Early-Solar and interstellar actinides

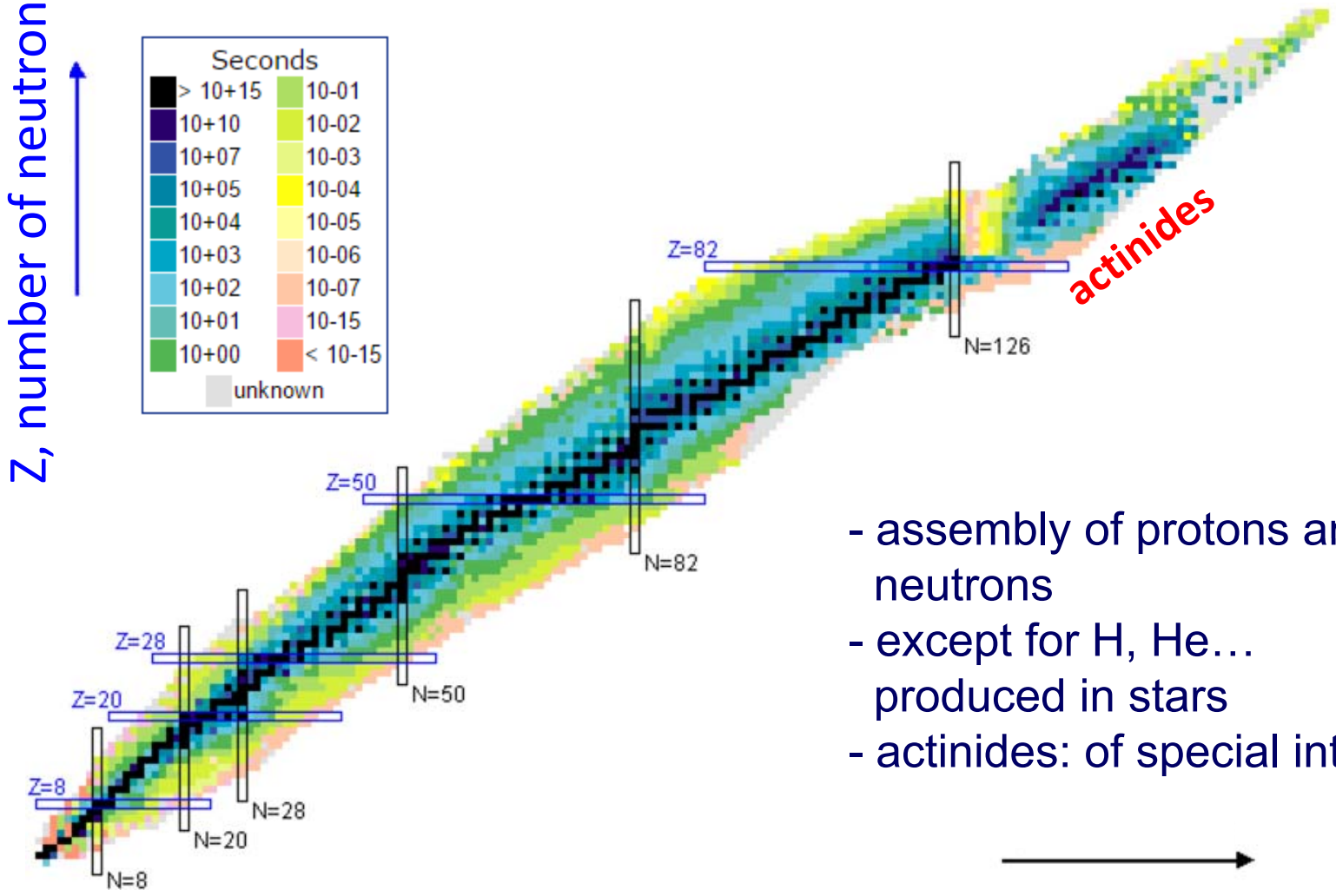
…and the r-process

Michael Paul
Hebrew University, Jerusalem

A humble tribute to a long-standing friendship with Yossi, Ruthy and Tsvi

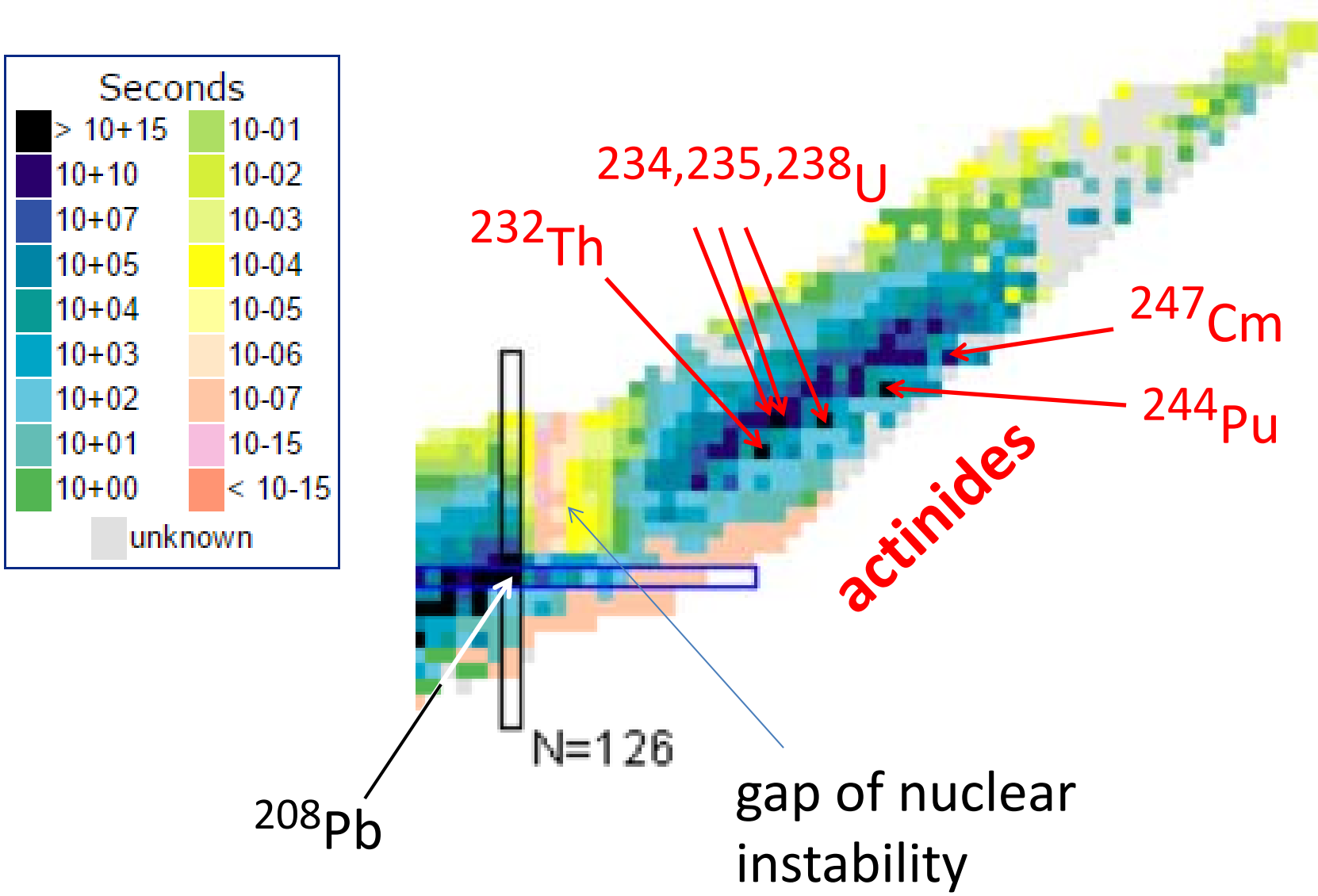
Recent Developments in General Relativity
in Memory of Joseph Katz(1930-2016)
Jerusalem, 21-23 May, 2017

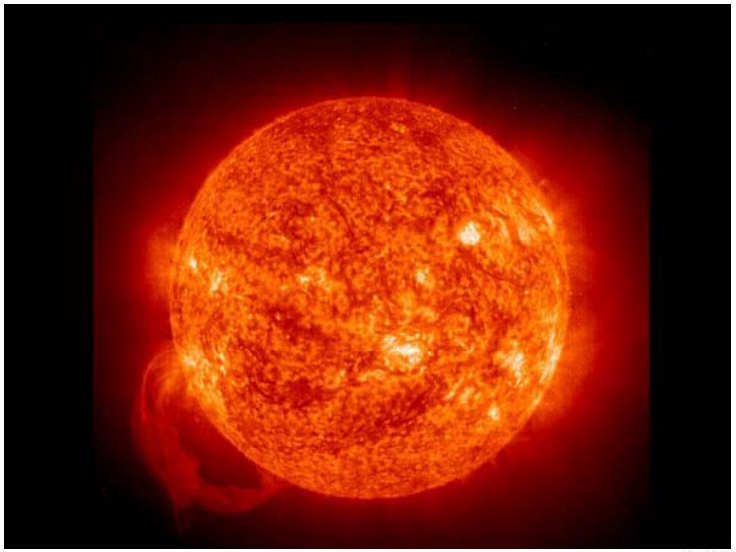
The Table of Nuclides



- assembly of protons and neutrons
- except for H, He… produced in stars
- actinides: of special interest

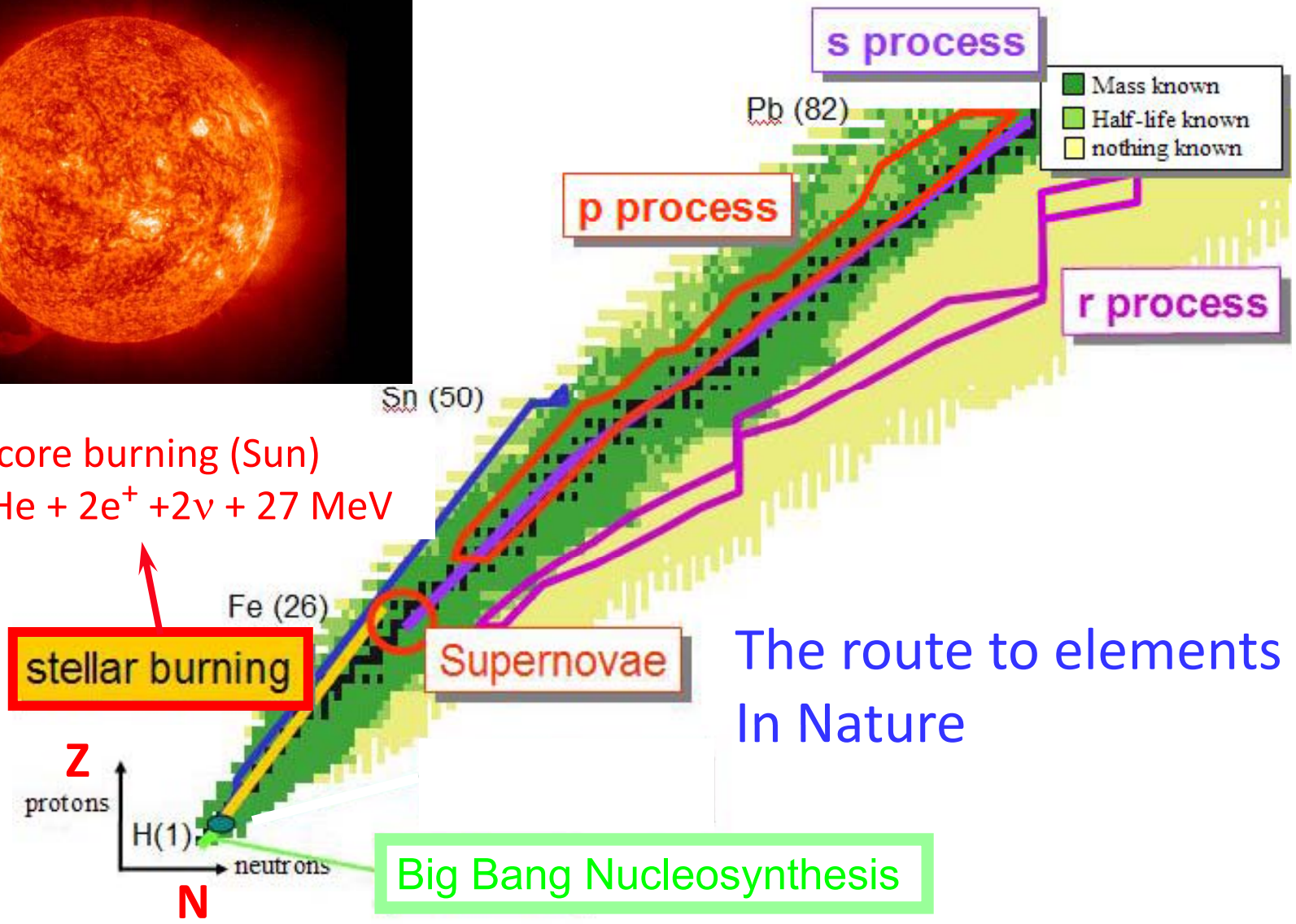
Z, number of protons


Seconds
> 10+15
10+10
10+07
10+05
10+04
10+03
10+02
10+01
10+00
10-01
10-02
10-03
10-04
10-05
10-06
10-07
10-15
< 10-15
unknown
234,235,238U
232Th
247Cm
244Pu
actinides
N=126
208Pb
gap of nuclear instability



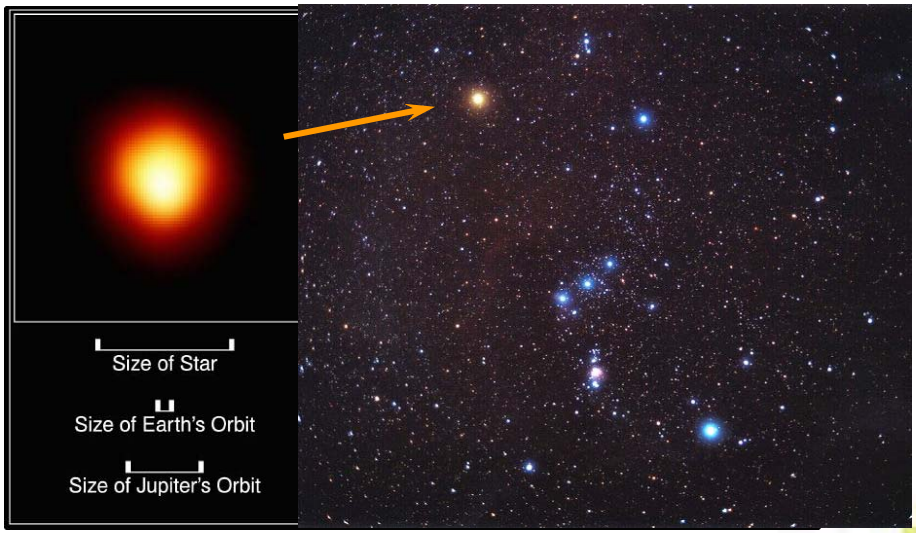
Proton core burning (Sun)

$4p \rightarrow {}^{4}He + 2e^{+} + 2\nu + 27\ MeV$



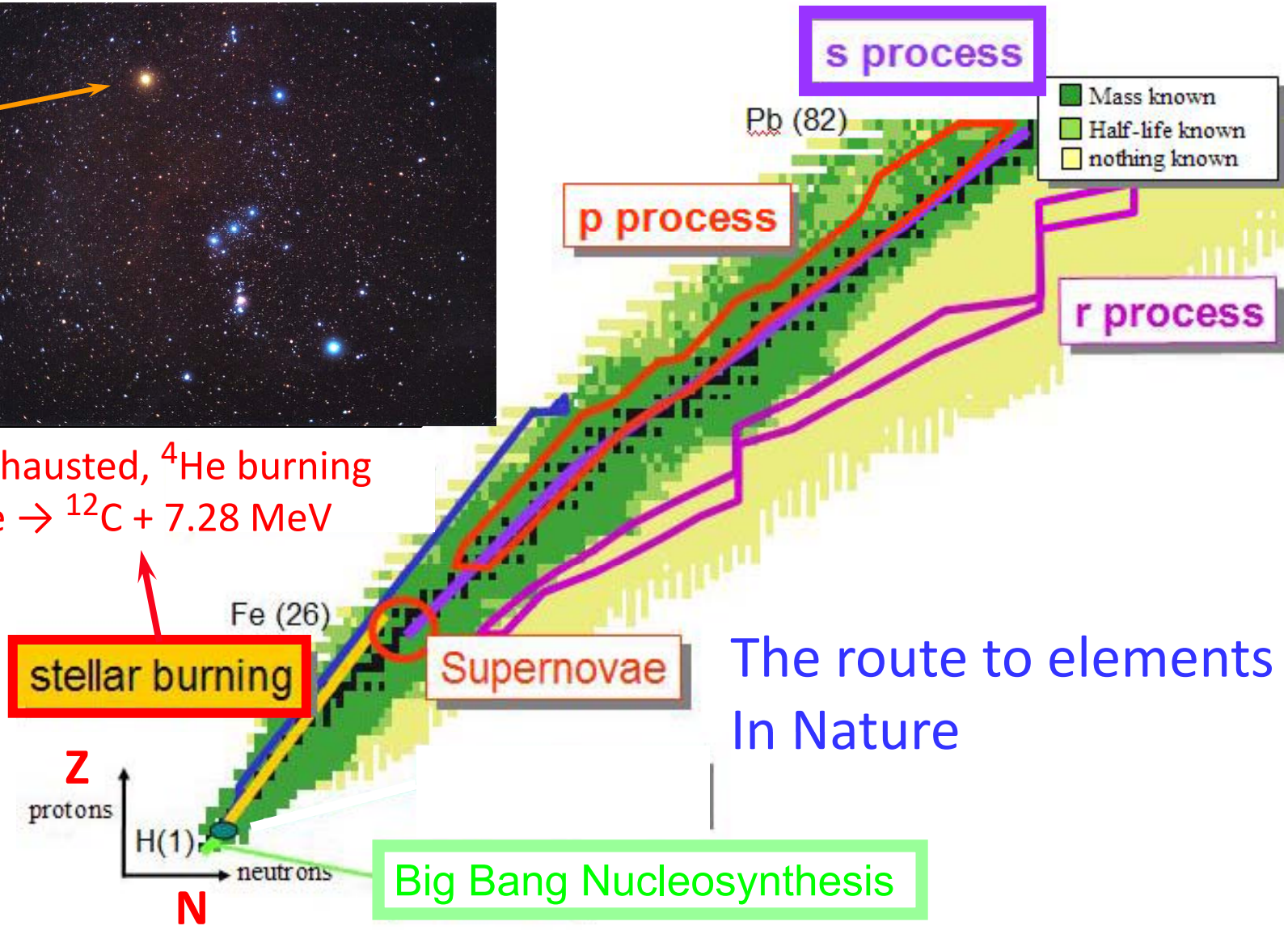
The route to elements In Nature

Red Giant Betelgeuse in constellation „Orion"

