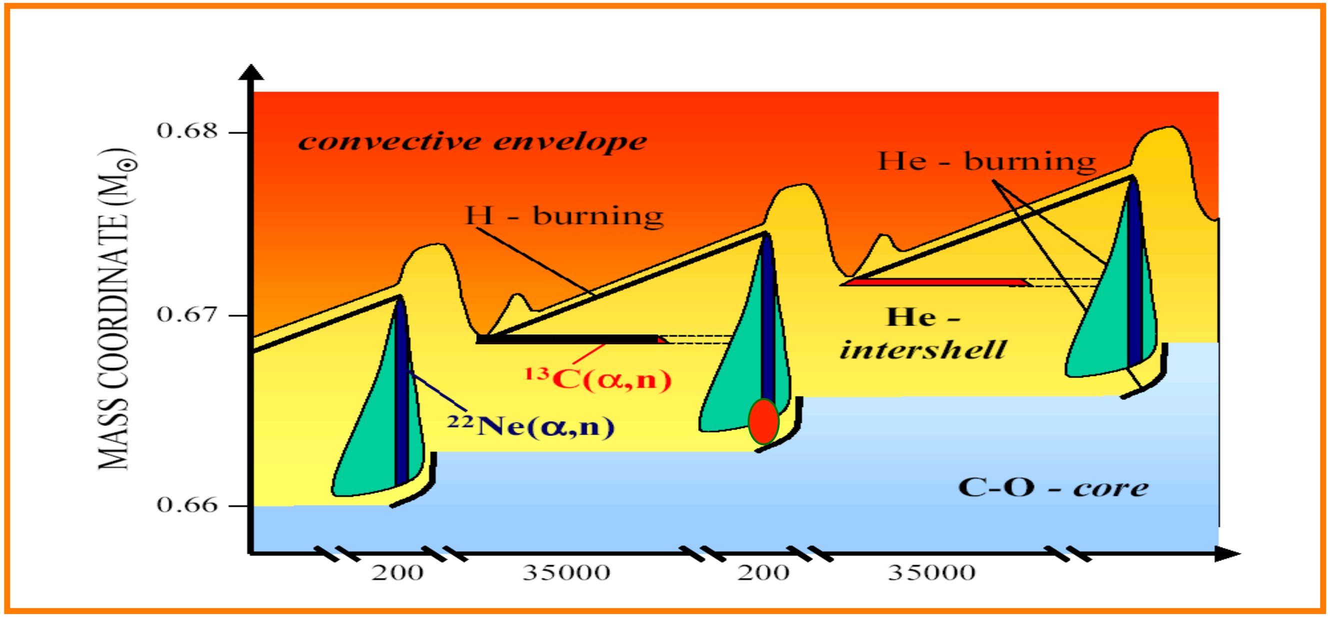
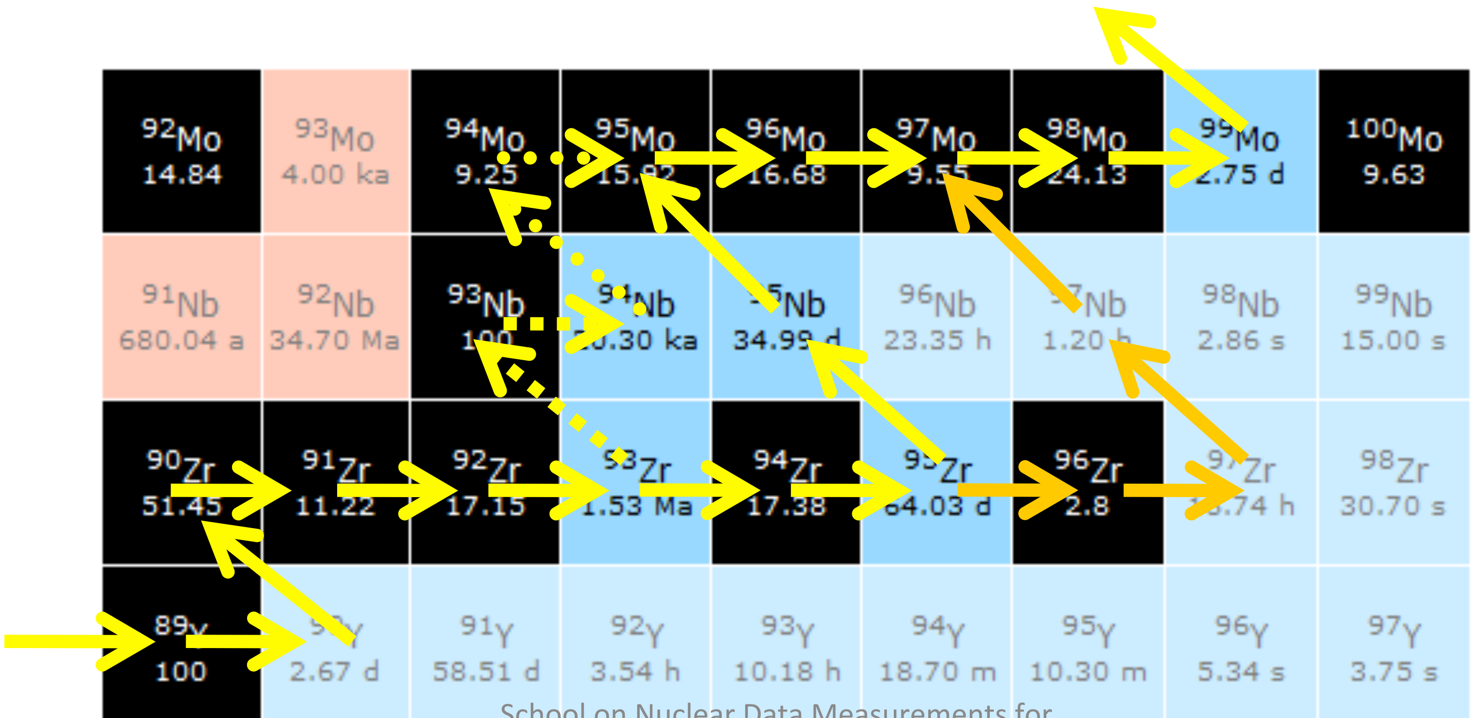
The Zr case

