nuclear clocks for the age of the Universe

Cosmic ages

- Cosmological way
  based on the Hubble time ("expansion age")
- Astronomical way
  based on observations of globular clusters
- Nuclear way
  based on long-lived radioactive nuclei

the nuclear way

traditional nuclear clocks

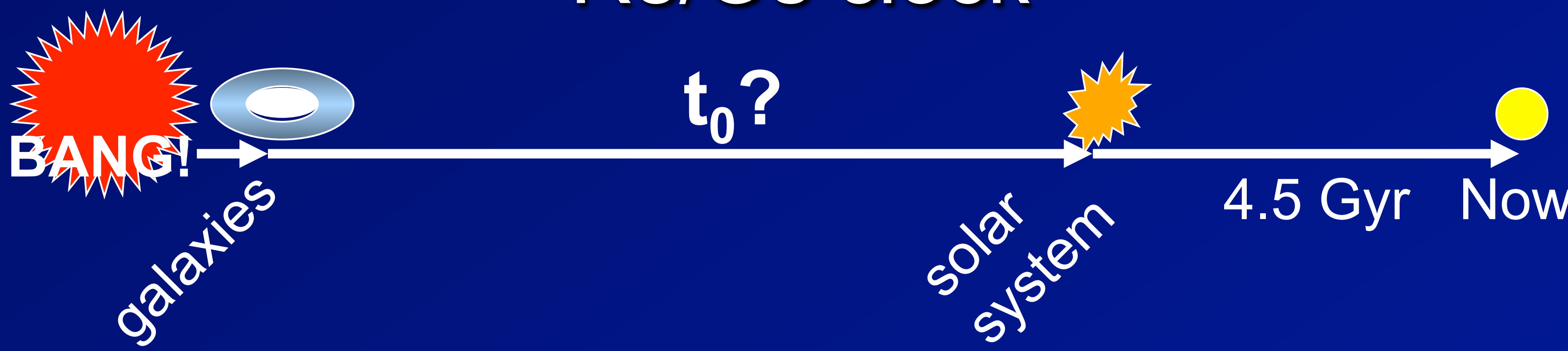
$$N = N_i \exp(-\lambda t)$$

- ^{235}U / ^{238}U
- ^{232}Th / ^{238}U
- ^{187}Re - ^{187}Os
- Th / U abundances in low-Z stars

potential chronometers

time scale	related phenomena	clock
min	fast convection	^{128}I
branching		
yr	neutron capture times mixing to stellar surface	s-branchings ^{99}Tc
Myr	condensation of solar system nearby supernova	$^{182}Hf/^{182}W$ ^{60}Fe
~~Gyr~~	~~the age of the r process~~	~~U/Th & Re/Os~~

