The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization
IAEA
International Atomic Energy Agency

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School on Physics, Technology and Applications of Accelerator Driven Systems (ADS)

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Nuclear Reactions and Related Data Libraries at Low Energies. Part II

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Ages

- 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

Age from Hubble time

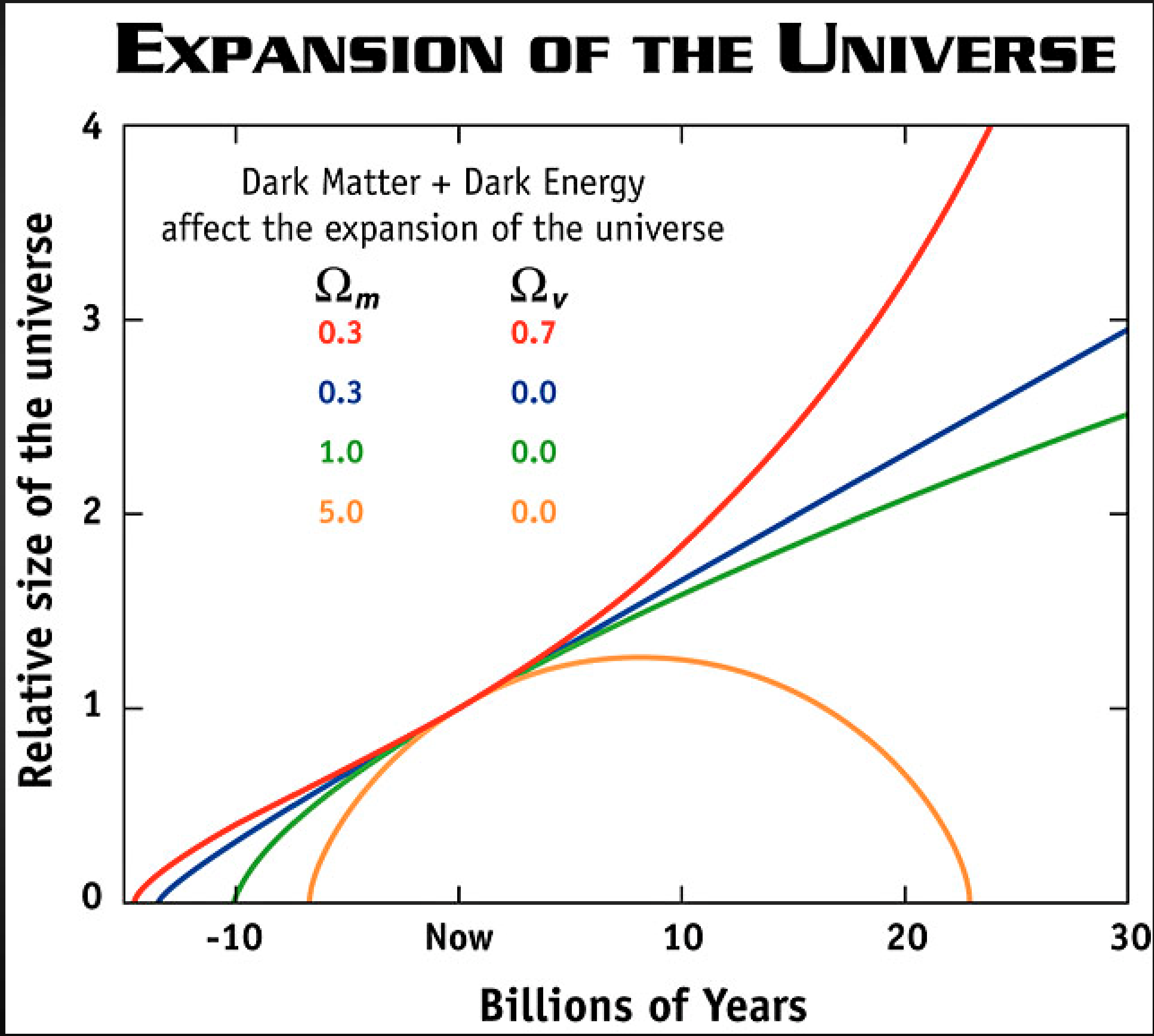
The most recent estimate of the Hubble constant based on observations provides(*) : $H_0 = 72 \pm 8$ km/sec/Mpc and implies an age of:

13.9 ± 1.5 Gyr

(*) HST Key Project
see: WL Friedman *et al*., ApJ **553**, (2001) 47

NB: if $\Omega = \Omega_m \sim 1$, then age=$2/3 \times 1/H_0$ = 9.3±**1.0 Gyr**

Cosmological "problems" with age



http://map.gsfc.nasa.gov/

Age from WMAP observations

The detailed structure of the cosmic microwave background fluctuations will depend on the current density of the universe, the composition of the universe and its expansion rate. WMAP has been able to determine these parameters with an accuracy of better than 5%. Thus, we can estimate the expansion age of the universe to better than 5%. When we combine the WMAP data with complimentary observations from other CMB experiments (ACBAR and CBI), we are able to determine an age for the universe closer to an accuracy of 1%.

13.7 ± 0.2 Gyr

Source: CL Bennett et al., ApJS, **148** (2003) 1

Age from globular clusters

The age derived from observation of the luminosity-color relation of stars in globular clusters

from **> 11.2 Gyr (*)**

to **14 ± 2.0 Gyr**

(*) LM Krauss and B Chaboyer, Science **299** (2003) 65

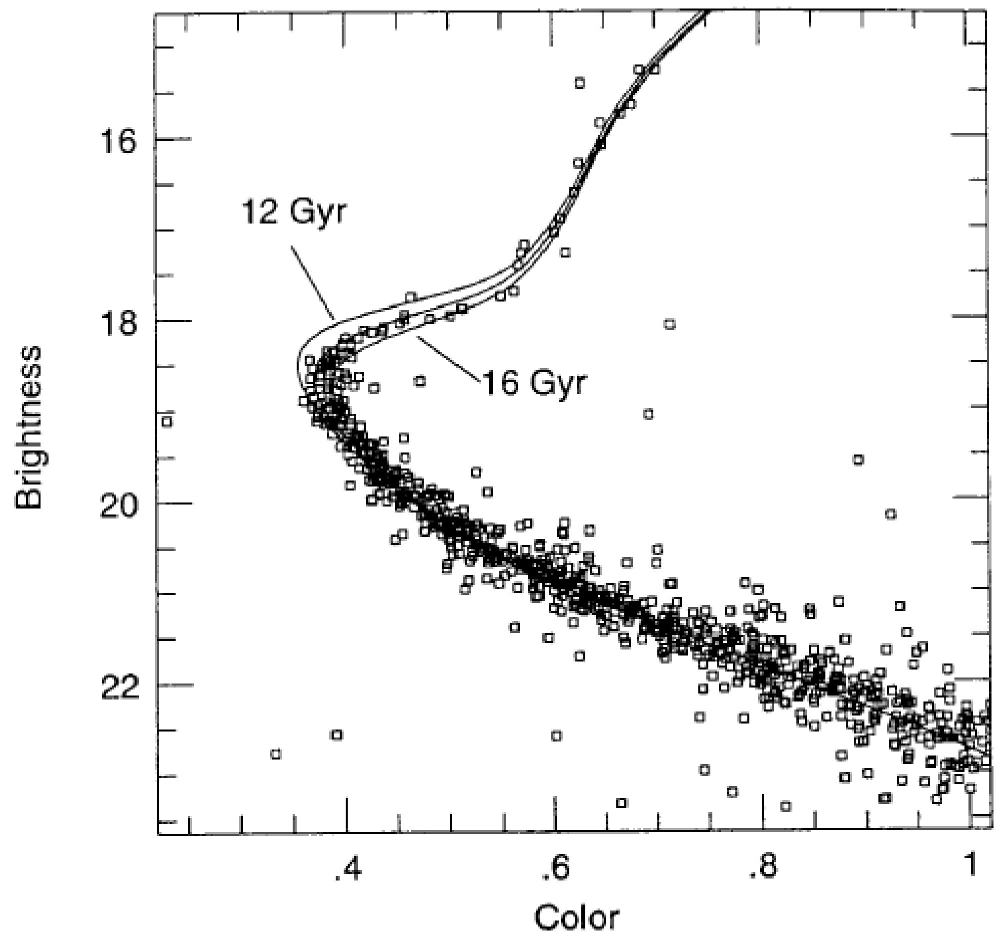


FIG. 2. HR diagram for M92. The squares are measured colors and brightnesses for individual stars in the cluster. The lines show model predictions for the positions of stars for cluster ages of 14, 16, and 18 billion years. The match of the models to the cluster data for an age of 16 billion years is remarkably good.

Source: DN Spergel et al.
Proc. Natl. Acad. Sci. USA **94** (1997) 6579

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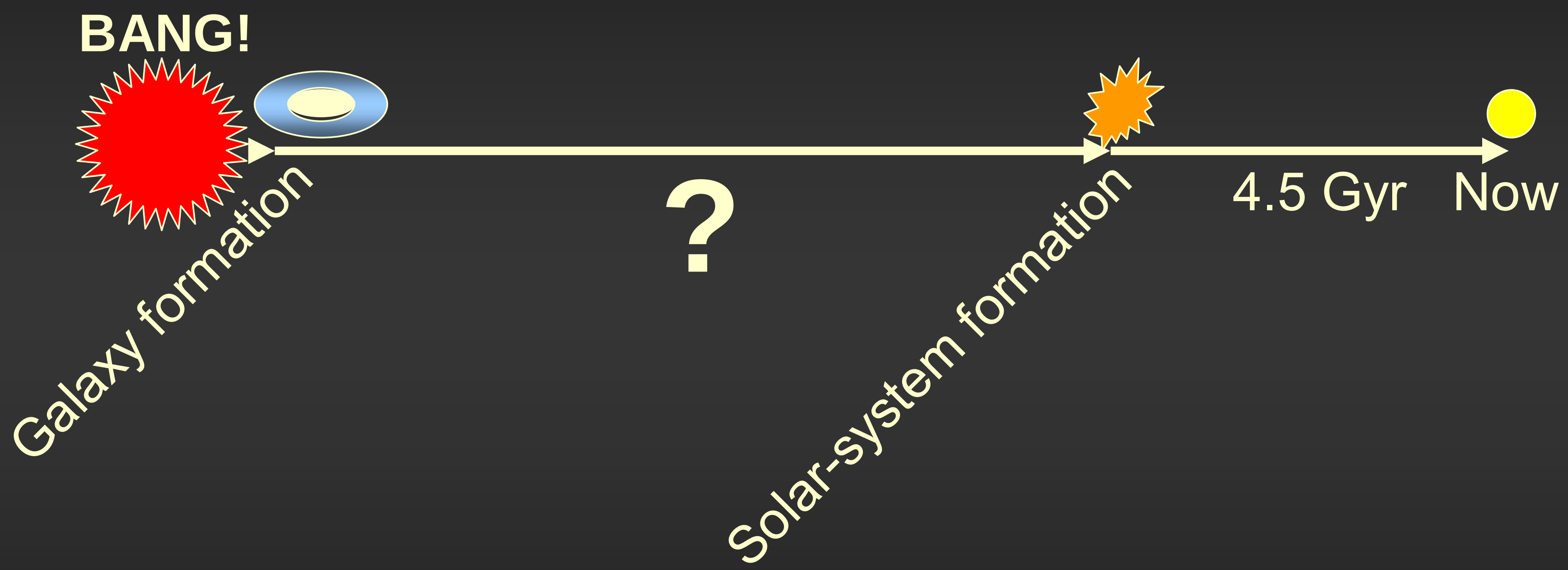
The nuclear way

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

Time



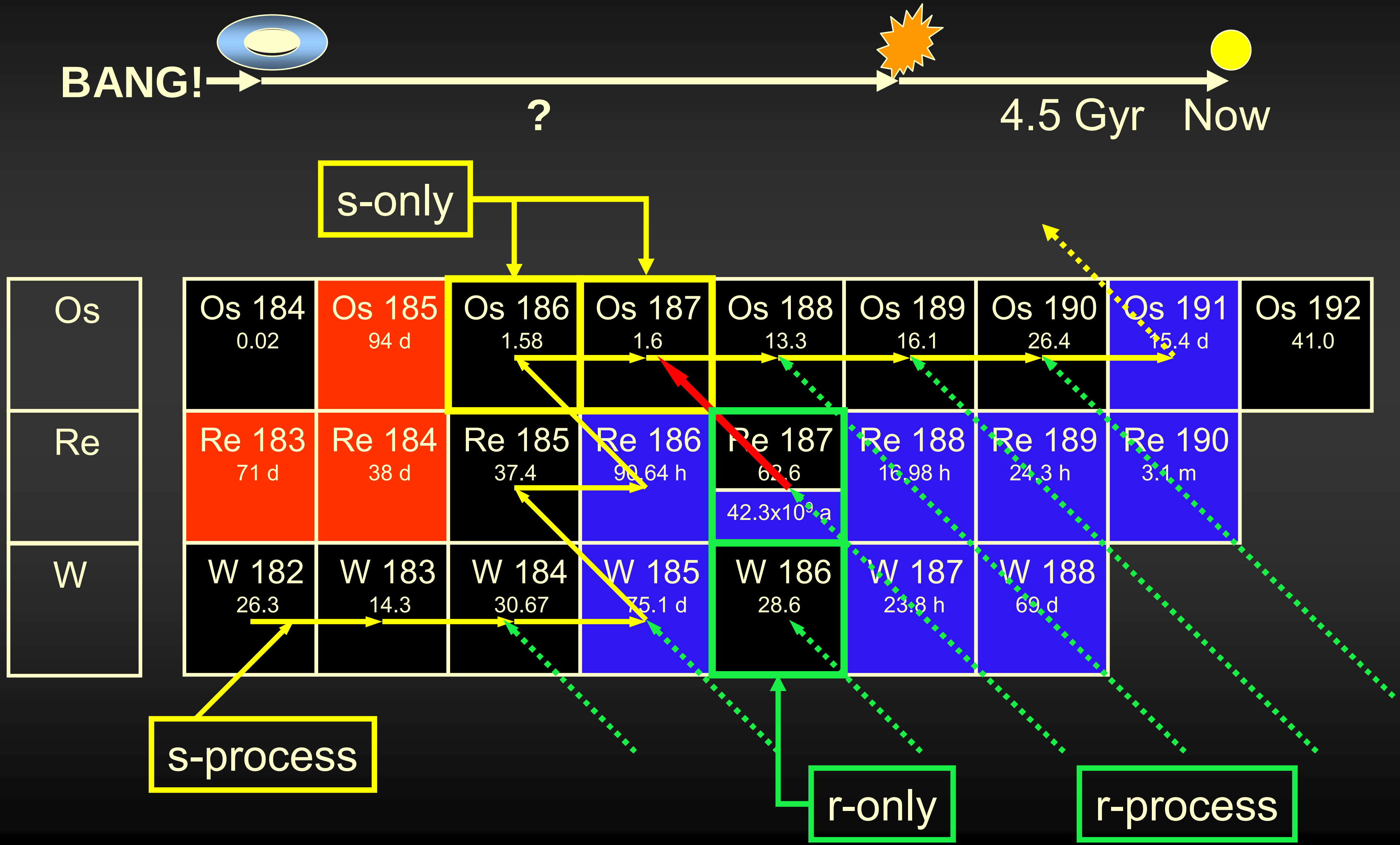
Re/Os clock

Os	Os 184 0.02	Os 185 94 d	Os 186 1.58	Os 187 1.6	Os 188 13.3	Os 189 16.1	Os 190 26.4	Os 191 15.4 d	Os 192 41.0
Re	Re 183 71 d	Re 184 38 d	Re 185 37.4	Re 186 90.64 h	Re 187 62.6 42.3×10^9 a	Re 188 16.98 h	Re 189 24.3 h	Re 190 3.1 m	
W	W 182 26.3	W 183 14.3	W 184 30.67	W 185 75.1 d	W 186 28.6	W 187 23.8 h	W 188 69 d		

