Explosive Nucleosynthesis in Novae & X-Ray Bursts

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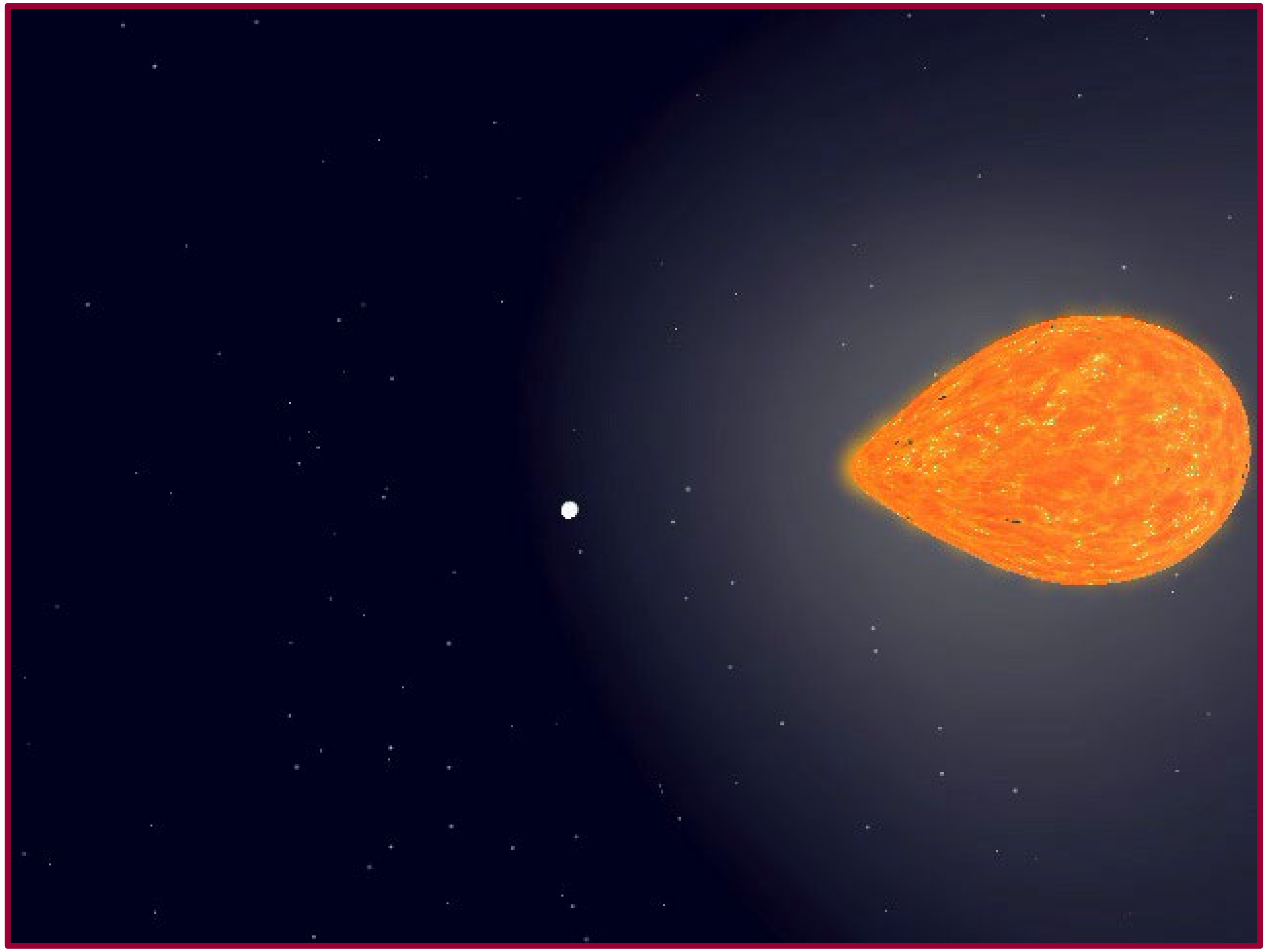
About a third (or a half) of the stars of our Galaxy form double or multiple systems, a fraction of which evolve into a close binary system containing a white dwarf.

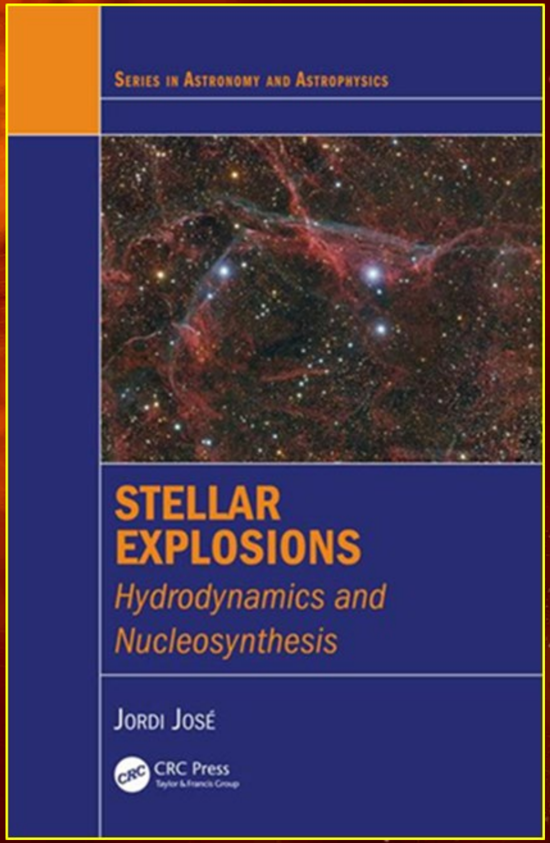
Gaia-calibrated models suggest that about 2–3% of binaries within 100 pc contain a WD, implying that between 10^8–10^9 such systems exist across the Milky Way. A subset of these binaries evolves into interacting systems where mass transfer onto the white dwarf occurs. These accreting systems (including cataclysmic variables, symbiotic stars, and supersoft X-ray sources) likely represent 1–5% of WD binaries



Type Ia (or thermonuclear) **Supernovae** [SN Ia]

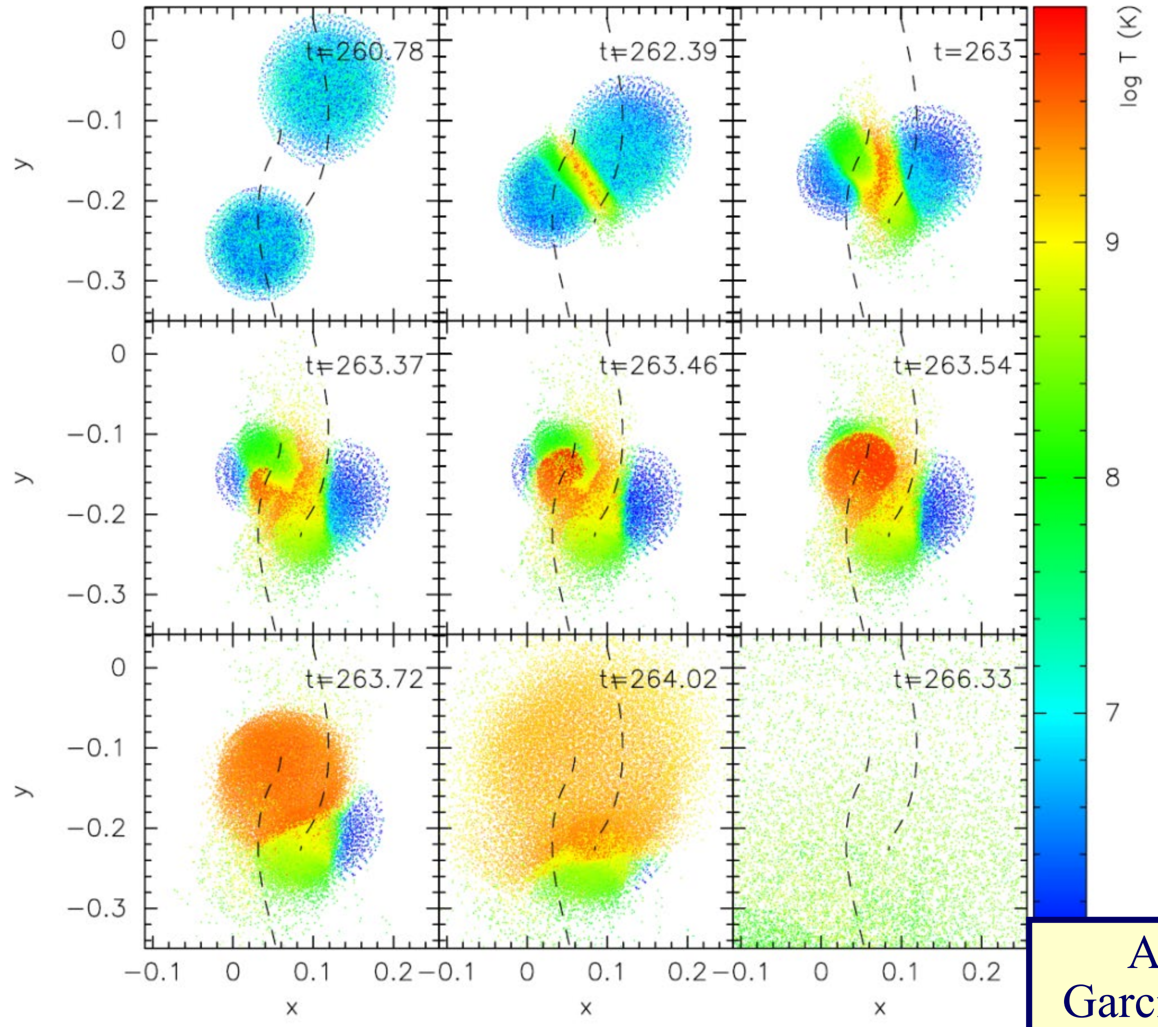
Classical Nova Outbursts [CN]