Re/Os clock

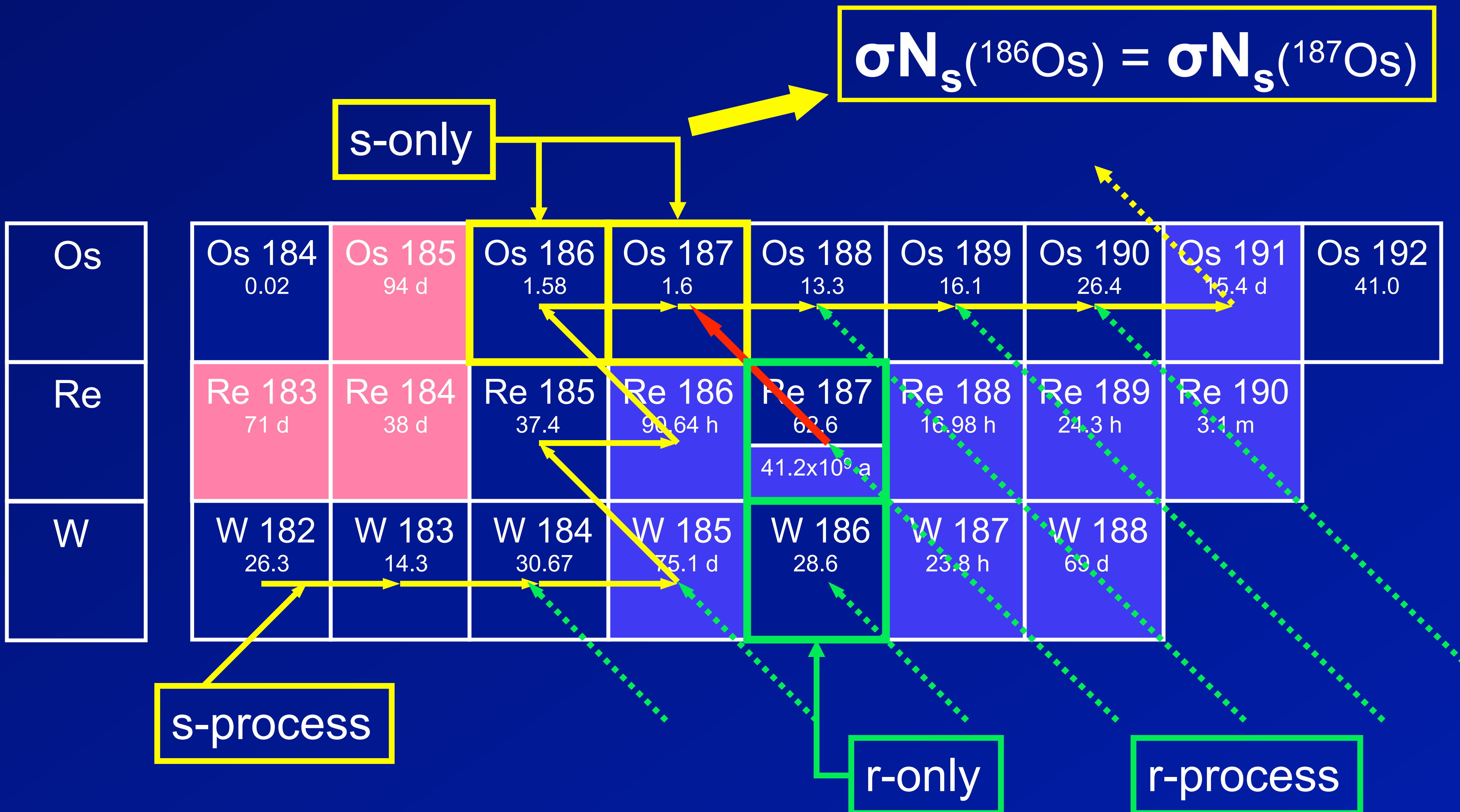


Os	Os 184 0.02	Os 185 94 d	Os 186 1.58	Os 187 1.6	Os 188 13.3	Os 189 16.1	Os 190 26.4	Os 191 15.4 d	Os 192 41.0
Re	Re 183 71 d	Re 184 38 d	Re 185 37.4	Re 186 90.64 h	Re 187 [illegible] 41.2×10^9 a	Re 188 16.98 h	Re 189 24.3 h	Re 190 3.1 m	
W	W 182 26.3	W 183 14.3	W 184 30.67	W 185 75.1 d	W 186 28.6	W 187 23.8 h	W 188 69 d		

the β-decay half-life of ^{187}Re is 41.2 Gyr

→ affects the abundance of the daughter ^{187}Os

Re/Os production



from x-sections to age

- ^{187}Os: s-process and radiogenic component

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

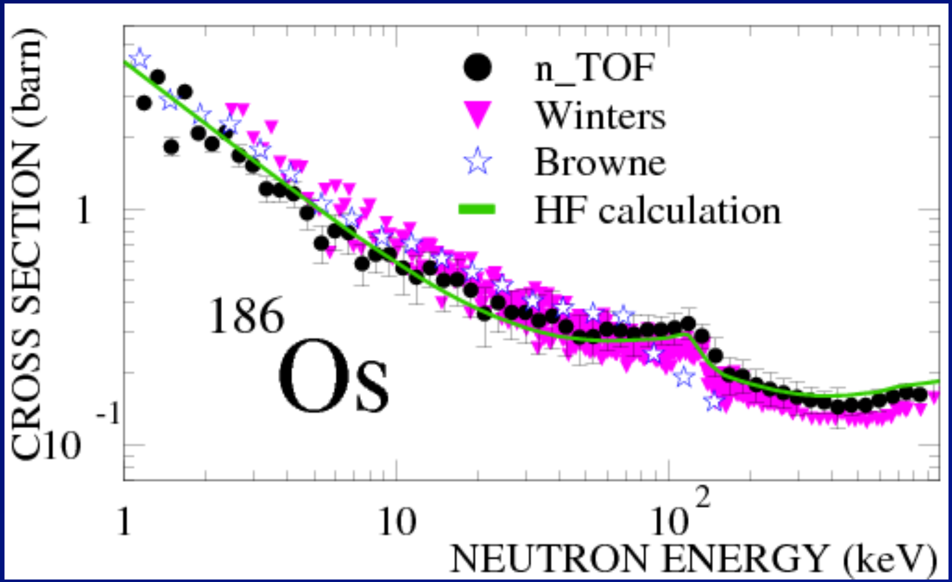
- $e^{-\Lambda t}$: r-process enrichment of ^{187}Re

