On the origin of the chemical elements: From Big Bang Nucleosynthesis to Neutron Star Mergers

Big Bang Nucleosynthesis and the Cosmological Lithium Problem
Steller nucleosynthesis (neutron capture elements)
Ages and old clocks

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Università di Torino, 1 February 2019

Introducing the Universe

Our universe is formed
of matter and radiation

Both of them come in quantized forms
(particles and photons)

Introducing the Universe

We live (now) in a universe of matter

$$\rho(E_{\text{matter}}) \gg \rho(E_{\text{rad}})$$

$\rho(\mathrm{E}_{\mathrm{matter}})$ = 4.08 x 10^{-28} Kg/m^3

= 0.24 N_H/m^3

= **220 MeV/m^3**

$\rho(\mathrm{E}_{\mathrm{rad}}) = aT^4$

= 7.6x10^{-15} $(2.728)^4$

= **0.26 MeV/m^3**

Introducing the Universe

Atomic nuclei exist in the universe

Radioactivity and nuclear reactions show that nuclei are NOT immutable objects but that they have been formed somewhere, sometime

Introducing the Universe

The matter in the universe is
essentially in the form of
Hydrogen and Helium
with a tiny addition of “metals”

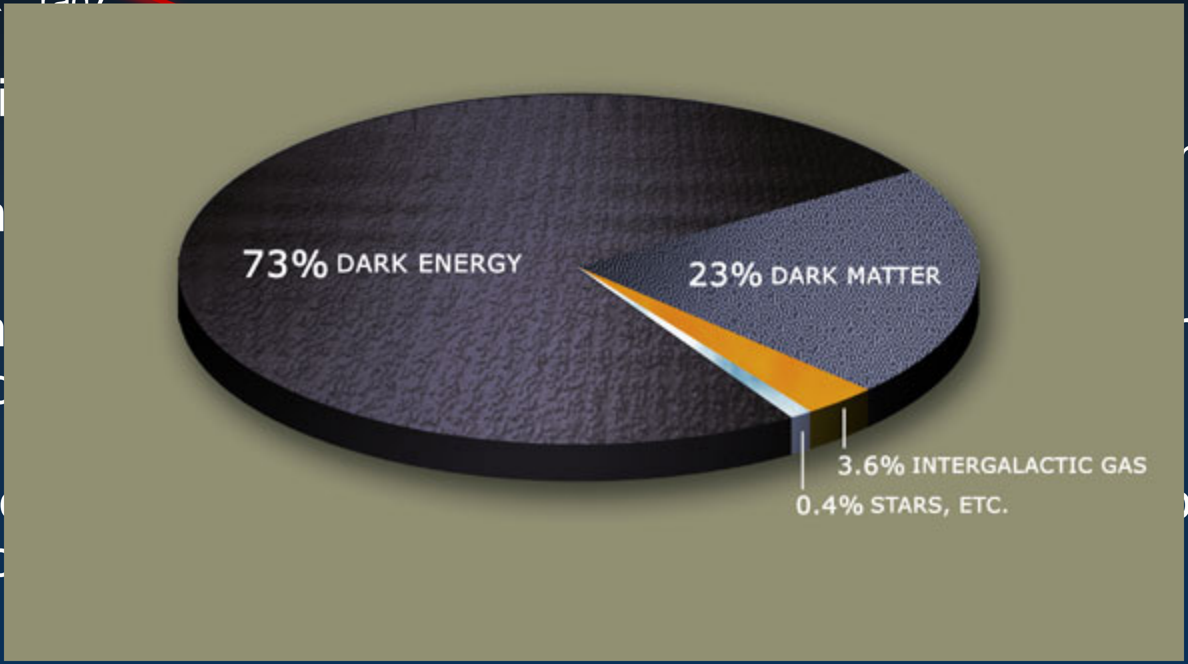
Introducing the Universe

The distribution of the abundance of the elements show common patterns for the stars of our galaxy

Introducing the Universe

- Our universe is formed of matter and radiation
  Both of them come in quantized forms (particles and photons)

- ~~We live (now) in a universe of matter~~
  ~~$\rho(E_{mvis}) >> \rho(E_{rad})$~~



- Atomic nuclei
  Radioactivity nmutable
  objects but th

- The matter in n and Helium
  with a tiny ac

- The distributi on patterns
  for the stars c

Source: for example C.E. Rolfs and W.S. Rodney, "Cauldrons in the Cosmos"
The University of Chicago Press (1988)

Introducing the Universe

- Our universe
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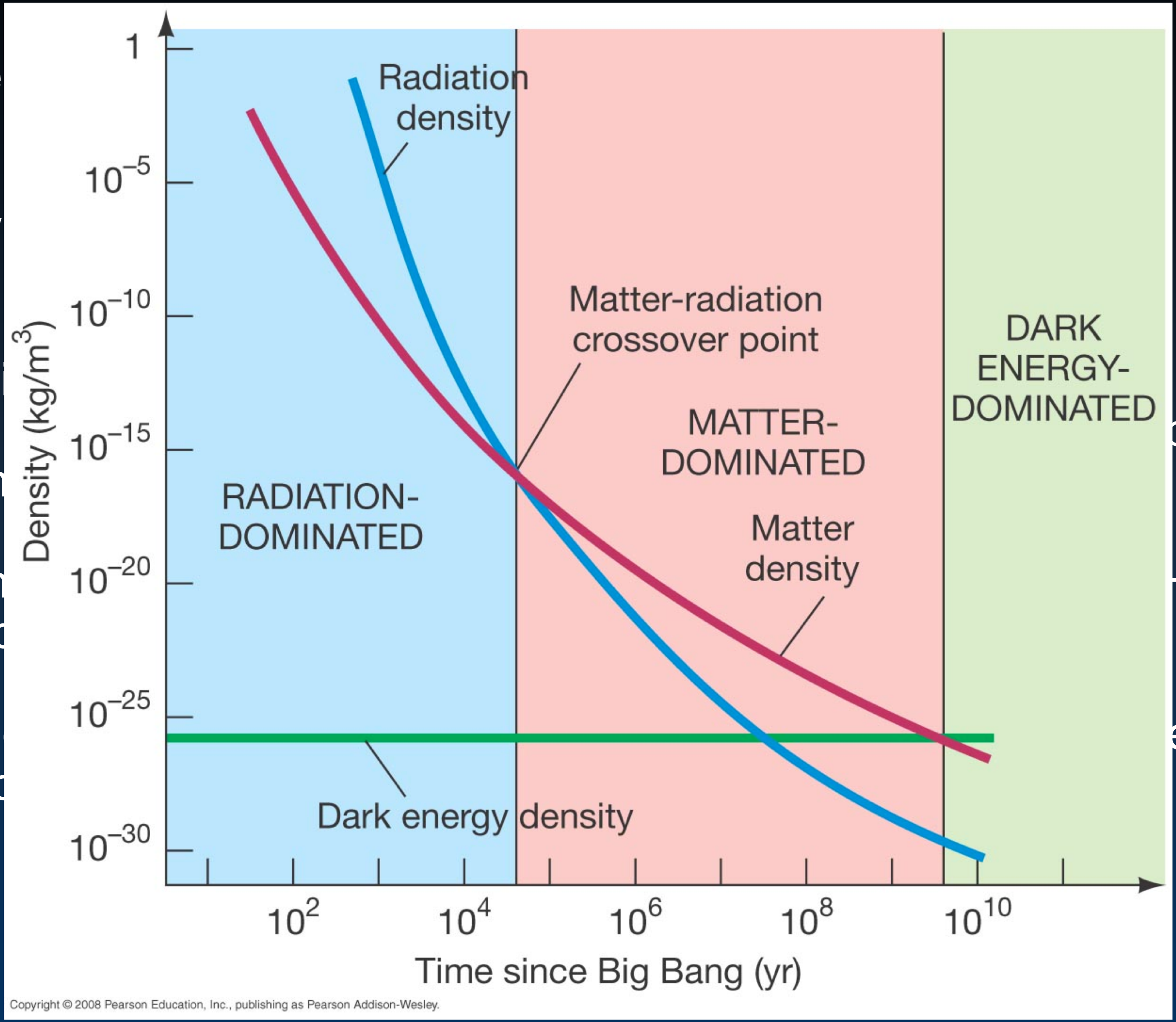


Introducing the Universe

- Our universe is formed of matter and radiation
  Both of them come in quantized forms (particles and photons)

- We live (now) in a Λ dominated universe

- Atomic nuclei exist in the universe
  Radioactivity and nuclear reactions show that nuclei are NOT immutable objects but that they have been formed somewhere, sometime

- The matter in the universe is essentially in the form of Hydrogen and Helium with a tiny addition of “metals”

- The distribution of the abundance of the elements show common patterns for the stars of our galax

A brief history of the Universe

BANG!

Galaxy formation

?

Solar-system formation

4.6 Gyr

Now
&
here

Thermal equilibria

Thermal equilibrium between particles and antiparticles in a photon bath

$x + \bar{x} \leftrightarrow 2\gamma$ as long as $\langle E_\gamma \rangle \sim kT \gg m_x c^2$

i.e. $p + \bar{p} \leftrightarrow 2\gamma$ when $kT \sim 10^3$ MeV $\sim 10^{13}\ ^\circ\mathrm{K} = 10^4 T_9$

$$T_9(10^9\ ^\circ\mathrm{K}) = \frac{kT\ [\mathrm{MeV}]}{0.08617}$$

Nucleo-synthesis is possible only when

$\langle E_\gamma \rangle \lesssim$ binding energy of nuclei ~ MeV

i.e. $T \lesssim 10^{10}\ ^\circ\mathrm{K}$ or $T_9 \lesssim 10$

ΛCDM cosmology

$$H(a) = \frac{\dot{a}}{a} = H_0\sqrt{(\Omega_{\rm cdm} + \Omega_b)a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda}$$

PLANCK CBM measurements (2015 results):

H_0 = 67.74 ± 0.46 km/s/Mpc

$\Omega_{\rm cdm}$ = 0.2589 ± 0.0057

Ω_b = 0.0486 ± 0.0010

Ω_Λ = 0.6911 ± 0.0062

$N_{\nu-eff}$ = 3.2 ± 0.5

age = 13.799 ± 0.021 Gyr

Key parameters for the BBN network calculations:

- $N_{\nu-eff}$
- $\eta \equiv \frac{n_b}{n_\gamma}$

$$\eta \times 10^{10} = 273.8\,\Omega_b h^2$$
$$= 6.13 \pm 0.03$$

source: the Planck Collaboration (2018)

Big bang nucleosynthesis

< 1 sec strongly radiation-dominated homogenous universe

$p + e^- \rightleftharpoons n + \nu_e$

$n + e^+ \rightleftharpoons p + \bar{\nu}_e$ $\qquad n/p = e^{-Q/kT} = e^{-1.293/kT}$

freeze-out weak interation at kT ~ 0.7 MeV or $T_9 \sim 8$

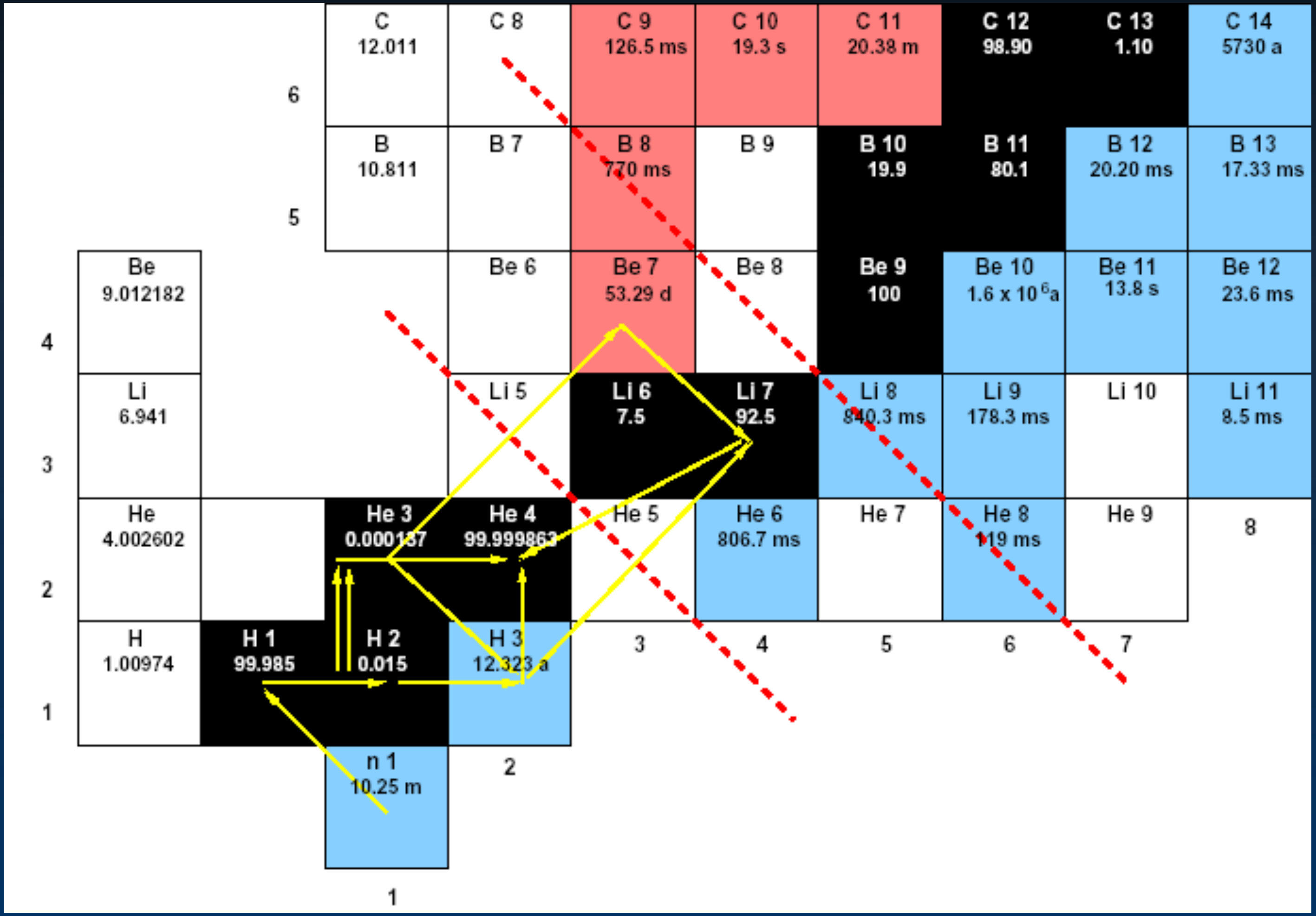
$n/p = e^{-1.293/0.7} = 1/6 \rightarrow 1/7$

then, the primordial mass fraction of ^{4}He is:

$$Y_p = \frac{2(n/p)}{1+(n/p)} \cong 0.25$$

Big bang nucleosynthesis

Reactions
n-decay
$p(n,\gamma)d$
$d(p,\gamma)^3\mathrm{He}$
$d(d,n)^3\mathrm{He}$
$d(d,p)t$
$^3\mathrm{He}(n,p)t$
$t(d,n)^4\mathrm{He}$
$^3\mathrm{He}(d,p)^4\mathrm{He}$
$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
$t(\alpha,\gamma)^7\mathrm{Li}$
$^7\mathrm{Be}(n,p)^7\mathrm{Li}$
$^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$



Light elements: observations

^{4}He

$$Y_p = 0.245 \pm 0.004$$

not measurable in stars, emission lines from gaseous nebulae in dwarf galaxies, with low metallicity

D

$$D/H = (2.53 \pm 0.04) \times 10^{-5}$$

from quasar absorption lines (nearly unprocessed gas)

^{3}He

Difficult to measure in unevolved objects + uncertain chemical evolution
less useful as an observational test

^{7}Li

$$^{7}Li/H=(1.6 \pm 0.3) \times 10^{-10}$$

from metal-poor stars in the Galactic halo
constant Li/H as function of metal content interpreted as primordial

^{4}He and ^{2}H concordance

- ✓ Yp = 0.245 ± 0.004 (calc.) Yp = 0.246
- ✓ D/H = (2.53 ± 0.04) x 10^{-5} (calc.) D/H = 2.43 x 10^{-5}

Reactions
n-decay
$p(n,\gamma)d$
$d(p,\gamma)^3\mathrm{He}$
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$d(d,p)t$
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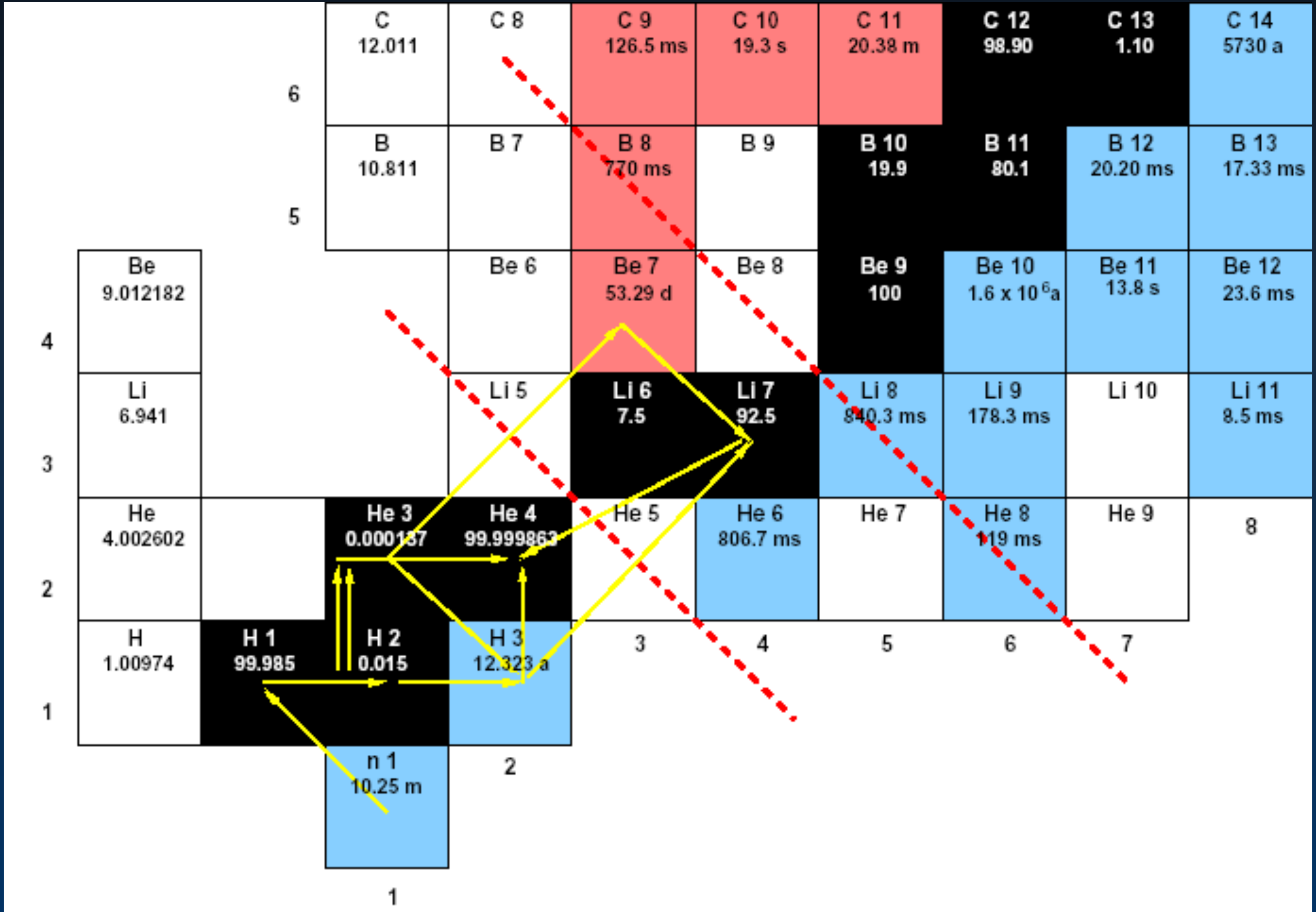
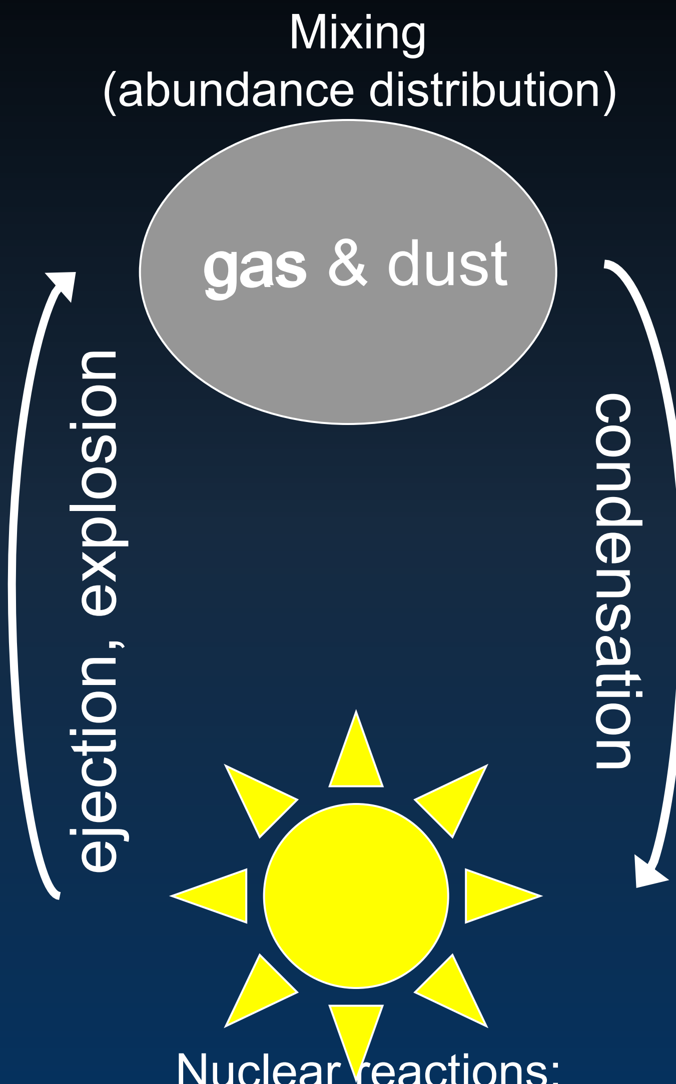


Stellar Nucleosynthesis



Mixing
(abundance distribution)

gas & dust

ejection, explosion

condensation

Nuclear reactions:
- energy generation
- nucleosynthesis

CLiP – Cosmological Lithium Problem

Best value from observations:
$[Li/H] = 1.6 \pm 0.3$

━

Expected from CMB analysis
and standard BBN

$[Li/H] = 4.45 \pm 0.05$

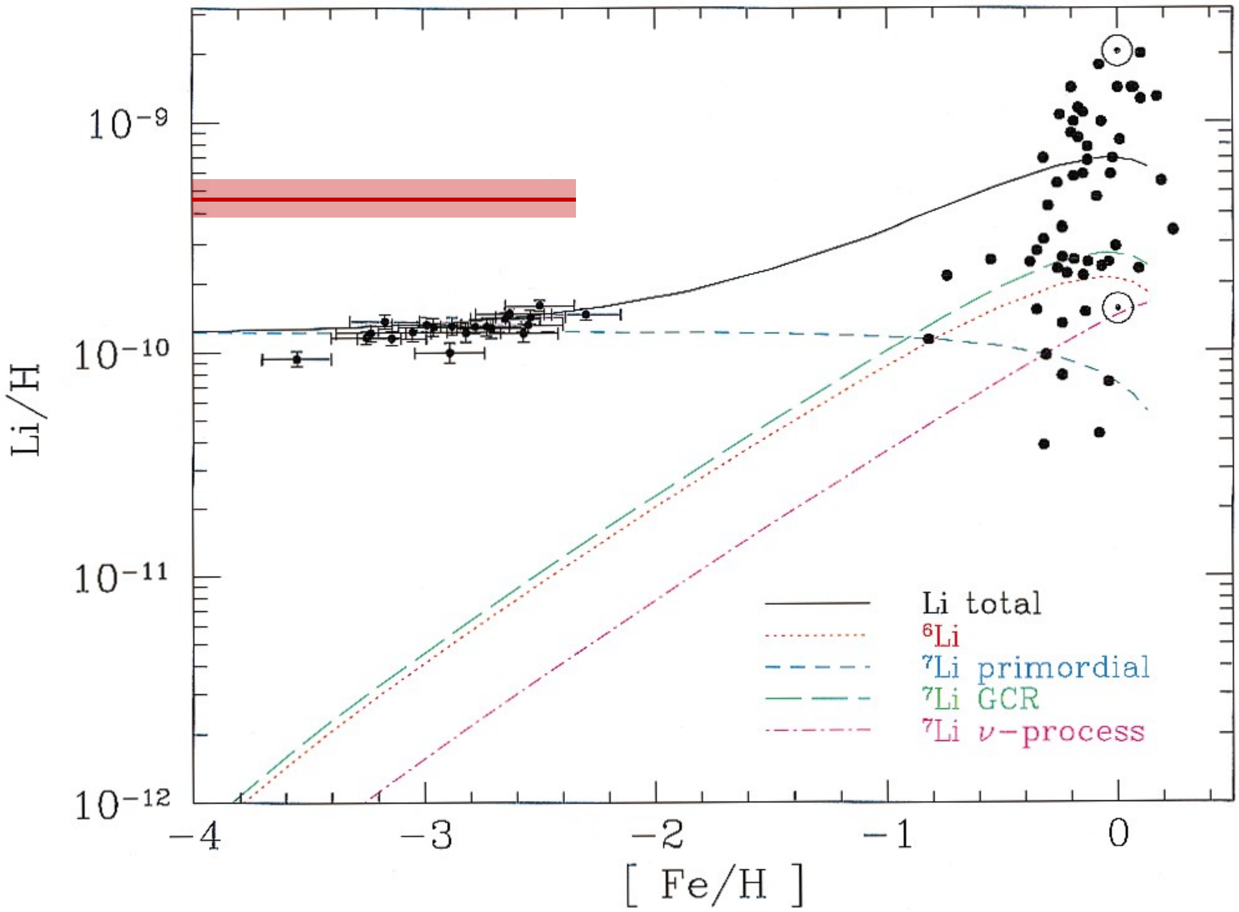
▬

Expected from standard BBN
Y_p and D
abundance concordance

$3.9 \leq [Li/H] \leq 5.3$

[ ] : 10^{-10}

BD Fields et al., PDG Review (2016)



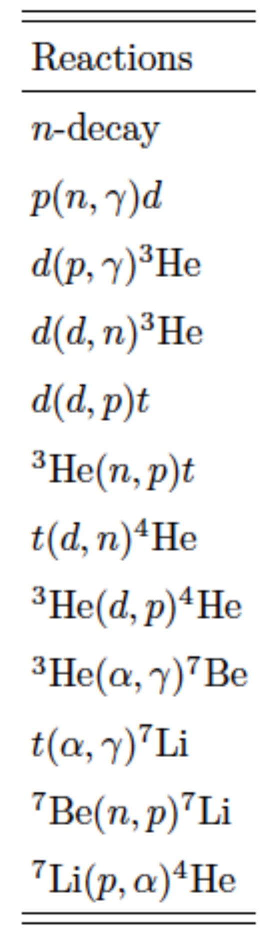
Contributions to the total predicted lithium abundance from the adopted GCE model of Fields & Olive (1999a, 1999b), compared with low metallicity stars (RNB) and high-metallicity stars (Lambert, Heath, & Edvardsson 1991). The solid curve is the sum of all components.

