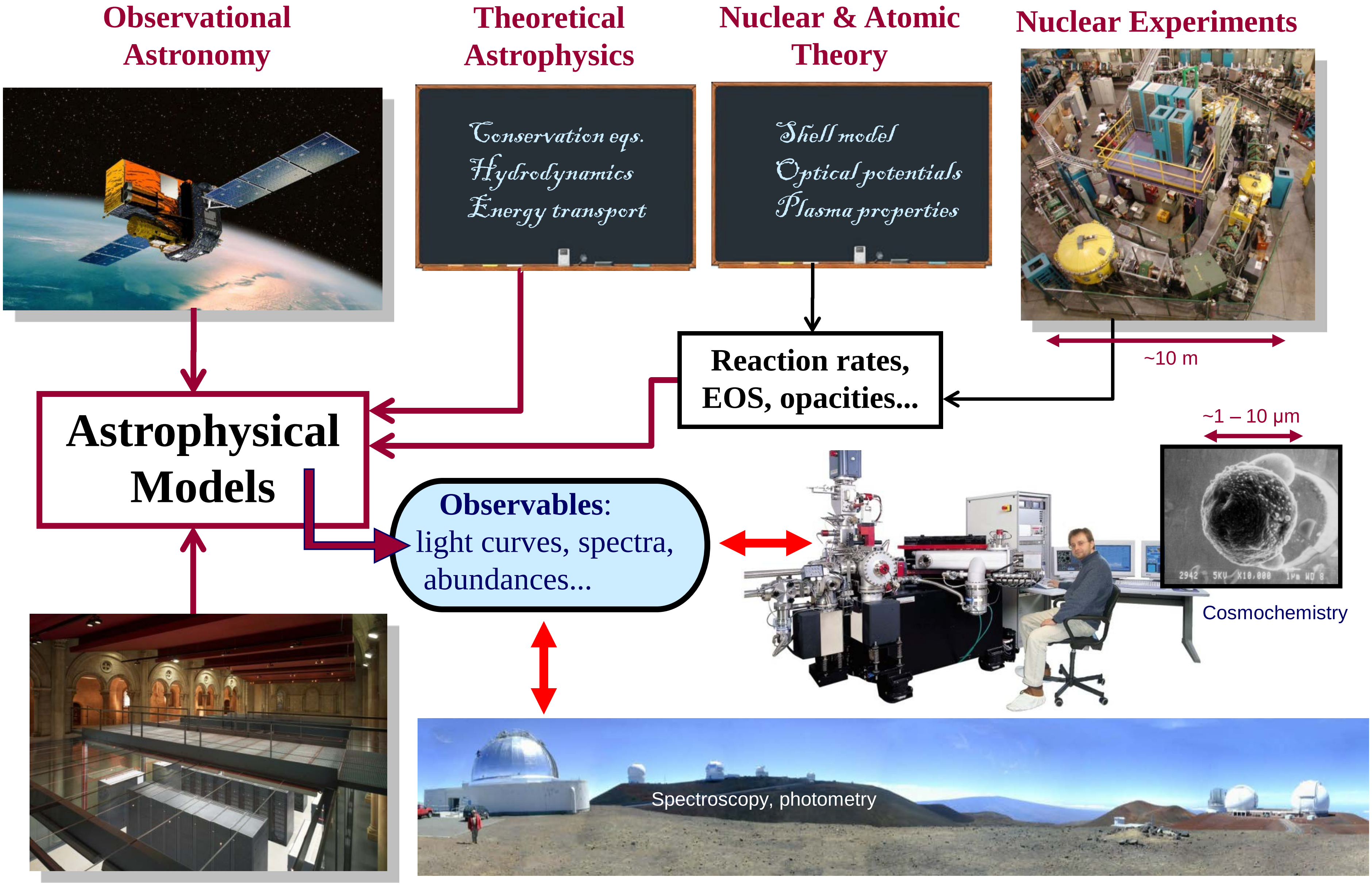
Challenges in Nuclear Astrophysics:

Nucleosynthesis in Type Ia Supernovae, Novae and X-Ray Bursts

Jordi José

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



Observational Astronomy

Theoretical Astrophysics

Conservation eqs.
Hydrodynamics
Energy transport

Nuclear & Atomic Theory

Shell model
Optical potentials
Plasma properties

Nuclear Experiments

~10 m

Reaction rates, EOS, opacities...

