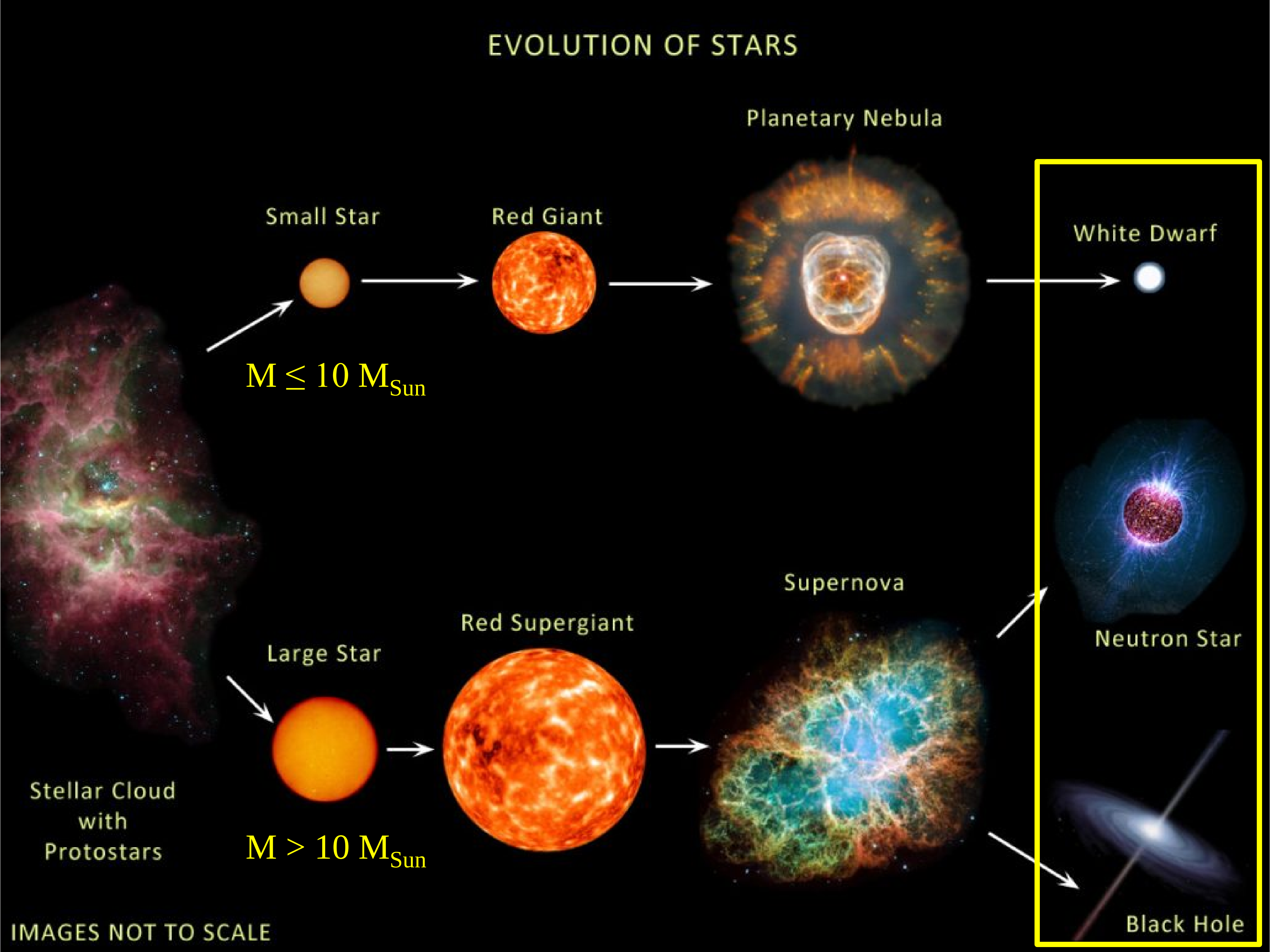
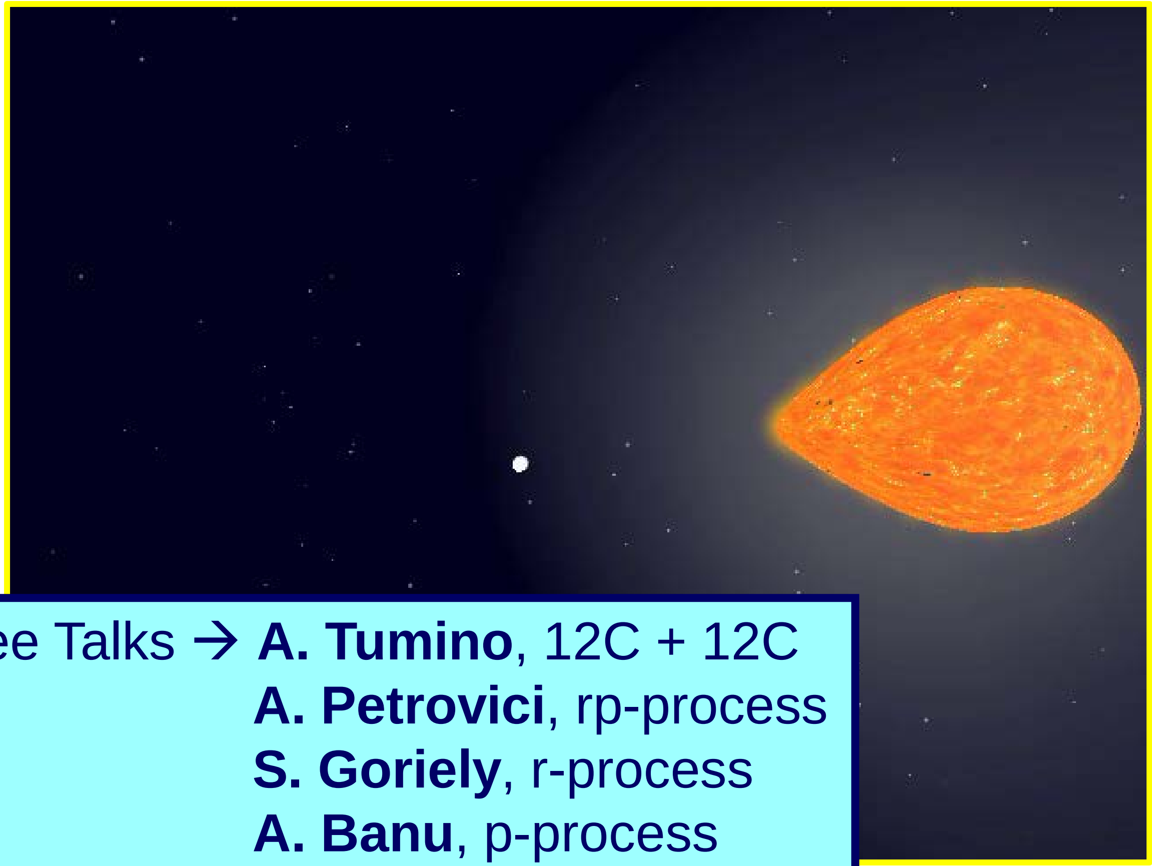
Stellar Pyrotechnics: Nucleosynthesis in Classical Nova Explosions

Jordi José

Dept. Física, Univ. Politècnica de Catalunya (UPC),
& Institut d’Estudis Espacials de Catalunya (IEEC), Barcelona
Catalonia


EVOLUTION OF STARS
Small Star
Red Giant
Planetary Nebula
White Dwarf
M ≤ 10 M_Sun
Neutron Star
Supernova
Red Supergiant
Large Star
Stellar Cloud with Protostars
M > 10 M_Sun
Black Hole
IMAGES NOT TO SCALE



See Talks → **A. Tumino**, 12C + 12C
A. Petrovici, rp-process
S. Goriely, r-process
A. Banu, p-process

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

X-Ray Bursts [XRBs]: NS

Classical Novae in a Nutshell

A nova is a thermonuclear explosion driven by mass transfer onto a WD that forms a binary system. They have been observed in all wavelengths (but detected in γ-rays only at E > 100 MeV)

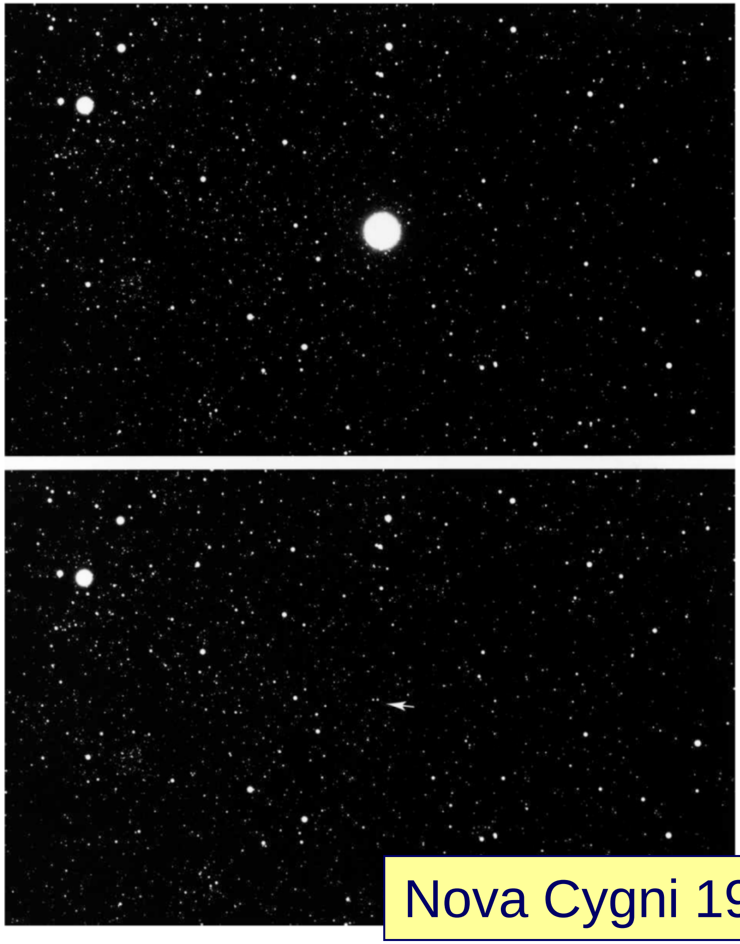
Moderate rise times (<1 – 2 days),
$L_{Peak} \sim 10^4 - 10^5 L_\odot$