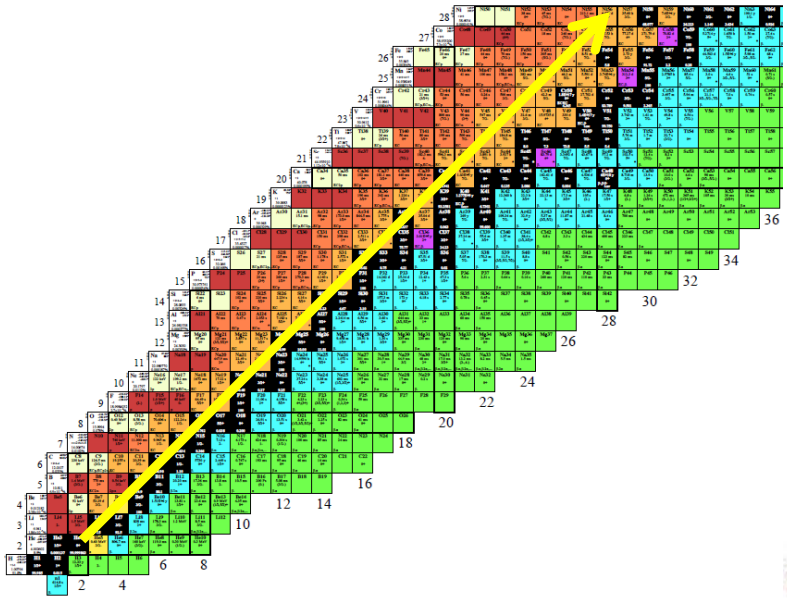


p fuel exhausted, ^{4}He burning

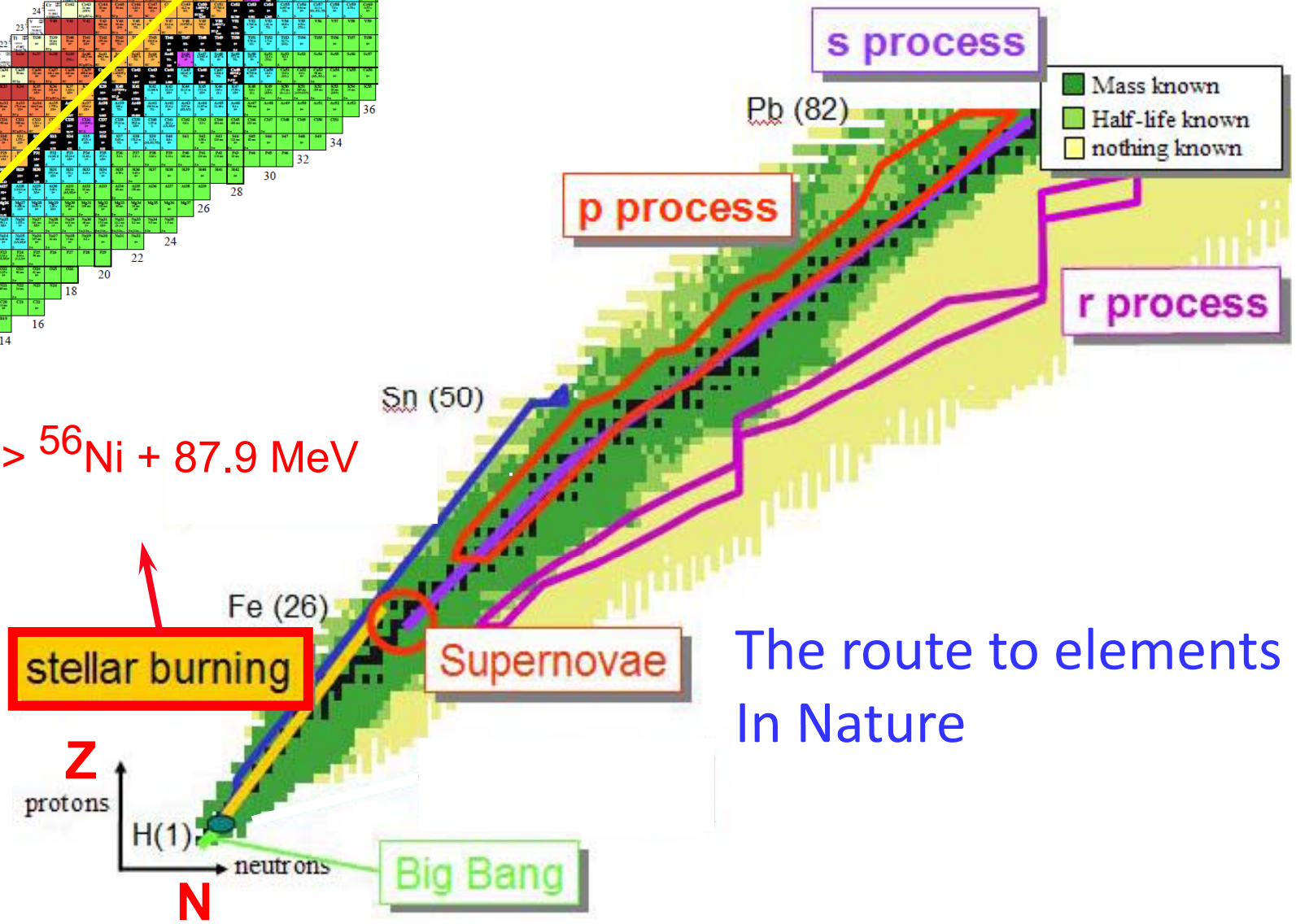
3 ^{4}He → ^{12}C + 7.28 MeV



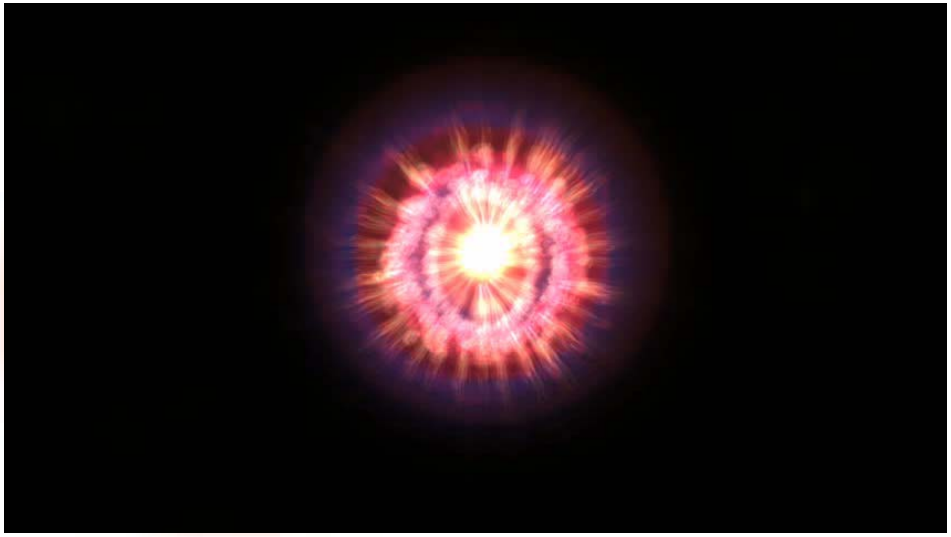
The route to elements In Nature



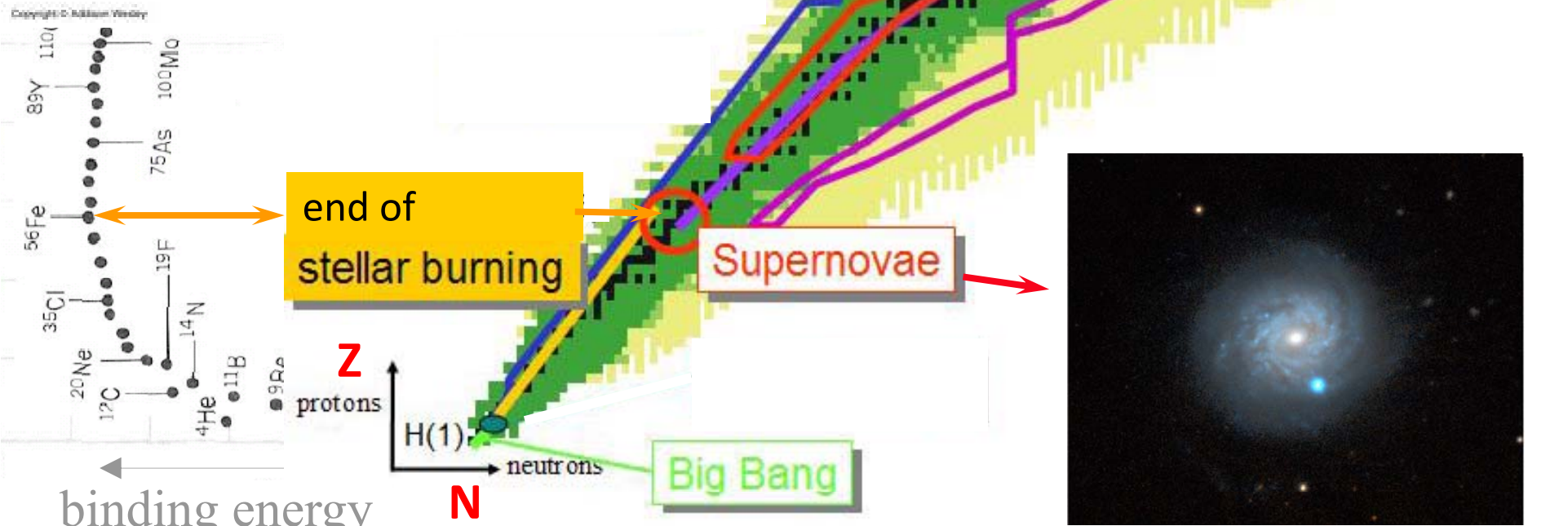
$14\ {}^{4}He \rightarrow {}^{56}Ni + 87.9\ MeV$



The route to elements
In Nature

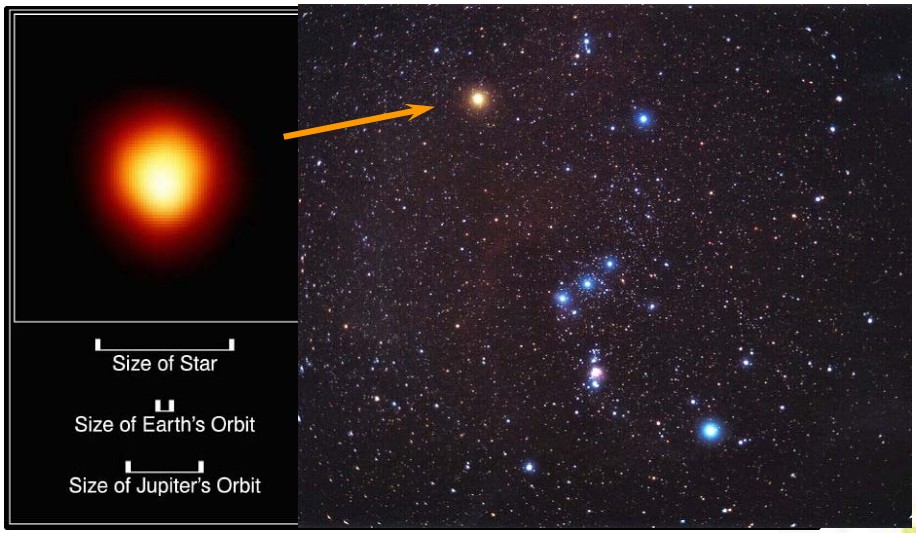


binding energy
nucleon

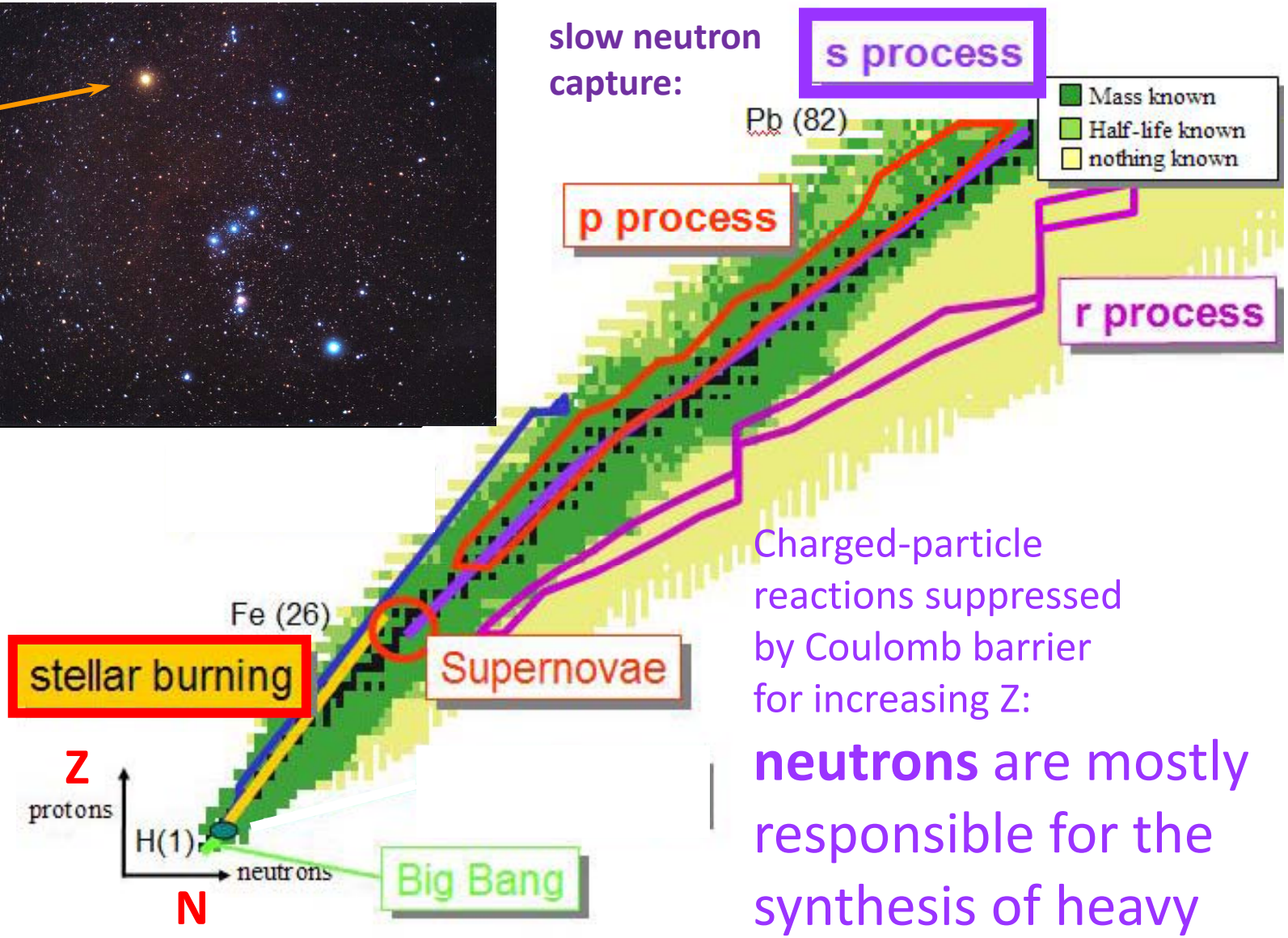


SN1998aa

Red Giant Betelgeuse in constellation „Orion"



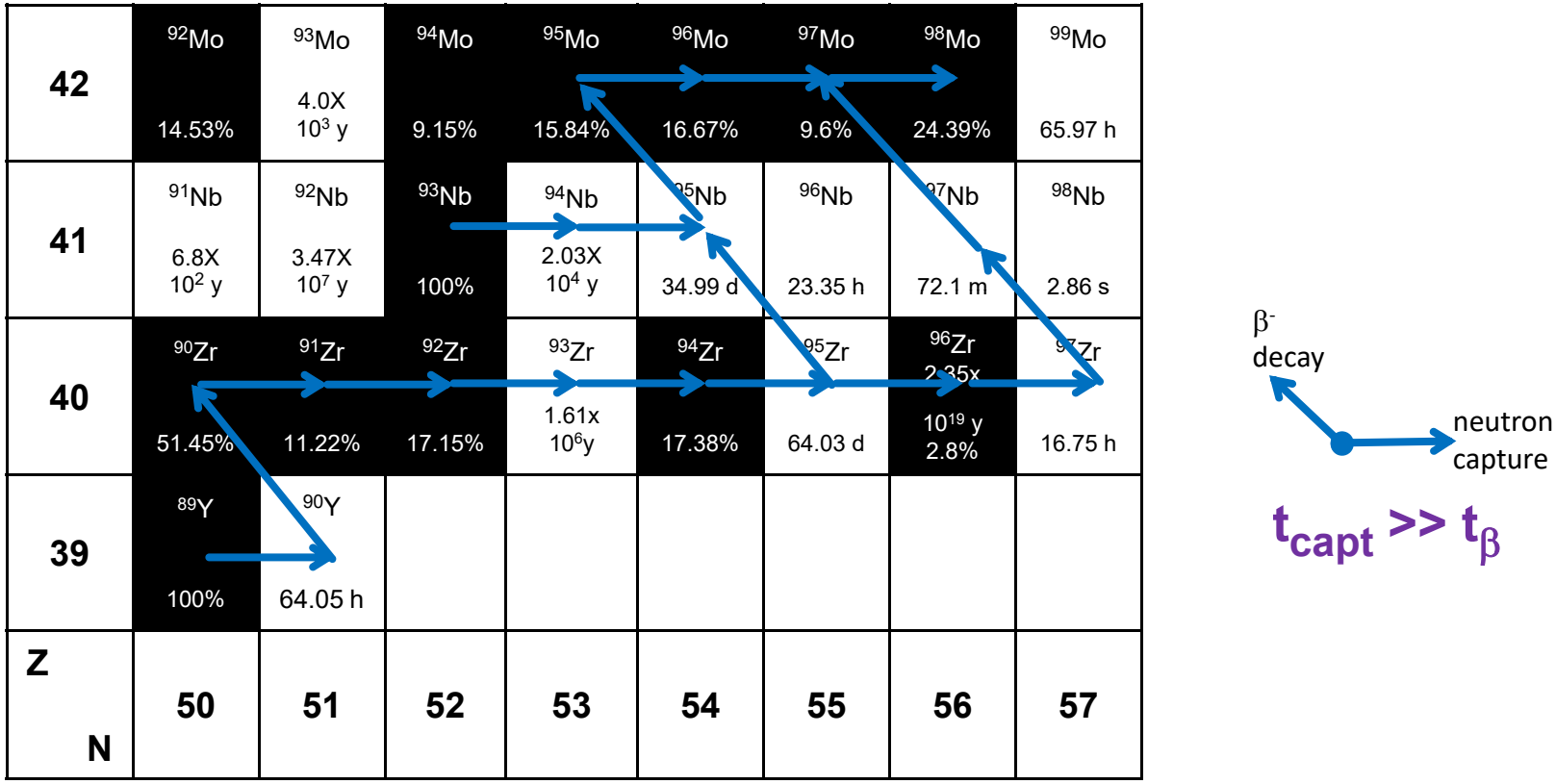
slow neutron capture:



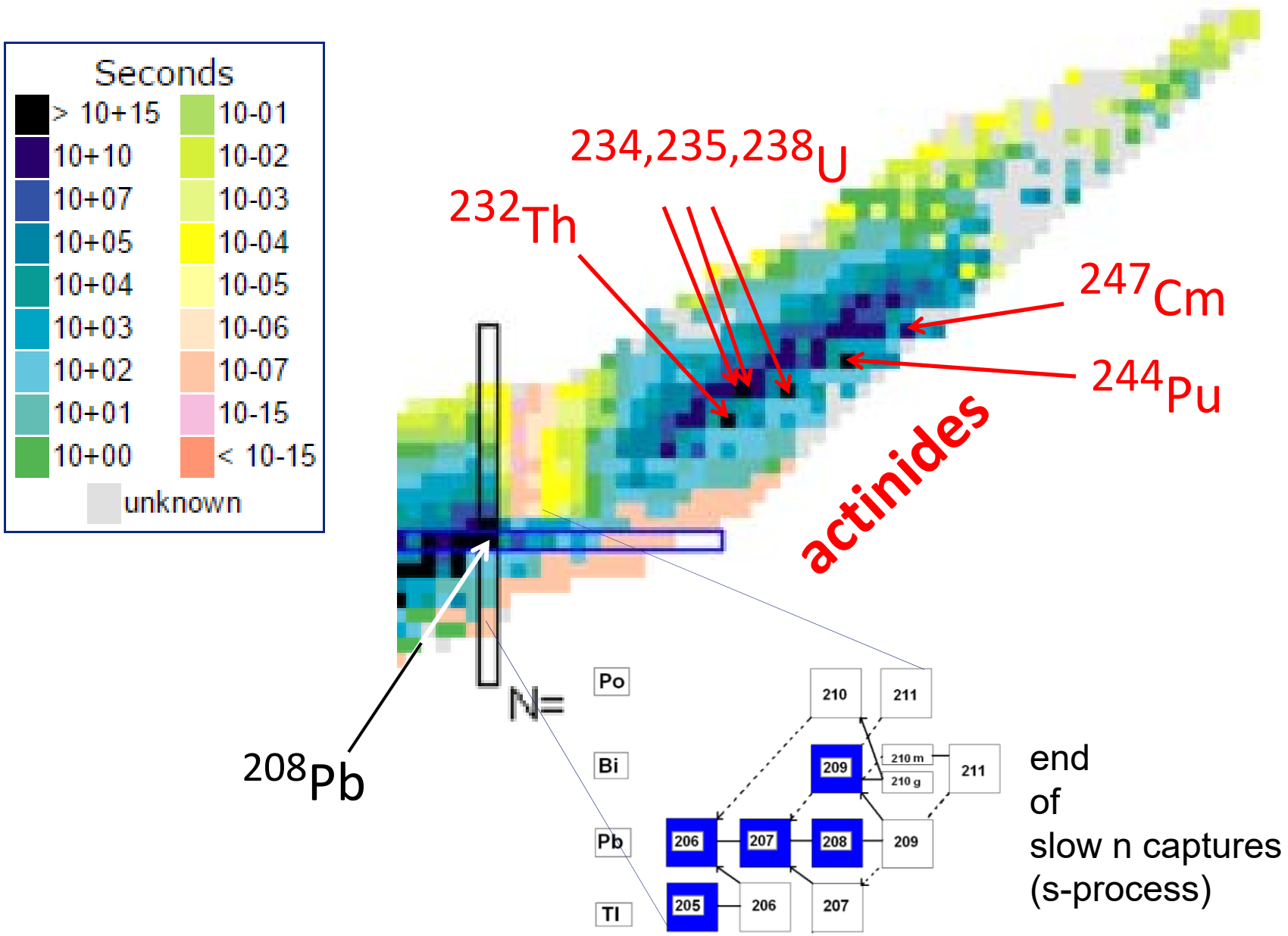
Charged-particle reactions suppressed by Coulomb barrier for increasing Z:

neutrons are mostly responsible for the synthesis of heavy elements

Slow neutron capture (s-)process



$t_{capt} >> t_{\beta}$

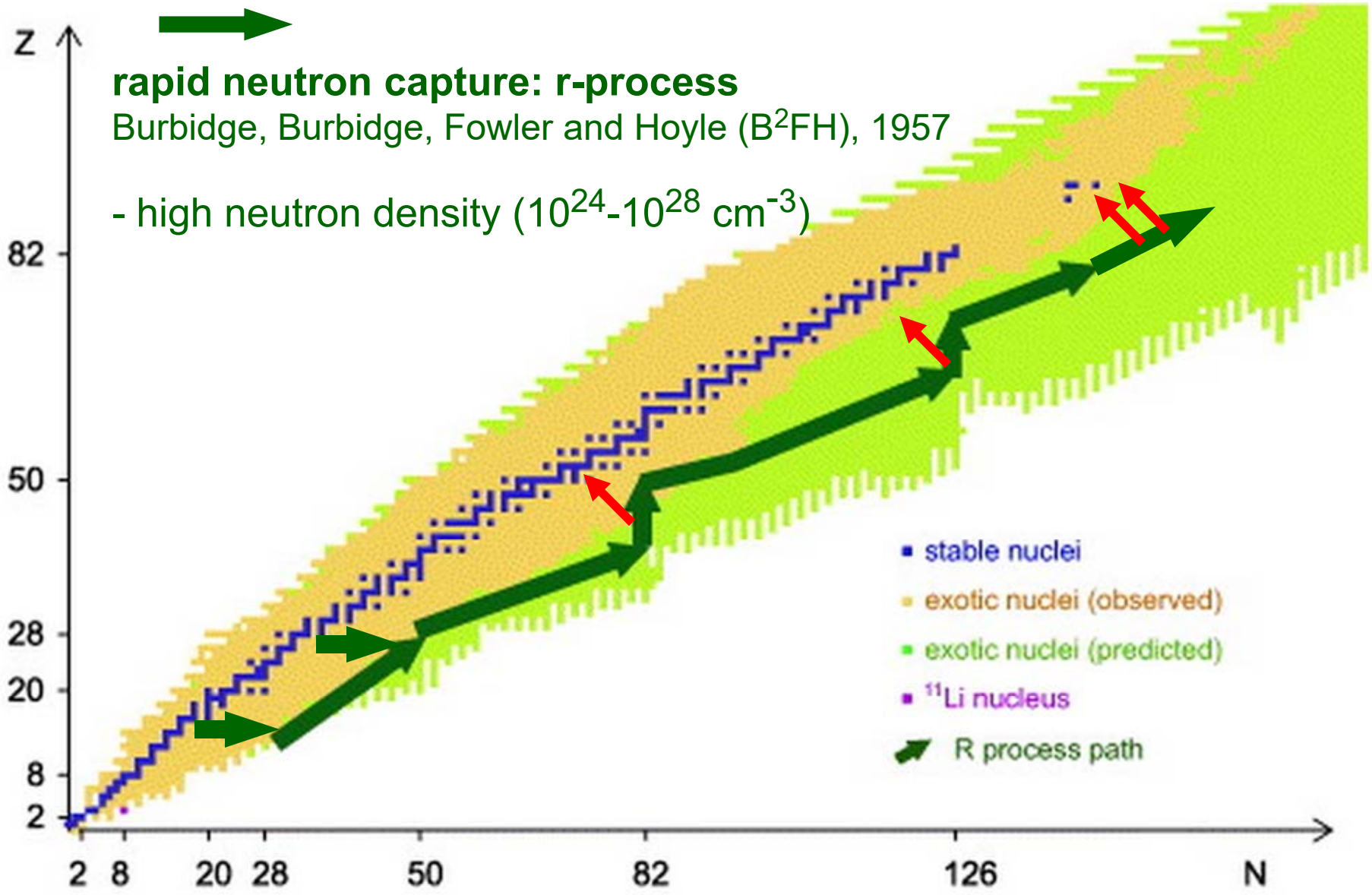


end
of
slow n captures
(s-process)

rapid neutron capture: r-process

Burbidge, Burbidge, Fowler and Hoyle (B^2FH), 1957

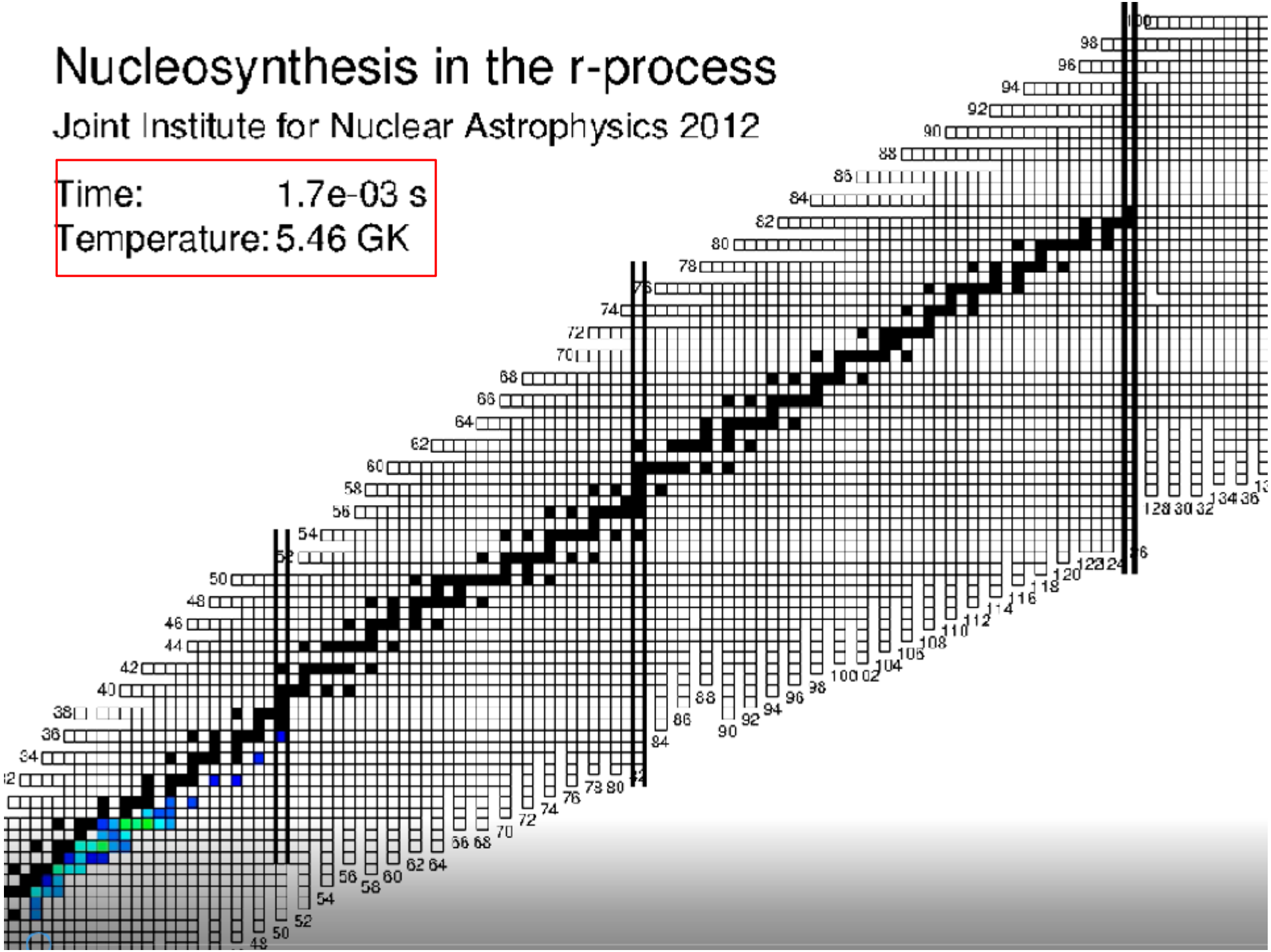
- high neutron density (10^{24}-10^{28} cm^{-3})



Nucleosynthesis in the r-process

Joint Institute for Nuclear Astrophysics 2012

Time: 1.7e-03 s
Temperature: 5.46 GK



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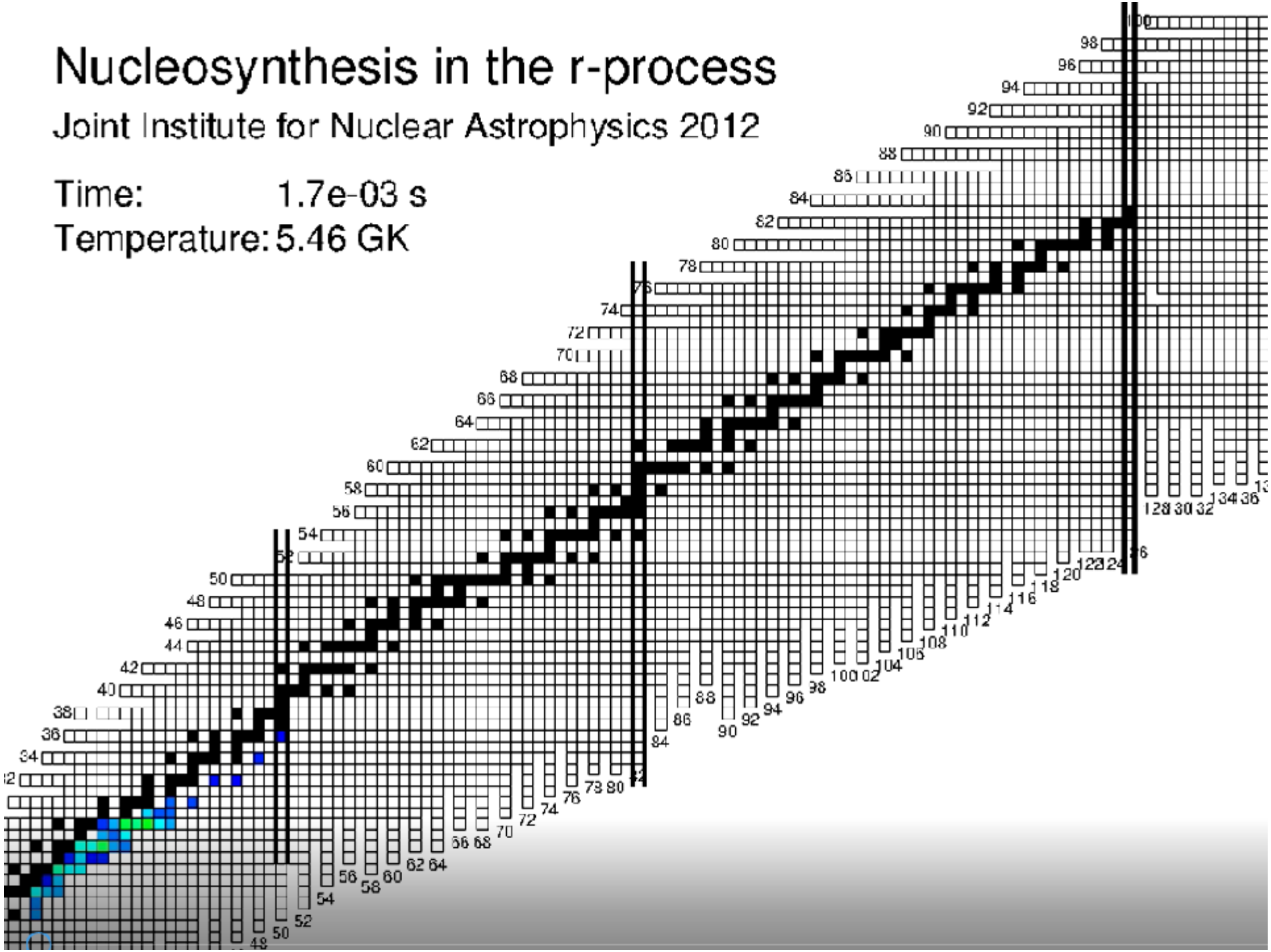
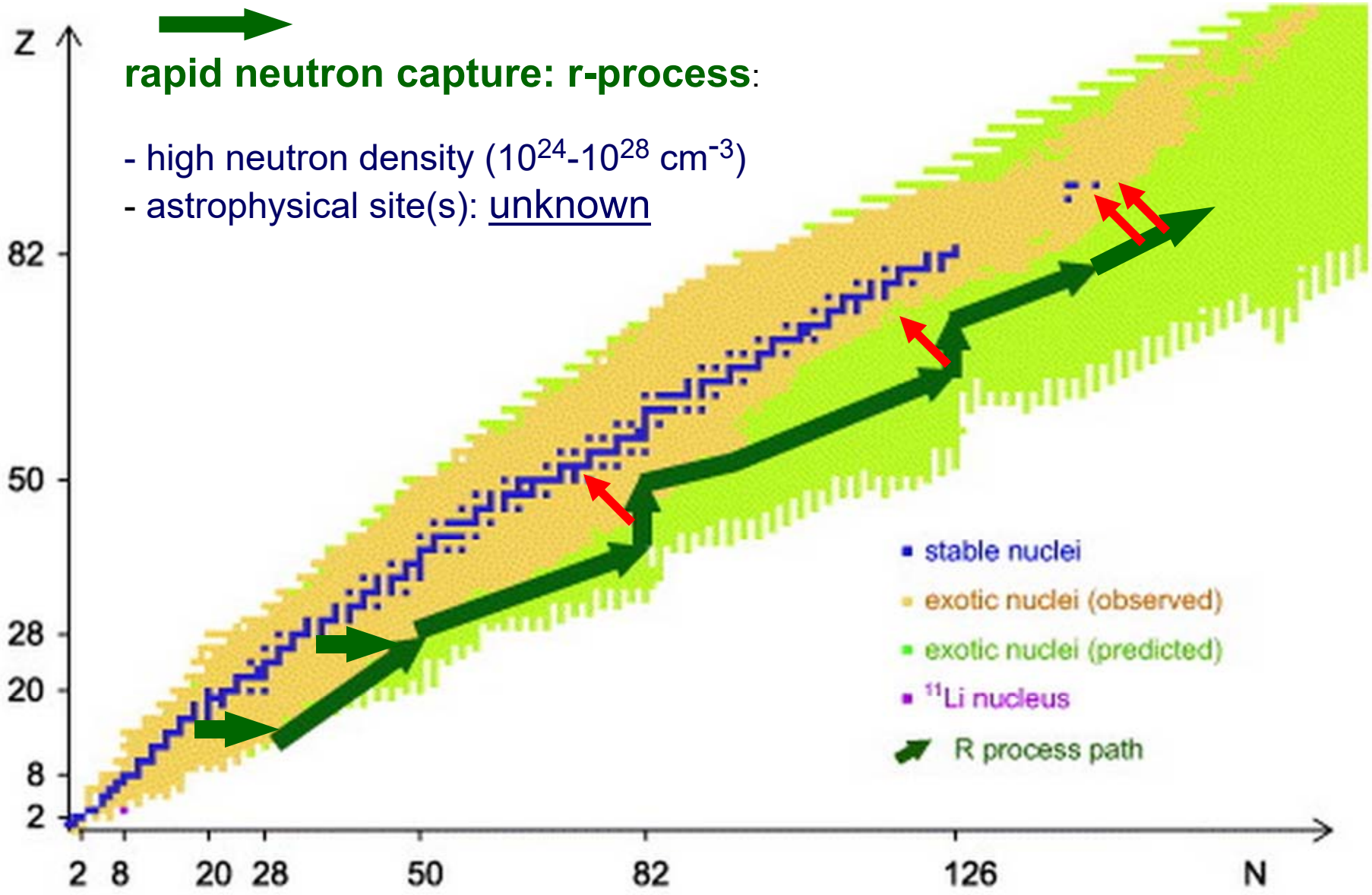


rapid neutron capture: r-process:

- high neutron density (10^{24}-10^{28} cm^{-3})
- astrophysical site(s): unknown



What is/are the natural site/s of r-process ? One of the important open question of nuclear astrophysics.

A critical parameter is the number of neutron per seed nucleus. In order to get to nuclei with A~200, it is necessary to have ~150 neutrons per seed nucleus (Fe being generally considered the lightest one). The likely candidates:

Type II (core-collapse) supernovae

As the core collapses it would eject a rich flux of neutrons that would account for the formation of r-process elements.

Many uncertainties remain: the explosion mechanism, the role of neutrino interaction, role of multidimensional hydrodynamic instabilities, the equation of state of ultradense matter, etc.

Neutron star mergers

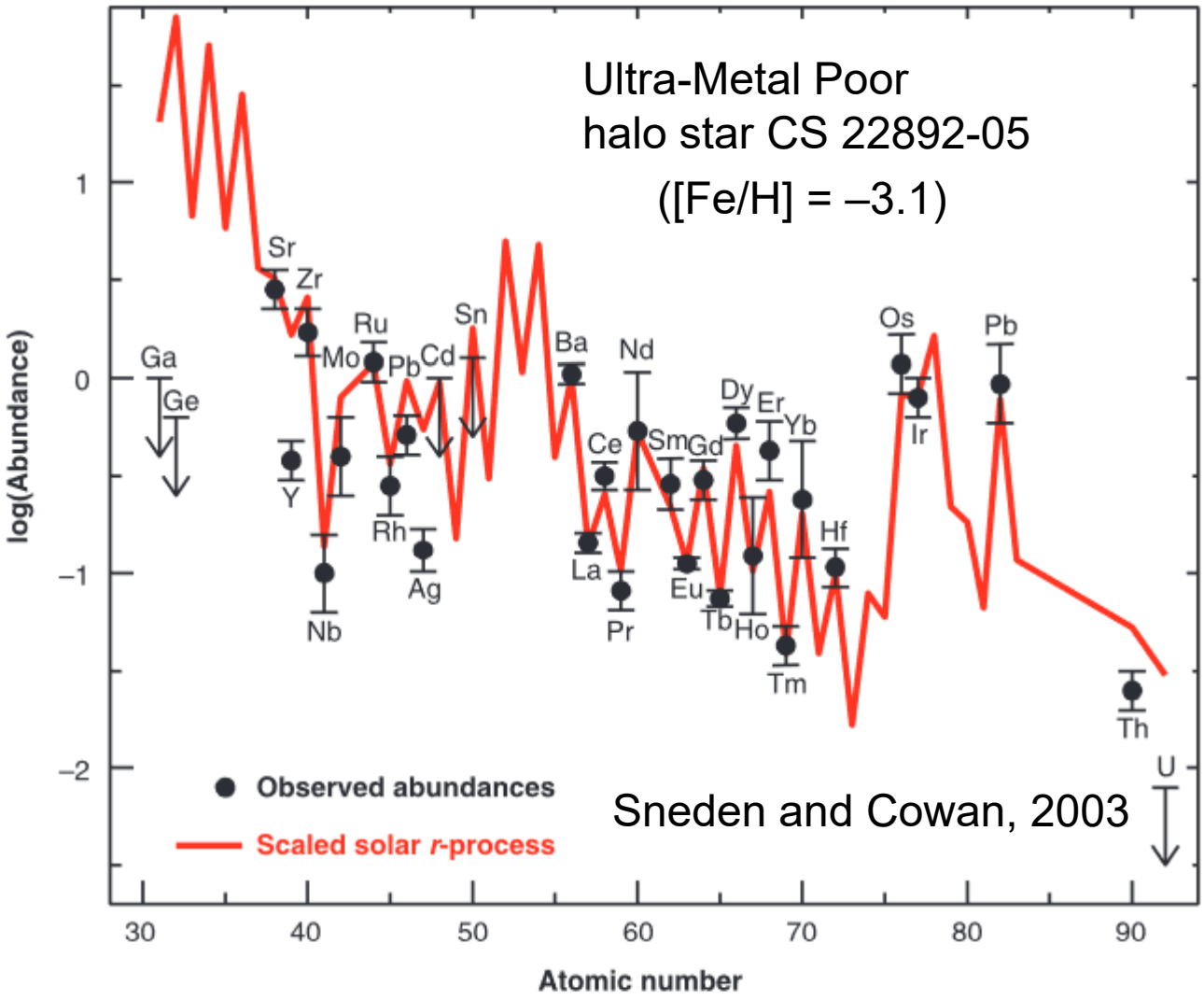
The enormous density of neutrons (~10^{33} cm^{-3}) available in the merger of neutron stars could build up heavy elements and lead to fission in very short time scales. Much larger yields of heavy elements but… rare and yet the r-process is “robust”.