The β-decay half-life of ^{187}Re is 42.3 Gy

Effect on the abundance of the decay daugther ^{187}Os

Re/Os clock



BANG!
?
4.5 Gyr
Now
s-only
Os
Re
W
Os 184
0.02
Os 185
94 d
Os 186
1.58
Os 187
1.6
Os 188
13.3
Os 189
16.1
Os 190
26.4
Os 191
15.4 d
Os 192
41.0
Re 183
71 d
Re 184
38 d
Re 185
37.4
Re 186
90.64 h
Re 187
62.6
42.3x10^9 a
Re 188
16.98 h
Re 189
24.3 h
Re 190
3.1 m
W 182
26.3
W 183
14.3
W 184
30.67
W 185
75.1 d
W 186
28.6
W 187
23.8 h
W 188
69 d
s-process
r-only
r-process

Enhanchement of [^{187}Os] by ^{187}Re(β^-)

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

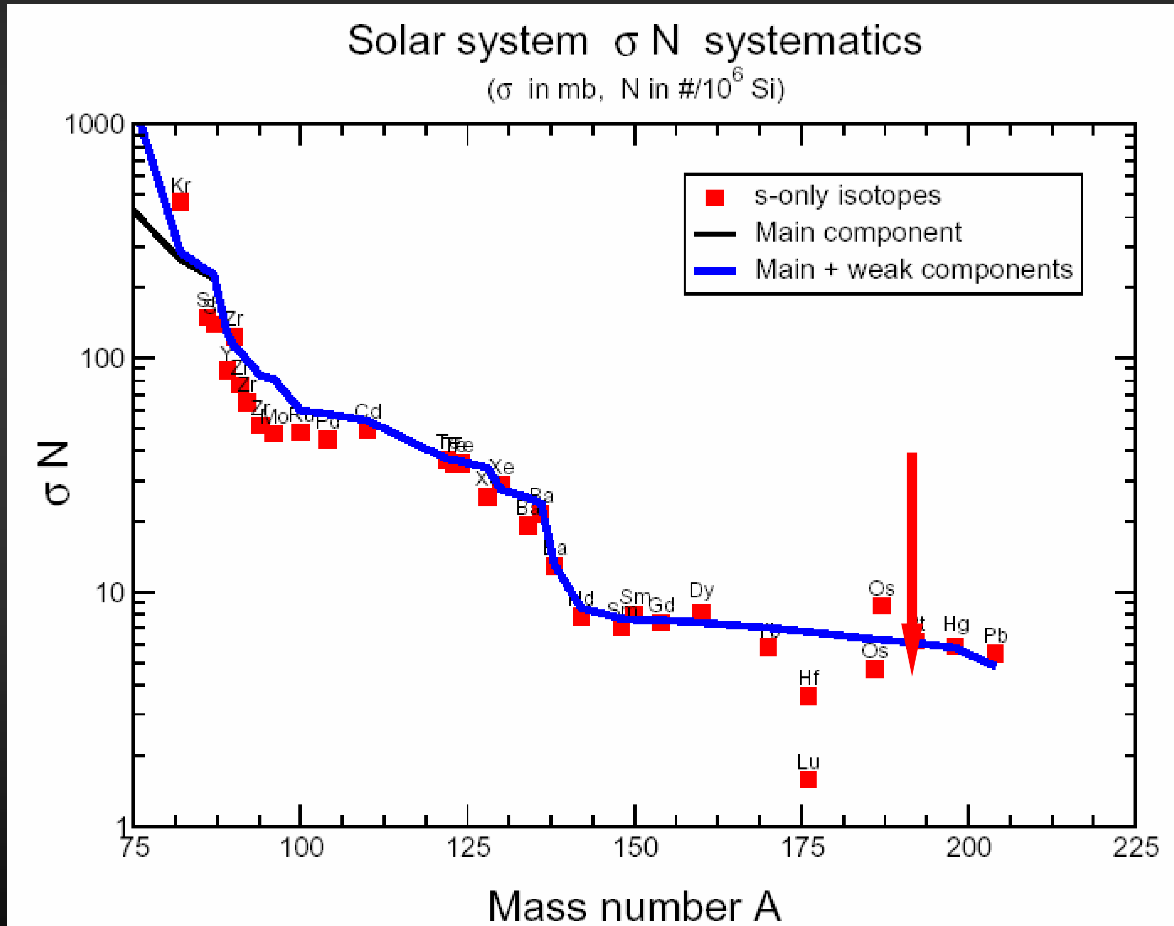
$$\sigma_{186}\,[^{186}\mathrm{Os}] = \sigma_{187}\,[^{187}\mathrm{Os}]$$

From (n,γ) systematics

$$\sigma_{186} / \sigma_{187} \sim \mathbf{0.5}$$

On the other hand, from solar-system abundances:

[^{187}Os] / [^{186}Os] = **0.7924 ± 0.0016**



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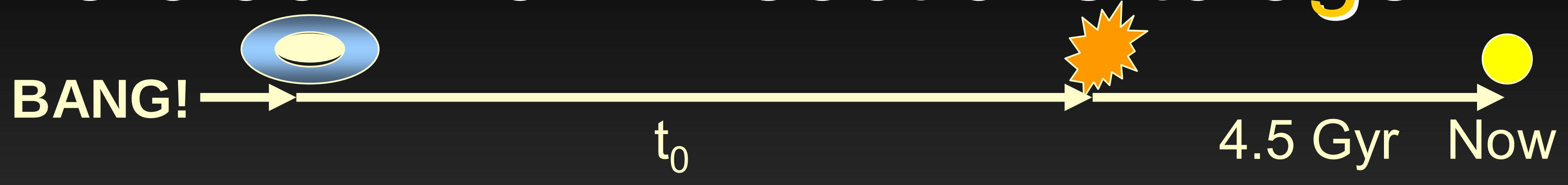
The clock: from x-sections to age



- s-process synthesis of ^{186,187}Os

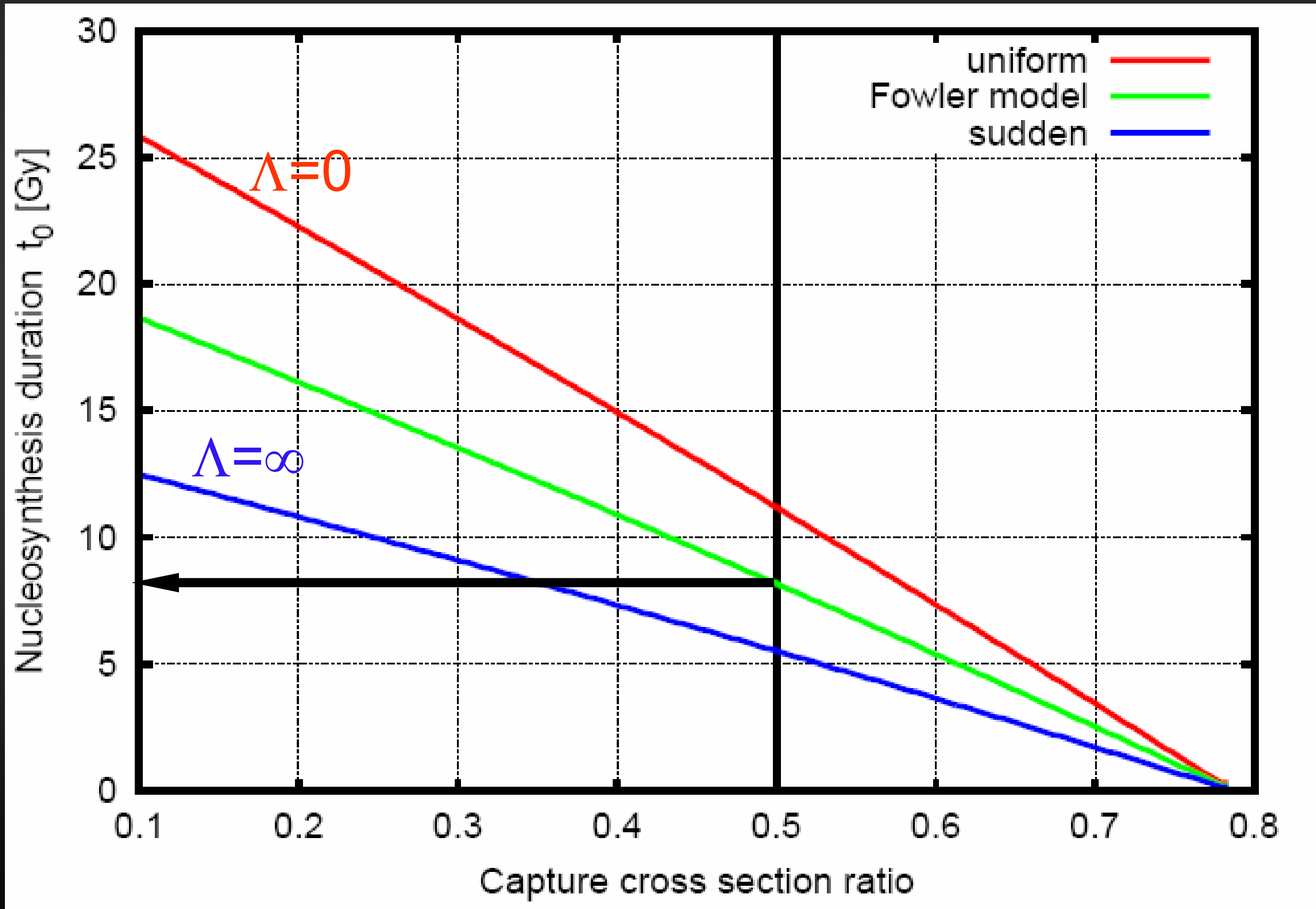
$$\frac{^{187}\mathrm{Os_c}}{^{187}\mathrm{Re}} = \frac{^{187}\mathrm{Os}/\mathrm{Os} - \frac{\sigma(186)}{\sigma(187)}\,^{186}\mathrm{Os}/\mathrm{Os}}{^{187}\mathrm{Re}/\mathrm{Re}}$$

- $e^{-\Lambda t}$ r-process enrichment of ^{187}Re

$$\frac{^{187}\mathrm{Os_c}}{^{187}\mathrm{Re}} = \frac{\Lambda - \lambda}{\Lambda}\,\frac{1 - e^{-\Lambda t}}{e^{-\lambda t} - e^{-\Lambda t}} - 1$$

$$\lambda = \ln(2)/\tau_\beta(^{187}\mathrm{Re})$$

The clock



assuming $R_\sigma = 0.5$
age:

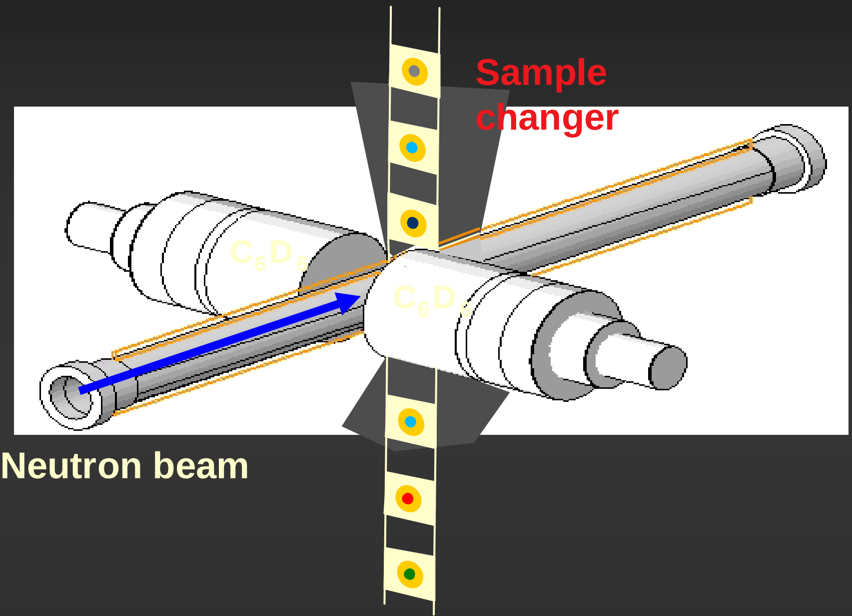
8.5+4.5= 13 Gyr

key quantity :

$$R_\sigma \equiv \frac{\sigma(186)}{\sigma(187)}$$

Os measurements setup

γ-ray detection: C_6D_6 scintillators



Pulse height weighting technique

Correction of the γ-response by weighting function to make the detector efficiency proportional to γ-ray energy

