Nuclear Data for Astrophysics

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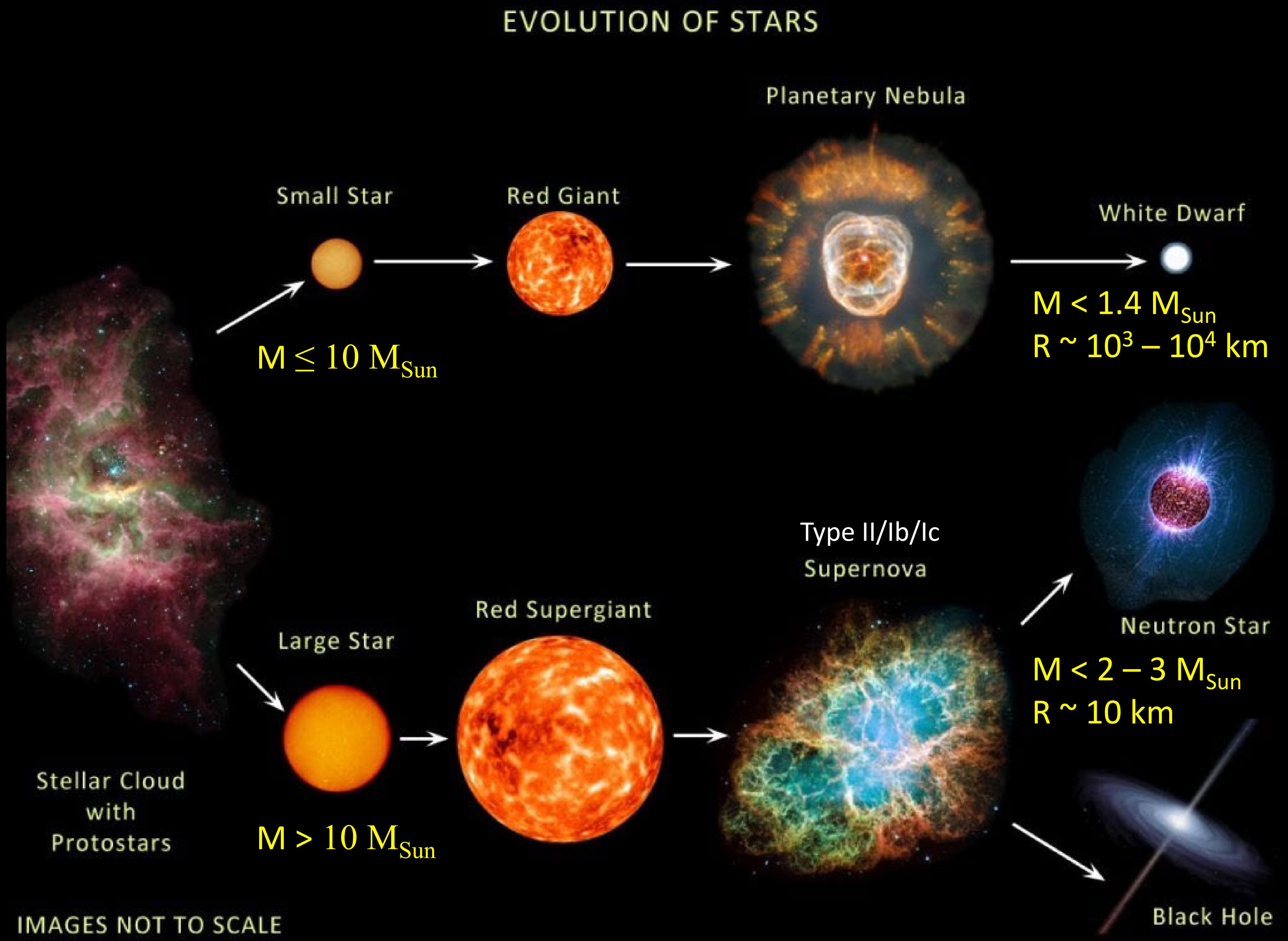
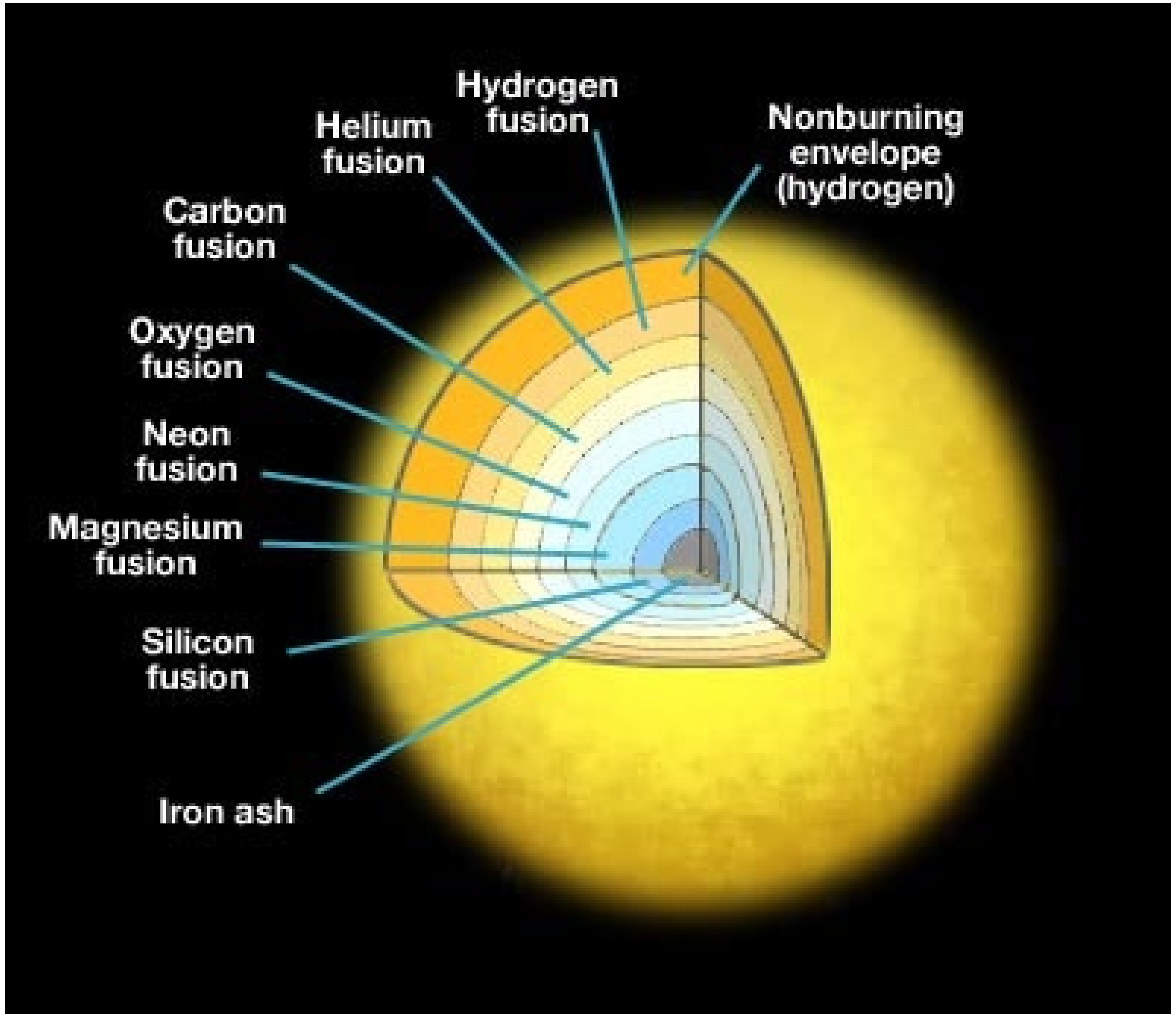

EVOLUTION OF STARS
Small Star
Red Giant
Planetary Nebula
White Dwarf
M ≤ 10 M_Sun
M < 1.4 M_Sun
R ~ 10^3 – 10^4 km
Type II/Ib/Ic
Supernova
Red Supergiant
Large Star
Neutron Star
M < 2 – 3 M_Sun
R ~ 10 km
Stellar Cloud
with
Protostars
M > 10 M_Sun
Black Hole
IMAGES NOT TO SCALE



