Stars and Bytes

Nuclear Astrophysics as Seen by an Stellar Modeler

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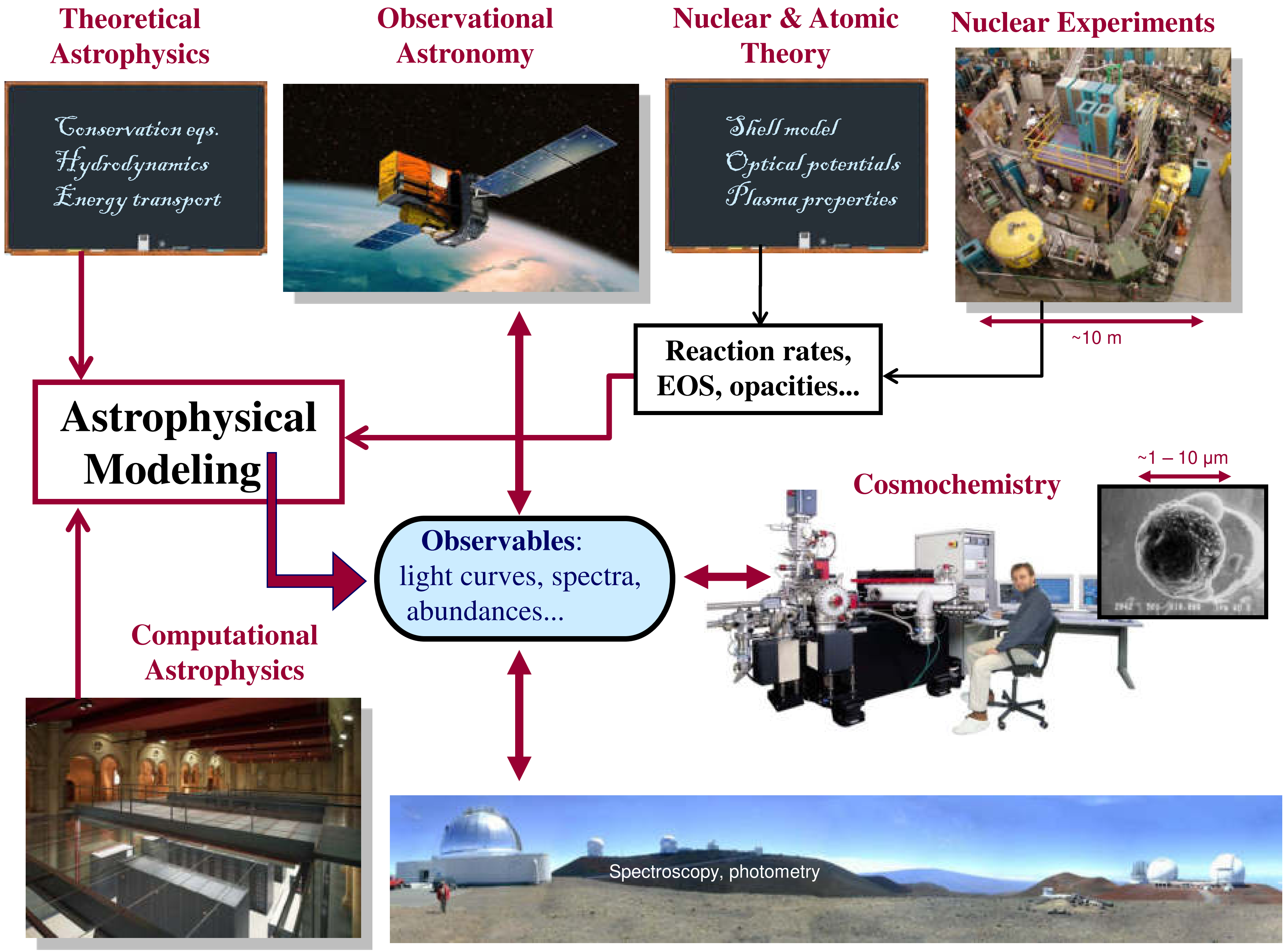

Theoretical Astrophysics
Conservation eqs.
Hydrodynamics
Energy transport
Observational Astronomy
Nuclear & Atomic Theory
Shell model
Optical potentials
Plasma properties
Nuclear Experiments
~10 m
Reaction rates, EOS, opacities...
Astrophysical Modeling
Cosmochemistry
~1 – 10 μm
Observables: light curves, spectra, abundances...
Computational Astrophysics
Spectroscopy, photometry


D. Mendeleev

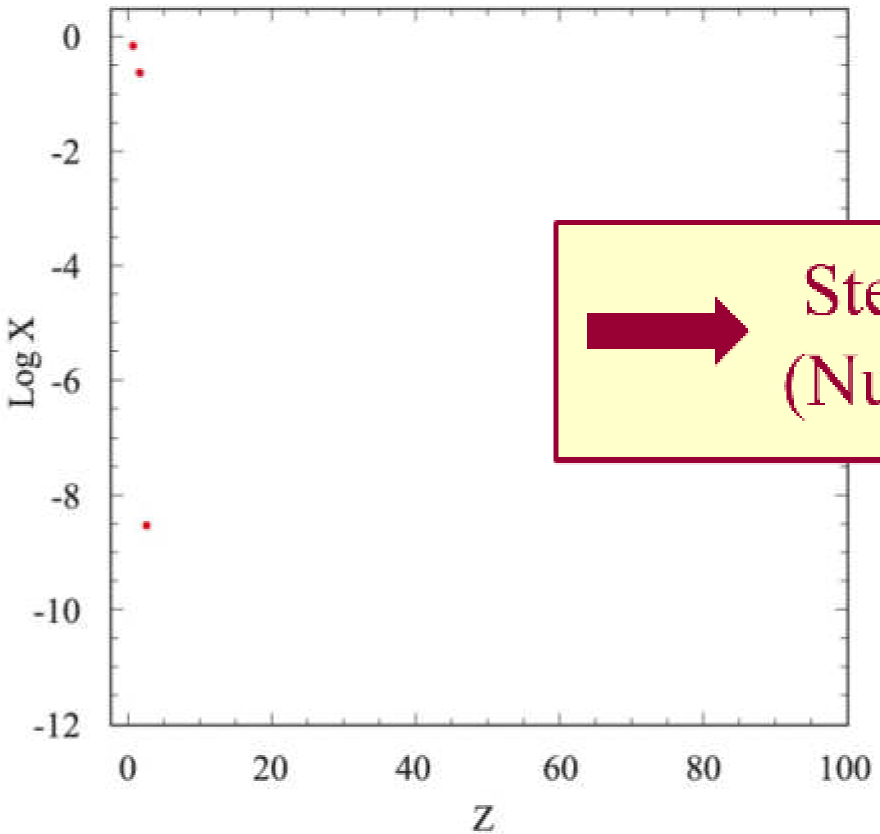
–																															–	–
H 1.008																															–	He 4
Li 7.03																										Be 9.1	B 11	C 12	N 14.04	O 16.00	Fl 19	Ne 20
Na 23.05																										Mg 24.36	Al 27.1	Si 28.4	P 31.0	S 32.06	Cl 35.45	A 39.9
K 39.15	Ca 40.1																Sc 44.1	Ti 48.1	V 51.2	Cr 52.1	Mn 55.0	Fe 55.9	Co 59.0	Ni 58.7	Cu 63.6	Zn 65.4	Ga 70	Ge 72	As 75.0	Se 79.1	Br 79.96	Kr 81.12
Rb 85.4	Sr 87.6																Y 89.0	Zr 90.7	Nb 94	Mo 96.0	–	Ru 101.7	Rh 103.0	Pd 106	Ag 107.93	Cd 112.4	Jn 114	Sn 118.5	Sb 120	Te 127.6	J 126.95	X 128
Cs 133	Ba 137.4	La 138	Ce 140	Nd 143.6	Pr 140.5	–	–	Sa 150.3	Eu 151.79	Gd 156	Tb 160	Ho 162	Er 166	–	Tu 171	Yb 173.0	–	–	Ta 183	W 184	–	Os 191	Ir 193.0	Pt 194.8	Au 197.2	Hg 200.3	Tl 204.1	Pb 206.9	Bi 208.5	–	–	–
–	Ra 225	Laα ?	Th 232.5	–	–	–	–	–	U 239.5	–	–	–	–	–	Ac ?	–	–	–	–	–	–	–	–	–	–	–	–	Pbα ?	Biα ?	Teα ?	–	–

Werner, A. (1905), Berichte der Deutschen Chemischen Gesellschaft 38, 914-21

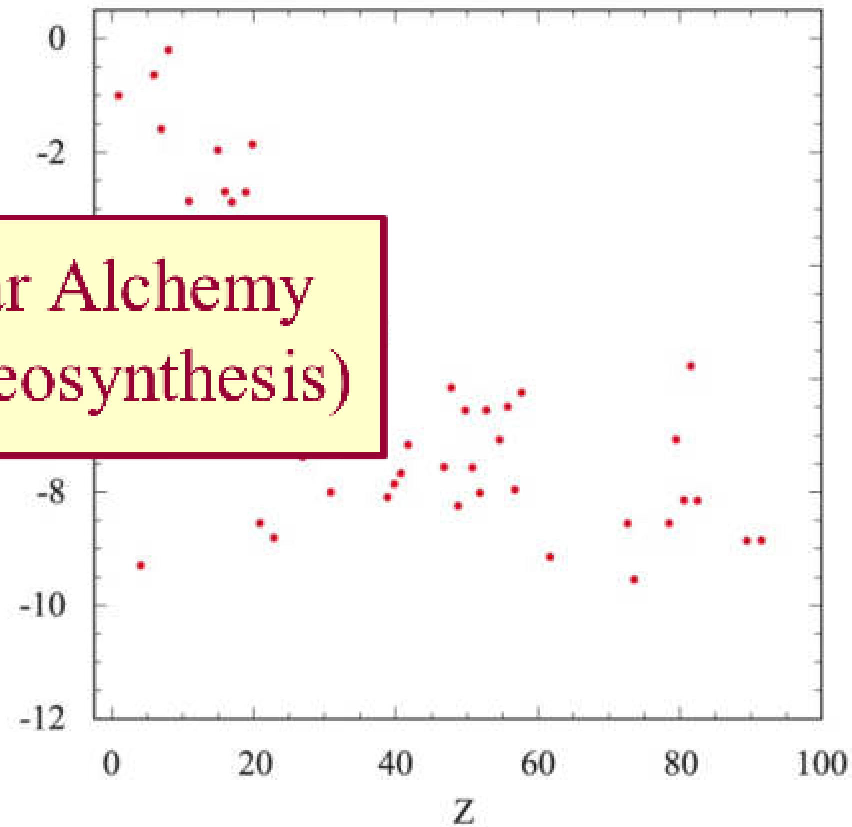
Stars as Nuclear Furnaces

Elemental composition

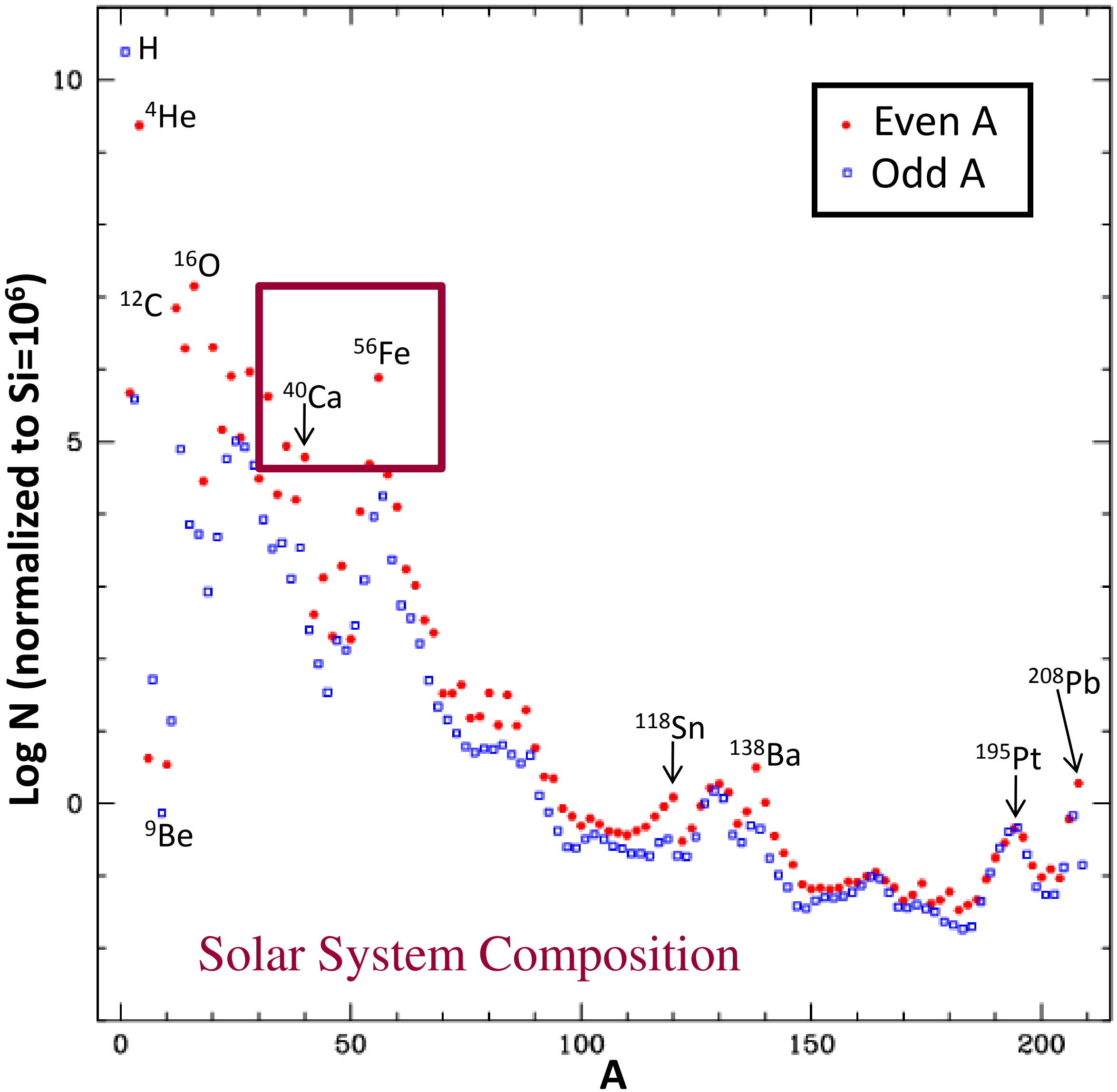
Early universe



A human being



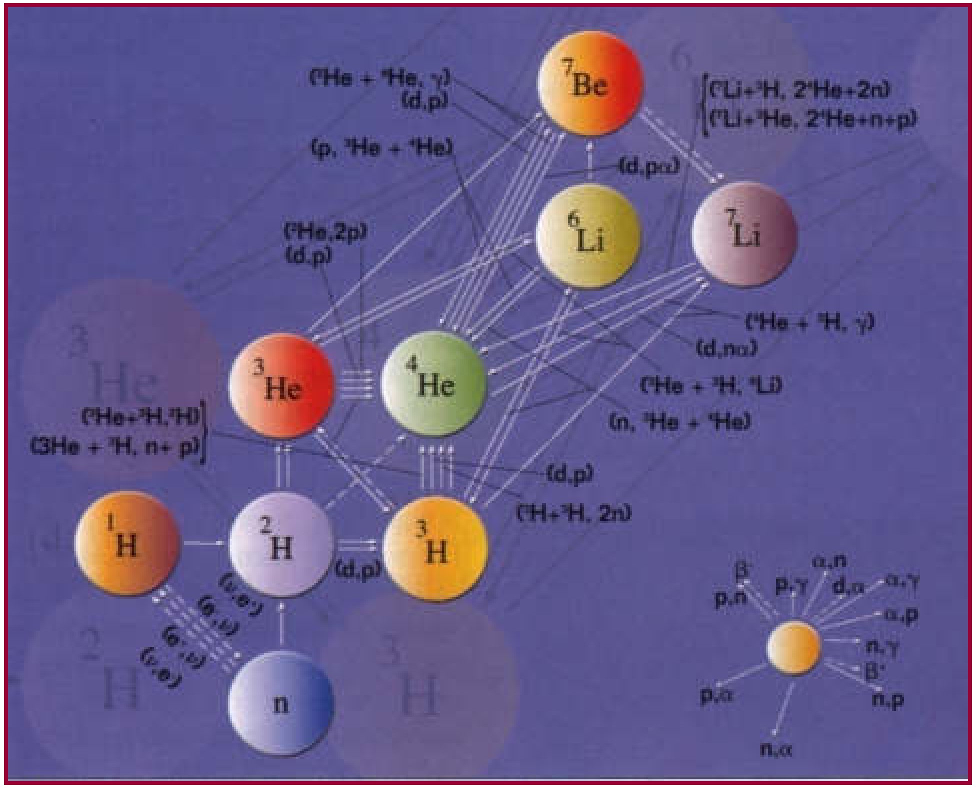
Stellar Alchemy
(Nucleosynthesis)



TALKS by **C. Sneden**, and **A. Tumino**, later today

JJ & Iliadis (2011), ROP

Primordial Nucleosynthesis: ~ some **minutes** after the Big Bang...



