STARS ON DEATH ROW

EVOLUTION AND FATE OF 8 – 10 SOLAR-MASS STARS

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HEIDELBERG INSTITUTE FOR THEORETICAL STUDIES

WED 20 JAN 2016
KAVLI IPMU

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STELLAR EVOLUTION

A CRASH COURSE

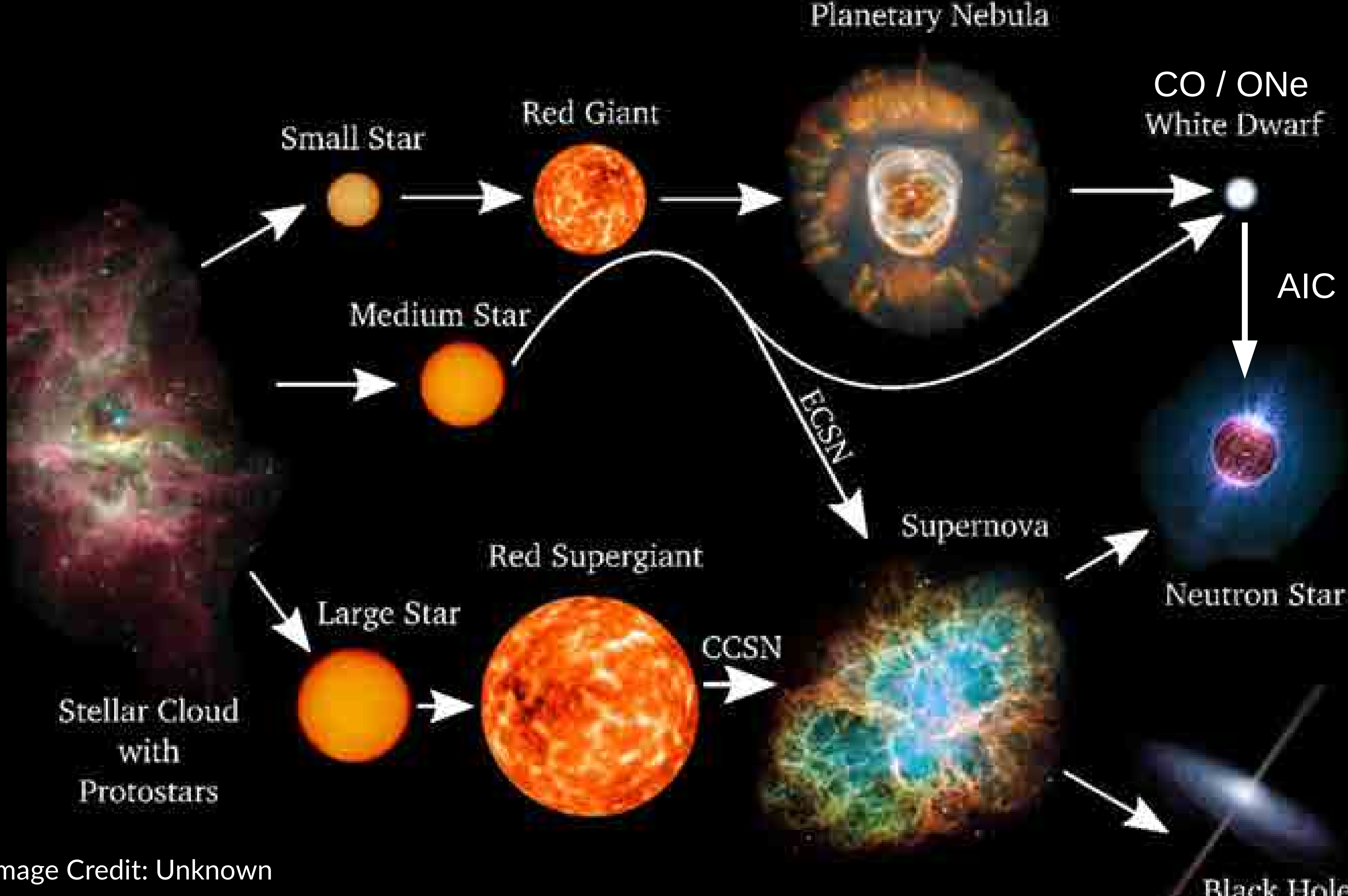


Image Credit: Unknown

LOW AND INTERMEDIATE MASS STARS

Image Credit: Solar Dynamics Observatory, NASA

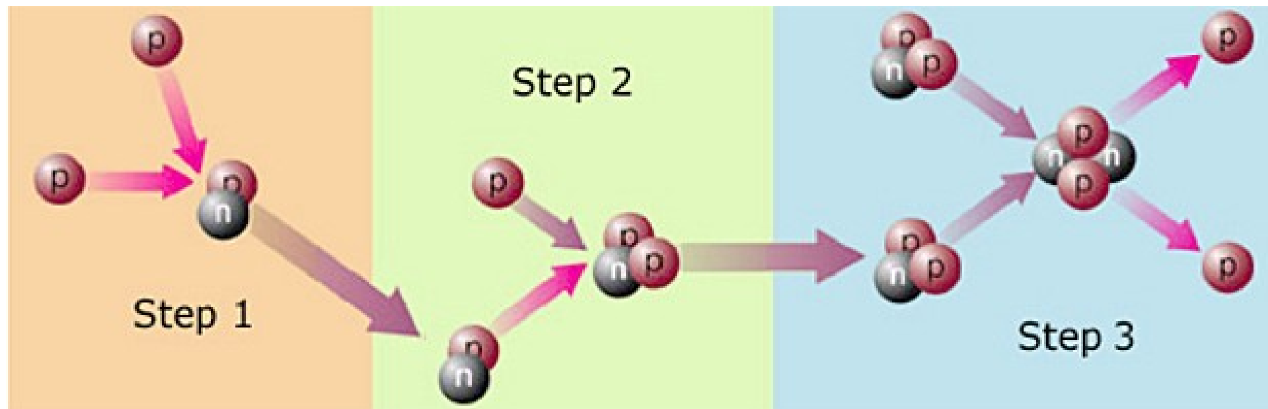
NUCLEAR POWER

H & He BURNING

Image Credit: David Taylor

H → He

p-p chain

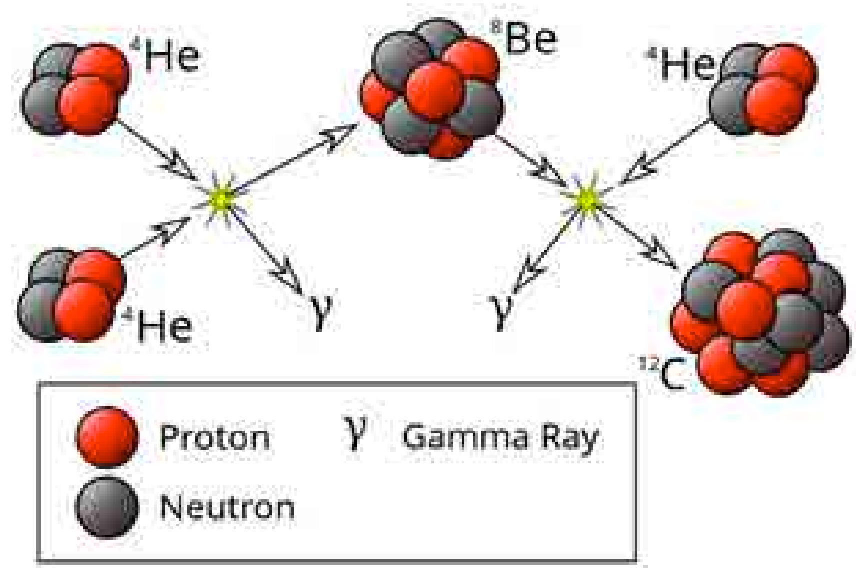


If the star is massive enough (> 0.8 solar masses):

He → C & O

Triple-α

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



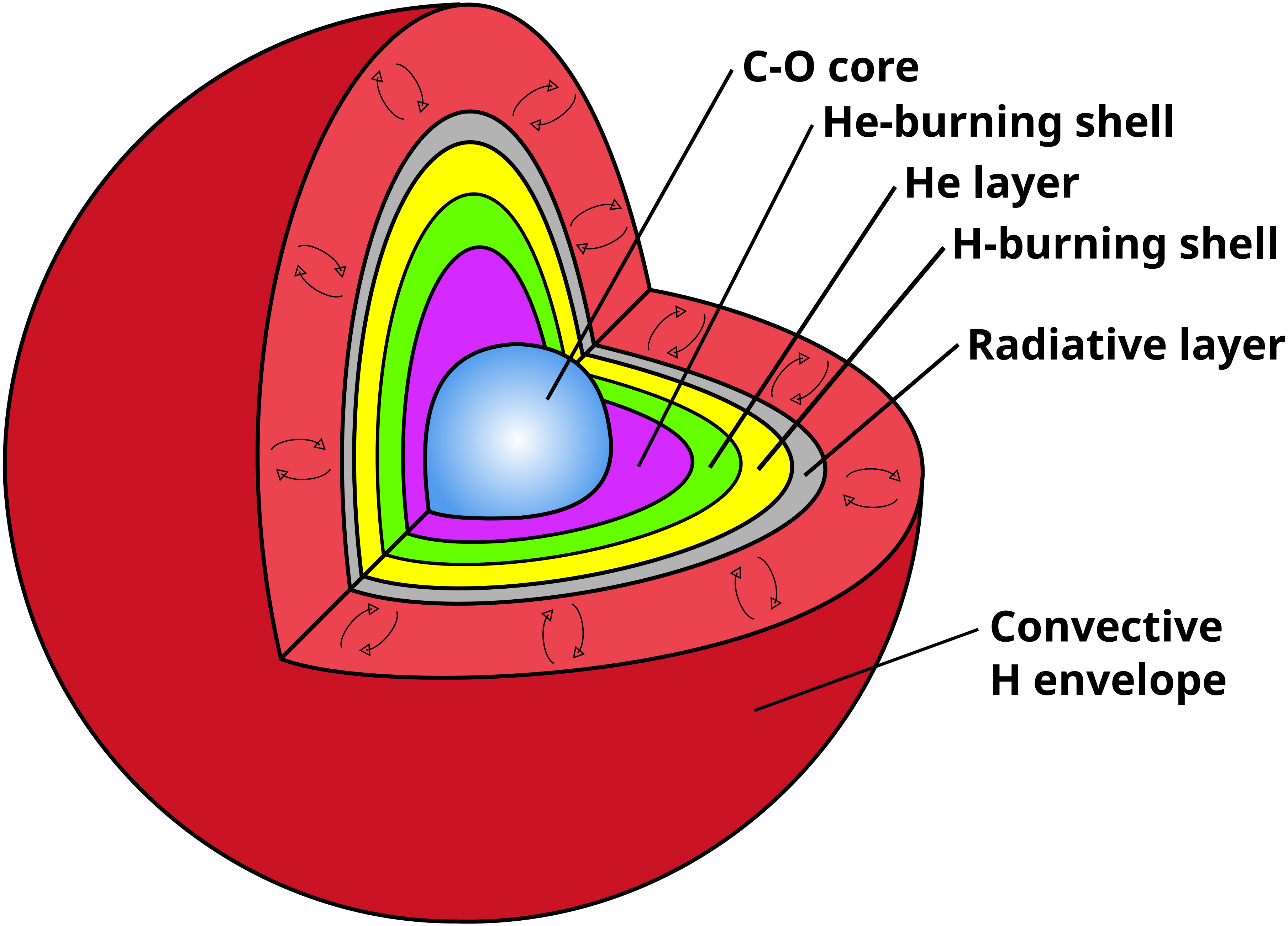


Image credit: Persson, Magnus Vilhelm (2013)

PLANETARY NEBULAE

& WHITE DWARFS

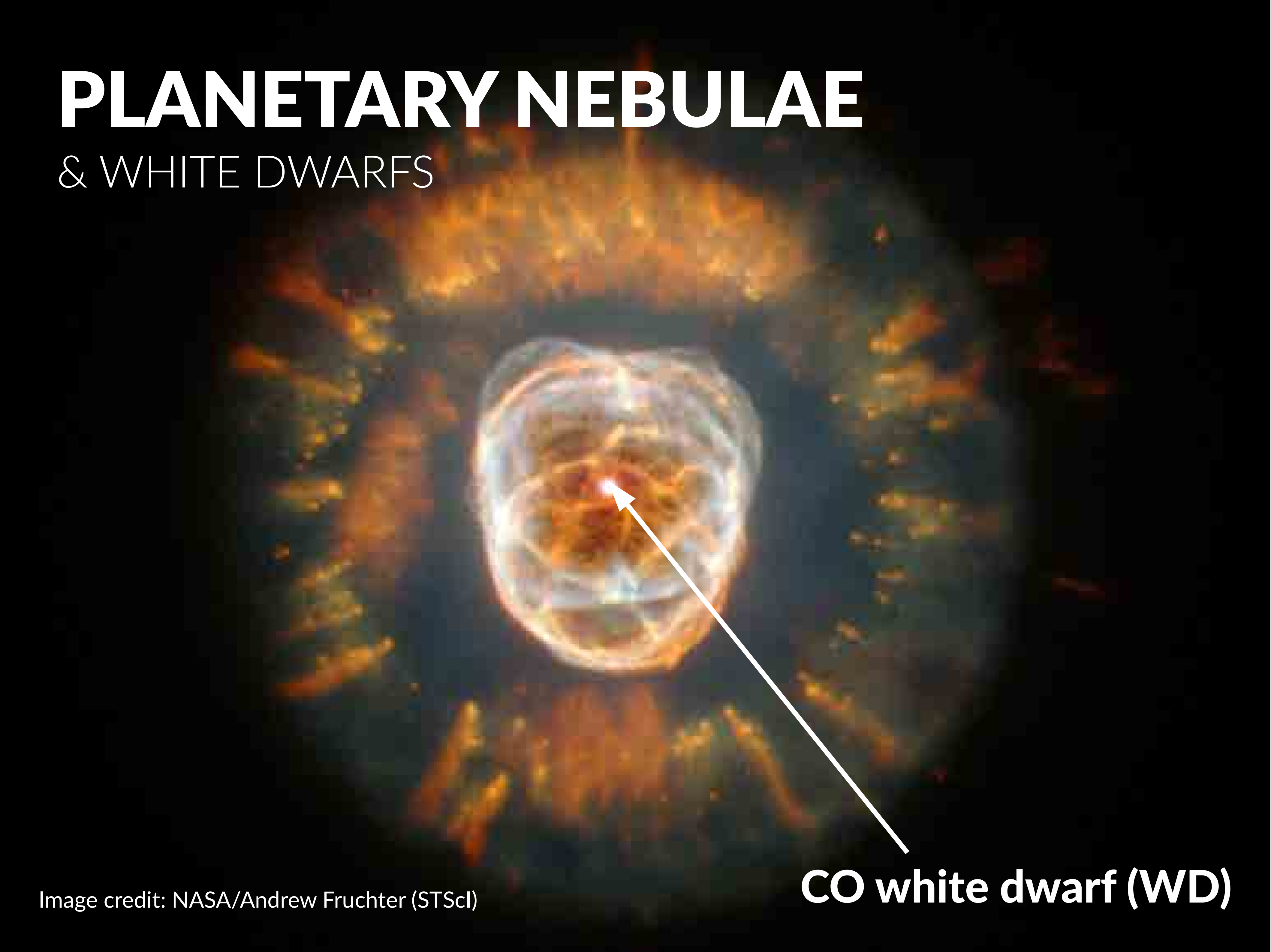


Image credit: NASA/Andrew Fruchter (STScI)

EXPLODING WHITE DWARFS

THERMONUCLEAR SUPERNOVAE

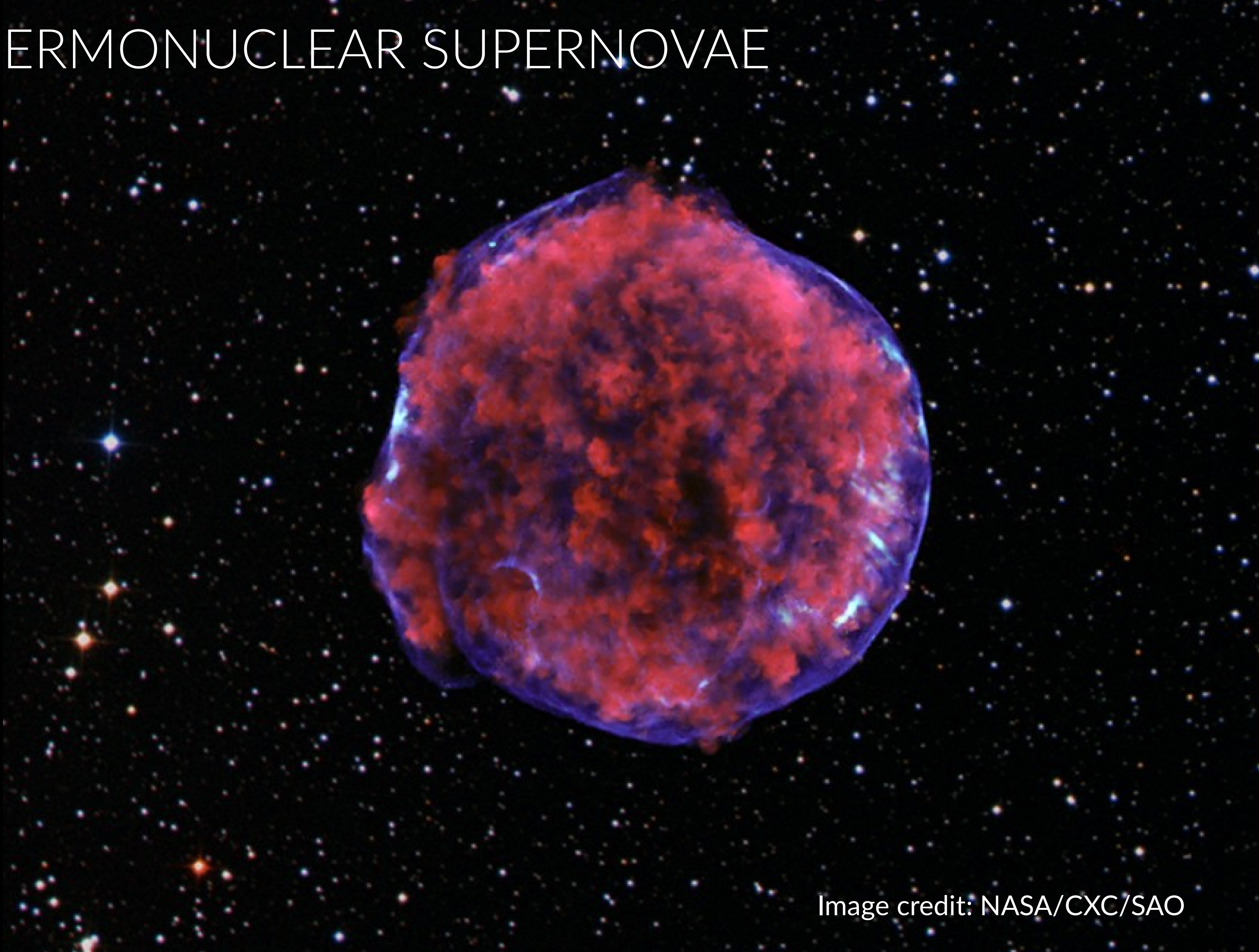


Image credit: NASA/CXC/SAO

EXPLODING WHITE DWARFS

THERMONUCLEAR SUPERNOVAE

Carbon ignition in high density, degenerate CO white dwarfs

But how is carbon ignited? Hot spots? Compression?