} WD



EXPLOSIONS

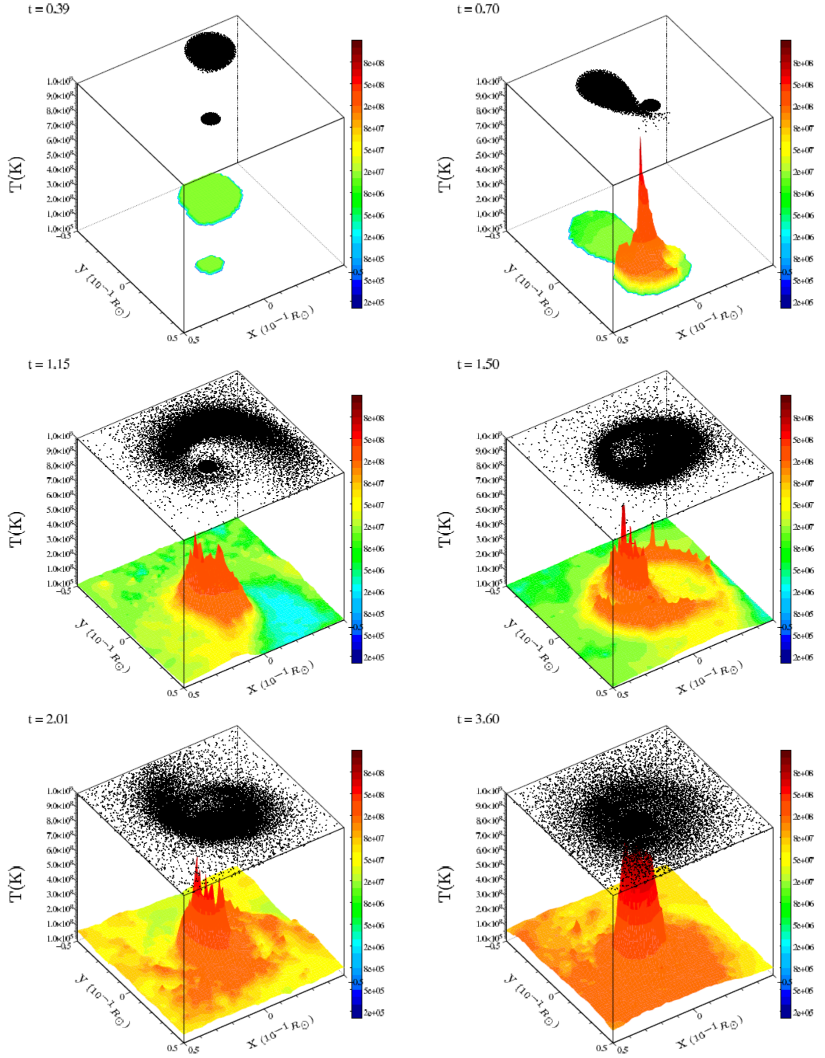
… but not only!



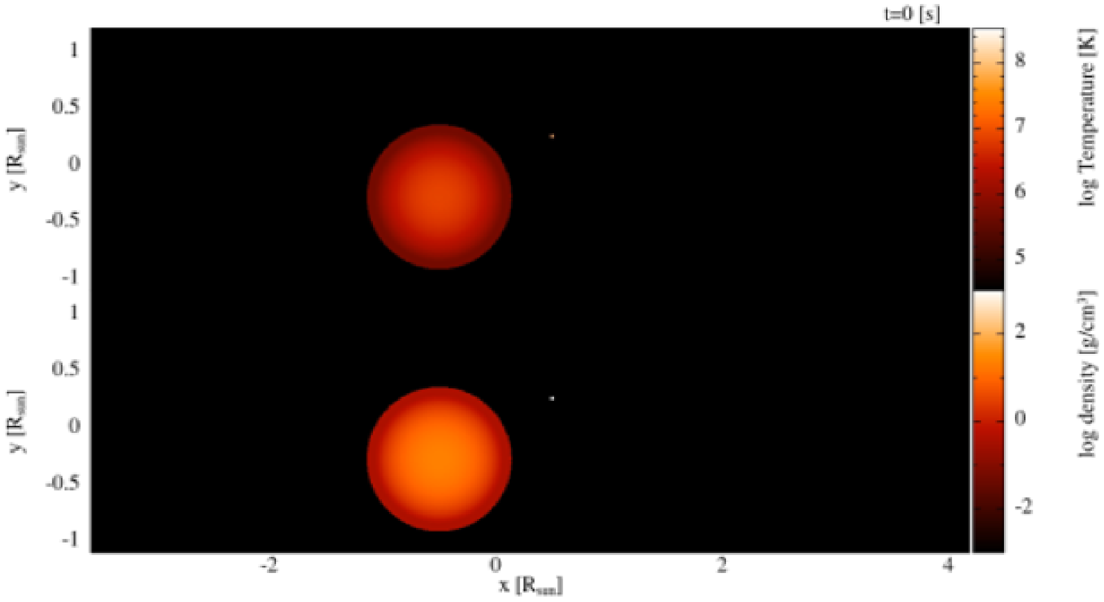
frequency ~ f(type Ia SNe)

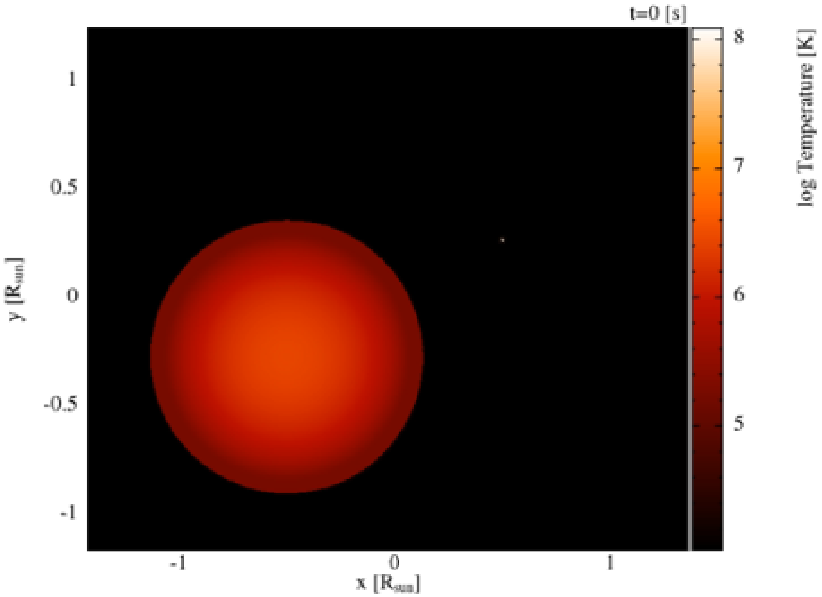
Aznar-Siguán, García-Berro, Lorén-Aguilar, JJ & Isern, MNRAS (2013)

WD + WD MERGERS



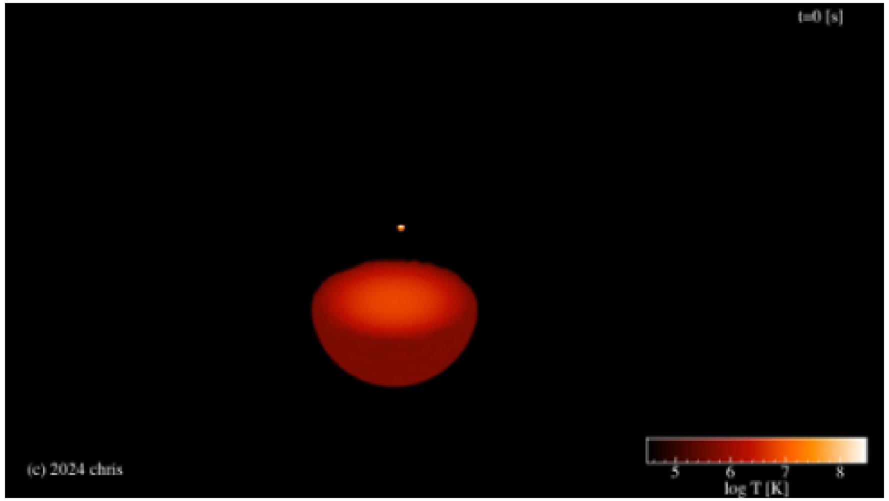
Guerrero, García-Berro & Isern, A&A (2004)