S G Ryan et al. ApJ 530 (2000) L57

BBN reaction network

Over 90% of the cosmological ^{7}Li derives from ^{7}Be + e^{-} → ^{7}Li + ν_e

^{7}Li is readily destroyed by ^{7}Li(p,α)^{4}He during BBN



Reactions
n-decay
$p(n,\gamma)d$
$d(p,\gamma)^{3}\mathrm{He}$
$d(d,n)^{3}\mathrm{He}$
$d(d,p)t$
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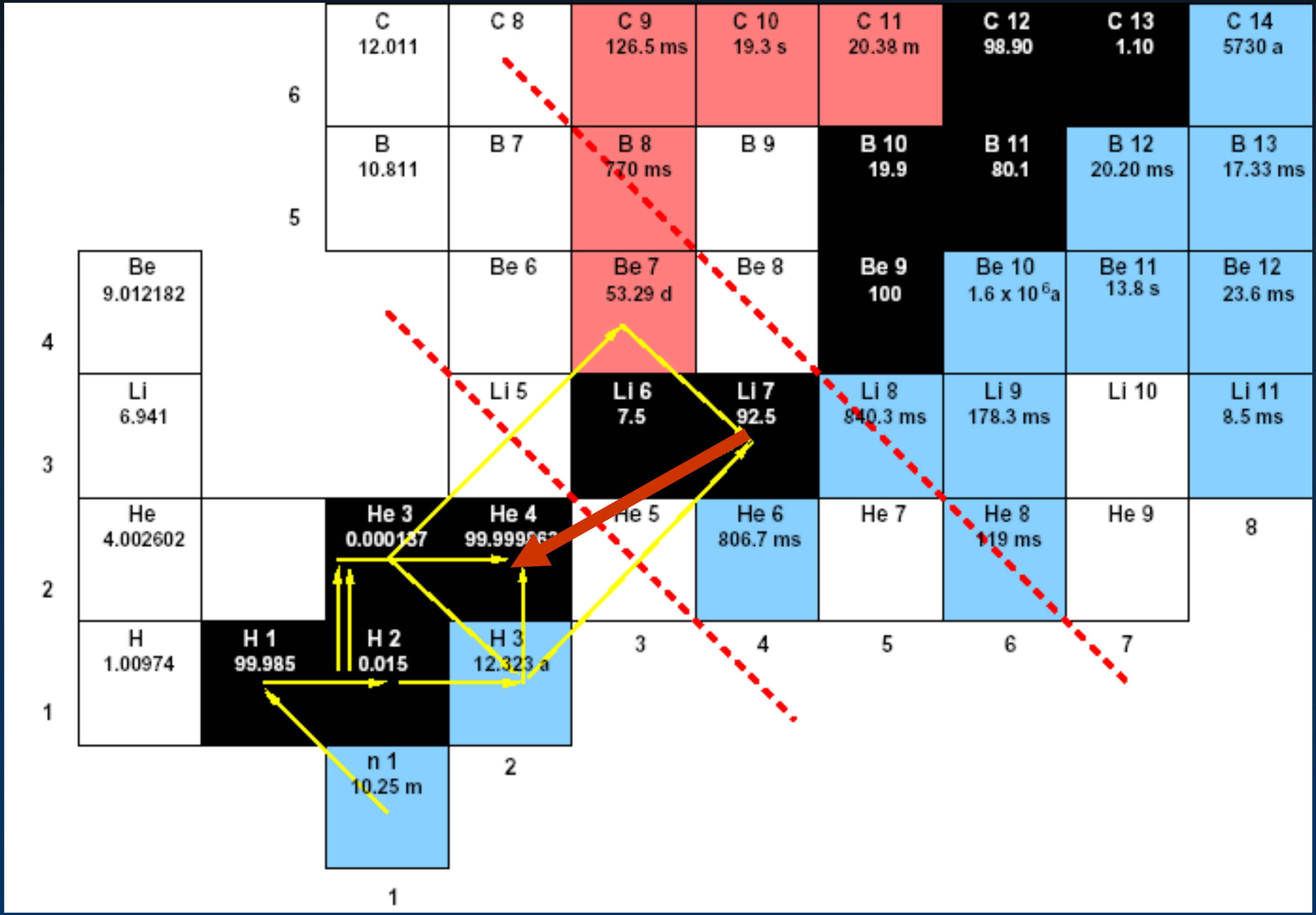
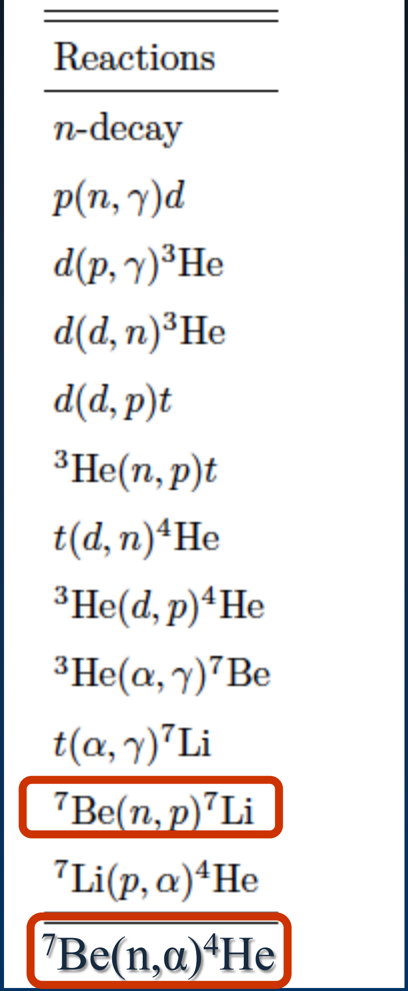


^{7}Be destruction by neutrons

Recent measurements @ CERN n_TOF



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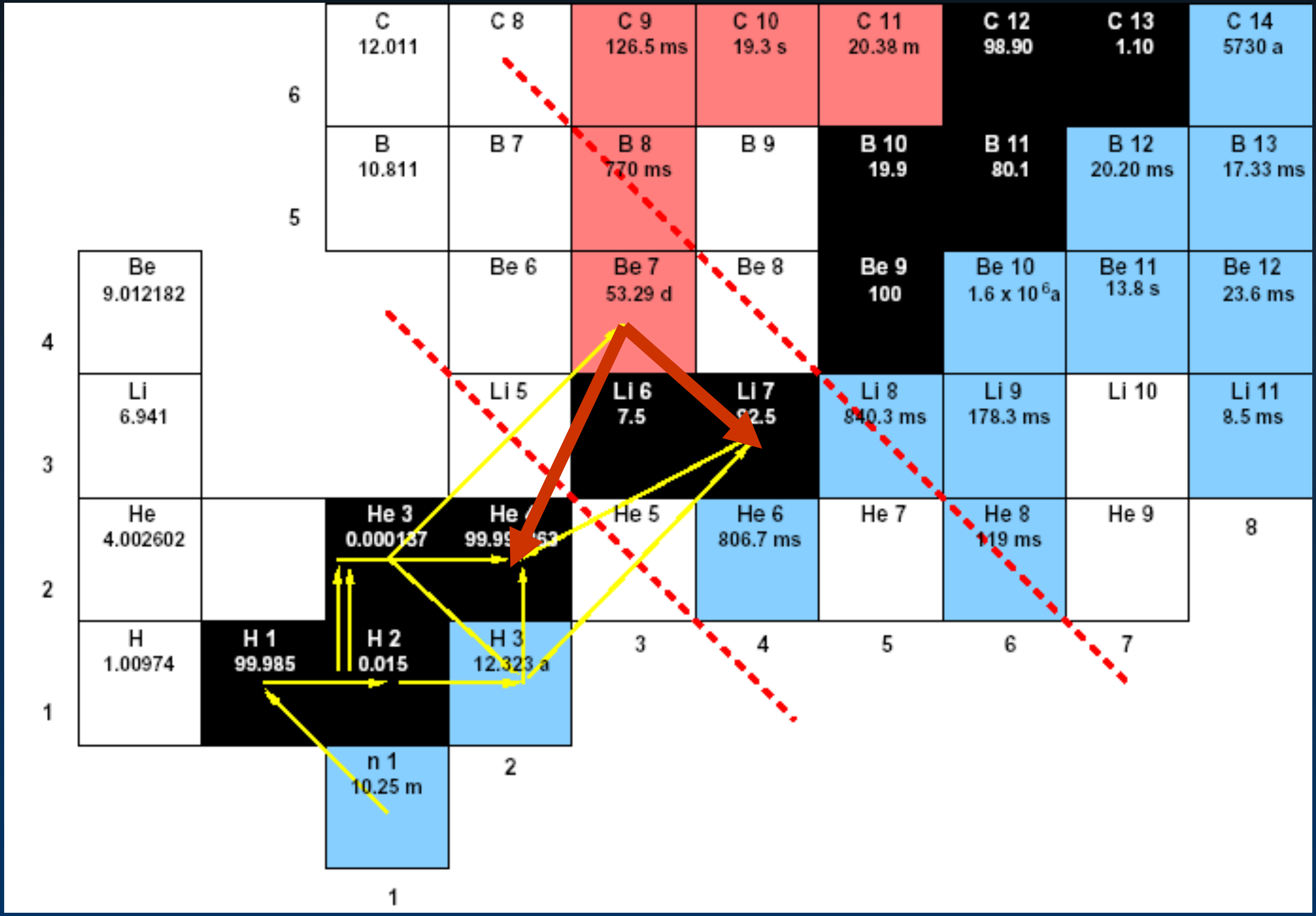
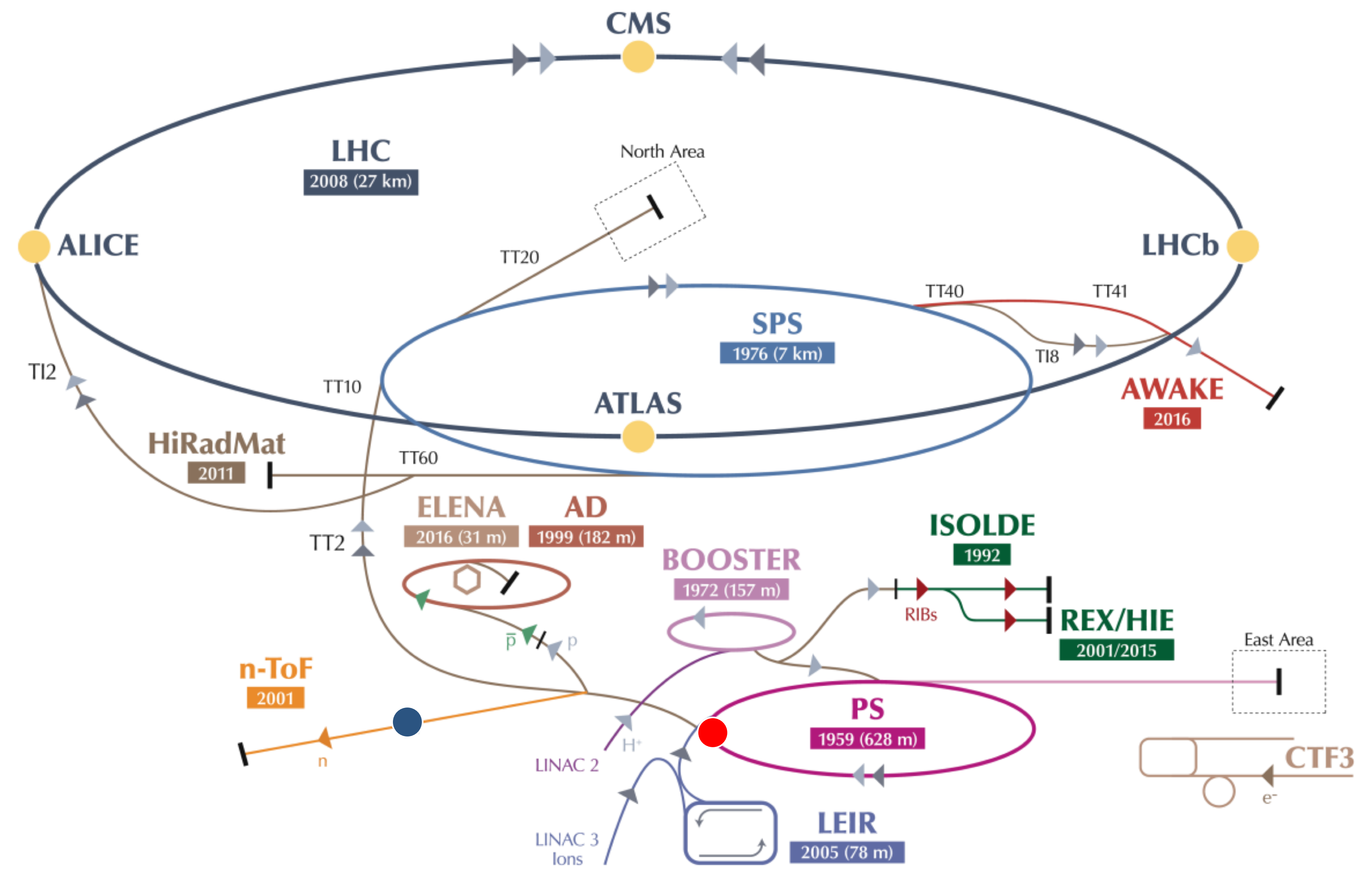
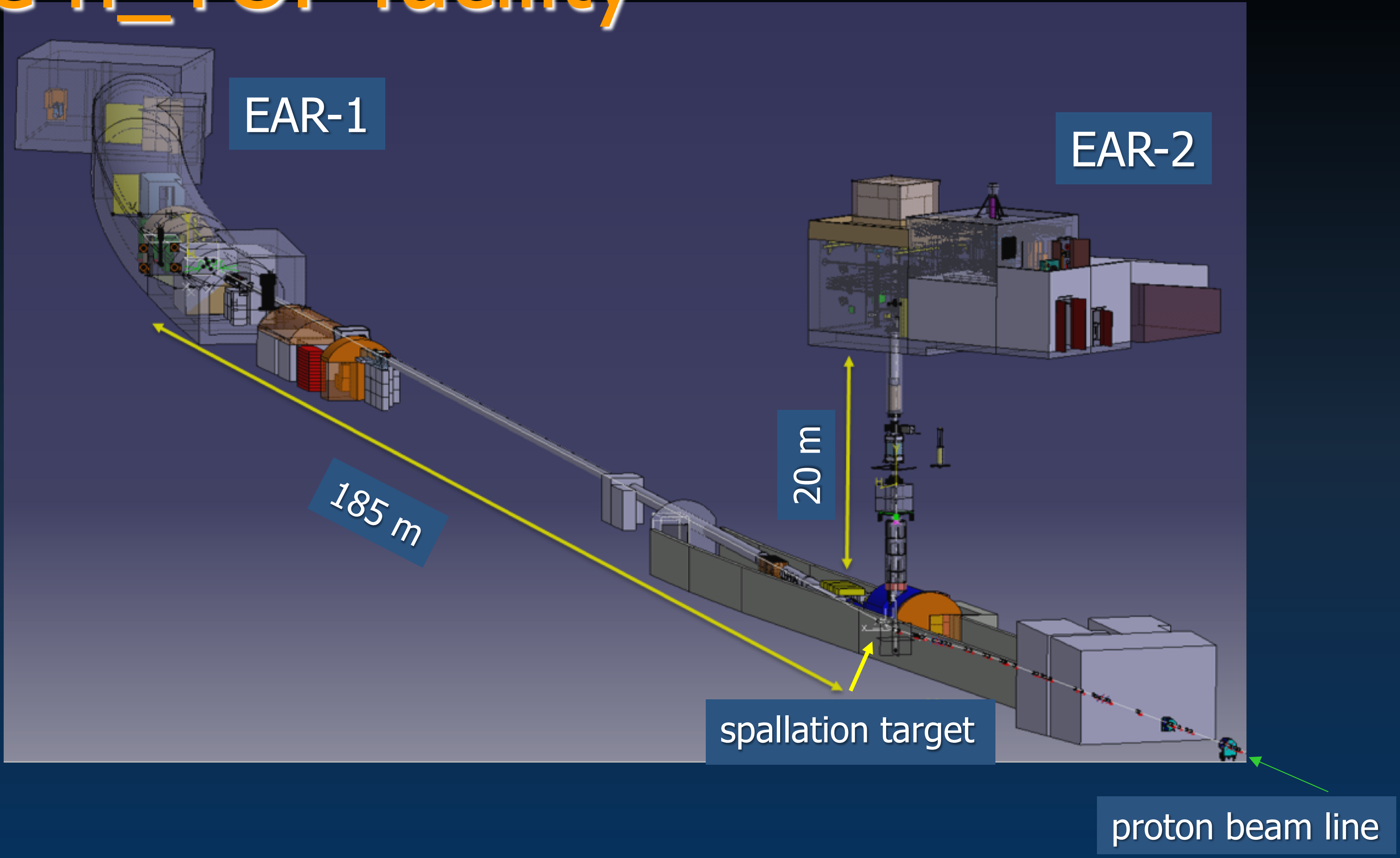


n_TOF @ CERN


CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT20
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
2011
TT60
ELENA
2016 (31 m)
AD
1999 (182 m)
TT2
ISOLDE
1992
BOOSTER
1972 (157 m)
RIBs
REX/HIE
2001/2015
East Area
p̄
p
n-ToF
2001
n
H+
LINAC 2
PS
1959 (628 m)
CTF3
e−
LINAC 3
Ions
LEIR
2005 (78 m)

The n_TOF facility



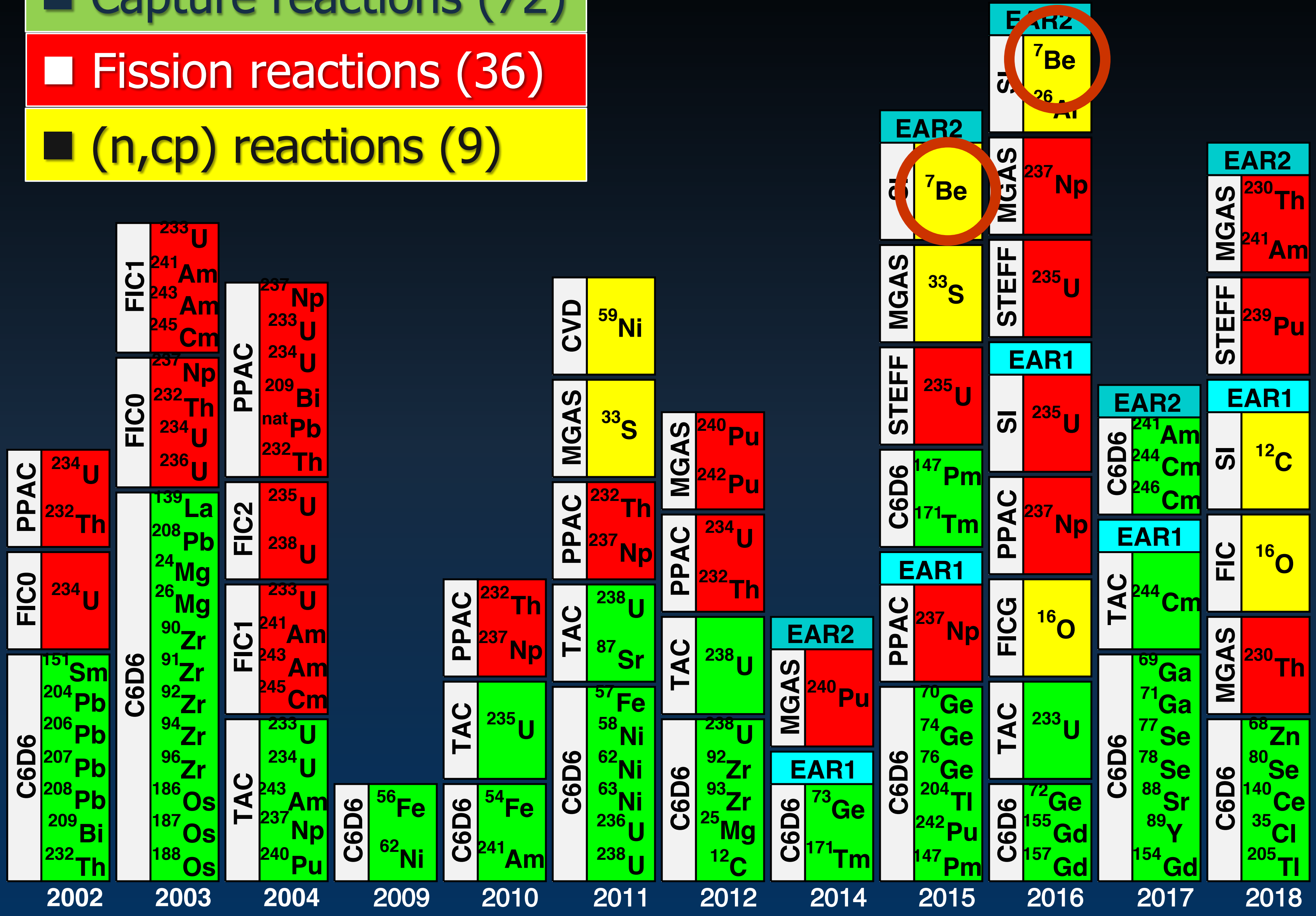
n_TOF basic parameters

proton beam momentum	20 GeV/c
intensity (dedicated mode)	7 x 10^{12} protons/pulse
repetition frequency	1 pulse/1.2s
pulse width	6 ns (rms)
n/p	300
lead target dimensions	80x80x60 cm^3
cooling & moderation material	H_2O (borated)
moderator thickness in the exit face	5 cm
neutron beam dimension in EAR-1 (capture mode)	2 cm (FWHM)

🟩 Capture reactions (72)

🟥 Fission reactions (36)

🟨 (n,cp) reactions (9)



courtesy of F Gunsing

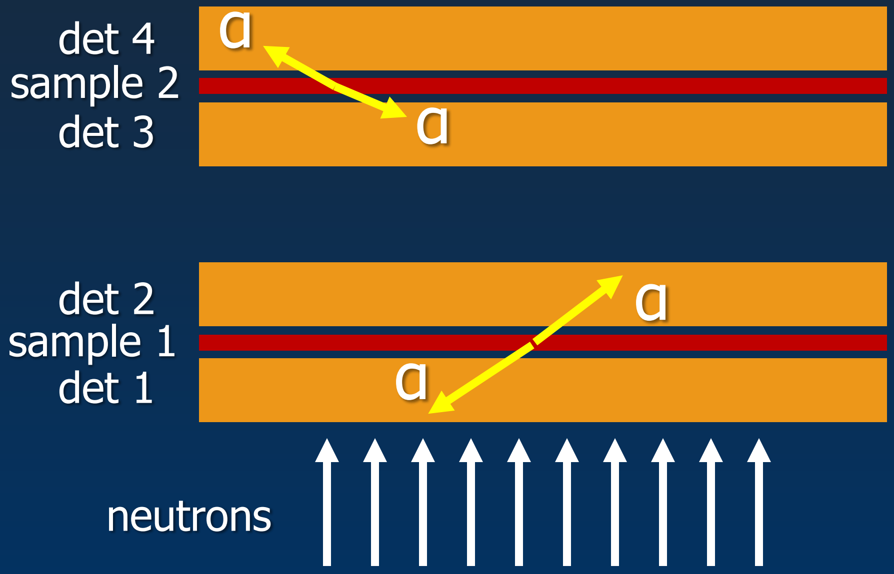
^{7}Be(n,α)^{4}He measurement

Silicon detectors insterted directly into the neutron beam

3x3 cm^2 active area, 140 μm thickness

Two samples with ~18 GBq activity each (~1.4 μg of ^{7}Be)

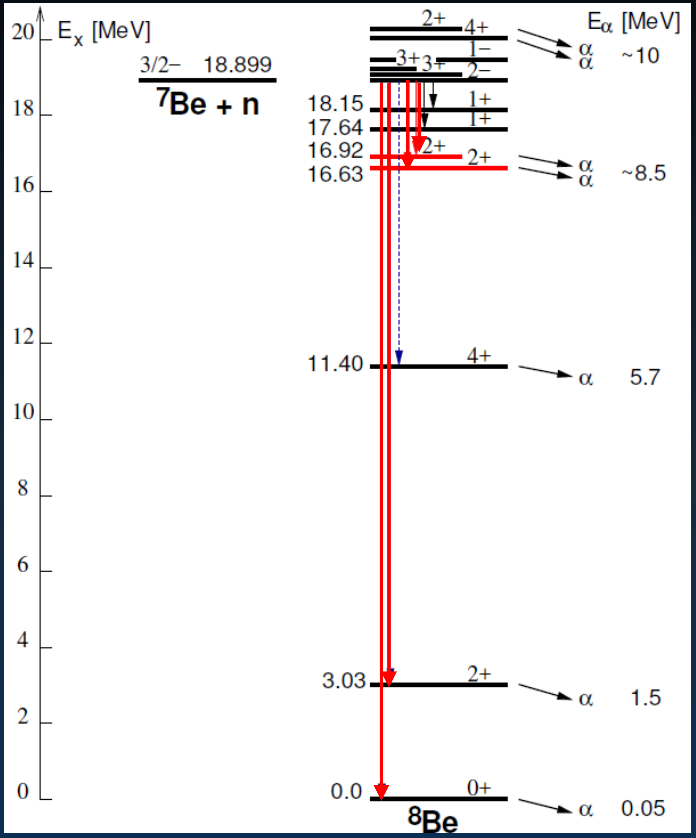
Strong rejection of BG events due to tof, low duty-cycle, coincidence signals for:



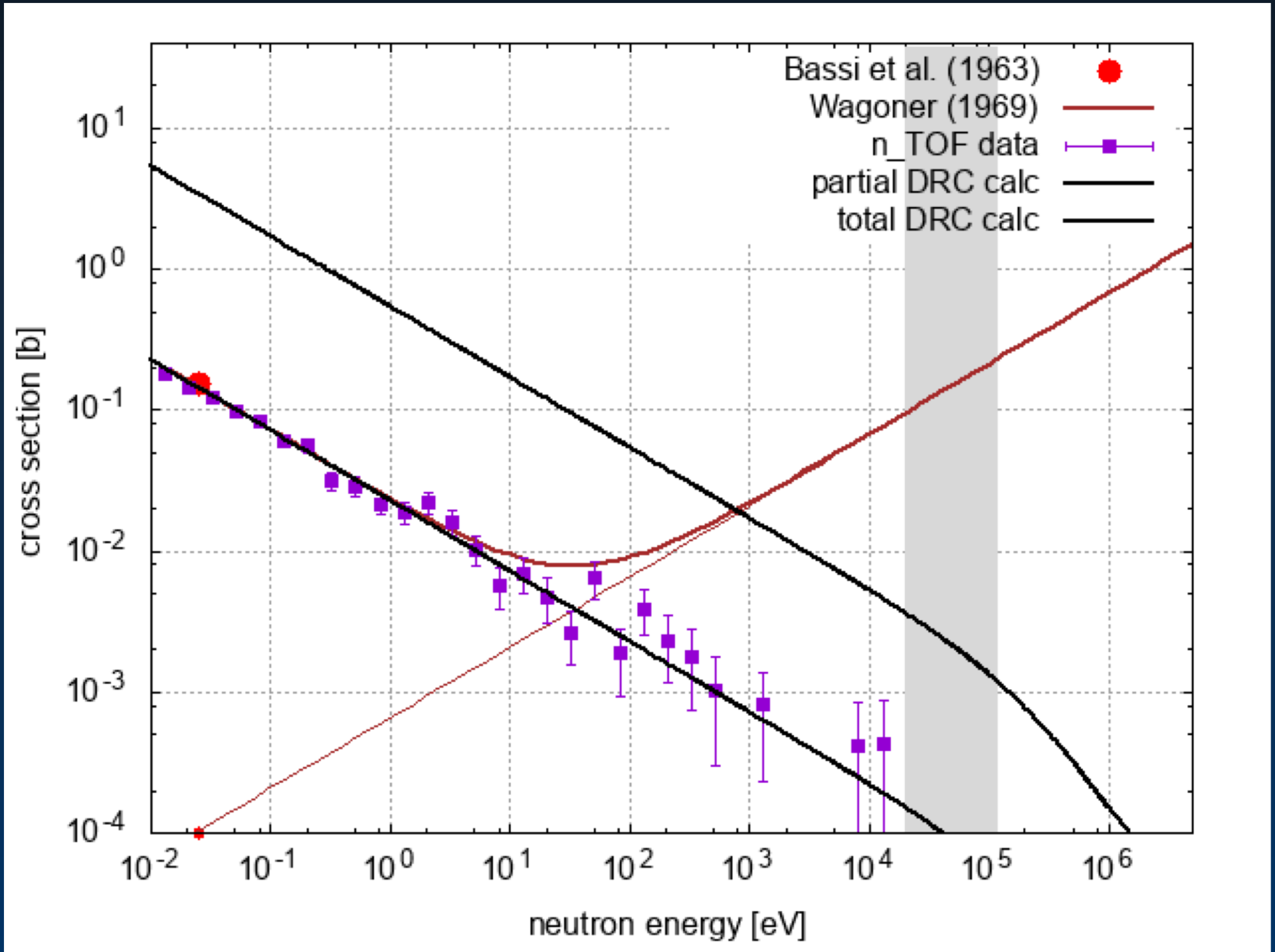
- protons from the (n,p) channel
- γ from ^{7}Be activity
- n+^{7}Li → ^{8}Li (β^-) 840 ms → ^{8}Be* → 2α

L. Cosentino et al. (n_TOF Collaboration), NIM A 830 (2016) 197-205

^{7}Be(n,α)^{4}He



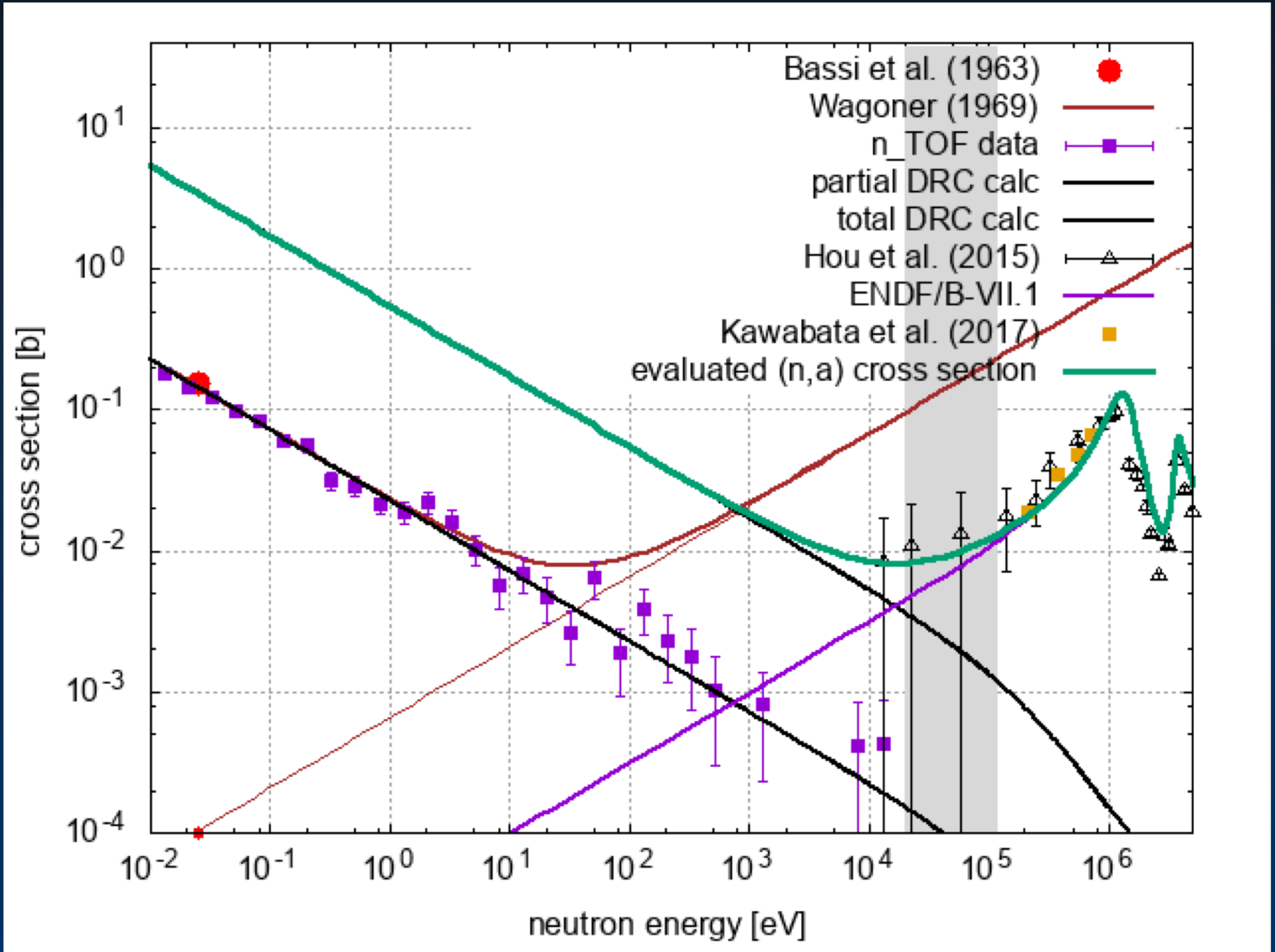
A factor of 25 larger (n,a) cross section at thermal energy!



