Evidence for Explosive Nucleosynthesis in the Helium Shell of Massive Stars from Cosmochemical Samples

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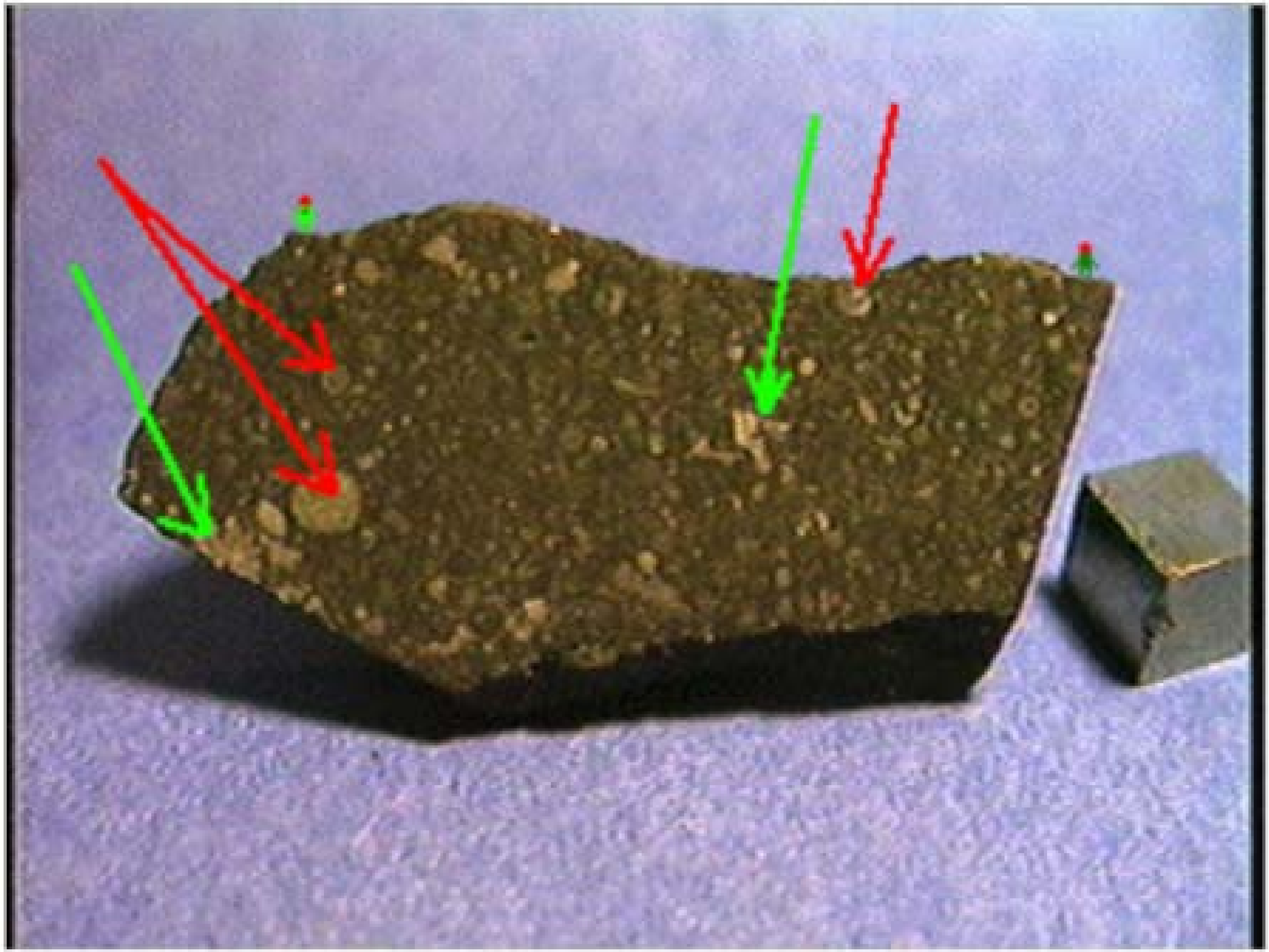
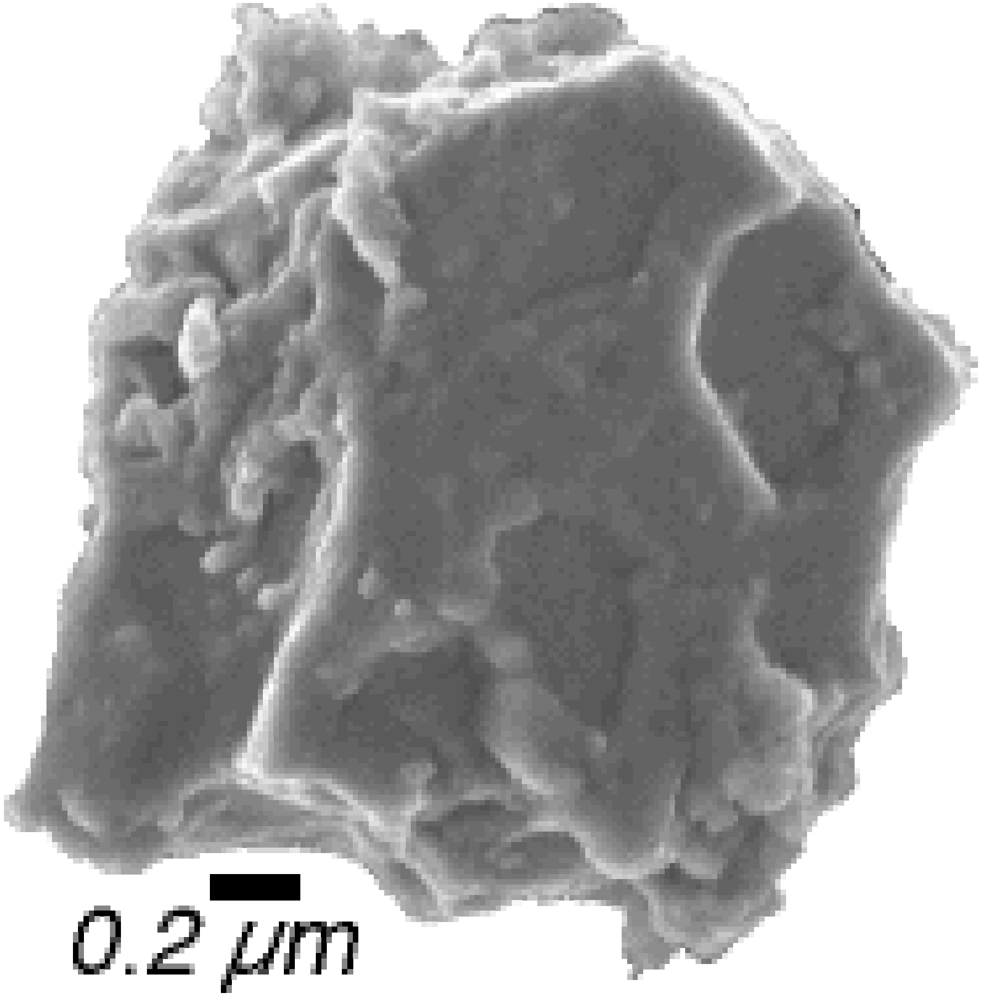
New York City
Newark
Cleveland
Philadelphia
Pittsburgh
Washington
Cincinnati
Louisville
Richmond
Raleigh
Durham
Knoxville
Charlotte
CLEMSON
Columbia
Atlanta
130 mi.
Charleston
230 mi.
Jacksonville
Miami

“Rocks” shed light on fundamental (astro)physics issues:

- Heavy element nucleosynthesis
- Mixing of ejecta in supernova debris
- Cycling of dust in the interstellar medium
- Circumstances of the Sun’s birth
- Formation of the planets
- Important nuclear reactions to measure

