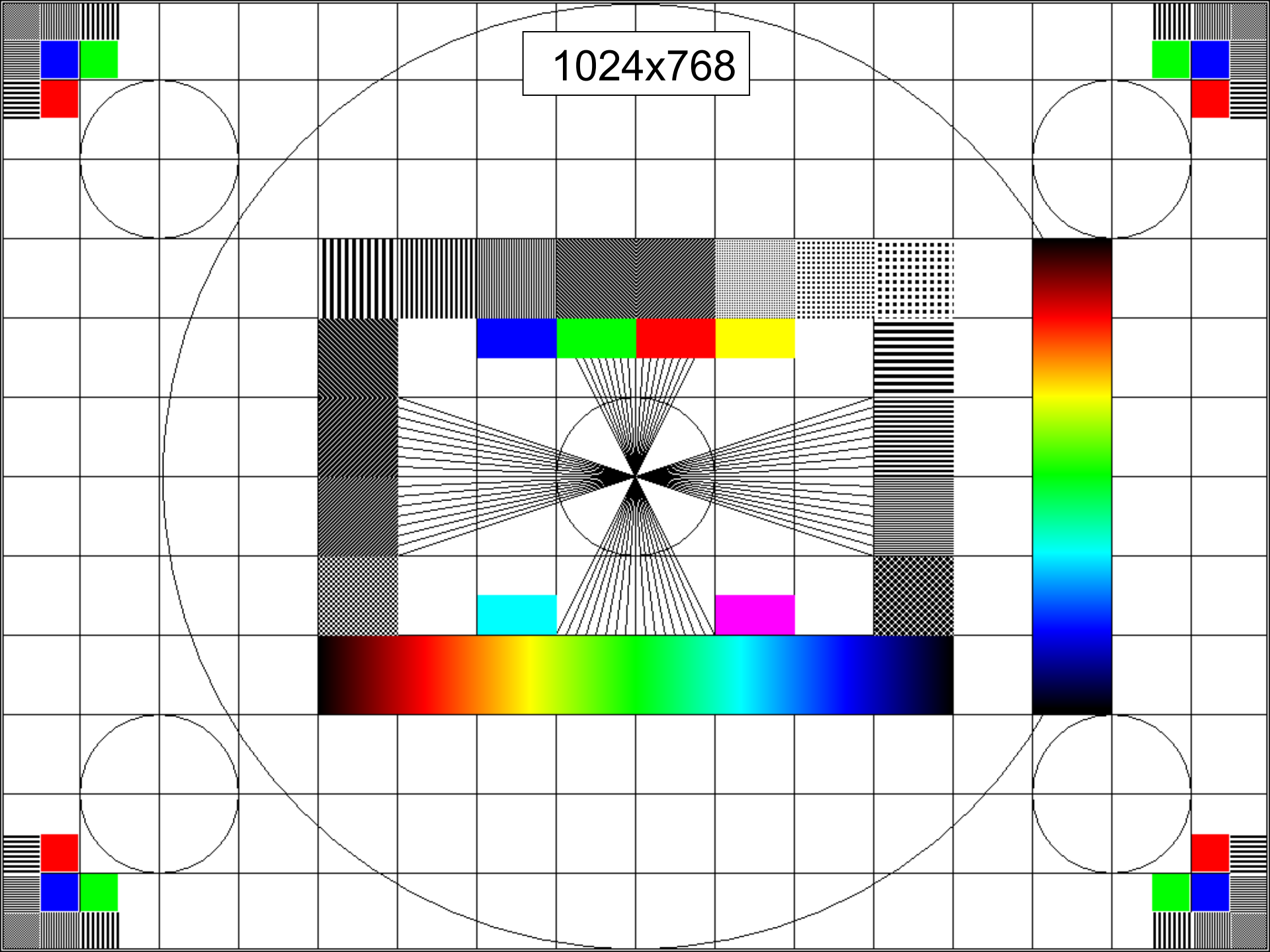
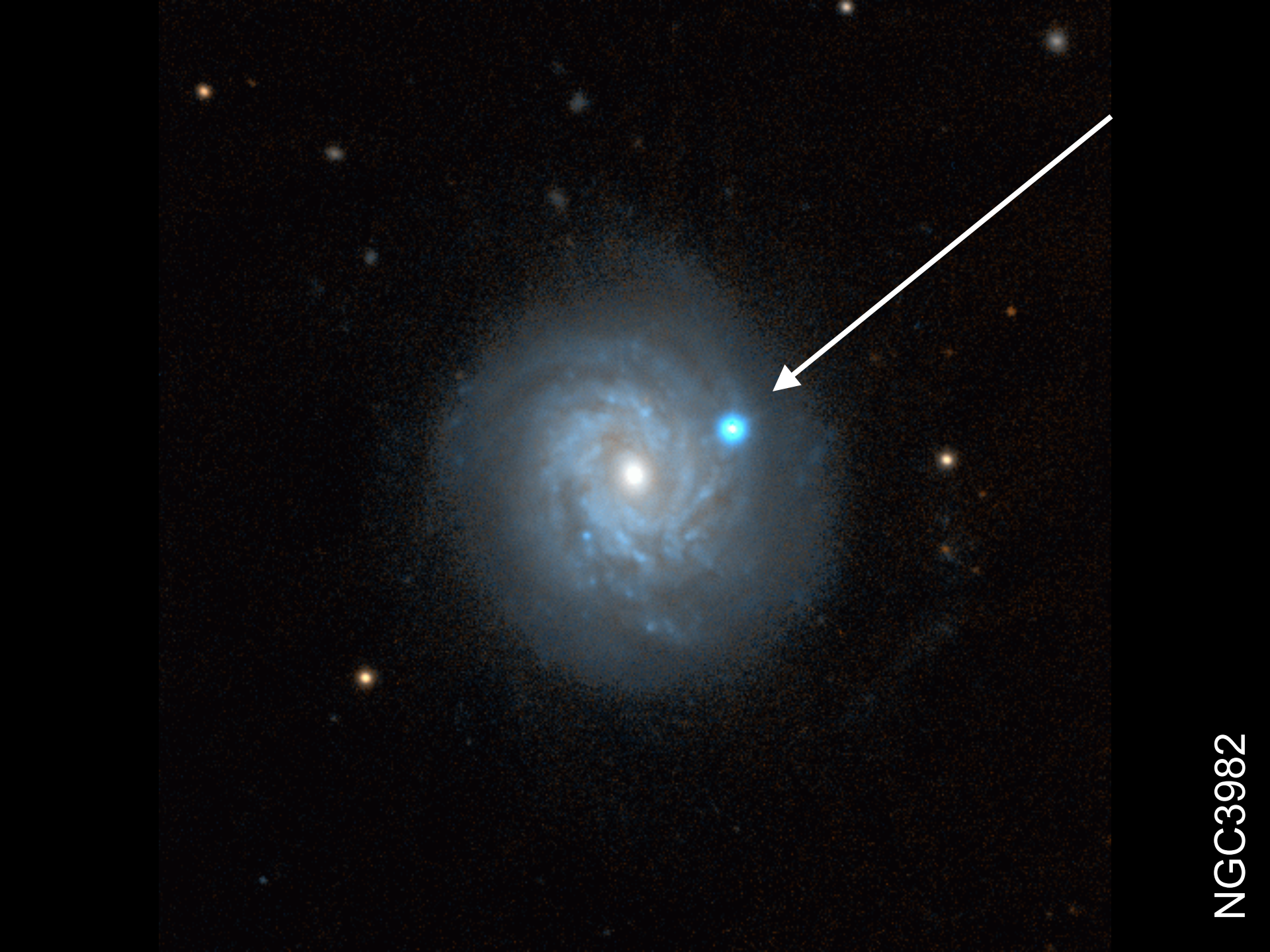