EXPLODING WHITE DWARFS

SN Ia SINGLE DEGENERATE SCENARIO

Image credit: David A. Hardy/AstroArt.org

EXPLODING WHITE DWARFS

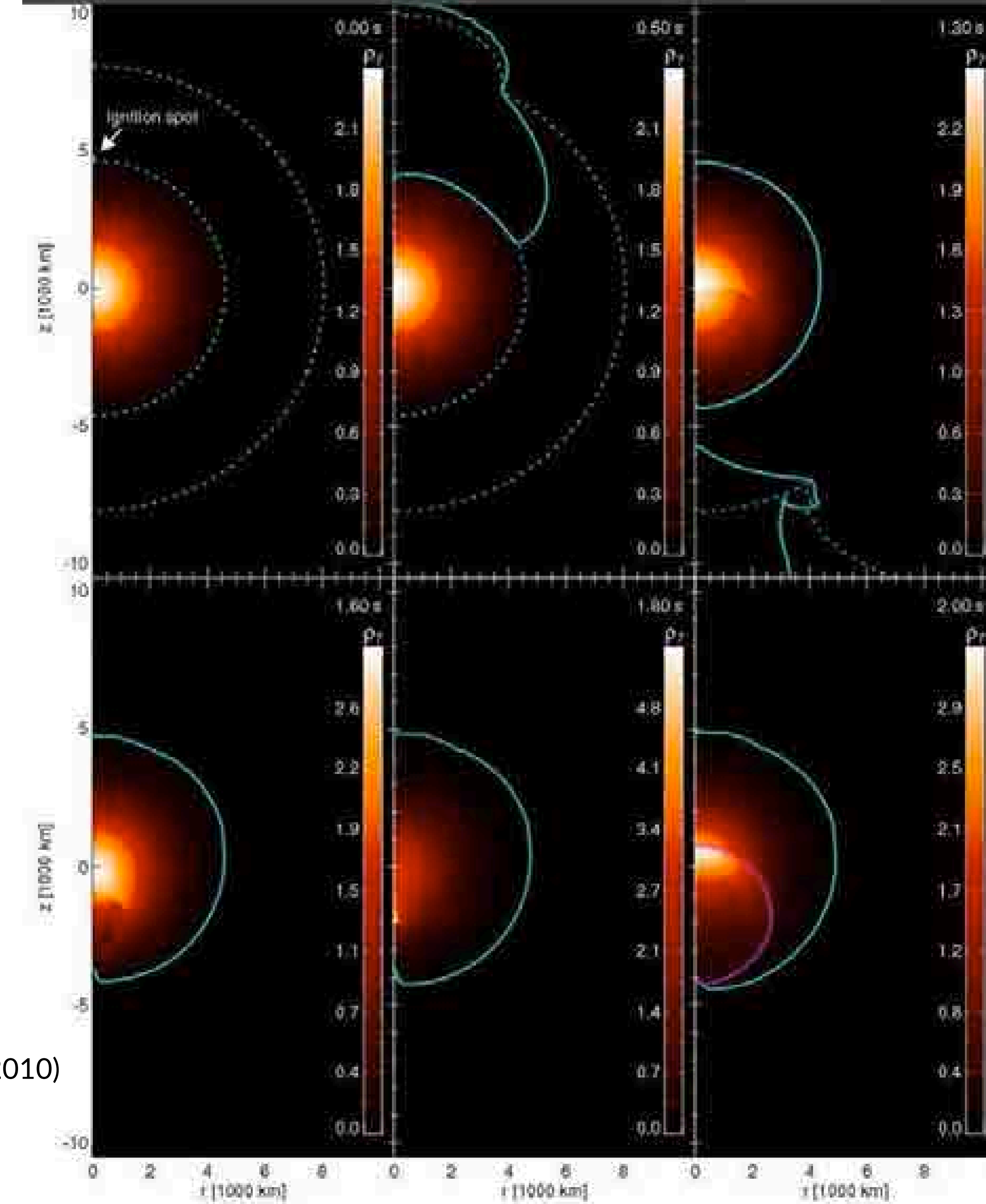
SN Ia MERGER SCENARIO

Image credit: GSFC/D. Berry

EXPLODING WHITE DWARFS

SN Ia DOUBLE DETONATION SCENARIO

Fink+ (2010)



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	$^{28}Si(\gamma,\alpha)$...

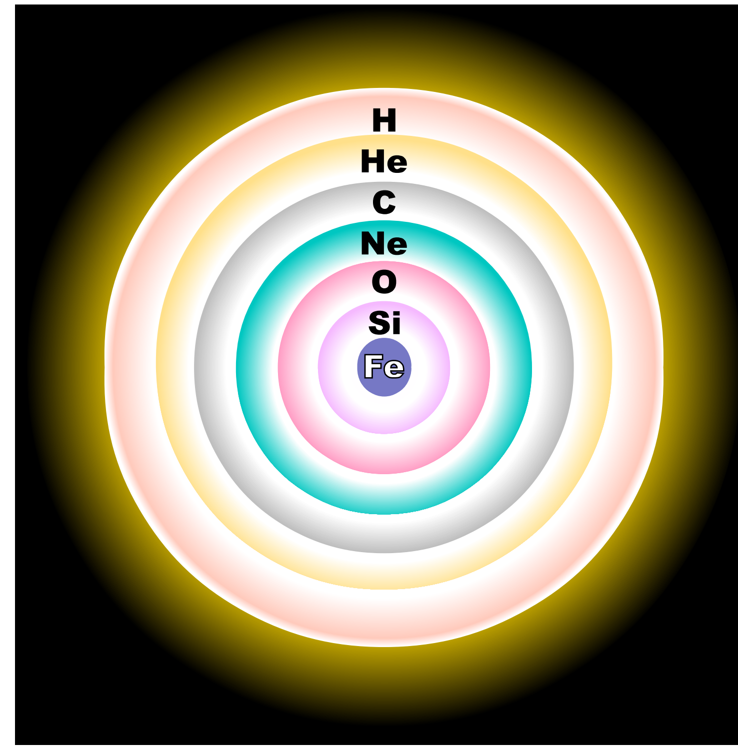
Image credit: Alexander Heger

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**

If the **electron fraction** Y_e (i.e. the number of electrons) *decreases*, the **effective Chandrasekhar mass decreases**



CORE-COLLAPSE SUPERNOVAE

THE SHORT VERSION

The core collapses until the central ~0.5 solar-masses of material reach **nuclear saturation density** (~10^{14} g/cc)

The infalling material **bounces**, launching a **shock wave**

The shock wave stalls under ram pressure from more infalling material. During this time, **material accretes onto the proto-neutron star**

Something (probably neutrino-driven convection) deposits enough energy behind the shock front to **revive** it, stopping the accretion and **blowing up the star**

CORE-COLLAPSE SUPERNOVAE

CAS A

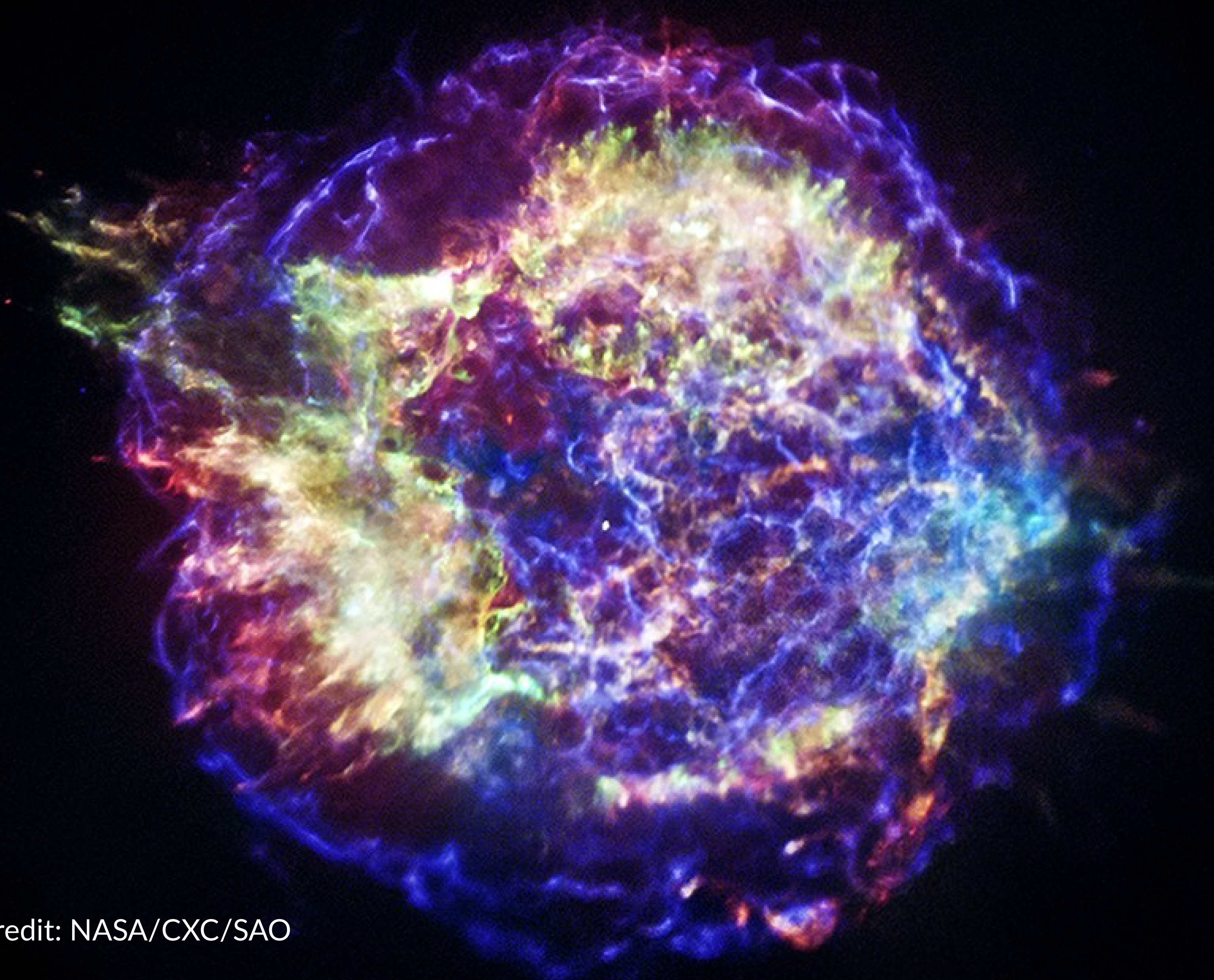


Image credit: NASA/CXC/SAO

STELLAR EVOLUTION

A CRASH COURSE

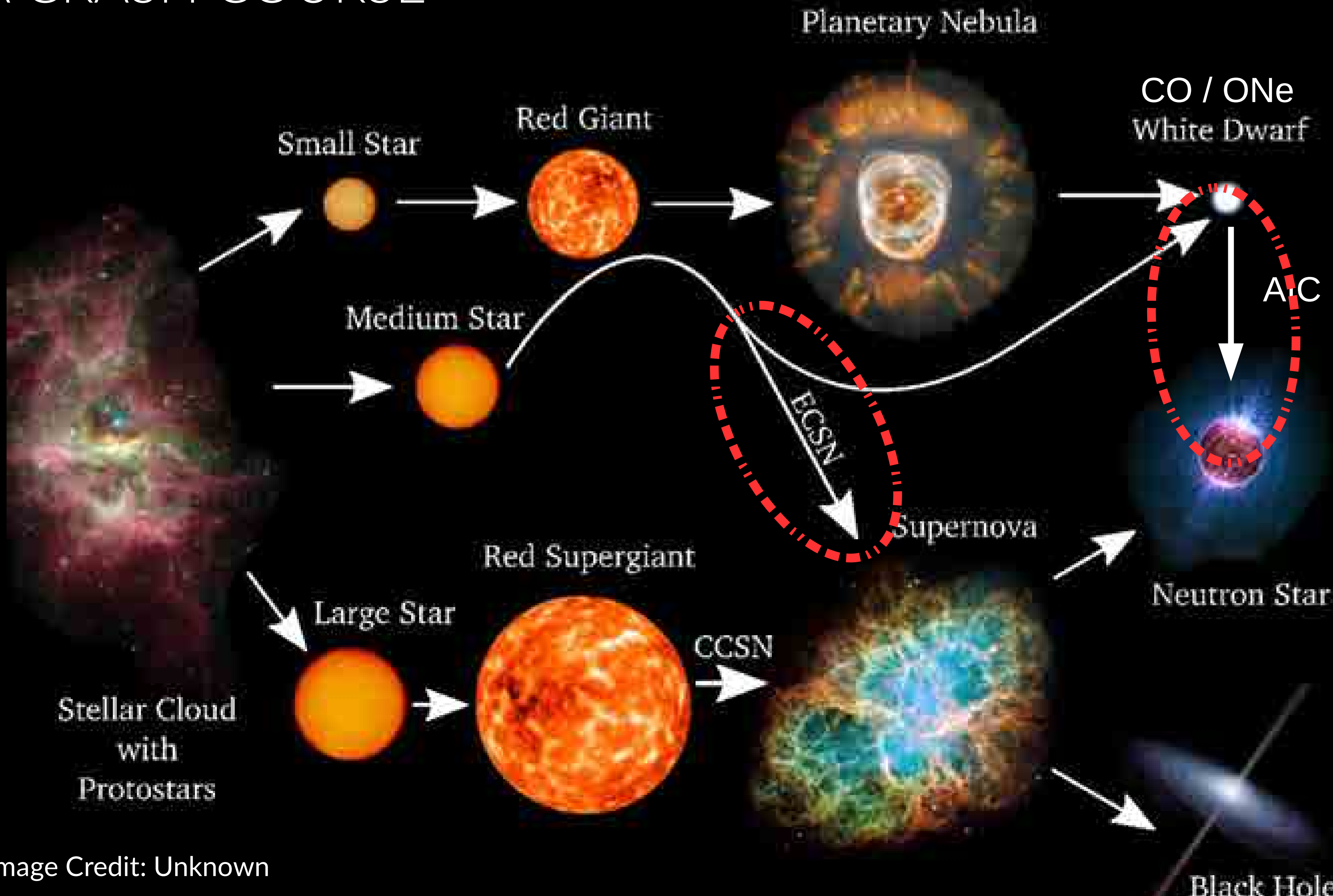


Image Credit: Unknown

WHAT HAPPENS TO 8-10 SOLAR-MASS STARS?

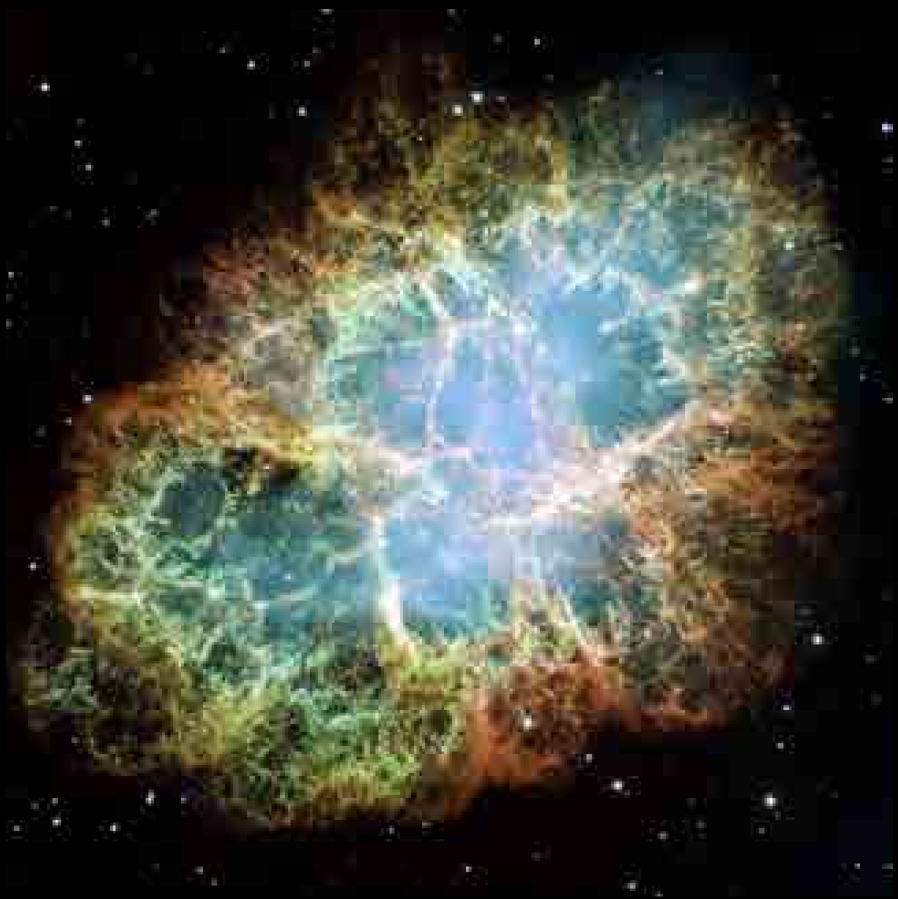


Image Credit: NASA, ESA, J. Hester, A. Loll (ASU)

Image credit: NASA/Andrew Fruchter (STScI)

WHAT HAPPENS TO 8-10 SOLAR-MASS STARS?

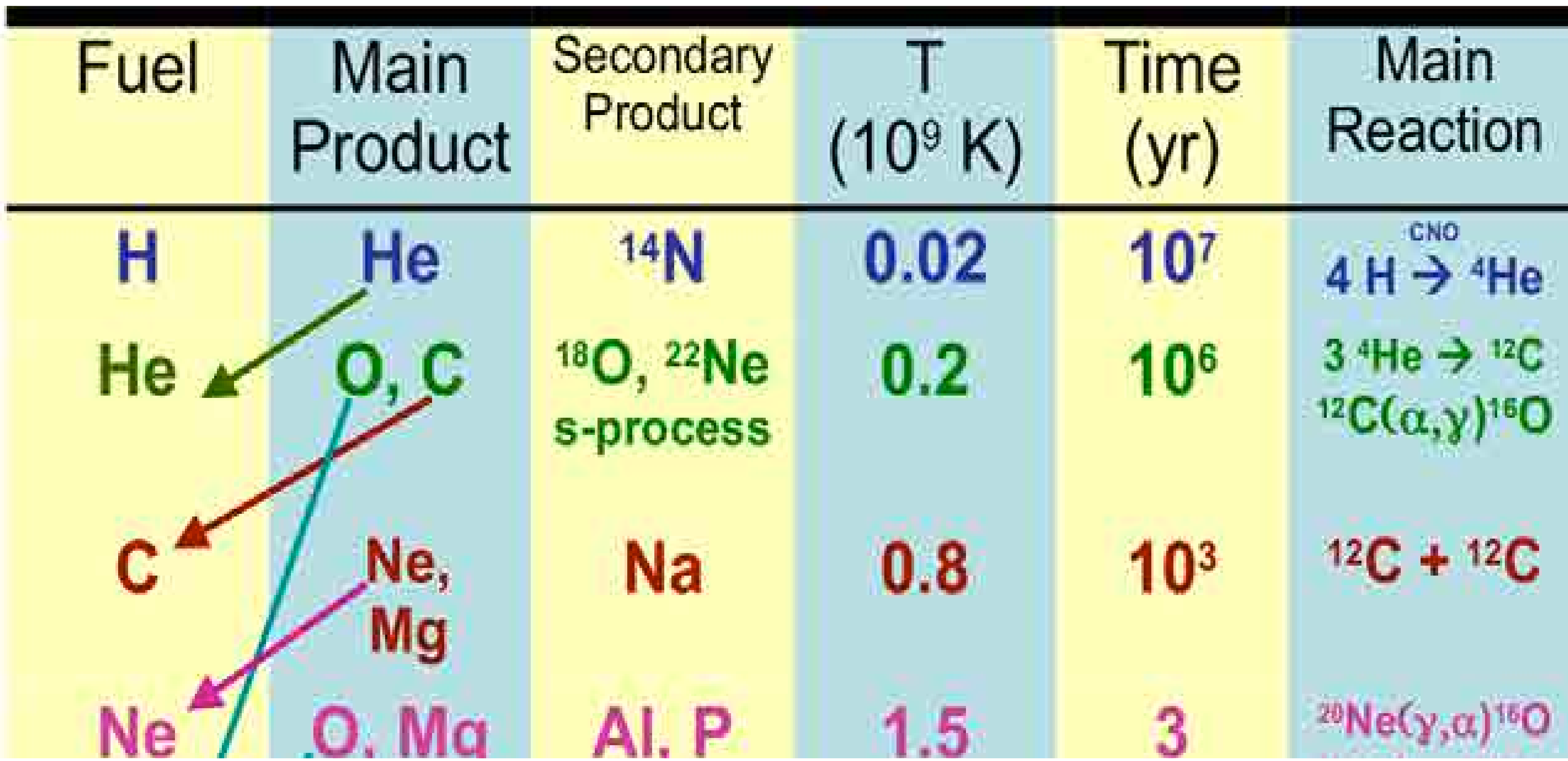
Image credit: David A. Hardy/AstroArt.org

WHAT HAPPENS TO 8-10 SOLAR-MASS STARS?

