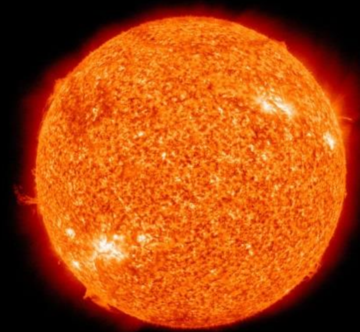
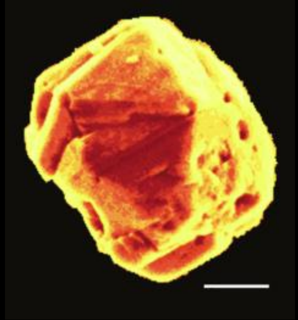
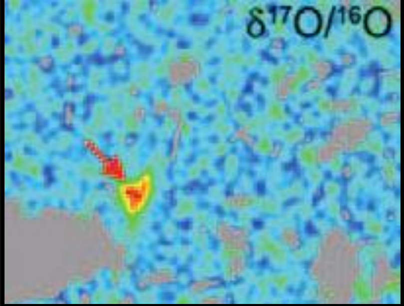
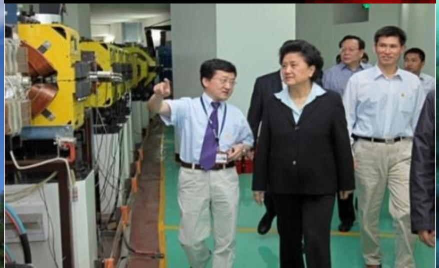



How to make Gold with Iron?

Nuclear physics problems in s-process nucleosyntehsis

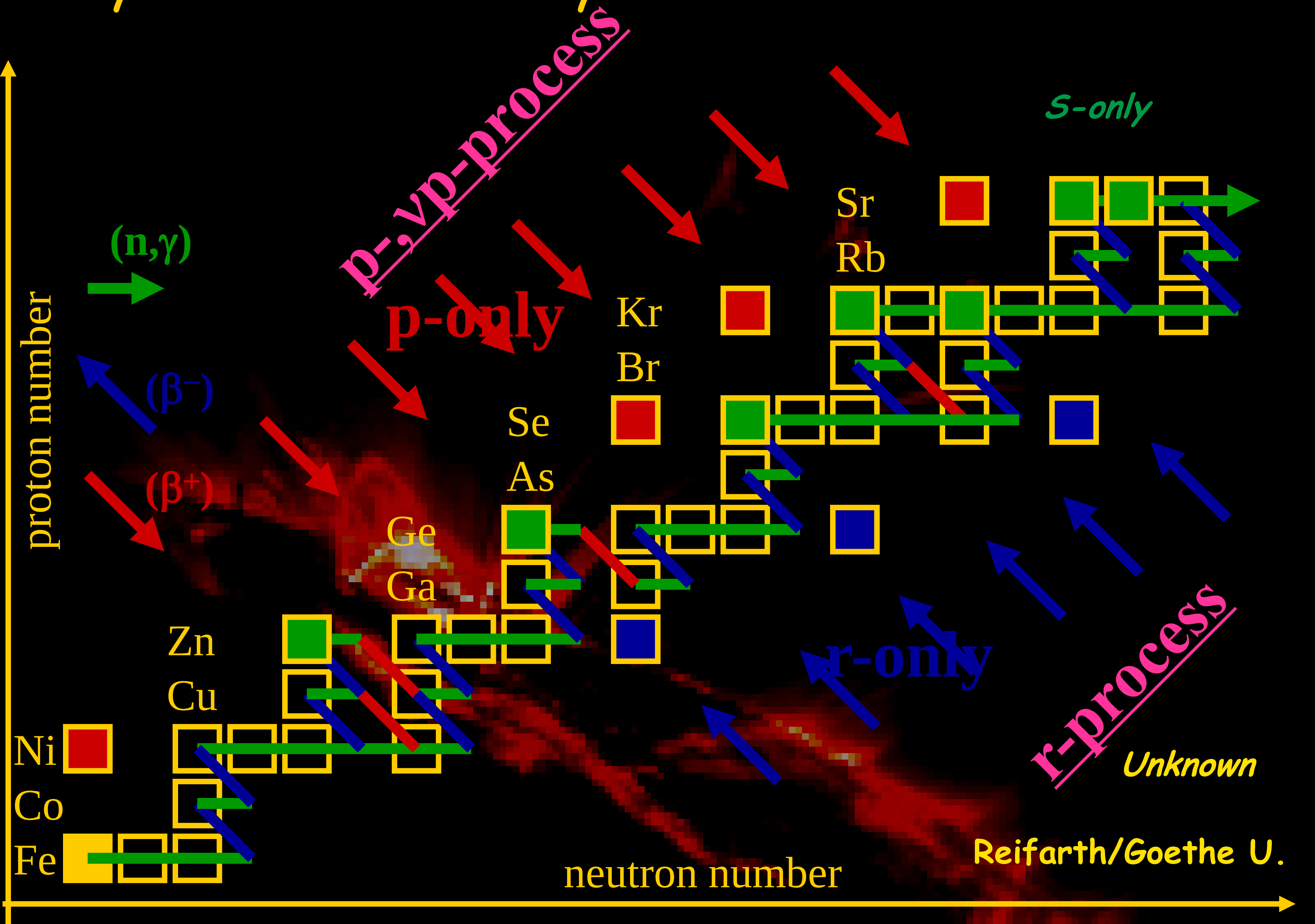
Xiaodong Tang
Institute of Modern Physics
Chinese Academy of Sciences

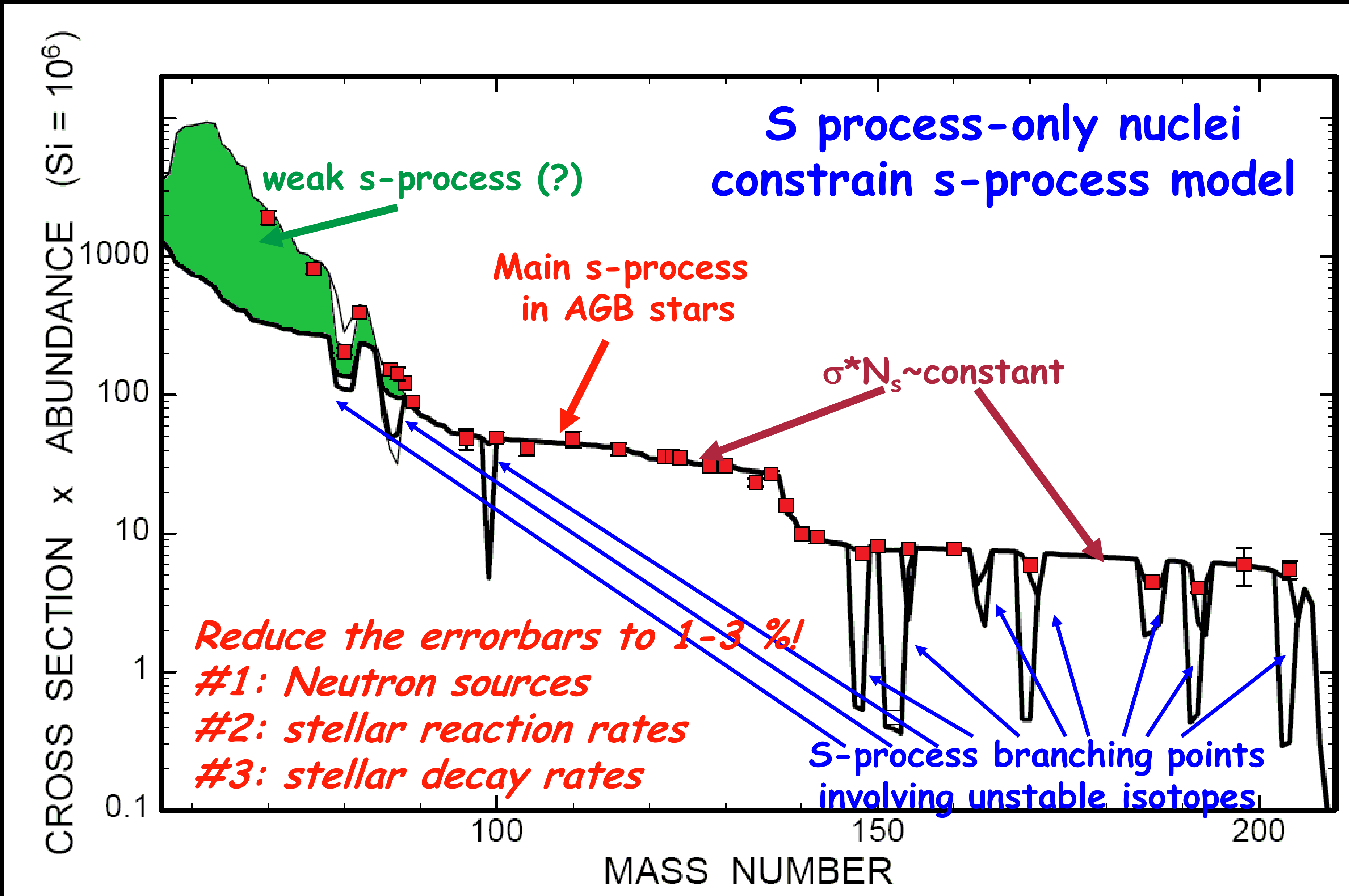

Outlines

S-process nucleosynthesis
#1: Neutron sources
#2: stellar reaction rates
#3: stellar decay rates