1024x768





NGC3982

**Origin of the Elements:
Supernovae from
Massive Stars and their
Nucleosynthesis**

Alexander Heger

Overview

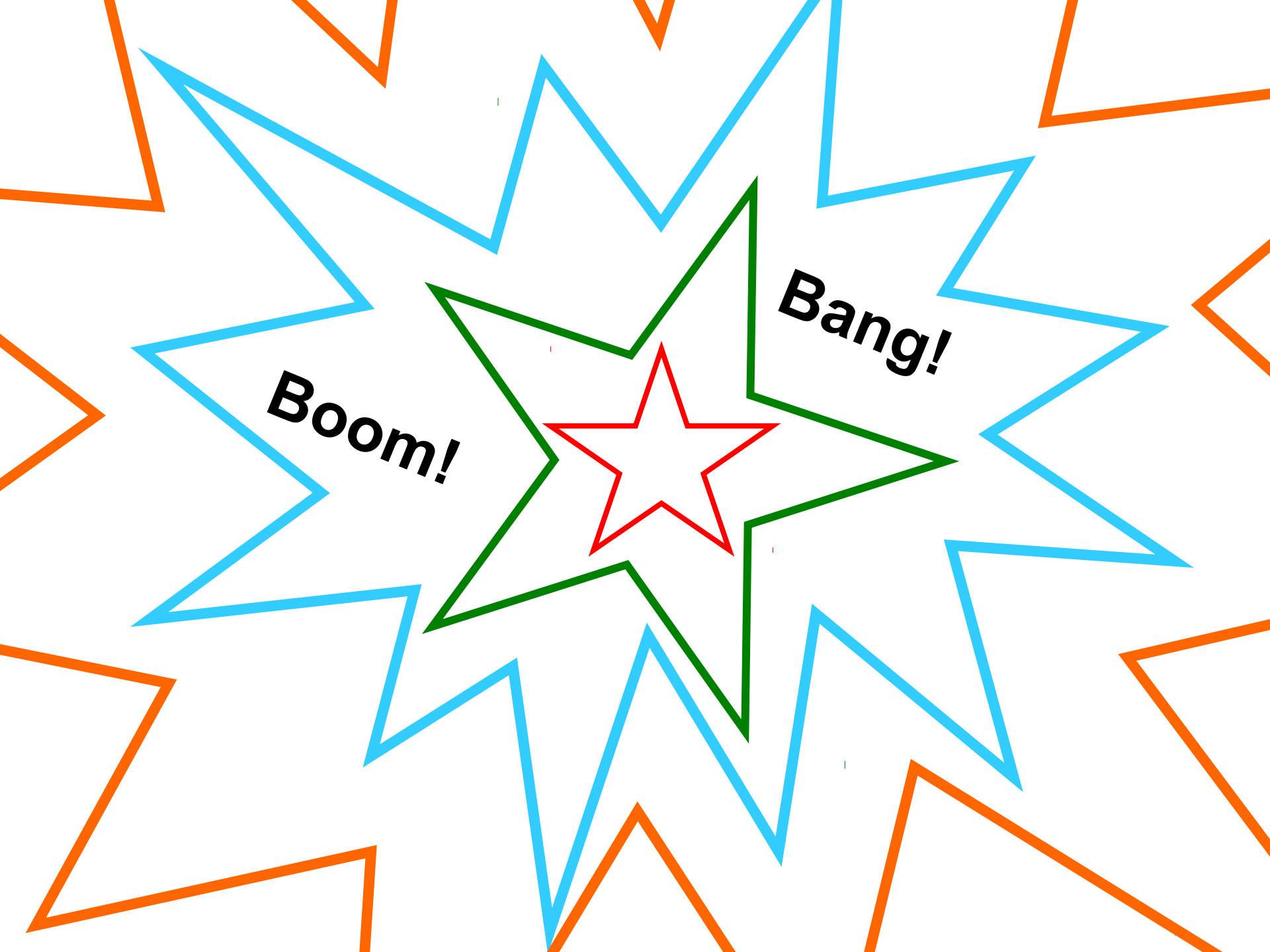
- **Nucleosynthesis in Supernova**
- **Varieties of Stellar Deaths**

The background of the slide features a construction site with a large, blue, triangular sign in the foreground. The sign has a white border and a white star in the center. The text is overlaid on the sign. The background also shows a steel structure under construction and a tower in the distance.

A First Look

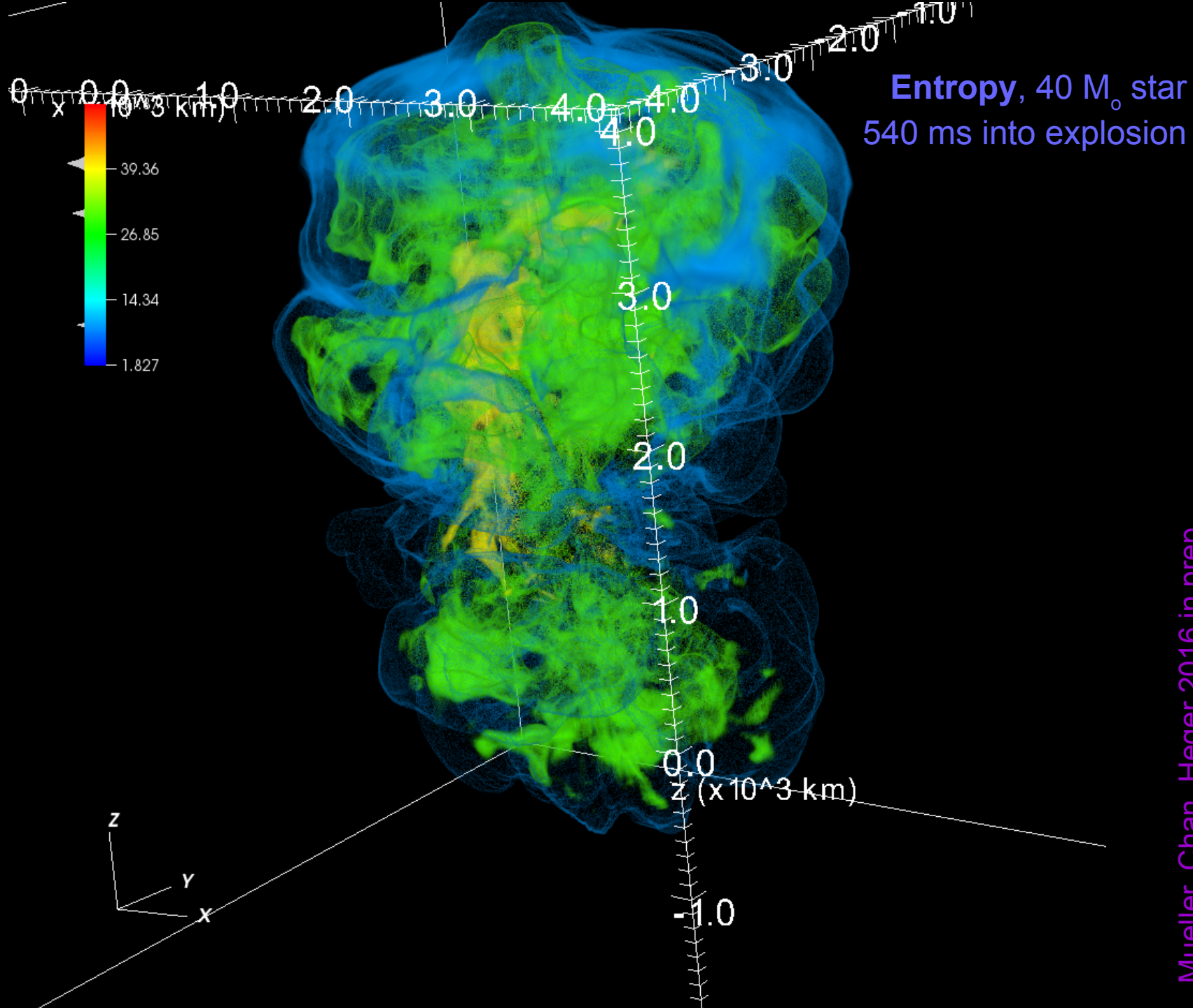
Core Collapse Supernovae

(Massive Stars, Pop I)

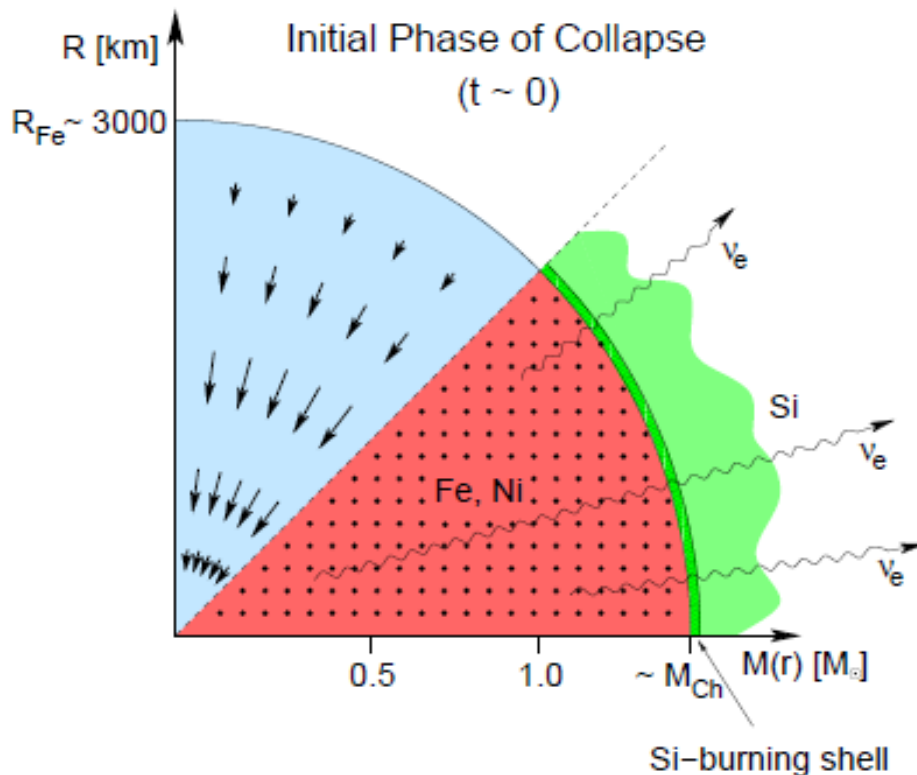


Boom!

Bang!