Image credit: NASA/CXC/SAO

ELECTRON-CAPTURE SUPERNOVAE

Image credit: Alexander Heger



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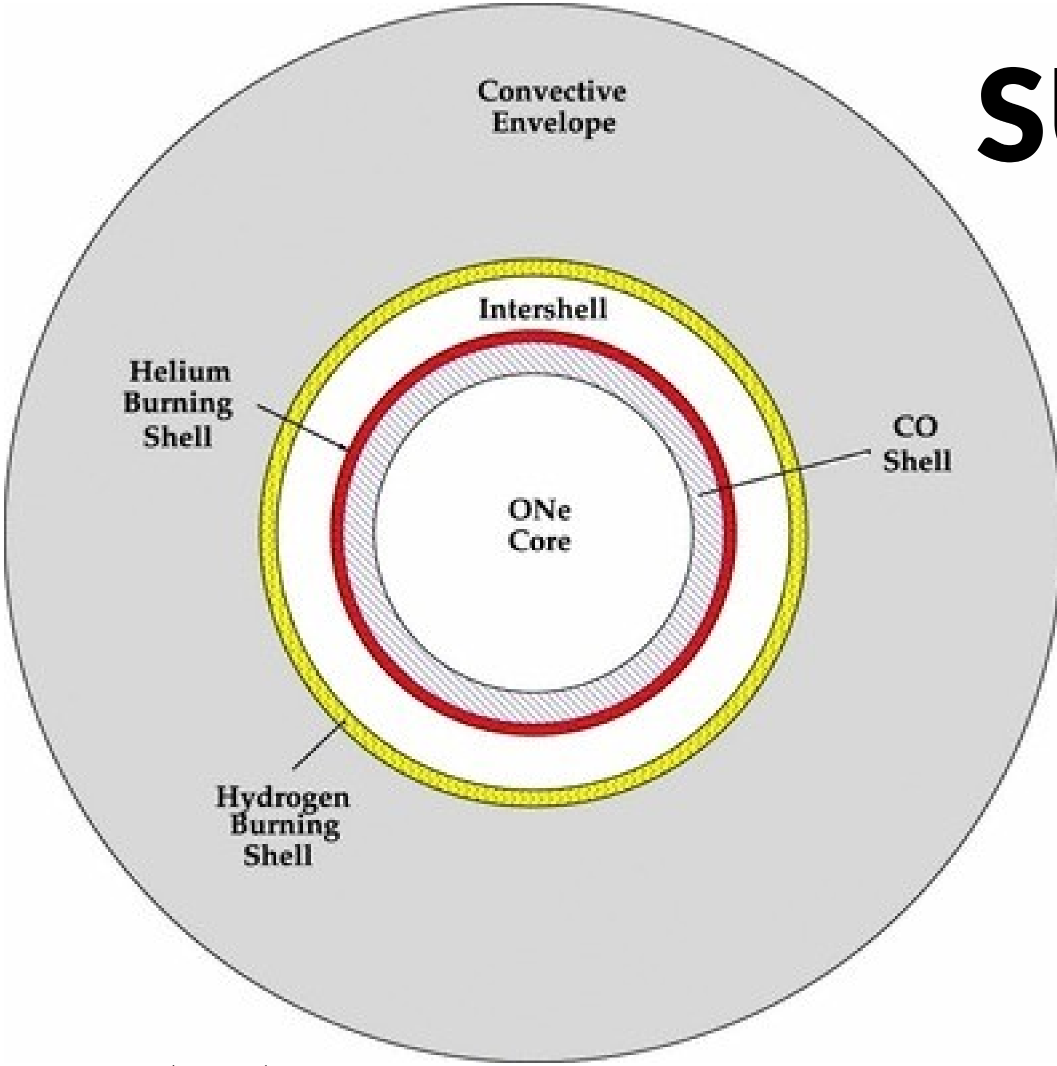
Nuclear burning is curtailed due to combined effects of neutrino losses and degeneracy, leaving an **ONe core**

SUPER-AGB STAR



Lugaro+ (2012)

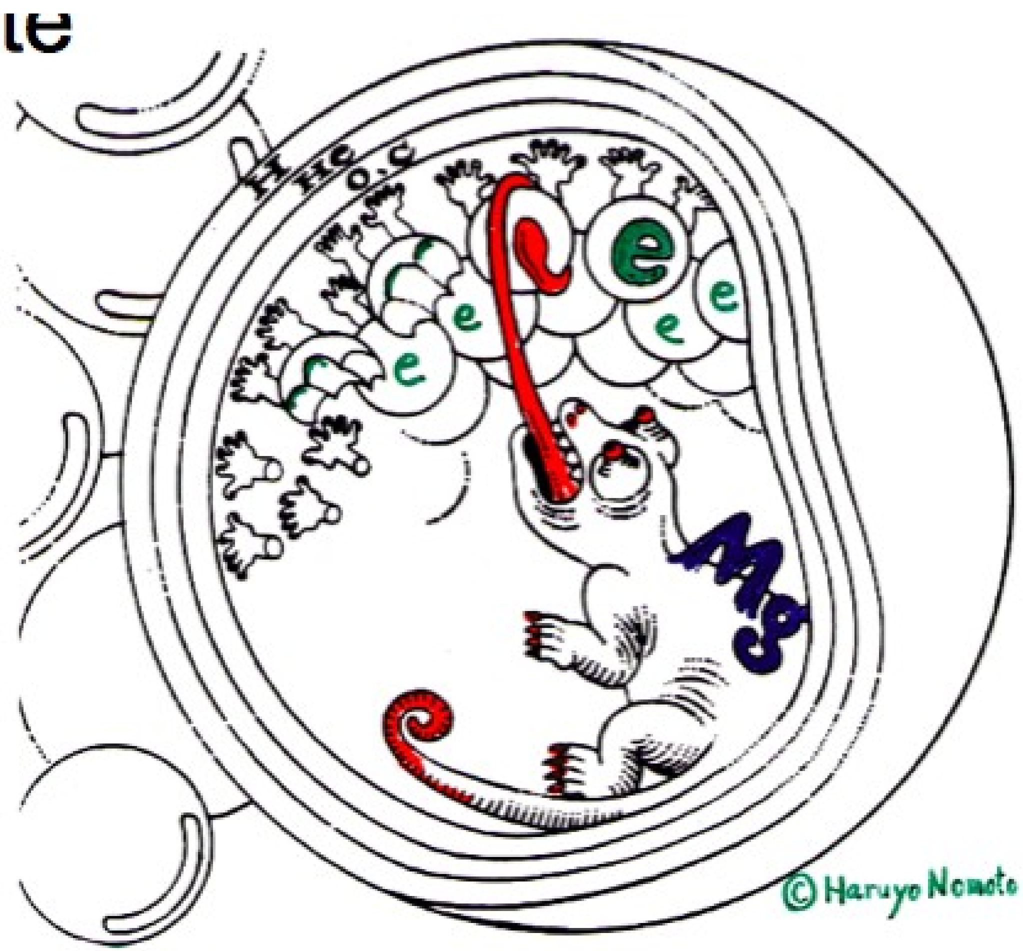
Two general classical scenarios:

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

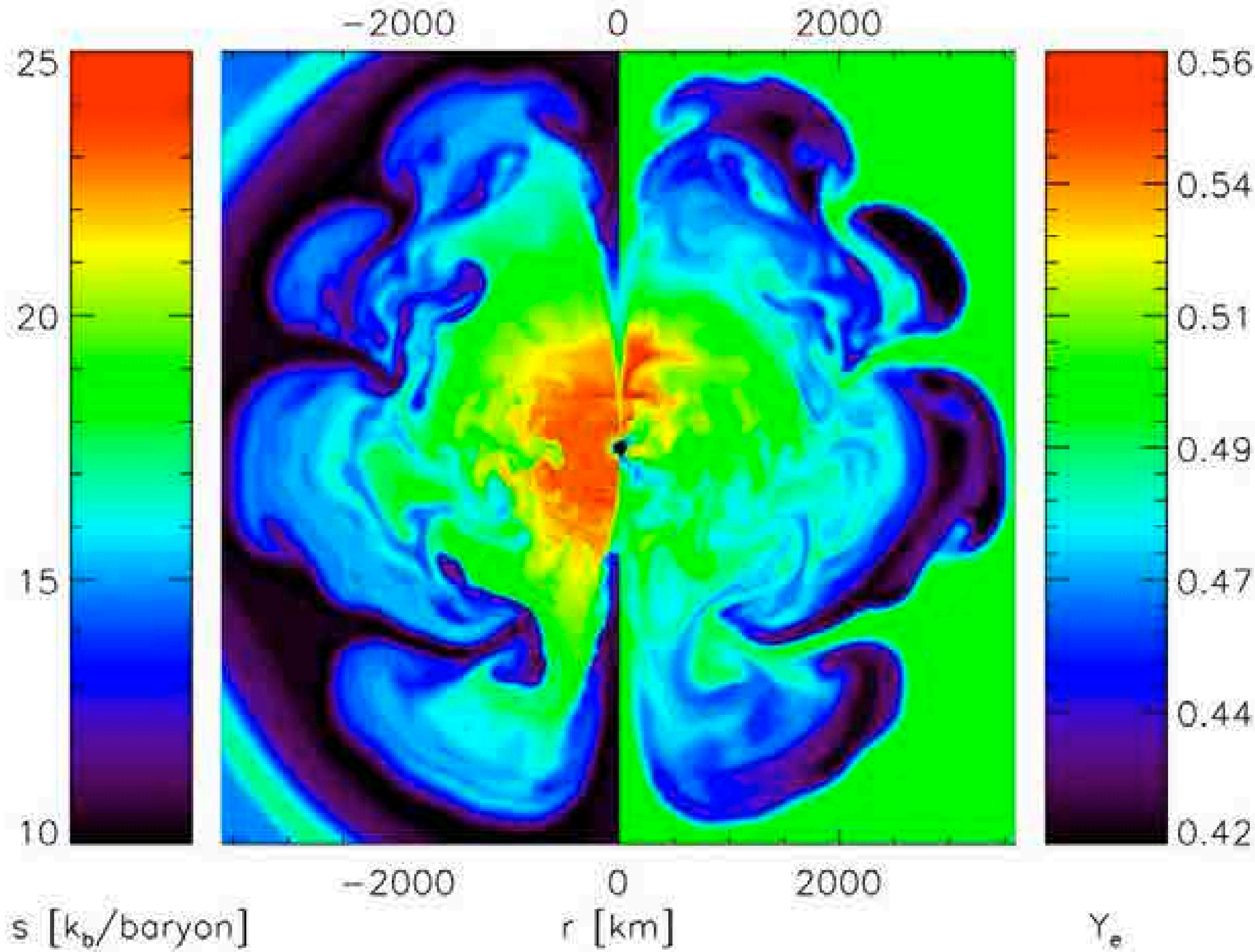


But it is ^{20}**Ne + 2e-**, activated at about 1e10 g/cc that releases enough energy to ignite an **oxygen deflagration wave** in the centre

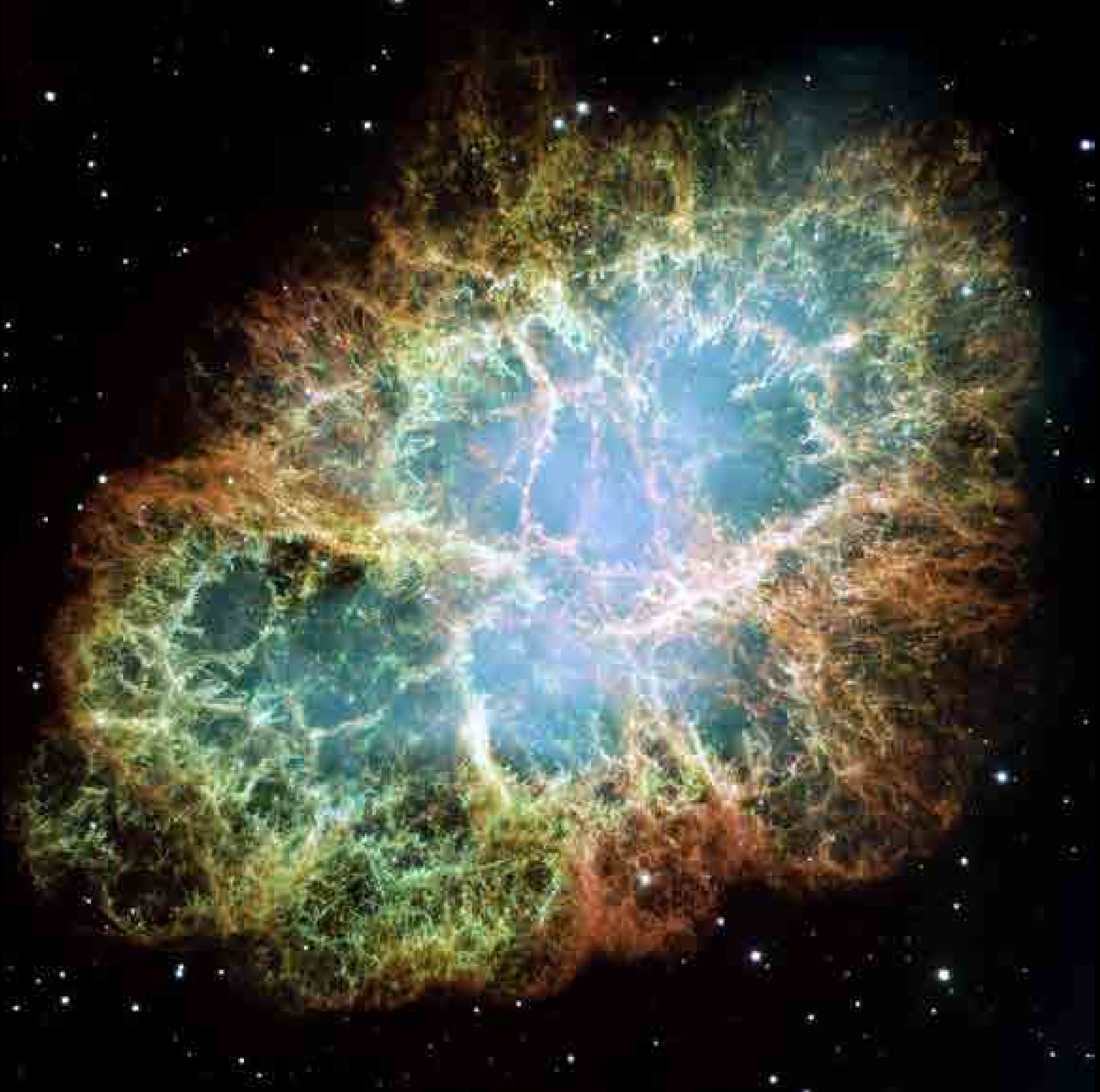
Miyaji+ (1980); Nomoto (1984,1987)

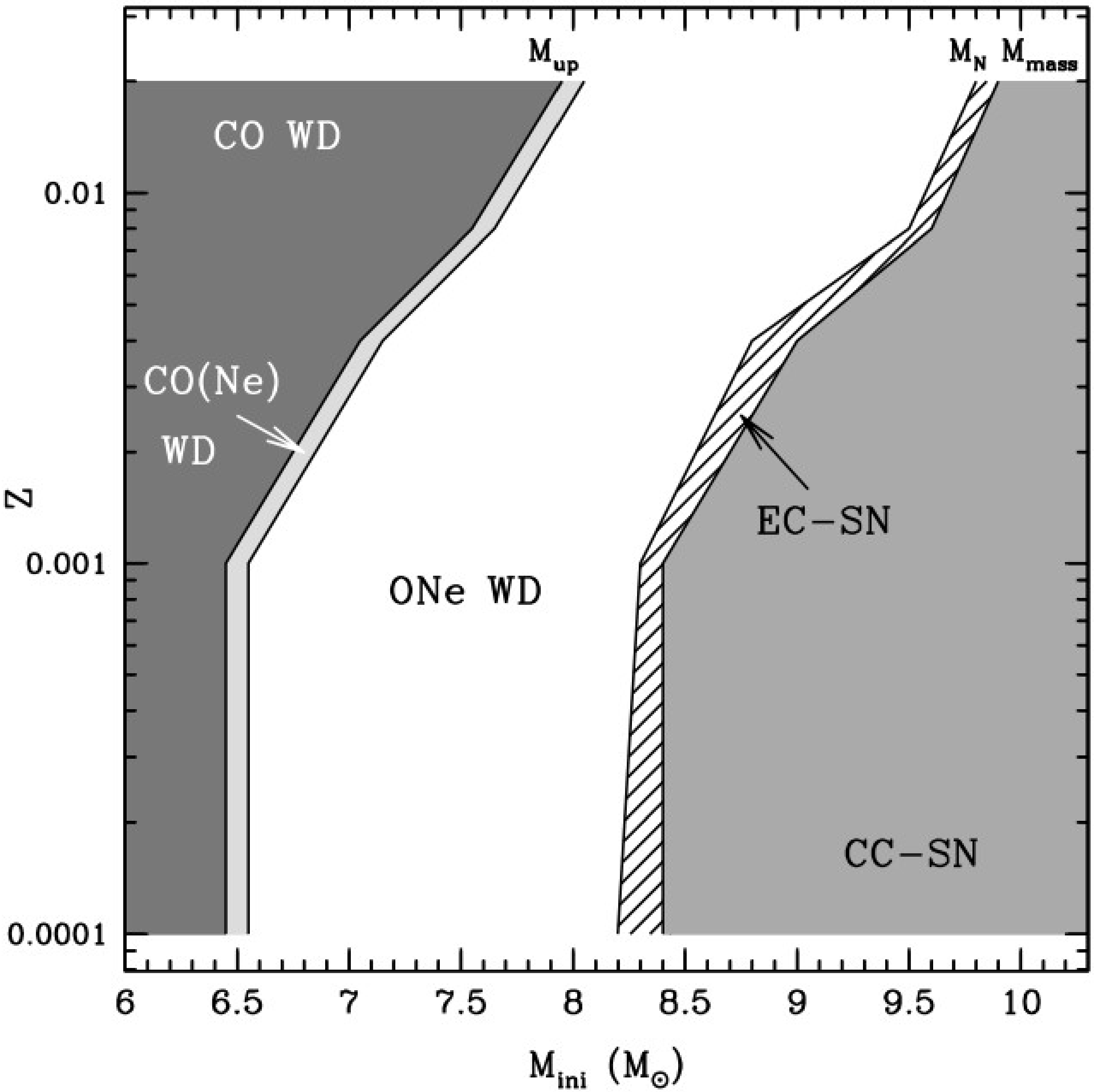
The energy release from burning **competes with electron capture** on the ash; in the classical picture the electron captures win and the star's **core collapses**

Wanajo+ (2011)



−2000
0
2000
25
20
15
10
0.56
0.54
0.51
0.49
0.47
0.44
0.42
s [k_b/baryon]
r [km]
Y_e





Doherty+ (2015)

ECSNe from single stars may be limited to a rather **narrow initial mass range**

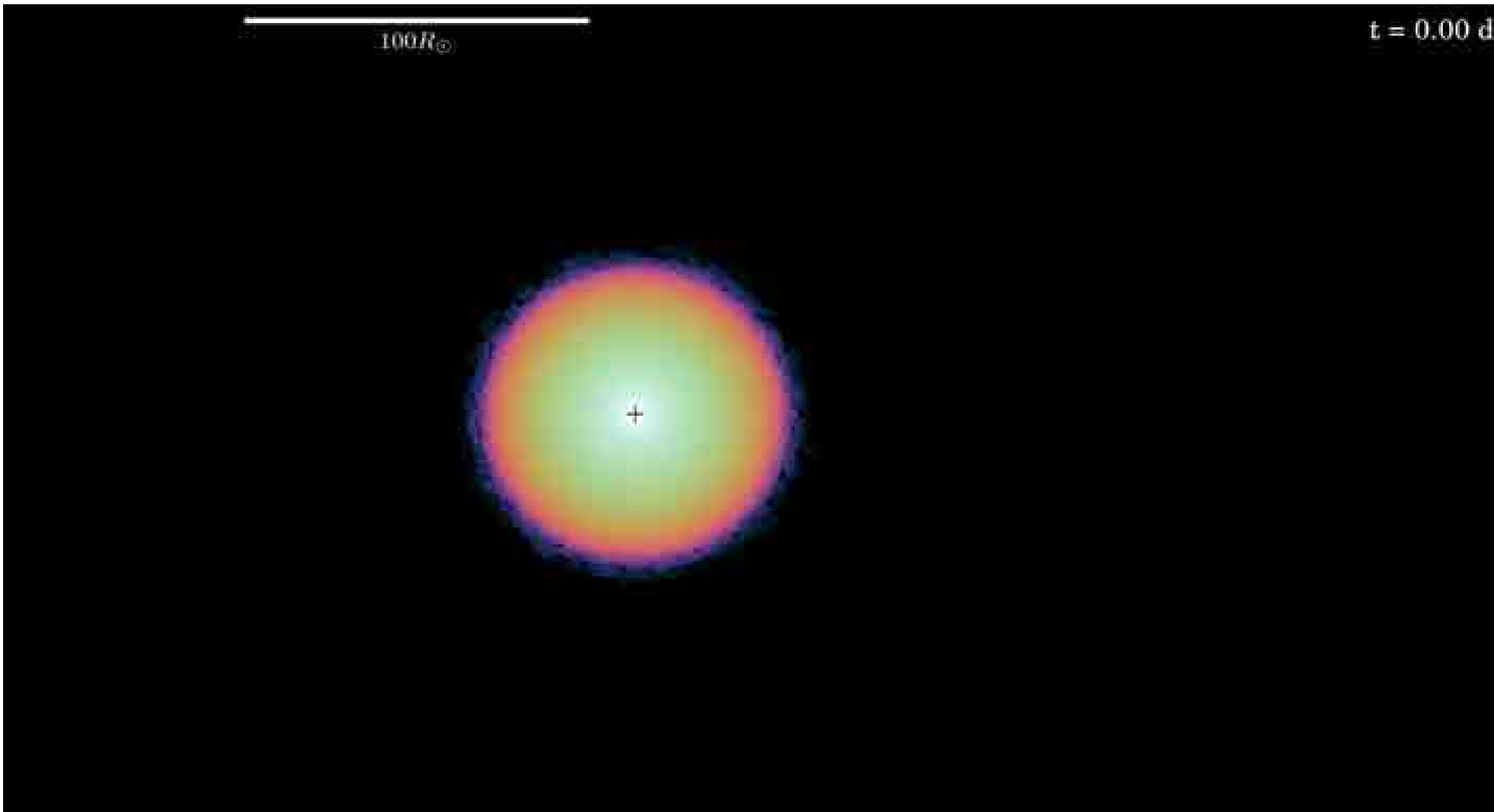
The H envelope recurrently reaches into the core and **reduces its mass**