February 8, 1969




0.2 μm

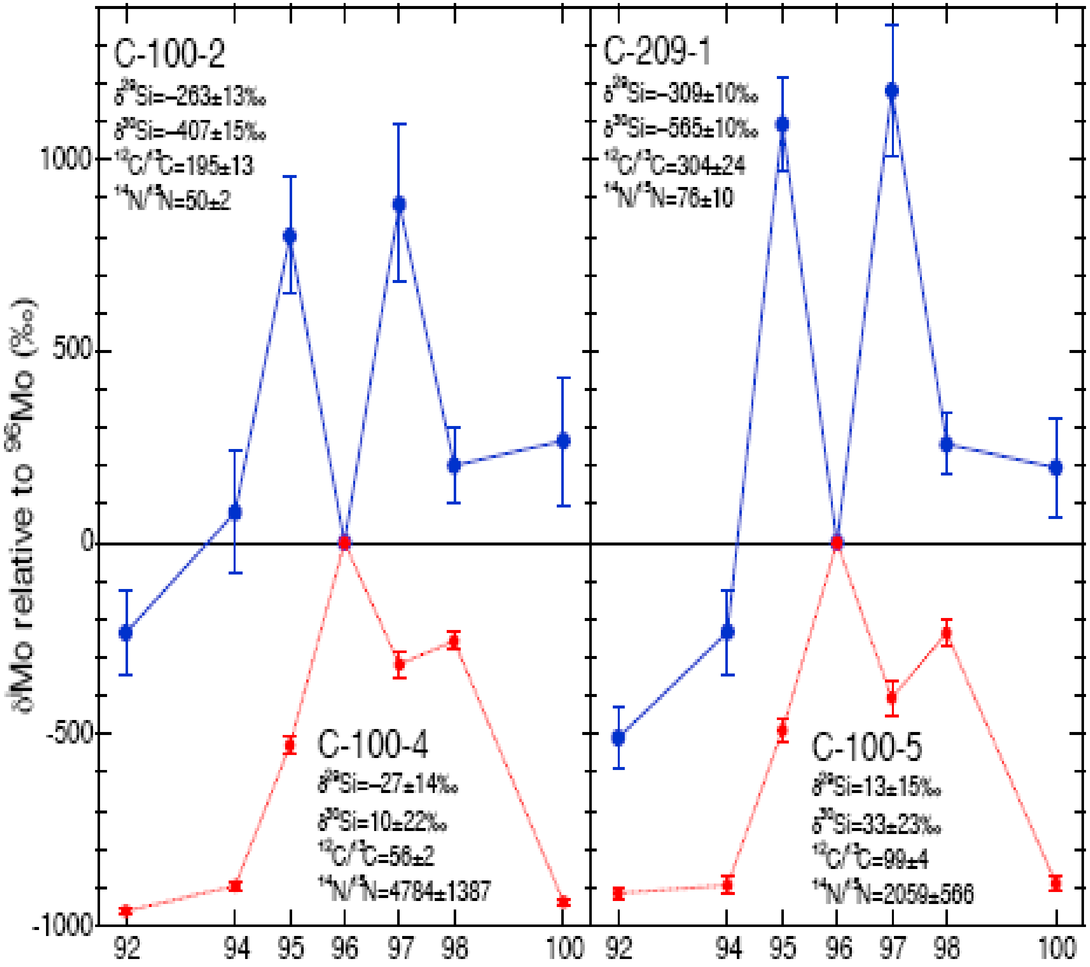
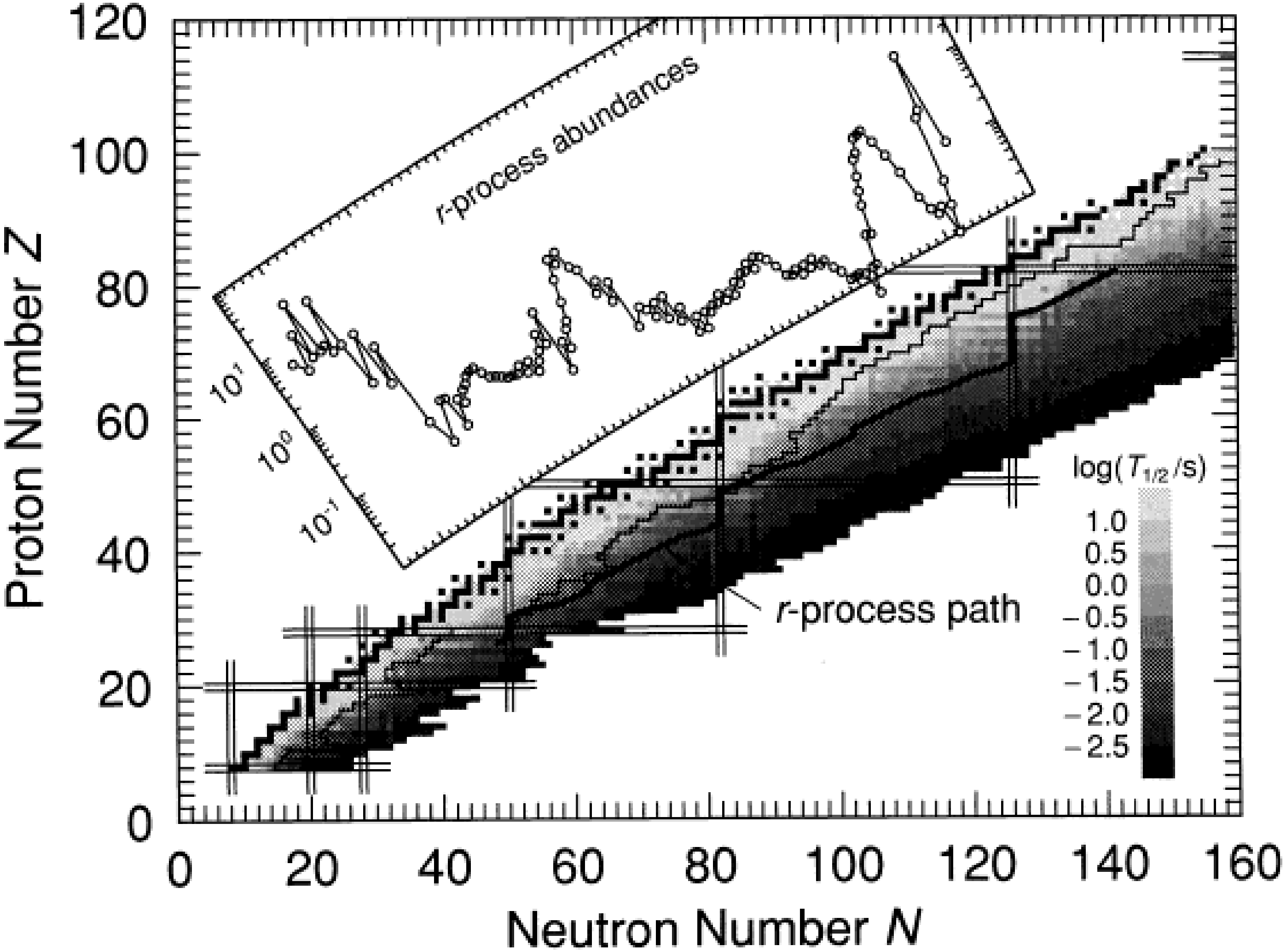
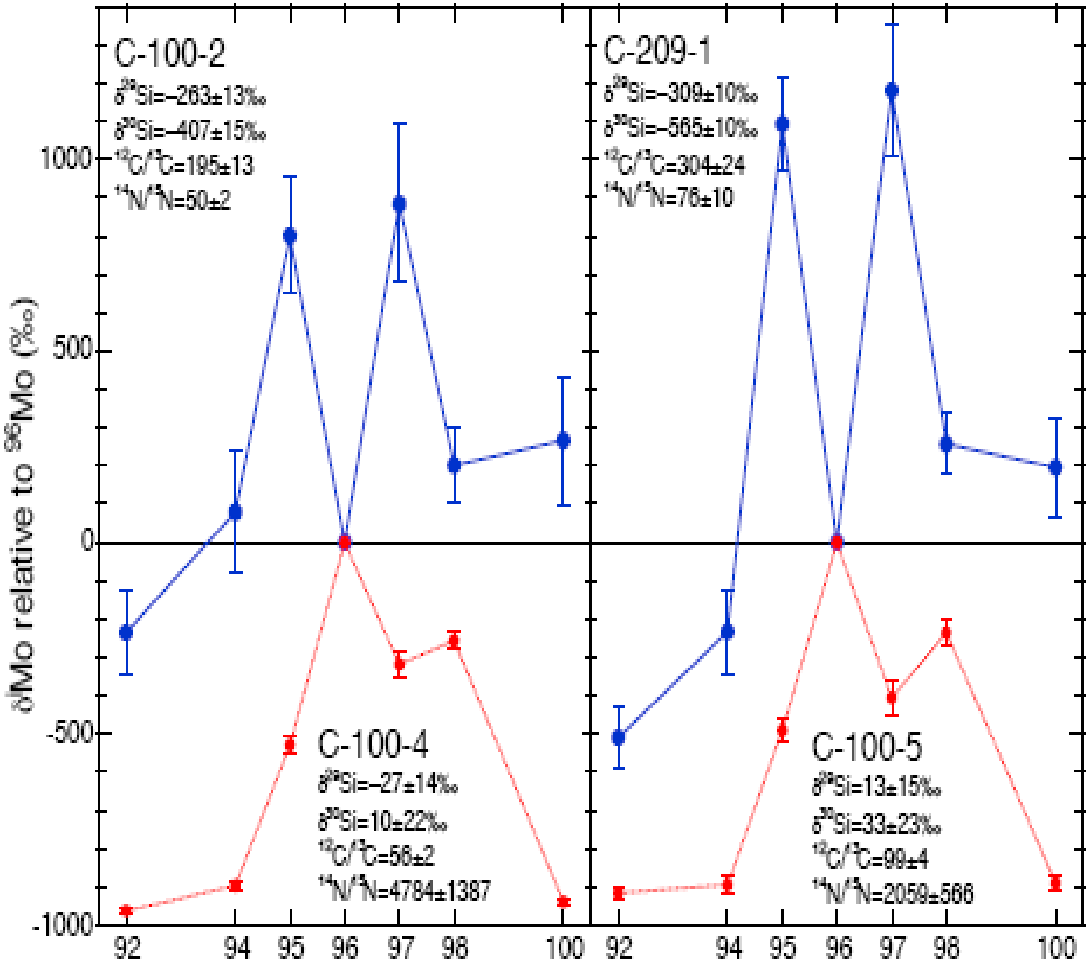


Fig. 2. Mo isotopic compositions (±2σ) of two X-grains (blue, generally positive δ-values) and two mainstream SiC grains (red, generally negative δ-values). The data are shown on two panels for clarity.