Intermediate-mass elements (e.g., up to **Fe**) are synthesized in different (central) fusion episodes during the (normal) life of stars, beginning with **H-fusion**, and continuing with (for high-enough M_{star}) **He-**, **C-**, **Ne-**, **O-**, and **Si-fusion**

Main uncertainties (to be reduced in the next Decade)

H-burning (fusion): $^{14}N(p, \gamma)^{15}O$ (the slowest CNO cycle reaction; uncertainty affects age determination of globular clusters and stellar evolution timescales), **$^{3}He(^{3}He, 2p)^{4}He$** and **$^{3}He(\alpha, \gamma)^{7}Be$** (Influence branching within the pp-chain → important for solar neutrino predictions; **$^{3}He(\alpha, \gamma)^{7}Be$** also important for ^{7}Li synthesis in classical novae)

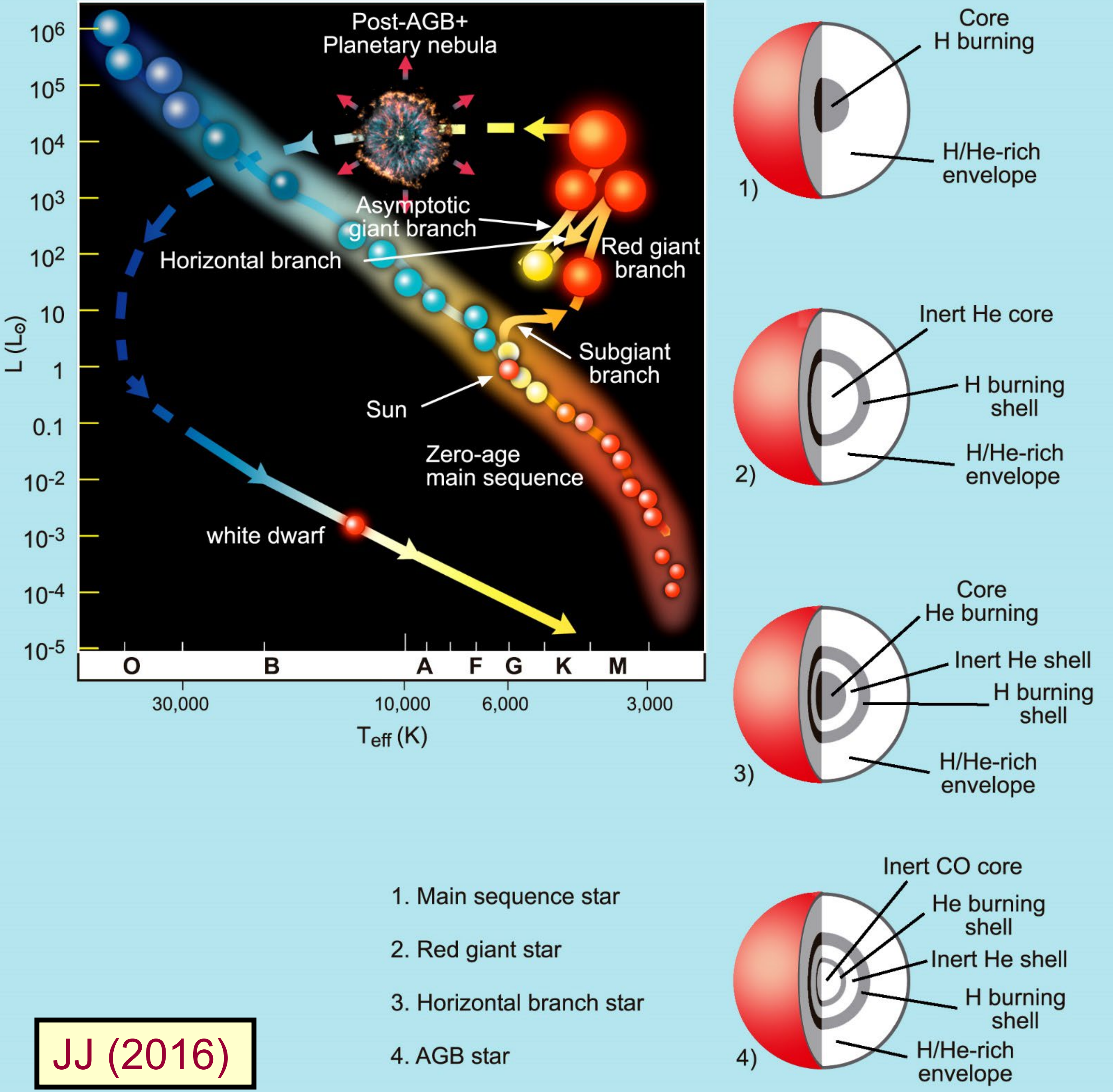
He-burning: $^{12}C(\alpha, \gamma)^{16}O$ (determines the C/O ratio in stellar cores; strongly impacts white dwarf composition → SN Ia explosions; also, later stages of stellar evolution), **$^{13}C(\alpha, n)^{16}O$** (neutron source for the main s-process in AGB stars [He-shell burning]), **$^{22}Ne(\alpha, n)^{25}Mg$** (neutron source for the weak s-process in massive stars, during core He-burning and C-shell burning)

C-burning: $^{12}C + ^{12}C$ (small cross section at low E, with possible resonances → need to extrapolate down to Gamow window; uncertainty affects SNIa, superbursts…)

Ne-burning: $^{20}Ne(\gamma, \alpha)^{16}O$

O-burning: $^{16}O + ^{16}O$ (small cross section at low E, with possible resonances → need to extrapolate down to Gamow window; uncertainty affects pre-SN II core composition)

Si-burning: uncertainty affects **(α, γ), (p,γ)** and **(n,γ) rates near the Fe group, weak interaction rates** (e.g., electron captures on Fe-group nuclei) → These affect the electron fraction and mass of the iron core in massive stars, which ultimately influence the core collapse)



JJ (2016)

1 – 8 M_{sun} stars during the AGB stage are the site of the **Main s-process** (sources of heavy elements, such as Sr, Pb, or Bi)

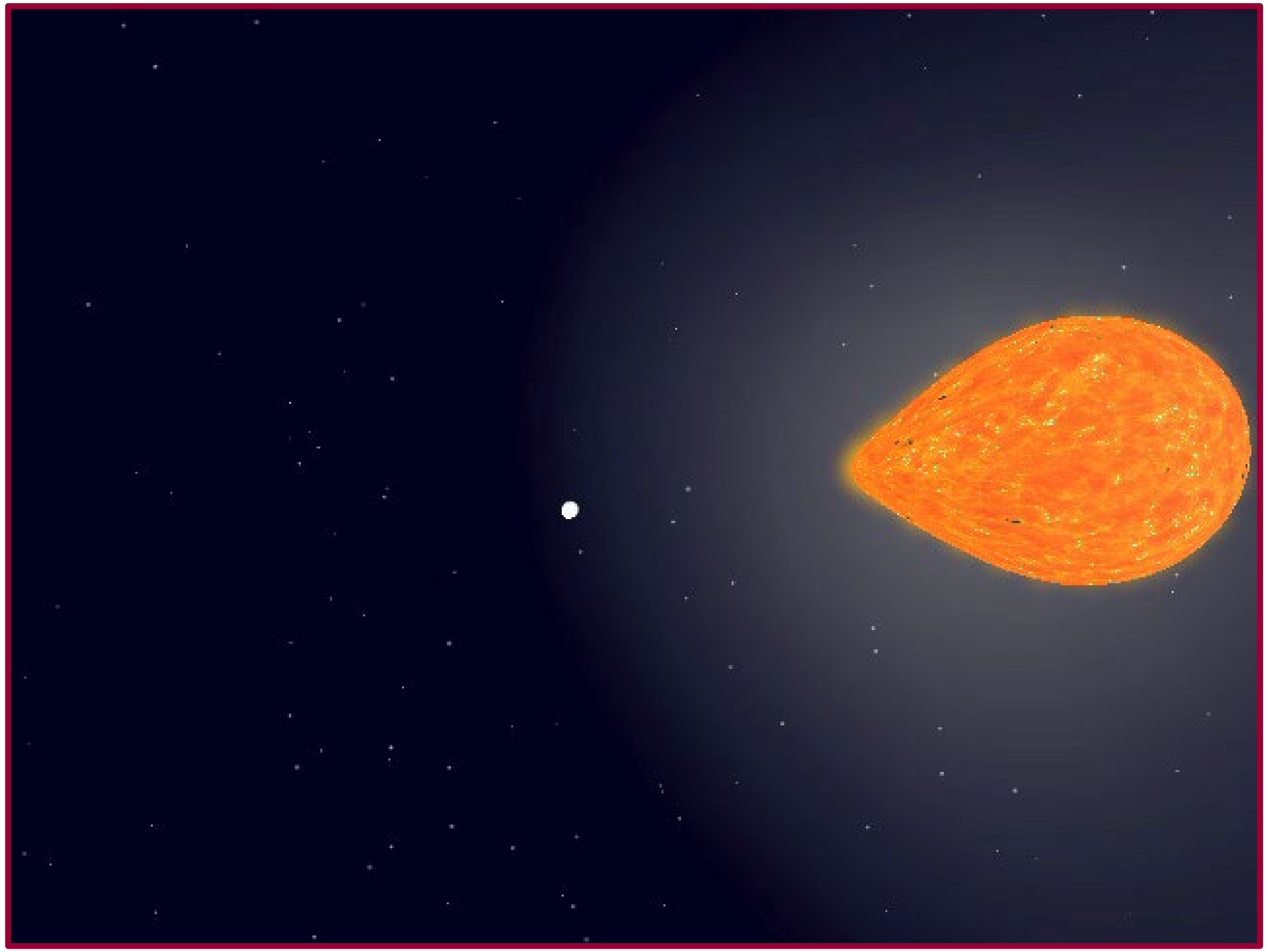
Stars with M > 8 M_{sun} produce lighther species (up to Sr, Y, Zr) through the **weak s-process**