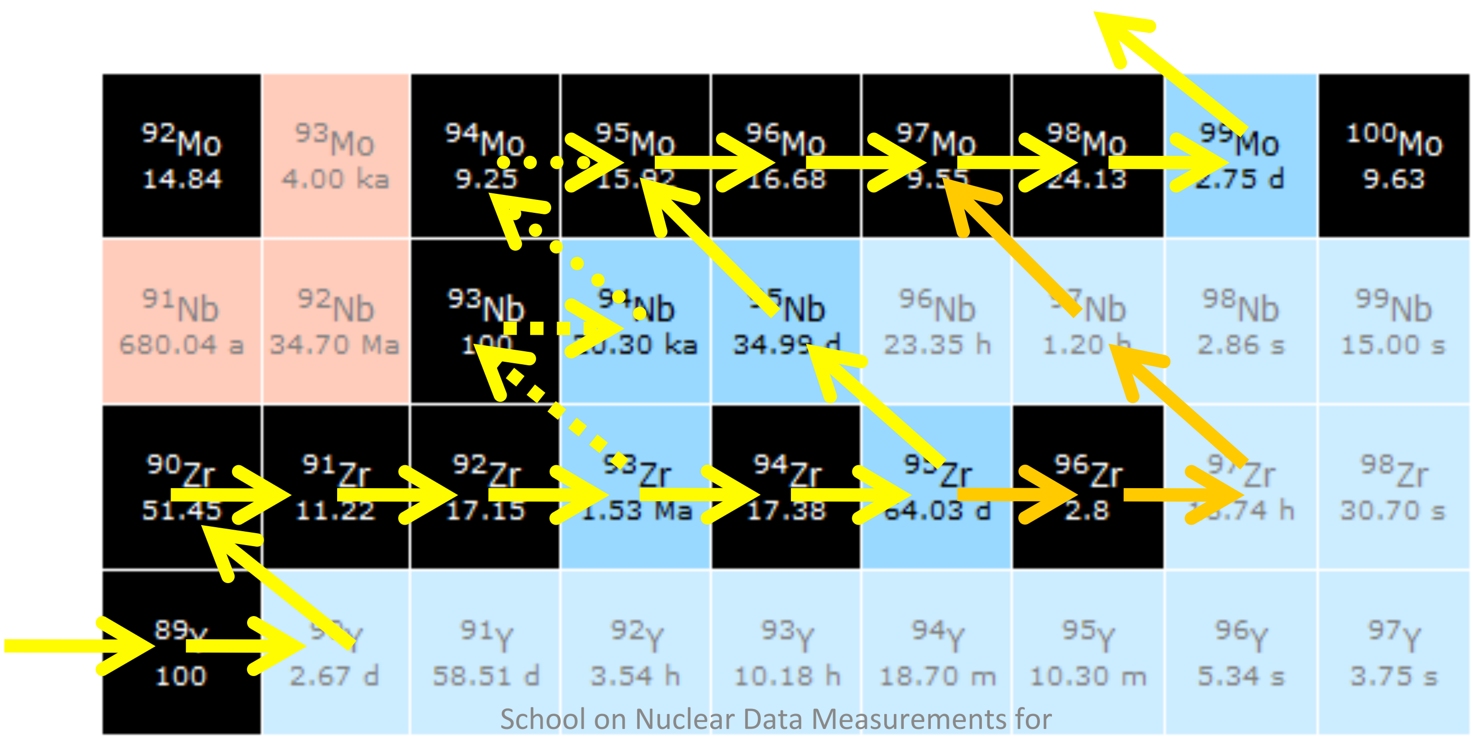
Neutron Magic Nuclei: the Zr case



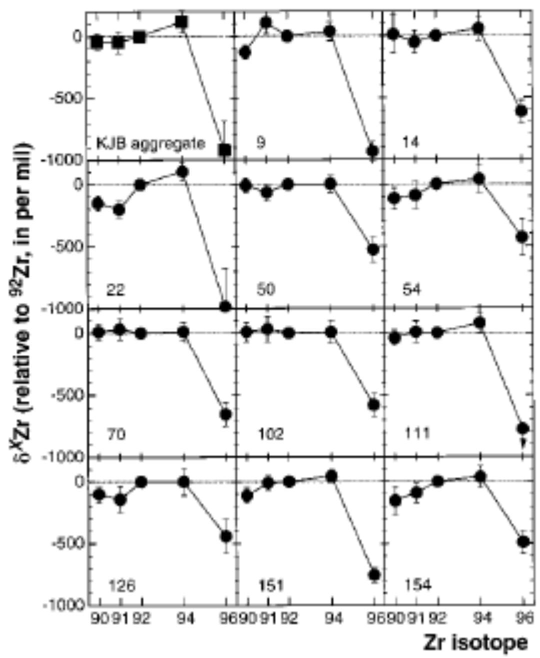

MASS COORDINATE ($M_\odot$)
0.68
0.67
0.66
convective envelope
H - burning
He - burning
He - intershell
$^{13}C(\alpha,n)$
$^{22}Ne(\alpha,n)$
C-O - core
200
35000
200
35000


^{92}Mo 14.84
^{93}Mo 4.00 ka
^{94}Mo 9.25
^{95}Mo
^{96}Mo 16.68
^{97}Mo
^{98}Mo 24.13
^{100}Mo 9.63
^{91}Nb 680.04 a
^{92}Nb 34.70 Ma
^{93}Nb
^{96}Nb 23.35 h
^{98}Nb 2.86 s
^{99}Nb 15.00 s
^{90}Zr 51.45
^{91}Zr 11.22
^{92}Zr 17.15
^{94}Zr 17.38
^{96}Zr 2.8
^{98}Zr 30.70 s
^{89}Y 100
^{91}Y 58.51 d
^{92}Y 3.54 h
^{93}Y 10.18 h
^{94}Y 18.70 m
^{95}Y 10.30 m
^{96}Y 5.34 s
^{97}Y 3.75 s

Nucleus	$N_{\odot}$ Normalized to $N(Si)=10^6$ atoms	$N_s / N_{\odot}$ %
^{90}Zr	**5.546**	**0.789**
^{91}Zr	**1.21**	**1.066**
^{92}Zr	**1.848**	**1.052**
^{94}Zr	**1.873**	**1.217**
^{96}Zr	**0.302**	**0.842**



