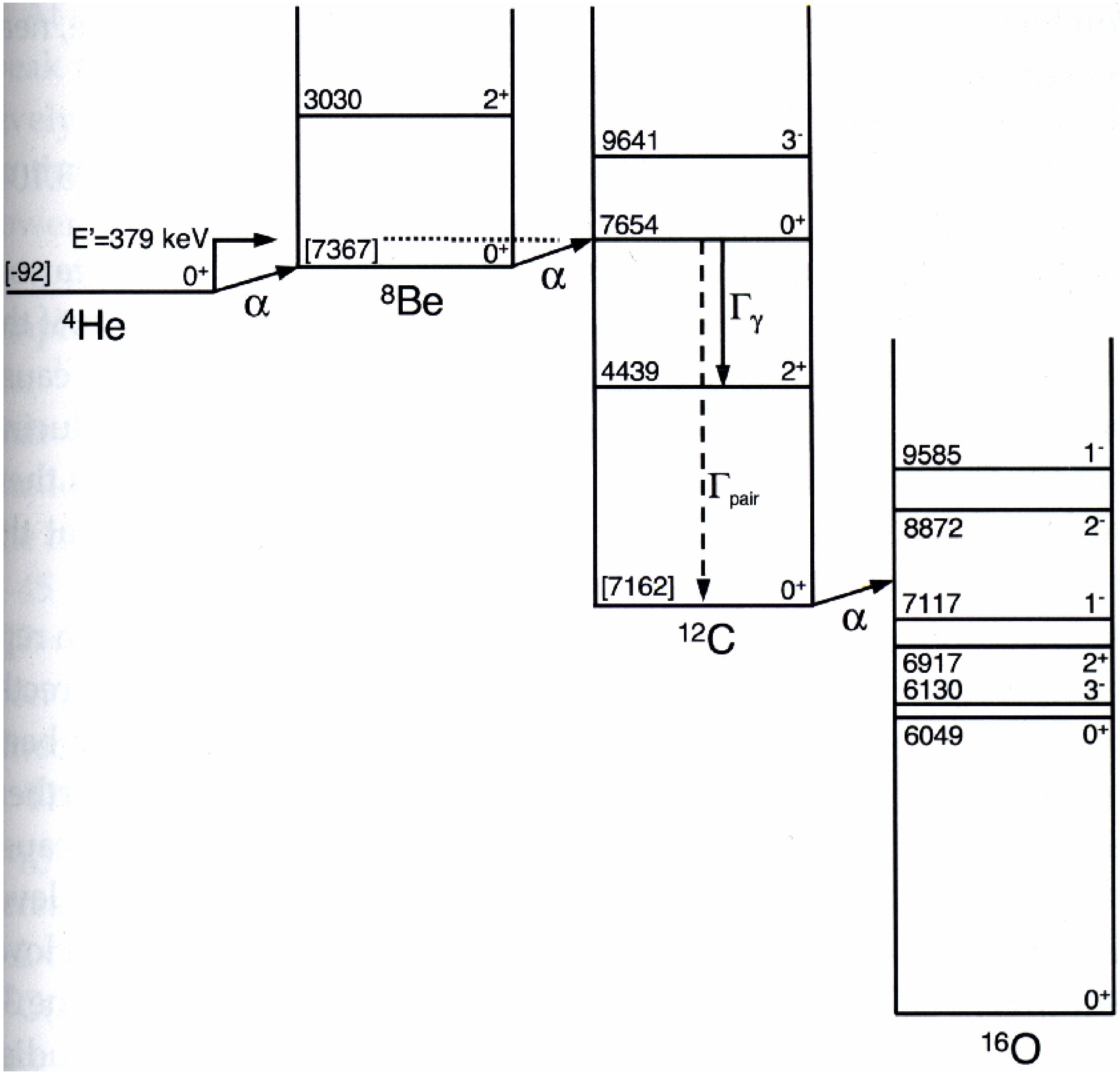
Helium Burning Level Scheme



Additional Helium Burning Reactions

Oxygen Production

$^{4}\text{He} + {}^{12}\text{C} \rightarrow {}^{16}\text{O} + \gamma$

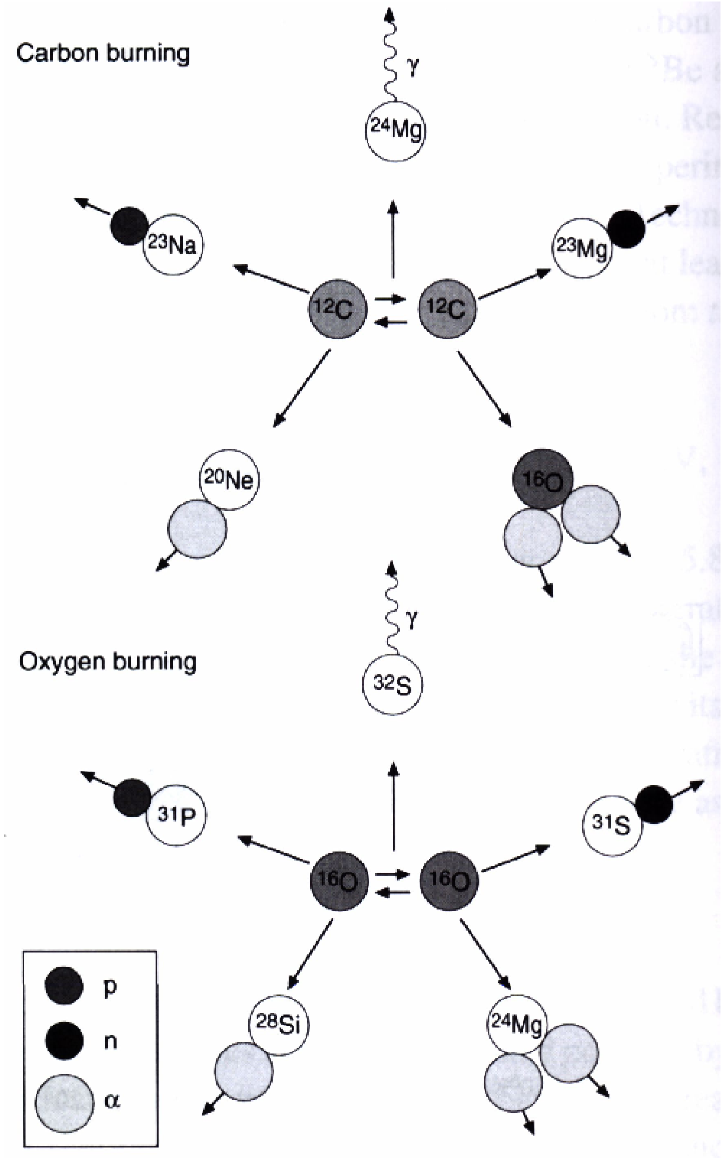
$Q = 7.162\,\text{MeV}$

$\langle \sigma v \rangle \;\propto \rho T^{40}$

The final abundance of carbon is set by the competition of 3α and $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reactions;

The production of ^{16}O can only start when a sufficient amount of ^{12}C has been made.

Carbon and Oxygen Burning



Carbon Burning

$$
\begin{array}{lll}
{}^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{24}\mathrm{Mg} + \gamma & , & 13.931 \\
\phantom{{}^{12}\mathrm{C} + {}^{12}\mathrm{C}} \rightarrow {}^{23}\mathrm{Mg} + n & , & -2.605 \\
\phantom{{}^{12}\mathrm{C} + {}^{12}\mathrm{C}} \rightarrow {}^{23}\mathrm{Na} + p & , & 2.238 \\
\phantom{{}^{12}\mathrm{C} + {}^{12}\mathrm{C}} \rightarrow {}^{20}\mathrm{Ne} + \alpha & , & 4.616 \\
\phantom{{}^{12}\mathrm{C} + {}^{12}\mathrm{C}} \rightarrow {}^{16}\mathrm{O} + 2\alpha & , & -0.114
\end{array}
$$

Average $Q = 13\,\mathrm{MeV}$

Oxygen Burning

$$