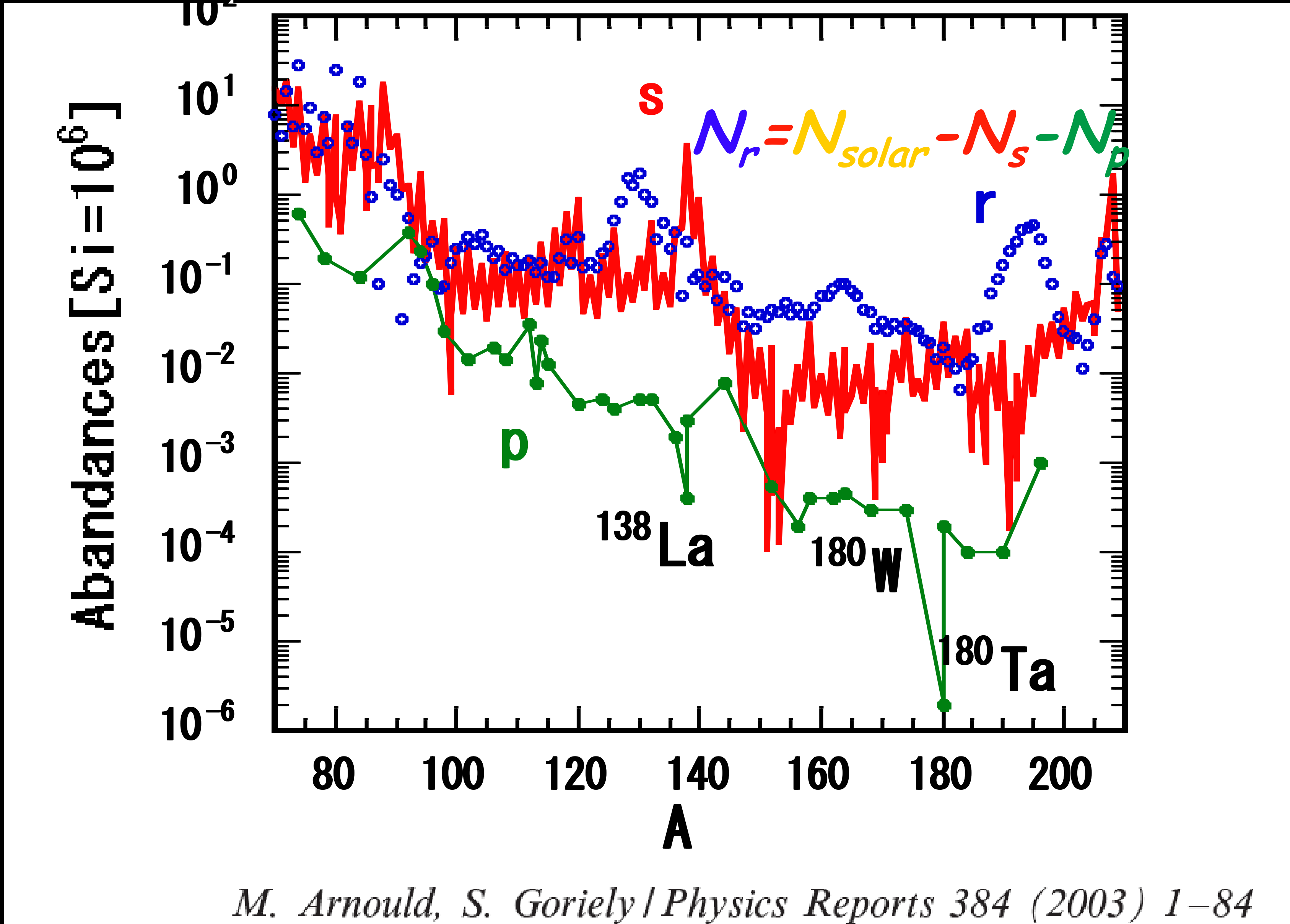
Beyond Iron – mainly neutron induced



s-only nuclei → main s-process models

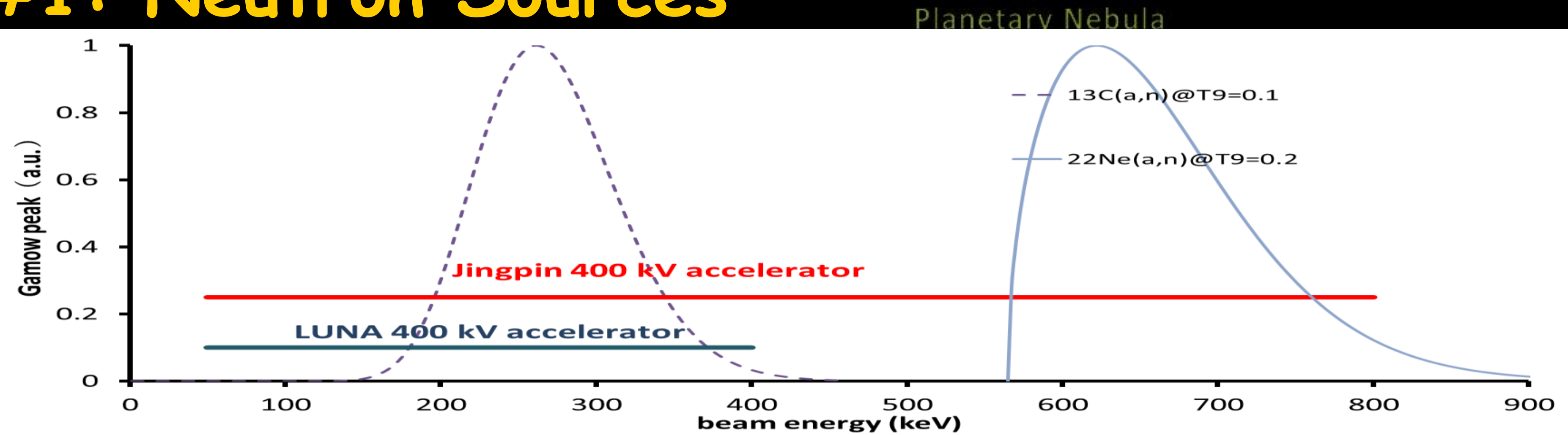


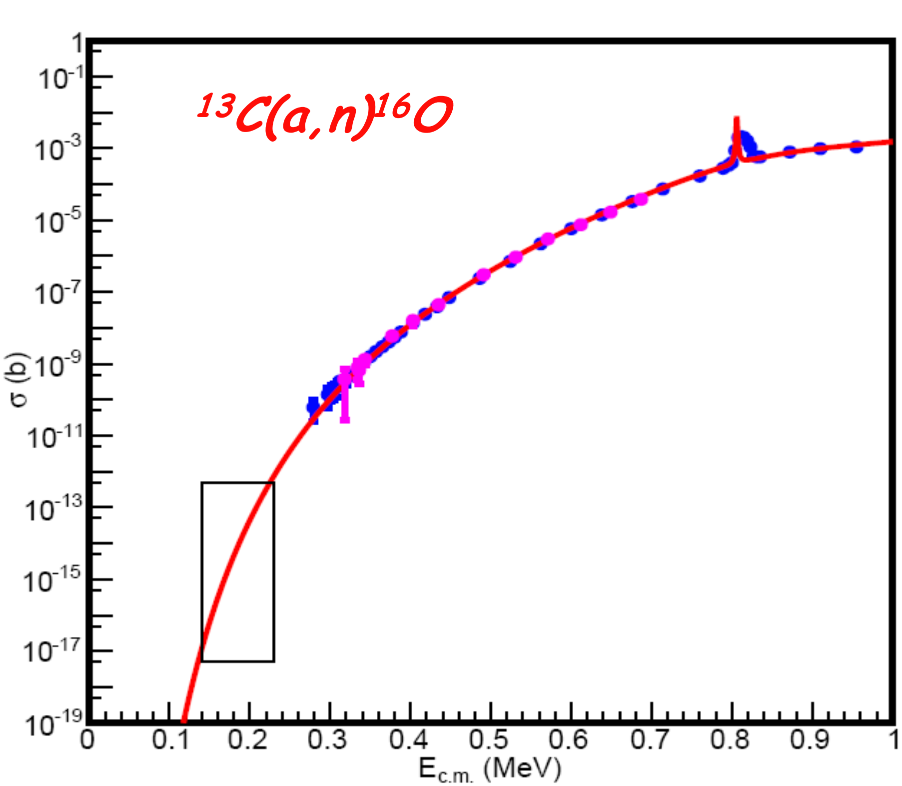
Decomposition of solar abundance

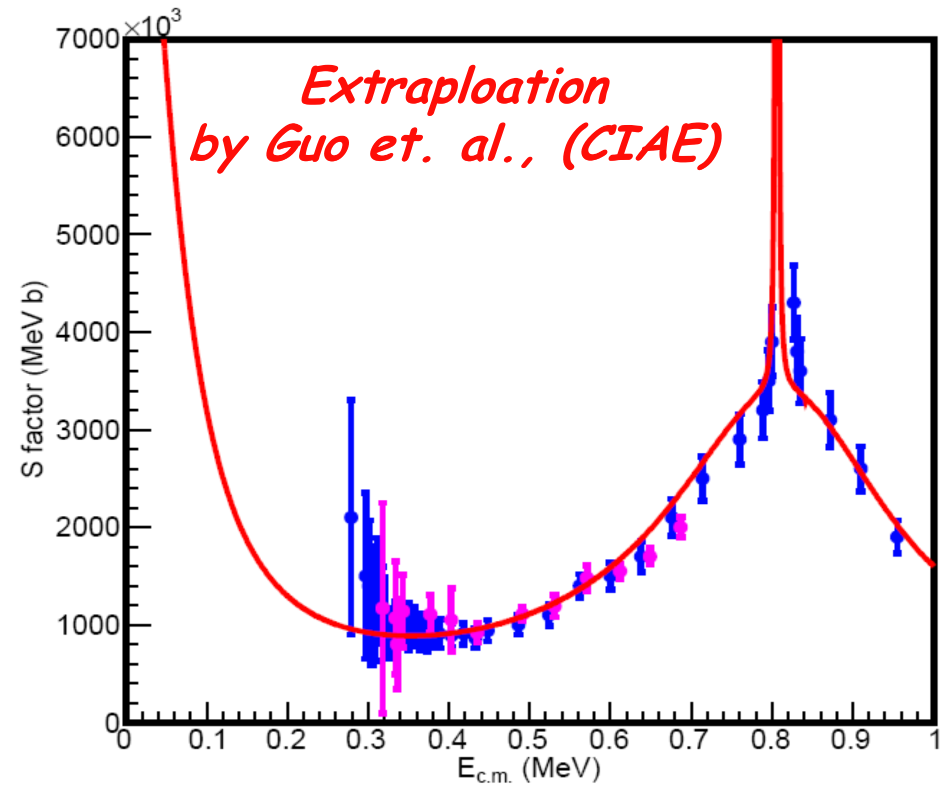


Accurate s-process model is the starting point to attach the mysterious r-process.