M Barbagallo et al. (The n_TOF Collaboration)
Phys. Rev. Lett. 117 (2016) 152701

$^{7}Be(n,\alpha)^{4}He$: new cross section

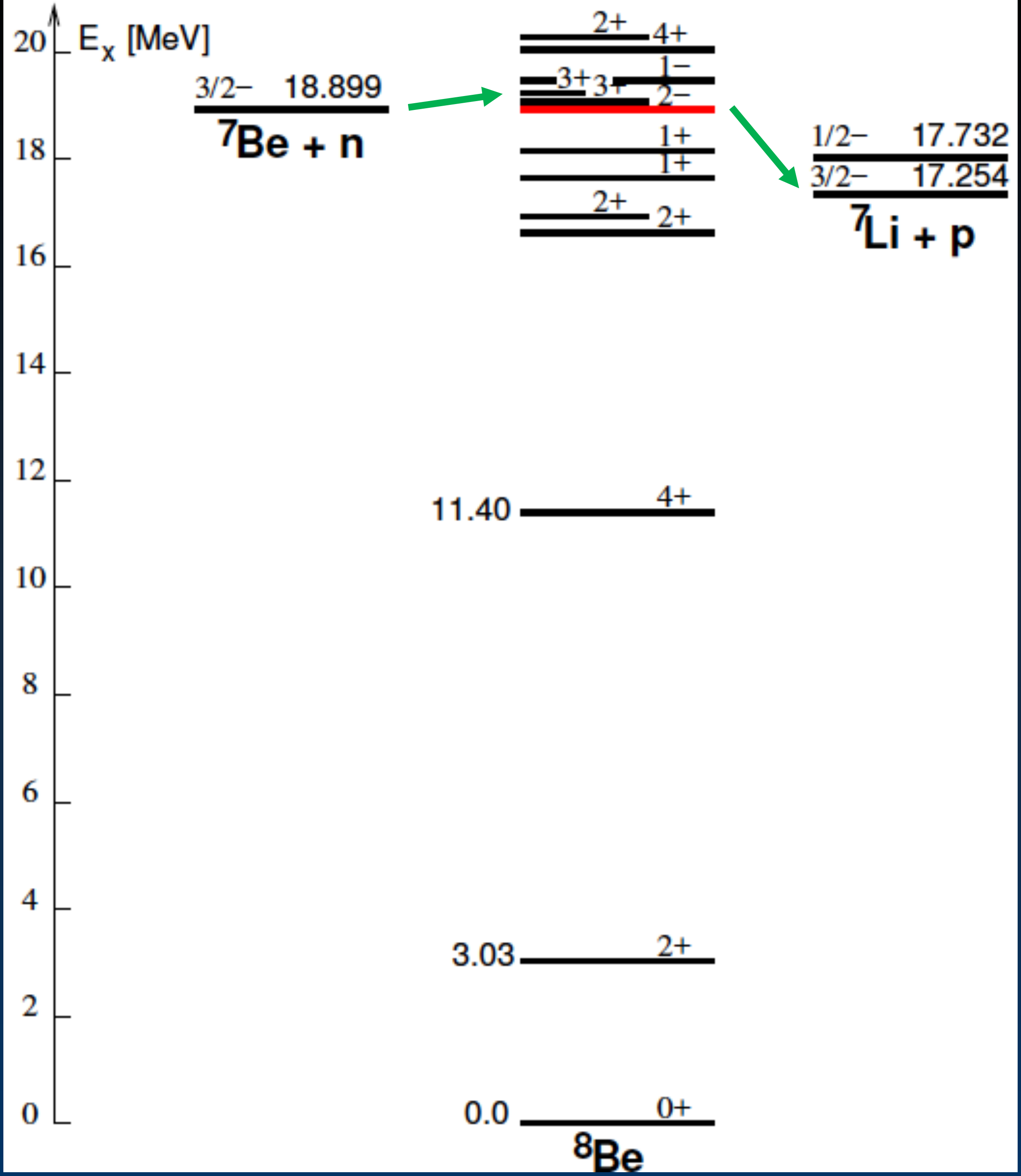
(n,α) data combined with measurements of time-reversal and/or indirect reactions, e.g. $\alpha(^{4}He,n)^{7}Be$



M Barbagallo et al. (The n_TOF Collaboration)
Phys. Rev. Lett. 117 (2016) 152701

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

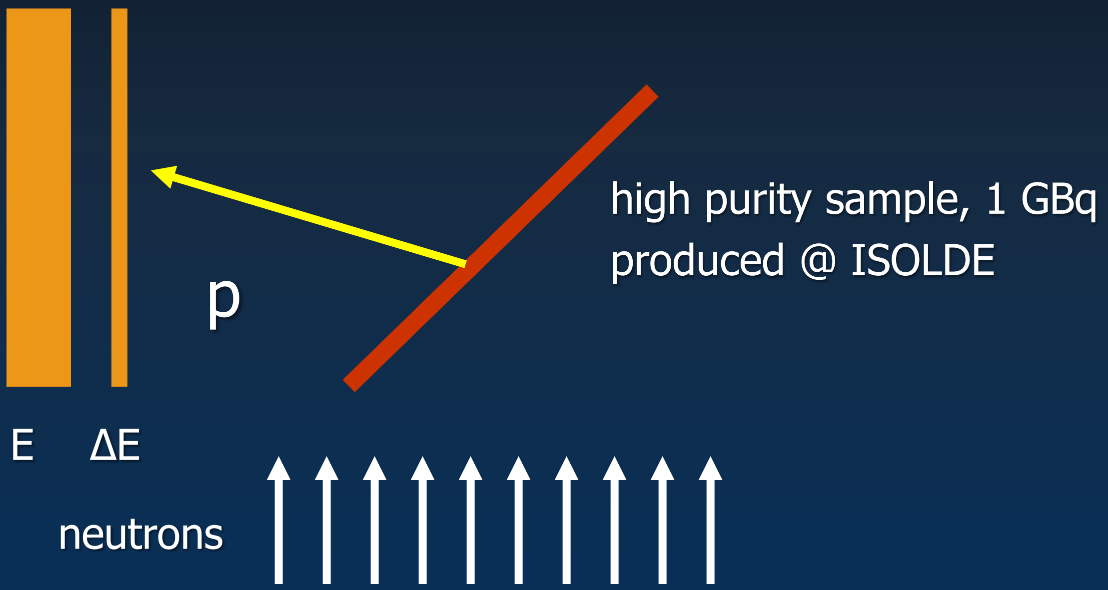
$^{7}Be(n,p)^{7}Li$

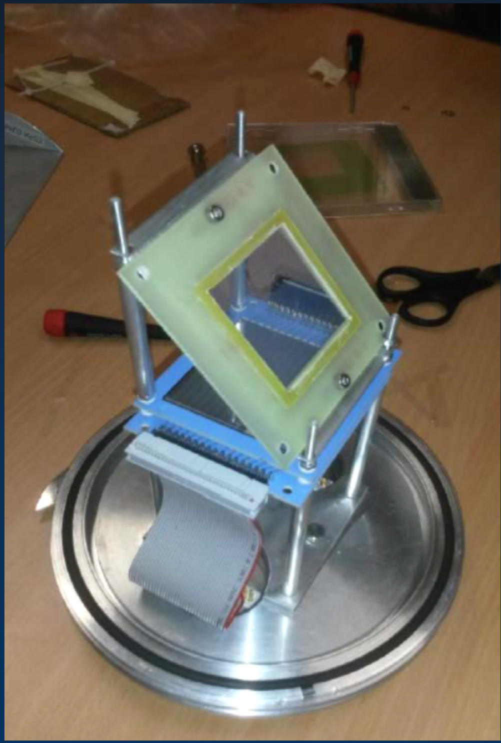

E$_x$ [MeV]
20
18
16
14
12
10
8
6
4
2
0
3/2− 18.899
^{7}Be + n
2+
4+
3+
3+
1−
2−
1+
1+
2+
2+
11.40
4+
3.03
2+
0.0
0+
^{8}Be
1/2− 17.732
3/2− 17.254
^{7}Li + p

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

Silicon telescope from Lodz University

Detection and identification of protons of 1 and 1.4 MeV





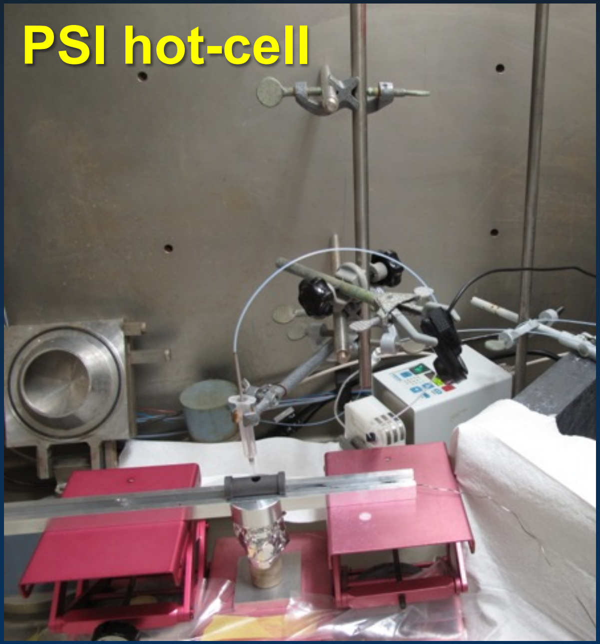
E. Maugeri *et al.* (The n_TOF Collaboration), Nucl. Instr. and Meth. A **889** (2018) 138

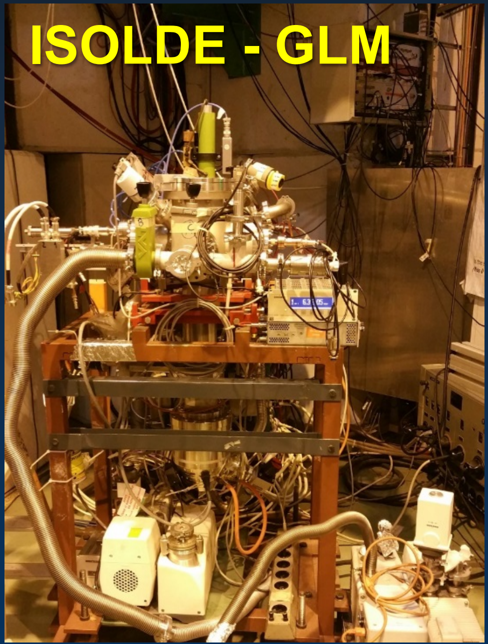
M. Barbagallo *et al.* (The n_TOF Collaboration), Nucl. Instr. and Meth. A **887** (2018) 27-3

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

A three steps experiment:

- Extraction of 200 GBq from water cooling of SINQ spallation source at PSI
- Implantation of 30 keV (~45 nA) ^{7}Be beam on suited backing using ISOLDE-GPS separator and RILIS
- Measurement at n_TOF-EAR2 using a silicon telescope (20 and 300 μm, 5x5 cm^{2} strip device)





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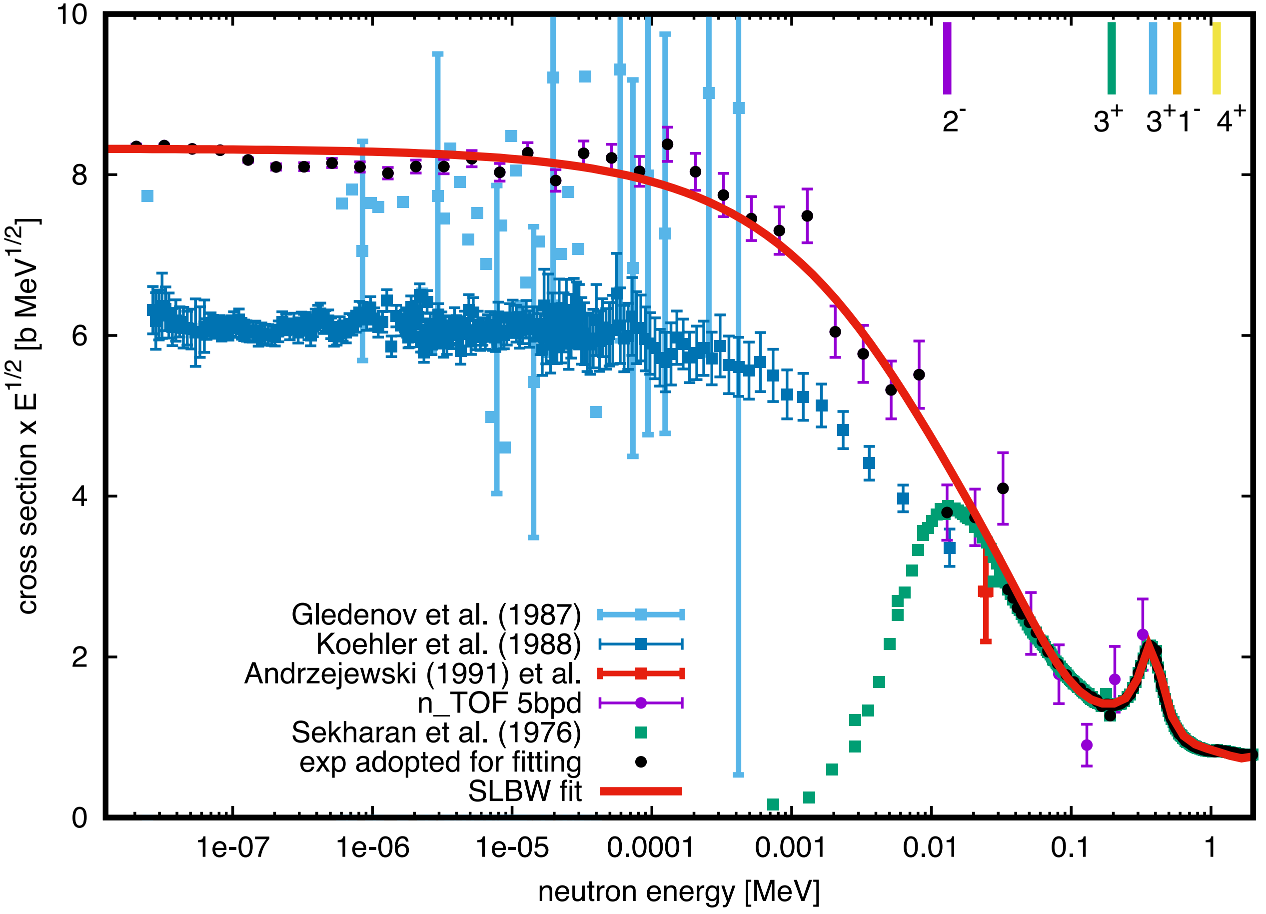
M. Barbagallo *et al.* (The n_TOF Collaboration), Nucl. Instr. and Meth. A **887** (2018) 27-3

^{8}B states included in the fitting

L Damone et al. (The n_TOF Collaboration), Phys. Rev. Lett. **121**, 042701 (2018)

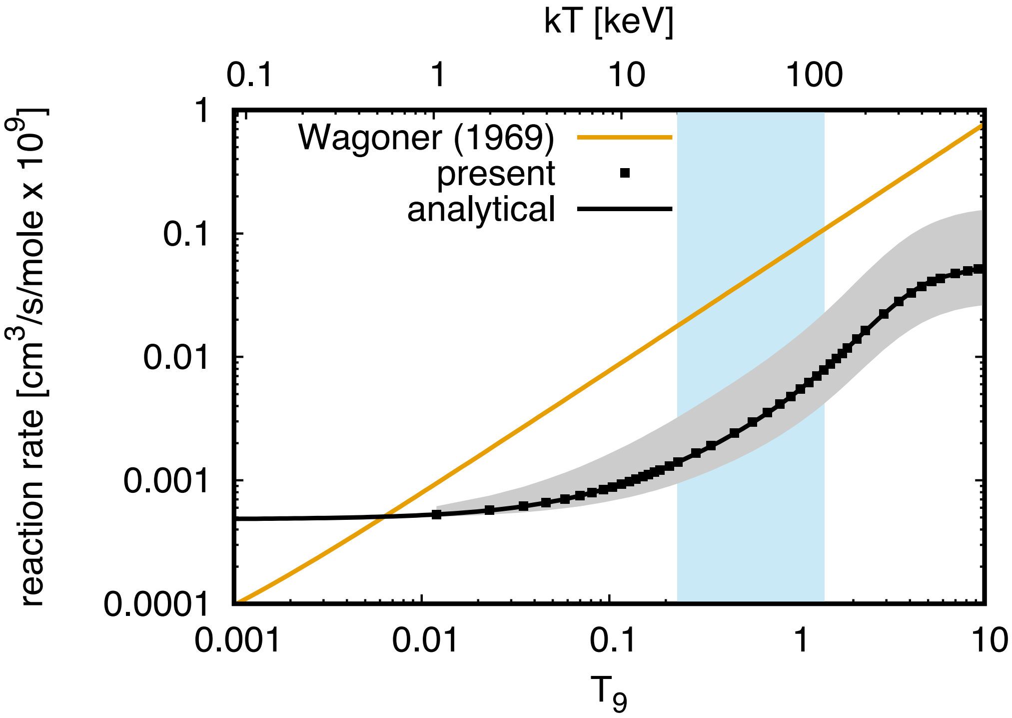
A total of 9 states included in the fit

- Single-level Breit-Wigner formalism (SLBW)
- E_n up to 2 MeV
- E_x and widths from other reaction channels
- Γ_n and/or Γ_p fitted

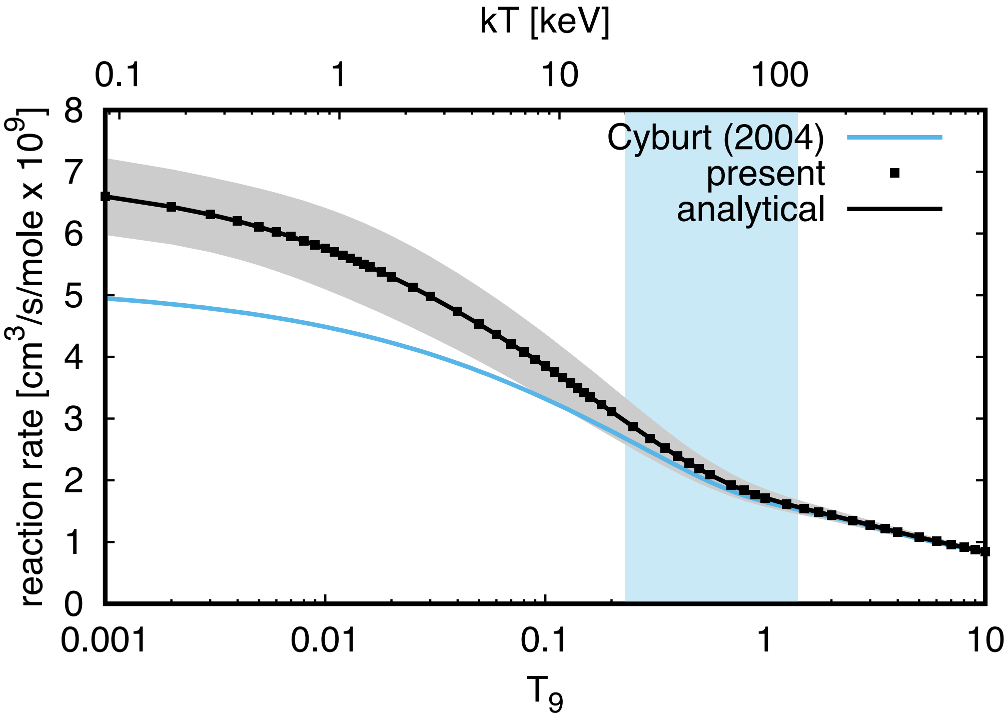


Reaction rates

$^{7}\mathrm{Be}(n,\alpha)^{4}\mathrm{He}$



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



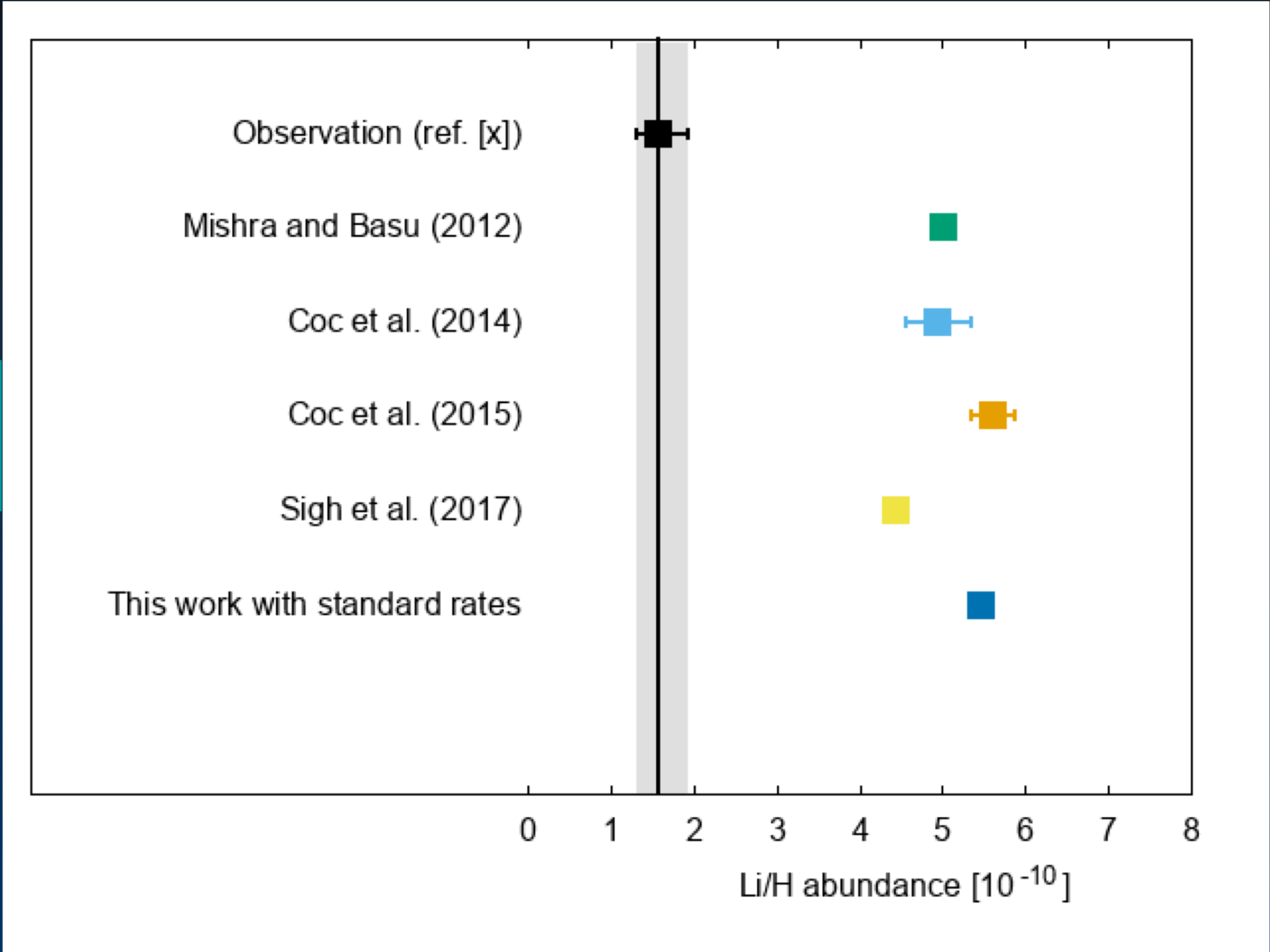
BBN Lithium production

Standard BBN calculations with:

neutron τ_n= 880.2 s
3 neutrino species
$\eta = 6.09 \times 10^{-10}$

[^{7}Li/H] = 5.46 (old rate)
= 5.26 ± 0.40 (new)

Best value from observations:
[Li/H] = 1.6 ± 0.3



Conclusion

New measurement of the ^{7}Be(n,α) and ^{7}Be(n,p) reactions
from thermal to keV neutron energies has been performed at n_TOF
high purity samples produced at PSI and ISOLDE
(demonstrating the feasibility of neutron measurements
on samples produced at radioactive beam facilities)

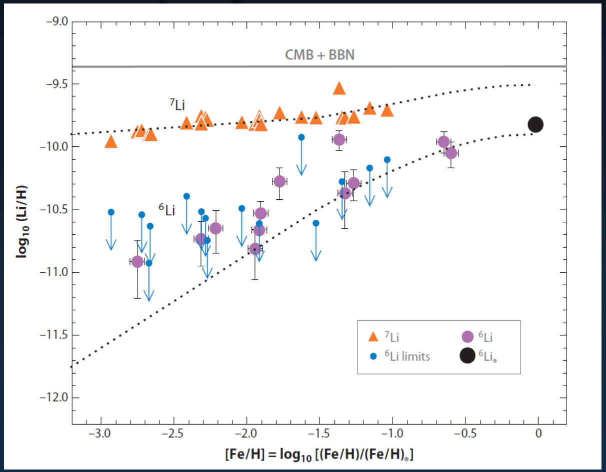
The cross sections are higher than previously recognized at low energies