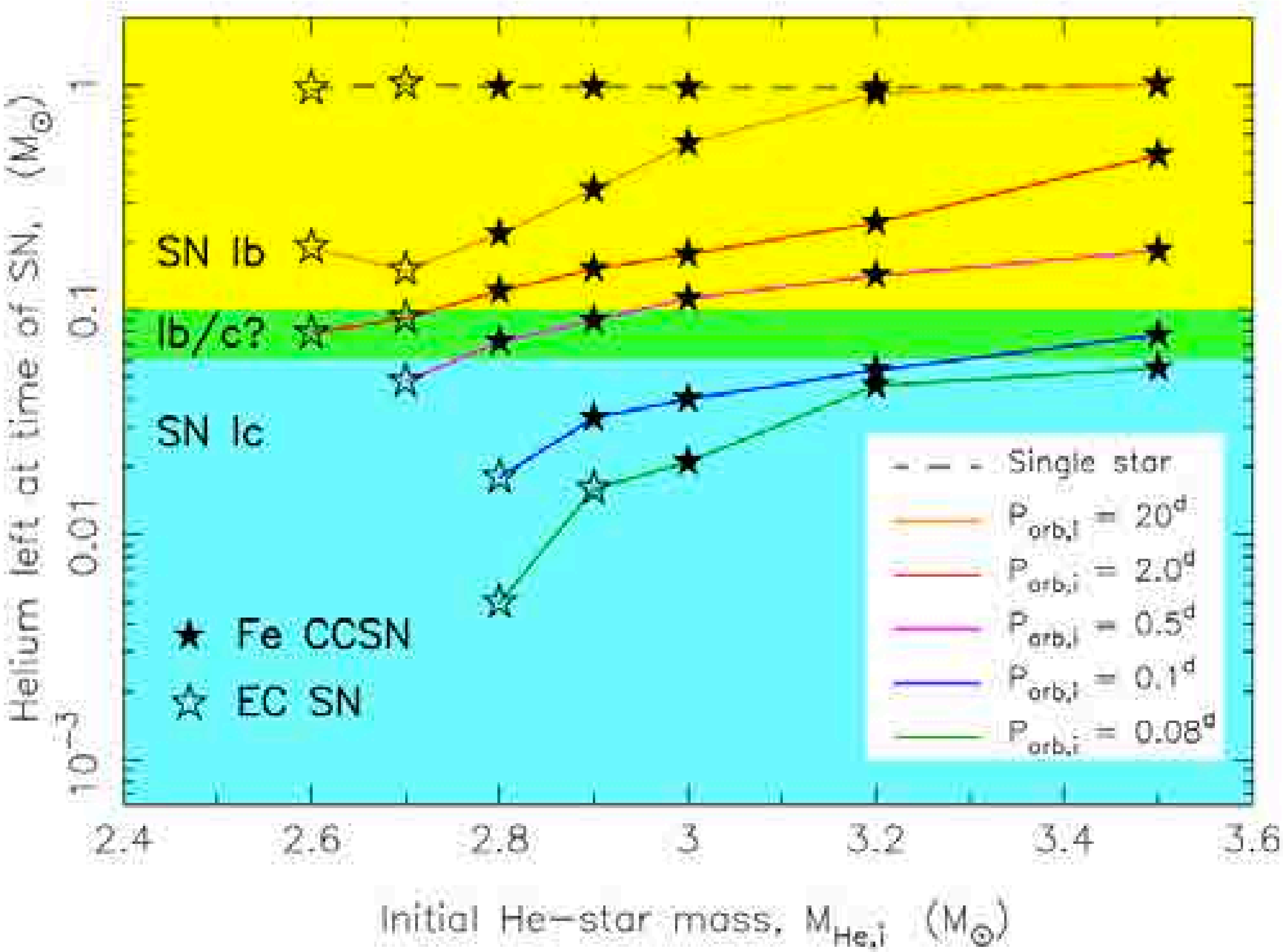
however

ECSNe may be more frequent in binary stars.

COMMON ENVELOPE PHASE

Ohlmann+ (2016 in press)





Tauris+ (2015)

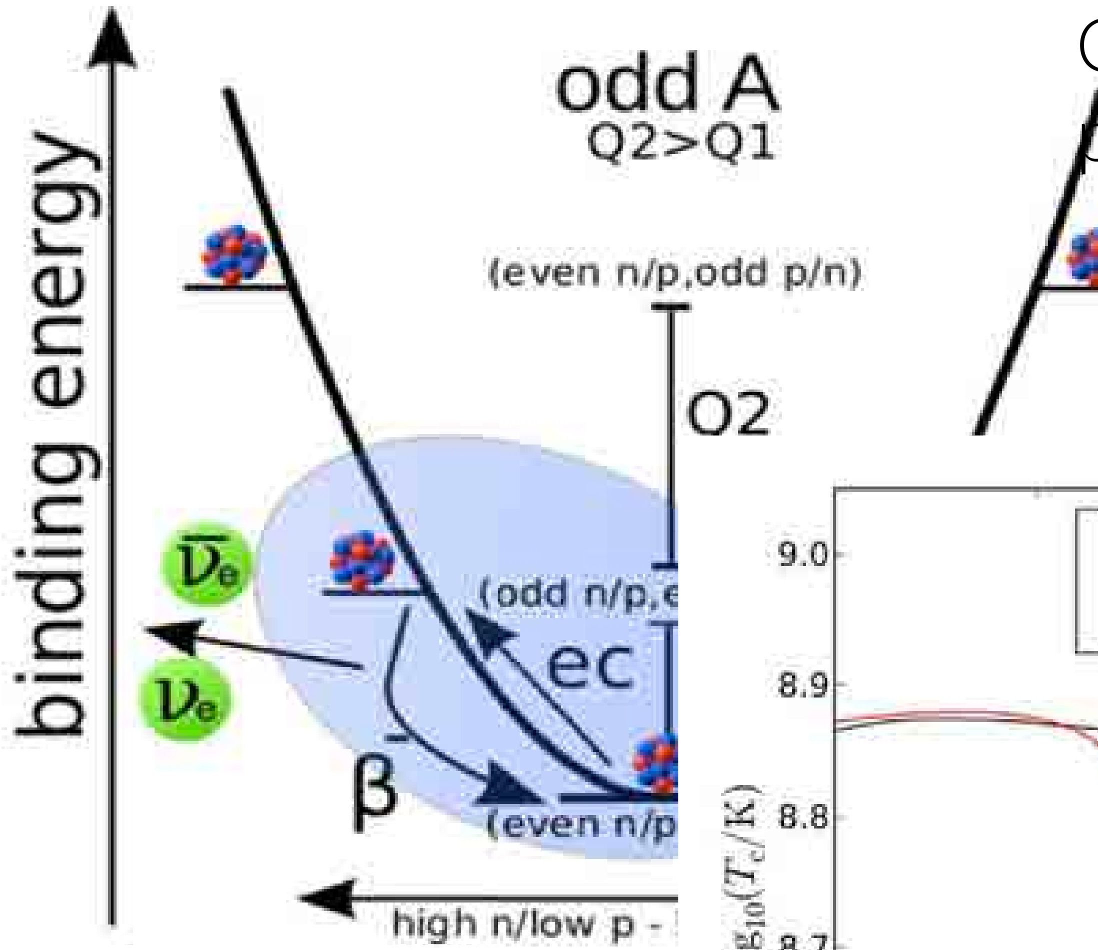
ECSNe may be more frequent in binary stars, where core growth is not stunted by core-envelope mixing because **the envelope was ejected**

60-70% of these stars are in close binary systems
(Sana+ 2012, Dunstall+, in press)

NUCLEAR PHYSICS DETAILS

URCA PROCESS AND ELECTRON CAPTURES

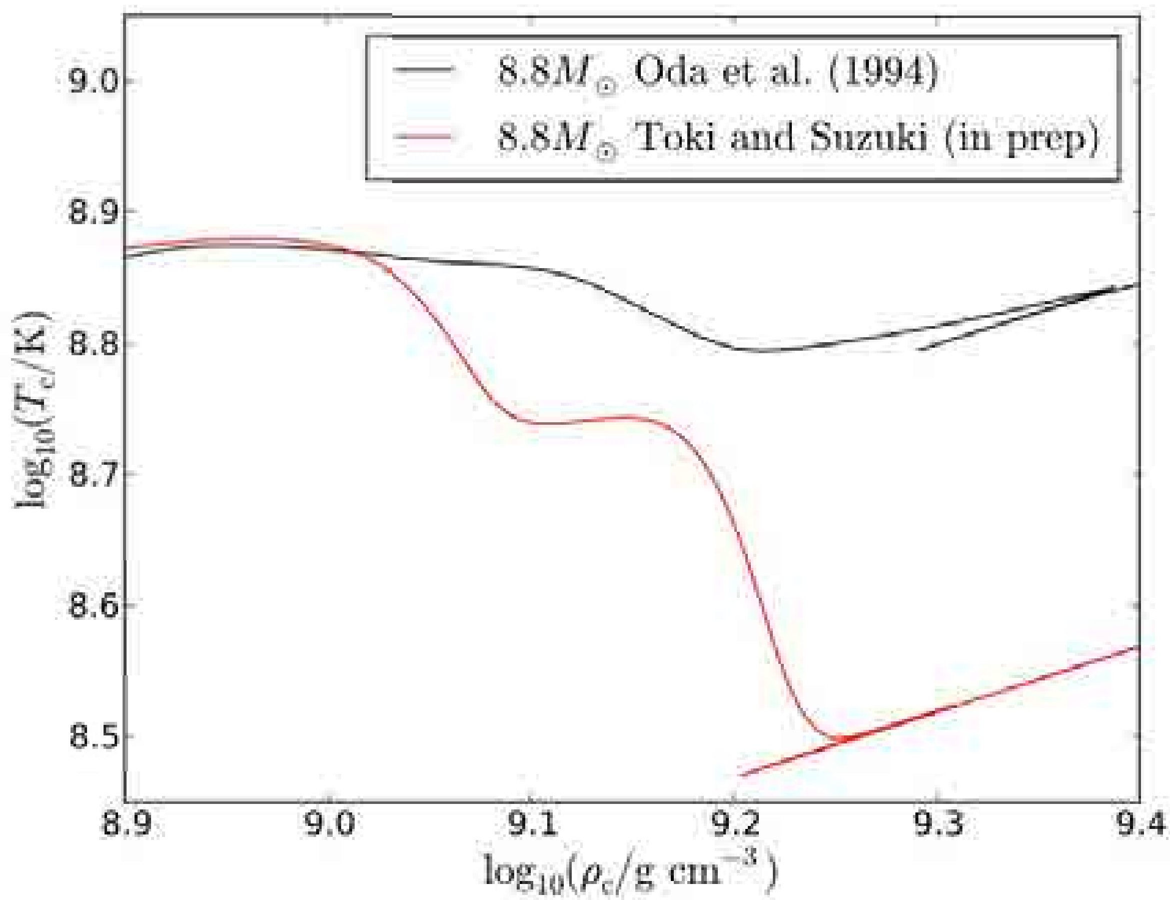
Cooling by odd-A nuclear pairs in **beta equilibrium**



Möller,Jones+ (2014)

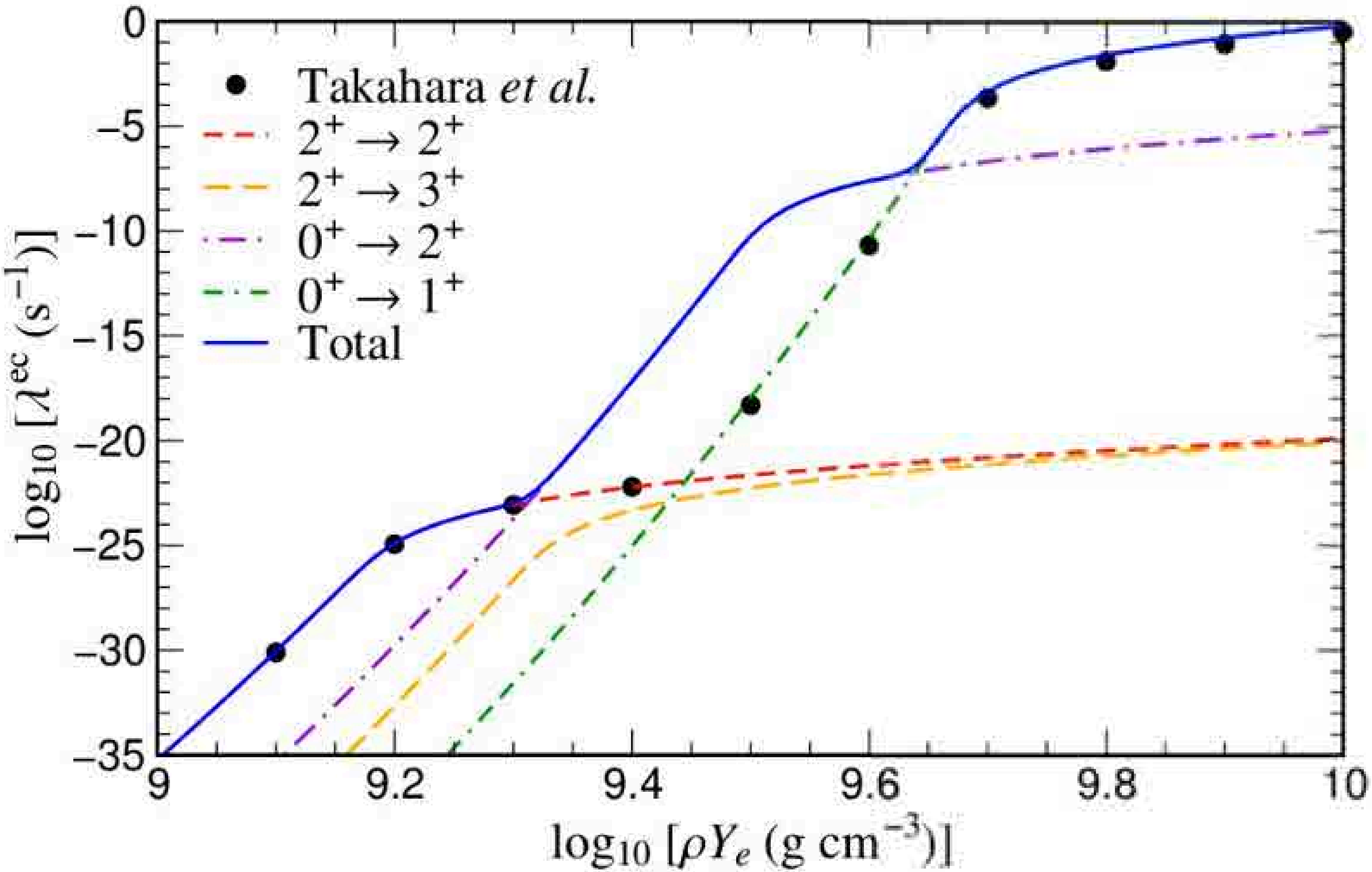
Toki,Nomoto,Jones+ (2013)

Jones,Nomoto+ (2013)

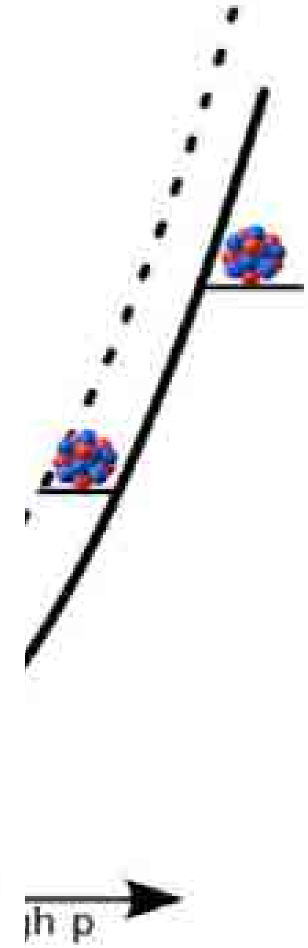


URCA PROC

NEUTRINO COOLING



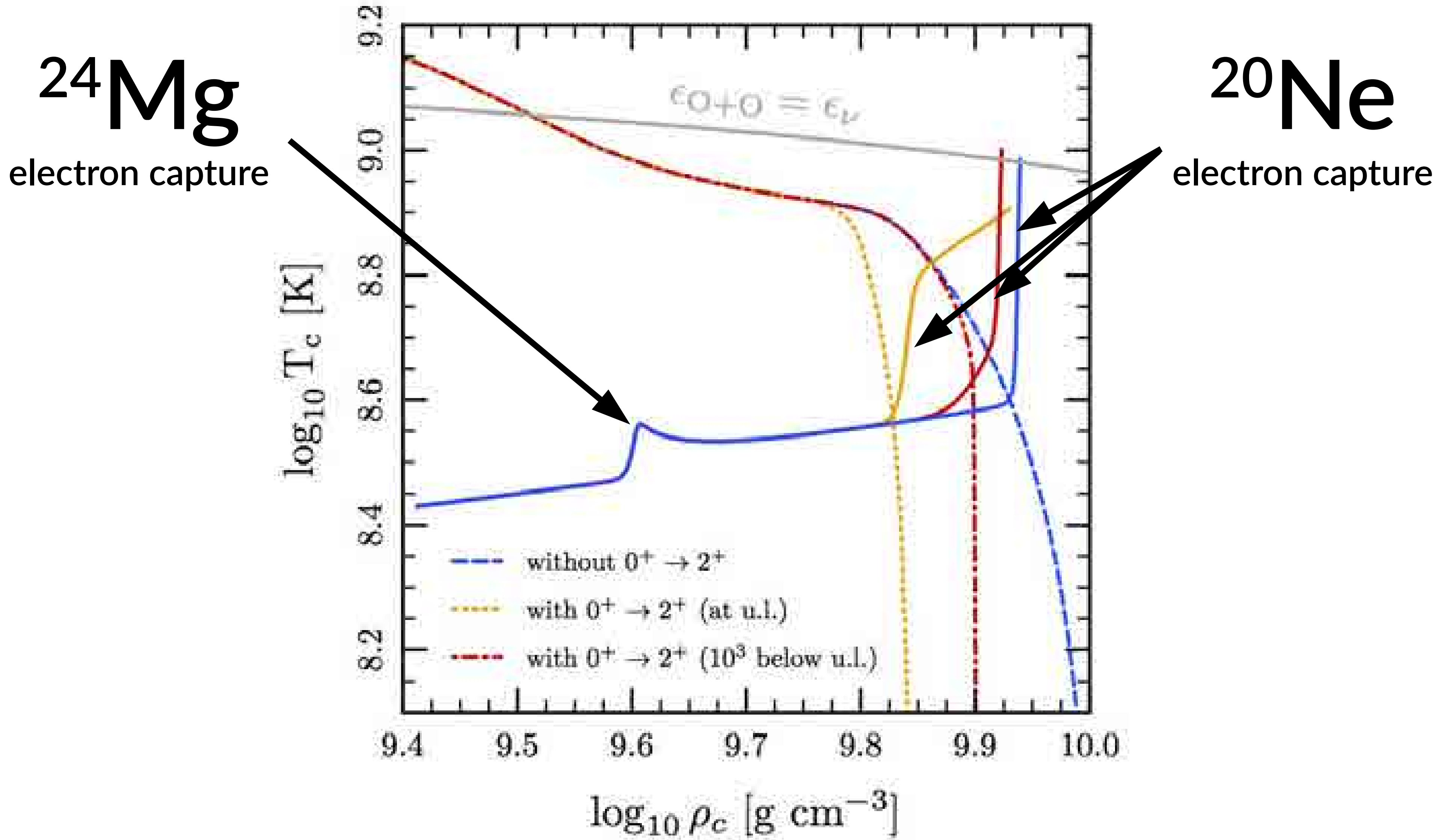
Martinez-Pinedo+ (2014)