#1: Neutron Sources







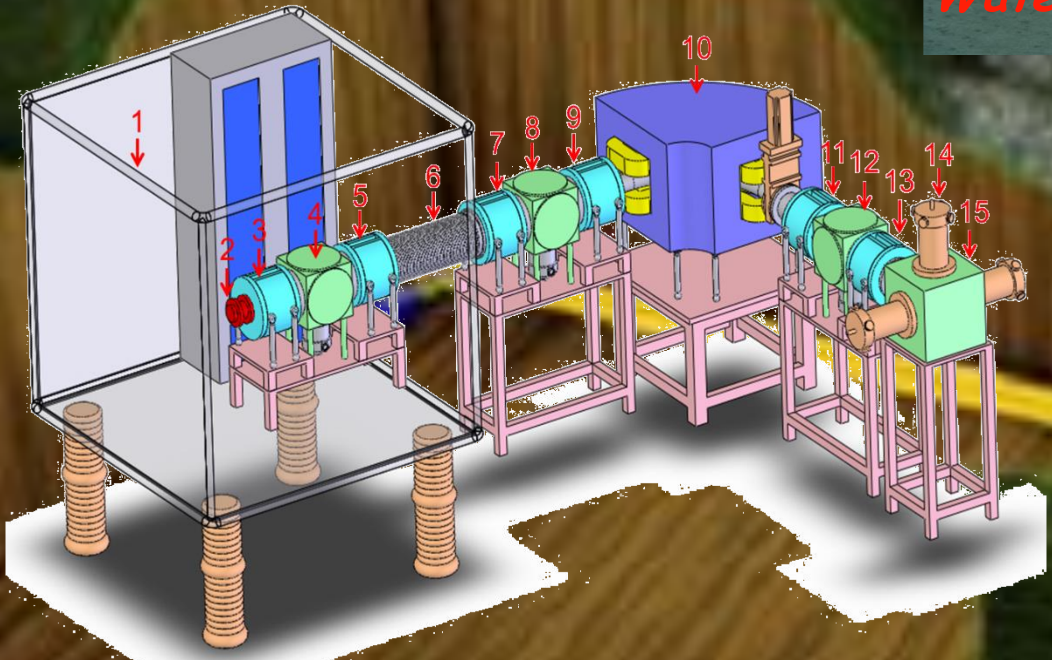
China Deep Underground Laboratory

$^{12}C(\alpha,\gamma)^{16}O$

$^{13}C(a,n)^{16}O$

$^{19}F(p,a)^{16}O$

$^{26}Mg(p,\gamma)^{27}Al$

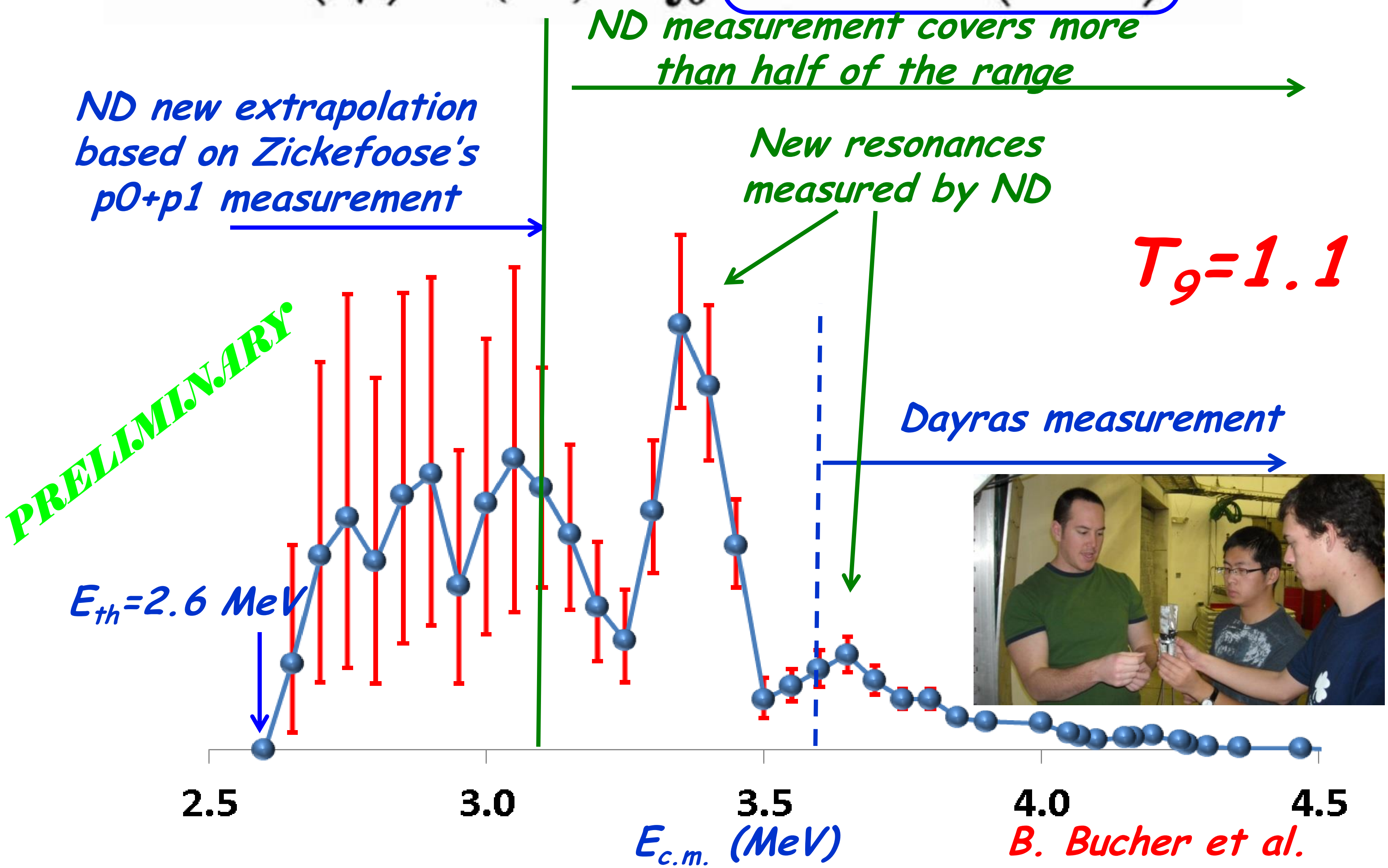


First underground accelerator based on ECR source

CIAE,IMP

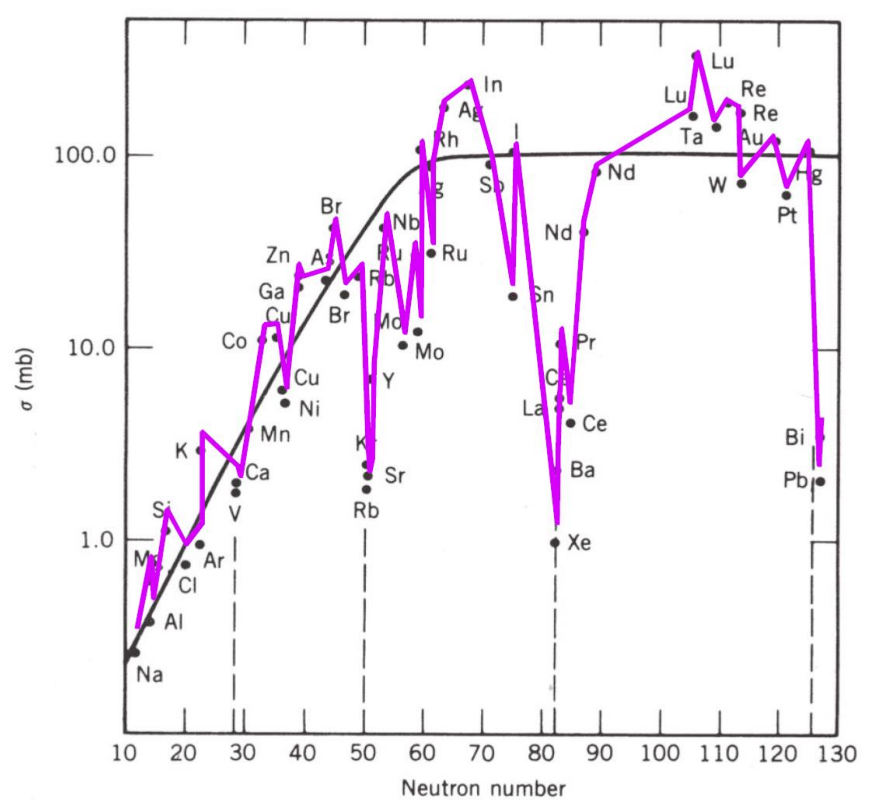
new neutron source: $^{12}C(^{12}C,n)^{23}Mg$

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) E \exp\left(-\frac{E}{kT}\right) dE$$



B. Bucher et al.

#2: Capture rates



Neutron Capture Cross Sections

Neutron capture cross section

-0.1 < E_n < 500 keV with uncertainties (<3%)

-accurate values for Maxwellian average needed

-Stellar Enhancement Factor (SEF) due to thermal corrections

Unstable isotopes

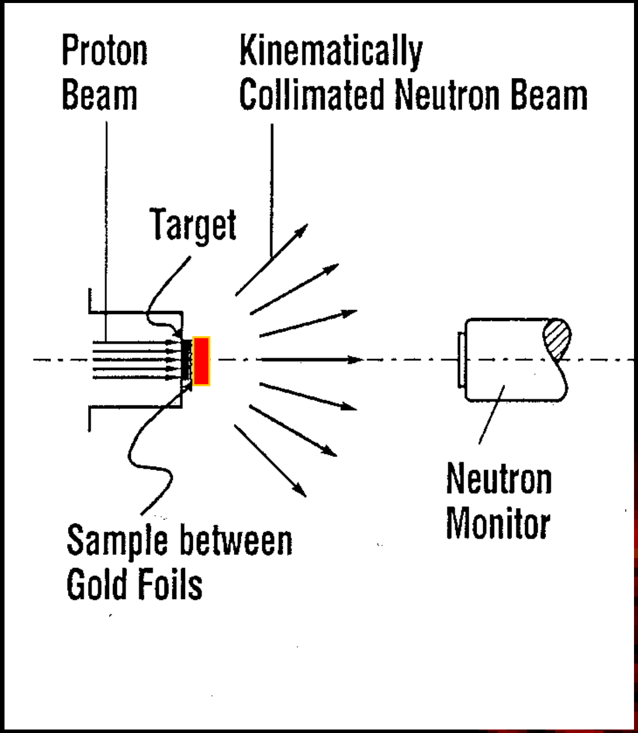
Capture by excited states

MACS

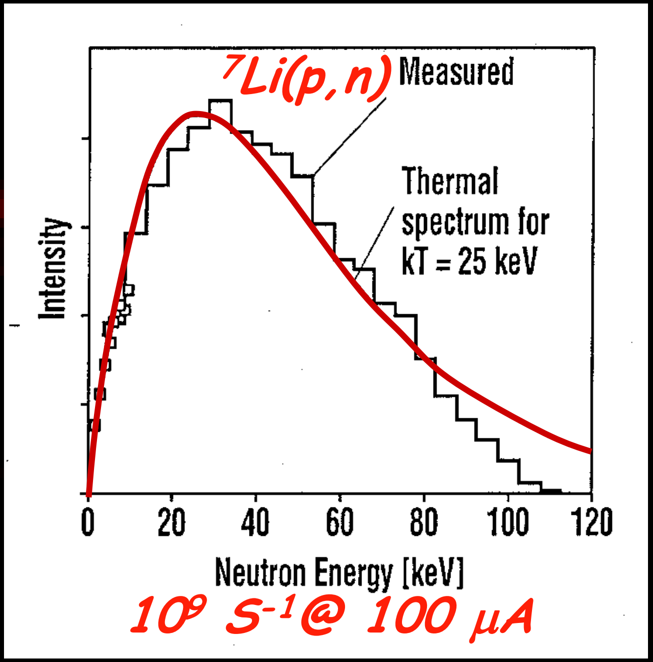
$$\langle\sigma\rangle_{kT} = \frac{2}{\sqrt{\pi}} \frac{\int_0^\infty \sigma(E_n)\, E_n\, e^{-E_n/kT}\, dE_n}{\int_0^\infty E_n\, e^{-E_n/kT}\, dE_n}$$

Activation technique at kT=25 keV

Neutron production via $^{7}Li(p,n)$ reaction at a proton energy of 1991 keV.



$^{18}O(p,n)$: 5.1 keV
$^{3}H(p,n)$: 52 keV



Induced activity can be measured after irradiation with HPGe detectors.