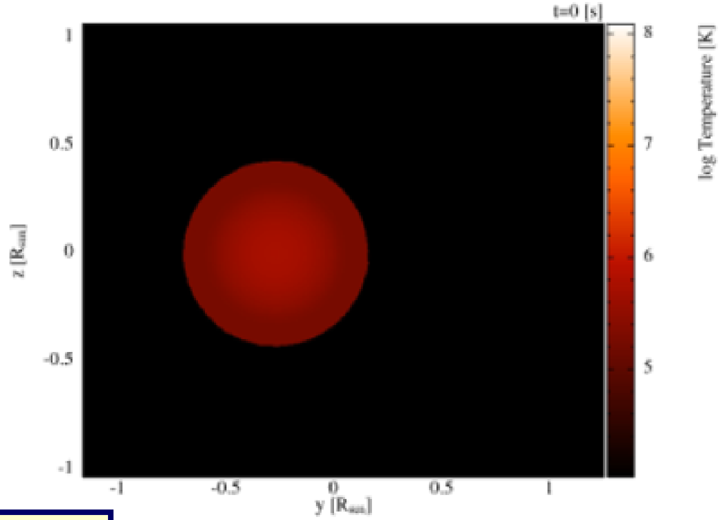




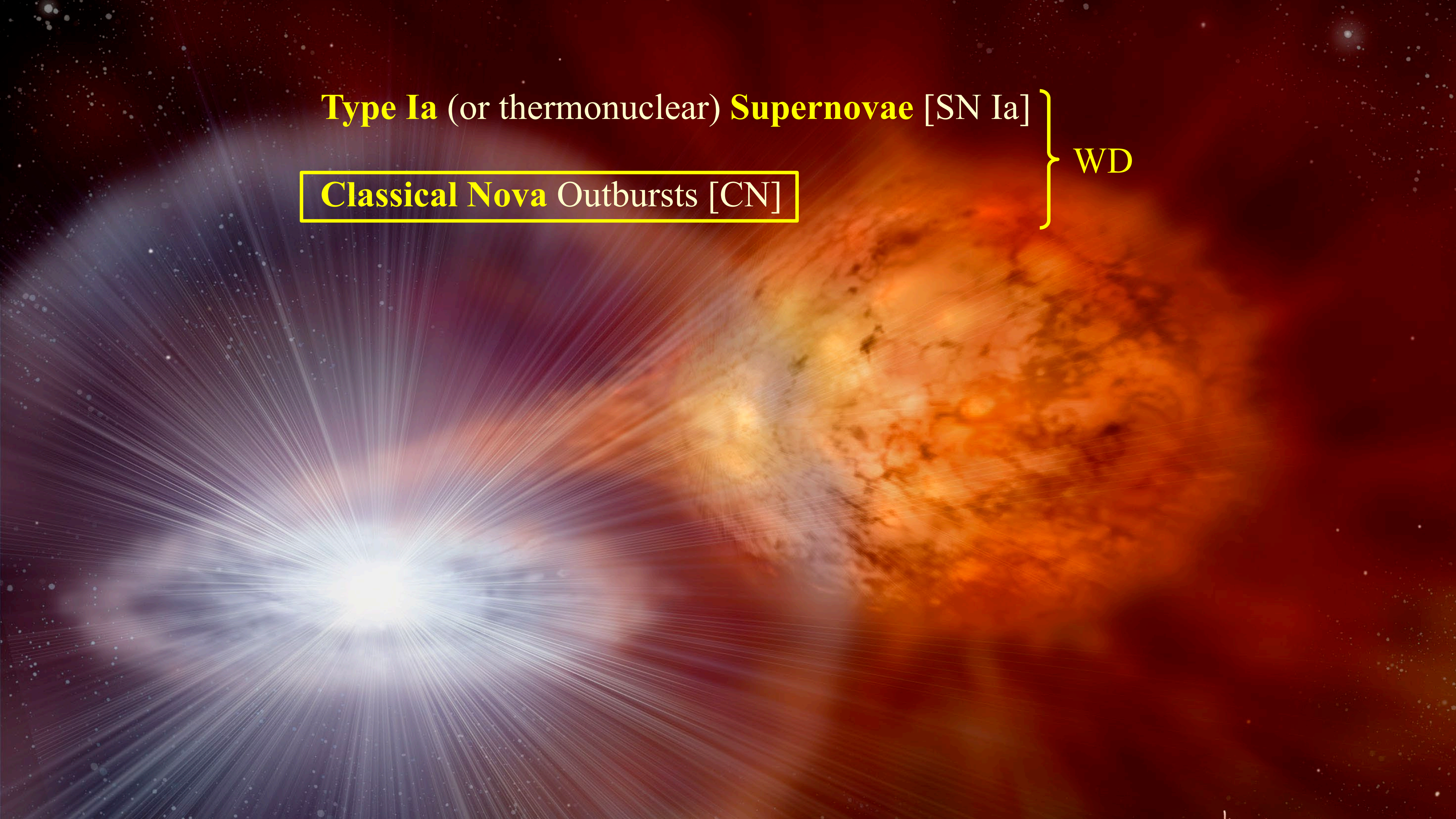
COLLISIONS

(eg., WD + MS)

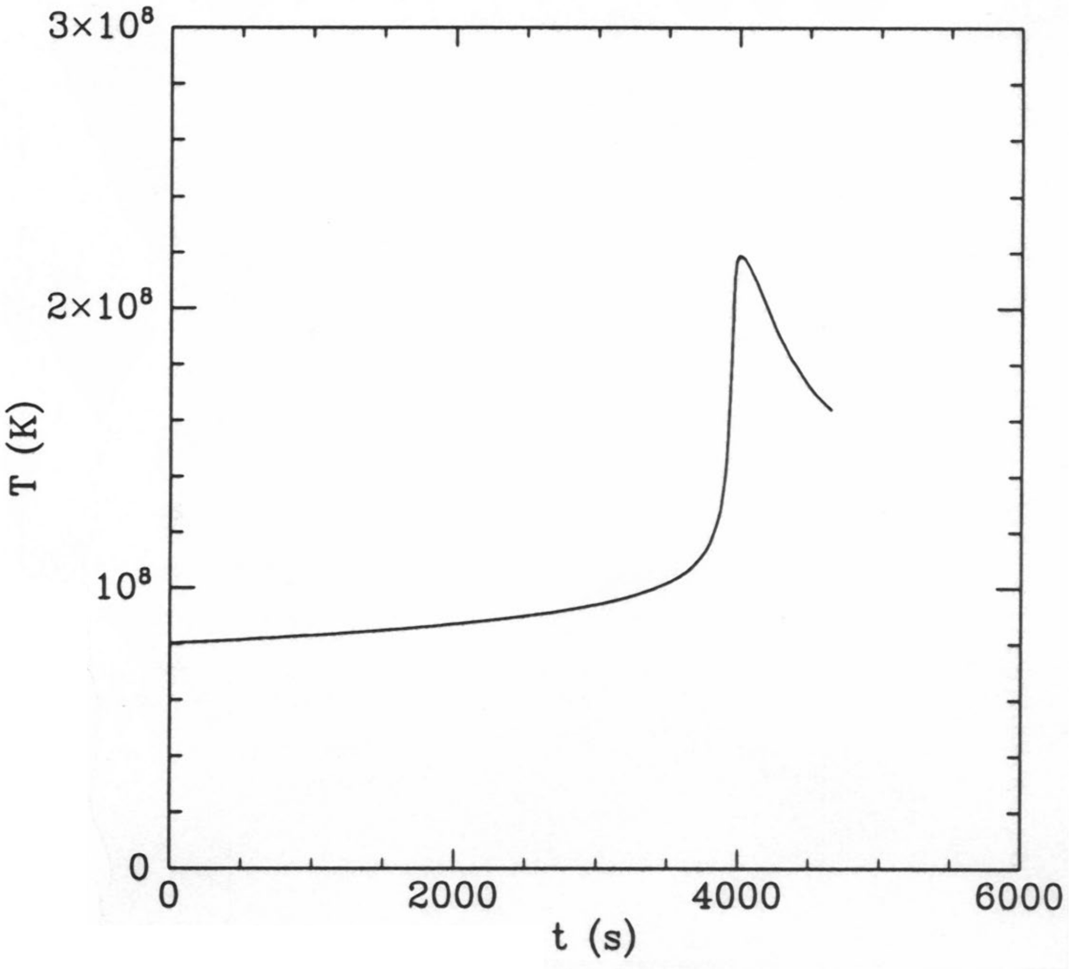




Van der Merwe, Mohamed, JJ, Shara & Kamisnki, MNRAS (2024, 2025, 2026)