Iron Core Collapse



- Iron core supported by degeneracy pressure of relativistic electrons:

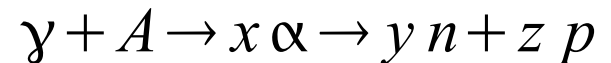
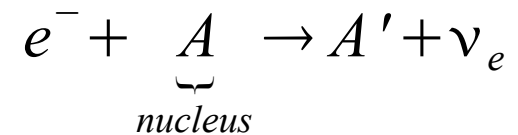
$$P = K (\rho Y_e)^{4/3}$$

Y_e : electrons per nucleon

- Polytrope! → Lecture 5
- Maximum mass:

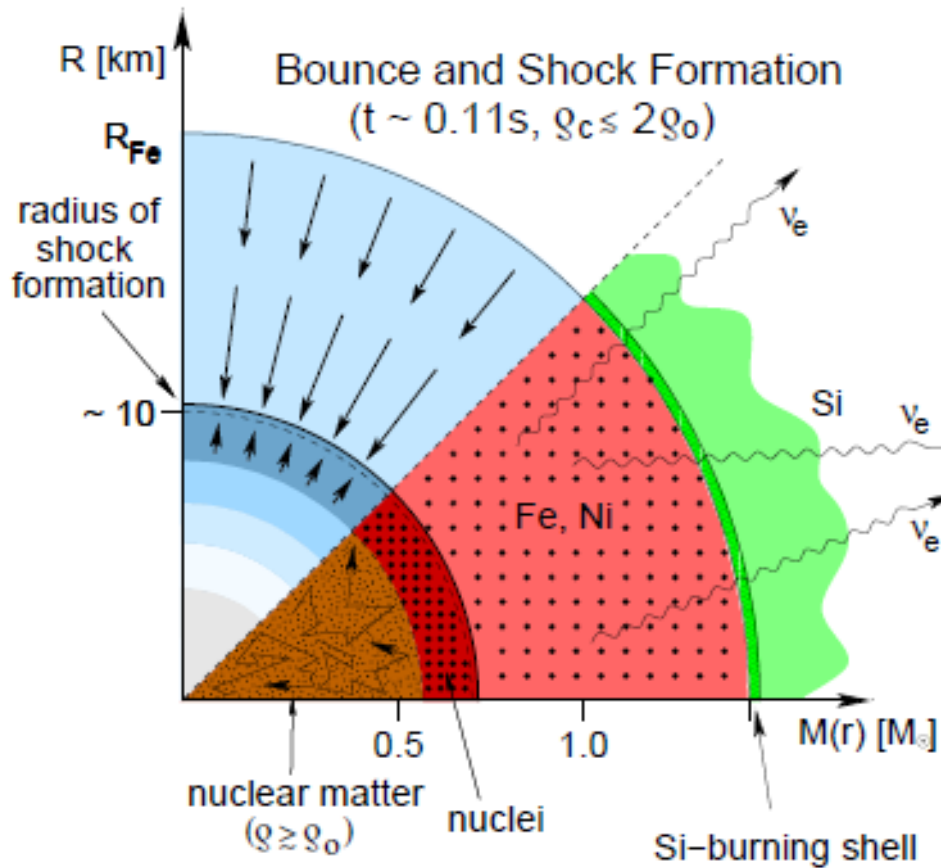
$$M_{\text{Ch}} \approx 5.84 M_{\odot} Y_e^2$$

- Core must contract, density and temperature go up, then:



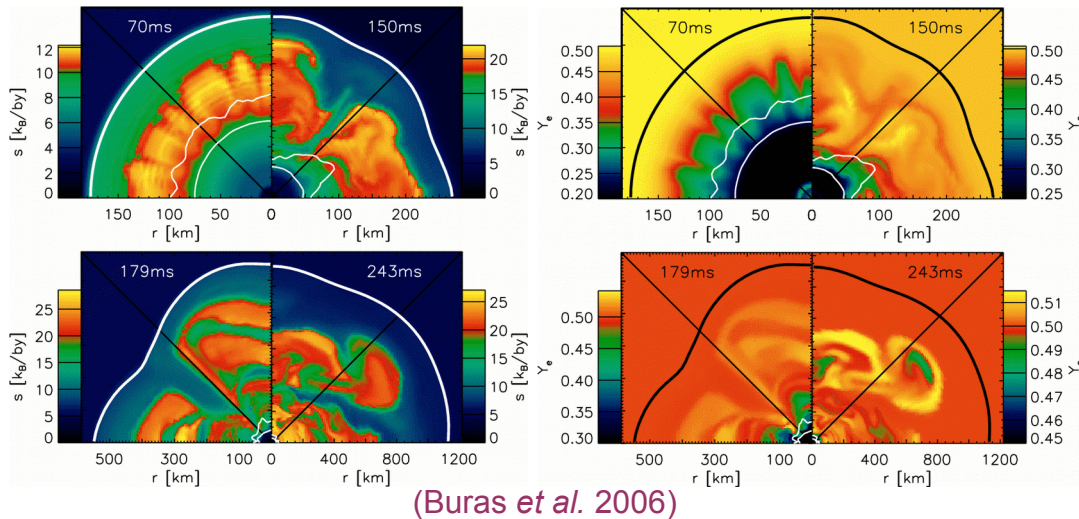
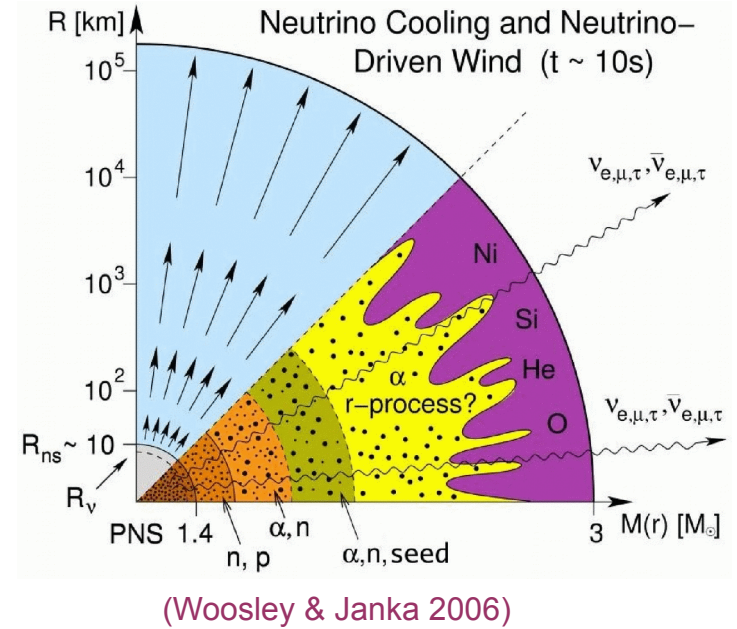
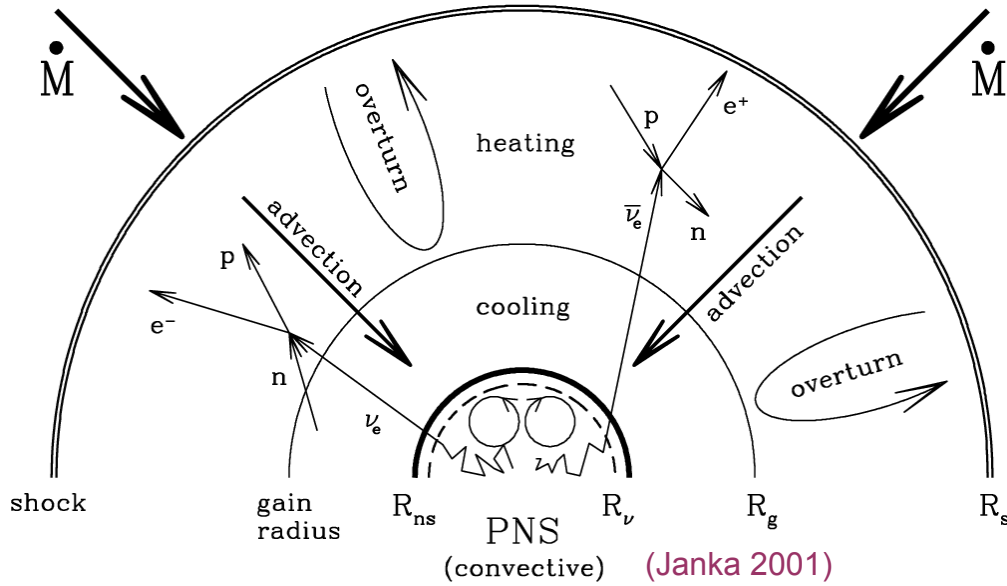
Pressure drain → collapse!

From Collapse to Explosion



- Nuclear forces become repulsive above $\sim 1.7 \times 10^{14} \text{g/cm}^3$.
- Collapse of inner core is stopped \rightarrow neutron star born.
- Rebounding neutron star crashes into outer shells, launches shock wave.
- Does the shock wave expel the envelope?
- No. Shock dies. Other mechanism have to do!