[**Low mass, low metallicity AGB stars** are also a likely site for the **i-process** (for which other sites, including super-AGBs and rapidly accretting WDs, have been proposed)]

Main uncertainties

s-process: neutron-capture rates on isotopes at branching points where β-decay and neutron capture compete → many branching isotopes are short lived and cross sections must often be theoretically estimated

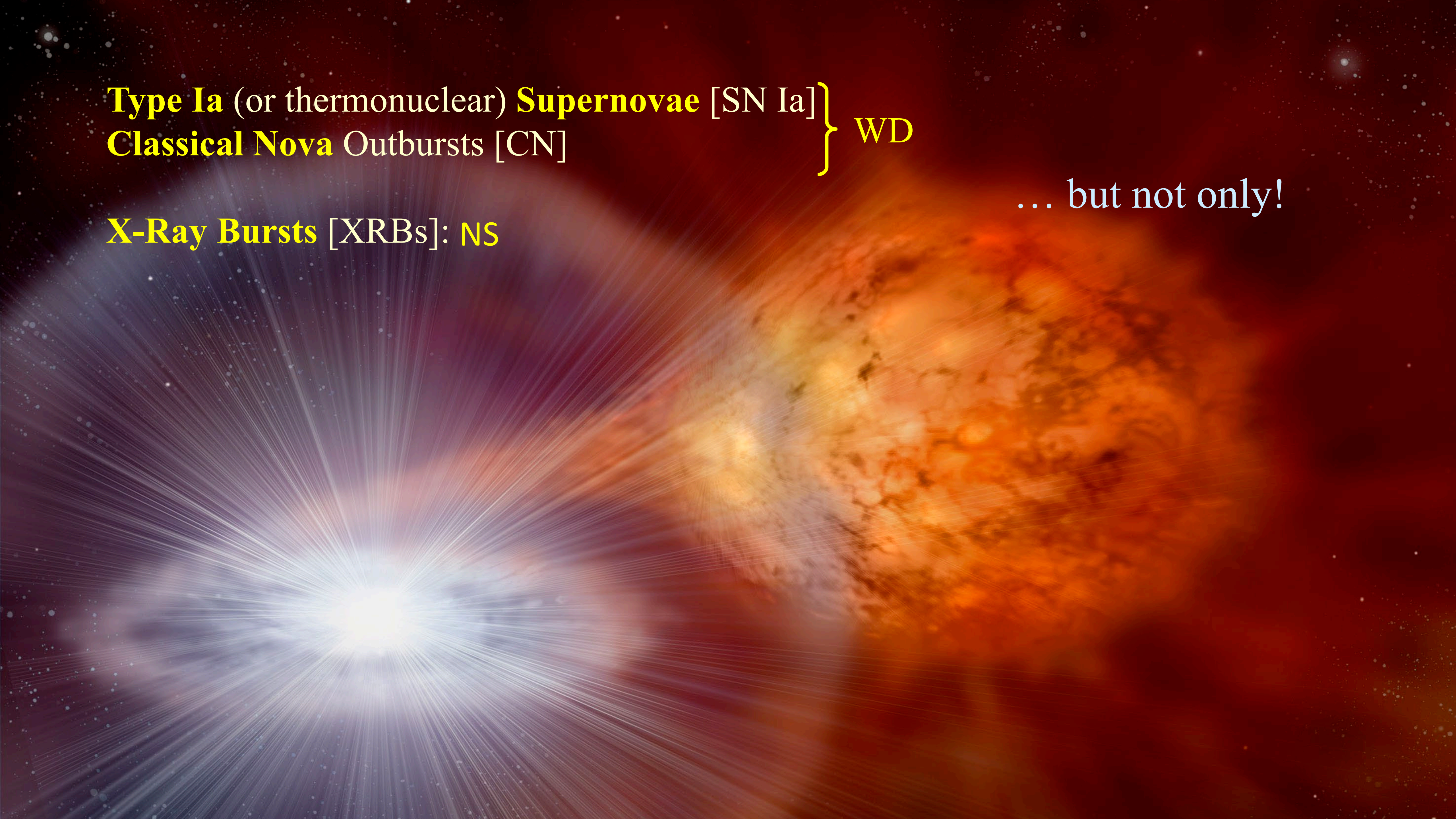
About a third (or a half) of the stars of our Galaxy form double or multiple systems, a fraction of which evolves into a close binary system containing a white dwarf and/or a neutron star



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

X-Ray Bursts [XRBs]: NS

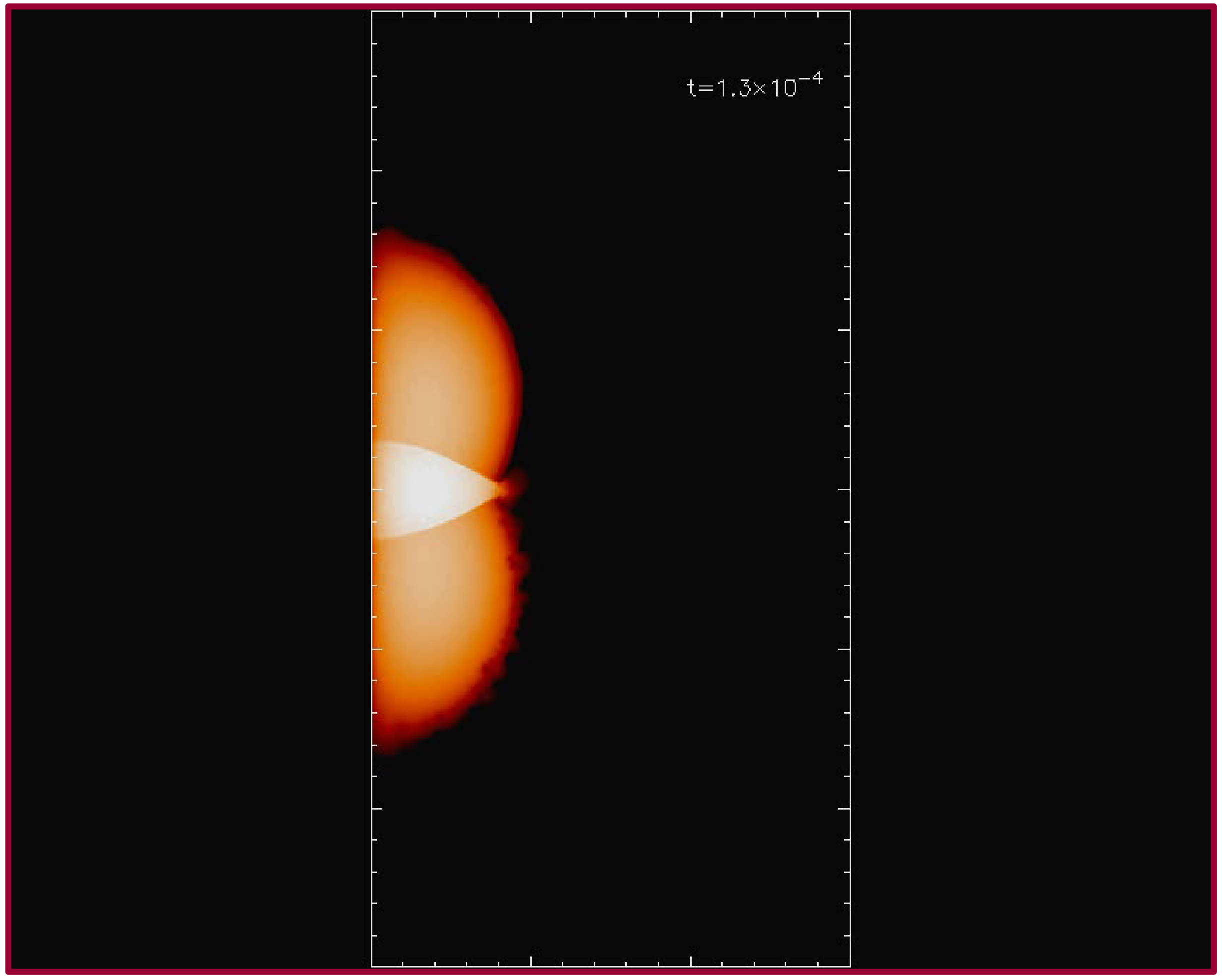
… but not only!