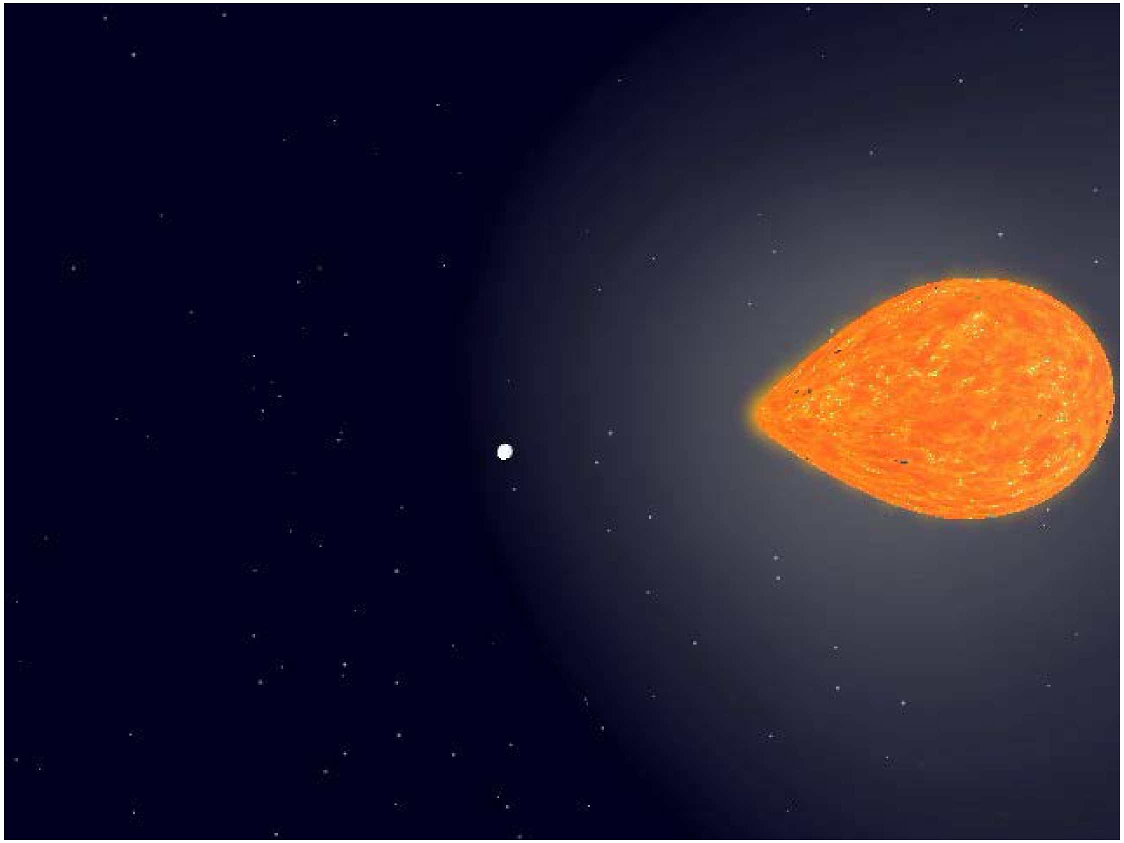
Astrophysical Models

Observables: light curves, spectra, abundances...

~1 – 10 μm

Cosmochemistry

Spectroscopy, photometry



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

X-Ray Bursts [XRBs]: NS

I. Type Ia Supernovae

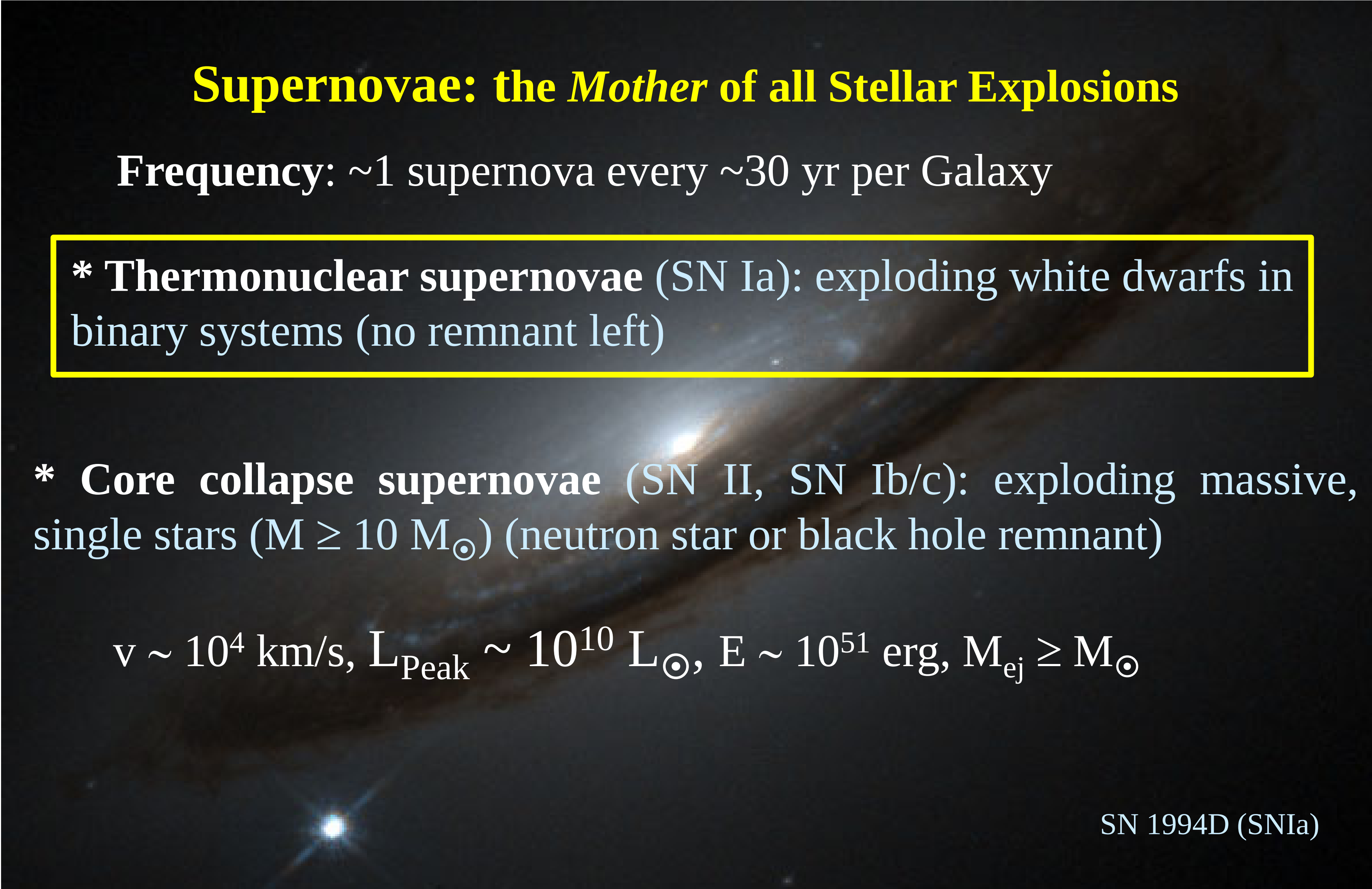
Supernovae: the *Mother* of all Stellar Explosions

Frequency: ~1 supernova every ~30 yr per Galaxy

*** Thermonuclear supernovae** (SN Ia): exploding white dwarfs in binary systems (no remnant left)

*** Core collapse supernovae** (SN II, SN Ib/c): exploding massive, single stars ($M \geq 10\ M_\odot$) (neutron star or black hole remnant)

$v \sim 10^4$ km/s, $L_{Peak} \sim 10^{10}\ L_\odot$, $E \sim 10^{51}$ erg, $M_{ej} \geq M_\odot$



SN 1994D (SNIa)

Thermonuclear Supernovae

Defined by the lack of **H** and the presence of a prominent, blueshifted absorption **Si II** feature (around λ6150) in the spectrum

