CONVECTION AND DEFLAGRATIONS IN THE PROGENITOR STARS OF SUPERNOVAE

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STELLAR EVOLUTION
AN OVERVIEW

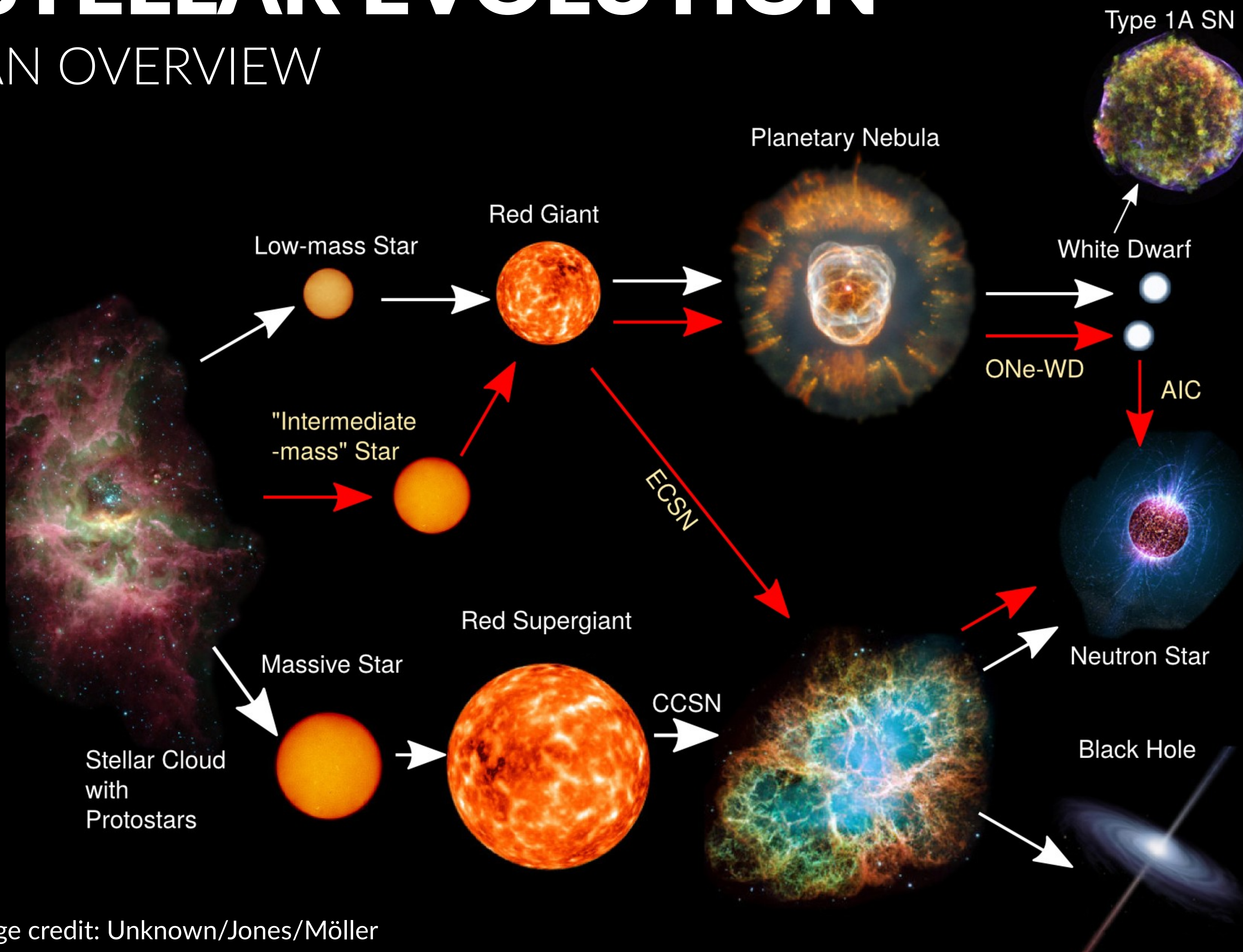


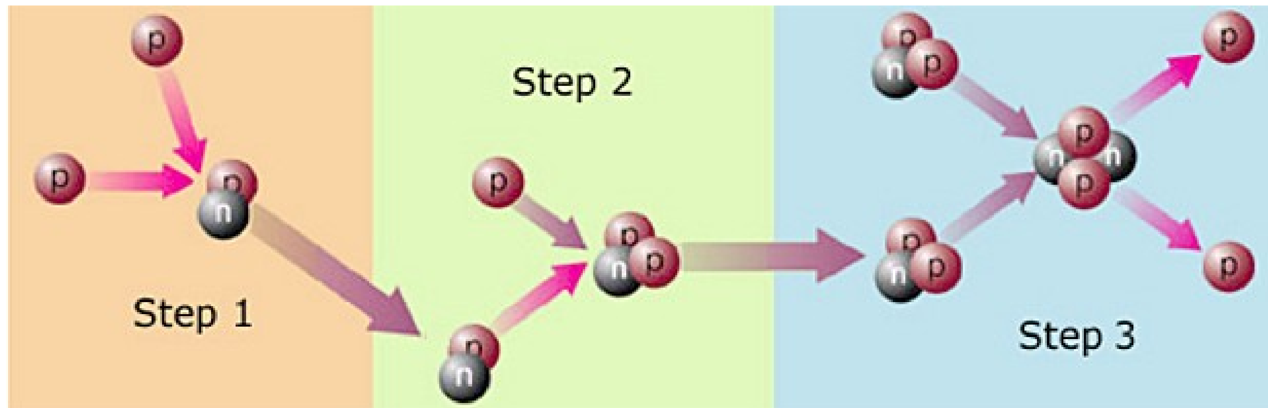
Image credit: Unknown/Jones/Möller

LOW AND INTERMEDIATE MASS STARS

Image Credit: David Taylor

H → He

p-p chain

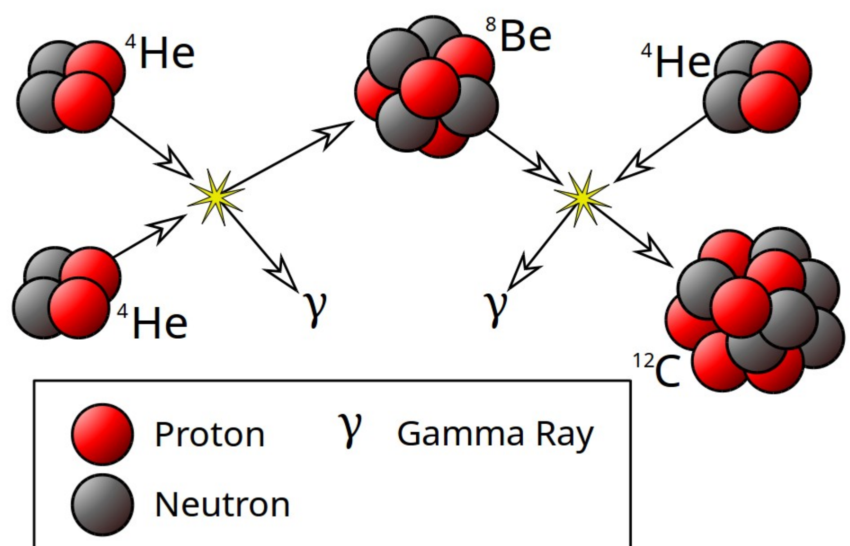


If the star is massive enough (> 0.8 solar masses):

He → C & O

Triple-α

$^{12}C\,(\alpha, \gamma)\,^{16}O$



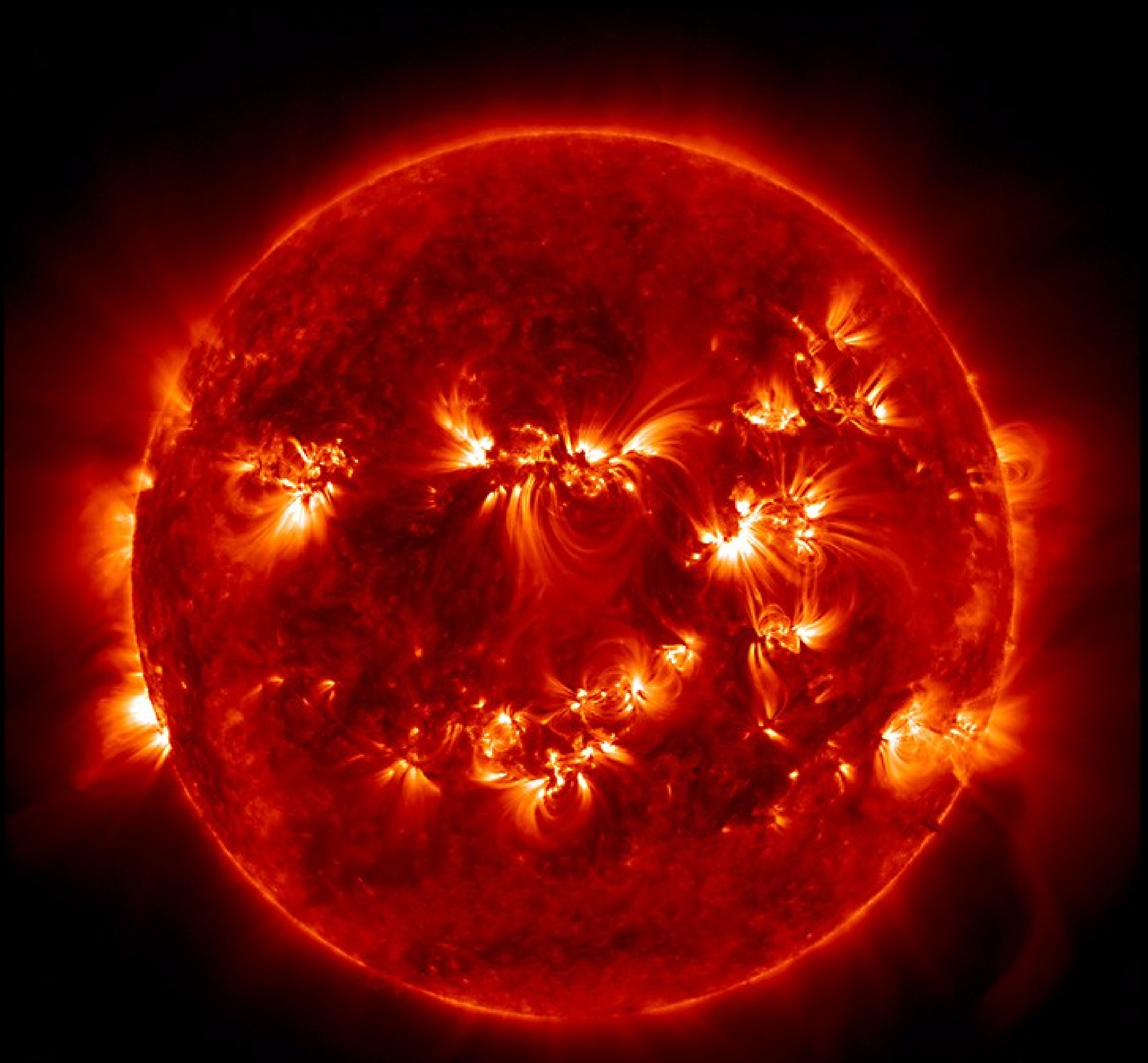


Image Credit: Solar Dynamics Observatory, NASA

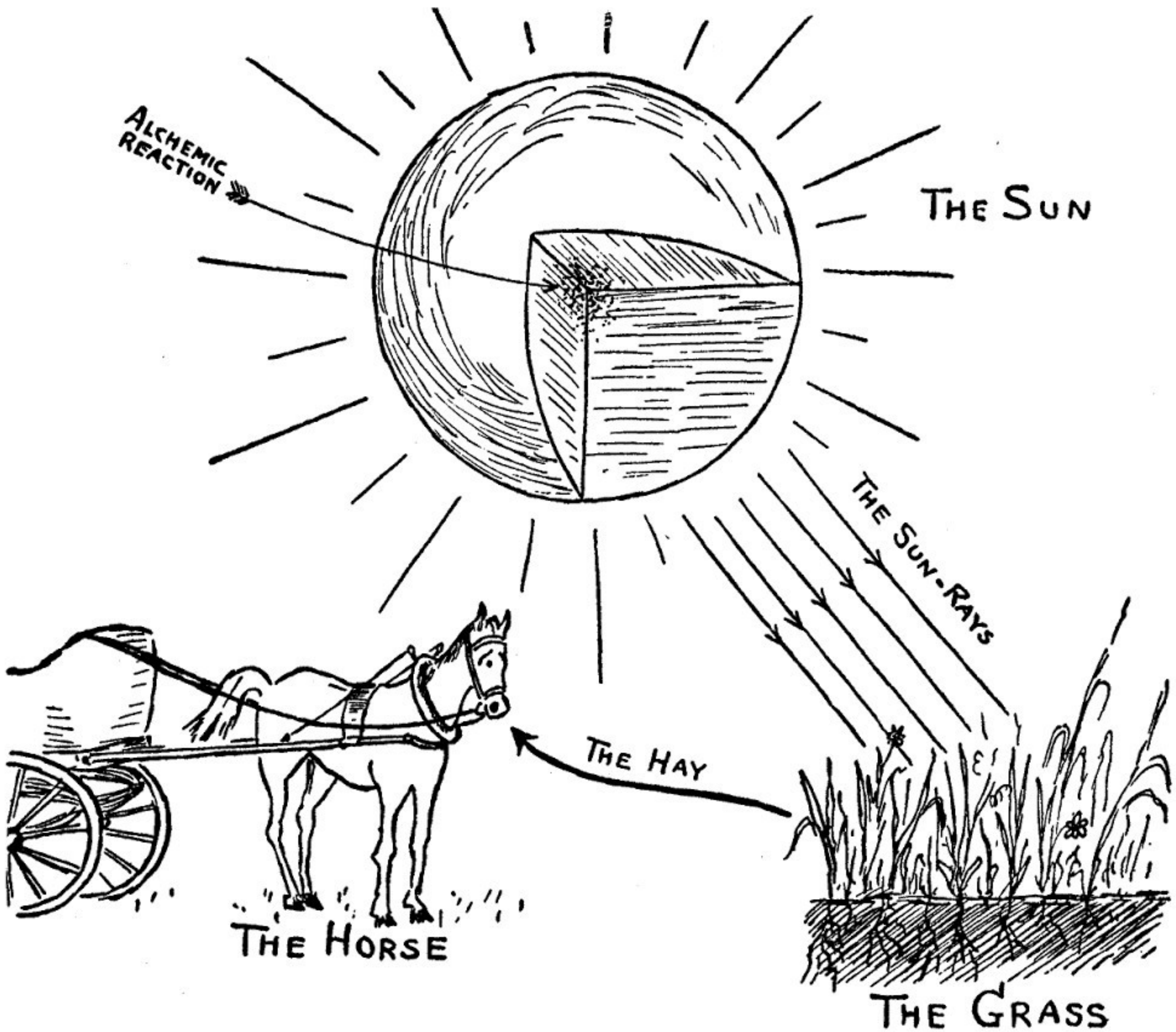
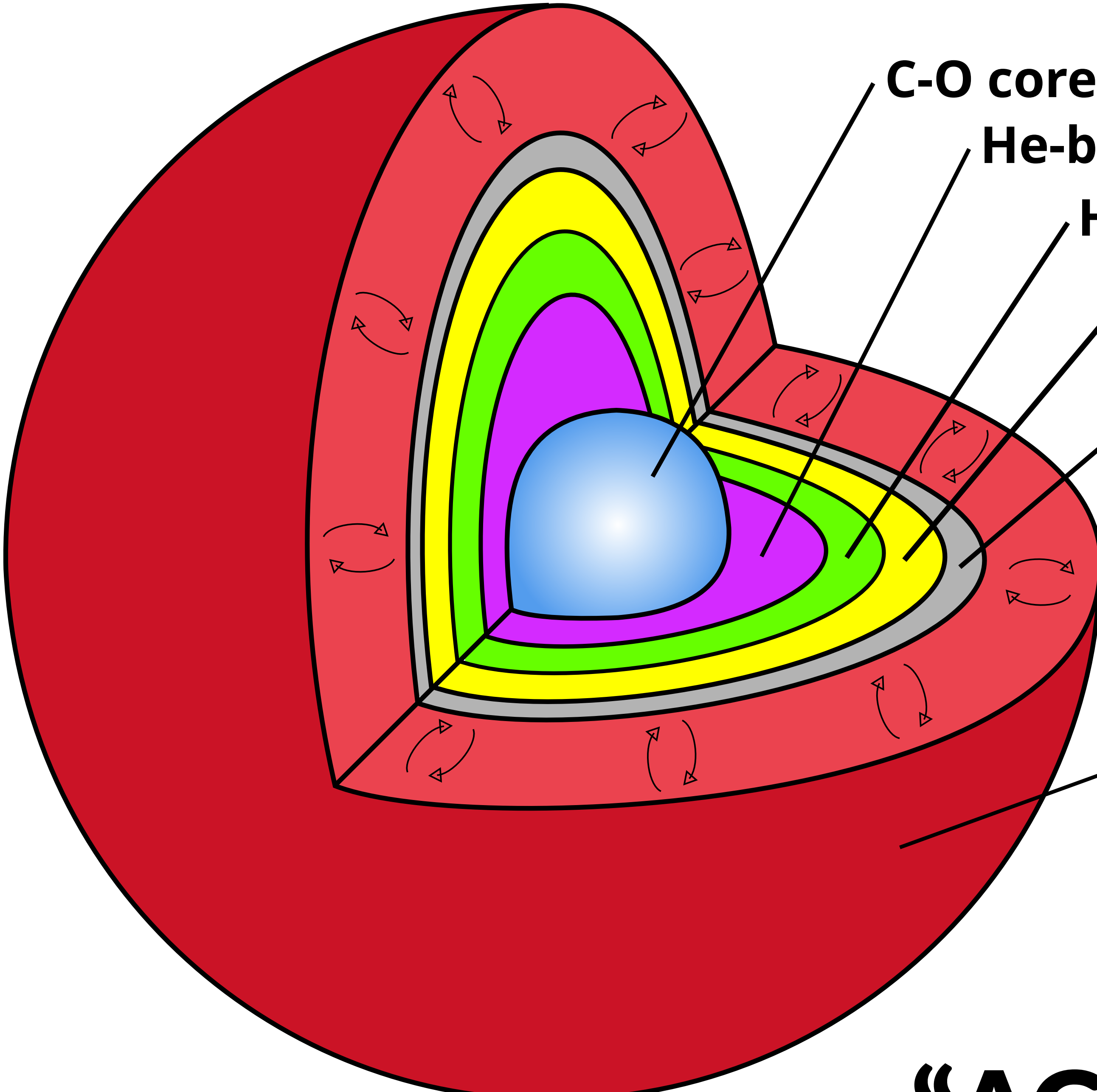


Fig. 22. The Horse as an atomic power motor.

George Gamow, *Atomic Energy in Cosmic and Human Life*, 1945/1947



"AGB" STAR

Image credit: Persson, Magnus Vilhelm (2013)

PLANETARY NEBULAE
& WHITE DWARFS

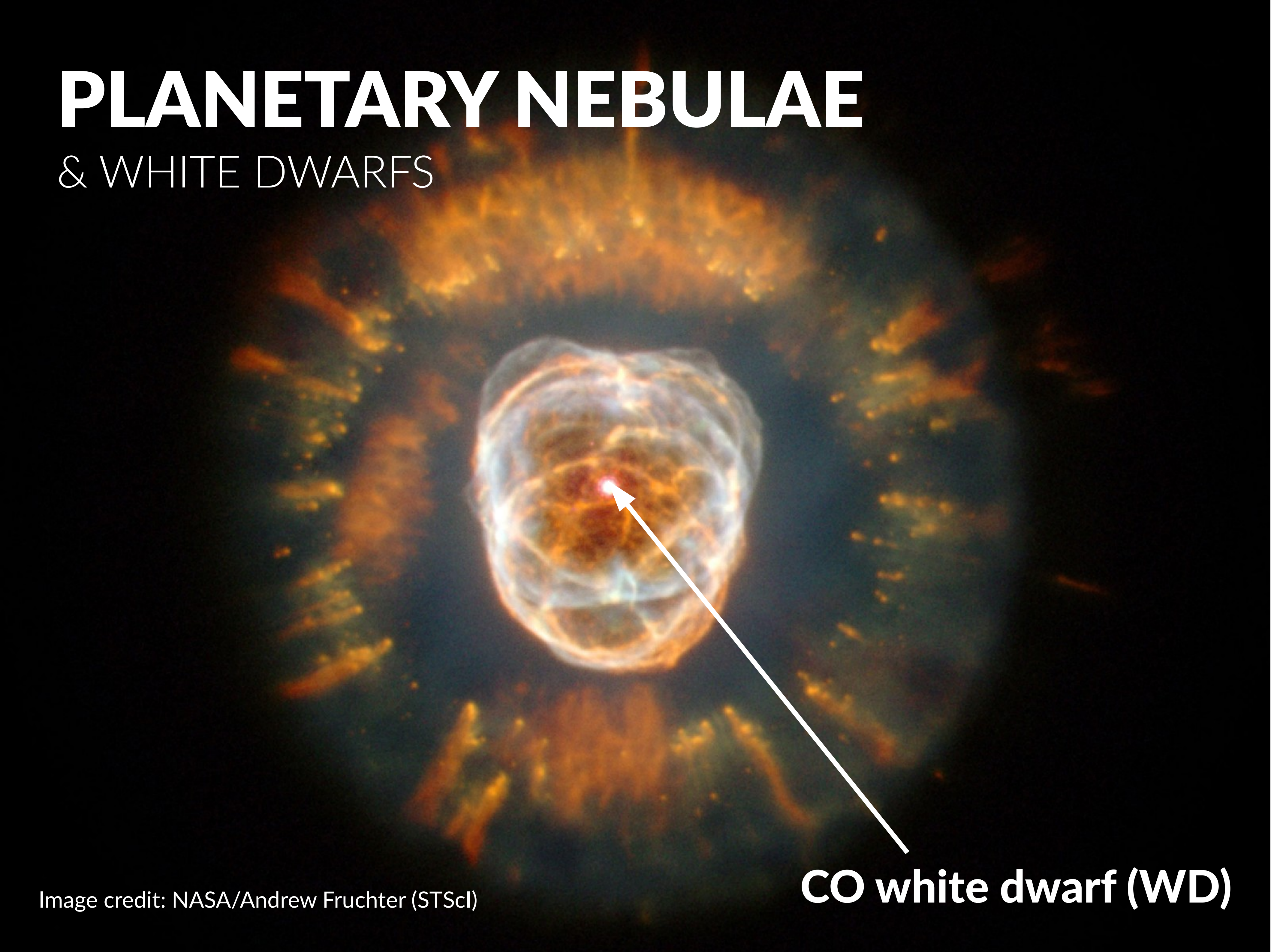


Image credit: NASA/Andrew Fruchter (STScI)

EXPLODING WHITE DWARFS

THERMONUCLEAR SUPERNOVAE

MASSIVE STARS

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^{4}He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,{}^{4}He \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si,S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)\ldots$