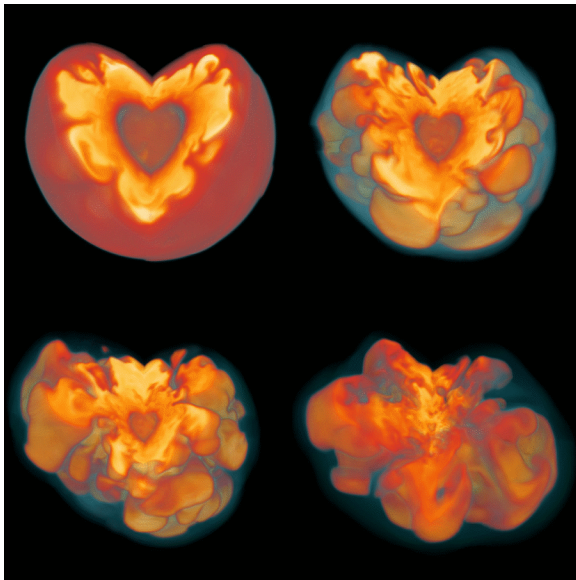
Core Collapse Supernovae



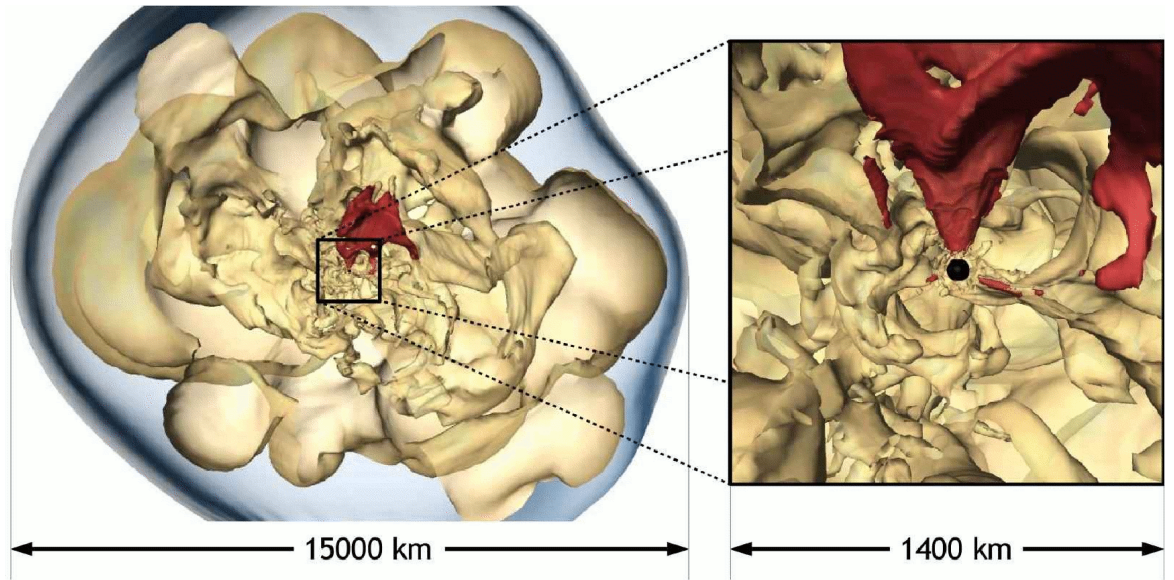
← Entropy and electron per baryon (Y_e) at different time snapshots in a core collapse supernova (simulation: equatorial band)

Core Collapse Supernovae – 3D

Cold inflow and hot outflow
in 3D simulations → similar to dipolar
flow pattern observed in 2D rotationally
symmetric simulations



(Scheck, Janka, *et al.* 2006)



(Janka *et al.* 2005)

The background features a semi-transparent teal overlay. In the center is a white triangular road sign with a thick white border and a white five-pointed star in the middle. To the left, a complex metal lattice structure, possibly a telescope or antenna, is visible. To the right, a tall, thin tower with a lattice structure is visible against a light sky.

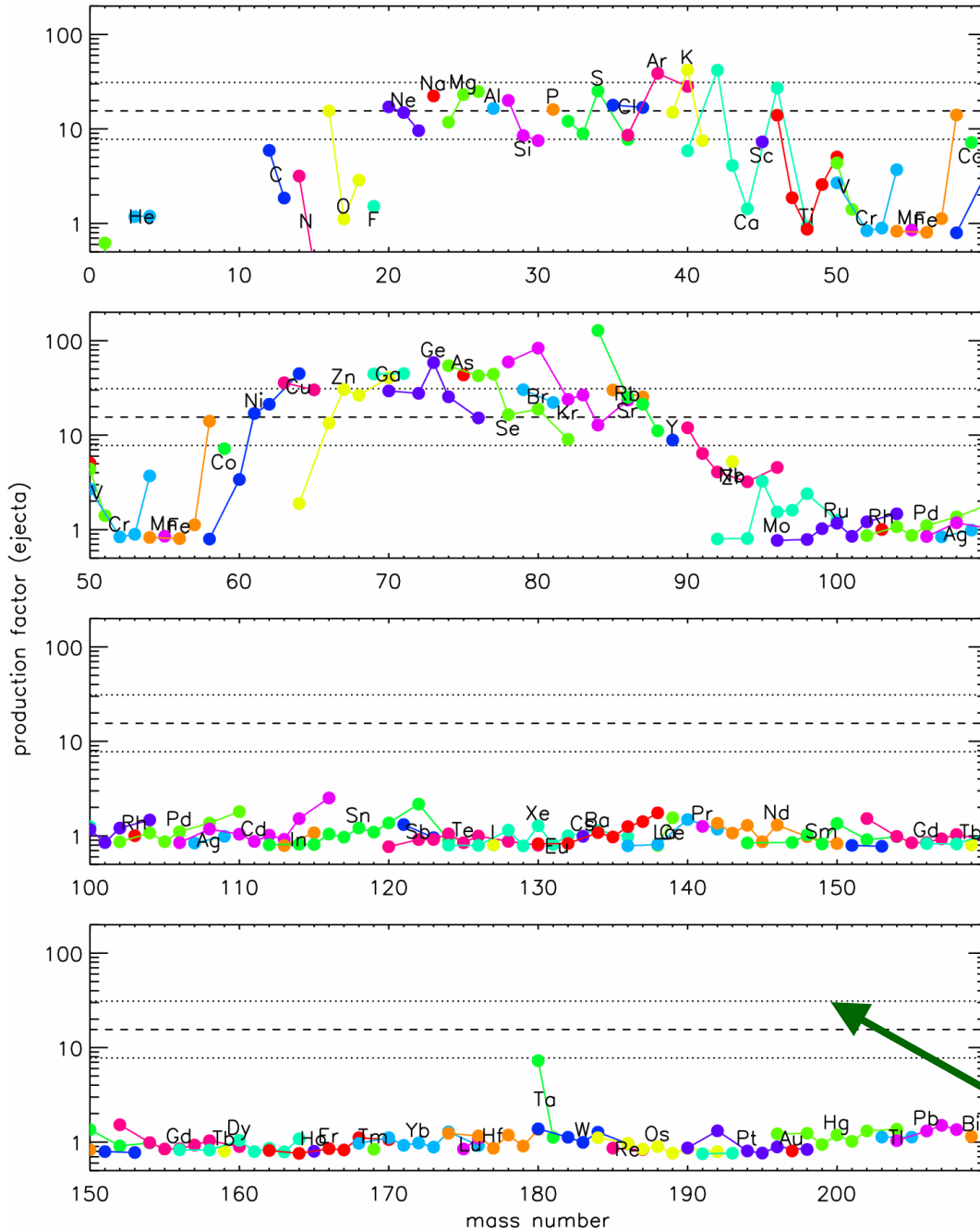
A First Look

Supernovae & Nucleosynthesis

(Massive Stars, Pop I)

25 M_⊙ star

Presupernova
production factors
relative to solar
composition



“band of acceptable
co-production”
defined by
 ^{16}O production
(\pm a factor 2)