\begin{array}{lll}
{}^{16}\mathrm{O} + {}^{16}\mathrm{O} \rightarrow {}^{32}\mathrm{S} + \gamma & , & 16.541 \\
\phantom{{}^{16}\mathrm{O} + {}^{16}\mathrm{O}} \rightarrow {}^{31}\mathrm{P} + p & , & 7.677 \\
\phantom{{}^{16}\mathrm{O} + {}^{16}\mathrm{O}} \rightarrow {}^{31}\mathrm{S} + n & , & 1.453 \\
\phantom{{}^{16}\mathrm{O} + {}^{16}\mathrm{O}} \rightarrow {}^{28}\mathrm{Si} + \alpha & , & 9.593 \\
\phantom{{}^{16}\mathrm{O} + {}^{16}\mathrm{O}} \rightarrow {}^{24}\mathrm{Mg} + 2\alpha & , & -0.393
\end{array}
$$

Average $Q = 16\,\mathrm{MeV}$

Neutrino losses from electron/positron pair annihilation

- Important for carbon burning and beyond
- For $T>10^9$ K (about 100 keV), occasionally:

  $$\gamma \rightarrow e^+ + e^-$$

  and usually

  $$e^+ + e^- \rightarrow 2\gamma$$

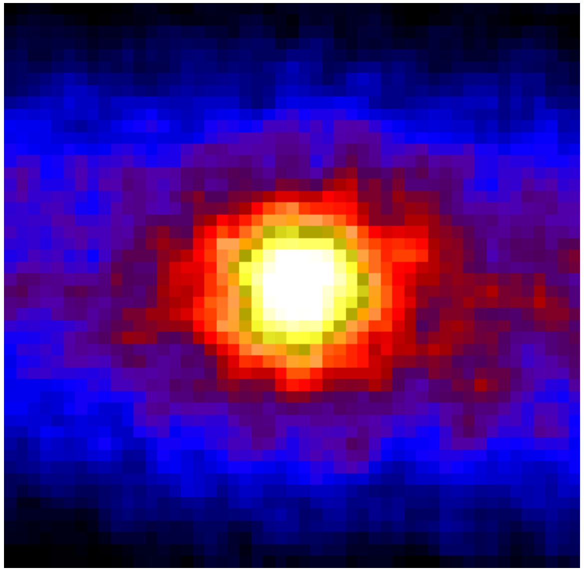
  but sometimes

  $$e^+ + e^- \rightarrow \overline{\nu}_e + \nu_e$$

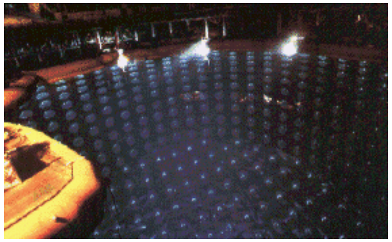
- The neutrinos exit the stars at the speed of light while the e^+, e^-, and the γ's all stay trapped.
- This is an important energy loss with

  $$\varepsilon_\nu \approx -10^{15}\, (T/10^9 K)^9 \text{ erg g}^{-1}\text{ s}^{-1}$$