WD + MS (often, K-M dwarfs),
WD + RG

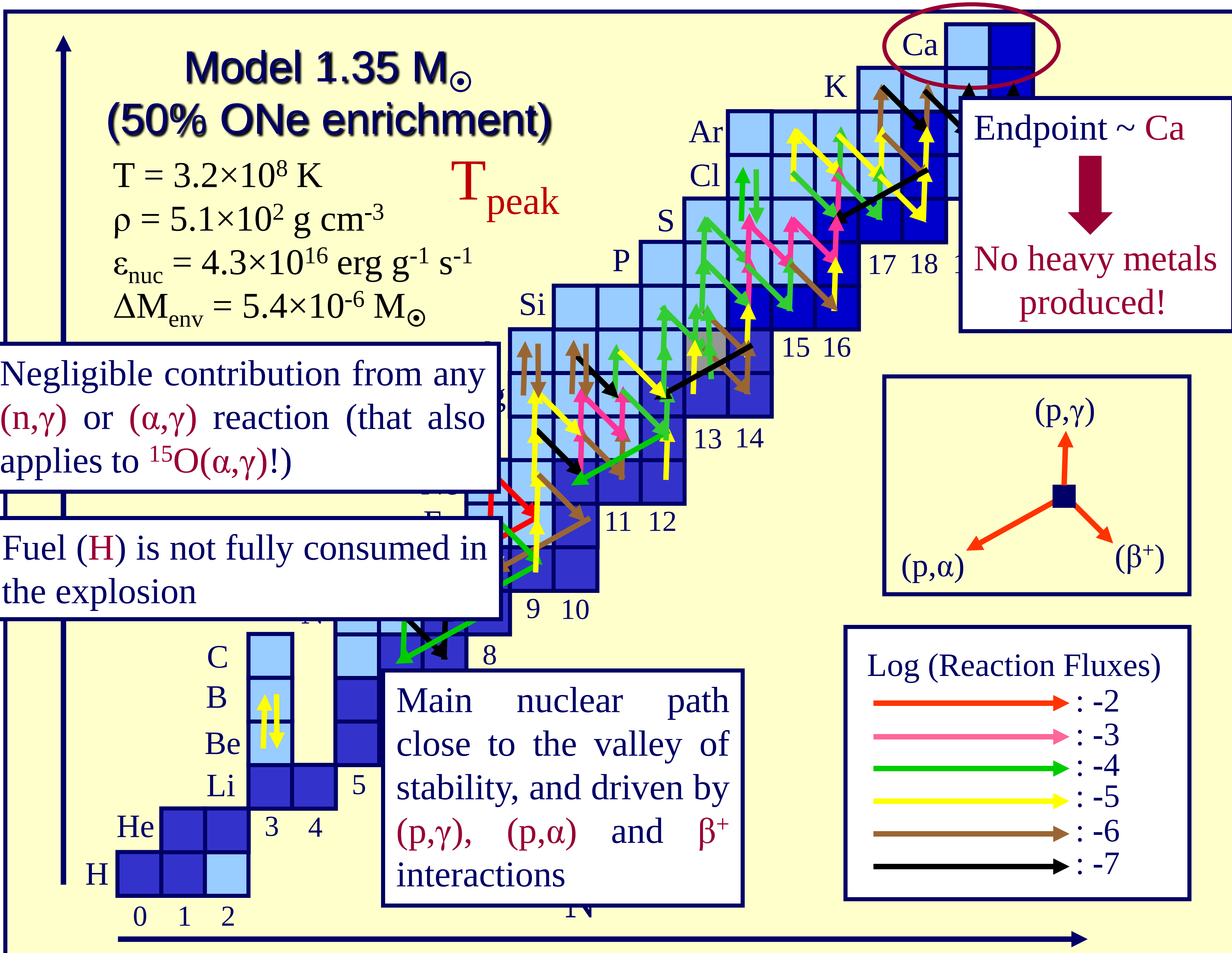
Mass ejected: $10^{-7} - 10^{-4} M_\odot$
($\sim 10^3$ km s^{-1})

Recurrence: ~ 1 - 100 yr (RNe) –
10^5 yr (CNe)

Frequency: 30 ± 10 yr^{-1}
[Obs. ~ 10 yr^{-1}]



Nova Cygni 1975


Model 1.35 M$_\odot$
(50% ONe enrichment)
T = 3.2×10^8 K
ρ = 5.1×10^2 g cm^{-3}
ε$_{nuc}$ = 4.3×10^{16} erg g^{-1} s^{-1}
ΔM$_{env}$ = 5.4×10^{-6} M$_\odot$
T$_{peak}$
Negligible contribution from any (n,γ) or (α,γ) reaction (that also applies to ^{15}O(α,γ)!)
Fuel (H) is not fully consumed in the explosion
Main nuclear path close to the valley of stability, and driven by (p,γ), (p,α) and β$^+$ interactions
Endpoint ~ Ca
No heavy metals produced!
(p,γ)
(p,α)
(β$^+$)
Log (Reaction Fluxes)
: -2
: -3
: -4
: -5
: -6
: -7
Ca
K
Ar
Cl
S
P
Si
C
B
Be
Li
He
H
0
1
2
3
4
5
8
9
10
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17
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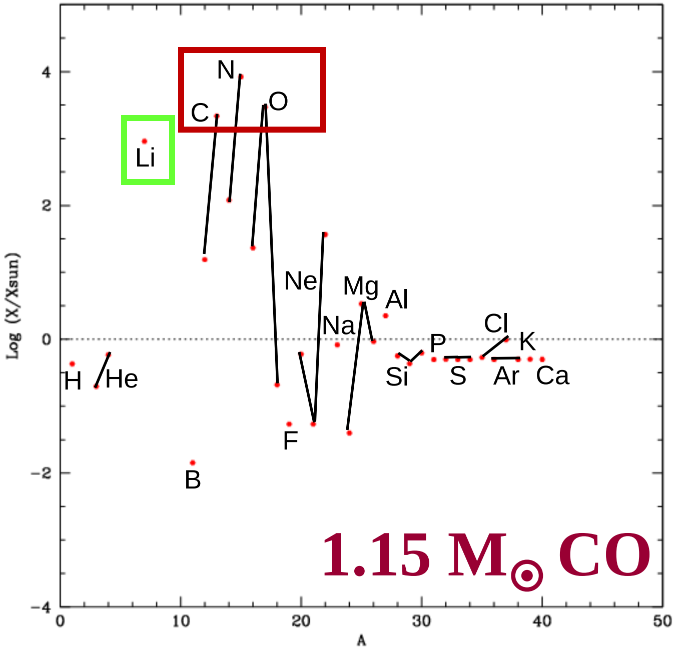
1.15 M☉ CO
Log (X/Xsun)
A
4
2
0
−2
−4
0
10
20
30
40
50
H
He
Li
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Mg
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Cl
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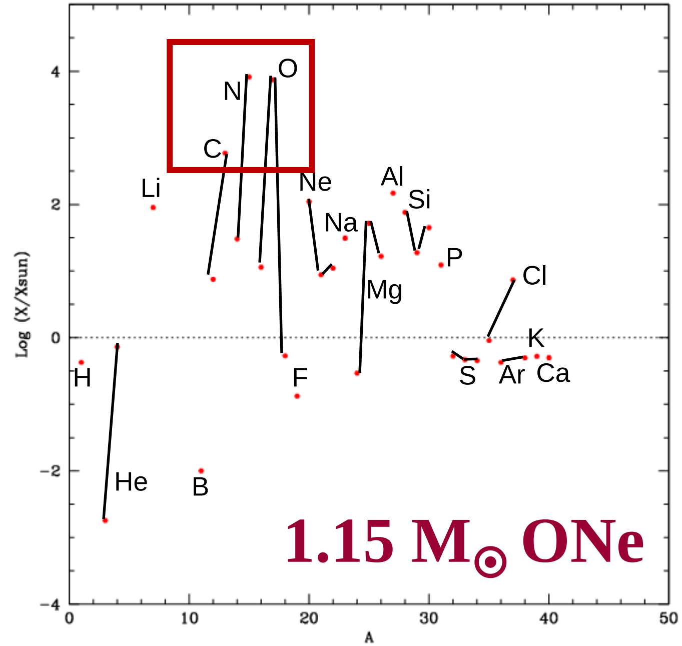
Ca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Log (X/Xsun)
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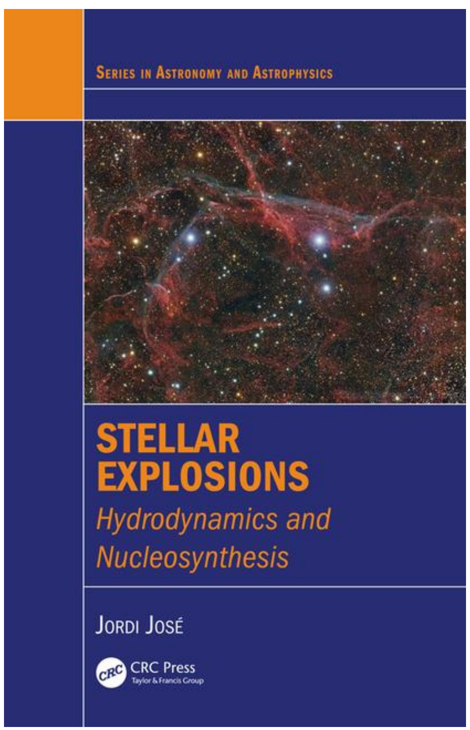
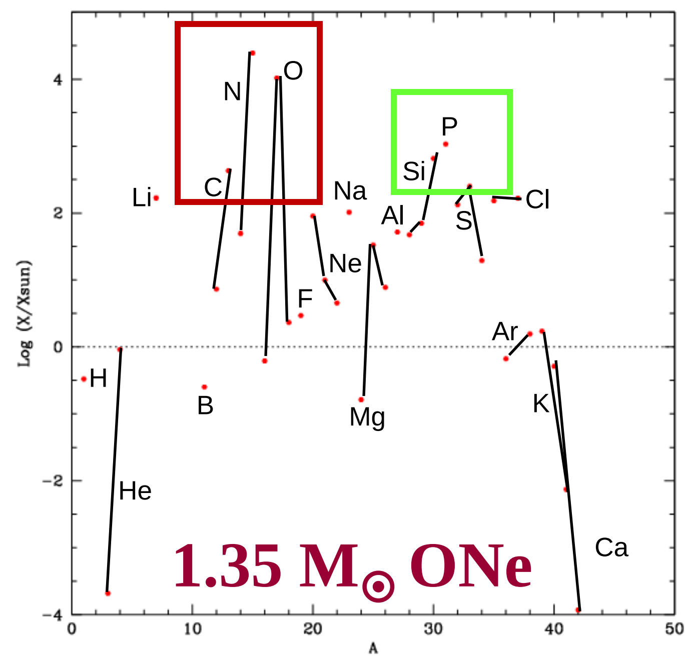