* **homogeneity:** ~70% of all **SN Ia** have similar spectra, light curves and peak absolute magnitudes: **unique progenitor????**
→ thermonuclear disruption of **mass-accreting white dwarfs**
* SN Ia: 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)

II. Classical Novae

Novae have been observed in all wavelengths (but never detected so far in γ-rays)

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: $30 \pm 10\ yr^{-1}$

Observed frequency: $\sim 5\ yr^{-1}$

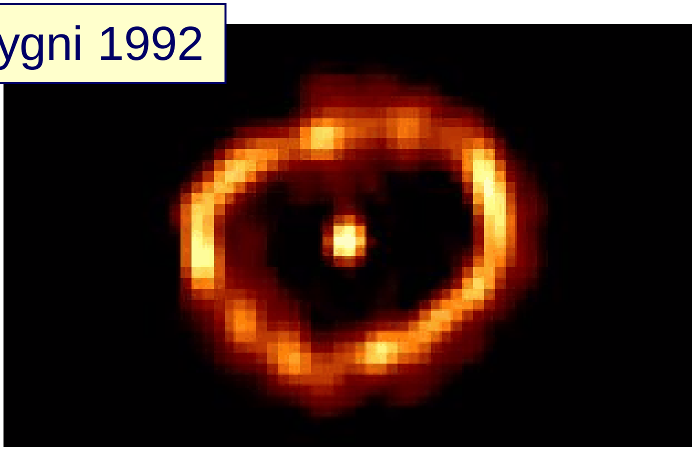
$E \sim 10^{45}$ ergs

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

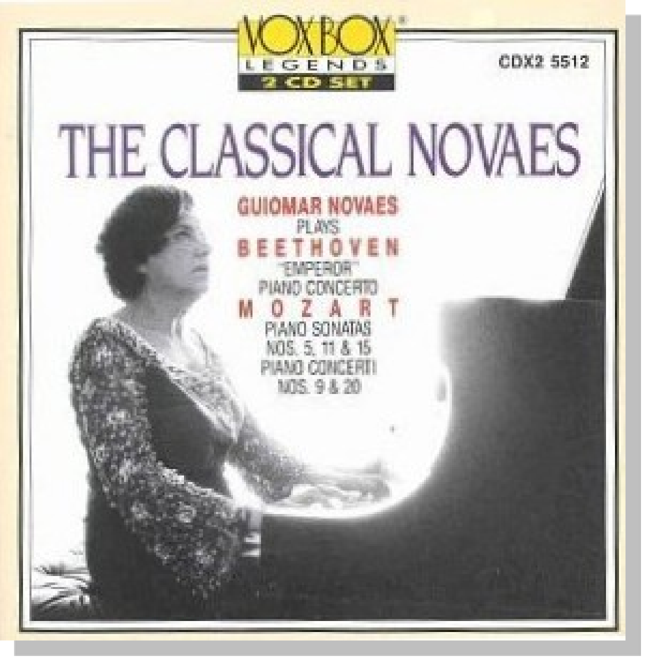
Early TNR models: Starrfield et al. 1972; Prialnik, Shara & Shaviv 1978

The Nova Nuclear Symphony

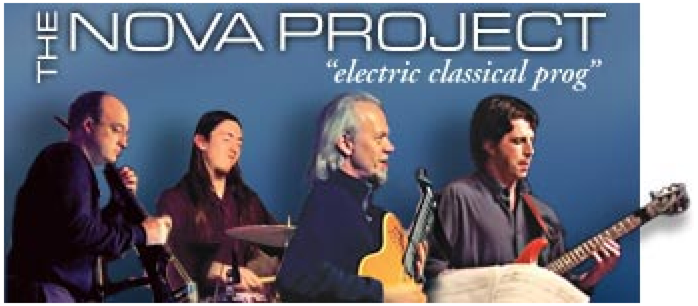
Classical Novae: ~**100** relevant isotopes **(A<40)** & a **(few) hundred** nuclear reactions **(T_{peak} ~ 100 – 400 MK)**



