SIMULATING THE LIVES AND DEATHS OF OF 8 – 10 SOLAR-MASS STARS

SAMUEL JONES
HEIDELBERG INSTITUTE FOR THEORETICAL STUDIES

TUE 21 JUN 2016
ICRANet, Pescara

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LOW AND INTERMEDIATE MASS STARS

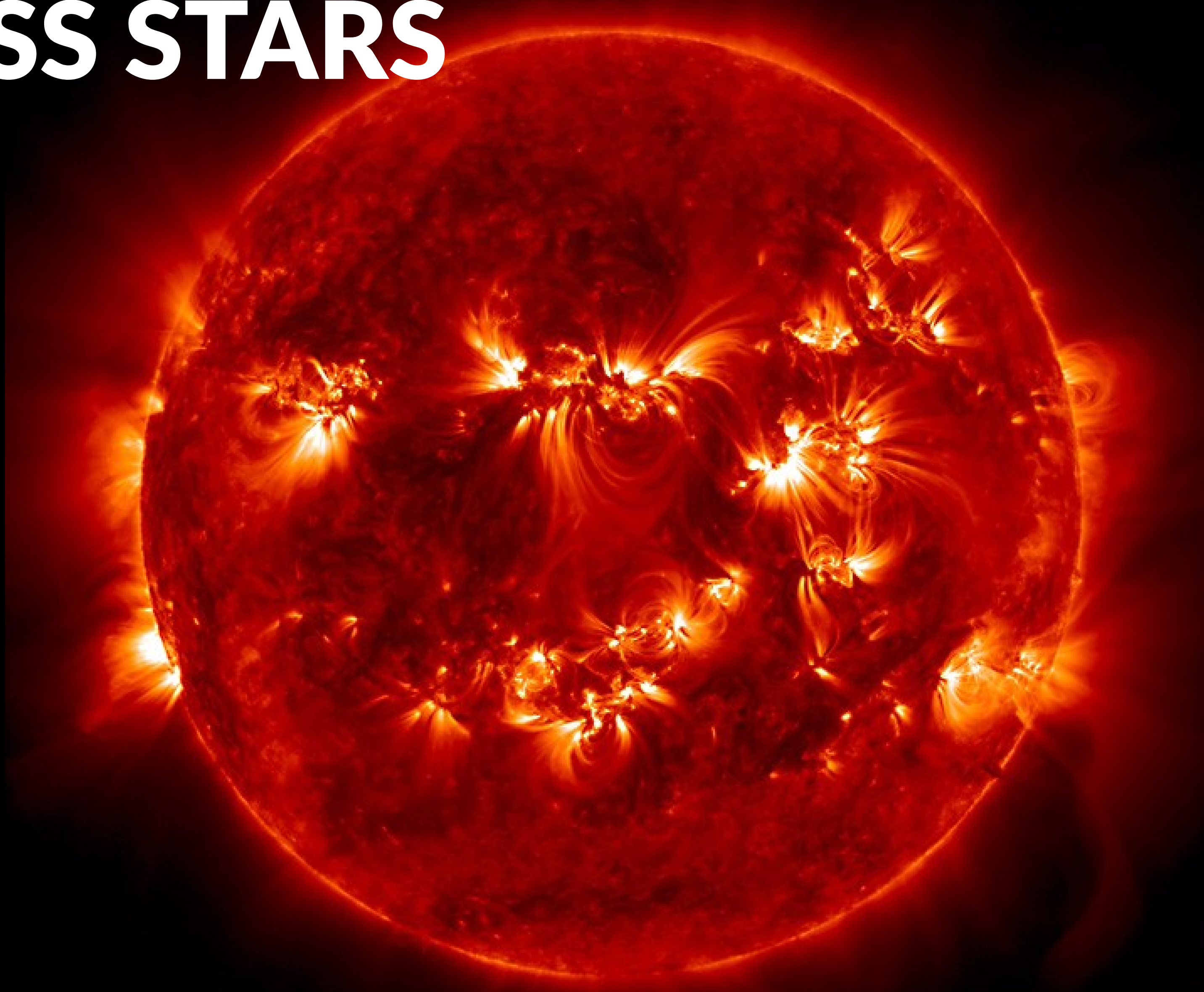


Image Credit: Solar Dynamics Observatory, NASA

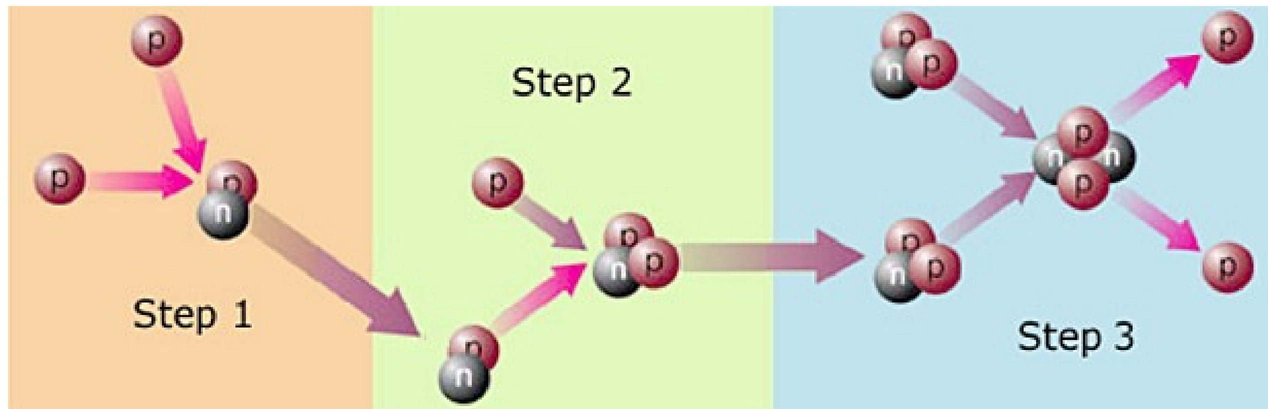
NUCLEAR POWER

H & He BURNING

Image Credit: David Taylor

H → He

p-p chain

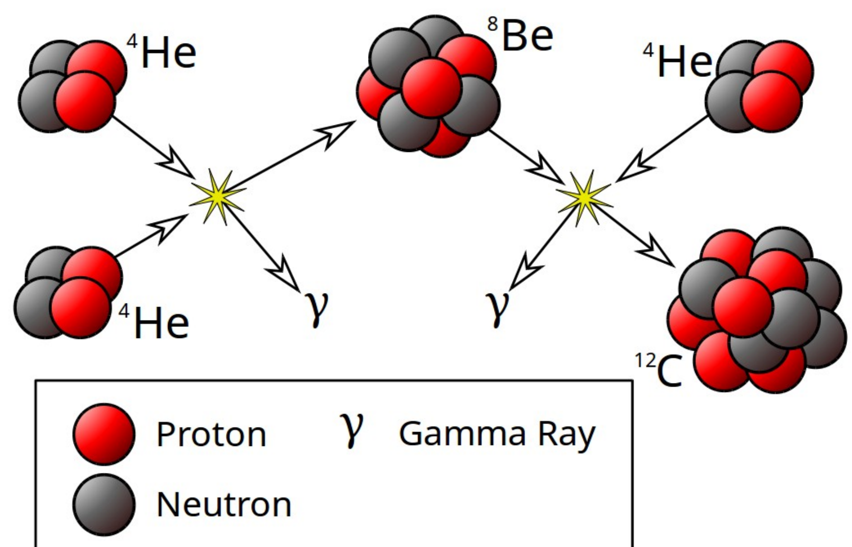


If the star is massive enough (> 0.8 solar masses):

He → C & O

Triple-α

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



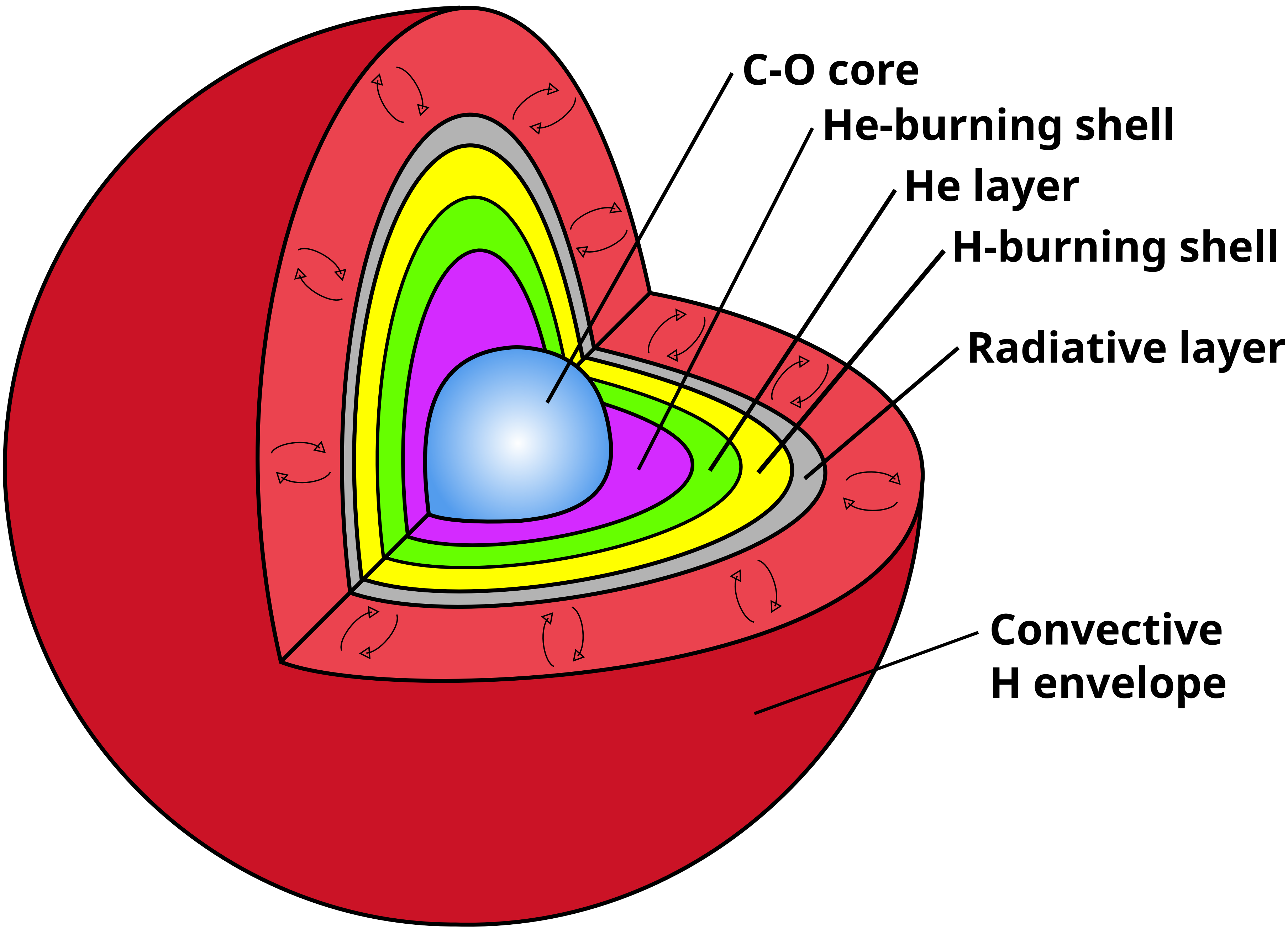


Image credit: Persson, Magnus Vilhelm (2013)

PLANETARY NEBULAE

& WHITE DWARFS

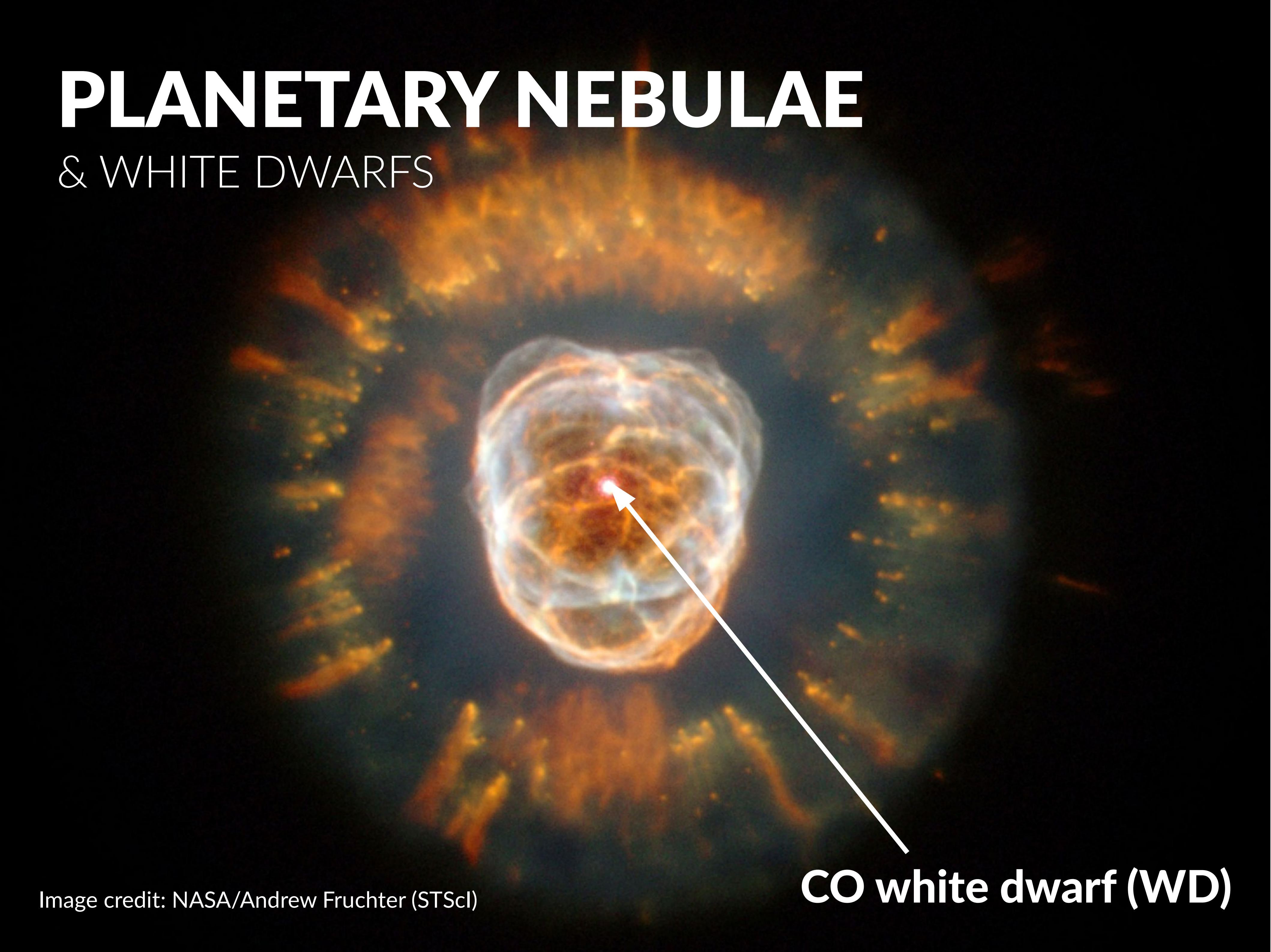


Image credit: NASA/Andrew Fruchter (STScI)

