Explosive Events in the Universe and H-Burning

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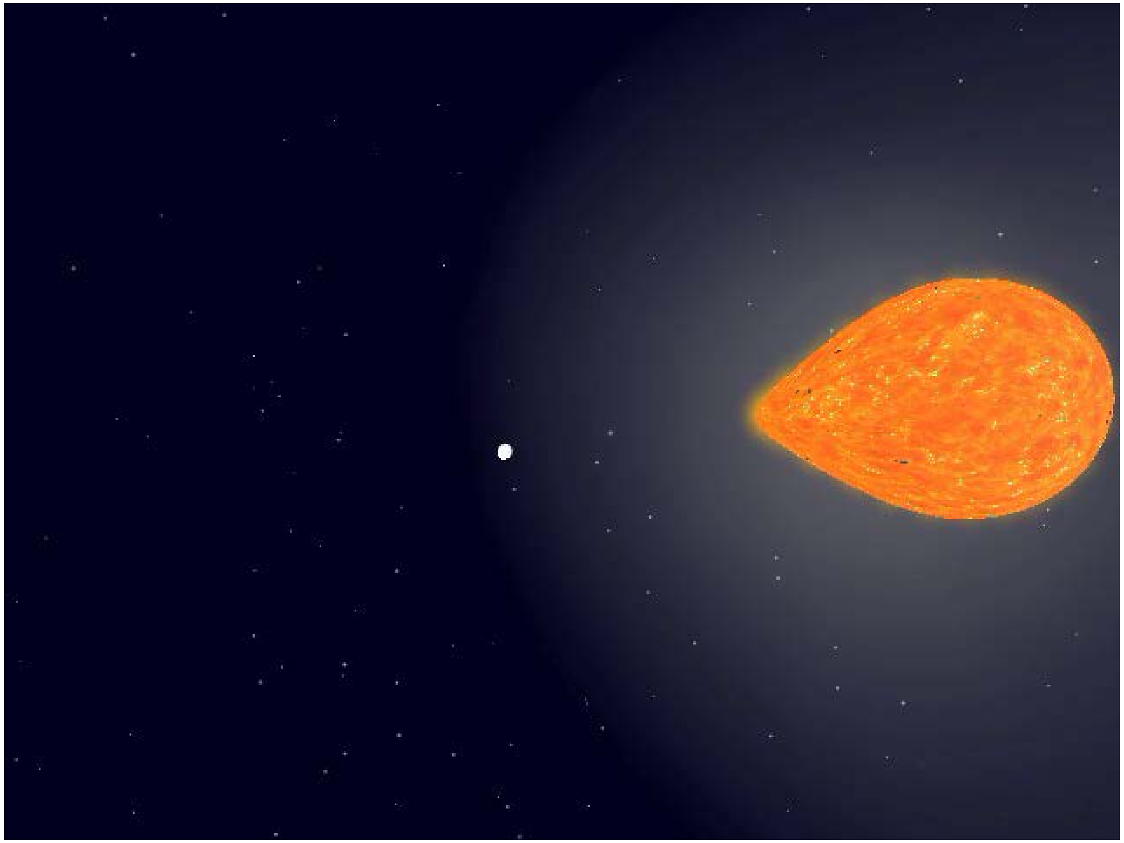
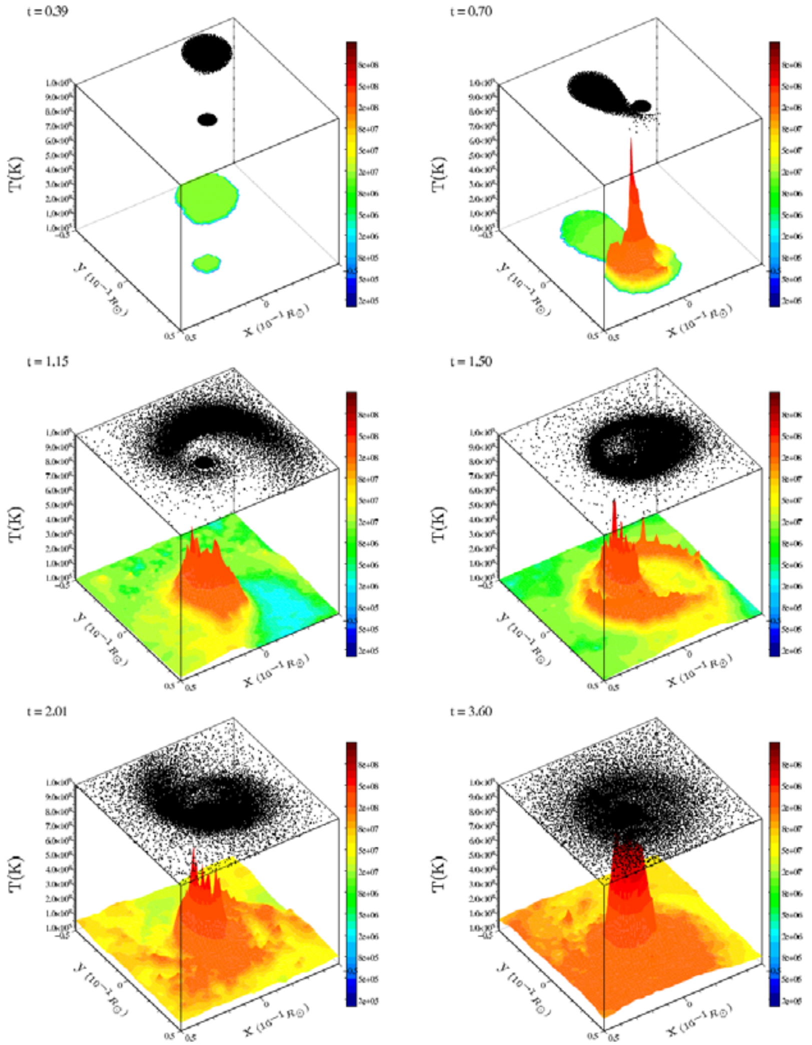