Series in Astronomy and Astrophysics
STELLAR EXPLOSIONS
Hydrodynamics and Nucleosynthesis
Jordi José
CRC Press
Taylor & Francis Group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Log (X/Xsun)
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H
He
Li
B
C
N
O
Na
Al
Ne
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Mg
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Si
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Cl
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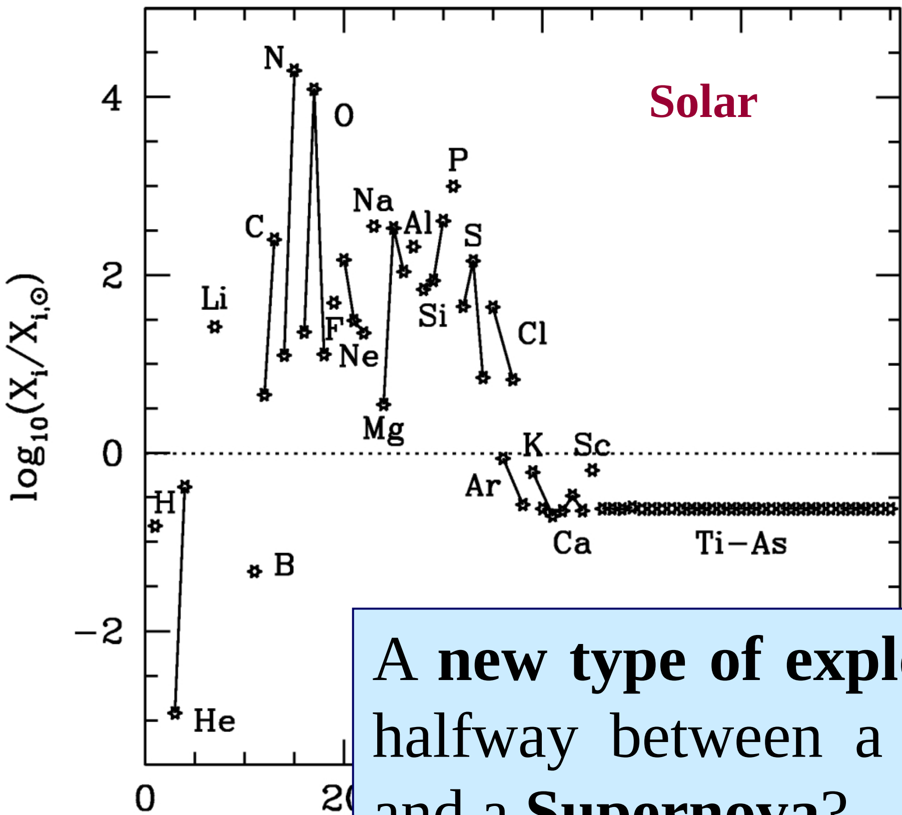
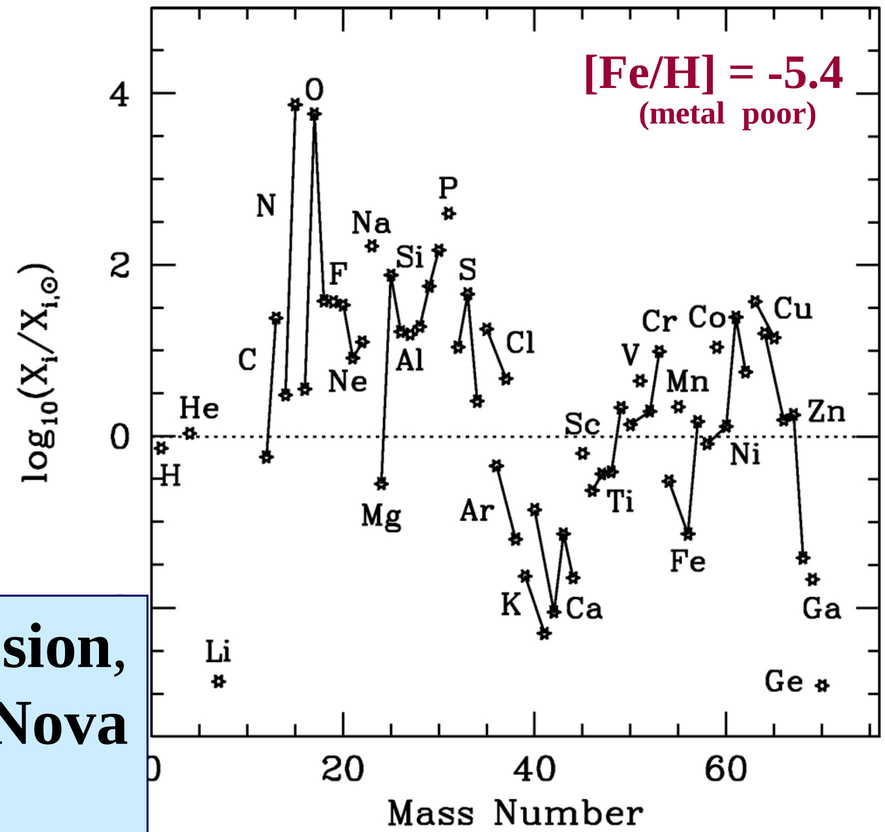
K
Ca

JJ (2016)

Primordial Novae: Nova-like, stellar explosions on white dwarfs evolved in a **cataclysmic primordial binary (Z_{ZAMS} ~ 0)**





A **new type of explosion**, halfway between a **Nova** and a **Supernova**?

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

γ-Ray Emission from Classical Novae

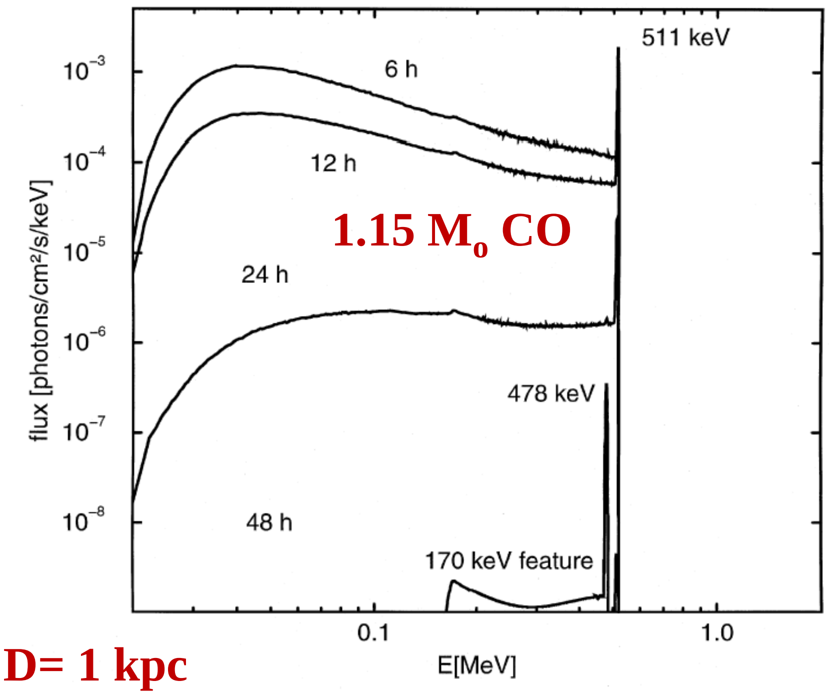
Isotope	Lifetime	Disintegration	Nova type
^{17}F	93 sec	β^+-decay	CO & ONe
^{14}O	102 sec	β^+-decay	CO & ONe
^{15}O	176 sec	β^+-decay	CO & ONe
^{13}N	862 sec	β^+-decay	CO & ONe
^{18}F	158 min	β^+-decay	CO & ONe
^{7}Be	77 day	e^--capture	CO
^{22}Na	3.75 yr	β^+-decay	ONe
^{26}Al	1.0 Myr	β^+-decay	ONe

* ^{14,15}O, ^{17}F (^{13}N): **Expansion and ejection stages**
* ^{13}N, ^{18}F: **Early** gamma-ray emission (**511 keV** plus continuum)
* ^{7}Be, ^{22}Na, ^{26}Al: Gamma-ray **lines**

^{18}F

* **γ-ray signature**: ^{18}F decay ($T_{1/2}$ **~ 110 min**) provides a source of gamma-ray emission at **511 keV and below** (related to electron-positron annihilation).