Nova Cygni 1992



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



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

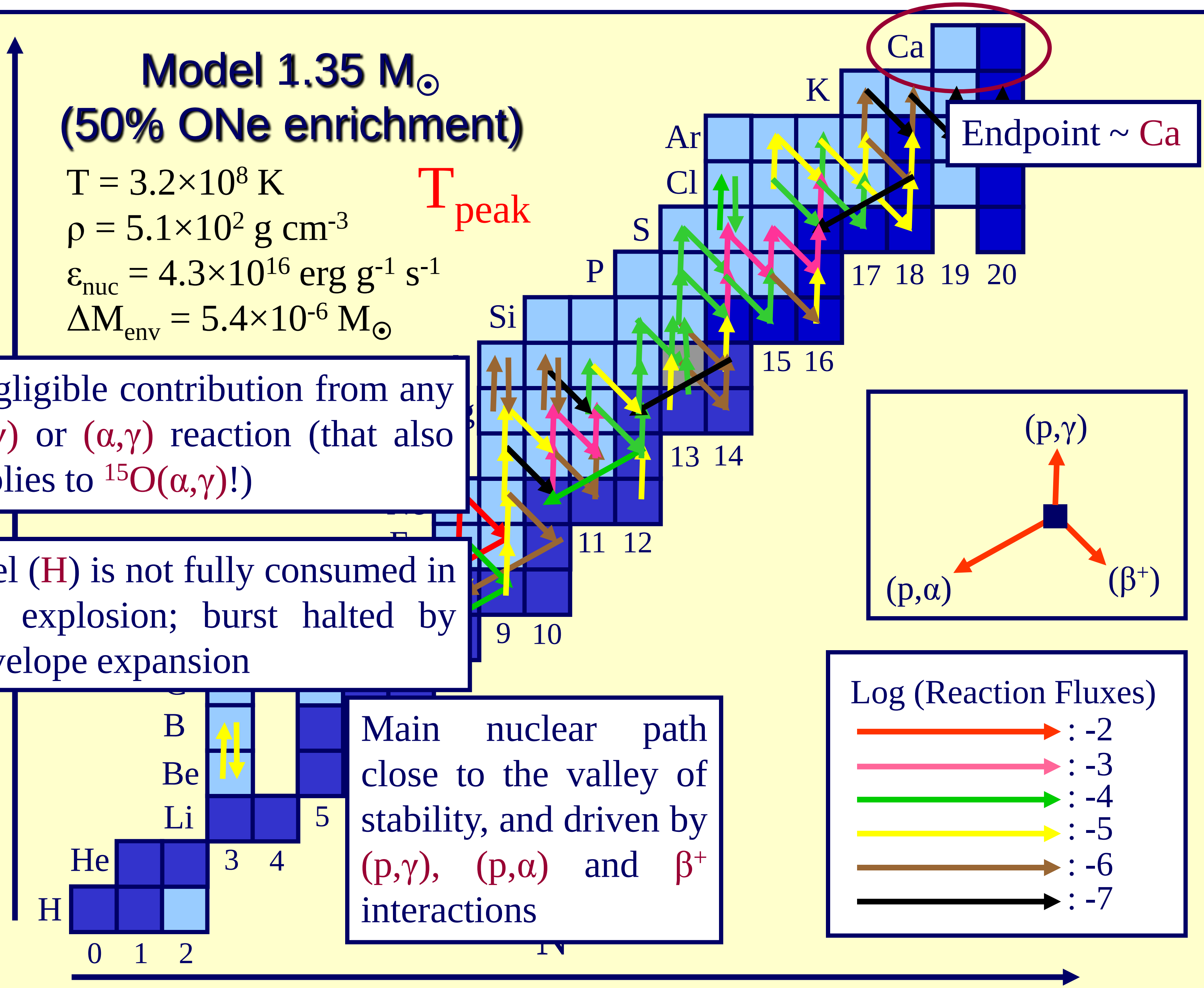
$T = 3.2\times10^{8}$ K

$\rho = 5.1\times10^{2}$ 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}

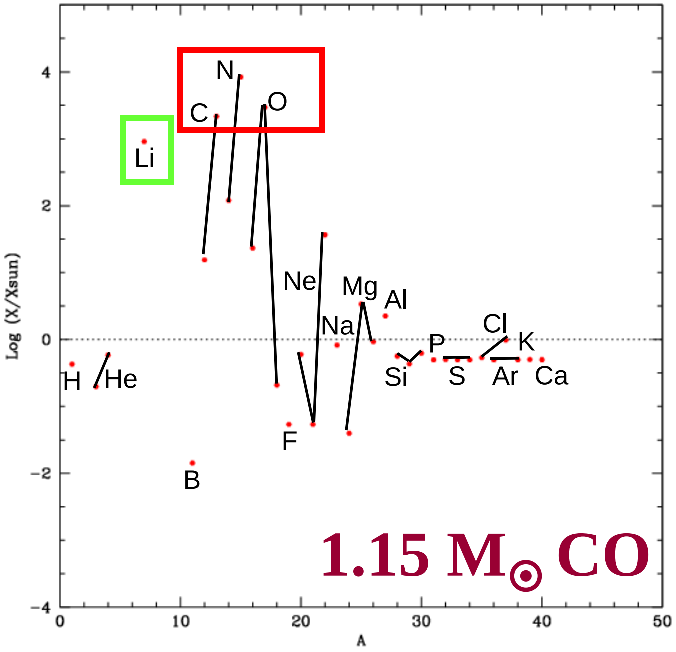


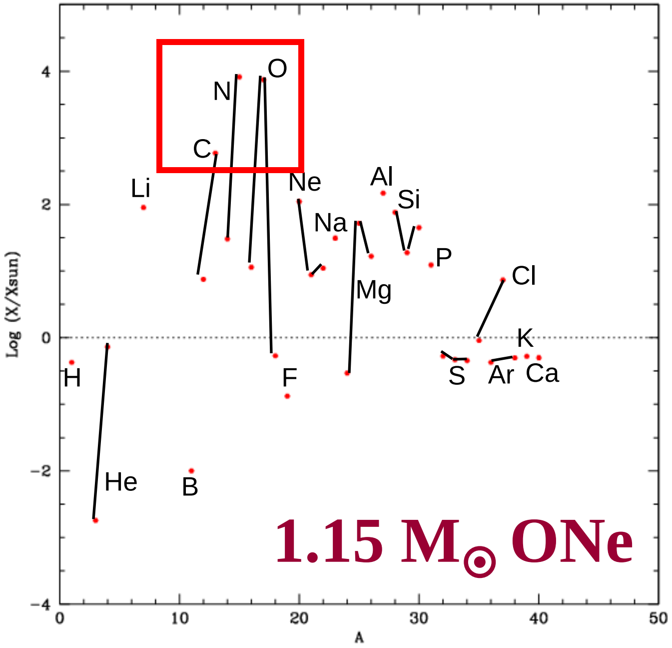
Endpoint ~ Ca

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

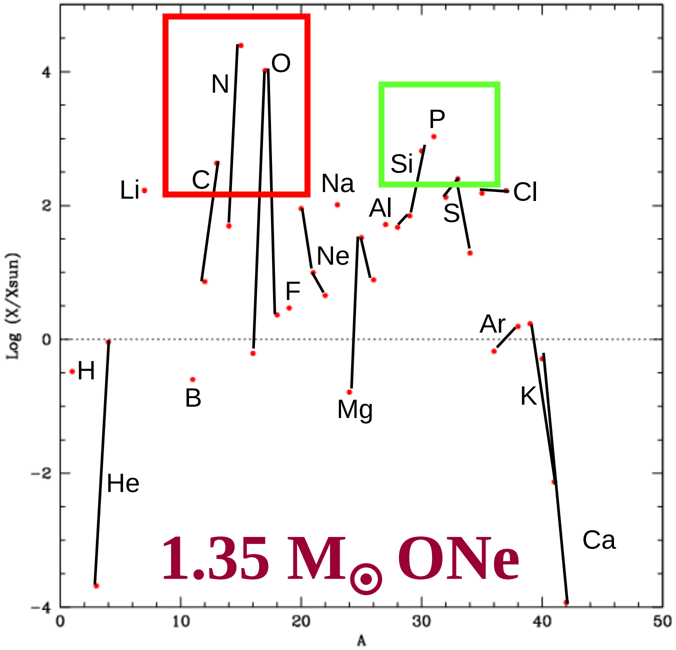
Fuel (H) is not fully consumed in the explosion; burst halted by envelope expansion