Pellin et al. 1999


r-process abundances
10^1
10^0
10^{-1}
r-process path
$\log(T_{1/2}/s)$
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
Proton Number Z
0
20
40
60
80
100
120
Neutron Number N
0
20
40
60
80
100
120
140
160



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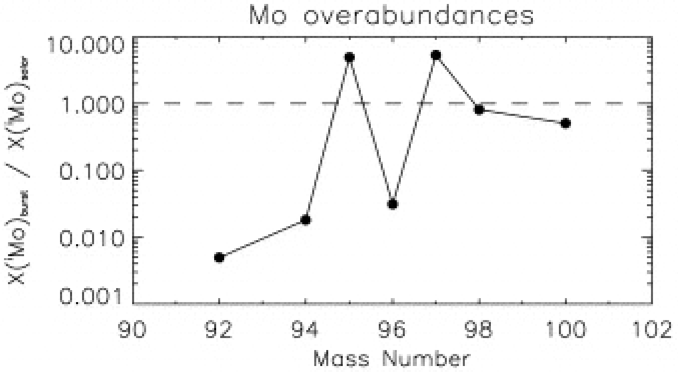
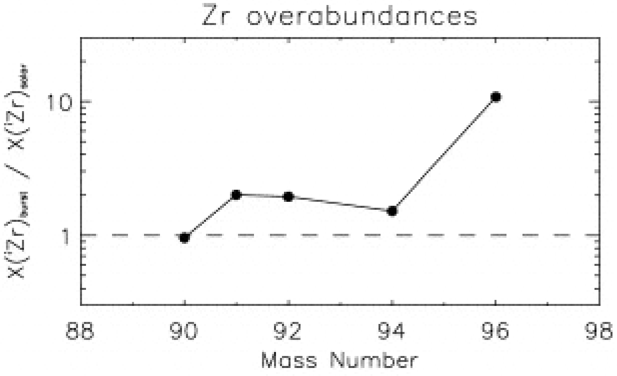
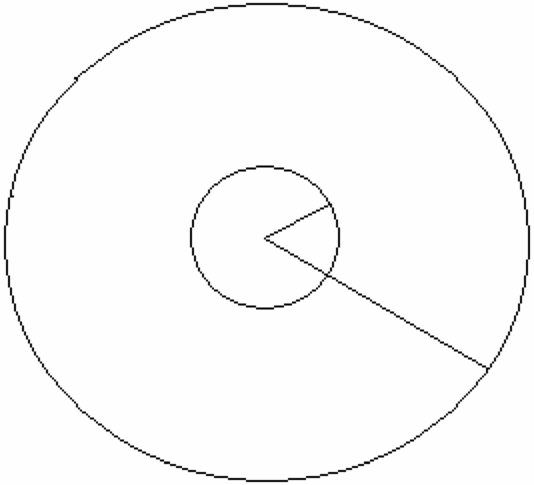
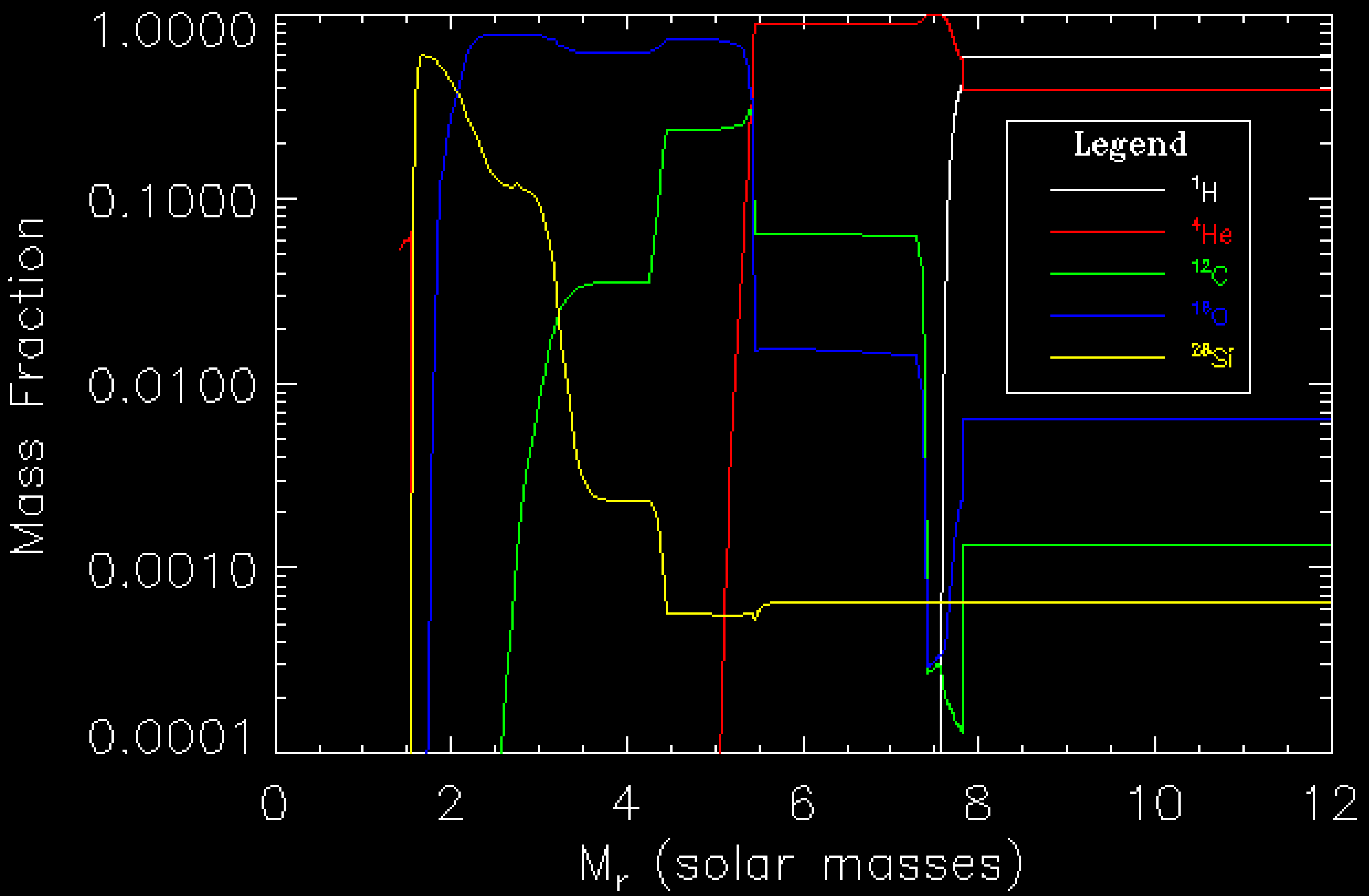

Mo overabundances
X(ⁱMo)burst / X(ⁱMo)solar
10.000
1.000
0.100
0.010
0.001
90
92
94
96
98
100
102
Mass Number