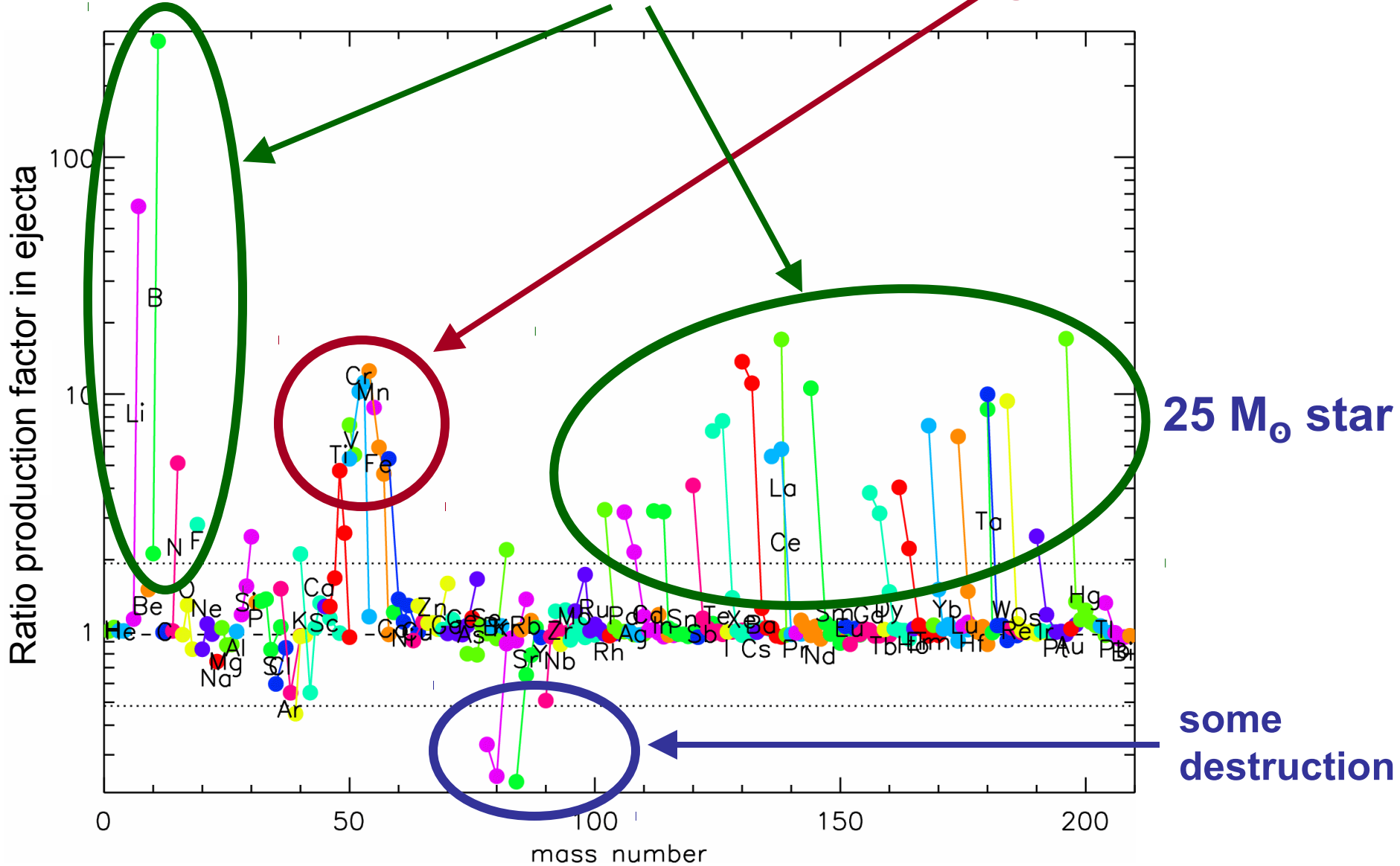
Explosive Nucleosynthesis

in supernovae from massive stars

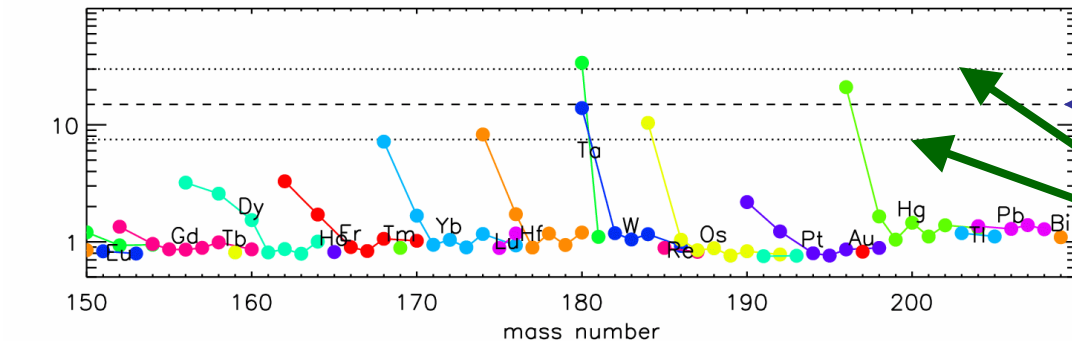
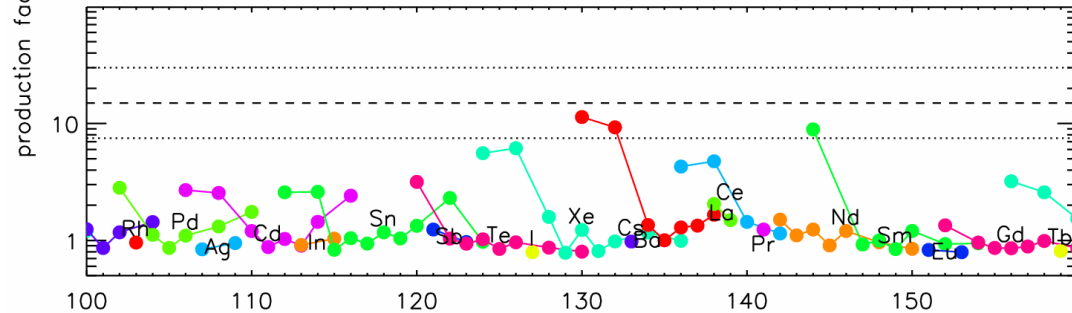
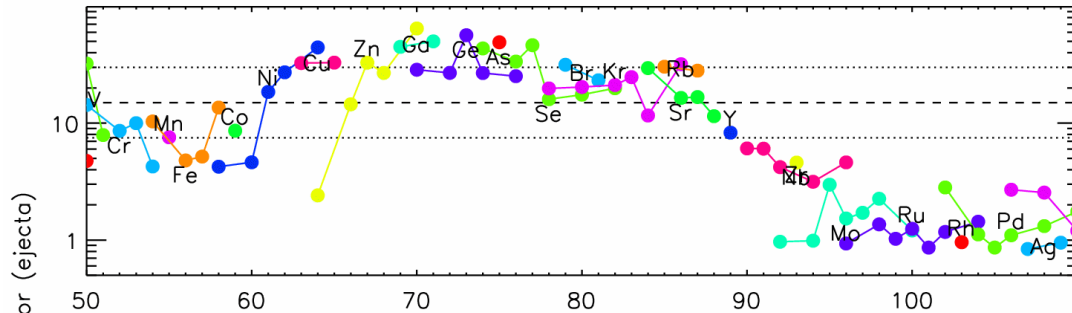
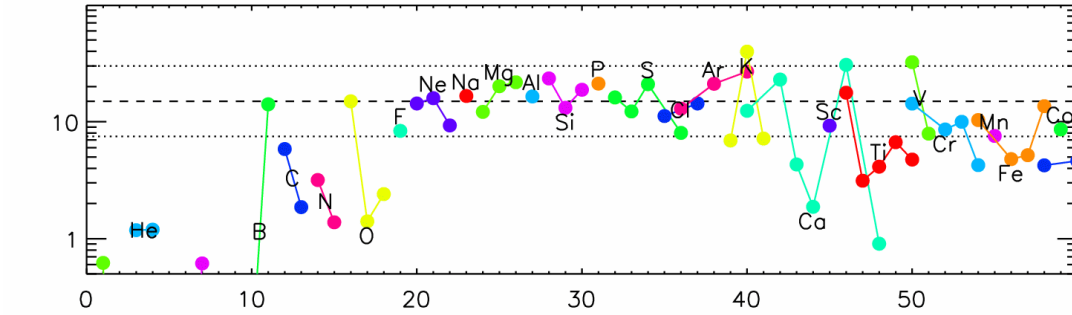
Fuel	Main Product	Secondary Product	T (10^9 K)	Time (s)	Main Reaction
Innermost ejecta	<i>r</i> -process <i>νp</i> -process	-	>10?	1	(n,γ), β ⁻
Si, O	⁵⁶ Ni	iron group	>4	0.1	(α,γ)
O	Si, S	Cl, Ar, K, Ca	3 - 4	1	¹⁶ O + ¹⁶ O
O, Ne	O, Mg, Ne	Na, Al, P	2 - 3	5	(γ,α)
		<i>p</i> -process ¹¹ B, ¹⁹ F, ¹³⁸ La, ¹⁸⁰ Ta	2 - 3	5	(γ,n)
		<i>ν</i> -process		5	(ν, ν'), (ν, e ⁻)

Explosive Nucleosynthesis contribution

→ production of p-process and iron group



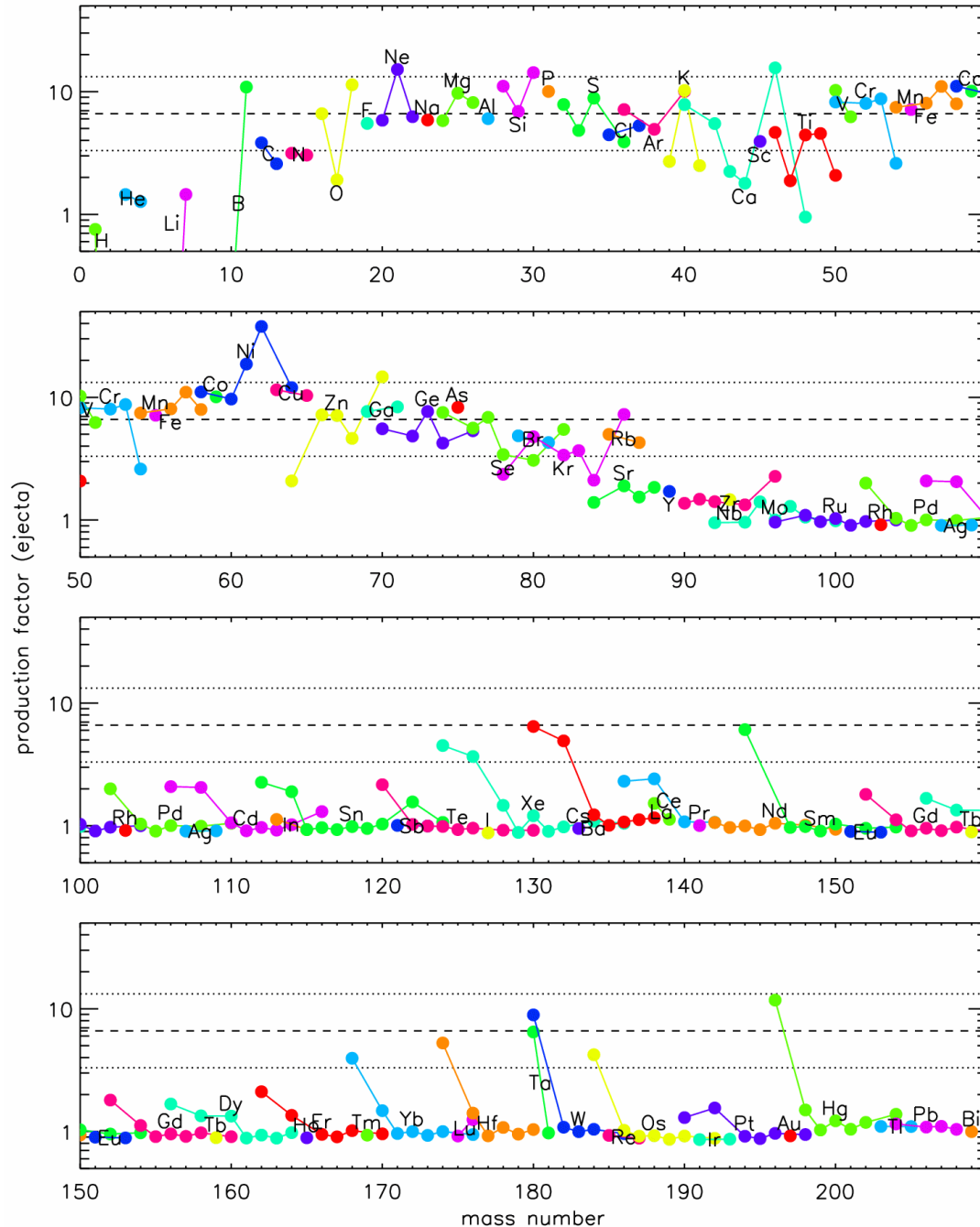
25 M_⊙ star



Production factors relative to solar composition

“band of acceptable co-production” defined by ^{16}O production (\pm a factor 2)