Lattimer, J. M. & Schramm, D. N. ApJL (1974)

Eichler, D. et al., Nature (1989)

A new approach: observation of “short-lived” r-process nuclides and in particular short-lived actinides.

Robustness of heavy r-process production



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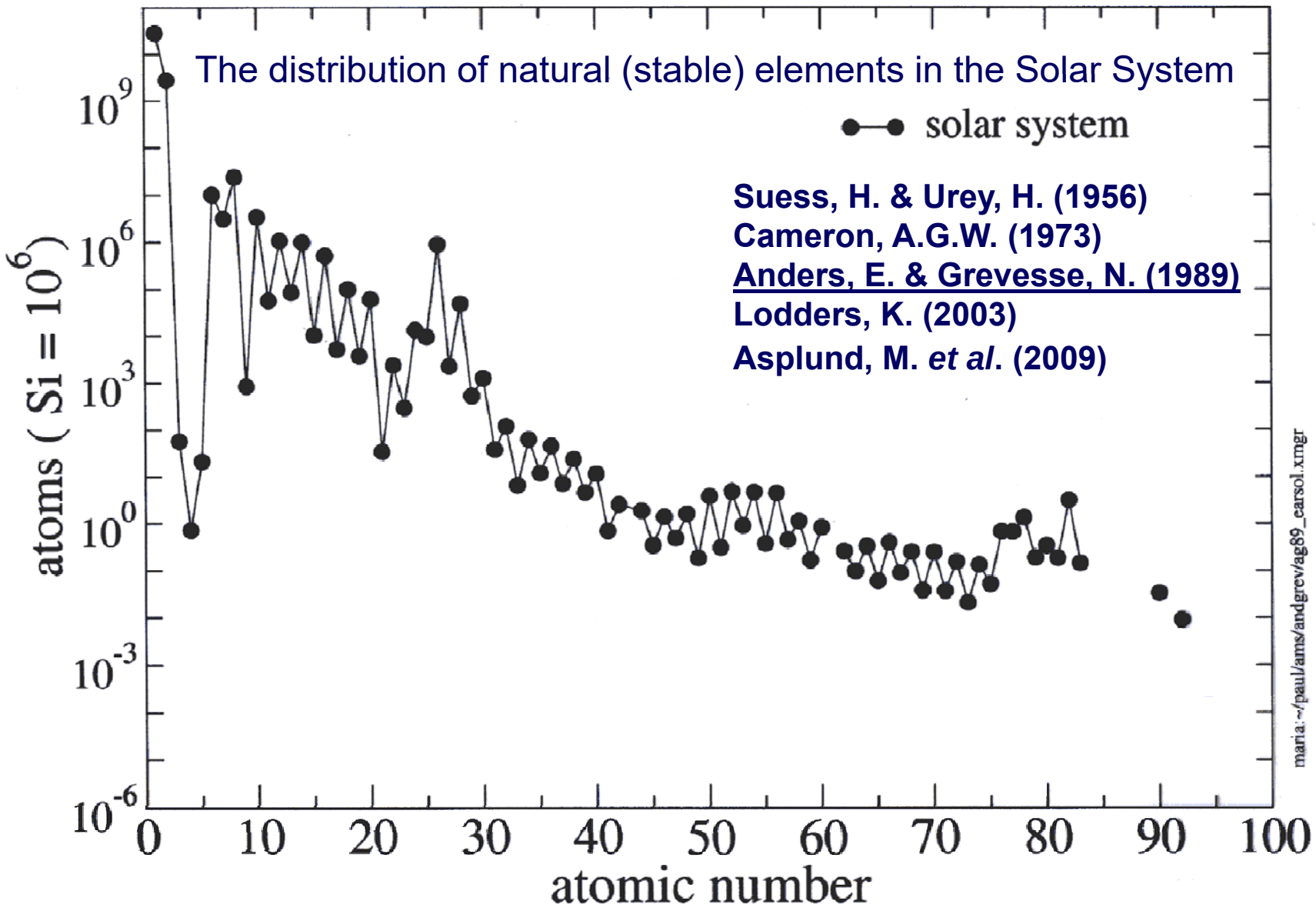

The distribution of natural (stable) elements in the Solar System
solar system
Suess, H. & Urey, H. (1956)
Cameron, A.G.W. (1973)
Anders, E. & Grevesse, N. (1989)
Lodders, K. (2003)
Asplund, M. et al. (2009)
atoms (Si = 10^6)
10^9
10^6
10^3
10^0
10^-3
10^-6
0
10
20
30
40
50
60
70
80
90
100
atomic number
maria:~/paul/ams/andgrev/ag89_carsol.xmgr

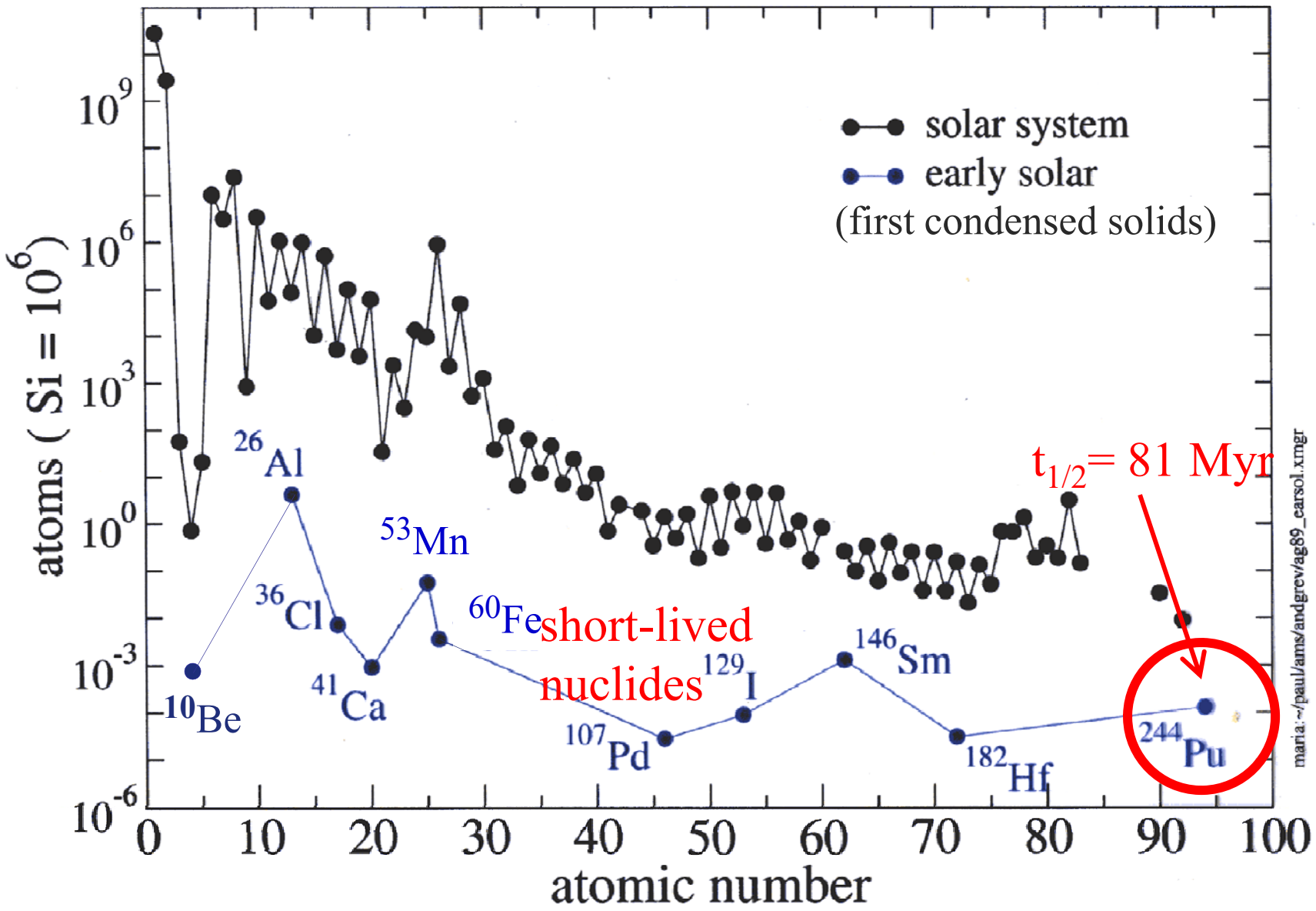
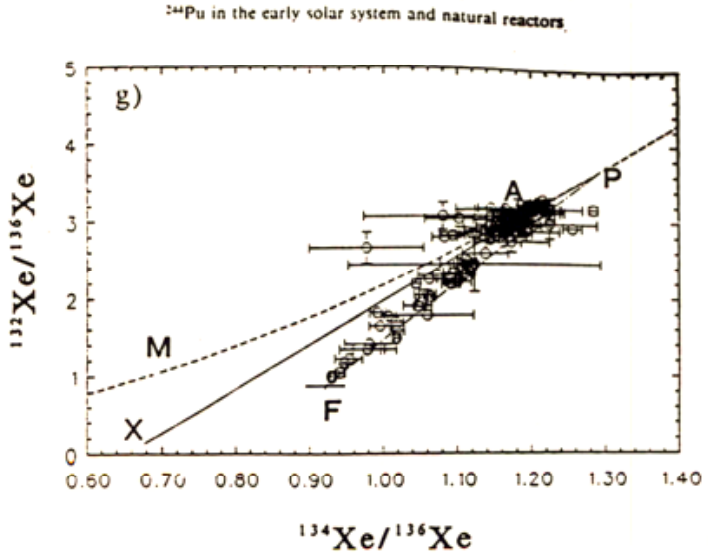
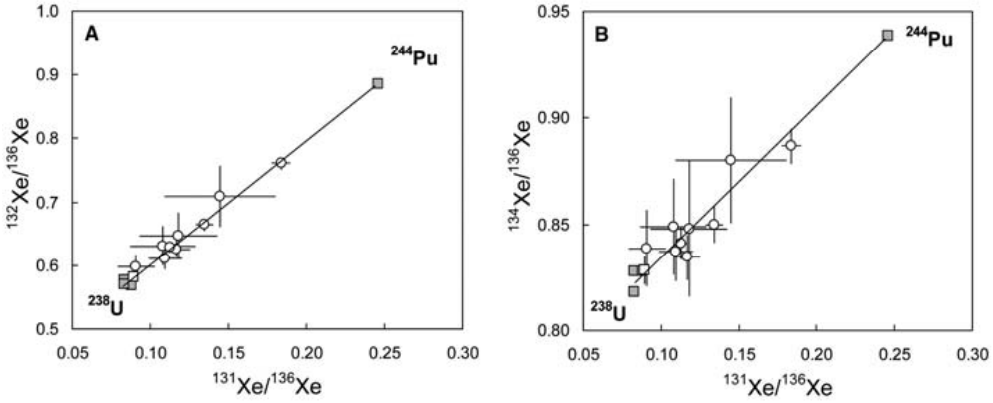

solar system
early solar
(first condensed solids)
atoms (Si = 10^6)
atomic number
10^9
10^6
10^3
10^0
10^-3
10^-6
0
10
20
30
40
50
60
70
80
90
100
26Al
53Mn
36Cl
60Fe
short-lived
nuclides
129I
146Sm
10Be
41Ca
107Pd
182Hf
244Pu
t1/2= 81 Myr
maria:~/paul/ams/andgrev/ag89_carsol.xmgr

Table 1. The experimental confirmation of the existence of ^{244}Pu spontaneous fission xenon in meteorites (Alexander et al., 1971)

Source	Fission yield			
	^{131}Xe	^{132}Xe	^{134}Xe	^{136}Xe
Pasamonte	33±3	93±8	91±2.5	100
Pasamonte	25±3	88.5±3	94±5	100
Whitlokite from St. Séverin	31±8	97±8	93±1	100
Kapoeta	26±3	88±4	91±5	100
$^{244}PuO_2$	25.1±2.2	87.6±3.1	92.1±2.7	100

P.K. Kuroda, Geochem J. (1992)

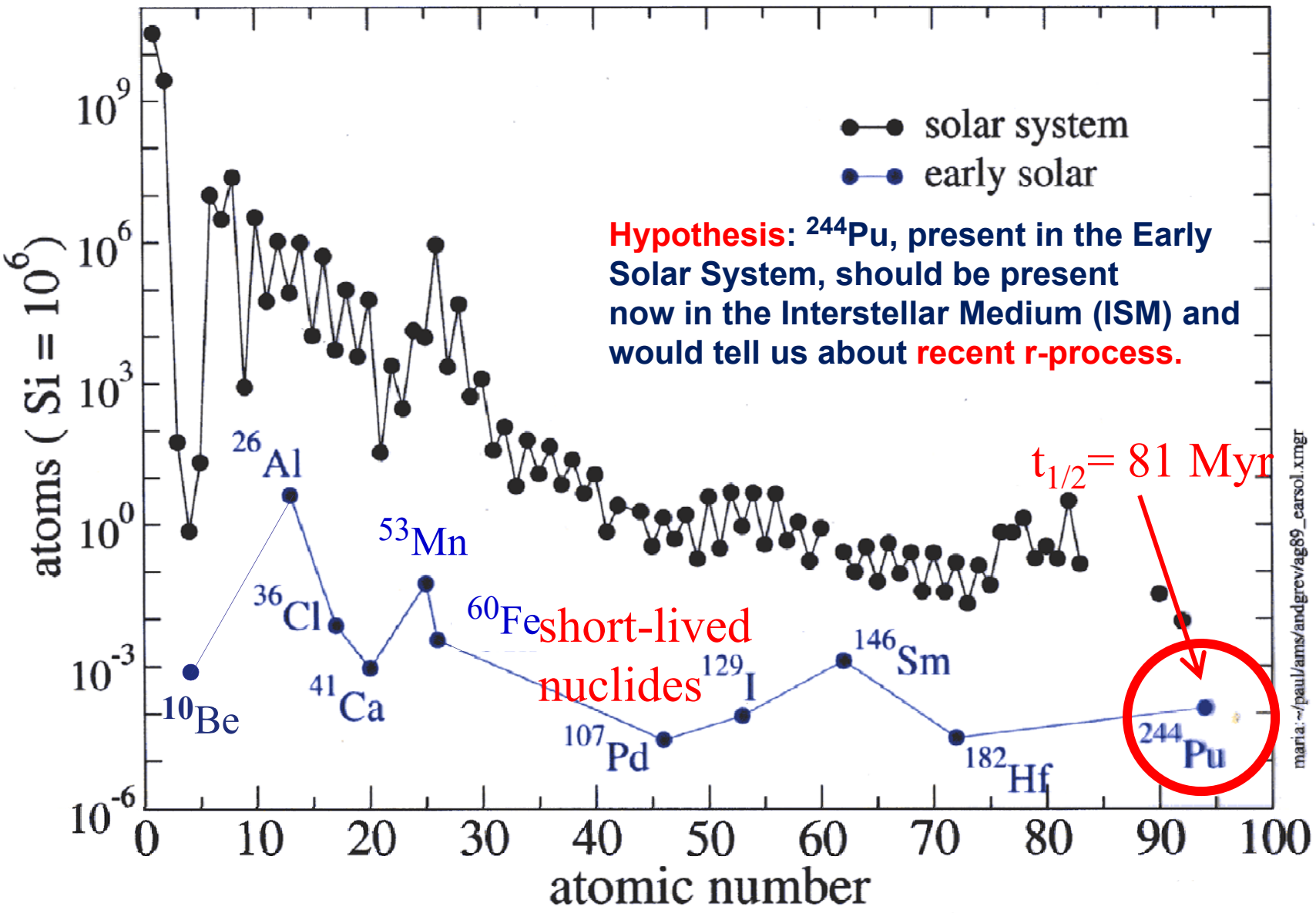


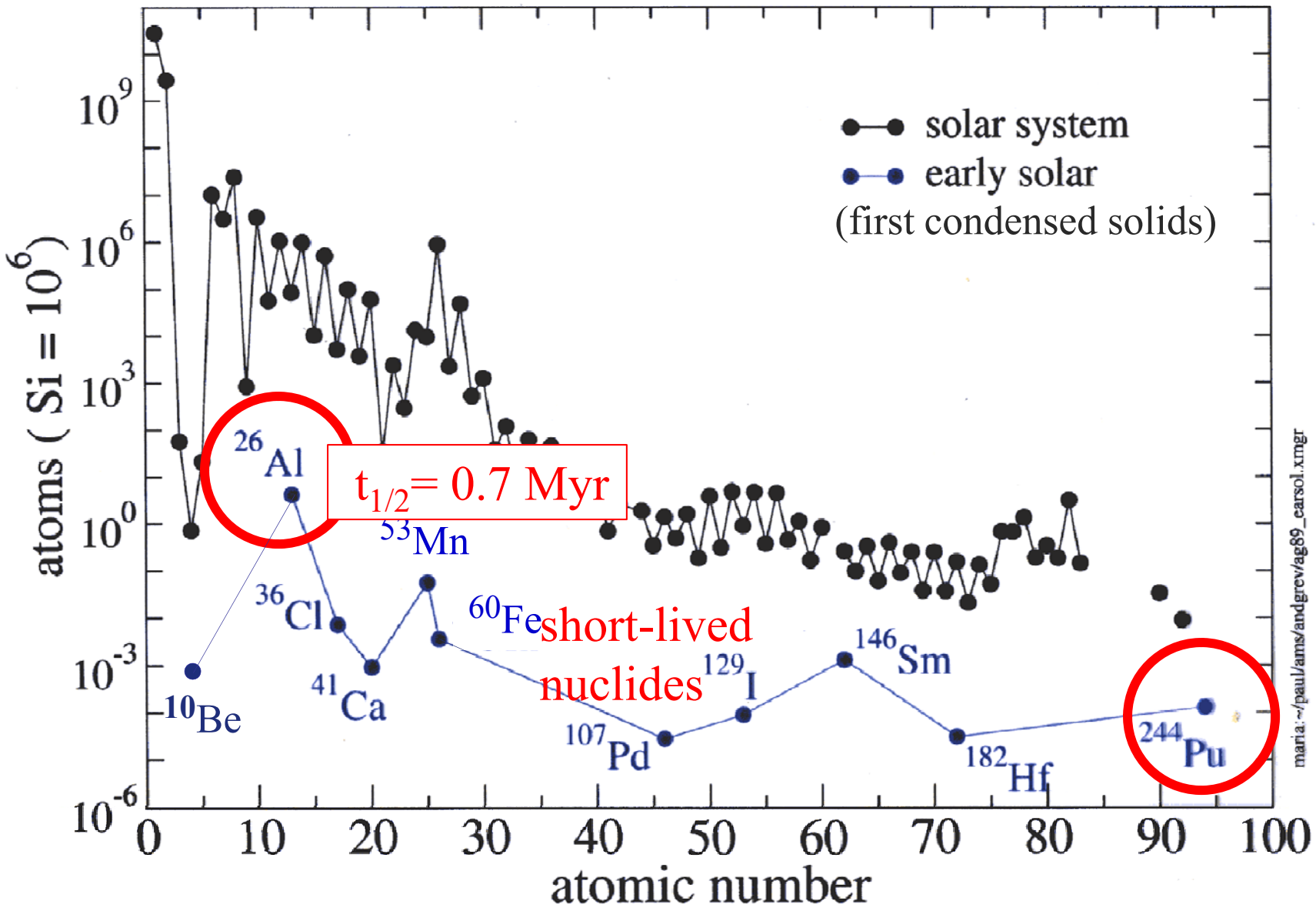


^{136}Xe, a noble (chemically inert) gas is mainly a fission product.
Xe isotopes extracted from an ancient zircon lie along a mixing line between ^{238}U and ^{244}Pu fission Xe, determining an initial $^{244}Pu/^{238}Pu$ ratio in the Early-Solar System:

$$(^{244}Pu/^{238}U)_{ESS} = 0.66\ (10)\ \%$$

G. Turner et al., Science 306, 89 (2004)


solar system
early solar
Hypothesis: 244Pu, present in the Early Solar System, should be present now in the Interstellar Medium (ISM) and would tell us about recent r-process.
t1/2= 81 Myr
short-lived nuclides
26Al
53Mn
36Cl
60Fe
10Be
41Ca
129I
146Sm
107Pd
182Hf
244Pu
atoms (Si = 10^6)
atomic number
maria:~/paul/ams/andgrev/ag89_carsol.xmgr


solar system
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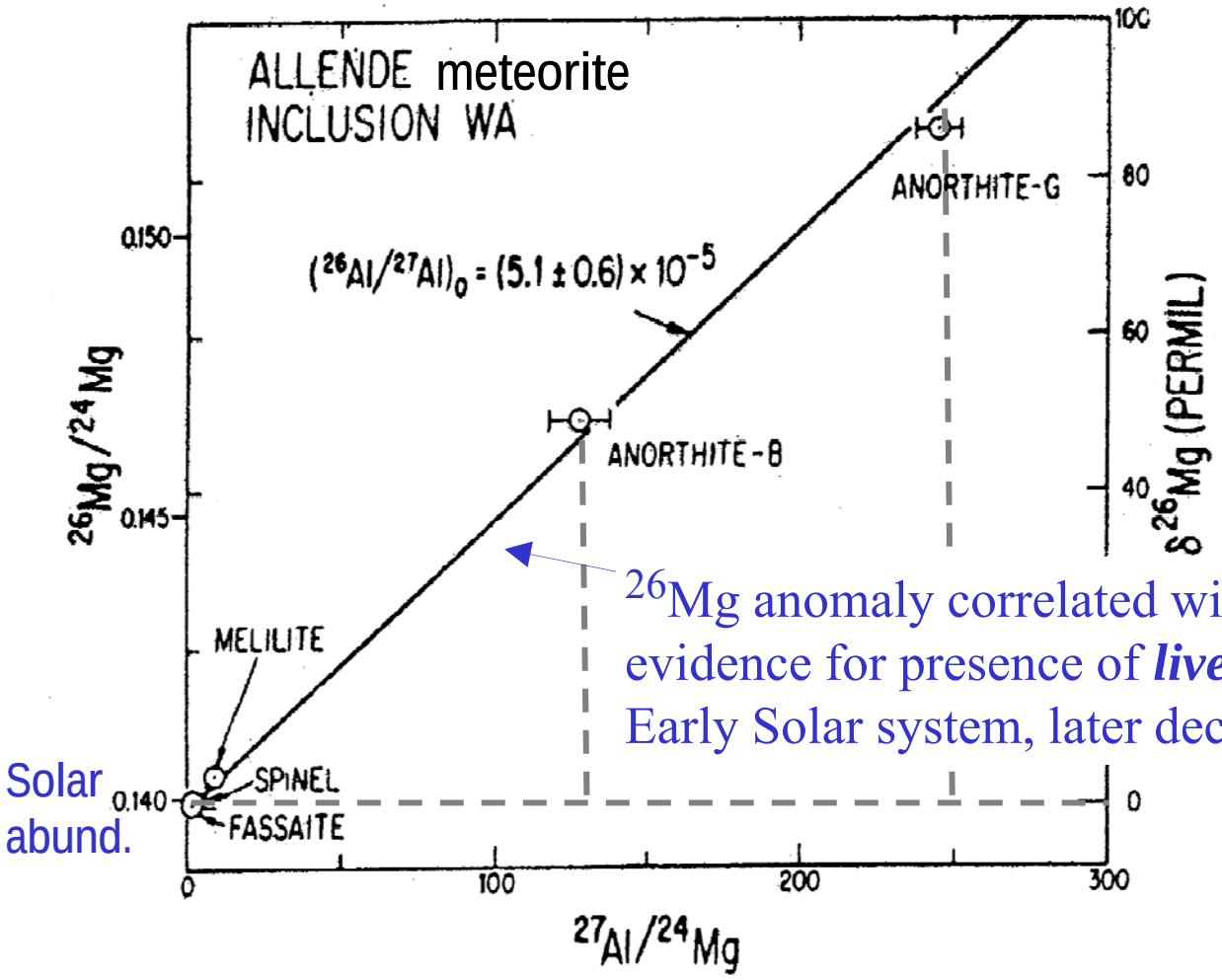
atomic number
10^9
10^6
10^3
10^0
10^-3
10^-6
0
10
20
30
40
50
60
70
80
90
100
26Al
t1/2= 0.7 Myr
53Mn
36Cl
60Fe
short-lived
nuclides
129I
146Sm
10Be
41Ca
107Pd
182Hf
244Pu
maria:~/paul/ams/andgrev/ag89_carsol.xmgr

Lee, Papanastassiou &Wasserburg, ApJL 211, L107 (1977)

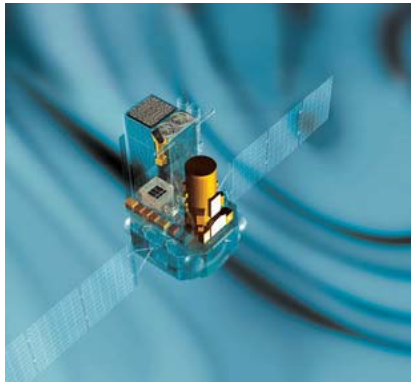


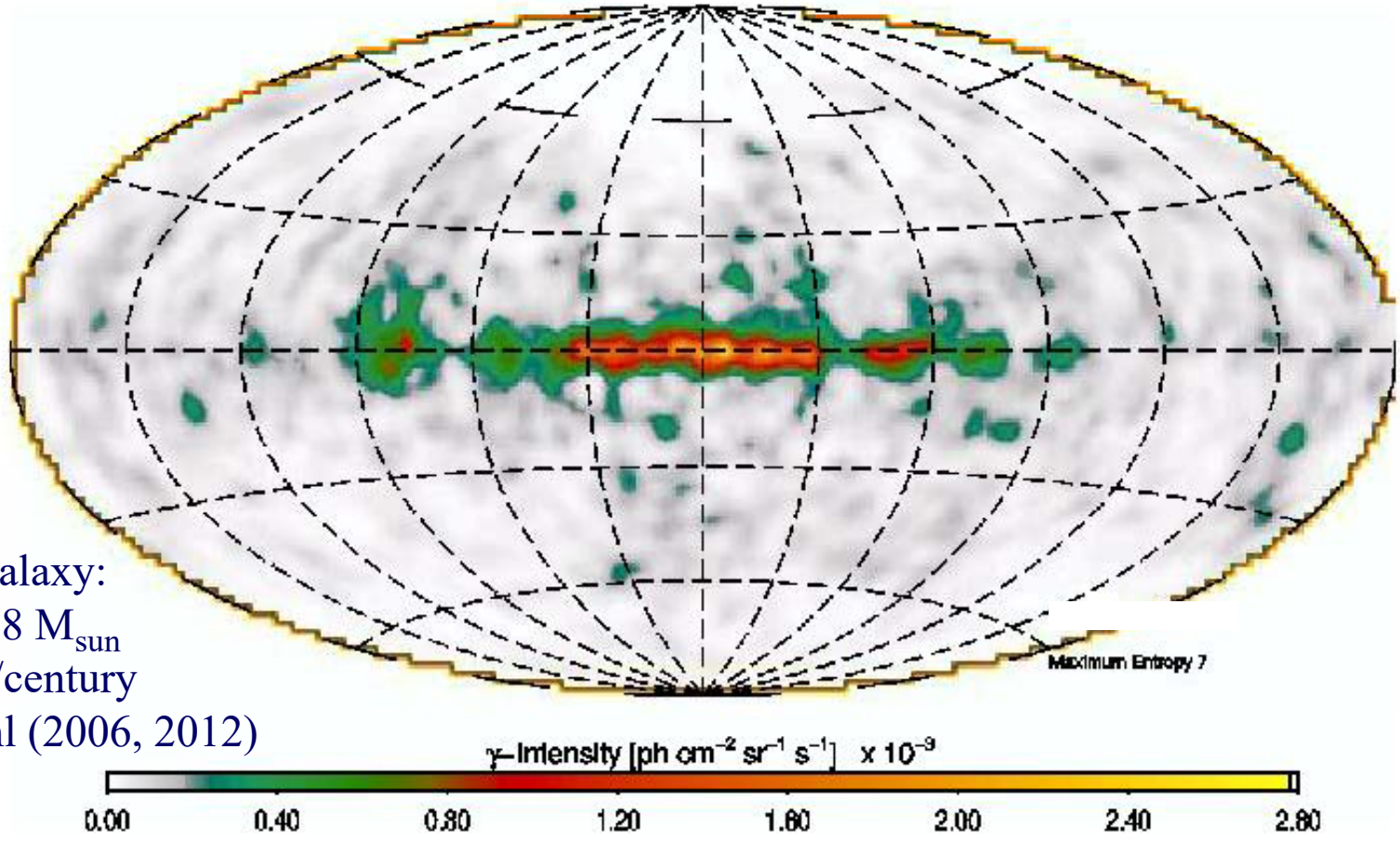
Solar abund.

^{26}Mg anomaly correlated with chemical Al : evidence for presence of ***live*** ^{26}Al in the Early Solar system, later decayed to ^{26}Mg

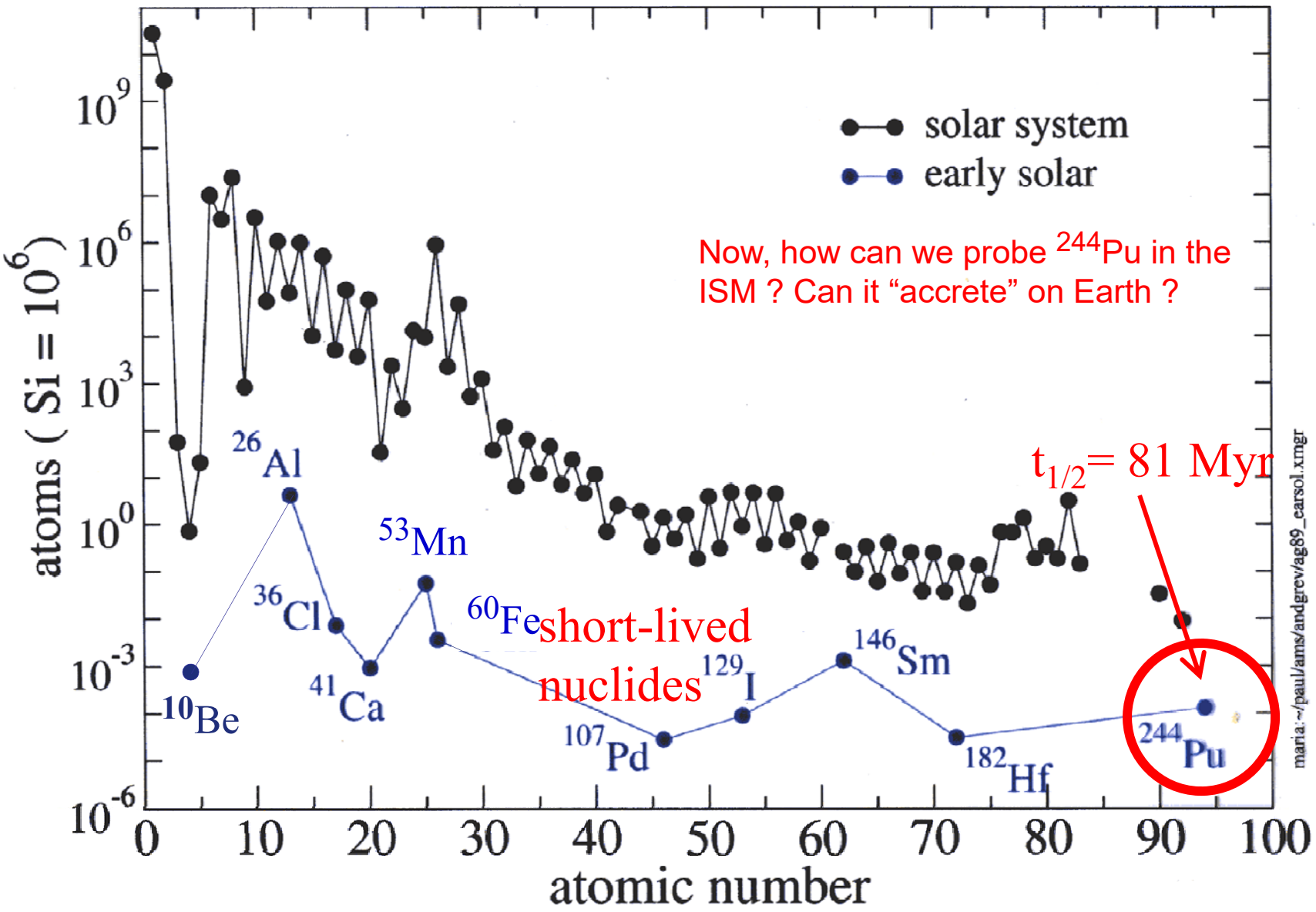
Live ^{26}Al was present in the Early-Solar System

Live ^{26}Al ($t_{1/2}$ = 0.72 My) ***radioactivity***
is observed ***today*** in the Galaxy,
a signature of ongoing nucleosynthesis
E_γ= 1.809 MeV light (**γ astronomy**)
R. Diehl *et al.*, Nucl. Phys. A (2005)





^{26}Al in Galaxy:
$2.8 \pm 0.8\ M_{sun}$
~ 1.9 SN/century
R. Diehl (2006, 2012)


solar system
early solar
Now, how can we probe ^{244}Pu in the ISM ? Can it "accrete" on Earth ?
$t_{1/2}$= 81 Myr
short-lived nuclides
^{10}Be
^{26}Al
^{36}Cl
^{41}Ca
^{53}Mn
^{60}Fe
^{107}Pd
^{129}I
^{146}Sm
^{182}Hf
^{244}Pu
atoms (Si = 10^6)
atomic number
10^9
10^6
10^3
10^0
10^{-3}
10^{-6}
0
10
20
30
40
50
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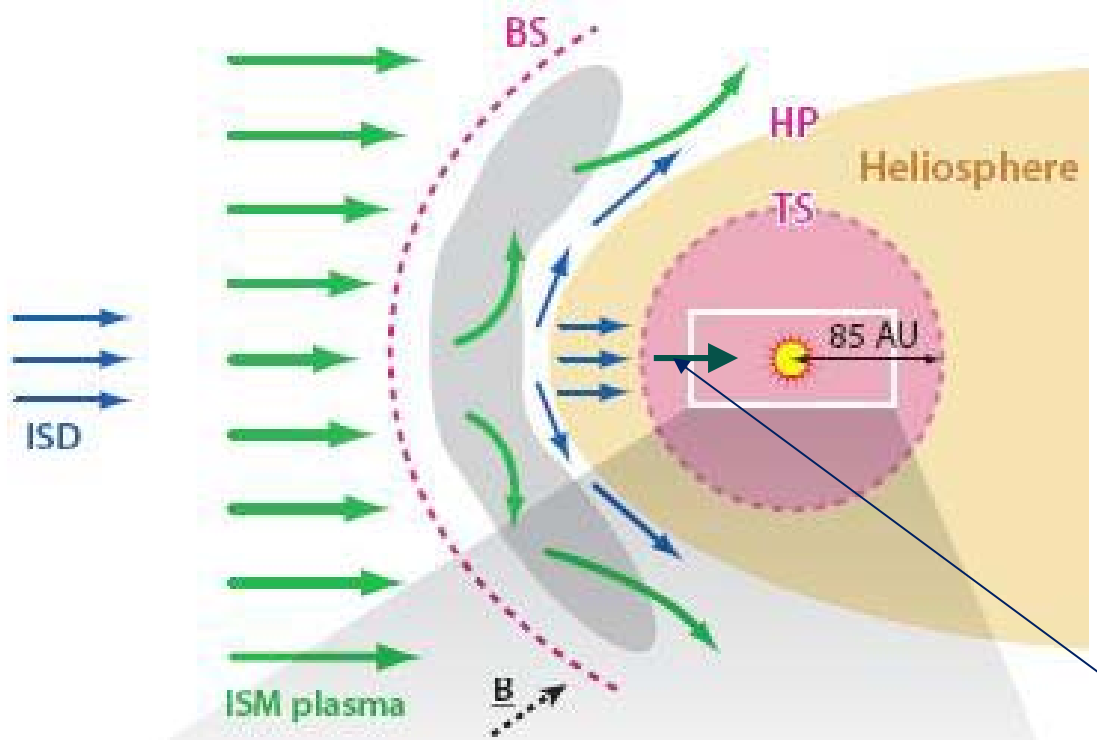
70
80
90
100
maria:~/paul/ams/andgrev/ag89_carsol.xmgr

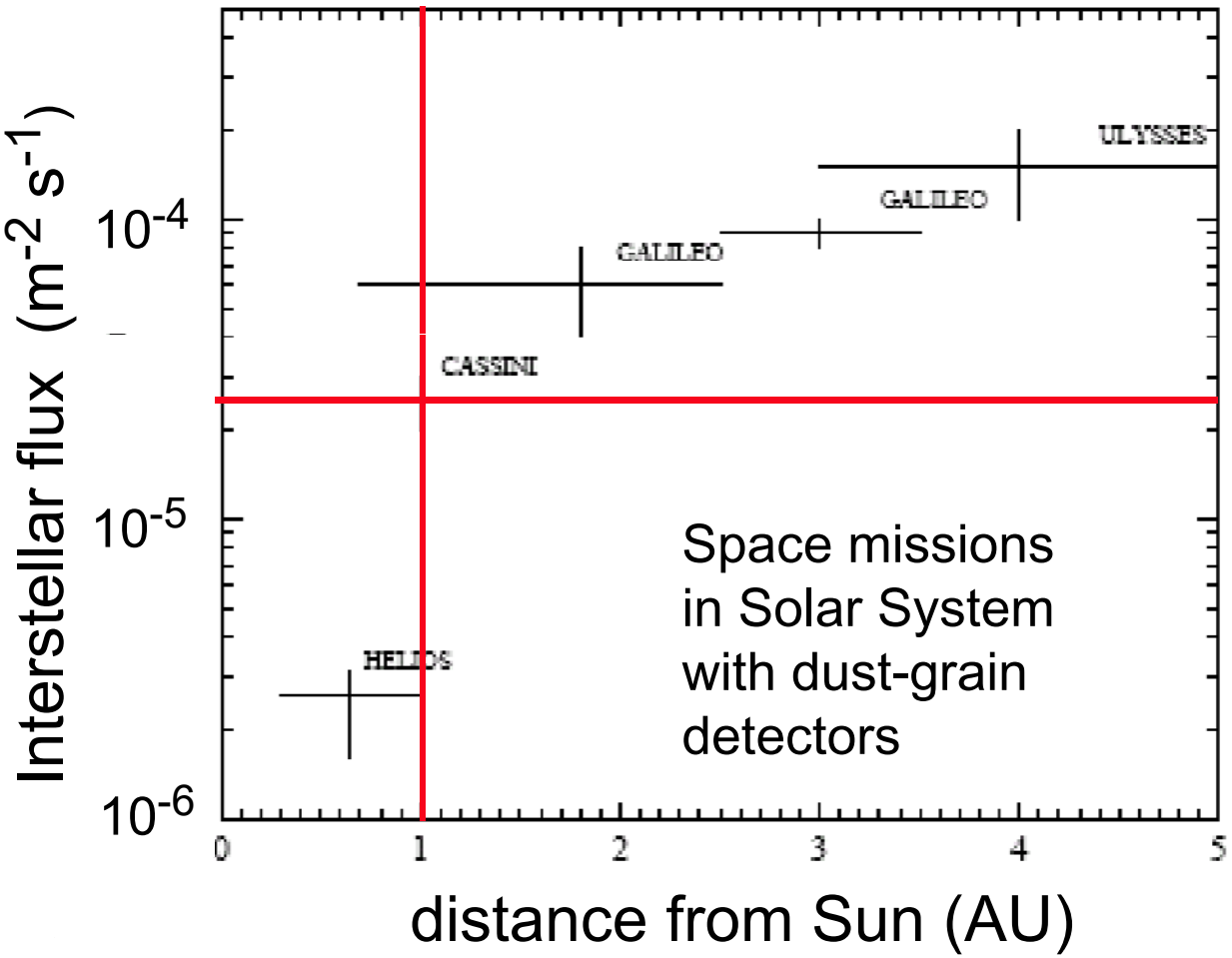
Interstellar Dust (ISD) penetration in the Solar System



ISD particles 0.1-5 μm

If present in the Interstellar Medium through recent r-process, ^{244}Pu could penetrate into the Solar System and be collected on Earth.