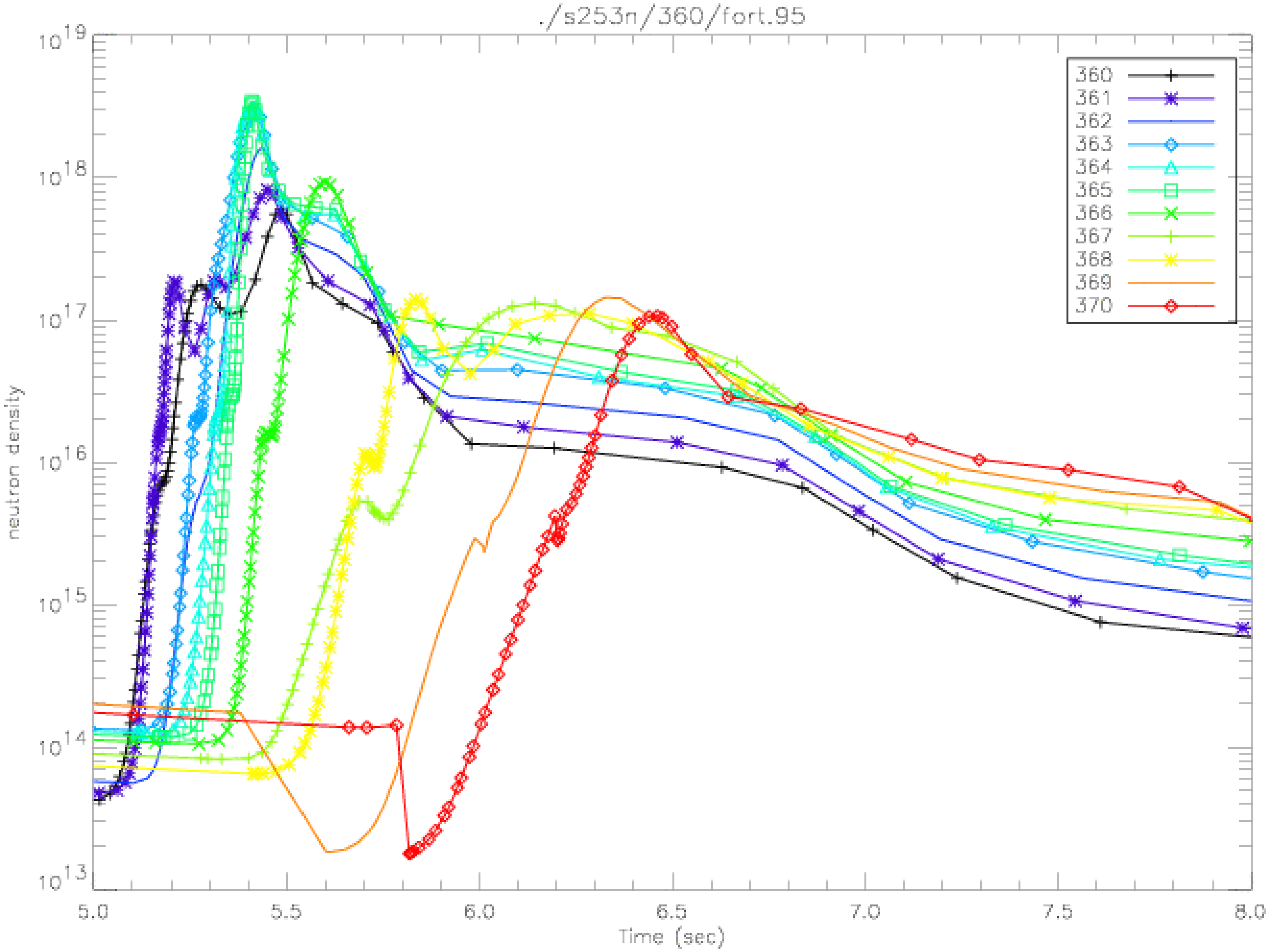

Zr overabundances
X(ⁱZr)burst / X(ⁱZr)solar
10
1
88
90
92
94
96
98
Mass Number

M_r: Lagrangian Mass Coordinate

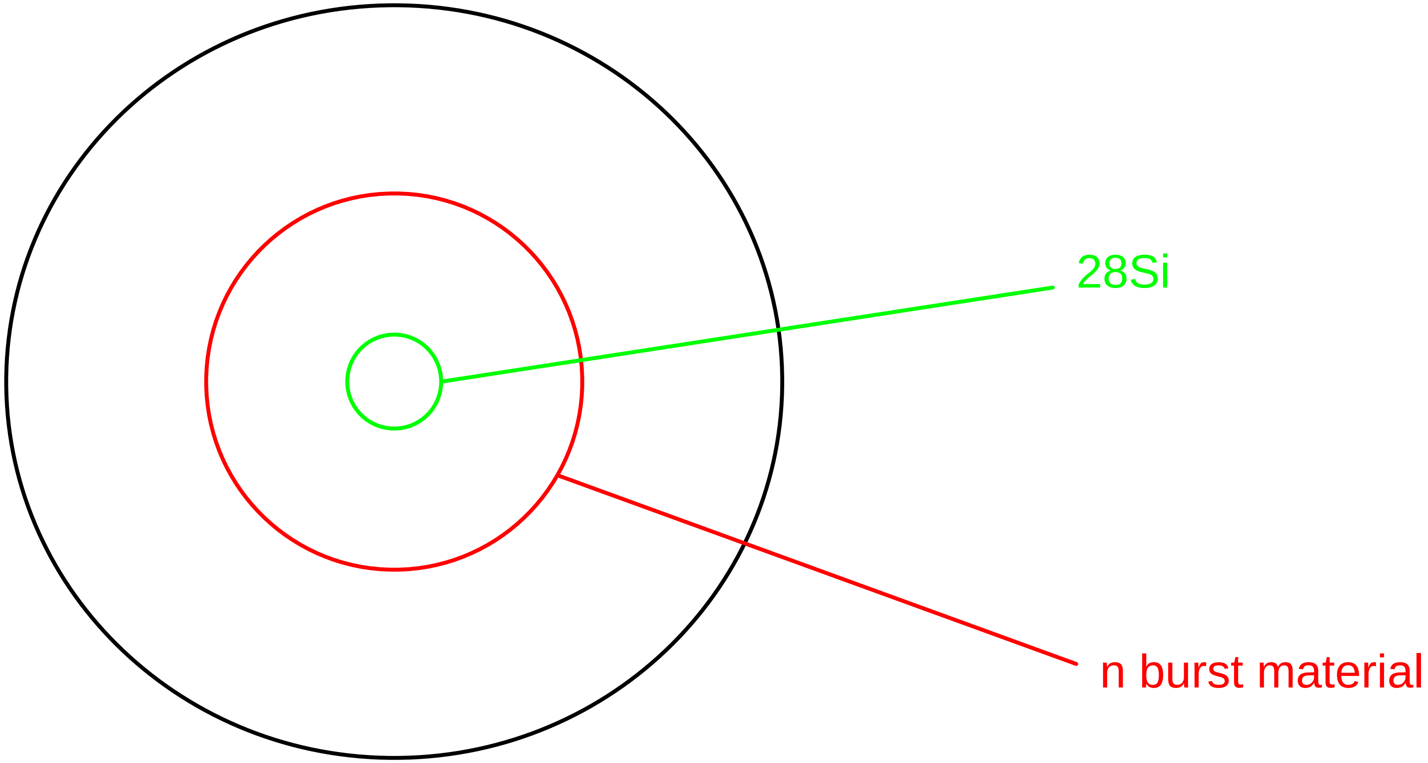


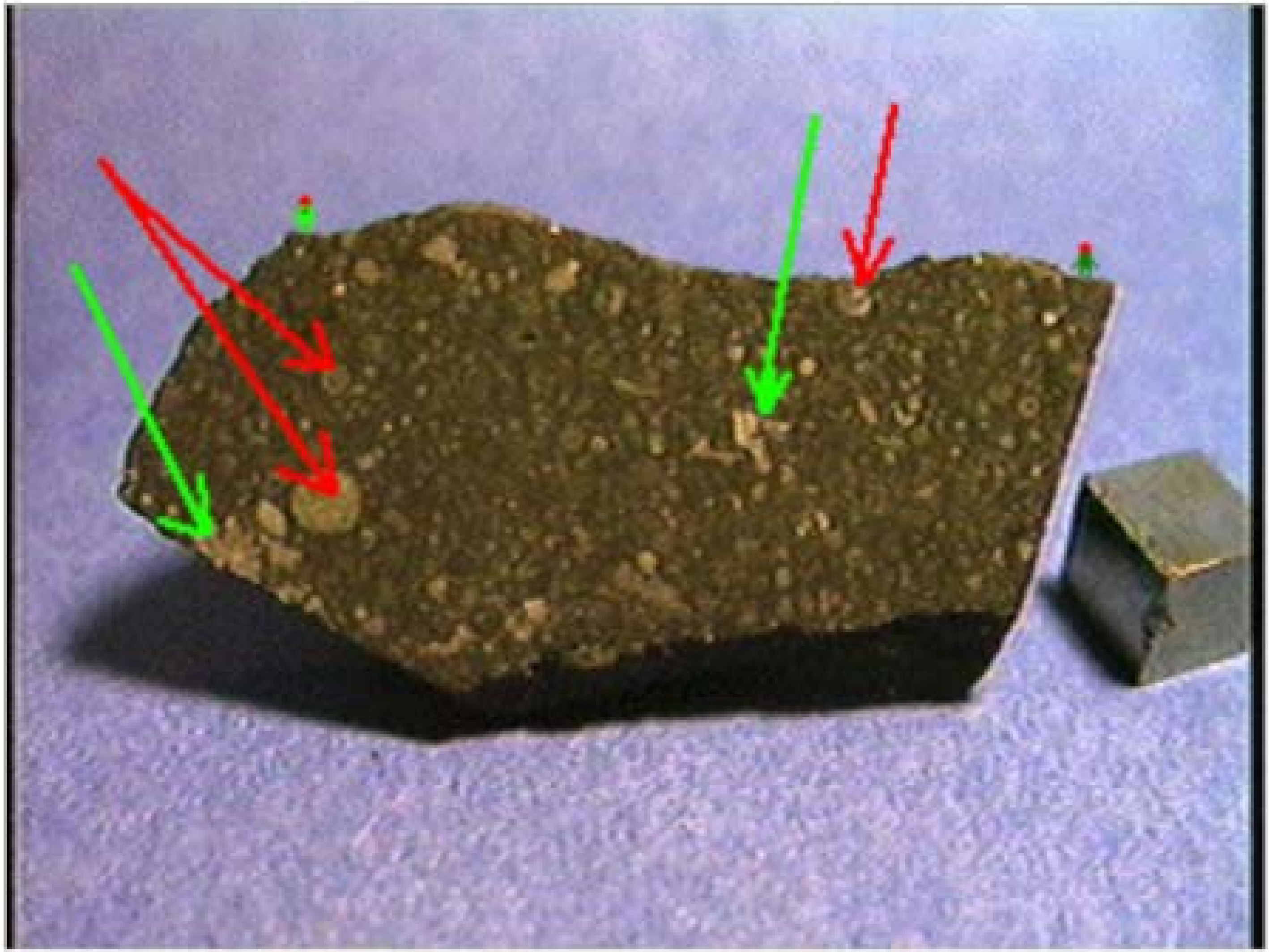
Center: $M_r = 0$
Outer boundary of star: $M_r = M$


Mass Fraction
1.0000
0.1000
0.0100
0.0010
0.0001
0
2
4
6
8
10
12
M_r (solar masses)
Legend
1H
4He
12C
16O
28Si