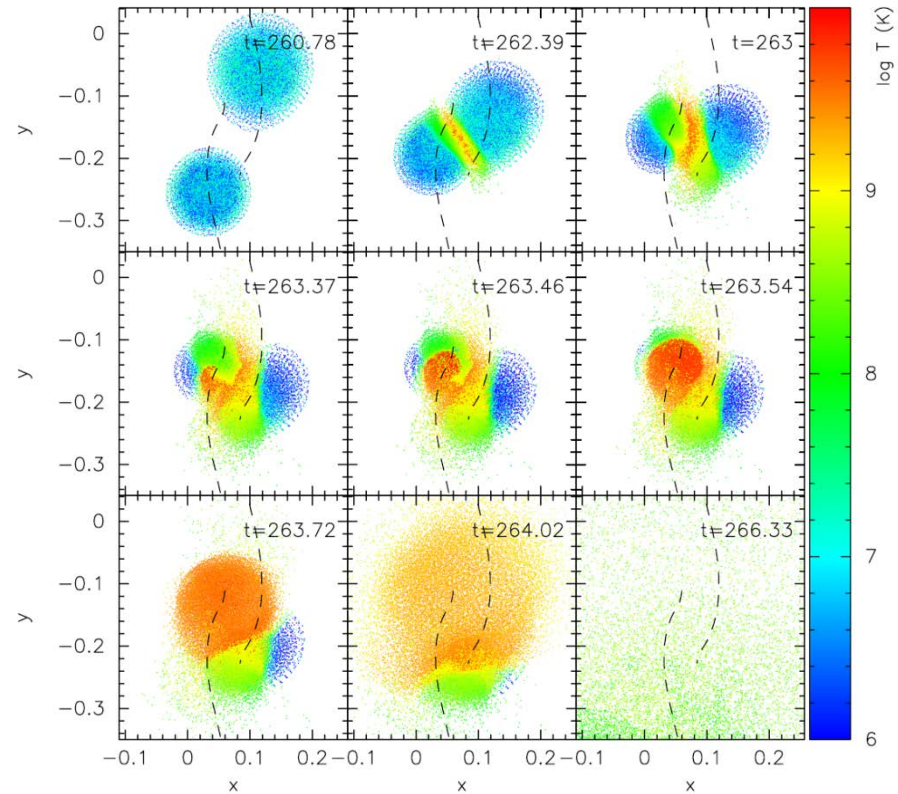
Type Ia (or thermonuclear) **Supernovae** [SN Ia]
Classical Nova Outbursts [CN]
} WD

X-Ray Bursts [XRBs]: NS

Stellar Mergers and Collisions



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



Detonations in white dwarf dynamic interactions
Aznar-Siguán, García-Berro, Lorén-Aguilar, JJ & Isern, MNRAS (2013)

f ~ f(SNIa in spiral galaxies)

I. Type Ia Supernovae

Thermonuclear Supernovae

v ~ 10^4 km/s, L_{Peak} ~ 10^{10} $L_\odot$, E ~ 10^{51} erg, M_{ej} = 1.4 $M_\odot$
no remnant left

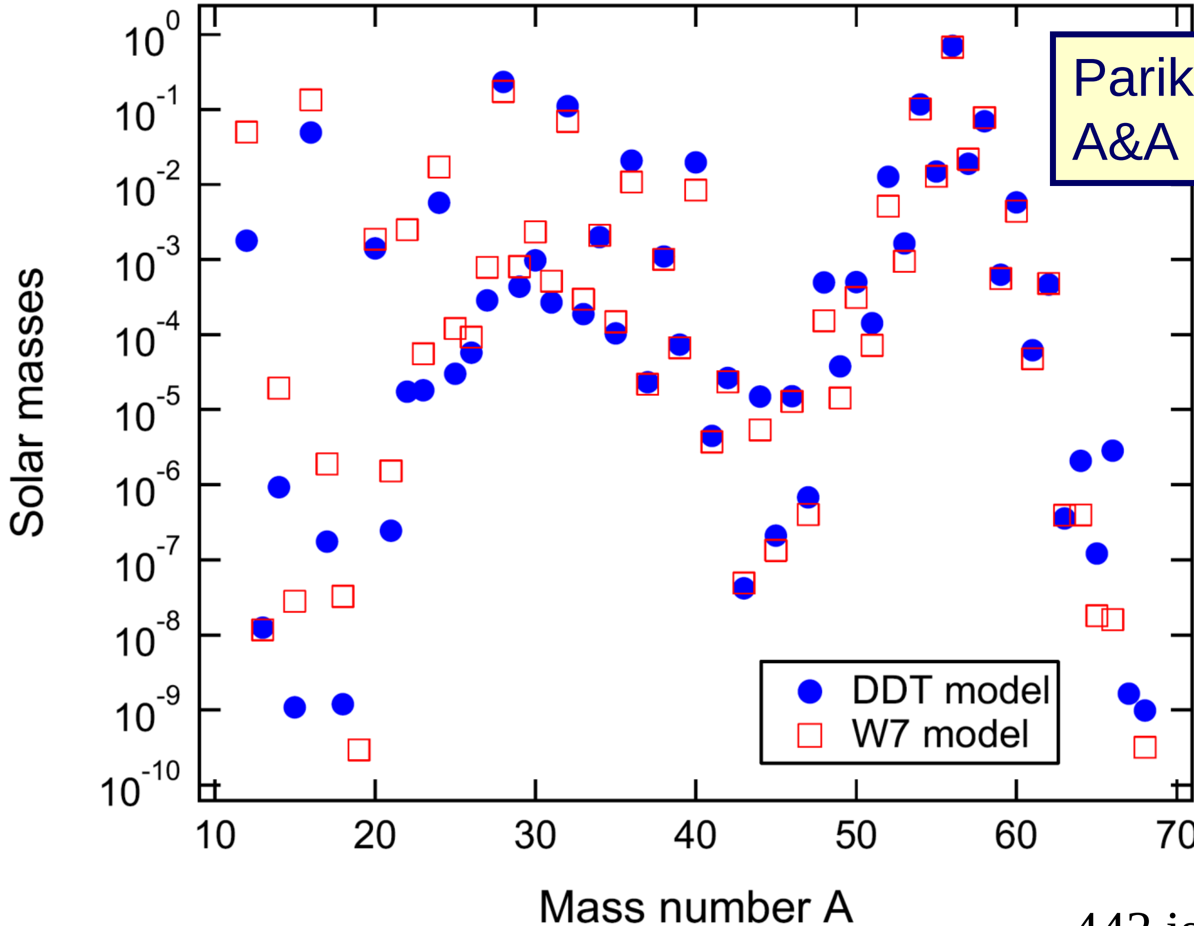
* **homogeneity:** ~70% of all **SN Ia** have similar spectra, light curves and peak absolute magnitudes (Li et al. 2011): **diversity of SNIa progenitors??**

* main **Fe factories** in the Universe (> SN II)

* Scenario: not fully understood
  - Single degenerate scenario: **WD + 'Normal' companion** (H or He accretion)
  - Double degenerate scenario: **WD + WD** (He or C-O accretion)

Thermonuclear Supernovae: Nucleosynthesis

Supernovae are crucial for life... But never get too close!