Image credit: Alexander Heger

Star develops an 'iron' core

COLLAPSE OF THE IRON CORE

Silicon burns into 'iron' in a shell until the iron core exceeds the critical mass that can be supported by its degenerate electron gas: the **effective Chandrasekhar limit**

The core collapses until the central region reaches **nuclear saturation density** (~10^{14} g/cc); The in-falling material **bounces**, launching a **shock wave; [shock stalling and revival]; supernova explosion**

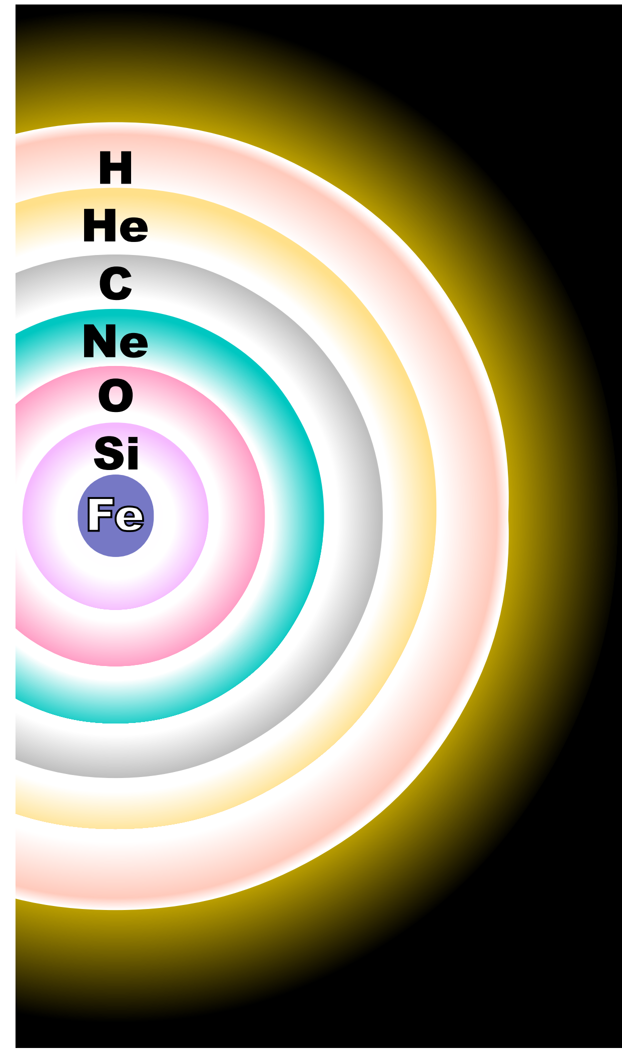


Image credit: R. J. Hall

CORE-COLLAPSE SUPERNOVAE

CAS A

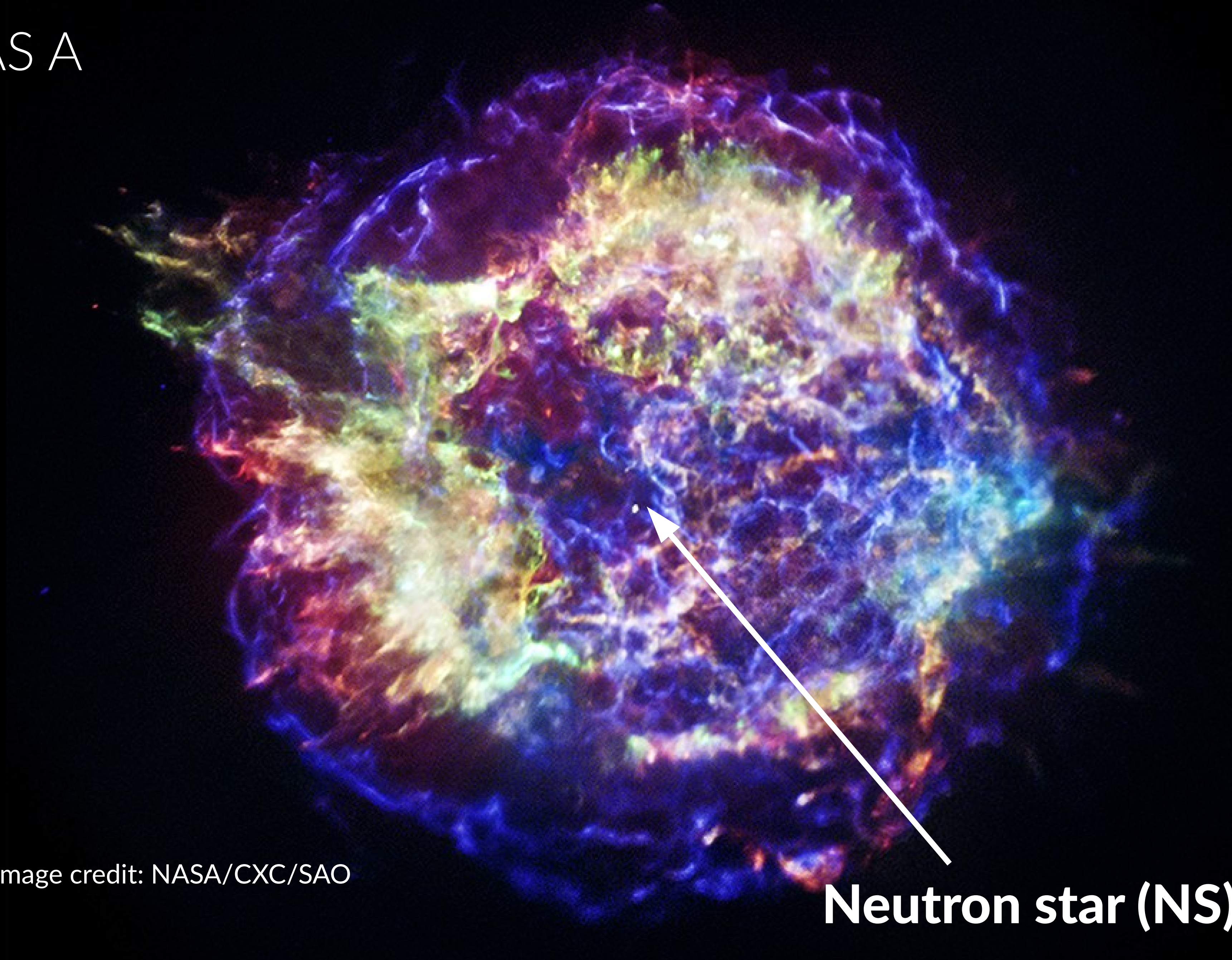
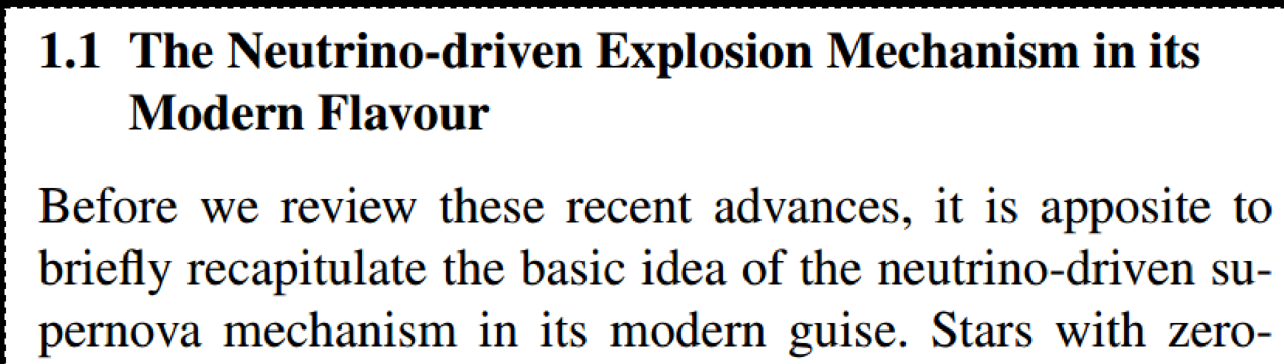


Image credit: NASA/CXC/SAO

CORE-COLLAPSE SUPERNOVAE

THEORETICAL UNDERSTANDING



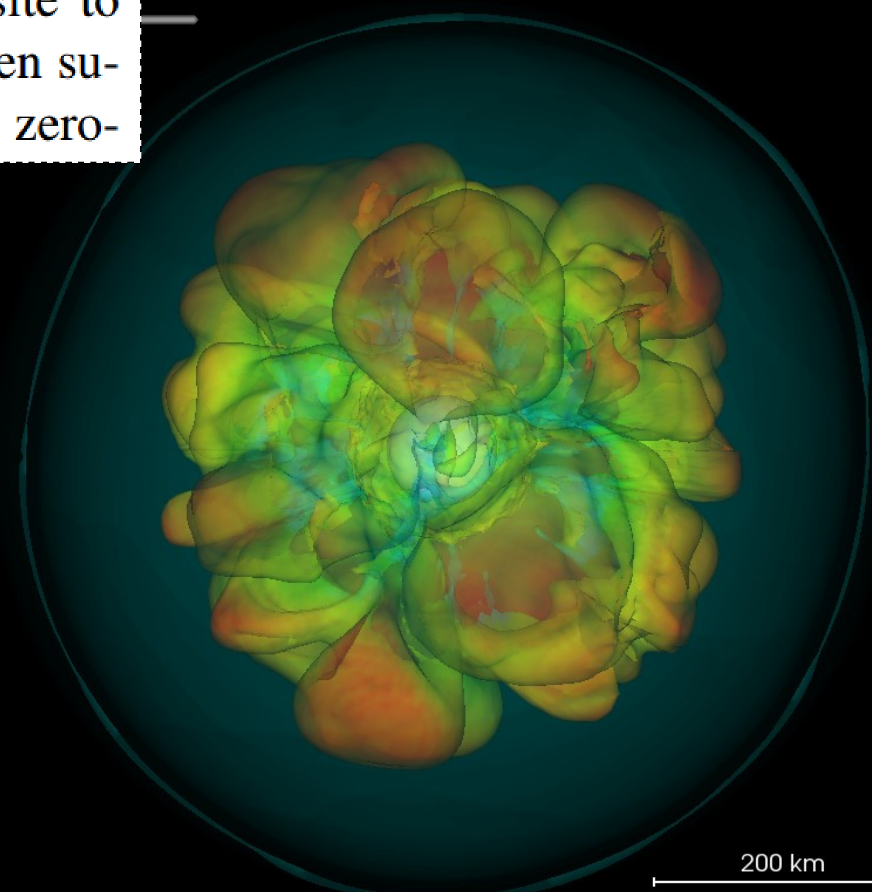
1.1 The Neutrino-driven Explosion Mechanism in its Modern Flavour

Before we review these recent advances, it is apposite to briefly recapitulate the basic idea of the neutrino-driven supernova mechanism in its modern guise. Stars with zero-

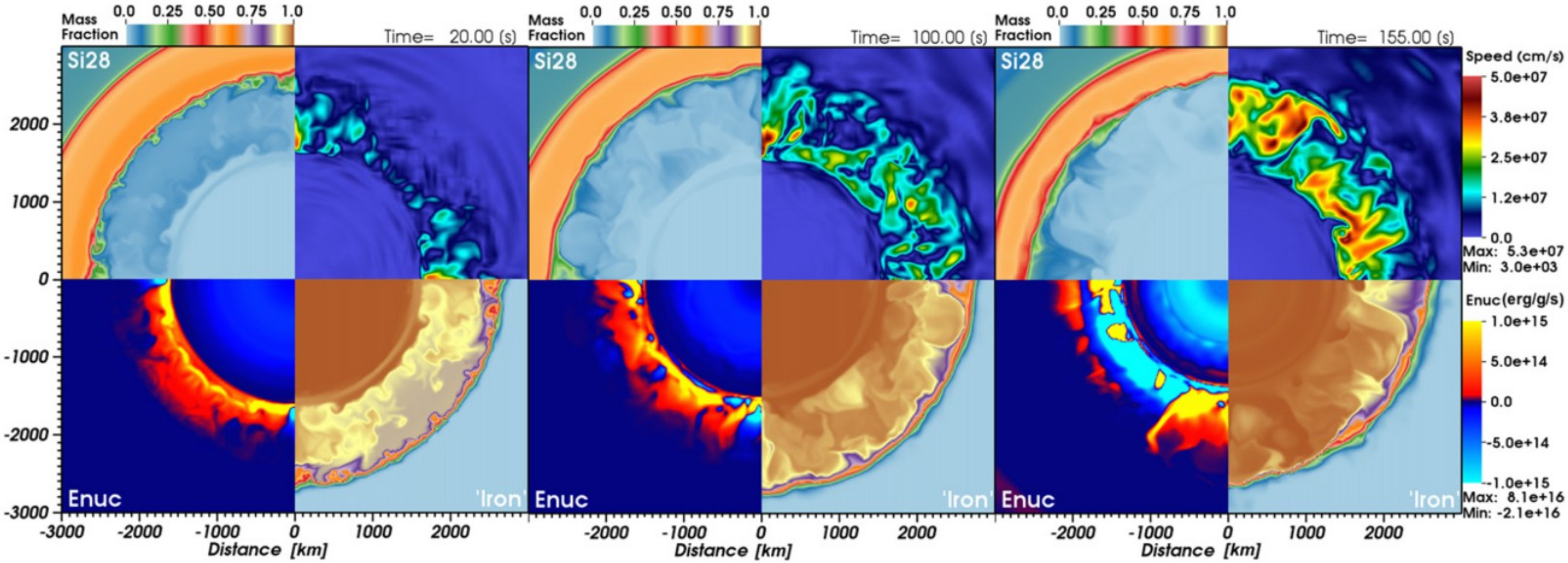
Bernhard Müller, 2016, PASA 33, 48

Successful simulations are very challenging:

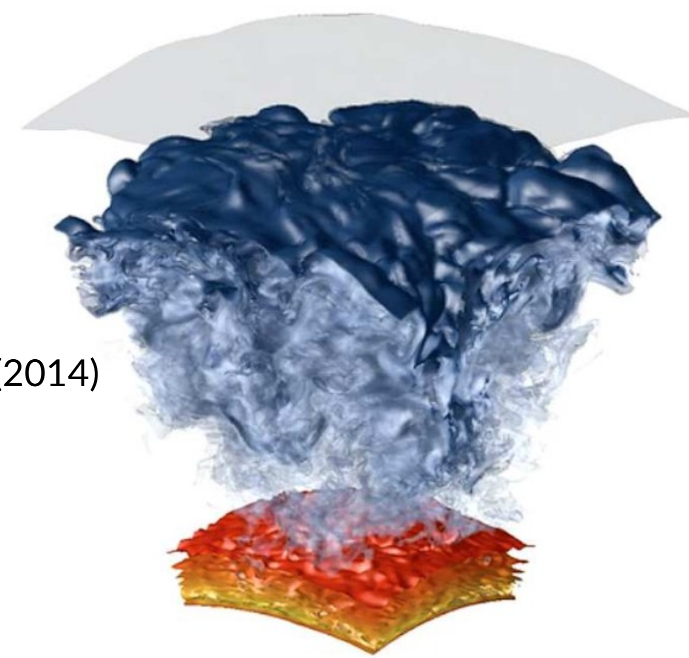
- Computation time
- Microphysics (EoS,...)
- Detailed neutrino transport
- Resolving required length scales (turbulence)
- **Adequate progenitor models**
    - **Stellar structure**
    - **Multidimensional phenomena**



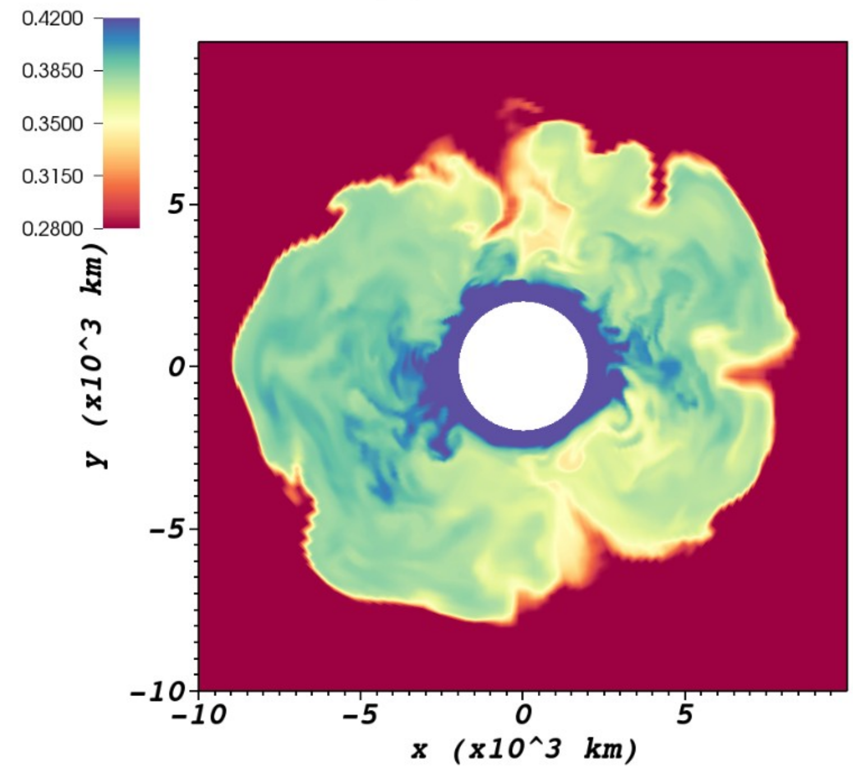
Melson+ (2015)



Couch+ (2015)



Arnett+ (2014)

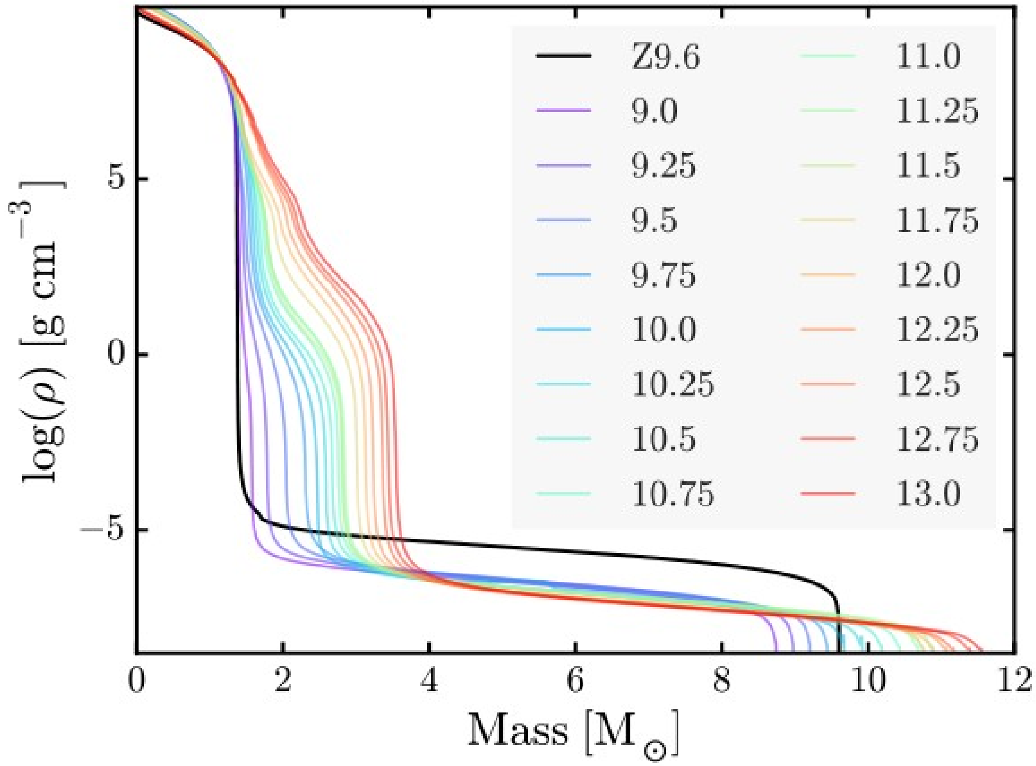


Müller+ (2016)

3D PROGENITORS

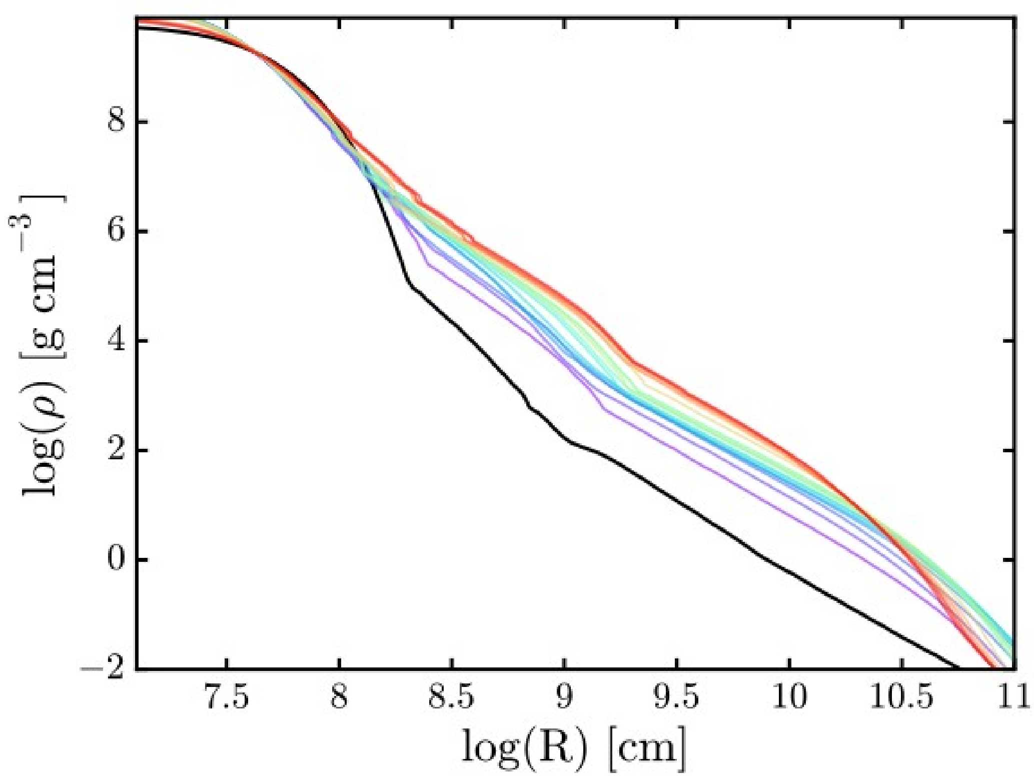
1D

Pre-supernova density profiles from the calculations of Tuguldur (Sukhbold)+ (2016) in spherical symmetry



The long-term structural evolution of stars must be calculated under the assumption of spherical symmetry, owing to the dynamic range of both the time and length scales involved.

Physical processes with unresolvable characteristic time and length scales, or with a symmetry other than spherical, must be treated approximately (e.g. convection, rotation, mass loss, binary interaction, flames, magnetic fields).