Neutron flux monitor

Silicon detectors viewing a thin ^{6}LiF foil

Samples & capture yields

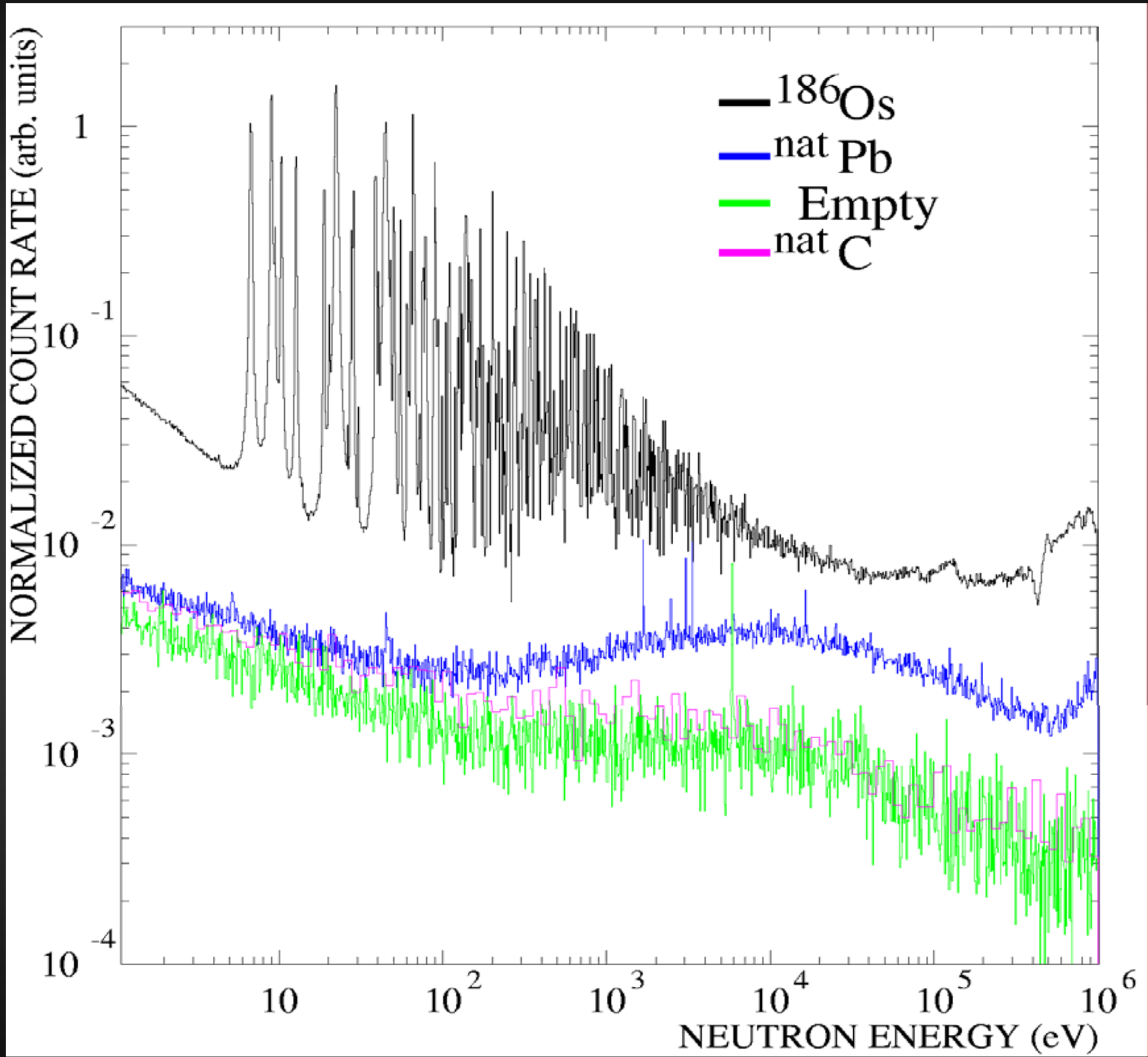
- ^{186}Os (2 g, 79 %)
- ^{187}Os (2 g, 70 %)
- ^{188}Os (2 g, 95 %)

- Al can
  environmental background

- ^{197}Au (1.2g)
  flux normalization
  (using Ratynski and Macklin
  high accuracy cross section data)

- ^{nat}Pb (2 g)
  in-beam gamma background

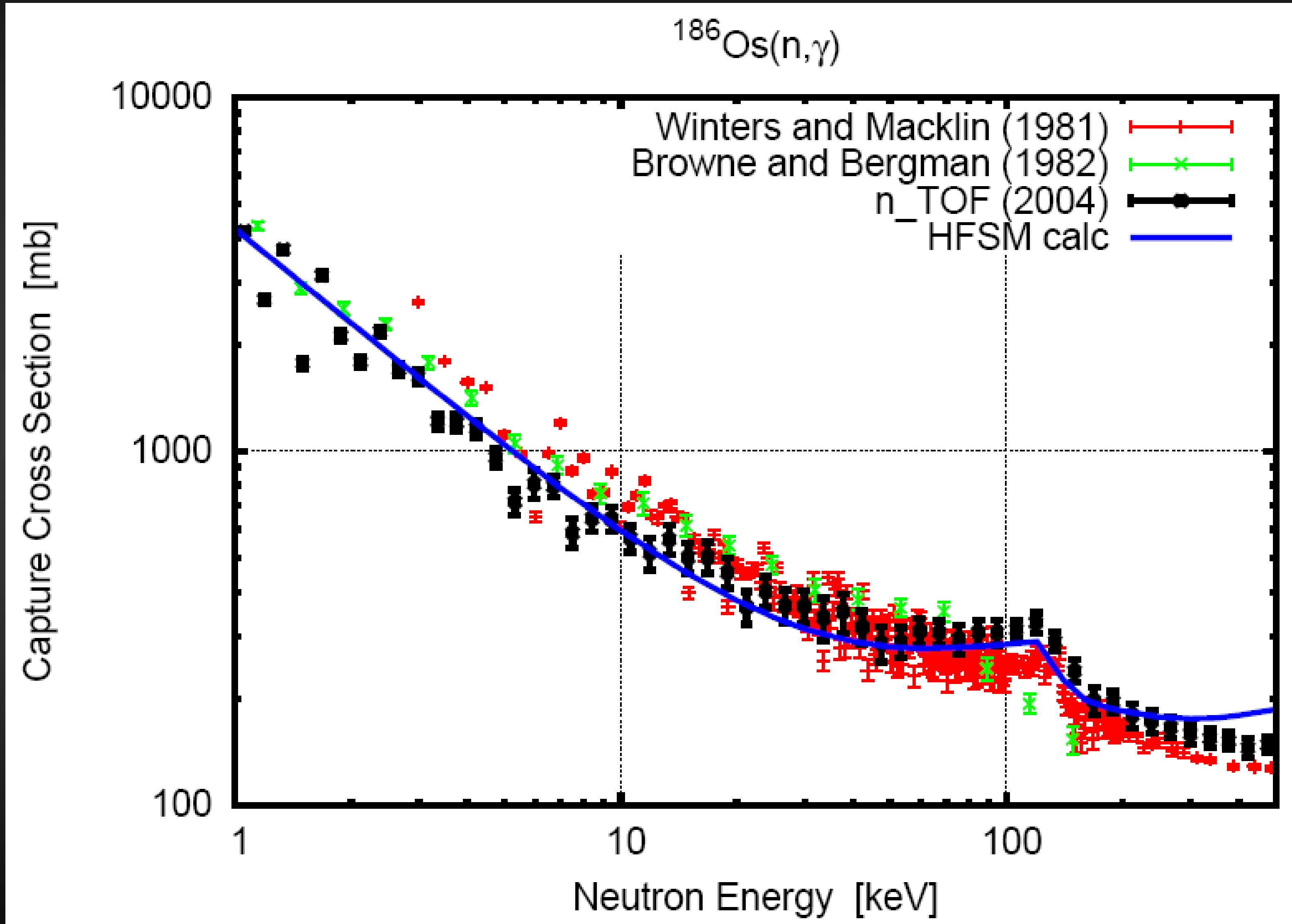
- ^{nat}C (0.5 g)
  neutron scattering background



M Mosconi, FZK

n_TOF-04: Os capture x-section

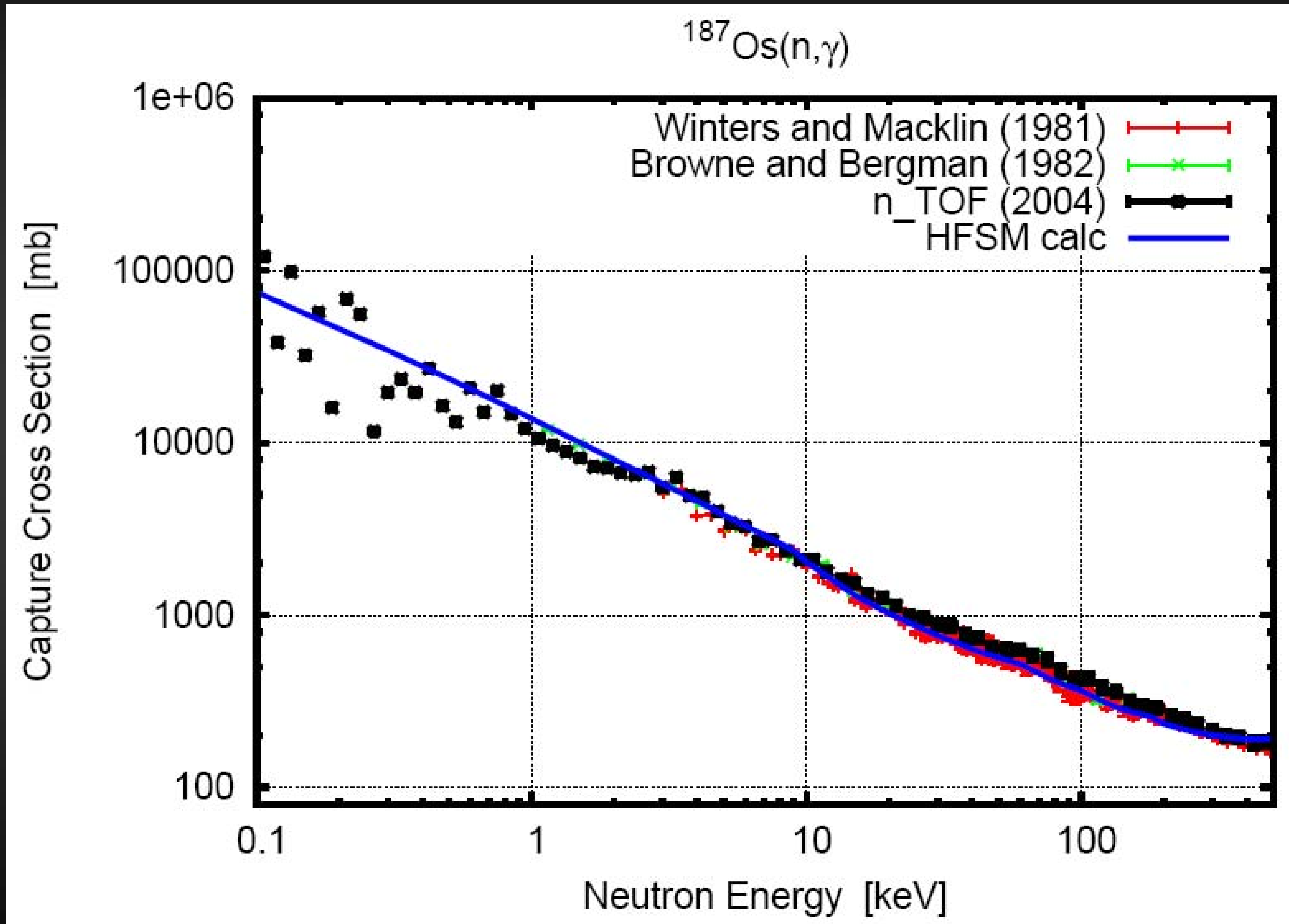
MACS-30	
BrB81	438 ± 30 mb
WiM82	418 ± 16 mb
n_TOF	409 ± 17 mb



NB: calculations constrained to reproduce experimental D_0, S_0, S_1, Γ_γ, $\sigma_{n,n'}$

n_TOF-04: Os capture x-section

MACS-30	
BrB81	919 ± 43 mb
WiM82	874 ± 28 mb
n_TOF	968 ± 18 mb



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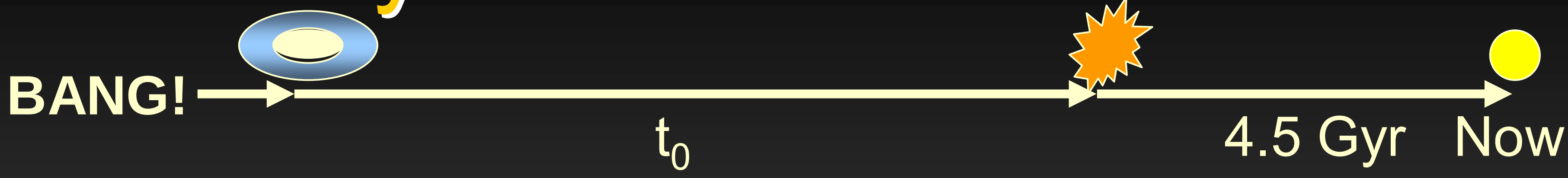
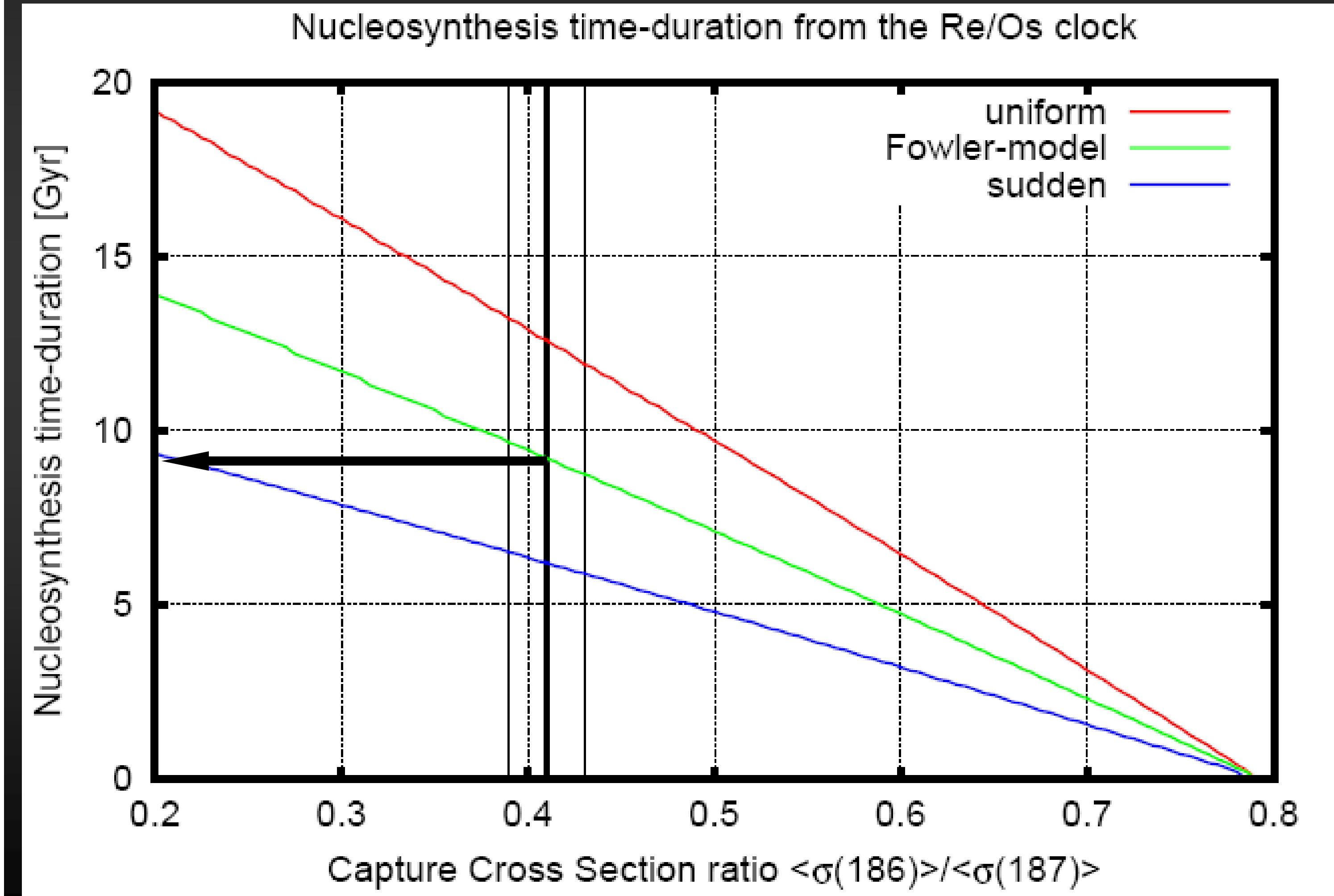
Laboratory cross sections & the clock