Möller,Jones+ (2014)

^{20}Ne ELECTRON CAPTURE

RAPID HEATING



1D SIMULATIONS

AIC of ONe white dwarf

Schwab+ (2015)

- The **mass loss rates** for these stars are **not well known** (e.g. Poelarends+ 2008)

- **Hydrodynamic instabilities** triggered by iron opacities (e.g. Lau+ 2012) or energy deposition by **H ingestion** in to He-burning convection zones (Jones+ 2015) may lead to **ejection of the envelope before it reaches critical mass**

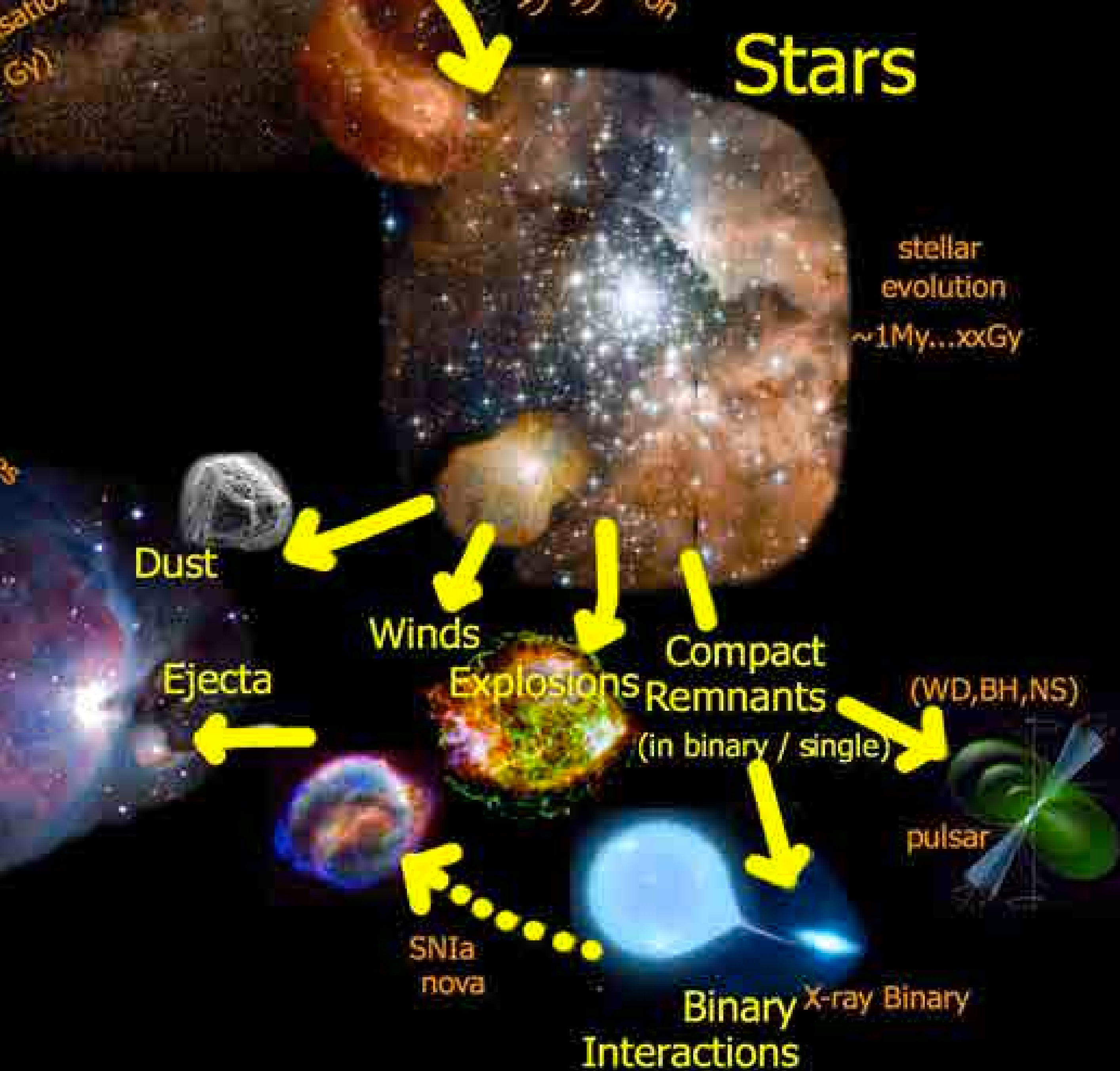
- Degenerate stars are extremely **sensitive to nuclear physics input; the deflagration ignition density is critical**

- In the only simulations of the O deflagration, both **neutron stars and WDs were both possible outcomes** (Isern+ 1991)

- Impact of **binarity** on the occurrence of ECSNe unclear

OUTSTANDING PROBLEMS

WHY DO WE CARE?


Stars
stellar
evolution
~1My...xxGy
Dust
Winds
Explosions
Compact
Remnants
(in binary / single)
(WD,BH,NS)
Ejecta
pulsar
SNIa
nova
Binary
Interactions
X-ray Binary

R. Diehl

O_2

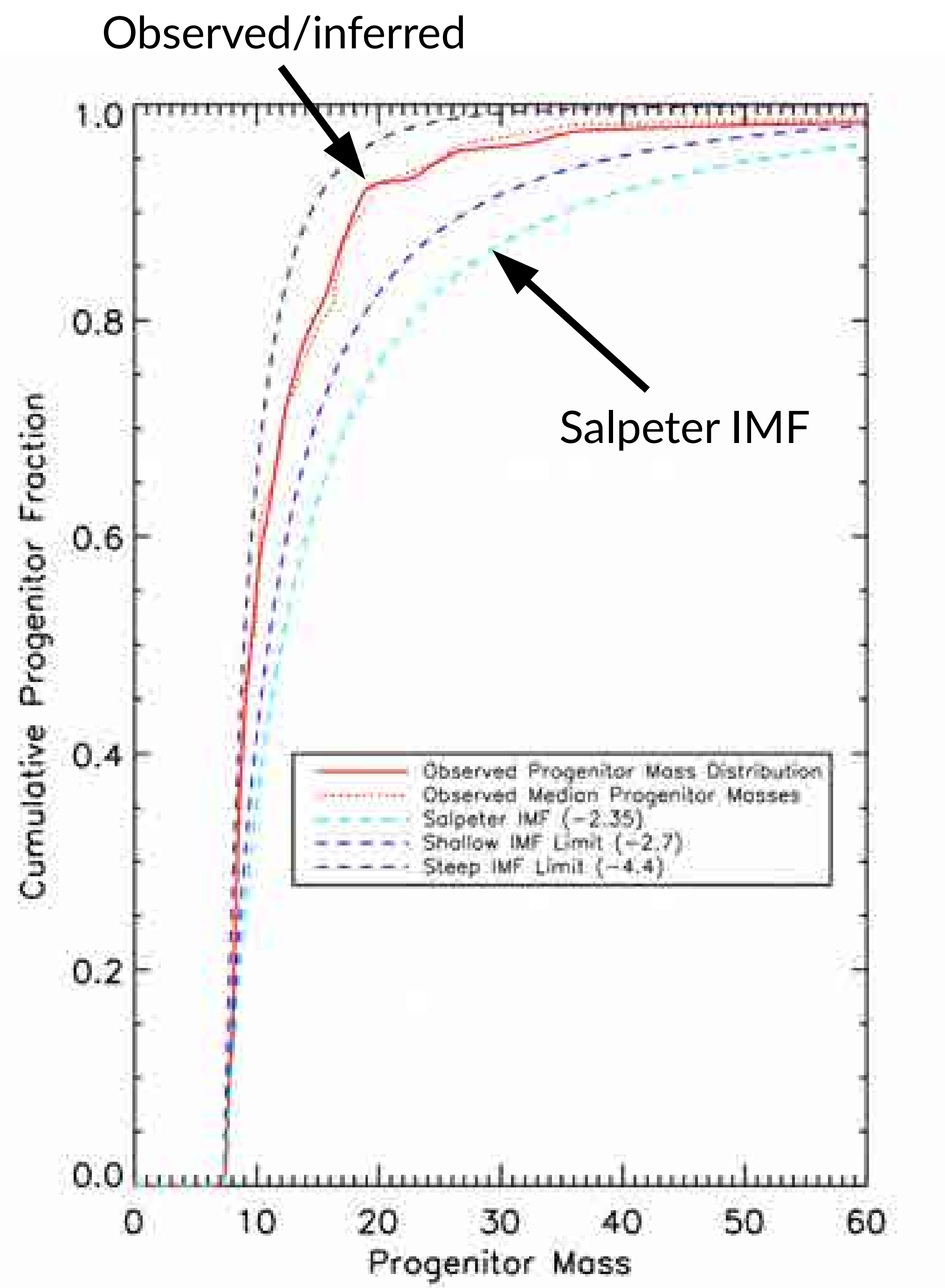
stories by williams.com

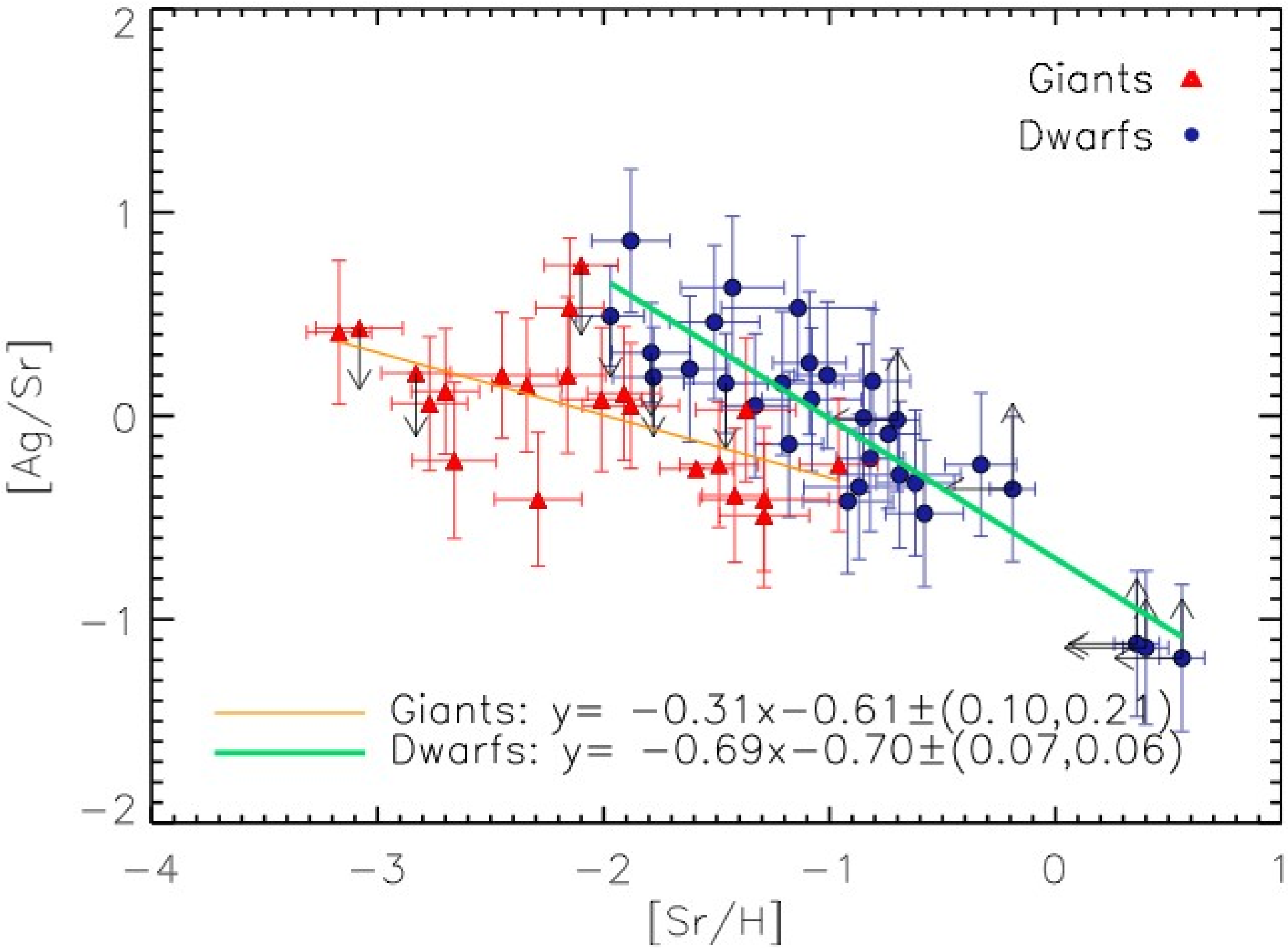
IMF

SNII PROGENITOR MASS DISTRIBUTION IN M31

Jennings+ (2012)

Assuming a *Salpeter* IMF, 8—10 solar-mass stars constitute 26 % of all massive stars. Probably more.





Anti-correlation of Ag and Pd with Sr and Y (s-process)

Anti-correlation of Ag and Pd with Eu (r-process)

Silver and Palladium are made in a different site/process to 'standard' s- and r-process elements

NUCLEOSYNTHESIS

ORIGIN OF SILVER AND PALLADIUM

Hansen+ (2012)

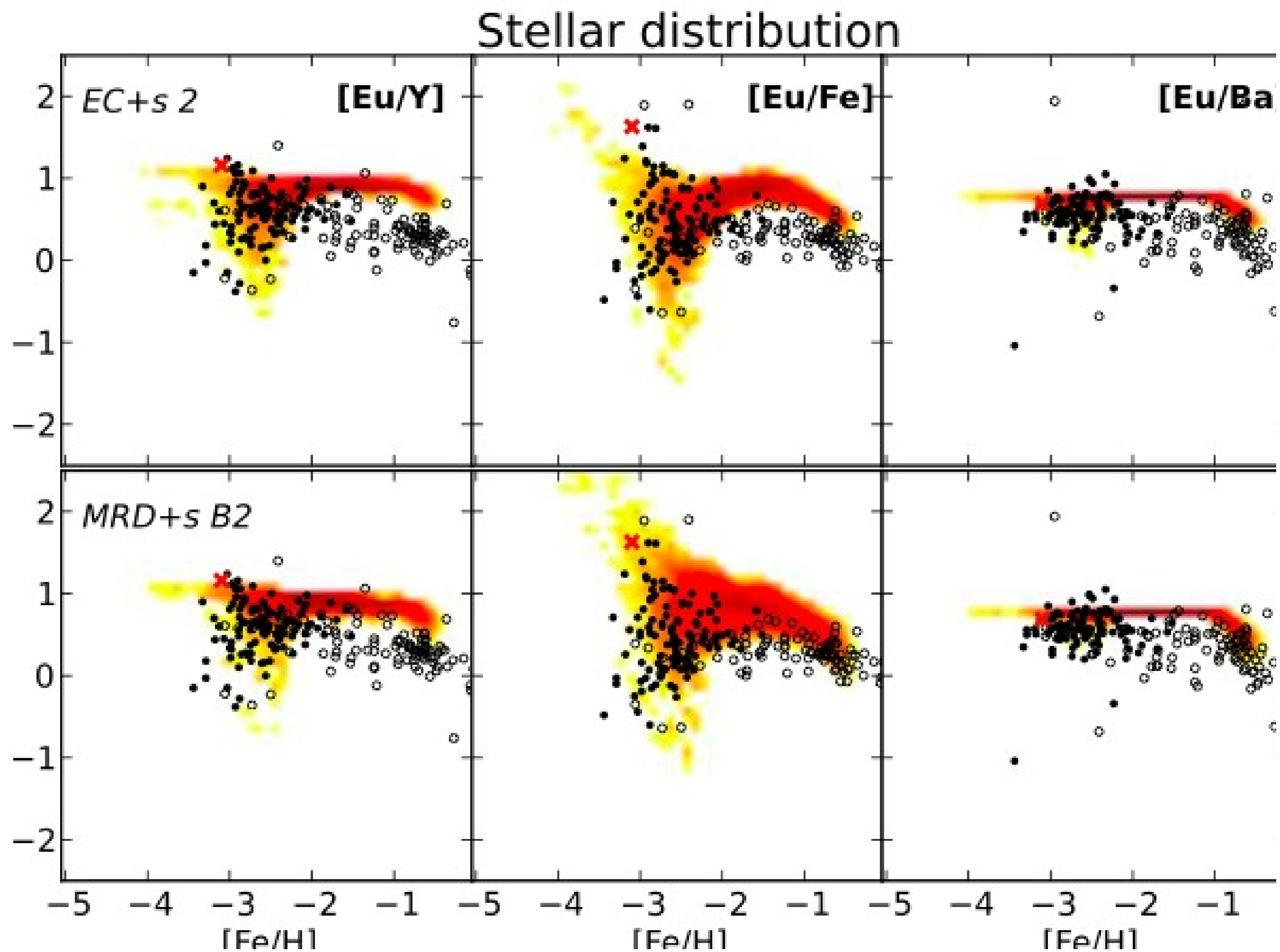
NUCLEOSYNTHESIS

ABUNDANCE RATIOS OF HALO STARS

Cescutti+ (2014)

Parametrised GCE models reproduce the data equally well assuming EC or MRD SNe host r-process

Proof that 8—12 solar-mass stars could produce r-process has yet to surface, yet so has evidence to the contrary



NEUTRON STARS

“BIMODAL” STATISTICAL PROPERTIES

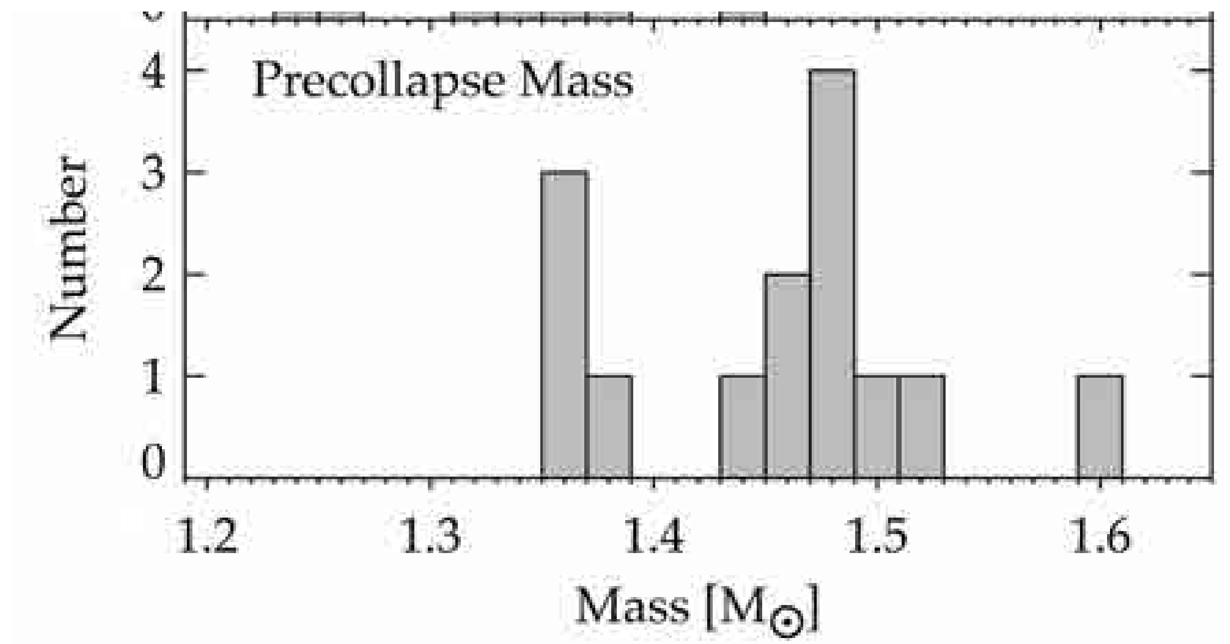
Sample size (14) too low

NS mass set during accretion phase before SN shock revival

Shock revival triggered by core structure of progenitor, which has no discrete jump

But do ECSNe even produce neutron stars?