1D MODELS

More generally, some goals of the 1D approach are:

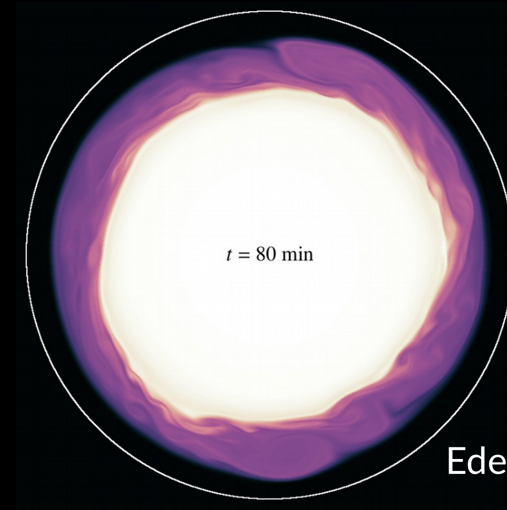
- Predictive models
- Include the full star; whole lifetime
- Initial—final (WD) mass relation
- Connect IMF to NS and BH mass function
- Progenitor models for SN simulations
- Isochrones
- Photometric characteristics
- Input for population synthesis
- Nucleosynthesis yields
- Input for galactic chemical evolution models

GENEC
KEPLER
STARS
FRANEC
TYCHO
STERN
EVOL
GARSTEC
MONSTAR
STAREVOL
MESA

Approach of **3D modelling of stars:**

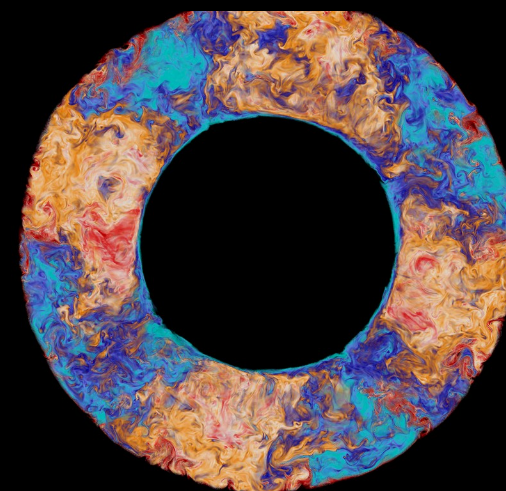
- Simulate inherently multi-dimensional phenomena
- Simulate dynamic phases and hydrodynamic instabilities in stars
- Improve predictive power of 1D models:
  - Testing approximations
  - Fixing free parameters

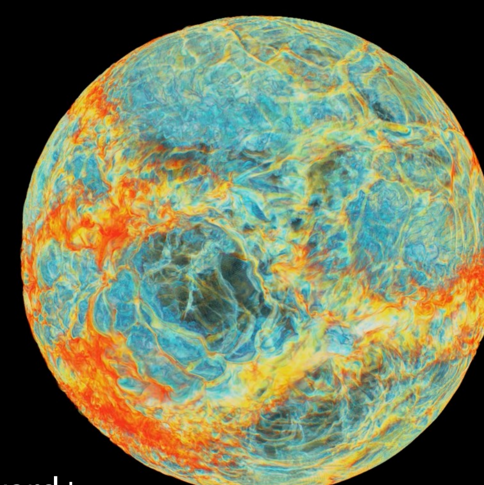
Long-term goal:
Develop improved models for convection, rotation, binary interactions, magnetic fields and winds in 1D models



Edelmann+ (2016, subm.)

Jones+ (2016)




Herwig & Woodward+

3D MODELS

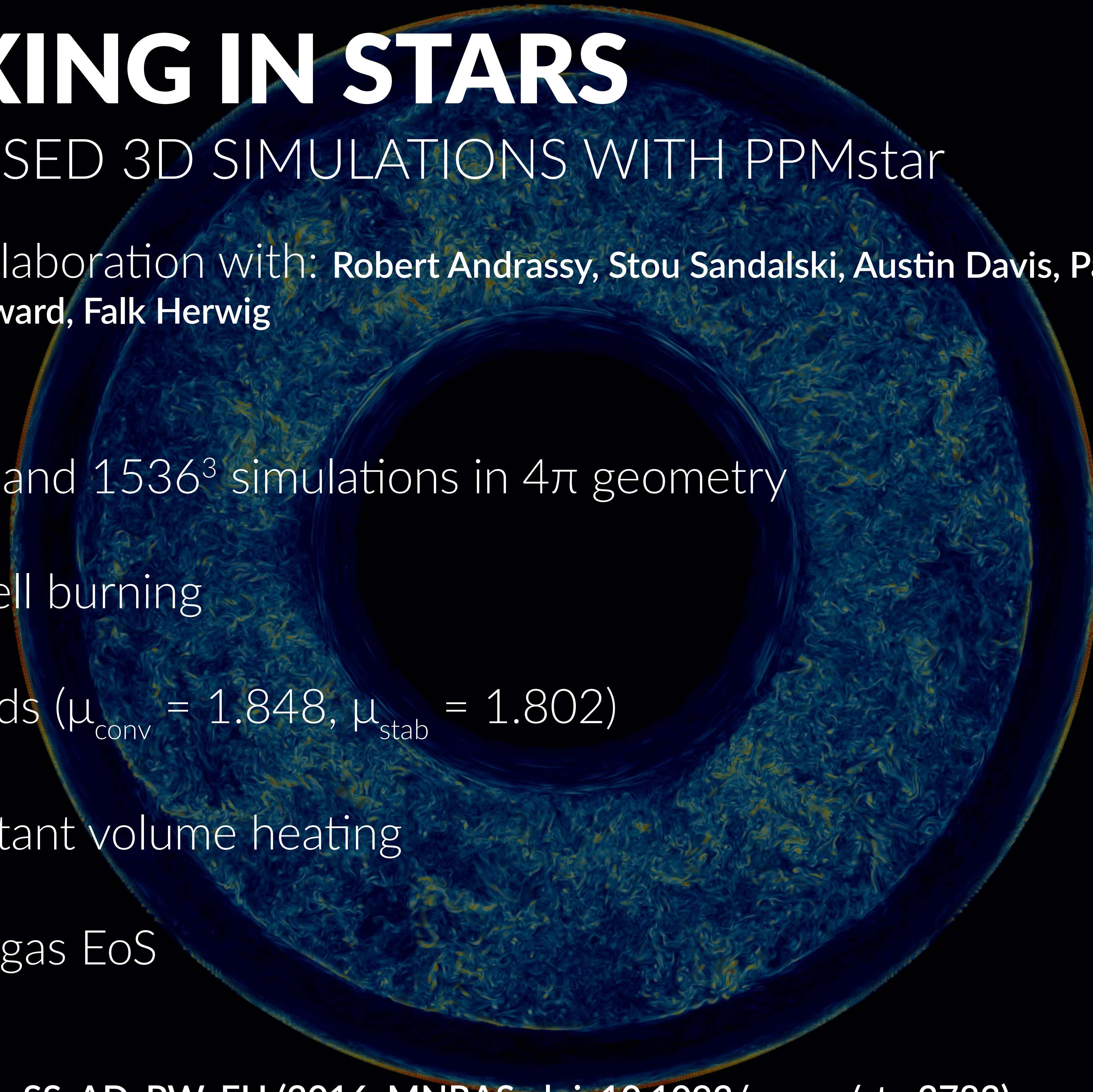
MIXING IN STARS

IDEALISED 3D SIMULATIONS TO INFORM 1D MODELS

S. Jones, RA, SS, AD, PW, FH (2016, MNRAS, doi: 10.1093/mnras/stw2783)

MIXING IN STARS

IDEALISED 3D SIMULATIONS WITH PPMstar



In collaboration with: **Robert Andrassy, Stou Sandalski, Austin Davis, Paul Woodward, Falk Herwig**

768^3 and 1536^3 simulations in 4π geometry

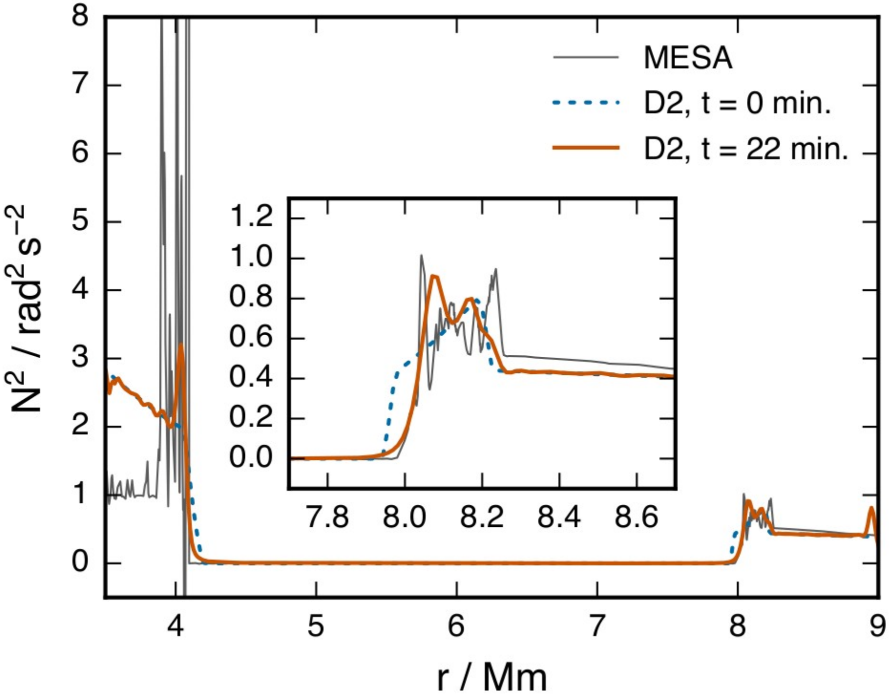
O shell burning

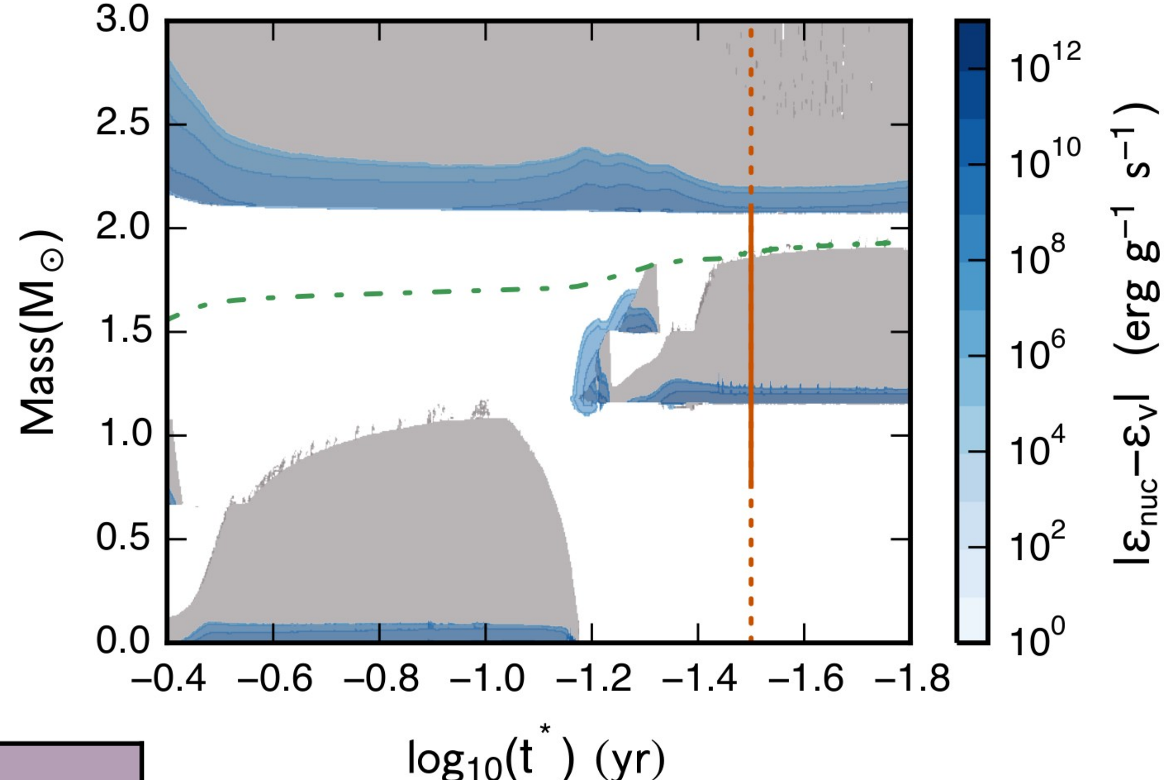
2 fluids ($\mu_{conv} = 1.848$, $\mu_{stab} = 1.802$)

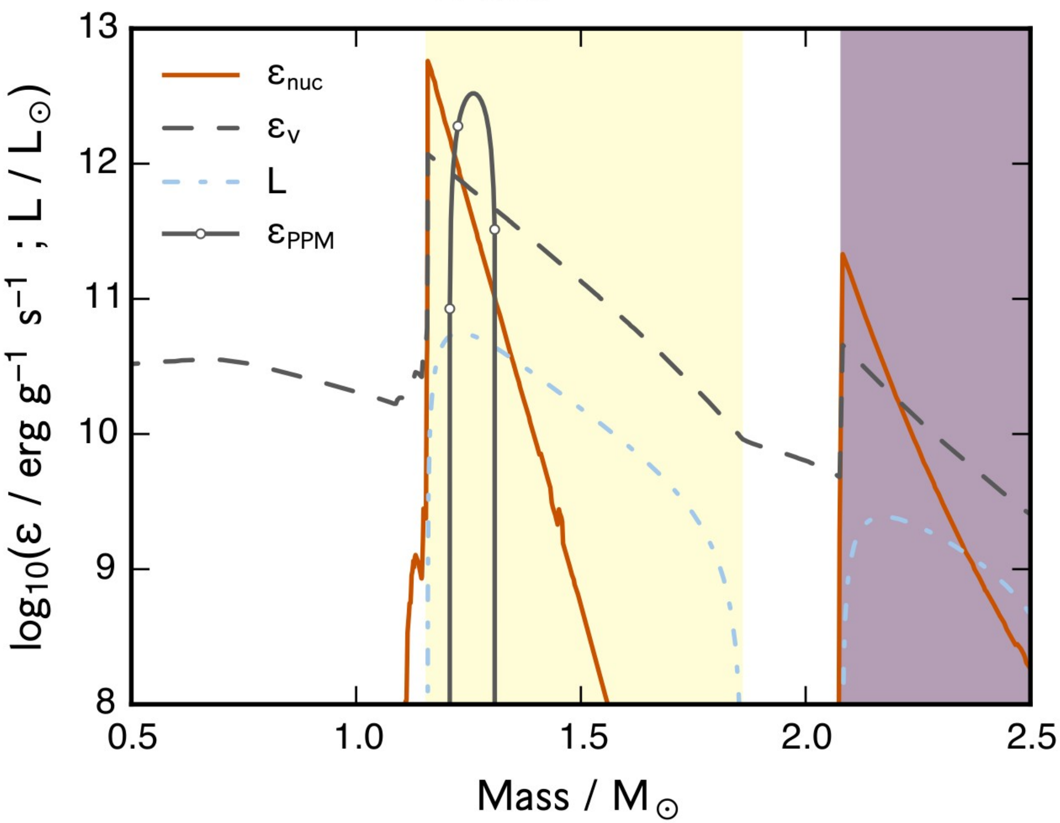
Constant volume heating

Ideal gas EoS

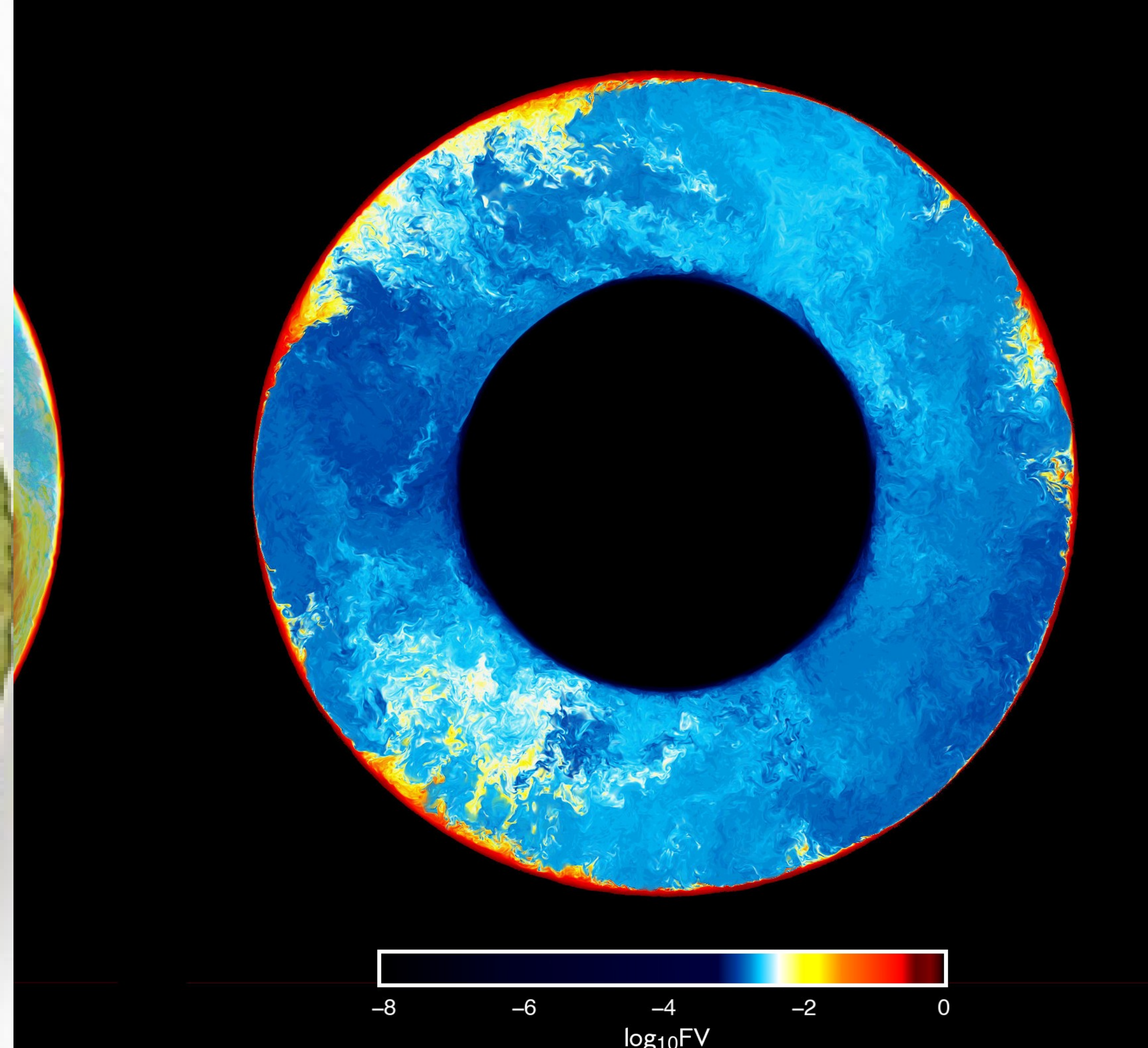
S. Jones, RA, SS, AD, PW, FH (2016, MNRAS, doi: 10.1093/mnras/stw2783)





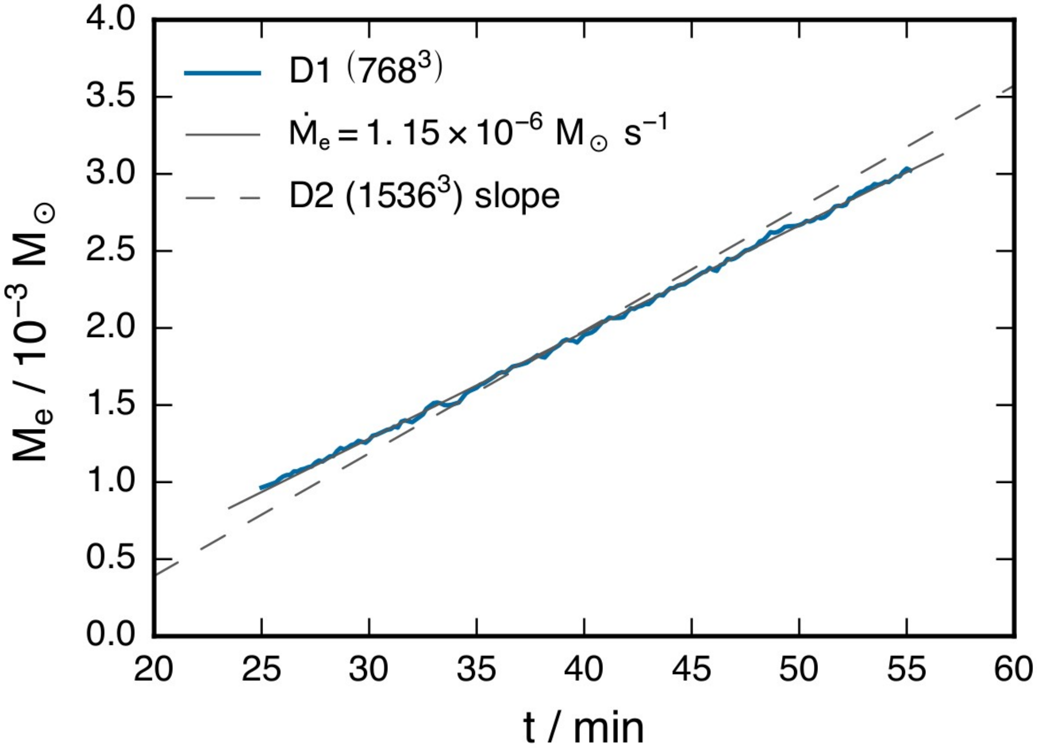


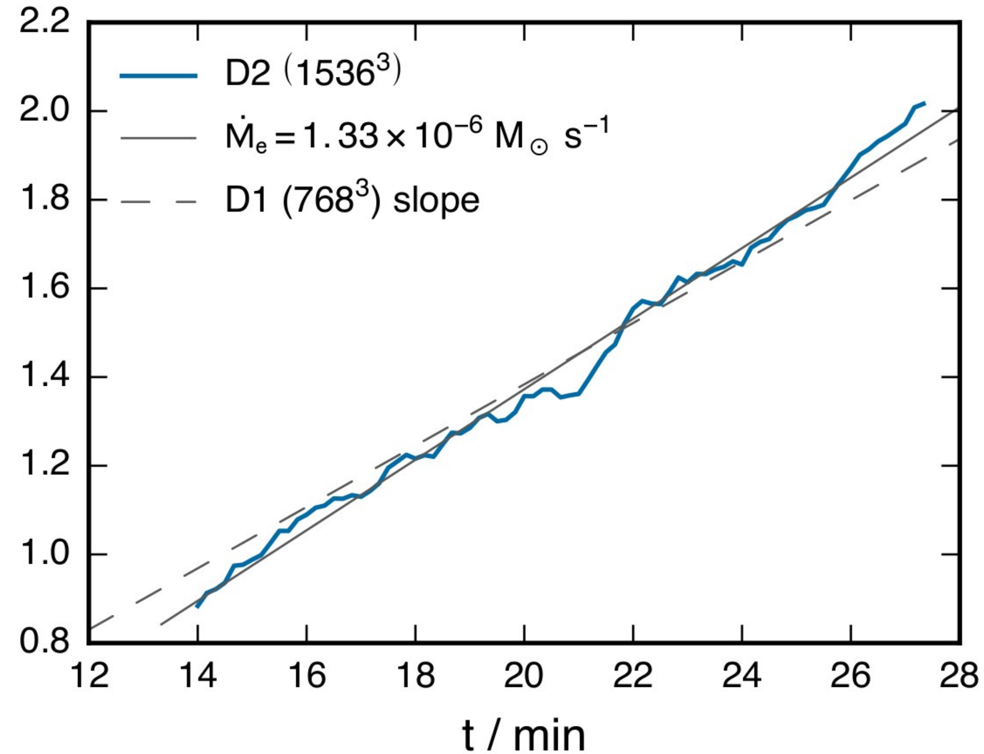
The hydrodynamic simulation is based on a 25 solar-mass, *Z*=0.02 1D hydrostatic model that was calculated using the MESA stellar evolution code (Paxton+ 2011, 2013, 2015) ne 1536^3 simulation at 27.2 minutes of simulated time