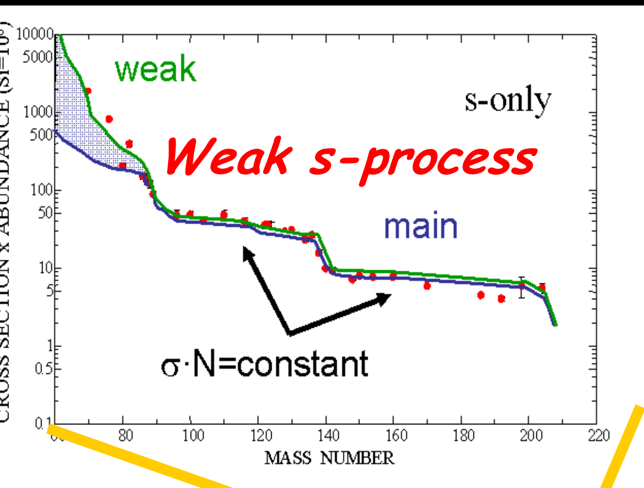
- **Only possible when product nucleus is radioactive (AMS for special case)**
- **Need theoretical extrapolation to the right temperatures**
- High sensitivity -> small sample masses or small cross sections
- Use of natural samples possible, no enriched sample necessary
- Direct capture component included

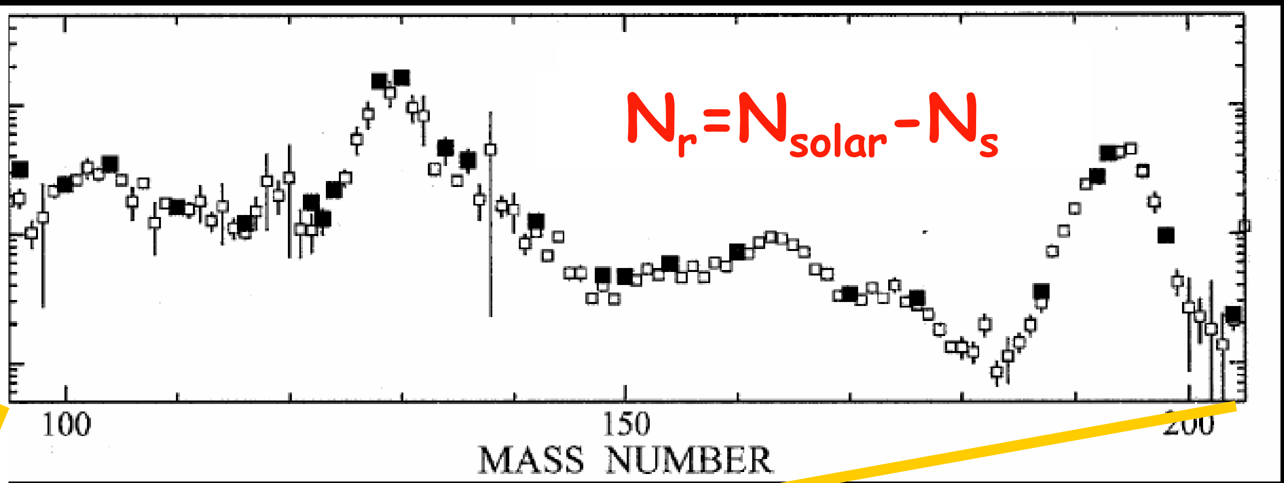
Neutron TOF facilities

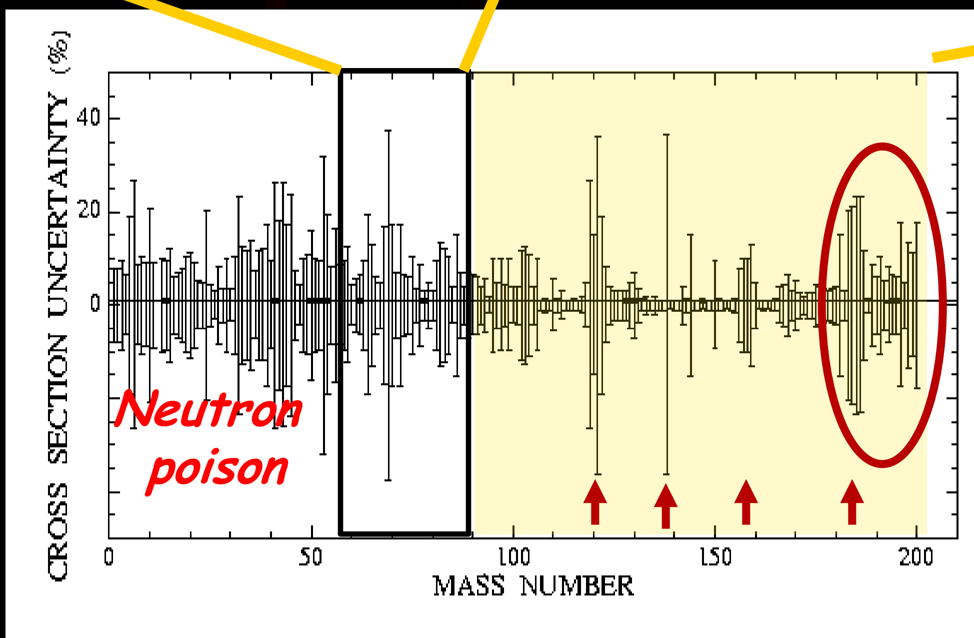
Facility Parameters	United States				Europe		China
	ORELA	LANSCE	IPNS	RPI	GELINA	n_TOF	Back-n
Source	e- linac	p -SNS	p -SNS	e- linac	e- linac	p -SNS	p -SNS
Particle E (MeV)	140	800	450	>60	150	20000 /24000	1600
Max Power (kW)	50	80 /4	6.3	>10	11	9 /5	100
Rep Rate (Hz)	1-1000	20 /50k	30	1-500	Up to 900	0.278-0.42	25
Flight Path (m)	10-200	7-55	~6-20	10-250	8-400	185	55, 80
e/p Pulse Width	2-30	125/0.125 (FWHM)	70-80	15-5000	1-2000	7 (rms)	<12 (rms)
Best Intrinsic Res. (ns/m)	0.01	3.9 /?	3.5	0.06	0.0025	0.034	0.65
Neutrons/s	1×10^{14}	7.5 /<<0.38×10^{15}	8.1×10^{14}	4×10^{13}	3.2×10^{13}	8.1×10^{14}	2.0×10^{16}

Back-n collaboration: IHEP+CIAE

Better uncertainties (1-3%)







Better uncertainties (1-3%)

S-only nuclei

Nuclei with small neutron cross section (around neutron magic numbers)

We need to measure (n,γ) cross sections between 0.1 and 500 keV.

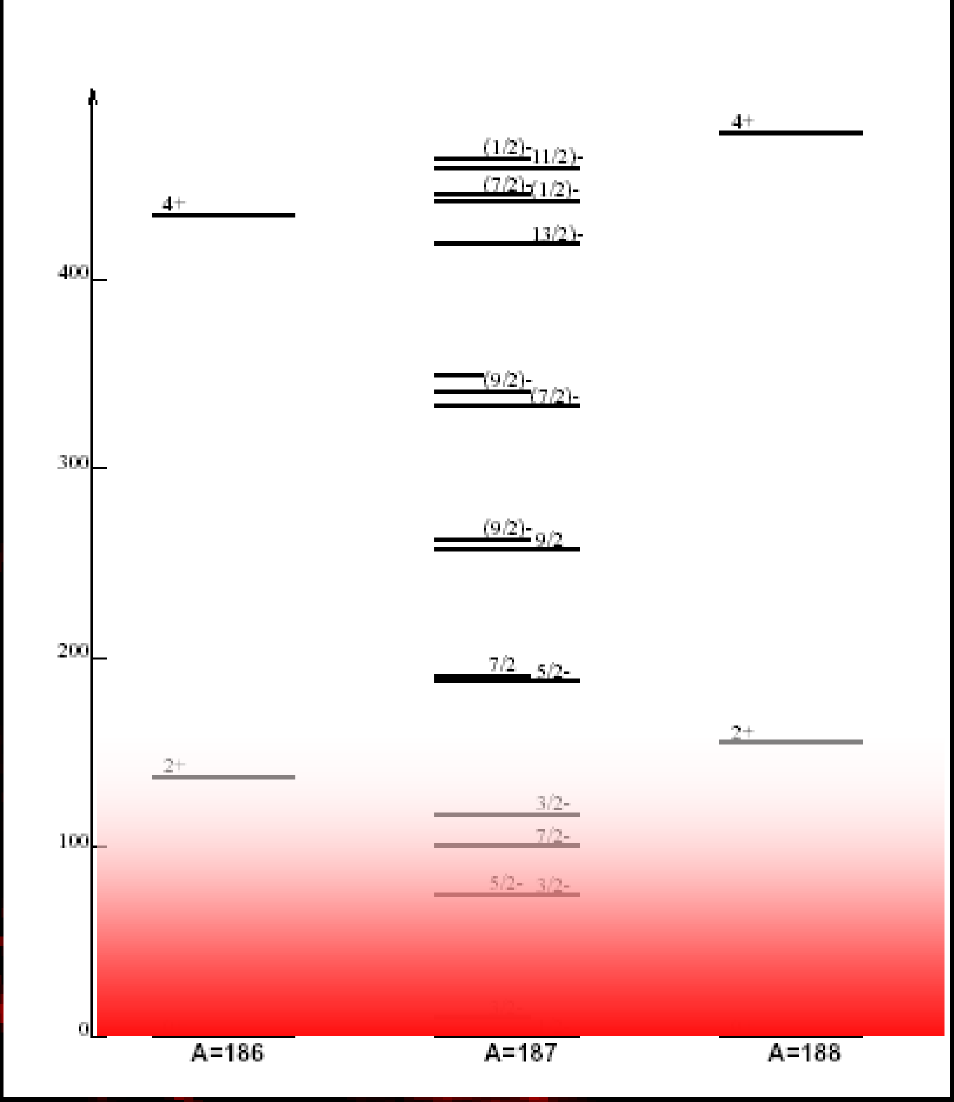
Re/Os clock: a example for thermal correction