EXPLODING WHITE DWARFS

THERMONUCLEAR SUPERNOVAE

Image credit: NASA/CXC/SAO

MASSIVE STARS

Artist's impression of Rigel

Image Credit: Adam Burn

NUCLEAR POWER

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**

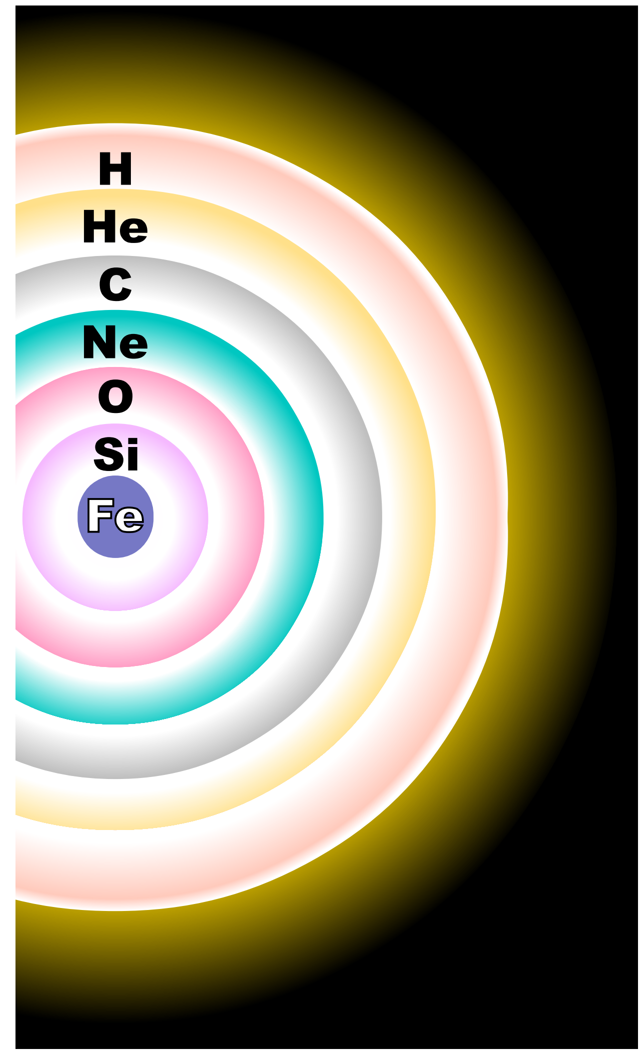


Image credit: R. J. Hall

CORE-COLLAPSE SUPERNOVAE

CAS A

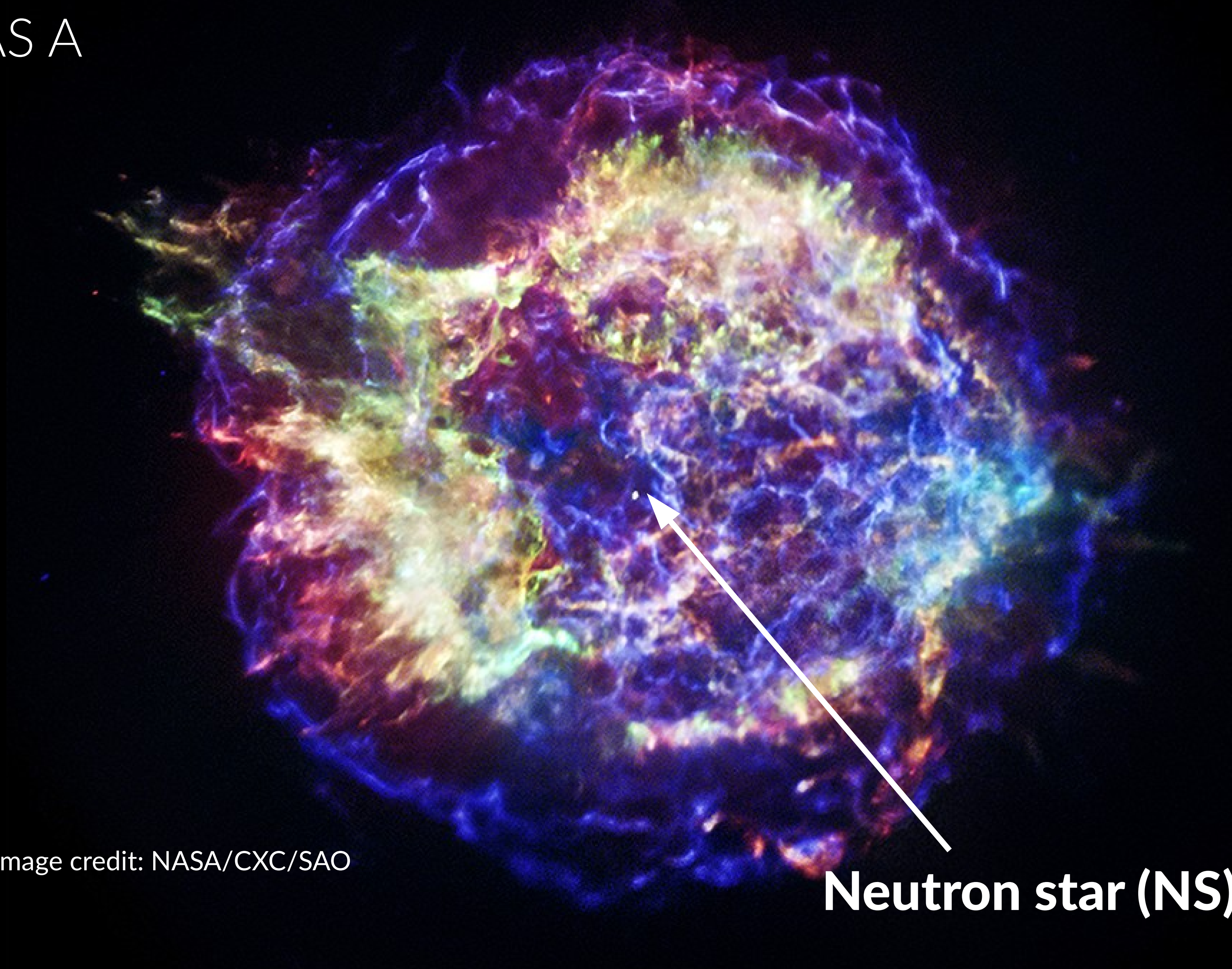
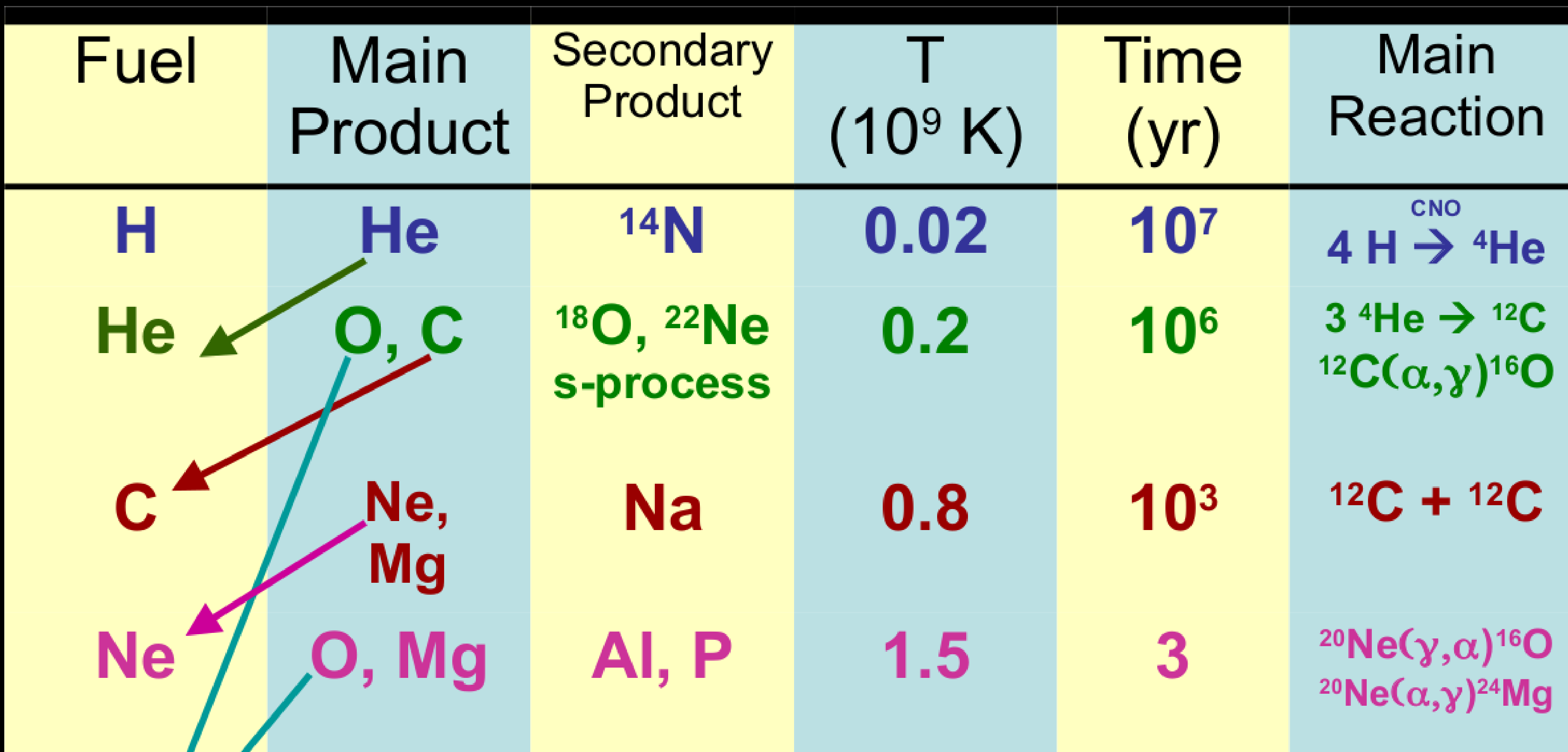


Image credit: NASA/CXC/SAO

SUPER-AGB STARS

"8-10 SOLAR-MASS" STARS

Image credit: Alexander Heger



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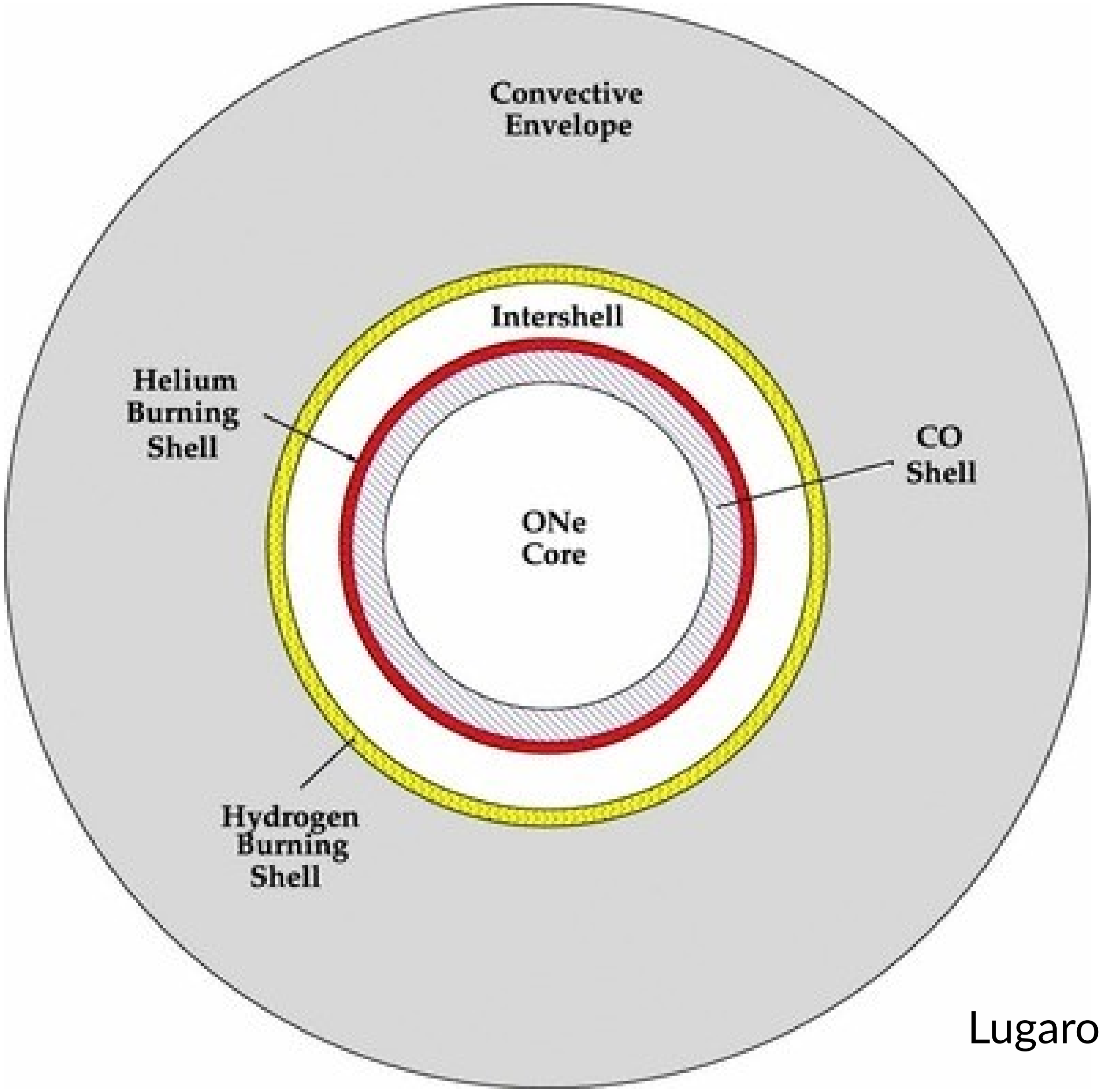
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$

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?

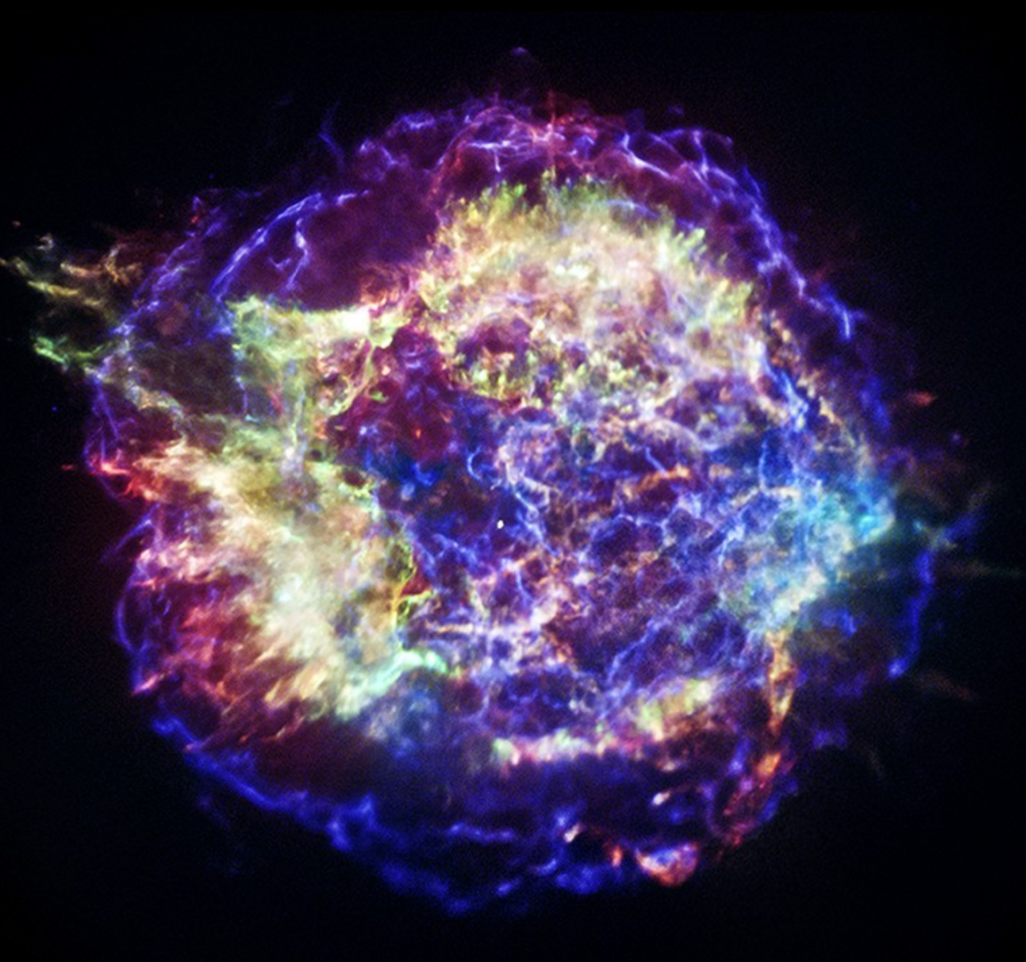
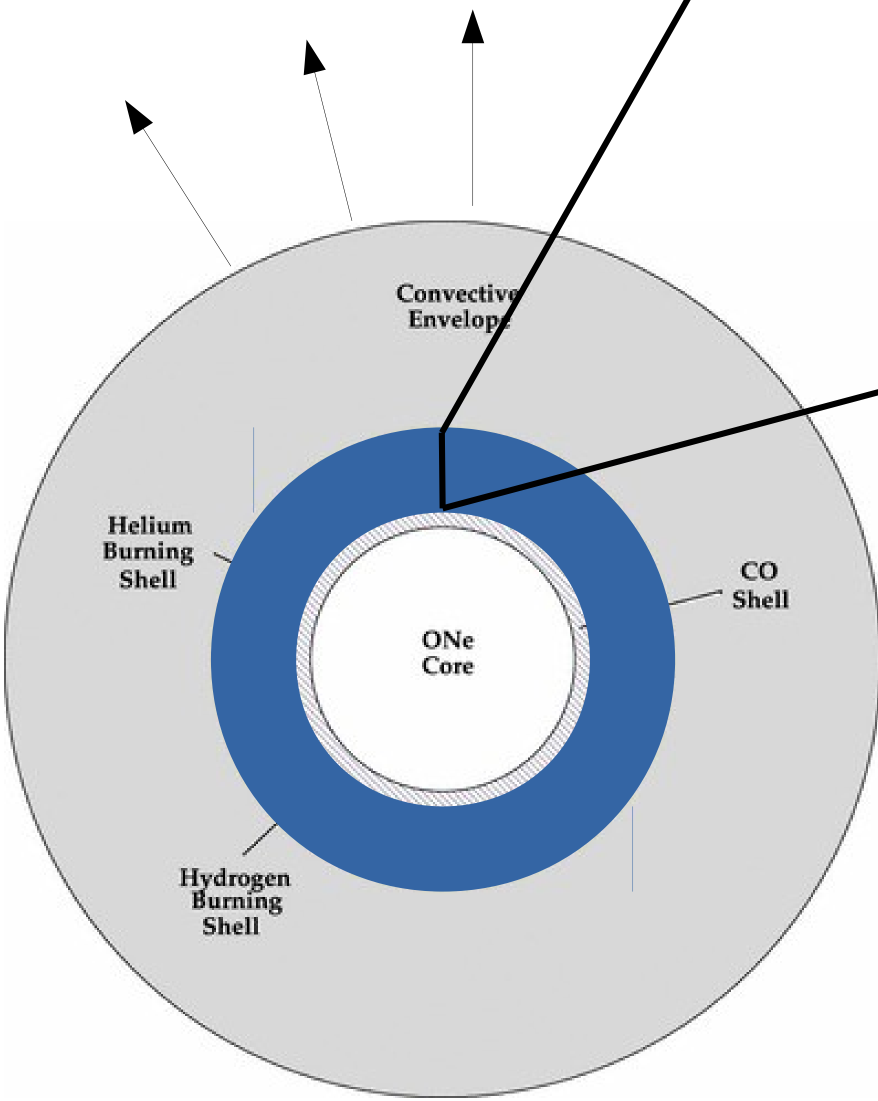


Image credit: NASA/CXC/SAO

Image credit: NASA/Andrew Fruchter (STScI)