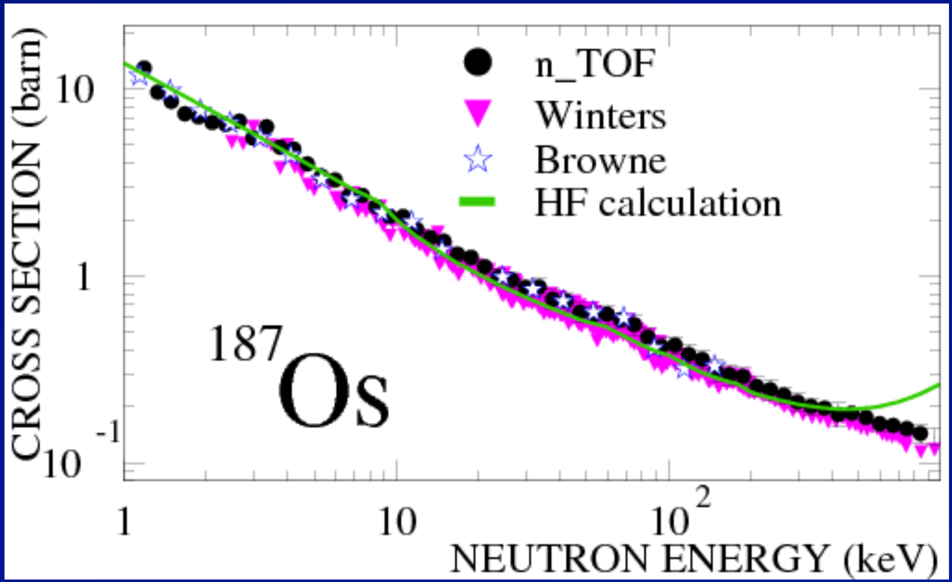
$$\frac{^{187}\mathrm{Os}_c}{^{187}\mathrm{Re}} = \left[\frac{\Lambda - \lambda}{\Lambda} e^{\Lambda t_0} \frac{1 - e^{-\Lambda t_0}}{1 - e^{-(\Lambda - \lambda) t_0}}\right] - 1$$

uniform synthesis: $\Lambda \to 0$

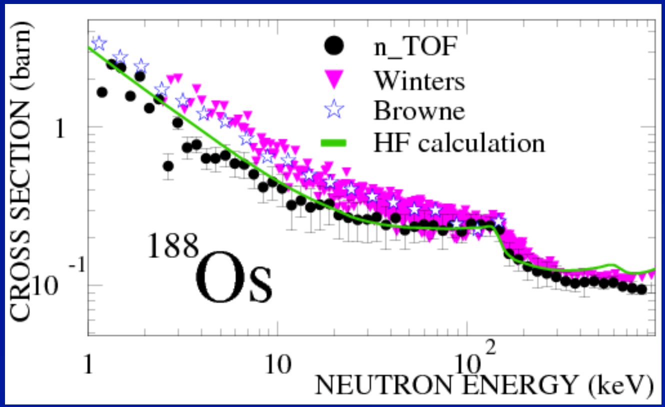
sudden synthesis: $\Lambda \to \infty$

(n,γ) cross sections





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



$$\frac{\sigma(186)}{\sigma(187)} = 0.42 \pm 0.02$$

clocks need adjustment

corrections for nuclear & stellar effects

nuclear & astro issues

- The β-decay half-life of ^{187}Re is strongly dependent on temperature
- The stellar (n, γ) cross section of ^{187}Os influenced by low-lying excited levels (strong population of 1st state at 9.8 keV, competition by inelastic channels)
- Branching(s) at ^{185}W and/or at ^{186}Re