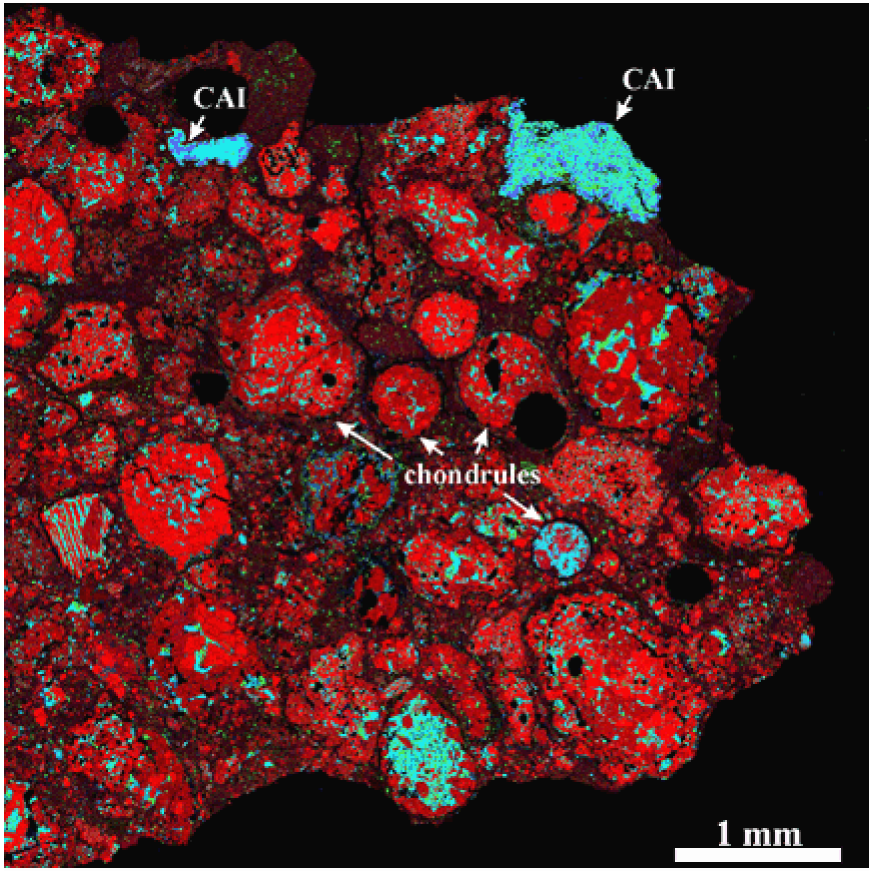


^{22}Ne(alpha,n)^{25}Mg

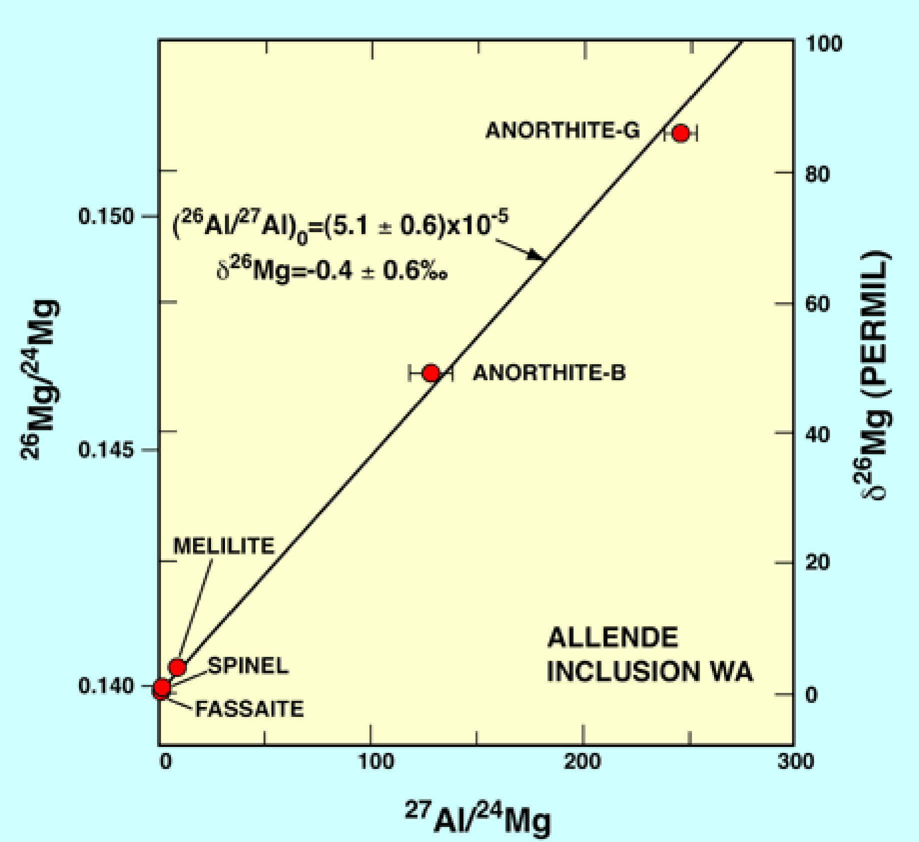

28Si
n burst material



PCA 91082

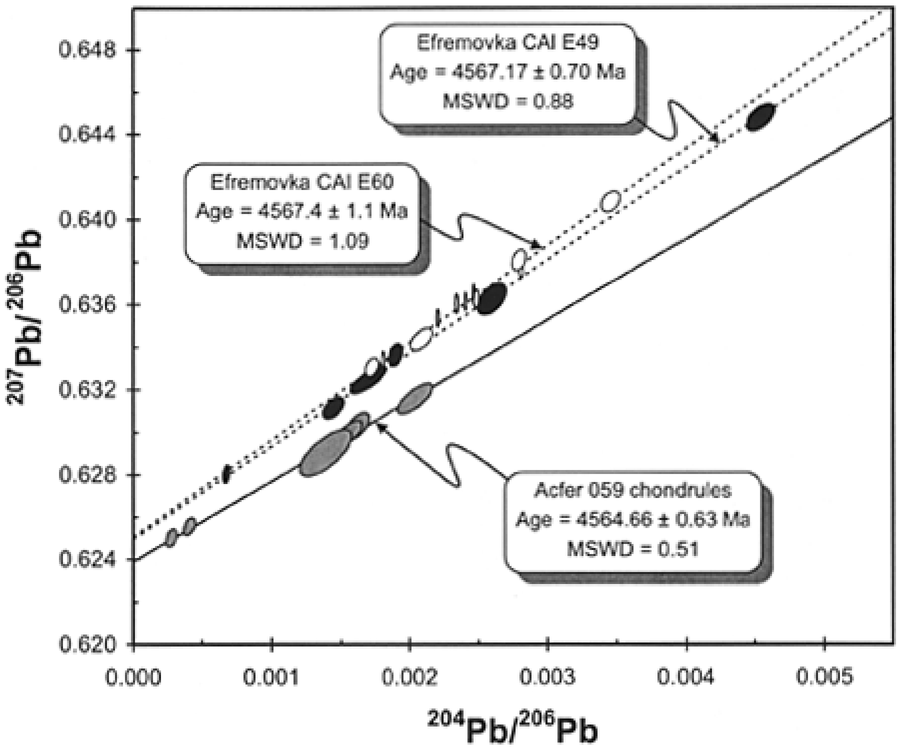


(Alexander Krot, University of Hawaii)