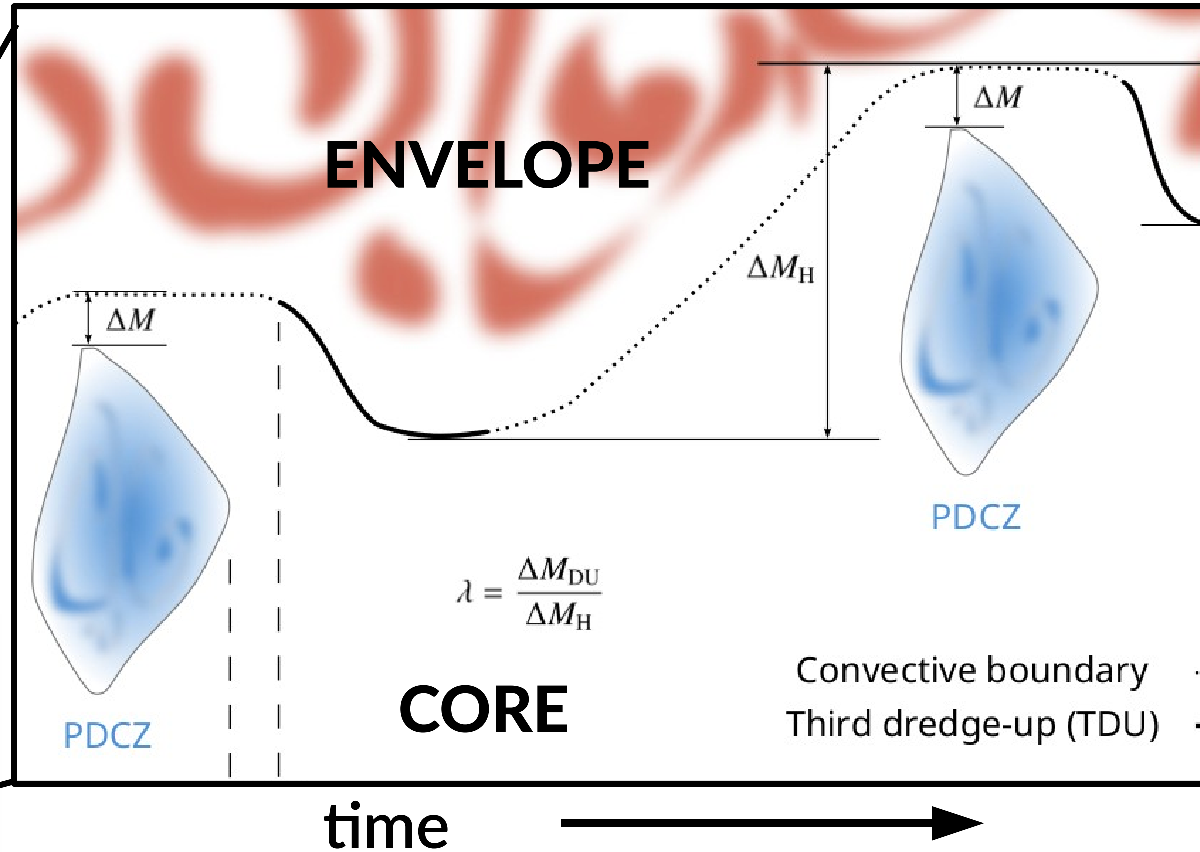
SUPER-AGB STARS

Envelope shedding due to stellar winds

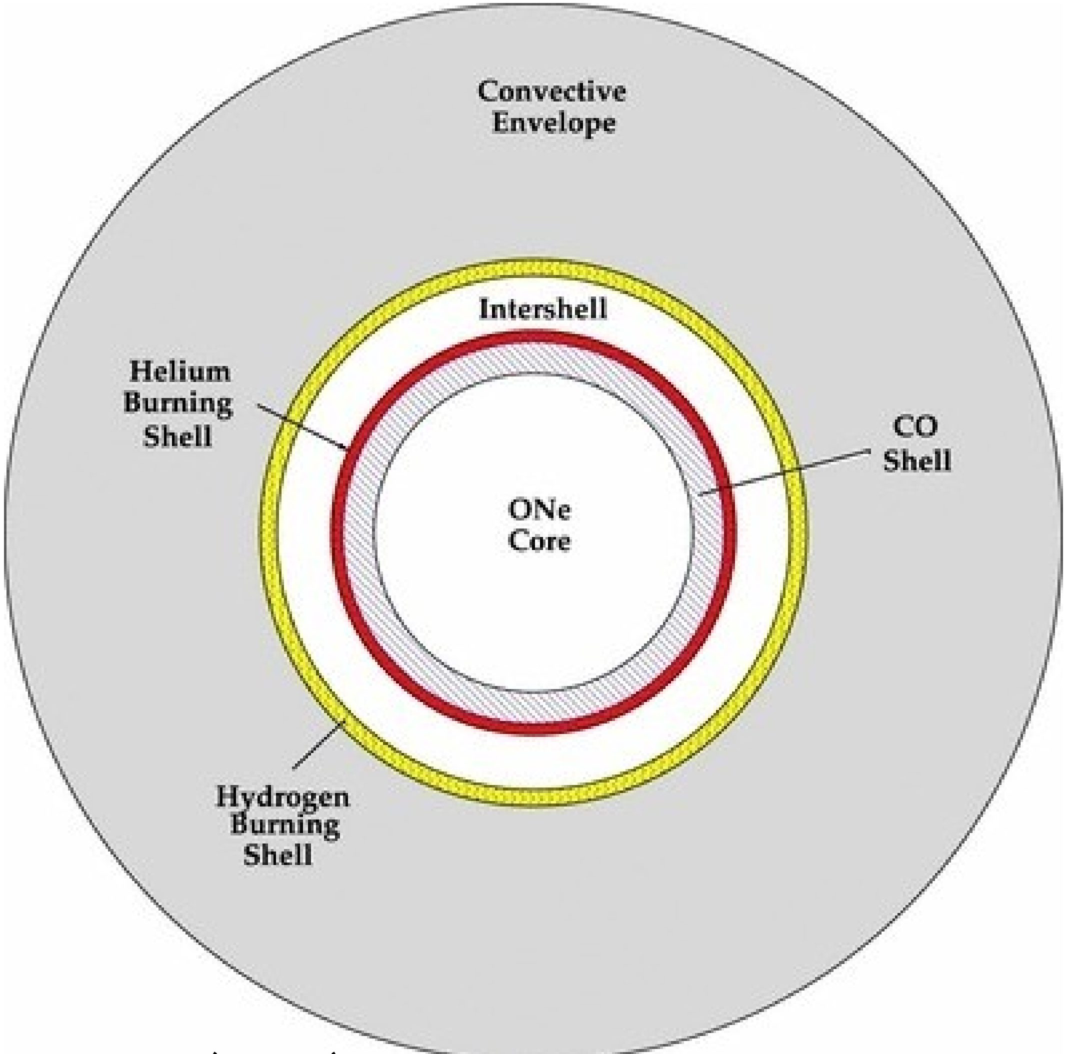


Lugaro+ (2012)

Jones+ (2016)



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



Lugaro+ (2012)

Two (three) general classical scenarios:

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

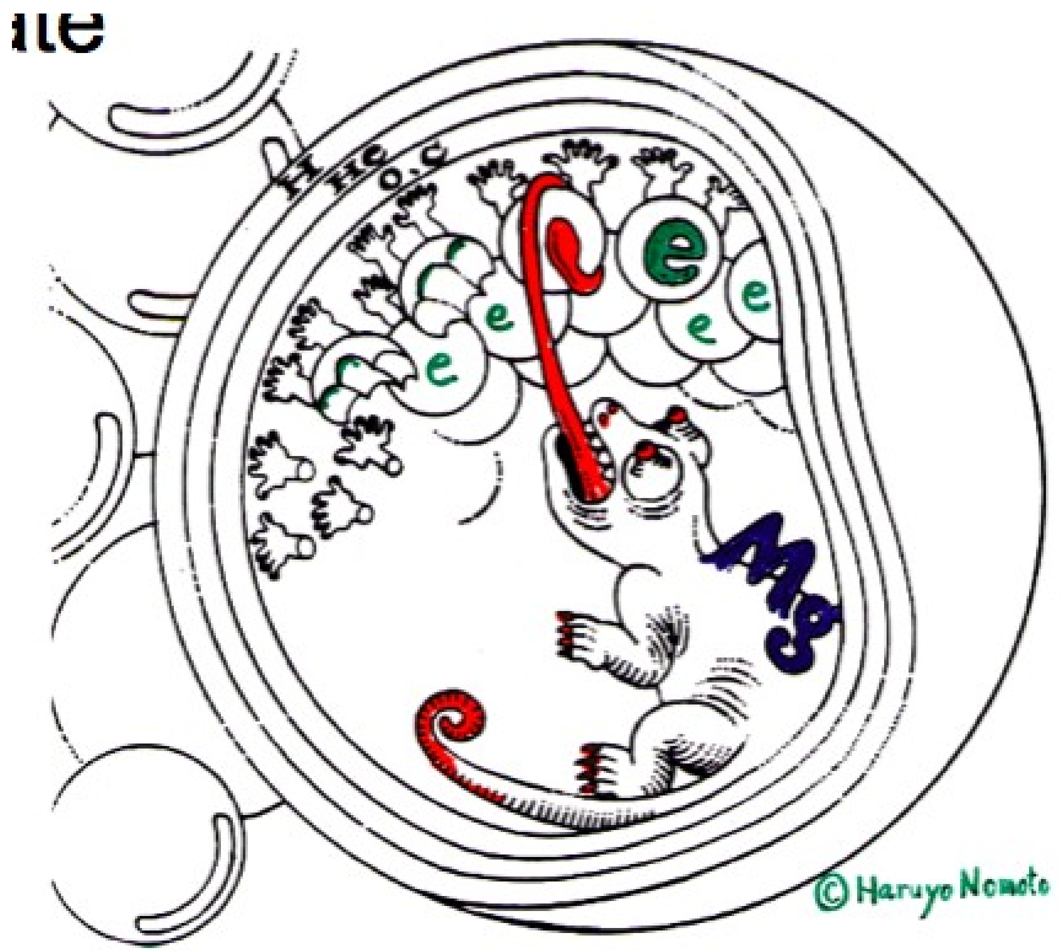
2. The core grows due to accumulation of ash from the burning shells, eventually exceeding the effective Chandrasekhar limit and **collapsing to a neutron star**

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 classical picture the electron captures win and the star's **core collapses (an electron-capture supernova; ECSN)**

WHAT HAPPENS TO 8-10 SOLAR-MASS STARS?

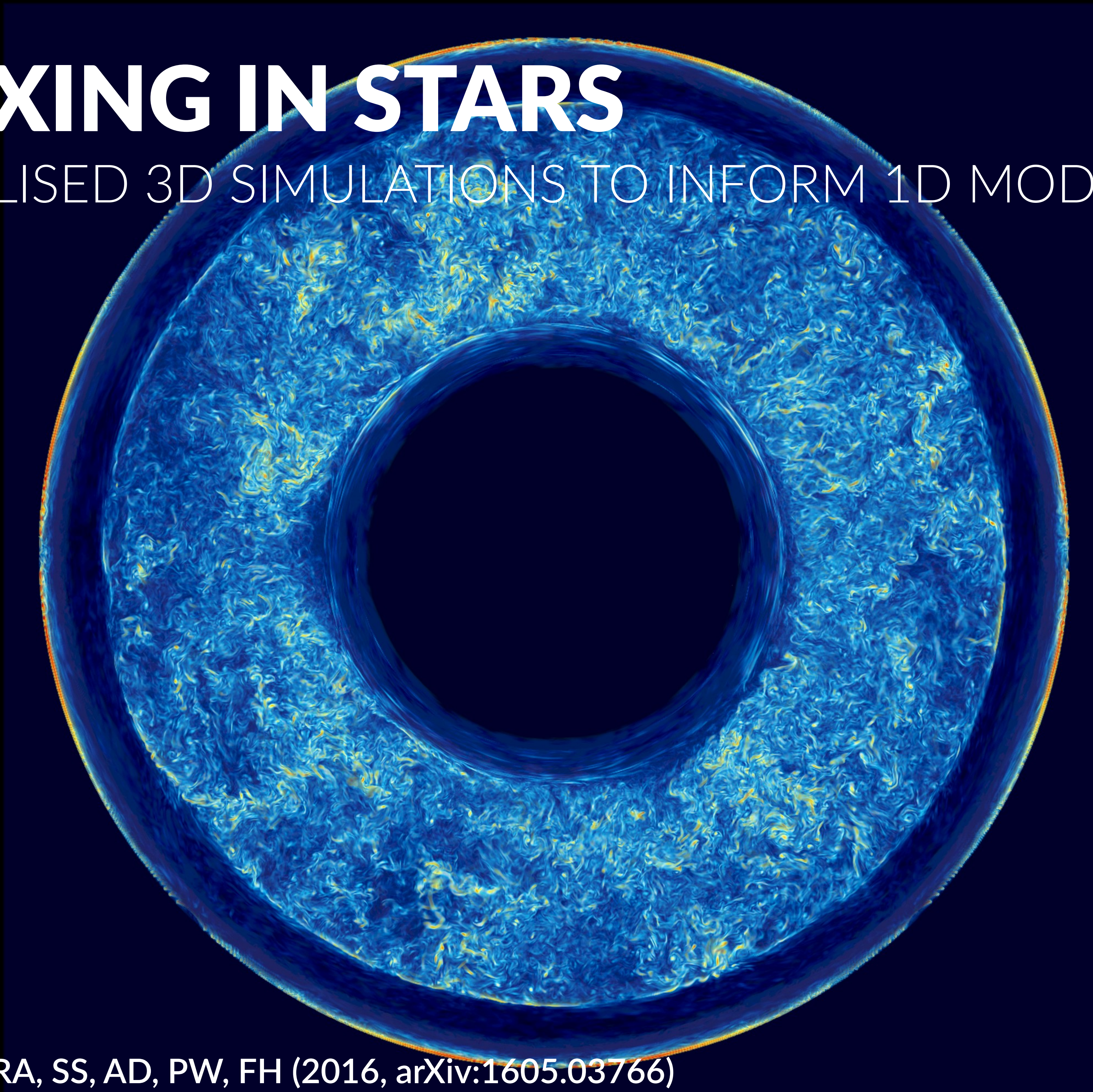
Determined by balance between **convective boundary (core-envelope) mixing** (uncertain) and **envelope shedding due to the stellar wind** (uncertain)

Image credit: NASA/CXC/SAO

Image credit: NASA/Andrew Fruchter (STScI)

MIXING IN STARS

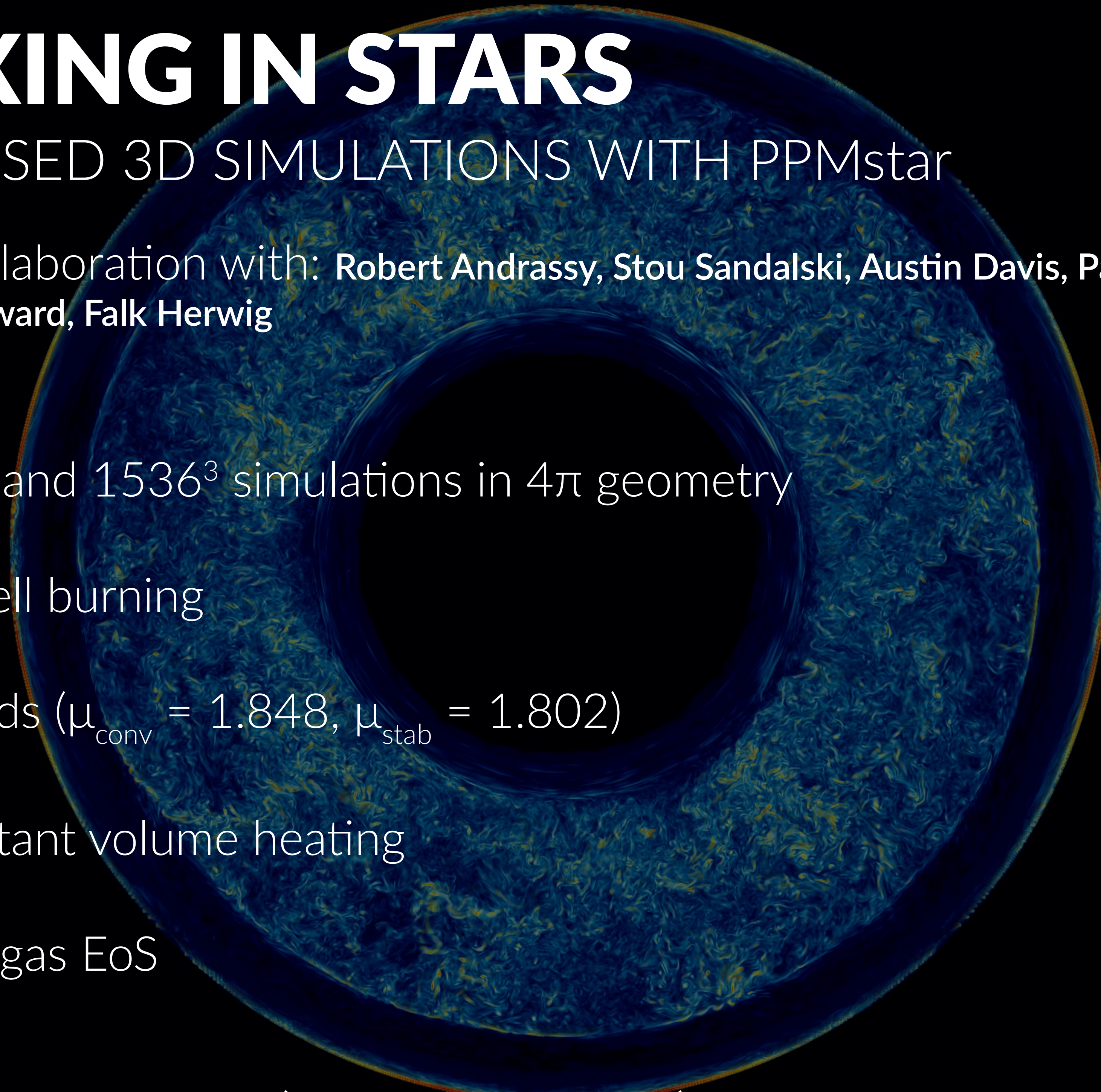
IDEALISED 3D SIMULATIONS TO INFORM 1D MODELS