But! **Uncertainties** in the rates translate into a factor **~ 5 - 10** uncertainty in the expected fluxes!

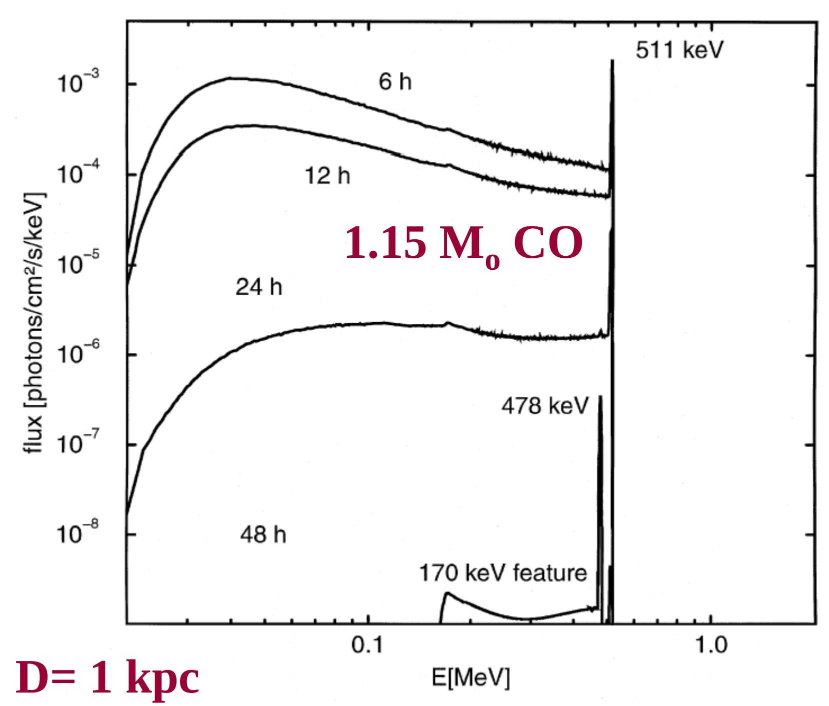


D= 1 kpc

Gómez-Gomar, Hernanz, JJ, & Isern (1998), MNRAS

^{7}Li

* γ-ray signature: **Peak fluxes** for the **478 keV γ-ray line** (transition: ^{7}Be to ^{7}Li) might be detectable by gamma-ray satellites (i.e. INTEGRAL) at **very short distances** (i.e., <**0.2 kpc**)



Gómez-Gomar, Hernanz, JJ, & Isern (1998), MNRAS

Observational evidence of ^{7}Li production in novae

* Li I doublet at 6708 A in the spectra of **V382 Vel** (Nova Velorum 1999) (Della Valle et al. 2002) and **V1369 Cen** (Nova Centauri 2013) (Izzo et al. 2015)
→ but hard to disentangle from other features, like the doublet associated with N I (Shore et al. 2003)

* Blueshifted ^{7}Be II (doublet at 3130 A) absorption lines in **V339 Del** (Nova Delphini 2013), **V5668 Sgr** (Nova Sagittarii 2015 #2), **V2944 Oph** (Nova Ophiuchi 2015) (Tajitsu et al. 2015, 2016; Molaro et al. 2016), and **V407 Lup** (Nova Lupi 2016) (Izzo et al. 2018)

A&A 615, A107 (2018)
https://doi.org/10.1051/0004-6361/201732514

Astronomy & Astrophysics

Gamma-ray observations of Nova Sgr 2015 No. 2 with INTEGRAL

Thomas Siegert[1,2], Alain Coc[3], Laura Delgado[4,5], Roland Diehl[1,2], Jochen Greiner[1], Margarita Hernanz[4,5], Pierre Jean[6], Jordi José[7,5], Paolo Molaro[8], Moritz M. M. Pleintinger[1], Volodymyr Savchenko[9], Sumner Starrfield[10], Vincent Tatischeff[3], and Christoph Weinberger[1]

No significant excess for the **478 keV**, the **511 keV**, or the **1275 keV** lines found

→ $M(^{7}Be) < 4.8\times10^{-9}\ d(kpc)^2\ M_\odot$
$M(^{22}Na) < 2.4\times10^{-8}\ d(kpc)^2\ M_\odot$

d ~ 1.6 kpc (Banerjee et al. 2016)

Novae: Nuclear Uncertainties

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

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

CHRISTIAN ILIADIS AND ART CHAMPAGNE
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SUMNER STARRFIELD
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AND

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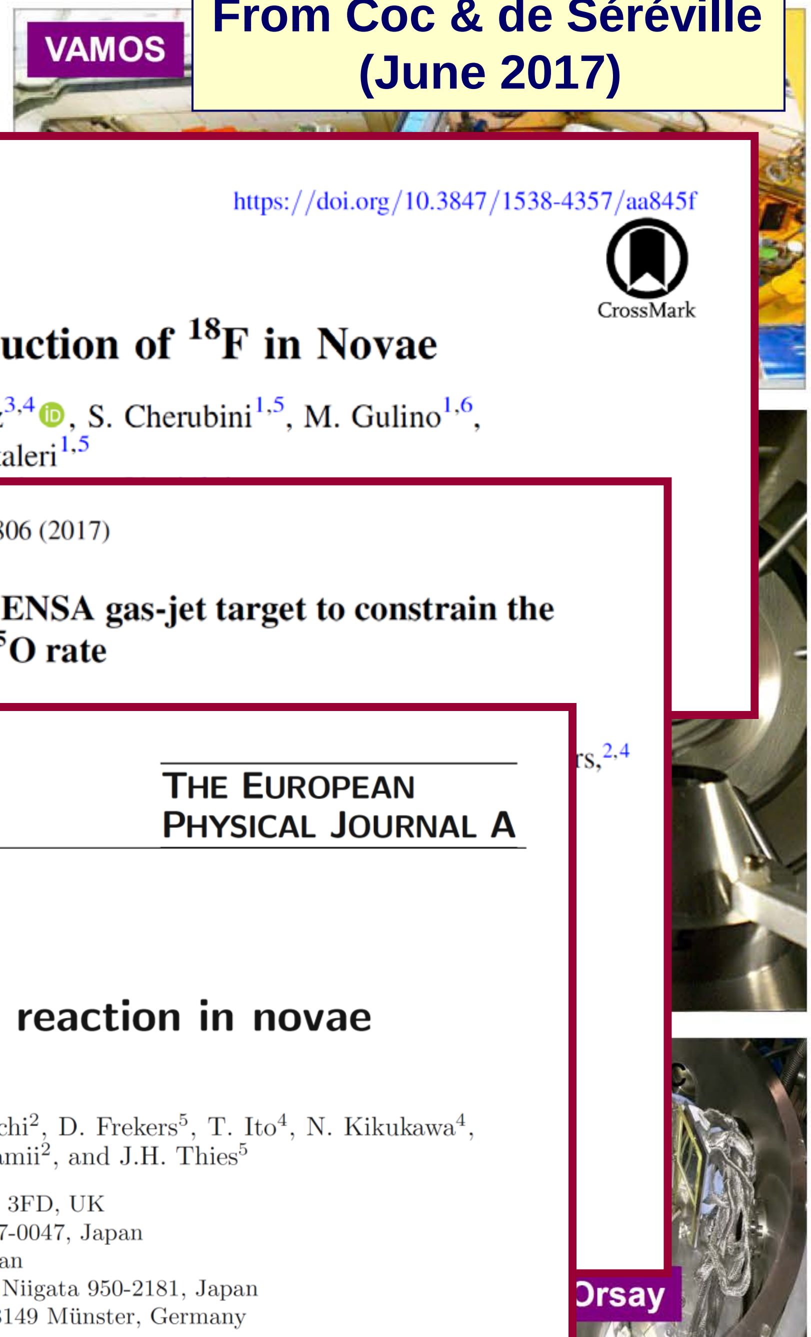
Received 2002 January 19; accepted 2002 April 25

$\approx$7350 nuclear reaction network calculations

Main nuclear uncertainties: [^{18}F(p,α)^{15}O, ^{25}Al(p,γ)^{26}Si, ^{30}P(p,γ)^{31}S]

^{18}F(p, α)



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)

Spectroscopic study of ^{20}Ne + p reactions using the JENSA gas-jet target to constrain the astrophysical ^{18}F(p,α)^{15}O rate

A. ... rs,[2,4]

Eur. Phys. J. A (2019) **55**: 4
DOI 10.1140/epja/i2019-12682-9

The European Physical Journal A

Letter

s-wave resonances for the ^{18}F(p, α)^{15}O reaction in novae

D. Kahl[1,a], P.J. Woods[1], Y. Fujita[2,3], H. Fujita[2,3], K. Abe[4], T. Adachi[2], D. Frekers[5], T. Ito[4], N. Kikukawa[4], M. Nagashima[4], P. Puppe[5], D. Sera[4], T. Shima[2], Y. Shimbara[4], A. Tamii[2], and J.H. Thies[5]

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[2] Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan
[3] Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
[4] Graduate School of Science and Technology, Niigata University, Nishi-ku, Niigata 950-2181, Japan
[5] Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, D-48149 Münster, Germany

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Still diff

^{30}P(p, γ)

Physics Letters B 769 (2017) 549–553

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Measurement of key resonance states for the $^{30}P(p,\gamma)^{31}S$ reaction rate, and the production of intermediate-mass elements in nova explosions