Main nuclear path close to the valley of stability, and driven by (p,γ), (p,α) and β^{+} interactions

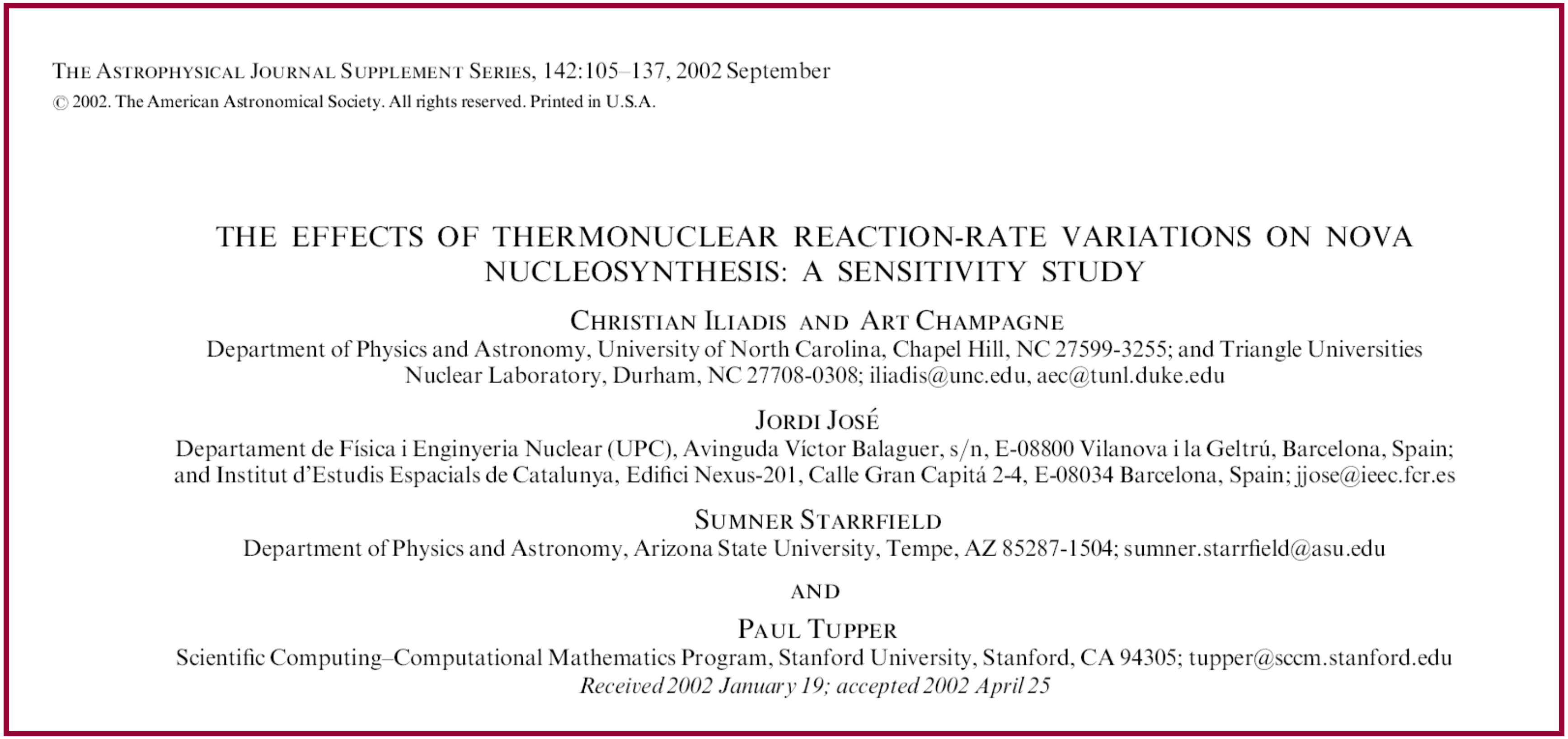




JJ, Hernanz, Coc & Iliadis (2013), in preparation



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

Christian Iliadis and Art Champagne
Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599-3255; and Triangle Universities Nuclear Laboratory, Durham, NC 27708-0308; iliadis@unc.edu, aec@tunl.duke.edu

Jordi José
Departament de Física i Enginyeria Nuclear (UPC), Avinguda Víctor Balaguer, s/n, E-08800 Vilanova i la Geltrú, Barcelona, Spain; and Institut d'Estudis Espacials de Catalunya, Edifici Nexus-201, Calle Gran Capitá 2-4, E-08034 Barcelona, Spain; jjose@ieec.fcr.es

Sumner Starrfield
Department of Physics and Astronomy, Arizona State University, Tempe, AZ 85287-1504; sumner.starrfield@asu.edu