- For carbon burning and beyond, each burning stage gives about the same energy per nucleon, thus the lifetime goes down as T^{-9}



The sun as seen by Kamiokande



Neon Burning

Neon burning proceeds by a combination of photo-disintegrations and α captures:

$$^{20}\mathrm{Ne} + \gamma \rightarrow {}^{16}\mathrm{O} + {}^{4}\mathrm{He} \; , \quad Q = -4.73\,\mathrm{MeV}$$

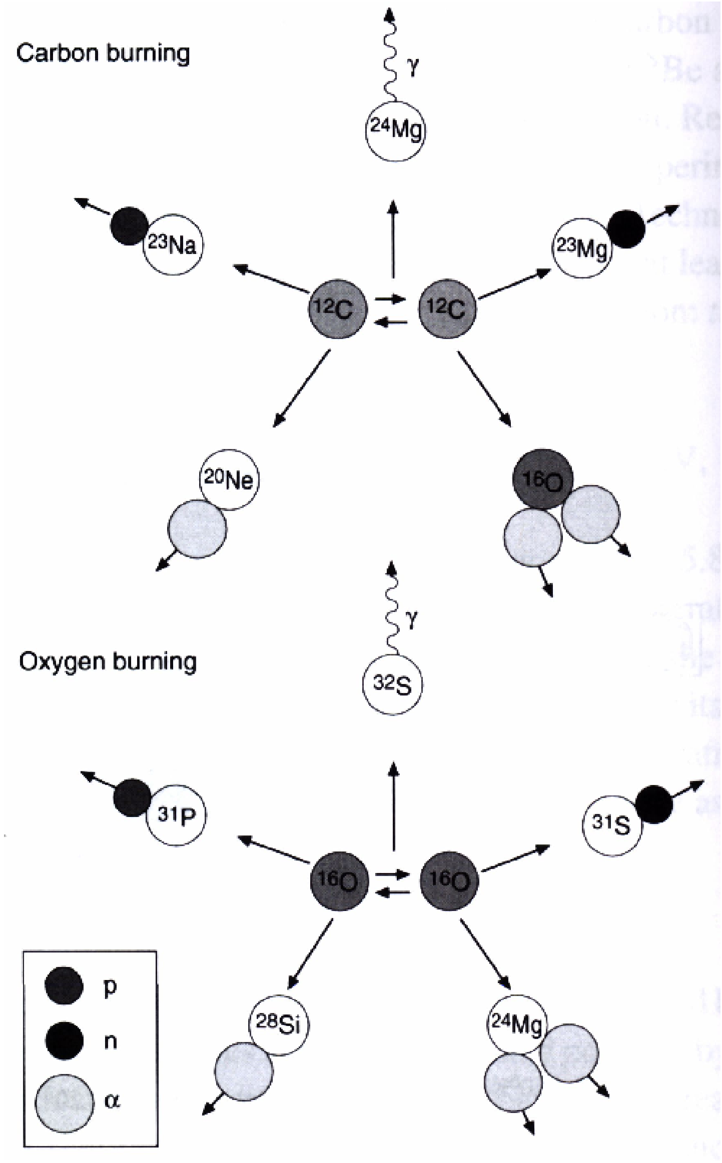
This reaction dominates over the inverse reaction known from helium burning for $T > 1.5 \times 10^{9}\,\mathrm{K}$.

Subsequently, the $^{4}\mathrm{He}$ is captured on another $^{20}\mathrm{Ne}$ nucleus:

$$^{20}\mathrm{Ne} + {}^{4}\mathrm{He} \rightarrow {}^{24}\mathrm{Mg} + \gamma .$$

The net result is
$$2\,{}^{20}\mathrm{Ne} + \gamma \rightarrow {}^{16}\mathrm{O} + {}^{24}\mathrm{Mg} + \gamma \; , \quad Q = +4.583\,\mathrm{MeV}$$

Carbon and Oxygen Burning



Carbon Burning

$$\begin{array}{llll} {}^{12}\mathrm{C} + {}^{12}\mathrm{C} & \rightarrow {}^{24}\mathrm{Mg} + \gamma & , & 13.931 \\ & \rightarrow {}^{23}\mathrm{Mg} + n & , & -2.605 \\ & \rightarrow {}^{23}\mathrm{Na} + p & , & 2.238 \\ & \rightarrow {}^{20}\mathrm{Ne} + \alpha & , & 4.616 \\ & \rightarrow {}^{16}\mathrm{O} + 2\alpha & , & -0.114 \end{array}$$