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

CLASSICAL & RECURRENT NOVAE



Temperature at the base of the accreted envelope

Timescales

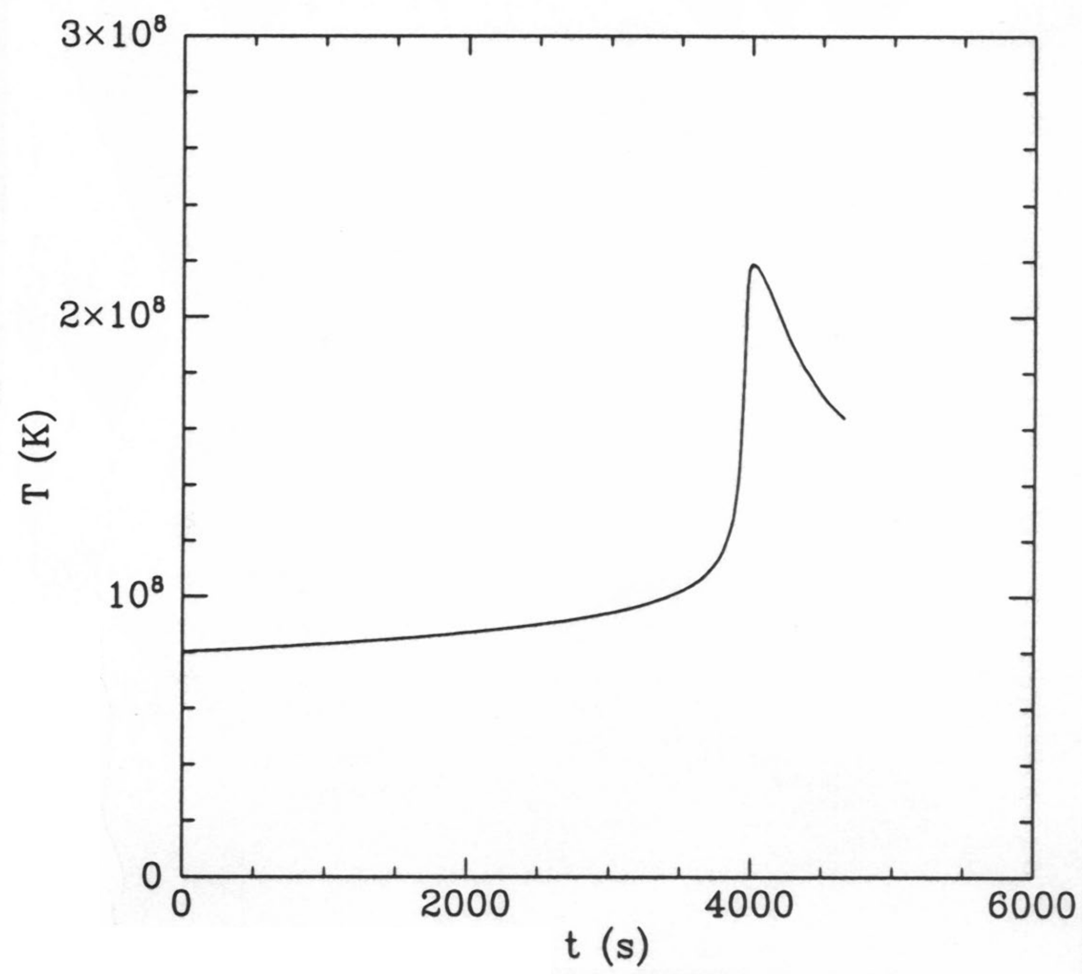
$\mathbf{t_{acc} \sim 10^4 - 10^5}$ **yr** (T_{base}: T_{ini} to $\mathbf{3\times10^7}$ **K**)
accretion stage (onset of convection and TNR; degeneracy lifting), $\tau_{acc} < \tau_{nuc}$

Accretion matters! → $$P_{ce} = \frac{GM_{wd}}{4\pi R_{wd}^4}\Delta M_{acc}$$

(Shara 1981, Fujimoto 1982, MacDonald 1983)

larger P_{ce} → more violent outbursts (T_{max}, K, ΔM_{eje}…)

Since the single, **most important** nuclear reaction that drives the TNR in novae is ^{12}**C(p, γ)** (JJ, Halabi & El Eid 2016), accretion of ^{12}C-deficient material will require the accumulation of more massive envelopes, leading to larger P_{ce} and resulting in more violent explosions



t_{rise} **~ 10 – 1000 d** (T_{base}: 3×10^7 to **10^8 K**)
nuclear stage (fully convective envelope), $\tau_{acc} > \tau_{nuc}$

t_{peak} **~ 100 – 1000 s** (T_{base}: 10^8 K to T_{peak})

Such timescales suggest a **deflagration (subsonic) flame** powering the explosion → interplay between convective transport, mild degeneracy, and nuclear reactions

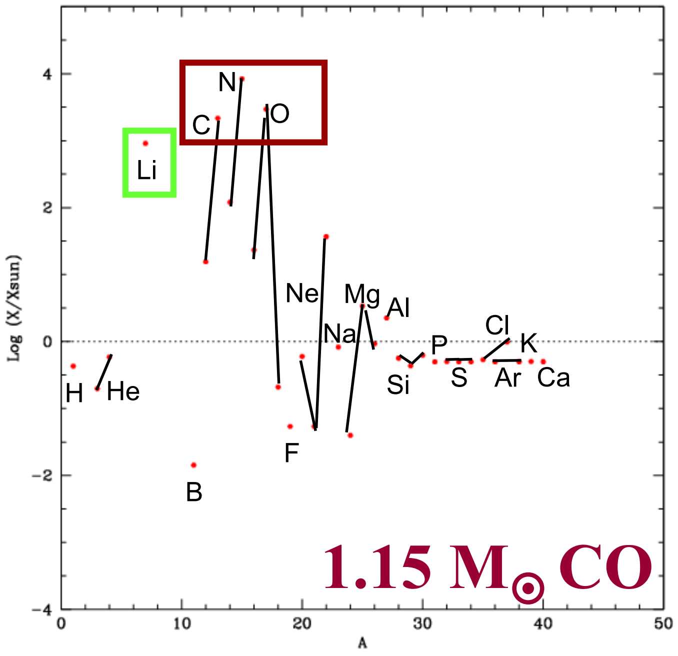
WHAT (WE THINK) WE KNOW

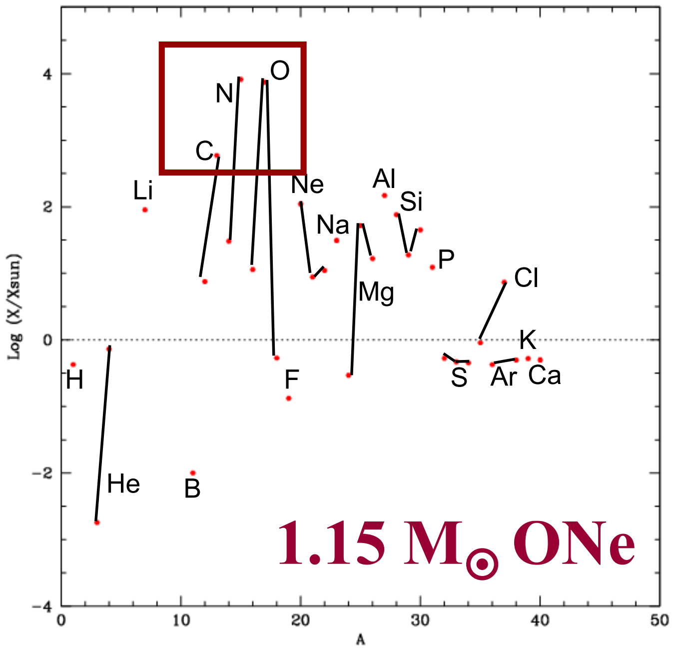
The **main nuclear path** runs close to the **valley of stability,** being driven by **(p,γ)**, **(p,α)** and **β^+** interactions

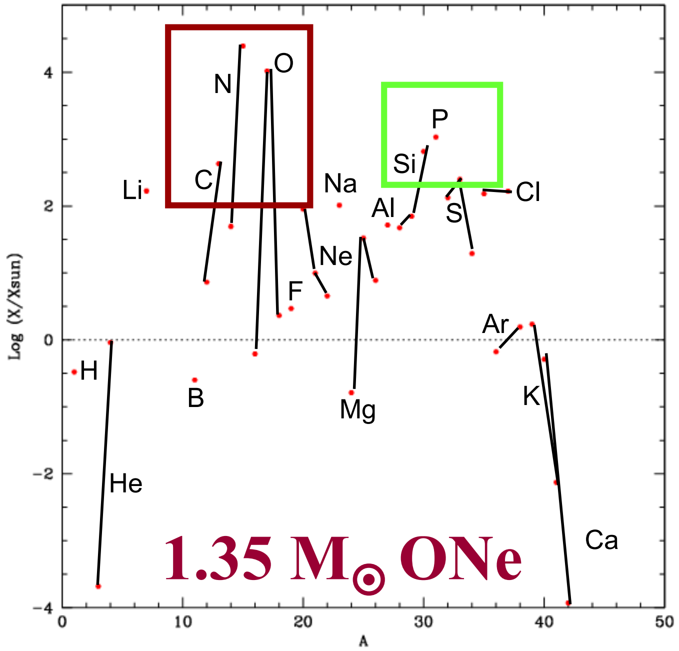
Negligible contribution from **(n,γ)** and **(α,γ)** reactions

Nucleosynthesis endpoint ~ **Ca** → No heavy metals produced!