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

443 isotopes (H − Kr); 5267 links

Nuclear Uncertainties

	W7	DDT	W7+DDT
Reaction	Importance		
	Case A	Case B	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

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

II. Classical Novae

Novae have been observed in all wavelengths (but detected in γ-rays only at E > 100 MeV)

The Classical Nova ID Card

Moderate rise times (<1 – 2 days):

8 – 18 magnitude increase in brigthness

$L_{Peak} \sim 10^4 - 10^5 L_\odot$

Stellar binary systems: WD + MS (often, K-M dwarfs)

Recurrence time: ~ 10 yr (RNe) – 10^5 yr (CNe)

Frequency: 30 ± 10 yr^{-1}

Observed frequency: ~ 5 yr^{-1}

E ~ 10^{45} ergs

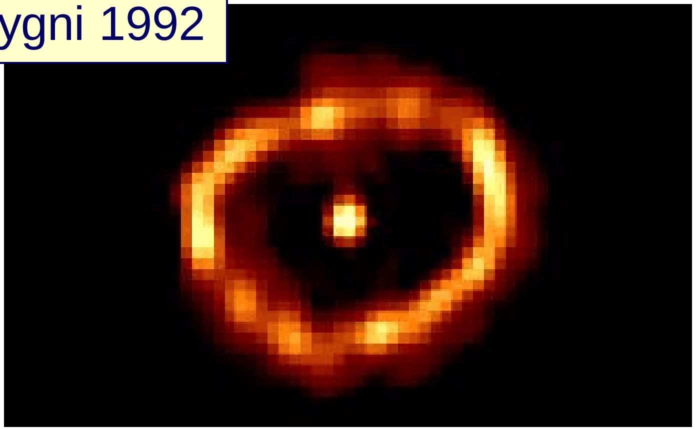
Mass ejected: $10^{-4} - 10^{-5} M_\odot$ (~10^3 km s^{-1})

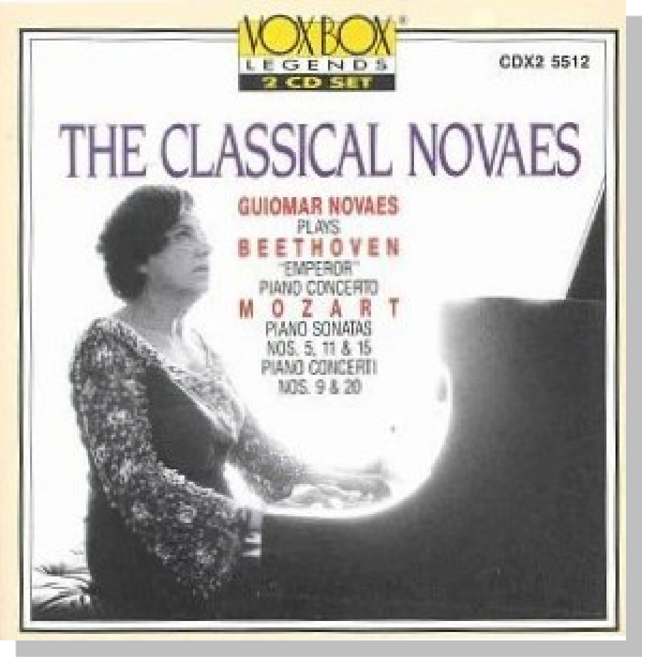
Nova Cygni 1975

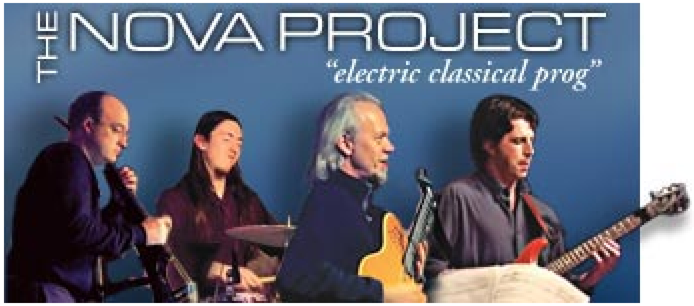
The Nova Nuclear Symphony

Classical Novae: ~**100** relevant isotopes **(A<40)** & a **(few) hundred** nuclear reactions **(T_{peak} ~ 100 – 400 MK)**

Nova Cygni 1992







Novae as **unique stellar explosions** for which the nuclear physics input is (will be) primarily based on <u>experimental information</u> (JJ, Hernanz & Iliadis, Nucl. Phys. A 2006)

Model 1.35 $M_\odot$
(50% ONe enrichment)