Zr in meteorites SiC grains

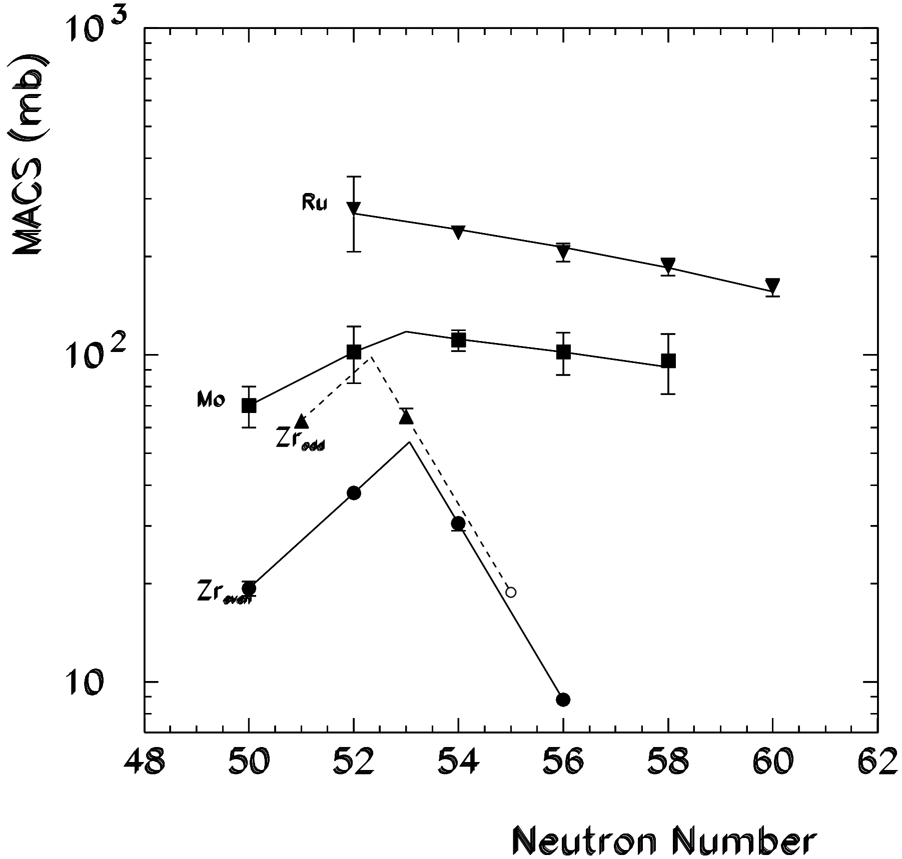


Zirconium isotopes patterns as function of mass for single SiC grains (circles) and an aggregate SiC grain (squares) from the Murchison meteorite.

MACS:@ 30 keV

MACS in mbarn

Isotope	KaDoNiS	N_TOF	MOST
^{90}Zr	21 ± 2	19.3 ± 0.9	
^{91}Zr	60 ± 8	63 ± 4	
^{92}Zr	34 ± 6	38 ± 3	
^{93}Zr	95 ± 10	**95.± 5**	
^{94}Zr	26 ± 1	30.5 ± 2	
^{95}Zr	79	**20.9 ± 0.9**	24.2
^{96}Zr	10.7 ± 0.5	8.9 ± 0.5	



Astrophysical implication: Abundances

Nucleus	$N_{\odot}$ Normalized to $N(Si)=10^{6}$ atoms	$N_s/N_{\odot}$ % Old MACS	$N_s/N_{\odot}$ % MACS from this work

The Astrophysical Journal, 780:95 (14pp), 2014 January 1 doi:10.1088/0004-637X/780/1/95

THE IMPACT OF UPDATED Zr NEUTRON-CAPTURE CROSS SECTIONS AND NEW ASYMPTOTIC GIANT BRANCH MODELS ON OUR UNDERSTANDING OF THE *S* PROCESS AND THE ORIGIN OF STARDUST

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Received 2013 August 5; accepted 2013 November 11; published 2013 December 13

ABSTRACT

Astrophysical implication: Abundances

THE ASTROPHYSICAL JOURNAL, 780:95 (14pp), 2014 January 1
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THE IMPACT OF UPDATED Zr NEUTRON-CAPTURE CROSS SECTIONS AND NEW ASYMPTOTIC GIANT BRANCH MODELS ON OUR UNDERSTANDING OF THE *S* PROCESS AND THE ORIGIN OF STARDUST