and

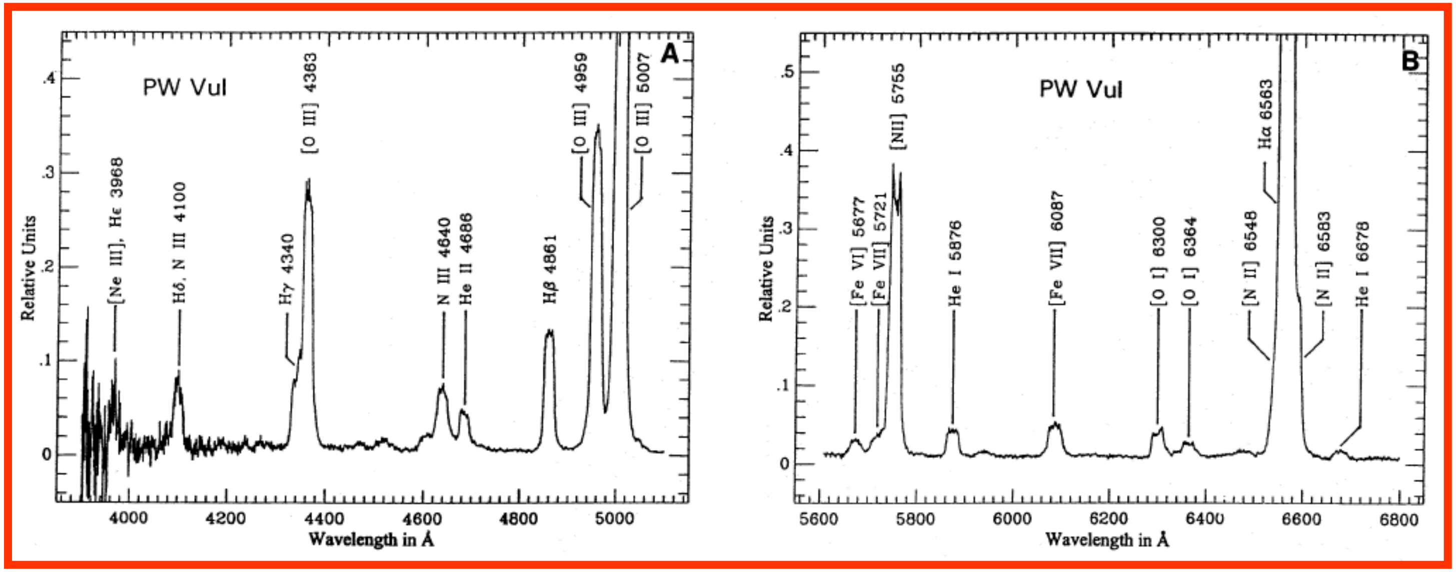
Paul Tupper
Scientific Computing–Computational Mathematics Program, Stanford University, Stanford, CA 94305; tupper@sccm.stanford.edu

Received 2002 January 19; accepted 2002 April 25

$\approx$7350 nuclear reaction network calculations

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

Observational Constraints



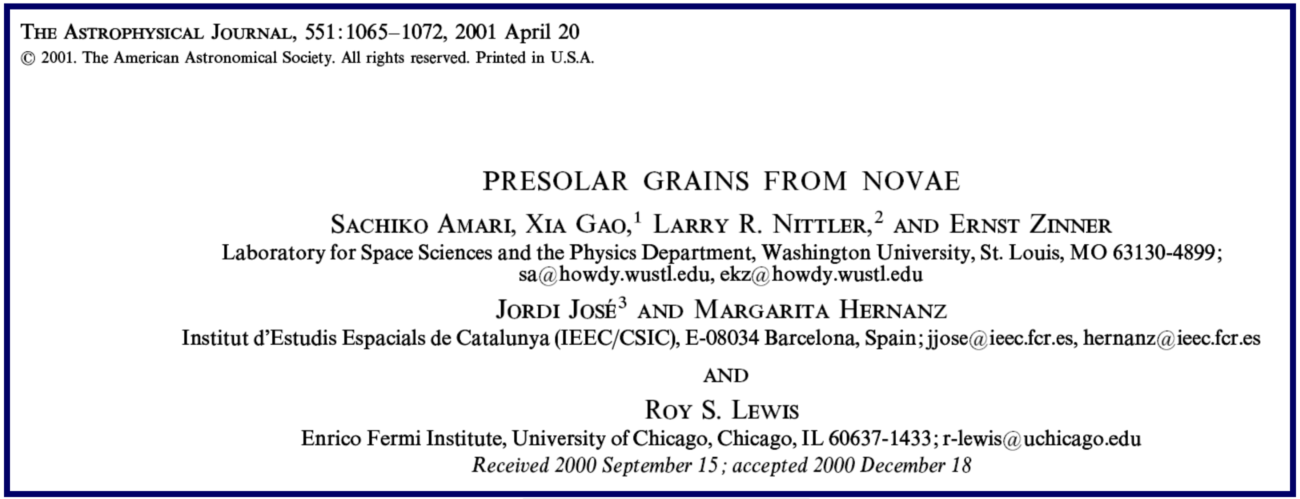
Andrëa et al. (1994)

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)