Two populations??



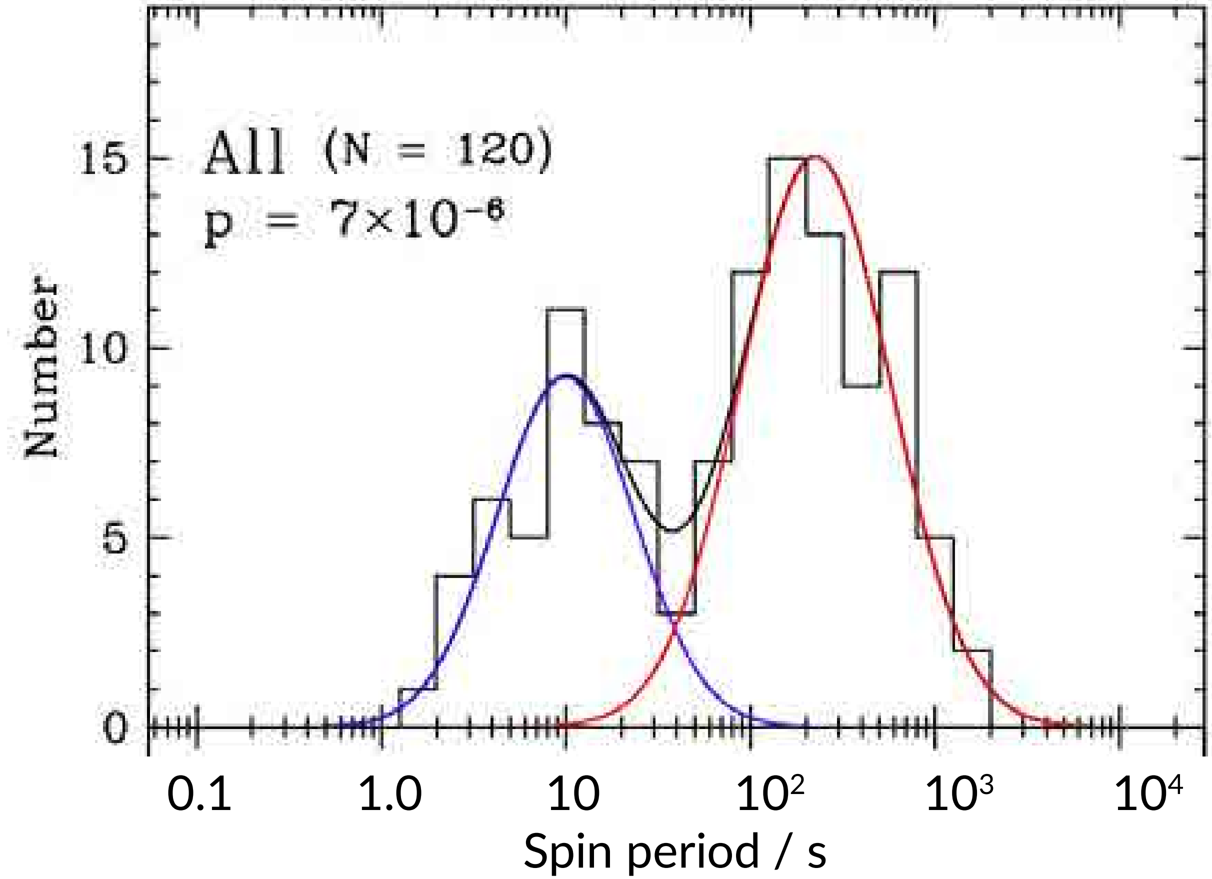
Schwab+ (2010)

Bimodal distribution of spin periods

Bimodal distribution of orbital eccentricities

Two populations claimed to be neutron stars formed by EC and iron core-collapse SNe

This again depends on core structure, which is not discrete



Be/X-ray binaries

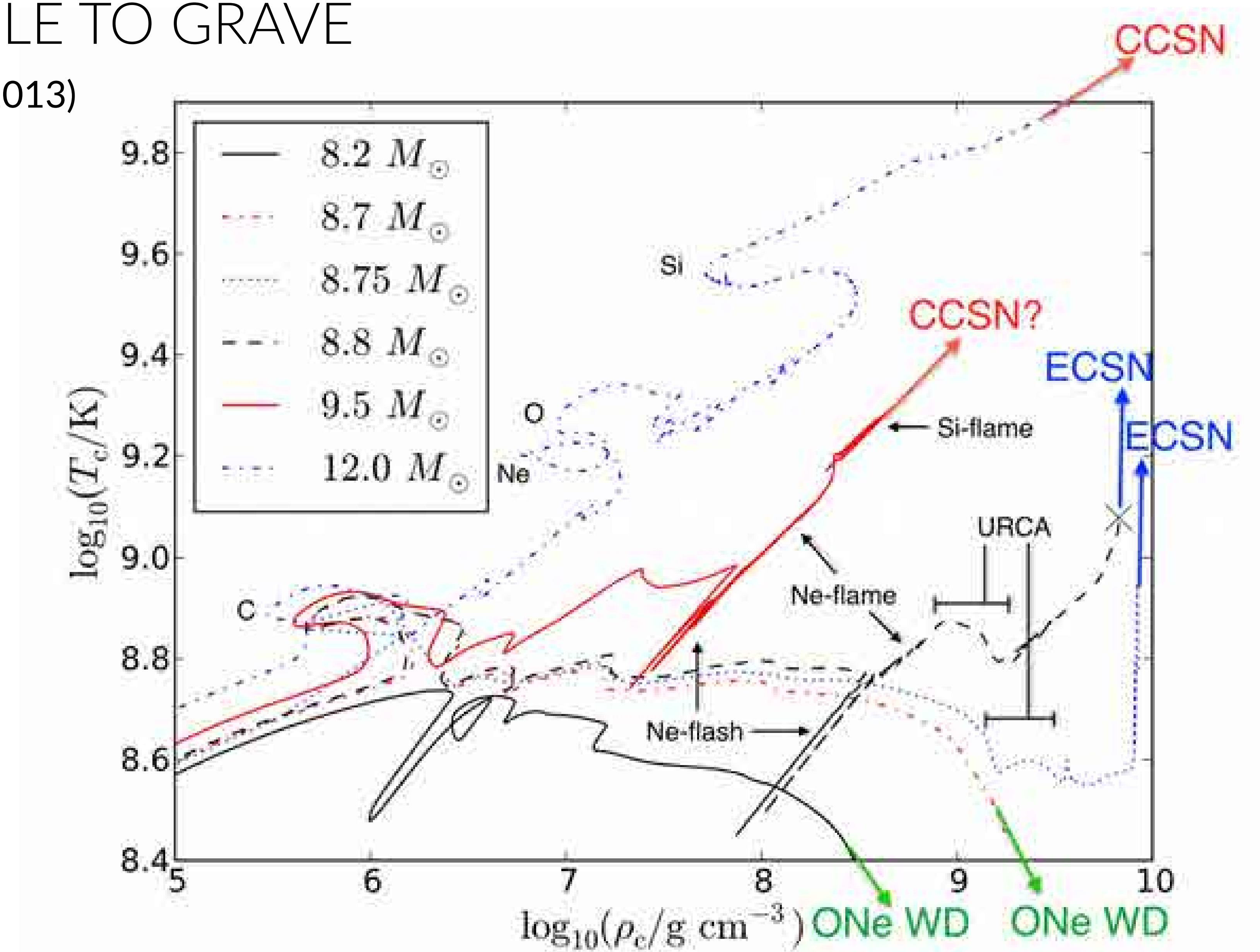
"BIMODAL" STATISTICAL PROPERTIES

Knigge+ (2011; Nature)

1D SIMULATIONS

CRADLE TO GRAVE

Jones+ (2013)



O DEFLAGRATION

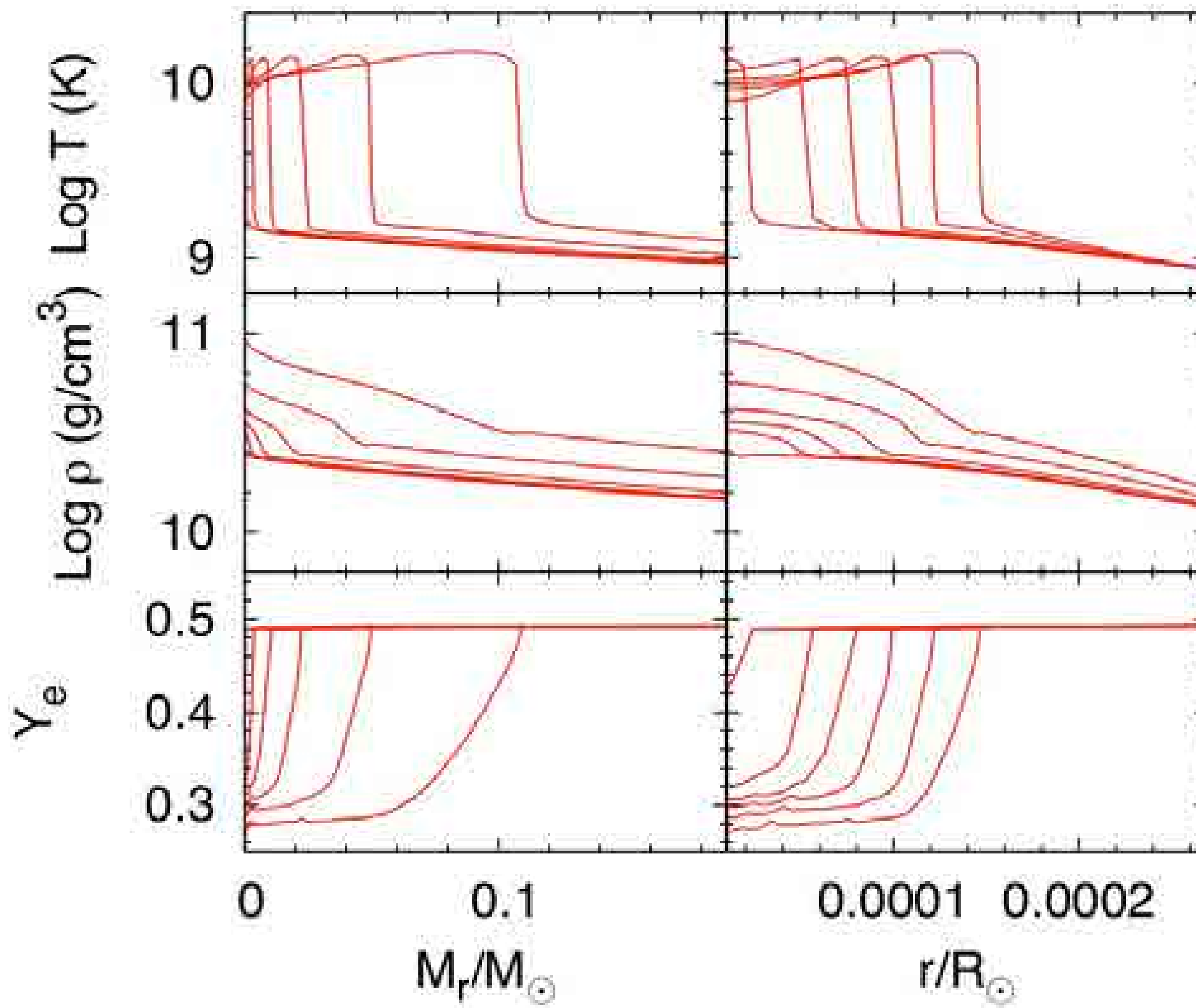
O IGNITED DUE TO γ-DECAY OF ^{20}O

Takahashi+ (2013)

Confirms Nomoto (84, 87): **O-deflagration leads to core collapse**

Still **no treatment** for conductive flame propagation

Ignition density **significantly higher** than found by Schwab+ (2015)



O DEFLAGRATION

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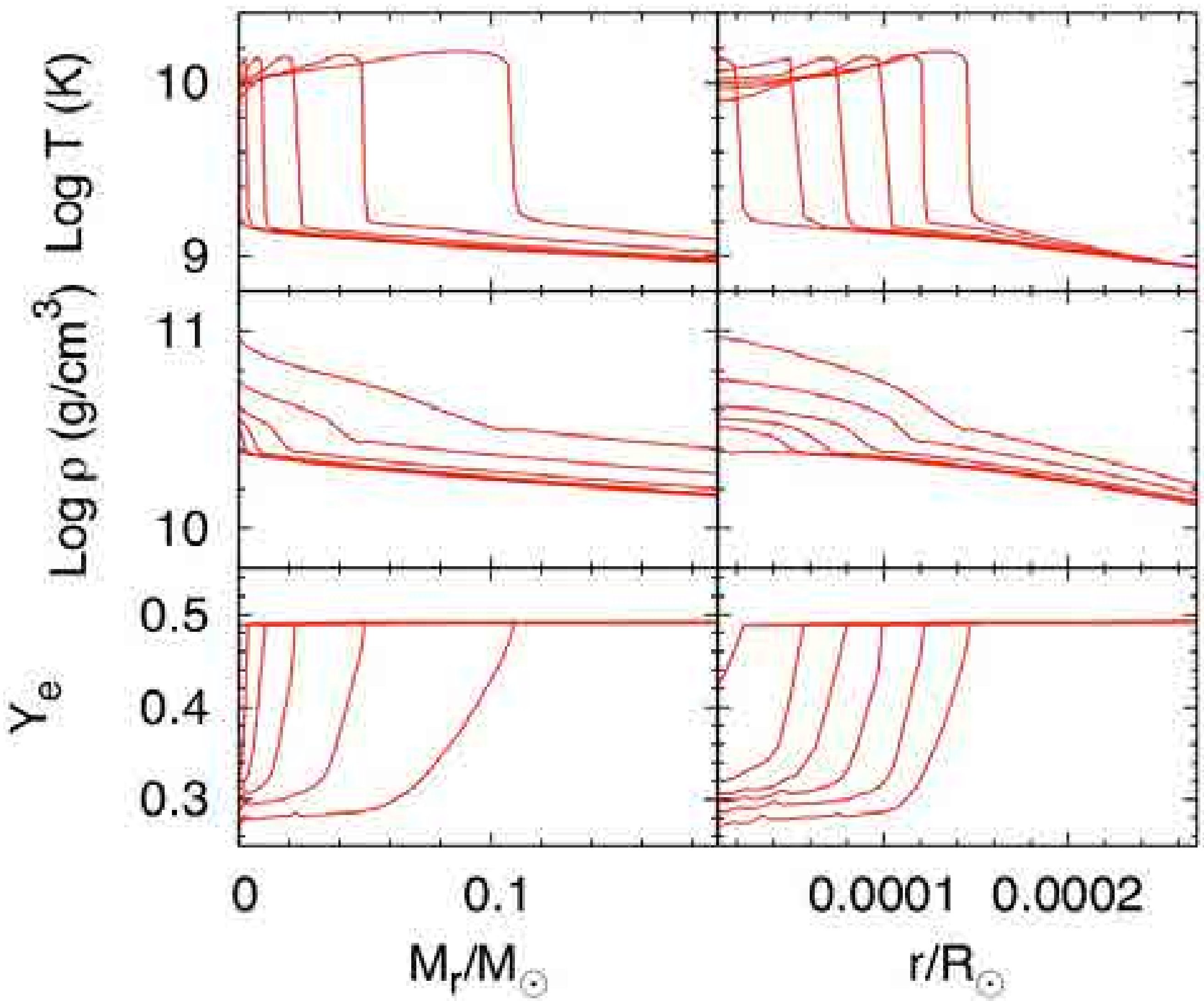
Electron-capture rates from Juodagalvis+ (2010)

No consistent beta-decay and positron-capture rates?

Results are the sum of several modelling and physics assumptions that all contribute towards a core collapse event



RAYLEIGH-TAYLOR?

UNCLEAR; MARGINAL STABILITY

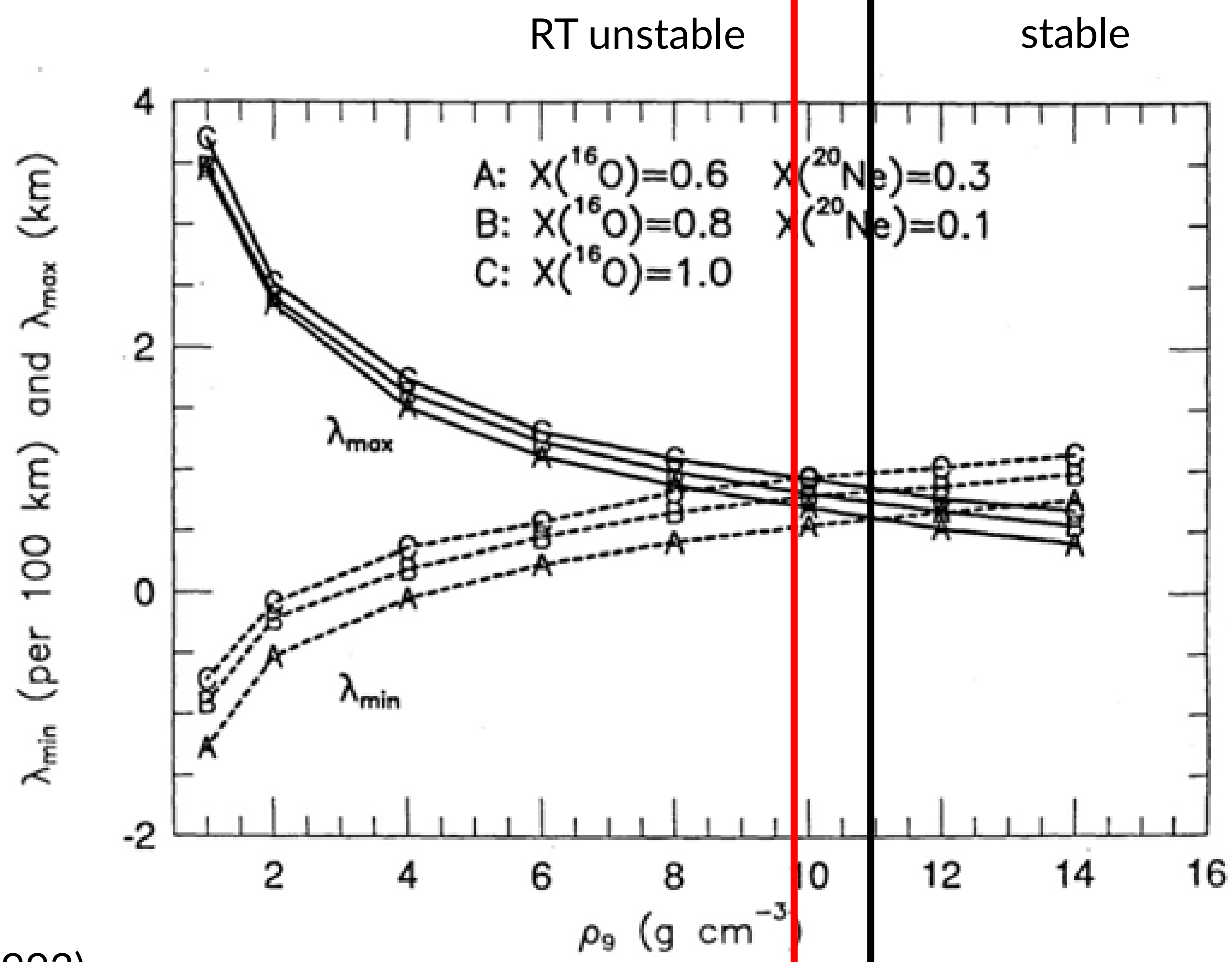


FIG. 9*b*

Timmes+ (1992)

O DEFLAGRATION

MULTI-DIMENSIONAL SIMULATIONS

Work-in-progress @ HITS

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

Isothermal ONe core/WD in HSE with **central density $10^{9.9}$ g / cc (Schwab+ 2015)**