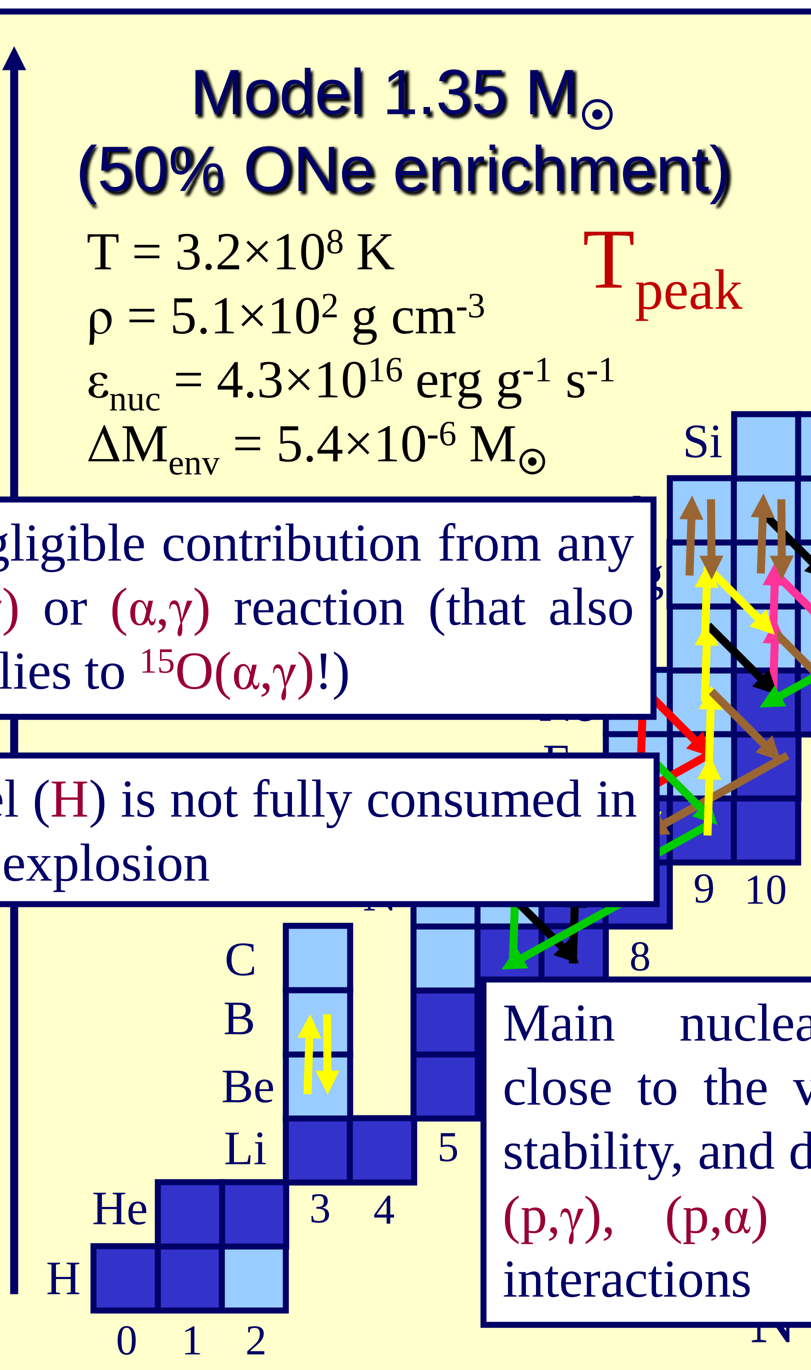
$T = 3.2\times10^{8}$ K

$\rho = 5.1\times10^{2}$ g cm^{-3}

$\varepsilon_{nuc} = 4.3\times10^{16}$ erg g^{-1} s^{-1}

$\Delta M_{env} = 5.4\times10^{-6}\ M_\odot$

T_{peak}



Endpoint ~ Ca

No heavy metals produced!

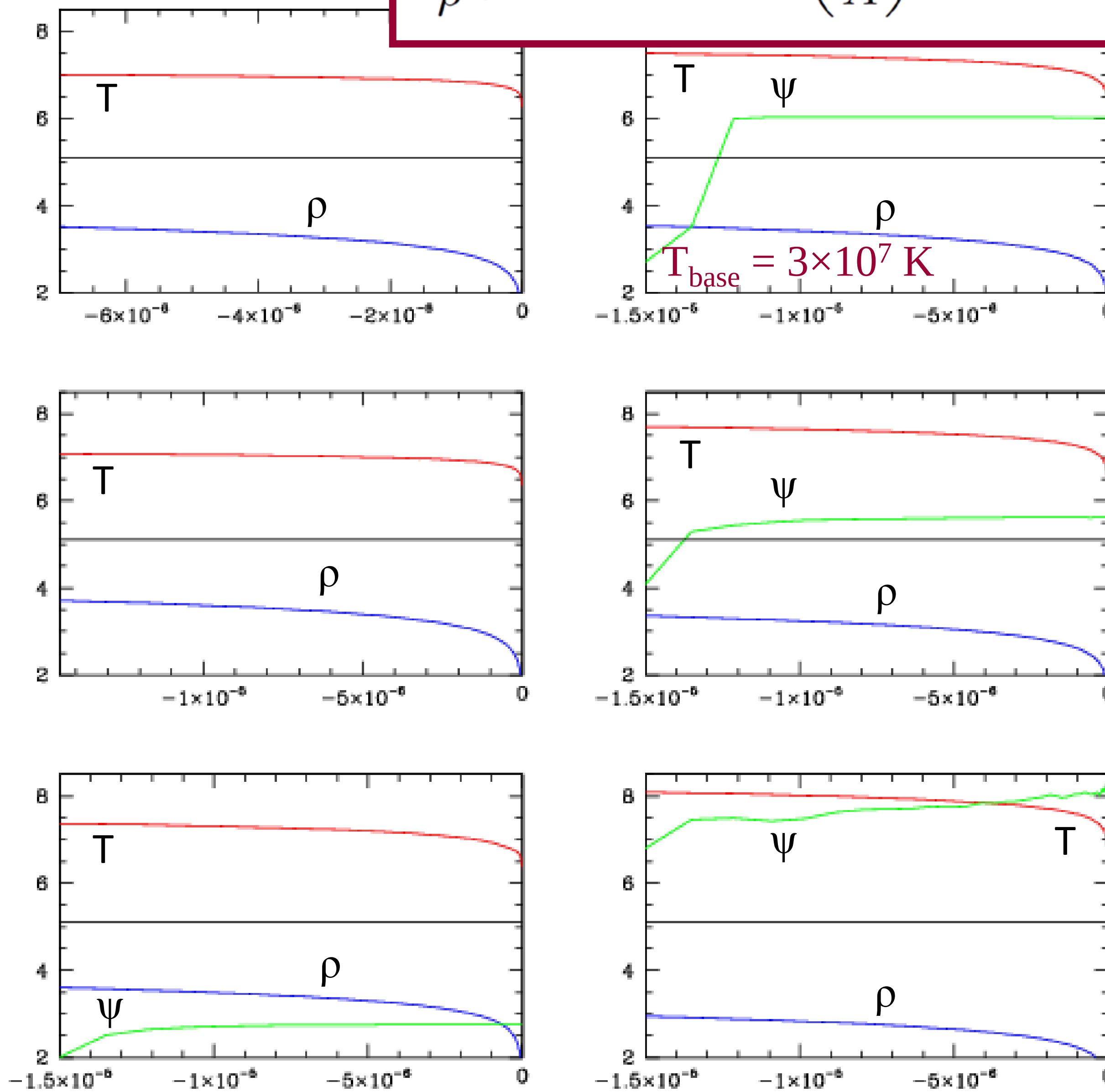
Negligible contribution from any (n,γ) or (α,γ) reaction (that also applies to $^{15}O(\alpha,\gamma)$!)