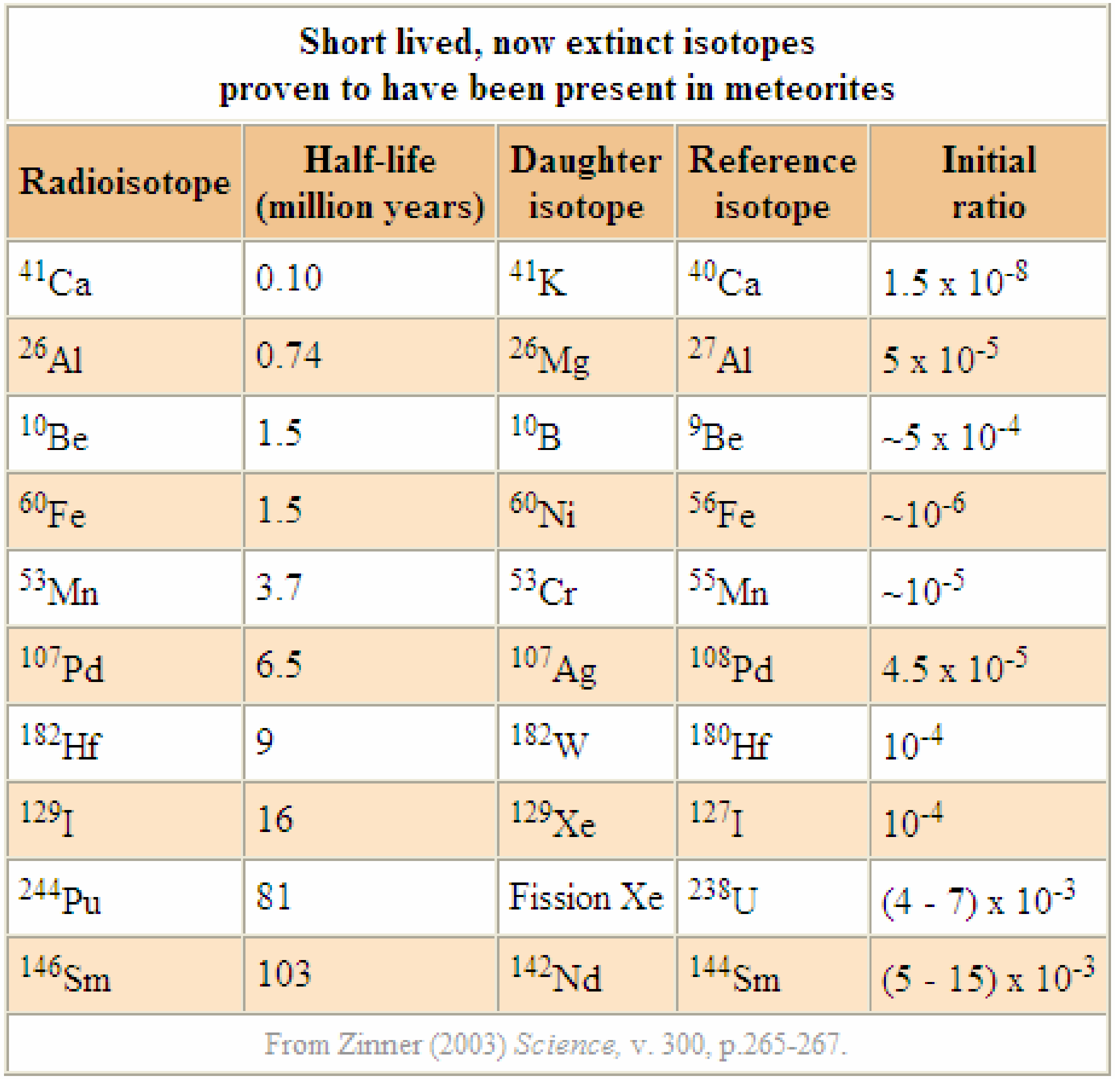


(From Lee *et.al.*, *Geophys. Res. Lett.*, 1976)

Pb-Pb isochrons



(from Amelin *et. al.*, *Science*, 2002)



**Short lived, now extinct isotopes
proven to have been present in meteorites**

Radioisotope	Half-life (million years)	Daughter isotope	Reference isotope	Initial ratio
^{41}Ca	0.10	^{41}K	^{40}Ca	1.5×10^{-8}
^{26}Al	0.74	^{26}Mg	^{27}Al	5×10^{-5}
^{10}Be	1.5	^{10}B	^{9}Be	$\sim 5 \times 10^{-4}$
^{60}Fe	1.5	^{60}Ni	^{56}Fe	$\sim 10^{-6}$
^{53}Mn	3.7	^{53}Cr	^{55}Mn	$\sim 10^{-5}$
^{107}Pd	6.5	^{107}Ag	^{108}Pd	4.5×10^{-5}
^{182}Hf	9	^{182}W	^{180}Hf	10^{-4}
^{129}I	16	^{129}Xe	^{127}I	10^{-4}
^{244}Pu	81	Fission Xe	^{238}U	$(4 - 7) \times 10^{-3}$
^{146}Sm	103	^{142}Nd	^{144}Sm	$(5 - 15) \times 10^{-3}$

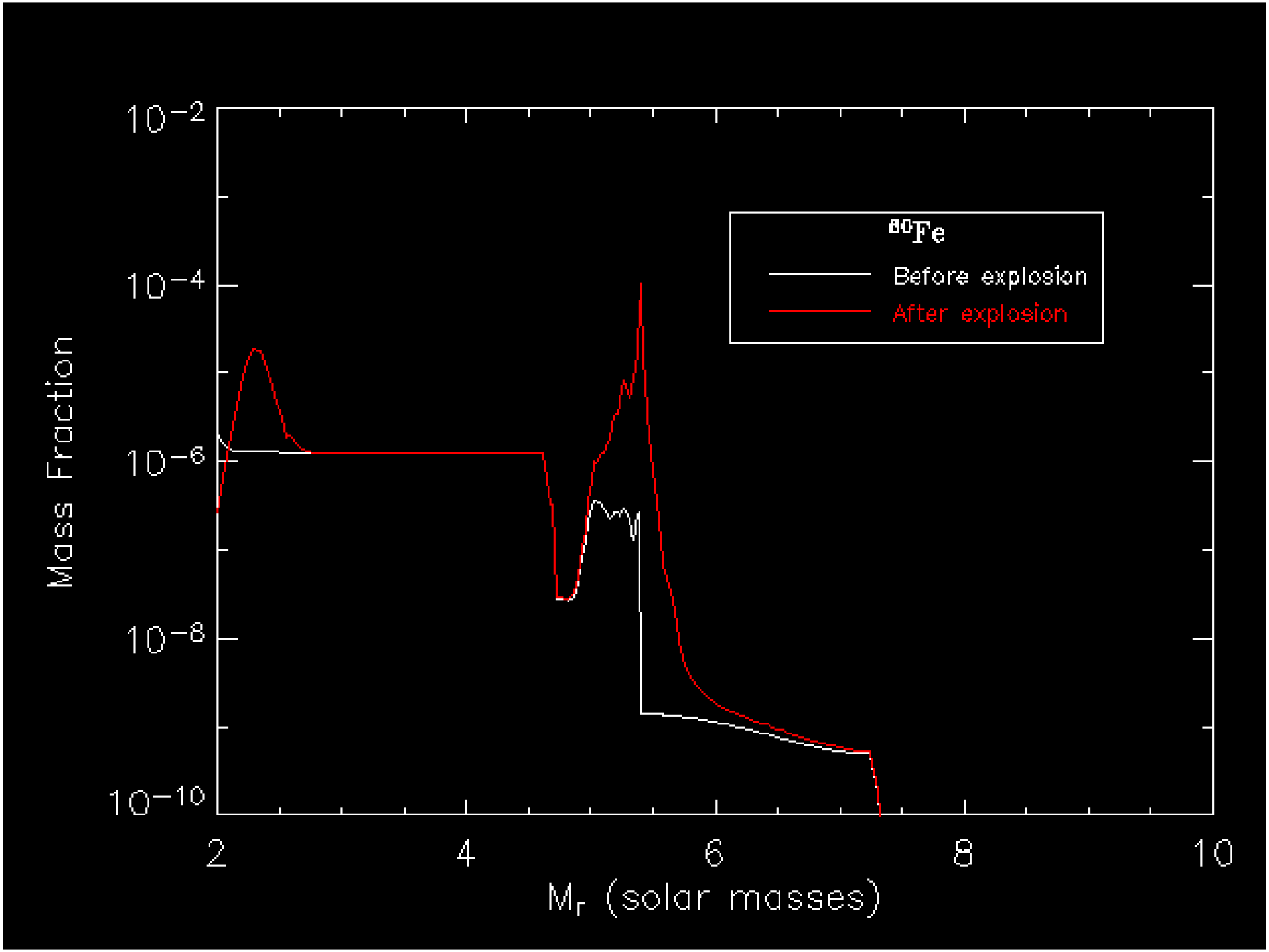
From Zinner (2003) *Science*, v. 300, p.265-267.

Steady-state solar system abundances

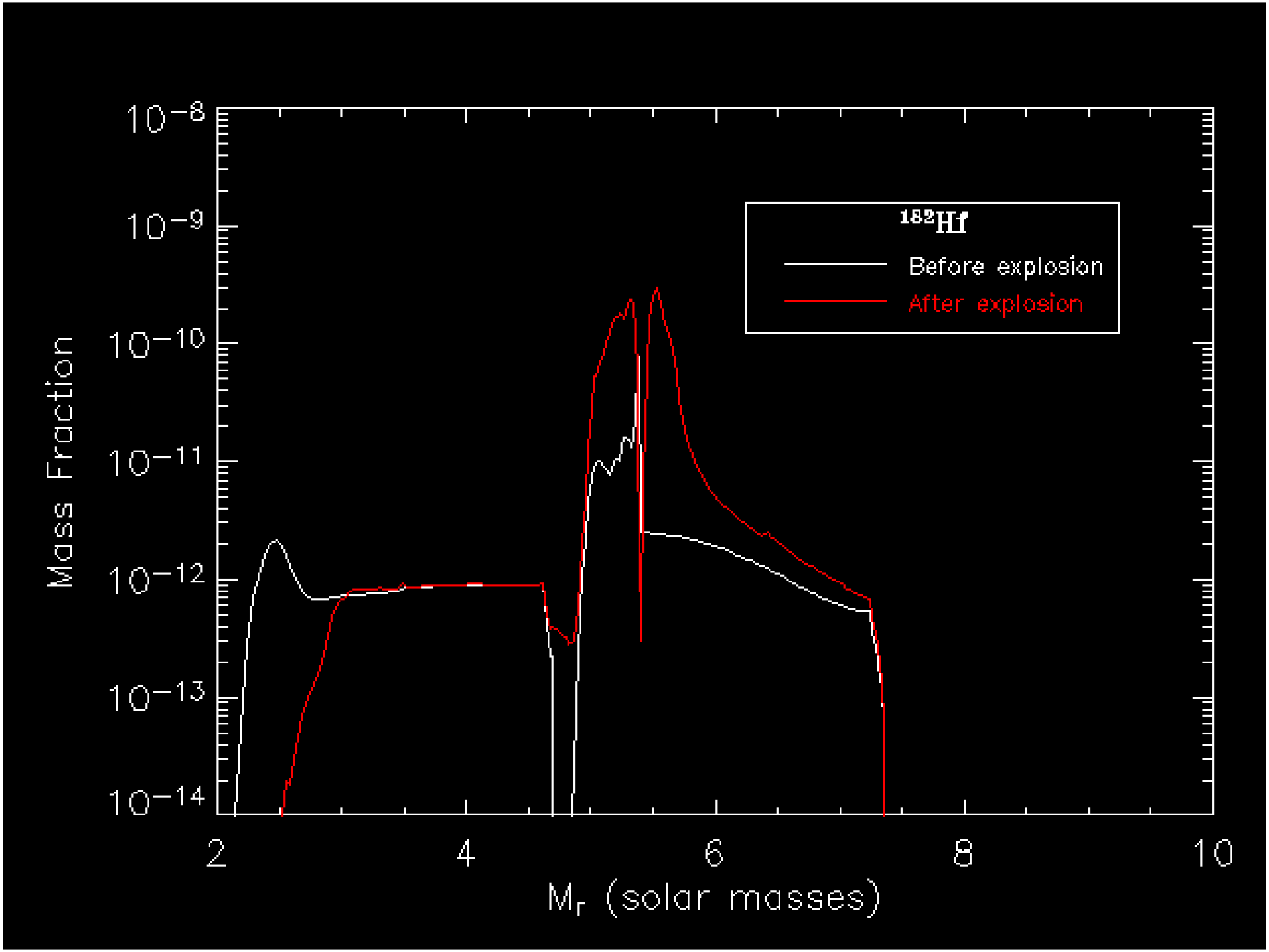
- Meteorites have the right amount of ^{53}Mn and ^{182}Hf
- Meteorites have too much ^{26}Al, ^{41}Ca, and ^{60}Fe
- Meteorites have too little ^{107}Pd and ^{129}I