S. Jones, RA, SS, AD, PW, FH (2016, arXiv:1605.03766)

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

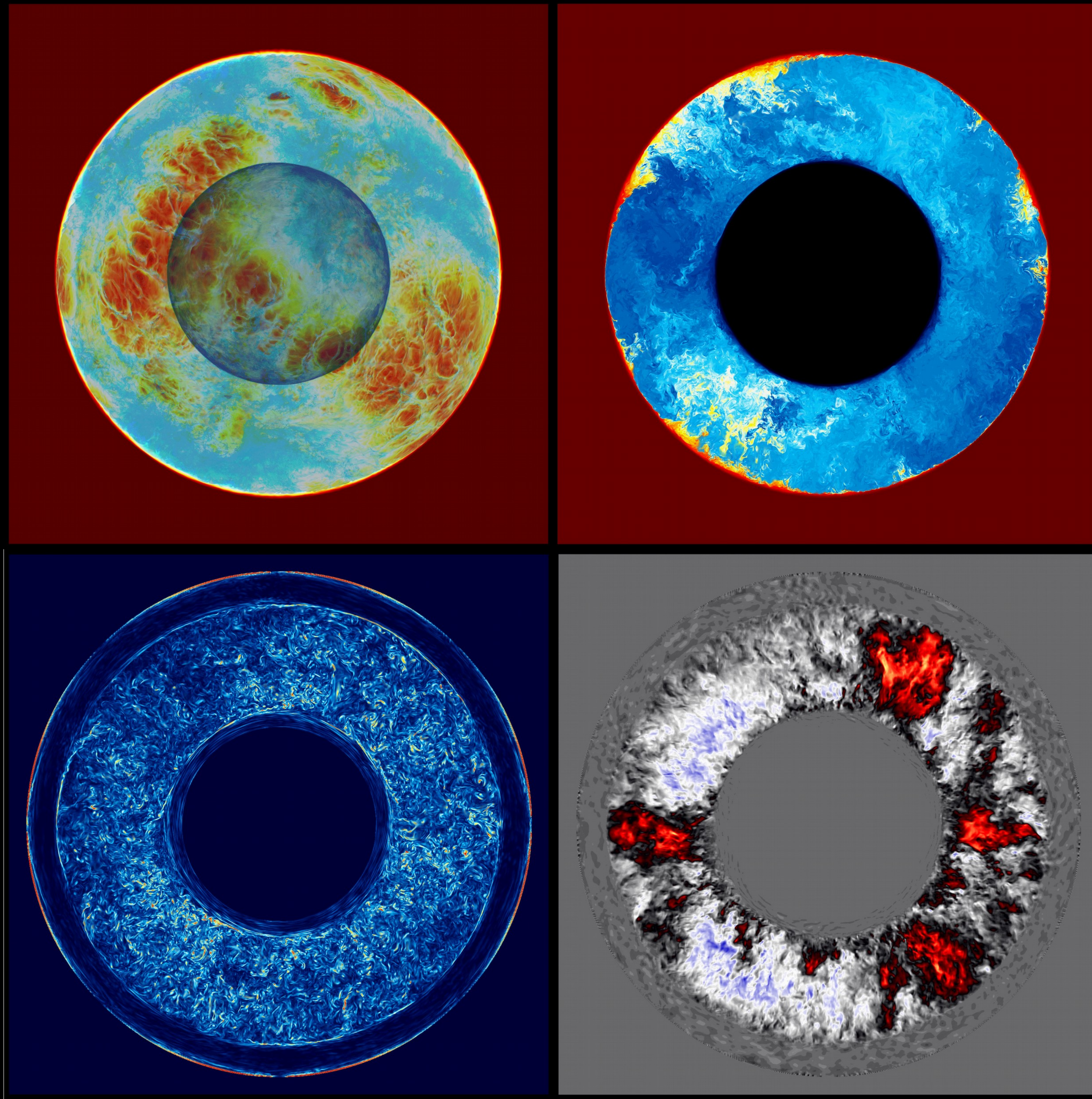
Constant volume heating

Ideal gas EoS

S. Jones, RA, SS, AD, PW, FH (2016, arXiv:1605.03766)

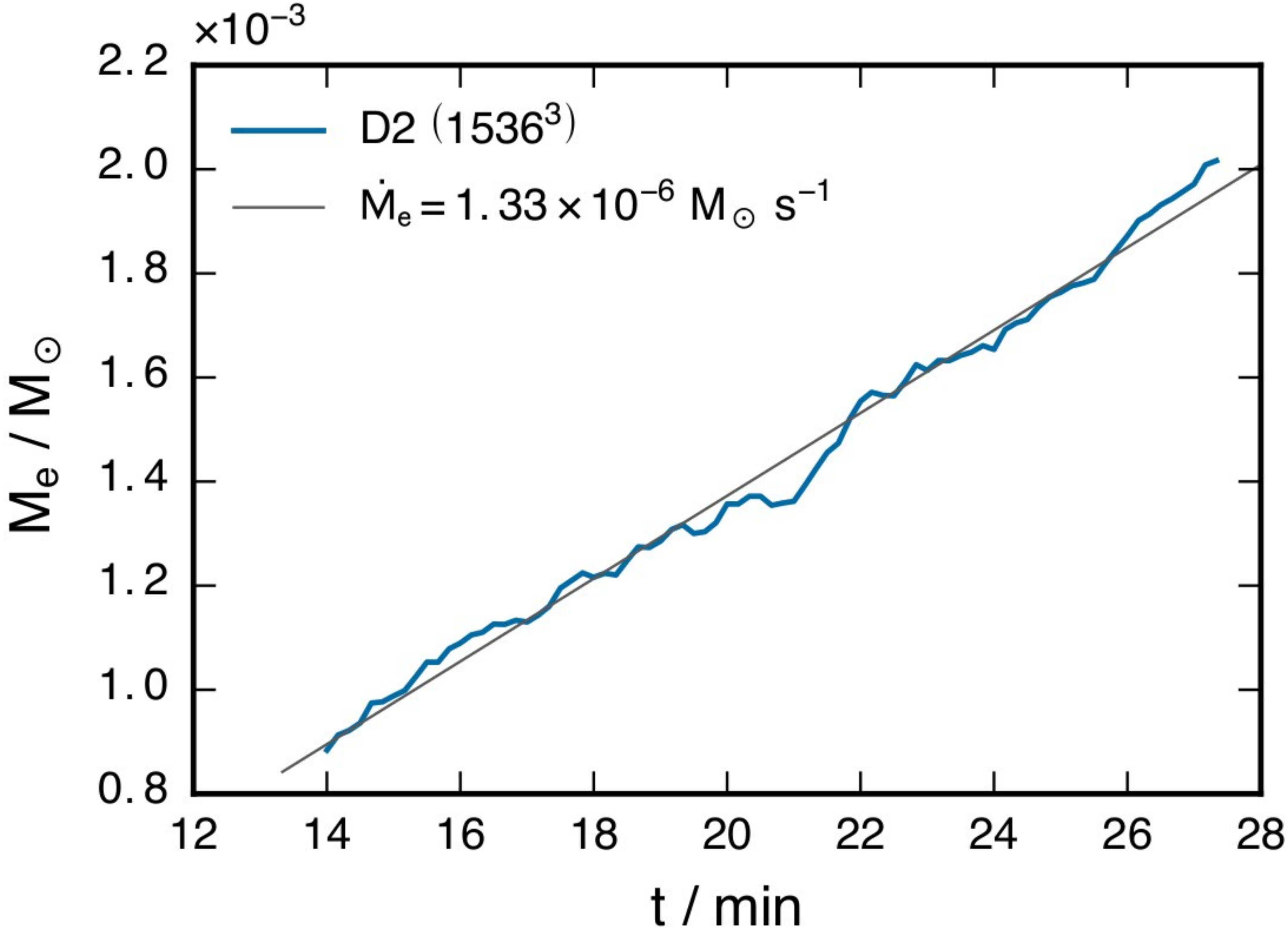
MIXING IN STARS

S. Jones, RA, SS, AD, PW, FH (2016, arXiv:1605.03766)



MIXING IN STARS

Entrainment rate = 1.33 x 10^{-6} $M_\odot$ s^{-1}



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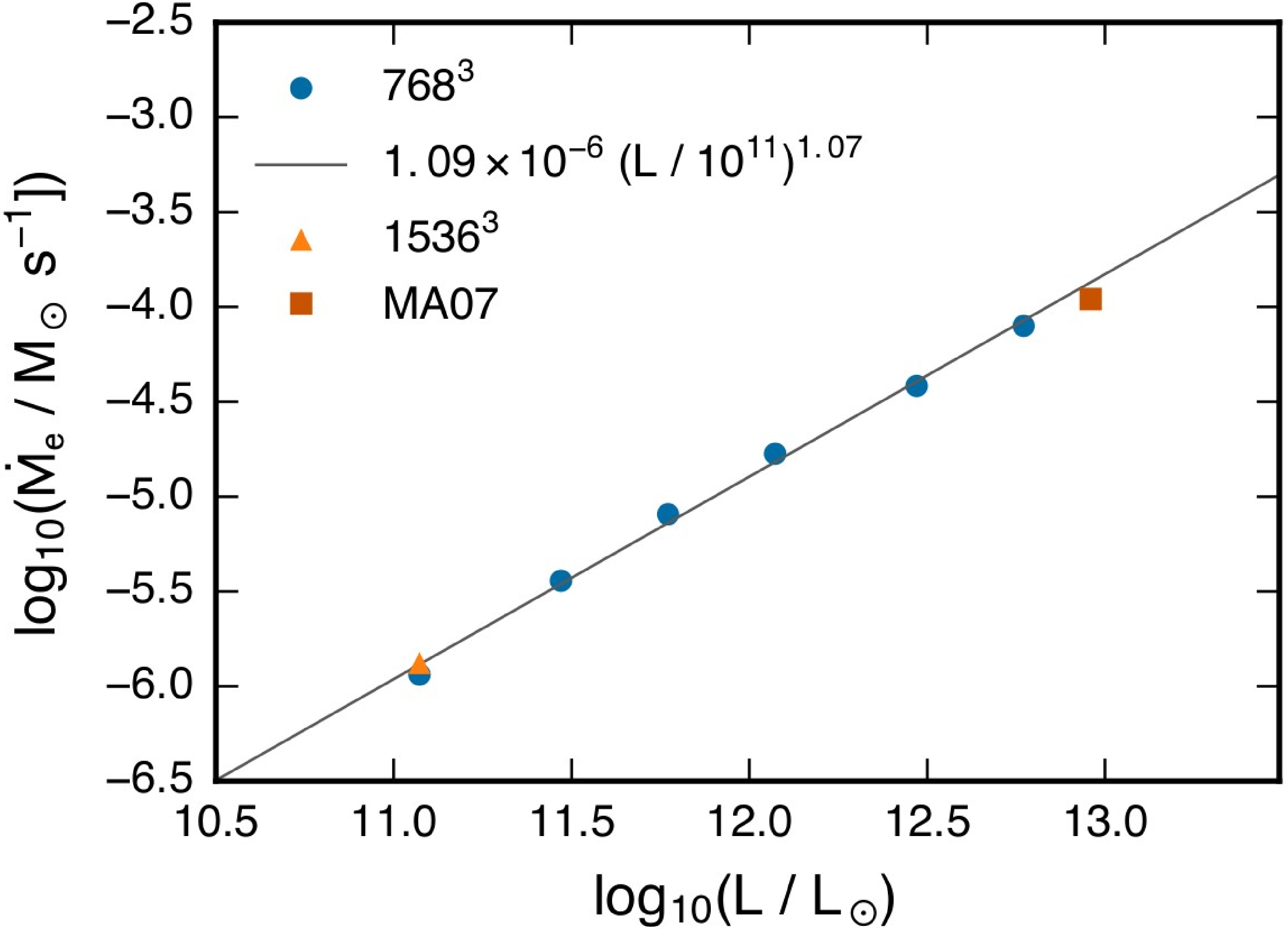
MIXING IN STARS



S. Jones, RA, SS, AD, PW, FH (2016, arXiv:1605.03766)

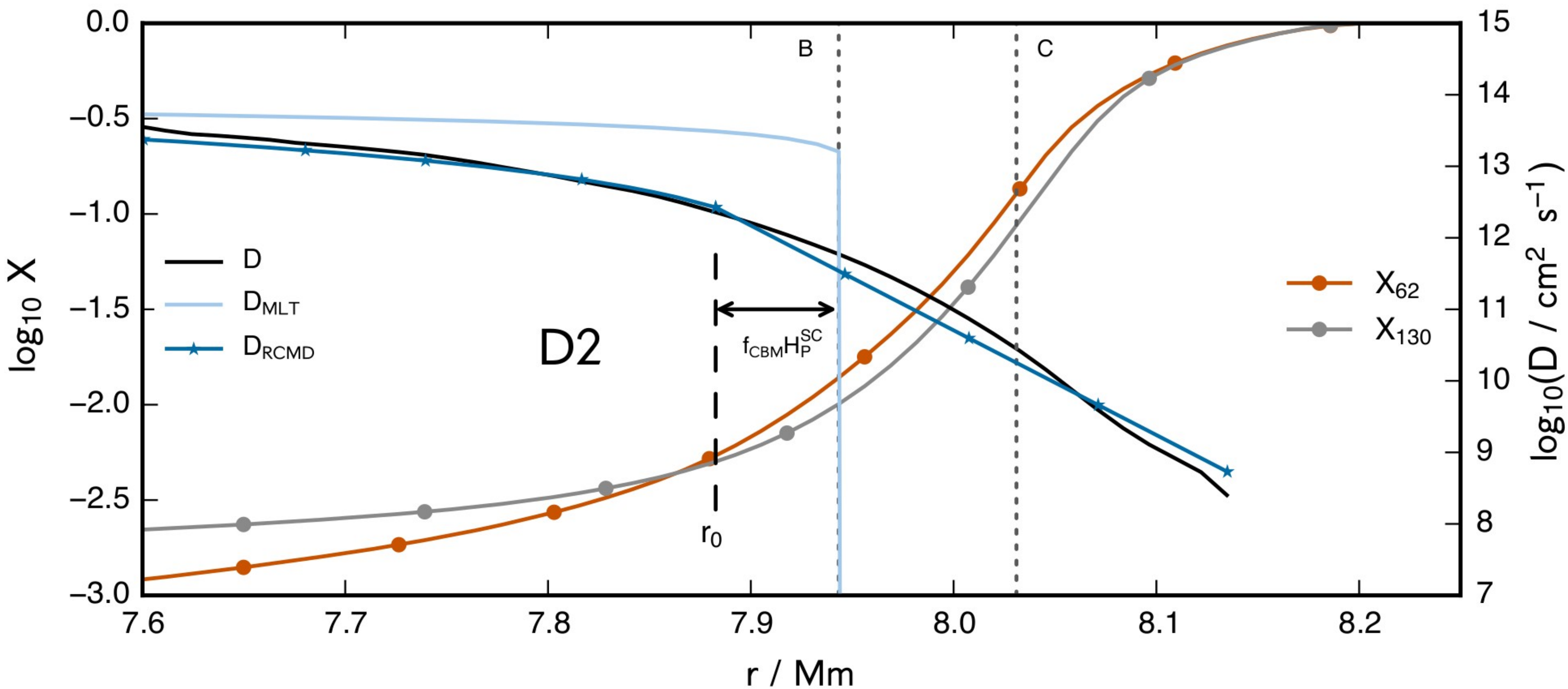
MIXING IN STARS

1D MIXING MODEL

$$\frac{1}{3} v_{MLT} \times \min(\ell, r_0 - r)$$

$f_{CBM} = 0.03$

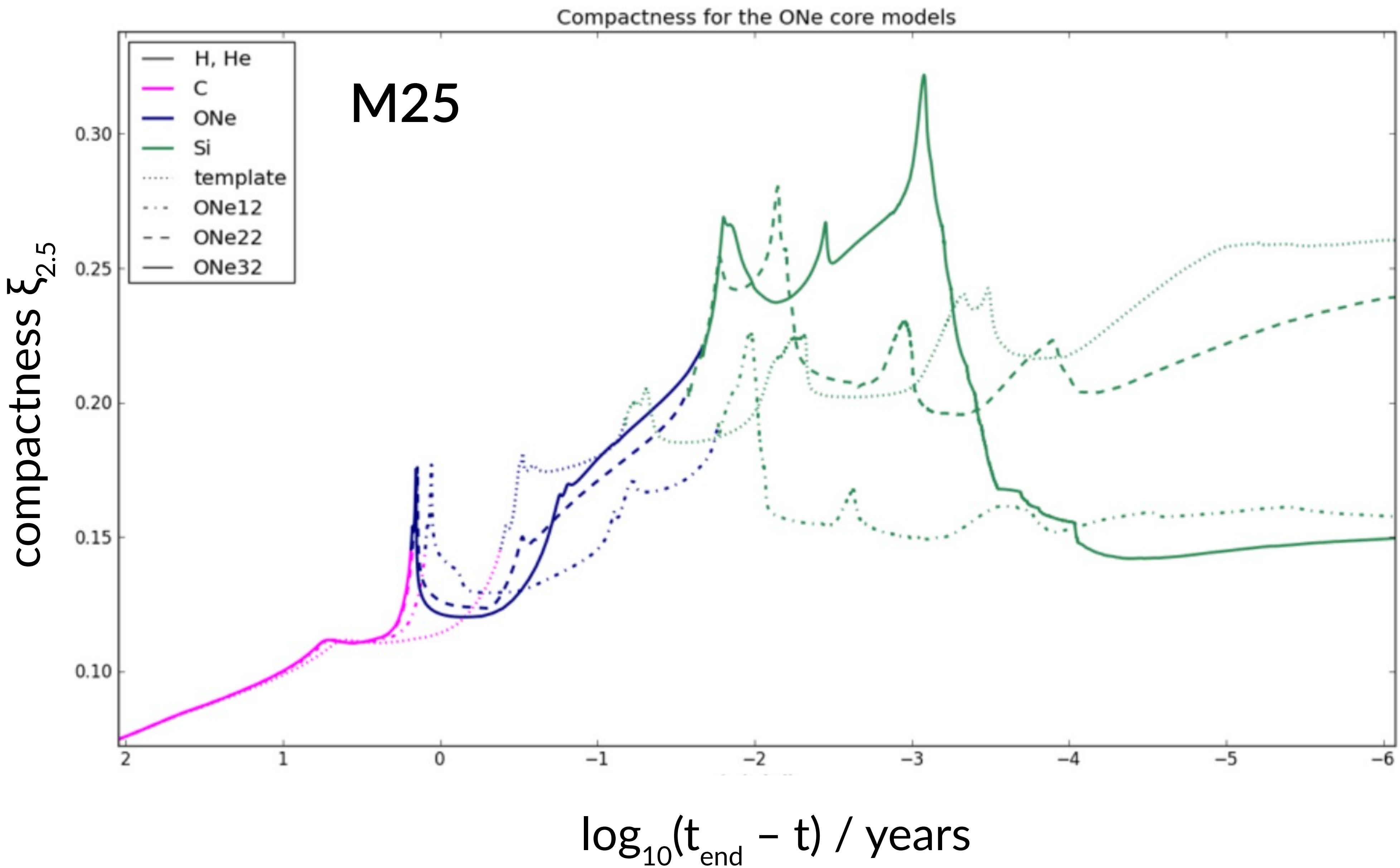
$$D(r) = D(r_0) \times \exp\left\{ -\frac{2(r - r_0)}{f_{CBM} H_P(r_0)} \right\}$$