TAKE AWAY BOX (I)

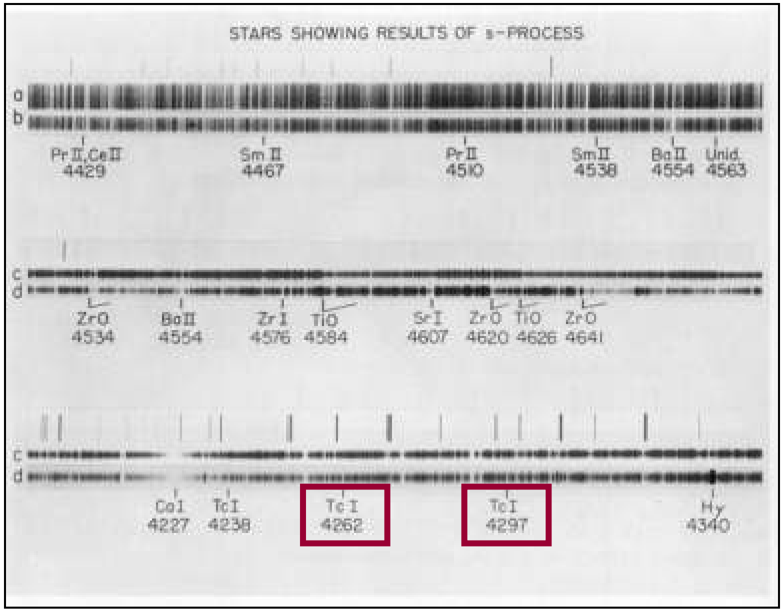
Big Bang Nucleosynthesis only produced:

75% **H**
25% **^{4}He**
+ traces of **D**, **^{3}He**, **^{7}Li** **($\leq 10^{-7}$ %!)**

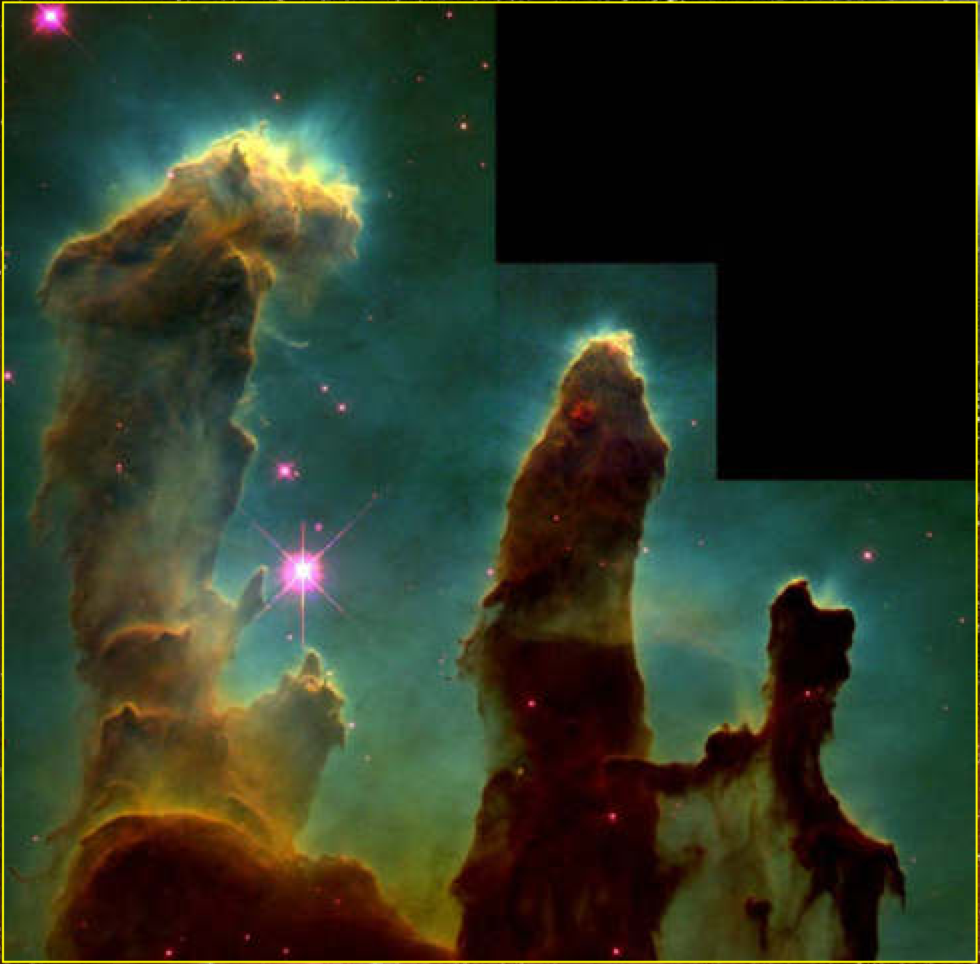
This composition remained almost "frozen" during several **Myr,** until the first **stars formed** and started to **pollute** the Cosmos

The idea that **elements** could be **synthesized in stellar environments** was developed in the mid 1940s by **F. Hoyle** (following early work on 1920/30s by Bethe, Gamow, von Weizsäcker, and others…)

P.W. Merrill detected ***technecium*** (1952) in several S stars → **Tc** has no stable isotopes (longest lived: τ ~ 4 Myr): **Stellar nucleosynthesis**



Star-Forming Regions
(*aka* Stellar Nurseries)



Structures at **equilibrium**:

Gravity ⟷ **Pressure** (Temperature)

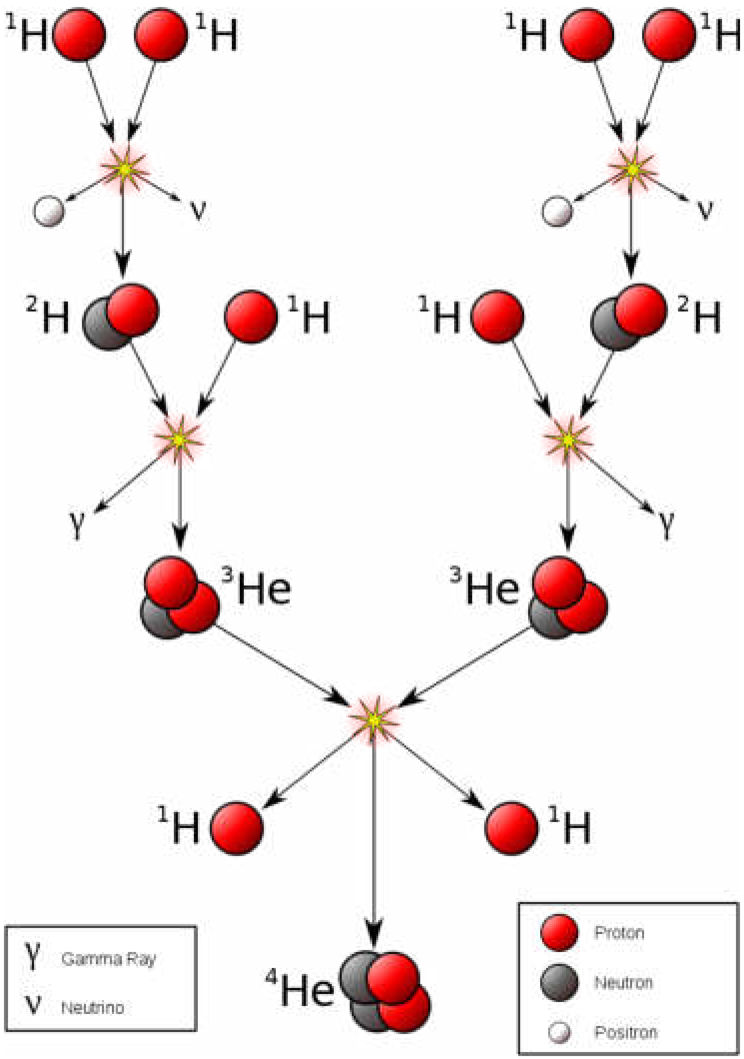
↑ Thermonuclear fusion reactions

Only objects with $\mathbf{M > M_{min,\ star}}$ become "**stars**" (i.e., powered by nuclear reactions)

Planets ⟷ **Stars**


Our Sun releases about 10^{26} W

Our **Sun** (and any star, in general) is powered by **nuclear reactions**



4 H → ^{4}He; 26.7 MeV = **4.3×10^{-12} J** [0.0000000000043 J]

This suggests than 1 nuclear reaction releases only a tiny amount of energy

Therefore, many (**MANY!**) nuclear reactions should take place simultaneously to account for **10^{26} J/s** !
[1 000 000 000 000 000 000 000 000 000 J per second]

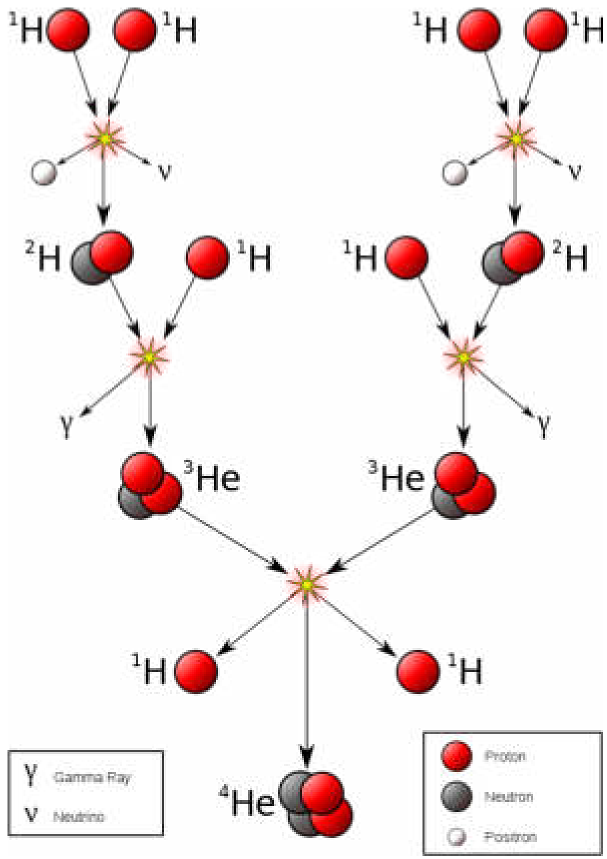
ALL STARS, at the beginning of their cosmic journey, are powered by **H fusion** reactions [**EXERCISE 1.** Find out that our Sun burns about **600 million tons of H per second**!]

An ultra-”shallow” image of the Sun...

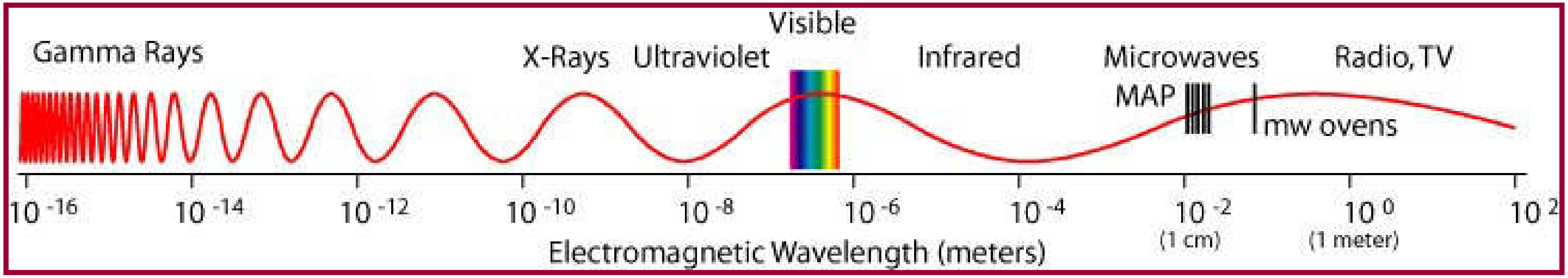
But why **not** all the H in the Sun undergoes nuclear fusion at the same time (i.e., why the Sun does not blow up?)

Quantum tunneling!