A. Kankainen [a,*,1], P.J. Woods [a], H. Schatz [b,c,d], T. Poxon-Pearson [b,c,d], D.T. Doherty [a,2], V. Bader [b,c], T. Baugher [b,3], D. Bazin [b], B.A. Brown [b,c,d], J. Browne [b,c,d], A. Estrade [a,4], A. Gade [b,c], J. José [e,f], A. Kontos [b], C. Langer [b,5], G. Lotay [a,2], Z. Meisel [b,c,d,6], F. Montes [b,d], S. Noji [b], F. Nunes [b,c,d], G. Perdikakis [d,g], J. Pereira [b,d], F. Recchia [b,7], T. Redpath [g], R. Stroberg [b,c], M. Scott [b,c], D. Seweryniak [h], J. Stevens [b,d], D. Weisshaar [b], K. Wimmer [g,8], R. Zegers [b,c,d]

^{25}Al(p, γ)

PHYSICAL REVIEW C **92**, 035808 (2015)

Structure of resonances in the Gamow burning window for the $^{25}\mathrm{Al}(p,\gamma)^{26}\mathrm{Si}$ reaction in novae

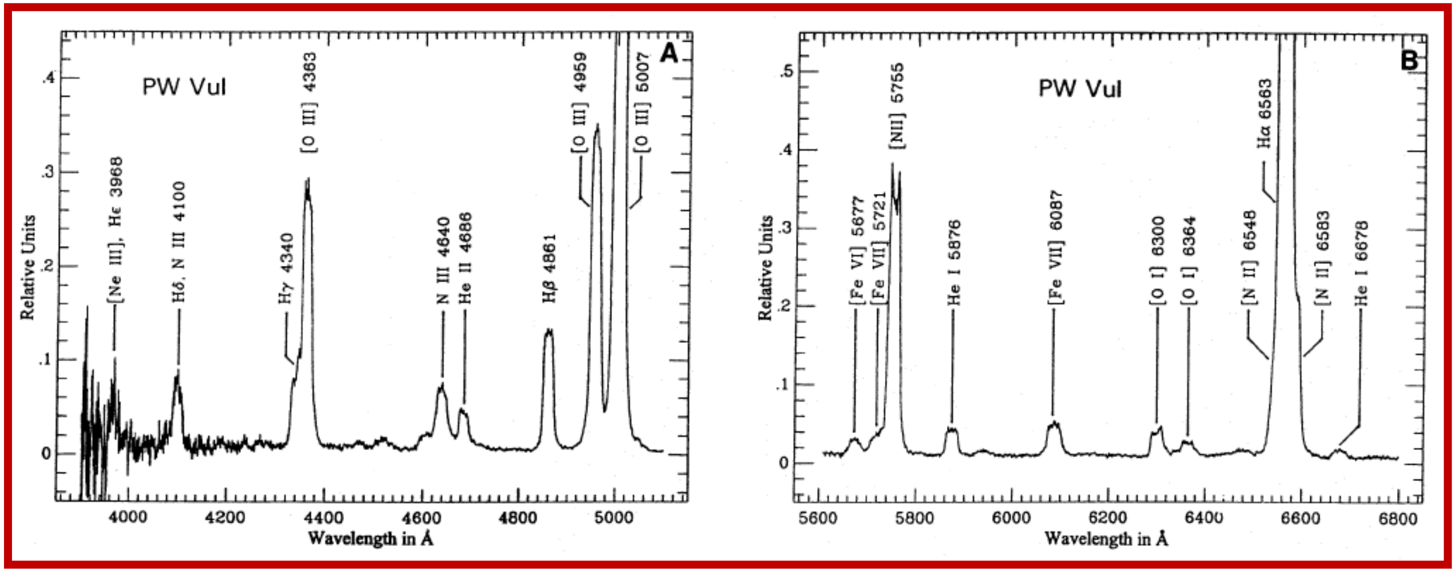
D. T. Doherty,[1,2] P. J. Woods,[1] D. Seweryniak,[3] M. Albers,[3,*] A. D. Ayangeakaa,[3] M. P. Carpenter,[3] C. J. Chiara,[3,4,†] H. M. David,[3] J. L. Harker,[3,4] R. V. F. Janssens,[3] A. Kankainen,[1] C. Lederer,[1] and S. Zhu[3]

[1]*School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[2]*CEA, Centre de Saclay, IRFU/Service de Physique Nucléaire, F-91191 Gif-sur-Yvette, France*
[3]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[4]*Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA*

(Received 8 July 2015; published 17 September 2015)

Observational Constraints

In situ observations (highly risky...)



Andrëa et al. (1994)

PW Vul 1984

	H	He	C	N	O	Ne	Na-Fe	Z
Observation	0.47	0.23	0.073	0.14	0.083	0.0040	0.0048	0.30
Theory	0.47	0.25	0.073	0.094	0.10	0.0036	0.0037	0.28

(JJ & Hernanz 1998)

THE ASTROPHYSICAL JOURNAL, 551:1065–1072, 2001 April 20

Presolar Grains

PRESOLAR GRAINS FROM NOVAE

SACHIKO AMARI, XIA GAO,[1] LARRY R. NITTLER,[2] AND ERNST ZINNER
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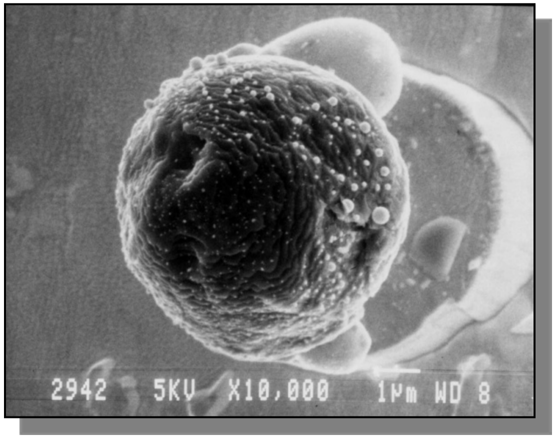
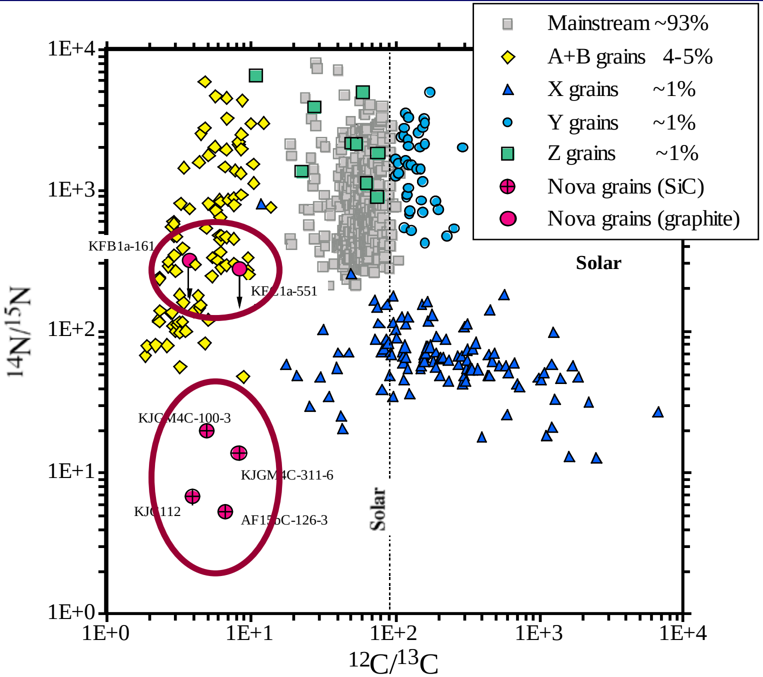
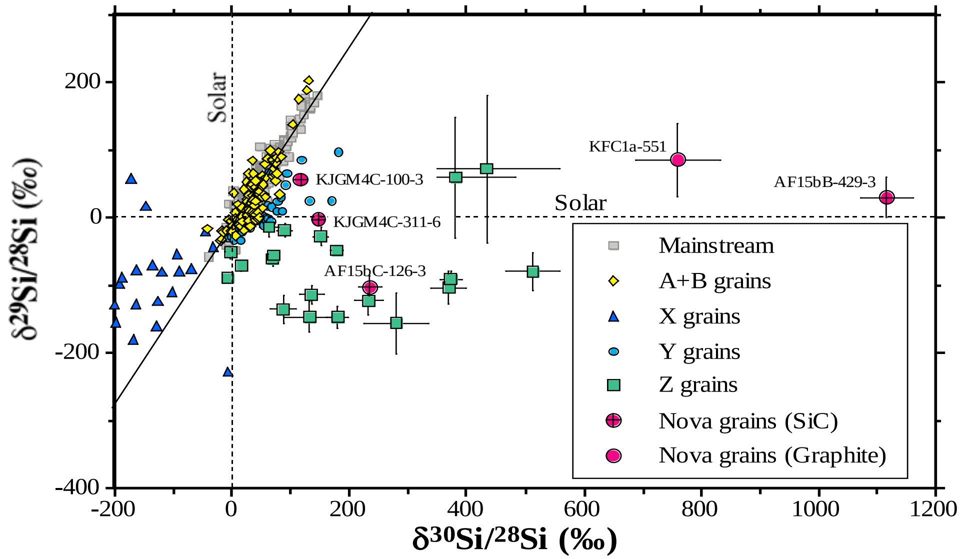
Enrico Fermi Institute, University of Chicago, Chicago, IL 60637-1433; r-lewis@uchicago.edu
Received 2000 September 15; accepted 2000 December 18







Recent updates on putative nova grains: identification of 18 presolar nova candidates among the inventory of grains

The Astrophysical Journal, 855:76 (14pp), 2018 March 10
https://doi.org/10.3847/1538-4357/aaabb6