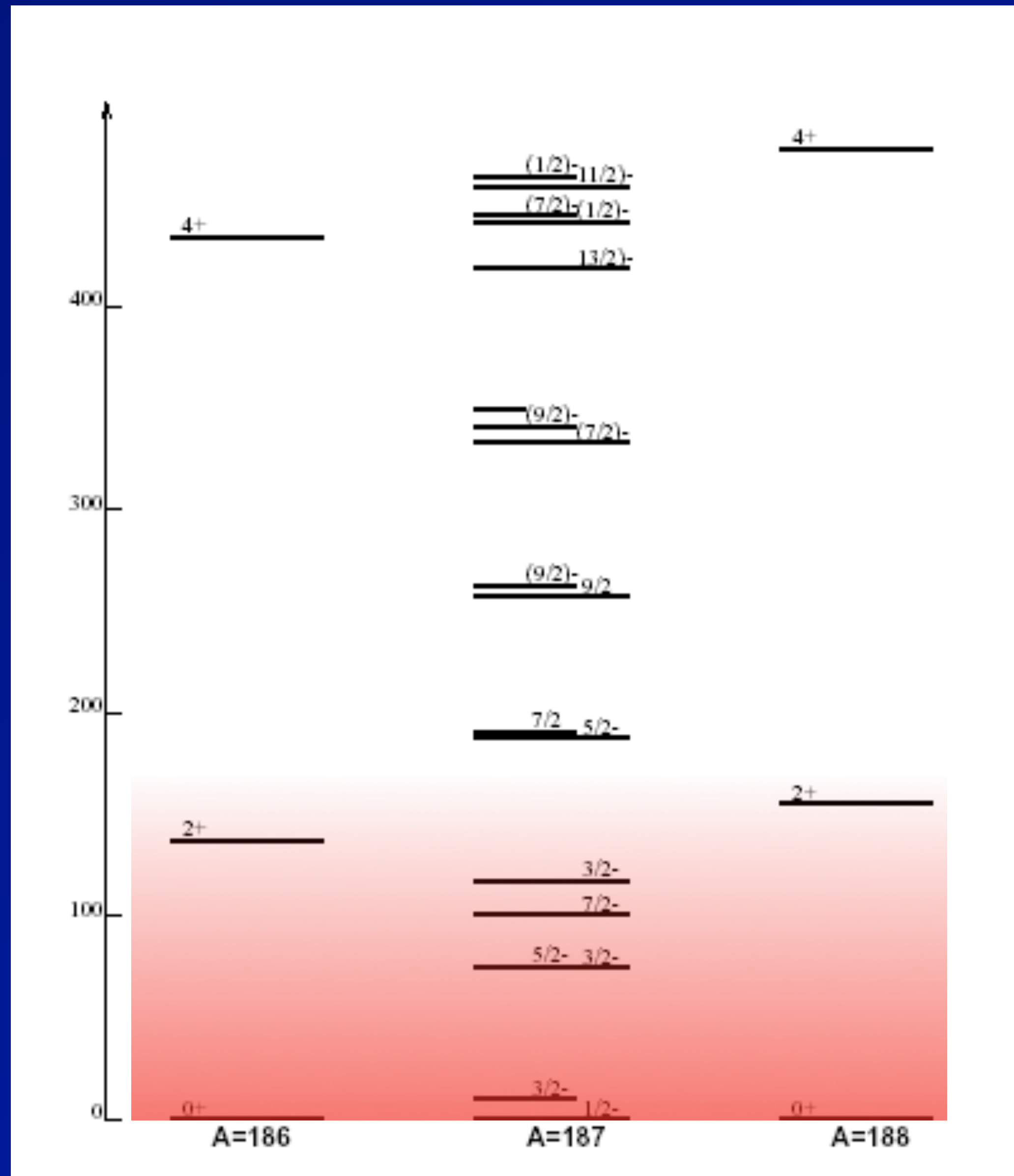
- Destruction of ^{187}Re in later stars (Astration)
- The chemical evolution of the galaxy was not uniform
- Re and Os abundance uncertainties

issue 2: thermal population

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

in ^{187}Os at *kT* = 30 keV:

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



cern.ch

stellar ^{187}Os(n,γ) cross section: theory

Hauser-Feshbach statistical model:

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

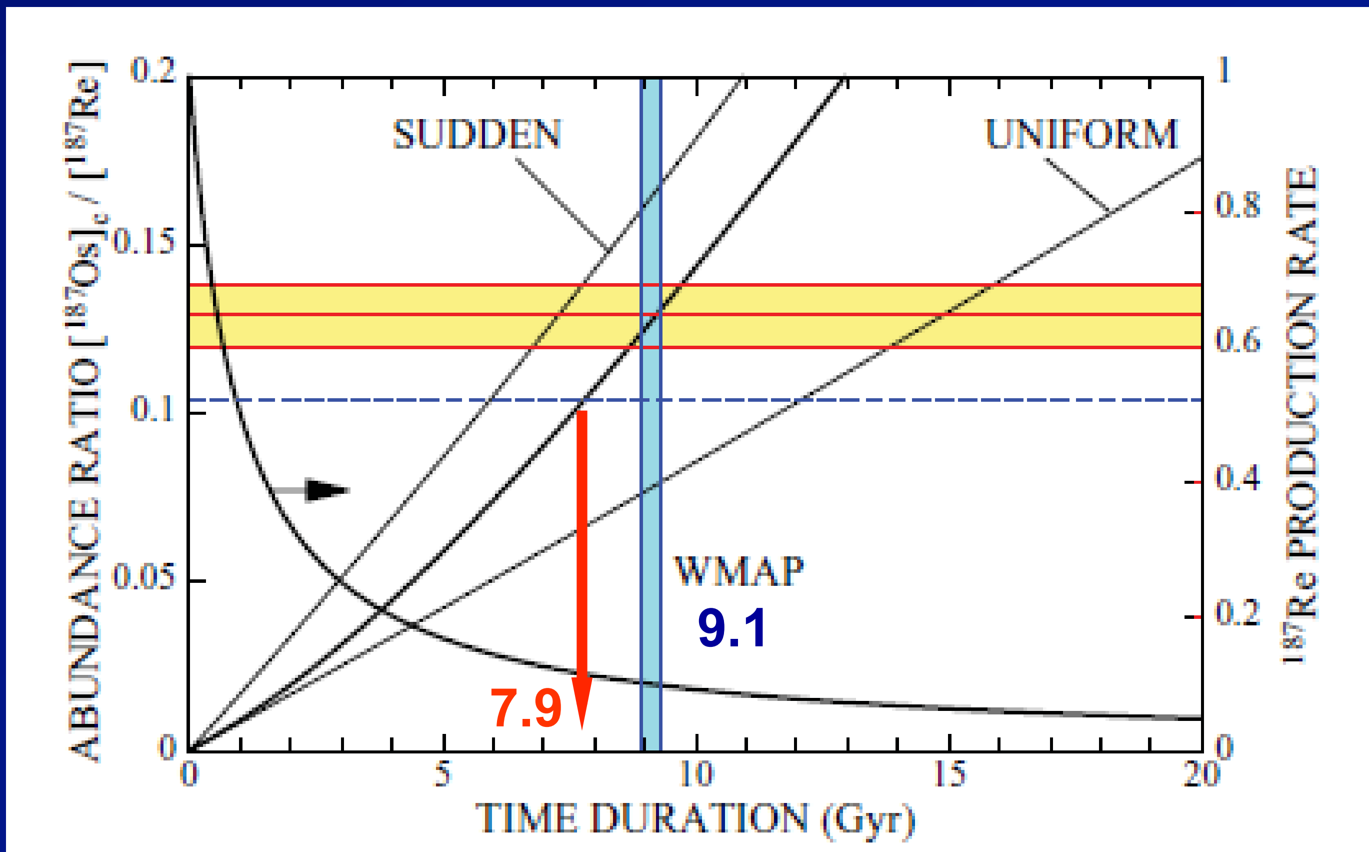
- neutron transmission coefficients, T_n : from OMP calculations
- γ-ray transmission coefficients, T_γ : from GDR (experimental parameters)
- nuclear level densities: fixed at the neutron binding from $<D>_{exp}$