TALK by **A. Tumino**, later today

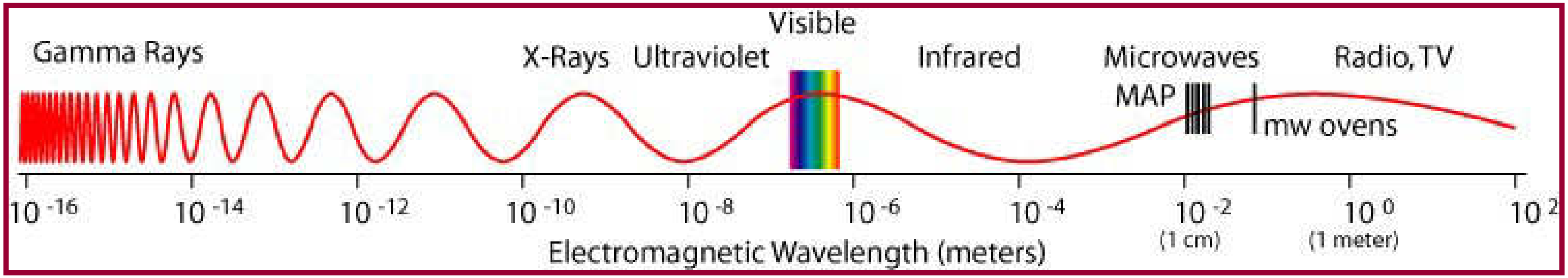


Stars produce **γ-ray photons**

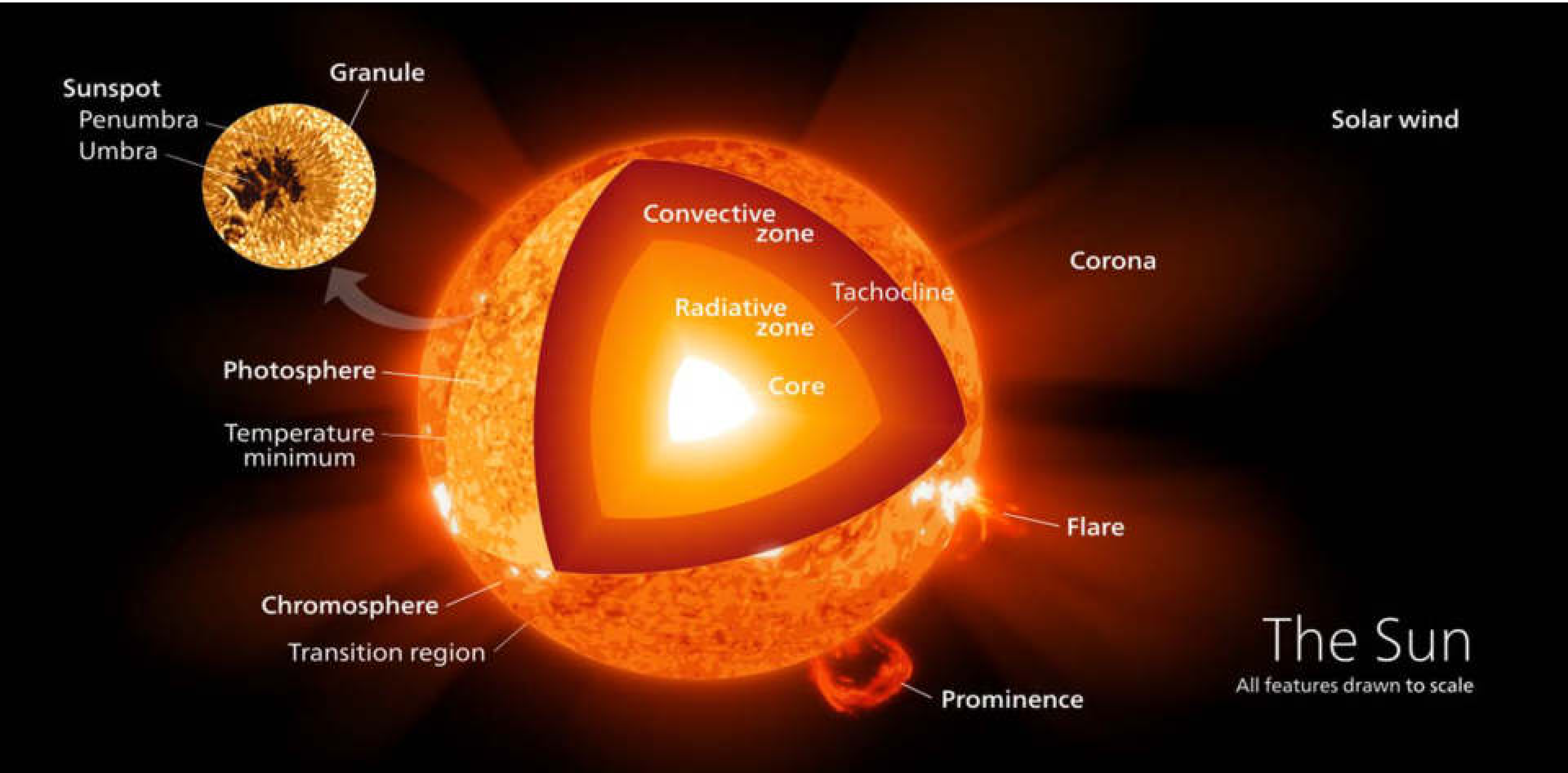


Stars produce **γ-ray photons**

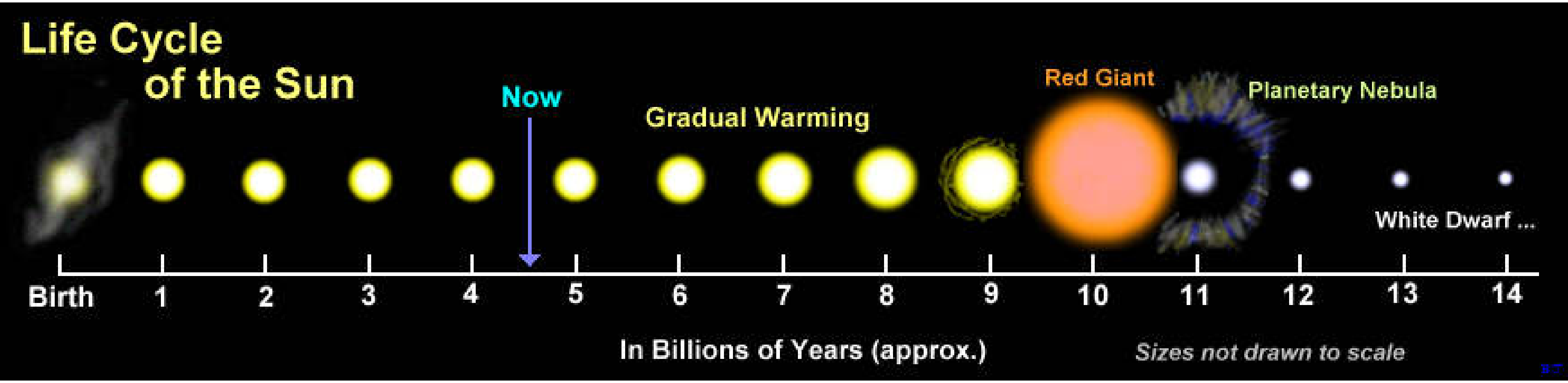
In the **Sun**, during their trip towards the photosphere (**$\tau \sim 10^4$ - 10^6 yr**), these γ-ray photons lose energy and emerge as **visible photons**



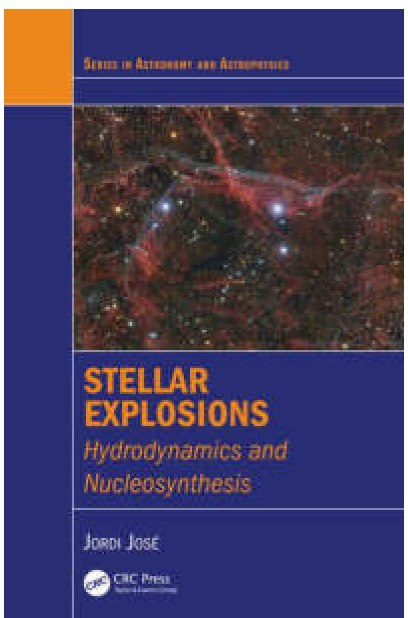
At the Sun's **core**, the hydrogen content has decreased from X = 0.71 → 0.34 (Y = 0.27 → 0.64), according to the **standard solar model** [at the **surface**, diffusive settling has increased the hydrogen mass fraction by 0.02 or so] → these compositional changes are responsible for a 40% increase in L_{surf} and 10% in R.

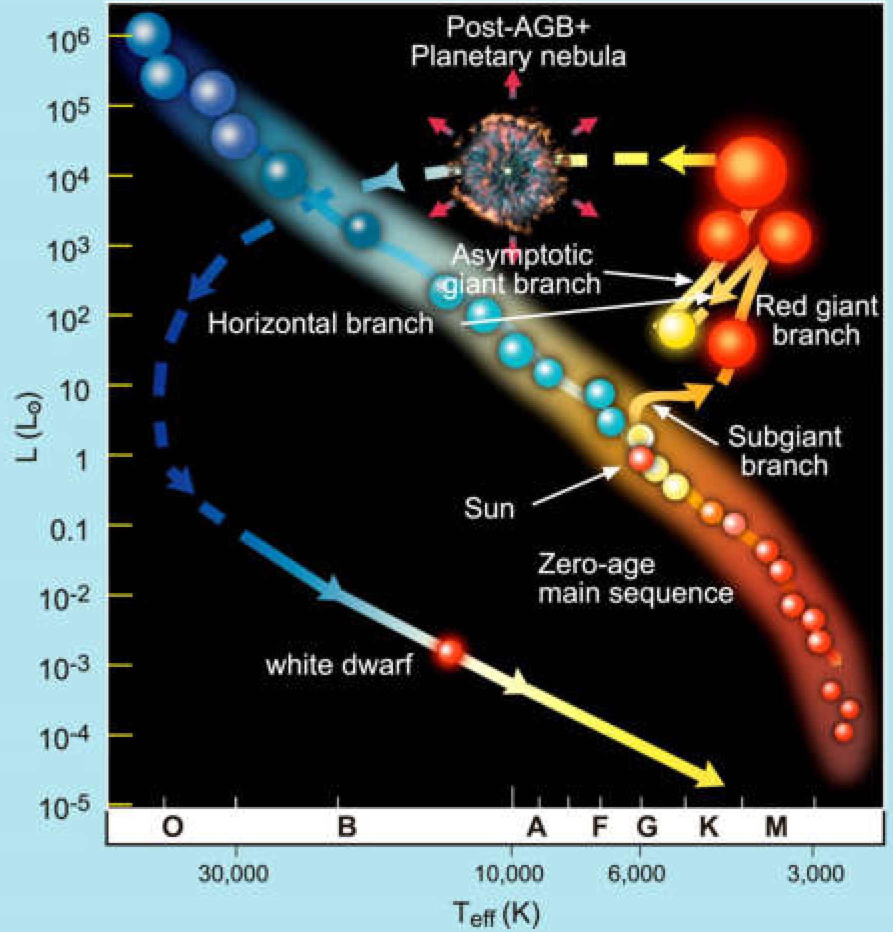


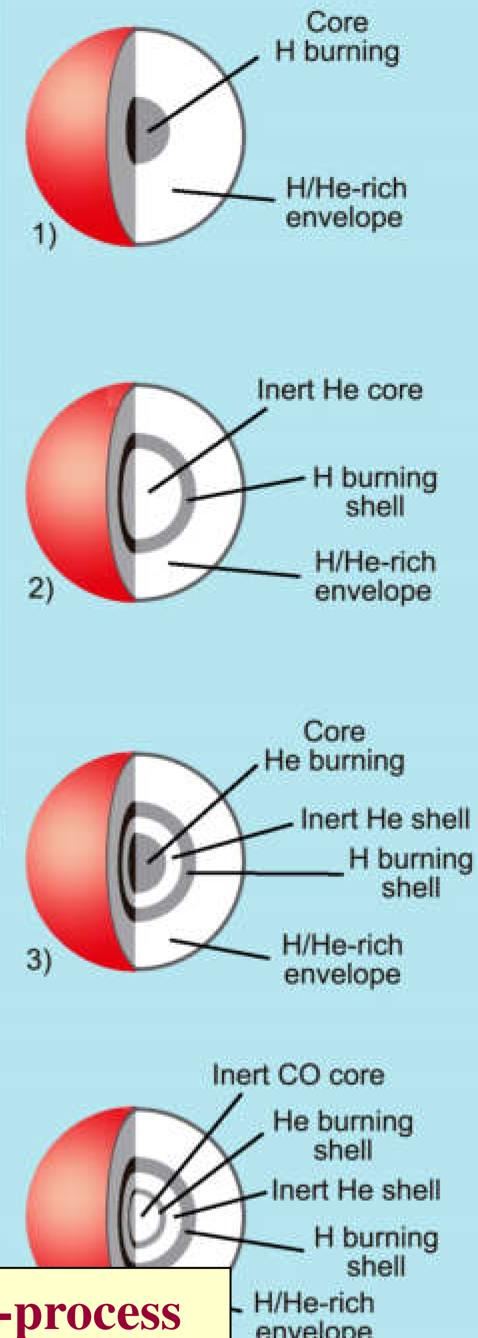
The Sun will only undergo **two sequential fusion stages**: **H** and **He fusion** → (CO-rich) **white dwarf star**



In the process, however, the **Earth will be destroyed** (in about **4 – 5 Gyr** from now; no rush!)





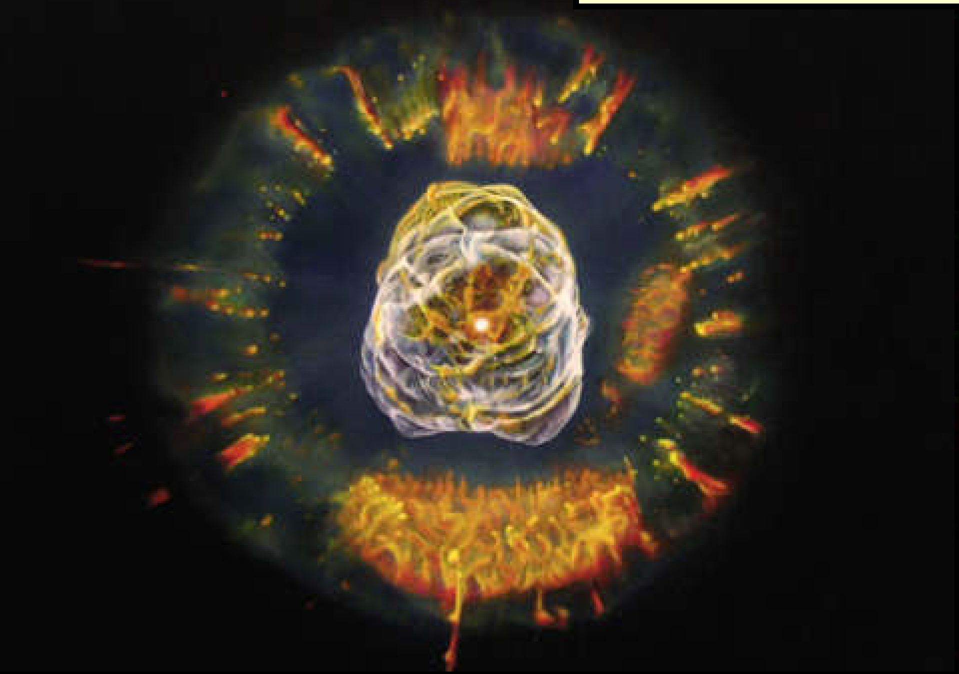


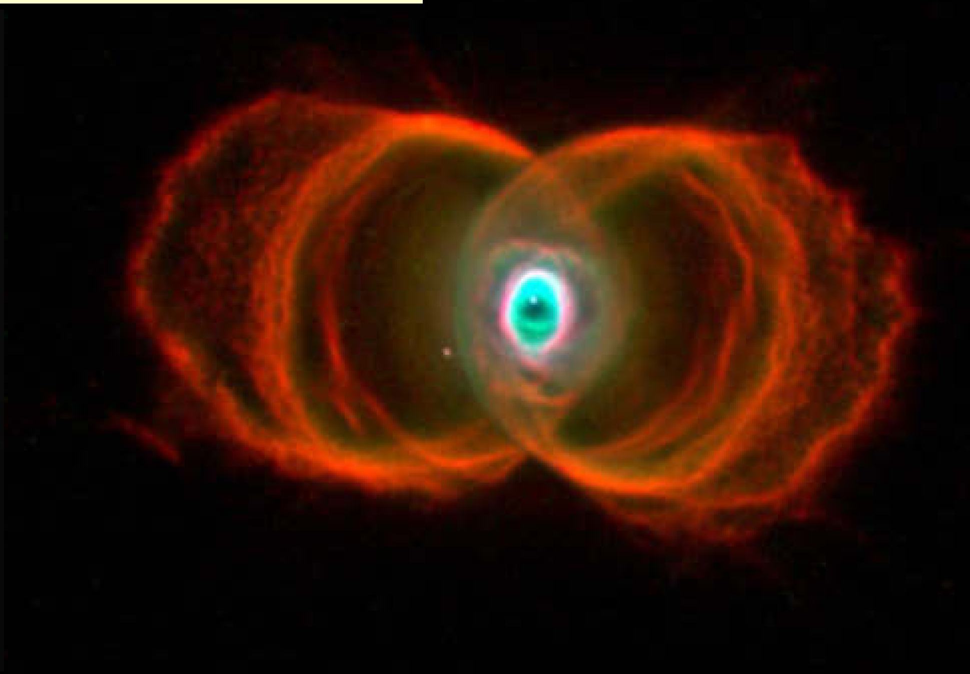
1. Main sequence star
2. Red giant star
3. Horizontal branch star
4. AGB star

JJ (2016)