The new estimate of the ^{7}Be destruction rate based on the new results
yield a decrease of the predicted cosmological Lithium abundance
insufficient to provide a viable solution to the CLiP

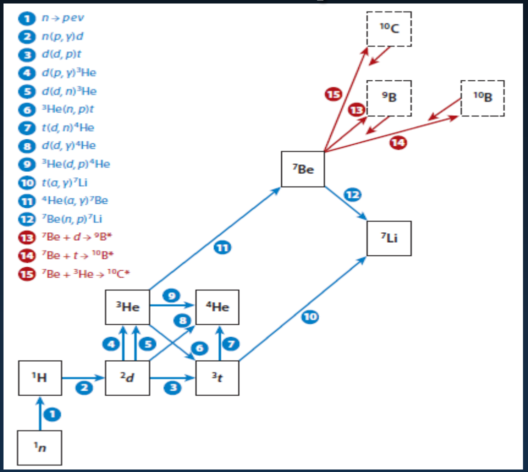
The two n_TOF measurements can finally rule out neutron-induced
reactions, and possibly Nuclear Physics, as a potential explanation
of the CLiP, leaving all alternative physics and astronomical scenarios
still open

Solutions for the CLiP

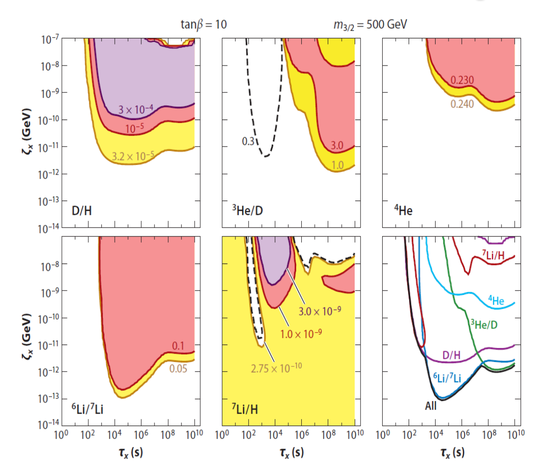
Astrophysiscs



Nuclear Physics

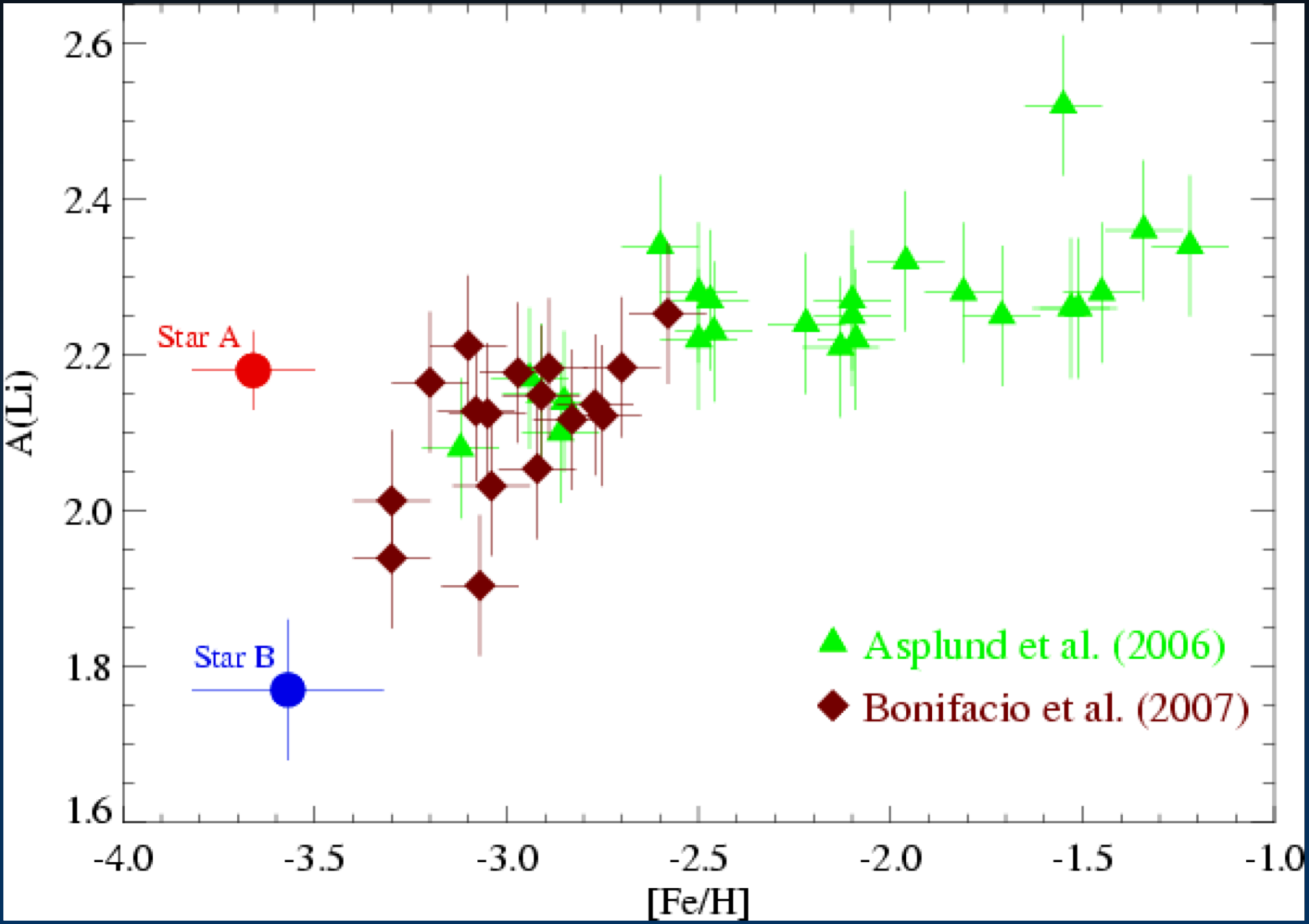


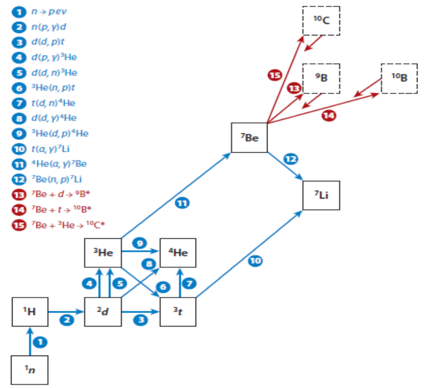
Non-standard Physics

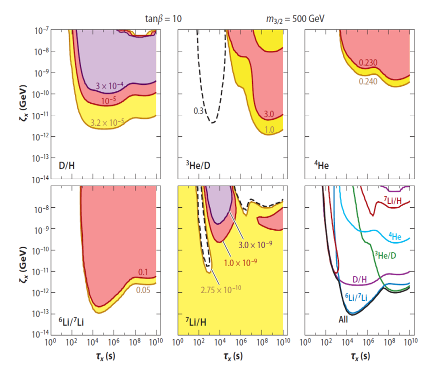


Solutions for the CLiP

Astrophysics

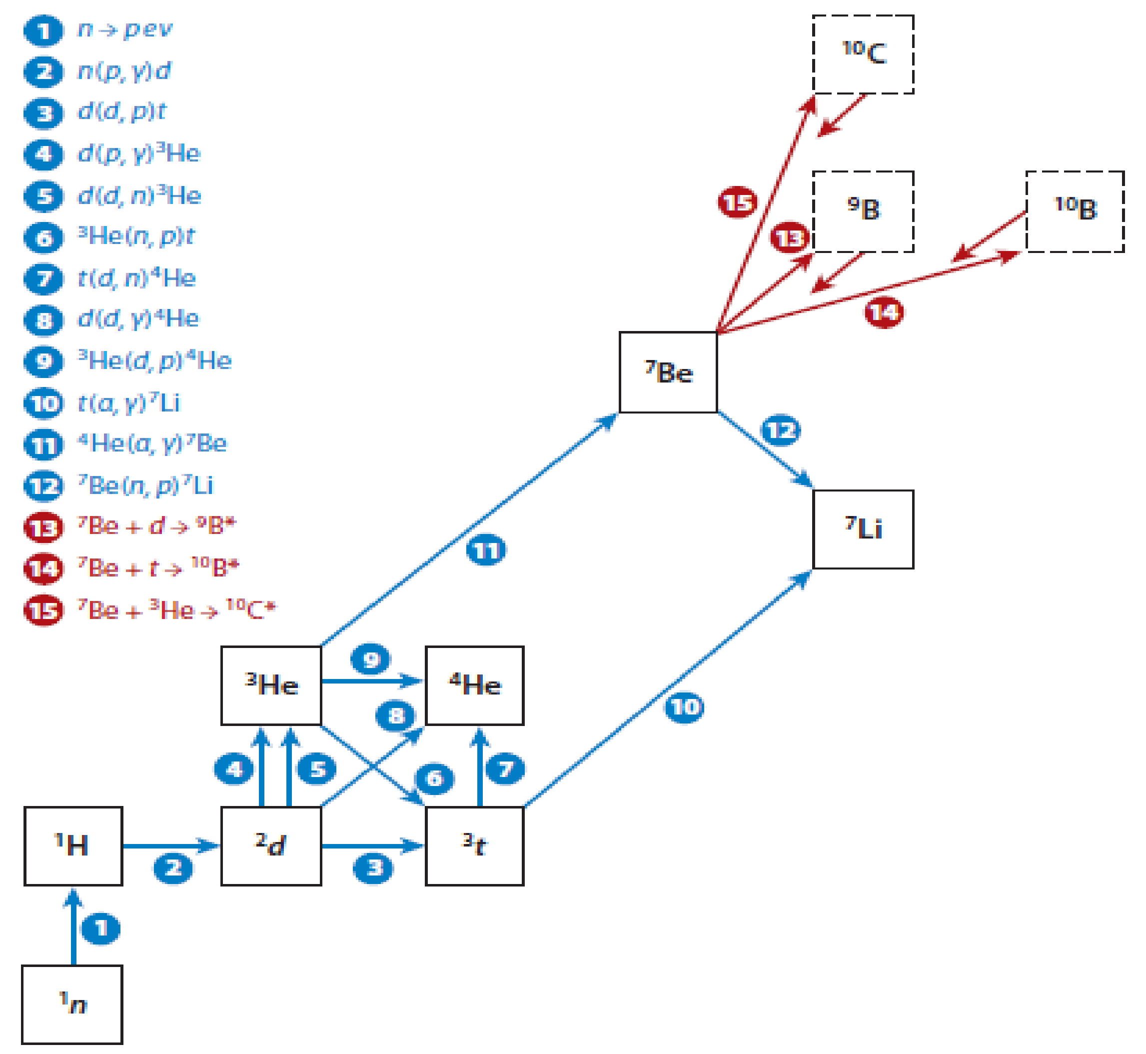


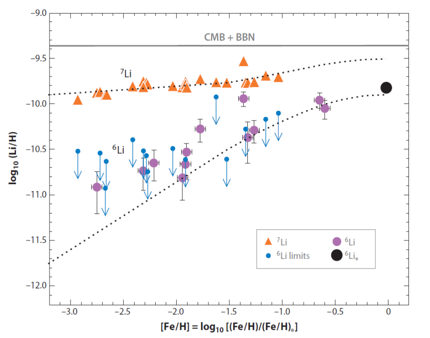


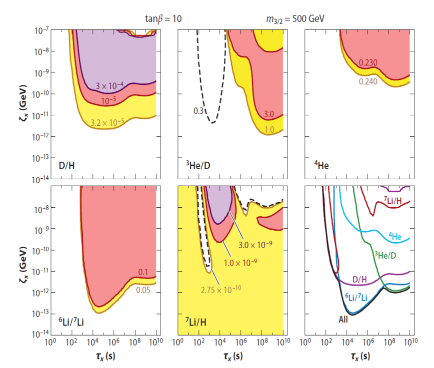


Solutions for the CLiP

Nuclear Physics

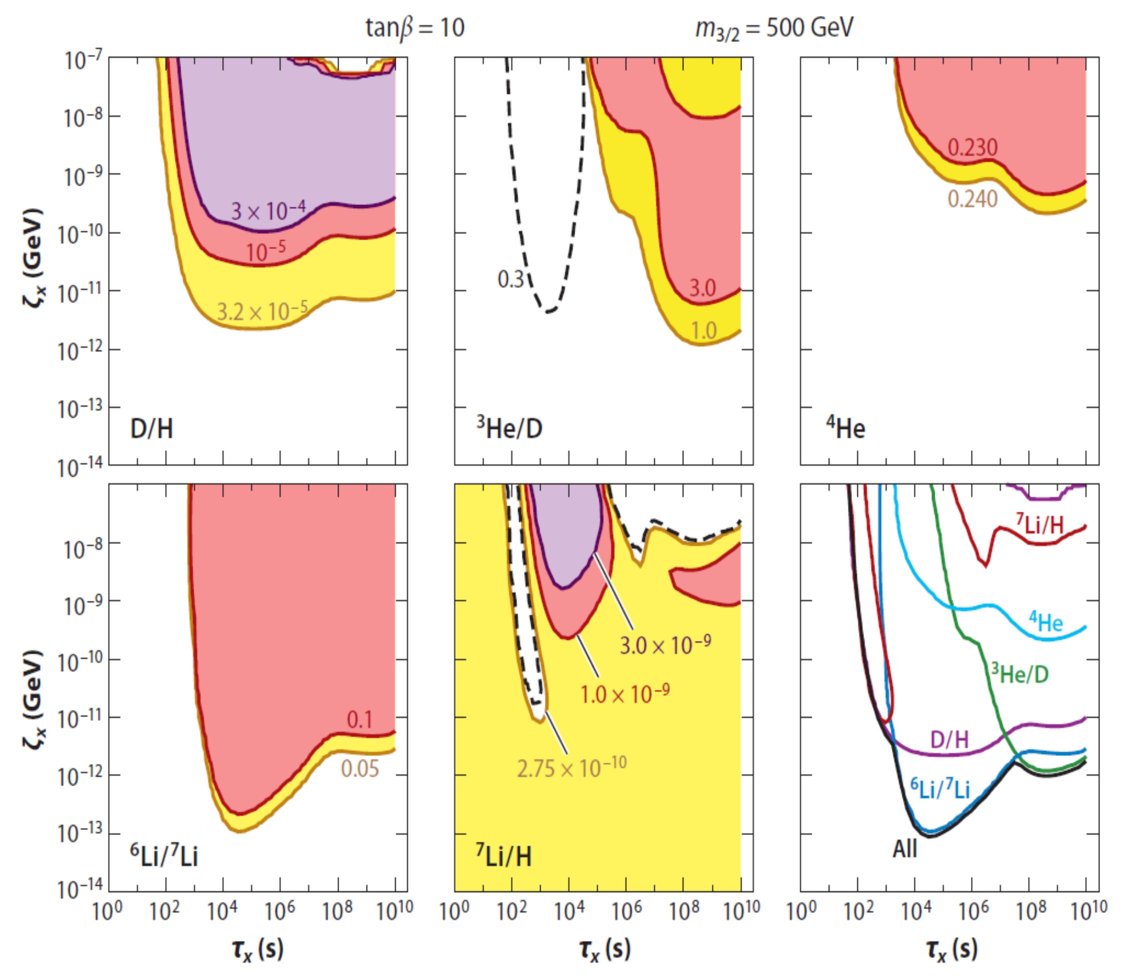


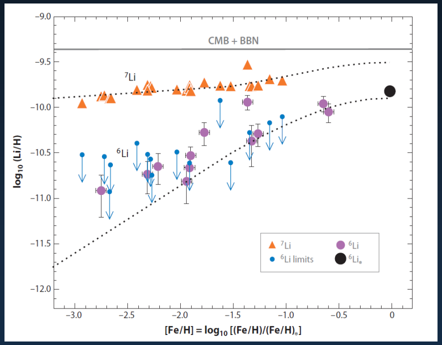


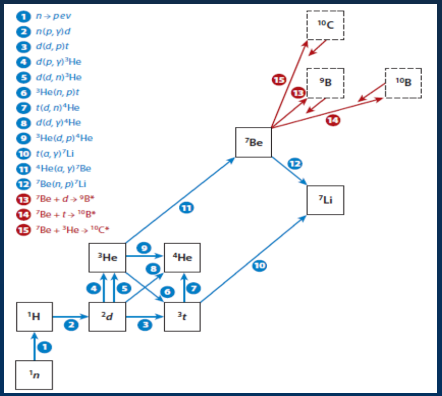


Solutions for the CLiP

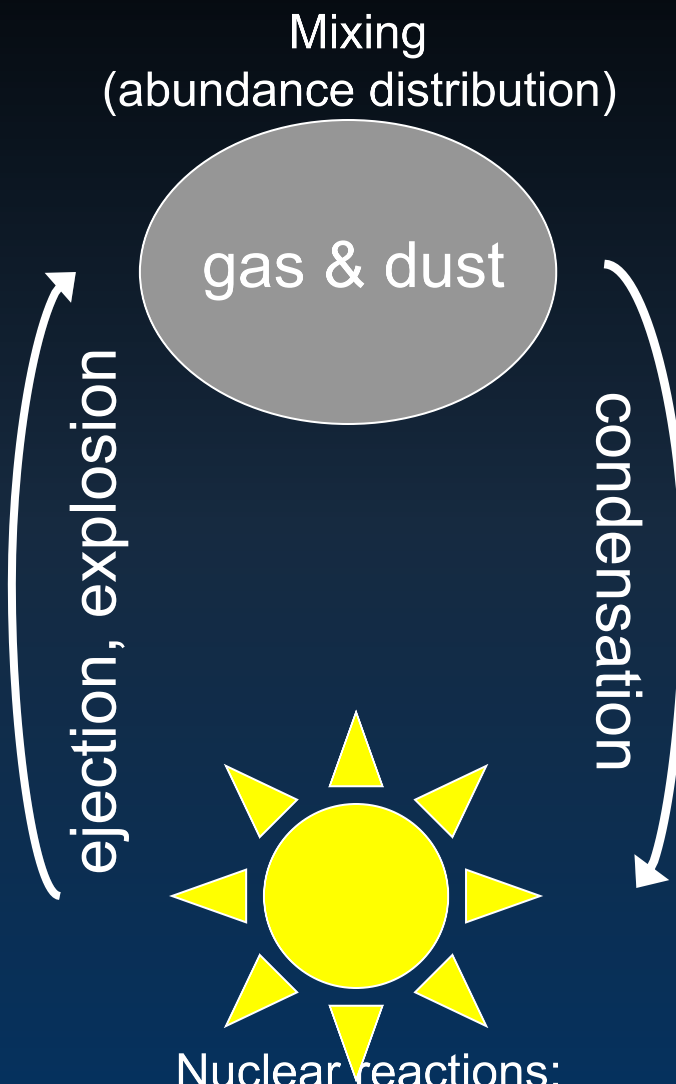
Non-standard Physics







Stellar Nucleosynthesis



Mixing
(abundance distribution)

gas & dust

ejection, explosion

condensation

Nuclear reactions:
- energy generation
- nucleosynthesis

B^2FH

E. Margaret Burbidge, G. R. Burbidge, William A. Fowler, and F. Hoyle
Rev. Mod. Phys. 29, 547 – Published 1 October 1957

1. Hydrogen burning: conversion of $4p \rightarrow {}^{4}He$ (sun energy production)

2. Helium burning: the 3α process and the formation of the CNO elements

3. α-process: nucleosynthesis beyond ^{16}O up to ^{40}Ca (now attributed to C and O burning)

4. e-process: NSE making of the iron peak (see supernovae)

5. s-process: trans-iron elements produced by neutron capture along the stability valley

6. r-process: to reproduce the double-peaks (neutron capture much faster than β-decay)

7. p-process: production of rare proton-rich nuclei

8. x-process: production of D, Li, Be and B (now attributed to BBN + cosmic-ray spallation)

Two classes of neutron capture processes

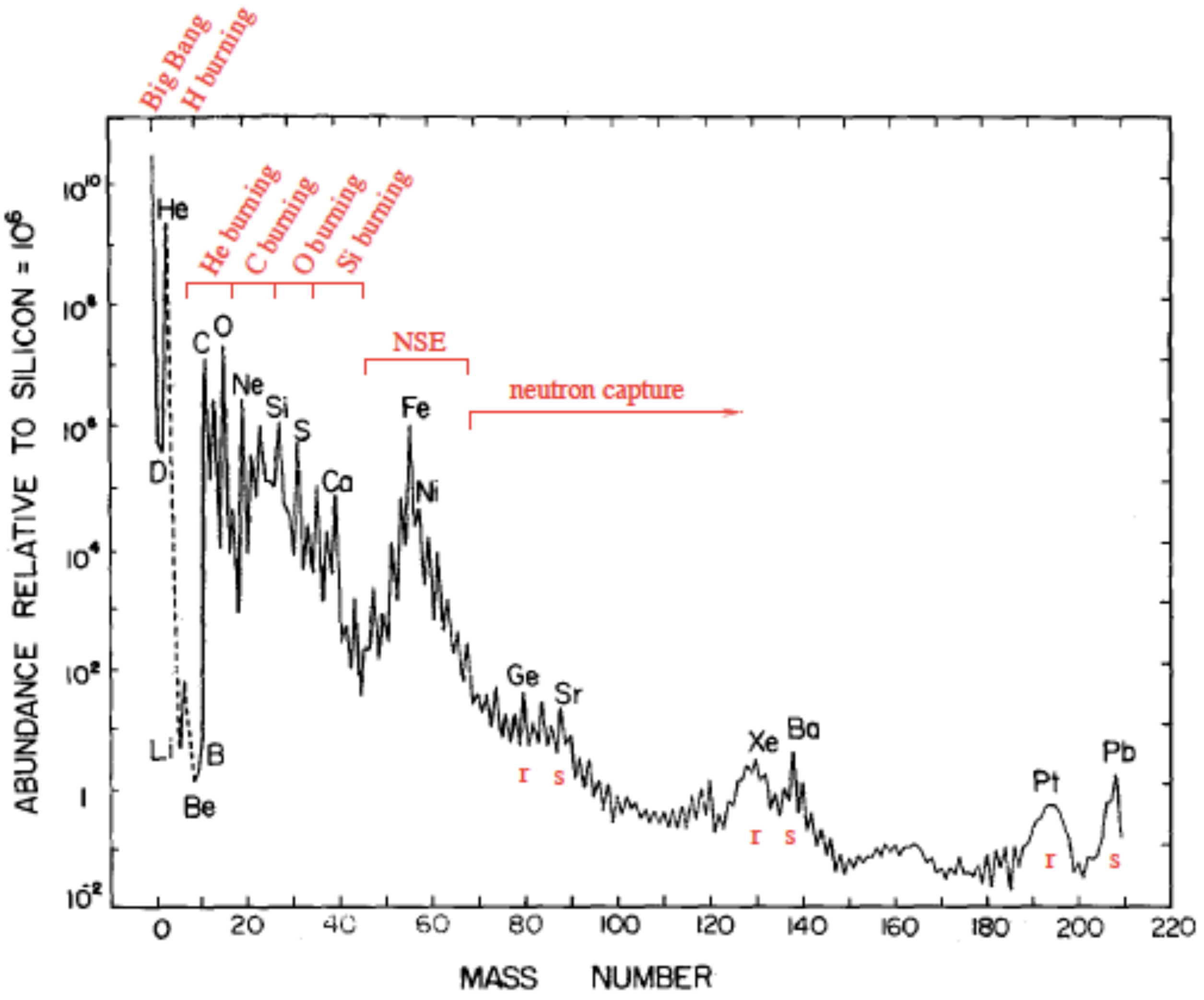
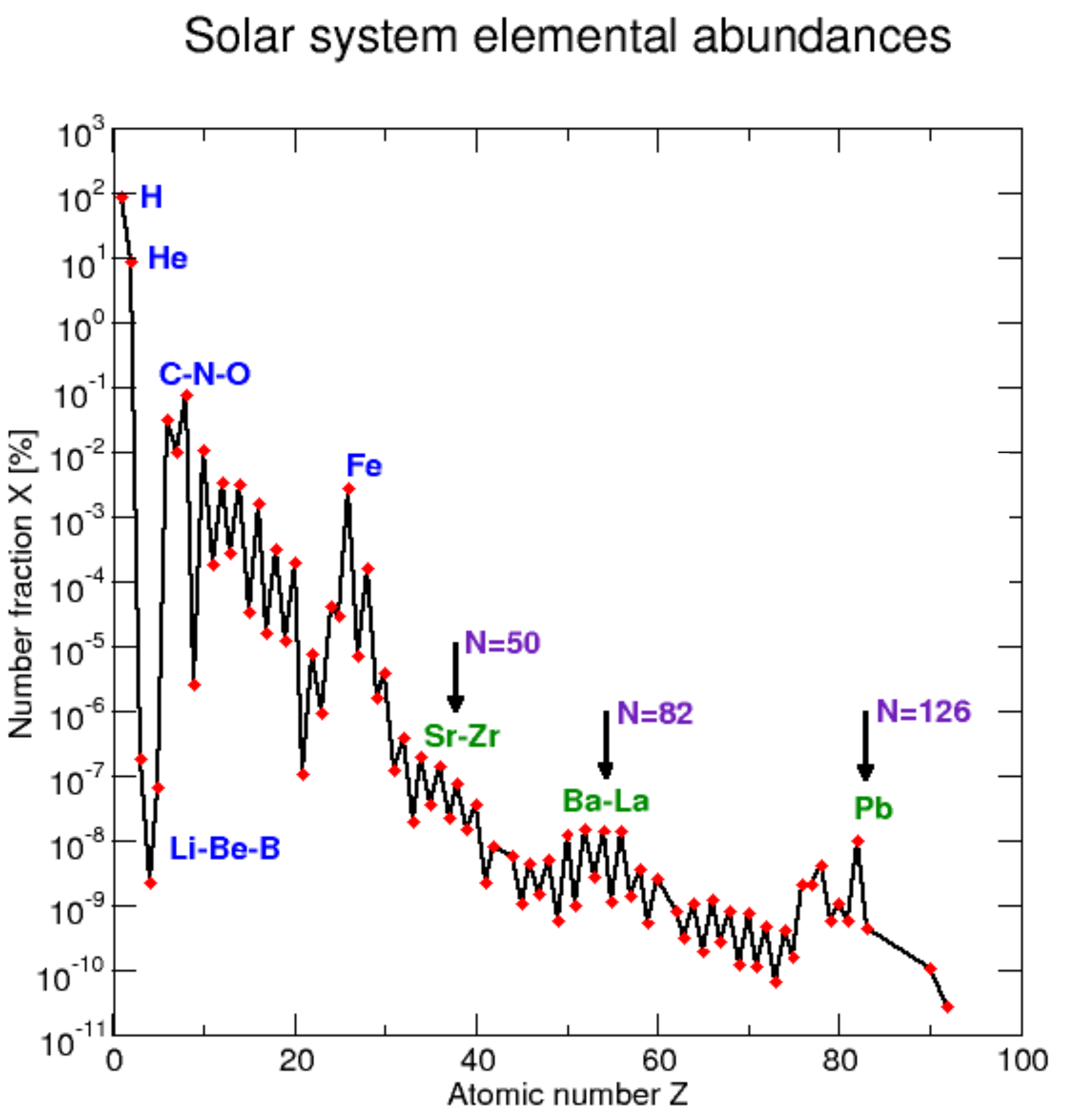


Figure 1.1: The 'local galactic' abundance distribution of nuclear species, as a function of mass number A. The abundances are given relative to the Si abundance which is set to 10^6. Peaks due to the r- and s-process are indicated. It is the main aim of this course to provide an understanding of this figure. Adapted from Cameron (1982).