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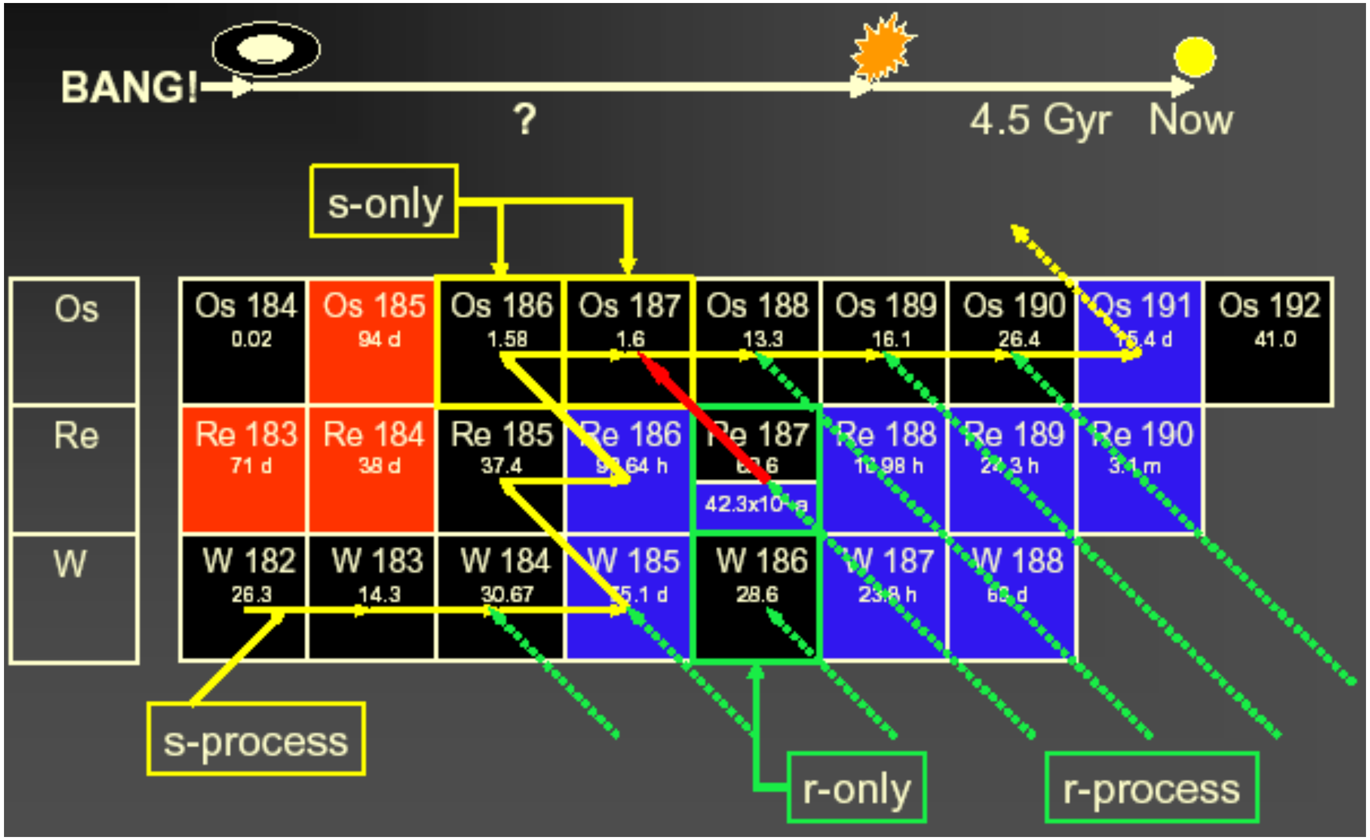
ABSTRACT

The Age of the Universe



^{187}**Re half-life = 41 Gyr**

The Age of the Universe

Physics

spotlighting exceptional research

America

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APS » Journals » Physics » Synopses » An ancient clock

An ancient clock

Illustration:
iStockphoto.com/Christian Wilkinson

Neutron physics of the Re/Os clock. I. Measurement of the (n,γ) cross sections of ^{186,187,188}Os at the CERN n_TOF facility

M. Mosconi et al. (The n_TOF Collaboration)

Phys. Rev. C 82, 015802 (Published July 15, 2010)

Neutron physics of the Re/Os clock. II. The (n,n') cross section of ^{187}Os at 30 keV neutron energy

M. Mosconi, M. Heil, F. Käppeler, R. Plag, and A. Mengoni

Phys. Rev. C 82, 015803 (Published July 15, 2010)

Neutron physics of the Re/Os clock. III. Resonance analyses and stellar (n,γ) cross sections of ^{186,187,188}Os

K. Fujii et al. (The n_TOF Collaboration)

Phys. Rev. C 82, 015804 (Published July 15, 2010)

- Cosmology
- Nuclear Physics

The Age of the Universe

- Cosmological way
  based on the Hubble time definition (“expansion age”)