I. Mann,
Annu. Rev. Astron. Astrophys. 48, 173 (2010)



flux of
interstellar
grains at Earth

H. Krueger et al.,
Space Sci. Rev. 2007

Hypothesis

• Interstellar Matter Medium (ISM) penetrates the Solar System, deposit and accumulate in Earth reservoirs.

• ISM contains in steady-state freshly synthesized radionuclides

(^{244}Pu, 81 My) maybe similarly to the Early-Solar System :

deposition on Earth

quantitatively : ϕ (gISM cm^{-2} yr^{-1}) ISM deposition flux

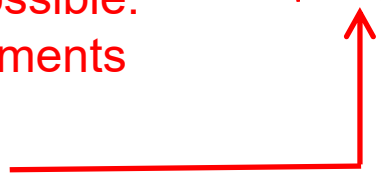
r (cm yr^{-1}) accumulation rate of sediment

ρ (g cm^{-3}) density

ISM concentration in the reservoir will be

$C = \phi / r \rho$ (gISM /g)

r as low as possible:
deep-sea sediments
and crusts

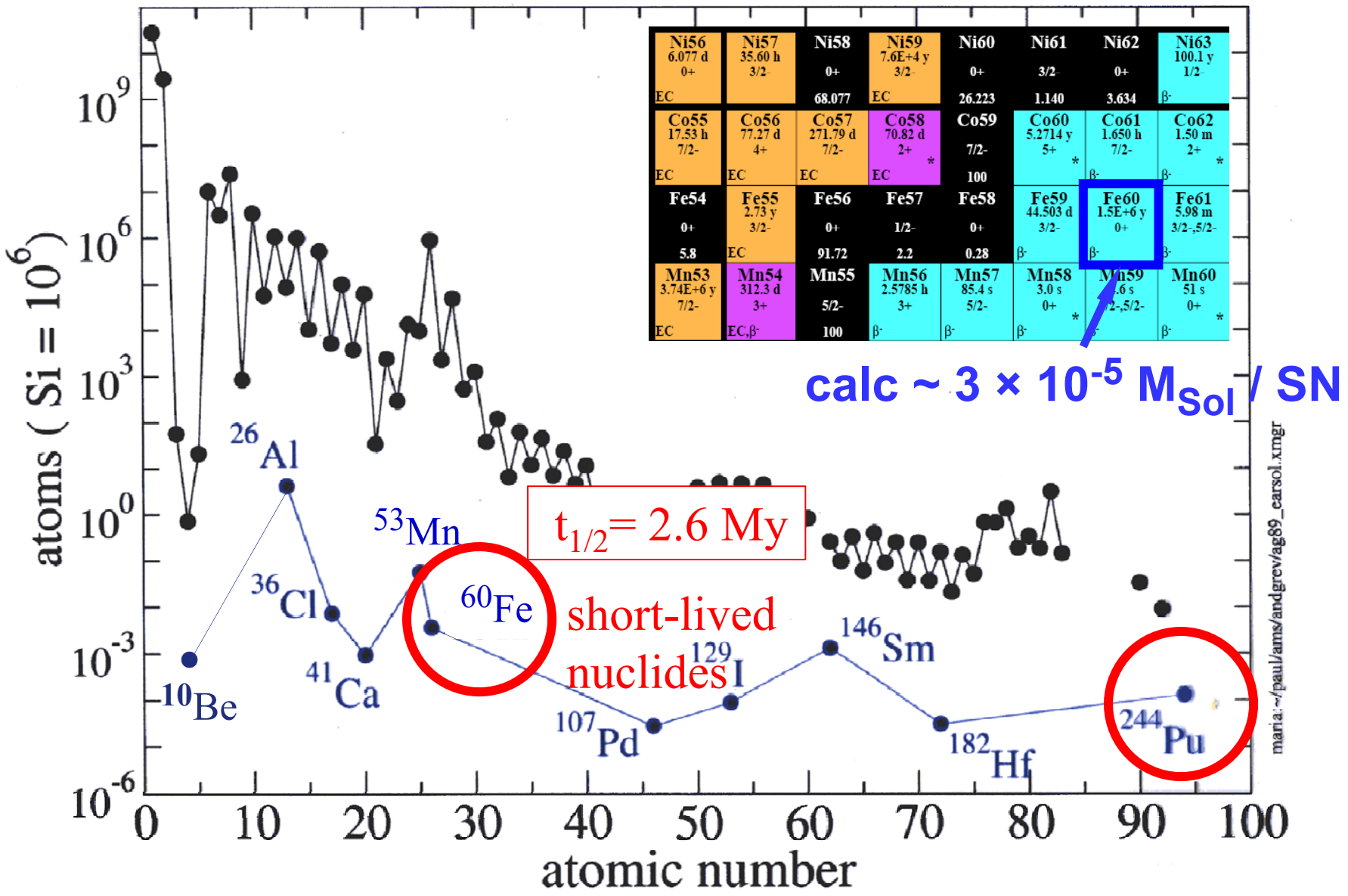


Deep-sea astronomy...

Deep-sea sediments (~ 1 mm/ky) and manganese crust (~3 mm/My) expected to accumulate extra-terrestrial (and interstellar) matter

Scripps Oceanographic Collection, UCSD

Manganese deep-sea crust sample


atoms (Si = 10^6)
atomic number
10^9
10^6
10^3
10^0
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10^-6
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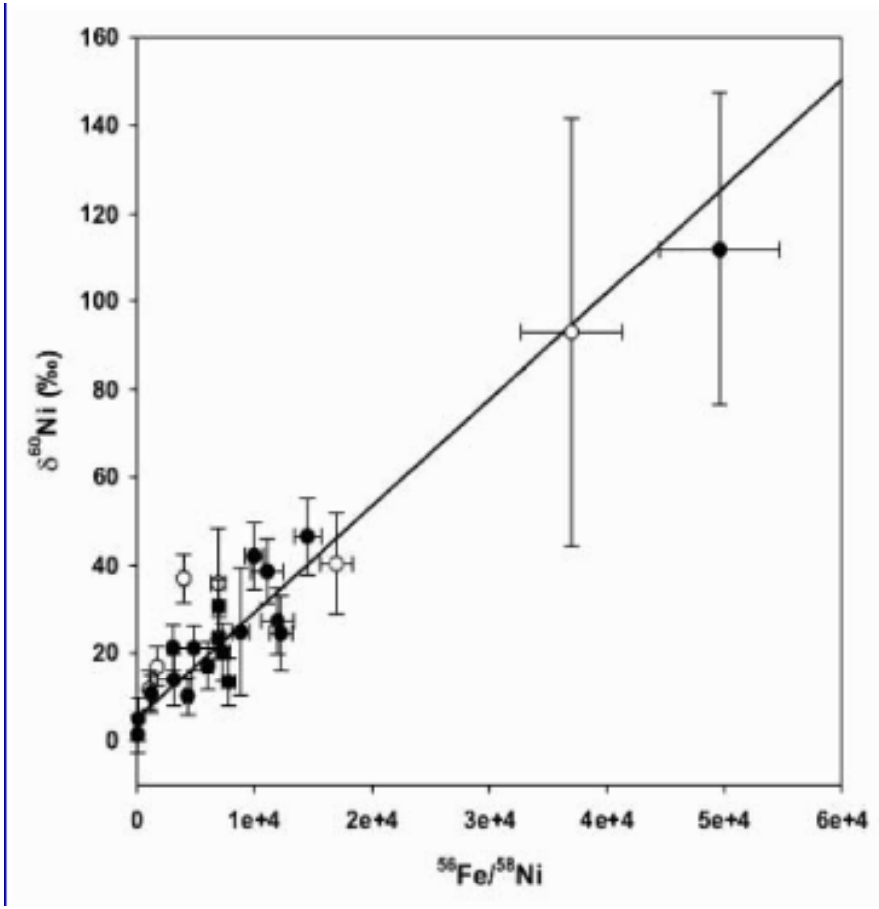
10
20
30
40
50
60
70
80
90
100
26Al
53Mn
60Fe
36Cl
41Ca
10Be
107Pd
129I
146Sm
182Hf
244Pu
t1/2= 2.6 My
short-lived nuclides
calc ~ 3 × 10-5 MSol / SN
Ni56 6.077 d 0+ EC
Ni57 35.60 h 3/2-
Ni58 0+ 68.077
Ni59 7.6E+4 y 3/2- EC
Ni60 0+ 26.223
Ni61 3/2- 1.140
Ni62 0+ 3.634
Ni63 100.1 y 1/2- β-
Co55 17.53 h 7/2- EC
Co56 77.27 d 4+ EC
Co57 271.79 d 7/2- EC
Co58 70.82 d 2+ * EC
Co59 7/2- 100
Co60 5.2714 y 5+ * β-
Co61 1.650 h 7/2- β-
Co62 1.50 m 2+ * β-
Fe54 0+ 5.8
Fe55 2.73 y 3/2- EC
Fe56 0+ 91.72
Fe57 1/2- 2.2
Fe58 0+ 0.28
Fe59 44.503 d 3/2- β-
Fe60 1.5E+6 y 0+ β-
Fe61 5.98 m 3/2-,5/2- β-
Mn53 3.74E+6 y 7/2- EC
Mn54 312.3 d 3+ EC,β-
Mn55 5/2- 100
Mn56 2.5785 h 3+ β-
Mn57 85.4 s 5/2- β-
Mn58 3.0 s 0+ * β-
Mn59 .6 s 2-,5/2- β-
Mn60 51 s 0+ * β-
maria:~/paul/ams/andgrev/ag89_carsol.xmgr

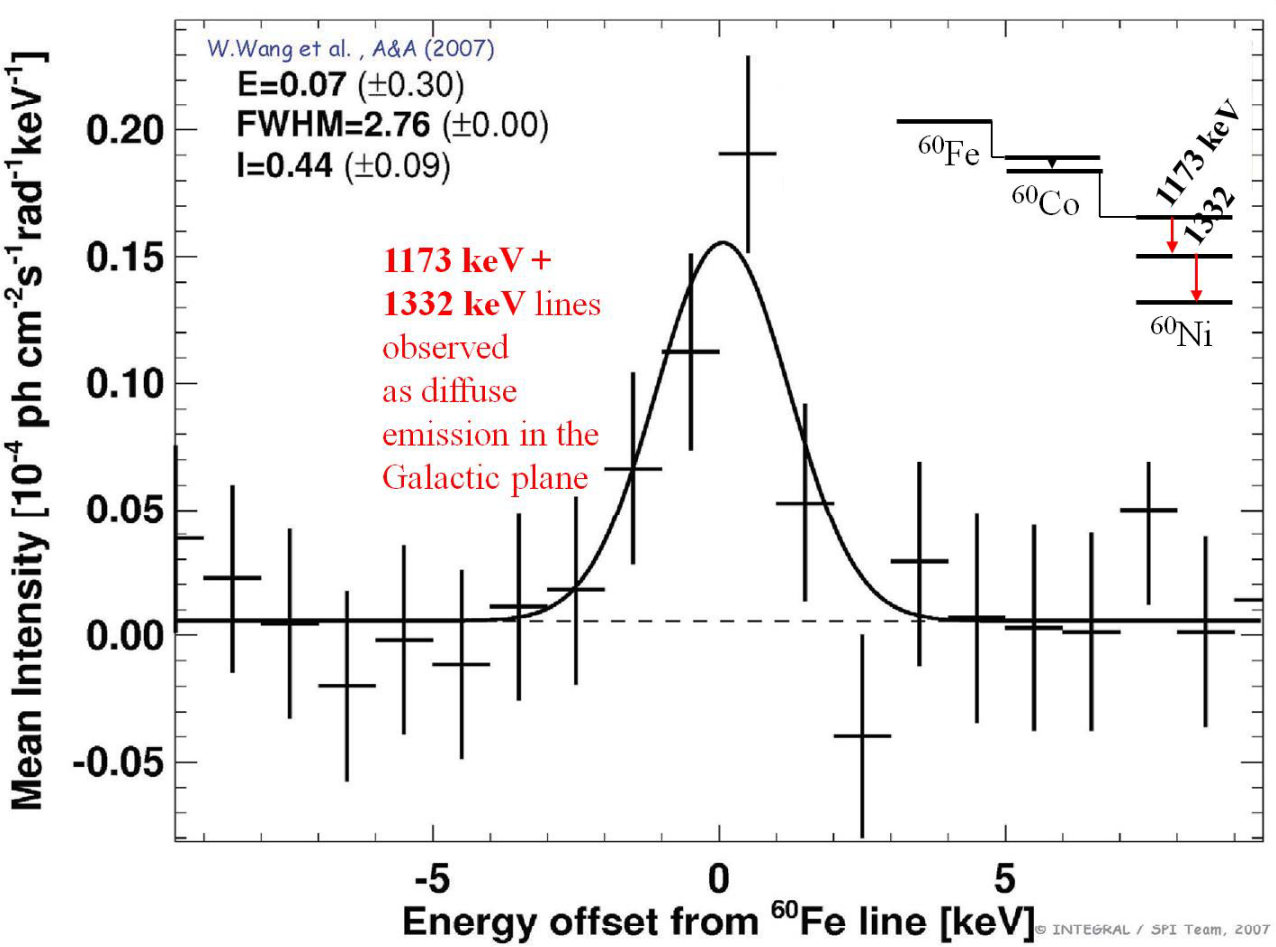
^{60}Fe in the Early-Solar system



e.g.
S. Mostefaoui et al., 2005

"60Fe/56Fe ratio of (0.92±0.24)x10-6
at the time of formation of these troilites."

^{60}Fe in the Interstellar Medium



Recent near–Earth supernovae probed by global deposition of interstellar radioactive ^{60}Fe

A. Wallner[1], J. Feige[2]†, N. Kinoshita[3], M. Paul[4], L. K. Fifield[1], R. Golser[2], M. Honda[5], U. Linnemann[6], H. Matsuzaki[7], S. Merchel[8], G. Rugel[8], S. G. Tims[1], P. Steier[2], T. Yamagata[9] & S. R. Winkler[2]

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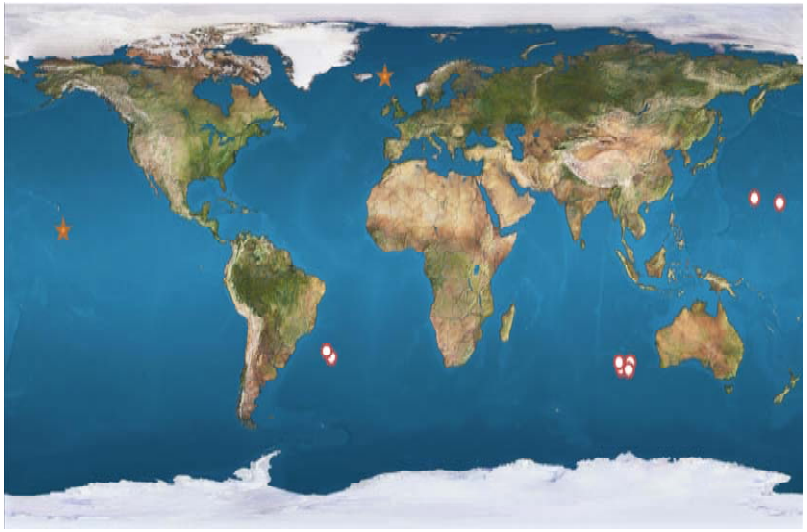
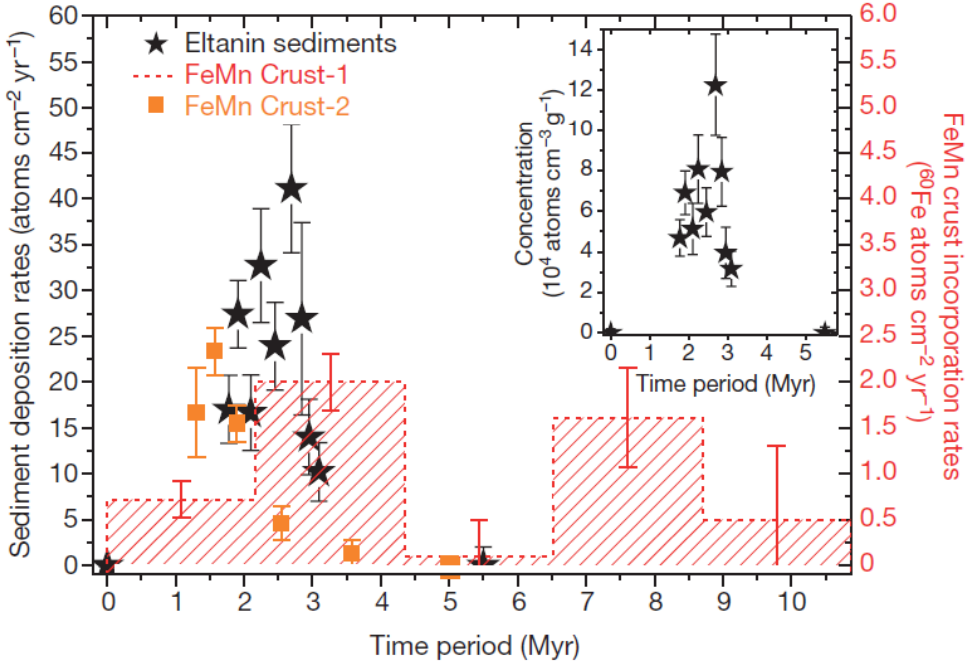
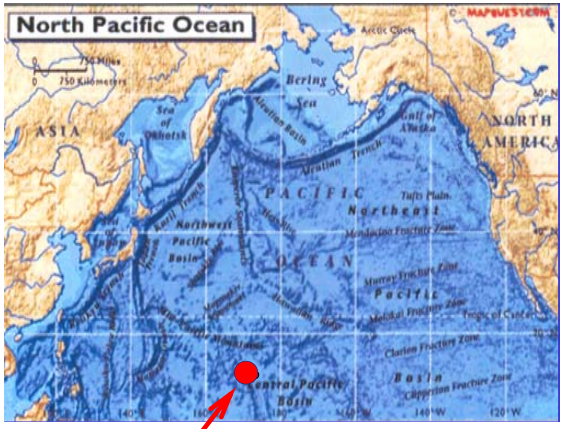