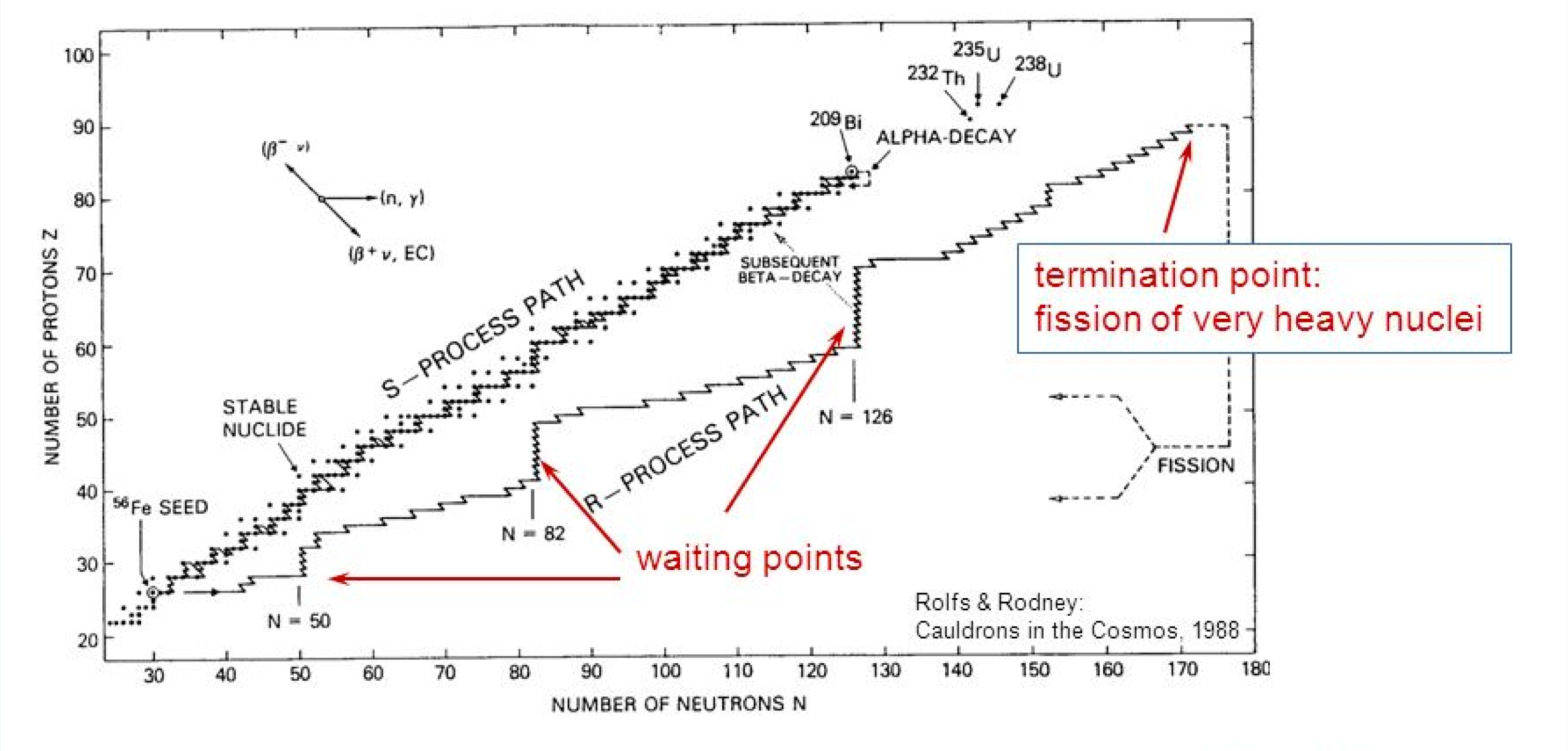
BB + Stellar Nucleosynthesis

The distribution of the abundance of the elements show common patterns for the stars of our galaxy

- Reaction rates for charged particle reactions are very slow for high-Z elements at low-Temperatures ($T \approx T_8$)
- At much higher T, there would be the onset of NSE and nuclei in the Iron-peak would be favored
- Neutrons are produced during stellar evolution
- Heavy nuclei have large $\sigma(n,\gamma)$, some correlated with abundances
- Double peaks can only be explained by neutron capture processes
- There is enough seed material (only ~3% of the iron-peak is needed to synthesize heavies)



Two classes:
s-process & r-process



termination point: fission of very heavy nuclei

waiting points

Rolfs & Rodney: Cauldrons in the Cosmos, 1988

s-process

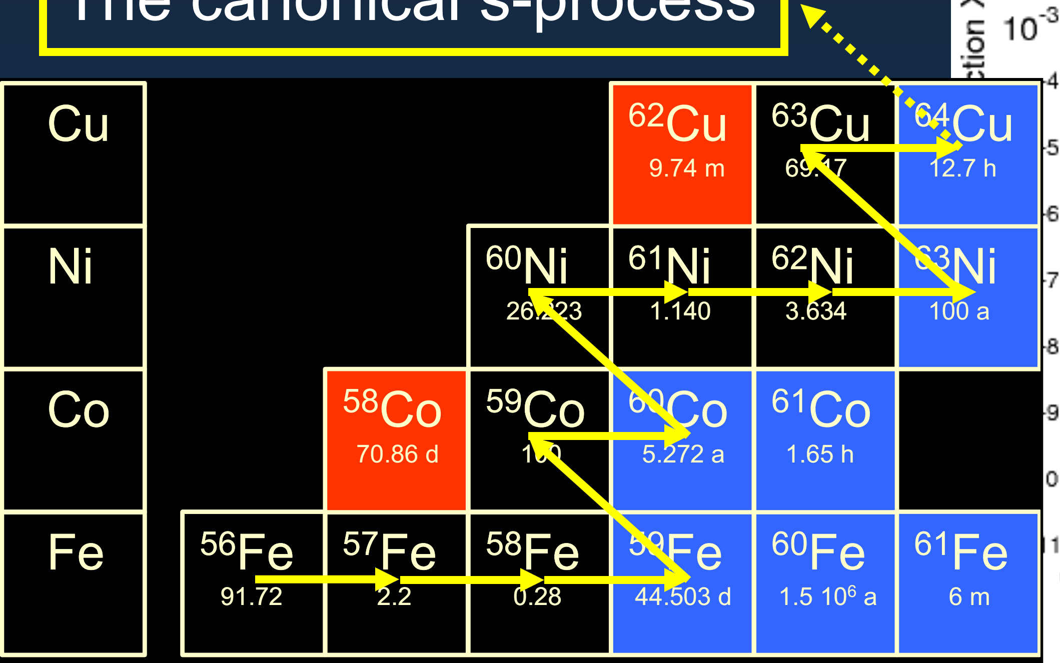
The lifetime of a nucleus against (n,γ) is:

$$\tau_{n,\gamma} \equiv \frac{1}{N_n \langle \sigma_{n,\gamma} v \rangle}$$

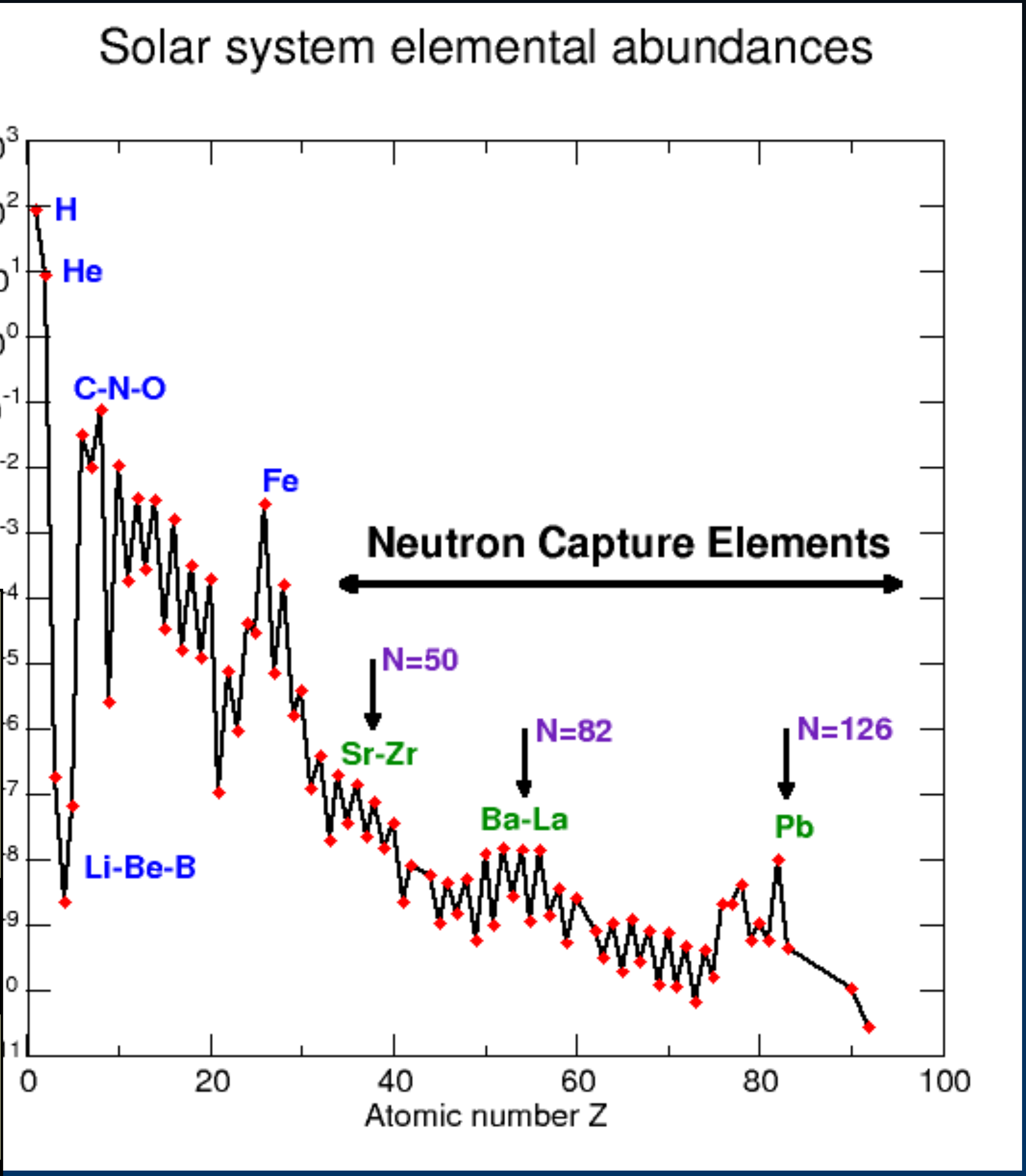
For $\sigma_{(n,\gamma)} \approx 100$ mb and $kT \approx 30$ keV, it is:

$$\tau_{n,\gamma} \approx \frac{10^9}{N_n} yr$$

The canonical s-process



Cu				^{62}Cu 9.74 m	^{63}Cu 69.17	^{64}Cu 12.7 h
Ni			^{60}Ni 26.223	^{61}Ni 1.140	^{62}Ni 3.634	^{63}Ni 100 a
Co		^{58}Co 70.86 d	^{59}Co 100	^{60}Co 5.272 a	^{61}Co 1.65 h	
Fe	^{56}Fe 91.72	^{57}Fe 2.2	^{58}Fe 0.28	^{59}Fe 44.503 d	^{60}Fe 1.5 10^6 a	^{61}Fe 6 m



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)

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

Assuming: i) $T \approx const.$

ii) neutron capture dominates over β-decay ($\lambda_\beta << \lambda_{n,\gamma}$)

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

It follows that along the s-process path:

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

Maxwellian averaged capture cross section

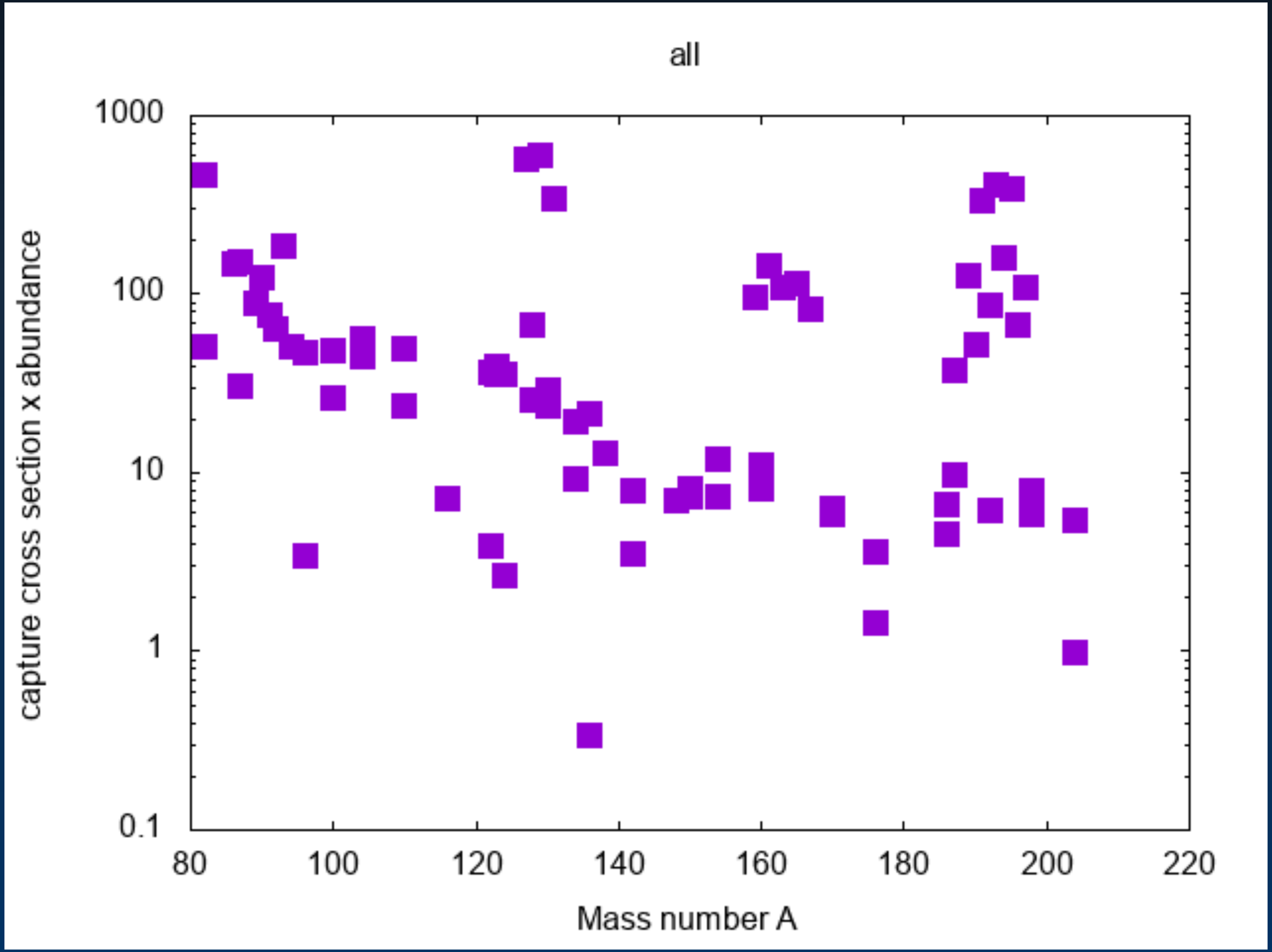
$$\boxed{\langle\sigma\rangle_{kT} = \frac{\langle\sigma v\rangle}{v_T} = \frac{2}{\sqrt{\pi}}\frac{1}{(kT)^2}\int_0^\infty E\,\sigma_{n,\gamma}(E)\exp\left(-\frac{E}{kT}\right)dE}$$

- measure $\sigma_{n,\gamma}(E_n)$ by time of flight, $0.3 < E_n < 300$ keV,
  determine average for stellar spectrum
  correct for SEF

- produce thermal spectrum in laboratory,
  measure stellar average directly by activation
  correct for SEF

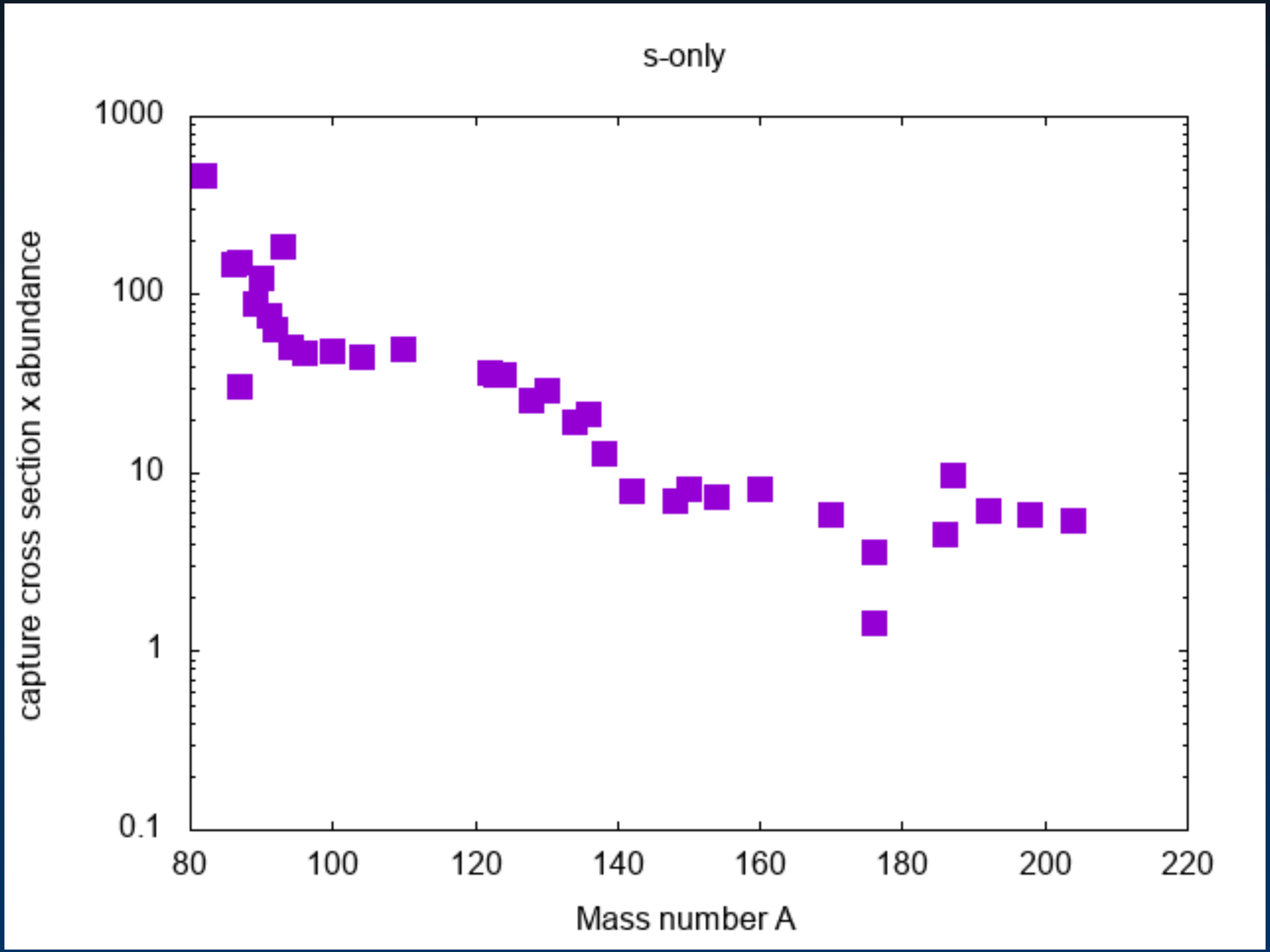
accurate experimental cross section data essential

$\sigma_{n,\gamma} \times N_{\odot}$ correlations: All nuclei



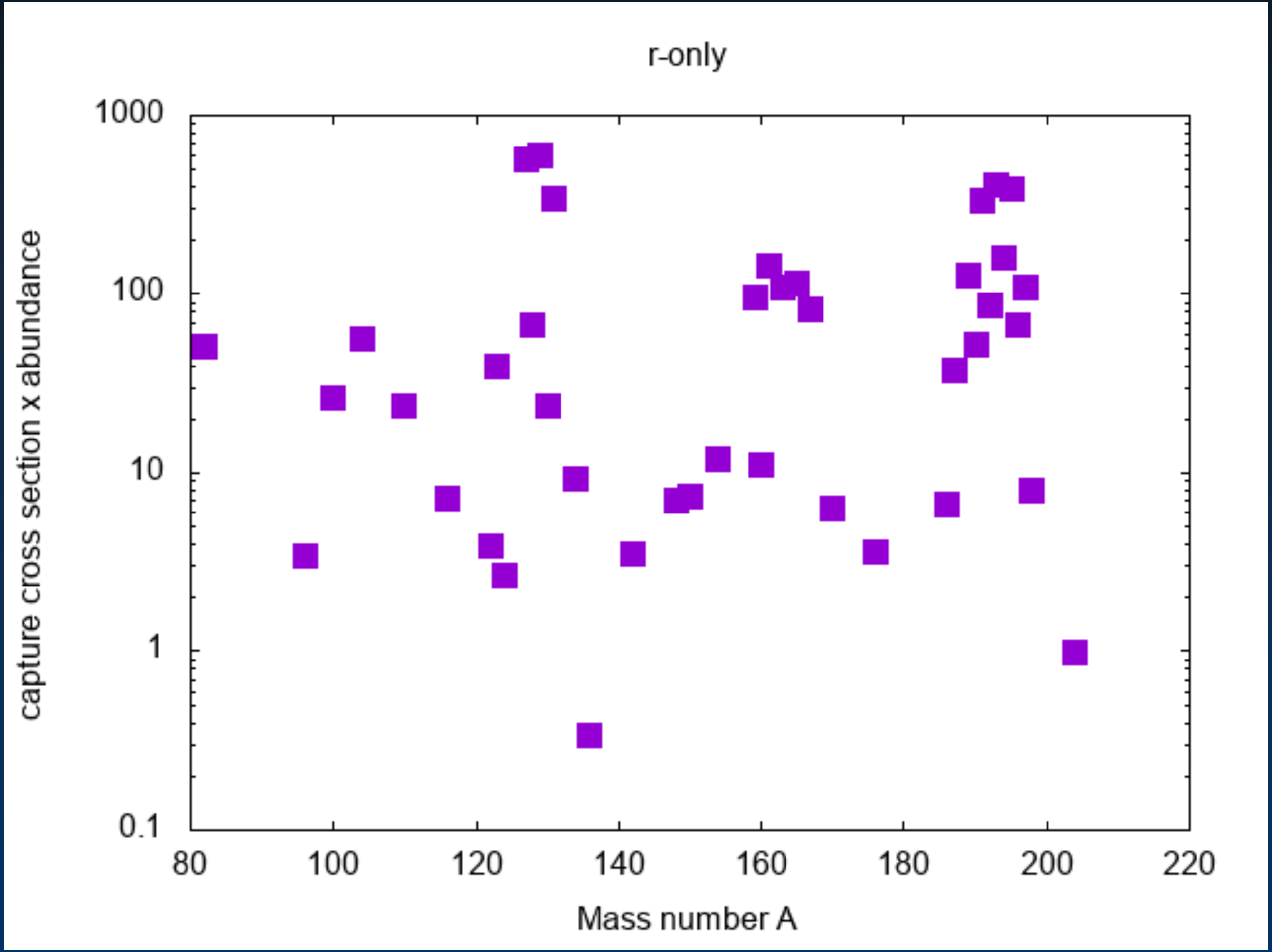
Abundances: Anders & Grevesse (1989)
Cross sections: Bao et al. (2000)

$\sigma_{n,\gamma} \times N_{\odot}$ correlations: s-only nuclei



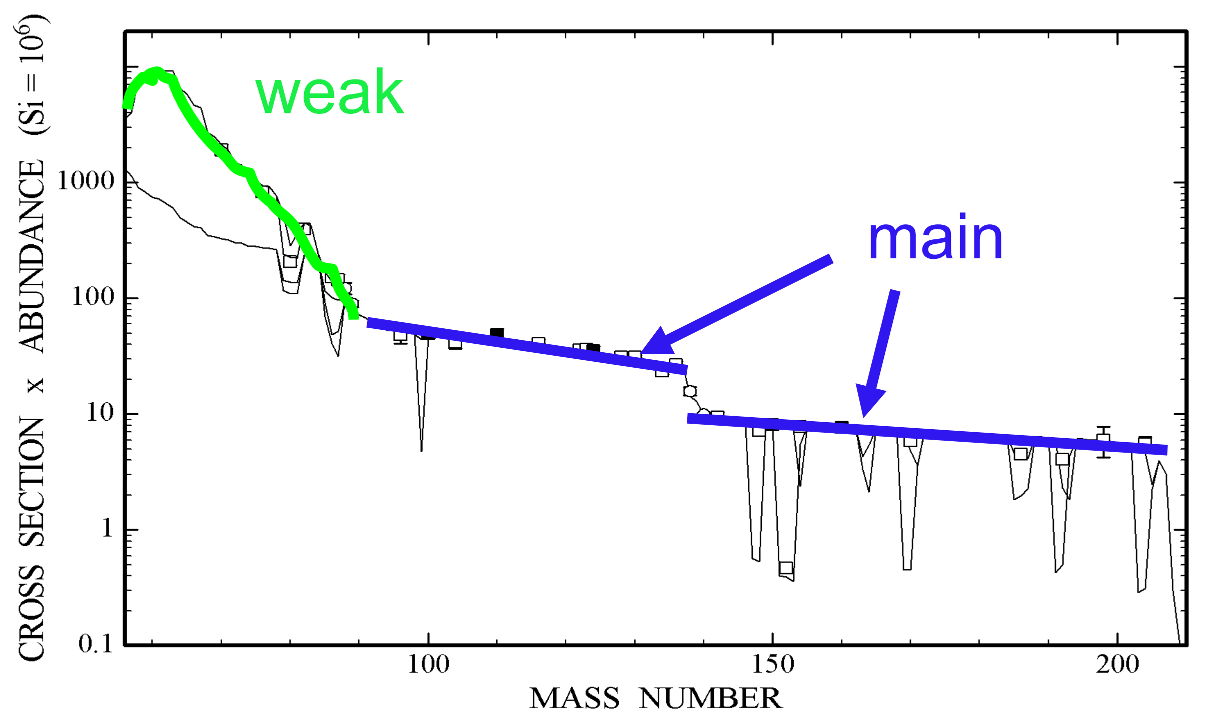
Abundances: Anders & Grevesse (1989)
Cross sections: Bao et al. (2000)

$\sigma_{n,\gamma}\times N_{\odot}$ correlations: r-only nuclei



Abundances: Anders & Grevesse (1989)
Cross sections: Bao et al. (2000)