Average $Q = 13\,\mathrm{MeV}$

Oxygen Burning

$$\begin{array}{llll} {}^{16}\mathrm{O} + {}^{16}\mathrm{O} & \rightarrow {}^{32}\mathrm{S} + \gamma & , & 16.541 \\ & \rightarrow {}^{31}\mathrm{P} + p & , & 7.677 \\ & \rightarrow {}^{31}\mathrm{S} + n & , & 1.453 \\ & \rightarrow {}^{28}\mathrm{Si} + \alpha & , & 9.593 \\ & \rightarrow {}^{24}\mathrm{Mg} + 2\alpha & , & -0.393 \end{array}$$

Average $Q = 16\,\mathrm{MeV}$

Silicon/Sulfur Burning

Actually, often we have more sulfur in the star than there is silicon, but it is custom to call this phase “silicon burning”.

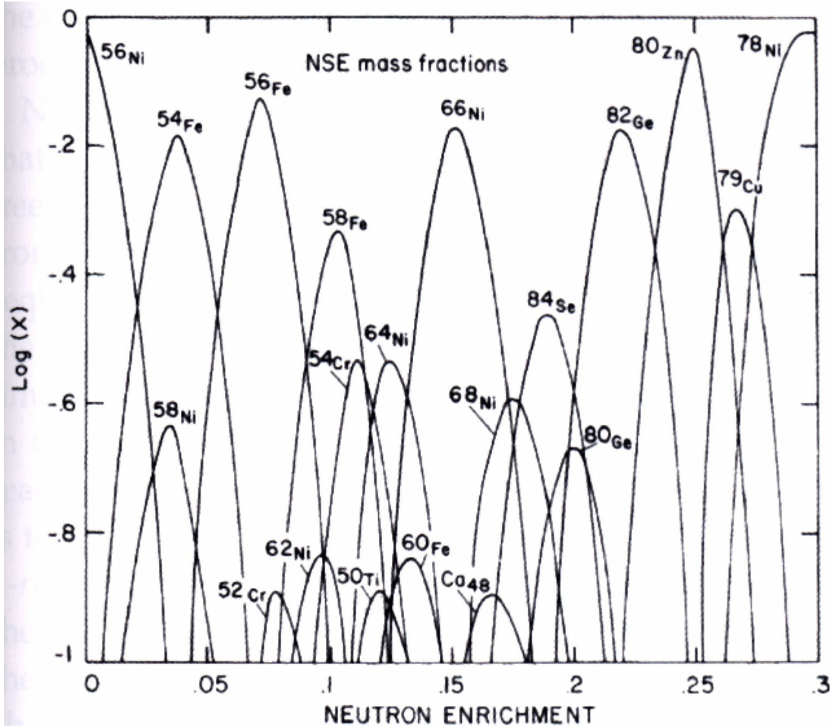
Typical burning temperature is $3 \ldots 3.5 \times 10^9\,\mathrm{K}$.

Similar to neon burning, silicon burning proceeds as a series of photo-disintegration reactions, mostly, (γ, α), and helium capture reactions, (α, γ) to build up iron group elements.

$(\gamma, \alpha) \rightleftharpoons (\alpha, \gamma)$

At the high T and ρ of these conditions, also *weak reactions* occur, converting protons into neutrons and leading to a *neutron excess*. This allows to actually make stable iron isotopes.