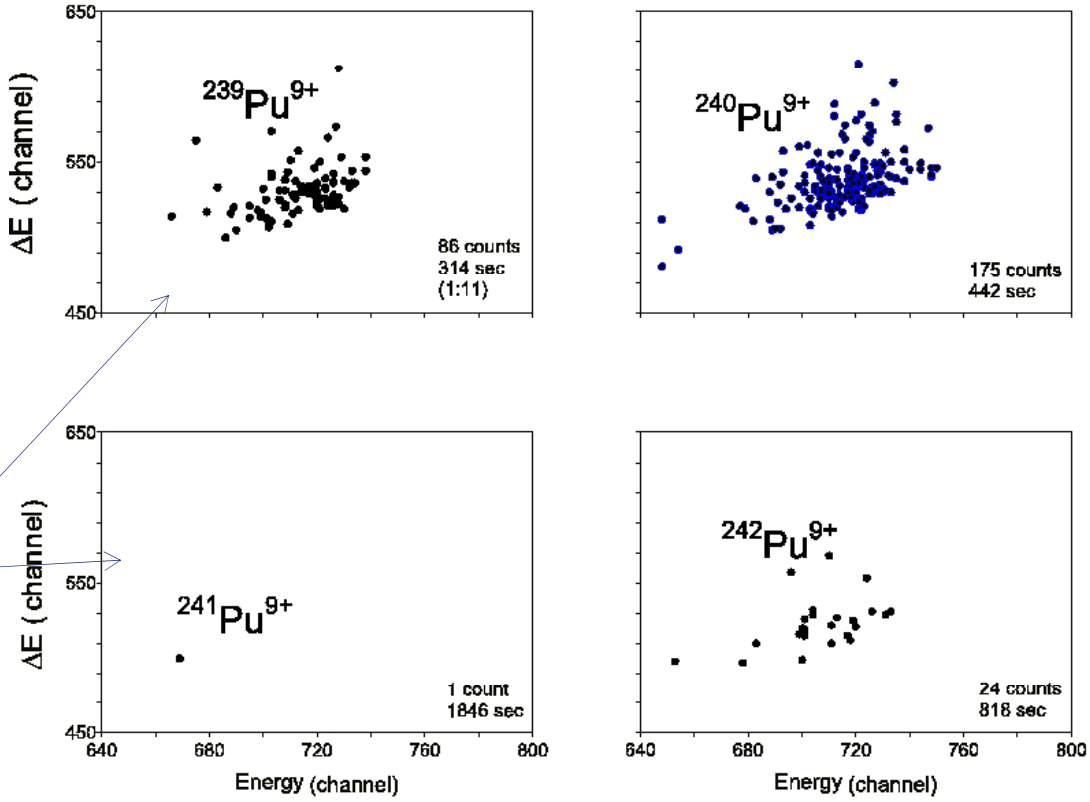


Pu ion counting by accelerator mass spectrometry in a deep-sea sediment sample



1-kg deep-sea floor sediment

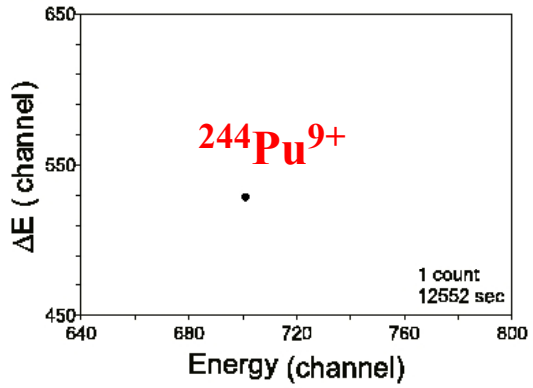
nuclear tests global fallout



under reasonable assumptions:

^{244}Pu(ISM) < 0.1-0.3 ^{244}Pu(ESS)

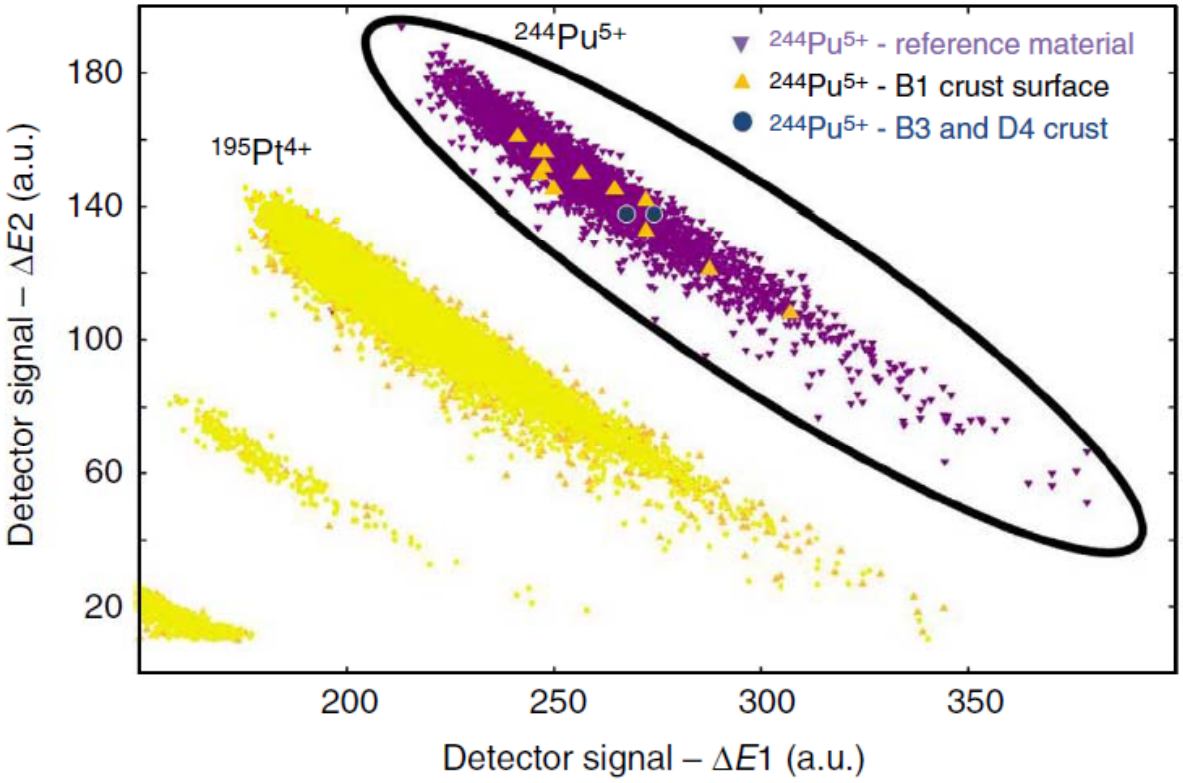
MP et al., ApJL (2001)

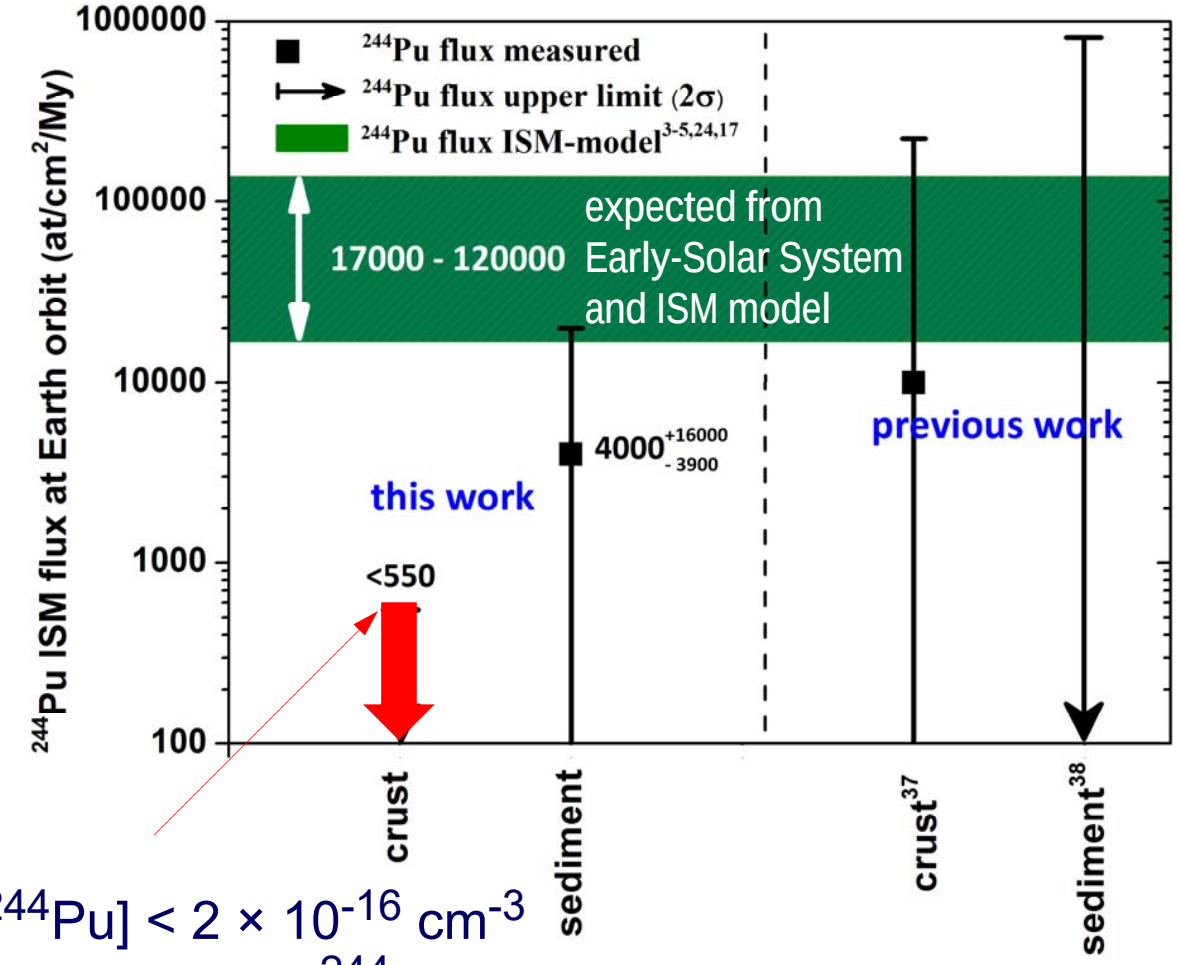


^{244}Pu/total ~ 1.5×10^{-20}

New data on ^{244}Pu
in deep-sea sediments
and manganese crusts

A. Wallner et al.,
Nature Commun. (2015)





$[^{244}Pu] < 2 \times 10^{-16}$ cm^{-3}
$< 0.03\ [^{244}Pu]_{ESS}$
(2σ limit)

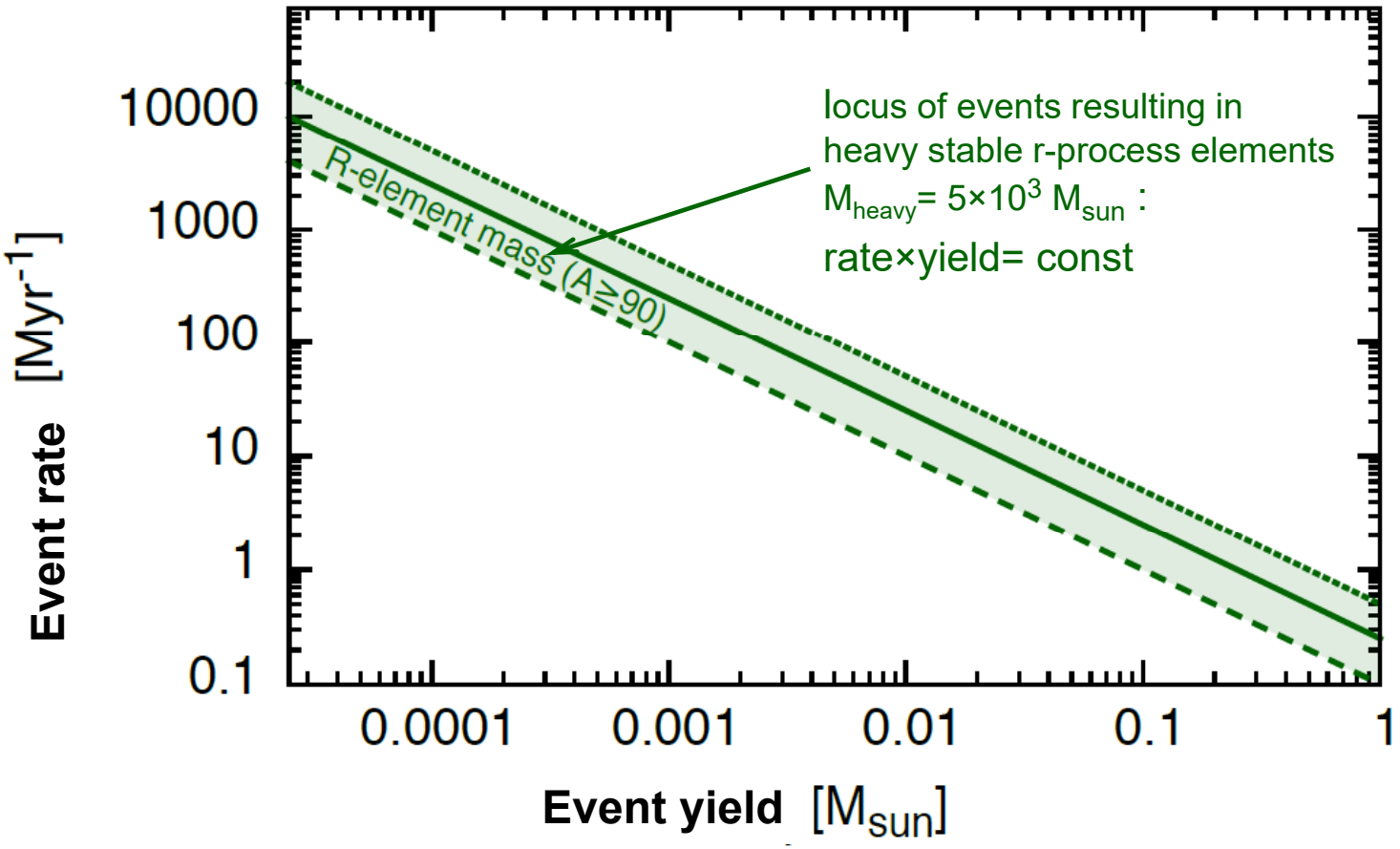
^{244}Pu seems to be "rare" compared to the ESS value and also to Uniform Production by supernovae: is it an evidence against SN heavy r-process ?

Maybe compatible with the Neutron Star Merger scenario as r-process site ?
See:
S. Rosswog et al., MNRAS (2014)

A. Wallner et al., Nature Commun. (2015)

Can the data tell us something about the r-process site candidates, core-collapse supernovae (**CCSN**) vs neutron star mergers (**NSM**)

CCSN: high-rate low-yield events
NSM: low-rate high-yield events
Stable r-process elements cannot resolve this ambiguity.



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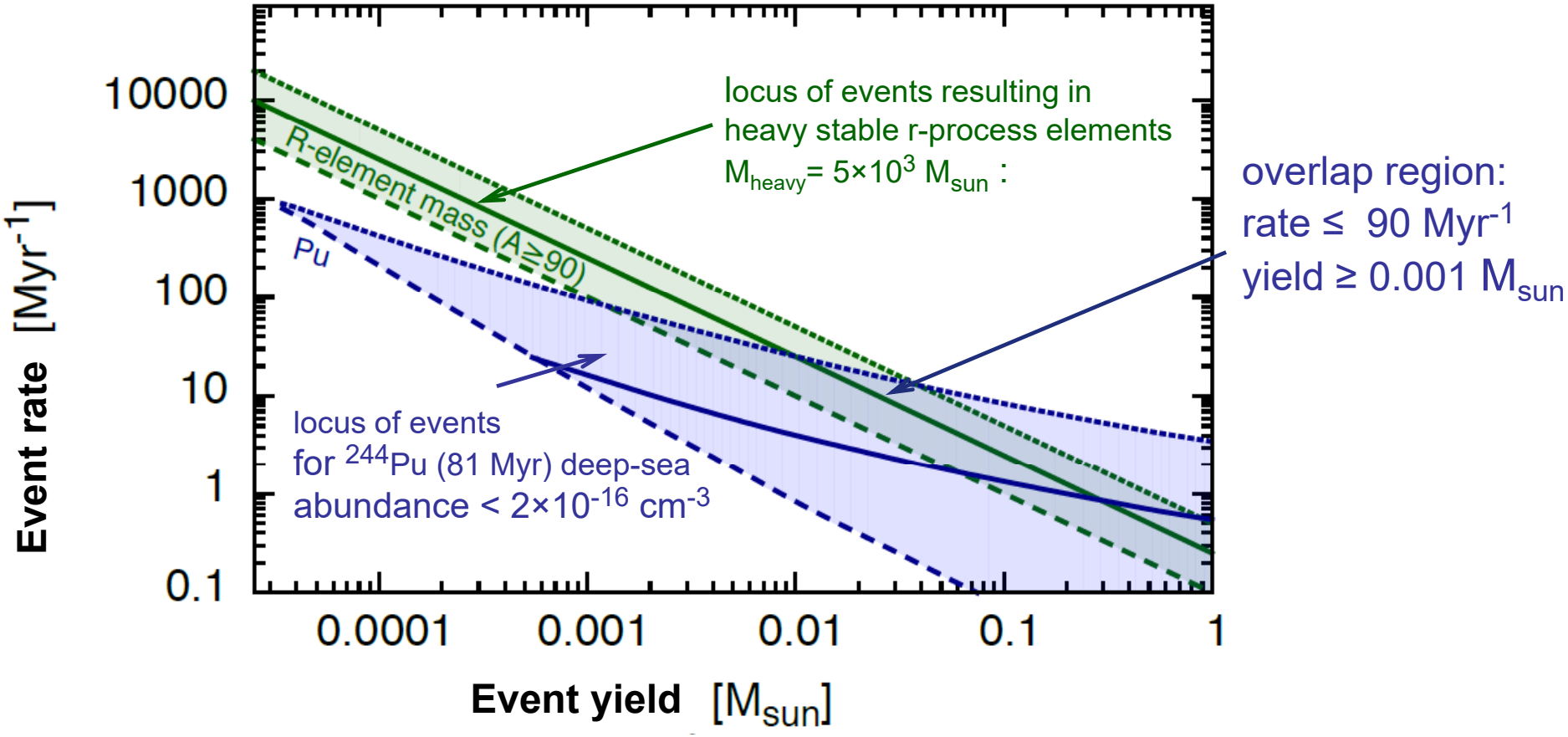
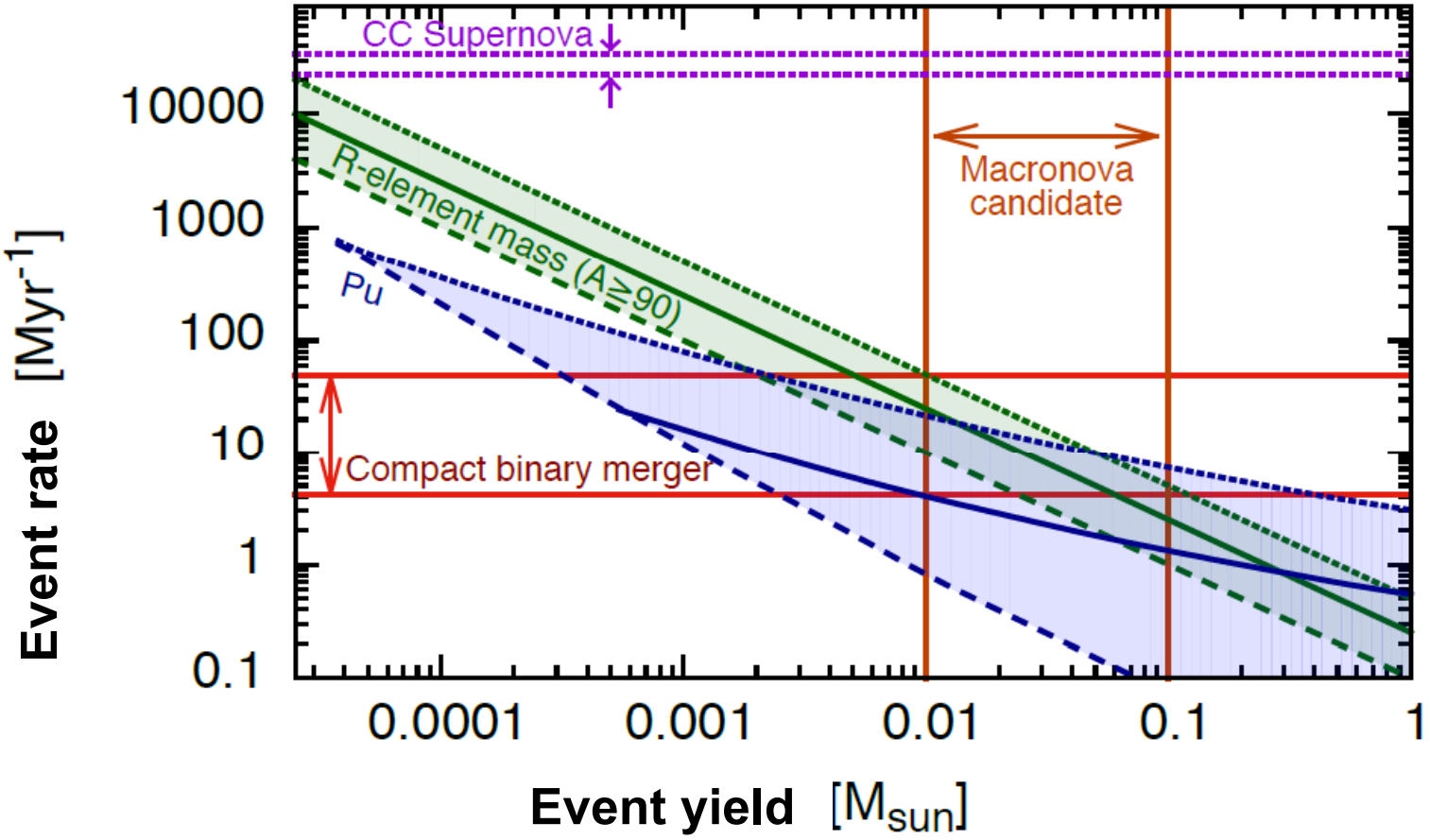
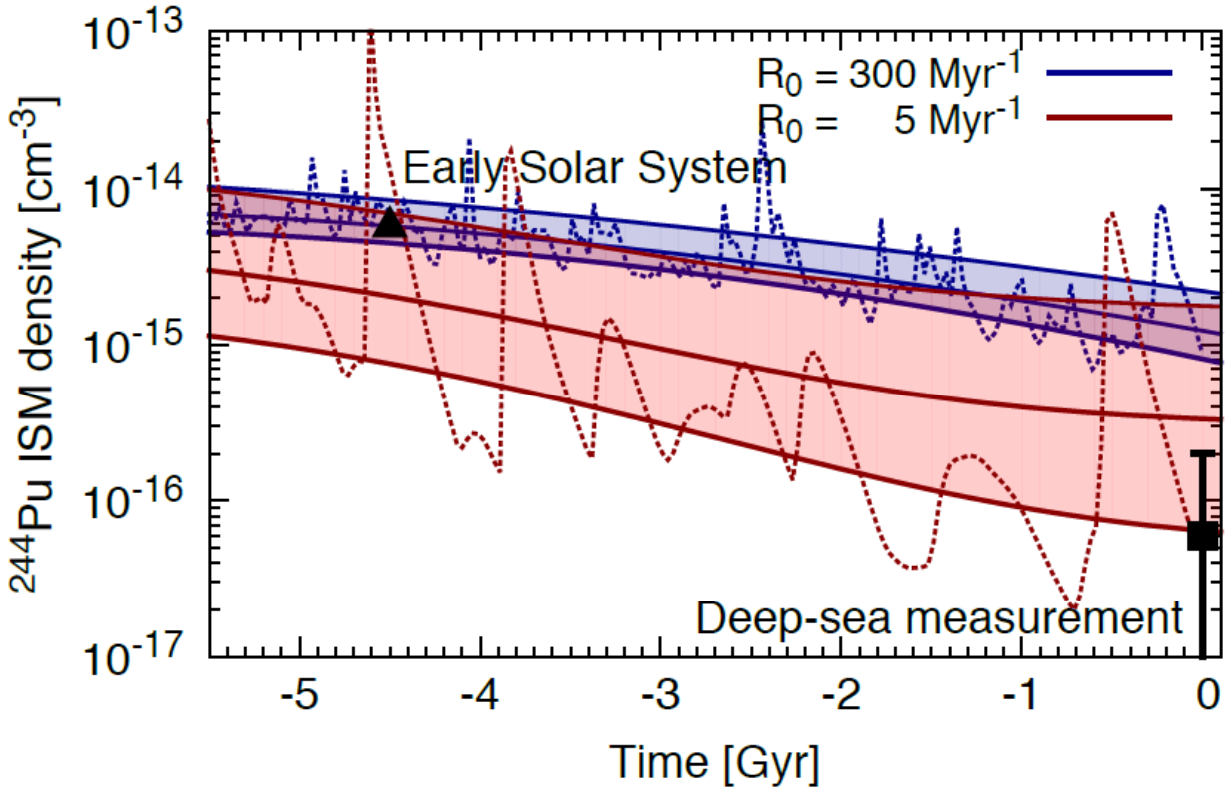