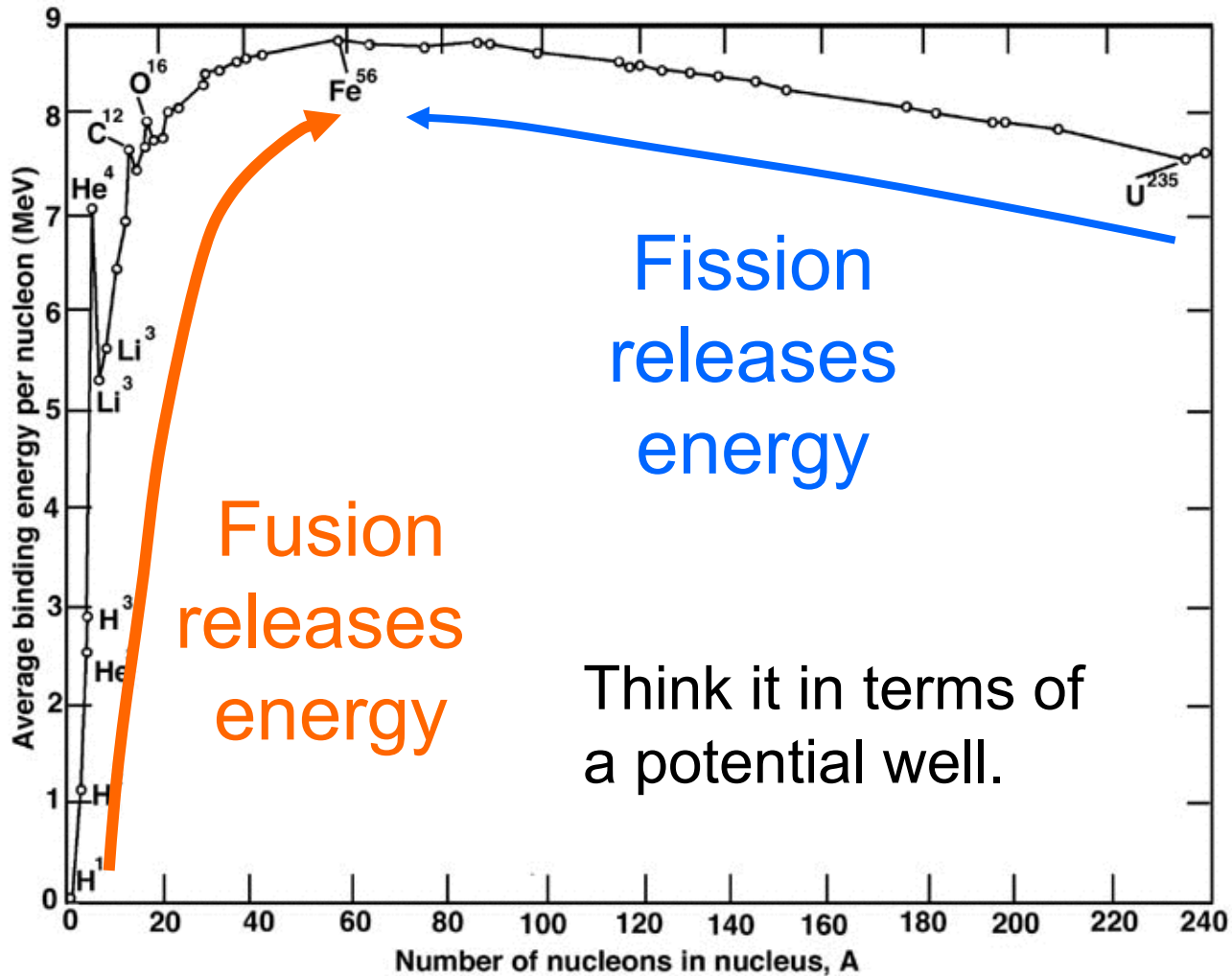
15 M_⊙ star



Production factors
relative to solar
composition

“band of acceptable
co-production”
defined by ^{16}O
production
(\pm a factor 2)

Binding Energy Curve



Beyond Fe

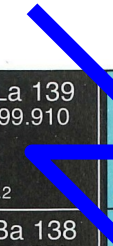
- Need to add energy to do fusion
- Nuclear reactions do not contribute anymore to the energy of a star
- High coulomb barrier prevents proton or alpha captures, because they are charged
- Have to add **neutrons** to make heavier elements!

Slow and Rapid neutron captures

During the *s* process:
 Time scale (n, γ) \gg time scale β -decay
 $N_n \sim 10^8$ n/cm 3

					La 132 91 h	La 134 6.67 m	La 135 19.4 h	La 136 9.9 m	La 137 $6 \cdot 10^4$ a	La 138 0.090	La 139 99.910								
					Ba 132 101	Ba 133 36.9 h	Ba 134 2.417	Ba 135 287 h	Ba 136 7.854	Ba 137 2.55 m	Ba 138 11.232								
Cs 124 30.8 s	Cs 125 45 m	Cs 126 1.6 m	Cs 127 6.25 h	Cs 128 3.8 m	Cs 129 32.06 h	Cs 130 3.46 m	Cs 131 29.21 m	Cs 132 6.47 d	Cs 133 100	Cs 134 2.06 a	Cs 135 53 m	Cs 136 $2 \cdot 10^6$ a	Cs 137 19 s	Cs 138 13.16 d	Cs 139 30.17 a				
Xe 123 2.08 h	Xe 124 0.0952	Xe 125 57 s	Xe 126 16.9 h	Xe 127 70 s	Xe 128 36.4 d	Xe 129 1.9102	Xe 130 8.89 d	Xe 131 26.4006	Xe 132 4.0710	Xe 133 11.9 d	Xe 134 21.2324	Xe 135 11.9 d	Xe 136 26.9086	Xe 137 2.2 d	Xe 138 5.25 d	Xe 139 10.4357	Xe 140 15.3 m	Xe 141 9.10 h	Xe 142 8.8573
I 122 3.6 m	I 123 13.2 h	I 124 4.15 d	I 125 59.41 d	I 126 13.11 d	I 127 100	I 128 135.0 m	I 129 1.57 $\cdot 10^7$ a	I 130 9.0 m	I 131 12.36 h	I 132 8.02 d	I 133 83 m	I 134 2.30 h	I 135 9 s	I 136 20.8 h	I 137 3.5 s	I 138 52.0 m	I 139 6.61 h	I 140 1678; 1458...	I 141 1678; 1458...
Te 121 16.8 d	Te 122 2.55	Te 123 0.89	Te 124 4.74	Te 125 57.4 d	Te 126 7.07	Te 127 18.84	Te 128 31.74	Te 129 9.35 h	Te 130 7.2 $\cdot 10^{24}$ a	Te 131 33.6 d	Te 132 69.6 m	Te 133 30 h	Te 134 25.0 m	Te 135 30 h	Te 136 25.0 m	Te 137 26.3 h	Te 138 55.4 m	Te 139 12.5 m	Te 140 4.8 m
Sb 120 16 d	Sb 121 15.9 m	Sb 122 4.2 m	Sb 123 2.70 d	Sb 124 20 m	Sb 125 1.6 m	Sb 126 60.3 d	Sb 127 2.77 a	Sb 128 ~ 11 s	Sb 129 19.0 m	Sb 130 12.4 d	Sb 131 10.6 m	Sb 132 9.0 h	Sb 133 17.7 m	Sb 134 4.40 h	Sb 135 39.5 s	Sb 136 6.3 m	Sb 137 23 m	Sb 138 4.7 m	Sb 139 2.8 m
Sn 119 3 d	Sn 120 8.59	Sn 121 27.0 h	Sn 122 4.63	Sn 123 40.1 m	Sn 124 129.2 d	Sn 125 5.79	Sn 126 9.5 m	Sn 127 9.64 d	Sn 128 3.7 s	Sn 129 3.17 s	Sn 130 4.4 m	Sn 131 4.4 m	Sn 132 4.4 m	Sn 133 4.4 m	Sn 134 4.4 m	Sn 135 4.4 m	Sn 136 4.4 m	Sn 137 4.4 m	Sn 138 4.4 m
In 118 4.4 m	In 119 5 s	In 120 18 m	In 121 2.3 m	In 122 47.3 s	In 123 3.1 s	In 124 3.8 m	In 125 23.1 s	In 126 10.8 s	In 127 10.3 s	In 128 1.5 s	In 129 47.8 s	In 130 5.98 s	In 131 3.7 s	In 132 3.17 s	In 133 3.17 s	In 134 3.17 s	In 135 3.17 s	In 136 3.17 s	In 137 3.17 s