The canonical s-process

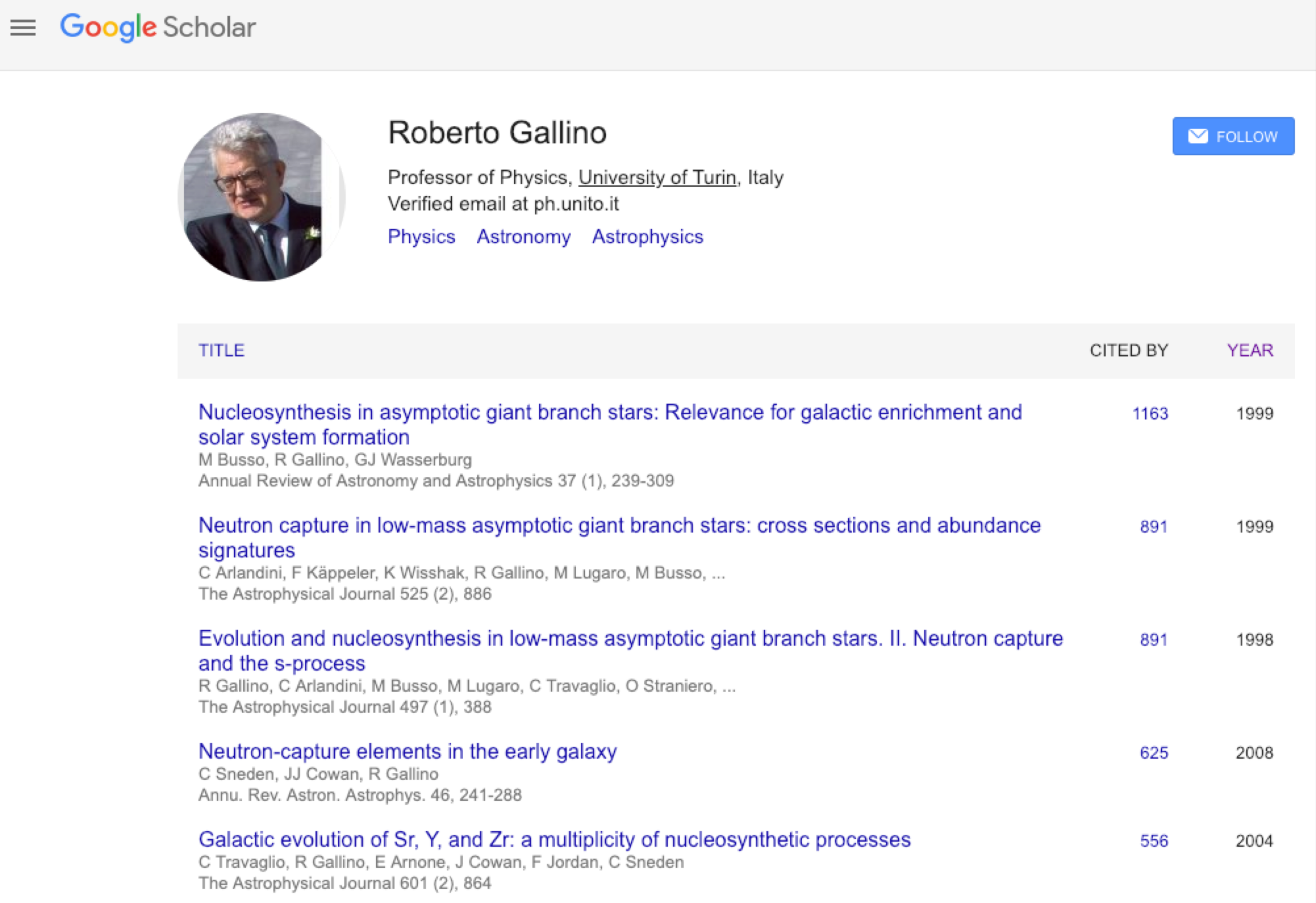


source: F Käppeler (Prog. Part. Nucl. Phys. 43, 1999)

weak: core He burning in massive stars (e.g. 8 solar masses)

main: He shell flashes in low mass TP-AGB stars

Nucleosynthesis in AGB stars



Roberto Gallino

Professor of Physics, University of Turin, Italy
Verified email at ph.unito.it

Physics Astronomy Astrophysics

TITLE	CITED BY	YEAR
Nucleosynthesis in asymptotic giant branch stars: Relevance for galactic enrichment and solar system formation M Busso, R Gallino, GJ Wasserburg Annual Review of Astronomy and Astrophysics 37 (1), 239-309	1163	1999
Neutron capture in low-mass asymptotic giant branch stars: cross sections and abundance signatures C Arlandini, F Käppeler, K Wisshak, R Gallino, M Lugaro, M Busso, ... The Astrophysical Journal 525 (2), 886	891	1999
Evolution and nucleosynthesis in low-mass asymptotic giant branch stars. II. Neutron capture and the s-process R Gallino, C Arlandini, M Busso, M Lugaro, C Travaglio, O Straniero, ... The Astrophysical Journal 497 (1), 388	891	1998
Neutron-capture elements in the early galaxy C Sneden, JJ Cowan, R Gallino Annu. Rev. Astron. Astrophys. 46, 241-288	625	2008
Galactic evolution of Sr, Y, and Zr: a multiplicity of nucleosynthetic processes C Travaglio, R Gallino, E Arnone, J Cowan, F Jordan, C Sneden The Astrophysical Journal 601 (2), 864	556	2004

AGB stars: s-processing

Thermal pulses of AGB stars (He-burning shell)

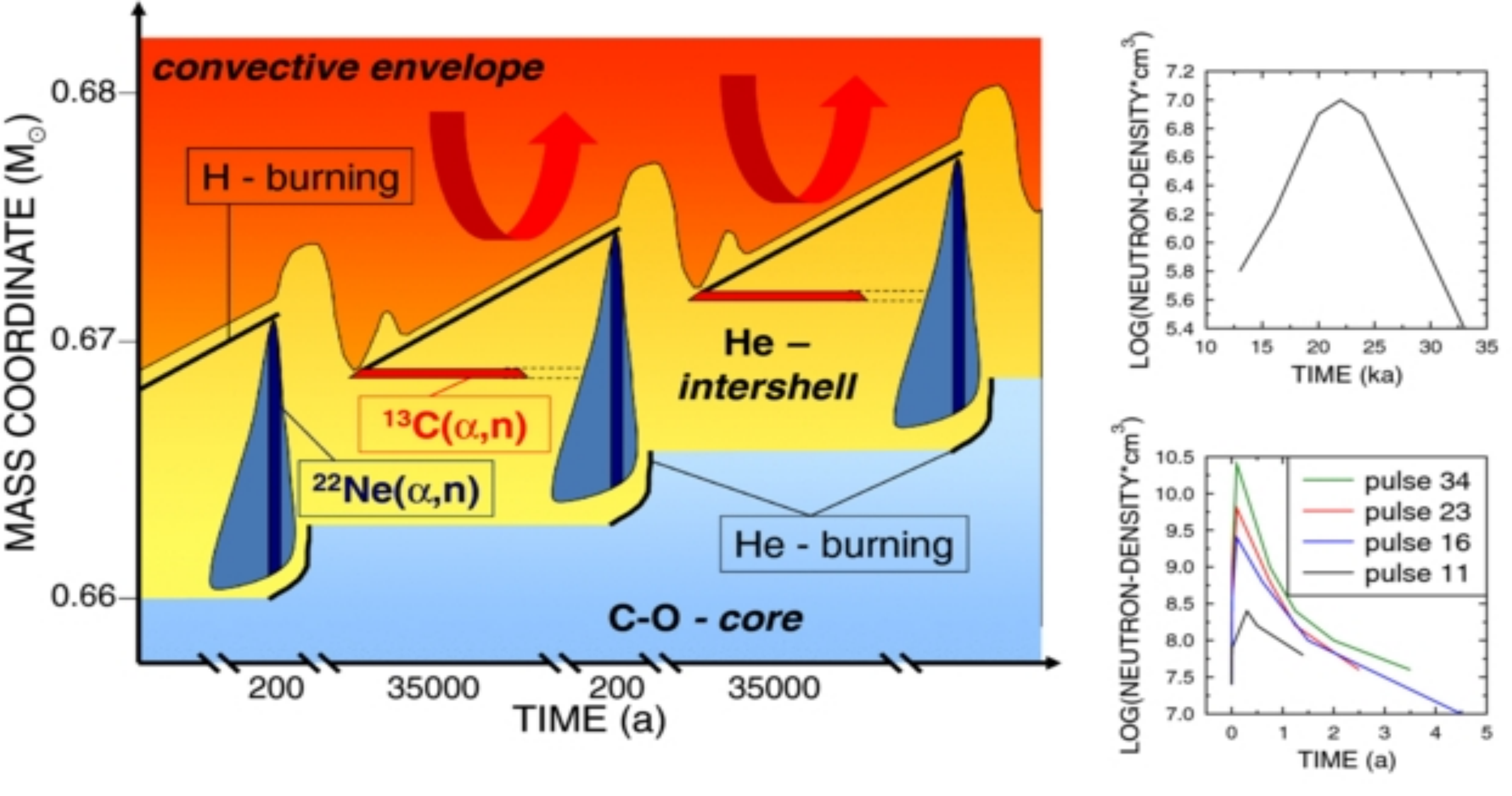
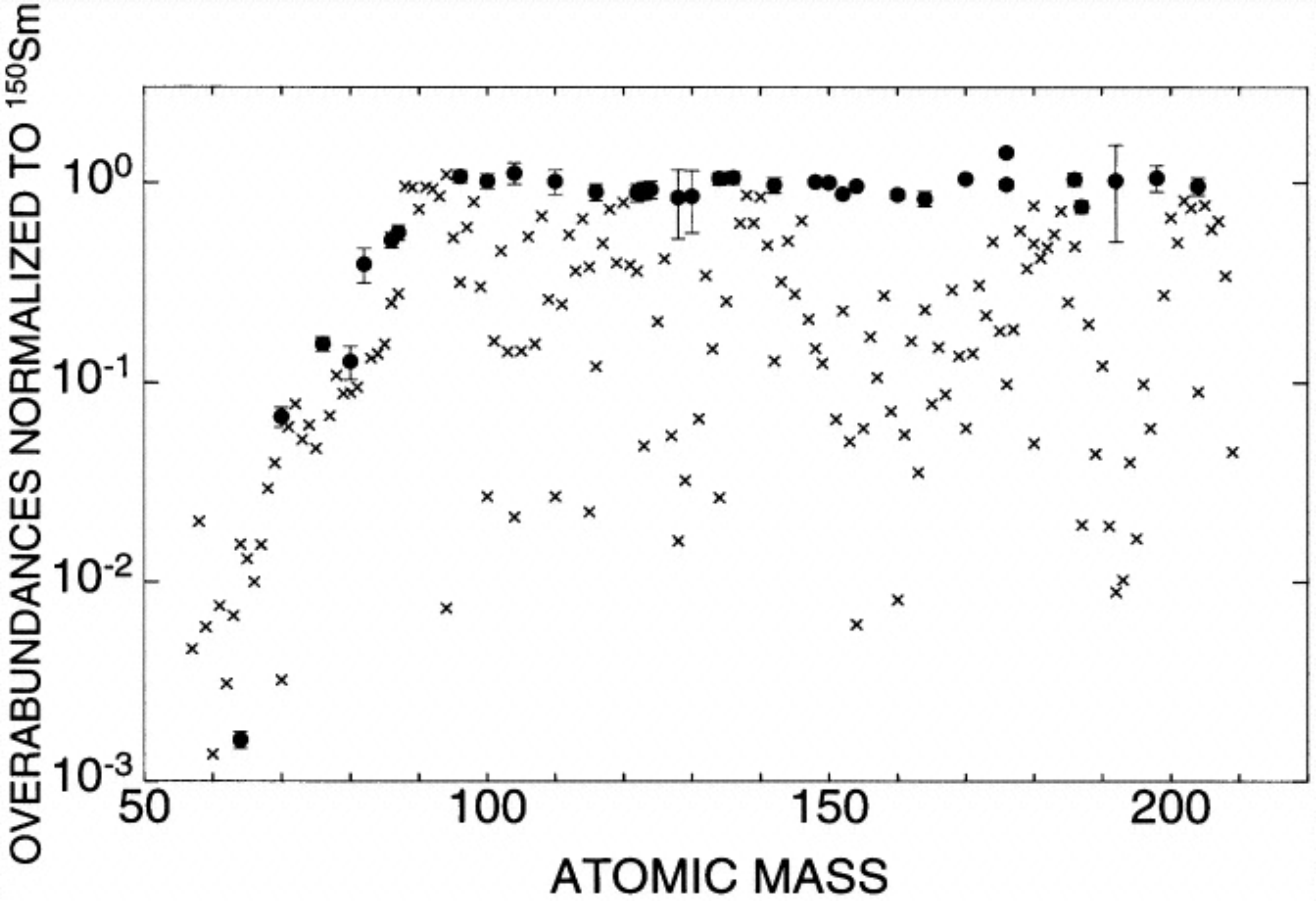


Figure 4 from Neutron reactions in astrophysics
R Reifarth et al 2014 J. Phys. G: Nucl. Part. Phys. 41 053101 doi:10.1088/0954-3899/41/5/053101

alberto.mengoni@cern.ch

AGB stars: s-processing

- $M = 2\ M_\odot$
- $Z = 0.5\ Z_\odot$



C Arlandini, *et al.:* ApJ 525 (1999) 886

alberto.mengoni@cern.ch

The s process in low mass stars (1-3 $M_\odot$)

- *s* abundances from ^{90}Zr – ^{209}Bi: **the main component**

H shell burning

$^{13}C(\alpha,n)$

kT ~ 8 keV

T ~ 90 MK

$n_n = 10^7 - 10^8\ cm^{-3}$

He flash

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

kT ~ 25 keV

T ~ 250 MK

$n_n = 10^{10} - 10^{11}\ cm^{-3}$

reaction flow in equilibrium

- abundances correlated with cross sections: σN_s = const
- detailed models for realistic description of stellar evolution

The s process in massive stars

- *s* abundances from ^{56}Fe – ^{89}Y: **the weak component**

He core burning
^{22}Ne(α,n)
kT ~ 25 keV
T ~ 300 MK
$n_n = 10^6$ cm^{-3}

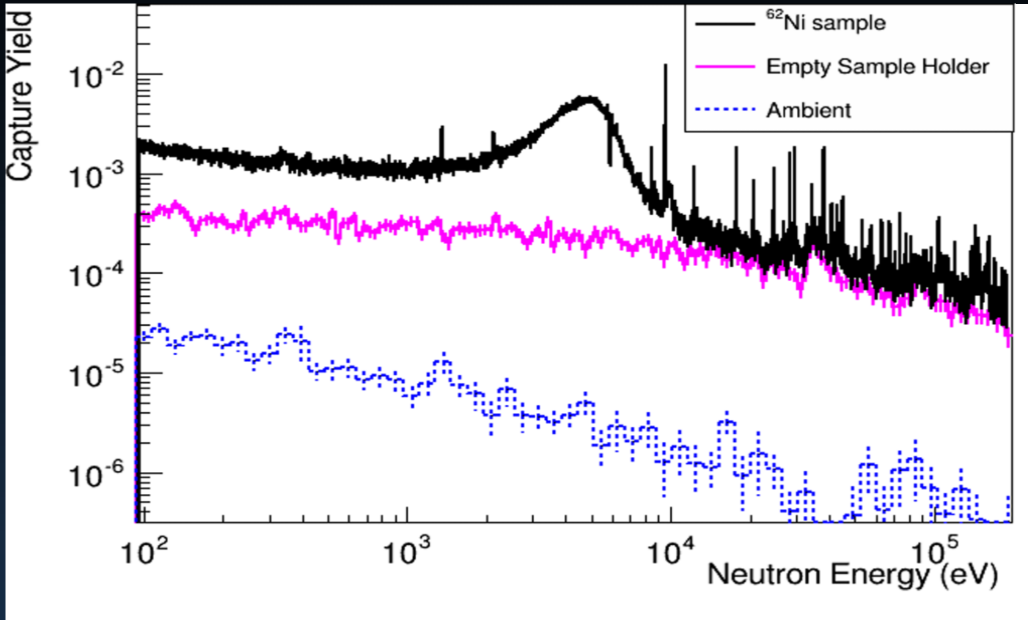
C shell burning
^{22}Ne(α,n)
kT ~ 90 keV
T ~ 10^9 K
$n_n = 10^{11} - 10^{12}$ cm^{-3}

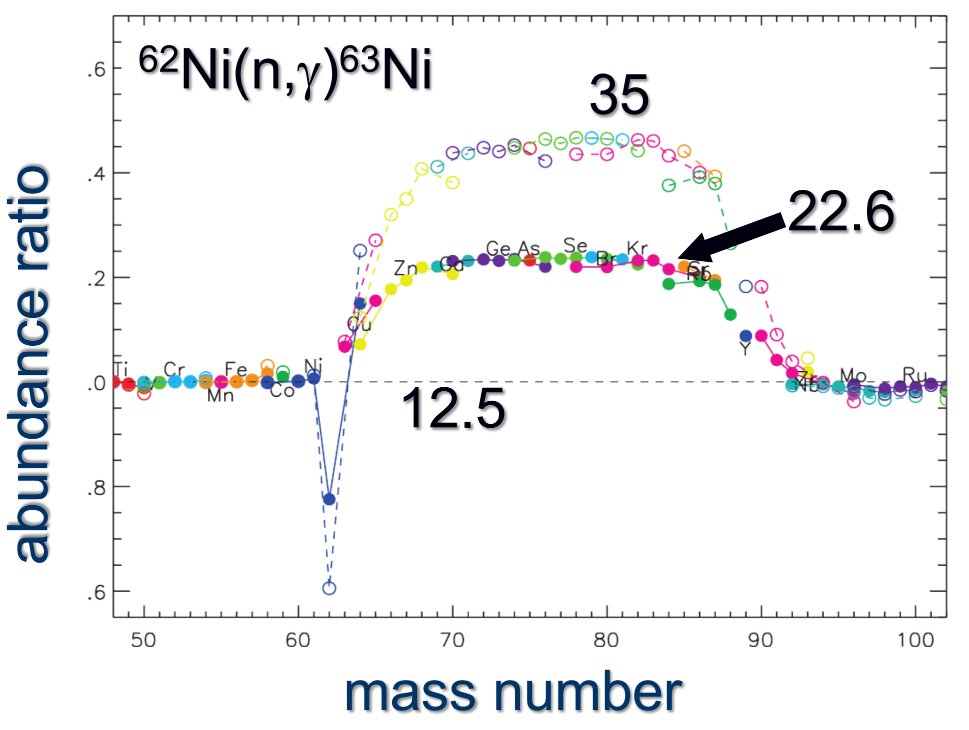
reaction flow NOT saturated > propagation waves!

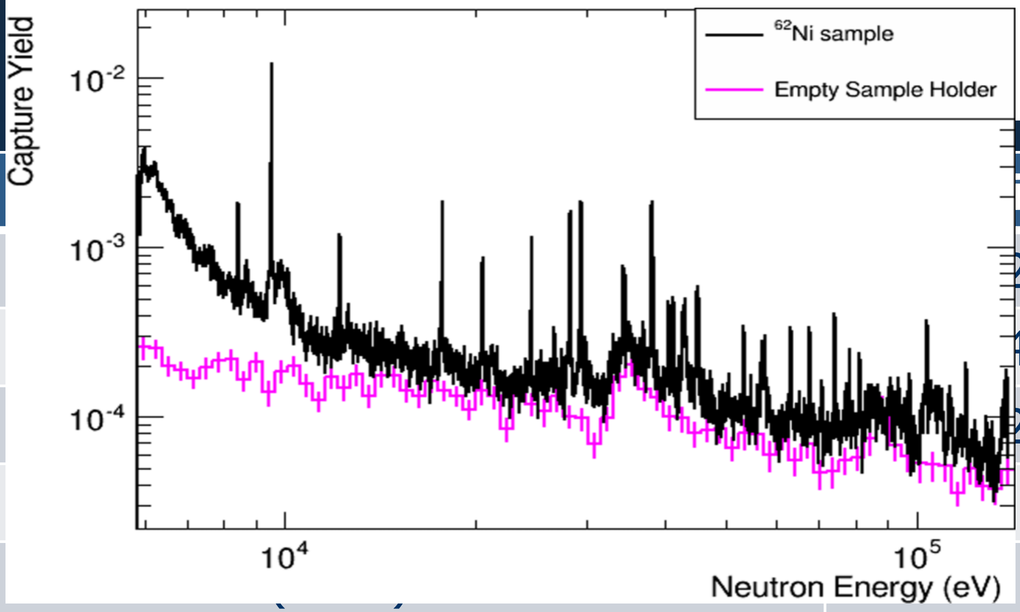
weak s process complicated by

- small and resonance dominated cross sections
- contributions from direct capture, SEF?

Propagation waves: the case of ^{62}Ni





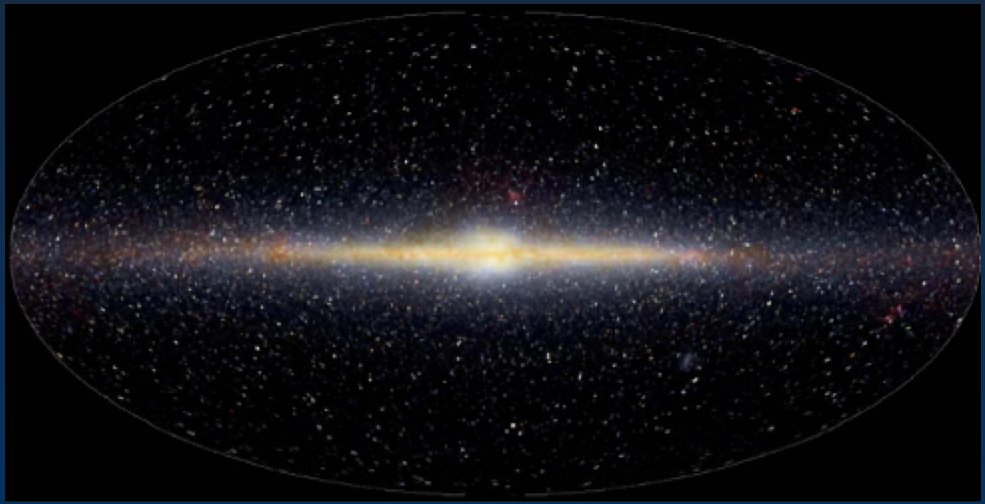


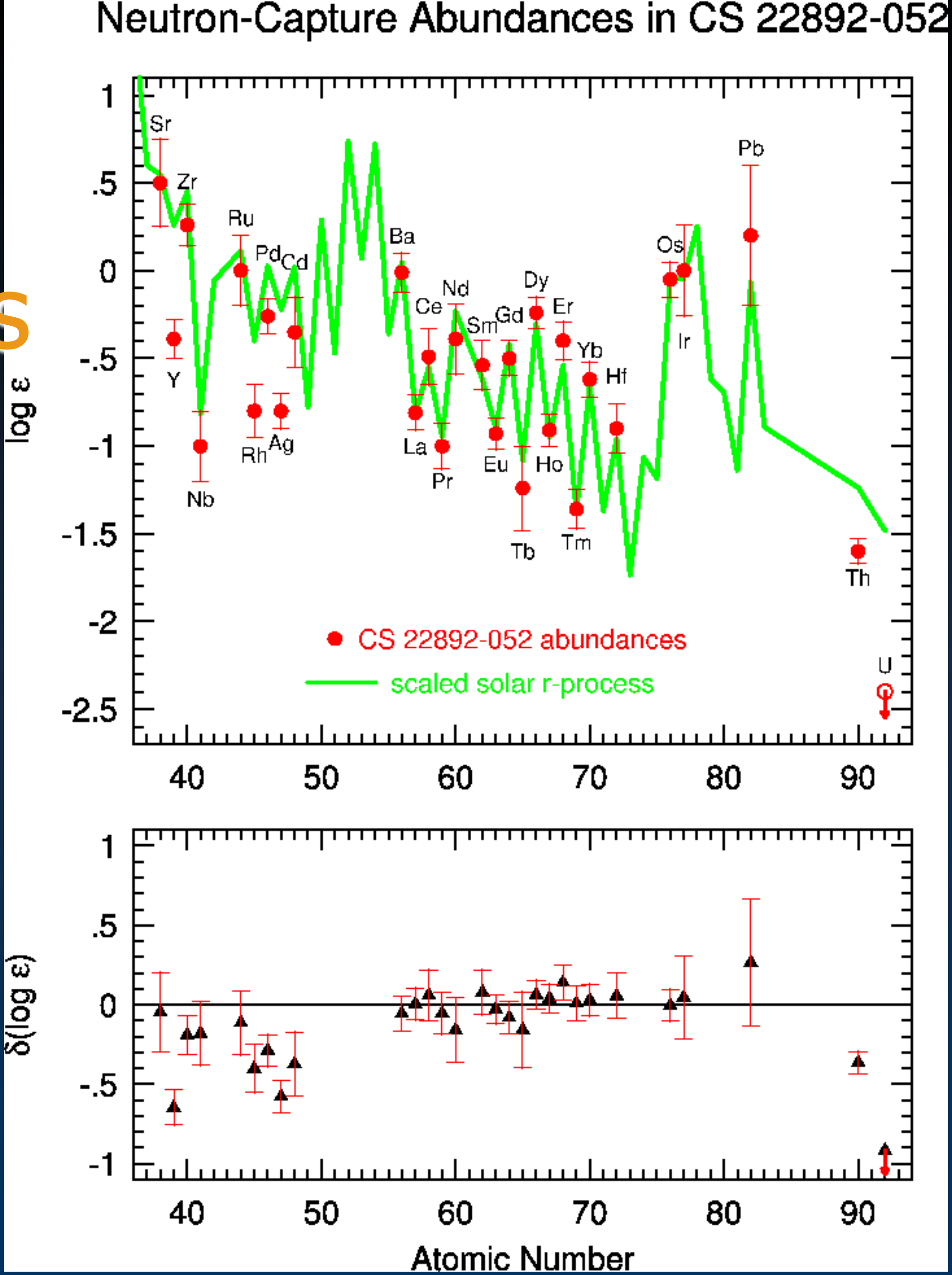
ion
.1 (2009)
.6 (2008)
.6 (2005)

n_TOF measurement:
C Lederer *et al.*
PRC 89, 025810 (2014)

Nucleosynthesis: the s-process & the r-process residuals

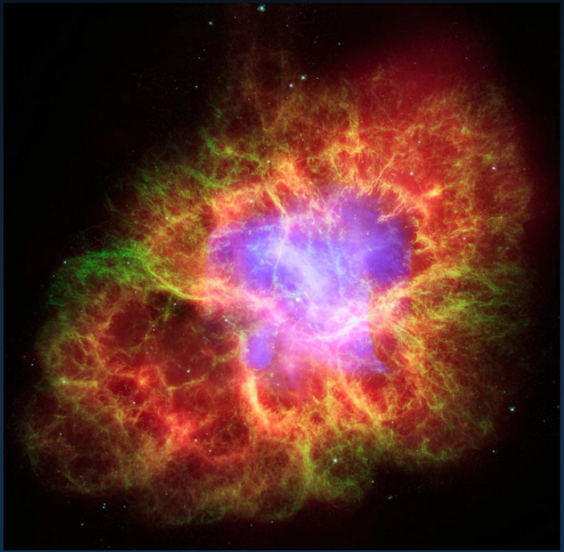
$$N_r = N_{solar} - N_s$$





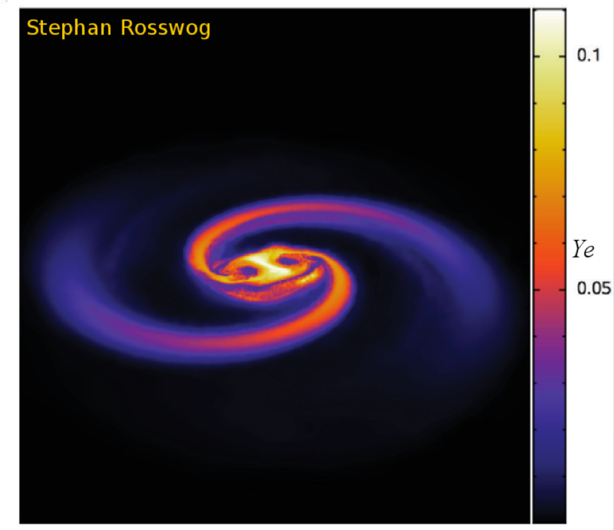
Possible r-process sites

Core collapse supernoave



- Explosion of massive stars, M > $9M_\odot$
- Neutrino-winds from proto-neutron stars. Strong sensitivity to neutrino interactions at subnuclear densities [see PRL 109, 251104 (2012)]
- Only intermediate mass elements are produced (A > 100) [see JPG 41, 044008 (2014)]