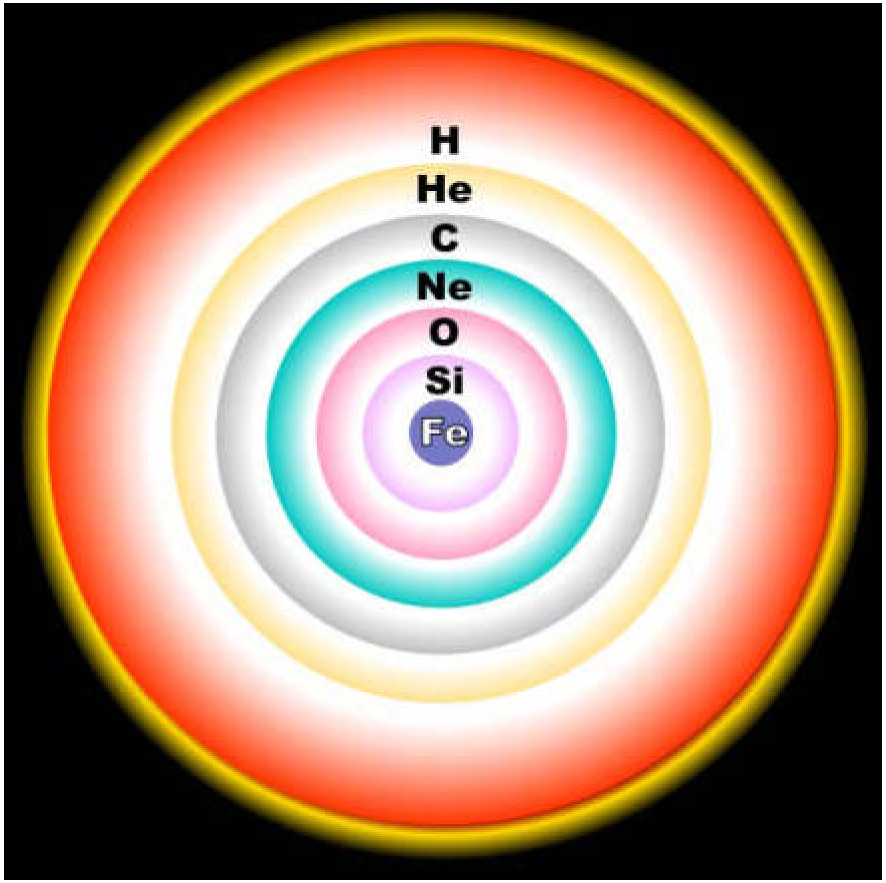
Site of s-process

Examples of Planetary Nebulae



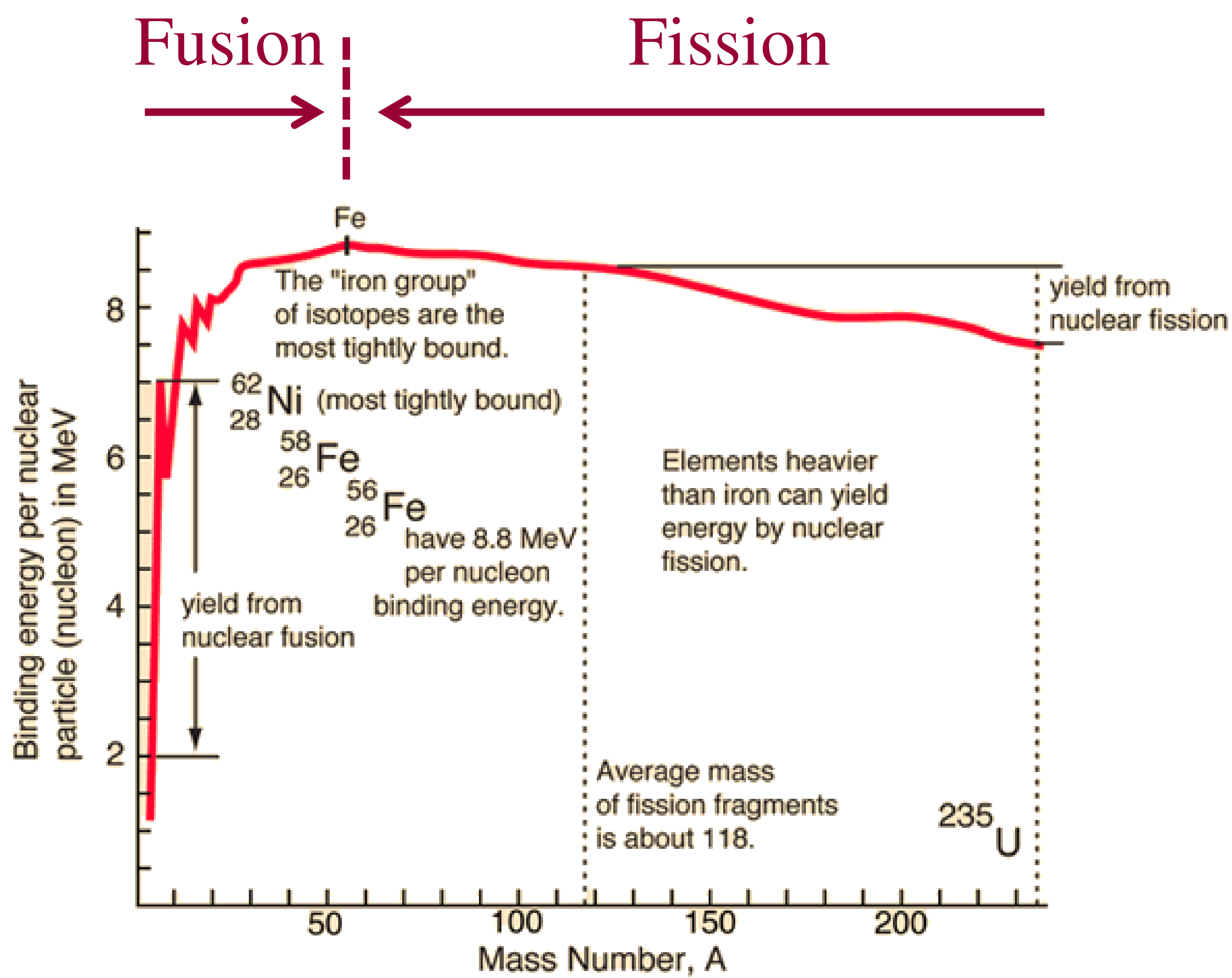


Only massive stars ($M > 10\ M_{Sun}$) undergo the full sequence of fusion stages: H → He → C → Ne → O → Si (which yields **Fe-peak nuclei**)



TAKE AWAY BOX (II)

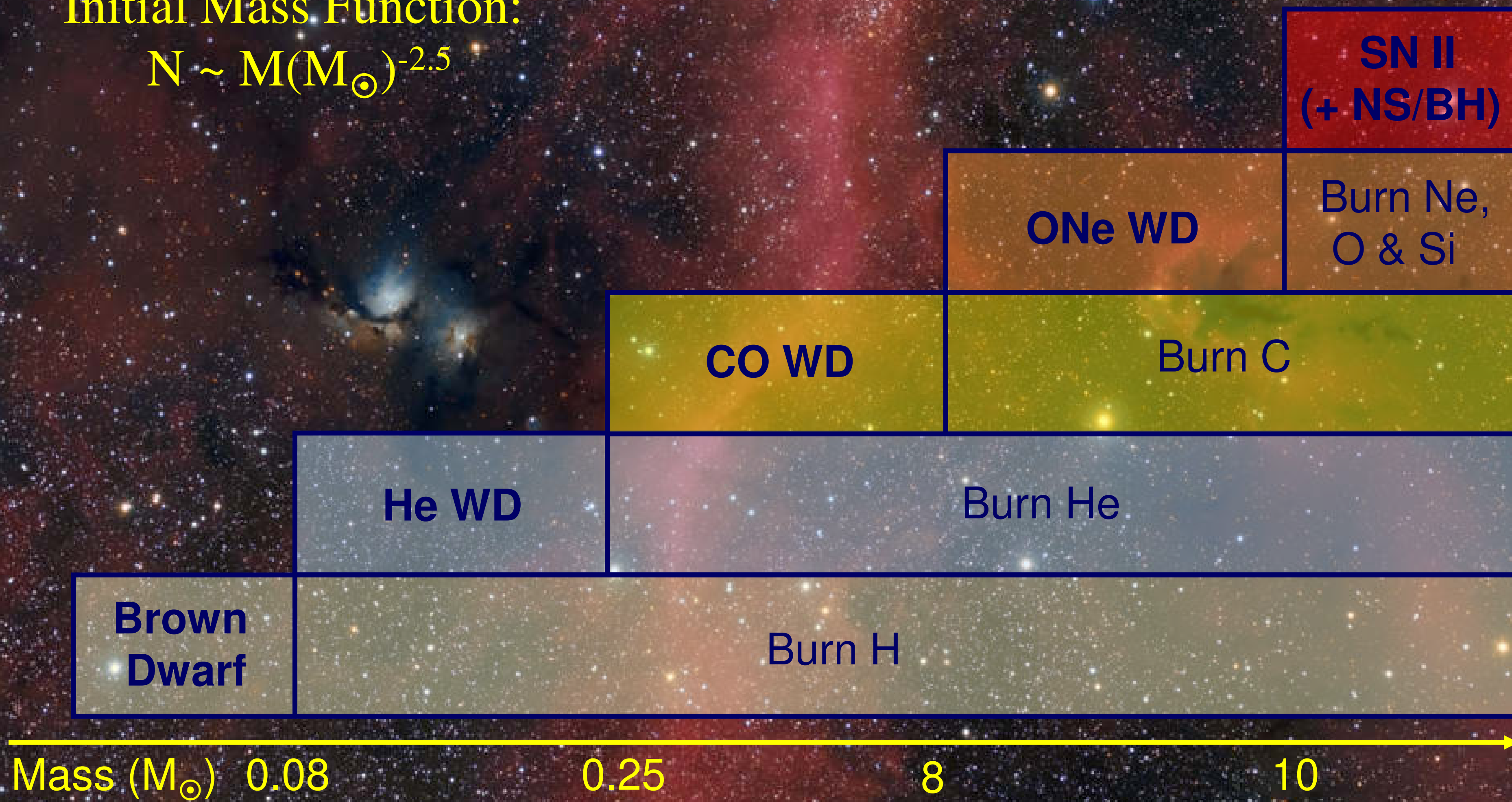
Intermediate-mass elements, such as **He**, **C, O, … Fe** are synthesized by stars during the **different fusion stages** encountered in their "normal" evolution

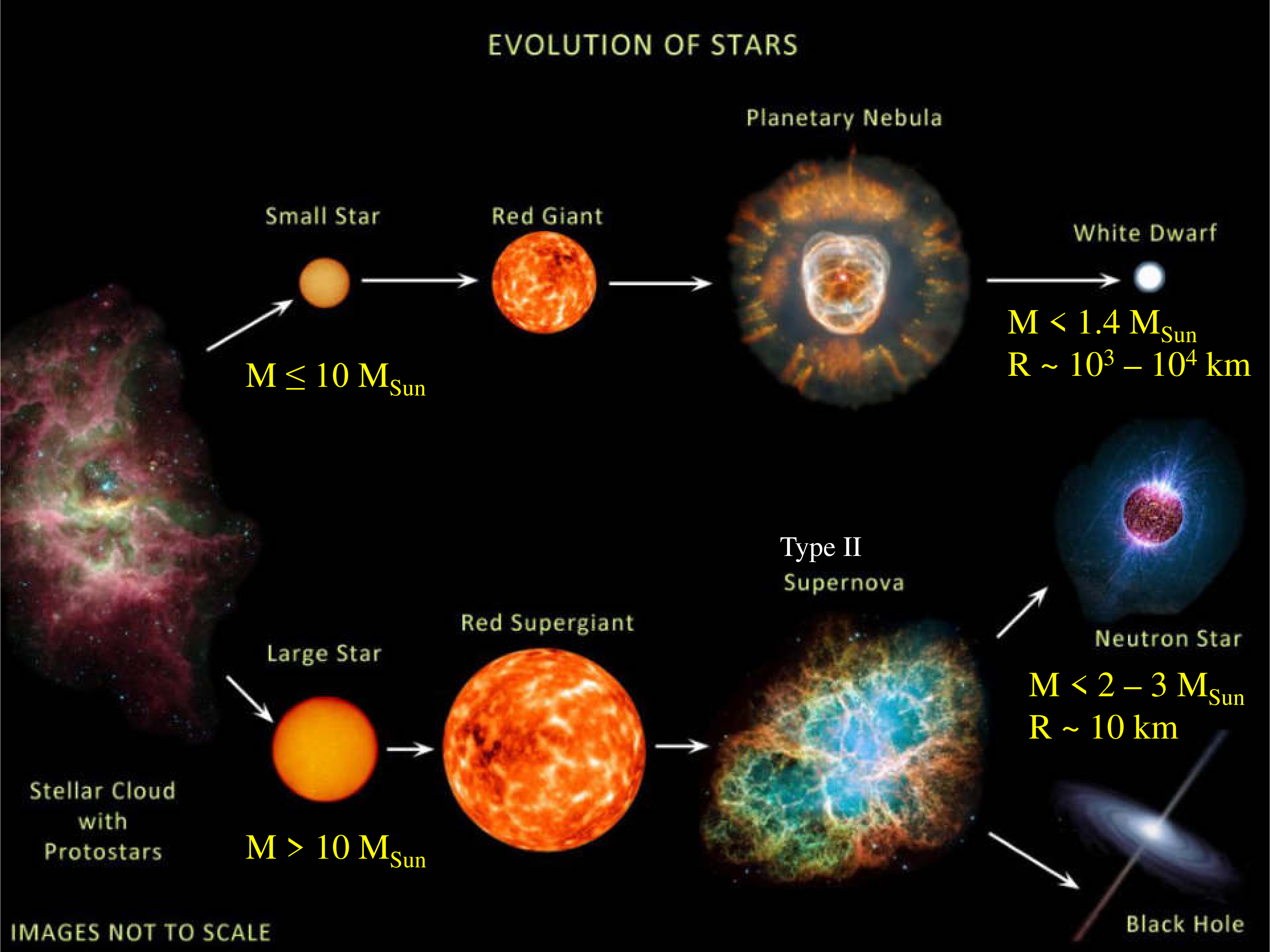

Fusion
Fission
Fe
The "iron group" of isotopes are the most tightly bound.
$^{62}_{28}$Ni (most tightly bound)
$^{58}_{26}$Fe
$^{56}_{26}$Fe
have 8.8 MeV per nucleon binding energy.
yield from nuclear fusion
yield from nuclear fission
Elements heavier than iron can yield energy by nuclear fission.
Average mass of fission fragments is about 118.
^{235}U
Binding energy per nuclear particle (nucleon) in MeV
Mass Number, A
2
4
6
8
50
100
150
200

A Primer on Stellar Evolution

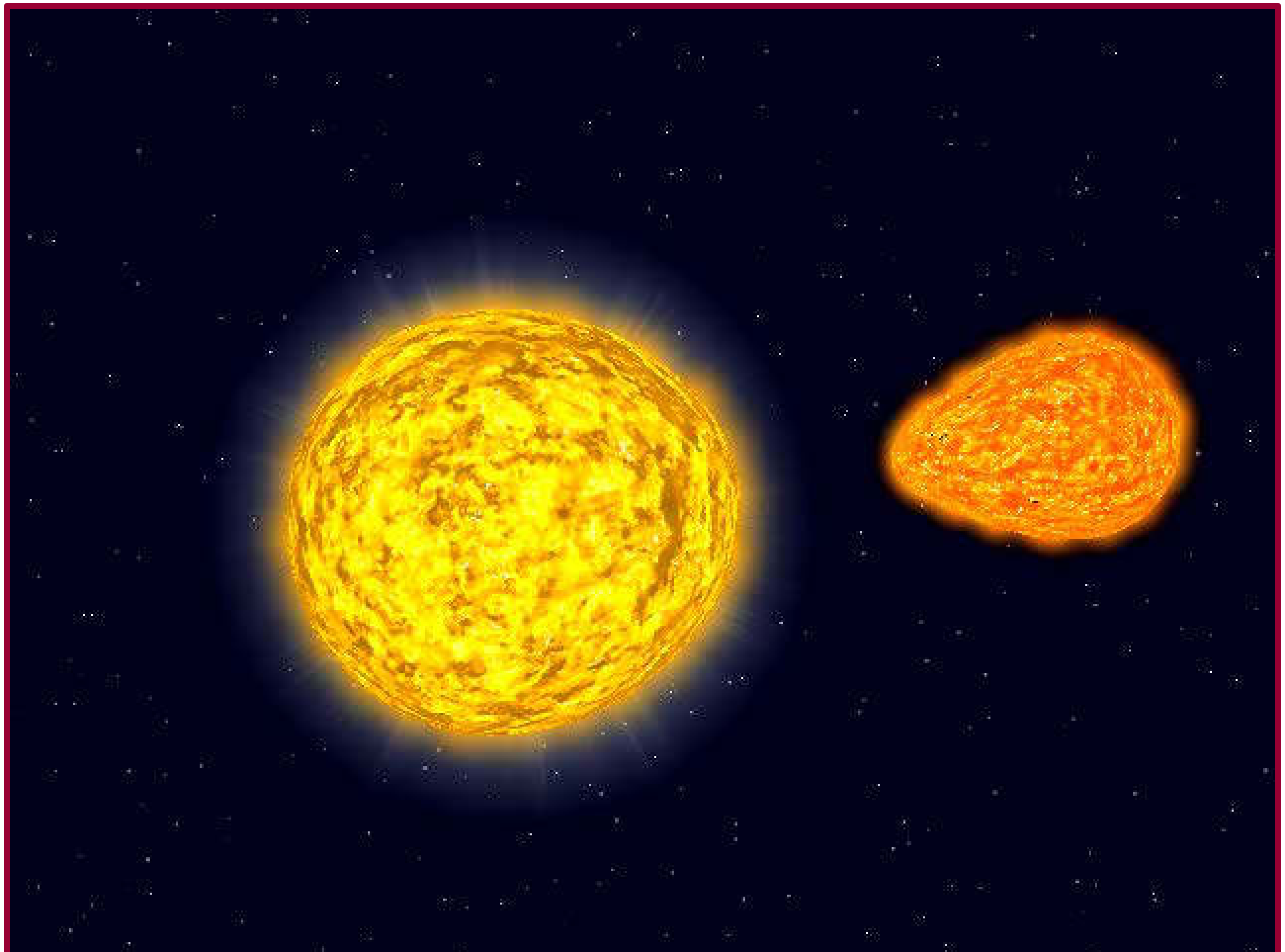
Initial Mass Function:

$N \sim M(M_\odot)^{-2.5}$

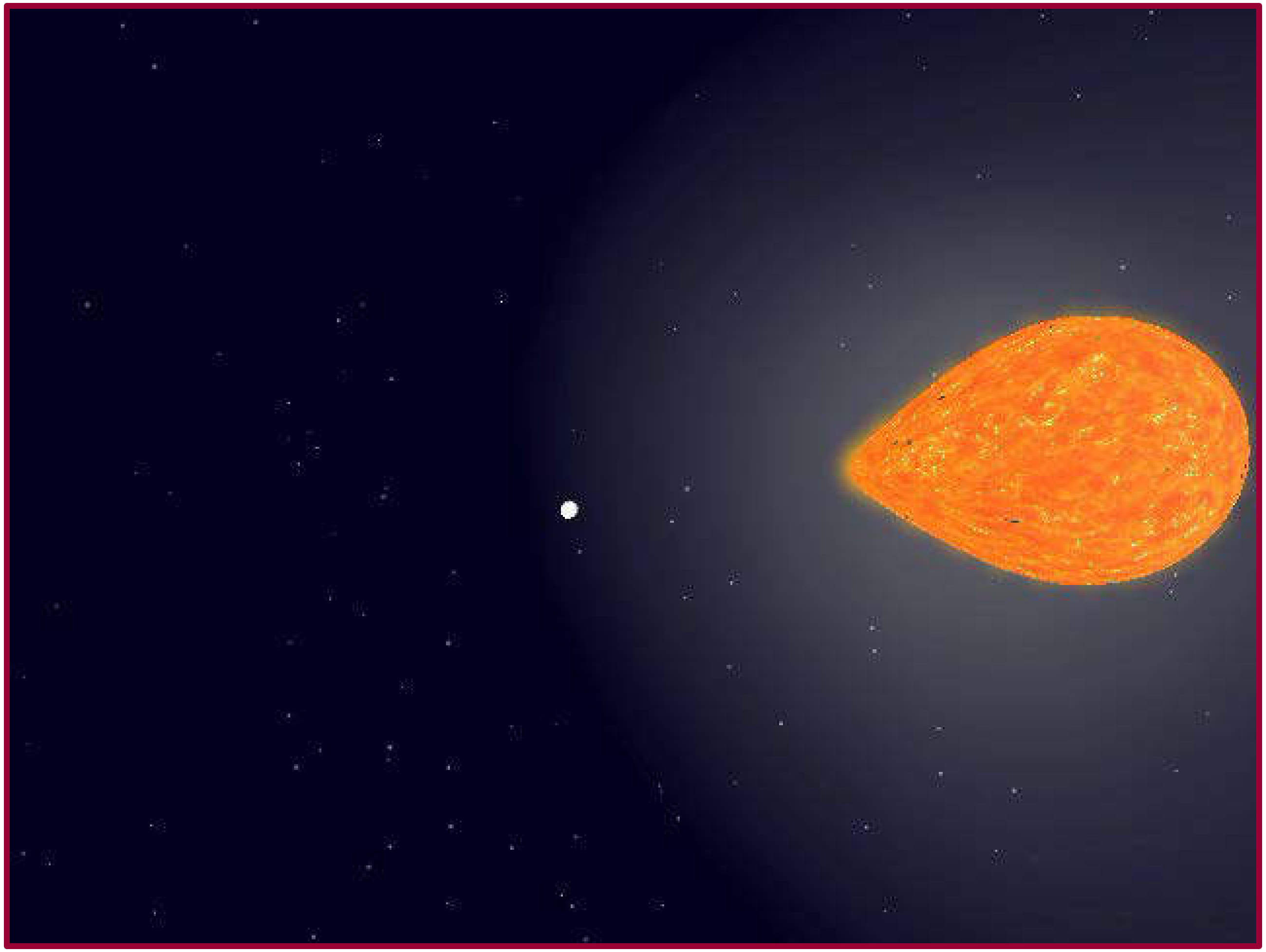



EVOLUTION OF STARS
Planetary Nebula
Small Star
Red Giant
White Dwarf
$M < 1.4\ M_{Sun}$
$R \sim 10^3 - 10^4$ km
$M \leq 10\ M_{Sun}$
Type II
Supernova
Red Supergiant
Large Star
Neutron Star
$M < 2 - 3\ M_{Sun}$
$R \sim 10$ km
Stellar Cloud
with
Protostars
$M > 10\ M_{Sun}$
IMAGES NOT TO SCALE
Black Hole

About 50% of the stars of our Galaxy form double or multiple systems…

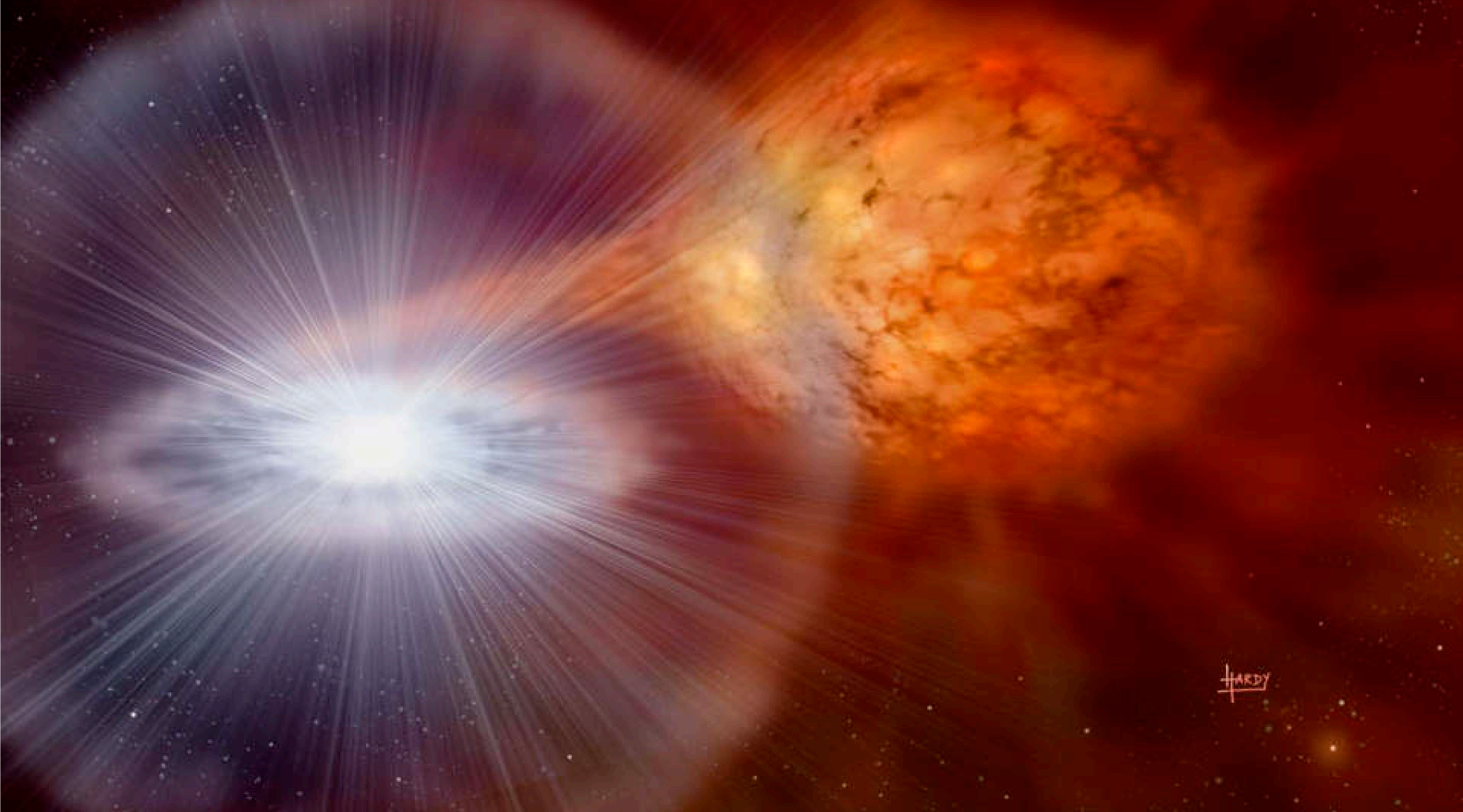


A fraction of which evolve into a compact binary system (containing a white dwarf or a neutron star)

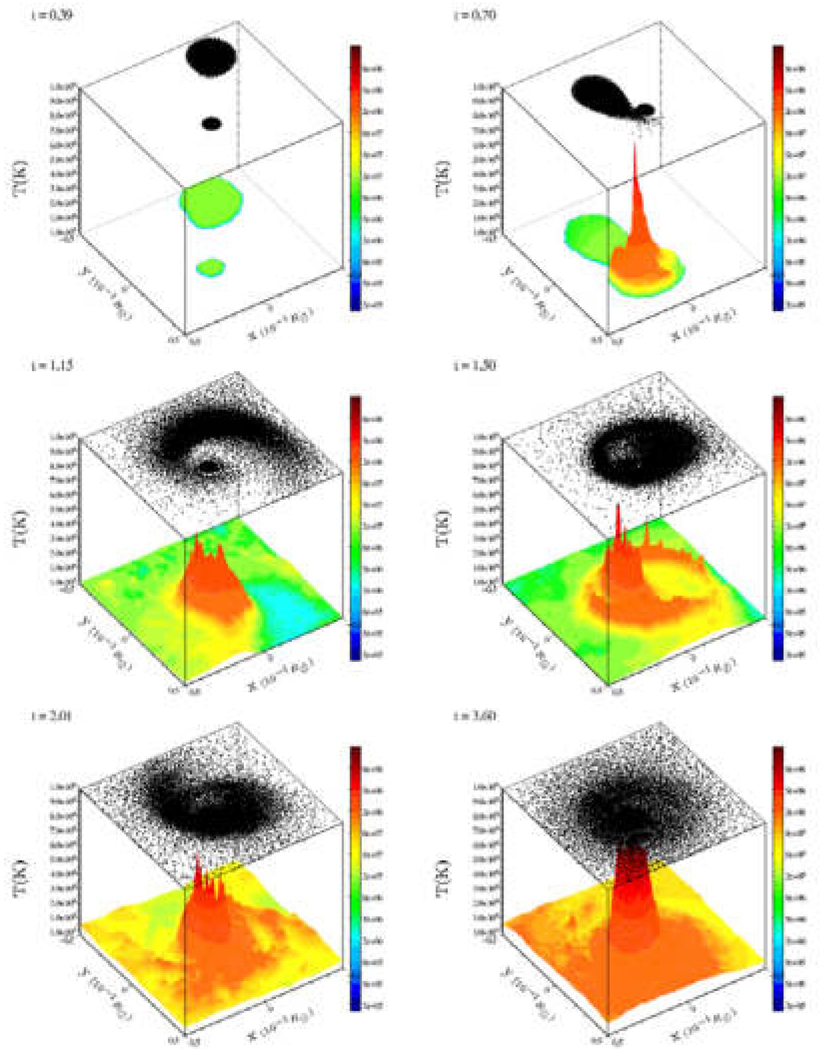


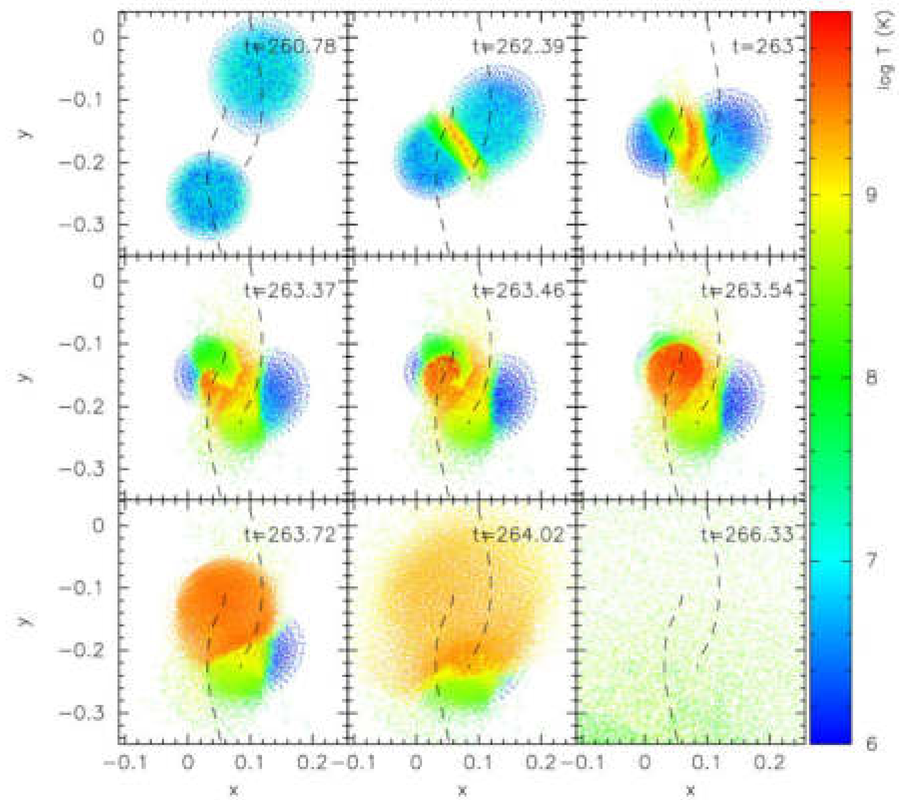
Type Ia (or thermonuclear) **Supernovae** [SN Ia]
Classical Nova Outbursts [CN]
WD