S. Jones, RA, SS, AD, PW, FH (2016, ArXiv e-prints, arXiv:1605.03766)

MIXING IN STARS

IMPLICATION FOR CCSN PROGENITORS

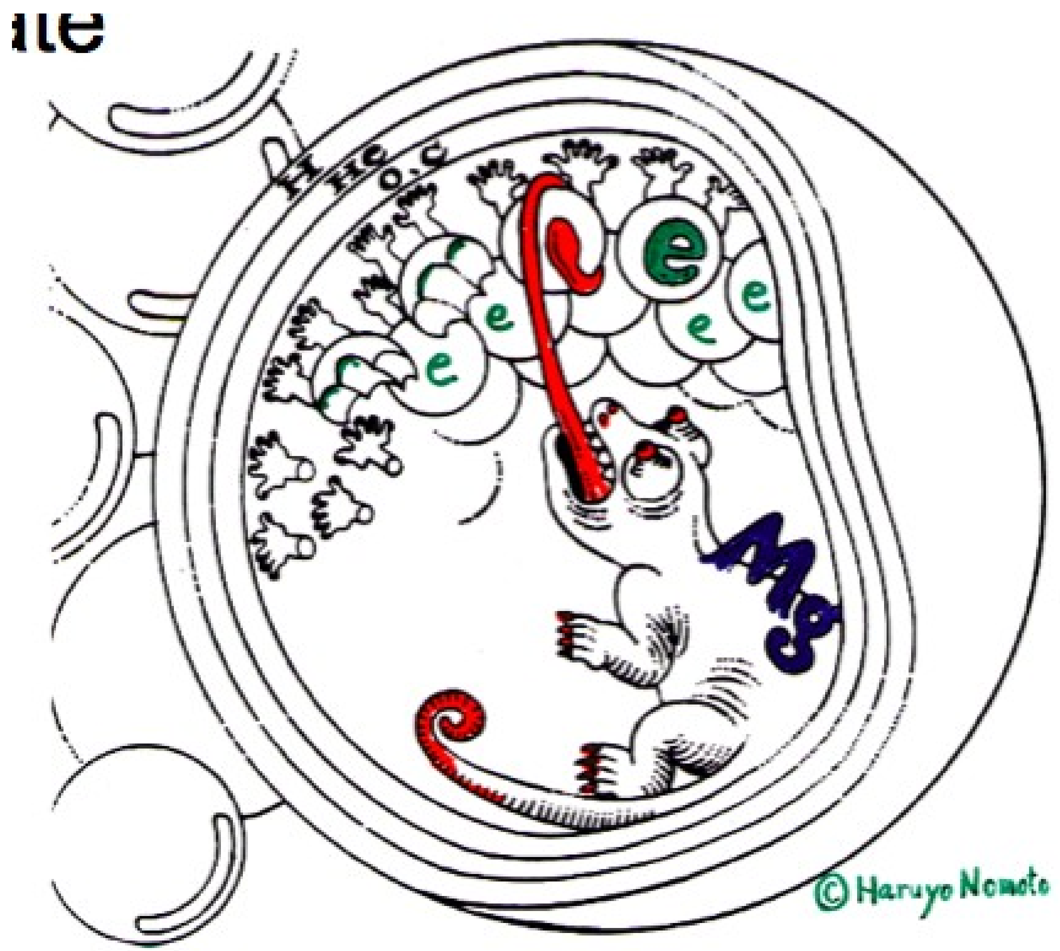


Let's pick up the story again at the ignition of an O deflagration wave (sub-sonic flame)

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

But it is ^{20}**Ne + 2e-**, activated at about 1e10 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 classical picture the electron captures win and the star's **core collapses (an electron-capture supernova; ECSN)**

WHAT ARE ELECTRON-CAPTURE SUPERNOVAE?

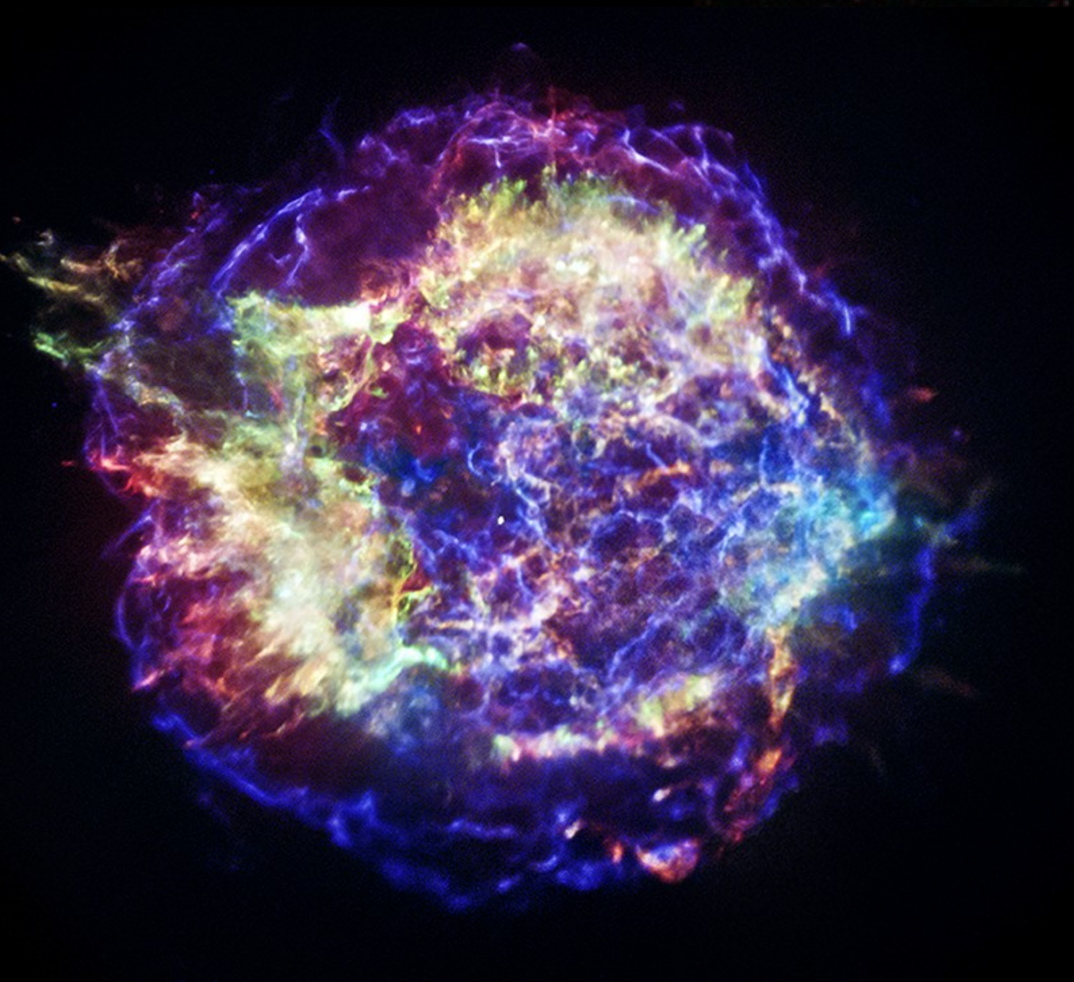


Image credit: NASA/CXC/SAO

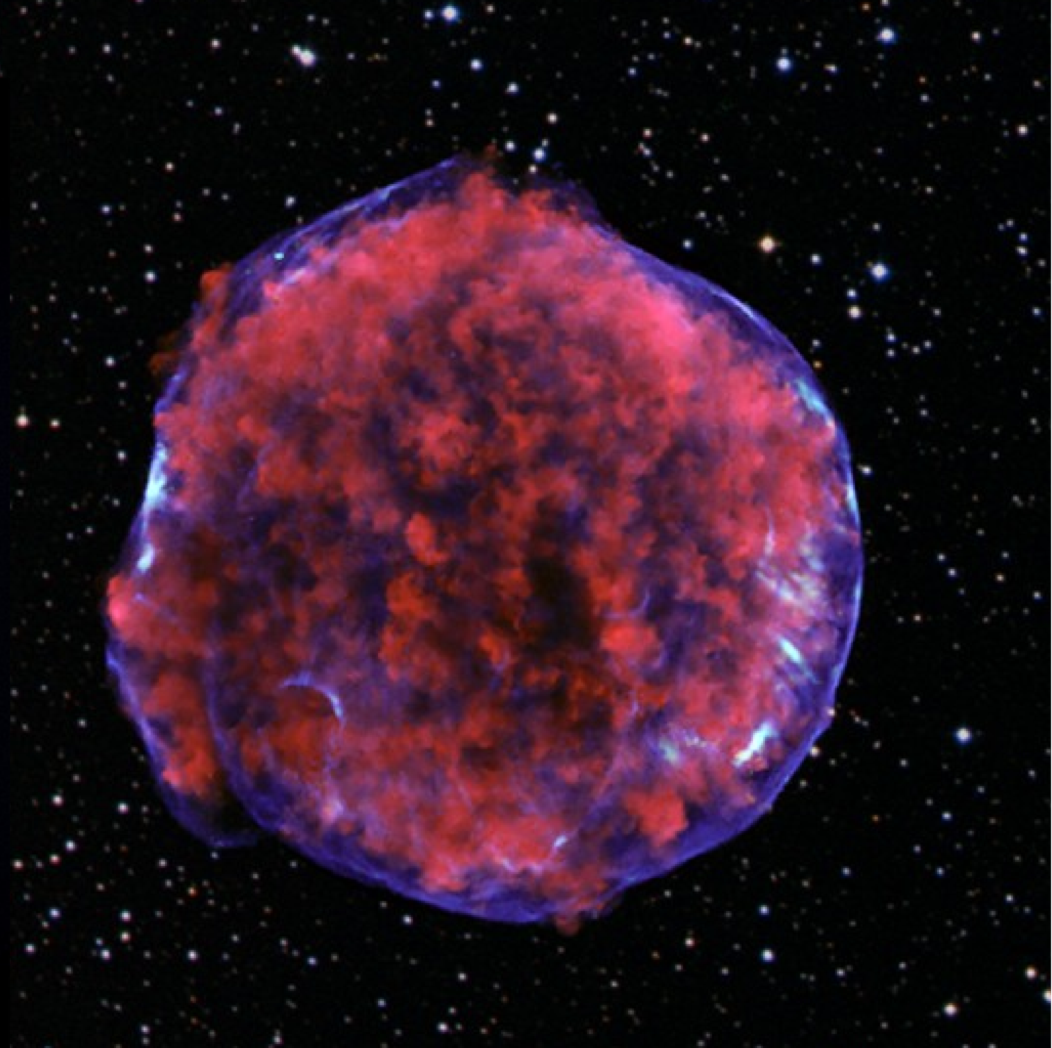
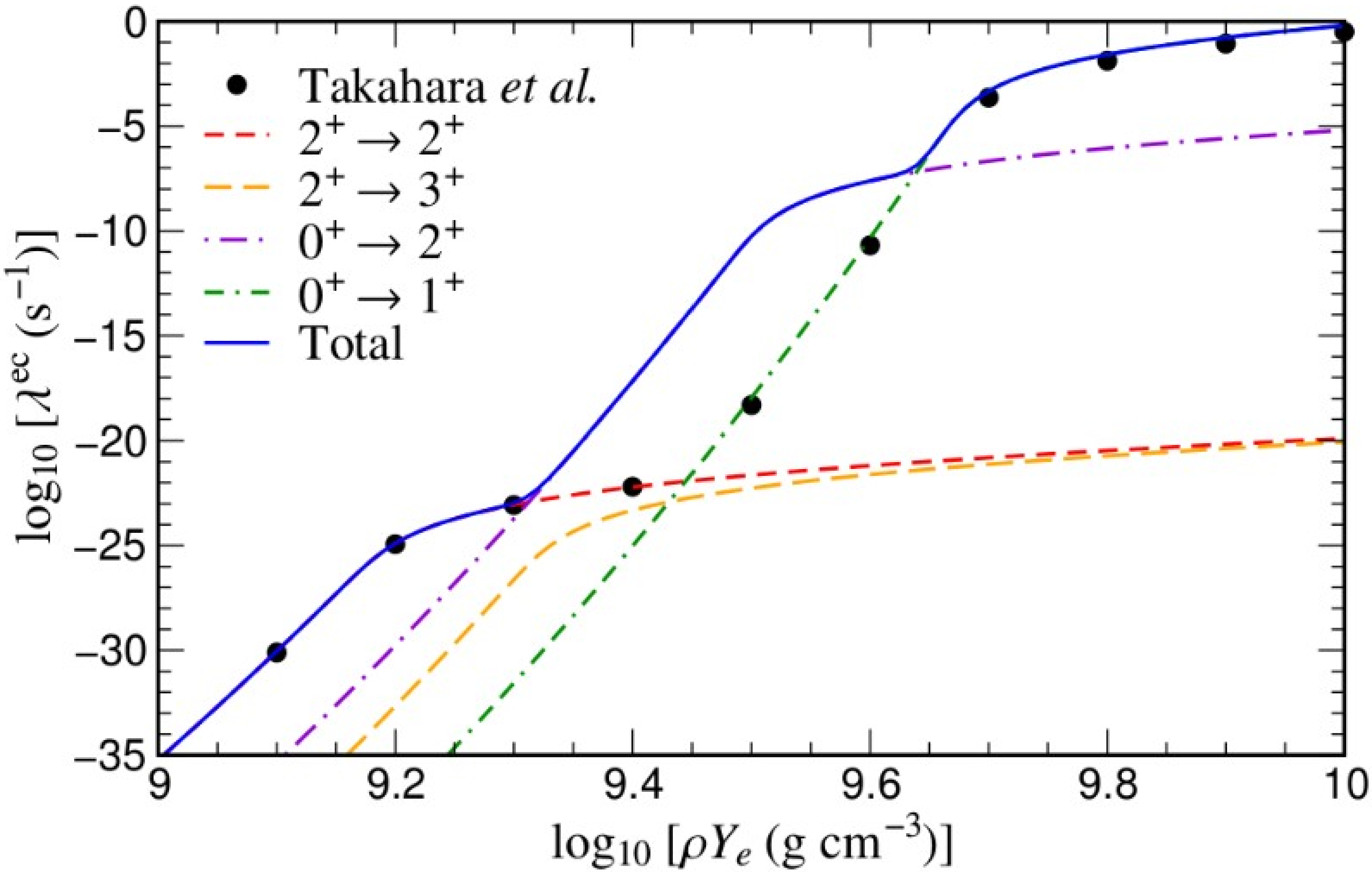


Image credit: NASA/CXC/SAO

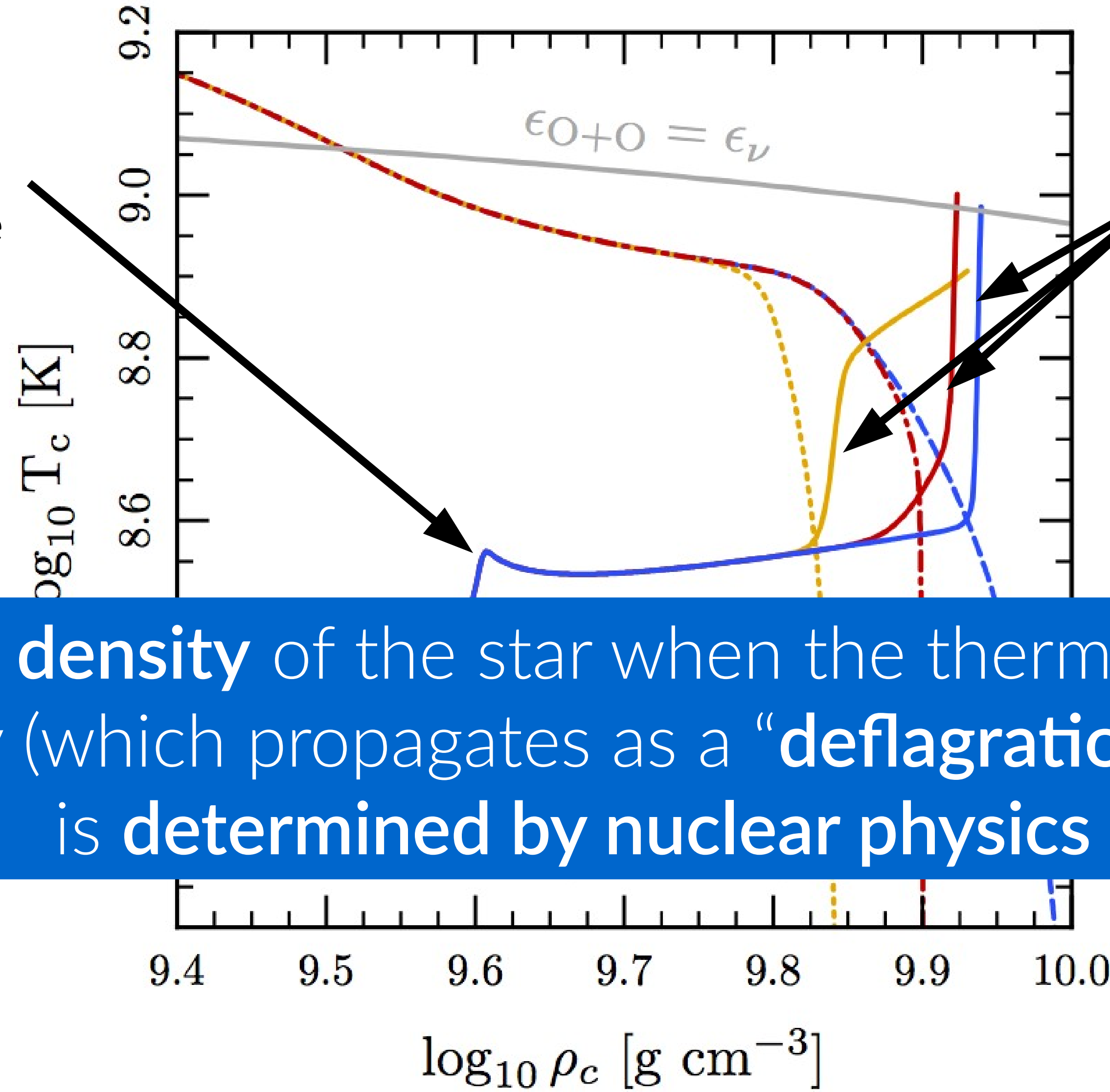


Martinez-Pinedo+ (2014)