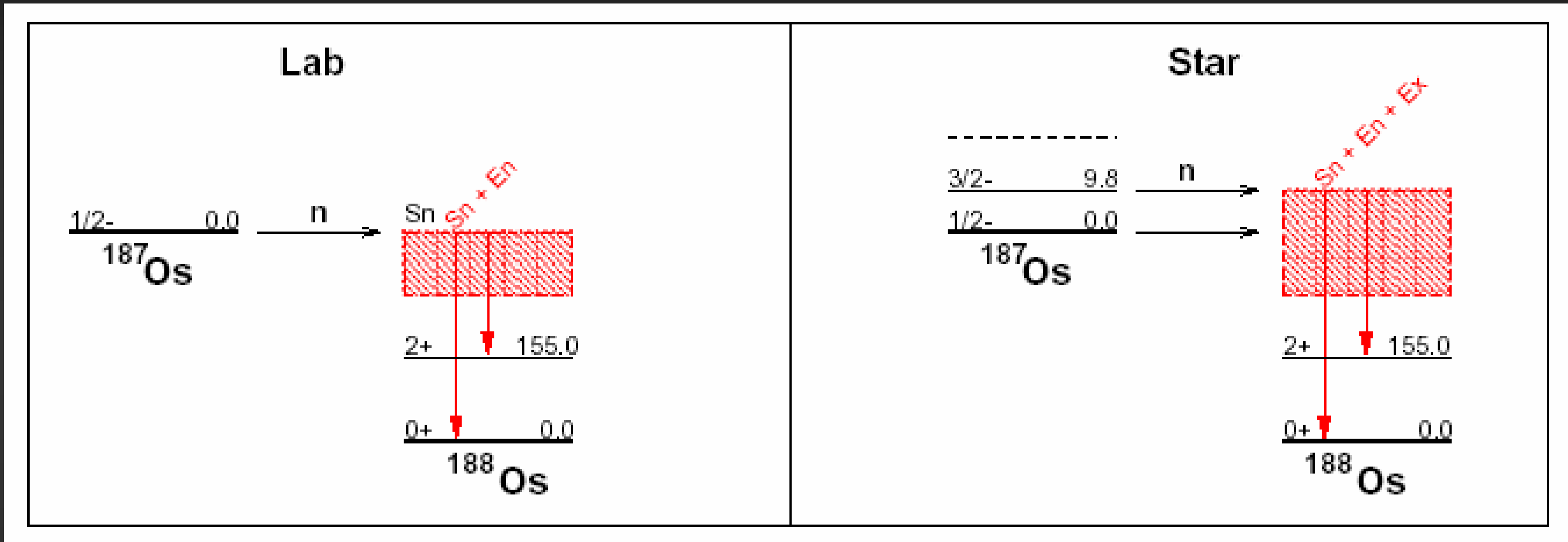


R_σ = 0.41±0.02

age:

9.2+4.6 =13.8 Gyr

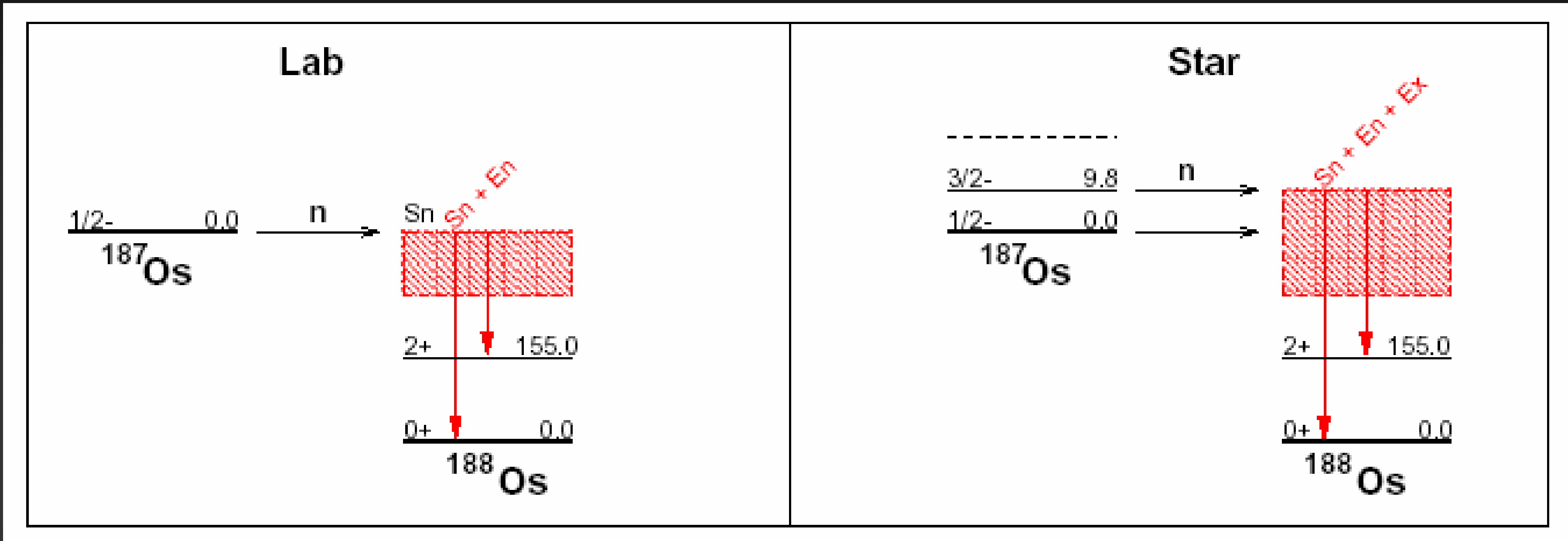
Stellar ^{187}Os(n,γ) rate



For example, in ^{187}Os at kT = 30 keV it is:

P(gs) = 33%
P(1st) = 47%
P(all others) = 20%

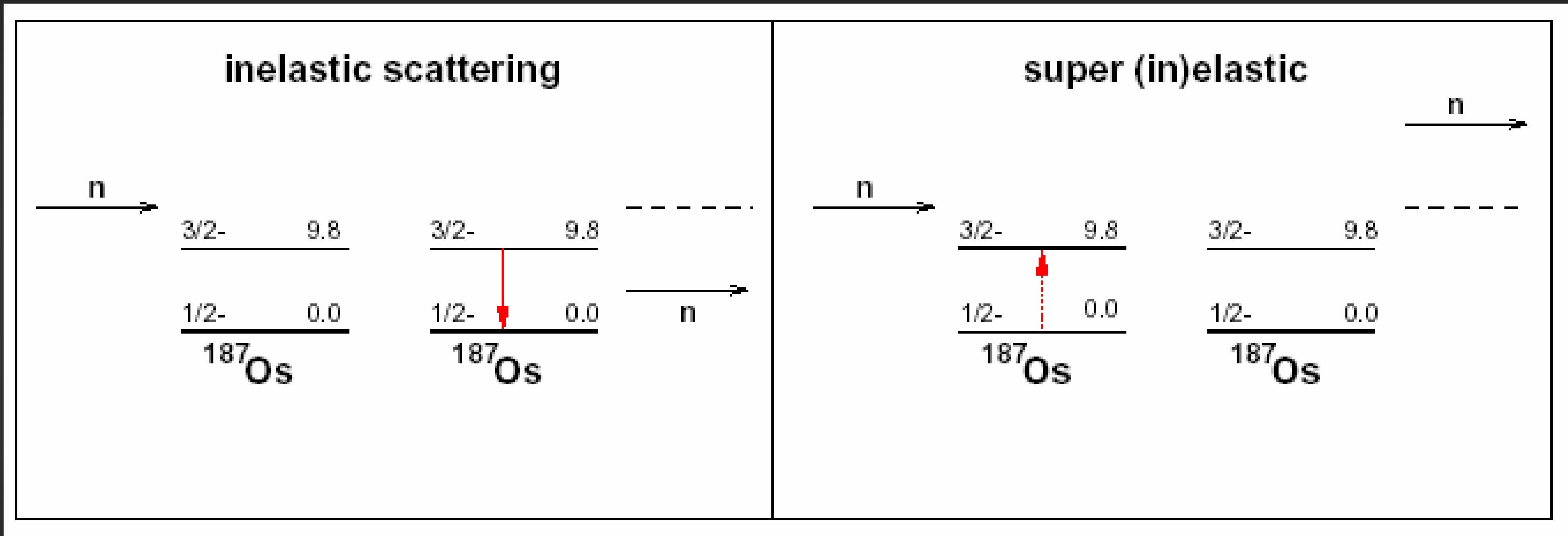
Stellar ^{187}Os(n,γ) rate



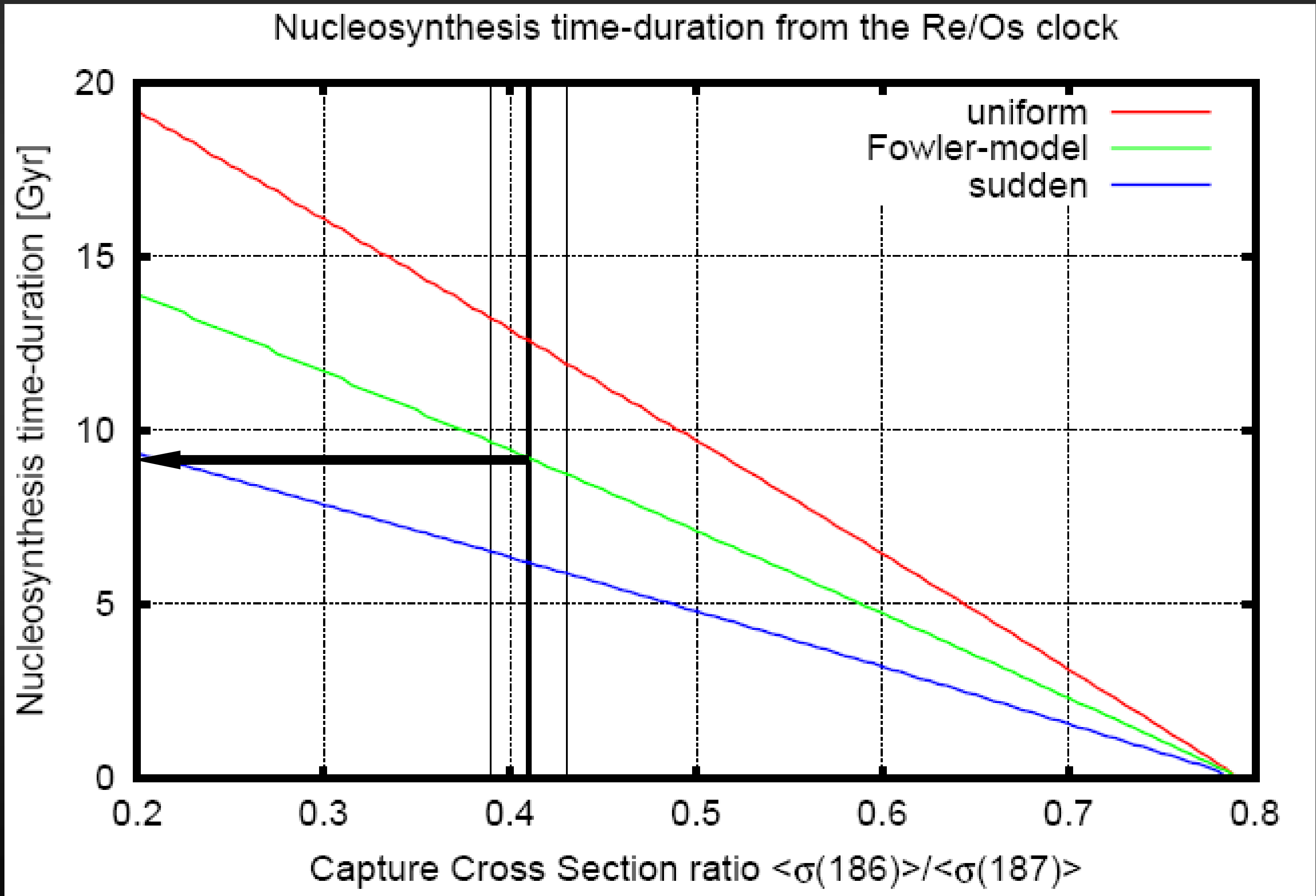
Calculation of the stellar correction factor $F_\sigma \equiv f_{186}/f_{187}$

Thermal energy KeV	$\langle\sigma(187)\rangle_{\rm Lab}$ mb	$\langle\sigma(187)\rangle_{\rm calc}$ mb	$\langle\sigma(187)\rangle_*$ mb	f_{187}	F_σ
10	1988 ± 100	2111	2324	1.10	0.91
20	1171 ± 39	1193	1402	1.18	0.85
30	874 ± 28	876	1059	1.21	0.86
40	715 ± 22	712	877	1.23	0.89
50	614 ± 12	610	766	1.26	0.93
100	—	395	571	1.45	1.03