Fuel (H) is not fully consumed in the explosion

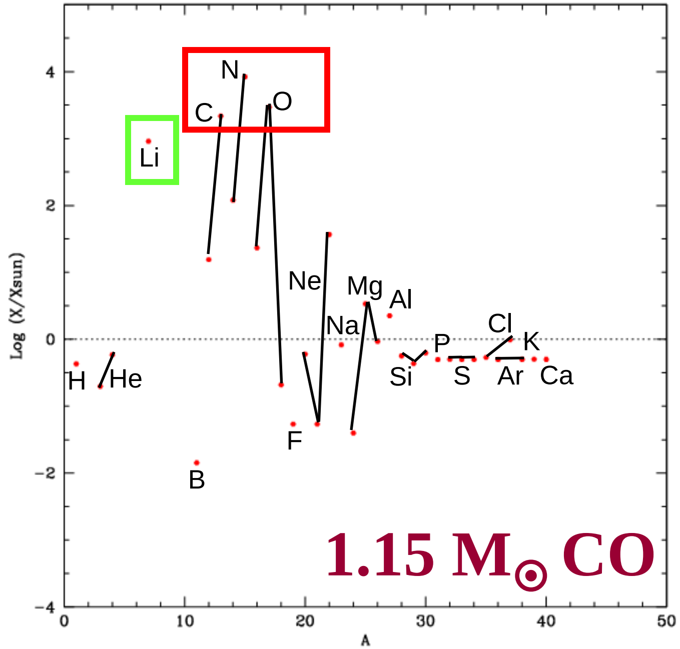
Main nuclea[...] close to the v[...] stability, and d[...] (p,γ), (p,α) and β[...] interactions

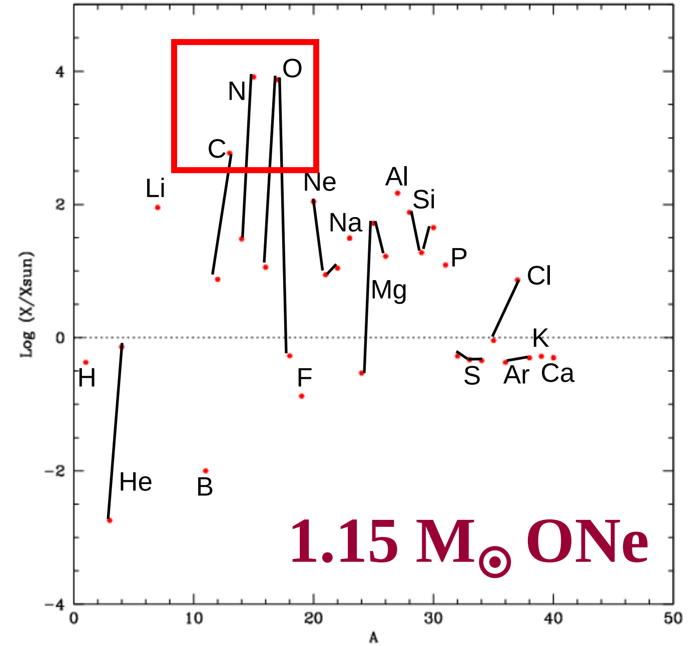
Degeneracy Lifting

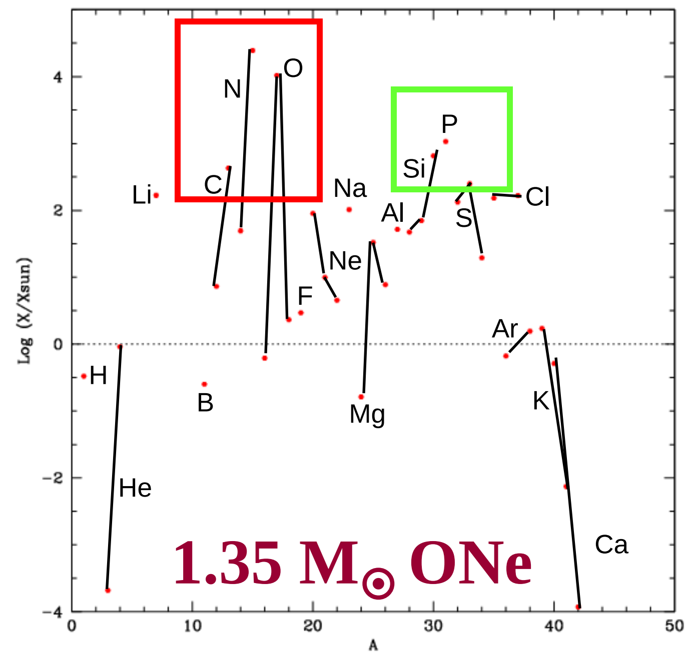
$$\frac{T}{\rho^{2/3}} < 1.3 \times 10^5 \left(\frac{Z}{A}\right)^{2/3} \mathrm{K\,cm^2\,g^{-2/3}}$$



JJ (2015),
in preparation







JJ (2015), in preparation

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

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Received 2002 January 19; accepted 2002 April 25

$\approx$7350 nuclear reaction network calculations

Main nuclear uncertainties: [**$^{18}F(p,\alpha)^{15}O$, $^{25}Al(p,\gamma)^{26}Si$, $^{30}P(p,\gamma)^{31}S$**]

PRL **111,** 232503 (2013) PHYSICAL REVIEW LETTERS week ending 6 DECEMBER 2013

Classical-Nova Contribution to the Milky Way's ^{26}Al Abundance: Exit Channel of the Key ^{25}Al(p, γ)^{26}Si Resonance

M. B. Bennett,[1,2,*] C. Wrede,[1,2,3,†] K. A. Chipps,[4] J. José,[5] S. N. Liddick,[6,2] M. Santia,[1,2] A. Bowe,[1,2,7] A. A. Chen,[8] N. Cooper,[9] D. Irvine,[8] E. McNeice,[8] F. Montes,[2,10] F. Naqvi,[9] R. Ortez,[1,2,3] S. D. Pain,[11] J. Pereira,[2,10] C. Prokop,[6,2] J. Quaglia,[12,10,2] S. J. Quinn,[1,2,10] S. B. Schwartz,[1,2,13] S. Shanab,[1,2] A. Simon,[2,10] A. Spyrou,[1,2,10] and E. Thiagalingam[8]

PHYSICAL REVIEW C **88**, 048801 (2013)

Spectroscopic factor of the 1^+, ^{25}Al(p,γ)^{26}Si resonance at $E_x = 5.68$ MeV