all these parameters can be derived and fixed from the analysis of experimental data at low-energy

stellar correction factor $F_\sigma = f_{186} / f_{187}$

kT (keV)	$\langle\sigma_{187}\rangle^{lab}$ (mbarn)	$\langle\sigma_{187}\rangle^{calc}$ (mbarn)	$\langle\sigma_{187}\rangle^{*}$ (mbarn)	f_{187}	F_σ
10	1988	2111	2324	**1.10**	0.91
20	1171	1193	1402	**1.18**	0.85
30	874	876	1059	**1.21**	0.86
40	715	712	877	**1.23**	0.89
50	614	610	766	**1.26**	0.93

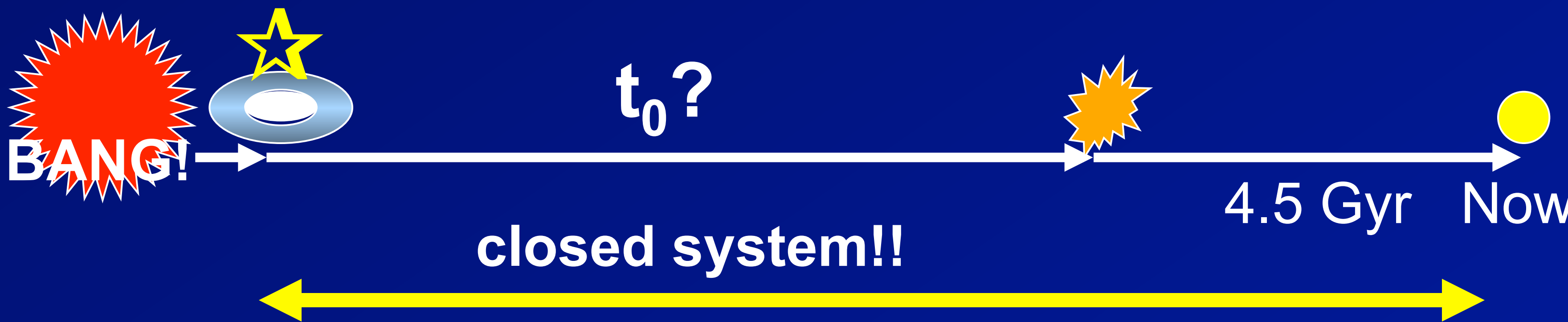
a toy model for the Re/Os clock



Age:

14 Gyr

U/Th chronometry



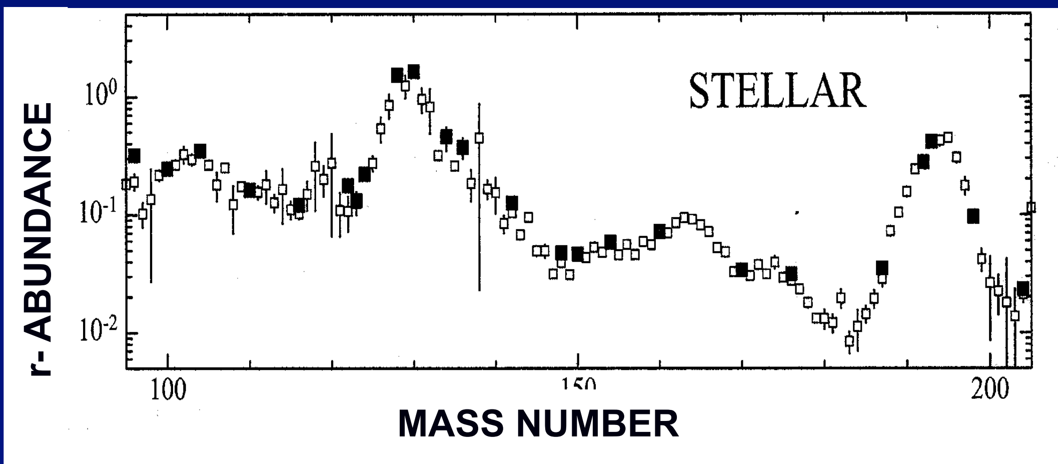
the β-decay half-lives shorter than ^{187}Re:

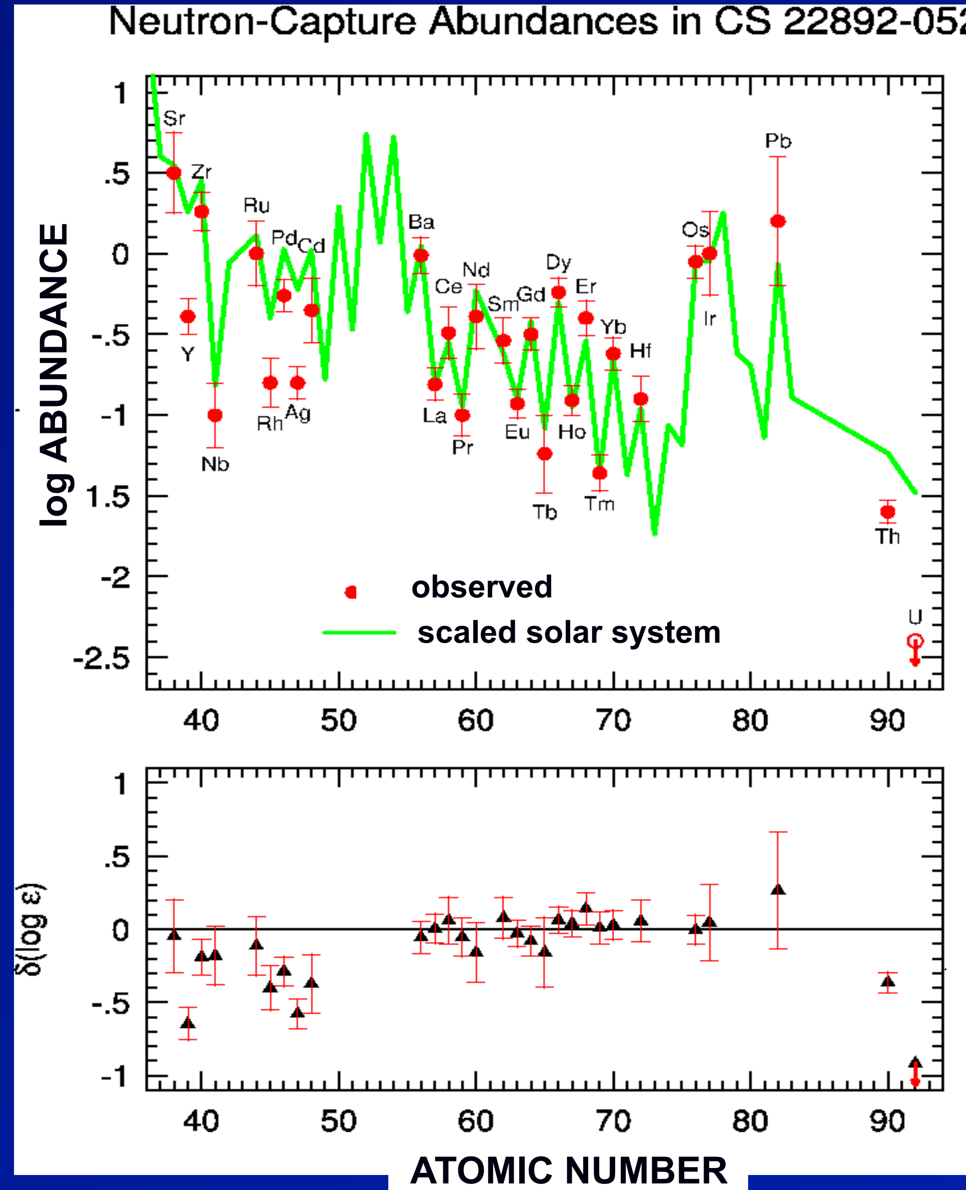
^{232}Th: 14 Gyr, ^{238}U: 4.5 Gyr

→ higher sensitivity

s- and *r*- abundances

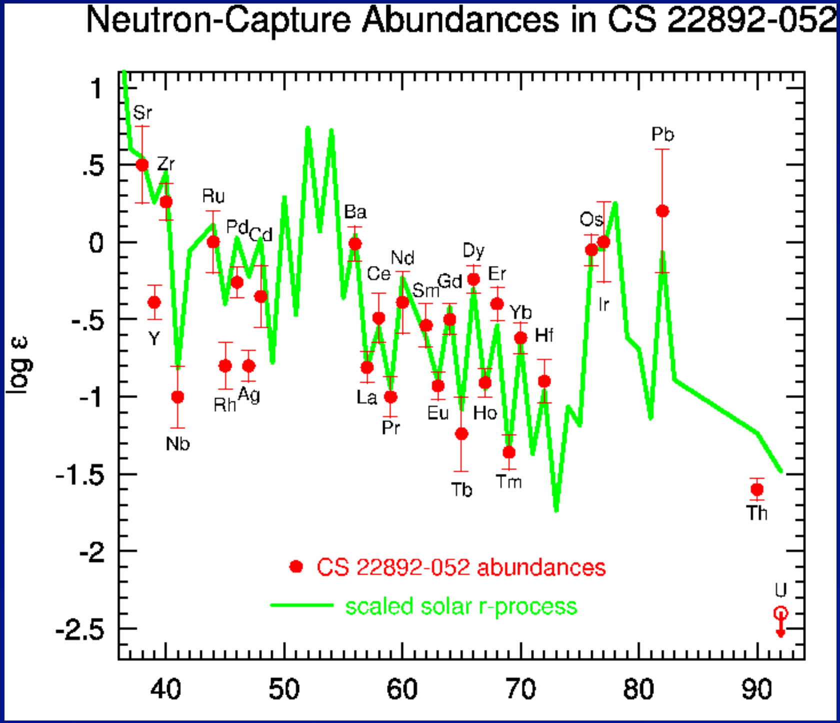
$$N_r = N_{\odot} - N_s$$



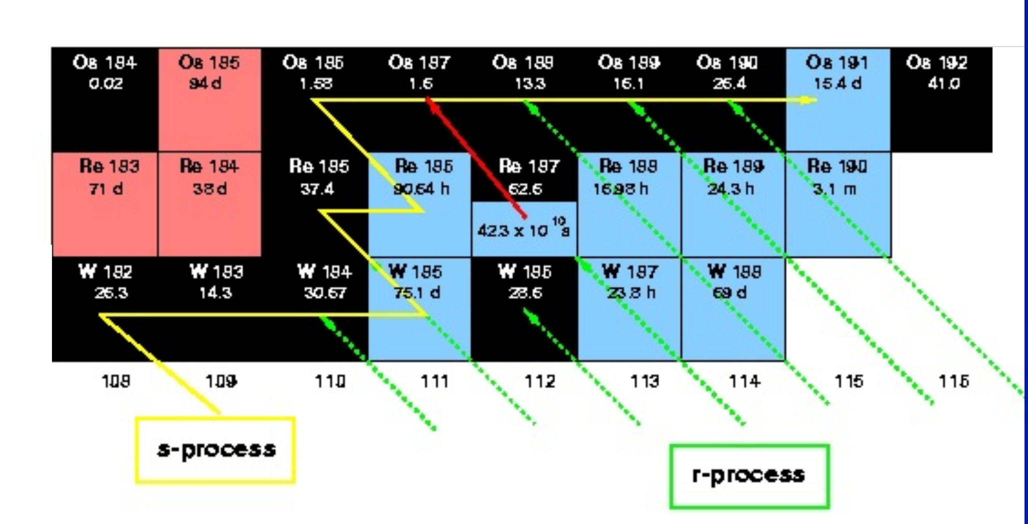


Th/U and Re/Os: clocks are complementary

+ independent of GCE
- initial yields uncertain
- observational uncertainties



+ mother/daughter well determined
- depends on GCE
- astrophysical uncertainties



summary – cosmic ages

- Cosmological way

13.9 ± 1.5 Gyr or 13.7 ± 0.2 Gyr

- Astronomical way

> 11.2 Gyr or 14 ± 2 Gyr

- Nuclear way

(14 ± ?) Gyr or 14.2 ± ~3 Gyr


Happy Birthday