- ***Thermal population***

$$p_i = \frac{(2J_i + 1)\exp(-E_i/kT)}{\sum_m (2J_m + 1)\exp(-E_m/kT)}$$

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

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

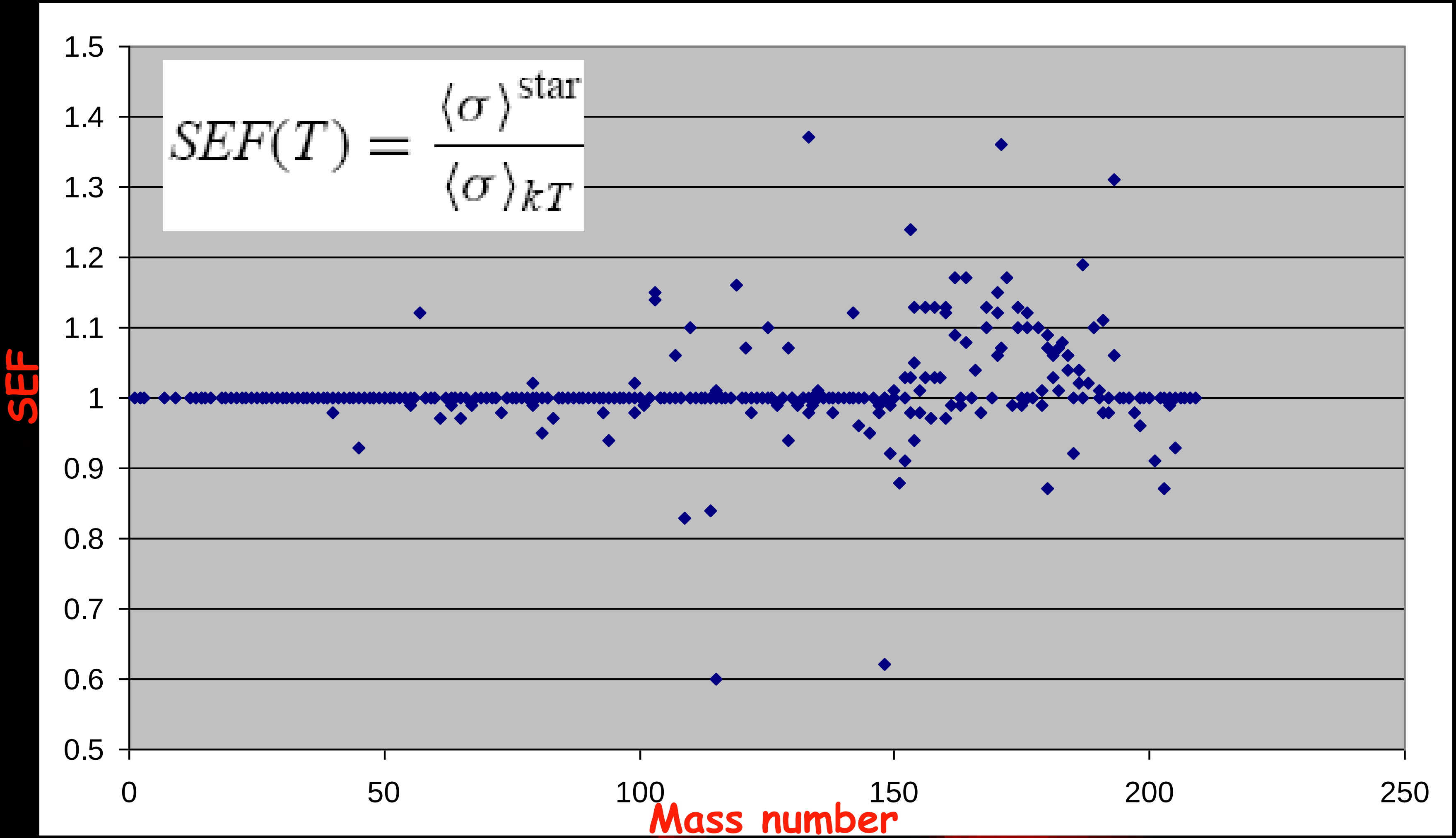


- ***Stellar enhancement factor***

$$SEF(T) = \frac{\langle\sigma\rangle^{\text{star}}}{\langle\sigma\rangle_{kT}}$$

$<\sigma>^{star} = 0.33 * <\sigma>^{lab} + 0.47 * <\sigma>^{1st} + ..$

Stellar enhancement factor



Calculation by T. Raucher

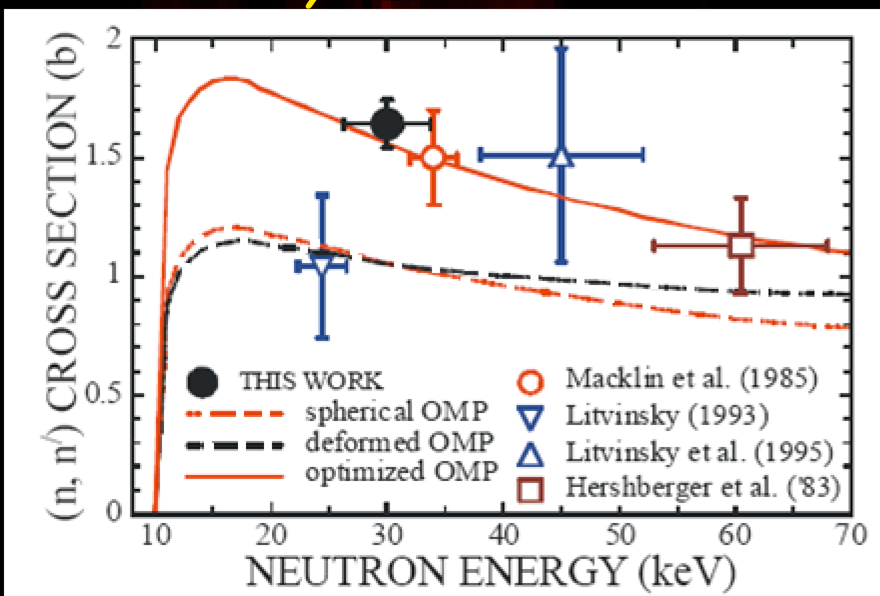
How to obtain a reliable ^{187}Os*(n,g)?

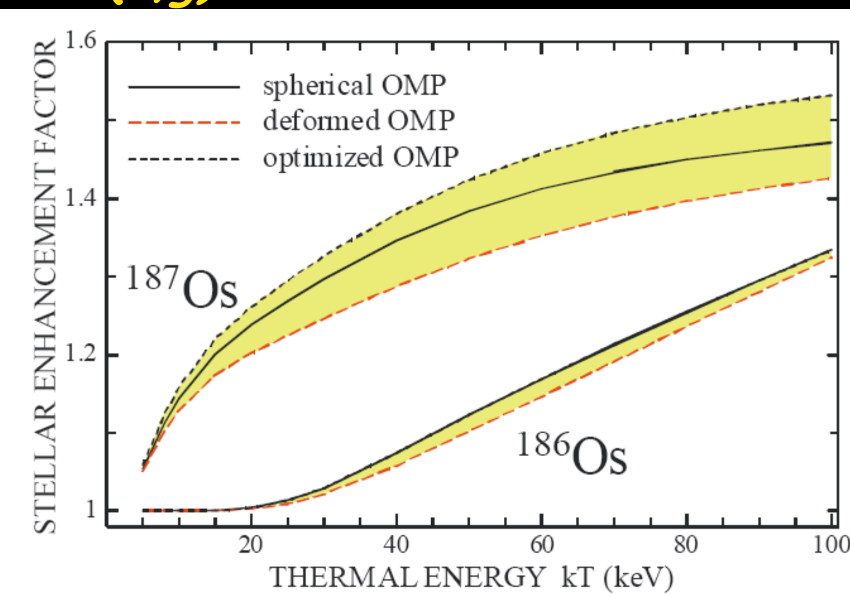
$$\sigma^{i}_{n,\gamma}(E_n) = \frac{\pi}{k_n^2} \sum_{J,\pi} g_J \frac{\sum_{ls} T_{n,ls} T_{\gamma,J}}{\sum_{ls} T_{n,ls} + \sum_{ls} T_{n',ls} + T_{\gamma,J}} W_{\gamma,J}$$

T_n : from elastic and inelastic experiment within astrophysics energy range ($1<E_n<500$ keV) [NOT many data around]

$T\gamma$: from GDR experiment (eg, (g,n))