^{20}Ne ELECTRON CAPTURE

RAPID HEATING IGNITES THERMONUCLEAR RUNAWAY

^{24}Mg
electron capture



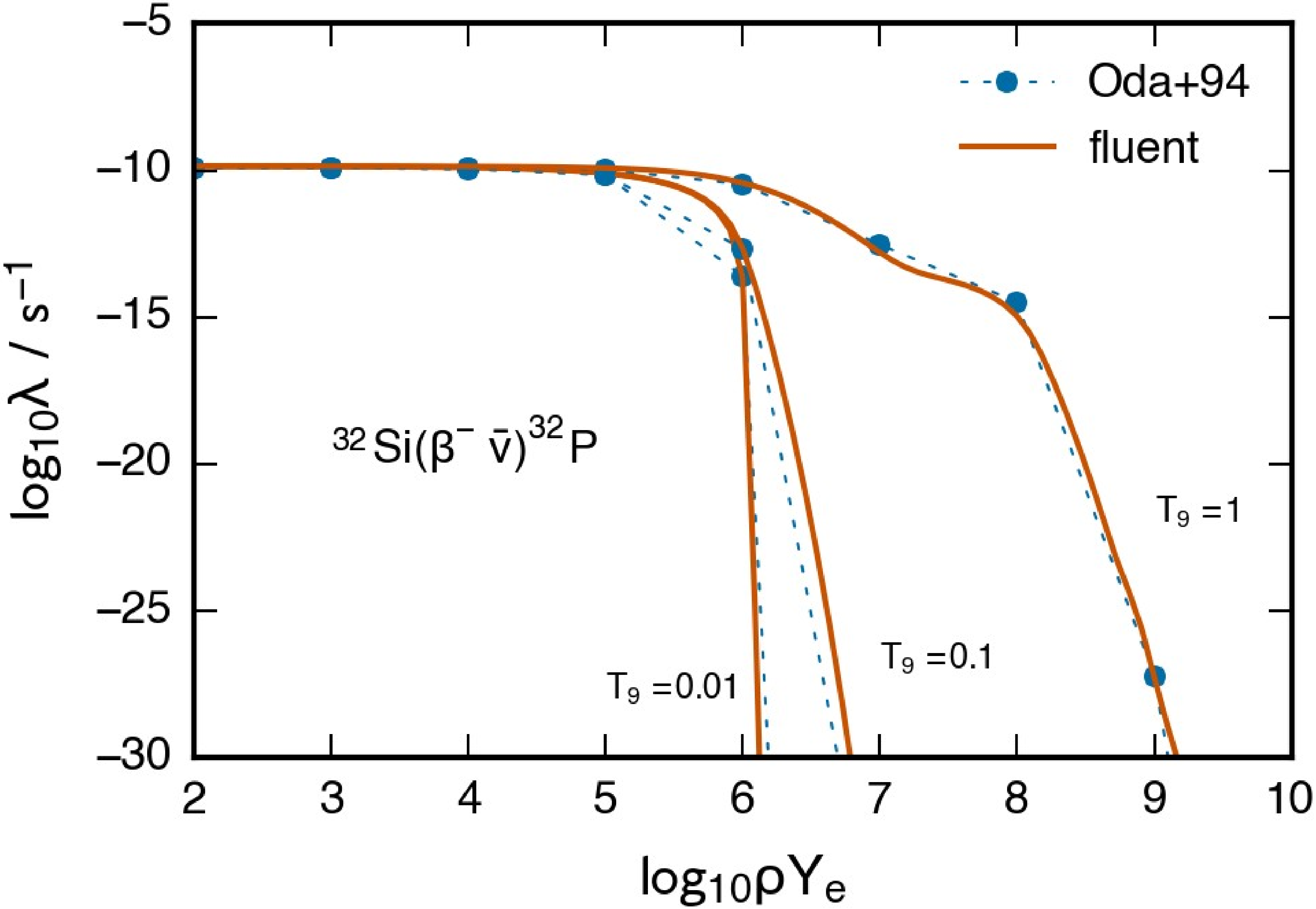
^{20}Ne
electron capture

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)



WEAK REACTIONS

INTERPOLATION ERRORS

Jones, Bertolli & Johnson (2016, subm.)

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

O DEFLAGRATION

O DEFLAGRATION

MULTI-DIMENSIONAL SIMULATIONS

in collaboration with: **F. Röpke, R. Pakmor, I. Seitenzahl, S. Ohlmann & P. Edelmann**

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 x 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
arXiv:1602.05771

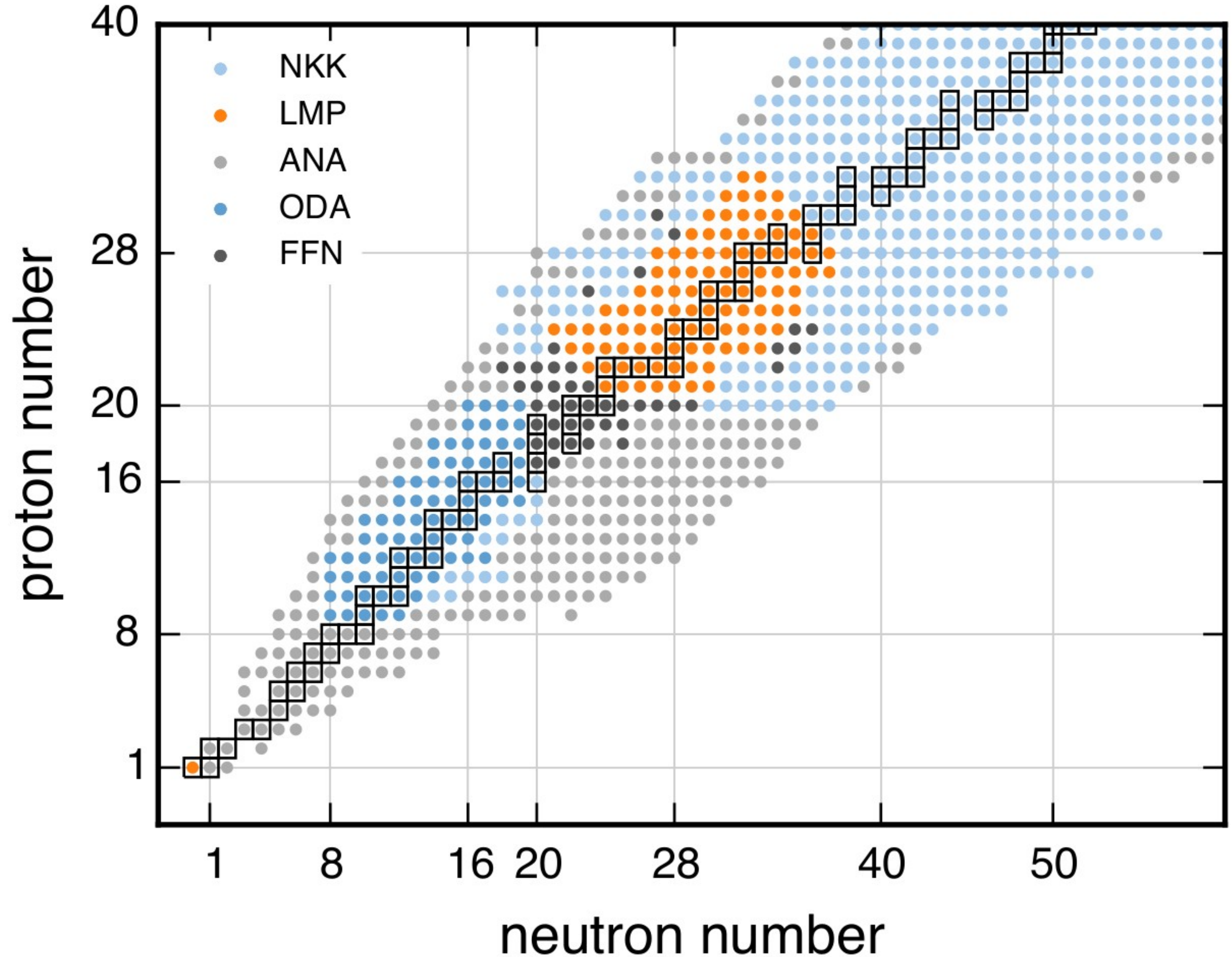
NKK: Nabi & Klapdor-Kleingrothaus

LMP: Langanke & Martinez-Pinedo (2001)

ODA: Oda+ (1994)

FFN: Fuller, Fowler & Newman (1985)

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



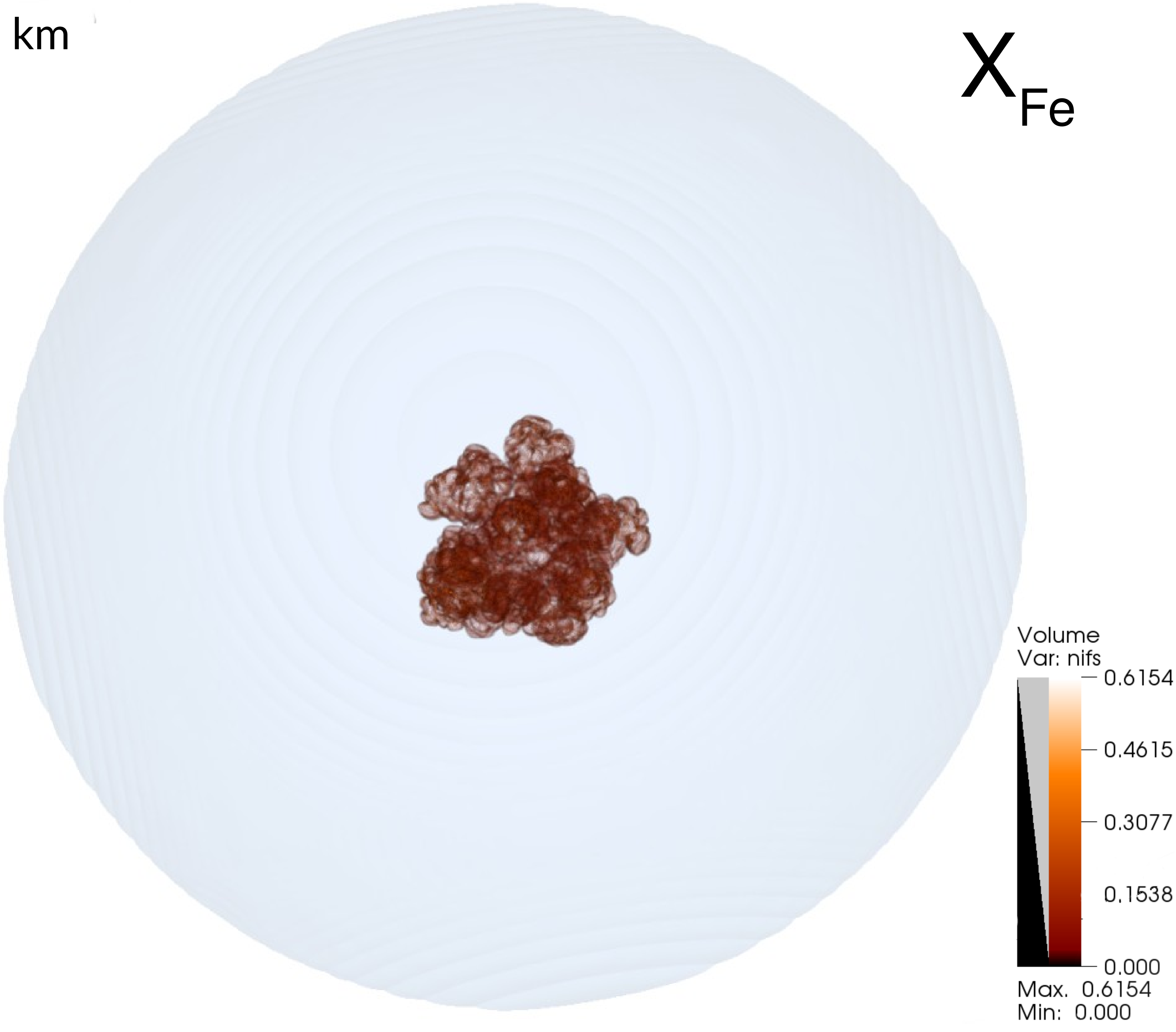
Scale: 1500 km
Time: 0.7 s

X_{Fe}

O DEFLAGRATION

3D 4π: 512^3

THERMONUCLEAR EXPLOSION?

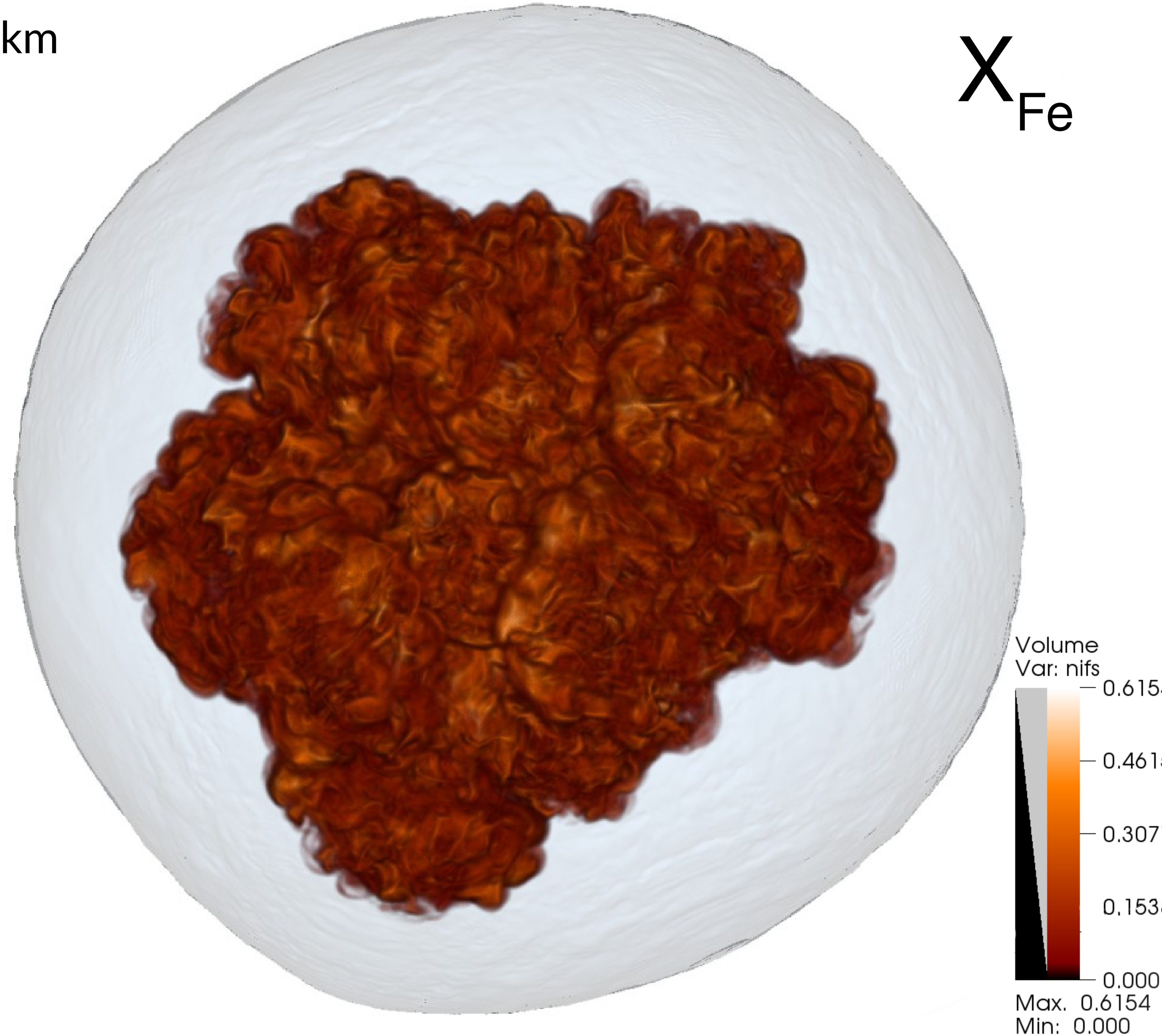


Scale: 2500 km
Time: 1.3 s

O DEFLAGRATION

3D 4π: 512^3

THERMONUCLEAR EXPLOSION?