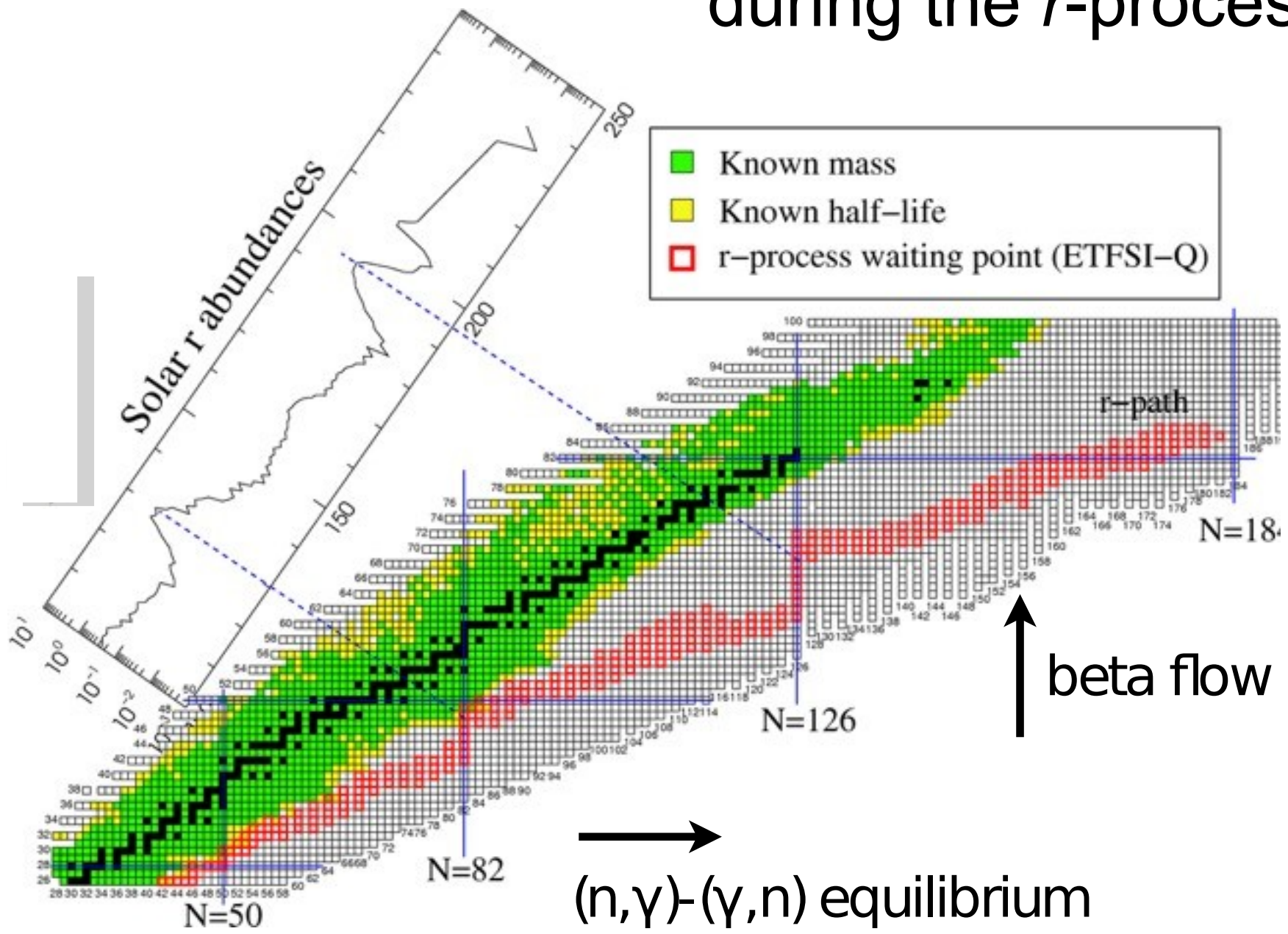
During the *r* process:
 Time scale (n, γ) \ll time scale β -decay
 $N_n > 10^{20}$ n/cm 3