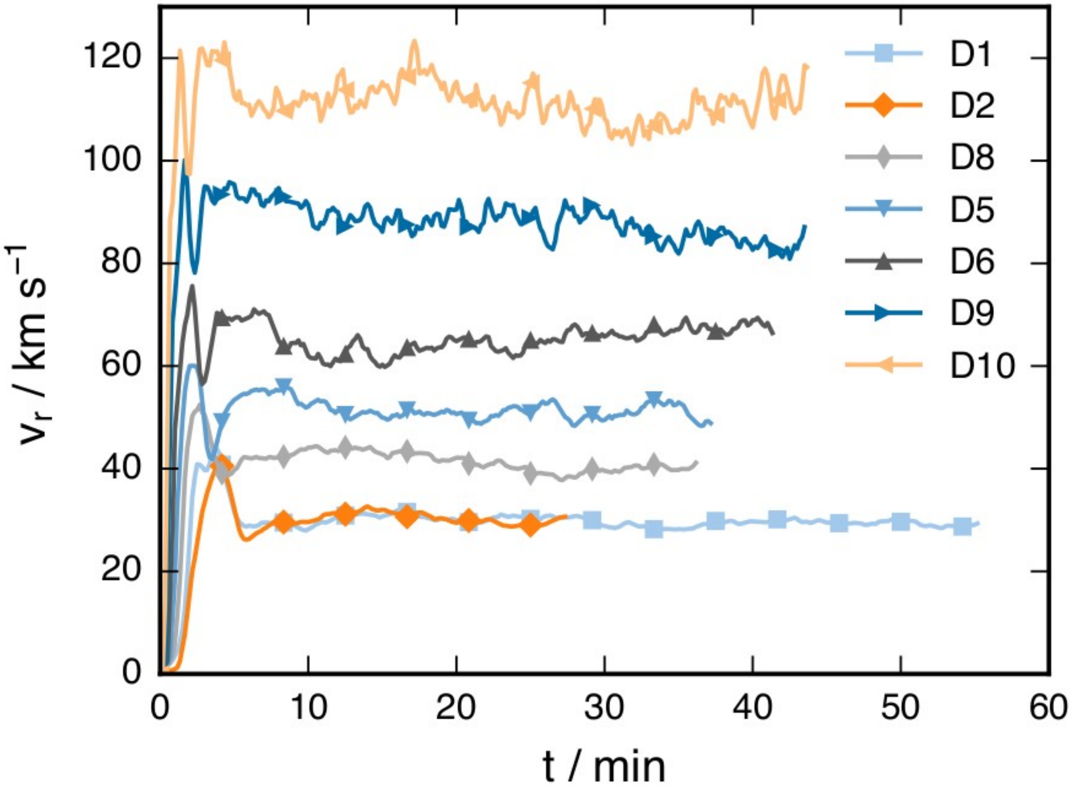
S. Jones, RA, SS, AD, PW, FH (2016, MNRAS, doi: 10.1093/mnras/stw2783)

Rate at which overlying stable fluid is entrained into the convection zone

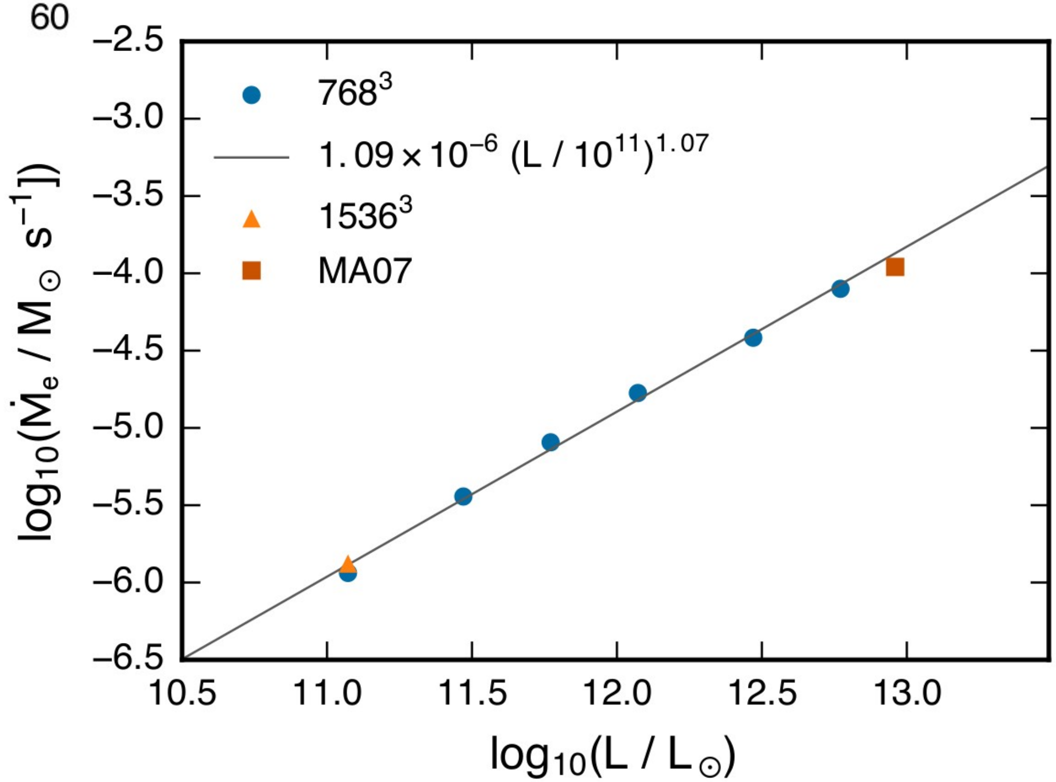




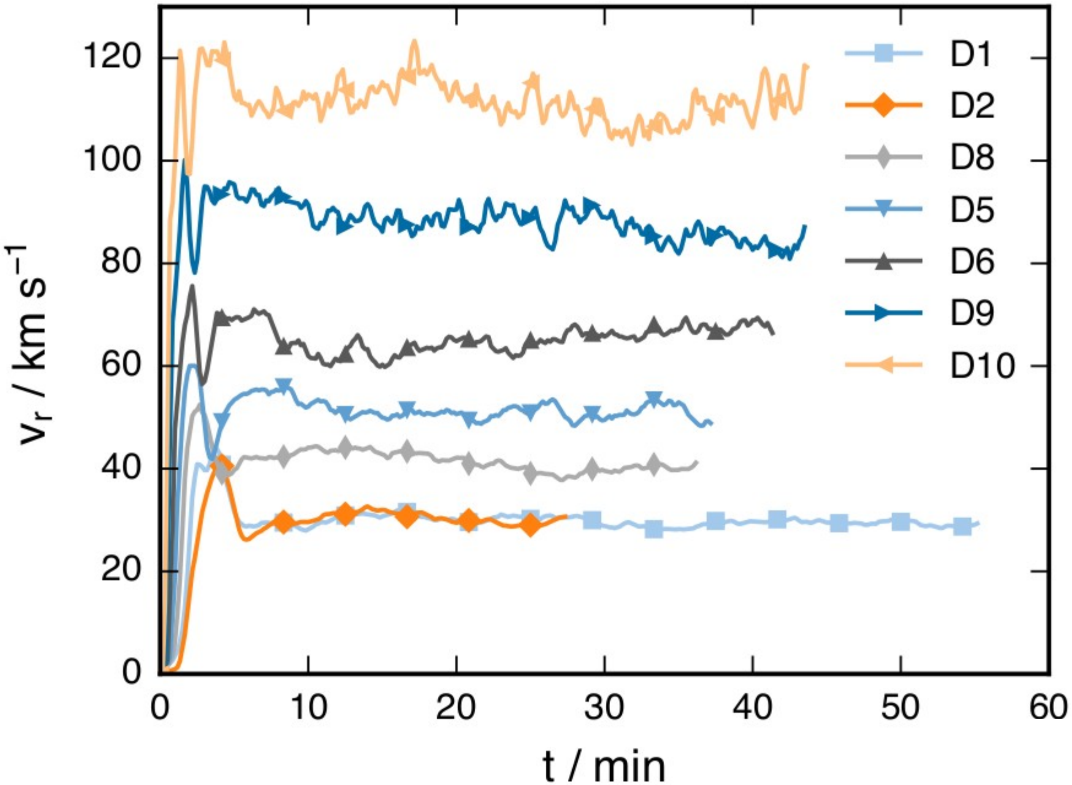
Entrainment rate from 768^3 and 1536^3 simulations agree to within 17%



id	grid [a]	t_{sim} [b] (min)	L [c] ($10^{10} L_\odot$)	$\dot{M}_{\mathrm{e}}$ [d] ($10^{-6}\ M_\odot/\mathrm{s}$)
D1	768^3	55.2	11.8	1.15
D2	1536^3	27.3	11.8	1.33
D8	768^3	36.2	29.5	3.60
D5	768^3	37.2	59.1	8.07
D6	768^3	41.3	118	16.8
D9	768^3	43.5	295	38.3
D10	768^3	43.7	591	79.4



Results of a heating series in 768^3 resolution



id	grid [a]	$t_{\rm sim}$ [b] (min)	L [c] ($10^{10} L_\odot$)	$\dot{M}_{\rm e}$ [d] ($10^{-6}\ M_\odot$/s)
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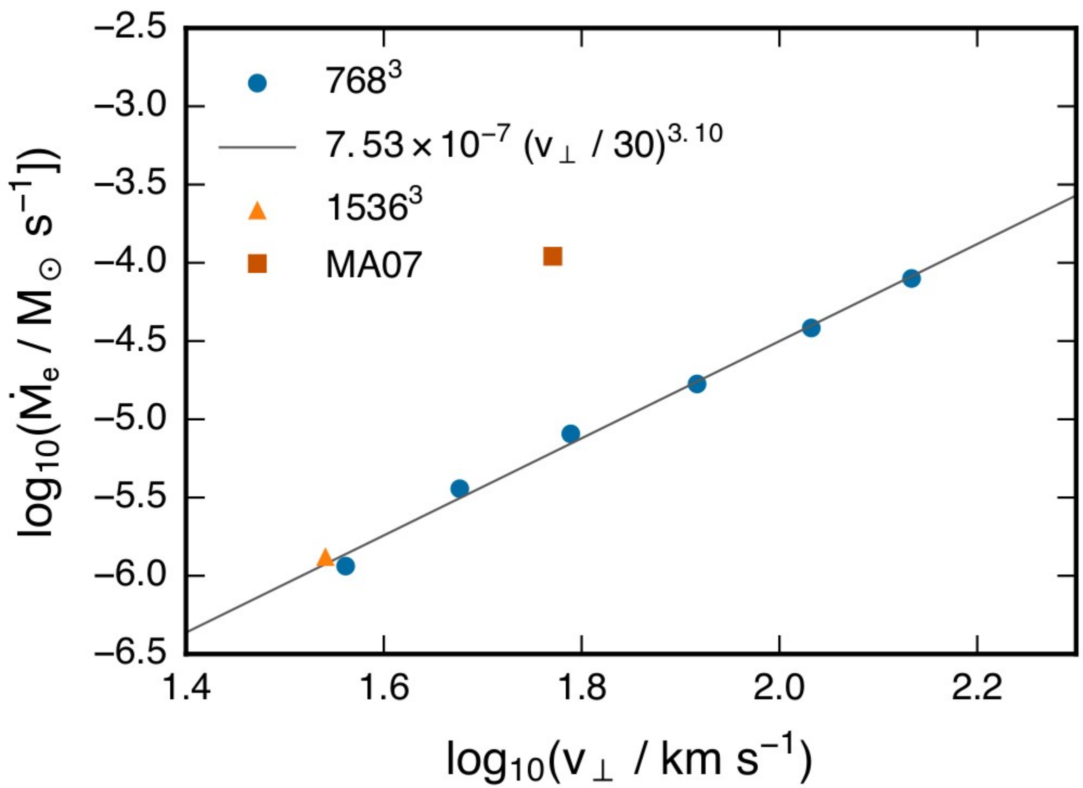


Results of a heating series in 768^3 resolution

MIXING MODEL

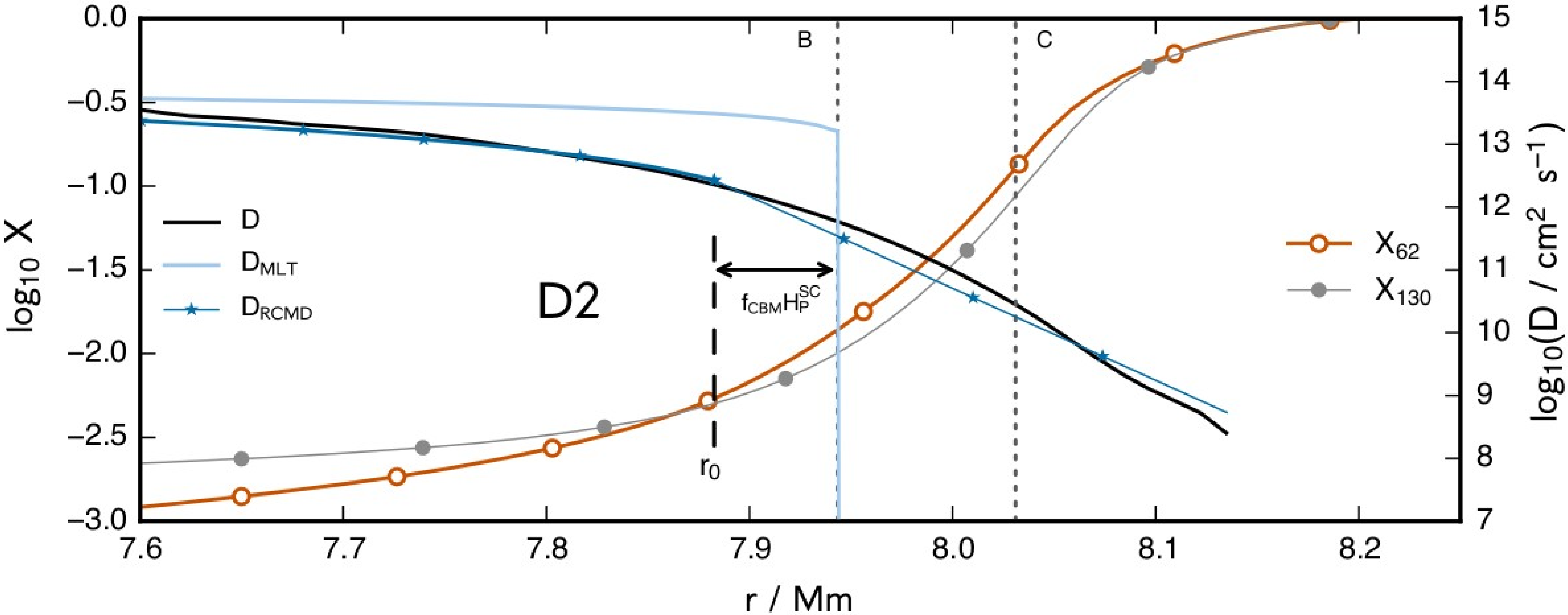
IMPROVE 1D STELLAR MODELS

(Eggleton 1972!)

$$D_{\mathrm{RCMD}} = v_{\mathrm{MLT}} \times \min(\alpha H_P, |r - r_{\mathrm{SC}}|)$$

$$D(r) = D(r_0) \times \exp\left\{-\frac{2|r - r_0|}{f_{\mathrm{CBM}} H_P(r_0)}\right\}$$

(f_{CBM} = 0.03)

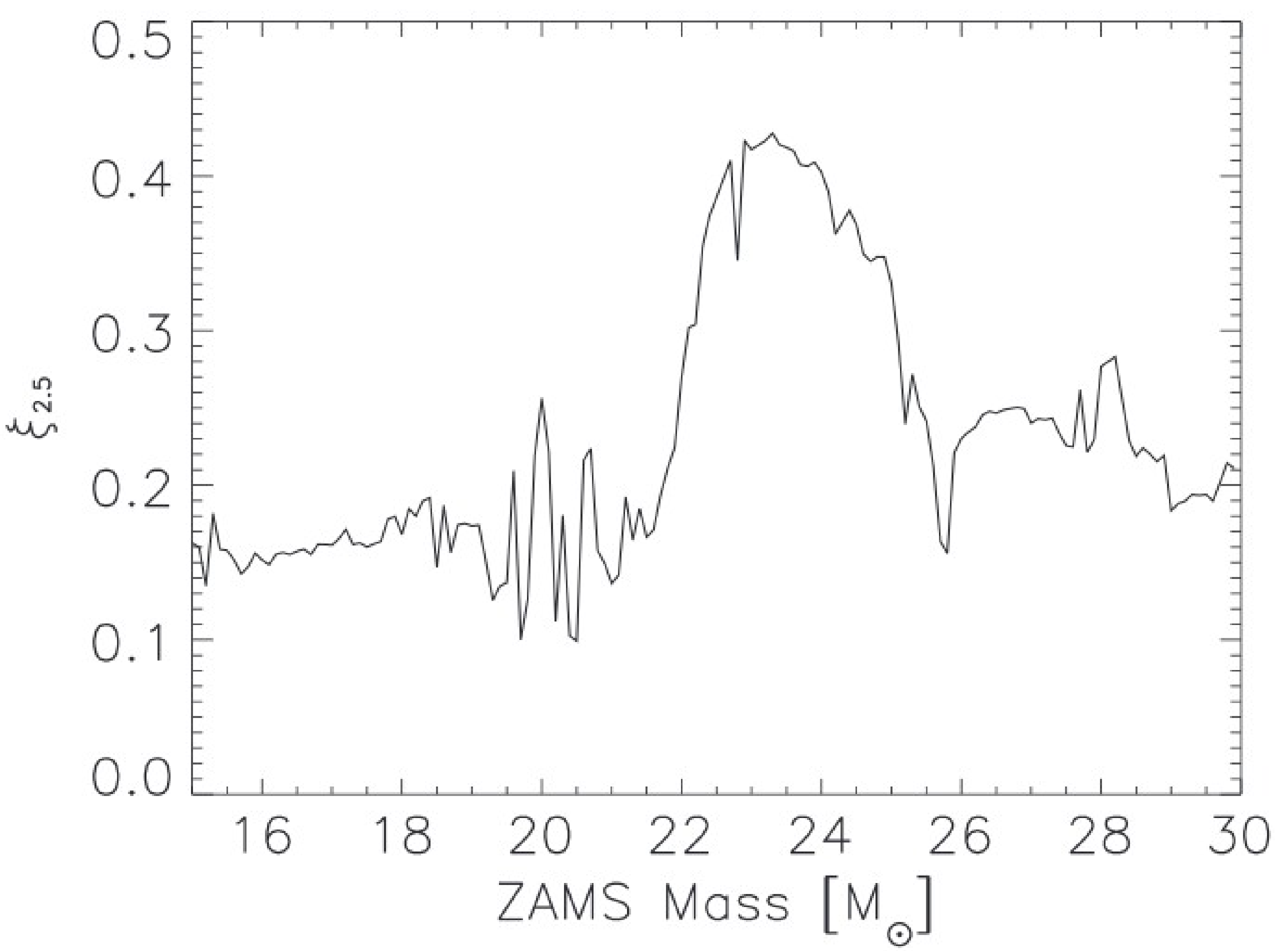


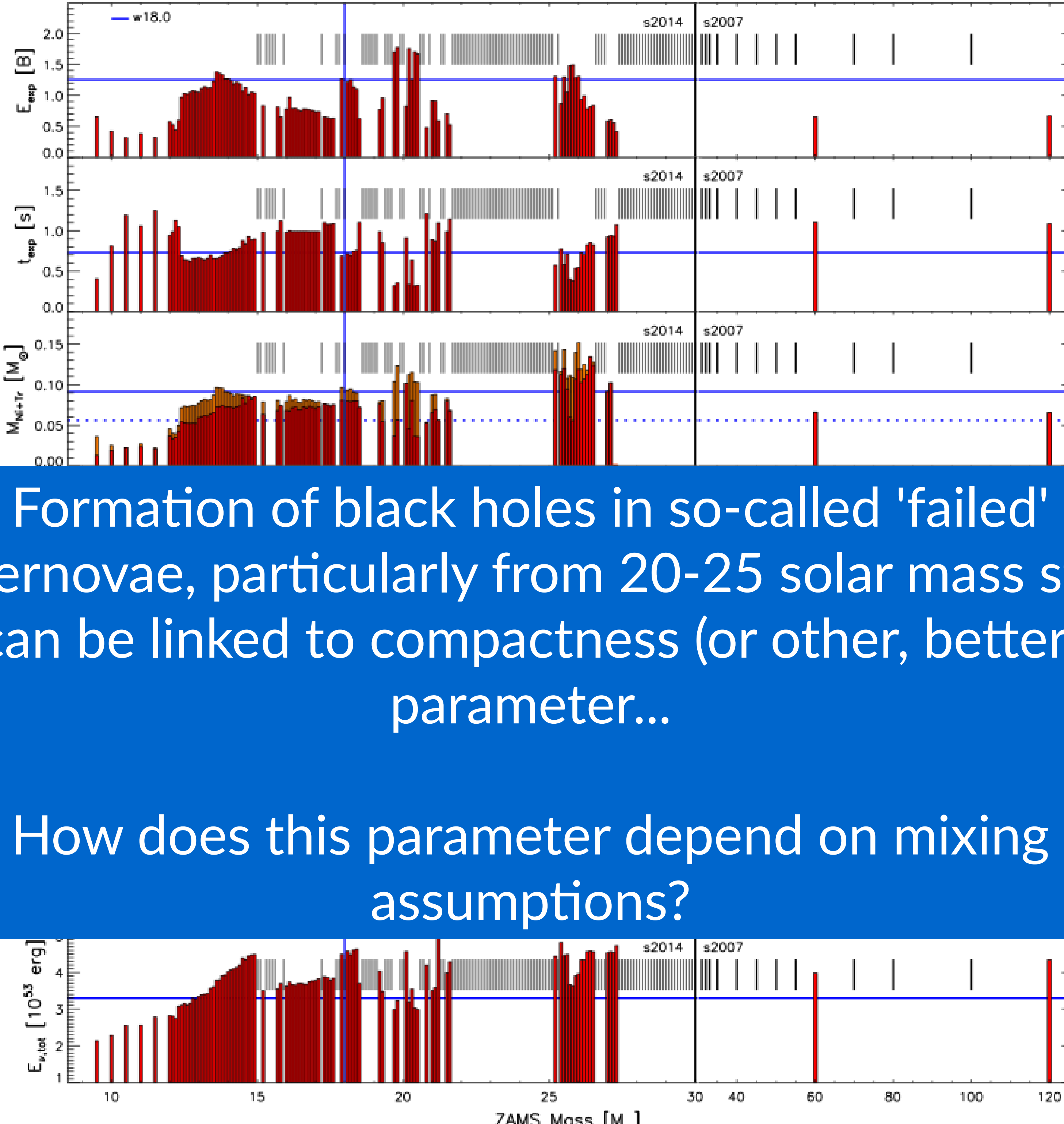
IMPLICATION FOR CCSN PROGENITORS

Compactness parameter

$$\xi_M = \frac{M/M_\odot}{R(M_{\rm bary} = M)/1000\,{\rm km}}\bigg|_{t_{\rm bounce}},$$