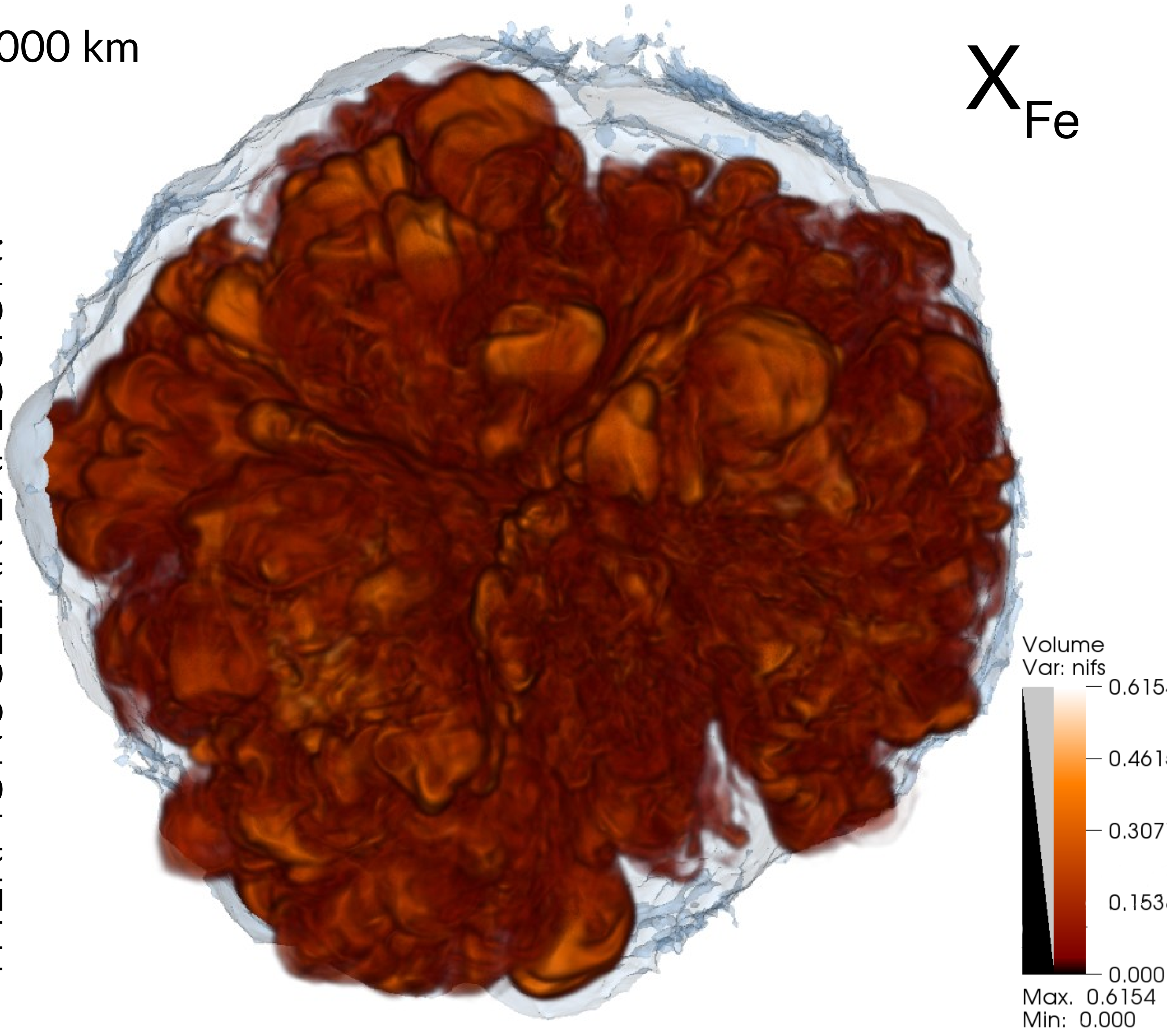


Scale: 400,000 km
Time: 60 s

O DEFLAGRATION

3D 4π: 512^3

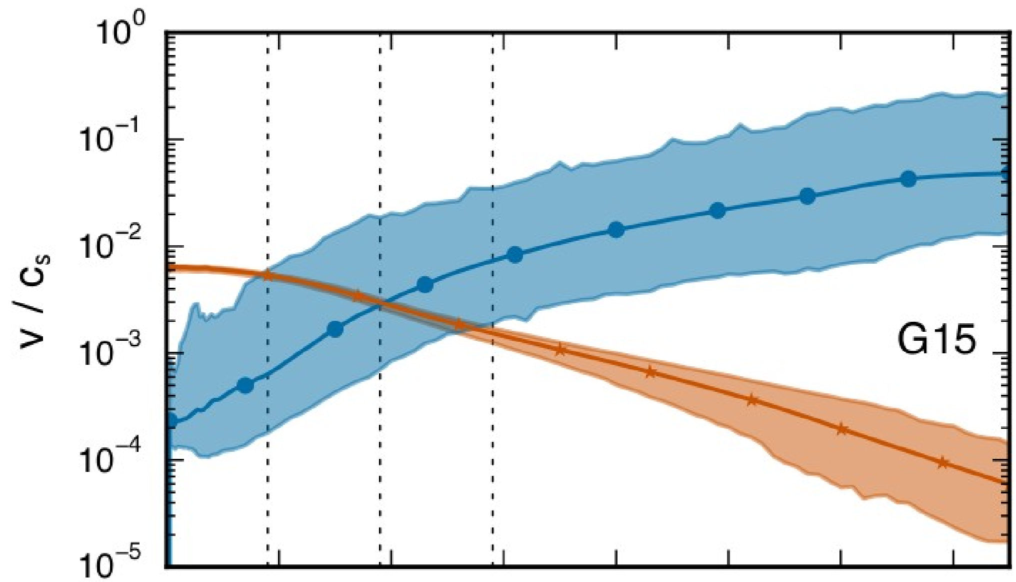
THERMONUCLEAR EXPLOSION?

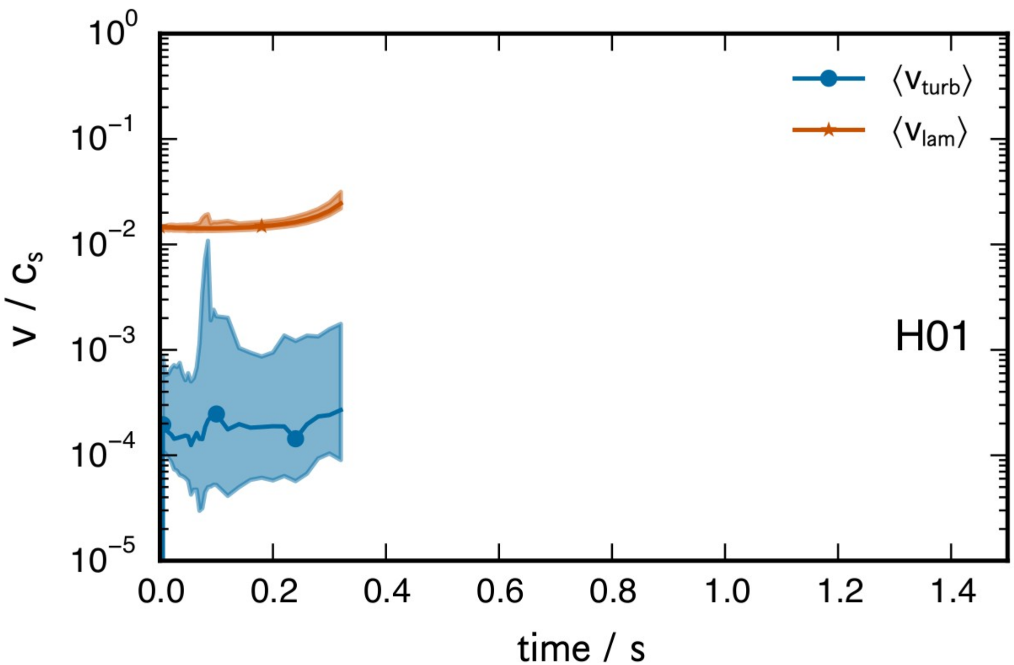


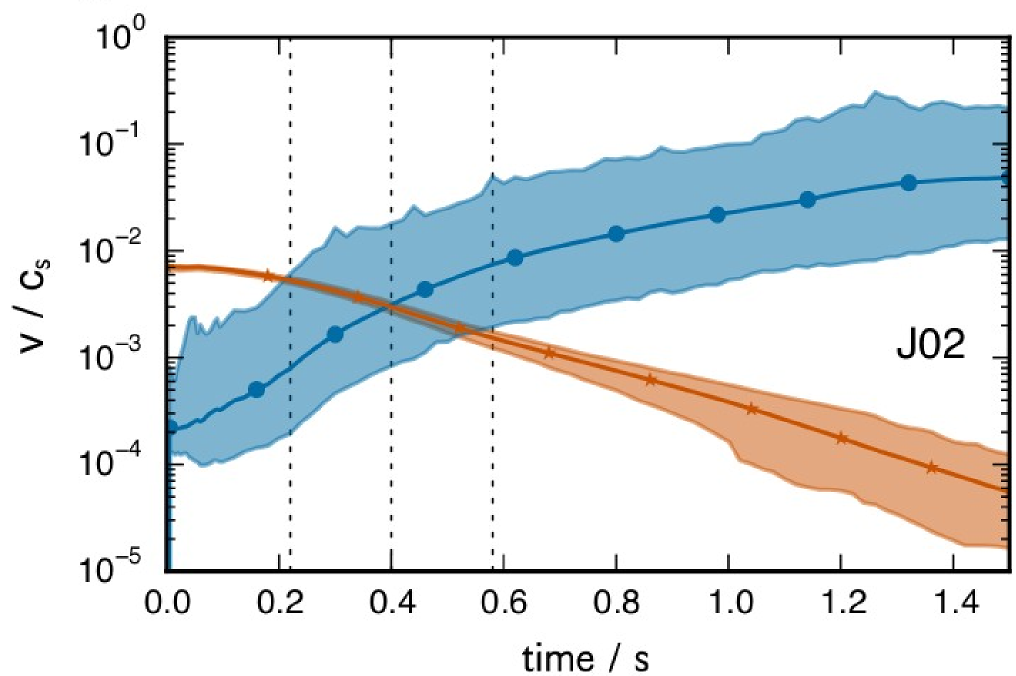
FLAME SPEEDS

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

Accurate predictions require these kinds of multi-D simulations



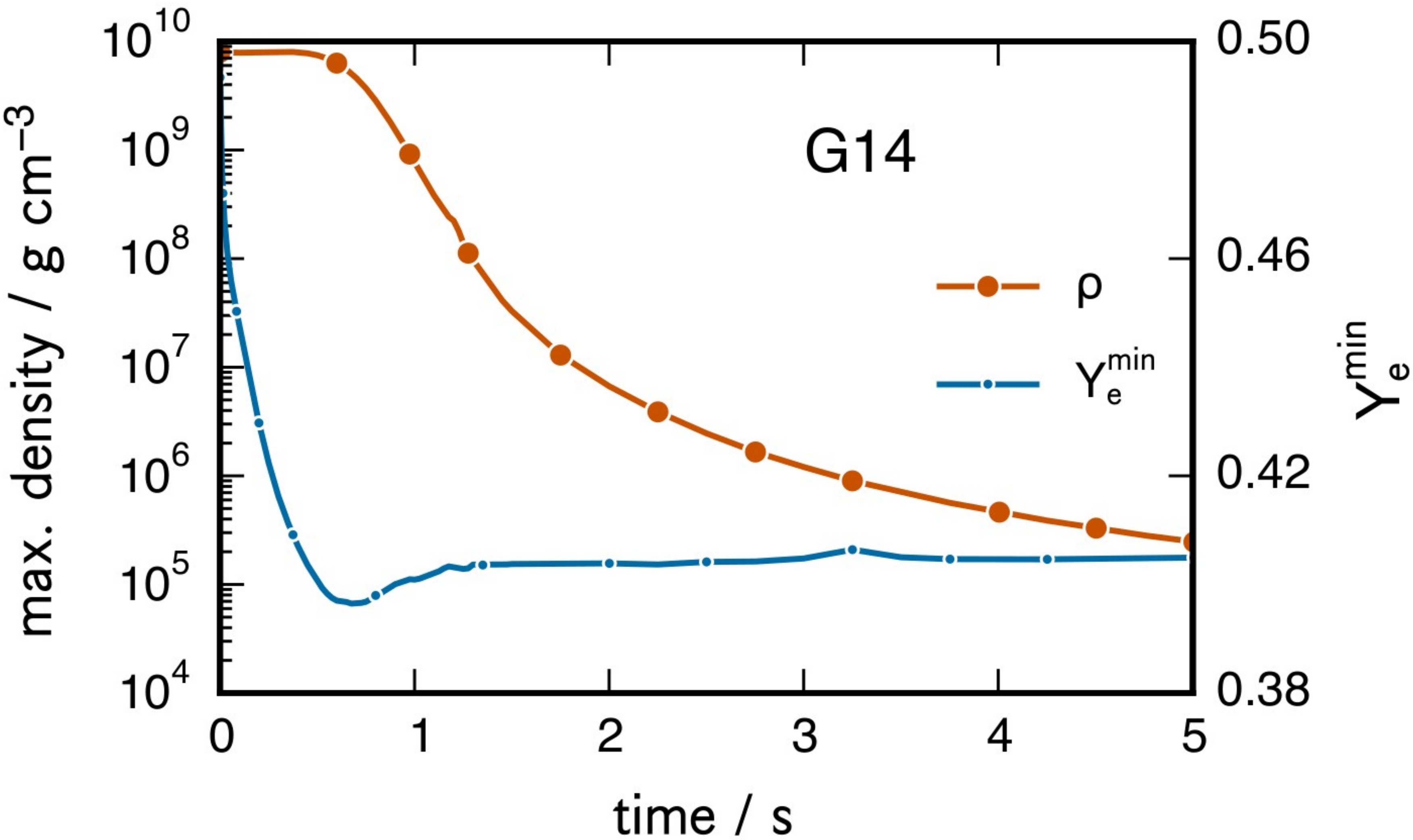




$\rho_{ign} = 10^{9.9}$ g cm^{-3}

SJ, FKR, RP, IRS, STO, PVFE
arXiv:1602.05771

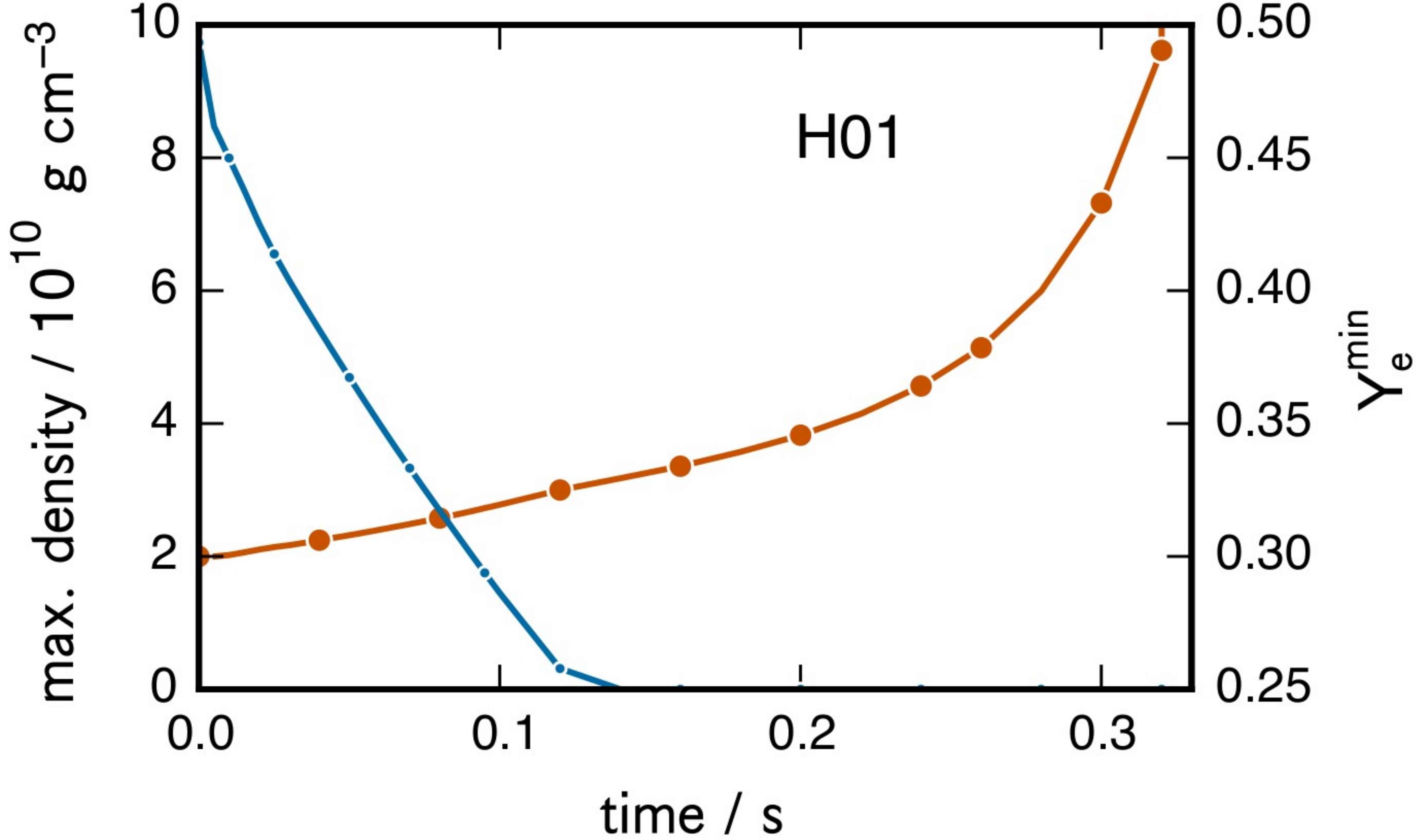
THERMONUCLEAR EXPLOSION?