More on stellar rates



Laboratory cross sections & the clock



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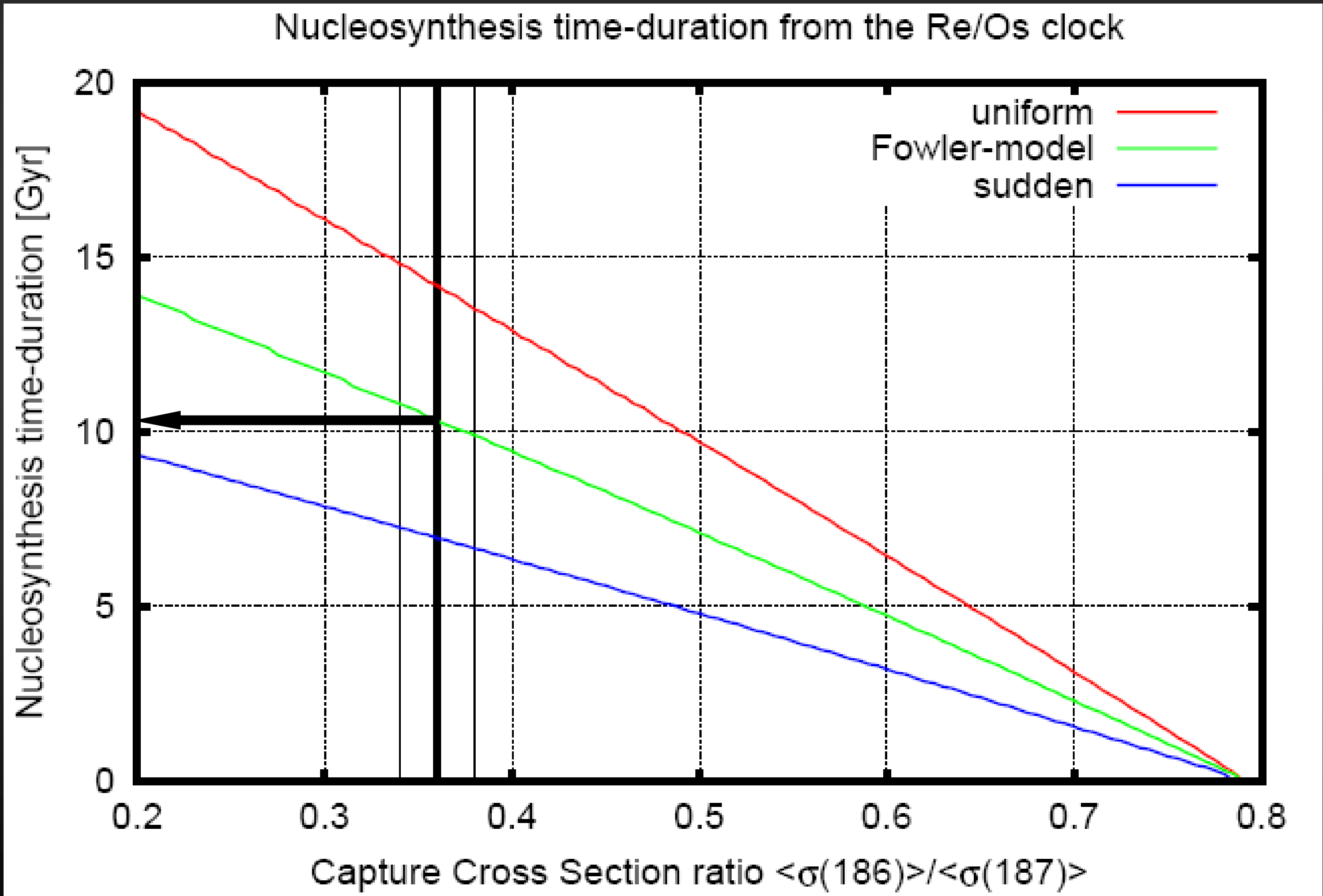
age:

9.2+4.6 =13.8 Gyr

Stellar cross sections & the clock



R^{*}_{σ} = 0.35

age:

10.3+4.6=14.9 Gyr

Summary

- Cosmological way

13.7 ± 0.2 Gyr

- Astronomical way

14 ± 2 Gyr

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

14.9 ± 2 Gyr(*)

$14.5 \pm^{2.8}_{2.2}$ Gyr

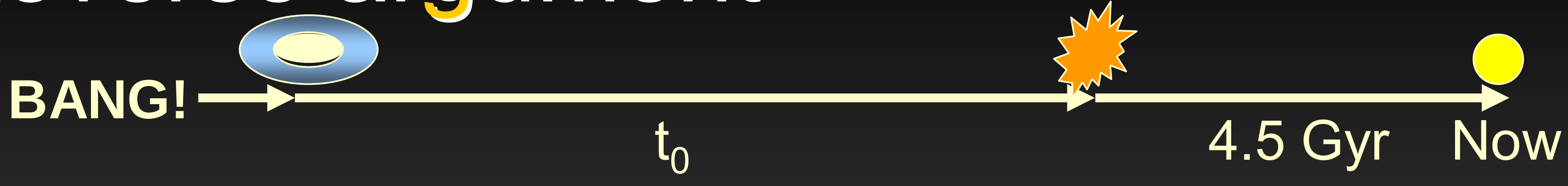
Source: Dauphas, Nature **435** (2005) 1203

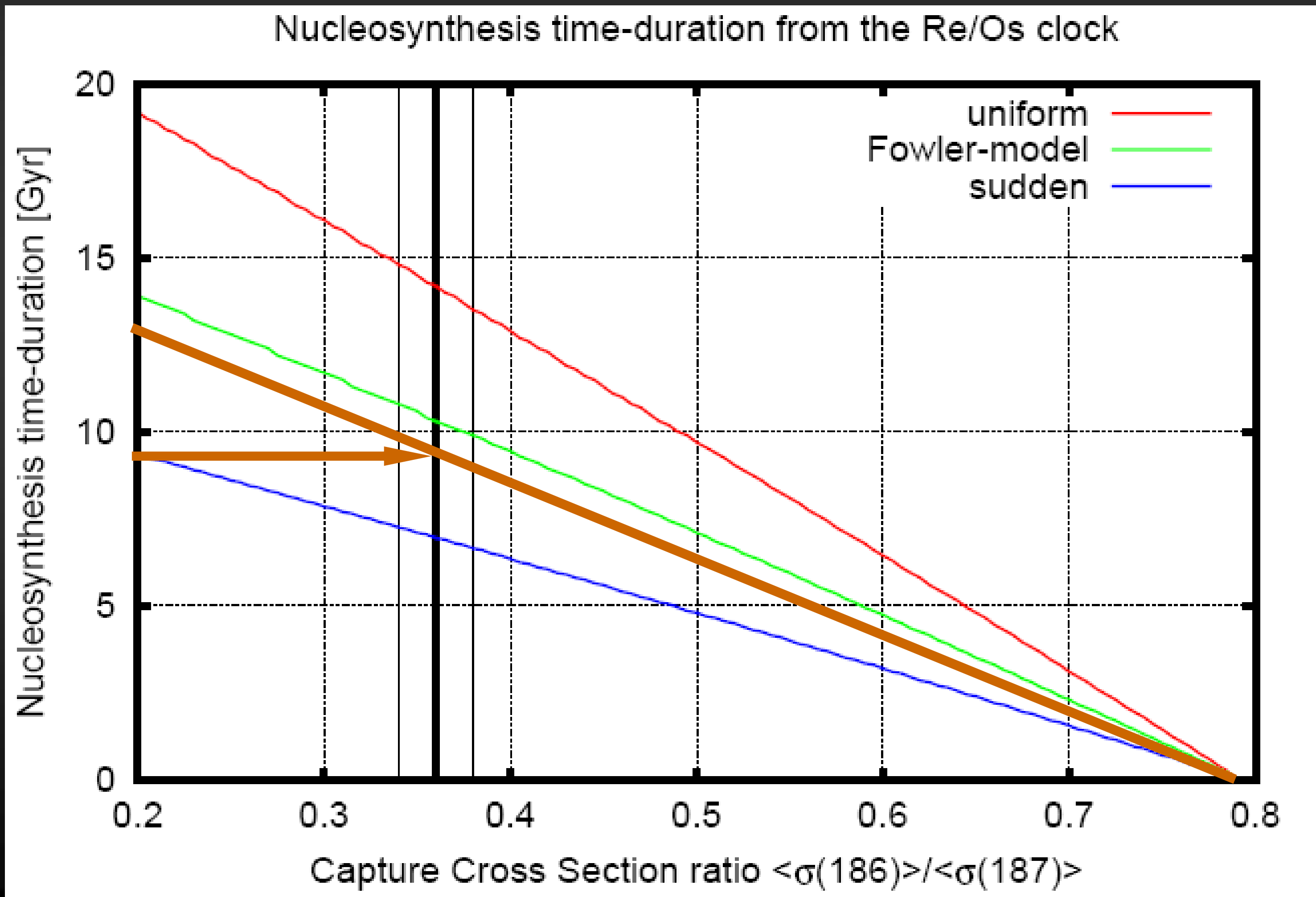
(*) 0.5 Gyr uncertainty due to exp. x-sections

Let's assume the age from WMAP is correct

13.7 ± 0.2 Gyr

Reverse argument



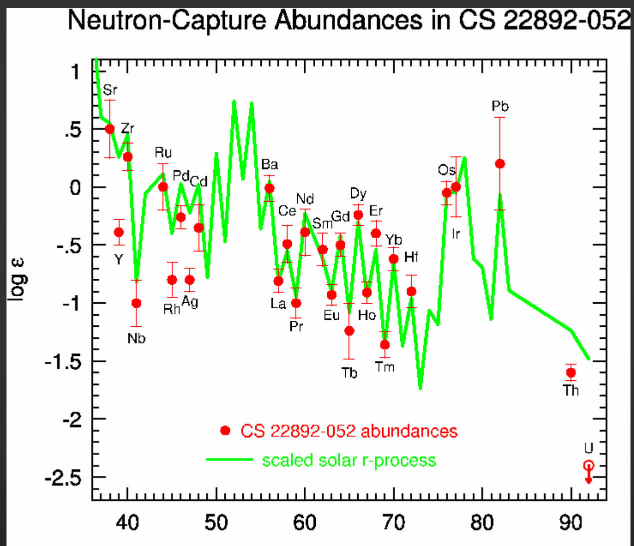


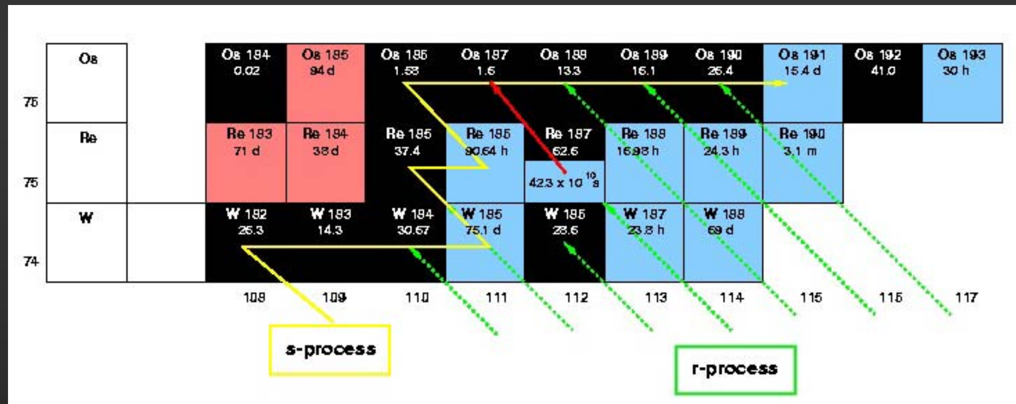
assuming

Age = 13.7 Gyr

or t_0 = 9.2 Gyr

Th/U and Re/Os clocks: complementary





GCE : independent
Primordial yields : model-dependent

GCE : dependent
Yield production : well determined

Cosmo-Chronology from others sources

http://www.geraldschroeder.com/age.html

Day 1	: 8 Gyr
Day 2	: 4 Gyr
Day 3	: 2 Gyr
Day 4	: 1 Gyr
Day 5	: 1/2 Gyr
Day 6	: 1/4 Gyr
Total	: 15 ¾ = 15.8 Gyr

back

Slides annex

Nuclear & Astro issues

In addition to the particular 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

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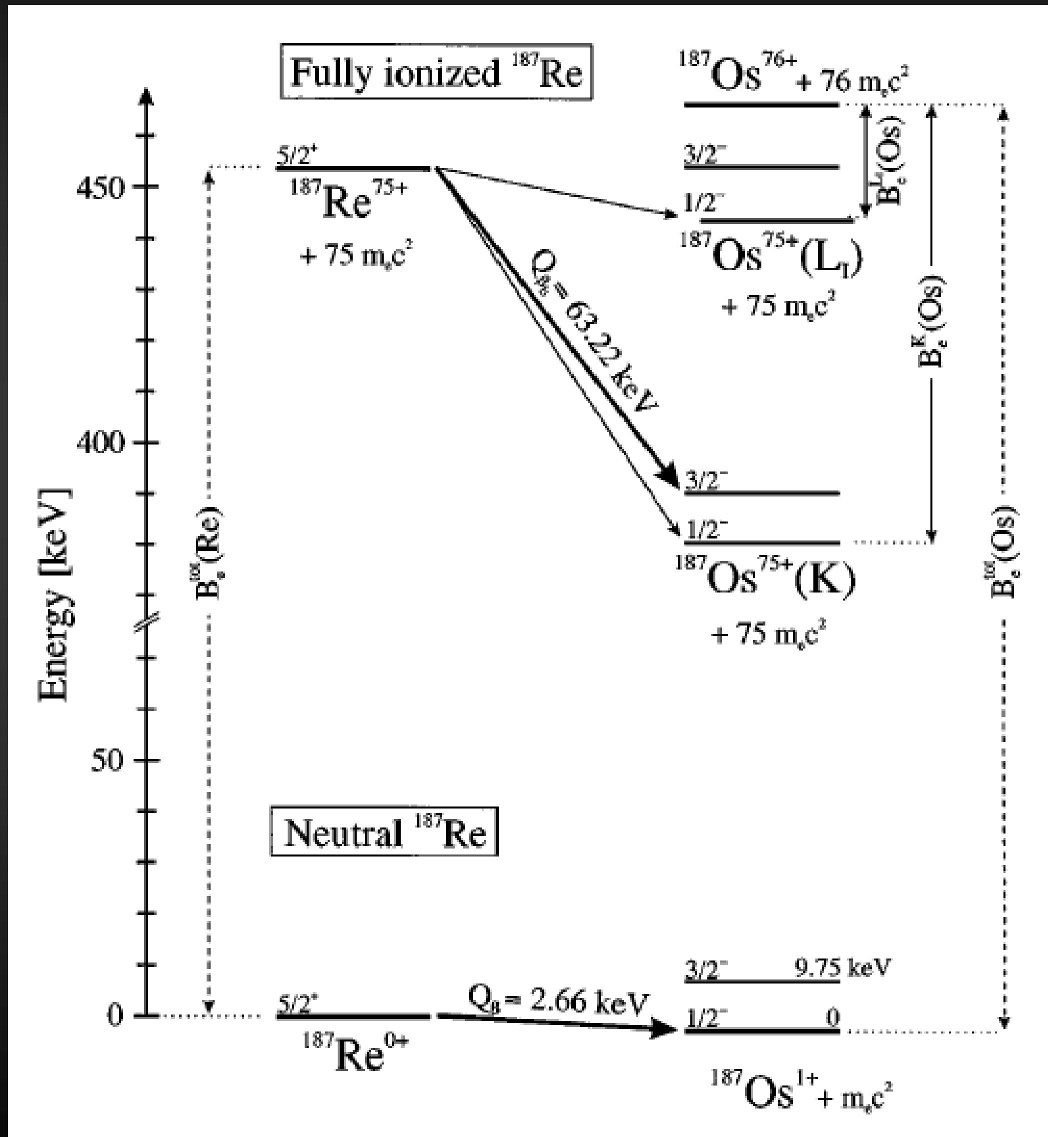
$^{187}Re(\beta^-)$ decay

The β-decay half-life of ^{187}Re is τ_β = 43.2 ± 1.3 Gyr. Under stellar conditions, the ^{187}Os and ^{187}Re atoms can be partly or fully ionized.
The β-decay rate can then proceed through a transition to bound-electronic states in ^{187}Os.
The rate for this process can be orders of magnitude faster than the neutral-atom decay.
The bound-state β-decay half-life of fully-ionized ^{187}Re has been measured @ GSI.



The half-life of fully-ionized ^{187}Re turns out to be: τ_β = 32.9 ± 2.0 yr.

(F. Bosch, *et al.*, PRL **77** (1996) 5190)

Impact on the age: ≈ 1 Gyr(?)