Fuel (H) is **not** fully consumed → **explosion halted by expansion**





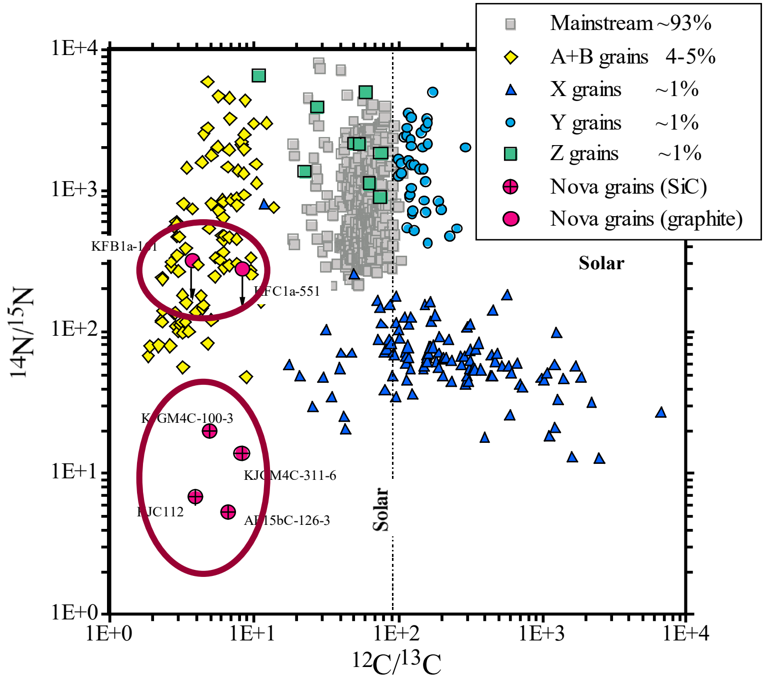


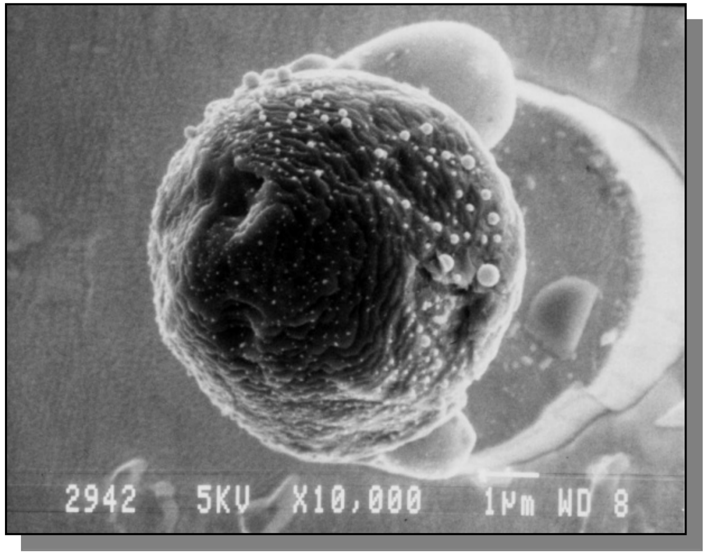
Novae are important **nuclear physics (stellar) laboratories** ~**100** relevant isotopes **(A<40)** & a **(few) hundred** nuclear reactions **(T_{peak} ~ 100 – 400 MK)**
→ **unique stellar explosions** for which the nuclear physics input is primarily based on experimental information (JJ, Hernanz & Iliadis, Nucl. Phys. A 2006)

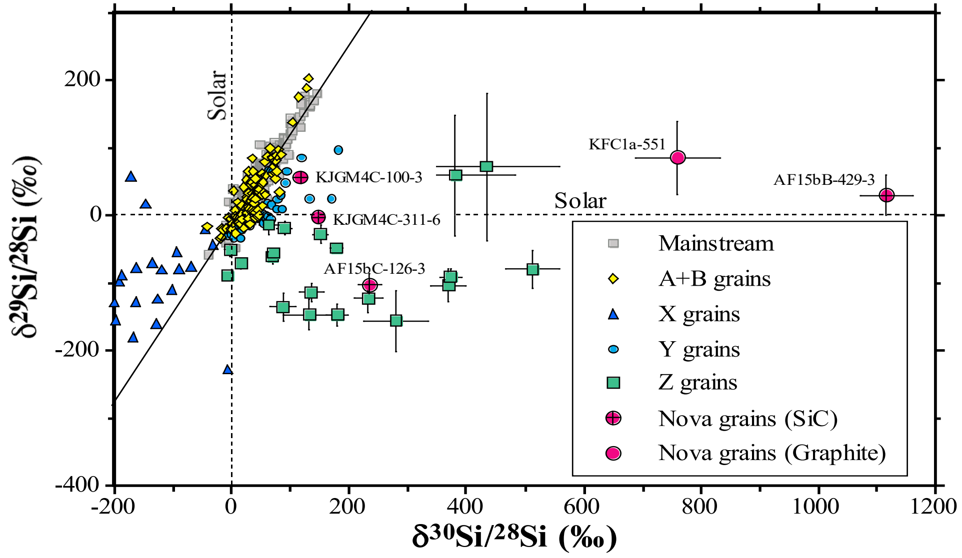
Novae are important sources of CNO-nuclei (^{13}C, ^{15}N, ^{17}O) and contribute to the Galactic ^{7}Li [mixing].
No indication of CNO-breakout! Ejecta characterized by low $^{12}C/^{13}C$ and (often) low $^{14}N/^{15}N$ ratios; ONe nova models show close-to- or lower-than-solar $\delta(^{29}Si/^{28}Si)$ values, $\delta(^{30}Si/^{28}Si)$ excesses, and high $^{26}Al/^{27}Al$ and $^{22}Ne/^{20}Ne$ ratios → signatures of a nova origin in the **presolar grain** inventory

Presolar Grains

TALK by Nan Liu







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PRESOLAR GRAINS FROM NOVAE

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Received 2000 September 15; accepted 2000 December 18

Low- to intermediate-mass **CO novae** (0.6–1.0 $M_\odot$) are the most plausible stellar **sources of ^{13}C-rich SiC dust lacking s-process signatures** (AB grains; 1–2% of all presolar SiC)

34 Hydrodynamic Nova Models analyzed

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https://doi.org/10.1140/epja/s10050-026-01882-9
THE EUROPEAN PHYSICAL JOURNAL A
Check for updates
Regular Article - Theoretical Physics

New NanoSIMS multielement isotope data reveal CO novae as key sources of ^{13}C-rich presolar silicon carbide grains