Multiple components required for the r-process?

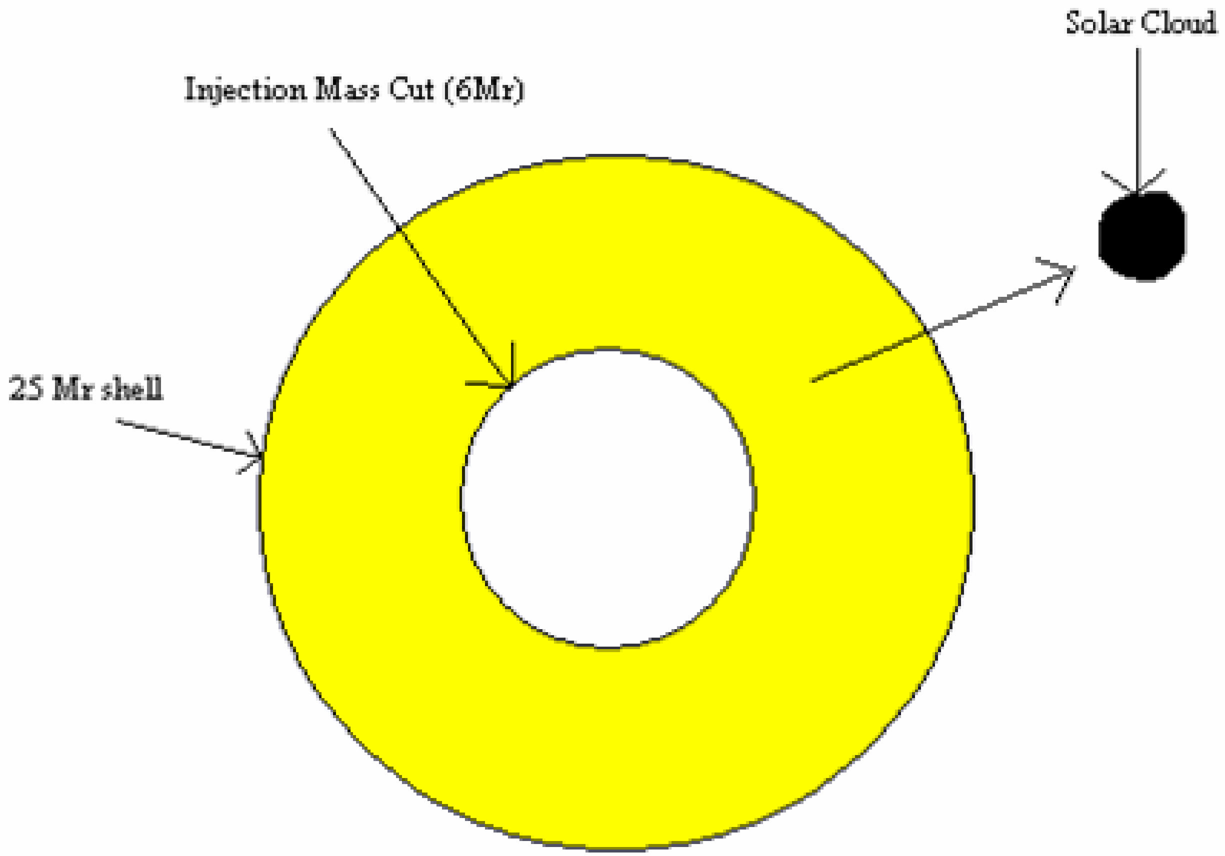
- Evidence:
  - Extinct $^{129}I/^{182}Hf$ discrepancy in the early solar system.
  - Variability of $A < 130$ abundances in metal-poor stars
- Possibilities:
  - Multiple r-process components (read “sites”).
  - Other sources of these “r-process isotopes”