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

CORE COLLAPSE

SJ, FKR, RP, IRS, STO, PVFE
arXiv:1602.05771



DIAGNOSTICS

SJ, FKR, RP, IRS, STO, PVFE
arXiv:1602.05771

Bound ONeFe remnants

id.	res.	[a] $\log_{10}\rho_c^{\rm ini}$ (g cm^{-3})	[b]CC (Y/N)	[c] $M_{\rm rem}$ ($M_\odot$)	[d] $M_{\rm rem}^{\rm Fe}$ ($M_\odot$)	[e] $M_{\rm ej}$ ($M_\odot$)	[f] $M_{\rm ej}^{\rm Fe}$ ($M_\odot$)	[g] $\langle Y_{\rm e,rem}\rangle$	[h] $M_{\rm Ch}^{\rm eff}$ ($M_\odot$)	[i] Δx (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 ... n^{-3},
exhibiting cle...
[a] Ignition
[c] Total ma
[e] Total eje
[g] Average
[i] Initial cell size for inner (flame) mesh

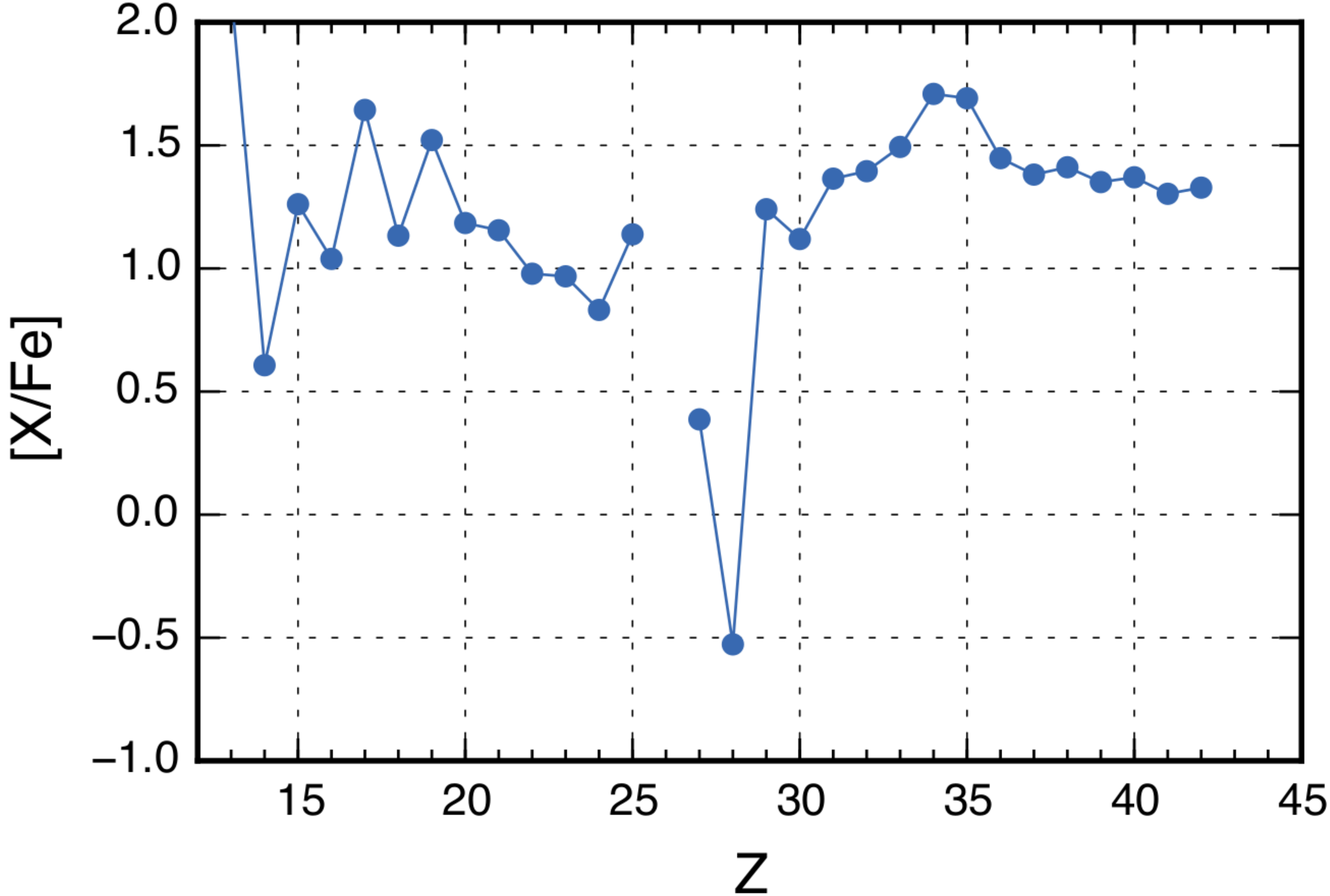
What would these things actually **look like**? Faint SN1a? Have we seen them? → **Radiative transfer calculations required**

Core collapse

Remarkably similar result to Isern+ (1991)

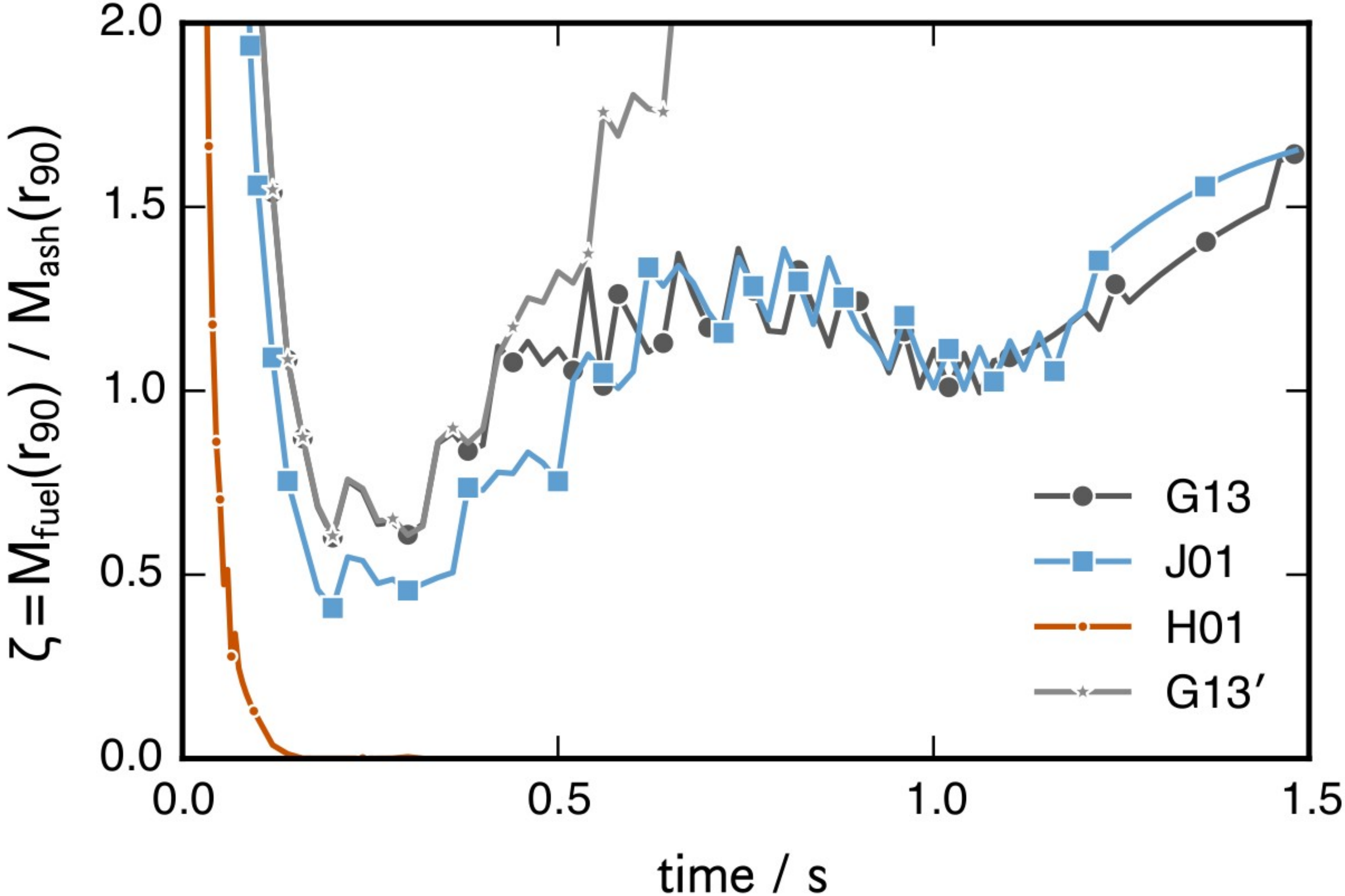
YIELDS

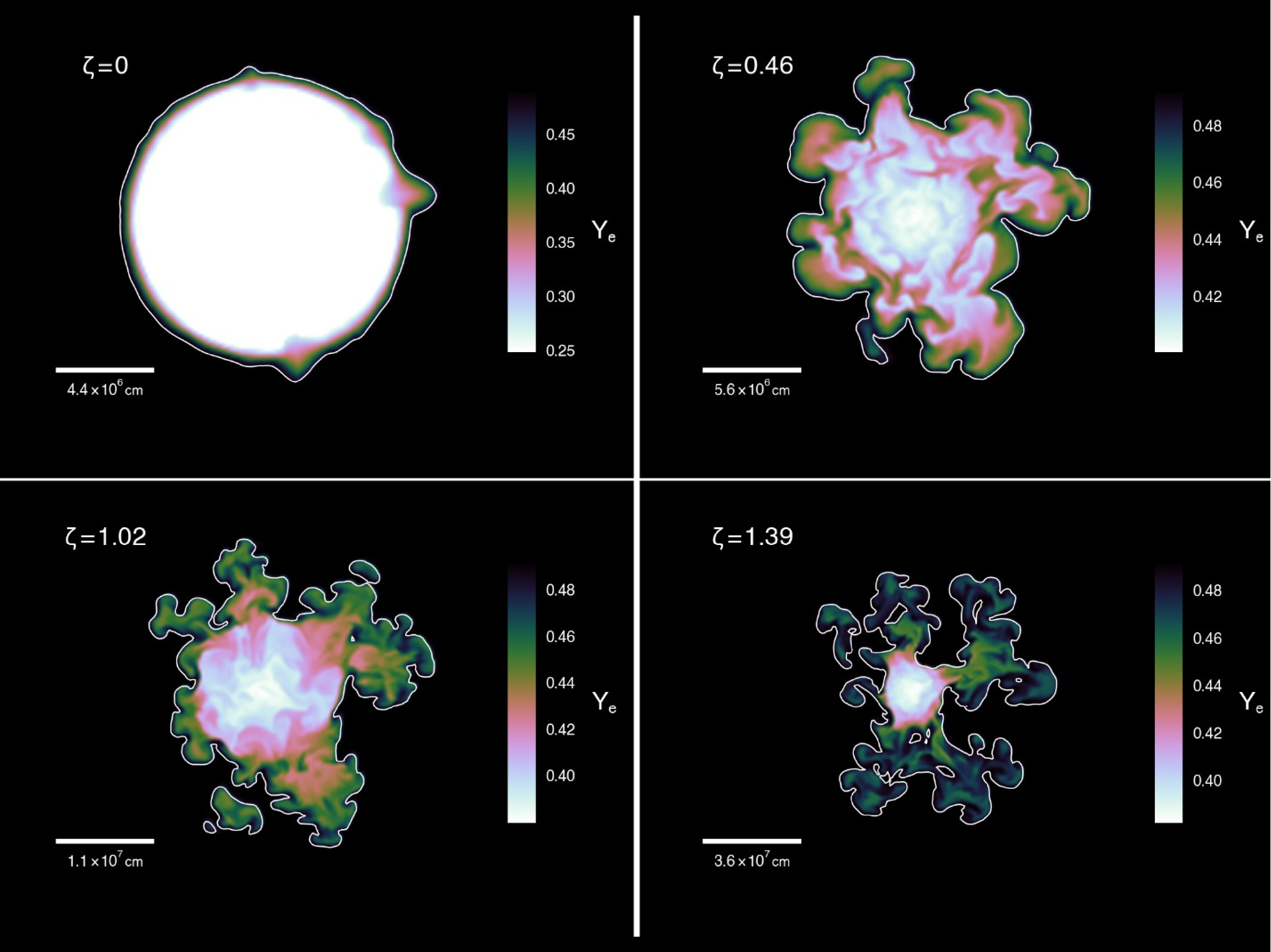
PRELIMINARY



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

NUCLEAR REACTIONS

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SJ, FKR, RP, IRS, STO, PVFE
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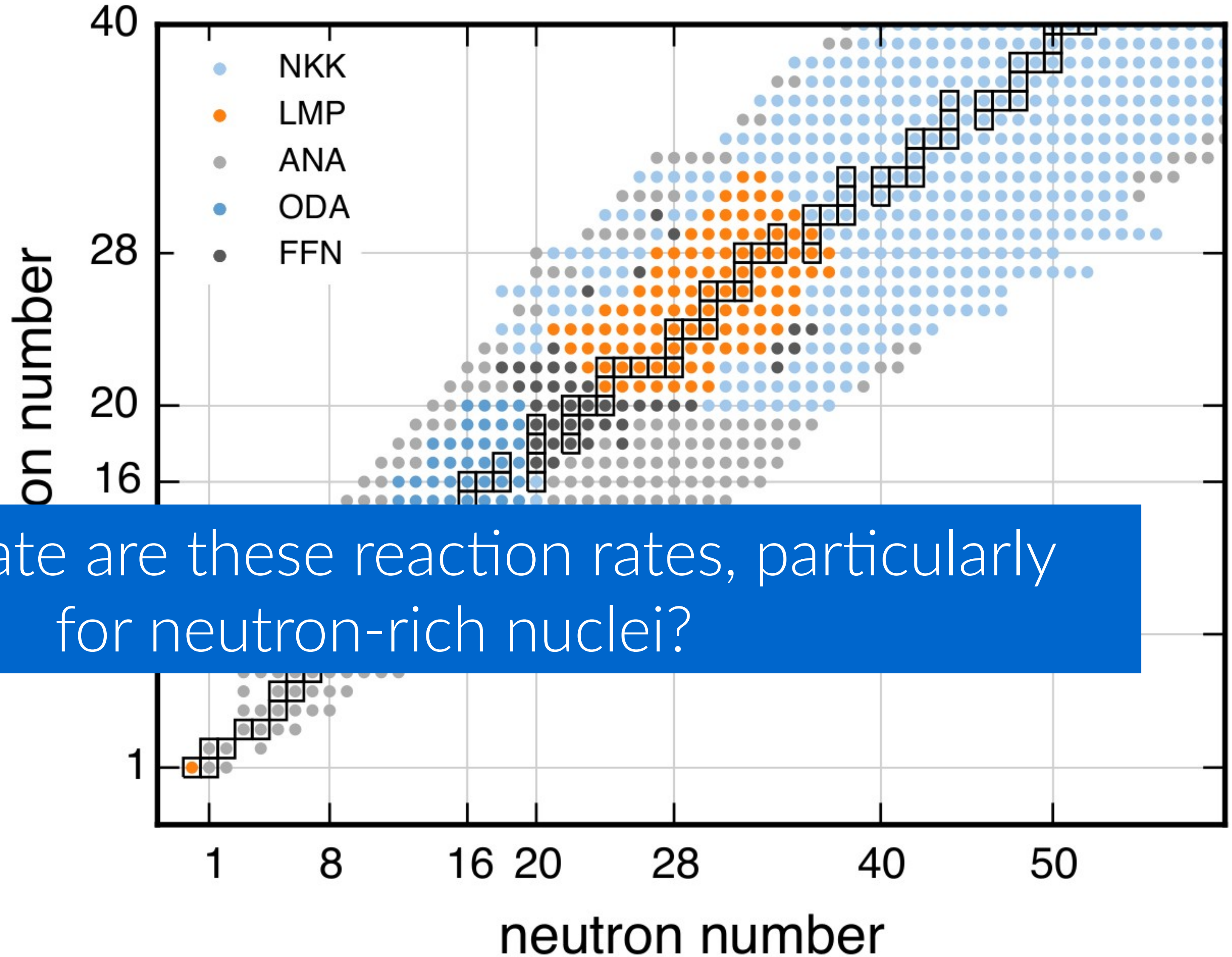
NKK: Nabi & Klapdor-Kleingrothaus

LMP: Langanke & Martinez-Pinedo (2001)

ODA: Oda+ (1994)

FFN: Fuller, Fowler & Newm

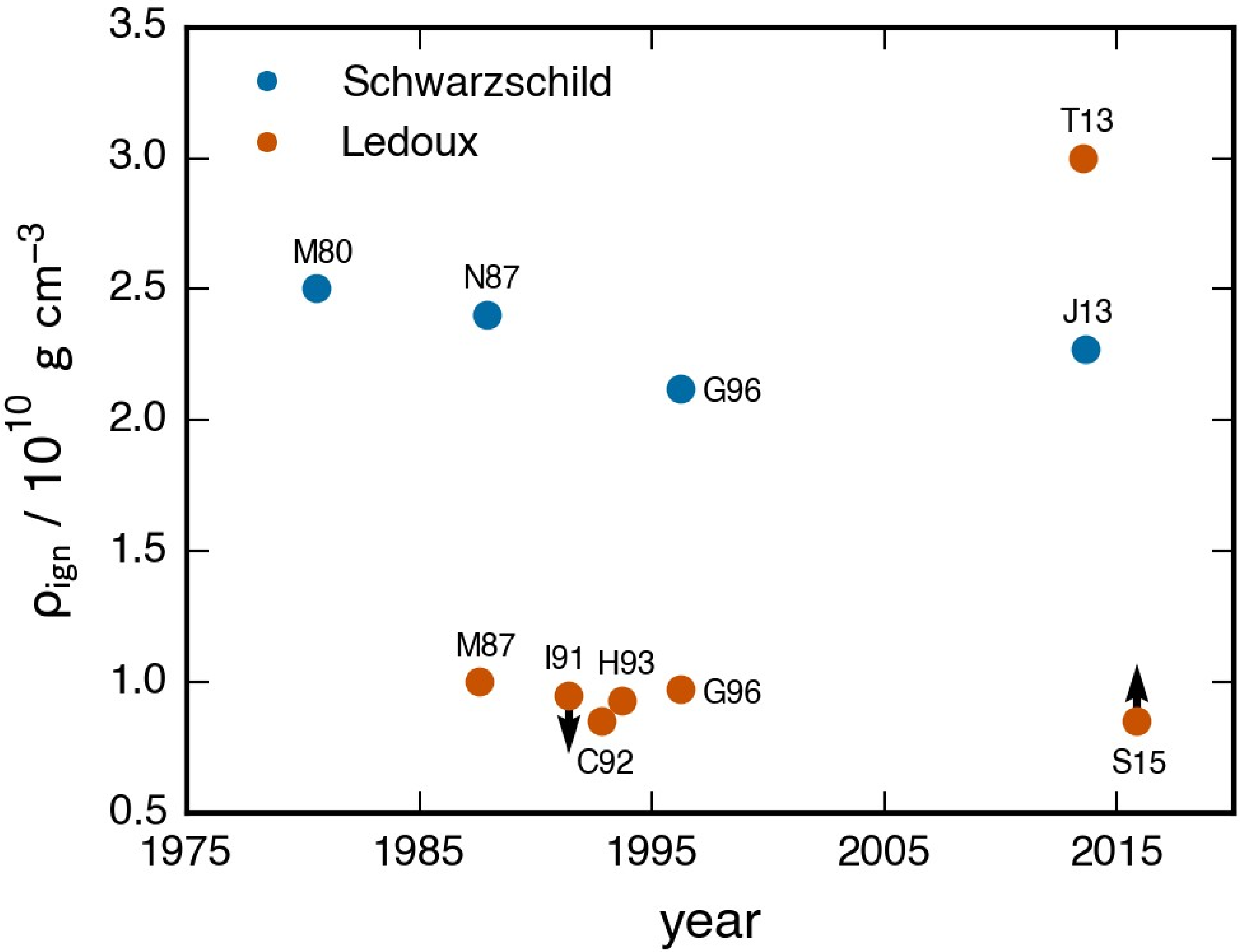
ANA: Gamow-Teller strength B = 4.6 (Arcones+ 2010)



How accurate are these reaction rates, particularly for neutron-rich nuclei?

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 ~$0.03H_\mathrm{P}$

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