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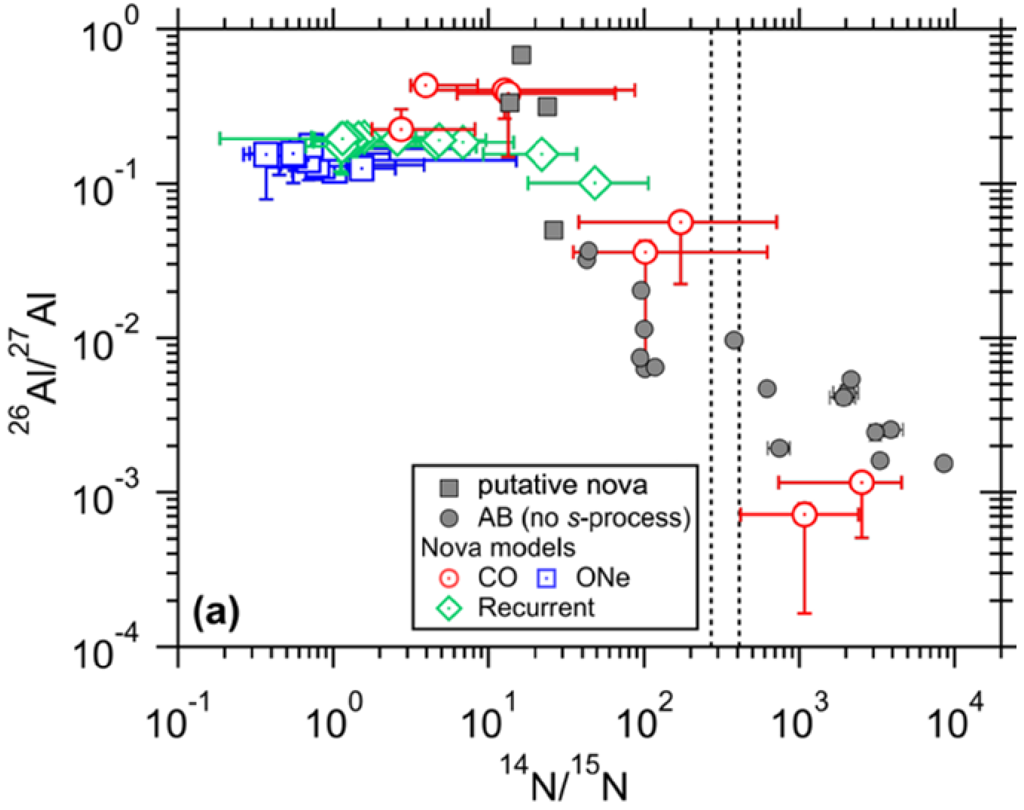
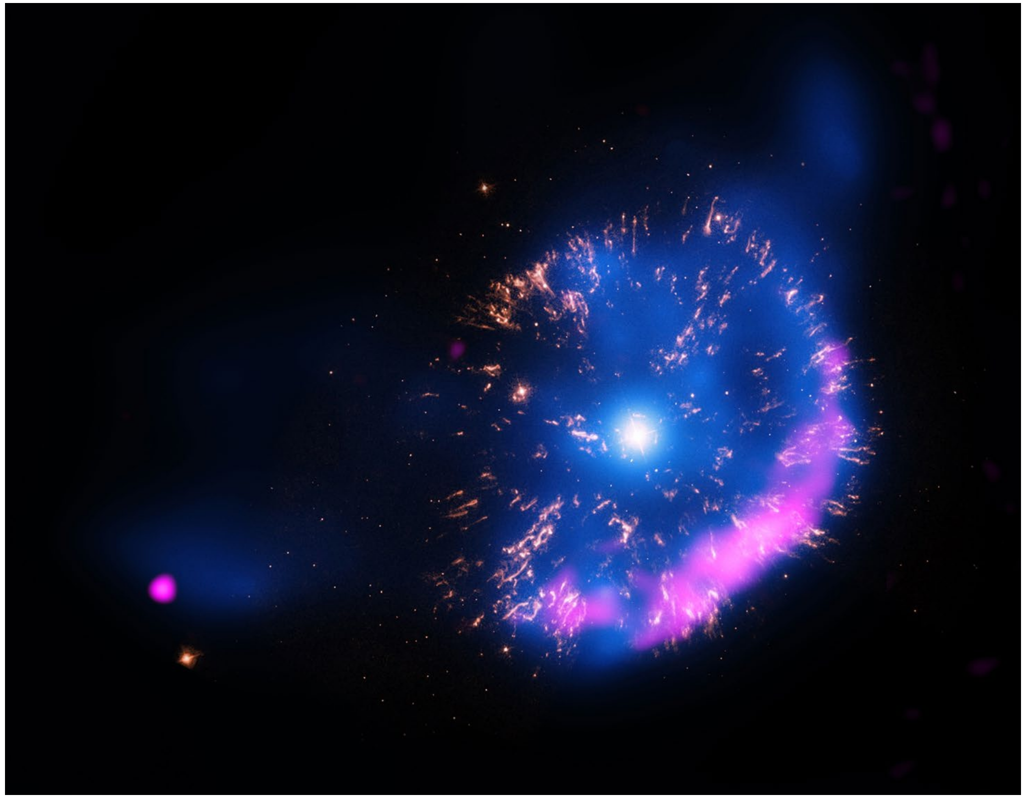


Nuclear Uncertainties

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



GK Persei (1901)

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

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Main nuclear uncertainties (remaining)

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

TALK by Nathan Giha

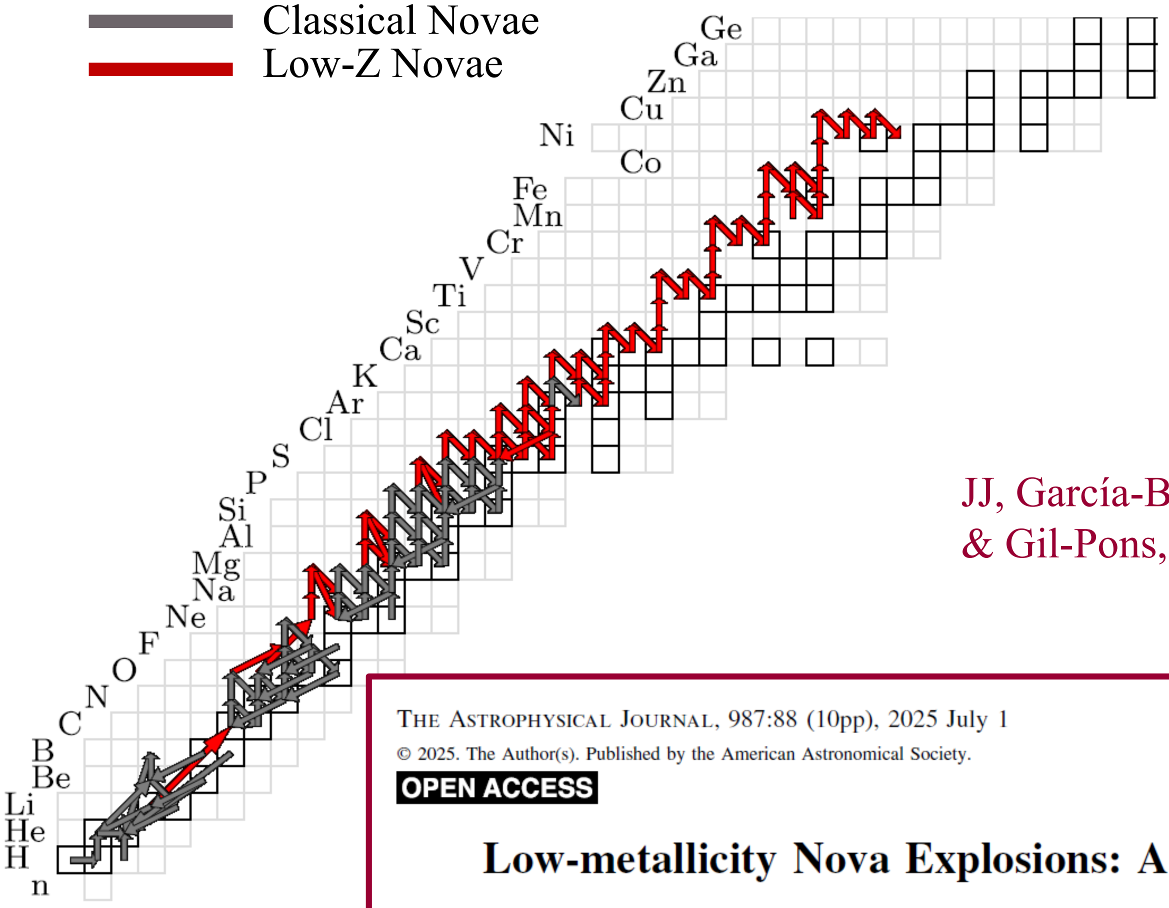
WHAT WE DON'T KNOW

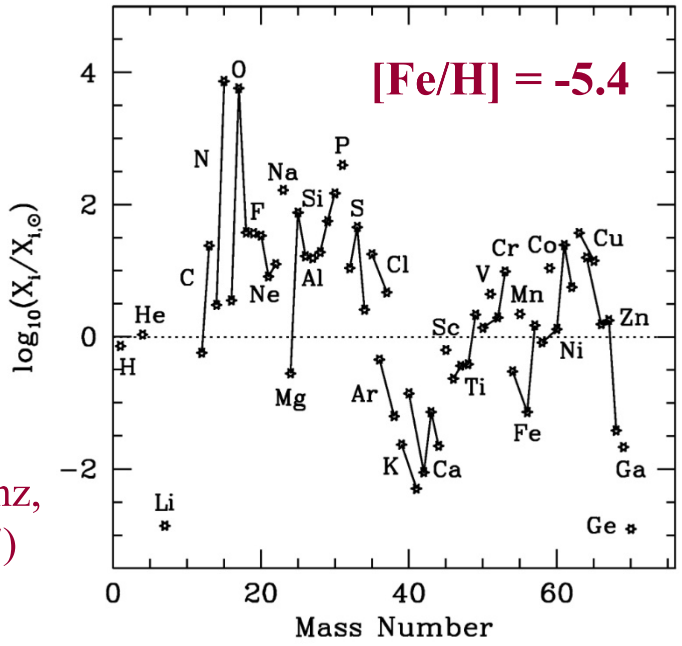
* How early the accreted envelope becomes chemically enriched/mixed with WD substrate material? Is mixing the result of multiple physical phenomena (probably yes: shear, difussion, multidimensional effects…)

* How important is rotation (pressure lifting, rotational mixing) in nova nucleosynthesis? Work in progress…

* Nuclear uncertainties (mainly **$^{18}F(p,\alpha)^{15}O$, $^{25}Al(p,\gamma)^{26}Si$, $^{30}P(p,\gamma)^{31}S$**) affect nova nucleosynthesis predictions (lack of precise spectroscopic information: spins and parities, interference between low-lying resonances…)→ accurate determinations of maximum detectability distances for gamma-rays emitted from novae, the contribution of novae to the Galactic ^{26}Al, and synthesis of Si – Ca in novae

* How the Galactic nova rate has evolved along the 10 Gyr of Galactic history? Are nova explosions in low-Z (and primordial) systems different from those produced in binaries with solar composition components? → Need of hi-res spectra of novae in low-Z systems