- Astronomical way
  based on observations of globular clusters

- Nuclear way
  based on abundances & decay properties of long-lived radioactive species

The nuclear way

Traditional nuclear clocks are those based on:

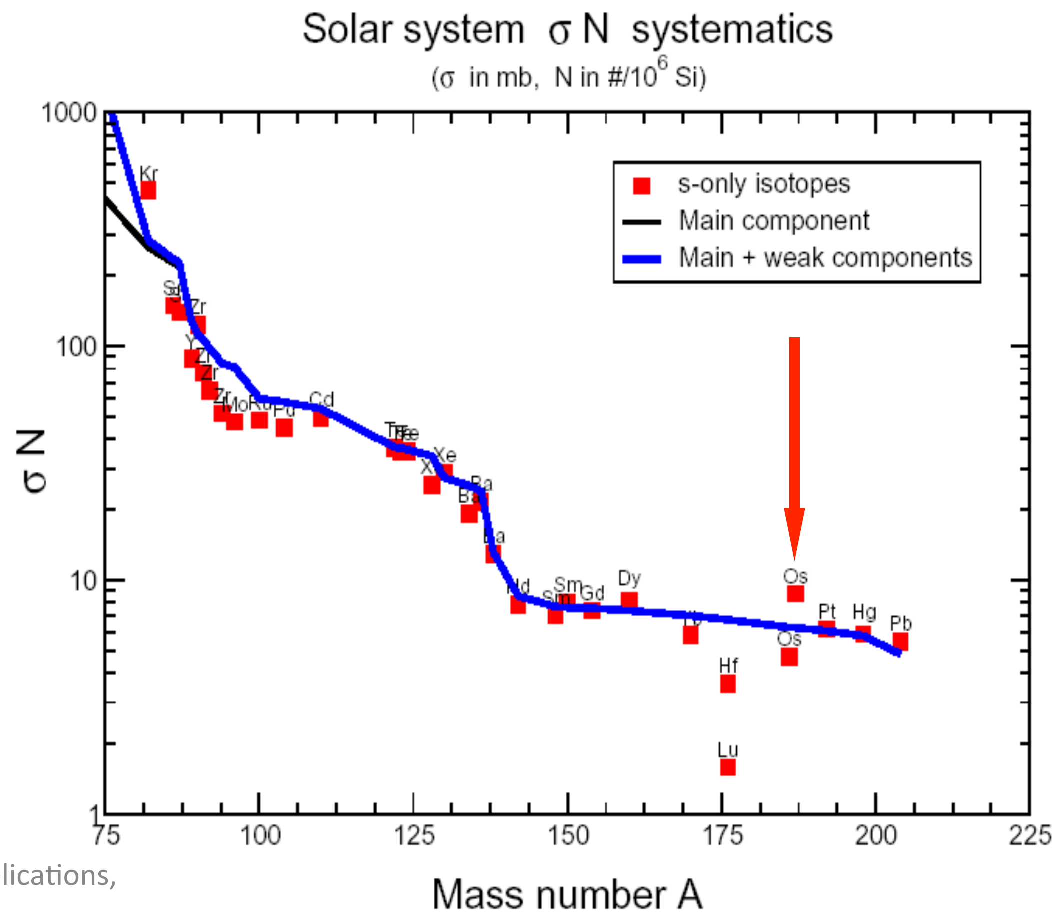
- $^{235}U/^{238}U$
- $^{232}Th/^{238}U$
- $^{187}Os/^{187}Re$
- Th/Eu, Th/X or Th/U abundances in low-Z stars

The Cosmocronometer

The *s*-process condition $\sigma_A N_A = const.$ implies that:

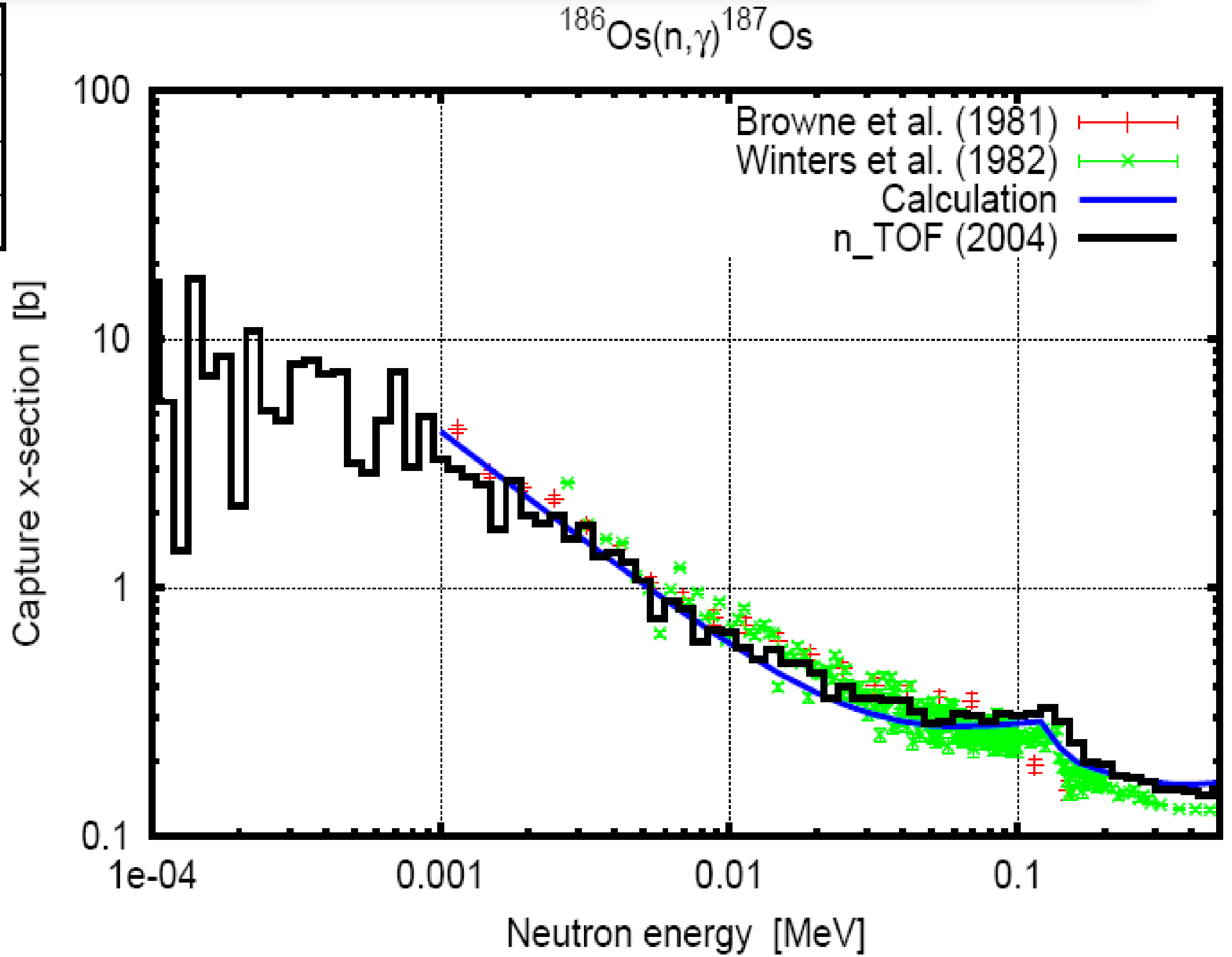
$$\sigma_{186}\,[^{186}\mathrm{Os}] = \sigma_{187}\,[^{187}\mathrm{Os}]$$

$$^{187}\mathrm{Os}_c = {}^{187}\mathrm{Os} - \frac{\sigma(186)}{\sigma(187)}\,{}^{186}\mathrm{Os}$$