Tuguldur (Sukhbold)+ (2014)



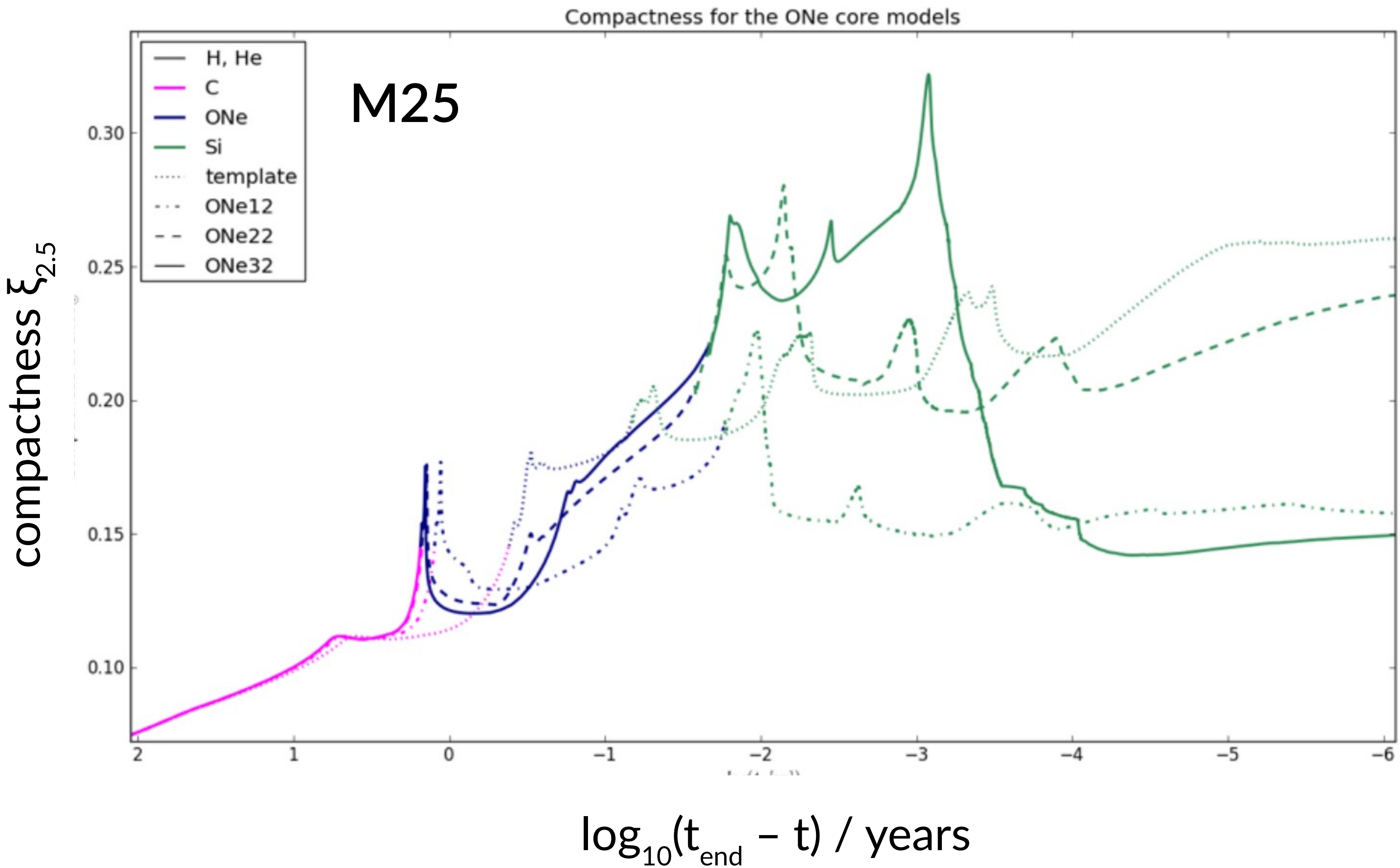


Formation of black holes in so-called 'failed' supernovae, particularly from 20-25 solar mass stars can be linked to compactness (or other, better) parameter…

How does this parameter depend on mixing assumptions?

IMPLICATION FOR CCSN PROGENITORS

Davis+ (in prep)



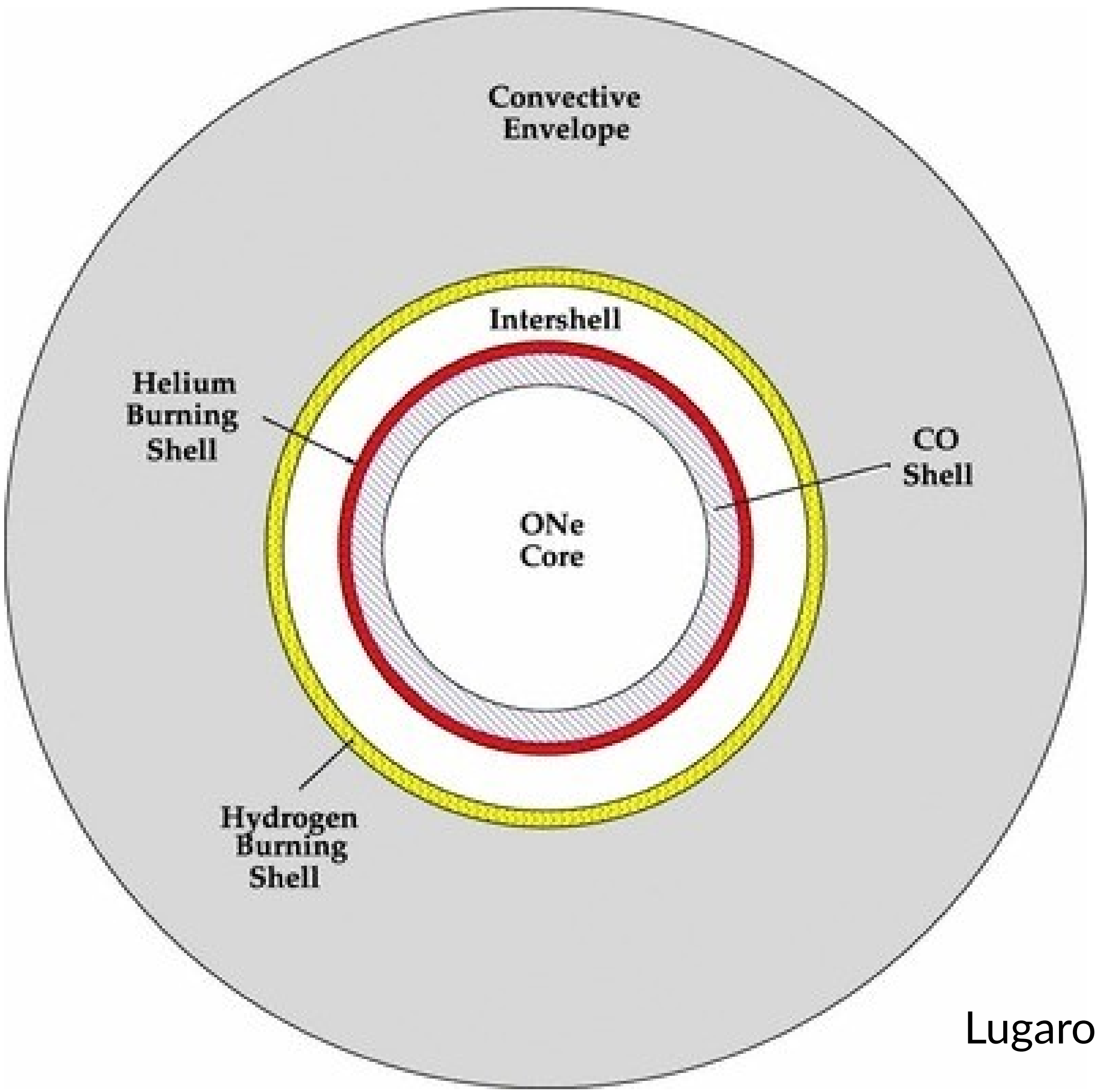
SUPER-AGB STARS

"8-10 SOLAR-MASS" STARS

Image credit: Alexander Heger

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^{4}He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,{}^{4}He \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$

Nuclear burning is curtailed due to combined effects of neutrino losses and degeneracy, leaving an **ONe core**



Lugaro+ (2012)

SUPER-AGB STARS

WHY?

WHY STUDY THESE STARS?

Assuming a *Salpeter* IMF, 8—10 solar-mass stars constitute **26 % of all massive stars**. Probably more (e.g. Jennings+ 2012).

SNe from these stars (electron capture SNe and/or accretion-induced collapse of ONe WDs) **postulated to explain many observations**, including:

Production of Ag and Pd (e.g. Hansen+ 2012)

Site for r-process (e.g. Cescutti+ 2014, but also Wanajo+ 2011)

“bimodal” NS mass distribution (e.g. Schwab+ 2010)

Bimodal BeX orbital eccentricity (e.g. Knigge+ 2011)

Low L transients (e.g. Thompson+ 2009)

WHAT HAPPENS TO 8-10 SOLAR-MASS STARS?

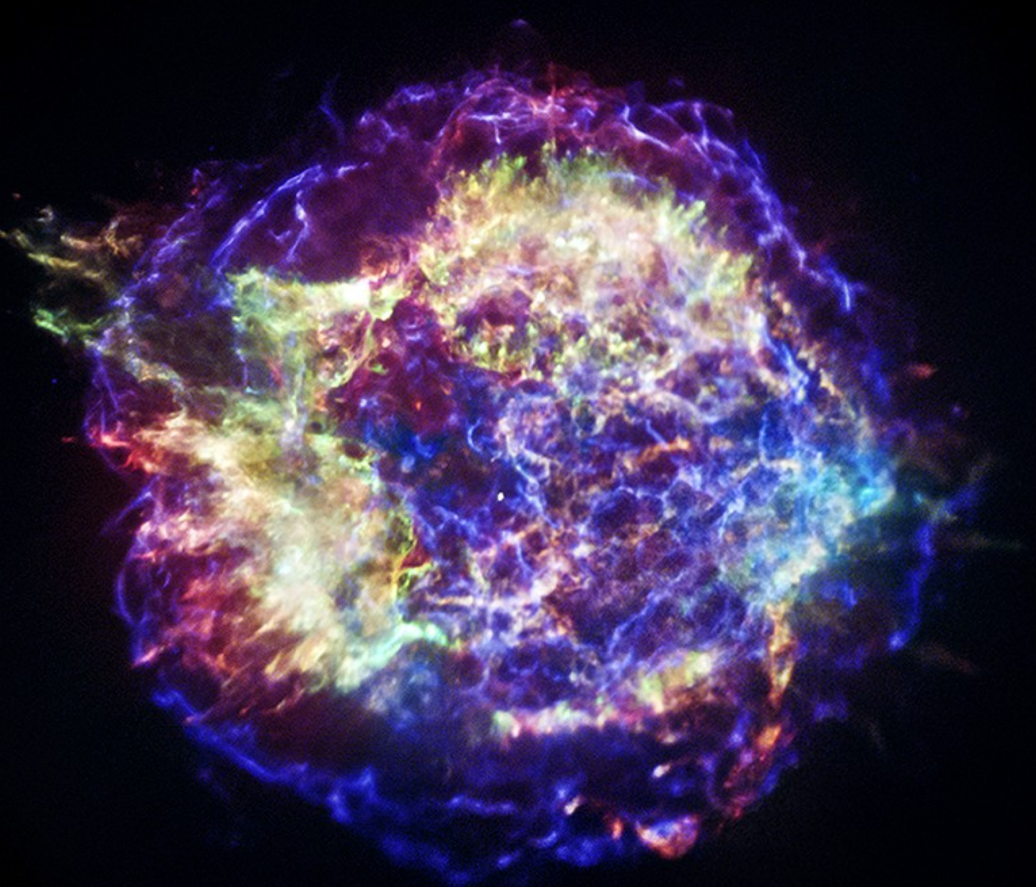


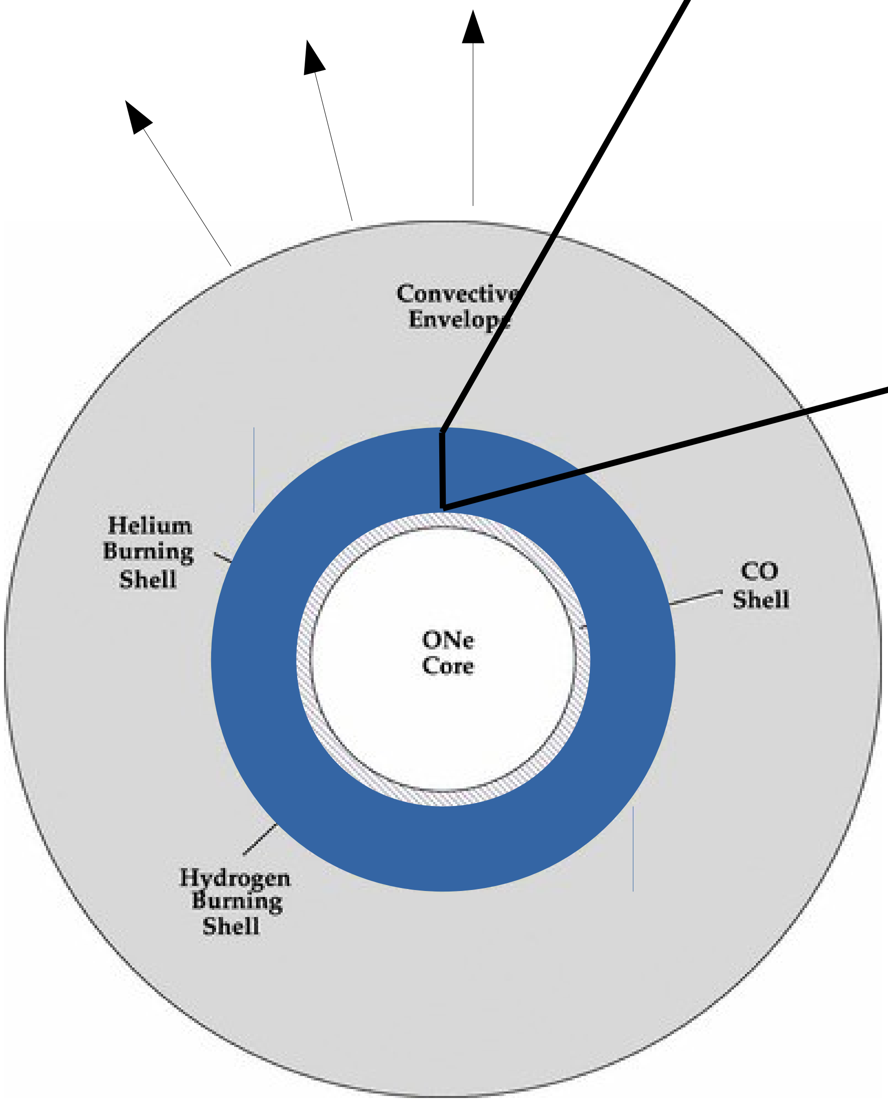
Image credit: NASA/CXC/SAO

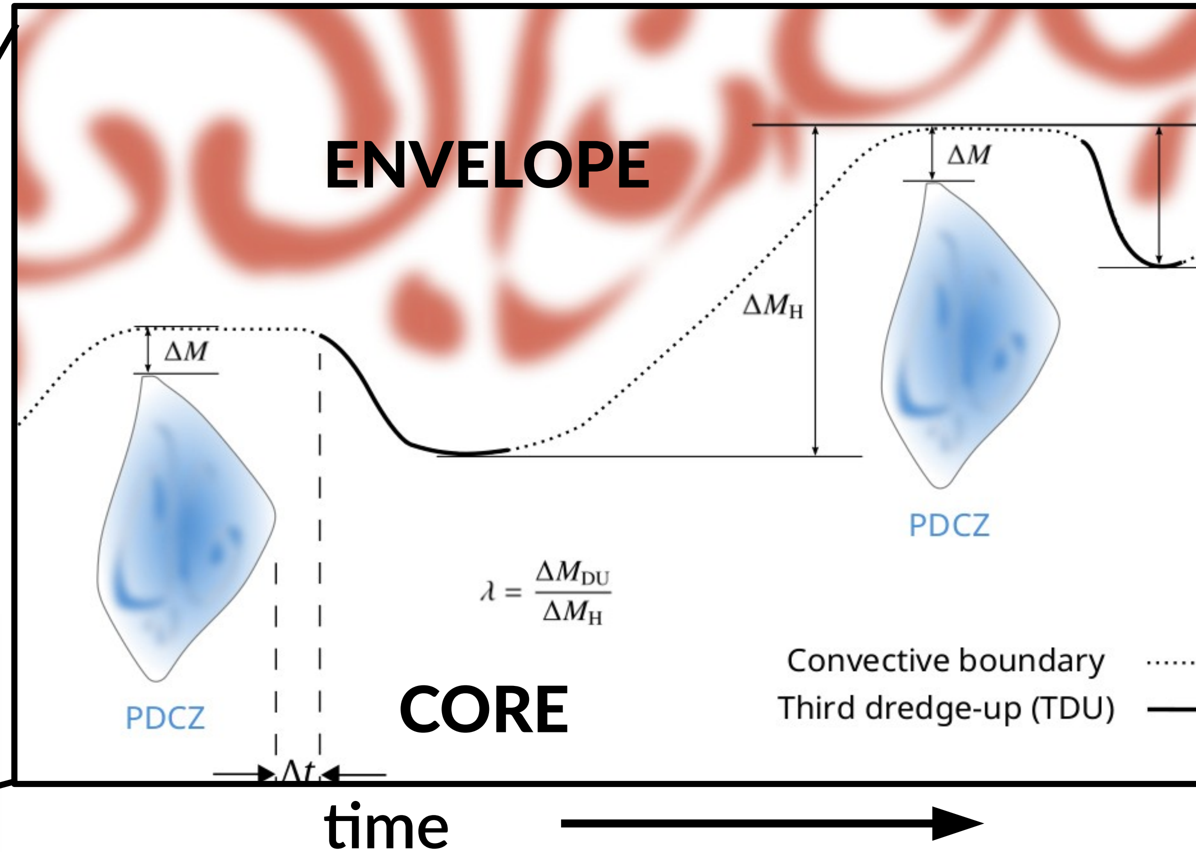
Image credit: NASA/Andrew Fruchter (STScI)

SUPER-AGB STARS

Jones+ (2016)

Envelope shedding due to stellar winds





Rate of mixing between the envelope and the core gives a core growth rate (solar masses per year)

Please see also work by Ritossa, Siess, Doherty, ...