CrossMark

On Presolar Stardust Grains from CO Classical Novae

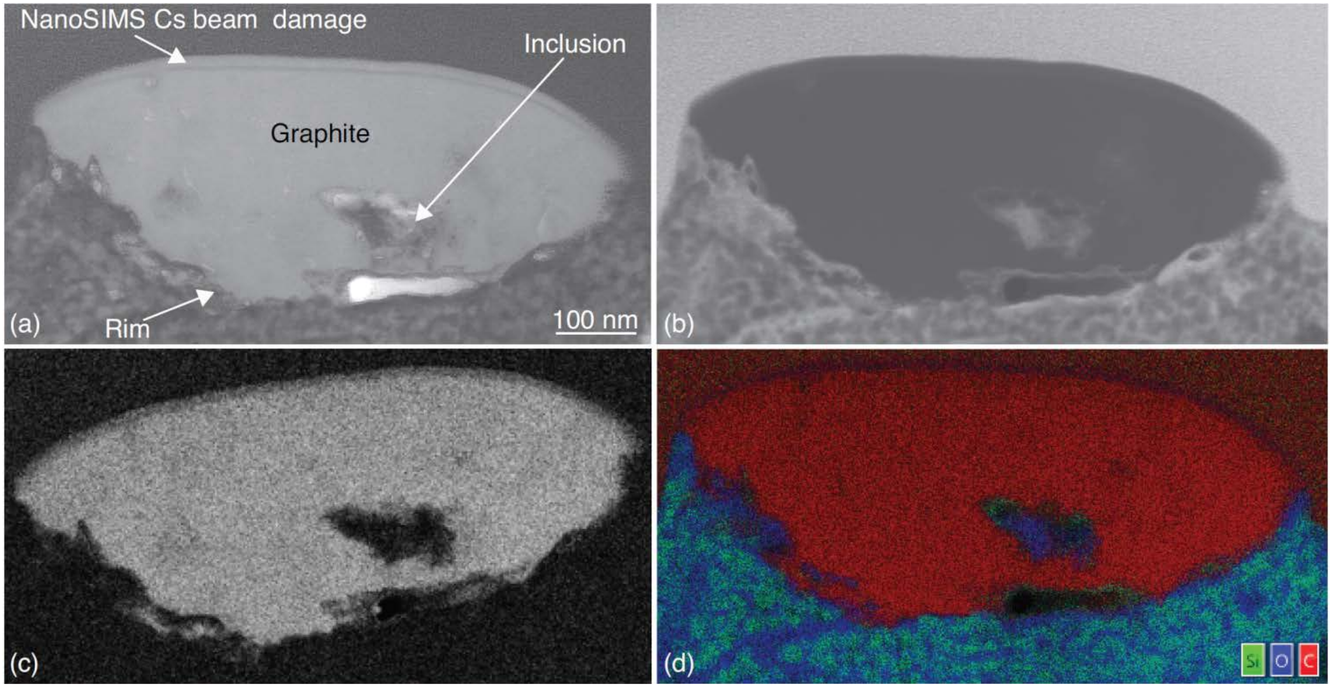
Christian Iliadis[1,2], Lori N. Downen[1,2], Jordi José[3,4], Larry R. Nittler[5], and Sumner Starrfield[6]
[1] Department of Physics & Astronomy, University of North Carolina, Chapel Hill, NC 27599-3255, USA; iliadis@unc.edu
[2] Triangle Universities Nuclear Laboratory, Durham, NC 27708-0308, USA
[3] Departament de Física, EEBE, Universitat Politècnica de Catalunya, c/Eduard Maristany 10, E-08930 Barcelona, Spain
[4] Institut d'Estudis Espacials de Catalunya, c/Gran Capità 2-4, Ed. Nexus-201, E-08034 Barcelona, Spain
[5] Department of Terrestrial Magnetism, Carnegie Institution for Science, Washington, DC 20015, USA
[6] Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-1404, USA
Received 2017 December 15; revised 2018 January 26; accepted 2018 January 28; published 2018 March 9

nature astronomy
LETTERS
https://doi.org/10.1038/s41550-019-0757-4

Laboratory evidence for co-condensed oxygen- and carbon-rich meteoritic stardust from nova outbursts

Pierre Haenecour[1*], Jane Y. Howe[2,9], Thomas J. Zega[1,3], Sachiko Amari[4,5], Katharina Lodders[5,6], Jordi José[7], Kazutoshi Kaji[8], Takeshi Sunaoshi[2] and Atsushi Muto[2]

April 2019



"12321" Models

1D (Spherically Symmetric) Models have been successful in reproducing the *gross* observational features that characterize Classical Nova outbursts (e.g., light curves, nucleosynthesis...)

But the assumption of spherical symmetry excludes an entire sequence of events, such as the way a **TNR initiates** (point-like ignition) and **propagates**

Ex. The long-term evolution of a classical nova requires to address the **interaction** between the nova ejecta, the disk and the stellar companion

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

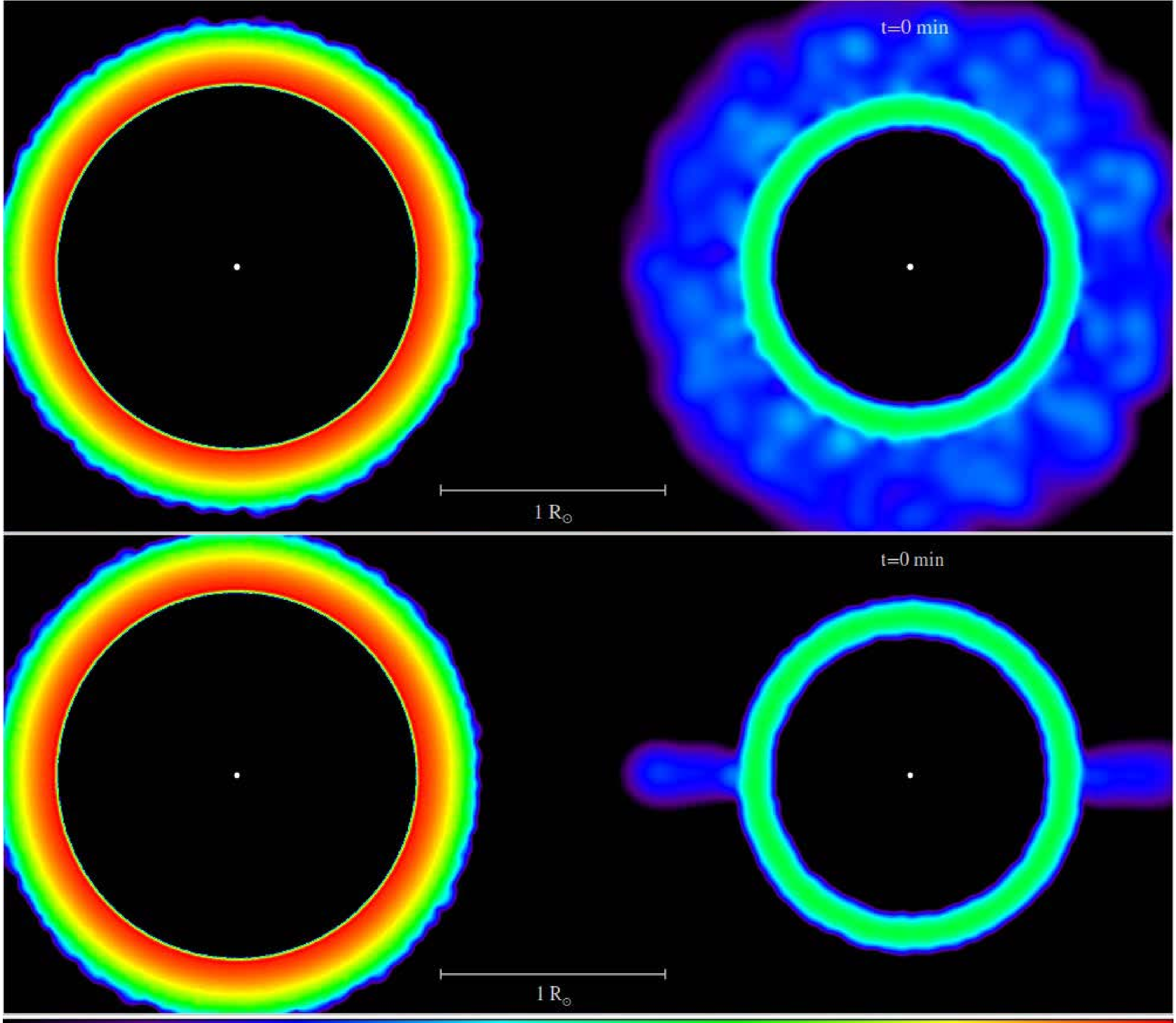
Astronomy & Astrophysics

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

Joana Figueira[1,2], Jordi José[1,2], Enrique García-Berro[2,3], Simon W. Campbell[4,5,6], Domingo García-Senz[1,2], and Shazrene Mohamed[7,8,9]