A. Parikh* and J. José

Strength of the $E_R = 127$ keV, ^{26}Al(p,γ)^{27}Si resonance

A. Parikh[1,2,*], J. José[1,2], A. Karakas[3], C. Ruiz[4], K. Wimmer[5]

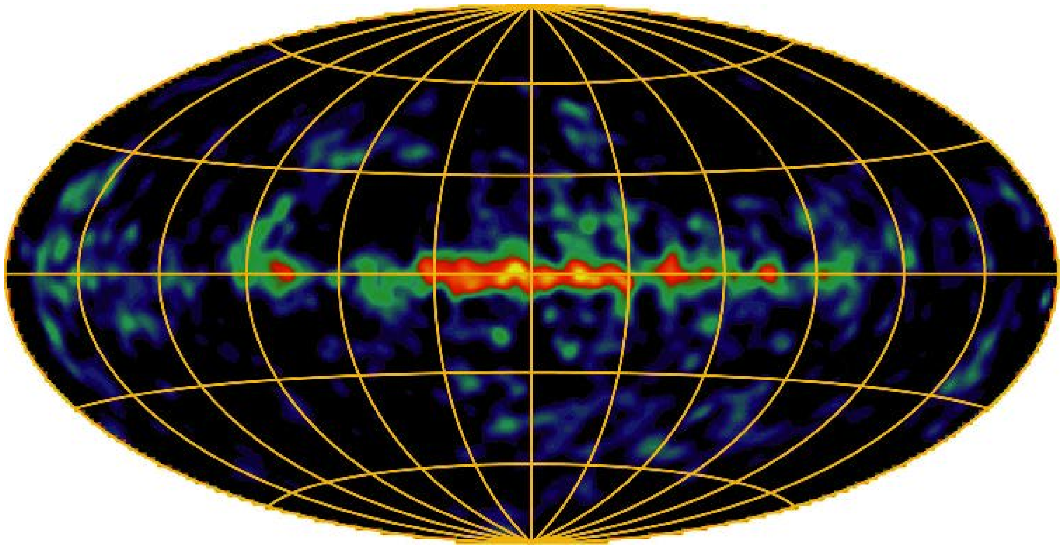
Phys. Rev. C, submitted

^{26}Al

$\tau \sim 1.04$ Myr

$^{26}\mathrm{Al} \longrightarrow {}^{26}\mathrm{Mg}^{*} \longrightarrow {}^{26}\mathrm{Mg}$

1.809 MeV



COMPTEL measurements: map of the **1.809 MeV** emission in the Galaxy (Diehl et al., A&A, 1995; Prantzos & Diehl, Phys. Rep. 1996)

Galactic ^{26}Al related to young progenitors

SN II vs. **WR stars**: → Diehl (2004), Diehl et al. (2006)

But **^{60}Fe**?

PHYSICAL REVIEW C **89**, 015803 (2014)

Underground study of the $^{17}O(p,\gamma)^{18}F$ reaction relevant for explosive hydrogen burning

A. Di Leva,[1,2,*] D. A. Scott,[3] A. Caciolli,[4,5] A. Formicola,[6,†] F. Strieder,[7] M. Aliotta,[3] M. Anders,[8] D. Bemmerer,[8] C. Broggini,[4] P. Corvisiero,[9,10] Z. Elekes,[8] Zs. Fülöp,[11] G. Gervino,[12] A. Guglielmetti,[13,14] C. Gustavino,[15] Gy. Gyürky,[11] G. Imbriani,[1,2] J. José,[16] M. Junker,[6] M. Laubenstein,[6] R. Menegazzo,[4] E. Napolitani,[17] P. Prati,[9,10] V. Rigato,[5] V. Roca,[1,2] E. Somorjai,[11] C. Salvo,[6,10] O. Straniero,[2,18] T. Szücs,[11] F. Terrasi,[2,19] and D. Trezzi[13,14]
(LUNA Collaboration)

PRL **110,** 032502 (2013) PHYSICAL REVIEW LETTERS week ending 18 JANUARY 2013

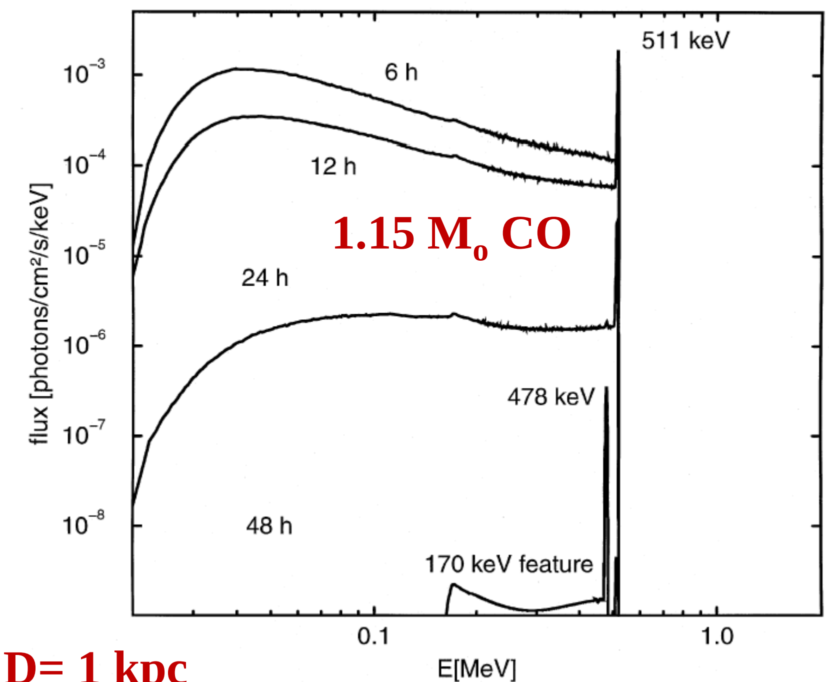
Is γ-Ray Emission from Novae Affected by Interference Effects in the $^{18}F(p,\alpha)^{15}O$ Reaction?

A. M. Laird,[1,*] A. Parikh,[2,3] A. St. J. Murphy,[4] K. Wimmer,[5,6] A. A. Chen,[7] C. M. Deibel,[8,9] T. Faestermann,[10,11] S. P. Fox,[1] B. R. Fulton,[1] R. Hertenberger,[11,12] D. Irvine,[7] J. José,[2,3] R. Longland,[2,3] D. J. Mountford,[4] B. Sambrook,[7] D. Seiler,[10,11] and H.-F. Wirth[11,12]