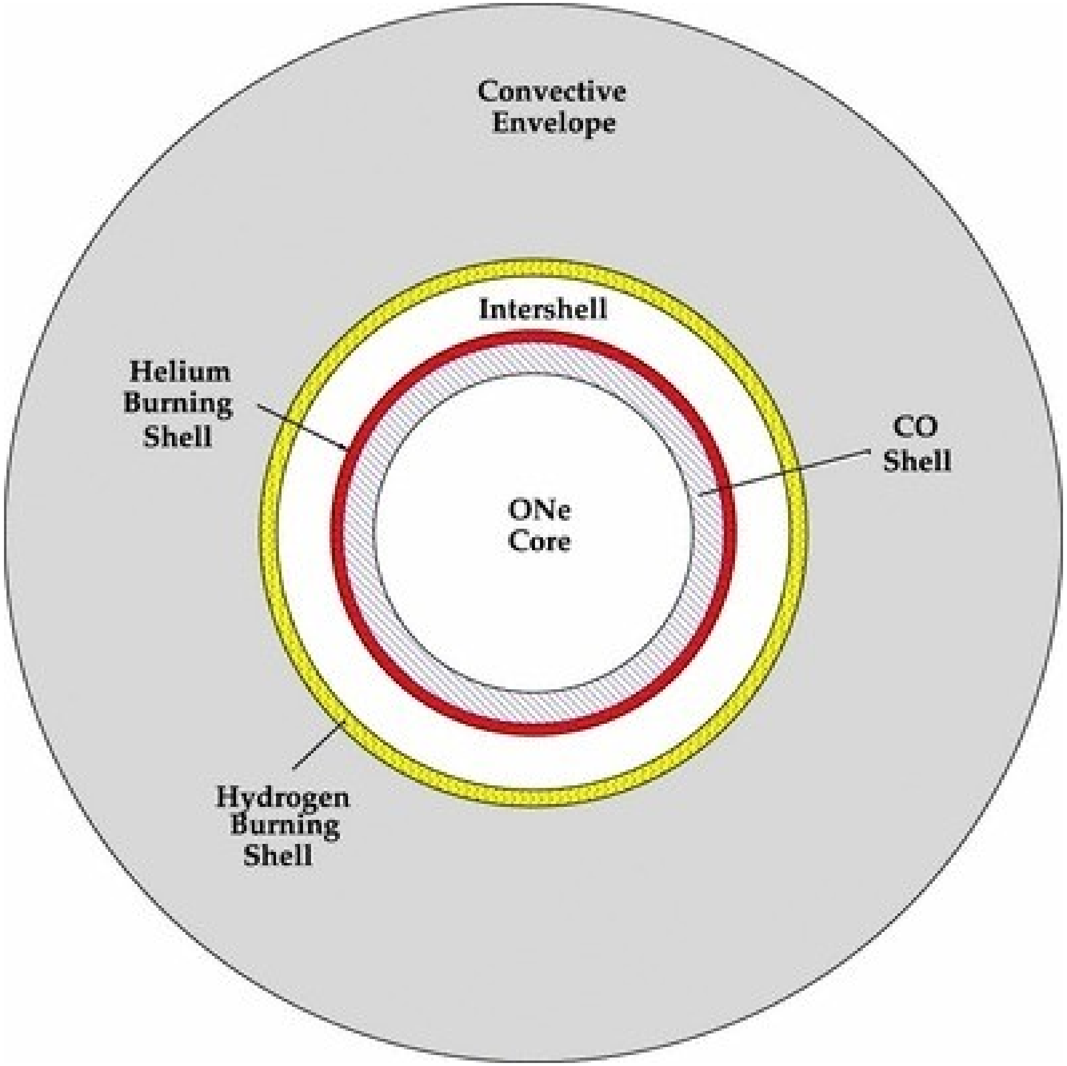


Image: Lugaro+ (2012)

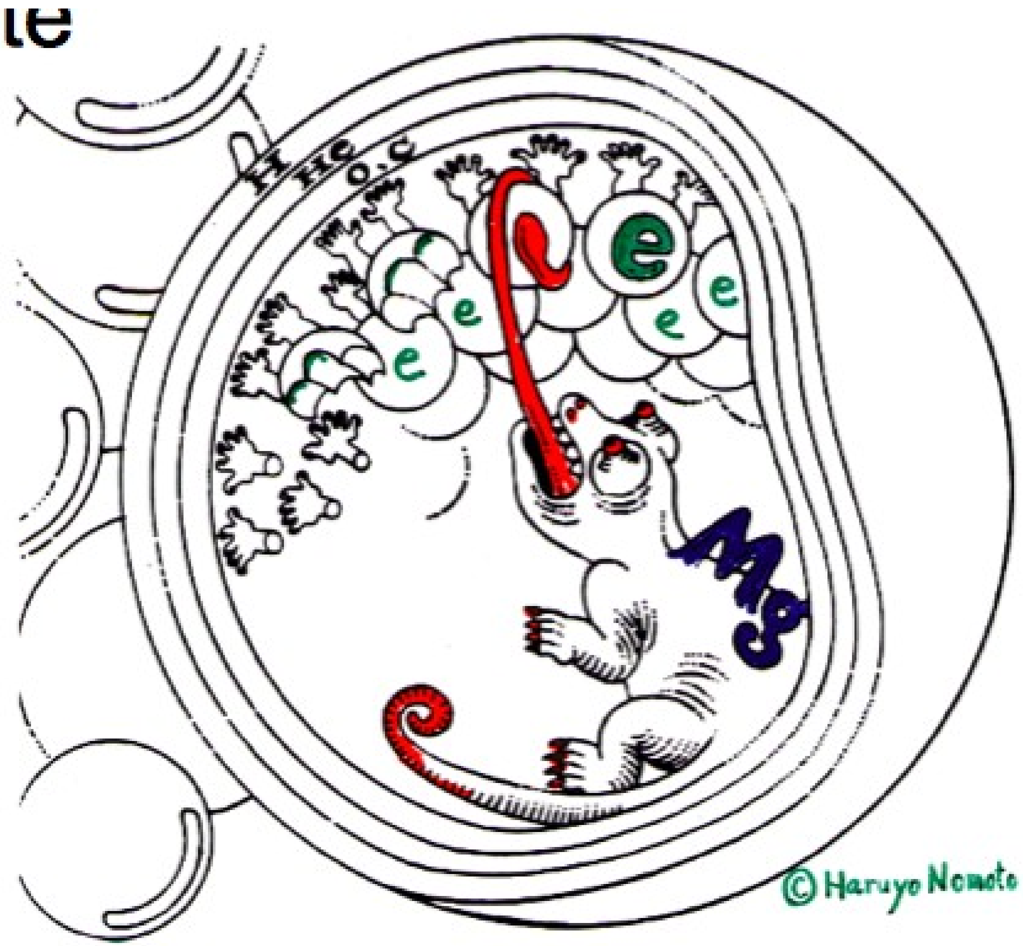
Two (three) scenarios:

1. The H envelope is ejected, producing a **planetary nebula and an ONe white dwarf**

2. The core grows due to accumulation of ash from the burning shells, eventually exceeding the effective Chandrasekhar limit and **collapsing to a neutron star**

3. An **ONe WD** is formed, but later **accretes** from a binary companion and **collapses to a neutron star**

At about 3e9 g/cc, ^{24}**Mg begins to capture electrons**, inducing a contraction



But it is ^{20}**Ne + 2e$^-$**, activated at about **10^{10} g/cc** that releases enough energy to ignite an **oxygen deflagration wave** in the centre

Miyaji+ (1980); Nomoto (1984,1987)

The energy release from burning **competes with electron capture** on the ash; in the current picture the electron captures win and the star's **core collapses (an electron-capture supernova; ECSN)**

WHAT HAPPENS TO 8-10 SOLAR-MASS STARS?

Determined by balance between **convective boundary (core-envelope) mixing** (uncertain) and **envelope shedding due to the stellar wind** (uncertain)

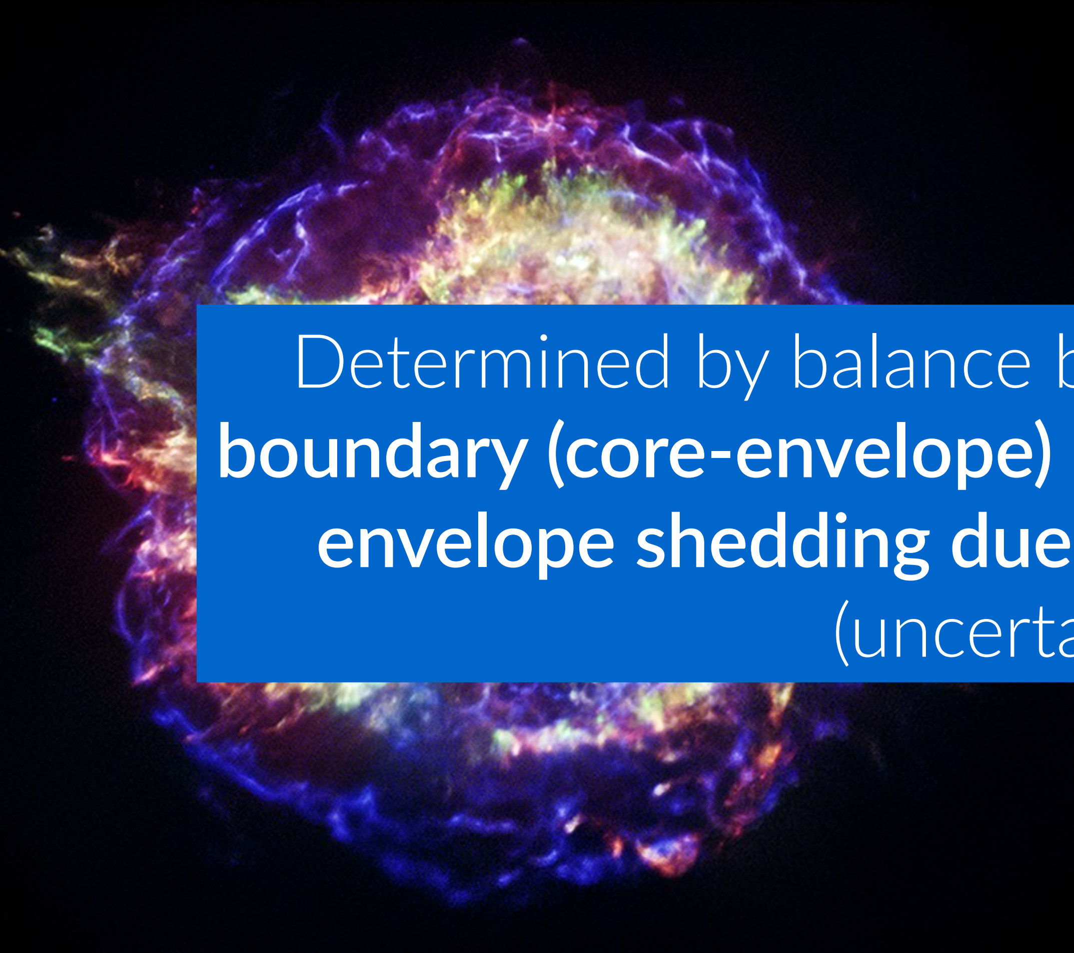


Image credit: NASA/CXC/SAO

Image credit: NASA/Andrew Fruchter (STScI)

WHAT ARE ELECTRON-CAPTURE SUPERNOVAE?

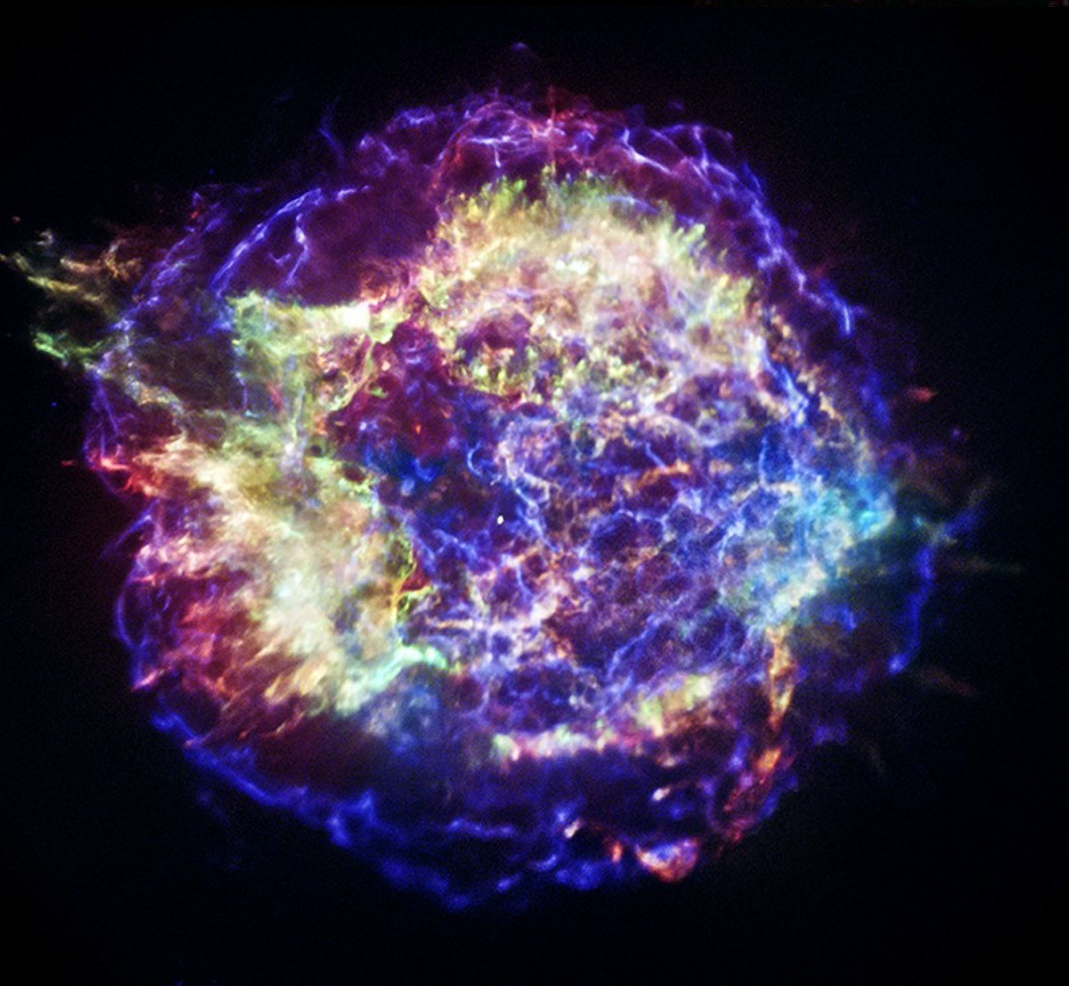


Image credit: NASA/CXC/SAO

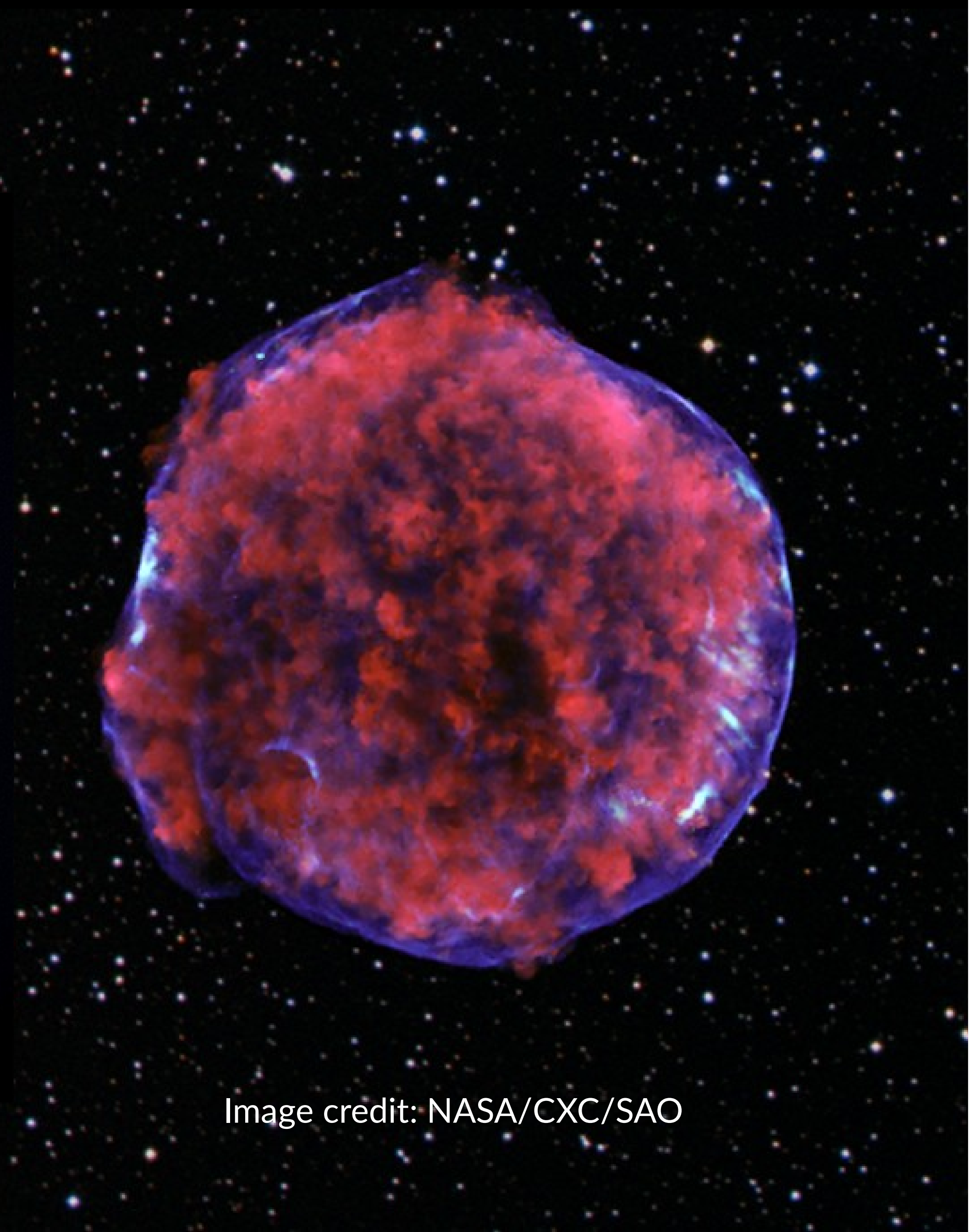
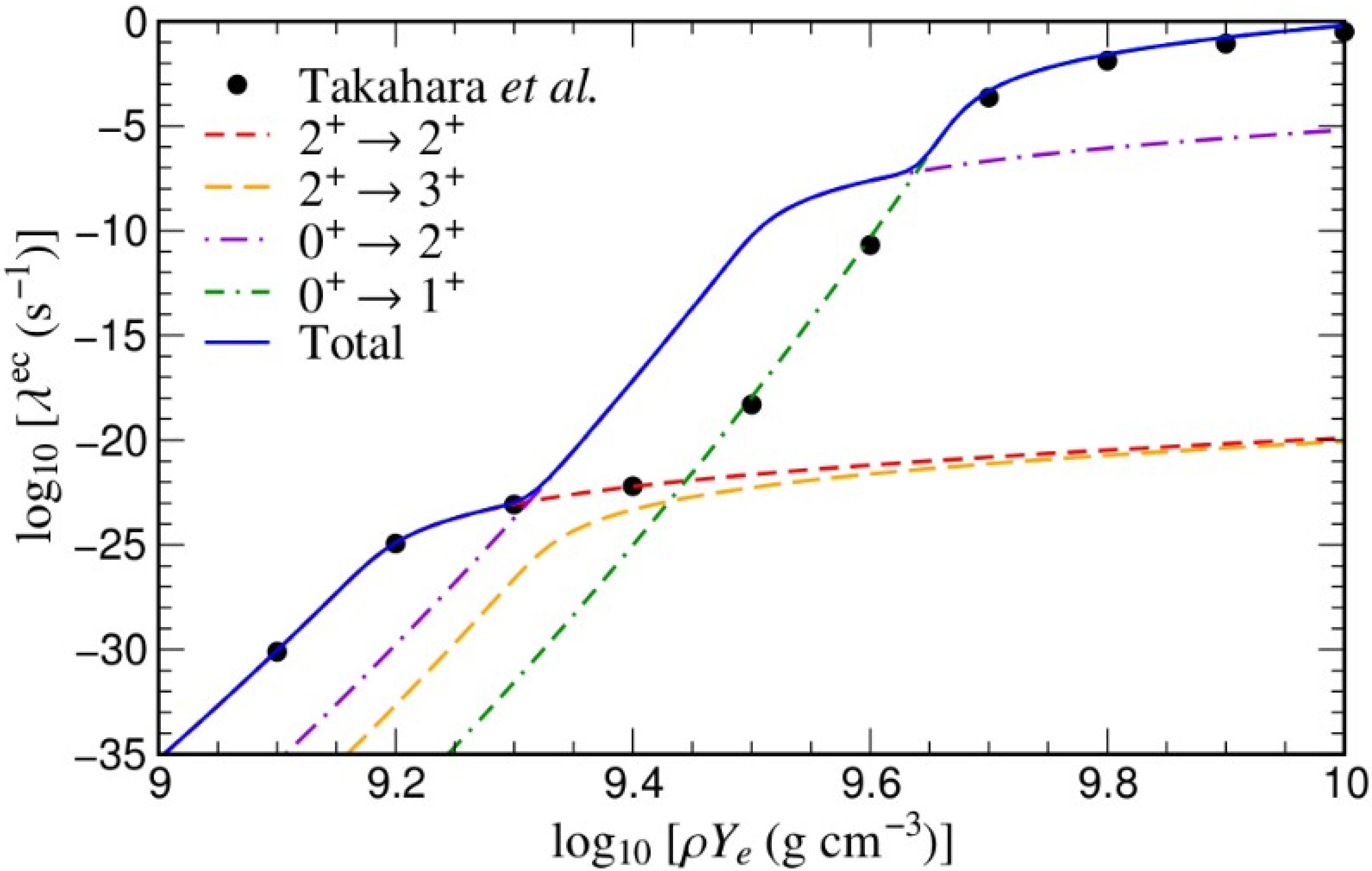


Image credit: NASA/CXC/SAO



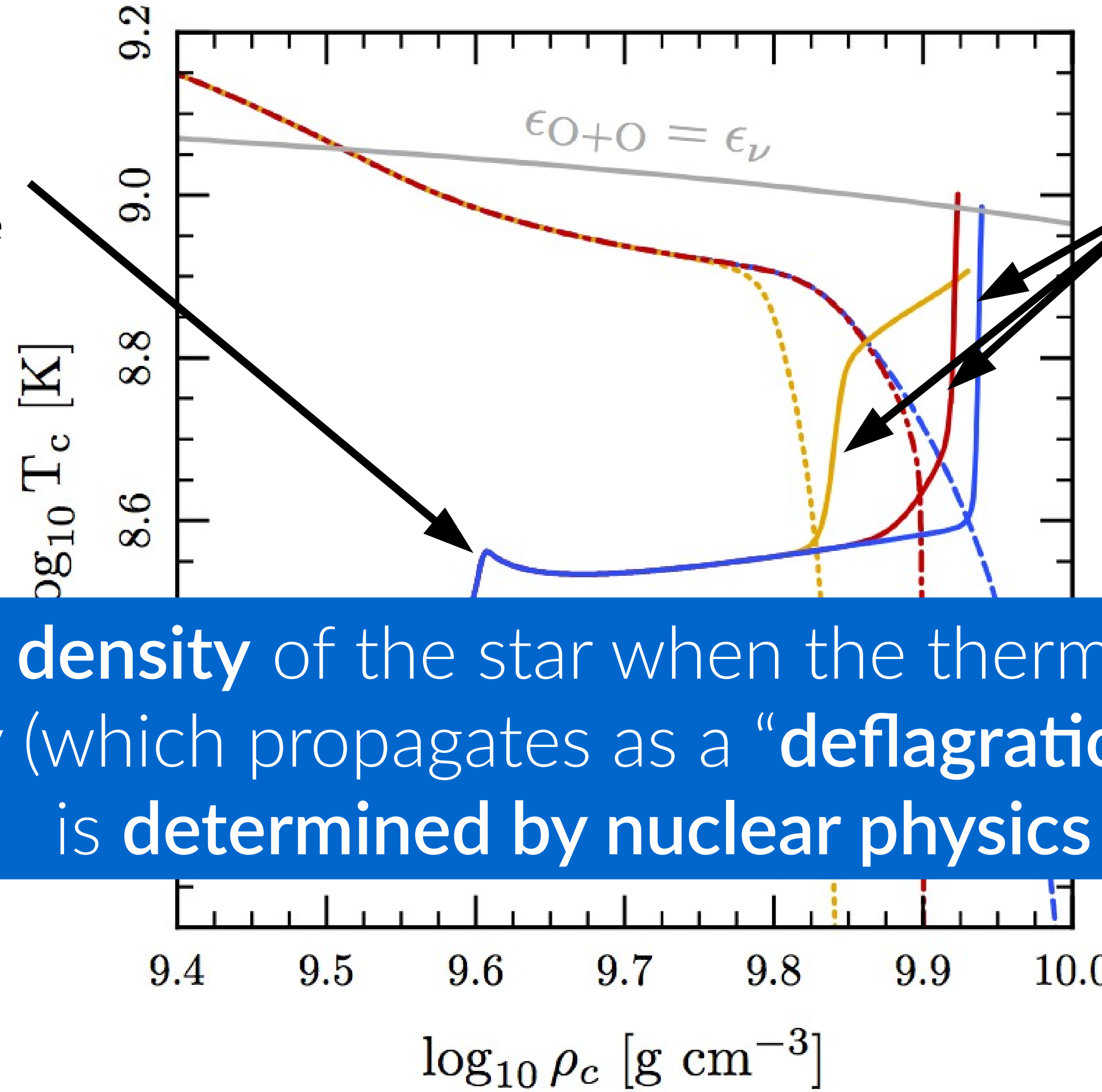
Martinez-Pinedo+ (2014)

^{20}Ne ELECTRON CAPTURE

RAPID HEATING IGNITES THERMONUCLEAR RUNAWAY

^{24}Mg
electron capture

^{20}Ne
electron capture



Central density of the star when the thermonuclear runaway (which propagates as a “**deflagration**”/flame) is **determined by nuclear physics**

1D SIMULATIONS

AIC of ONe white dwarf

Schwab+ (2015)

In 1D simulations of the O deflagration, **neutron stars, WDs and thermonuclear SNe were all possible outcomes** (Nomoto & Kondo 1991, Isern+ 1991, Canal+ 1992)

The situation is incredibly marginal.