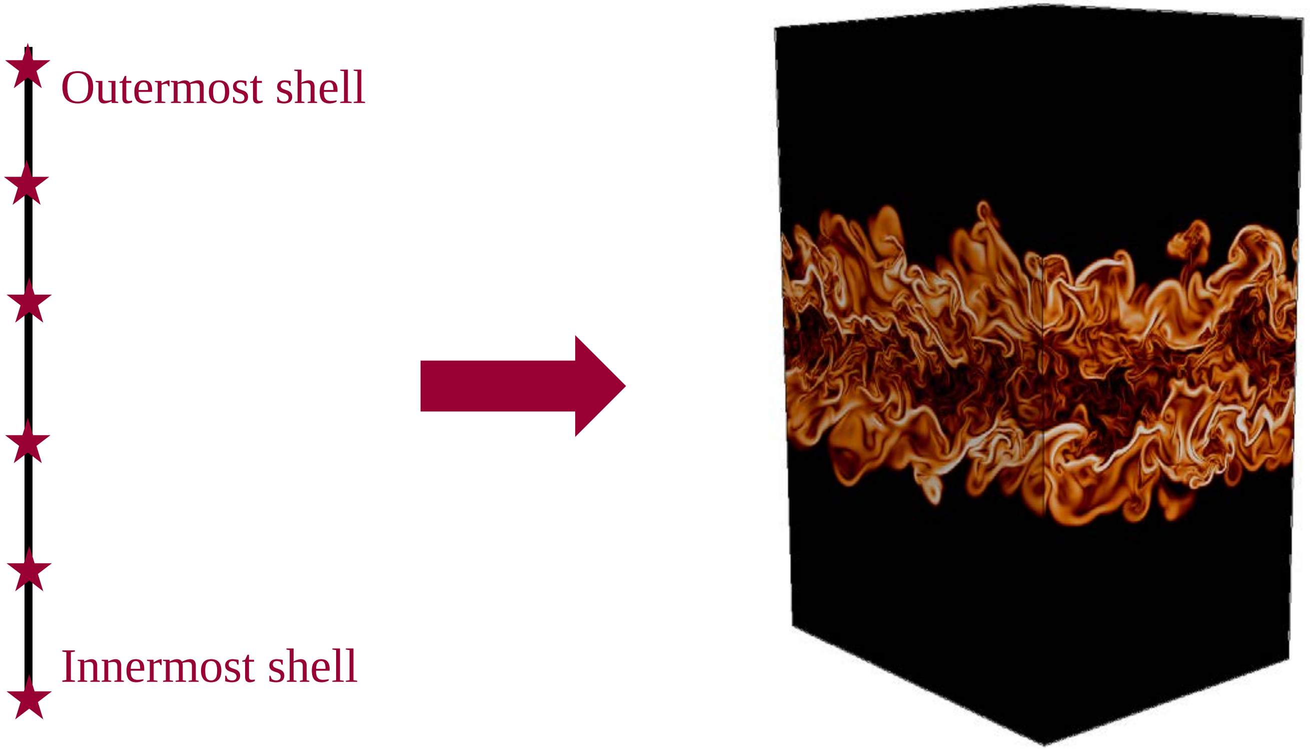
XY
Plane

YZ
Plane



Interest of **multiD models:** to improve state-of-the-art, 1-D models with large nuclear reaction networks

a) "123" (or *1 to 3*) Models: 1D simulation of accretion and early stages of the TNR → mapping onto a 3D domain



b) "convection-in-a-box/cube" studies: multiD simulations

Multidimensional Models @ UPC Barcelona

2D Simulations

A&A 513, L5 (2010)
DOI: 10.1051/0004-6361/201014178

Astronomy & Astrophysics

LETTER TO THE EDITOR

On mixing at the core-envelope interface during classical nova outbursts

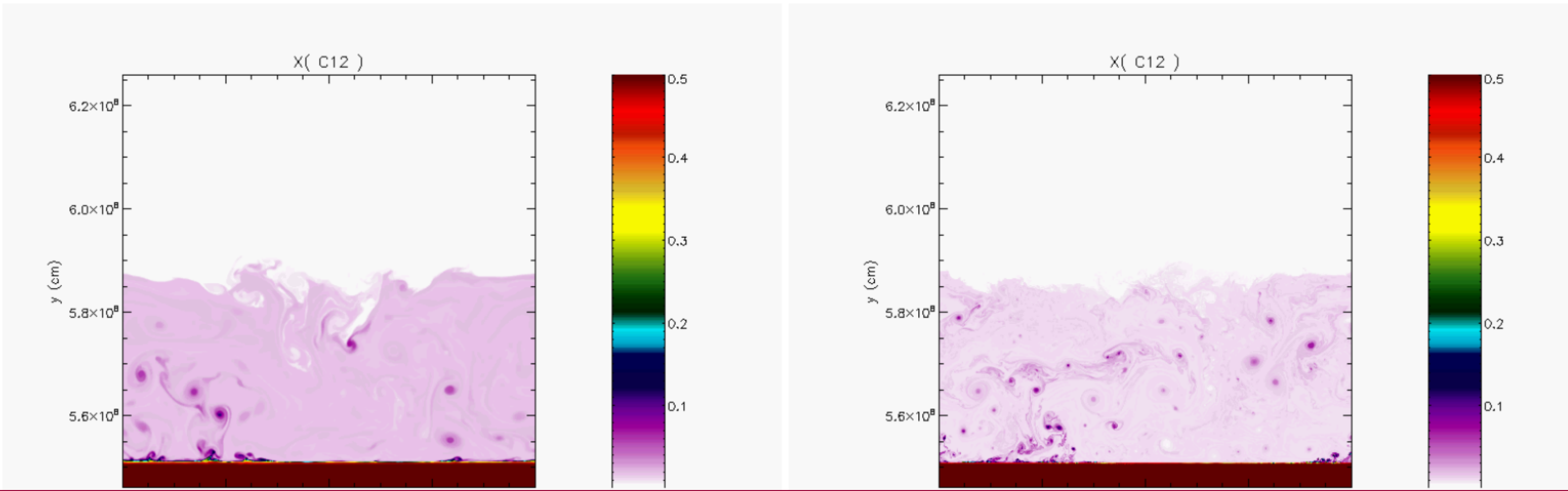
J. Casanova[1], J. José[1], E. García-Berro[2], A. Calder[3], and S. N. Shore[4]

A&A 527, A5 (2011)
DOI: 10.1051/0004-6361/201015895

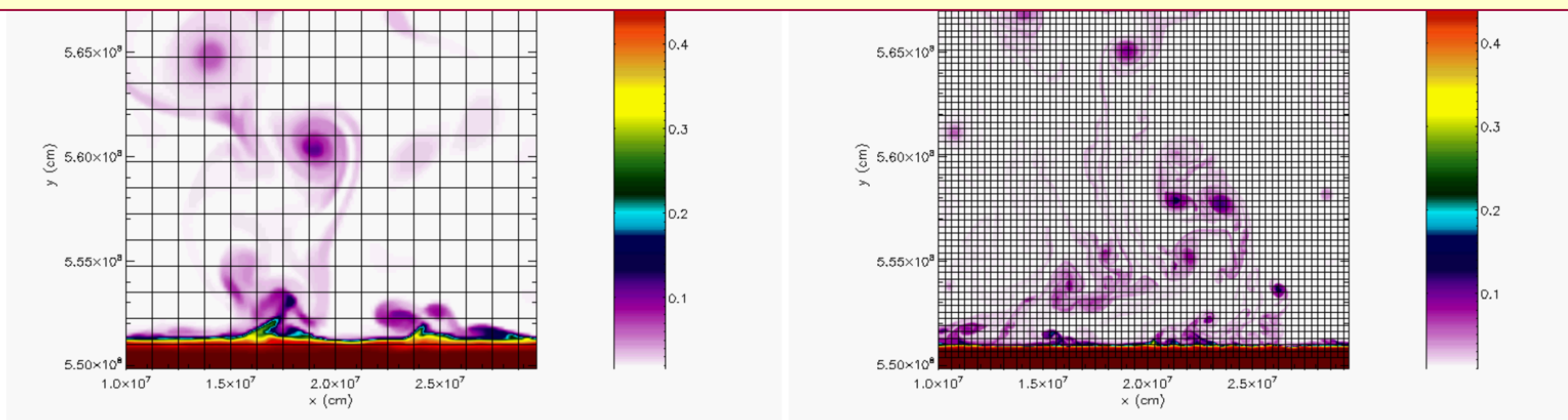
Astronomy & Astrophysics

Mixing in classical novae: a 2-D sensitivity study★

J. Casanova[1,2], J. José[1,2], E. García-Berro[3,2], A. Calder[4], and S. N. Shore[5]



Results are **independent** of the specific choice of the **initial perturbation** (duration, strength, location, and size), **the resolution adopted**, or the **size of the computational domain**



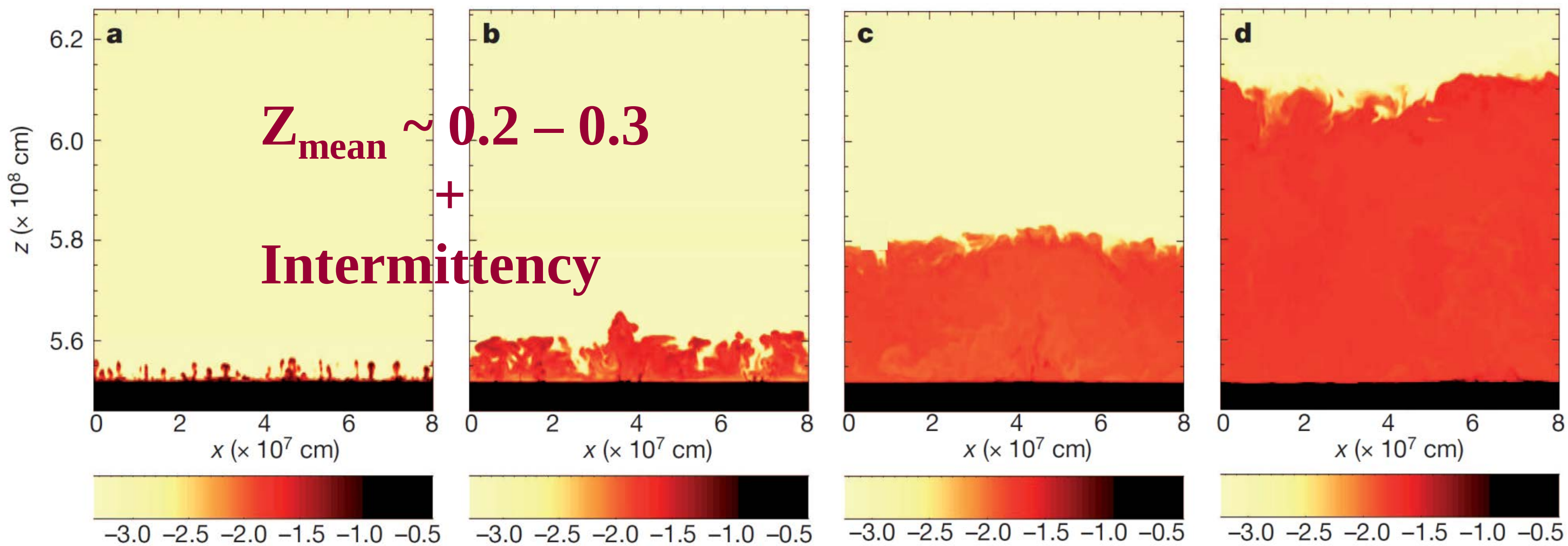
3D Models of Mixing

LETTER

doi:10.1038/nature10520

Kelvin–Helmholtz instabilities as the source of inhomogeneous mixing in nova explosions