Neutron star mergers

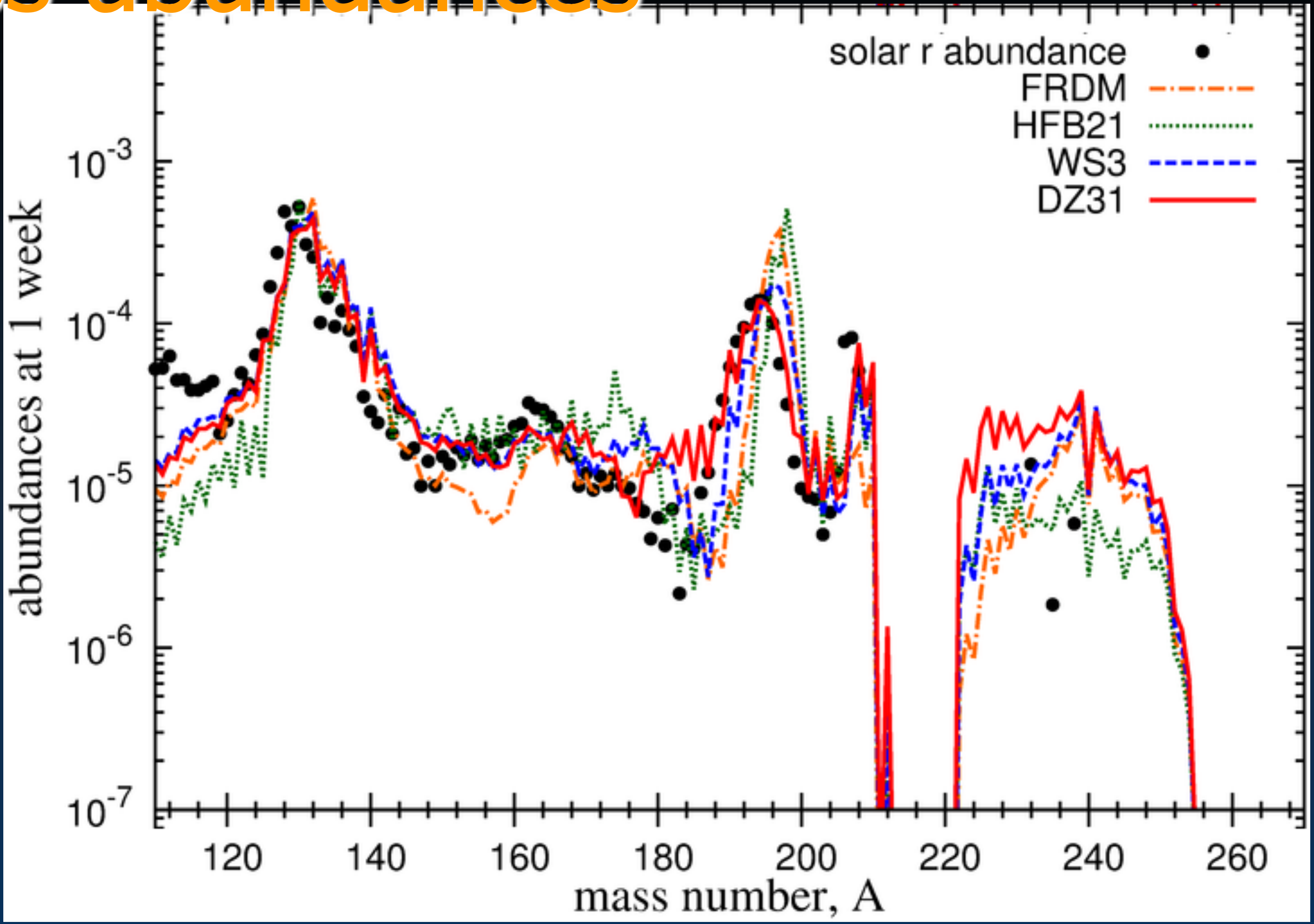


- Mergers eject around $0.01M_\odot$ of very neutron rich-material ($Y_e \sim 0.01$). Similar amount of less neutron-rich matter ($Y_e \gtrsim 0.2$) ejected from accretion disk
- Low frequency, high yield: consistent with astronomical observations.
- Observational signature: electromagnetic transient from radioactive decay of r-process nuclei

r-process abundances

Remember:

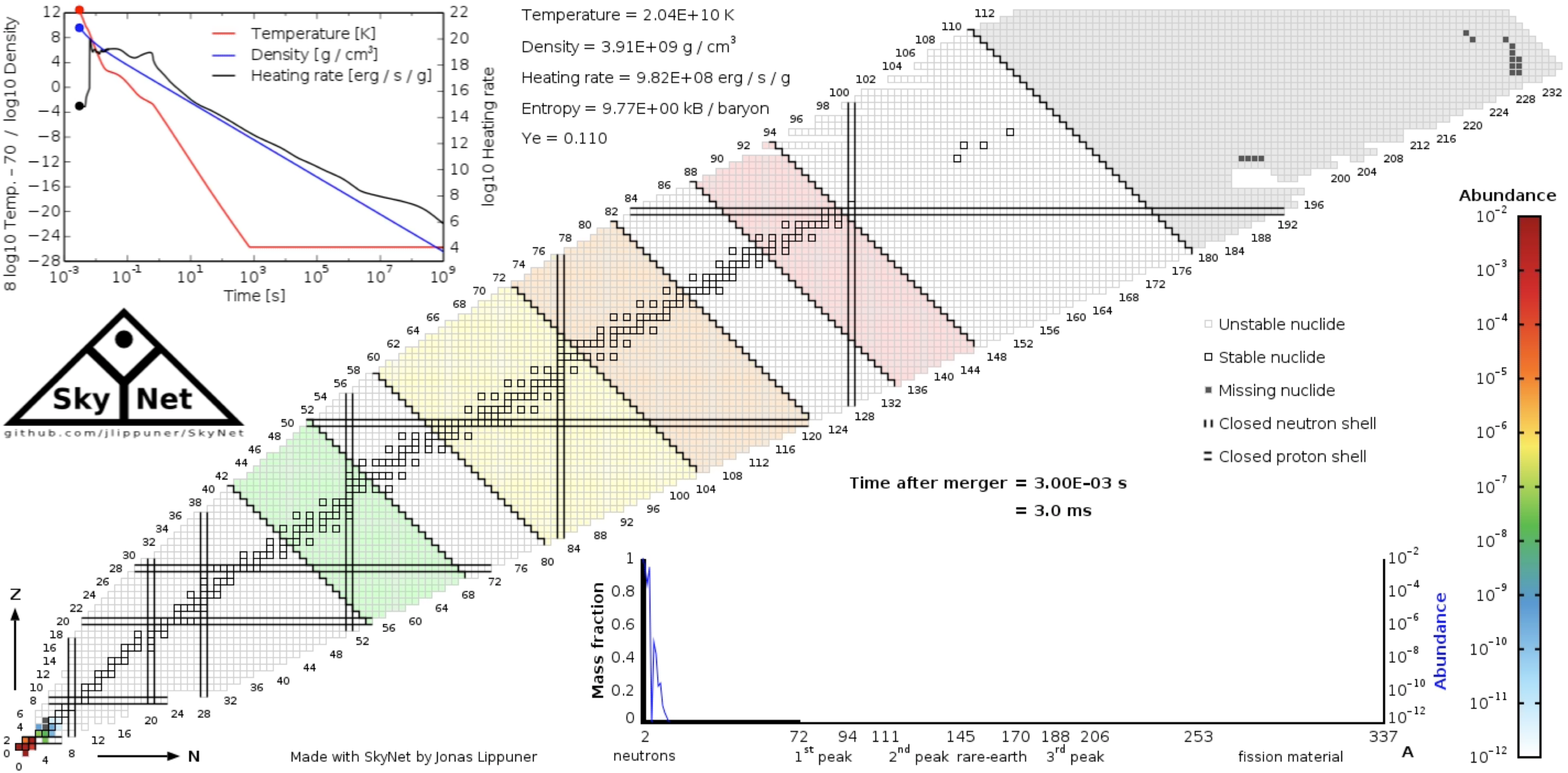
$N_r = N_{solar} - N_s$



- Actinides can be an important opacity source at timescales of weeks
- They can substantially contribute to energy production via alpha decay

Source: Mendoza-Temis, Wu, Langanke, Martinez-Pinedo, Bauswein, Janka, Phys. Rev. C 92, 055805 (2015)

r-process in NS mergers



Temperature = 2.04E+10 K

Density = 3.91E+09 g / cm^3

Heating rate = 9.82E+08 erg / s / g

Entropy = 9.77E+00 kB / baryon

Ye = 0.110

Time after merger = 3.00E-03 s

= 3.0 ms

Made with SkyNet by Jonas Lippuner

Ages

- Cosmological way

  based on the Hubble time definition or cosmic microwave background observation ("expansion age")

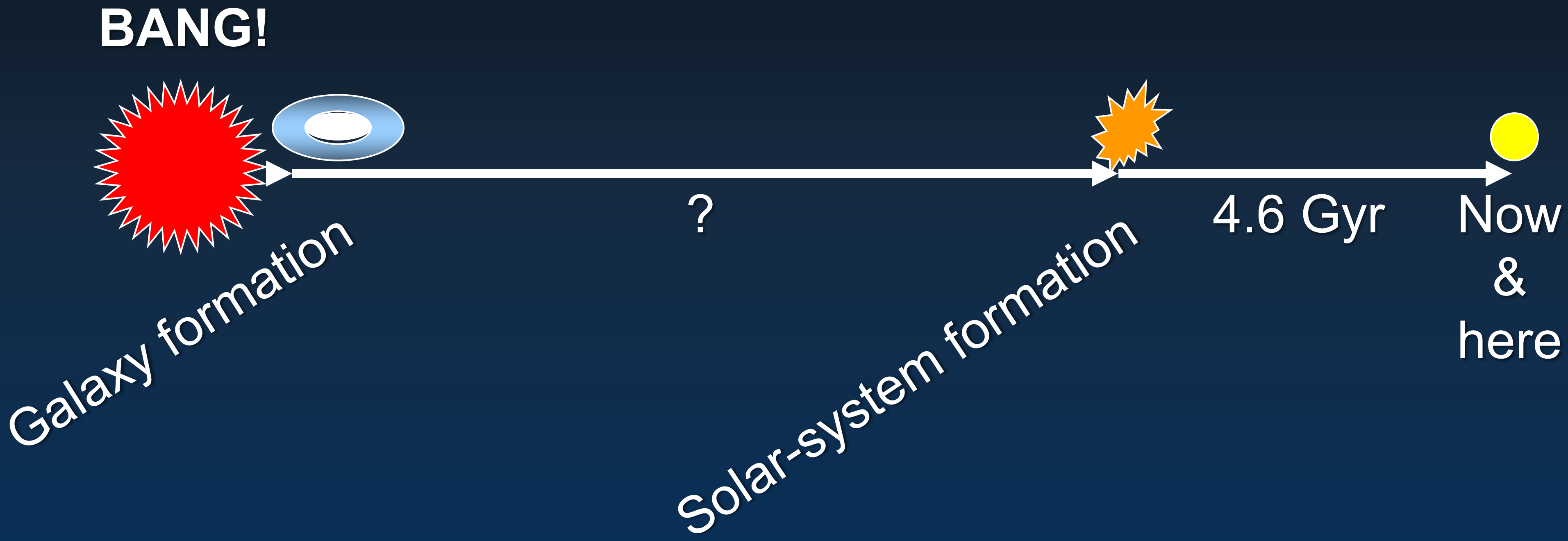
- Astronomical way

  based on observations of globular clusters

- Nuclear way

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

A brief history of the Universe



BANG!

Galaxy formation

?

Solar-system formation

4.6 Gyr

Now
&
here

Age from CMB observations

The detailed structure of the cosmic microwave background fluctuations depends on the current density of the universe, the composition of the universe and its expansion rate. WMAP, PLANCK and others have been able to determine these parameters with an accuracy of better than 1%. When we combine the CMB data with ΛCDM, we are able to determine an age for the universe closer to an accuracy of 0.15%

13.799 ± 0.021 Gyr

based on the ΛCDM model:

$$H(a) = \frac{\dot{a}}{a} = H_0\sqrt{(\Omega_{\rm cdm} + \Omega_b)a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda}$$

H_0 = 67.74 ± 0.46 km/s/Mpc

$\Omega_{\rm cdm}$ = 0.2589 ± 0.0057

Ω_b = 0.0486 ± 0.0010

Ω_r ~ 0

Ω_Λ = 0.6911 ± 0.0062

source: Planck Collaboration (2015 results)
A&A **594** (2016) A13

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

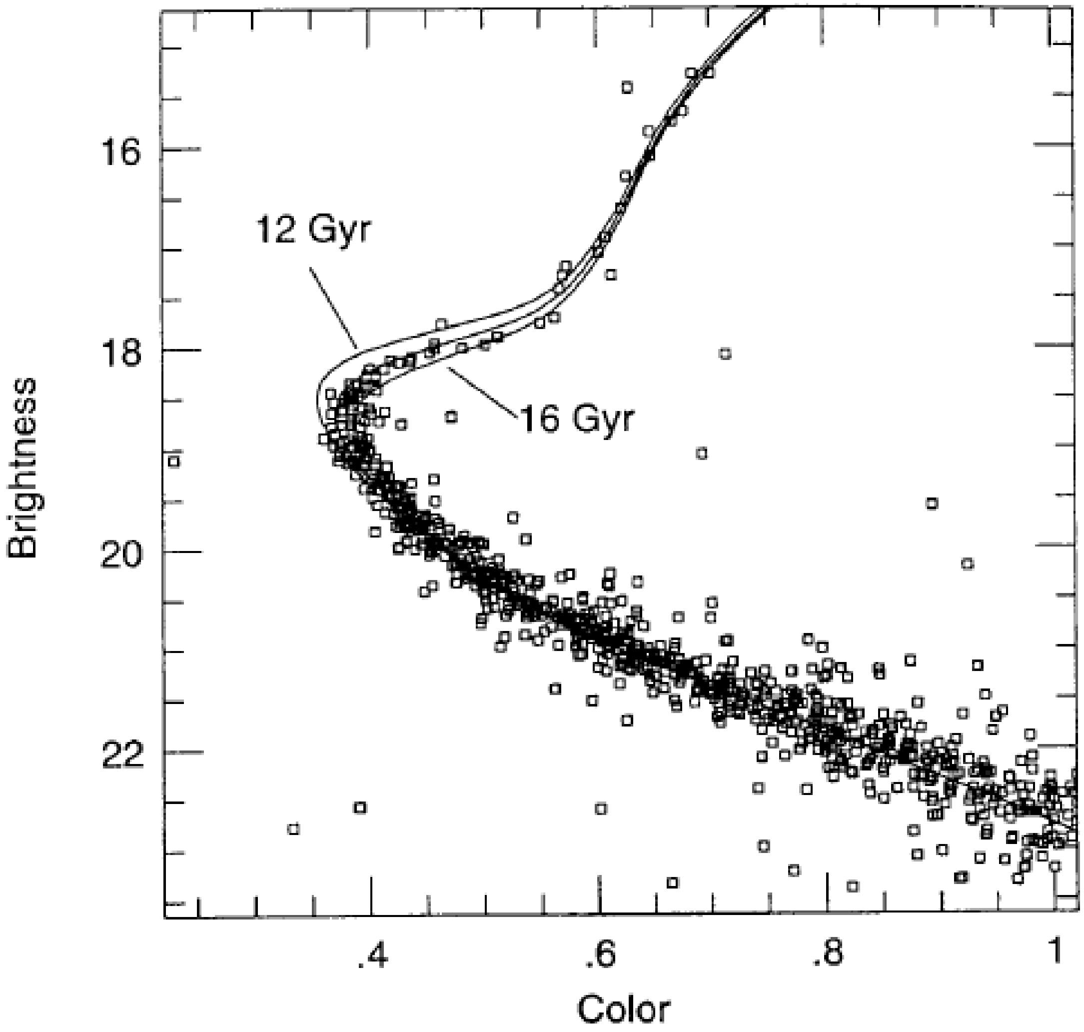


FIG. 2. HR diagram for M92. The squares are measured colors and brightnesses for individual stars in the cluster. The lines show model predictions for the positions of stars for cluster ages of 14, 16, and 18 billion years. The match of the models to the cluster data for an age of 16 billion years is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

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

Cosmological "problems" with age

H_0 = 67.74 ± 0.46 km/s/Mpc

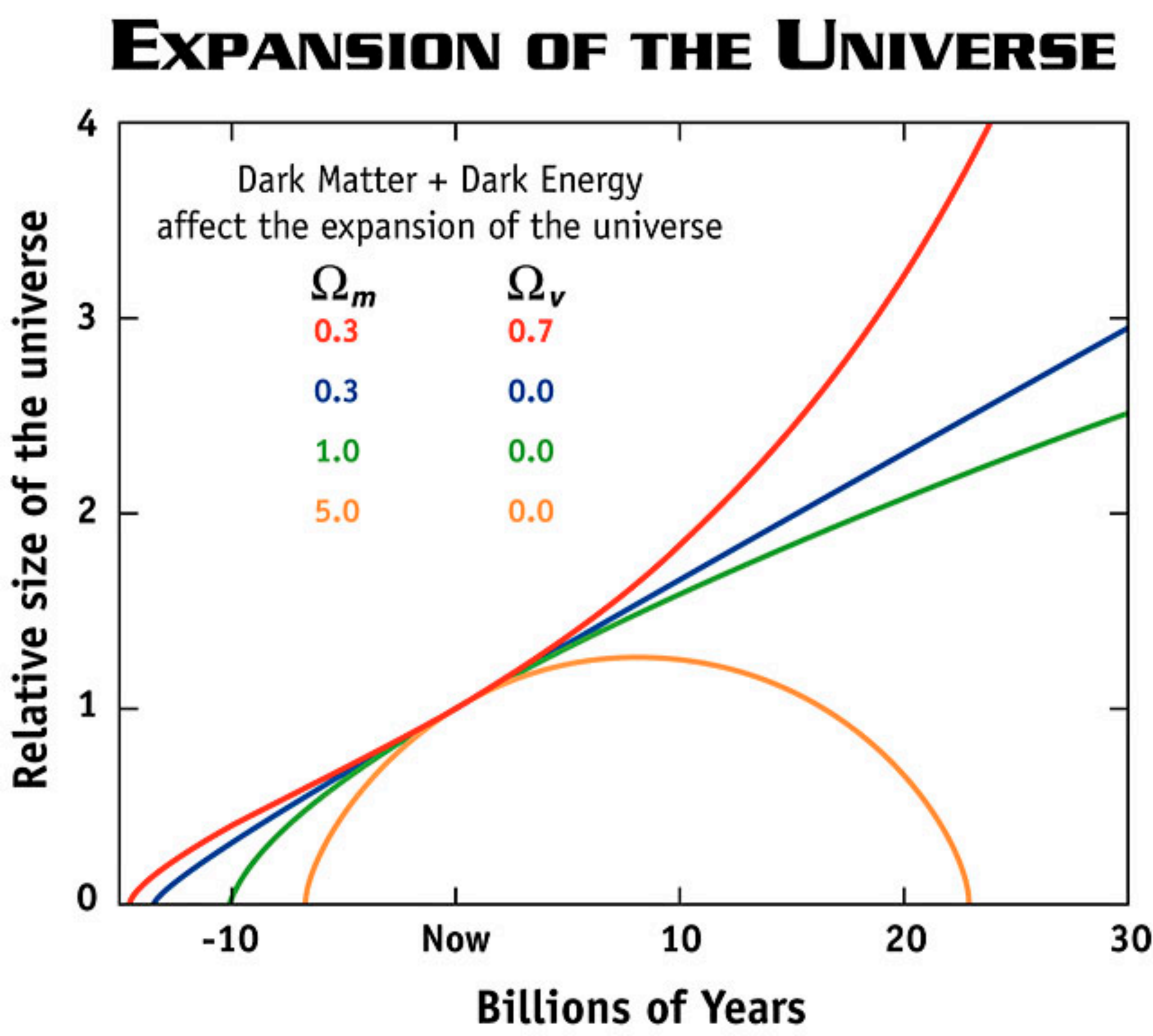
Ω_{cdm} = 0.2589 ± 0.0057

Ω_b = 0.0486 ± 0.0010

Ω_r ~ 0

Ω_Λ = 0.6911 ± 0.0062

for example, if $\Omega = \Omega_m \sim 1$
age = $2/3 \times 1/H_0 \sim 10$ Gyr



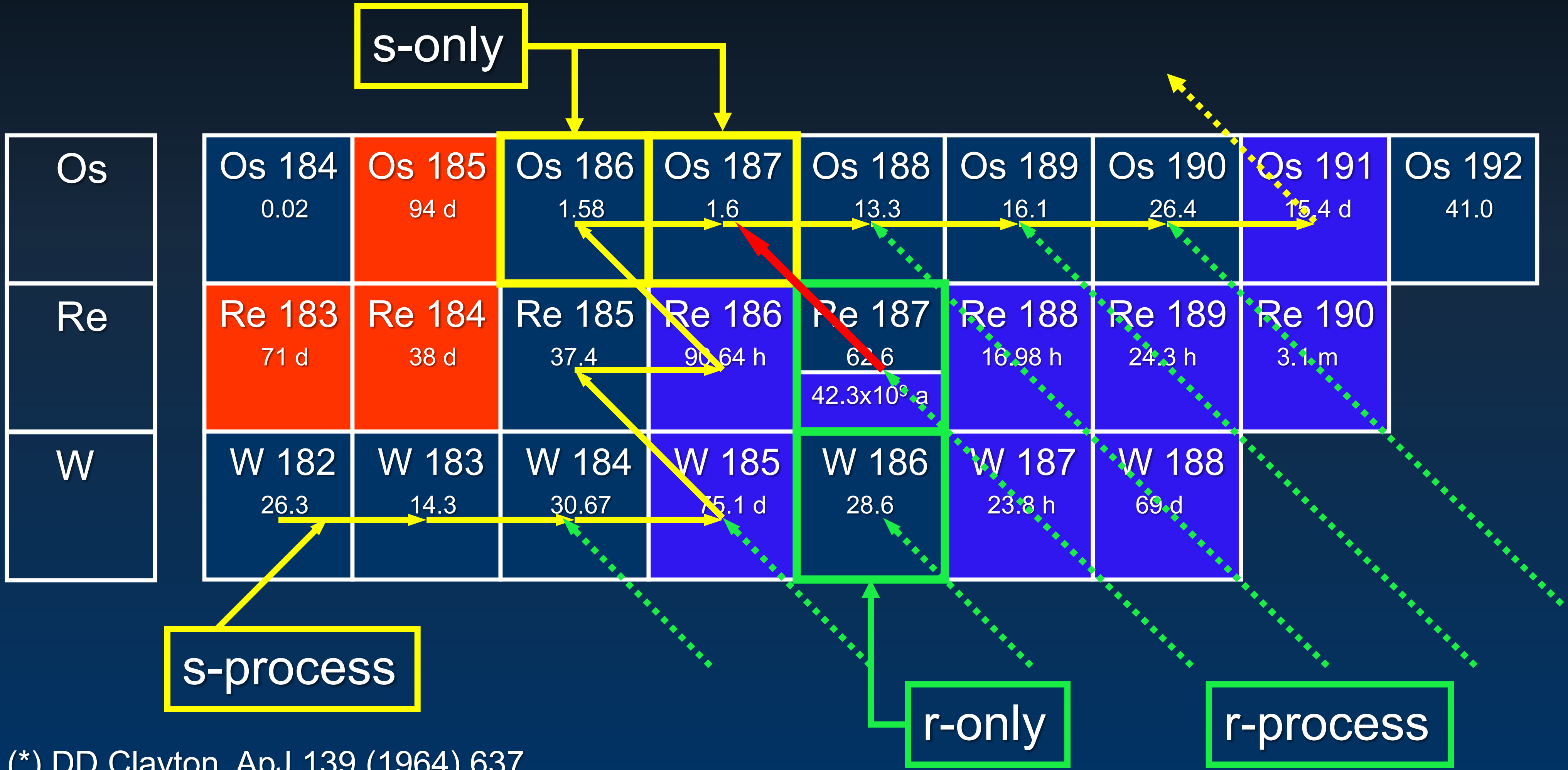
http://map.gsfc.nasa.gov/

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 U/Th abundances in low-Z stars

s-process nucleosynthesis



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		

(*) DD Clayton, ApJ 139 (1964) 637

Necessity for the time-evolution

$$\sigma(A)\times N(A) \approx \text{const.}$$

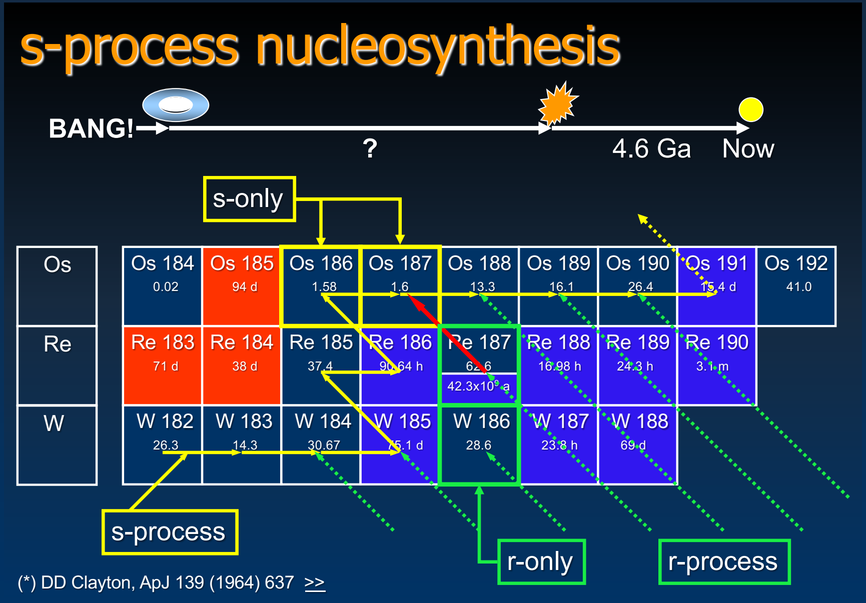
$$R_N \equiv \frac{N(187)}{N(186)} = 1.0 \quad \text{(present)}$$

$$= 0.8 \quad (\text{at } \odot \text{ formation})$$

$$R_\sigma \equiv \frac{\sigma(186)}{\sigma(187)} \sim 0.5 \qquad \text{(from syst.)}$$

$$= 0.43 \pm 0.02 \quad \text{(lab)}$$

$$= 0.35 \pm 0.02 \quad \text{(stellar)}$$



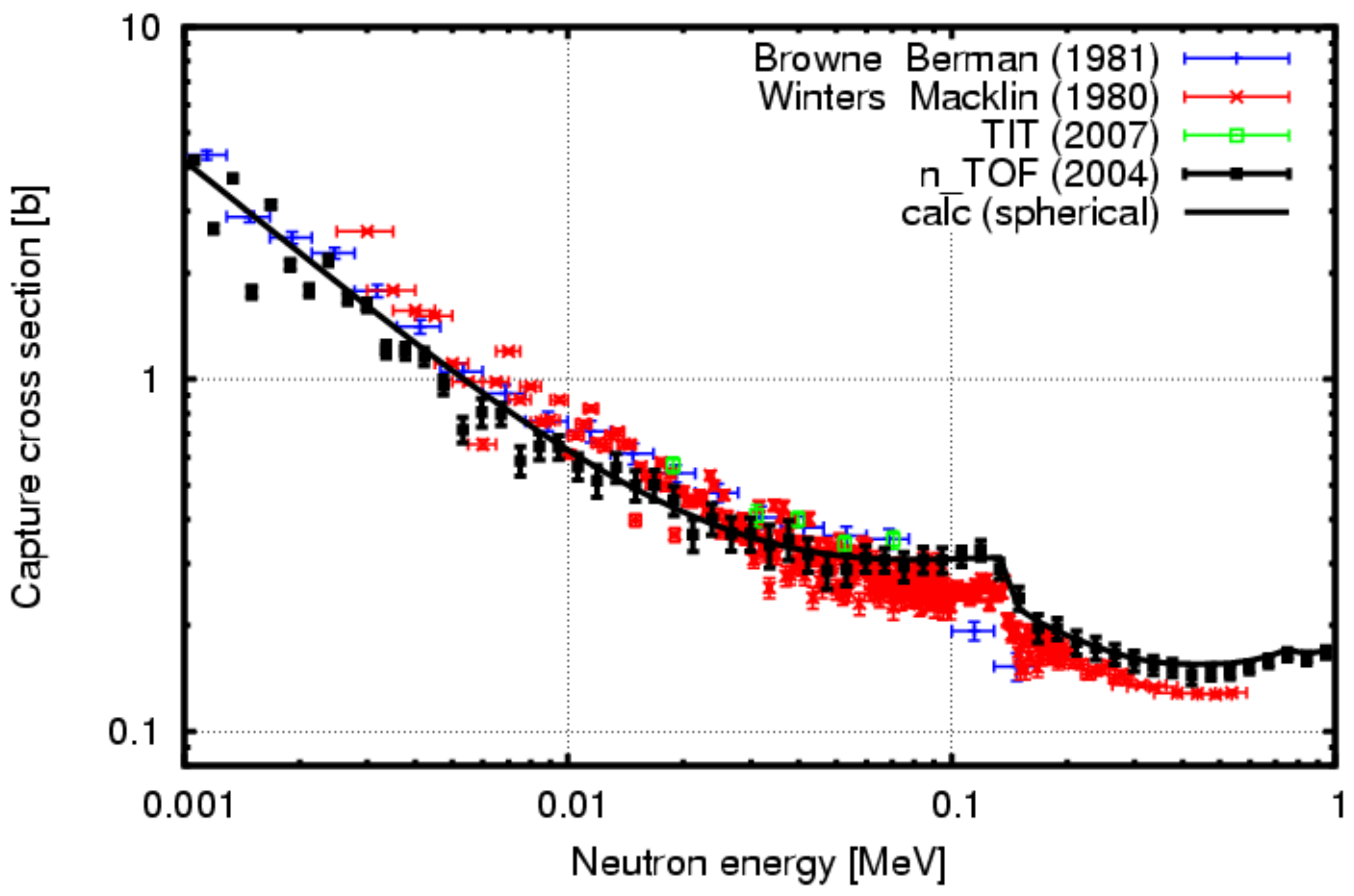
s-process nucleosynthesis

(*) DD Clayton, ApJ 139 (1964) 637 >>

n_TOF-04: ^{186}Os capture x-section

MACS-30	
BrB81	438 ± 30 mb
WiM82	418 ± 16 mb
n_TOF	**414 ± 17 mb**

NB: the calculation is normalized NOT fitted to experimental data



M Mosconi et al. (The n_TOF Collaboration), Physical Review C **82**, 015802 (2010) – I