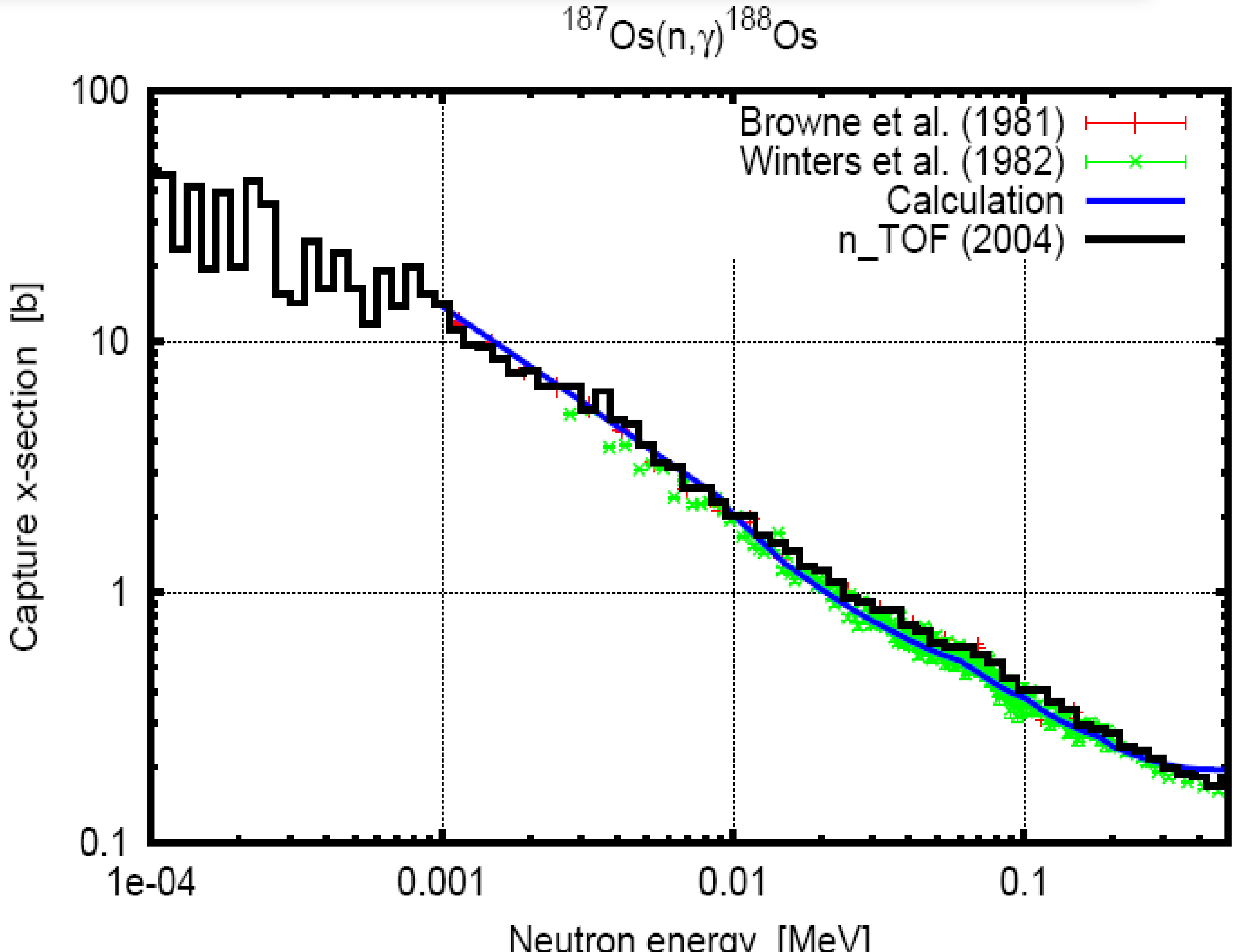
The Cosmocronometer: Os results

MACS-30	
BrB81	438 ± 30 mb
WiM82	418 ± 16 mb
n_TOF	384 ± 17 mb



The Cosmocronometer: Os results

MACS-30	
BrB81	919 ± 28 mb
WiM82	874 ± 28 mb
n_TOF	940 ± 18 mb



The Age of the Universe

- Cosmological way

13.7 ± 0.2 Gyr

- Astronomical way

14 ± 2 Gyr

- Nuclear way: Re/Os clock Th/U clock

14.9 ± 2 Gyr(*)

13 ± 4 Gyr

(*) 0.4 Gyr uncertainty due to x-sections

The Cosmocronometer: Complications

In addition to the fortunate conditions which allows to use the Re/Os abundance pair as a clock there are a number of complications:

The β-decay half-life of ^{187}Re is strongly dependent on temperature

The stellar neutron capture cross section of ^{187}Os is influenced by the population of low-lying excited levels
(the 1st excited states is at 9.8 keV)

Branching(s) at ^{185}W and/or at ^{186}Re

The chemical evolution of the galaxy influences the history of the nucleosynthesis
Re and Os abundances uncertainties

Conclusion

In the last fifty years there have been an extraordinary progress in the modeling of the stellar evolution. One of the main ingredients for the stellar model are the neutron cross sections

There is a need of accurate new data on neutron cross section

In the last ten years several results for stellar nuclesynthesis have been produced (Sm, Os, Zr, Ni, Fe, etc...).

Further progress are needed to measure short-lived radionuclides aimed at solving key remaining questions in nuclear astrophysics.