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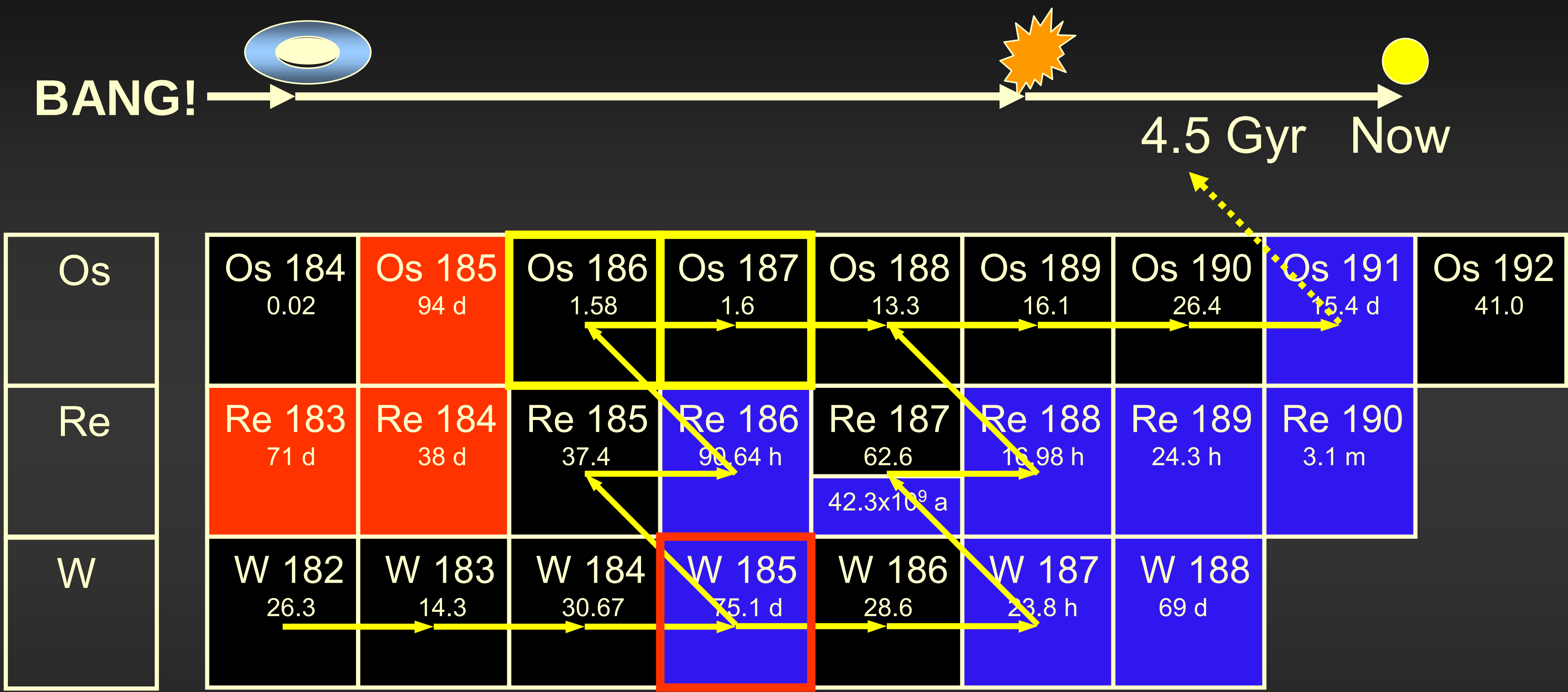
Brancing(s)



The $^{185}W(n,\gamma)^{186}W$ rate is needed

The inverse $^{186}W(\gamma,n)^{185}W$ cross section has been measured

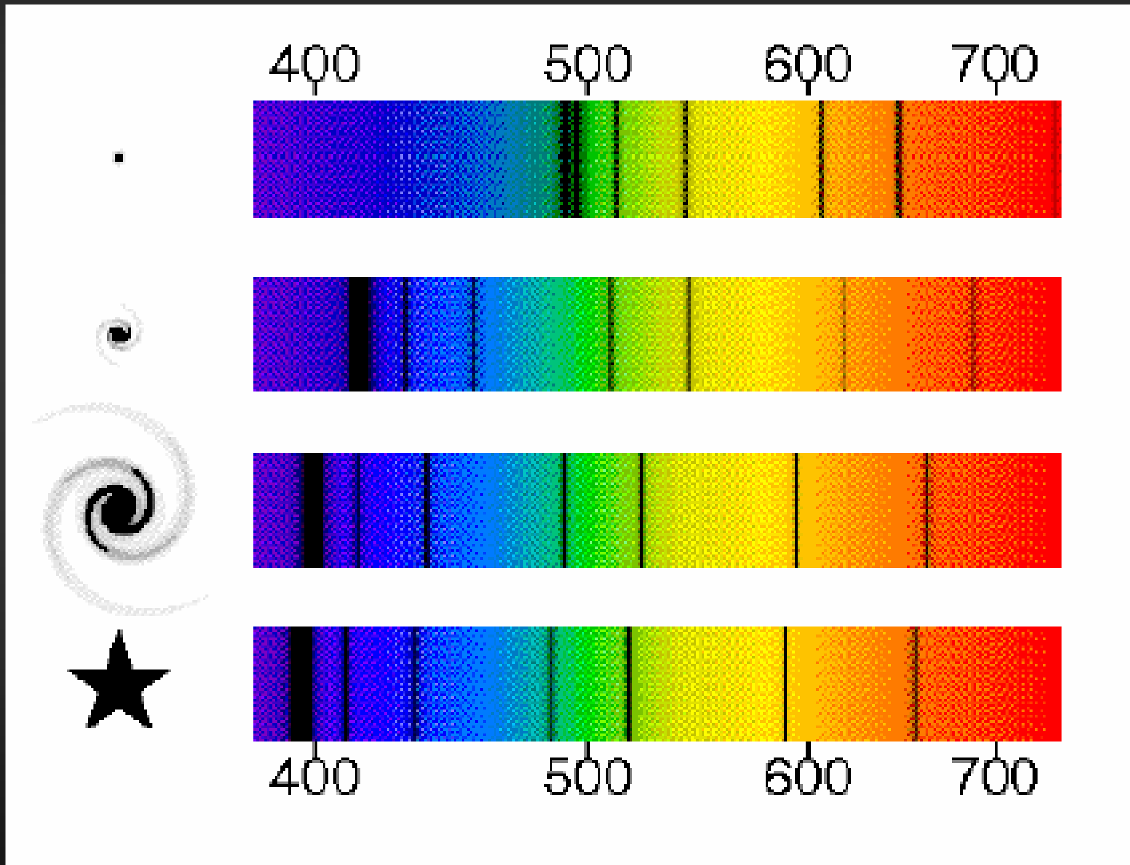
K. Sonnabend *et al*. ApJ **583** (2003), 506-513.

Impact on the age: negligible

Red shift

<back

The red-shift z is defined as: $$1 + z = \frac{\lambda_{obs}}{\lambda_{emitted}}$$



- z = 0.01 (v = 3,000 Km/s)
- z = 0.05 (v = 15,000 Km/s)
- z = 0.25 (v = 75,000 Km/s)

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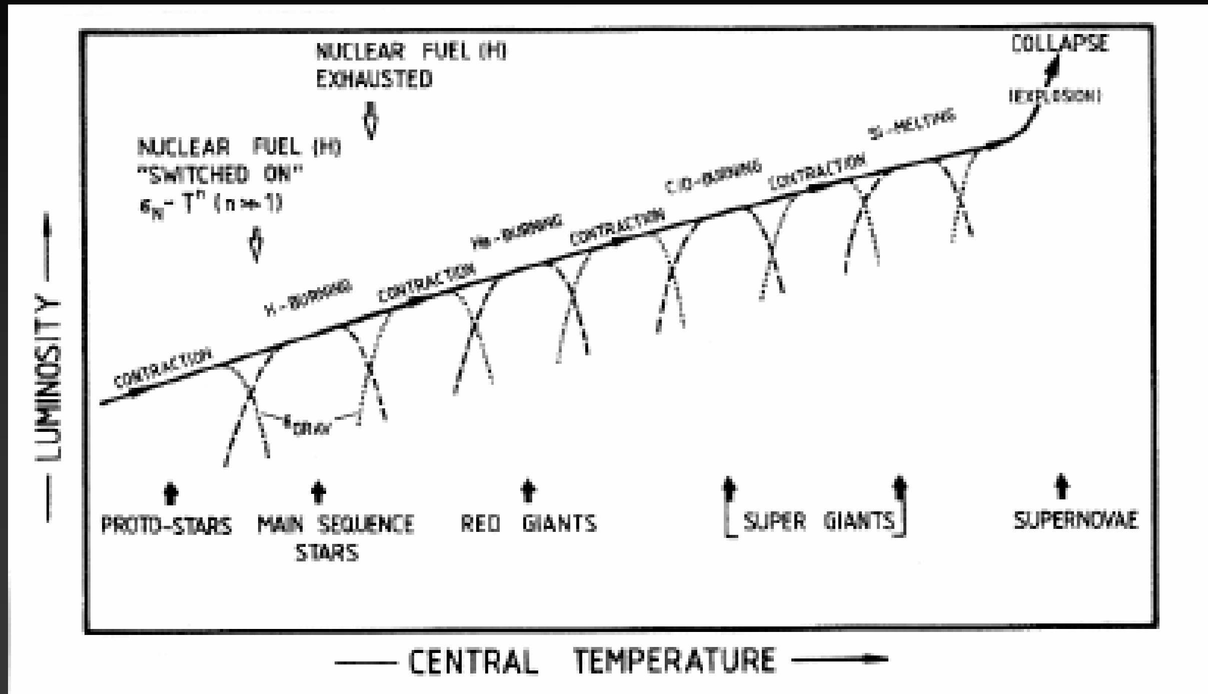
Life of a star



Stage	Time scale	Temperature $T_9 = 10^9$ K	Density g cm^{-3}
Hydrogen burning	7×10^6 yr	0.06	5
Helium burning	5×10^5 yr	0.23	7×10^2
Carbon burning	600 yr	0.93	2×10^5
Neon burning	1 yr	1.7	4×10^6
Silicon burning	1 d	4.1	1×10^7
Core collapse	seconds	8.1	3×10^9
Core bounce	milliseconds	34.8	3×10^{14}
Explosive burning	$0.1 - 10$ s	$1.2 - 7.0$	varies

Evolutionary stages of a 25 $M_\odot$ star

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Main sequence Stars

Spectral Class	Color	Mass $[M_\odot]$	Luminosity $[L_\odot]$	Surface Temperature K	Lifetime Myr	# of stars in Milky way	Radius $[R_\odot]$	Central Temperature T_6	Central Density g/cm^3
O	blue	32	600,000	40,000	1	20,000	18	37.3	3.3
B0		16	16,000	28,000	10		7.4	34.3	6.3
B5	blue	6	600	15,500	100	100,000,000	3.8	26.8	20.0
A0		3	60	9,900	500		2.5		
A5	white	2	20	8,500	1,000	1,200,000,000	1.7	20.9	67
F0		1.75	6	7,400	2,000		1.4	18.5	87
F5	white	1.25	3	6,500	4,000	3,700,000,000	1.2		
G0		1.06	1.3	6,000	10,000		1.1	13.5	90
G5	yellow	0.92	0.8	5,500	15,000	11,000,000,000	0.9		
K0		0.80	0.4	4,900	20,000		0.8	11.4	84
K5	orange	0.69	0.1	4,100	30,000	17,000,000,000	0.7		
M0		0.48	0.02	3,500	75,000		0.6		
M5	red	0.20	0.001	2,800	200,000	89,000,000,000	0.3		

The canonical s-process

The time dependence of the abundances, N_A, is given by:

$$\frac{dN_A}{dt} = N_n(t)N_{A-1}(t)\langle\sigma_{n,\gamma}\mathrm{v}\rangle_{A-1} - N_n(t)N_A(t)\langle\sigma_{n,\gamma}\mathrm{v}\rangle_A - \lambda_\beta N_A(t)$$

We can define a time-integrated neutron flux (neutron exposure)

$$\tau = \int_0^t \phi_n(t')dt' = v_T \int_0^t N_n(t)dt$$

Then, assuming: *i*) $T \approx const.$ and *ii*) $\lambda_\beta \gg \lambda_{n,\gamma}$ or $\lambda_\beta \ll \lambda_{n,\gamma}$ it is

$$\frac{dN_A}{d\tau} = \langle\sigma_{n,\gamma}\rangle_{A-1} N_{A-1} - \langle\sigma_{n,\gamma}\rangle_A N_A$$

It follows that along the s-process path:

$$\boxed{\langle\sigma_{n,\gamma}\rangle_{A-1} N_{A-1} = \langle\sigma_{n,\gamma}\rangle_A N_A = const.}$$