Stellar Mergers and Collisions

+ Kilonovae (eg., AT 2017gfo/GW170817)

r-process: **NS mergers** vs.
core-collapse SN

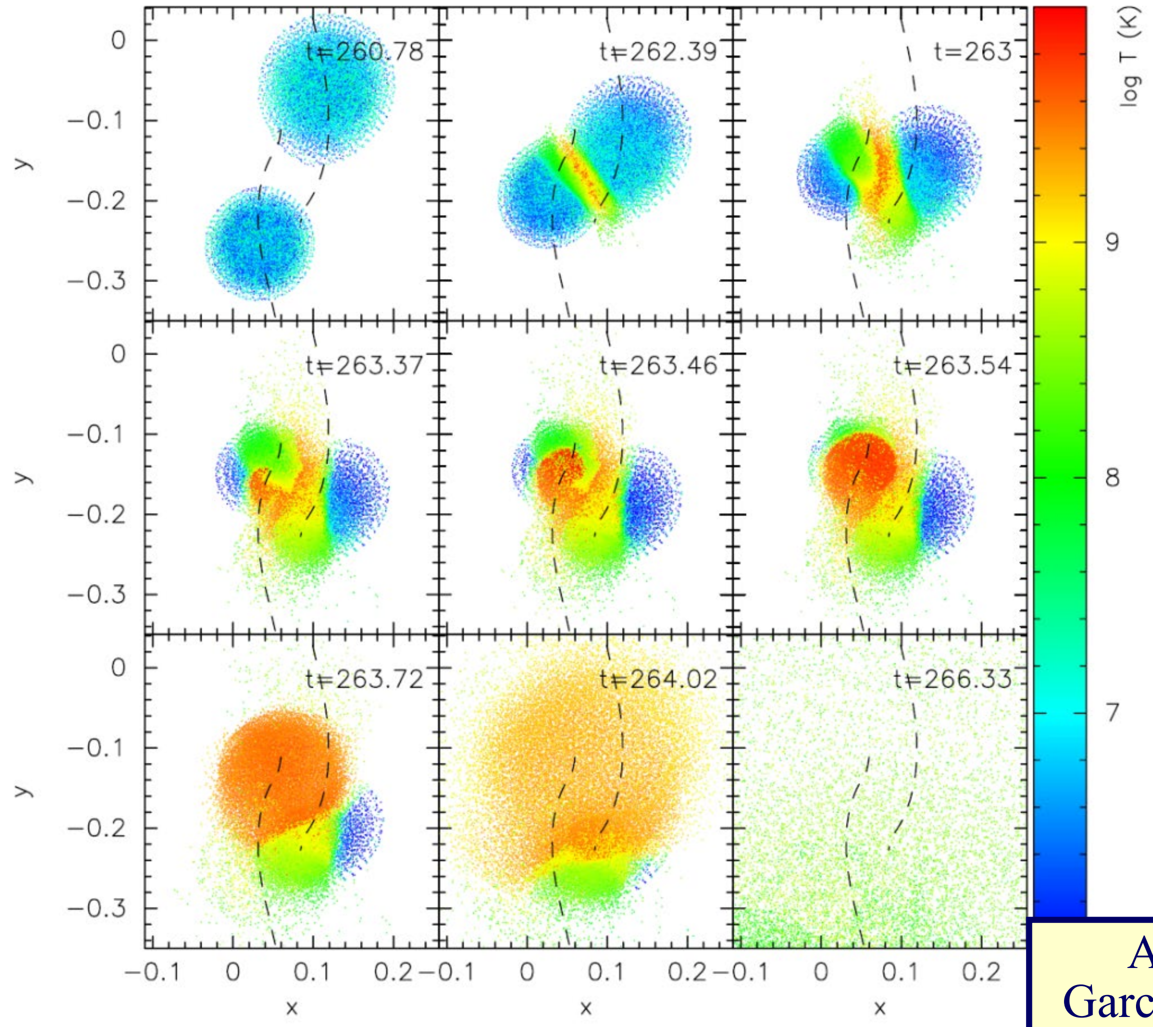


Head-on collision of two neutron stars
(R. Cabezón, D. García-Senz et al., UPC Barcelona)

Main uncertainties

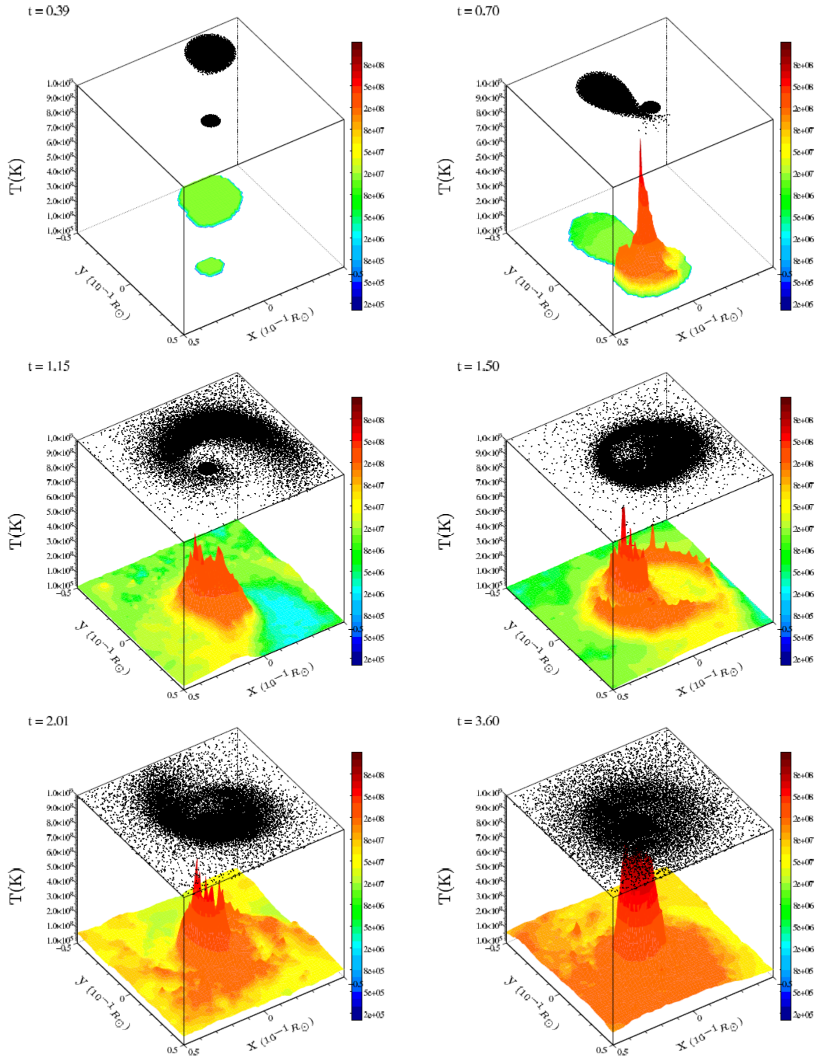
r-process: poorly known nuclear properties of extremely neutron-rich nuclei far from stability. The r-process path runs through nuclei that are not experimentally accessible, so most reaction rates rely on theoretical models.