^{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

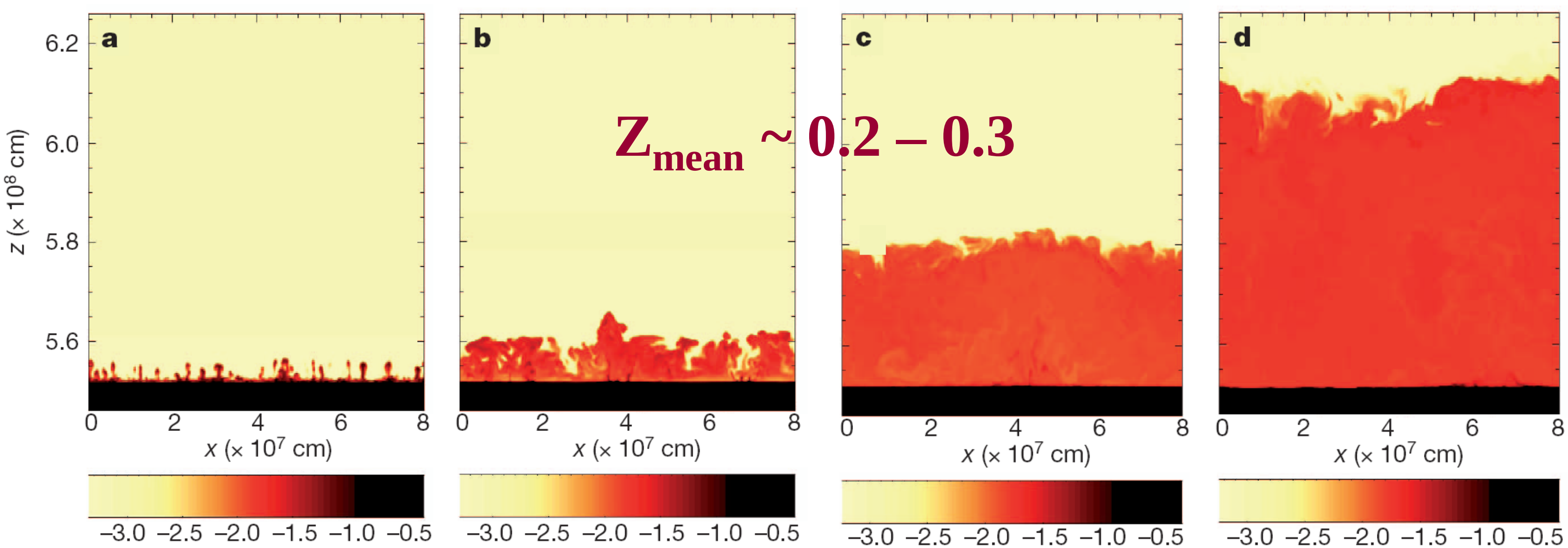
Multidimensional Models

LETTER

doi:10.1038/nature10520

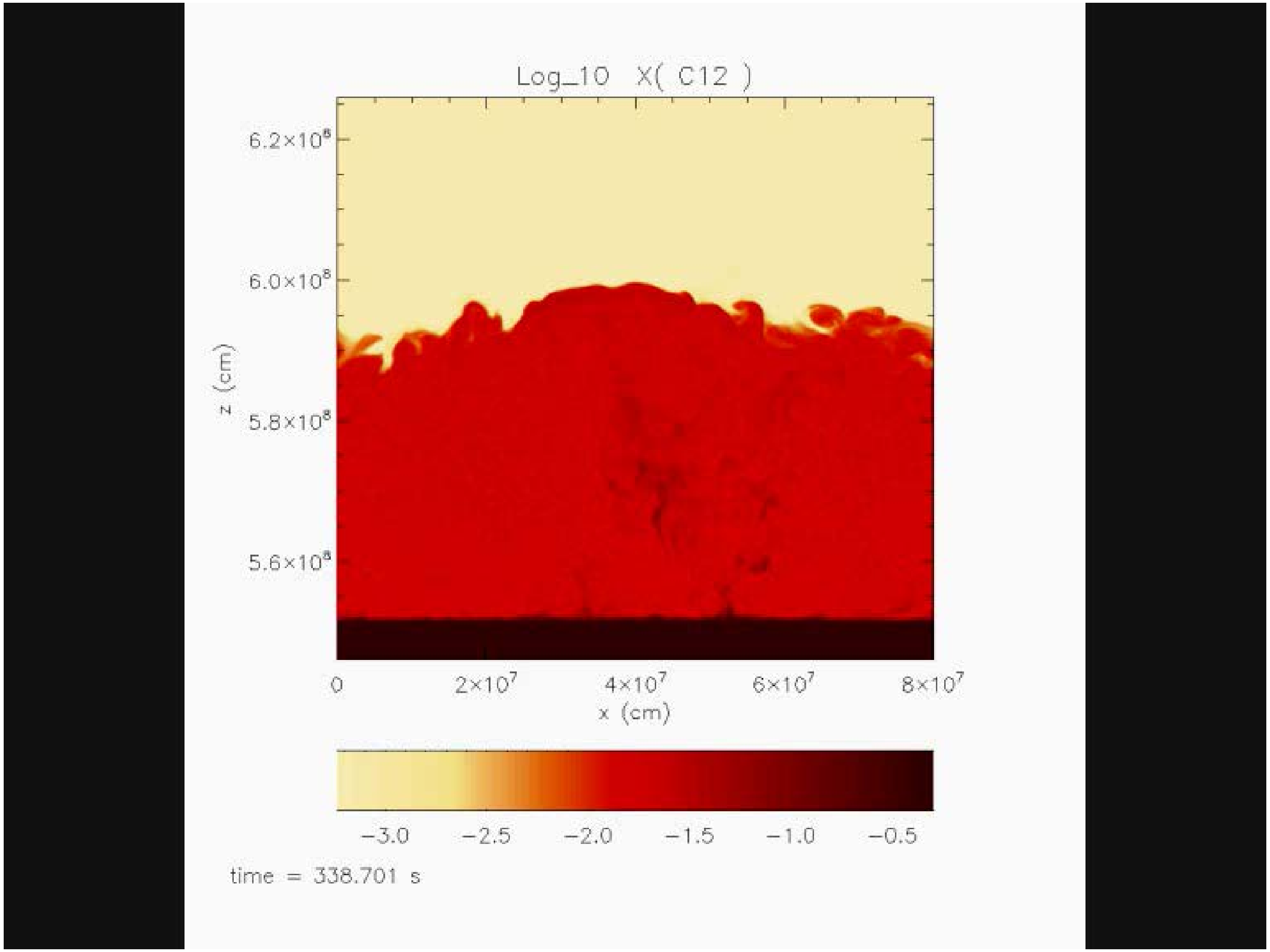
Kelvin–Helmholtz instabilities as the source of inhomogeneous mixing in nova explosions