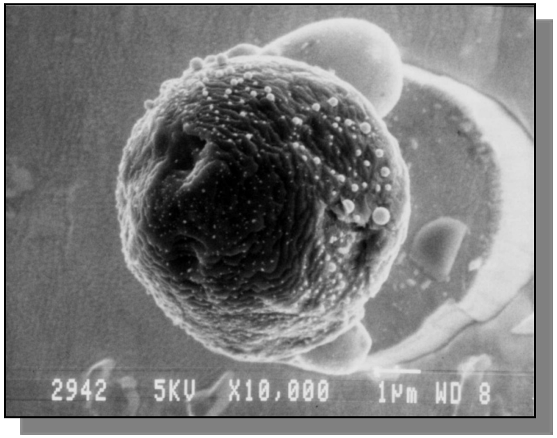
Presolar Grains

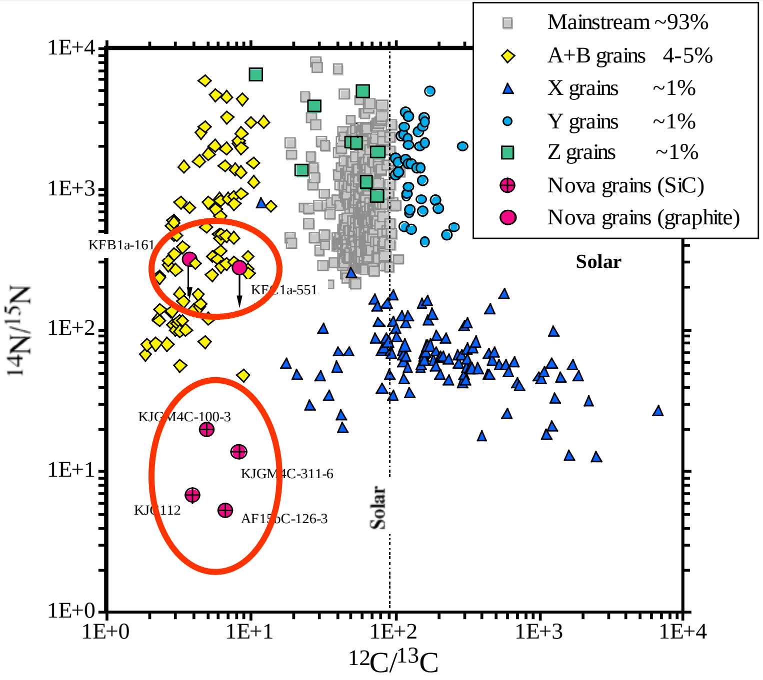


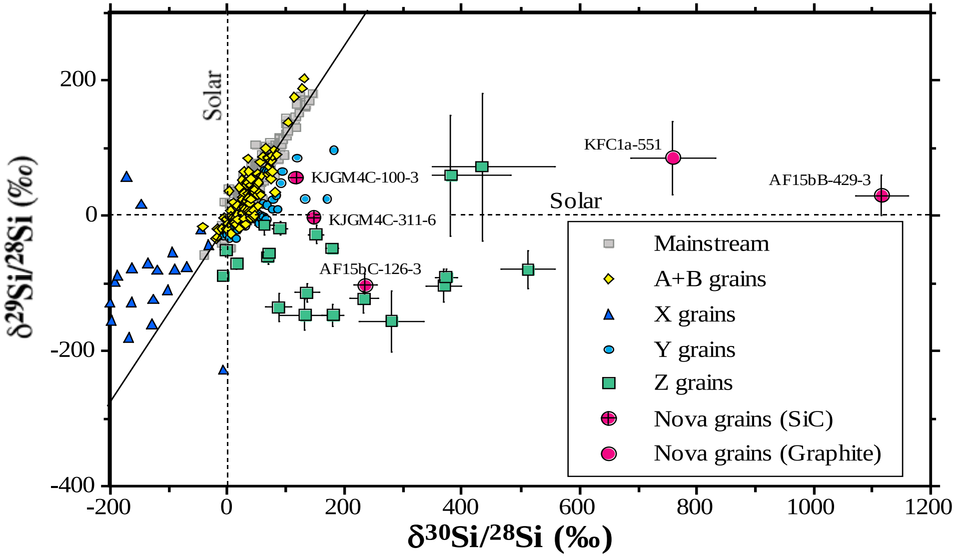
The Astrophysical Journal, 551:1065–1072, 2001 April 20

PRESOLAR GRAINS FROM NOVAE

Sachiko Amari, Xia Gao,[1] Larry R. Nittler,[2] and Ernst Zinner
Laboratory for Space Sciences and the Physics Department, Washington University, St. Louis, MO 63130-4899;
sa@howdy.wustl.edu, ekz@howdy.wustl.edu
Jordi José[3] and Margarita Hernanz
Institut d'Estudis Espacials de Catalunya (IEEC/CSIC), E-08034 Barcelona, Spain; jjose@ieec.fcr.es, hernanz@ieec.fcr.es
and
Roy S. Lewis
Enrico Fermi Institute, University of Chicago, Chicago, IL 60637-1433; r-lewis@uchicago.edu
Received 2000 September 15; accepted 2000 December 18