Key nuclear data that dominate the uncertainty: Nuclear masses (even small mass uncertainties can shift the path to different isotopes and change predicted abundances); β-decay half-lives (how quickly matter moves toward heavier elements; particularly important at waiting-point nuclei near closed neutron shells); neutron-capture rates (mostly derived from Hauser–Feshbach statistical models, with uncertainties of factor ~2–10 for exotic nuclei); fission properties (for very heavy nuclei; important for fission cycling in neutron star mergers)



frequency ~ f(type Ia SNe)

Aznar-Siguán, García-Berro, Lorén-Aguilar, JJ & Isern, MNRAS (2013)



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

A Primer on Stellar Models – Atomic and Nuclear Inputs

The core of a stellar evolution code is a set of differential equations:

- Conservation of Mass

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

- Conservation of Momentum

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

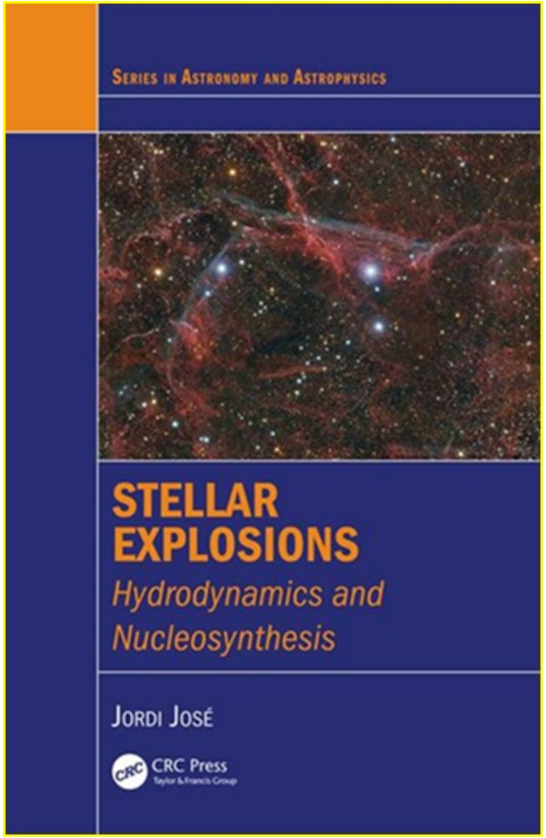
- Conservation of Energy

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

- Energy transport
 (radiation, convection, conduction)

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

- Time-evolution of the chemical composition



The set of differential eqs is linked to the constitutive eqs:

- Pressure and internal energy: $P = P(T, \rho, X)$, $E = E(T, \rho, X)$
- Opacity: $\kappa = \kappa(T, \rho, X)$
- Nuclear energy generation and neutrino losses: $\varepsilon = \varepsilon(T, \rho, X)$

EoS

Intermediate Densities ($\rho \leq 10^8$ g/cm³)

- EoS is **well constrained (1 – 5%)**
- EoS dominated by the electron degenerate (Fermi) pressure and a Coulomb plasma of ions
- Main uncertainty (small): Coulomb interactions in dense plasmas; ion crystallization and lattice corrections; composition uncertainty
- Regime accessible experimentally, with direct laboratory tests of dense plasma physics, condensed matter, and Fermi gas thermodynamics
- EoS is fully calculable (theoretically) from quantum statistical mechanics
- Conditions achieved in white dwarf interiors (+ pre-explosion stages of SNIa progenitors), outer crust of neutron stars, late stages of stellar evolution in degenerate cores

Astrophysical scenarios: **isolated WDs** (cooling and crystallization), **Novae, WD mergers, WD+MS collisions, XRBs***

Intermediate/High Density ($\rho \sim 10^{10}$ g/cm³)

•EoS is **reasonably well constrained (5 – 10%)**
•EoS still dominated by the electron degenerate (Fermi) pressure; Coulomb plasma of ions; possibly beginning neutron drip ($\sim 4\times10^{11}$ g cm^{-3})
•Main uncertainty: nuclear masses of extremely neutron-rich isotopes, neutron drip threshold, nuclear shell effects far from stability
•Regime accessible experimentally for some rare isotopes: nuclear mass measurements, and β-decay measurements of neutron-rich nuclei
•EoS is approximately calculable (theoretically) from quantum statistical mechanics; masses of neutron-rich nuclei near neutron drip line, and improved nuclear density functionals needed
•Conditions achieved in white dwarf interiors, outer crust of neutron stars, accreting neutron stars, central regions of massive stars

Astrophysical scenarios: **isolated massive WDs** (cooling and crystallization), **WD mergers, SNIa, NS formation by AIC, XRBs***

Below 10^{11} g/cm^3 pressure is controlled mainly by electrons and electromagnetic forces; above this density, however, the strong force (more uncertain) begins to dominate

Nuclear saturation density (~ 2 × 10^{14} g/cm^3)

•EoS becomes **quite uncertain (30 – 50%)**
•Matter transitions to uniform nuclear matter, with mostly neutrons; Pressure depends strongly on nuclear incompressibility, symmetry energy, three-nucleon forces
•Main uncertainty: Three-body nuclear forces, density dependence of the symmetry energy, many-body nuclear correlations
•Experimental constraints: Heavy ion collisions (probe densities up to roughly 1–3 ρ_0), nuclear structure (neutron skins, giant monopole resonances); astrophysical constraints (neutron star mass–radius measurements, gravitational wave measurements [e.g., GW170817, tidal deformability from NS mergers], NS maximum masses…)

•Theoretically, EoS is moderately known near ρ_0, but rapidly worsening above it. Best microscopic theory: chiral effective field theory (reliable up to 1–2 ρ_0). Improvements needed: better understanding of three-nucleon forces, higher-order chiral EFT calculations, more precise heavy-ion constraints, more NS observations

•Conditions achieved in central regions (core) of neutron stars, plasma before black hole formation

Astrophysical scenarios: **NSs, WD+NS and NS+NS mergers (kilonovae), XRBs***

Opacities (relevant for energy transport)

Stellar opacities are geerally known to about **5–10% accuracy in hot stellar interiors**, but uncertainties can be larger in:

•Regions dominated by heavy-element line transitions (especially Fe)

•Cool, molecule-rich stellar atmospheres

The **main source of uncertainty** is incomplete (inaccurate) atomic data for heavy elements (especially Fe-group), including line transitions and line broadening in dense plasmas.

Solar-type stars: For temperatures 10^6–10^7 K and densities typical of stellar interiors, opacity calculations (e.g., OPAL and OP) are thought to be relatively accurate (5 to 10%)

Cool stars (outer envelopes): For T $\lesssim 10^4$ K opacity becomes much more uncertain due to formation of molecules, dust grains, and complex chemistry, in general
→ expected 10%–30% uncertaintry in brown dwarfs, M dwarfs, RG stars…

Massive stars: For T $\gtrsim 10^7$ K, opacity is dominated by electron scattering (well known), and bound–free and free–free processes (uncertainty ~few percent, except near the Fe opacity bump [at about 200 000 K], where detailed atomic structure matters

In **white dwarf envelopes** and **neutron star atmospheres** opacity calculations are more uncertain because plasma effects are strong, pressure ionization matters and non-ideal EoS effects appear

Experiments at Sandia National Laboratories have measured Fe opacities under near-solar-interior conditions and found values **higher than predicted by models** → theoretical opacities may be underestimated in some T – ρ regions

LETTER

doi:10.1038/nature14048

A higher-than-predicted measurement of iron opacity at solar interior temperatures

J. E. Bailey[1], T. Nagayama[1], G. P. Loisel[1], G. A. Rochau[1], C. Blancard[2], J. Colgan[3], Ph. Cosse[2], G. Faussurier[2], C. J. Fontes[3], F. Gilleron[2], I. Golovkin[4], S. B. Hansen[1], C. A. Iglesias[5], D. P. Kilcrease[3], J. J. MacFarlane[4], R. C. Mancini[6], S. N. Nahar[7], C. Orban[7], J.-C. Pain[2], A. K. Pradhan[7], M. Sherrill[3] & B. G. Wilson[5]