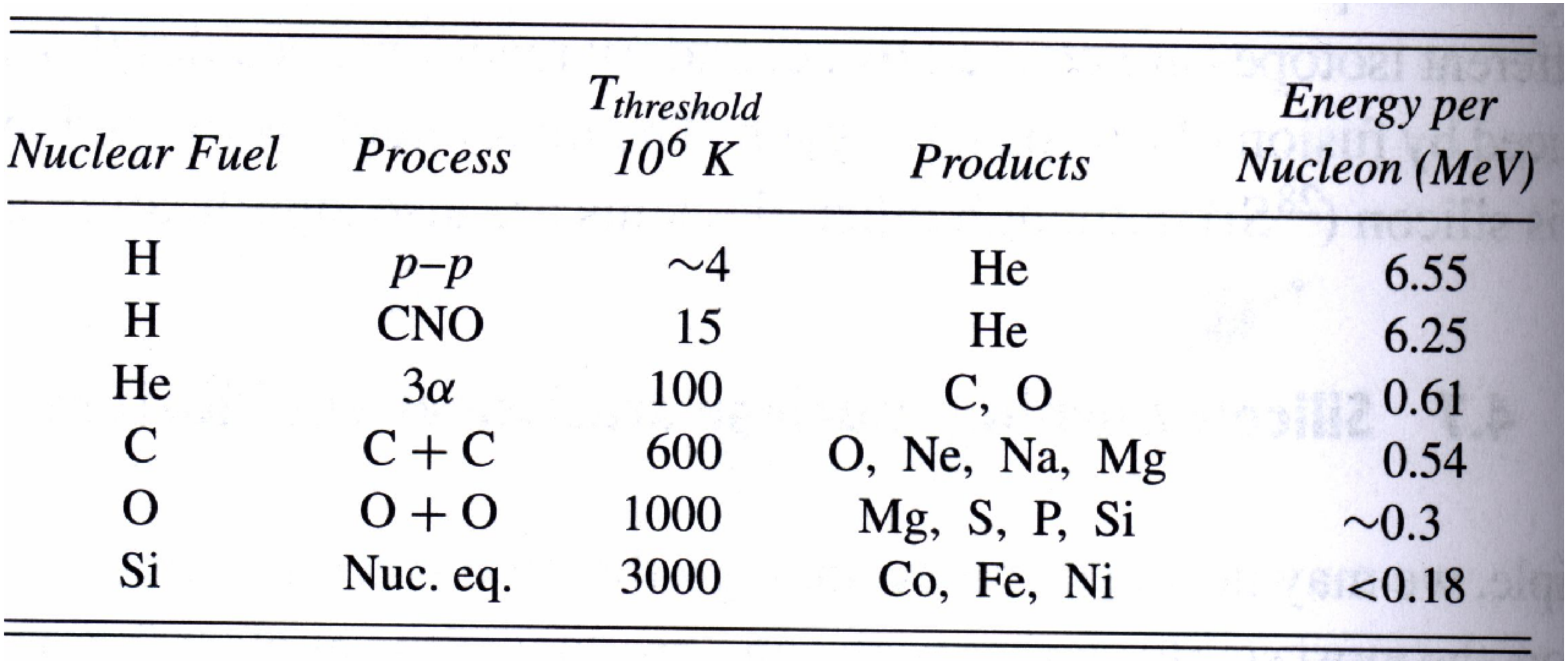
Beyond Silicon Burning



NSE distribution for
$T = 3.5 \times 10^9\,\mathrm{K}$,
$\rho = 10^7\,\mathrm{g/cm^3}$

After silicon burning T and ρ is so high that the nuclei are in **nuclear statistical equilibrium**, i.e., the reactions are fast compared to the evolution time-scale of the star, and the abundance distribution of the nuclei is given by a *Saha equation*.