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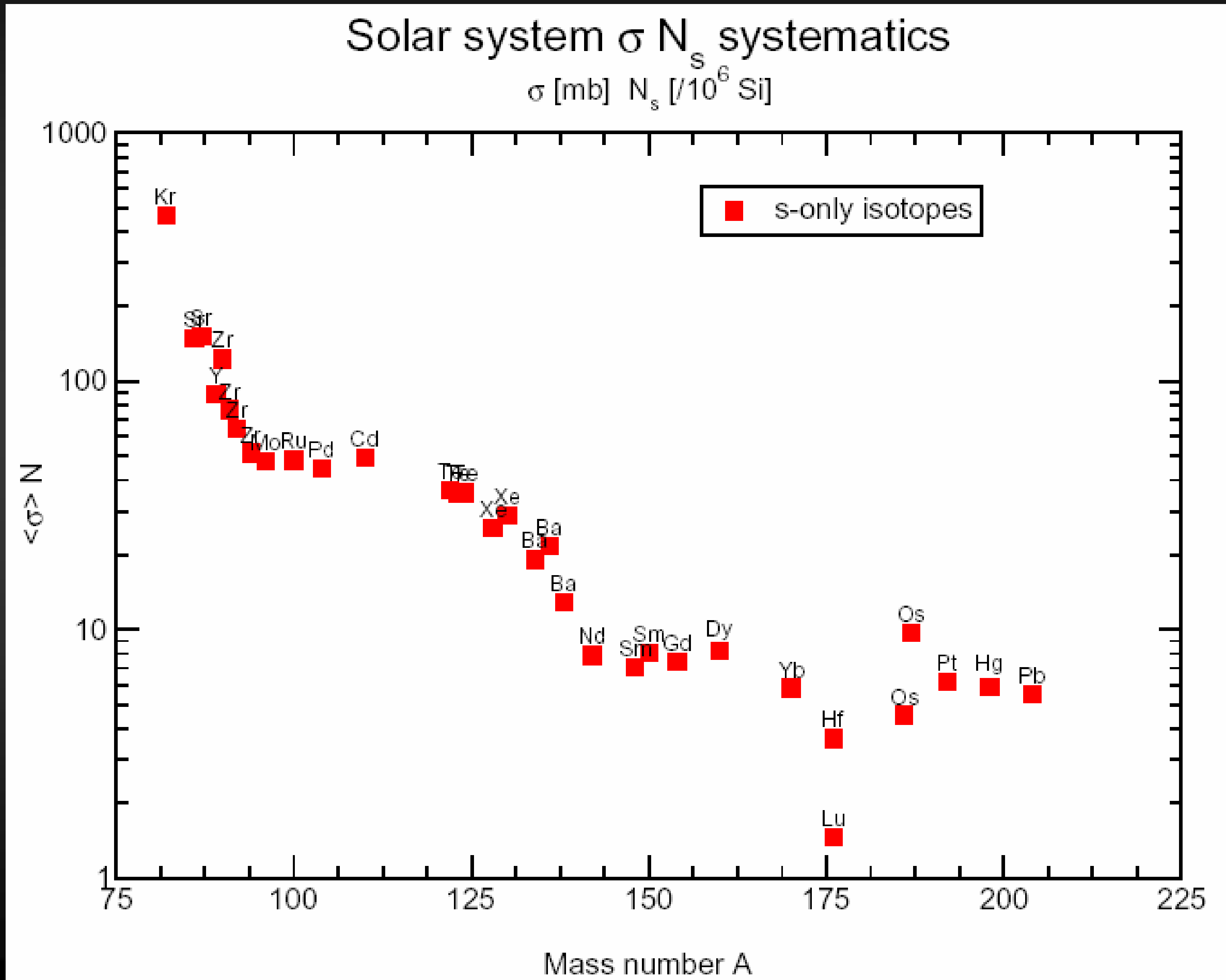
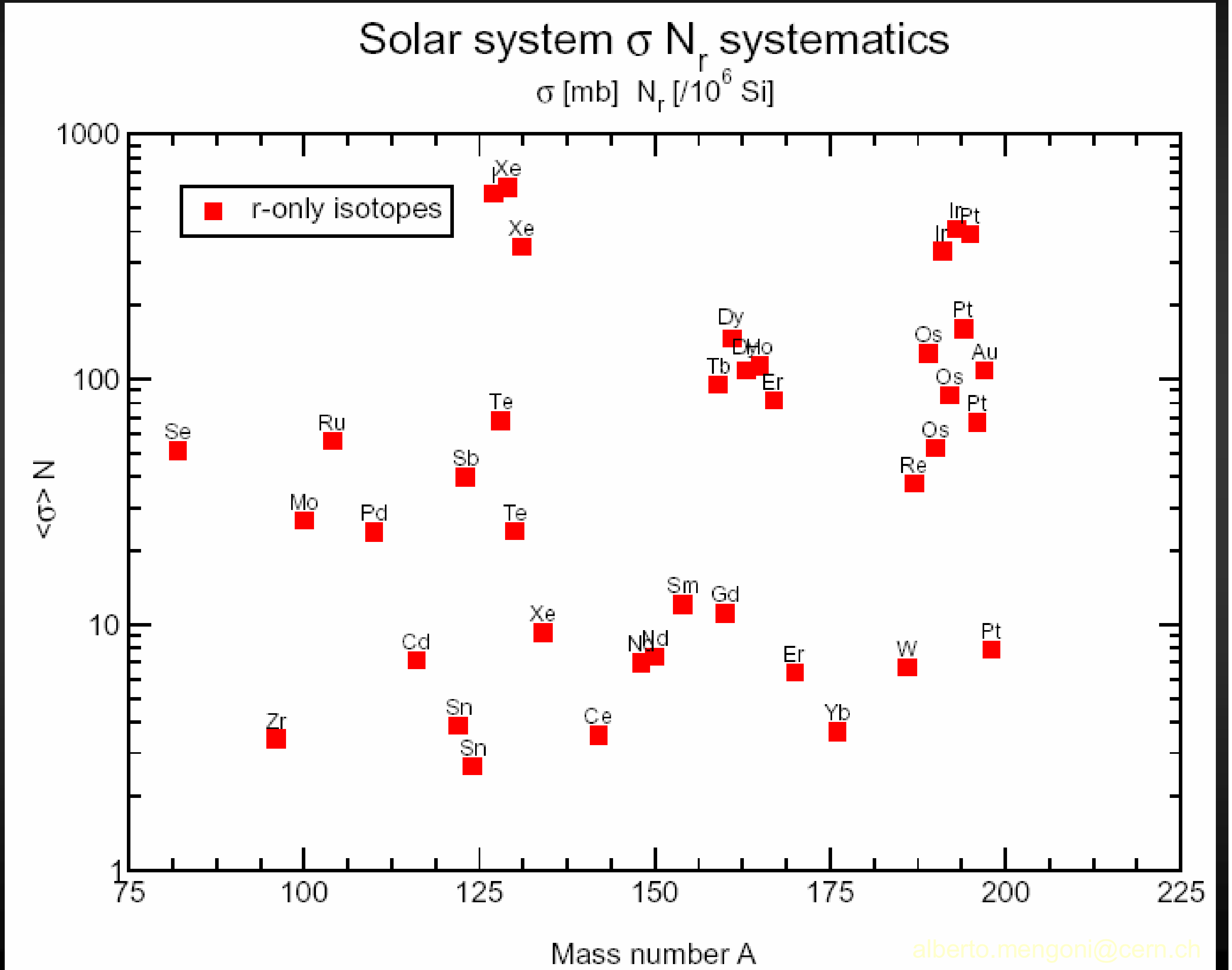
The canonical s-process



The canonical s-process

No $<\sigma>N$ correlation observed for nuclei **not** in the s-process path



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- 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 own uncertainties

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Issue 1: $^{187}Re(\beta^-)$ decay

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Under stellar conditions, the ^{187}Os and ^{187}Re atoms can be partly or fully ionized.
The β-decay rate can then proceed through a transition to bound-electronic states in ^{187}Os.
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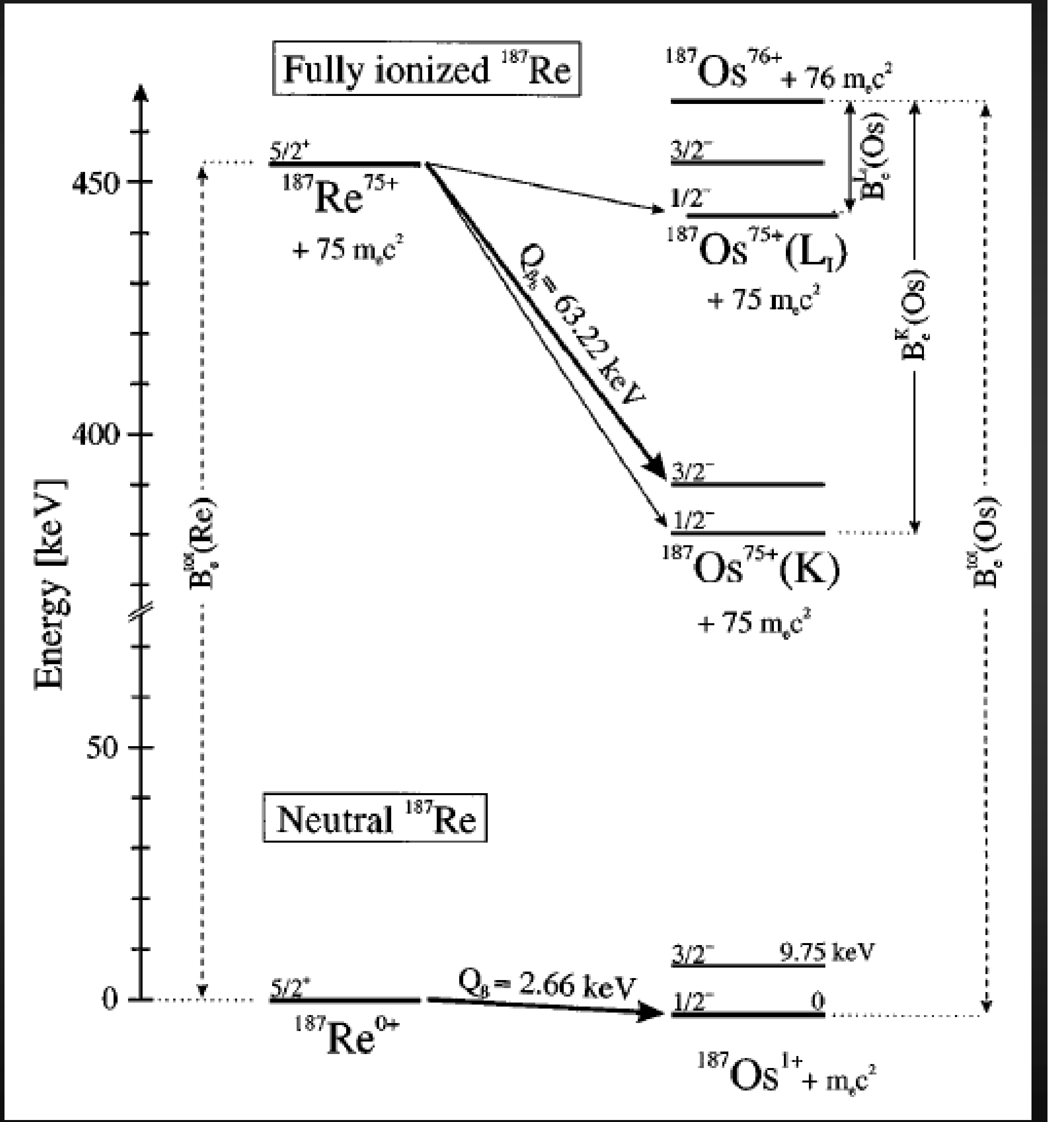

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(F. Bosch, *et al.*, PRL **77** (1996) 5190)

Impact on the age: ≈ 1 Gyr

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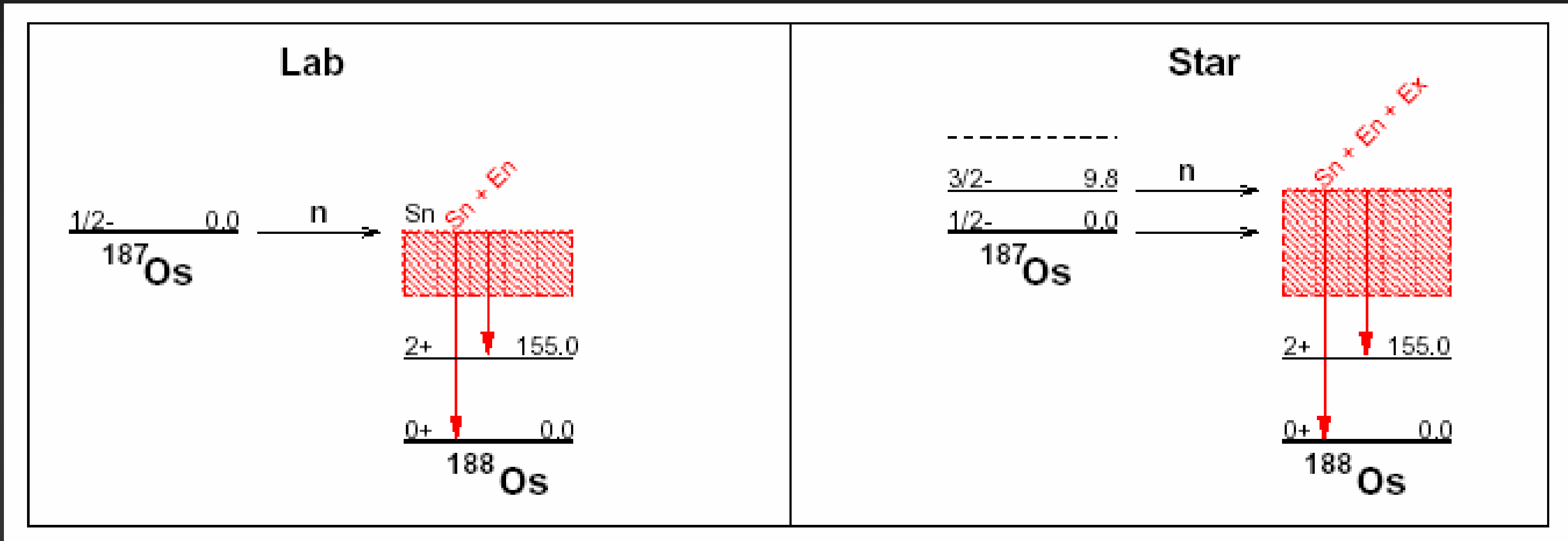
Stellar ^{187}Os(n,γ) rate

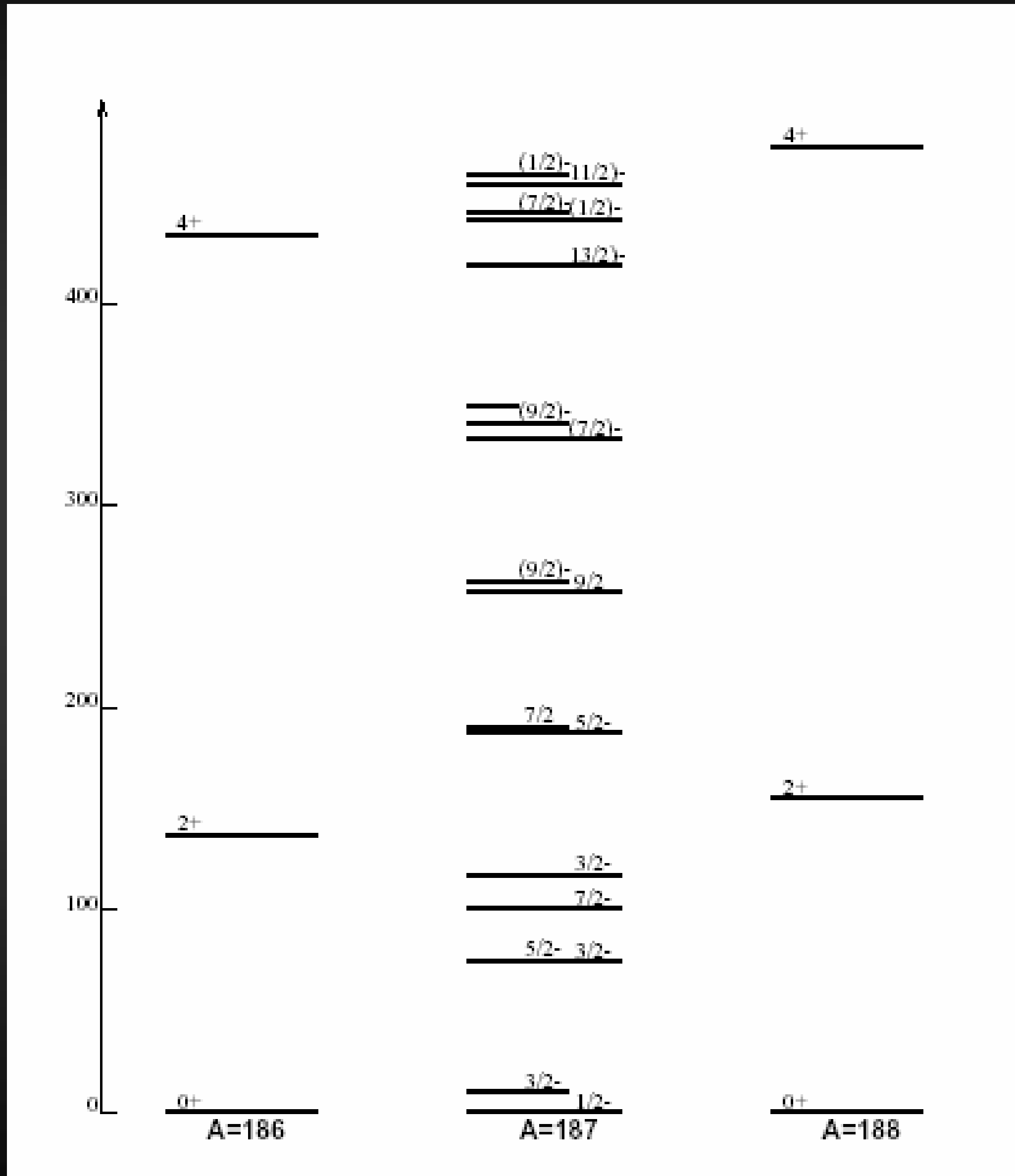


For example, in ^{187}Os at kT = 30 keV it is:

P(gs) = 33%
P(1st) = 47%
P(all others) = 20%

Thermal population

$$P(E_k) = \frac{(2J_k + 1)e^{-E_k/kT}}{\sum_m (2J_m + 1)e^{-E_m/kT}}$$



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The ^{186}Os(n,γ) cross section: theory

Hauser-Feschbach theory:
(statistical model)

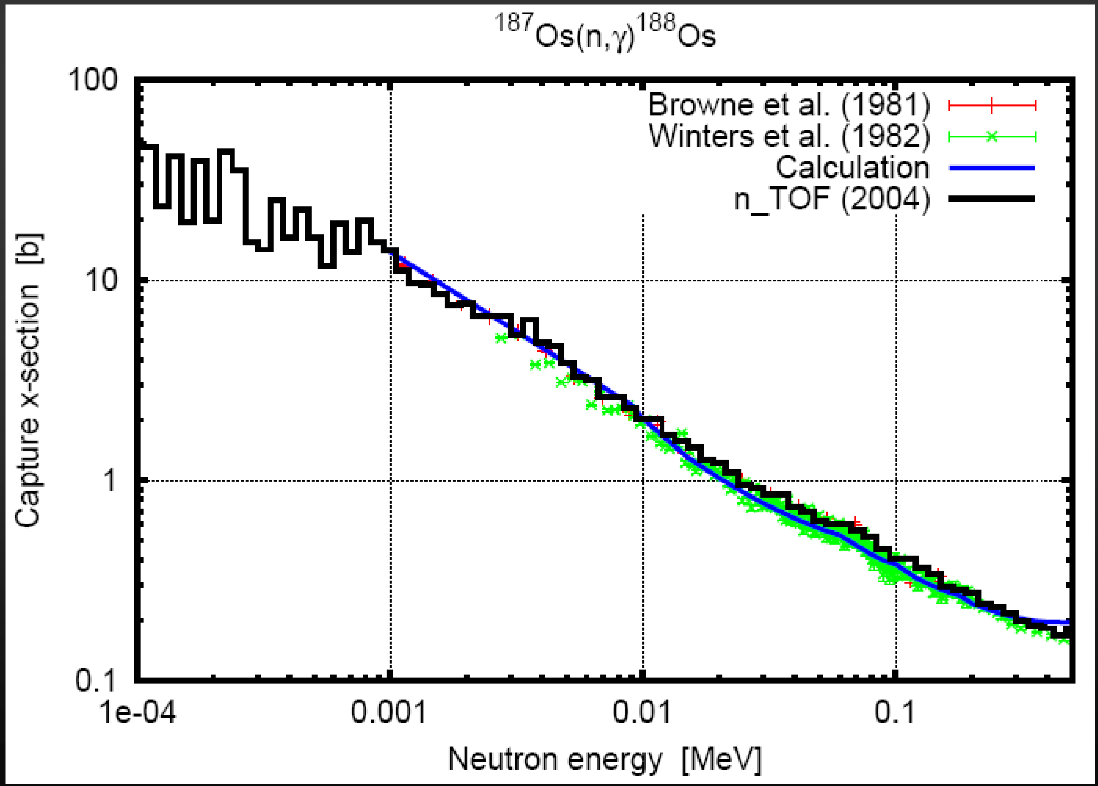
$$\sigma_{n,\gamma}(E_n) = \frac{\pi}{k_n^2} \sum_{J\pi} g_J \frac{\sum_{ls} T_{n,ls} T_{\gamma,J}}{\sum_{ls} T_{n,ls} + \sum_{ls} T_{n',ls} + T_{\gamma,J}} W_{\gamma,J}$$

• Neutron transmission coefficients, T_n :
from OMP calculations

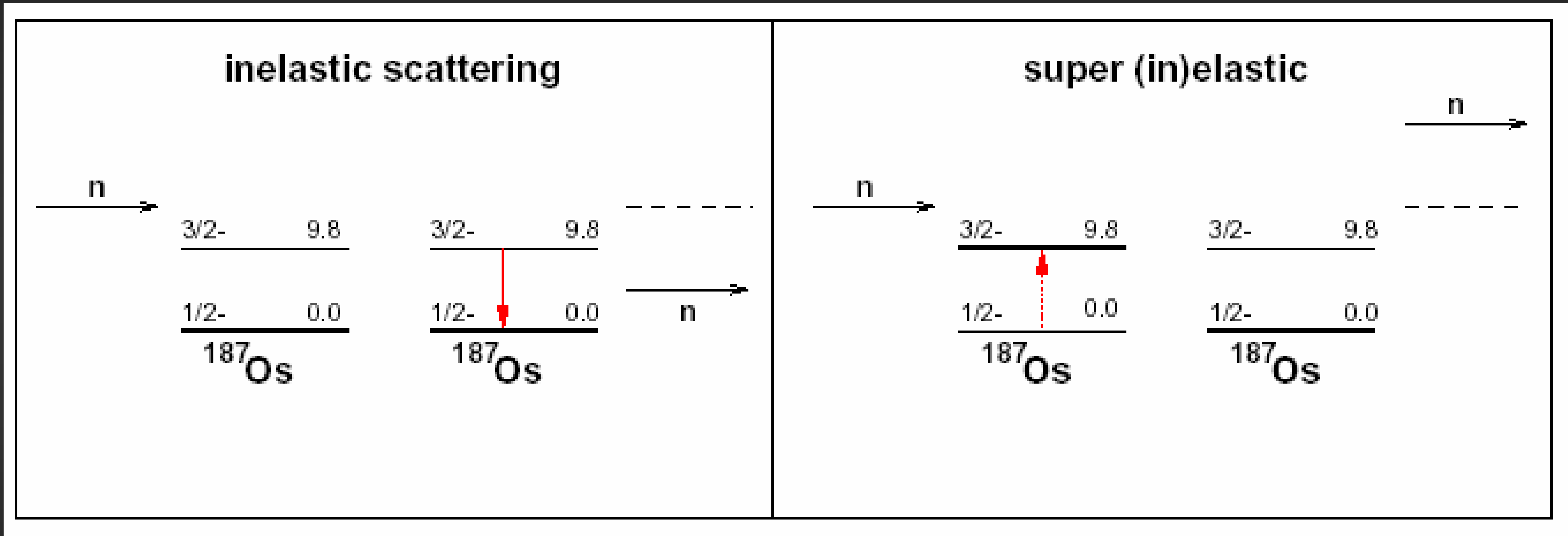
• γ-ray transmission coefficients, T_γ :
from GDR (experimental parameters)

• Nuclear level densities:
fixed at the neutron binding from $<D>_{exp}$

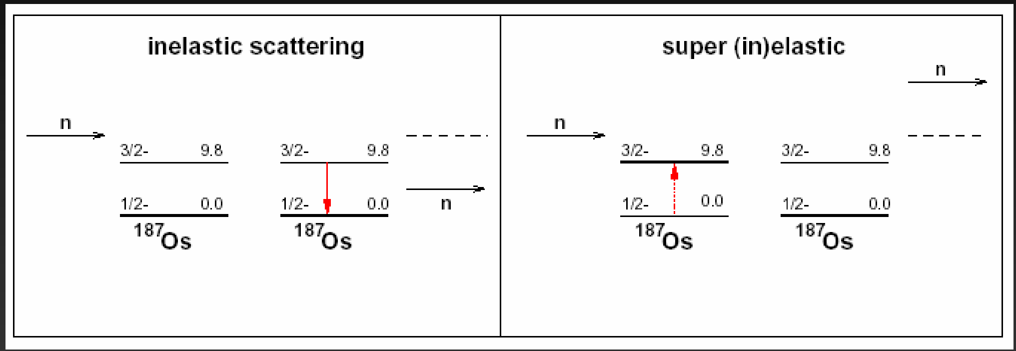
All these parameters can be derived and fixed from the analysis of the experimental data at low-energy in the resolved resonance region



More on stellar rates



(n,n’)



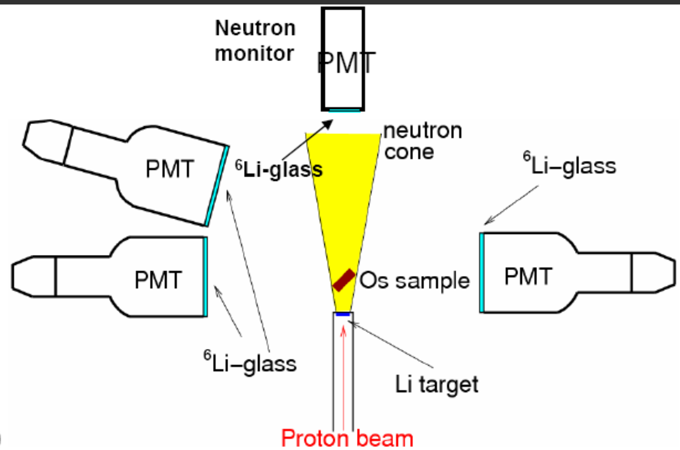
A neutron (inelastic) scattering experiment performed at FZK-Karlsruhe

Drawbacks of **^{7}Li(p,n)^{7}Be at threshold**:

1. small yield
2. neutron energy distribution unstable due to the standard tiny fluctuations on the accelerator settings

Solutions:

1. improved neutron detection efficiency by use of KG2 (NE912)
1. improved background subtraction by pulse shape analysis
2. new beam line with an improved setting of the analyzer magnet and computer monitoring of the neutron energy distribution



Samples measured

- ^{187}Os
- ^{188}Os → pure elastic component
- Empty canning → background

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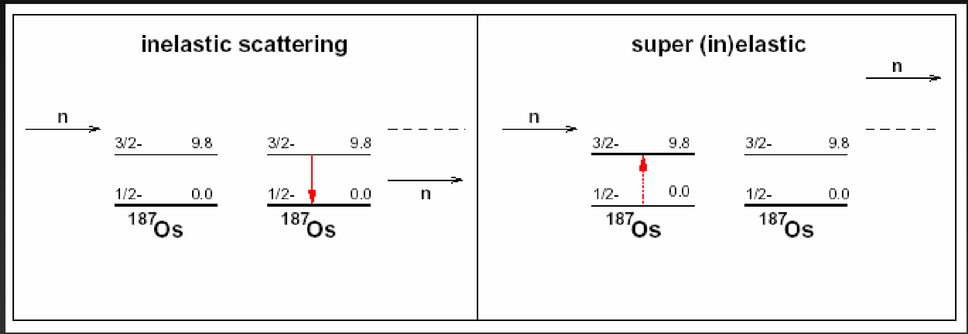
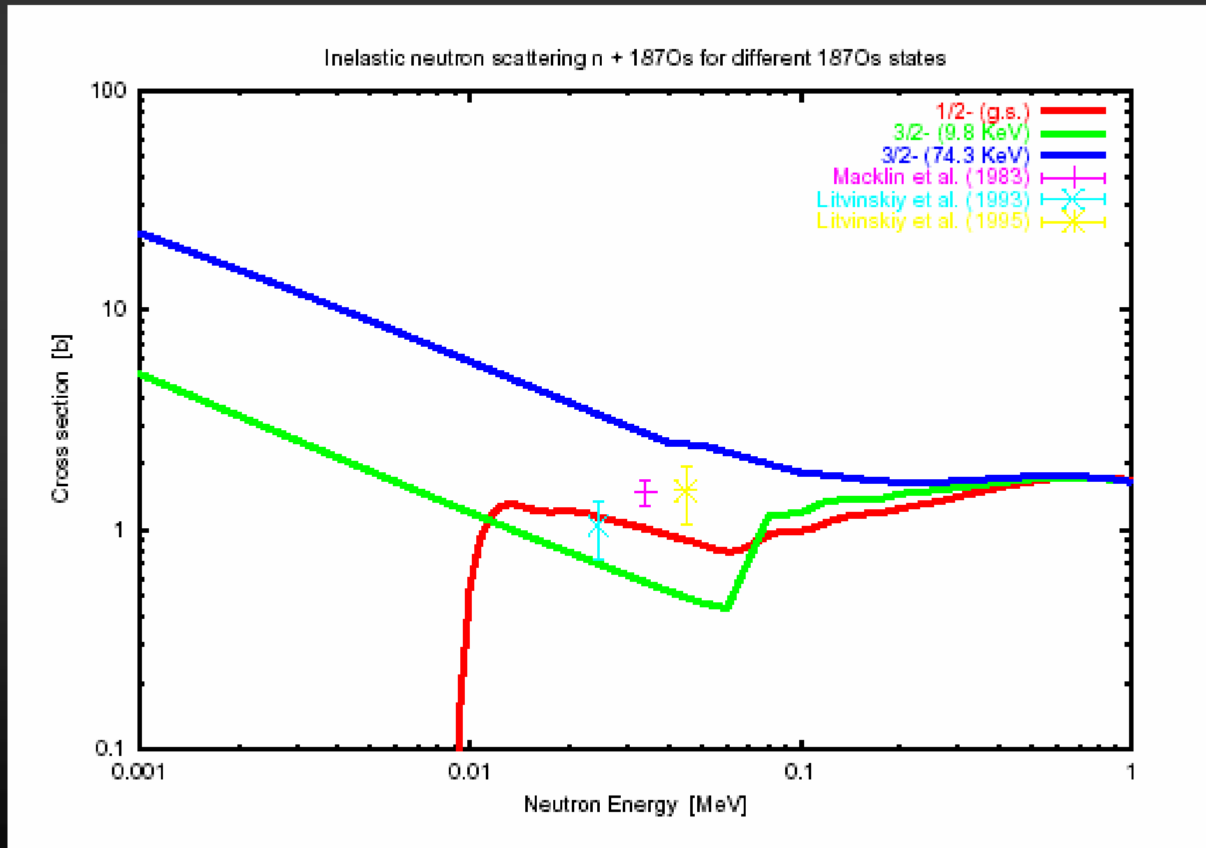
(n,n') + theory needed





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