O DEFLAGRATION

O DEFLAGRATION

MULTI-DIMENSIONAL SIMULATIONS

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LEAFS code (Reinecke+ 1999, Röpke & Hillebrandt 2005, Röpke 2005, 2006)

Isothermal ONe core/WD in HSE with **central densities $10^{9.9}$, $10^{9.95}$, $10^{10.3}$ g / cc**

Centrally-confined ignition: 300 'bubbles' within 50 km sphere, < 5×10^{-4} $M_\odot$ inside initial flame

Laminar **flame speeds** from Timmes+ (1992); turbulent from Schmidt+ (2006)

NUCLEAR REACTIONS

DELEPTONISATION OF NSE ASH

SJ, FKR, RP, IRS, STO, PVFE
A&A 593, 72

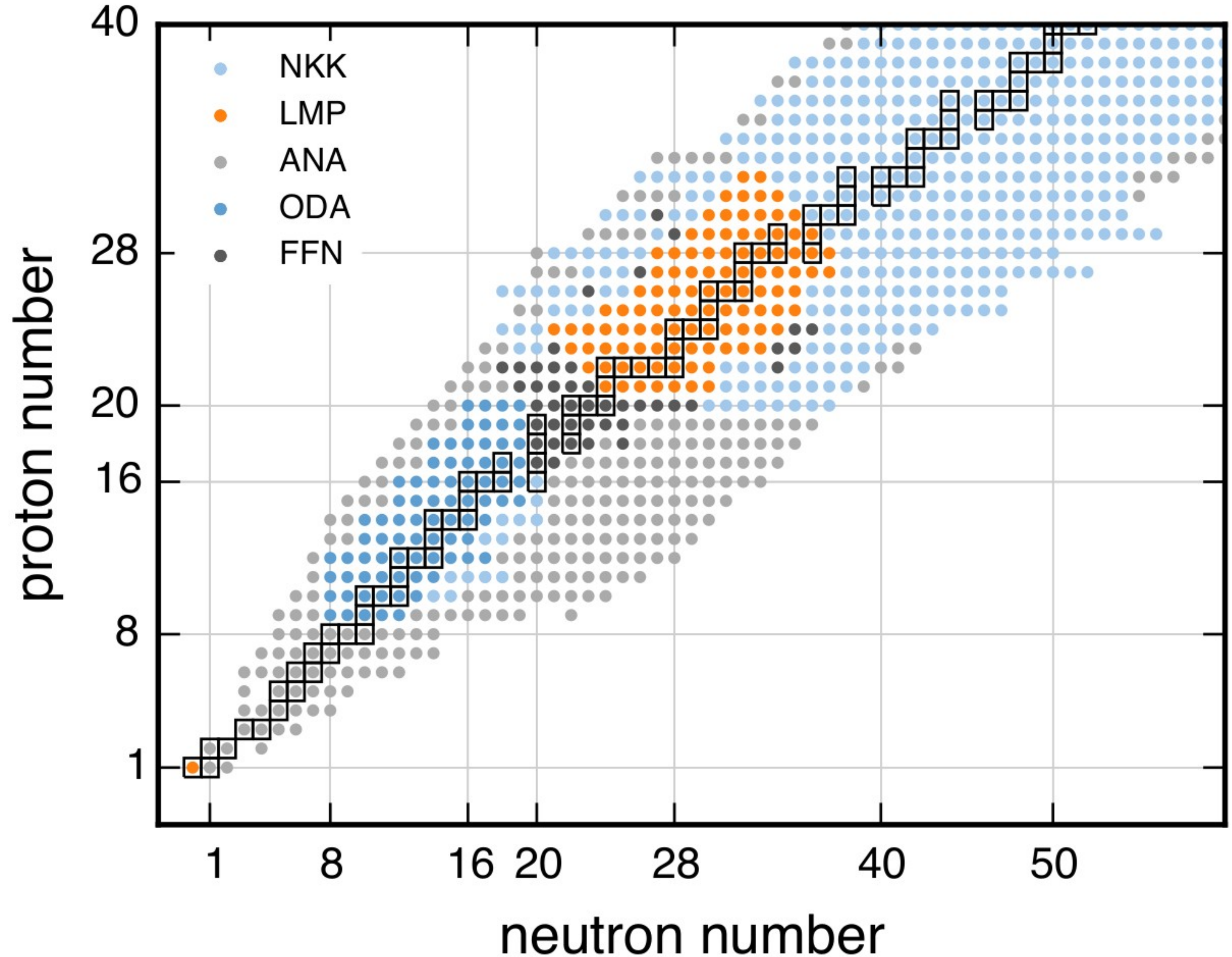
NKK: Nabi & Klapdor-Kleingrothaus

LMP: Langanke & Martinez-Pinedo (2001)

ODA: Oda+ (1994)

FFN: Fuller, Fowler & Newman (1985)

ANA: Analytical rates; Gamow-Teller strength B = 4.6 (Arcones+ 2010)

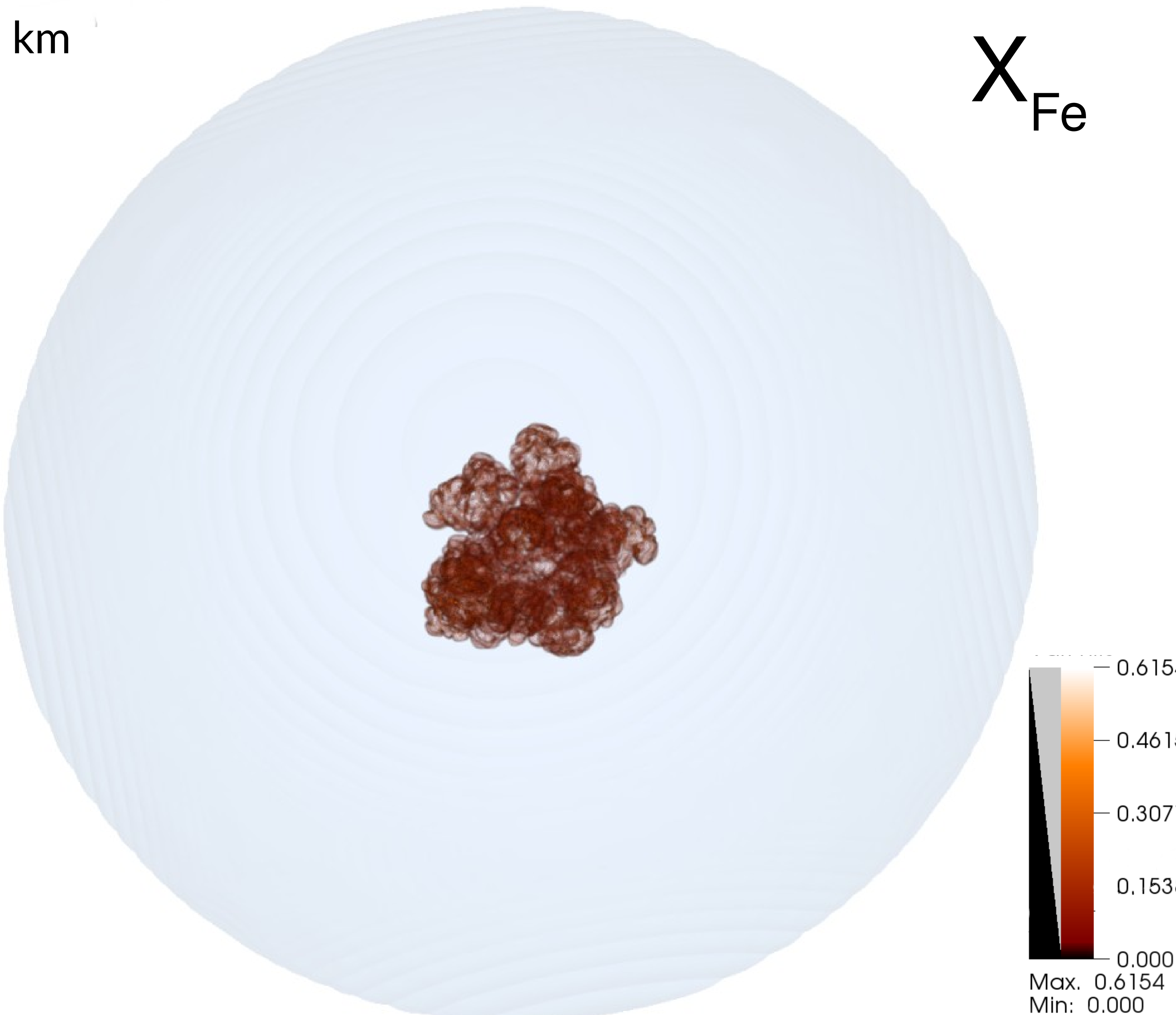


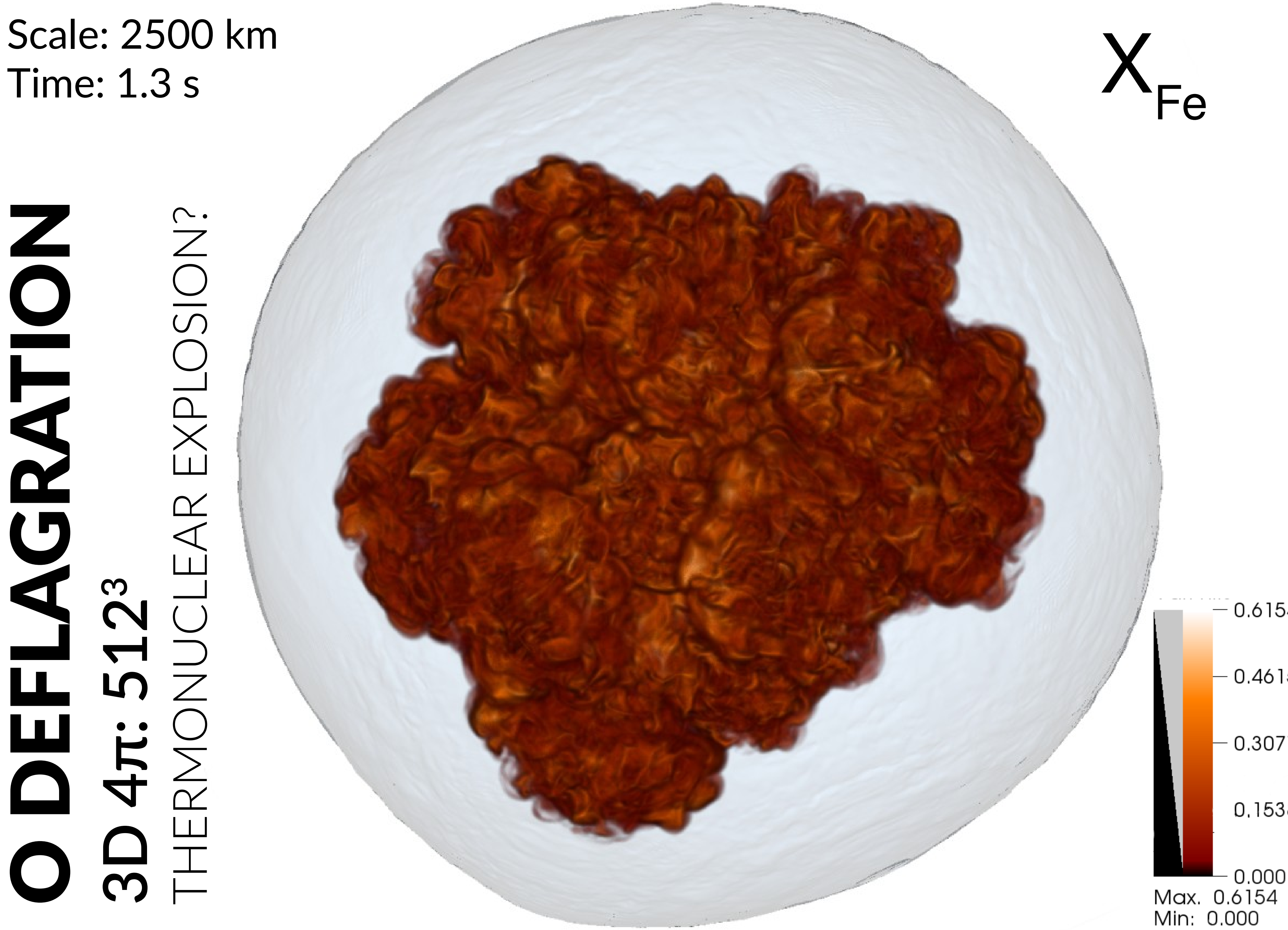
Scale: 1500 km
Time: 0.7 s

O DEFLAGRATION

3D 4π: 512^3

THERMONUCLEAR EXPLOSION?



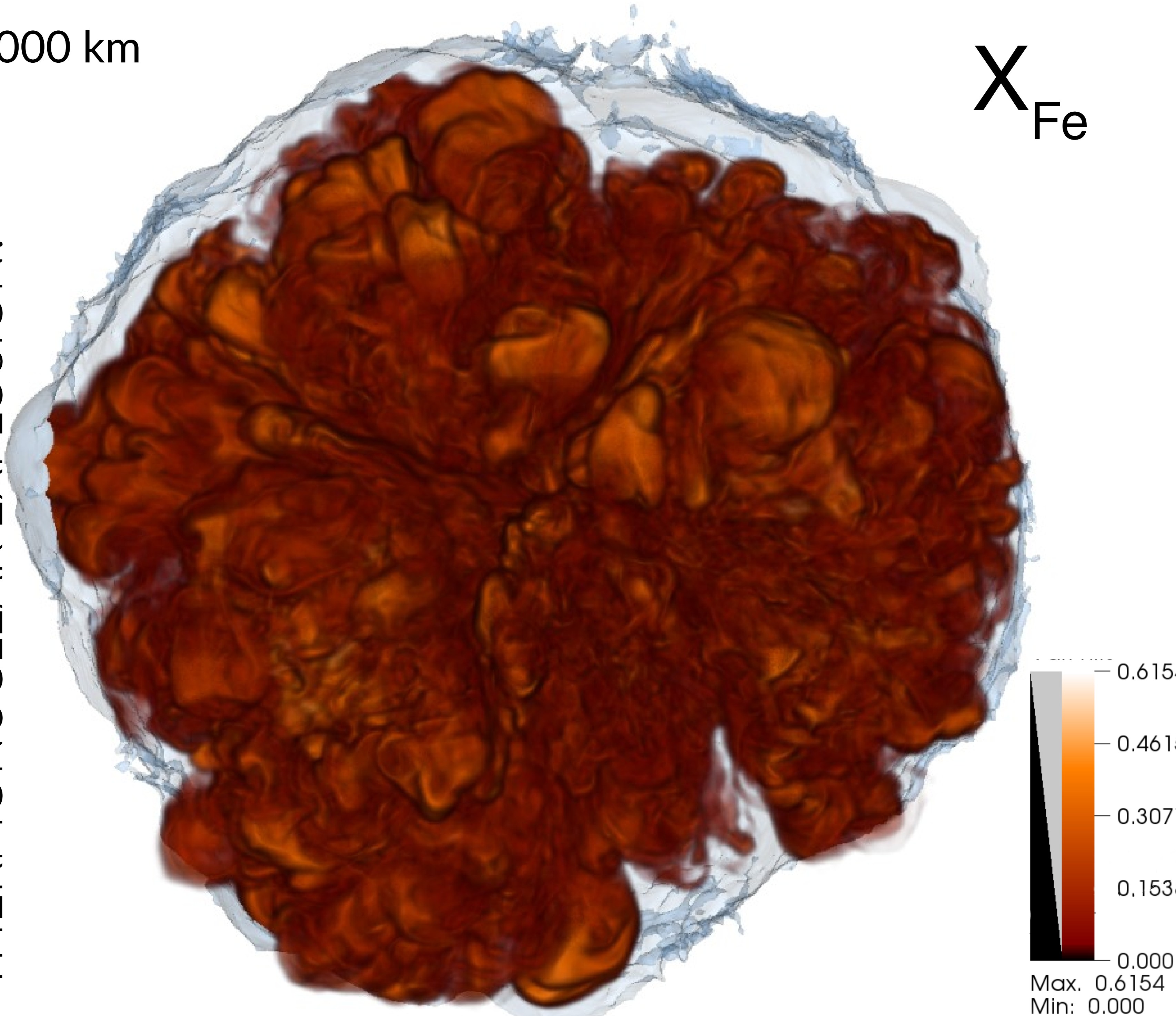

Scale: 2500 km
Time: 1.3 s
X Fe
O DEFLAGRATION
3D 4π: 512³
THERMONUCLEAR EXPLOSION?
0.6154
0.4615
0.3077
0.1538
0.000
Max. 0.6154
Min: 0.000

Scale: 400,000 km
Time: 60 s

O DEFLAGRATION

3D 4π: 512^3

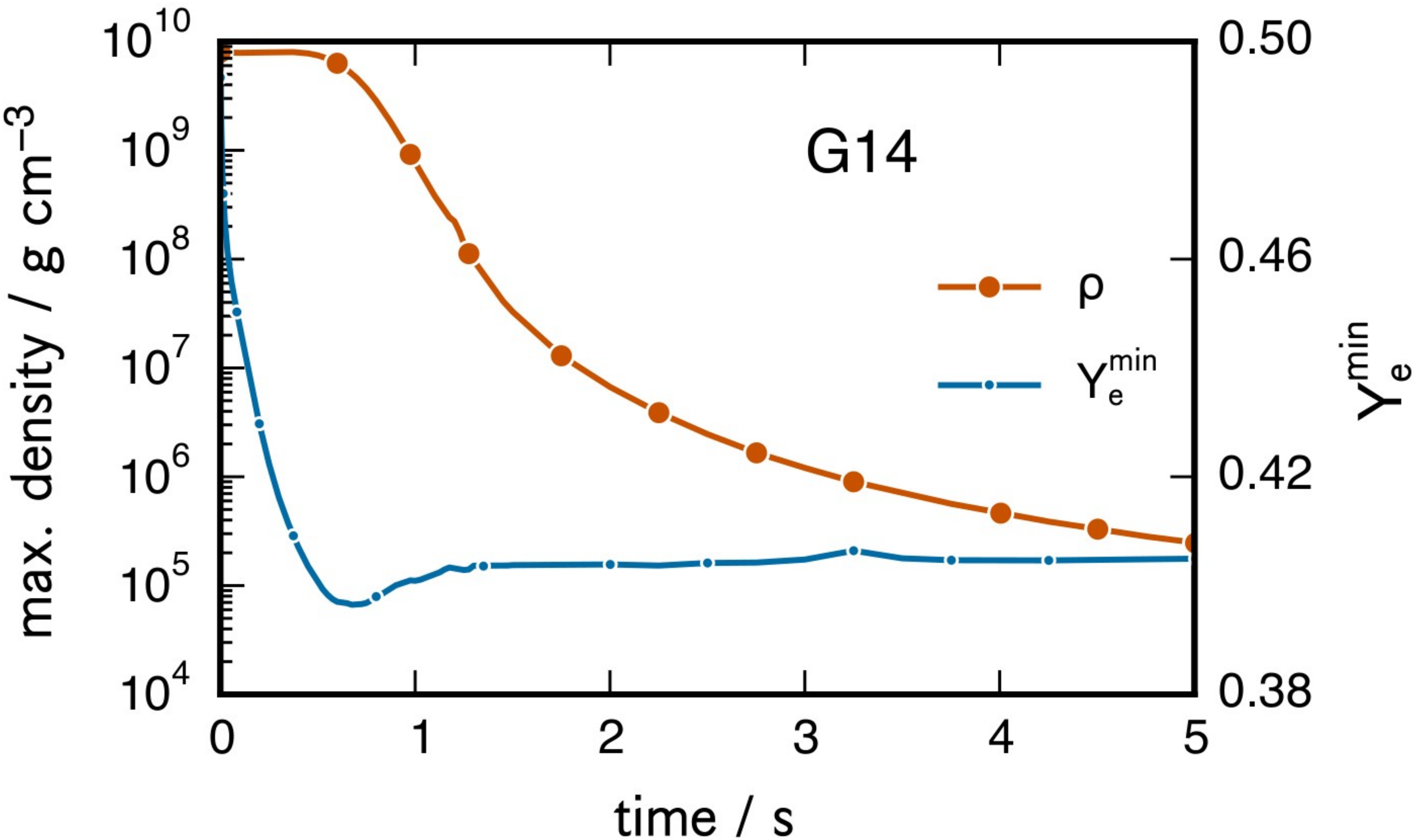
THERMONUCLEAR EXPLOSION?



$\rho_{ign} = 10^{9.9}$ g cm^{-3}

THERMONUCLEAR EXPLOSION?