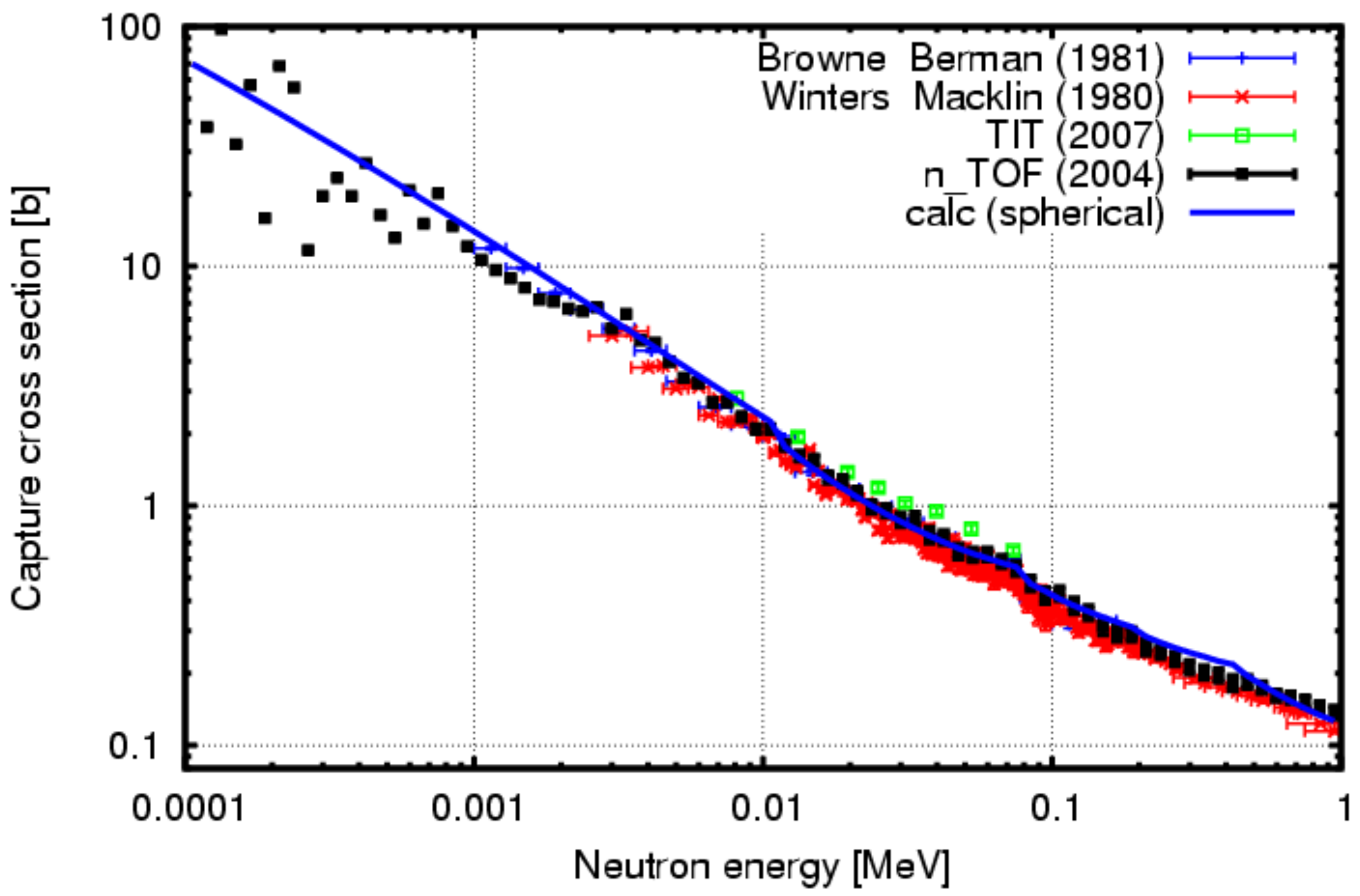
M Mosconi et al. Physical Review C **82**, 015803 (2010) – II

K Fujii et al. (The n_TOF Collaboration), Physical Review C **82**, 015804 (2010) – III

n_TOF-04: ^{187}Os capture x-section

MACS-30	
BrB81	919 ± 43 mb
WiM82	874 ± 28 mb
n_TOF	**969 ± 32 mb**

NB: the calculation is normalized NOT fitted to experimental data



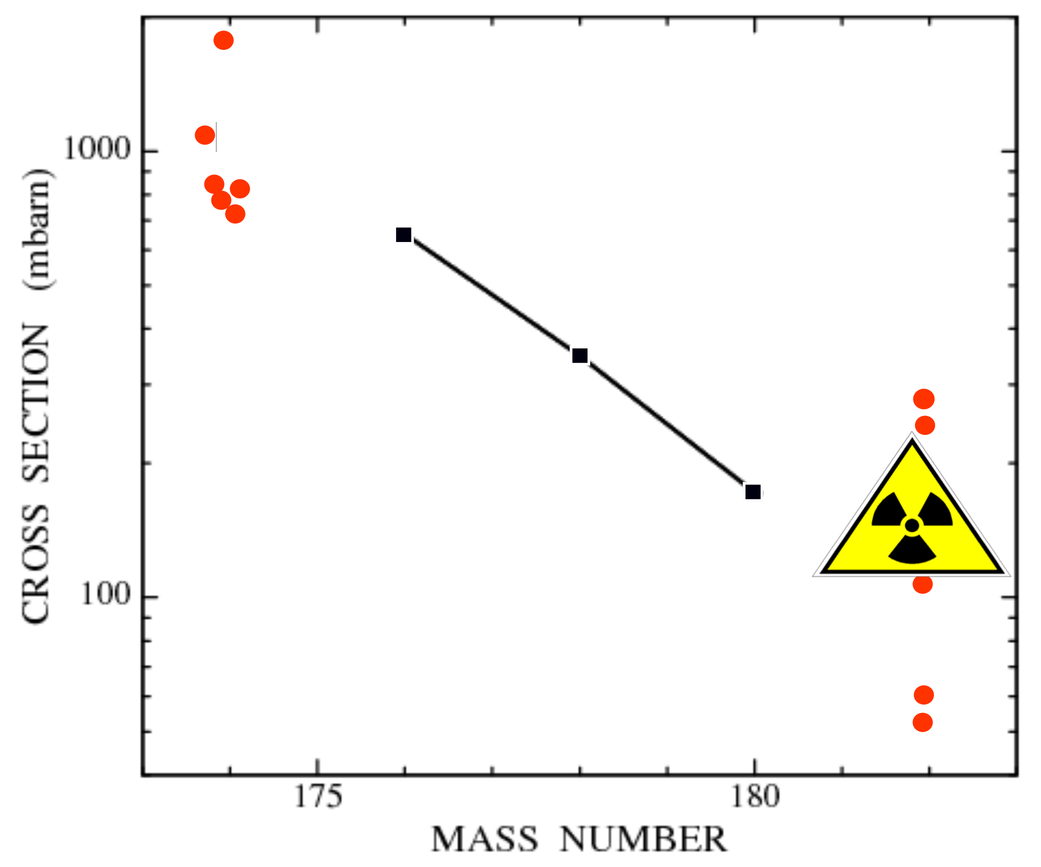
M Mosconi et al. (The n_TOF Collaboration), Physical Review C **82**, 015802 (2010) – I

M Mosconi et al. Physical Review C **82**, 015803 (2010) – II

K Fujii et al. (The n_TOF Collaboration), Physical Review C **82**, 015804 (2010) – III

What about theory?

C. Vockenhuber, I. Dillmann, M. Heil, F. Käppeler et al. (2007), Phys. Rev. C **75**, 015804



^{176}Hf, ^{178}Hf, ^{180}Hf:

MACS uncertainties

1 - 2%

exercise joined

by 6 leading groups:

calculate MACS of

^{174}Hf and **^{182}Hf**

prior to measurement

… but: theory indispensable for stellar corrections!

courtesy of Franz Käppeler

^{186}Os capture x-section

Hauser-Feschbach theory:

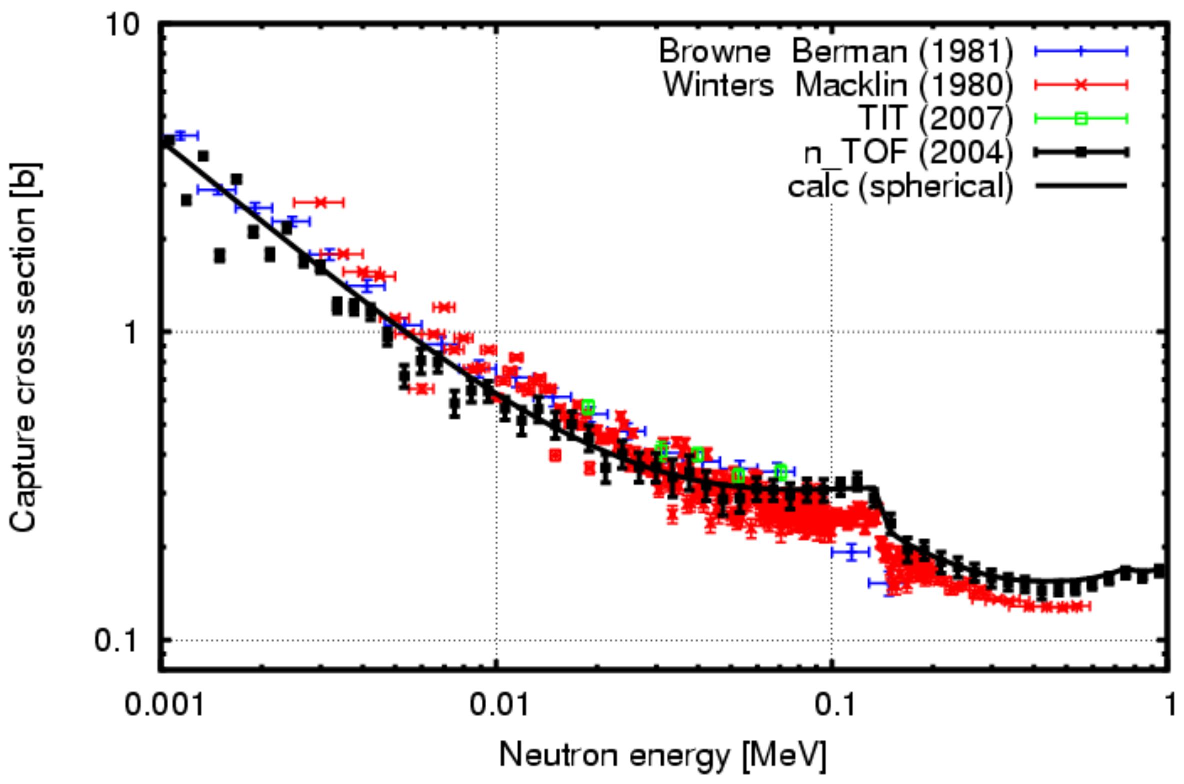
(statistical model)

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

- 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 $<D>_{exp}$



Thermal population of nuclear excited states

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

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

P(gs) = 33%

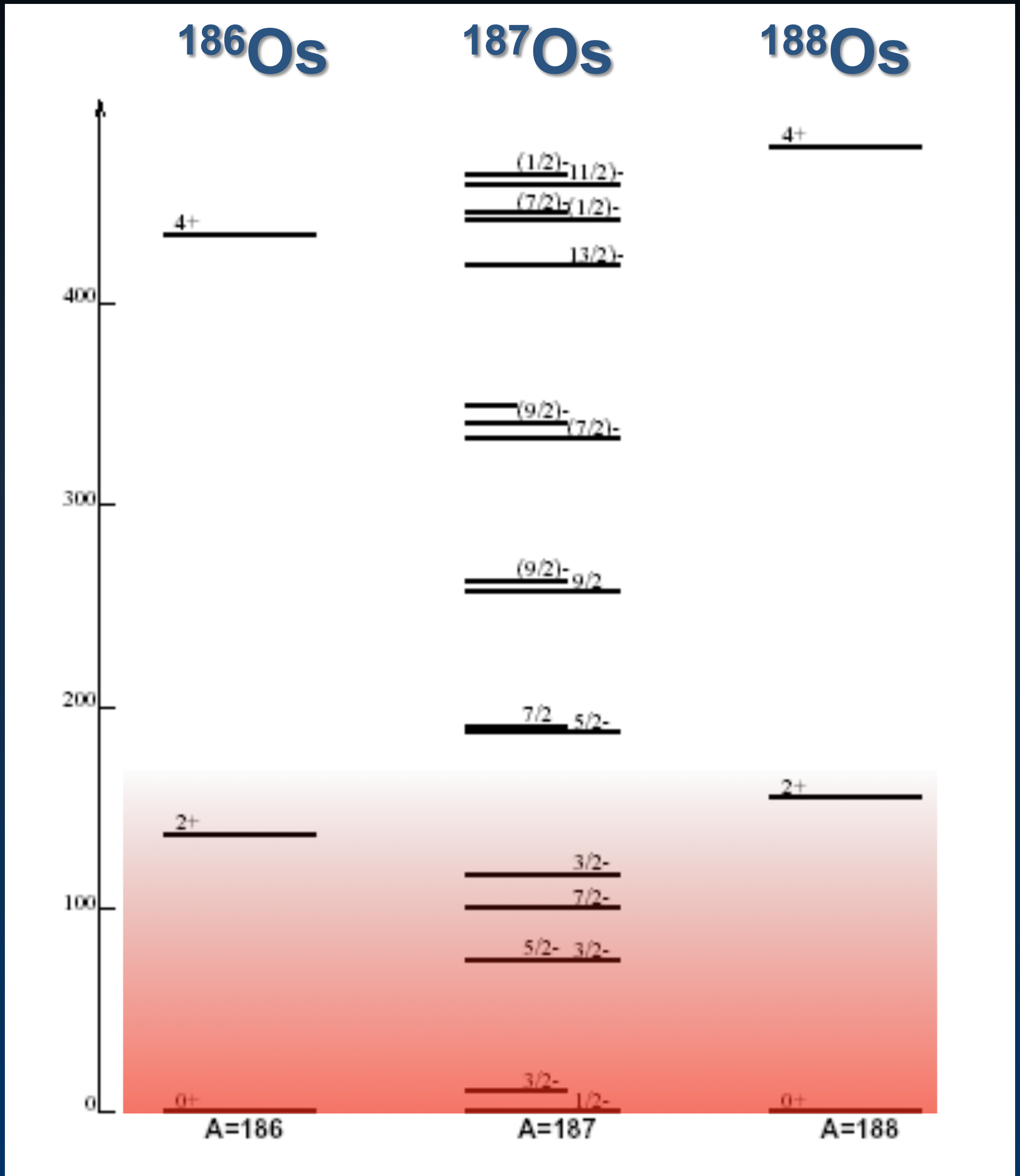
P(1st) = **47%**

P(all others) = 20%

stellar enhancement factor

SEF = $\sigma* / \sigma_{exp}$

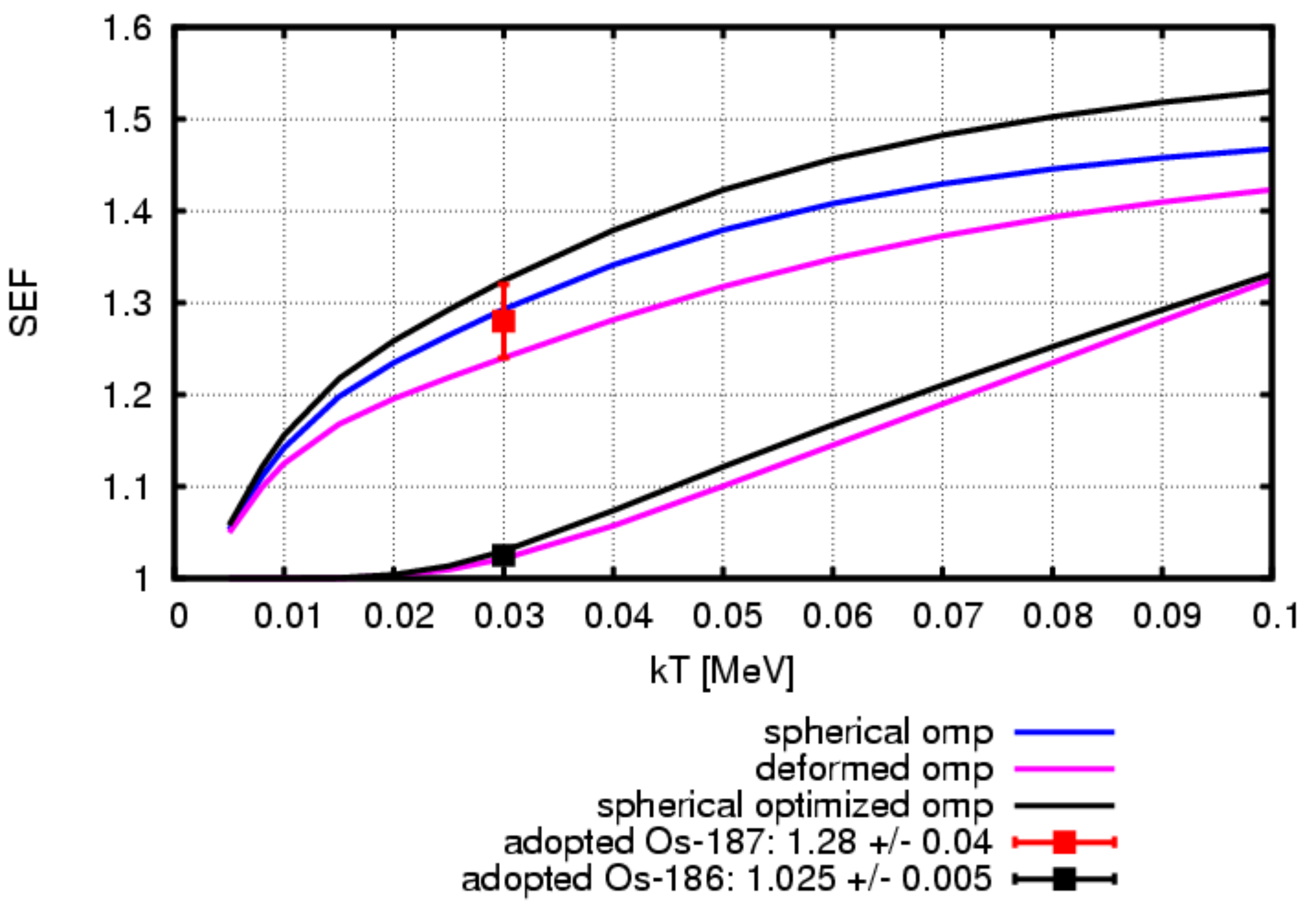
SE Woosley and WA Fowler, ApJ 233 (1979) 411



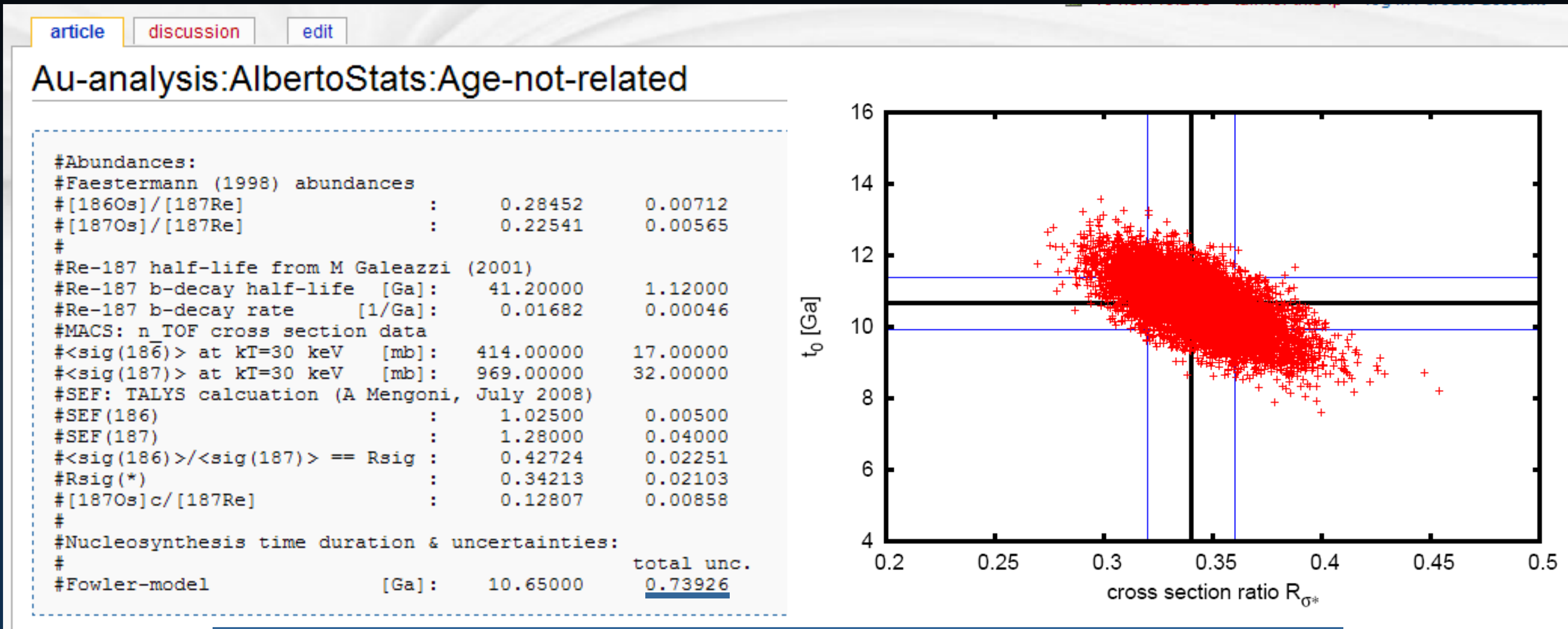
Stellar enhancement factor

$$\langle\sigma_{n,\gamma}\rangle^* = \mathrm{SEF} \cdot \langle\sigma_{n,\gamma}\rangle$$

Physical Review C **82**, 015802 (2010) – I
Physical Review C **82**, 015803 (2010) – II
Physical Review C **82**, 015804 (2010) – III



Nuclear Data & Abundances



Au-analysis:AlbertoStats:Age-not-related

```
#Abundances:
#Faestermann (1998) abundances
#[186Os]/[187Re]              :     0.28452     0.00712
#[187Os]/[187Re]              :     0.22541     0.00565
#
#Re-187 half-life from M Galeazzi (2001)
#Re-187 b-decay half-life  [Ga]:    41.20000     1.12000
#Re-187 b-decay rate     [1/Ga]:     0.01682     0.00046
#MACS: n_TOF cross section data
#<sig(186)> at kT=30 keV   [mb]:   414.00000    17.00000
#<sig(187)> at kT=30 keV   [mb]:   969.00000    32.00000
#SEF: TALYS calcuation (A Mengoni, July 2008)
#SEF(186)                     :     1.02500     0.00500
#SEF(187)                     :     1.28000     0.04000
#<sig(186)>/<sig(187)> == Rsig :     0.42724     0.02251
#Rsig(*)                      :     0.34213     0.02103
#[187Os]c/[187Re]             :     0.12807     0.00858
#
#Nucleosynthesis time duration & uncertainties:
#                                             total unc.
#Fowler-model              [Ga]:    10.65000     0.73926
```

Abundances : 0.49 Gyr

x-section ratio* : 0.47 Gyr

Re-187 β-decay half-life : 0.29 Gyr

Total uncertainty : < 1 Gyr

Summary on age

- Cosmological way (CMB observation & ΛCDM)

13.799 ± 0.021 Gyr

The Planck Collaboration, 2015 results

- Astronomical way (globular clusters)

14 ± 2 Gyr

G Imbriani et al., A&A **420** (2004) 625

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

15.0 ± 0.8 ± 2 Gyr (*)

>13.4 ± 0.9 ± 2.2 Gyr

A Frebel et al. ApJ 660 (2007) L117

(*) 2 Ga uncertainty assigned to GCE modeling + astration(?)

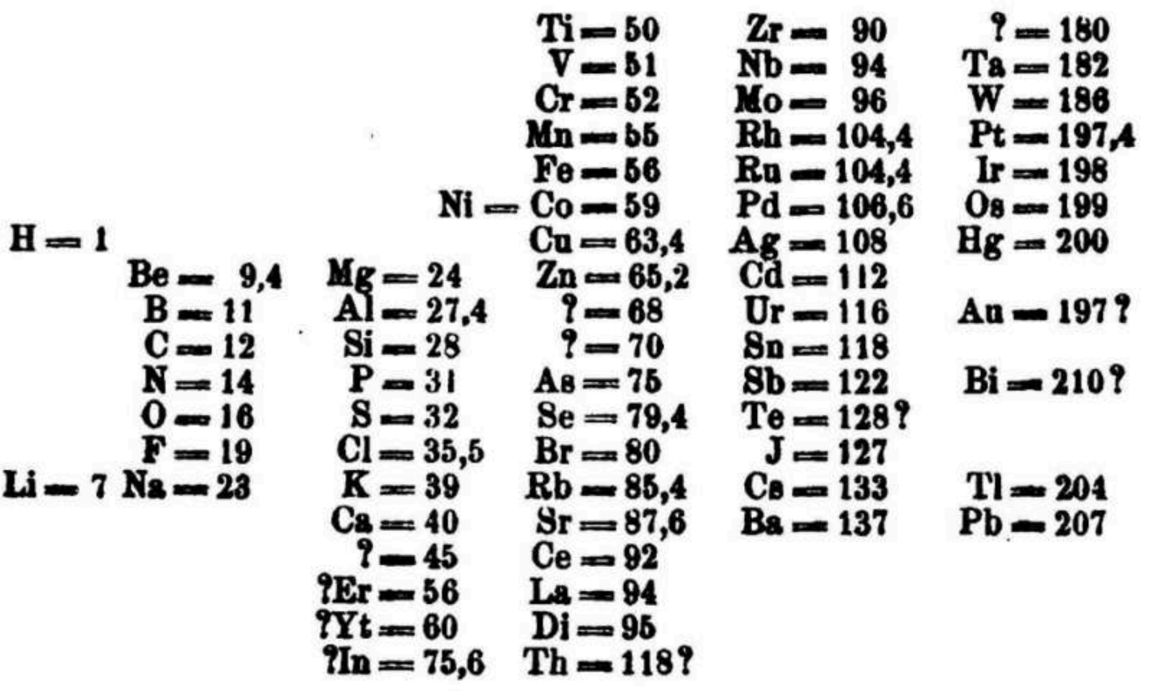
Overall

H, He (Li) : CLiP still there

metals: : nuclear physics - accuracy not yet enough

astrophysics - stellar modeling for s-process,

NSM vs/and SNe dilemma for the r-process



			Ti = 50	Zr = 90	? = 180
			V = 51	Nb = 94	Ta = 182
			Cr = 52	Mo = 96	W = 186
			Mn = 55	Rh = 104,4	Pt = 197,4
			Fe = 56	Ru = 104,4	Ir = 198
			Ni = Co = 59	Pd = 106,6	Os = 199
H = 1			Cu = 63,4	Ag = 108	Hg = 200
	Be = 9,4	Mg = 24	Zn = 65,2	Cd = 112	
	B = 11	Al = 27,4	? = 68	Ur = 116	Au = 197?
	C = 12	Si = 28	? = 70	Sn = 118	
	N = 14	P = 31	As = 75	Sb = 122	Bi = 210?
	O = 16	S = 32	Se = 79,4	Te = 128?	
	F = 19	Cl = 35,5	Br = 80	J = 127	
Li = 7	Na = 23	K = 39	Rb = 85,4	Cs = 133	Tl = 204
		Ca = 40	Sr = 87,6	Ba = 137	Pb = 207
		? = 45	Ce = 92		
		?Er = 56	La = 94		
		?Yt = 60	Di = 95		
		?In = 75,6	Th = 118?		

A version of Mendeleev's 1869 periodic table: *An experiment on a system of elements based on their atomic weights and chemical similarities.* This early arrangement presents the periods vertically and the groups horizontally.

The End