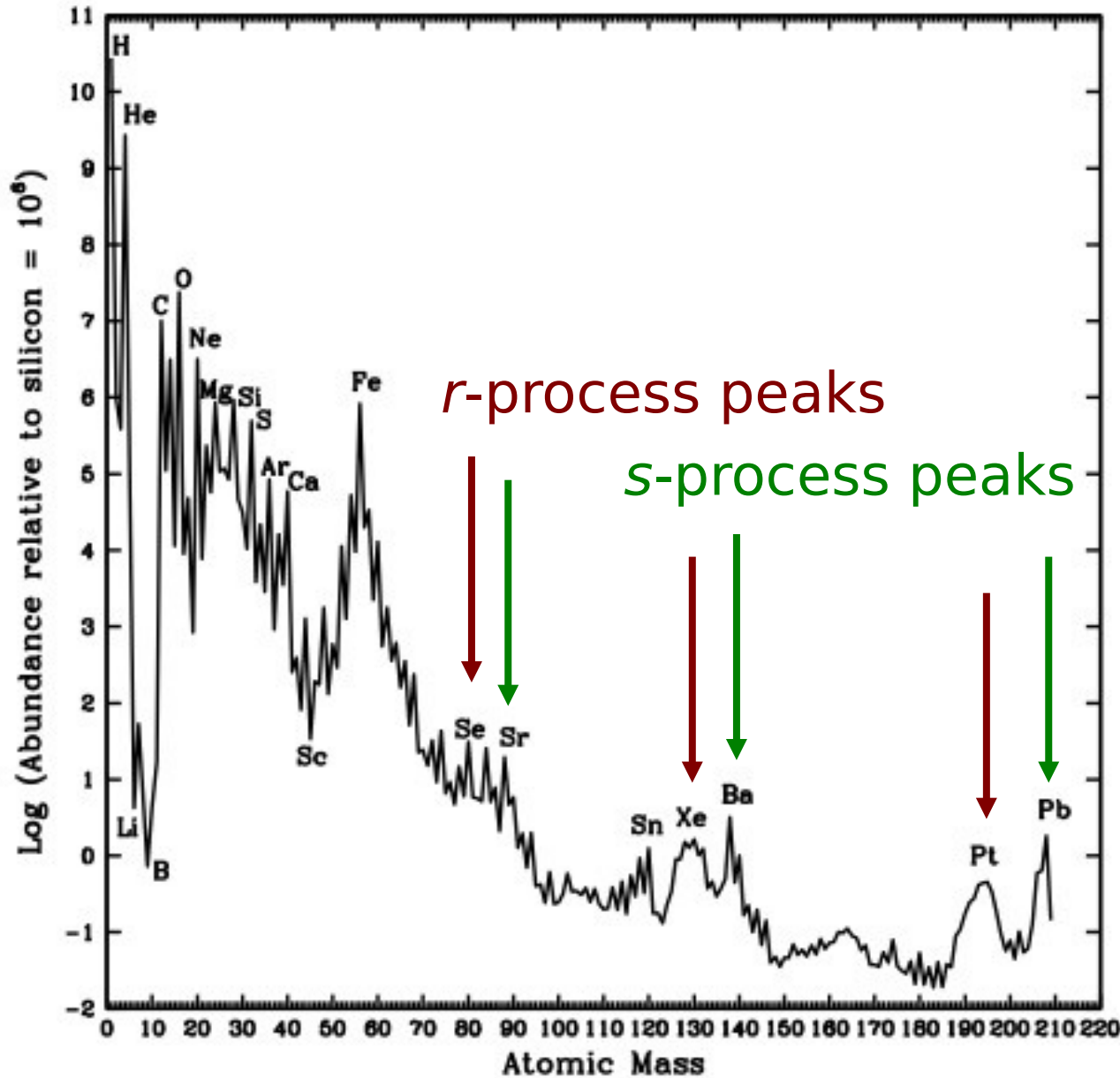
r-only s-only p-only

La 126	La 127	La 128	La 129	La 130	La 131	La 132	La 133	La 134	La 135	La 136	La 137	La 138	La 139
0 s	54 s	<1.4 m	5.18 m	11.6 m	8.7 m	24.3 m	4.8 h	3.91 h	19.4 h	9.9 m	6 · 10 ⁴ a	0.090	99.910
β ⁺ 256; 455...	β ⁺ 56; 25	β ⁺ 284; 659...	β ⁺ 284; 679...	β ⁺ 2.4; 2.7... γ 279; 111; 254; 457... g	β ⁺ 357; 551; 544; 908...	β ⁺ 1.4; 1.9... γ 108; 418; 365; 286...; g	β ⁺ 3.2; 3.7... γ 465; 567; 663; 265...; 1910...	β ⁺ 1.2 γ 279; 302; 290; 633; 618... g	β ⁺ 2.7... γ 605; (1555...)	β ⁺ 1.9... γ 481; (875; 588...)	no γ	β ⁻ 0.3 γ 1436; 789 σ 57	σ 9.2
Ba 125	Ba 126	Ba 127	Ba 128	Ba 129	Ba 130	Ba 131	Ba 132	Ba 133	Ba 134	Ba 135	Ba 136	Ba 137	Ba 138
3 m	3.5 m	1.9 s	12.7 m	2.13 h	2.20 h	0.106	0.101	36.9 h	2.417	28.7 h	6.592	2.55 m	11.232
β ⁺ 3.4 γ 78; 85...; 141; 181...	β ⁺ 234; 258; 241...	β ⁺ 2.4... γ 181; γ 234; 258; 241...	no β ⁺ γ 273...	β ⁺ 1.4... γ 182; 1459; 202...	β ⁺ 1.4... γ 214; 221; 129...	β ⁺ 1.4... γ 496; 124; 216...	β ⁺ 0.84 + 9.7	β ⁺ 2.0... γ 372; 411; 549...; g	β ⁺ 2.7... γ 605; (1555...)	β ⁺ 1.9... γ 481; (875; 588...)	β ⁺ 1.9... γ 481; (875; 588...)	β ⁺ 1.9... γ 481; (875; 588...)	β ⁺ 1.9... γ 481; (875; 588...)
Cs 124	Cs 125	Cs 126	Cs 127	Cs 128	Cs 129	Cs 130	Cs 131	Cs 132	Cs 133	Cs 134	Cs 135	Cs 136	Cs 137
3 s	30.8 s	45 m	1.6 m	6.25 h	3.8 m	32.06 h	9.69 d	6.47 d	100	2.06 a	53 m	13.16 d	30.17 a
β ⁺ 4.9... γ 354; 915; 493...	β ⁺ 2.1... γ 526; 112; 412...	β ⁺ 3.8... γ 389; 491; 925...	β ⁺ 0.7; 1.1... γ 411; 125; 462...; g	β ⁺ 2.9... γ 443; 527...	β ⁺ 2.9... γ 443; 527...	β ⁺ 2.0... γ 372; 411; 549...; g	no β ⁺ no γ	β ⁺ 0.8... γ 668; 465; 630... σ _{n,α} < 0.15	β ⁺ 2.7 + 27...	β ⁺ 0.7... γ 605; 796... g	β ⁻ 0.2 no γ	β ⁻ 0.3; 0.7... γ 819; 1048... σ 1.3	β ⁻ 0.5; 1.2 m; g σ 0.20 + 0.07
Xe 123	Xe 124	Xe 125	Xe 126	Xe 127	Xe 128	Xe 129	Xe 130	Xe 131	Xe 132	Xe 133	Xe 134	Xe 135	Xe 136
2.08 h	0.0952	57 s	16.9 h	70 s	1.9102	8.89 d	26.4006	4.0710	11.9 d	21.2324	26.9086	15.3 m	9.10 h
β ⁺ 1.5... γ 49; 178; 154...	β ⁺ 2.8 + 137	β ⁺ 1.8... γ 188; 243; 55...; σ _{n,α} < 0.1	β ⁺ 0.45 + 3.0	β ⁺ 2.03; 172; 375... σ _{n,α} < 0.01	β ⁺ 0.48 + 4.7	β ⁺ 0.48 + 4.7	β ⁺ 0.45 + 4.35	β ⁺ 0.45 + 4.35	β ⁺ 0.05 + 0...	β ⁻ 0.3... γ 81... σ 190	β ⁻ 0.2 γ 81... σ 190	β ⁻ 0.9... γ 250; 608...; σ 2.65 · 10 ⁻³	β ⁻ 0.9... γ 250; 608...; σ 2.65 · 10 ⁻³
I 122	I 123	I 124	I 125	I 126	I 127	I 128	I 129	I 130	I 131	I 132	I 133	I 134	I 135
3.6 m	13.2 h	4.15 d	59.41 d	13.11 d	100	35.0 m	1.57 · 10 ⁷ a	9.0 m	12.36 h	8.02 d	2.30 h	9 s	20.8 h
no β ⁺ γ 159... g	β ⁺ 2.1... γ 603; 1691; 723...	β ⁺ 2.1... γ 603; 1691; 723...	β ⁺ 0.7; 1.1... γ 411; 125; 462...; g	β ⁺ 0.9; 1.3... β ⁺ 1.1... γ 389; 666... σ 5960	β ⁺ 1.1... γ 389; 666... σ 5960	β ⁺ 1.1... γ 389; 666... σ 5960	β ⁻ 0.2 γ 40 e ⁻ ; g σ 20.7 + 10.3	β ⁻ 1.0; 1.8... γ 536; β ⁻ 2.5... γ 536... σ 18	β ⁻ 0.6; 0.8... γ 364; 637; 284...; g σ ~ 0.7	β ⁻ 2.1... γ 668; 465; 630... σ _{n,α} < 0.15	β ⁻ 1.2; 1.5... γ 530; 875... σ 84; 234	β ⁻ 1.5; 2.2... γ 1260; 1132; 1678; 1458... g; m	
Te 121	Te 122	Te 123	Te 124	Te 125	Te 126	Te 127	Te 128	Te 129	Te 130	Te 131	Te 132	Te 133	Te 134
16.8 d	2.55	0.89	4.74	57.4 d	7.07	18.84	31.74	33.6 d	69.6 m	30 h	25.0 m	26.3 h	55.4 m
β ⁺ 0.4 + 3	β ⁺ 0.4 + 3	β ⁺ 0.4 + 3	β ⁺ 0.4 + 3	β ⁺ 0.7... γ (58...)	β ⁺ 0.7... γ (58...)	β ⁺ 0.7... γ (58...)	β ⁺ 0.7... γ (58...)	β ⁻ 1.5... γ 28; β ⁻ 1.6... γ 696...	β ⁻ 1.5... γ 28; β ⁻ 1.6... γ 696...	β ⁻ 0.5; γ 774; β ⁻ 2.1... γ 150; 452...	β ⁻ 0.2 γ 228; 50... g	β ⁻ 0.7; 3.3... γ 913; 648...; g γ 334	β ⁻ 2.2; 2.7... γ 312; 408; 1333...; g
Sb 120	Sb 121	Sb 122	Sb 123	Sb 124	Sb 125	Sb 126	Sb 127	Sb 128	Sb 129	Sb 130	Sb 131	Sb 132	Sb 133
16 d	15.9 m	57.21	42.79	20 m	1.6 m	60.3 d	2.77 a	3.85 d	9.0 h	17.7 m	4.40 h	23 m	2.5 m
β ⁺ 1.7... γ 1171...	β ⁺ 1.7... γ 1171...	β ⁺ 1.7... γ 1171...	β ⁺ 1.7... γ 1171...	β ⁺ 1.7... γ 1171...	β ⁺ 0.3; 0.6... γ 428; 601; 636; 463... g; m	β ⁺ 0.3; 0.6... γ 428; 601; 636; 463... g; m	β ⁻ 0.9; 1.5... γ 686; 473; 784... g; m	β ⁻ 0.9; 1.5... γ 686; 473; 784... g; m	β ⁻ 0.9; 1.5... γ 686; 473; 784... g; m	β ⁻ 1.3; 3.0... γ 943; 933; 642... g; m	β ⁻ 1.3; 3.0... γ 943; 933; 642... g; m	β ⁻ 1.3; 3.0... γ 943; 933; 642... g; m	β ⁻ 1.2; 2.4... γ 1096; 818; 2755; 837... g; m
Sn 119	Sn 120	Sn 121	Sn 122	Sn 123	Sn 124	Sn 125	Sn 126	Sn 127	Sn 128	Sn 129	Sn 130	Sn 131	Sn 132
3 d	8.59	27.0 h	4.63	40.1 m	129.2 d	5.79	9.5 m	9.64 d	2.345 · 10 ⁵ a	4.1 m	2.1 h	6.3 m	39.7 s
β ⁺ 0.35 γ 87	β ⁺ 0.35 γ 87	β ⁺ 0.35 γ 87	β ⁺ 0.35 γ 87	β ⁺ 1.3... γ (1089...)	β ⁺ 1.3... γ (1089...)	β ⁺ 1.3... γ (1089...)	β ⁻ 2.0... 823; 916...	β ⁻ 2.0... 823; 916...	β ⁻ 0.3 γ 88; 64; 87... m	β ⁻ 2.7 γ 491	β ⁻ 2.7 γ 491	β ⁻ 2.7 γ 491	β ⁻ 1.8... γ 341; 86; 899; 247; 993... g
In 118	In 119	In 120	In 121	In 122	In 123	In 124	In 125	In 126	In 127	In 128	In 129	In 130	In 131
4.4 m	5 s	18 m	2.3 m	47.3 s	46.2 s	3.1 s	3.8 m	23.1 s	10.8 s	10.3 s	1.5 s	47.8 s	5.98 s
β ⁻ 1.3; β ⁻ 4.2	β ⁻ 2.7... γ 1065;	β ⁻ 2.1 γ 22; 42...; β ⁻ 5.3	β ⁻ 3.7 γ 37	β ⁻ 0.6; 2.3... γ 603; 1691...; σ 17	β ⁻ 0.6; 2.3... γ 603; 1691...; σ 17	β ⁻ 0.6; 2.3... γ 603; 1691...; σ 17	β ⁻ 4.5... β ⁻ 3.3; 3.4	β ⁻ 4.1; 4.3...	β ⁻ 4.5... β ⁻ 3.9;	β ⁻ 5.3; β ⁻ 5.5; 7.6...;	β ⁻ 5.4; β ⁻ 5.7; β ⁻ 5.7; β ⁻ 5.7; β ⁻ 5.7;	β ⁻ 5.4; β ⁻ 5.7; β ⁻ 5.7; β ⁻ 5.7;	β ⁻ 5.4; β ⁻ 5.7; β ⁻ 5.7; β ⁻ 5.7;

Unstable magic nuclei act as “waiting points” during the r -process



The Solar System abundances



The *r*-process peaks correspond to *unstable nuclei* with $N=50,82,126$

The *s*-process peaks correspond to *stable nuclei* with **Neutron Magic Numbers** $N=50,82,126$

Abundance relative to 10^6 silicon