Summary of Energies

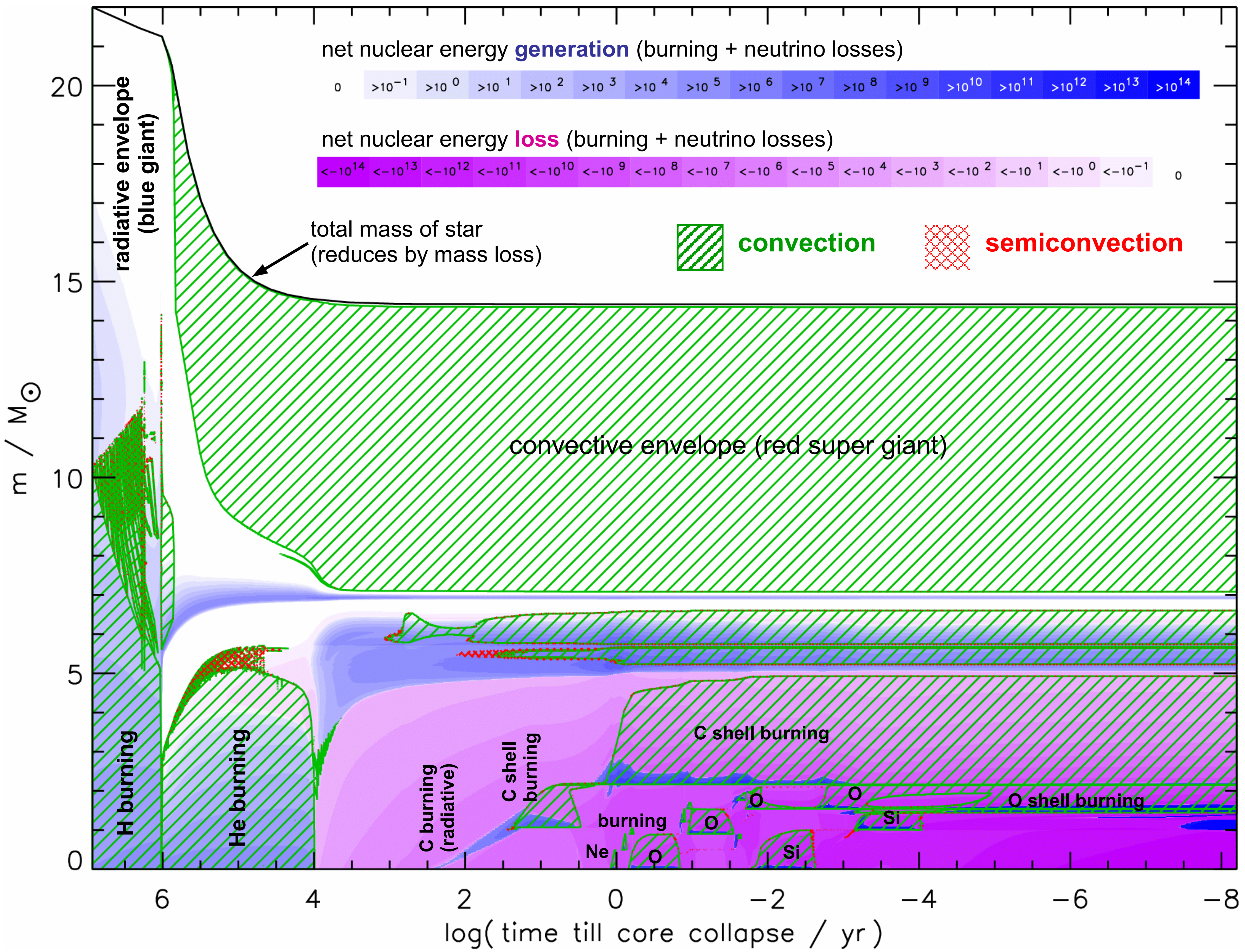


Nuclear Fuel	*Process*	$T_{threshold}$ 10^6 *K*	*Products*	*Energy per Nucleon (MeV)*
H	p–p	~4	He	6.55
H	CNO	15	He	6.25
He	3α	100	C, O	0.61
C	C + C	600	O, Ne, Na, Mg	0.54
O	O + O	1000	Mg, S, P, Si	~0.3
Si	Nuc. eq.	3000	Co, Fe, Ni	<0.18

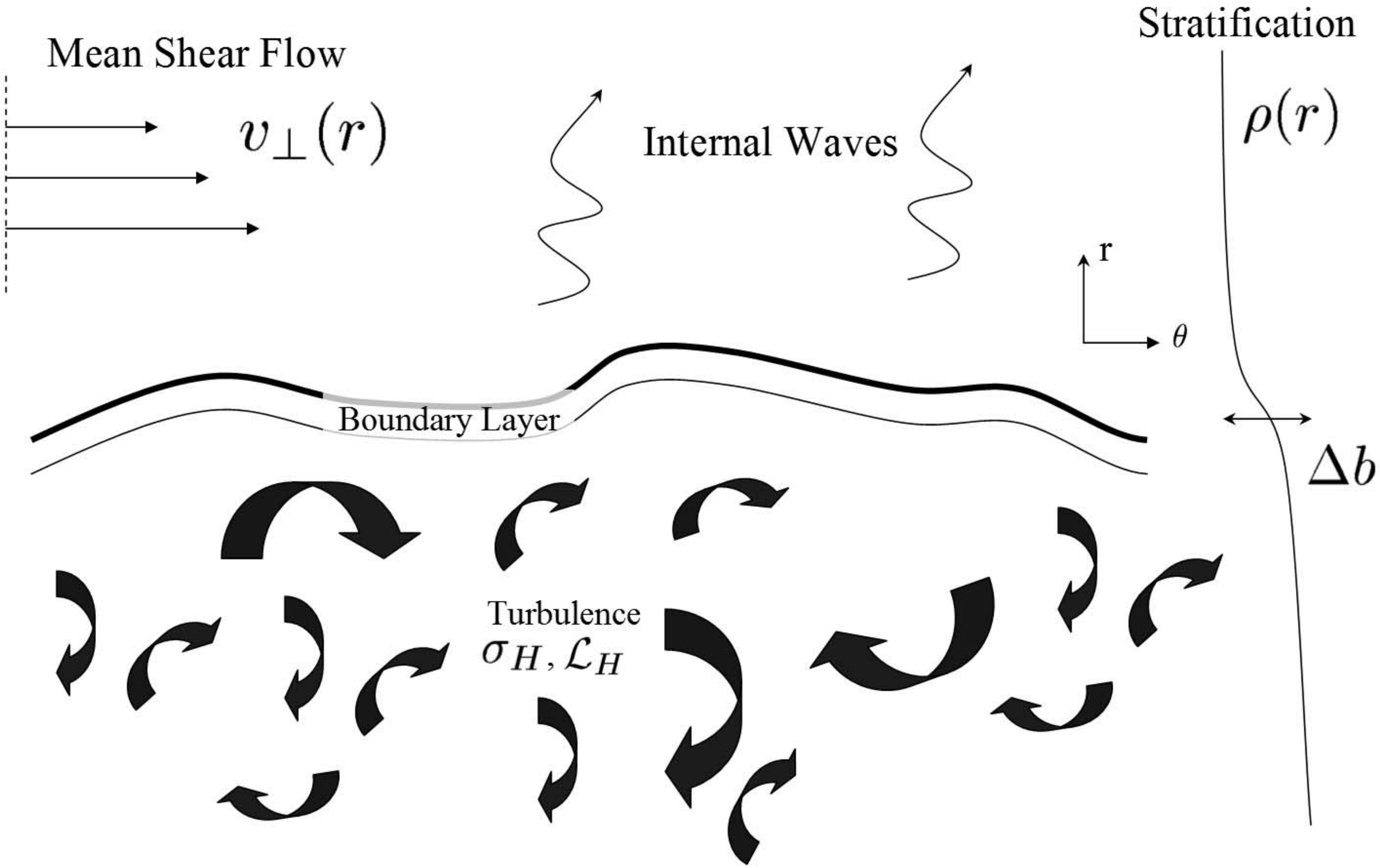
Nitrogen Burning

$$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+}\nu_{e})^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$$

- ^{14}N is made as slowest reactant in CNO cycle
- It is made from initial metals, not as a primary product
- Depending on metallicity, the abundance can be come significant; it will be more important for more metal-rich stars.
- ^{14}N burning occurs at the onset – before – central helium burning and can have its own convective burning phase, take a few % of helium burning time.