Level density at neutron threshold <D>: (n,g) with NTOF

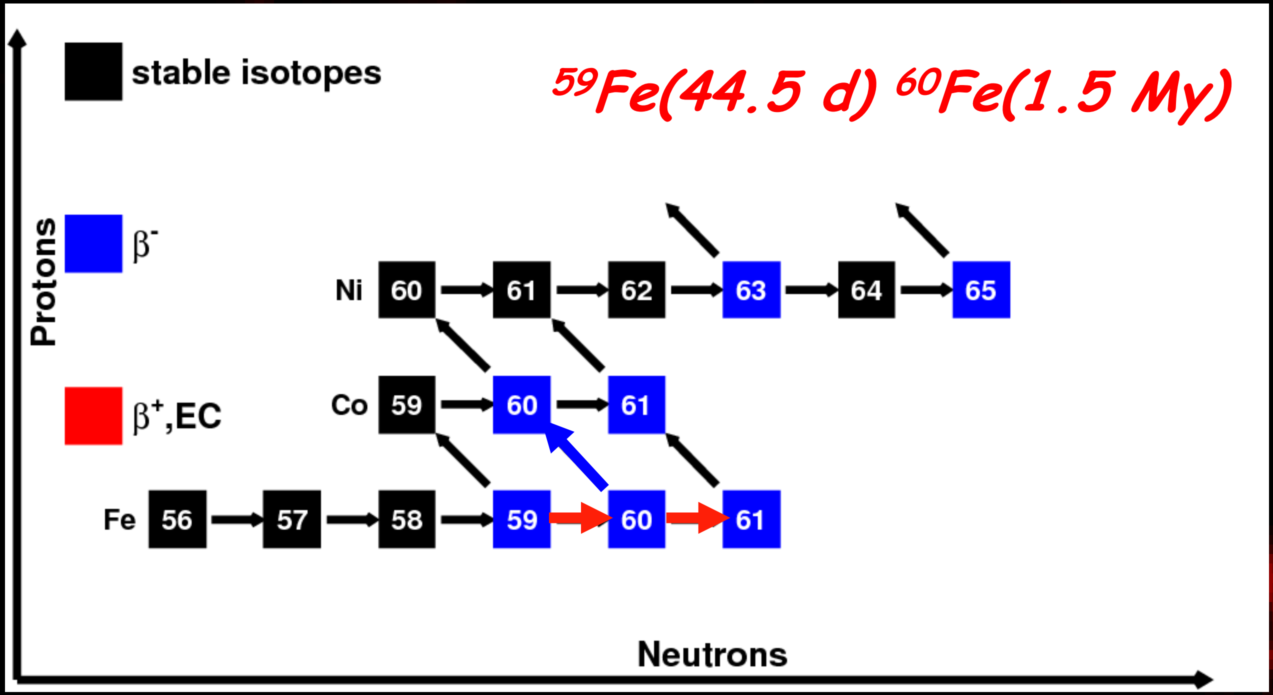


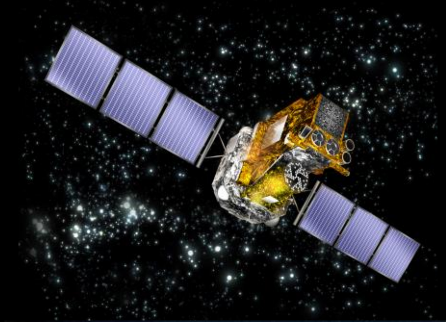


K. Fuji et al., PRC 82, 015804 (2010)

Production of ^{60}Fe

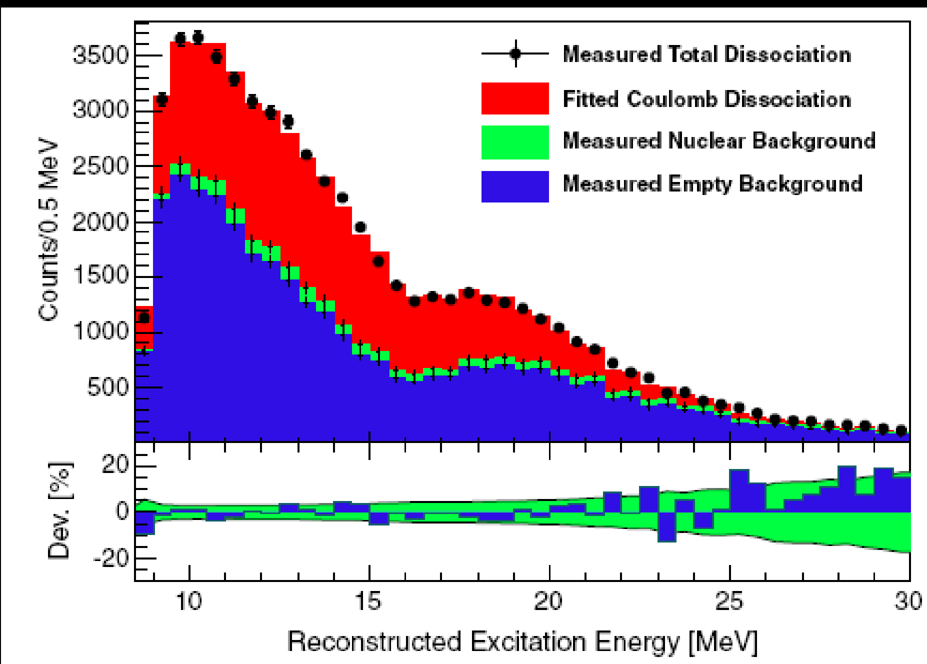
- Weak s-process component in massive stars
- During He-core and C-shell burning
- $^{59,60}Fe(n,\gamma)$ cross section needed
- Precise ^{60}Fe lifetime

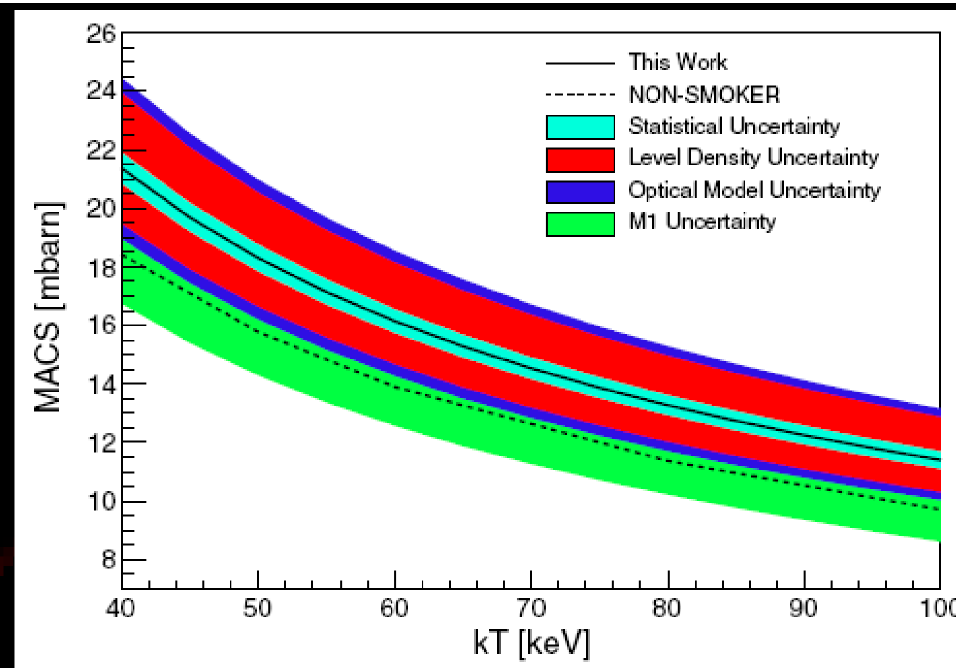




PRL **112,** 211101 (2014) PHYSICAL REVIEW LETTERS week ending 30 MAY 2014

First Experimental Constraint on the $^{59}Fe(n,\gamma)^{60}Fe$ Reaction Cross Section at Astrophysical Energies via the Coulomb Dissociation of ^{60}Fe





Number of dissociated ^{60}Fe

Maxwellian-Averaged xsec

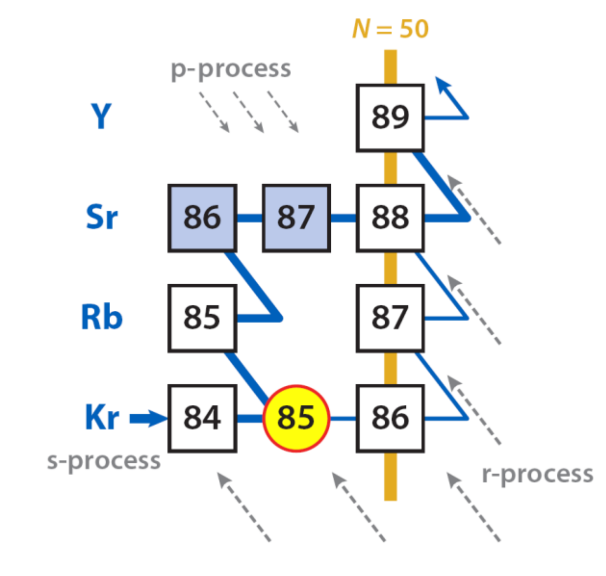
$$\sigma_{\gamma,\mathrm{abs}}(E_\gamma) = \sigma_0 \Gamma \frac{E_\gamma^2 \Gamma}{(E_\gamma^2 - E_0^2)^2 + (E_\gamma \Gamma)^2}$$

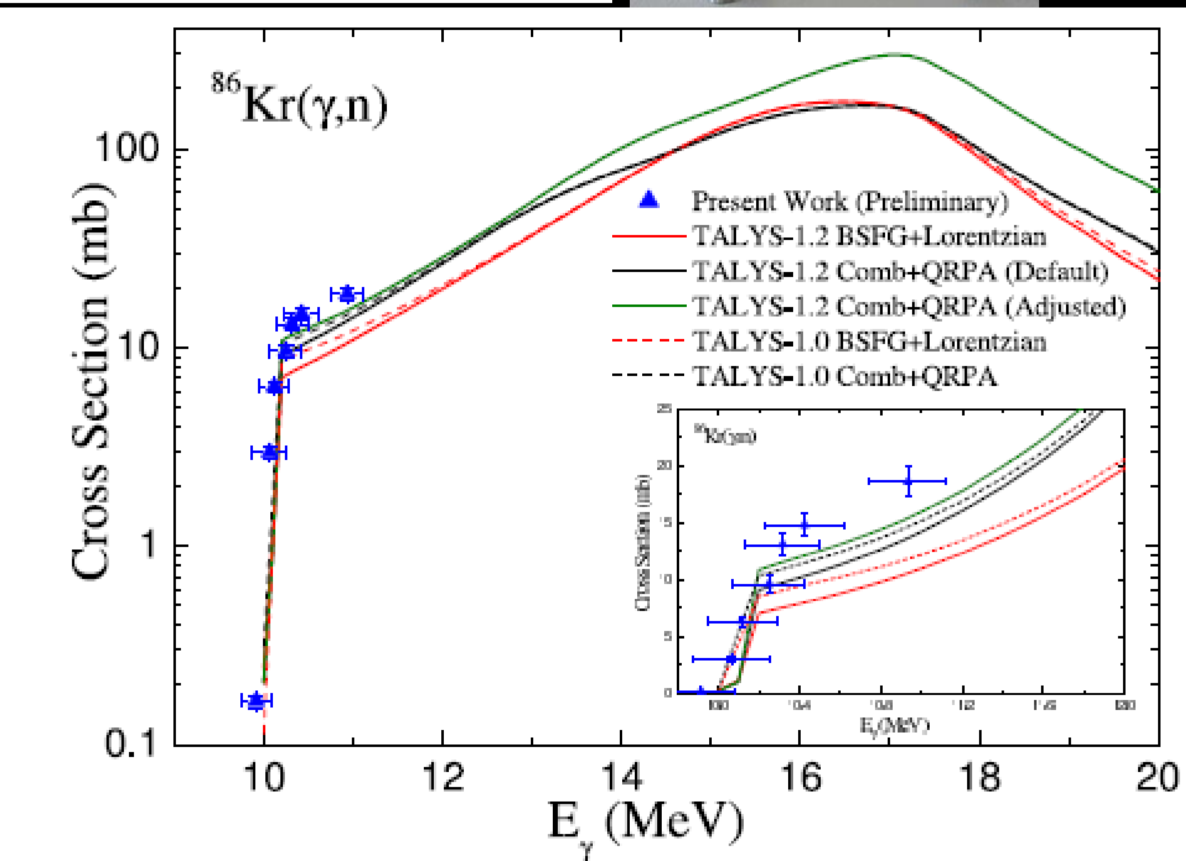
$$\Gamma(E_\gamma) = \Gamma_0 \left(\frac{E_\gamma}{E_o}\right)^{\frac{1}{2}}$$

$\sigma_{E1} * \Gamma_0 = 565(15)$ mb

E. Uberseder et al.

^{86}kr(γ,n)^{85}Kr with HIγs





^{85}Kr (10.5 y)

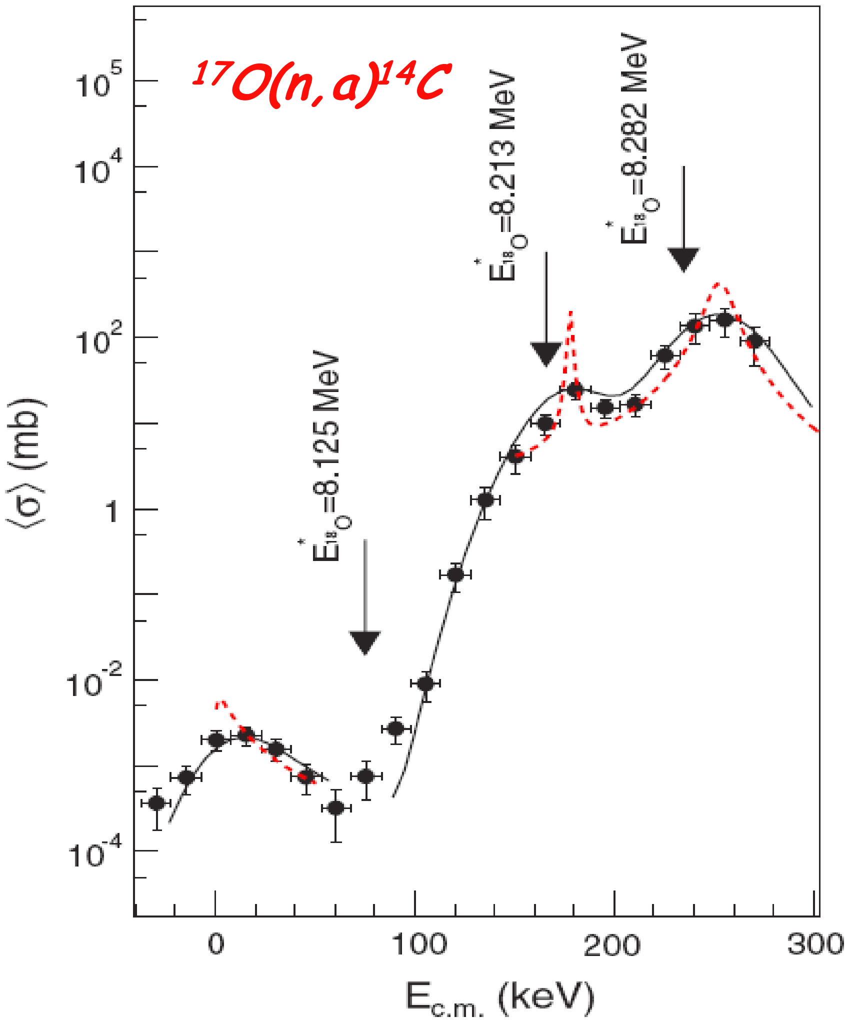
R. Raut et al.,
Phys. Rev. Lett. 111, 112501 (2013)