Jordi Casanova[1,2], Jordi José[1,2], Enrique García-Berro[3,2], Steven N. Shore[4] & Alan C. Calder[5]



$Z_{mean} \sim 0.2 – 0.3$

+

Intermittency

490 | NATURE | VOL 478 | 27 OCTOBER 2011

Kelvin-Helmholtz instabilities

Casanova, JJ, García-Berro, Shore & Calder (2011), Nature


MareNostrum II (BSC, 2006), 94.21 Tflops/s, 10,240 cores
MareNostrum III (BSC, Jan. 2013), >1 Petaflop/s, 48,000 cores
MareNostrum IV (BSC, Jun. 2017), >11 Petaflop/s, 165,888 cores

A&A 619, A121 (2018)
https://doi.org/10.1051/0004-6361/201833422

Astronomy & Astrophysics

Two-dimensional simulations of mixing in classical novae: The effect of white dwarf composition and mass★

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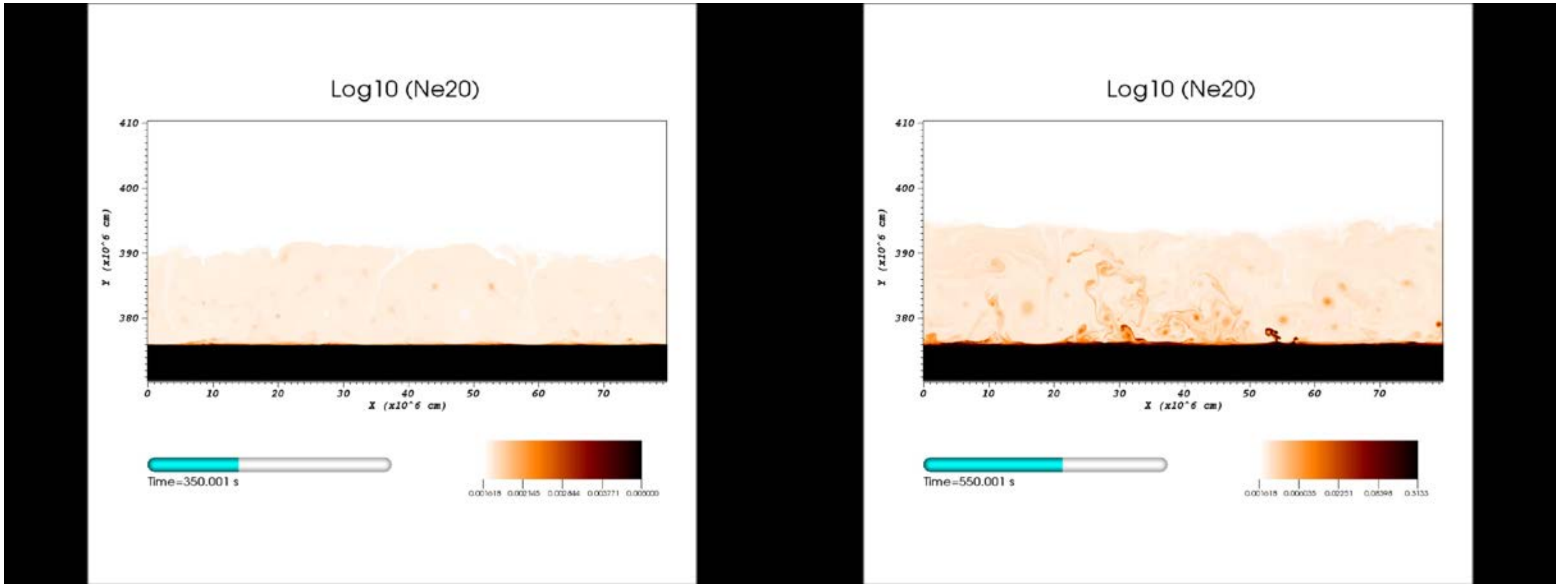
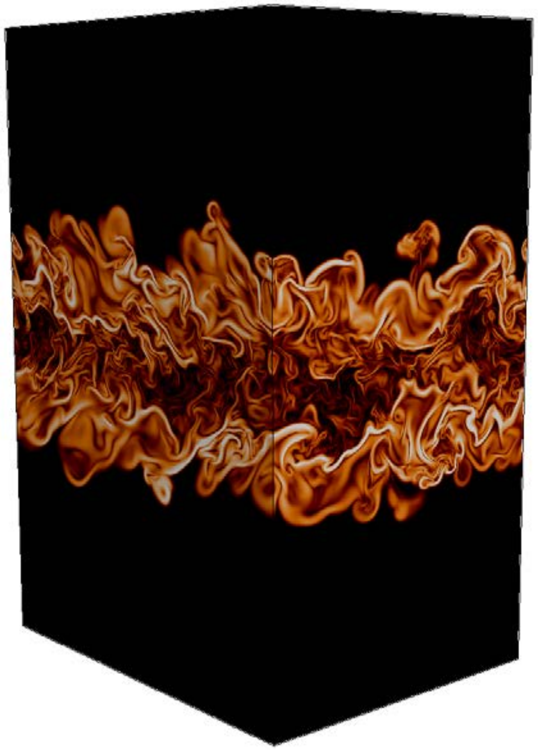
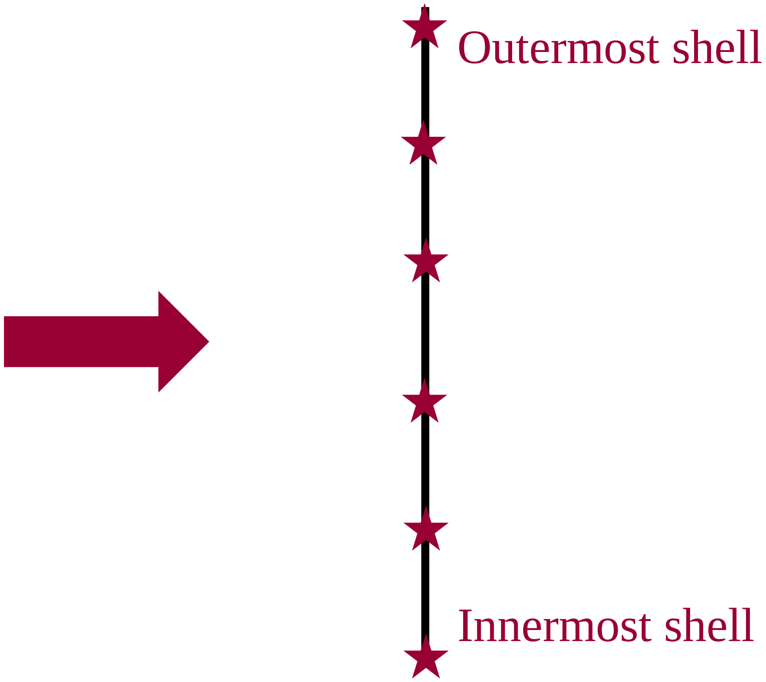


c) "321" (or *3 to 1*) Models: prescriptions of 3D turbulent convection (**v_{conv}(t), $m_{dredge\text{-}up}$(t), ...**) are implemented in 1D simulations to follow the final stages of a nova (expansion and ejection)





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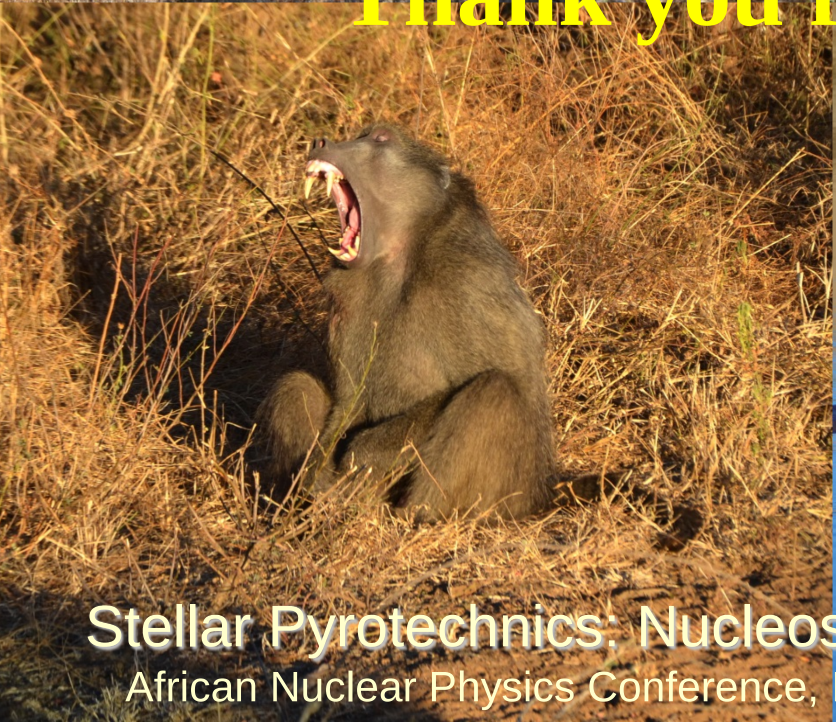
Thank you for your attention!



Stellar Pyrotechnics: Nucleosynthesis in Classical Nova Explosions

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