JJ, García-Berro, Hernanz, & Gil-Pons, ApJL (2007)

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https://doi.org/10.3847/1538-4357/addfd5
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Low-metallicity Nova Explosions: A Site for Weak *rp*-process Nucleosynthesis

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1D have been successful in reproducing the *gross* observational features that characterize CNe (e.g., light curves, nucleosynthesis...), but the assumption of spherical symmetry excludes an entire sequence of events

* Ignition and front propagation

* Mixing between the accreted matter and the WD substrate

* The long-term evolution of a nova involves the **interaction** between the ejecta, the disk, and the stellar companion

J. Figueira

A&A 613, A8 (2018)
https://doi.org/10.1051/0004-6361/201731545
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Astronomy & Astrophysics

Three-dimensional simulations of the interaction between the nova ejecta, accretion disk, and companion star★

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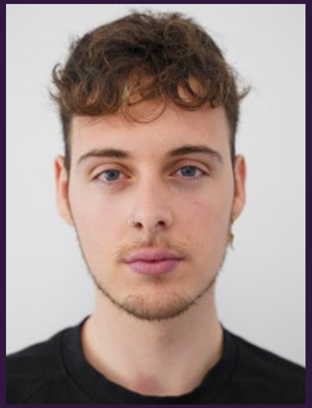
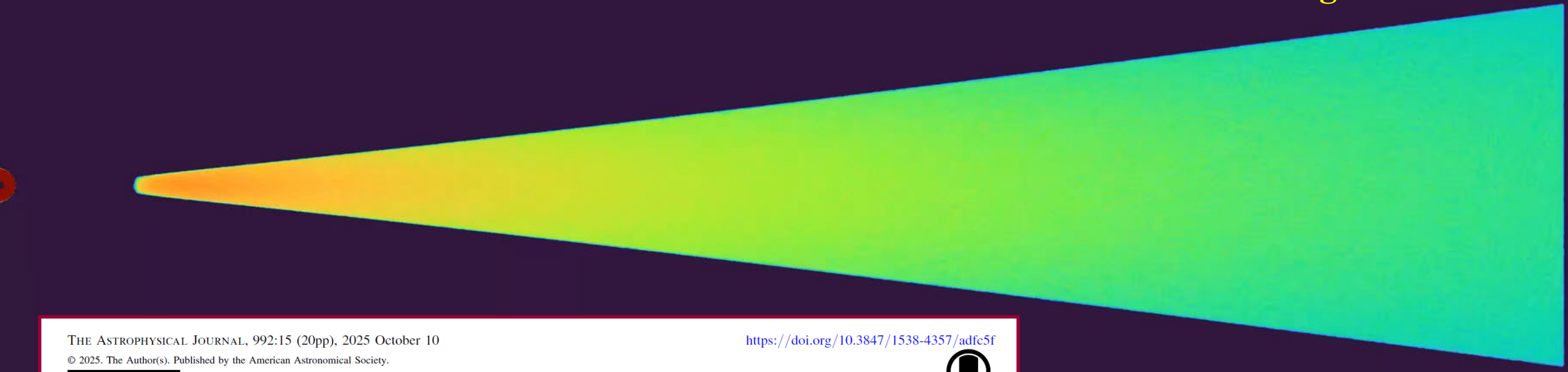
10^6 SPH particles (2D axisym.) → **10^9 particles (3D)**



A. S. Lechuga



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High-resolution Simulations of the Interaction between the Nova/Supernova Ejecta and the Accretion Disk

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Day 1 00:00

X-RAY BURSTS

Classical Novae

WD + MS (RG) star
Moderate rise times (<1 – 2 days)
$L_{Peak} \sim 10^4 - 10^5\ L_\odot$
$E_{output} \sim 10^{45}$ ergs

Mass ejected: $10^{-7} - 10^{-4}\ M_\odot$ ($\sim 10^3$ km s^{-1})
Recurrence: $\sim 10^4 - 10^5$ yr
Frequency: $\sim 50\ yr^{-1}$ [Obs. $\sim 10\ yr^{-1}$]

X-Ray Bursts (Type I)

NS + MS (RG) star
Fast rise times (<1 – 10 s)
$L_{Peak} \sim 10^4 - 10^5\ L_\odot$
$E_{output} \sim 10^{39-40}$ ergs [in 10- 100 s]
$\alpha = L_{persistent}/L_{burst} \sim 100$

Mass ejected: by radiation-driven winds
Recurrence: ~ hrs – days
Sources detected: ~ 100

Novae are XRBs in slow motion…
…XRBs are novae in fast forward

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
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Hydrodynamic simulations of thermonuclear bursts on accreting neutron stars: a showcase of burning regimes

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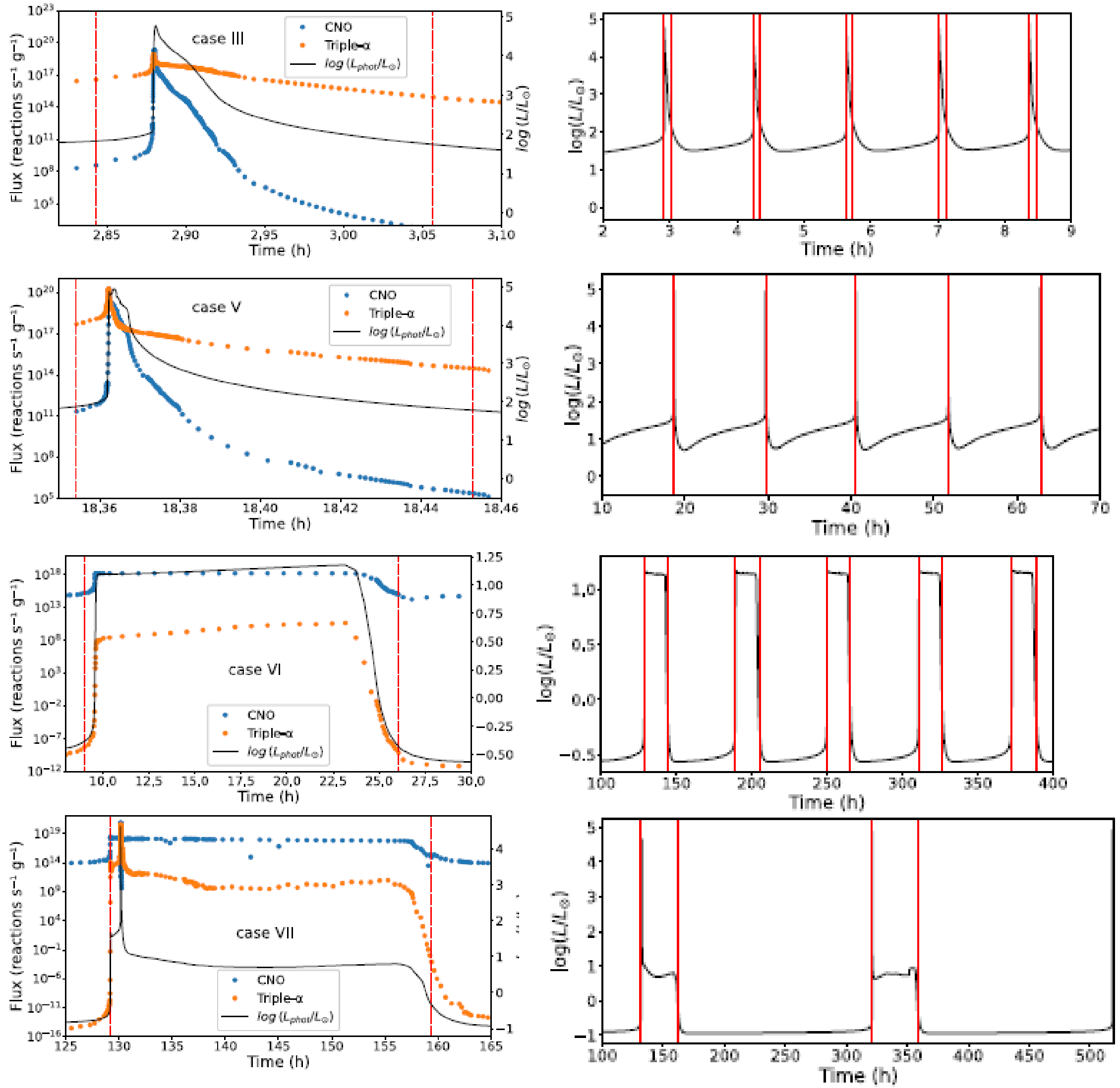
Case	Burning regime	L. Bildsten (1998)	D. K. Galloway & L. Keek (2020)
I	Stable H and He burning	$>2.6 \times 10^{-8}$	$>1.75 \times 10^{-8}$
II	Marginally stable He burning (stable H burning)	–	$\sim 1.75 \times 10^{-8}$
III	He ignition (followed by mixed H and He burning)	$10^{-9} - 2.6 \times 10^{-8}$	$1.9 \times 10^{-9} - 1.75 \times 10^{-8}$
IV	Stable H and He burning	–	$(1.4 - 1.9) \times 10^{-9}$
V	He ignition in a H-depleted layer	$2 \times 10^{10} - 10^{-9}$	$7 \times 10^{-11} - 1.4 \times 10^{-9}$
VI	Shallow H bursts, deep He burst	$<2 \times 10^{-10}$	$(1.8 - 7) \times 10^{-11}$
VII	Deep H ignition (followed by He ignition)	–	$<1.8 \times 10^{-11}$