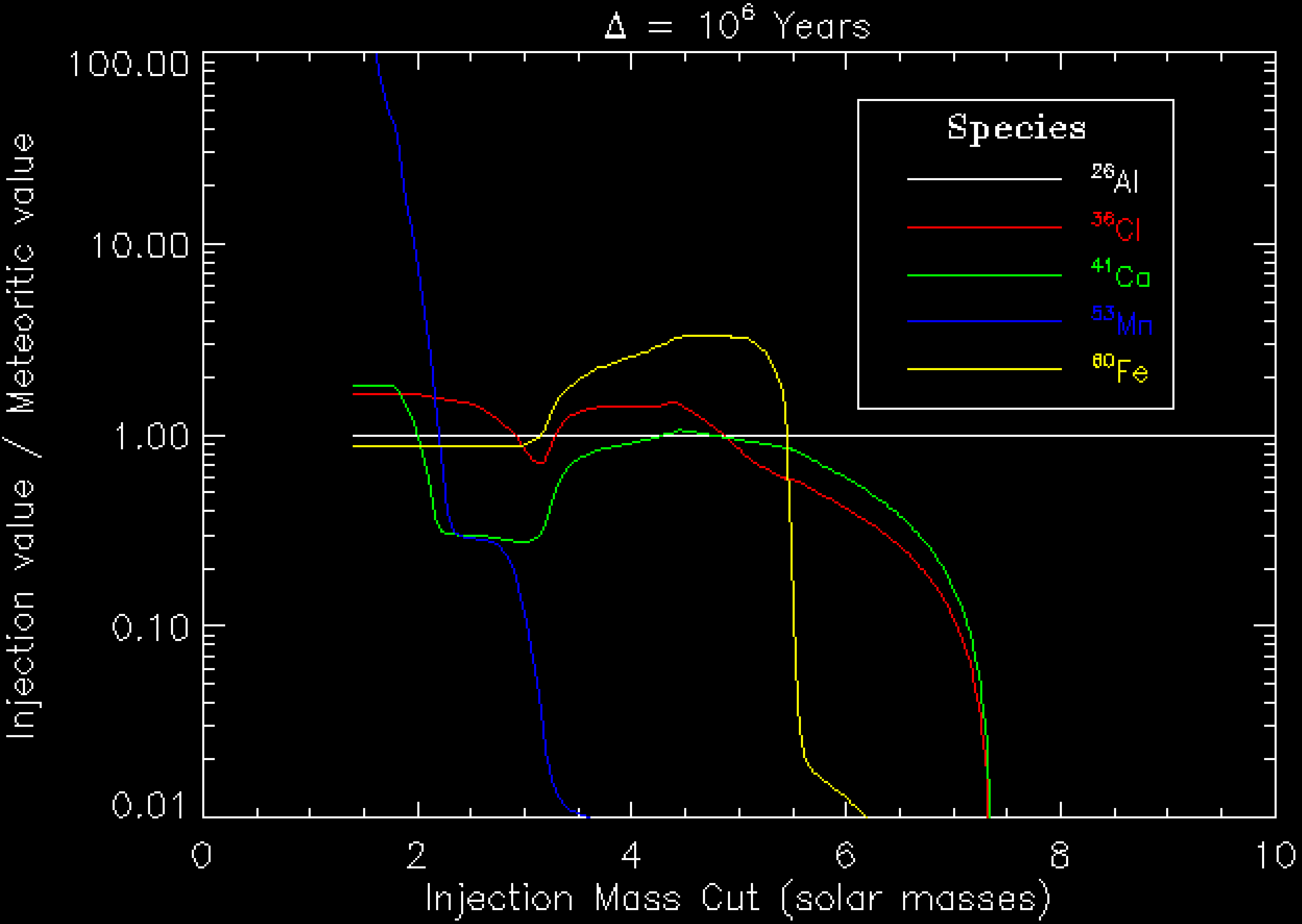


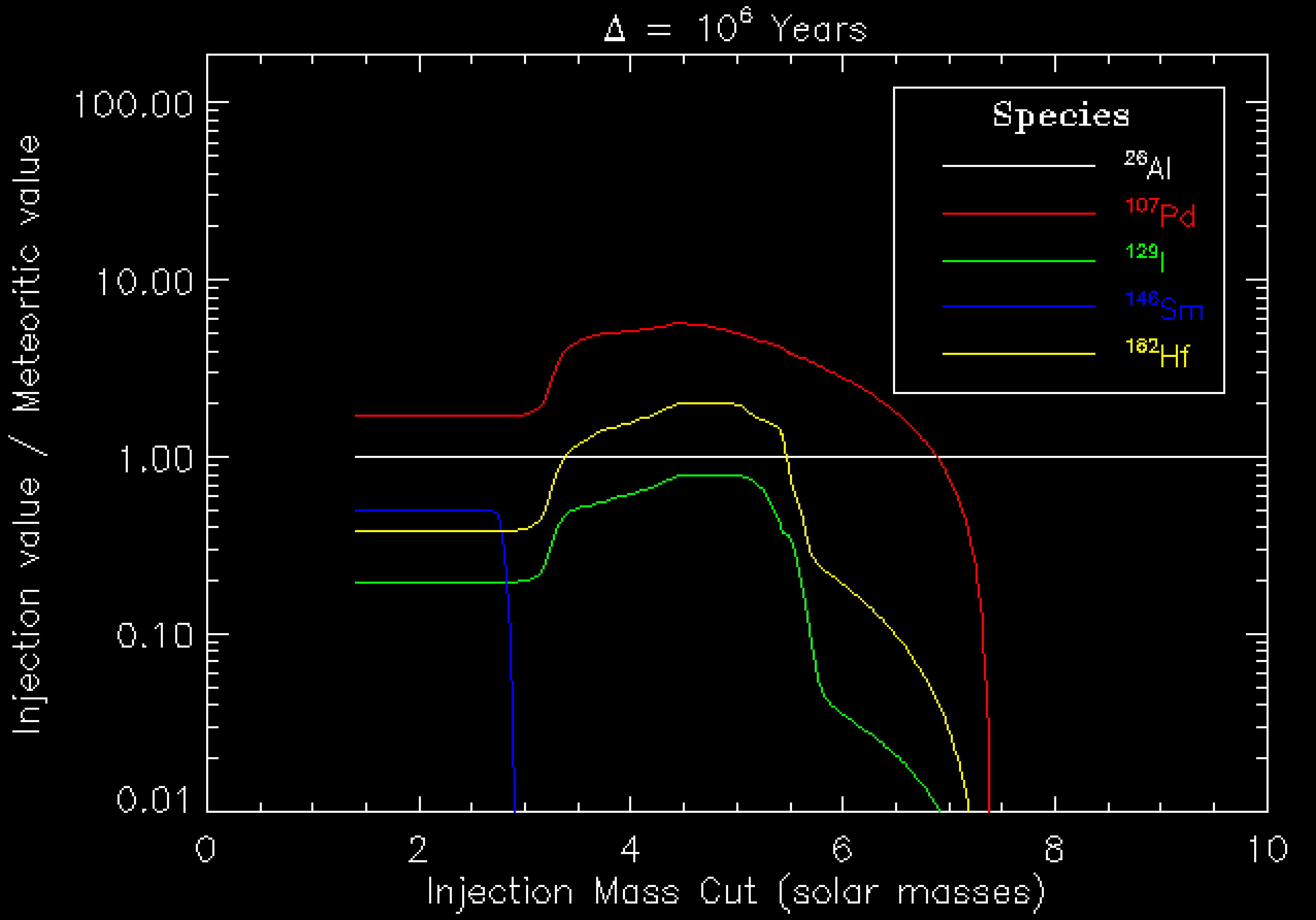
^{60}Fe
Before explosion
After explosion
Mass Fraction
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
2
4
6
8
10
M_r (solar masses)


^{182}Hf
Before explosion
After explosion
Mass Fraction
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
2
4
6
8
10
M_r (solar masses)

Injection picture




Δ = 10^6 Years
100.00
10.00
1.00
0.10
0.01
Injection value / Meteoritic value
0
2
4
6
8
10
Injection Mass Cut (solar masses)
Species
26Al
36Cl
41Ca
53Mn
60Fe

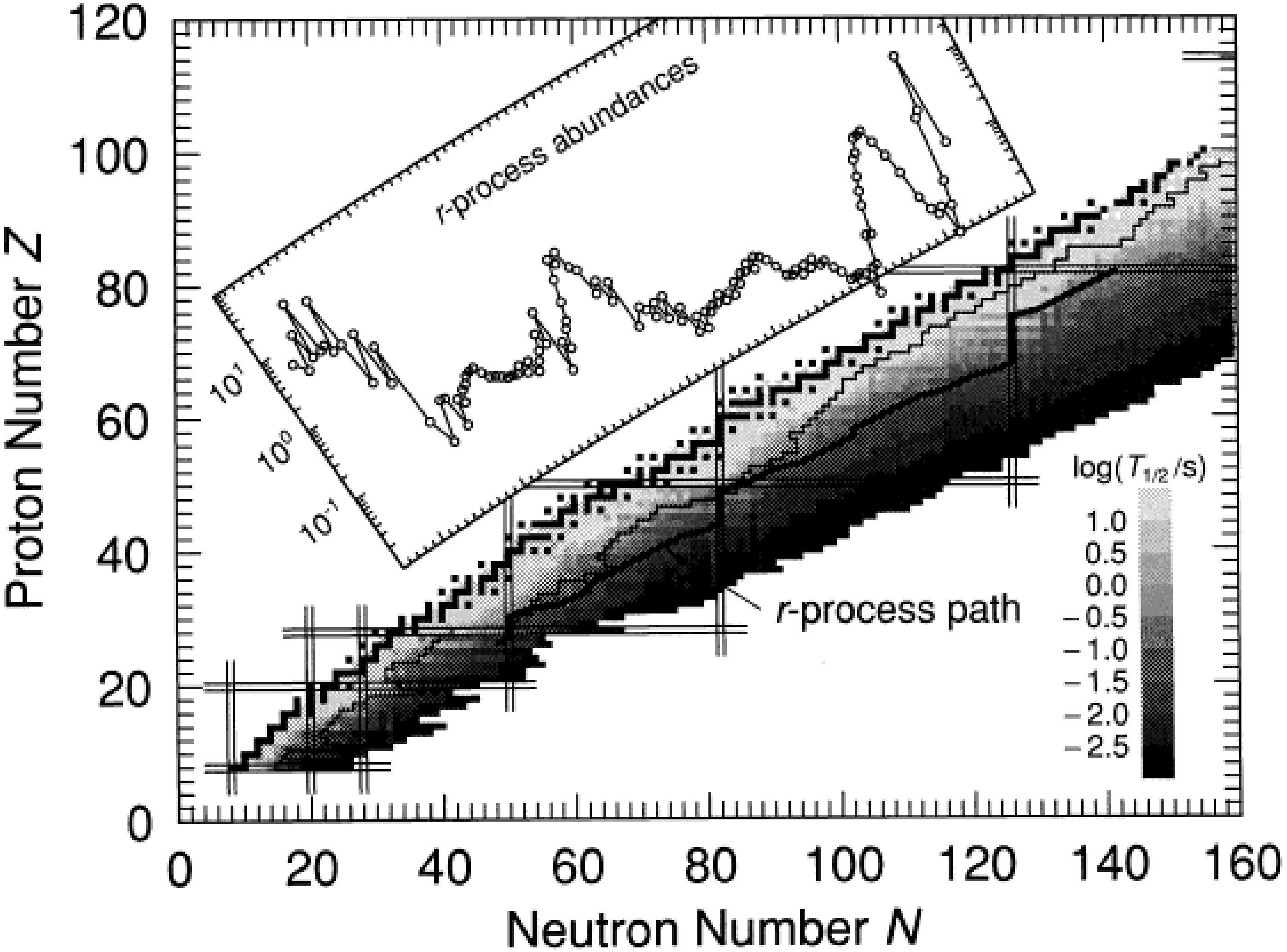

Δ = 10^6 Years
Species
^{26}Al
^{107}Pd
^{129}I
^{146}Sm
^{182}Hf
100.00
10.00
1.00
0.10
0.01
0
2
4
6
8
10
Injection value / Meteoritic value
Injection Mass Cut (solar masses)

Injection of Radioactivities from a Supernova

- With appropriate mass cut can explain early solar system abundance of ^{26}Al, ^{60}Fe, ^{107}Pd, ^{129}I, and ^{182}Hf
- Steady-state Galactic nucleosynthesis accounts for ^{53}Mn, ^{146}Sm, and the actinides
- This scenario decouples extinct ^{129}I and ^{182}Hf from the r-process; therefore, it does not demand multiple r-process components.

Important nuclear reactions

- Neutron-producing reactions like ^{22}Ne(alpha,n)^{25}Mg at temperatures T_9=0.5-1.5
- Neutron-capture reactions on nuclear several mass units neutron rich of stability


r-process abundances
10^1
10^0
10^{-1}
r-process path
log($T_{1/2}$/s)
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
Proton Number Z
0
20
40
60
80
100
120
Neutron Number N
0
20
40
60
80
100
120
140
160

Take home message

- Fascinating cosmochemical and astronomical data on r-process isotopes and elements are not easily explained by the “standard” r-process.
- Rather than indicating multiple r-process components, however, this may be indicating (minor) non r-process contributions to the production of these species from He shell nucleosynthesis
- Helium-shell nucleosynthesis products in cosmochemical samples thus have implications for the astronomy of supernova, the circumstances of the Sun’s birth, and identification of important nuclear reaction cross sections to measure.