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



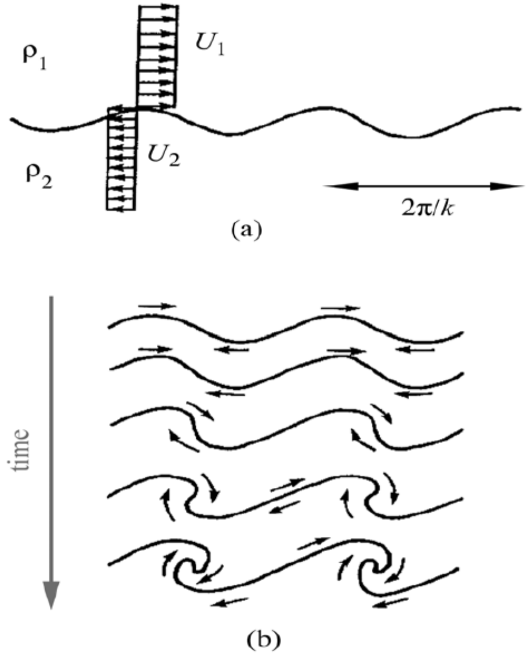
490 | NATURE | VOL 478 | 27 OCTOBER 2011

Multi-D Hydro Simulations with the FLASH Code



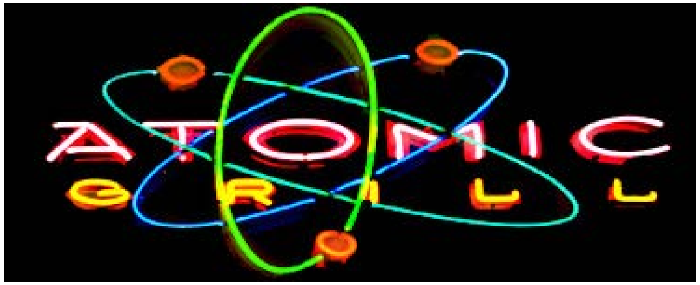
Movie available at: http://www.fen.upc.edu/users/jjose/Downloads.html

Kelvin-Helmholtz instabilities



III. Type I X-Ray Bursts

Nucleosynthesis in Type I X-Ray Bursts

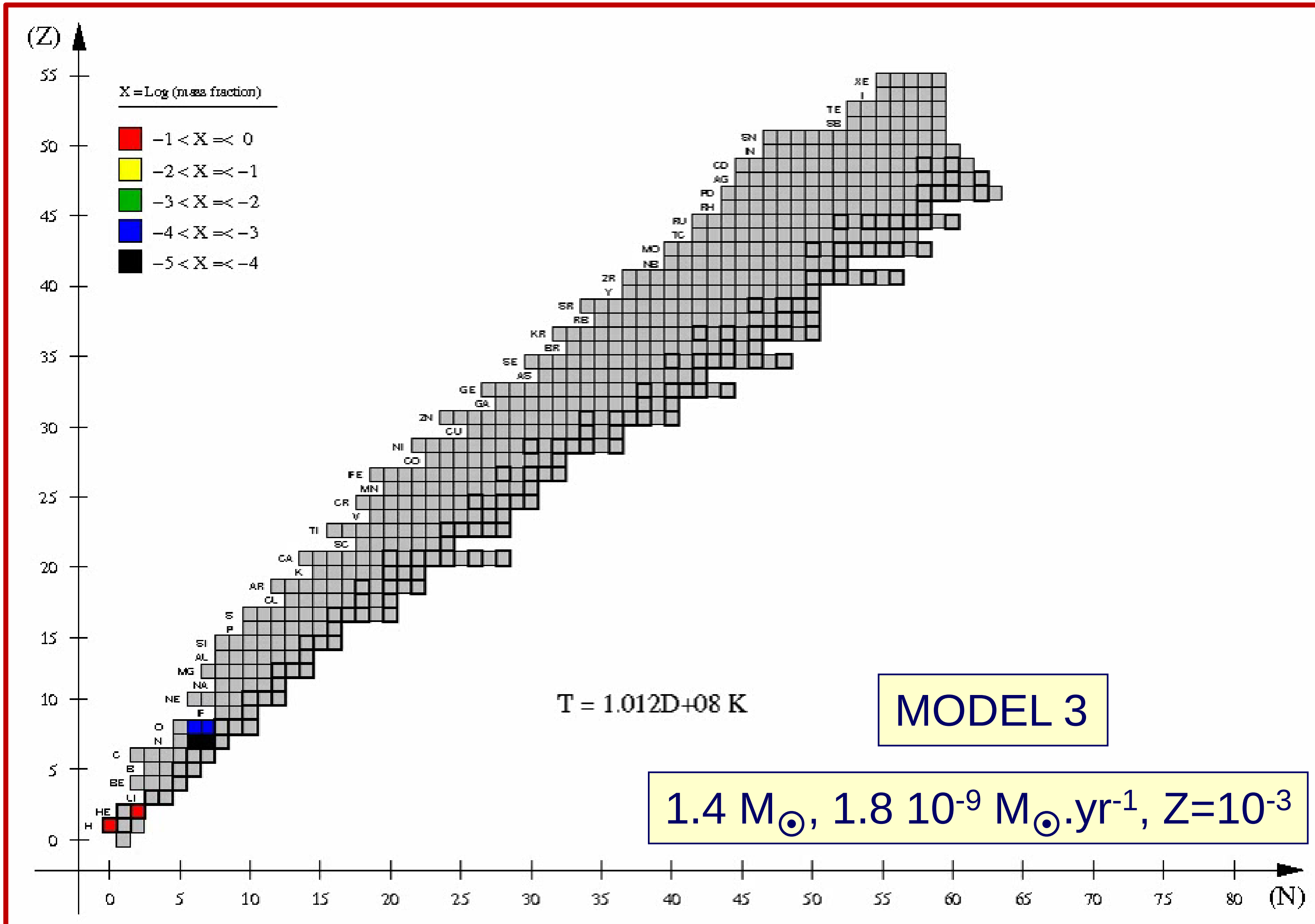


Santa Fe, NM

NS → $T_{peak} > 10^9$ **K,** $\rho_{max} \sim 10^6$ **g.cm**$^{-3}$

Detailed nucleosynthesis studies require **hundreds of isotopes**, up to **SnSbTe** mass region (Schatz et al. 2001) or beyond (the flow in Koike et al. 2004 reaches ^{126}Xe), and thousands of nuclear interactions

Main nuclear reaction flow driven by 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), and proceeds away from the valley of stability, merging with the proton drip-line beyond **A = 38** (Schatz et al. 1999)



Type I XRB: JJ, Moreno, Parikh & Iliadis (2010), ApJS

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

Thank you for your attention!

Explosive Events in the Universe and H-Burning

2nd Conference on Advances in Radioactive Isotope Science (ARIS2014)

Tokyo (Japan), June 4, 2014