Model number	M_{NS} ($M_\odot$)	Z_{CNO}	L_{base} ($L_\odot$)	$\dot{M}$($M_\odot$ yr^{-1})	$\dot{M}$ ($\dot{M}_{Edd}$)	t_{rec} (h)	Regime (Table 1)
1	1.0	0.02	1.0	3.48×10^{-8}	2.8	Stable	I
2	1.0	0.02	1.0	5×10^{-9}	0.40	1.6	III
3	1.0	0.02	1.0	5×10^{-10}	0.040	12.8	V
4	1.0	0.02	1.0	5×10^{-11}	0.0040	6460 [a]	V
5	1.4	0.2	1.0	3.48×10^{-8}	2.0	0.1	II
6	1.4	0.2	1.0	5×10^{-9}	0.29	0.86	III
7	1.4	0.2	1.0	5×10^{-10}	0.029	123	V
8	1.4	0.2	1.0	5×10^{-11}	0.0029	17 617 [b]	V
9	1.4	0.1	1.0	5×10^{-10}	0.029	73 [a]	V
10	1.4	0.02	1.0	3.48×10^{-8}	2.0	Stable	I
11	1.4	0.02	1.0	5×10^{-9}	0.29	1.8	III
12	1.4	0.02	1.0	5×10^{-10}	0.029	14.1	V
13	1.4	0.02	1.0	1×10^{-10}	0.0057	1860 [b]	V
14	1.4	0.02	1.0	5×10^{-11}	0.0029	10 422 [a]	V
15	1.4	0.002	1.0	3.48×10^{-8}	2.0	Stable	I
16	1.4	0.002	1.0	5×10^{-9}	0.29	3.4	III
17	1.4	0.002	1.0	5×10^{-10}	0.029	43	III
18	1.4	0.002	1.0	5×10^{-11}	0.0029	3333 [a]	V
19	1.4	0.0002	1.0	3.48×10^{-8}	2.0	Stable	I
20	1.4	0.0002	1.0	5×10^{-9}	0.29	5	III
21	1.4	0.0002	1.0	5×10^{-10}	0.029	116 [b]	III
22	1.4	0.0002	1.0	5×10^{-11}	0.0029	943 [a]	III
23	1.4	0.02	0.1	3.48×10^{-8}	2.0	Stable	I
24	1.4	0.02	0.1	5×10^{-9}	0.29	1.9	III
25	1.4	0.02	0.1	5×10^{-10}	0.029	16	V
26	1.4	0.02	0.1	5×10^{-11}	0.0029	226 [b]	VII
27	1.4	0.02	0.1	5×10^{-12}	0.00029	1880	VII
28	1.4	0.02	0.25	5×10^{-11}	0.0029	76	VI
29	1.4	0.02	10	3.48×10^{-8}	2.0	Stable	I
30	1.4	0.02	10	5×10^{-9}	0.29	1.6	III
31	1.4	0.02	10	5×10^{-10}	0.029	11	III
32	1.4	0.02	10	5×10^{-11}	0.0029	Stable	I
33	2.0	0.02	1.0	3.48×10^{-8}	1.4	Stable	I
34	2.0	0.02	1.0	5×10^{-9}	0.20	2.2	III
35	2.0	0.02	1.0	5×10^{-10}	0.020	18.2	V
36	2.0	0.02	1.0	5×10^{-11}	0.0020	18 929 [a]	V

[a]Single burst only.
[b]Less than 5 bursts computed.



Kormpakis, JJ & Linares (2026), MNRAS

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

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~ **50,000** post-processing calculations

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
[illegible]	K04-B3, K04-B7
[illegible]	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

WARNING!

Parikh et al. (2008), ApJS

**TALK by
Nicolas de Séréville**

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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).

Mass Ejection

The potential impact of XRB nucleosynthesis on **Galactic abundances** is still a matter of debate:

Ejection from a NS **unlikely** because of its large **gravitational potential** (ejection from the surface a NS of mass M and radius R requires $GMm_p/R \sim 200$ MeV/nucleon, whereas only a few MeV/nucleon are released from thermonuclear fusion)

NS → $M_{NS} \sim 1.4\ M_\odot$, $R_{NS} \sim 10$ km → $v_{esc} = \sqrt{2G\ M_{NS}/R_{NS}} \sim$ **190 000 km s^{-1}**

WD → $M_{WD} \sim 1\ M_\odot$, $R_{WD} \sim 6000$ km → $v_{esc} \sim$ **7000 km s^{-1}**

→ **XRBs halted by fuel consumption** (due to efficient CNO–breakout) rather than by expansion → nearly **constant pressure** at ignition depth

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Astronomy & Astrophysics

Mass-loss and composition of wind ejecta in type I X-ray bursts

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Y. Herrera

XRB Model with 1.4 M_{sun}, 13.1 km NS; $Z_{acc} = 0.02$, and $M_{acc} = 1.75\times10^{-9}$ M_{sun} yr^{-1} → $M_{ejec} = 3.1\times10^{-14}$ M_{sun}!

0.1% of the envelope is ejected per burst (mostly as ^{60}Ni, ^{64}Zn, [^{68}Ge], and ^{58}Ni). The ejecta also contains some tiny amounts of light **p-nuclei**, but **not enough** to account for their Galactic abundances

XRBs **do contribute** (to some extent!) to the Galactic abundances

Type I XRB Models with Rotation

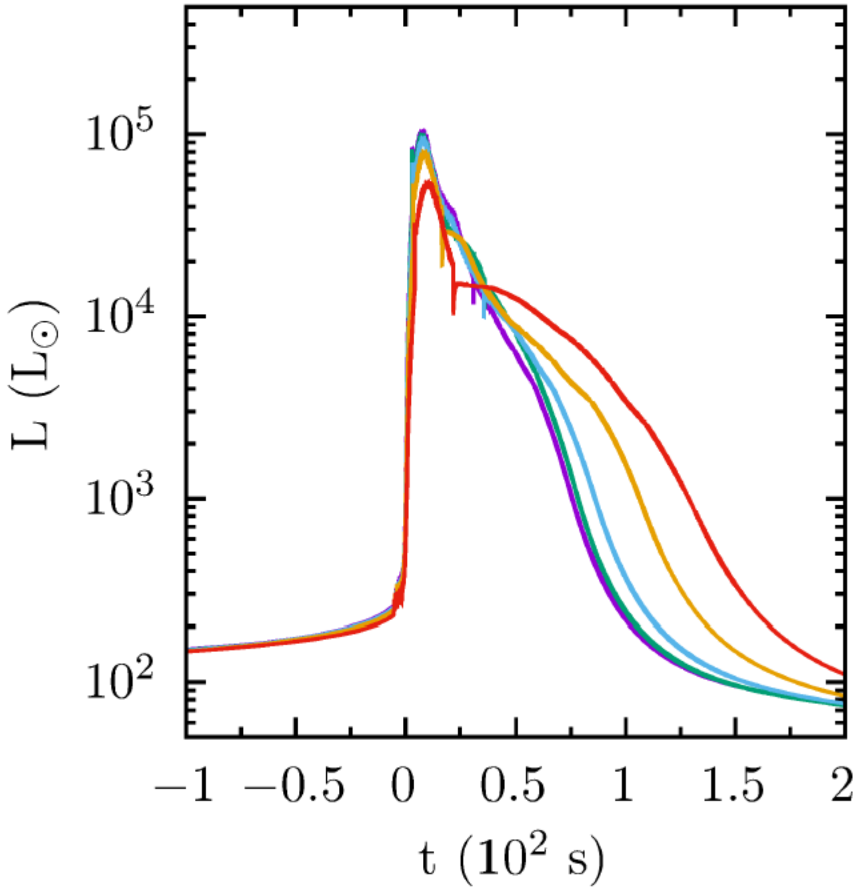
First models with rotation!

Study of the effect of (**shellular**) **rotation** on type I X-ray burst properties

D. Martin

- **Pressure-lifting effect** caused by rotation: maximum density and pressure at the base of the envelope decrease as the angular velocity of the envelope increases
- The **size** of the **envelope shows a significant growth** with the increase of the angular velocity (up to 66% for the fastest rotation model considered)
- Rotation influences the **extent of the nuclear activity** during XRBs, limiting the **nucleosynthesis endpoint**: differences of **up to five mass units** are found between the fastest-rotating and non-rotating models.
- Bursts with **higher angular velocities have smaller recurrence times**

Brighter bursts for **small angular velocities Ω_0** (bursts with **high rotation rates** have **long decays [increase up to 125%] and broad light curves**)



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Type I X-Ray Burst Models with Rotation

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Thank you for your attention!

Jordi José

Explosive Nucleosynthesis in Novae & X-Ray Bursts

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