SLEGS at Shanghai (photo nuclear reaction)

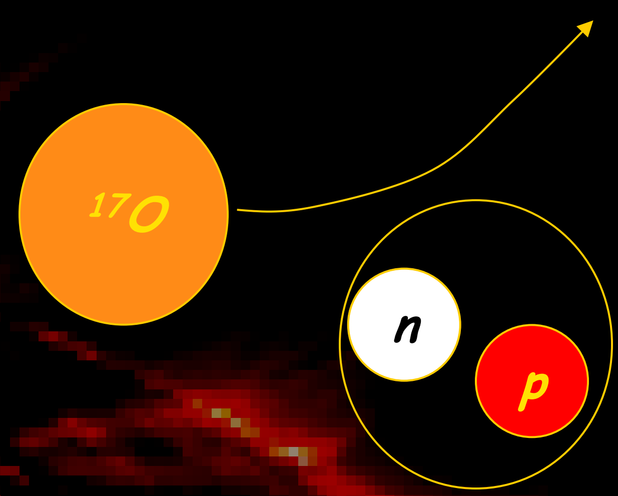
PHYSICAL REVIEW C **87**, 012801(R) (2013)

Suppression of the centrifugal barrier effects in the off-energy-shell neutron + ^{17}O interaction

M. Gulino,[1,2] C. Spitaleri,[1,3] X. D. Tang,[4] G. L. Guardo,[1,3] L. Lamia,[1,3] S. Cherubini,[1,3] B. Bucher,[4] V. Burjan,[5] M. Couder,[4] P. Davies,[4] R. deBoer,[4] X. Fang,[4] V. Z. Goldberg,[6] Z. Hons,[5] V. Kroha,[5] L. Lamm,[4,*] M. La Cognata,[1] C. Li,[7] C. Ma,[4] J. Mrazek,[5] A. M. Mukhamedzhanov,[6] M. Notani,[4] S. O'Brien,[4] R. G. Pizzone,[1] G. G. Rapisarda,[1,3] D. Roberson,[4] M. L. Sergi,[1,3] W. Tan,[4] I. J. Thompson,[8] and M. Wiescher[4]



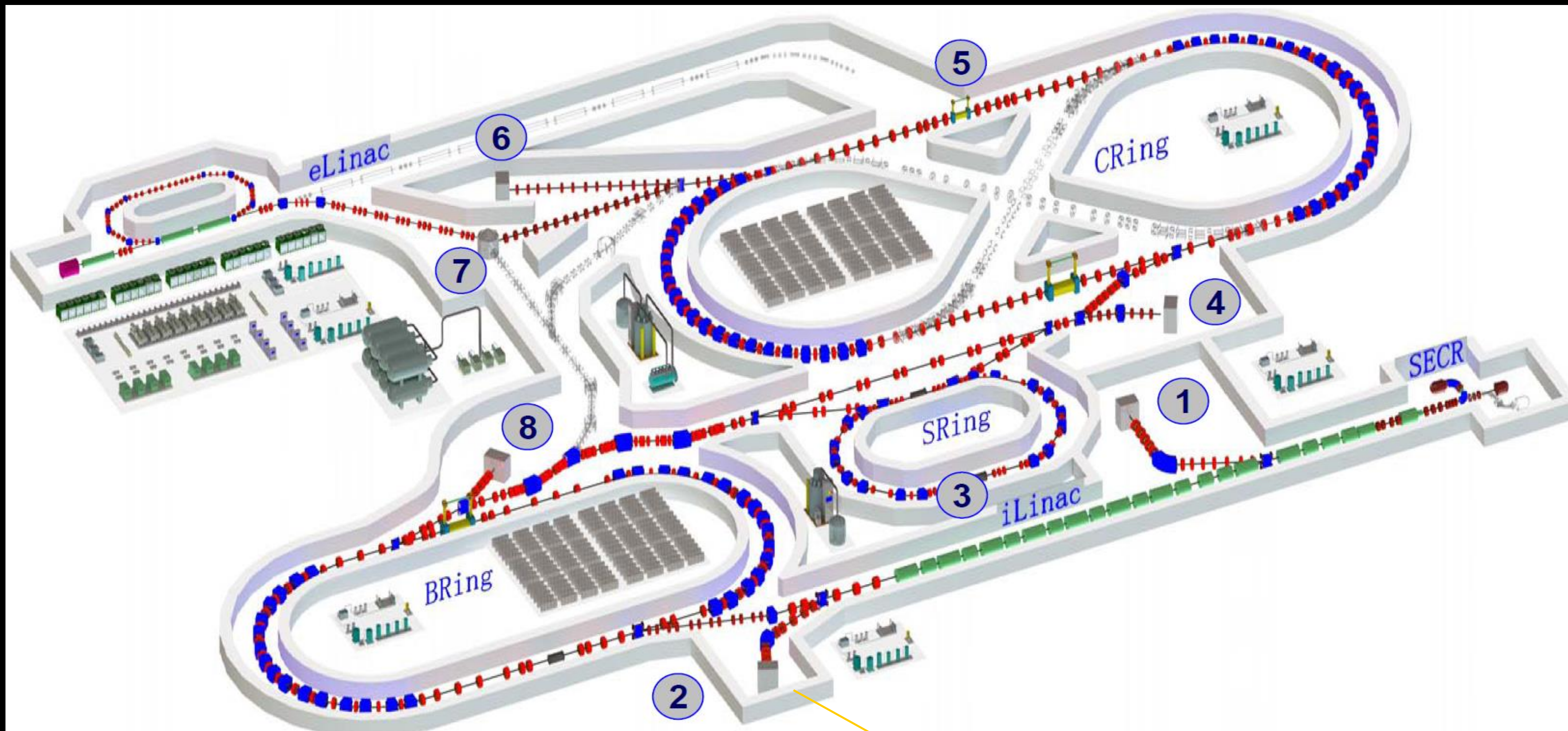
Study of ^{17}O(n,α)^{14}C with ^{17}O+d→α+^{14}C+p



Can be used with RIBs!

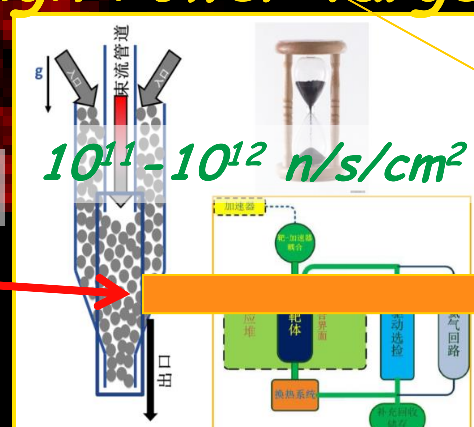
See Pizzone's talk

High Intensity Accelerator Facility (HIAF)



High Power target

ADS accelerator



RIB

Radioactive sample from HIAF

#3: Decays

NUCLEAR β-DECAYS OF HIGHLY IONIZED HEAVY ATOMS IN STELLAR INTERIORS†

NPA404 (1983) 578-598

KOHJI TAKAHASHI and KOICHI YOKOI

$$(Z, N, j; Kk)_I \to (Z+1, N-1, j+1; K'k')_F + e^- + \bar{\nu}_e$$

continuum-state β^- decay,

$$\to (Z+1, N-1, j; K'k')_F + \bar{\nu}_e$$

bound-state β^- decay,

$$\to (Z-1, N+1, j; K'k')_F + \nu_e$$

orbital e^- capture,

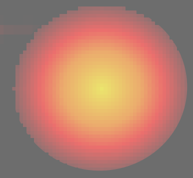
$$\to (Z-1, N+1, j-1; K'k')_F + e^+ + \nu_e$$

continuum-state β^+ decay,

$$(Z, N, j; Kk)_I + e^- \to (Z-1, N+1, j-1; K'k')_F + \nu_e$$

free e^- capture.