Nature (2015)

ARTICLES

Astrophysical Opacity

Forrest J. Rogers and Carlos A. Iglesias

Science (1996)

Rogers and Iglesias OPAL opacities work well for the Sun and "normal stars" → but (heavy) extrapolation is needed to handle more evolved stars (e.g., novae, XRBs…), with high metallicity

The Realm of Nuclear Reaction Networks

Sensitivity studies

Reduced vs. extended networks (energetics vs nucleosynthesis)

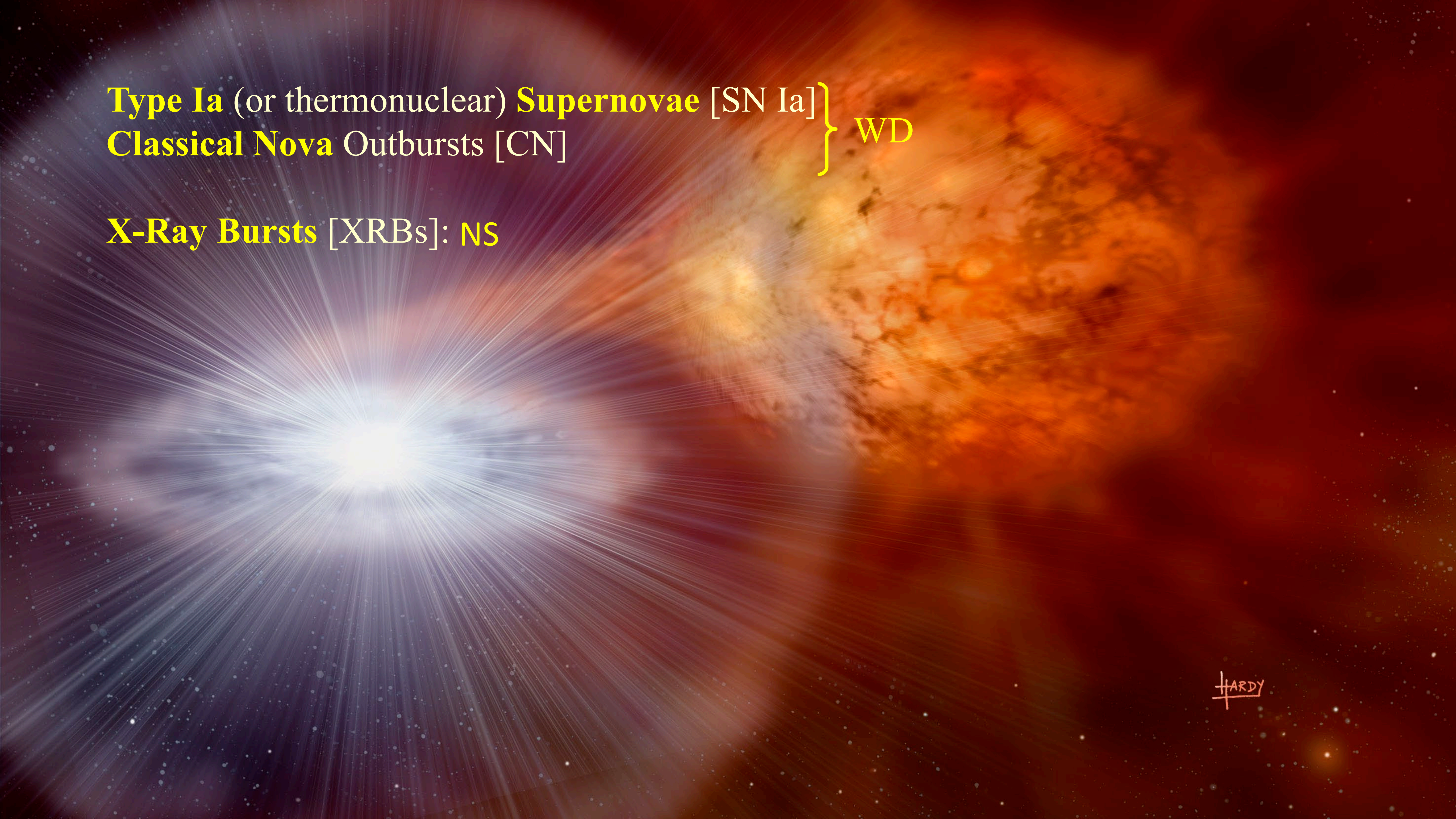
Accuracy: Case by case scenario – BBN requires rates with a 1% accuracy;
classical novae about 20% accuracy

Different nuclear regimes, with n-, p-, α-captures, β-decays, fission…
and different endpoints

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

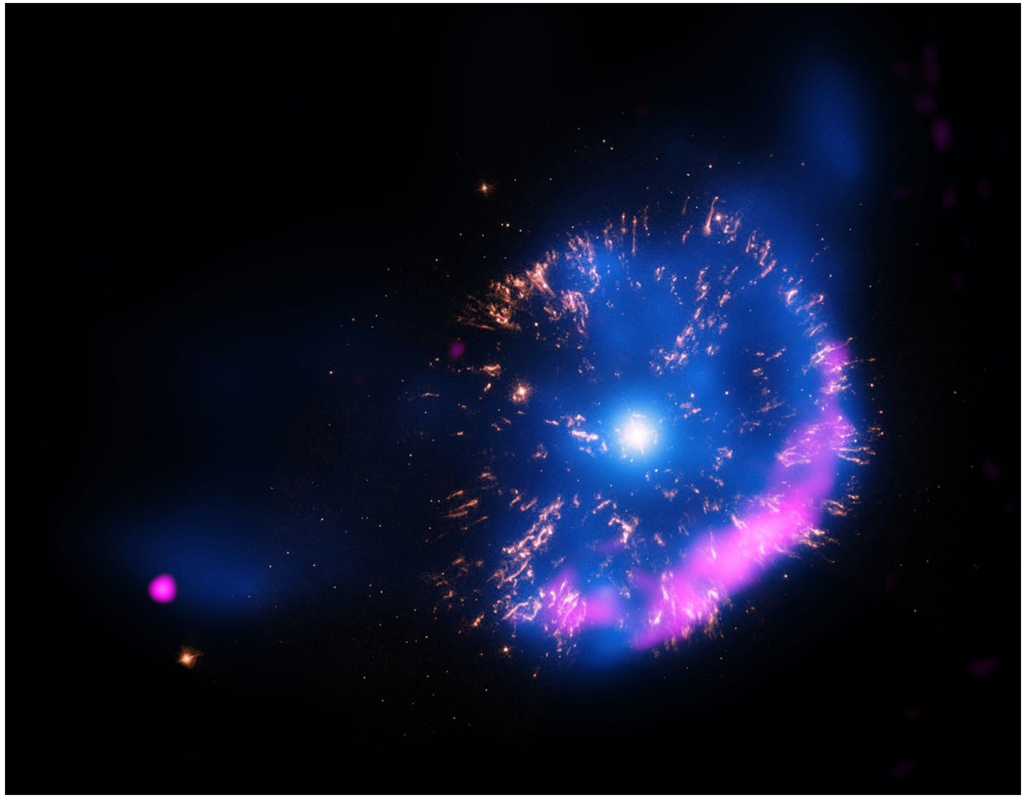
} WD

X-Ray Bursts [XRBs]: NS



Classical and Recurrent Novae

Main nuclear path: p-capture reactions and β^+ decays, close to the valley of stability, up to Ca



GK Persei (1901)

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 142:105–137, 2002 September

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

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Received 2002 January 19; accepted 2002 April 25

$\approx$7350 nuclear reaction network calculations

TABLE 12
INFLUENCE OF REACTION-RATE VARIATIONS ON ISOTOPIC ABUNDANCES IN NOVA NUCLEOSYNTHESIS[a]