X-Ray Bursts [XRBs]: NS



Stellar Mergers and Collisions

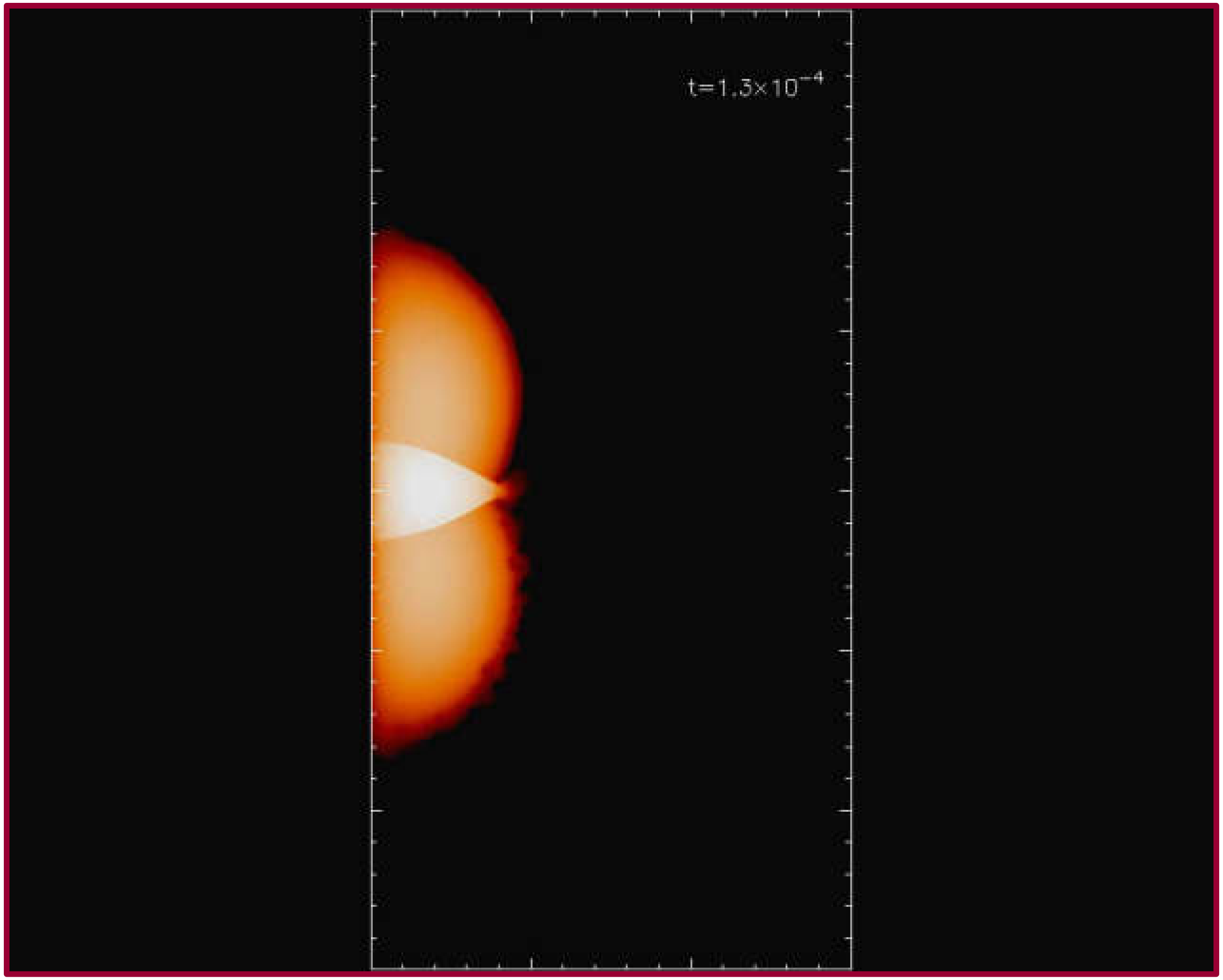




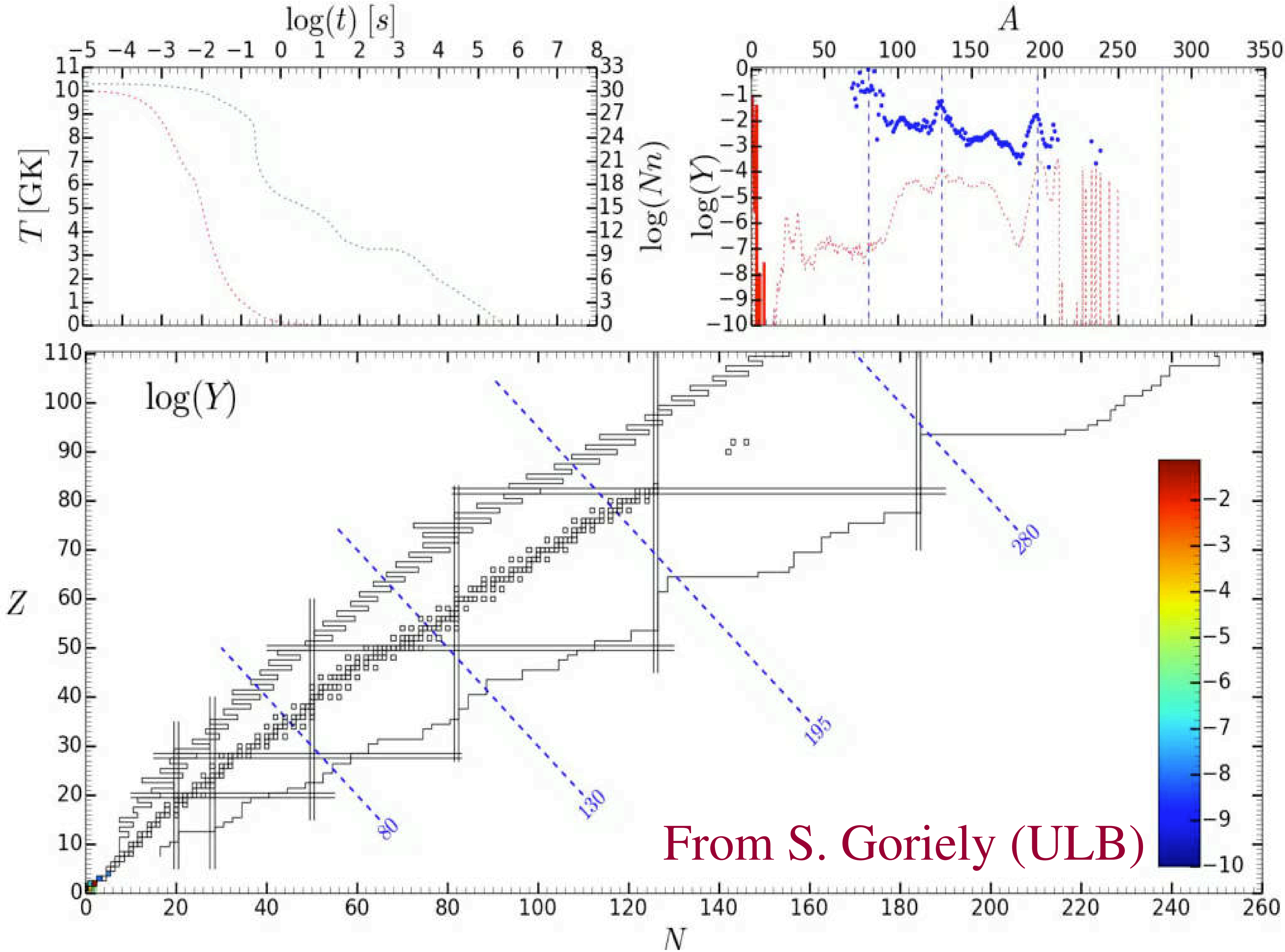
Detonations in WD dynamic interactions
Aznar-Siguán, García-Berro, Lorén-Aguilar, JJ & Isern, MNRAS (2013)

Guerrero, García-Berro & Isern, A&A (2004)

frequency ~ f(Supernovae Ia)



Head-on collision of two neutron stars
(R. Cabezón, D. García-Senz et al., UPC Barcelona)



log(t) [s]
T [GK]
log(Nn)
A
log(Y)
log(Y)
Z
N
80
130
195
280
From S. Goriely (ULB)

TAKE AWAY BOX (III)

Elements **heavier than Fe (Ni)** are synthesized mostly by **neutron-capture reactions** (s- and r-process). Secondary channels include **proton-captures** (rp-process) or **photodisintegrations**.

S-process mostly occurs in AGB stars
R-process sites are controversial: neutron star mergers vs SN II

Classical Novae

A **nova** is a thermonuclear explosion driven by mass transfer onto a WD in a close binary system (P_{orb} ~ 1 – 50 hr, mostly **3 – 4 hr**). Observed in all λ's (but detected in γ-rays only at E > 100 MeV)

Moderate rise times (<1 – 2 days),

$L_{Peak} \sim 10^4 - 10^5\ L_\odot$

$E_{output} \sim 10^{45}$ ergs

WD + MS (often, K-M dwarfs),

WD + RG

Mass ejected: $10^{-7} - 10^{-4}\ M_\odot$

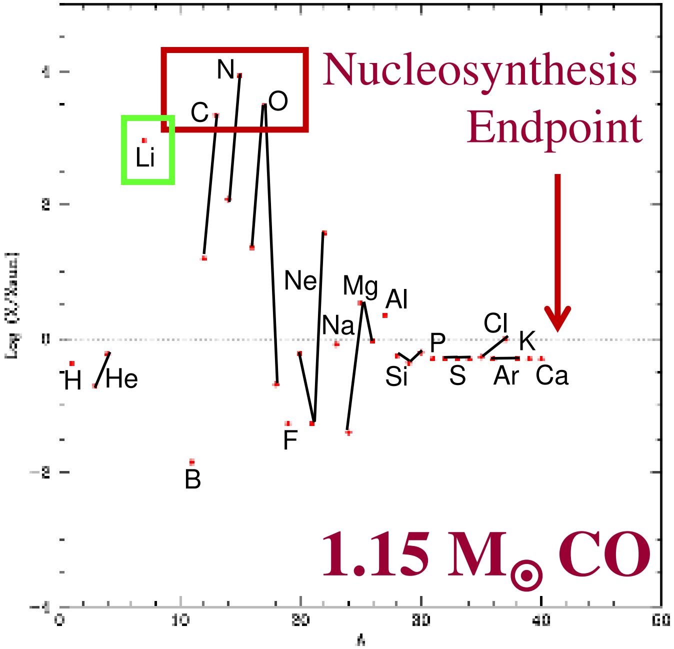
($\sim 10^3$ km s^{-1})

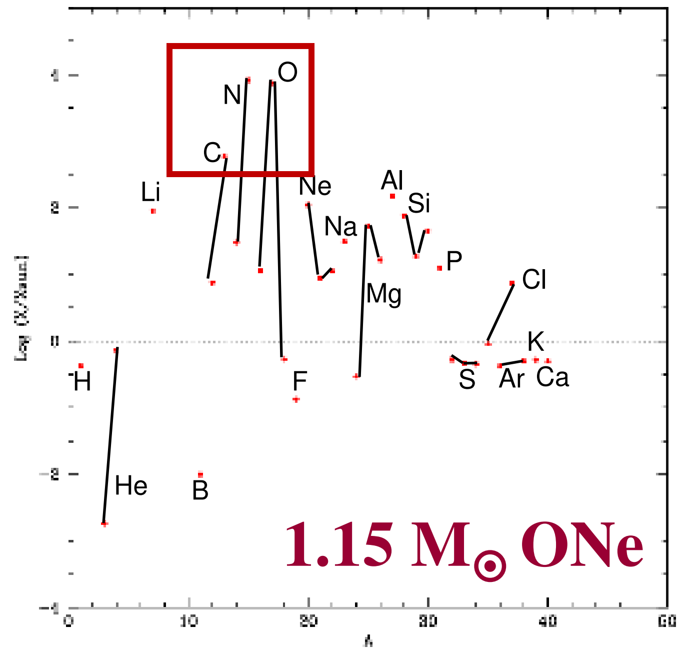
Recurrence: ~ 1 – 100 yr (RNe) to

$10^4 - 10^5$ yr (CNe)

Frequency: 50^{+31}_{-23} yr^{-1} (Shafter 2017)

[Obs. ~ 10 yr^{-1}]


Nucleosynthesis
Endpoint
1.15 M⊙ CO
Li
C
N
O
H
He
B
Ne
F
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca


1.15 M⊙ ONe
Li
C
N
O
Ne
Na
Al
Si
P
Mg
Cl
H
He
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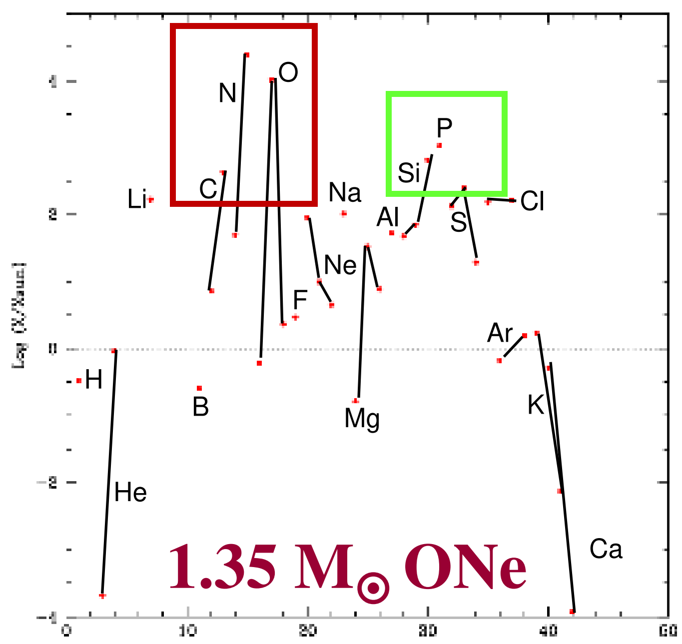
S
Ar
K
Ca


1.35 M⊙ ONe
Li
C
N
O
Na
Al
Si
P
S
Cl
Ne
F
H
B
Mg
Ar
K
He
Ca

JJ (2016)

Nuclear uncertainties

The Astrophysical Journal Supplement Series, 142:105–137, 2002 September

THE EFFECTS OF THERMONUCLEAR REACTION-RATE VARIATIONS ON NOVA NUCLEOSYNTHESIS: A SENSITIVITY STUDY

Christian Iliadis and Art Champagne
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and

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Received 2002 January 19; accepted 2002 April 25

$\approx$7350 nuclear reaction network calculations

Main nuclear uncertainties: [^{18}F(p,α)^{15}O, ^{25}Al(p,γ)^{26}Si, ^{30}P(p,γ)^{31}S]

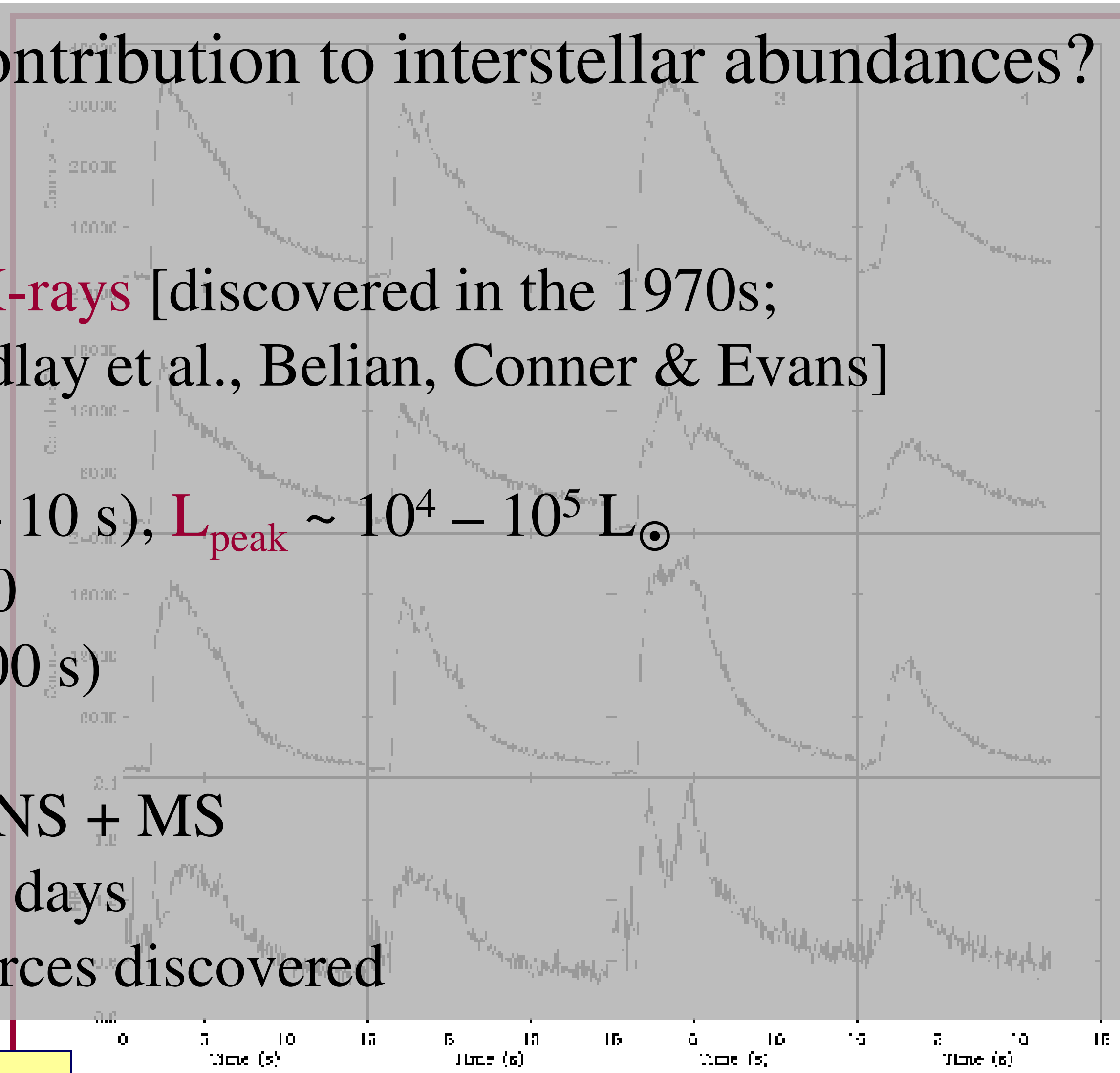
Type I X-Ray Bursts

Main uncertainty: contribution to interstellar abundances?
[ejection unlikely]