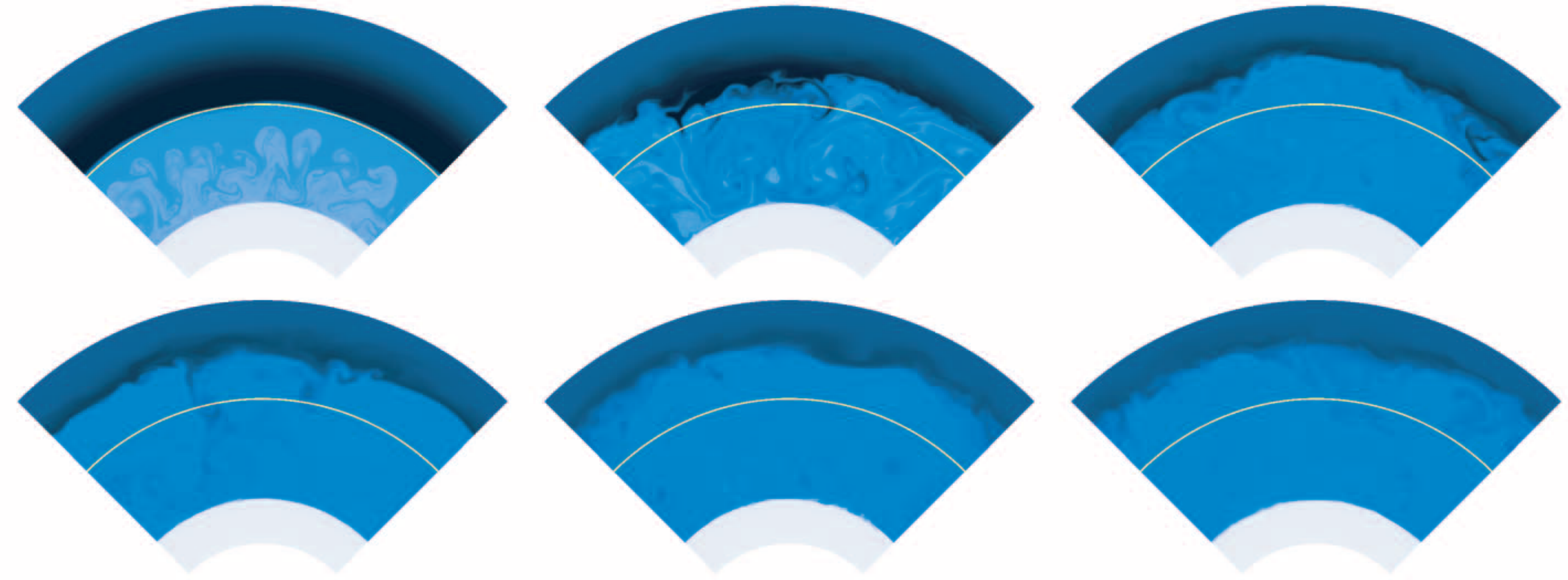

net nuclear energy generation (burning + neutrino losses)
0
>10−1
>10 0
>10 1
>10 2
>10 3
>10 4
>10 5
>10 6
>10 7
>10 8
>10 9
>1010
>1011
>1012
>1013
>1014
net nuclear energy loss (burning + neutrino losses)
<−1014
<−1013
<−1012
<−1011
<−1010
<−10 9
<−10 8
<−10 7
<−10 6
<−10 5
<−10 4
<−10 3
<−10 2
<−10 1
<−10 0
<−10−1
0
convection
semiconvection
total mass of star
(reduces by mass loss)
radiative envelope
(blue giant)
convective envelope (red super giant)
H burning
He burning
C burning
(radiative)
C shell
burning
C shell burning
Ne
burning
O
O
O
O
O shell burning
Si
Si
m / M⊙
20
15
10
5
0
6
4
2
0
−2
−4
−6
−8
log(time till core collapse / yr)