Reaction-Rate Variation[b]	Isotopic Abundance Change[c]
CO Nova Models	
$^{17}O(p,\gamma)^{18}F$	^{18}F
$^{17}O(p,\alpha)^{14}N$	^{17}O, ^{18}F
$^{18}F(p,\alpha)^{15}O$	^{18}F
$^{22}Ne(p,\gamma)^{23}Na$	^{22}Ne, ^{23}Na, ^{24}Mg, ^{25}Mg, ^{26}Al
$^{23}Na(p,\gamma)^{24}Mg$	^{24}Mg
$^{26}Mg(p,\gamma)^{27}Al$	^{26}Mg
$^{26}Al^{g}(p,\gamma)^{27}Si$	^{26}Al
ONe Nova Models	
$^{17}O(p,\gamma)^{18}F$	^{17}O, ^{18}F
$^{17}O(p,\alpha)^{14}N$	^{17}O, ^{18}F
$^{17}F(p,\gamma)^{18}Ne$	^{17}O, ^{18}F
$^{18}F(p,\alpha)^{15}O$	^{16}O, ^{17}O, ^{18}F
$^{21}Na(p,\gamma)^{22}Mg$	^{21}Ne, ^{22}Na, ^{22}Ne
$^{22}Ne(p,\gamma)^{23}Na$	^{22}Ne
$^{23}Na(p,\gamma)^{24}Mg$	^{20}Ne, ^{21}Ne, ^{22}Na, ^{23}Na, ^{24}Mg, ^{25}Mg, ^{26}Mg, ^{26}Al, ^{27}Al
$^{23}Mg(p,\gamma)^{24}Al$	^{20}Ne, ^{21}Ne, ^{22}Na, ^{23}Na, ^{24}Mg
$^{26}Mg(p,\gamma)^{27}Al$	^{26}Mg
$^{26}Al^{g}(p,\gamma)^{27}Si$	^{26}Al
$^{26}Al^{m}(p,\gamma)^{27}Si$	^{26}Mg
$^{29}Si(p,\gamma)^{30}P$	^{29}Si
$^{30}P(p,\gamma)^{31}S$	^{30}Si, ^{32}S, ^{33}S, ^{34}S, ^{35}Cl, ^{37}Cl, ^{36}Ar, ^{37}Ar, ^{38}Ar
$^{33}S(p,\gamma)^{34}Cl$	^{33}S, ^{34}S, ^{35}Cl, ^{36}Ar
$^{33}Cl(p,\gamma)^{34}Ar$	^{33}S
$^{34}S(p,\gamma)^{35}Cl$	^{34}S, ^{35}Cl, ^{36}Ar
$^{34}Cl(p,\gamma)^{35}Ar$	^{34}S
$^{37}Ar(p,\gamma)^{38}K$	^{37}Cl, ^{37}Ar, ^{38}Ar
$^{38}K(p,\gamma)^{39}Ca$	^{38}Ar

Main nuclear uncertainties (remaining)

$^{18}F(p,\alpha)^{15}O$, $^{25}Al(p,\gamma)^{26}Si$, $^{30}P(p,\gamma)^{31}S$

$^{18}F(p,\alpha)^{15}O$

spins, and parities of the relevant, low-energy levels at E_r(c.m.) = –121 keV, 8 keV, and 38 keV are yet not unambiguously determined and need to be confirmed experimentally.

Depending on the actual choice of spins and parities for the subthreshold resonance at –121 keV and for the 38 keV one, interference between the tails of these broad resonances and the one at 665 keV may play an important role → large **uncertainty** (by a factor ~ **50**) in the overall reaction rate

$^{18}F(p,\alpha)^{15}O$

VAMOS

From Coc & de Séréville (June 2017)

THE ASTROPHYSICAL JOURNAL, 846:65 (6pp), 2017 September 1
https://doi.org/10.3847/1538-4357/aa845f

CrossMark

A Trojan Horse Approach to the Production of ^{18}F in Novae

M. La Cognata[1], R. G. Pizzone[1], J. José[2,3], M. Hernanz[3,4], S. Cherubini[1,5], M. Gulino[1,6], G. G. Rapisarda[1,5], and C. Spitaleri[1,5]

PHYSICAL REVIEW C 96, 055806 (2017)

Eur. Phys.
DOI 10.114

Letter

s-wave

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A&A 653, A64 (2021)
https://doi.org/10.1051/0004-6361/202140339

Astronomy & Astrophysics

Uncertainties in the $^{18}F(p,\alpha)^{15}O$ reaction rate in classical novae

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^{25}Al(p,γ)^{26}Si

uncertainty due to the lack of spectroscopic information (i.e., spins and parities) for some of the levels of interest in the range E_r(c.m.) = 163 – 965 keV. The estimated **uncertainty** amounts to a factor of **~ 2**

^{30}P(p,γ)^{31}S

lack of detailed spectroscopic information on spins and parities for relevant ^{31}S states (within ~ 600 keV of the ^{30}P+p threshold in **31**S). This results in a factor of **20** uncertainty in the ^{30}P(p, γ) rate that, coupled to the lack of information on spectroscopic factors, translates into a huge **uncertainty** (maybe by a factor of **100** or more) on the overall rate

Type I (Normal) X-Ray Bursts

Main nuclear path: the *rp-process* (rapid p-captures and β^+-decays), the 3α-reaction, and the *αp-process* (a sequence of (α,p) and (p,γ) reactions), away from the valley of stability, merging with the proton drip-line beyond A = 38

Star Trek – The Next Generation (1987 - 1994)

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 178:110–136, 2008 September

THE EFFECTS OF VARIATIONS IN NUCLEAR PROCESSES ON TYPE I X-RAY BURST NUCLEOSYNTHESIS

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~ **50,000** post-processing calculations [21 CPU months!]

606 isotopes (**^{1}H** to **^{113}Xe**) and **3551** nuclear processes

TABLE 19

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

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

TABLE 20

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

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

Parikh et al. (2008)

PHYSICAL REVIEW C **79**, 045802 (2009)

Impact of uncertainties in reaction Q values on nucleosynthesis in type I x-ray bursts

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TABLE IV. Summary of reactions whose ΔQ significantly affect XRB nucleosynthesis in our models. These are the only reactions with $Q < 1$ MeV that modify the final XRB yield of at least one isotope by at least a factor of two in at least one model, when their nominal Q-values are varied by $\pm\Delta Q$. ΔQ for the ^{64}Ge$(p,\gamma)^{65}$As reaction affects by far the most final XRB yields (see Table III) in the most models. All Q-values and ΔQ are from [55]; only $Q(^{30}\mathrm{S}(p,\gamma)^{31}\mathrm{Cl})$ and $Q(^{60}\mathrm{Zn}(p,\gamma)^{61}\mathrm{Ga})$ are experimental (the others have been estimated from systematic trends).

Reaction	$Q \pm \Delta Q$ (keV)	Model affected
^{25}Si$(p,\gamma)^{26}$P	140 ± 196	short
^{26}P$(p,\gamma)^{27}$S	719 ± 281	K04, low$Z$,[a] short
^{30}S$(p,\gamma)^{31}$Cl	294 ± 50	hi$T$, short
^{42}Ti$(p,\gamma)^{43}$V	192 ± 233	S01, low$T$, low$Z$, short
^{45}Cr$(p,\gamma)^{46}$Mn	694 ± 515	F08
^{46}Cr$(p,\gamma)^{47}$Mn	78 ± 160	K04, low$T$, hi$T$, low$Z$, short
^{50}Fe$(p,\gamma)^{51}$Co	88 ± 161	short
^{55}Ni$(p,\gamma)^{56}$Cu	555 ± 140	K04, low$T$, low$Z$, short
^{60}Zn$(p,\gamma)^{61}$Ga	192 ± 54	K04, low$T$, hi$T$,[a] low$Z$
^{64}Ge$(p,\gamma)^{65}$As	-80 ± 300	K04,[a] S01,[a] low$T$,[a] hi$T$,[a] low$Z$,[a] hi$Z$, hi$Z$2, long,[a] short
^{68}Se$(p,\gamma)^{69}$Br	-450 ± 100	hi$T$
^{89}Ru$(p,\gamma)^{90}$Rh	992 ± 711	long
^{98}Cd$(p,\gamma)^{99}$In	932 ± 408	S01
^{105}Sn$(p,\gamma)^{106}$Sb	357 ± 323	hi$T$
^{106}Sn$(p,\gamma)^{107}$Sb	518 ± 302	S01[a]

[a]Variation of this reaction Q-value affects the nuclear energy generation rate in this model (see text).