The ISM data probed by deep-sea ^{244}Pu measurements are :
incompatible with the CC SNae rate
consistent with compact binary mergers



K. Hotokezaka, T. Piran, MP, Nature Physics (2015)

The NSM “low rate-high yield” scenario can also explain the discrepancy between ^{244}Pu present ISM abundance limit from deep-sea measurements and that of the Early Solar System on the basis of time dependence of star formation rate and NSM rate.



with star formation rate

with NSM formation rate

K. Hotokezaka, T. Piran, MP, Nature Physics (2015)

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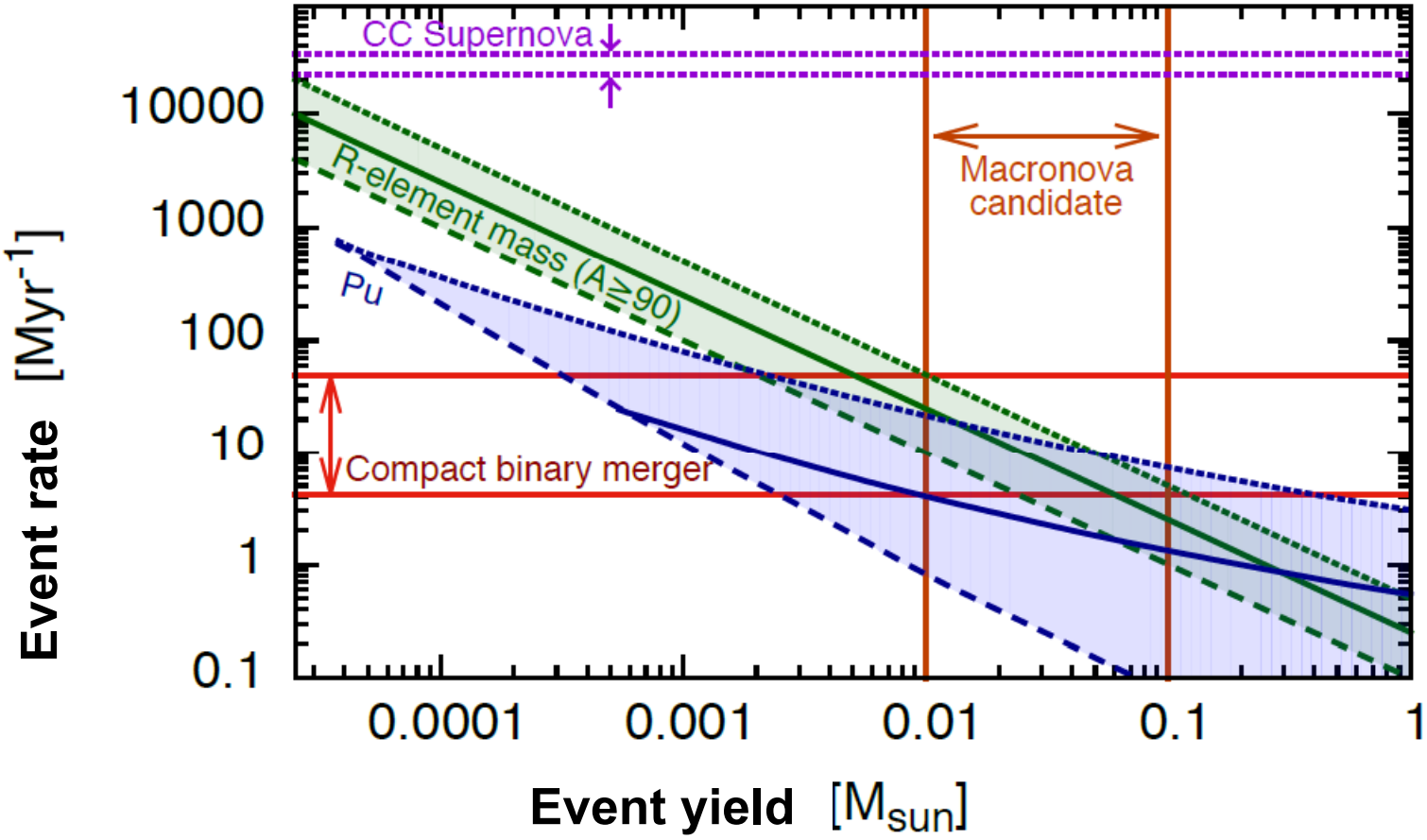
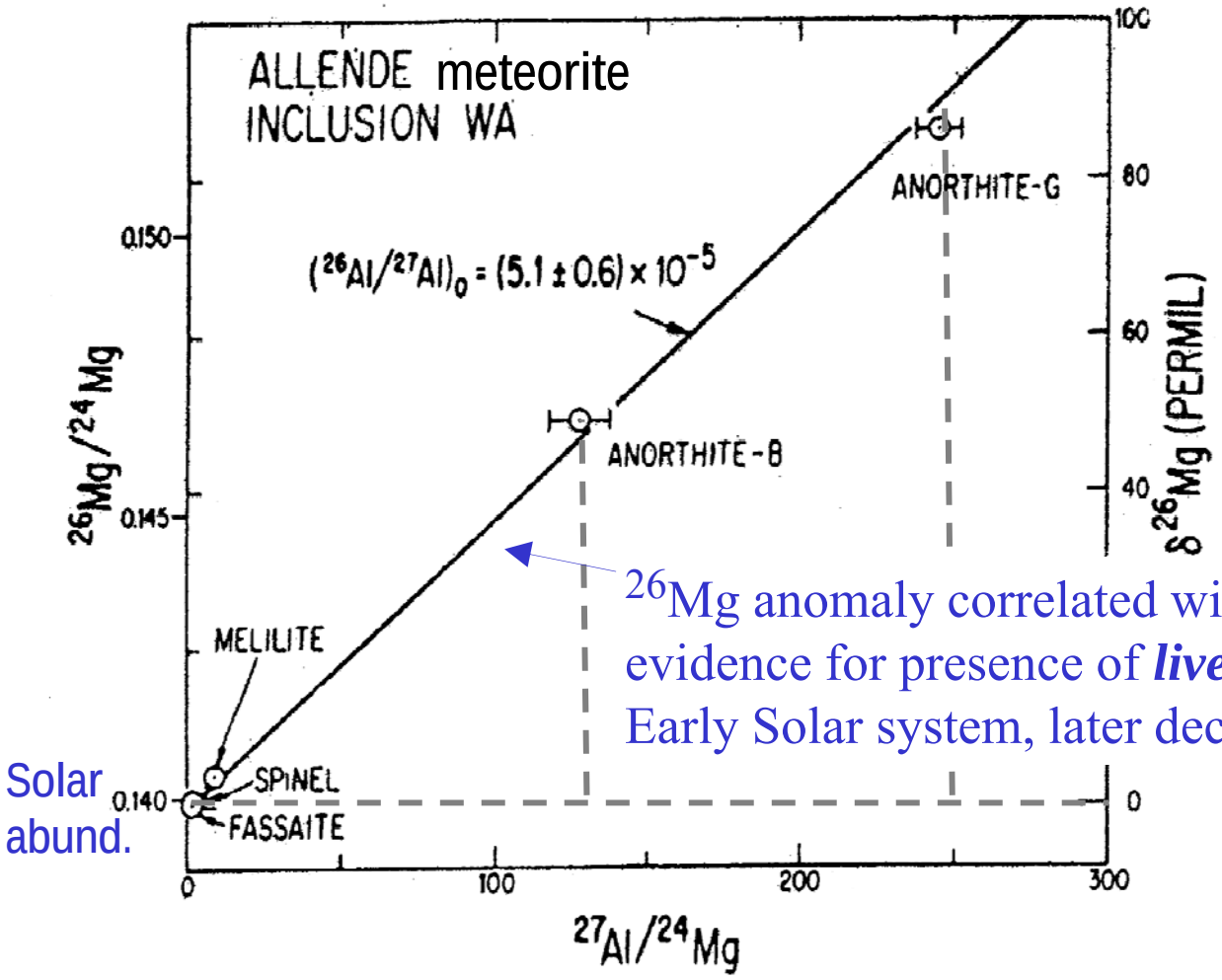


K. Hotokezaka, T. Piran, MP, Nature Physics (2015)

Collaborators:

Hebrew U: C. Feldstein, K. Hotokezaka, A. Ofan, T. Piran, MP
Australian National U. and U. Vienna: A. Wallner
U. Vienna: J. Feige, F. Quinto, P. Steier
Tech. U. Munich: T. Faestermann, K. Knie
GSI, Darmstadt: K. Knie

Lee, Papanastassiou &Wasserburg, ApJL 211, L107 (1977)

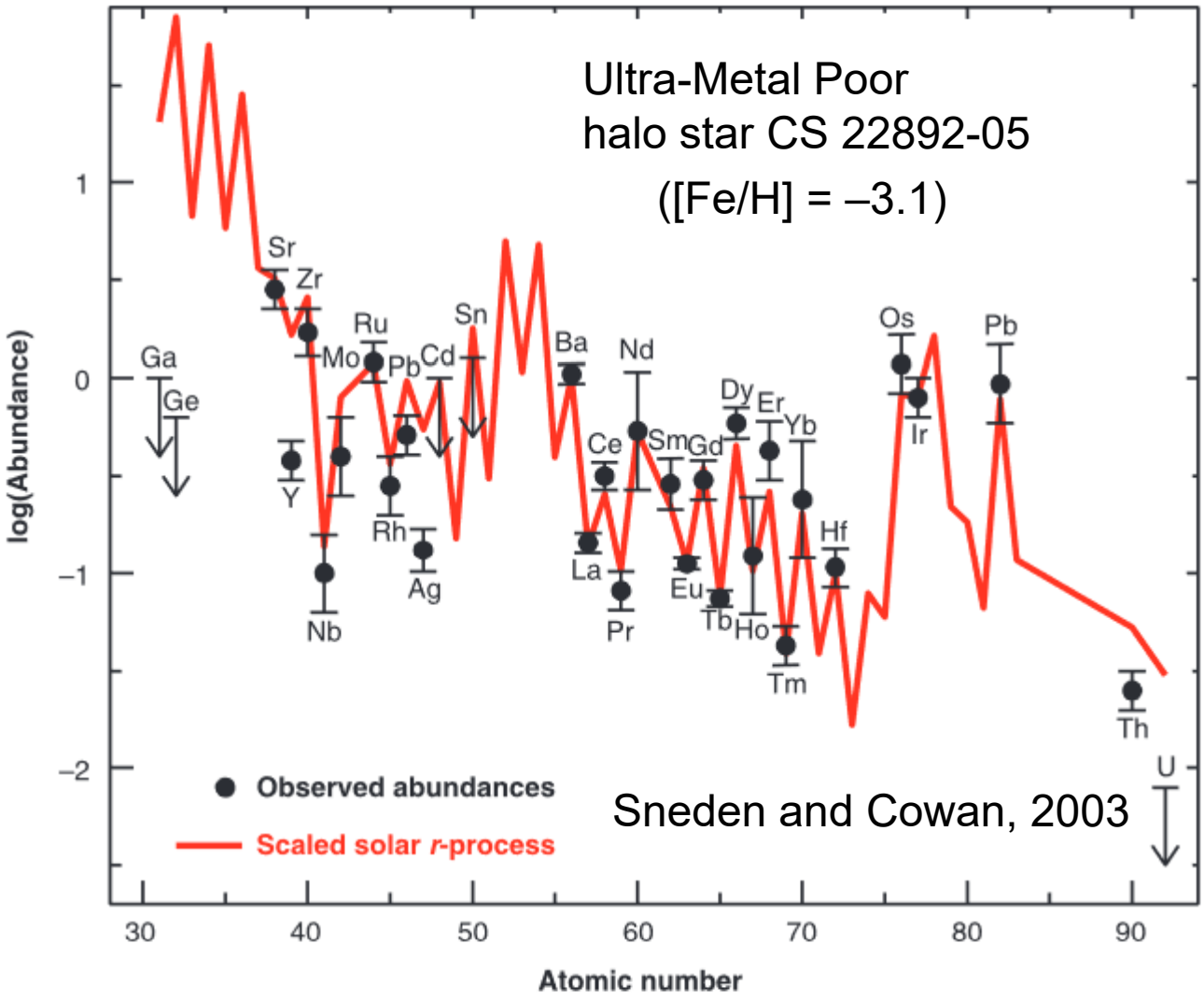


Solar abund.

^{26}Mg anomaly correlated with chemical Al : evidence for presence of ***live*** ^{26}Al in the Early Solar system, later decayed to ^{26}Mg

Live ^{26}Al was present in the Early-Solar System

Robustness of heavy r-process production

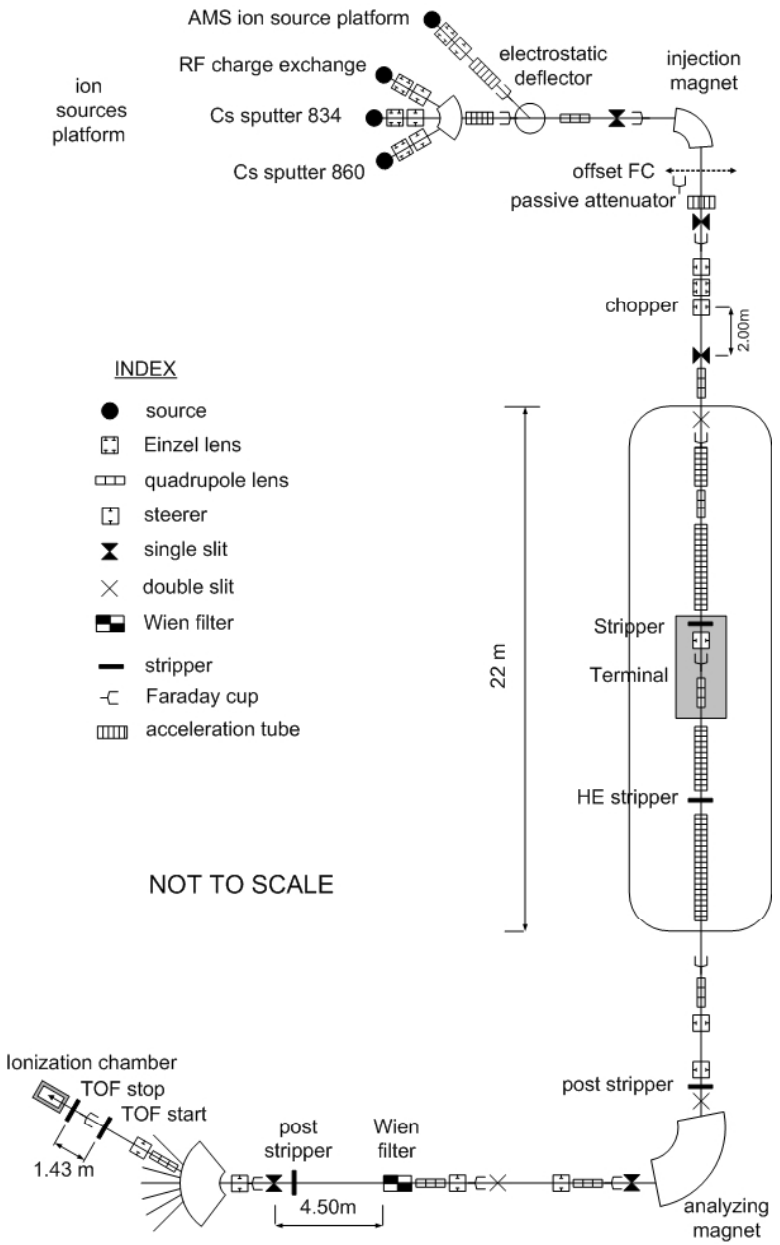


r-process:

Supernovae Uniform Production scenario:

steady-state in the Interstellar Medium (ISM) in the Galaxy:

$[^{244}Pu]=1\text{-}10\times10^{12}$ at/g ISM

Meyer&Clayton,
Space Sci. Rev. (2000)

Accelerator Mass Spectrometry (AMS):
- Negative ion formation
- Stripping to positive ions
- 2 stages of electrostatic analysis
- 3 stages of magnetic analysis
- ion time-of-flight measurement
- ion energy measurement (E~ tens MeV)
- no dark current, no stable molecules, isobaric and isotopic identification