Electron soup



Highly ionized atoms

Storage Ring @ GSI, IMP , ISODE,RIKEN

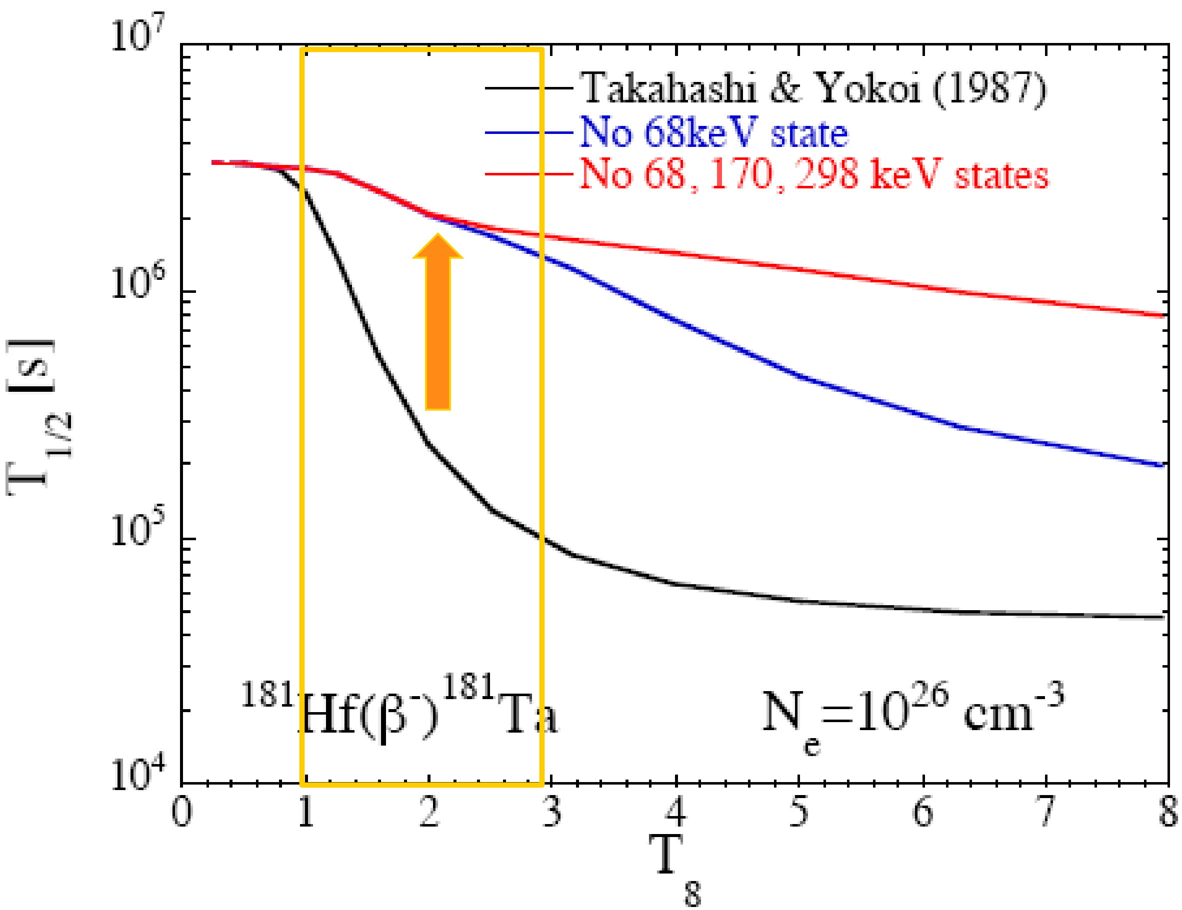
See Litvinov's talk

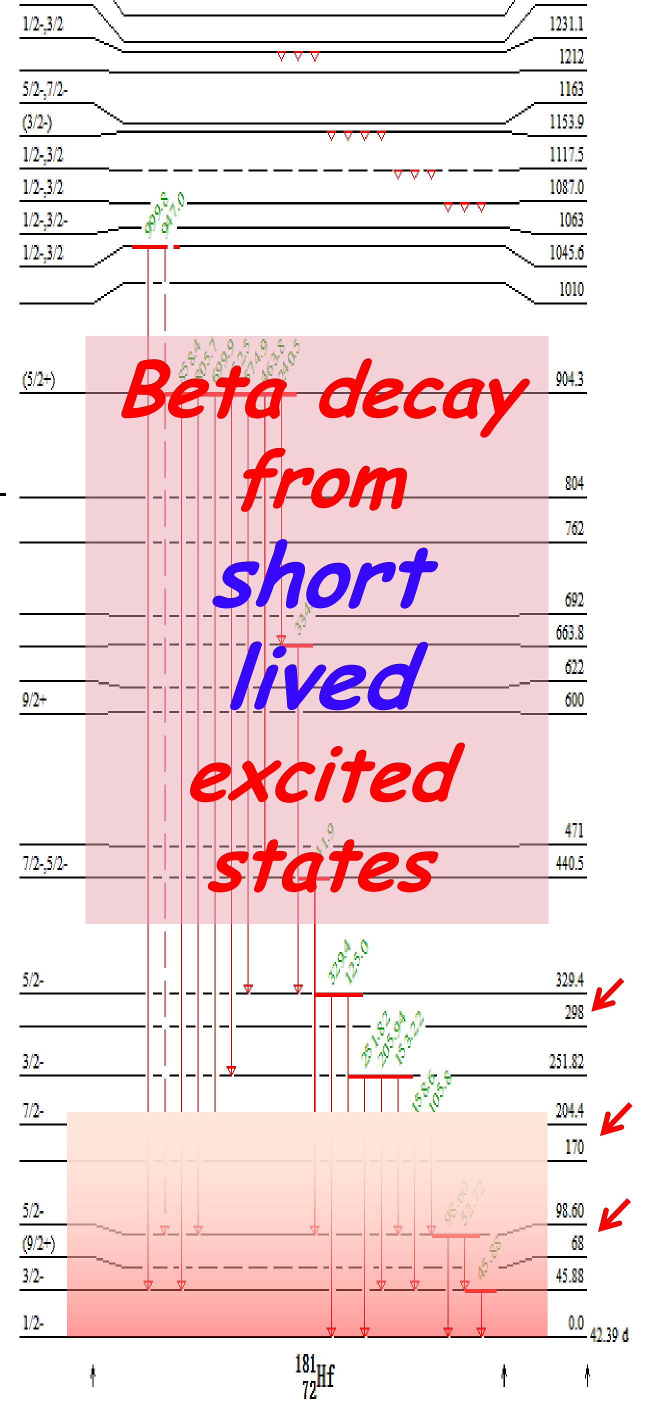
EARLY SOLAR SYSTEM

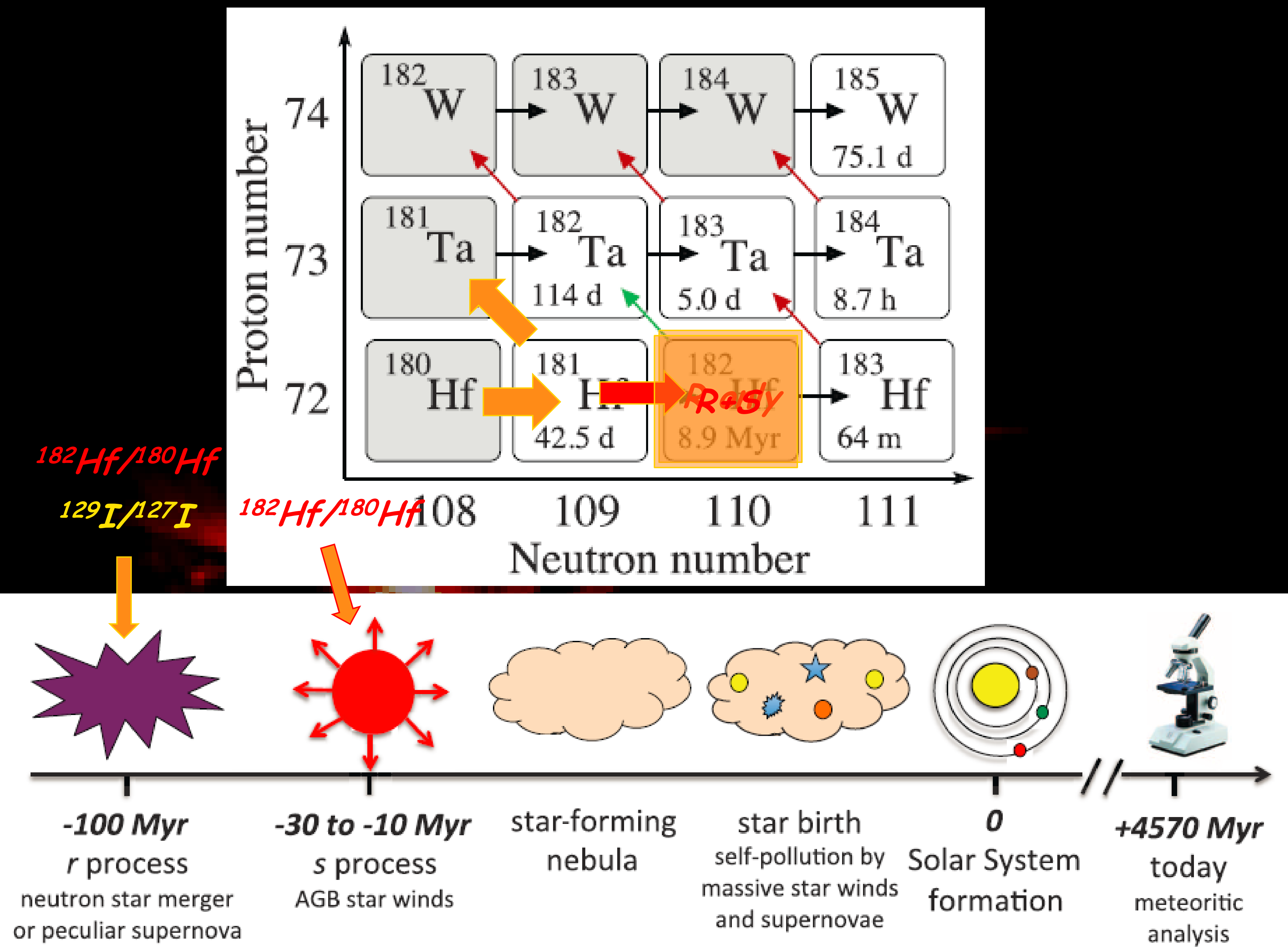
Science 345, 650 (2014)

Stellar origin of the ^{182}Hf cosmochronometer and the presolar history of solar system matter

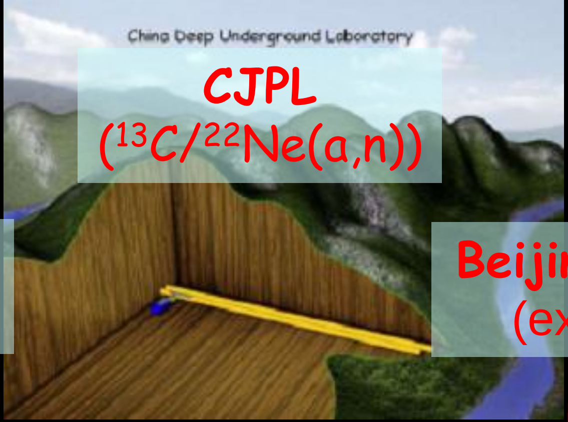
Maria Lugaro,[1*] Alexander Heger,[1,2,3] Dean Osrin,[1] Stephane Goriely,[4] Kai Zuber,[5] Amanda I. Karakas,[6,7] Brad K. Gibson,[8,9,10] Carolyn L. Doherty,[1] John C. Lattanzio,[1] Ulrich Ott[11]

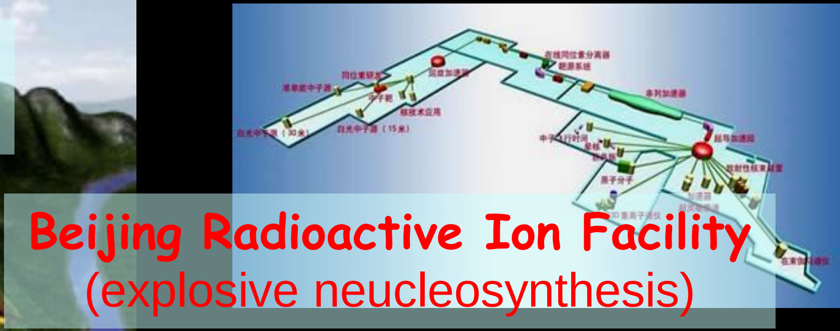






Proton number
74
73
72
182 W
183 W
184 W
185 W
75.1 d
181 Ta
182 Ta
114 d
183 Ta
5.0 d
184 Ta
8.7 h
180 Hf
181 Hf
42.5 d
182 Hf
8.9 Myr
R+S
183 Hf
64 m
108
109
110
111
Neutron number
182Hf/180Hf
129I/127I
182Hf/180Hf
-100 Myr
r process
neutron star merger
or peculiar supernova
-30 to -10 Myr
s process
AGB star winds
star-forming
nebula
star birth
self-pollution by
massive star winds
and supernovae
0
Solar System
formation
+4570 Myr
today
meteoritic
analysis





#1: Neutron sources
#2: stellar reaction rates
#3: stellar decay rates