Type Ia Supernovae

Main nuclear path: 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

SN 1994D

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Astronomy & Astrophysics

The effects of variations in nuclear interactions on nucleosynthesis in thermonuclear supernovae

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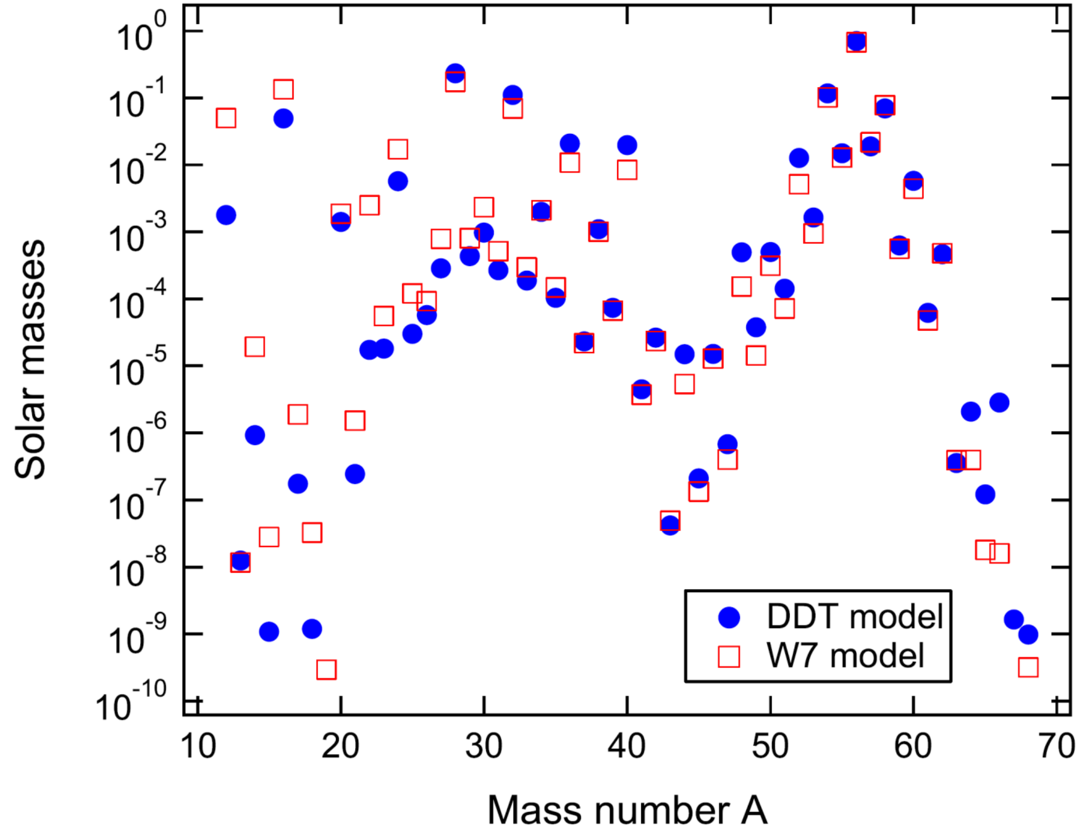
~ **several million** post-processing calculations
443 isotopes (**^{1}H** to **^{86}Kr**) and **2305** nuclear processes

Jordi José



W7 DDT W7+DDT

Reaction	Importance Case A	Importance Case B	Importance Case C
$^{12}C(\alpha,\gamma)^{16}O$	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

→ Weak interactions: stellar vs laboratory decay rates

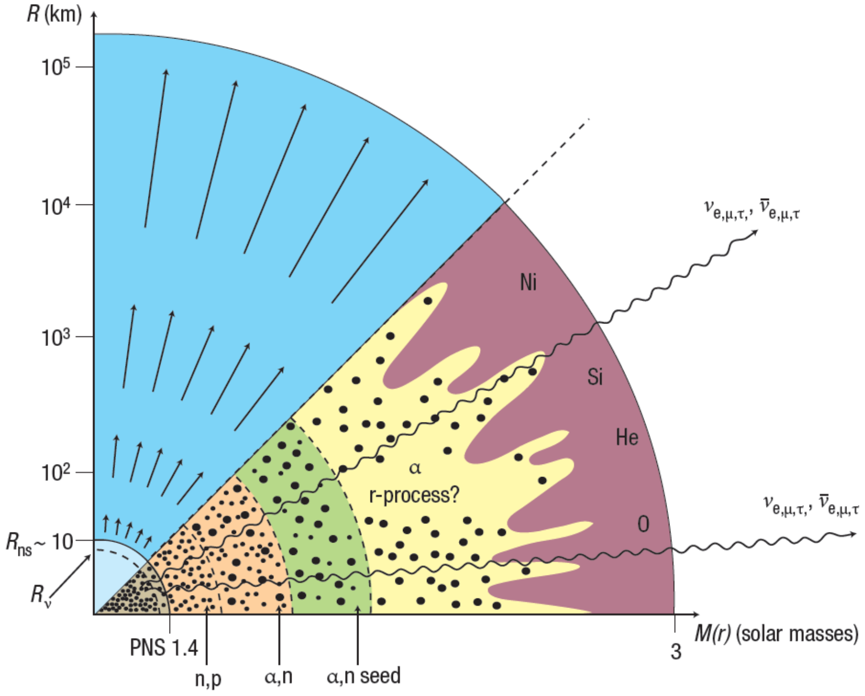
Parikh, JJ, Seitenzahl & Röpke, A&A (2013)

Neutrinos

Relevant to determine the energy effectively generated by nuclear reactions in stars

Some astrophysical environments in which neutrinos are important

* Core-collapse supernovae: explosion mechanism (99% of the gravitational energy released, ~10^{53} erg, is emitted as neutrinos), nucleosynthesis
* Neutron star mergers/kilonovae: cooling, nucleosynthesis (ν's emitted from the hot remnant interact with the ejected material via weak interactions, setting the n/p ratio, which in turn determines which heavy elements can form via the r-process, affecting kilonova lightcurves)
* Big Bang: nucleosynthesis, cosmic neutrino background
* Sun: solar neutrino detection → standard solar model
* GRBs: jet dynamics
* Neutron stars and black holes: cooling, energy deposition in jets



Several nucleosynthesis processes occurring in **core-collapse SNe** are named (after the major role played by neutrinos) as the ν-process, the νp-process, or ν-driven winds

Processes such as ν heating in SN II and ν-process nucleosynthesis are **relatively well established**, supported by simulations and observations (e.g., neutrino detections from SN 1987A). The νp-process and ν-driven wind nucleosynthesis are **moderately understood** (uncertainties in neutrino spectra, and poorly known reaction rates far from stability). In neutron-star merger simulations **uncertainties** arise from complex neutrino transport and flavor oscillations in dense matter

ν–nucleon interactions have been measured experimentally; ν–electron scattering precisely measured; some ν–nucleus reactions partially measured; neutrino nucleosynthesis processes (ν-process, νp-process) are mostly theoretical with indirect observational support; neutrino transport in SNe and mergers relies on numerical simulations constrained by observations

Screening (relative importance of Coulomb versus thermal energy)

$R_{screened} = f\ R_{bare}$

Coupling parameter, $\Gamma = \frac{Z_1\, Z_2\, e^2}{a\, k_B\, T}$

Weak screening ($\rho \sim 10^{-4} - 10^{2}$ g/cm³, $\Gamma \ll 1$)

H-burning shells (novae, XRBs*; core fusion in MS stars)

Reasonable accurate

Intermediate screening ($\rho \sim 10^{2} - 10^{5}$ g/cm³, $\Gamma \sim 0.1 - 1$)

He-burning shells (RG stars; XRBs*; subChandrasekhar SNIa*)

Less accurate (analytical prescriptions with approximate treatment of ion-ion correlations and electron degeneracy)

Strong screening ($\rho \sim 10^{6} - 10^{9}$ g/cm³, $\Gamma > 1$)

WD interiors; NS crust)

Less accurate (deficient treatment of many-body ion correlations in strongly coupled plasmas)

Screening Effects in Stars and in the Laboratory

Marialuisa Aliotta[1*] *and Karlheinz Langanke*[2,3]

Frontiers in Physics (2022)

Improvement of electron screening treatment mainly theoretical; experimental approaches are restricted to studies of light-ion fusion reactions where the presence of electrons in the nuclear target screens the Coulomb barrier, enhancing the relative energy of the collision partners during tunneling (for heavier nuclei, the energies reachable in accelerator experiments are too high for screening effects to be relevant)

Thank you for your attention!

Jordi José

Nuclear Data for Astrophysics

Perspectives on Nuclear Data for the Next Decade, P(ND)2 – 3, Paris (France), March 9 – 13, 2026