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

NUCLEAR REACTIONS

DELEPTONISATION OF NSE ASH

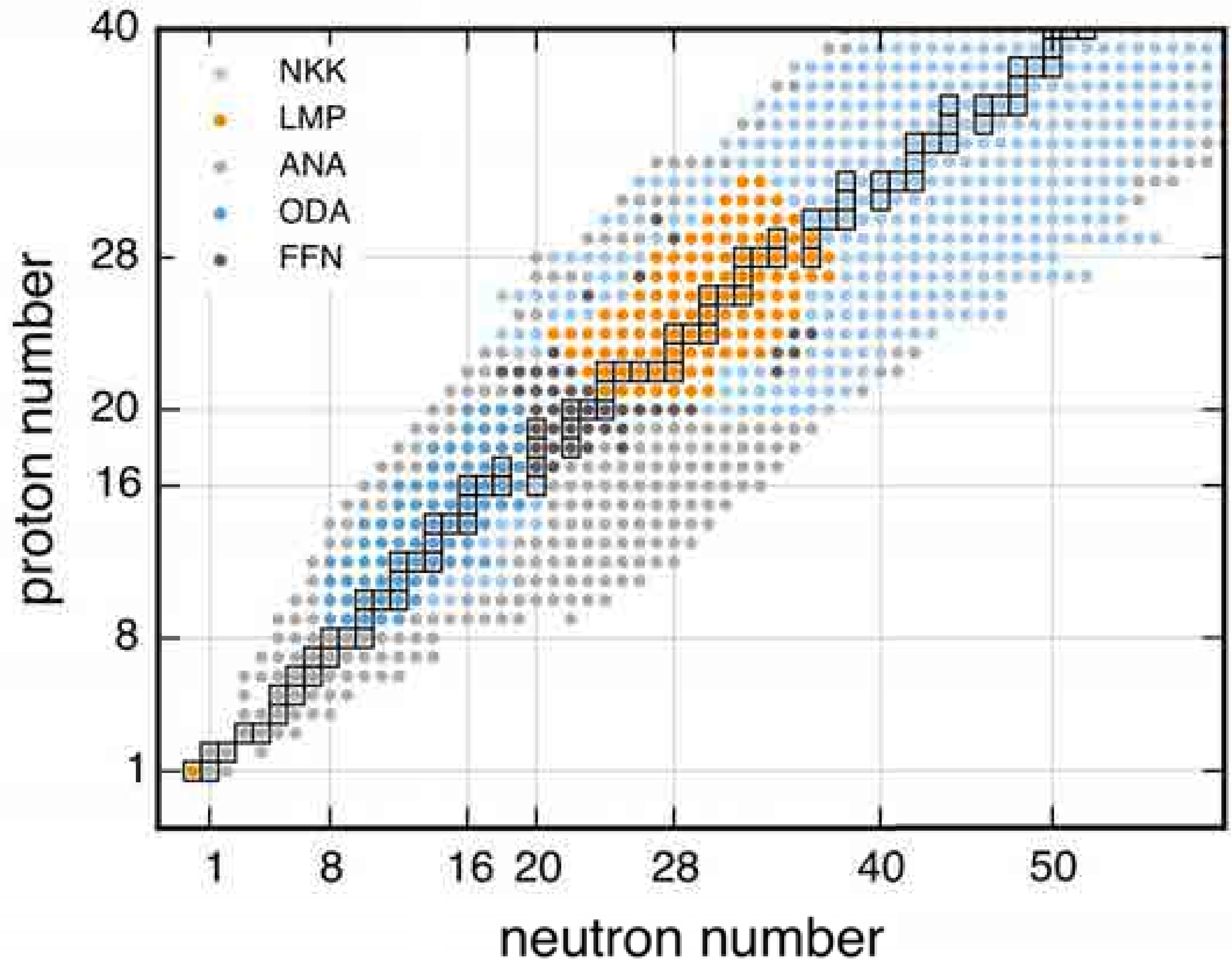
NKK: Nabi & Klapdor-Kleingrothaus

LMP: Langanke & Martinez-Pinedo (2001)

ODA: Oda+ (1994)

FFN: Fuller, Fowler & Newman (1985)

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



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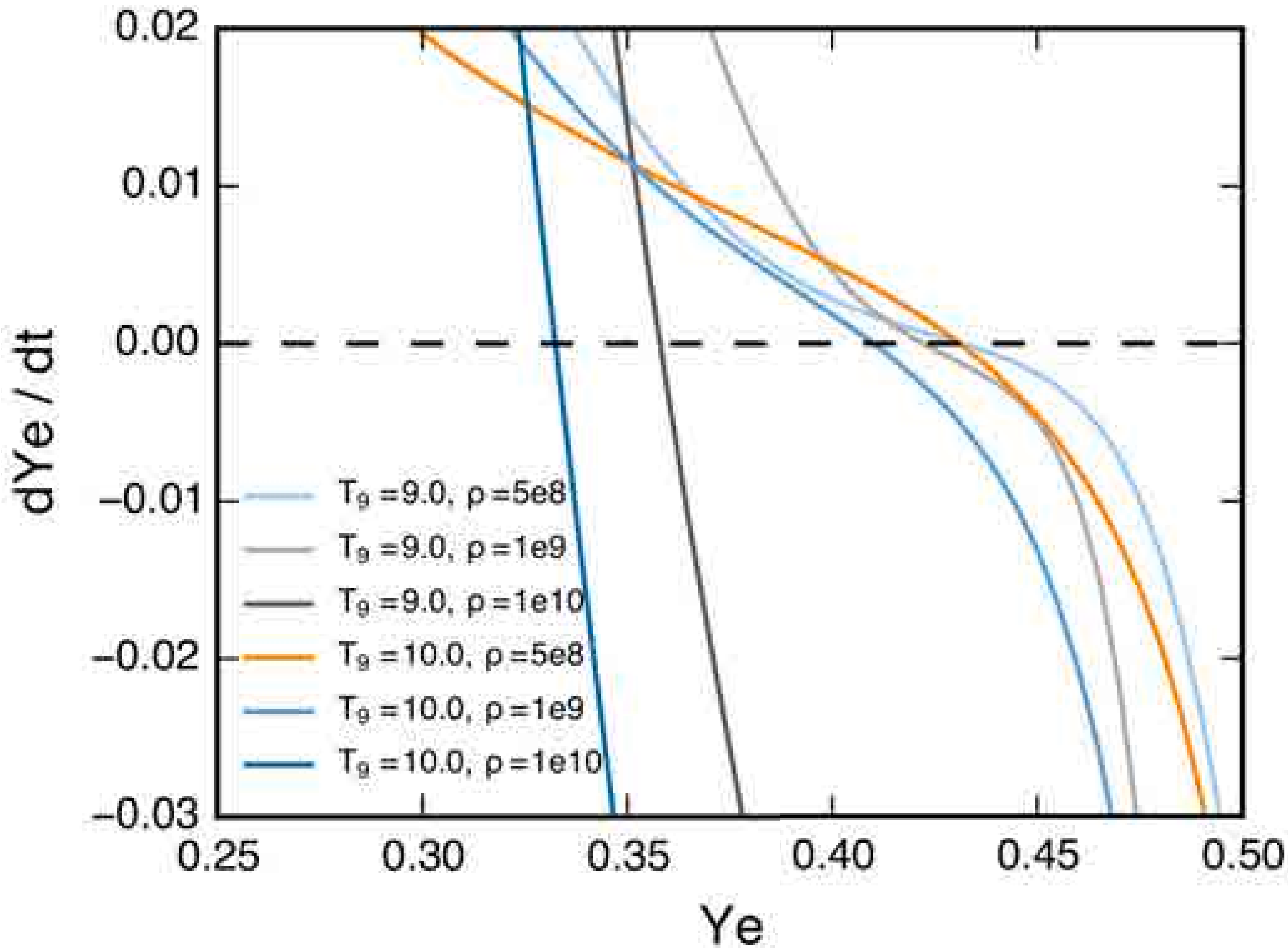
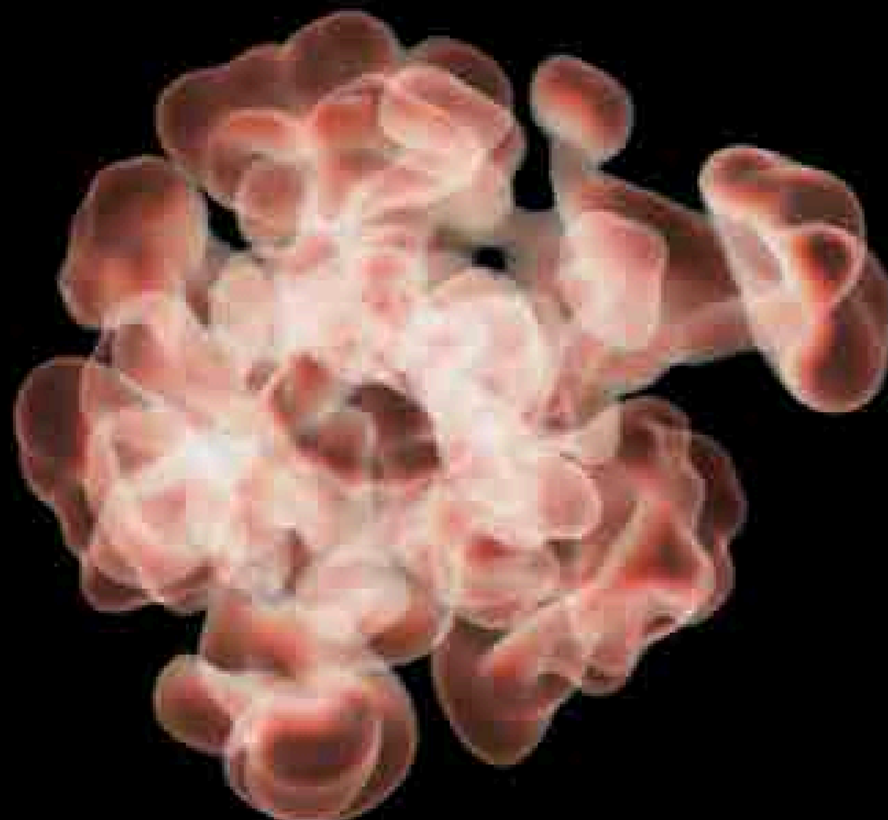


3D 4π: 128³

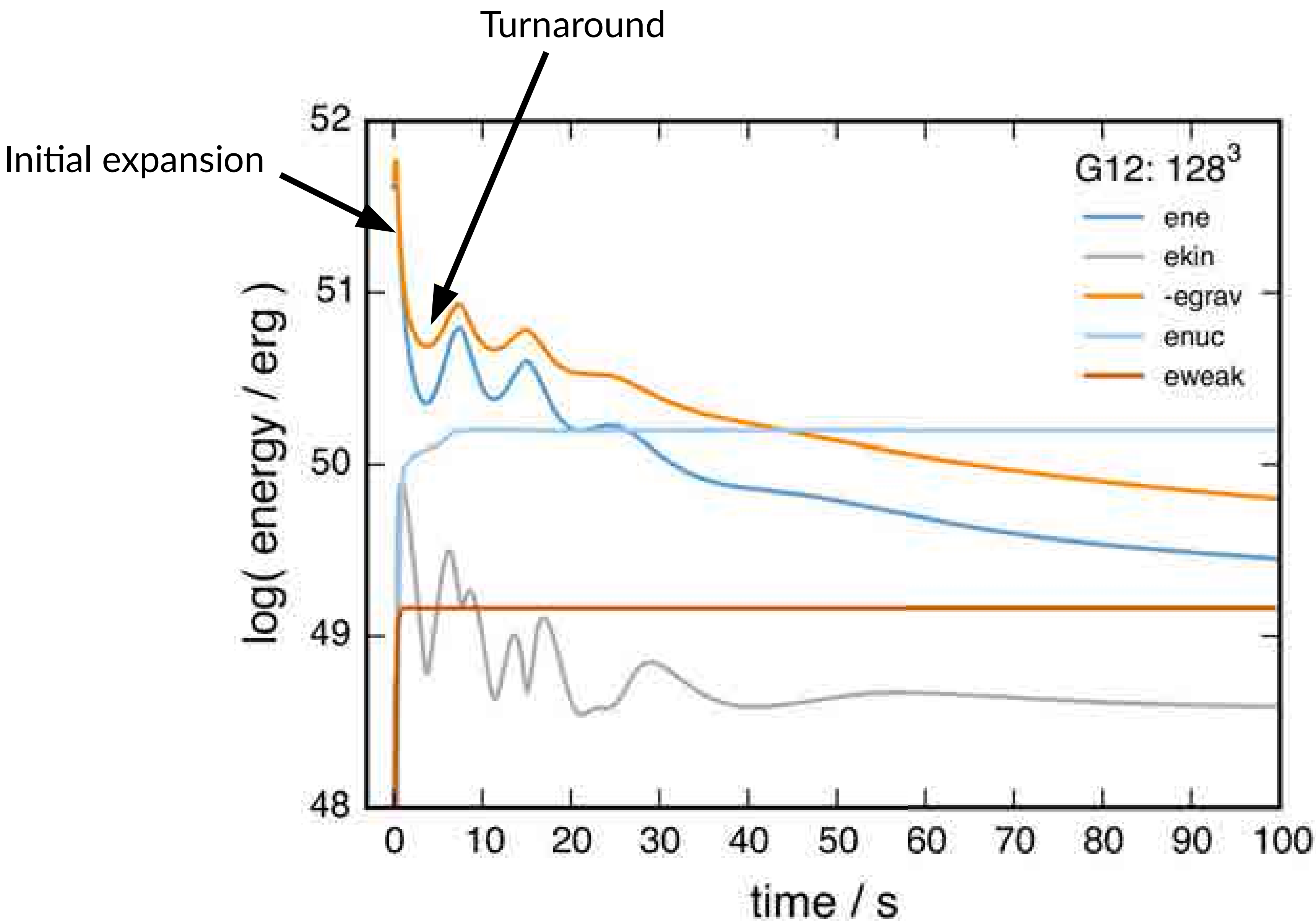
FLAME SURFACE



scale: 3.66E+03 km time: 9.02E-01 s

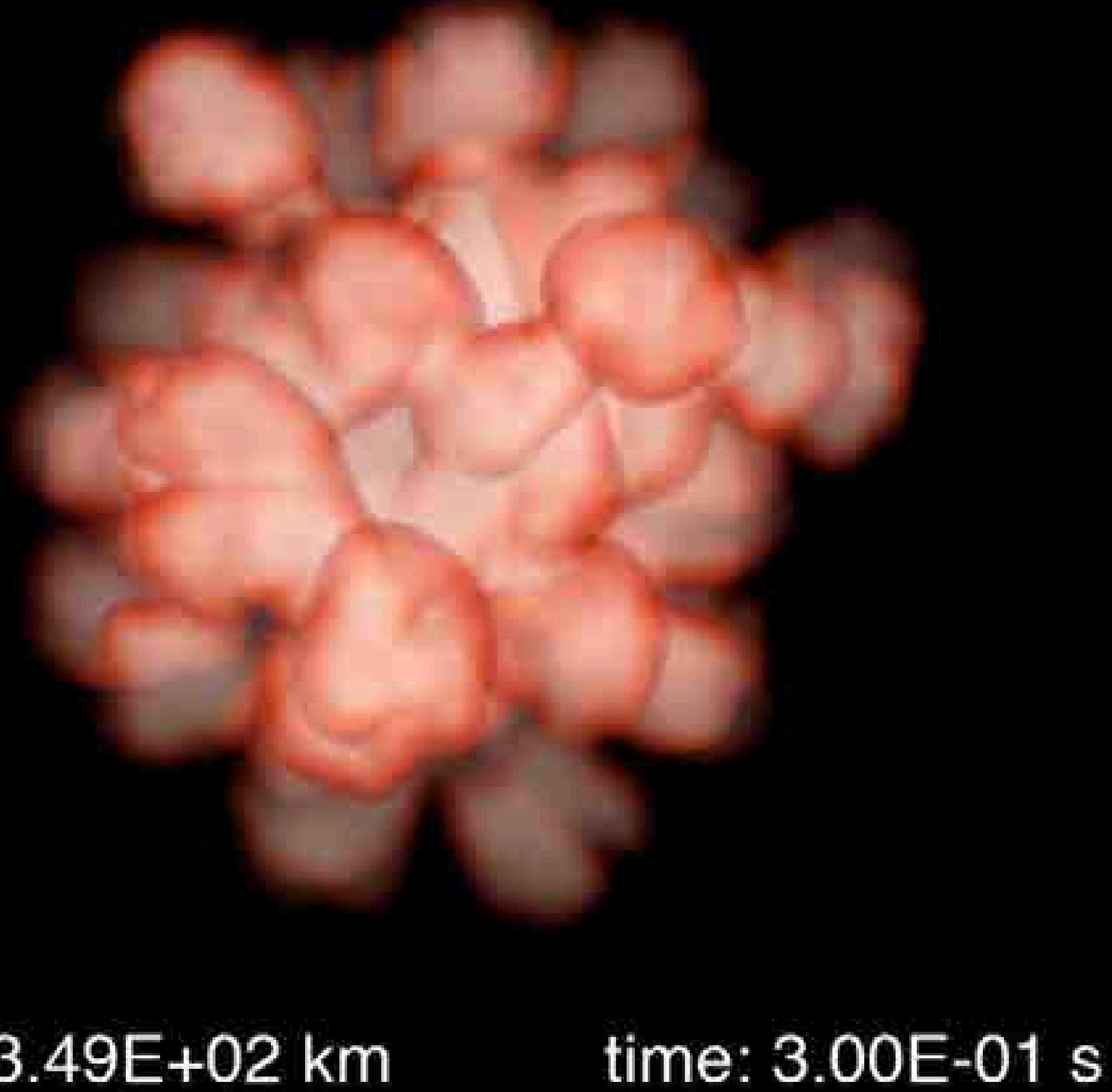
3D 4π: 128^3

COLLAPSE? BOUND REMNANT?