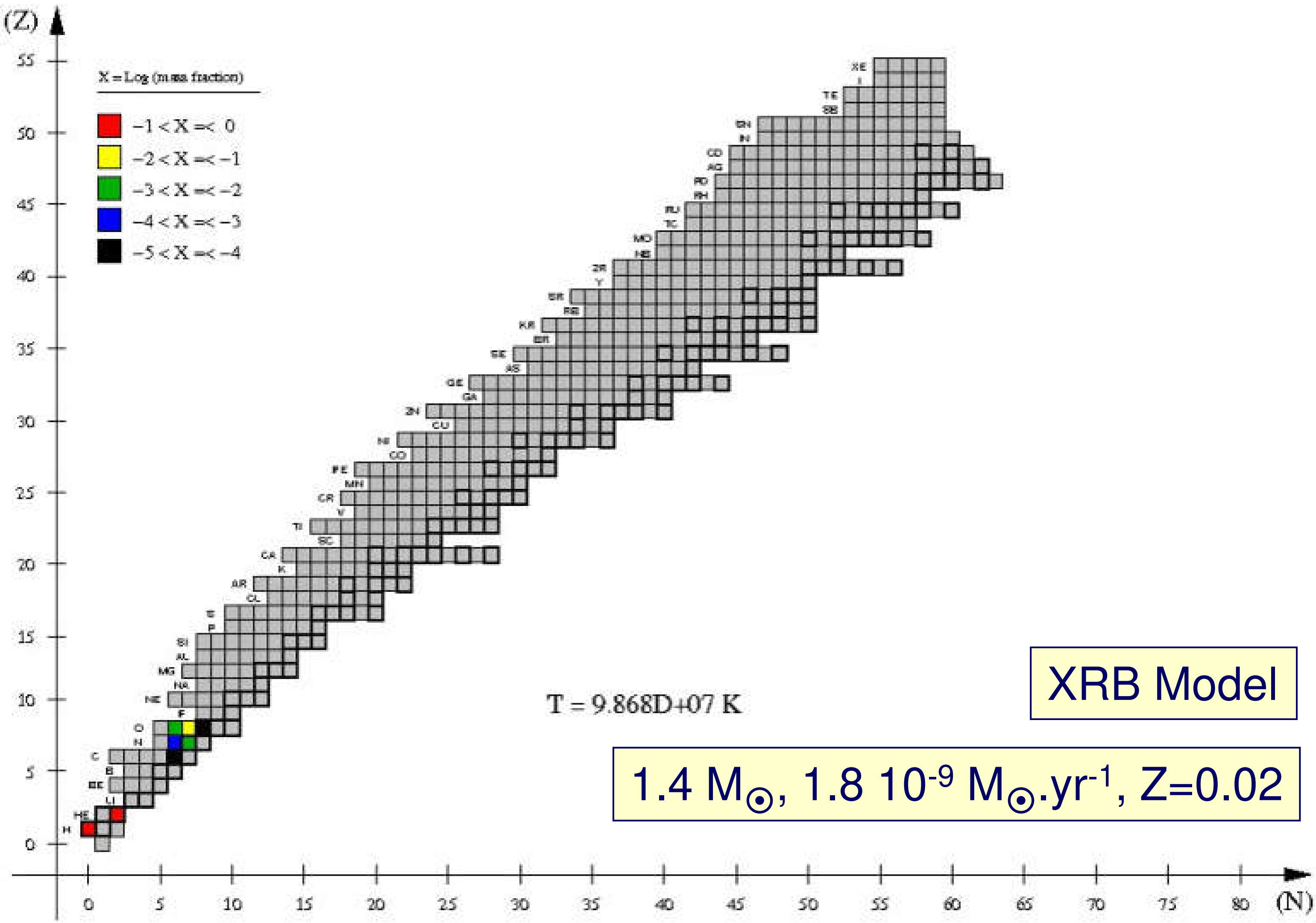
Prominent emitters in X-rays [discovered in the 1970s; Babushkina et al., Grindlay et al., Belian, Conner & Evans]

Very fast rise times (1 – 10 s), $L_{peak} \sim 10^4 - 10^5\ L_\odot$
$\alpha = L_{persistent}/L_{burst} \sim 100$
$E \sim 10^{39}$ ergs (in 10 - 100 s)

Stellar binary systems: NS + MS
Recurrence time: ~ hr – days
About 100 Galactic sources discovered



Strohmeyer & Bildsten (2002)
4U 1728 –34, RXTE



XRB Model

1.4 $M_{\odot}$, 1.8 10^{-9} $M_{\odot}.yr^{-1}$, Z=0.02

Type I XRB: JJ, Moreno, Parikh & Iliadis (2010), ApJS

Nuclear Uncertainties

TABLE 19

Summary of the Most Influential Nuclear Processes, as Collected from Tables 1–10

Reaction	Models Affected
^{12}C(α, γ)^{16}O[a]	F08, K04-B2, K04-B4, K04-B5
^{18}Ne(α, p)^{21}Na[a]	K04-B1[b]
^{25}Si(α, p)^{28}P	K04-B5
^{26g}Al(α, p)^{29}Si	F08
^{29}S(α, p)^{32}Cl	K04-B5
^{30}P(α, p)^{33}S	K04-B4
^{30}S(α, p)^{33}Cl	K04-B4,[b] K04-B5[b]
^{31}Cl(p, γ)^{32}Ar	K04-B1
^{32}S(α, γ)^{36}Ar	K04-B2
^{56}Ni(α, p)^{59}Cu	S01,[b] K04-B5
^{57}Cu(p, γ)^{58}Zn	F08
^{59}Cu(p, γ)^{60}Zn	S01,[b] K04-B5
^{61}Ga(p, γ)^{62}Ge	F08, K04-B1, K04-B2, K04-B5, K04-B6
^{65}As(p, γ)^{66}Se	K04,[b] K04-B1, K04-B2,[b] K04-B3,[b] K04-B4, K04-B5, K04-B6
^{69}Br(p, γ)^{70}Kr	K04-B7
^{75}Rb(p, γ)^{76}Sr	K04-B2
^{82}Zr(p, γ)^{83}Nb	K04-B6
^{84}Zr(p, γ)^{85}Nb	K04-B2
^{84}Nb(p, γ)^{85}Mo	K04-B6
^{85}Mo(p, γ)^{86}Tc	F08
^{86}Mo(p, γ)^{87}Tc	F08, K04-B6
^{87}Mo(p, γ)^{88}Tc	K04-B6
^{92}Ru(p, γ)^{93}Rh	K04-B2, K04-B6
^{93}Rh(p, γ)^{94}Pd	K04-B2
^{96}Ag(p, γ)^{97}Cd	K04, K04-B2, K04-B3, K04-B7
^{102}In(p, γ)^{103}Sn	K04, K04-B3
^{103}In(p, γ)^{104}Sn	K04-B3, K04-B7
^{103}Sn(α, p)^{106}Sb	S01[b]

TABLE 20

Nuclear Processes Affecting the Total Energy Output by More than 5% and at Least One Isotope

Reaction	Models Affected
^{15}O(α, γ)^{19}Ne[a]	K04, K04-B1, K04-B6
^{18}Ne(α, p)^{21}Na[a]	K04-B1, K04-B6
^{22}Mg(α, p)^{25}Al	F08
^{23}Al(p, γ)^{24}Si	K04-B1
^{24}Mg(α, p)^{27}Al[a]	K04-B2
^{26g}Al(p, γ)^{27}Si[a]	F08
^{28}Si(α, p)^{31}P[a]	K04-B4
^{30}S(α, p)^{33}Cl	K04-B4, K04-B5
^{31}Cl(p, γ)^{32}Ar	K04-B3
^{32}S(α, p)^{35}Cl	K04-B2
^{35}Cl(p, γ)^{36}Ar[a]	K04-B2
^{56}Ni(α, p)^{59}Cu	S01
^{59}Cu(p, γ)^{60}Zn	S01
^{65}As(p, γ)^{66}Se	K04, K04-B2, K04-B3
^{69}Br(p, γ)^{70}Kr	S01
^{71}Br(p, γ)^{72}Kr	K04-B7
^{103}Sn(α, p)^{106}Sb	S01

s

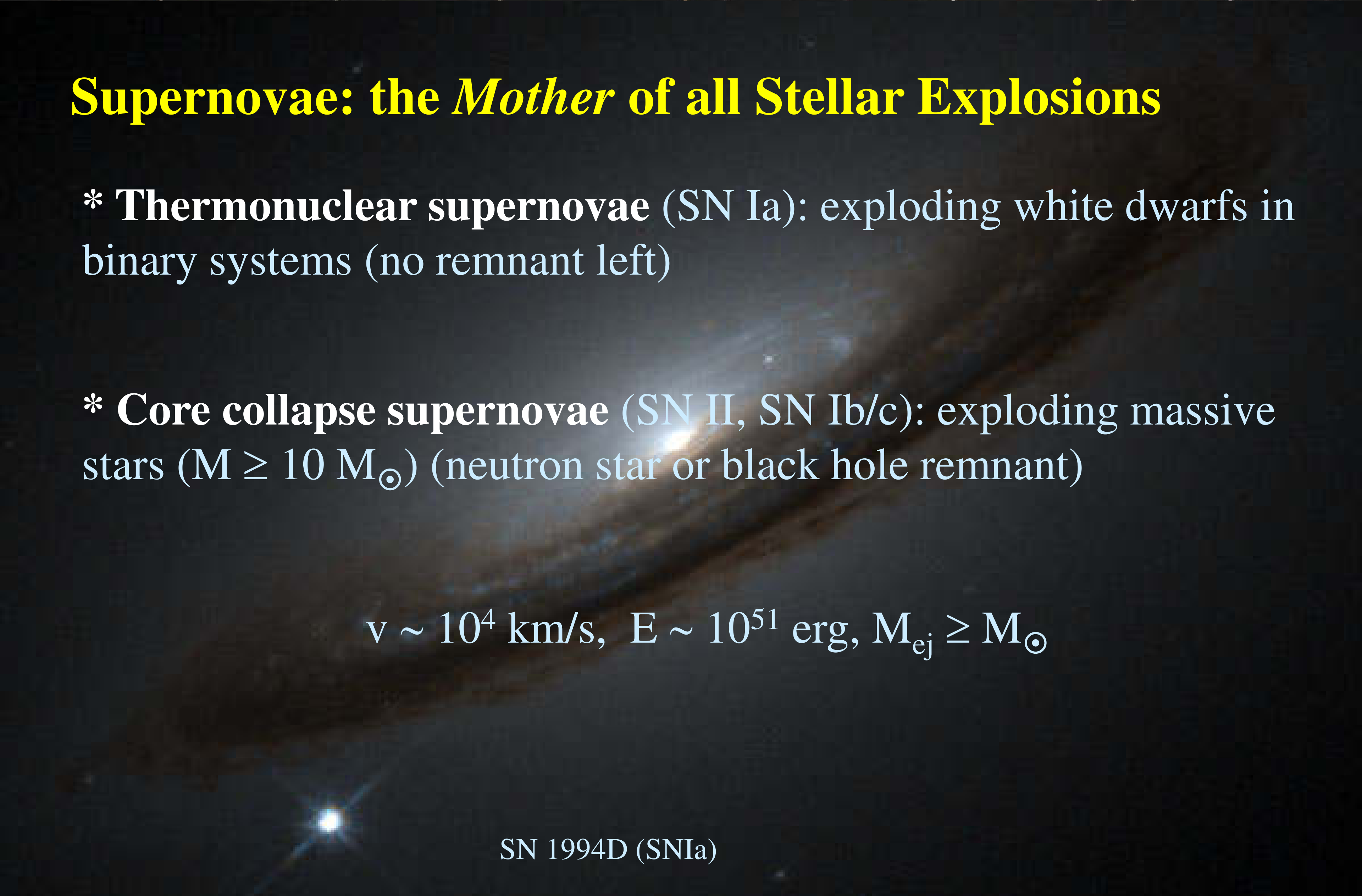
nuclear processes

Supernovae: the *Mother* of all Stellar Explosions

* **Thermonuclear supernovae** (SN Ia): exploding white dwarfs in binary systems (no remnant left)

* **Core collapse supernovae** (SN II, SN Ib/c): exploding massive stars ($M \geq 10\ M_\odot$) (neutron star or black hole remnant)

$$v \sim 10^4\ \mathrm{km/s},\quad E \sim 10^{51}\ \mathrm{erg},\ M_{ej} \geq M_\odot$$



SN 1994D (SNIa)

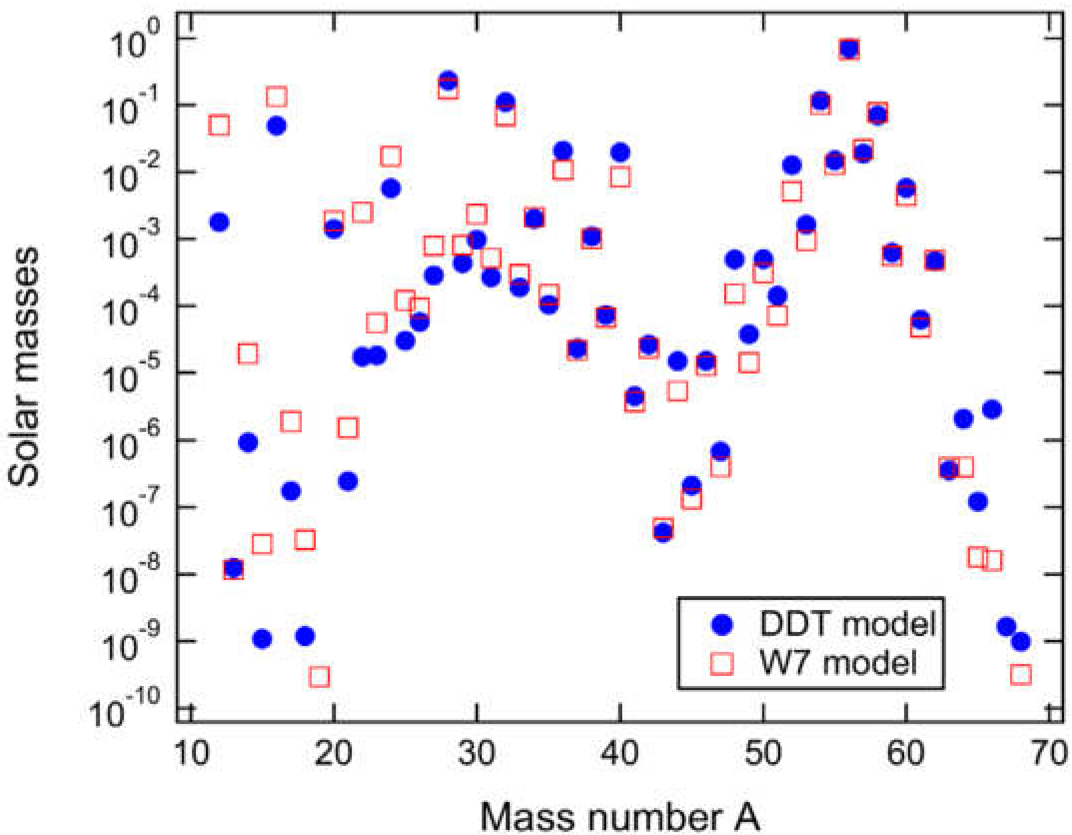
Type Ia Supernovae – problems, challenges, & mysteries

* **homogeneity:** only ~70% of all **SN Ia** have similar spectra, light curves and peak absolute magnitudes (Li et al. 2011): diversity of SNIa progenitors?

* **Scenario:** not understood → single degenerate (WD + MS companion) vs double degenerate (WD + WD)

* **Propagation of the burning front:** subsonic vs supersonic (what causes the predicted deflagration /detonation transition?)

Nucleosynthesis: five burning regimes: "normal" and "α-rich" freeze-out from nuclear statistical equilibrium (NSE) in the inner regions, and incomplete Si-, O-, and C/Ne-burning in the outermost layers (Thielemann et al. 1986; Woosley 1986)



* main **Fe factories**

Parikh, JJ, Seitenzahl & Röpke, A&A (2013)

443 isotopes (H – Kr); 5267 links

Nuclear Uncertainties

Reaction	Importance		
	Case A	Case B	Case C
	W7	**DDT**	**W7+DDT**
^{12}C$(\alpha,\gamma)^{16}$O	X	X	X
^{12}C$(^{12}$C$,\alpha)^{20}$Ne	X	X	X
^{12}C$(^{12}$C$,p)^{23}$Na	X	X	X
^{16}O$(n,\gamma)^{17}$O	X		
^{16}O$(\alpha,\gamma)^{20}$Ne	X		
^{20}Ne$(n,\gamma)^{21}$Ne			X
^{20}Ne$(\alpha,p)^{23}$Na	X	X	X
^{20}Ne$(\alpha,\gamma)^{24}$Mg	X	X	X
^{22}Ne$(p,\gamma)^{23}$Na	X		X
^{22}Ne$(\alpha,n)^{25}$Mg			X
^{23}Na$(n,\gamma)^{24}$Na			X
^{23}Na$(\alpha,p)^{26}$Mg		X	
^{24}Na$(p,n)^{24}$Mg			X
^{24}Mg$(\alpha,\gamma)^{28}$Si			X
^{25}Mg$(n,\gamma)^{26}$Mg		X	X
^{25}Mg$(p,\gamma)^{26}$Al			X
^{26}Mg$(p,n)^{26}$Al			X
^{27}Al$(p,\gamma)^{28}$Si			X
^{27}Al$(\alpha,p)^{30}$Si	X		X
^{28}Si$(\alpha,p)^{31}$P			X
^{30}Si$(p,\gamma)^{31}$P	X		
^{30}Si$(\alpha,\gamma)^{34}$S	X		X
^{30}Si$(\alpha,n)^{33}$S			X
^{32}P$(p,n)^{32}$S			X
^{34}S$(\alpha,p)^{37}$Cl			X
^{36}S$(p,n)^{36}$Cl			X
^{42}Ca$(\alpha,\gamma)^{46}$Ti			X
^{45}Sc$(p,\gamma)^{46}$Ti		X	
^{45}Sc$(p,n)^{45}$Ti			X

Parikh, JJ, Seitenzahl & Röpke, A&A (2013)

Thank you for your attention!