SJ, FKR, RP, IRS, STO, PVFE
A&A 593, 72



$\rho_{ign} = 10^{10.3}$ g cm^{-3}

CORE COLLAPSE

SJ, FKR, RP, IRS, STO, PVFE
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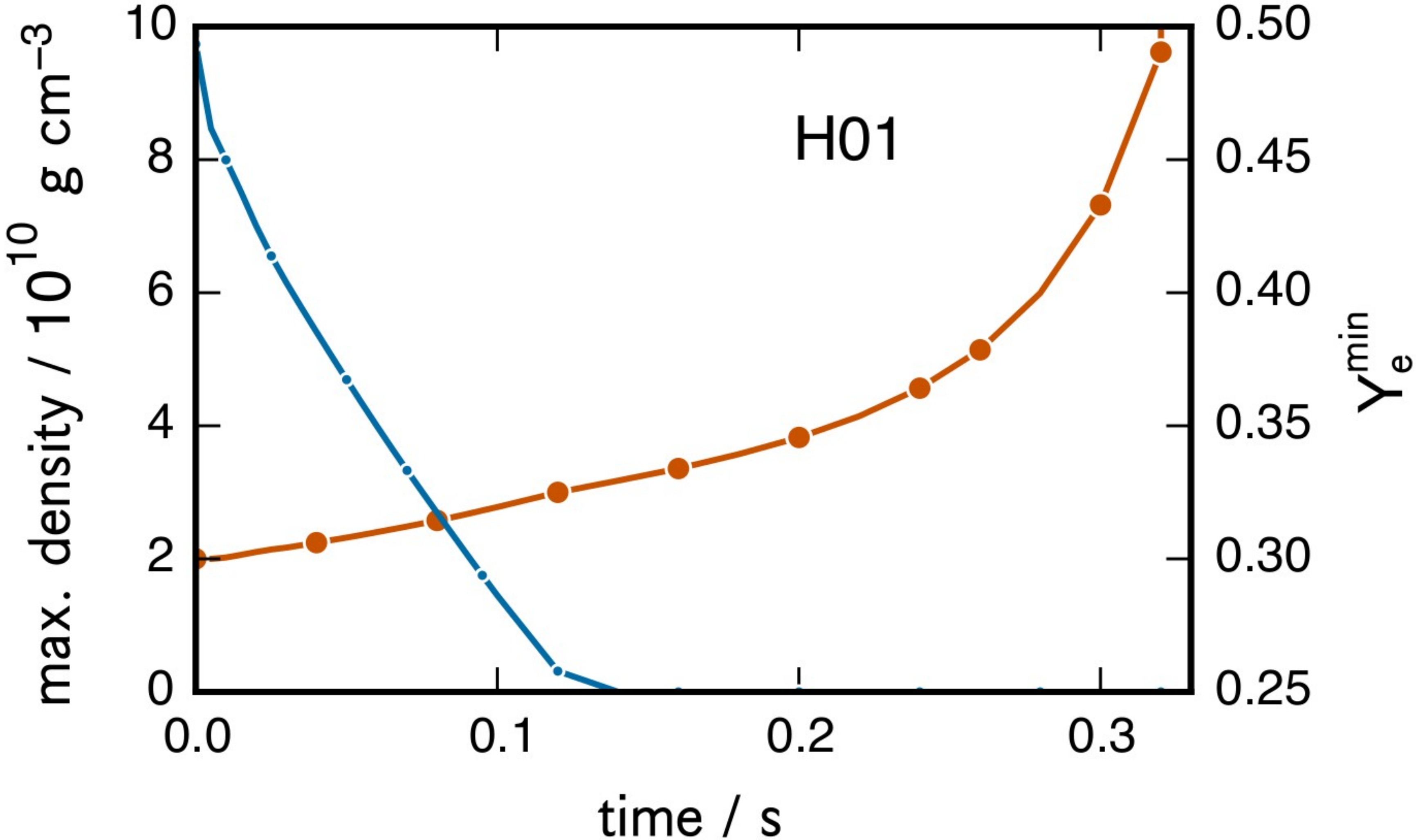


DIAGNOSTICS

SJ, FKR, RP, IRS, STO, PVFE
A&A 593, 72

Bound ONeFe remnants

id.	res.	$^a\log_{10}\rho_c^{\rm ini}$ ($\mathrm{g\ cm^{-3}}$)	^{b}CC (Y/N)	$^cM_{\rm rem}$ ($M_\odot$)	$^dM_{\rm rem}^{\rm Fe}$ ($M_\odot$)	$^eM_{\rm ej}$ ($M_\odot$)	$^fM_{\rm ej}^{\rm Fe}$ ($M_\odot$)	$^g\langle Y_{\rm e,rem}\rangle$	$^hM_{\rm Ch}^{\rm eff}$ ($M_\odot$)	$^i\Delta x$ (km)
G13	256^3	9.90	N	0.647	0.173	0.741	0.231	0.491	1.384	0.870
G14	512^3	9.90	N	0.438	0.115	0.951	0.362	0.491	1.381	0.427
G15	256^3	9.90	Y	1.212	0.223	0.177	0.047	0.493	1.392	0.870
J01	256^3	9.95	N	0.631	0.171	0.768	0.233	0.491	1.379	0.870
J02	256^3	9.95	Y	1.291	0.226	0.104	0.025	0.493	1.392	0.870
H01*										.870

*These diagno … $\mathrm{n^{-3}}$,
exhibiting cle…
^{a} Ignition …
^{c} Total ma…
^{e} Total eje…
^{g} Average…
^{i} Initial cell size for inner (flame) mesh

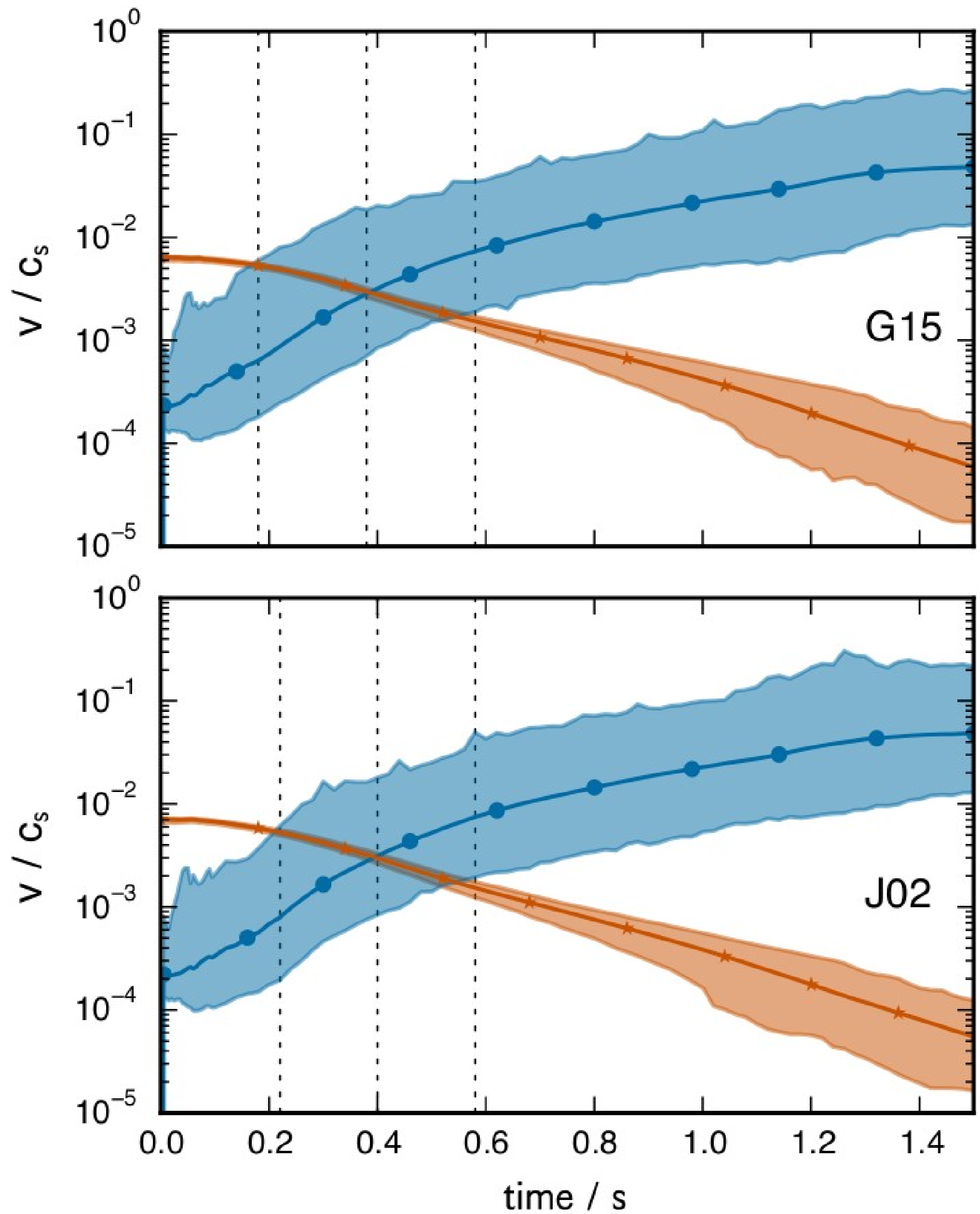
What would these things actually **look like**? Faint SN1a? Have we seen them? → **Radiative transfer calculations required**

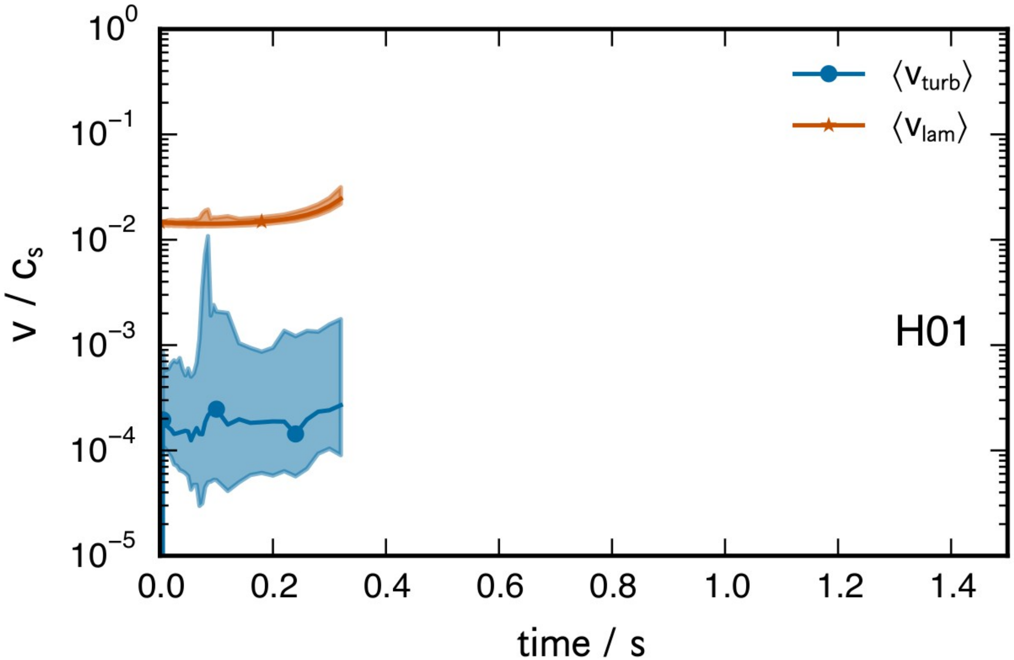
Core collapse

Remarkably similar result to Isern+ (1991)

Outcome dictated by speed of flame and growth of Rayleigh-Taylor instability

Accurate predictions require these kinds of multi-D simulations

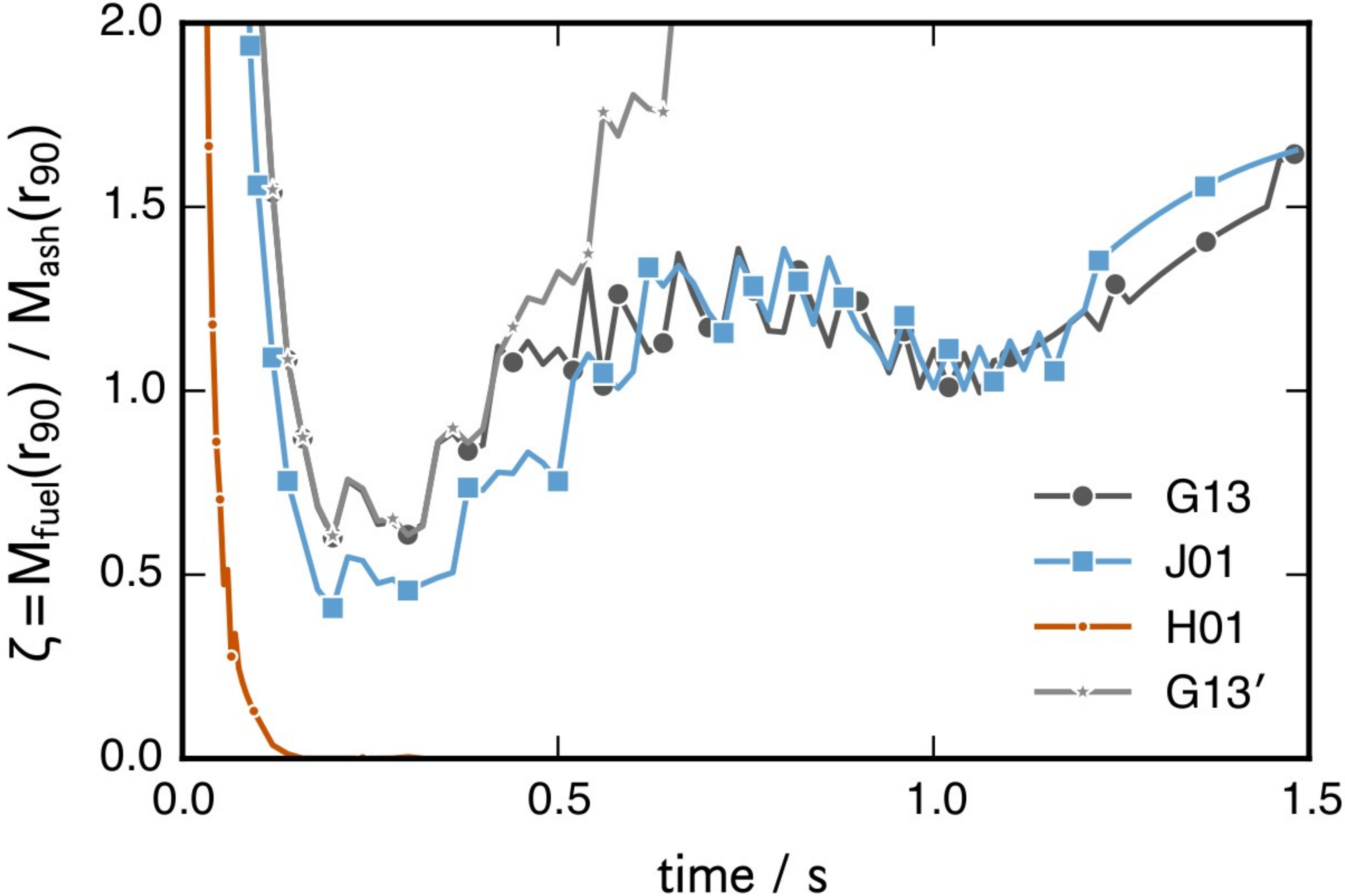


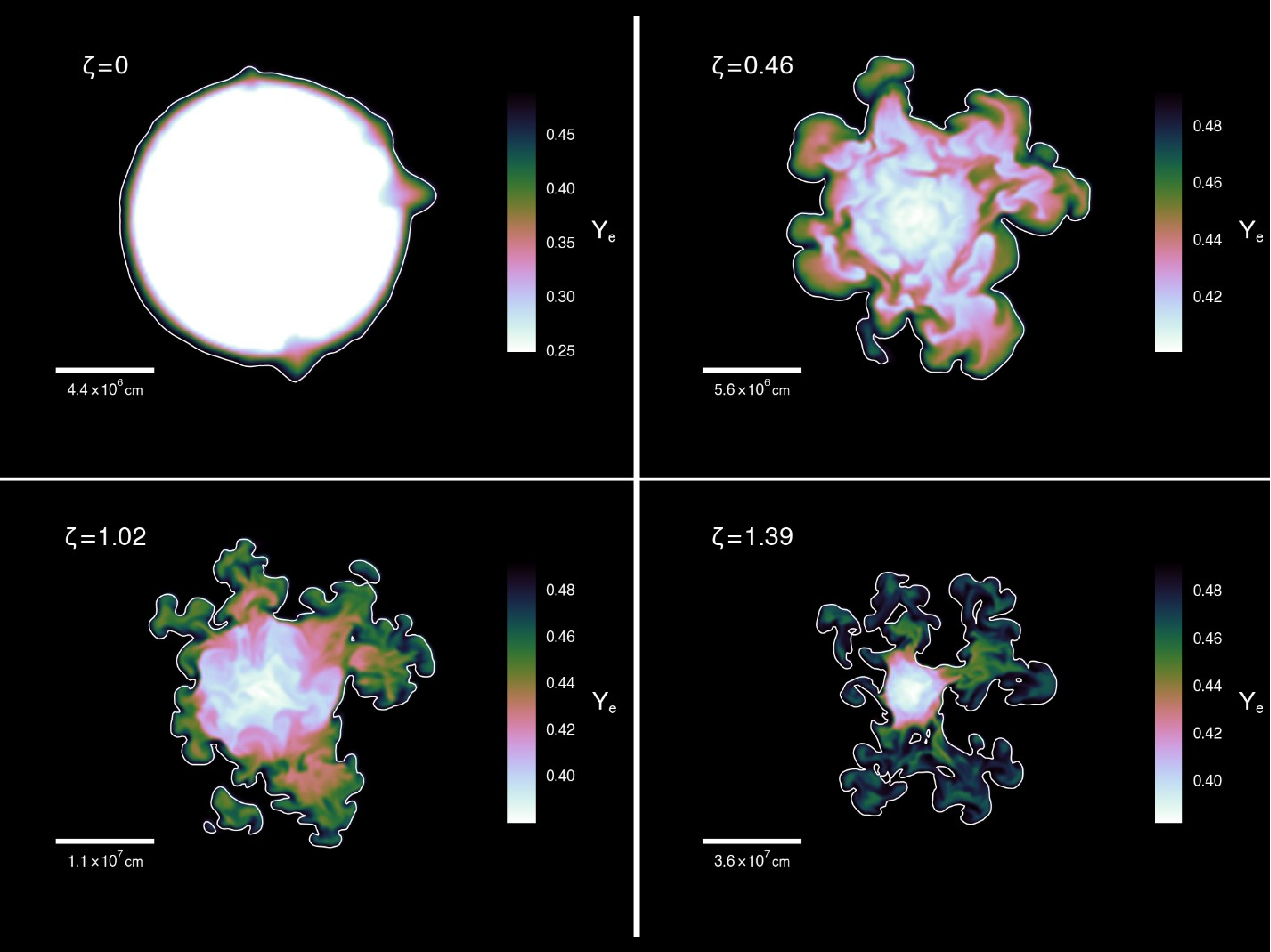


FLAME SPEEDS

SPHERICAL FLAME?

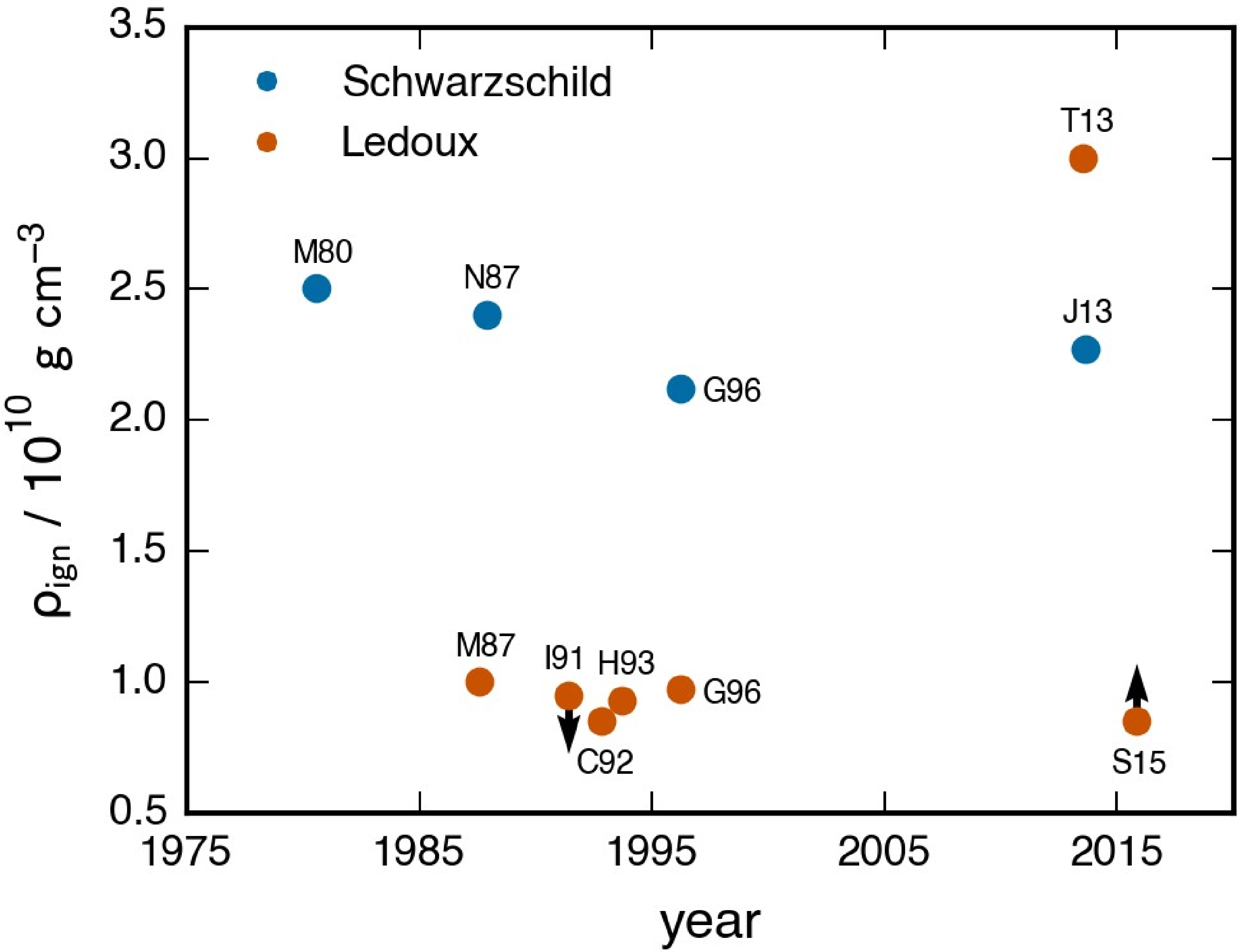
Quantitative measure of flame asymmetry




ζ=0
0.45
0.40
0.35
0.30
0.25
Y_e
4.4×10^6 cm
ζ=0.46
0.48
0.46
0.44
0.42
Y_e
5.6×10^6 cm
ζ=1.02
0.48
0.46
0.44
0.42
0.40
Y_e
1.1×10^7 cm
ζ=1.39
0.48
0.46
0.44
0.42
0.40
Y_e
3.6×10^7 cm

IGNITION DENSITY

SENSITIVITY TO MIXING PROCESSES



M80: Miyaji+ (1980)

N87: Nomoto (1987)

M87: Miyaji & Nomoto (1987)

I91: Isern+ (1991)

C92: Canal+ (1992)

H93: Hashimoto+ (1993)

G96: Gutierrez+ (1996)

J13: Jones+ (2013)

T13: Takahashi+ (2013)

S15: Schwab+ (2015)

SUMMARY

ECSNe and AIC of ONe Wds postulated to explain many astrophysical observations, including:

- Abundance anti-correlations
- Site for r-process
- "bimodal" NS mass distribution
- Bimodal BeX orbital eccentricity
- Low L transients

In recent 2-3 years we have improved:

- Nuclear physics input
- Progenitor models
- Deflagration simulations

Next: pre-ignition mixing

Temporally and spatially averaged mixing properties of 3D hydrodynamic O-shell burning simulations can be well approximated in 1D codes when:

- the local MLT mixing length is limited to the distance to the convective boundary
- Exponential-diffusive CBM is employed, with an e-folding length of ~$0.03H_P$

This is a promising start to improving the treatment of CBM in stellar models and is important for determining pre-SN structure