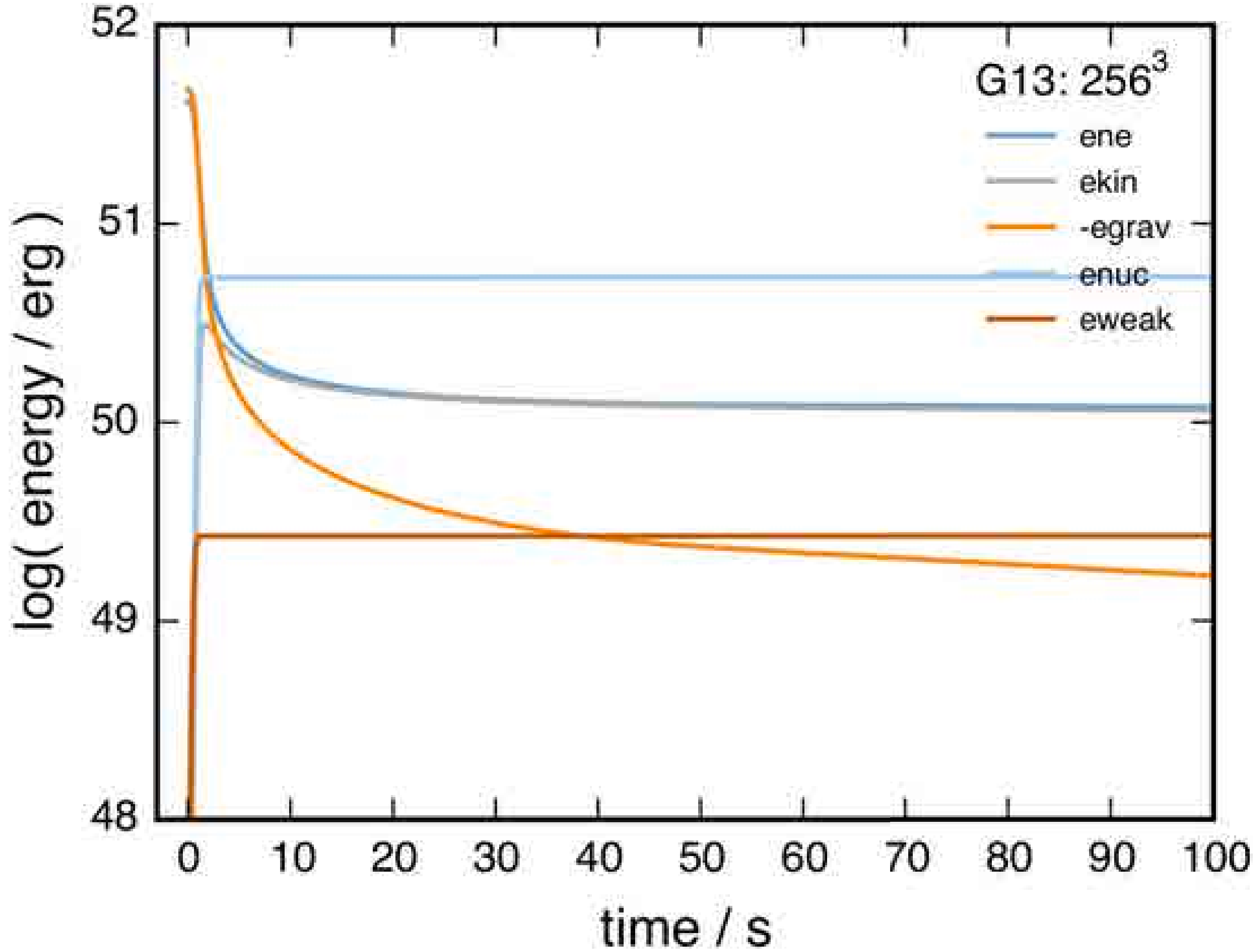
3D 4π: 256^3

FLAME SURFACE



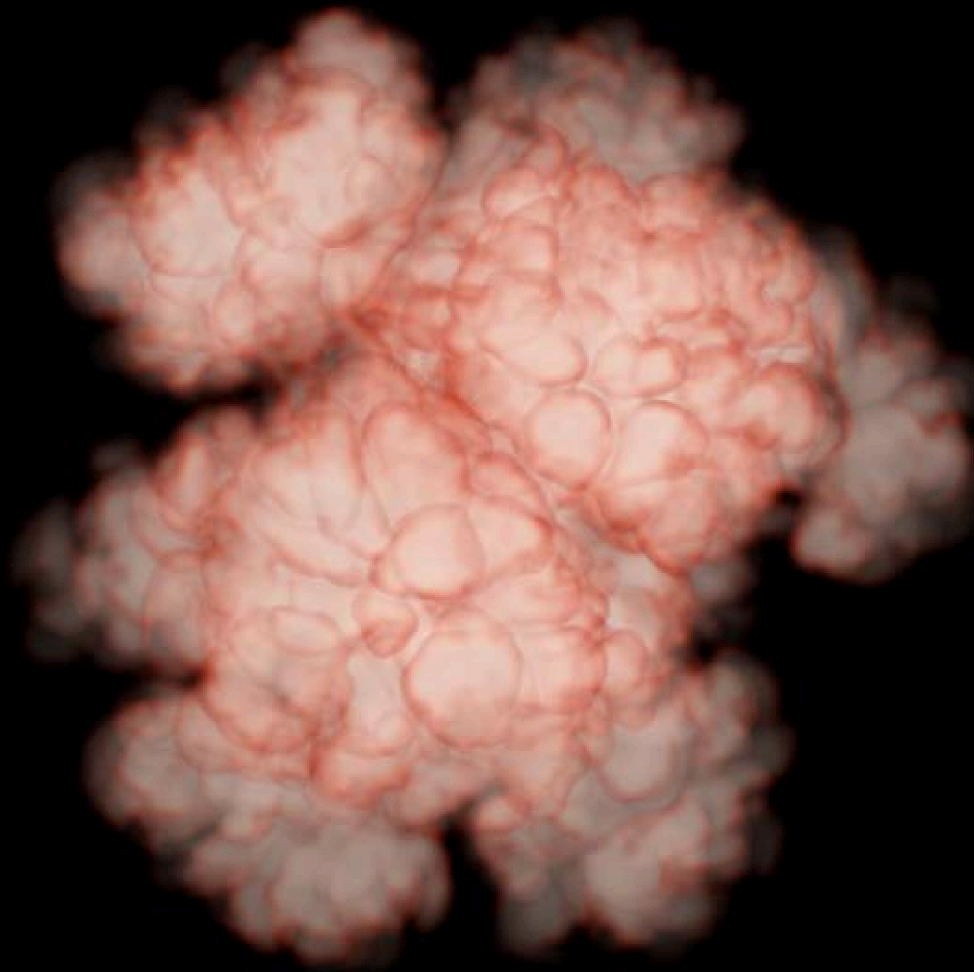
3D 4π: 256^3

EXPLOSION? NO REMNANT?



3D 4π: 512^3

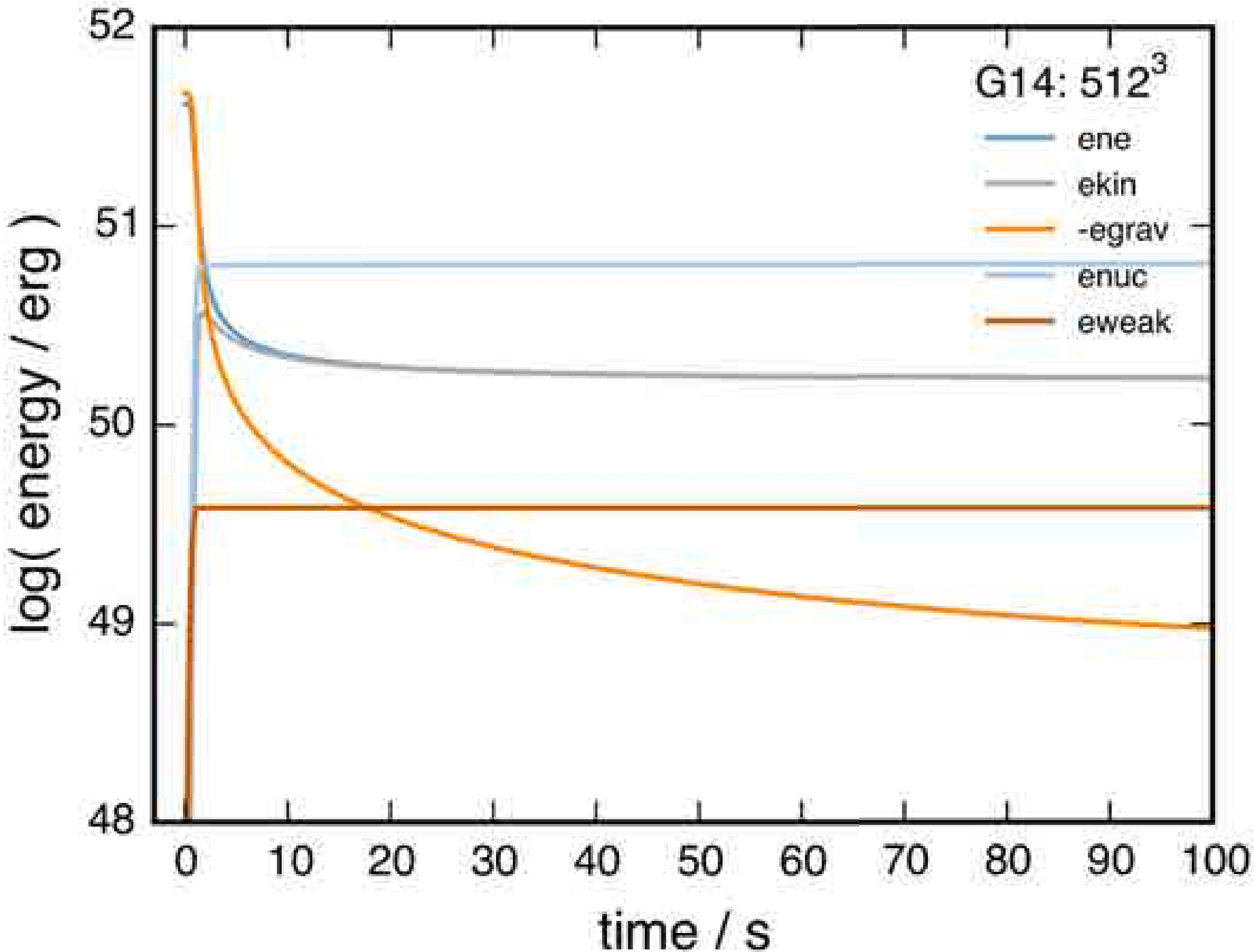
FLAME SURFACE



scale: 1.71E+04 km time: 1.50E+00 s

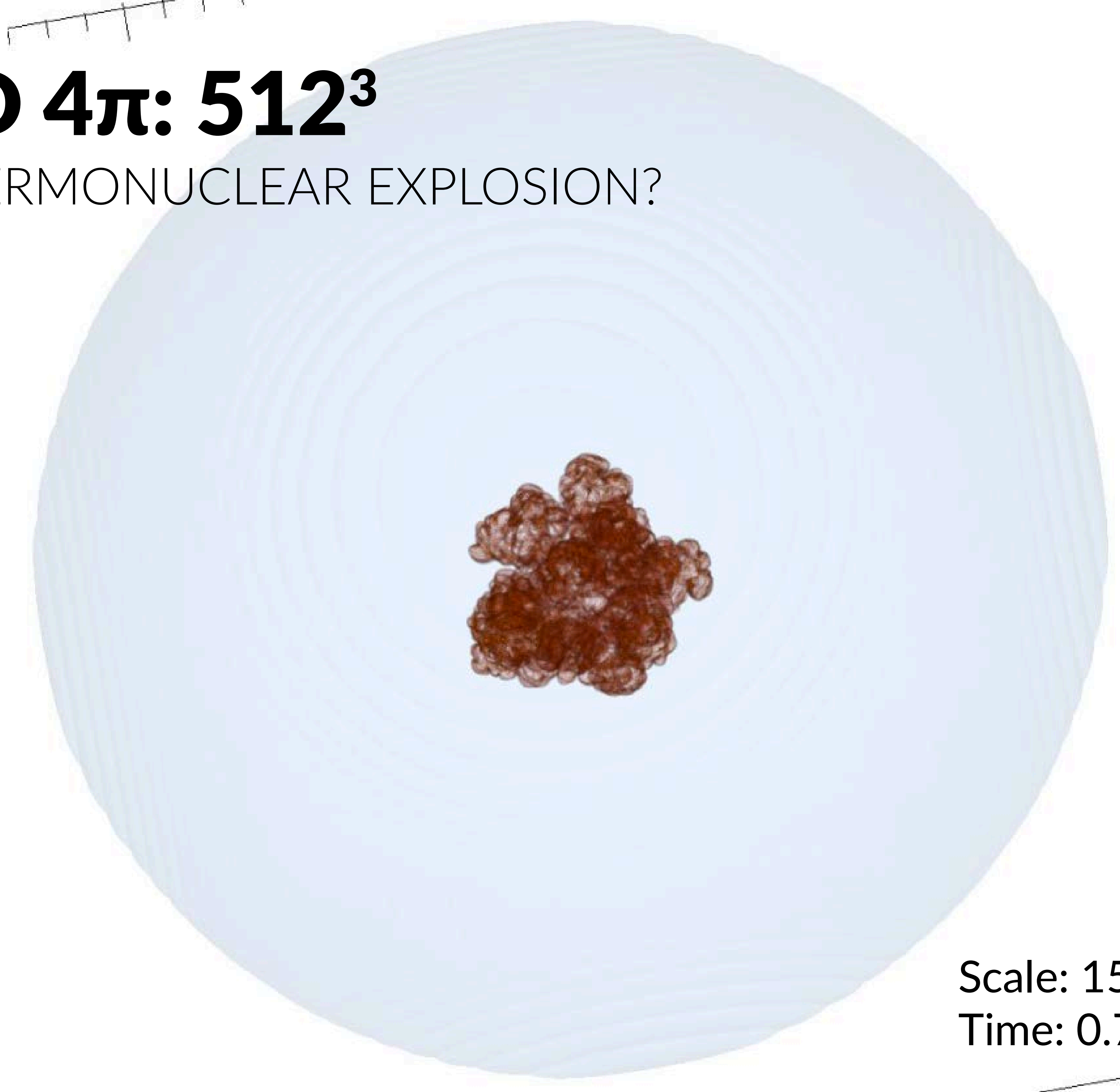
3D 4π: 512^3

EXPLOSION? NO REMNANT?



3D 4π: 512^3

THERMONUCLEAR EXPLOSION?



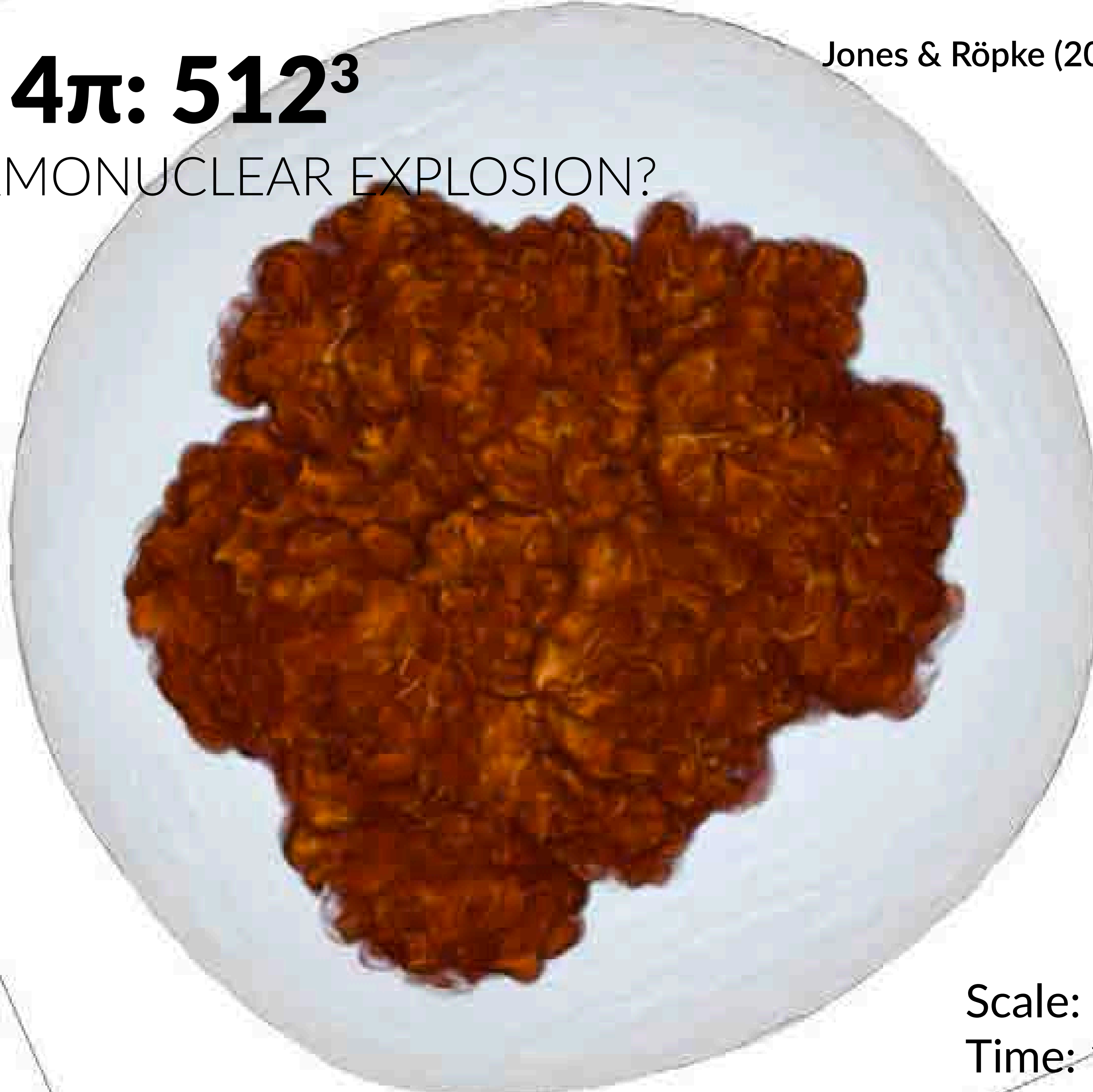
^{56}Ni

Scale: 1500 km
Time: 0.7 s

3D 4π: 512^3

THERMONUCLEAR EXPLOSION?

Jones & Röpke (2016, in prep)



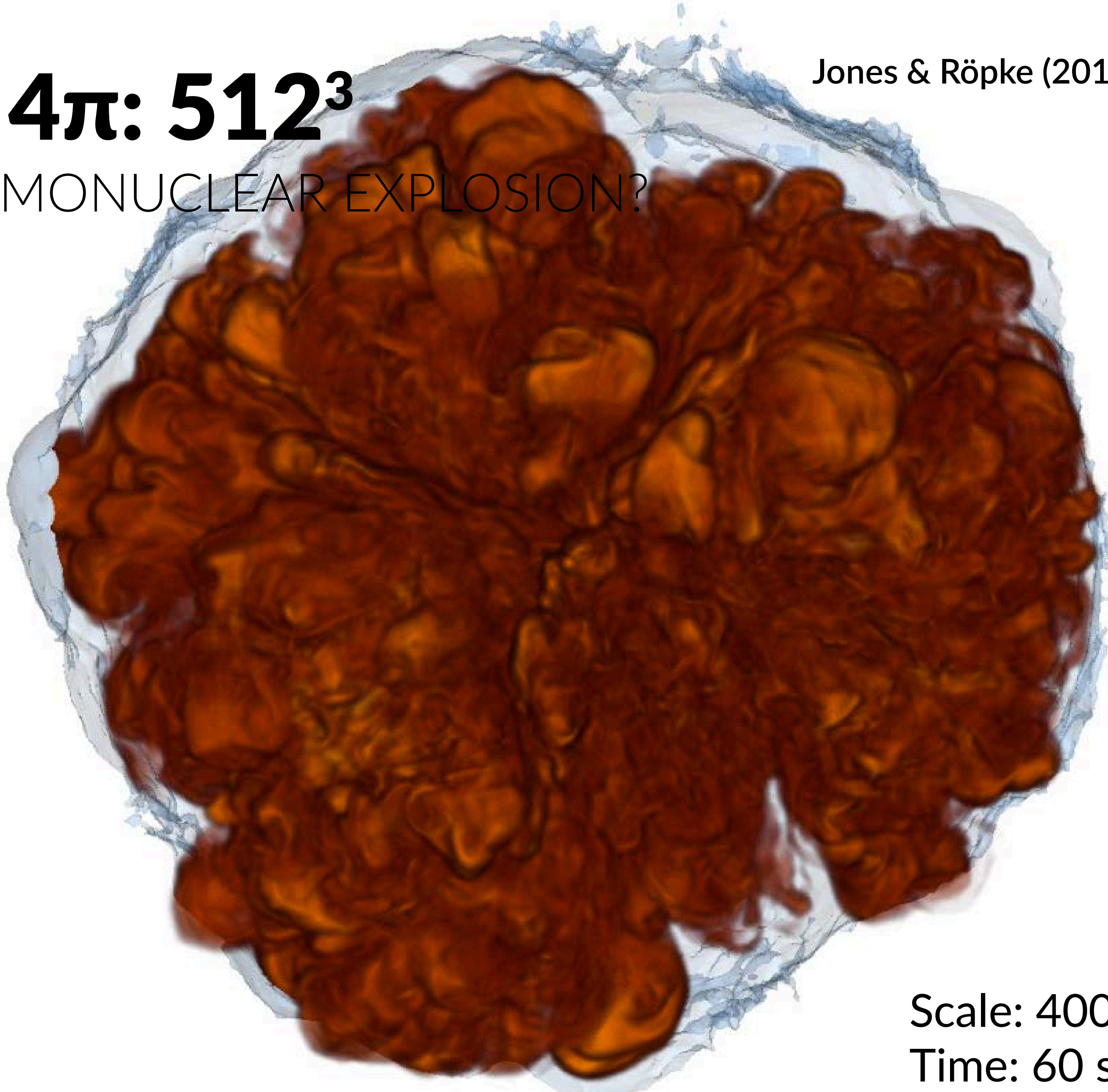
^{56}Ni

Scale: 2500 km
Time: 1.3 s

3D 4π: 512^3

THERMONUCLEAR EXPLOSION?

Jones & Röpke (2016, in prep)



^{56}Ni

Scale: 400,000 km
Time: 60 s

Jones & Röpke (2016, in prep)

DIAGNOSTICS

PRELIMINARY RESULTS

Bound ONeFe WD remnants?

id.	res.	$\log_{10}(\rho_c^{ini})$ (g cm^{-3})	CC (Y/N)	M_{rem}	M_{rem}^{Ni} ($M_\odot$)	M_{ej}	M_{ej}^{Ni}	$\langle Y_{e,rem} \rangle$	M_{Ch}^{eff}
G13	256^3	9.90	N	0.653	0.168	0.735	0.236	0.491	1.385
G14	512^3	9.90	N	0.462	0.137	0.929	0.349	0.490	1.379
G15	256^3	9.90	Y	1.231	0.217	0.158	0.044	0.493	1.392
J01	256^3	9.95	N	0.606	0.157	0.798	0.254	0.490	1.378
J02	256^3	9.95	Y	1.297	0.227	0.100	0.021	0.493	1.392
J03	512^3	9.95	Y						

Table 1. Summary of the 3D O-deflagration simulations. [a] initial central density of ONe core at ignition of O-deflagration.

Coulomb Corrections are critical input

Remarkably similar result to Isern+ (1991)

SUMMARY

The final fate and chemical yield from 8-10 solar-mass stars is still unclear

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

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

In recent 2-3 years we have refined:

- Nuclear physics input
- Progenitor models
- Deflagration simulations

I declare the question of whether 8-10 solar-mass stars and AIC of ONe WDs make core-collapse or thermonuclear supernovae to be reopened