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Stars and Bytes – Nuclear Astrophysics as Seen by an Stellar Modeler

ChETEC-INFRA SNAQs [Schools on Nuclear Astrophysics Questions],
February 17, 2021

Bonus Slides

1-D Hydrodynamics

* Lagrangian differential equations

- Conservation of mass

$$V = \frac{4}{3}\pi \frac{\partial r^3}{\partial m}$$

- Conservation of momentum

$$\frac{\partial u}{\partial t} + 4\pi r^2 \frac{\partial (P+q)}{\partial m} = -\frac{Gm}{r^2}$$

- Conservation of energy

$$\frac{\partial E}{\partial t} = \varepsilon - \frac{\partial L}{\partial m} - (P+q)\frac{\partial V}{\partial t}$$

- Energy transport (radiation and convection)

$$L = -\frac{256\sigma \pi^2 r^4 T^3}{3K}\frac{\partial T}{\partial m} + L_{conv}$$

- Lagrangian velocity

$$\frac{\partial r}{\partial t} = u$$

q = artificial viscosity term

Stellar Modeling: The Art of Stellar Cooking

Ingredients: Input Physics

- EOS
- Opacities
- Nuclear reactions ⟷ Initial composition

Cooking conditions:

- Initial model
- Initial conditions (M_{star}, T_{center}, ...)

Cooking devices:

Stellar codes

From C. Iliadis's web page

"For many problems in the theory of the stellar interior the speed of numerical integrations by hand is entirely sufficient. A person can usually accomplish more than twenty integration steps per day for a set of differential equations [...] Thus for a typical single integration consisting of, say, forty steps less than two days are needed. Correspondingly, if, for example, a set of models is to be determined and if these models are to be constructed of a one-parameter family starting from the surface and a one-parameter family starting from the core, and if each of these two families can be represented with sufficient accuracy by, say, six individual integrations, then the entire numerical work for this fairly typical case can be accomplished by one person in one month. However, if extensive evolutionary model sequences including a variety of physical complications are to be derived, then numerical integrations by hand may become prohibitive and the advantage of large electronic machines will be incontestable."

Martin Schwarzschild, *Structure and Evolution of the Stars* (1958)

12321 Models

A&A 634, A5 (2020)
https://doi.org/10.1051/0004-6361/201936893

Astronomy & Astrophysics

123–321 models of classical novae

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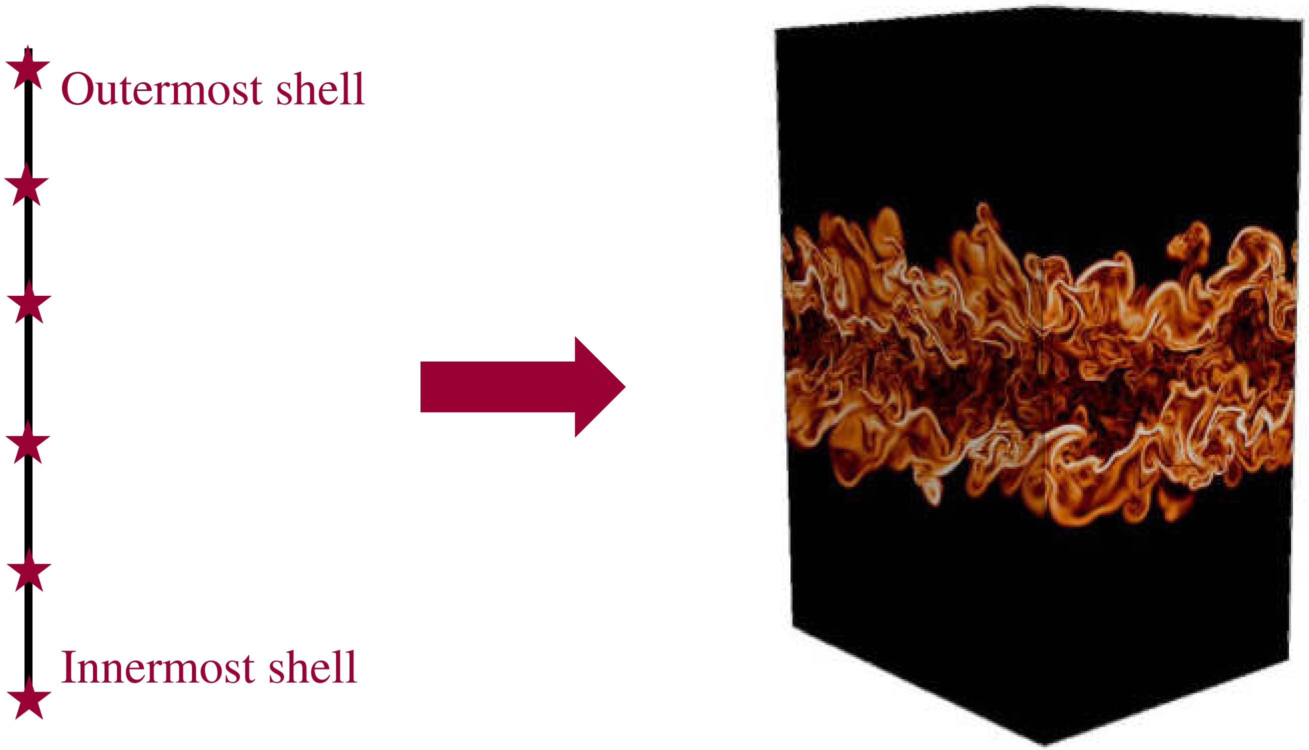
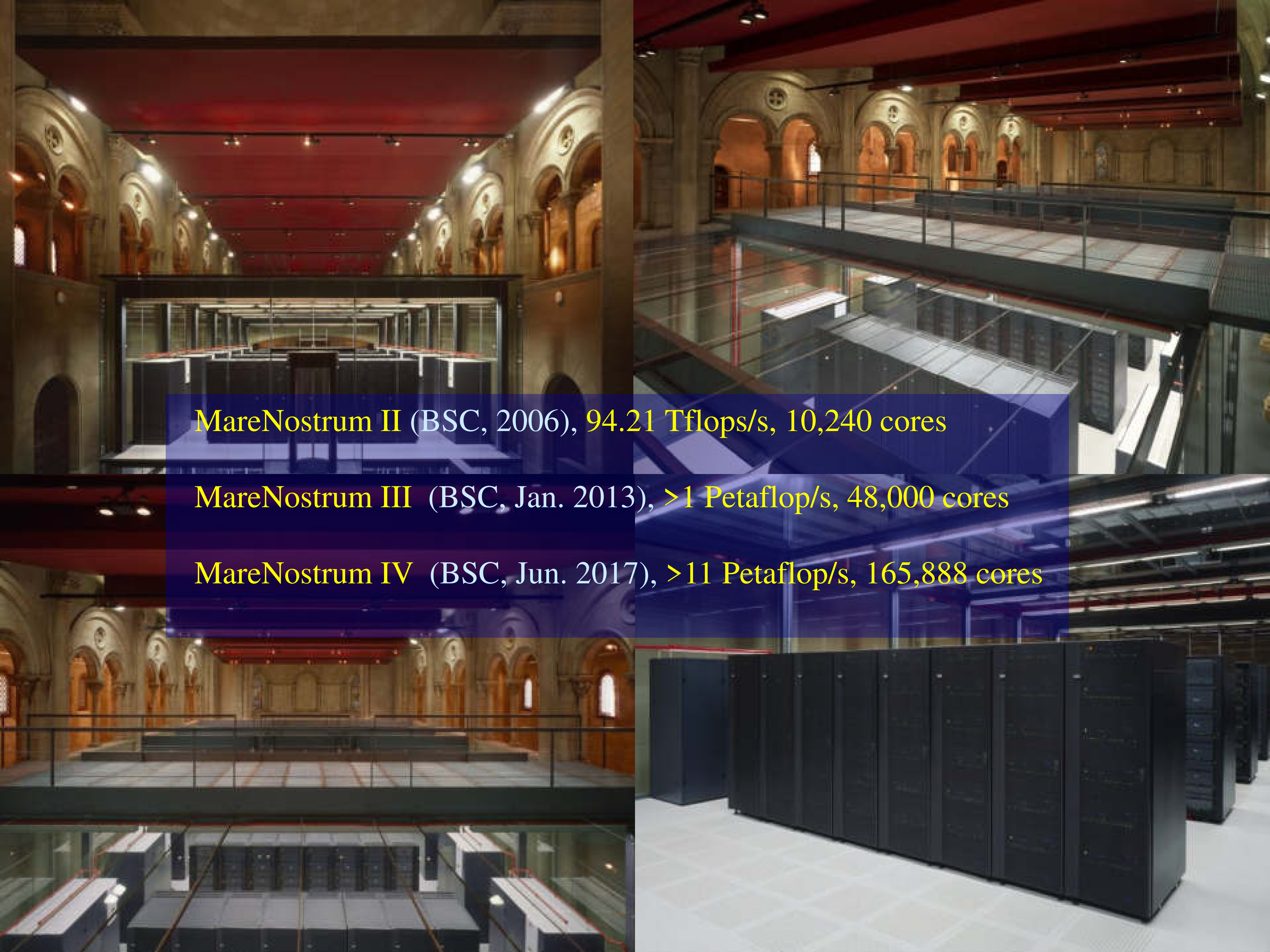
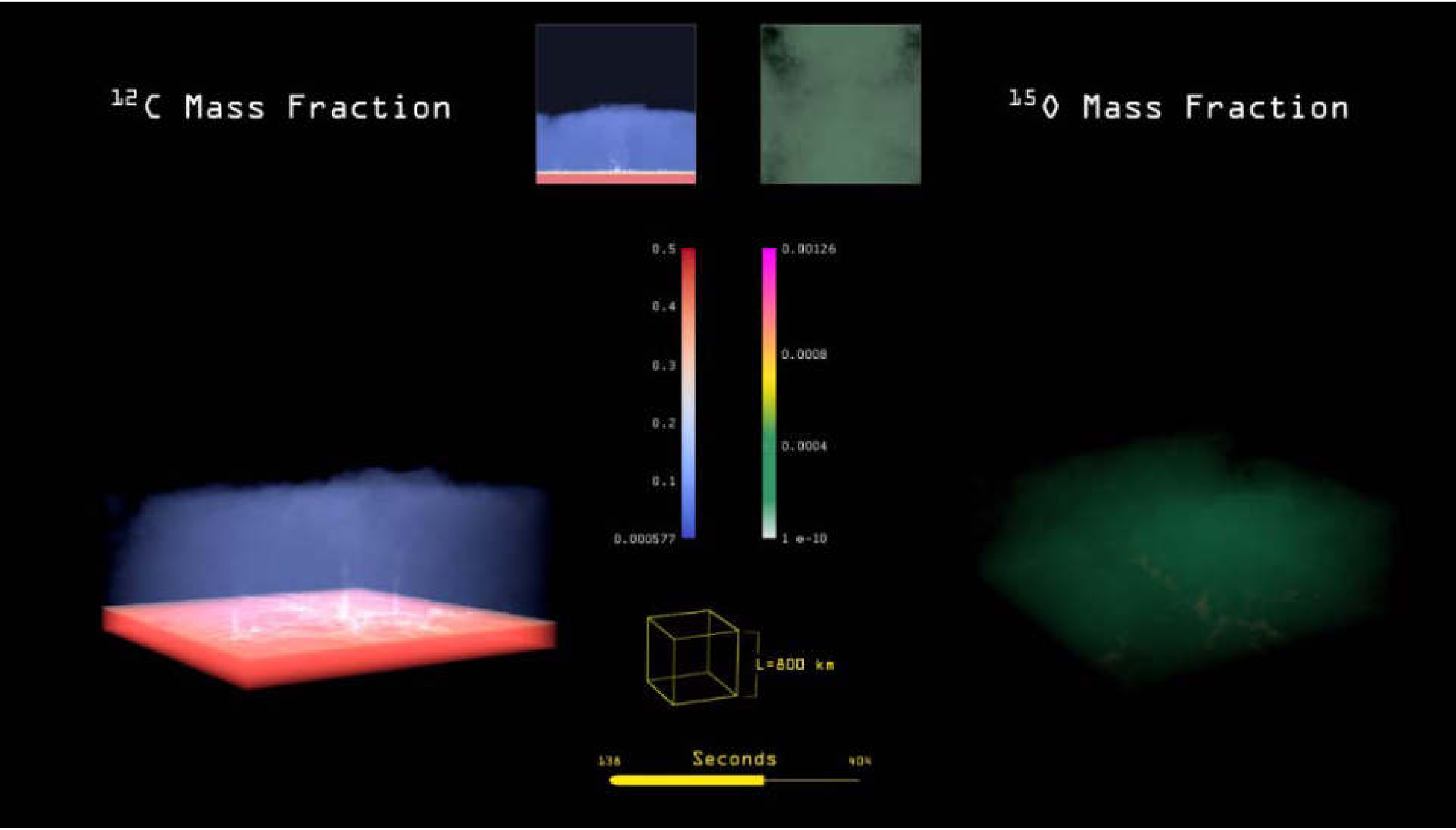
Interest of **multiD models:** to improve state-of-the-art, 1-D models with large nuclear reaction networks

a) "123" (or *1 to 3*) Models: 1D simulation of accretion and early stages of the TNR → mapping onto a 3D domain




MareNostrum II (BSC, 2006), 94.21 Tflops/s, 10,240 cores
MareNostrum III (BSC, Jan. 2013), >1 Petaflop/s, 48,000 cores
MareNostrum IV (BSC, Jun. 2017), >11 Petaflop/s, 165,888 cores



Casanova, JJ, García-Berro, Shore & Calder (2011), Nature

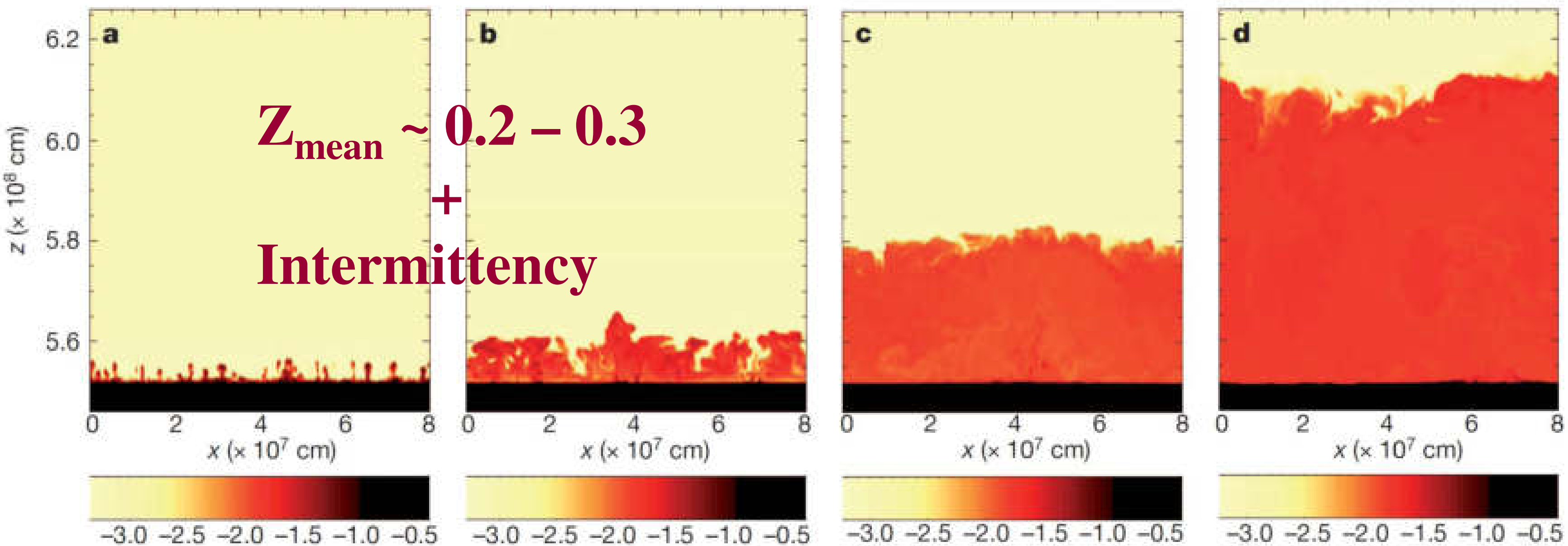
3D Models of Mixing

LETTER

doi:10.1038/nature10520

Kelvin–Helmholtz instabilities as the source of inhomogeneous mixing in nova explosions

Jordi Casanova[1,2], Jordi José[1,2], Enrique García-Berro[3,2], Steven N. Shore[4] & Alan C. Calder[5]



$Z_{mean} \sim 0.2 – 0.3$

+

Intermittency


Kelvin-Helmholtz instabilities

b) "convection-in-a-box/cube" studies: multiD simulations

c) "321" (or *3 to 1*) Models: prescriptions of 3D turbulent convection (**v_{conv}(t), $m_{dredge-up}$(t), ...**) are implemented in 1D simulations to follow the final stages of a nova (expansion and ejection)