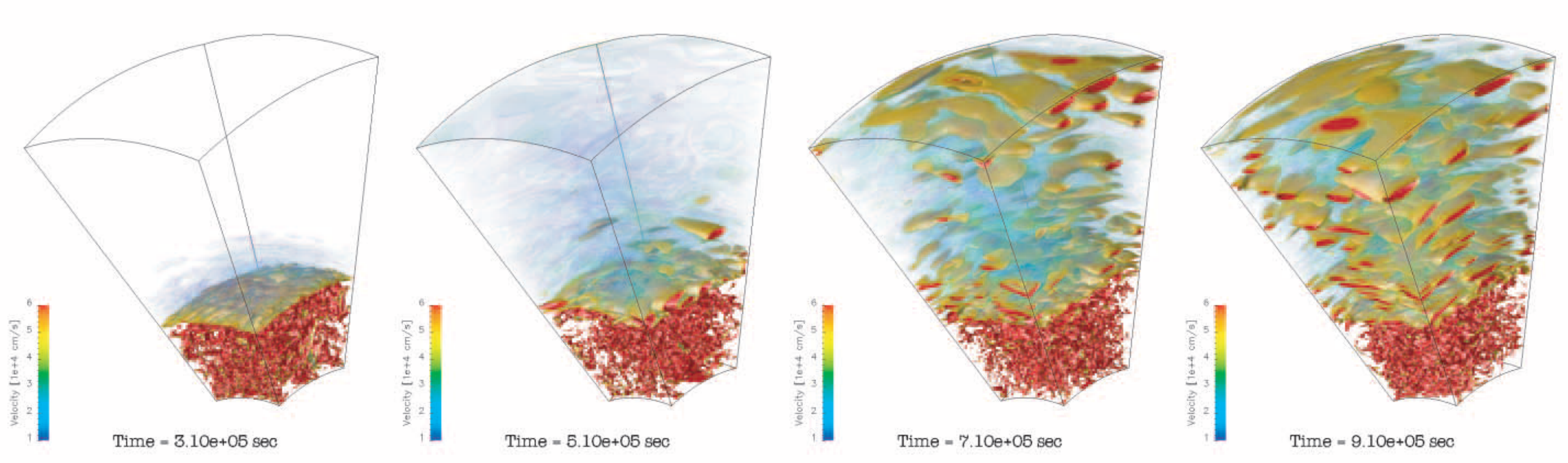
Mufti-Dimensional Convection



(Meaken & Arnett 2007)

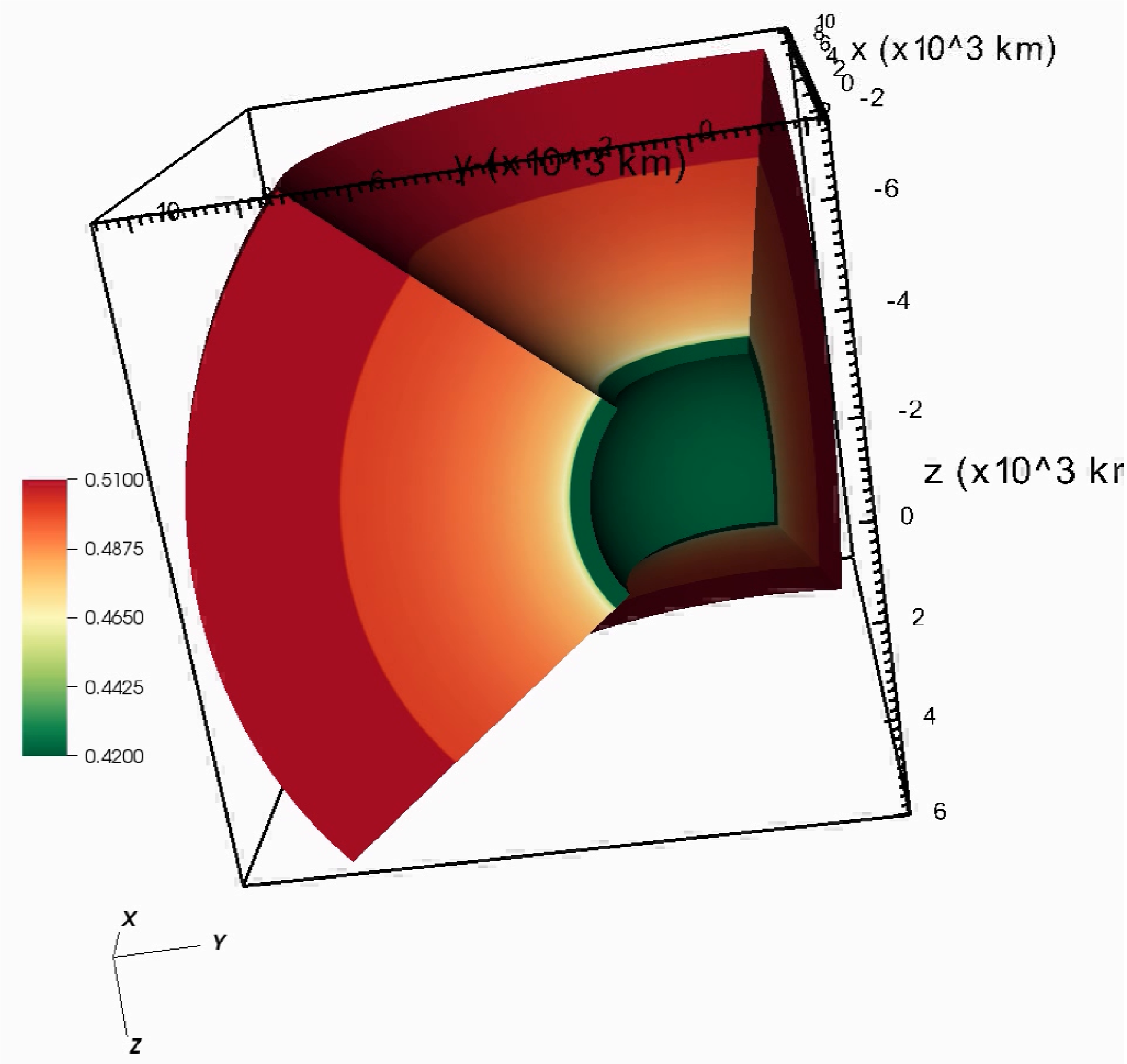
Multi-Dimensional Convection





(Meaken & Arnett 2007)

The Last Three Minutes of a Star



Mueller+ 2016 in prep.