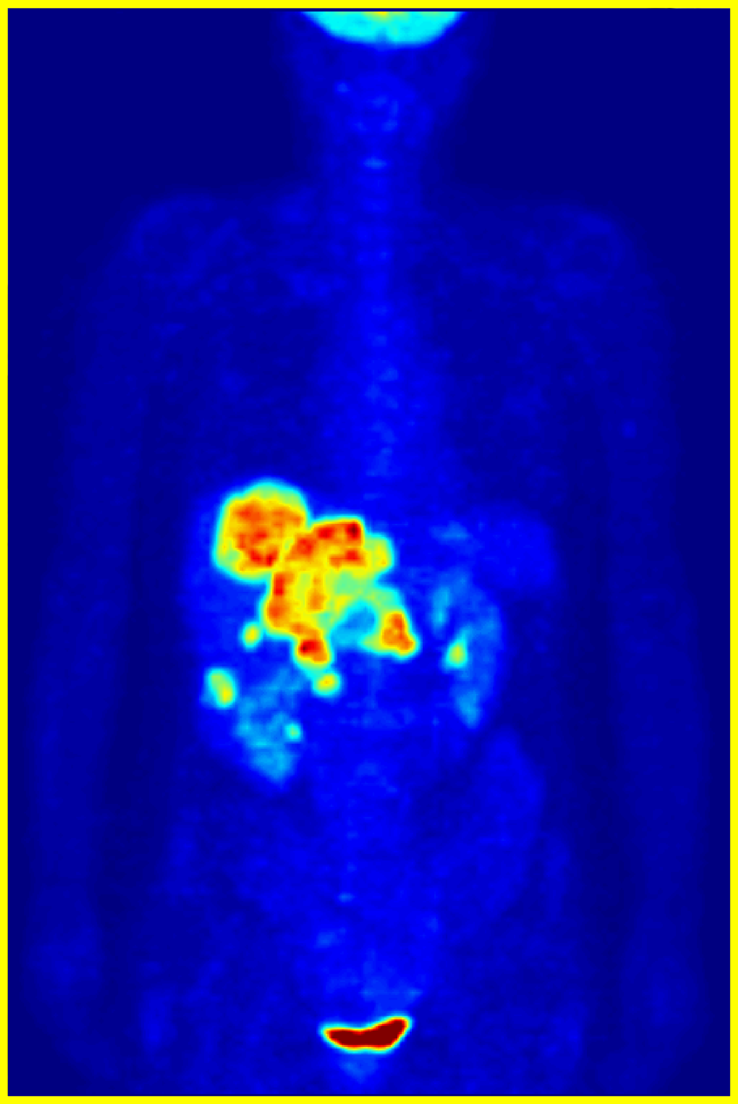


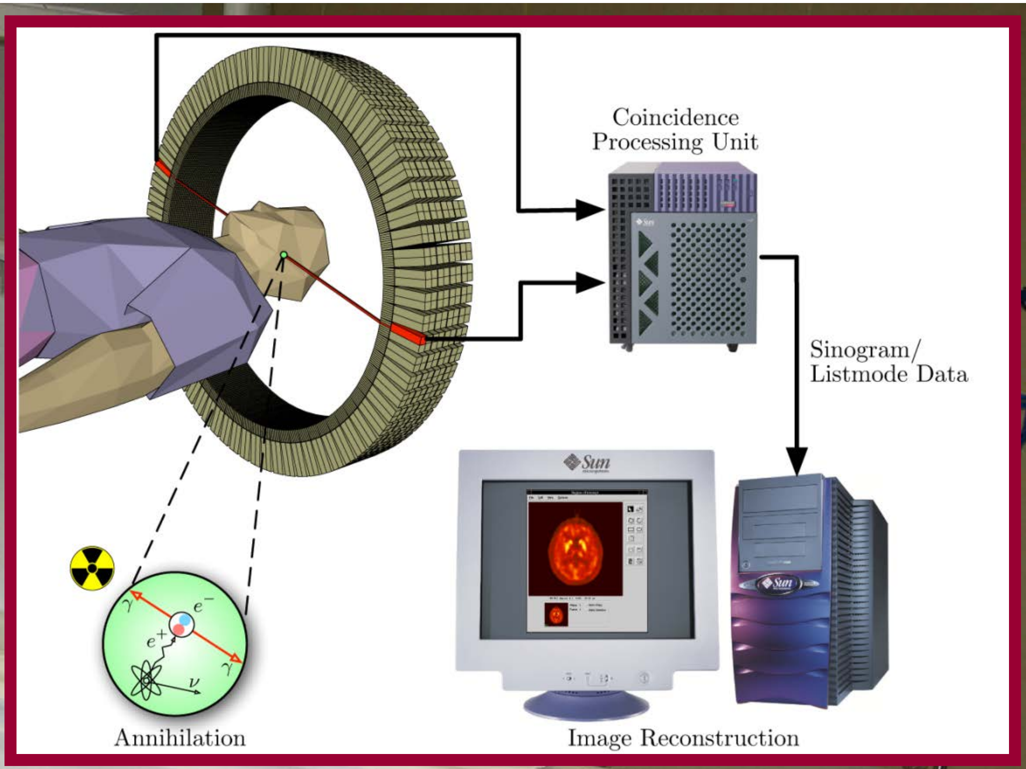


γ-Ray Emission from Classical Novae

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**



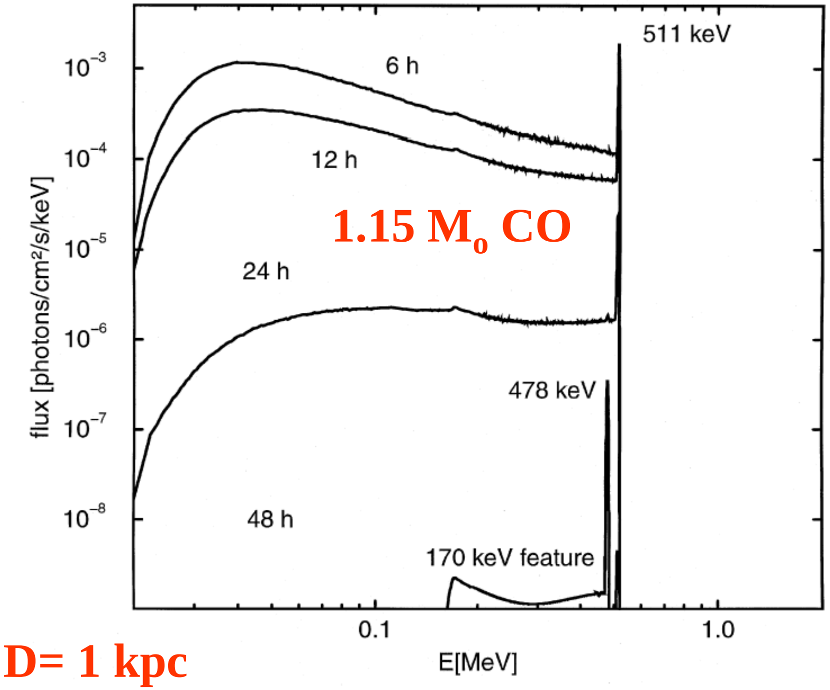


Positron Emission Tomography (**PET**)

^{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!

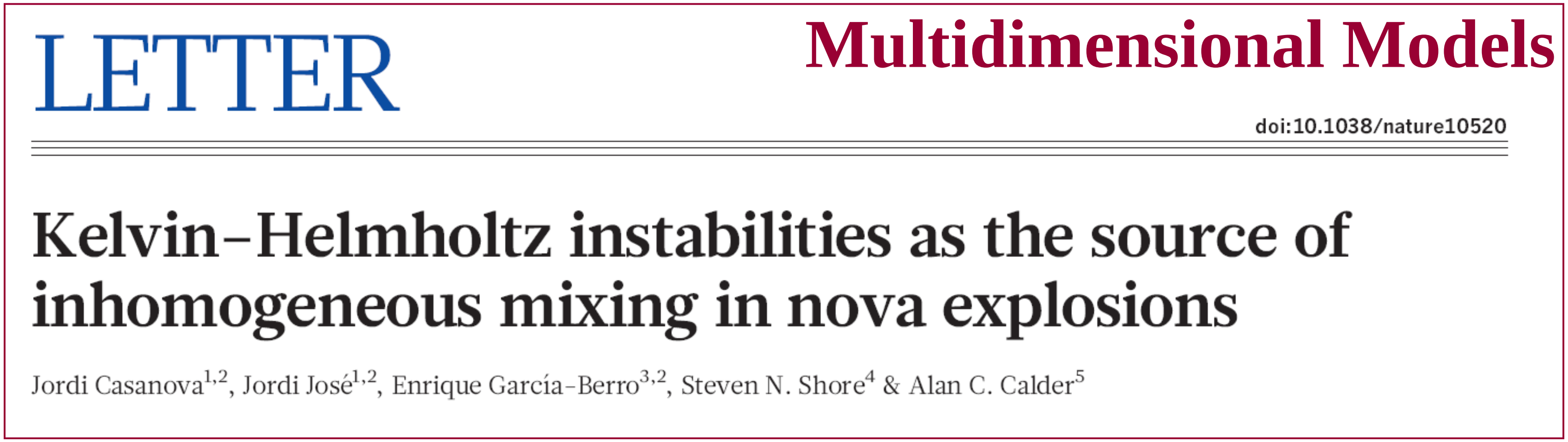


1.15 M_o CO

D= 1 kpc

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

Multidimensional Models

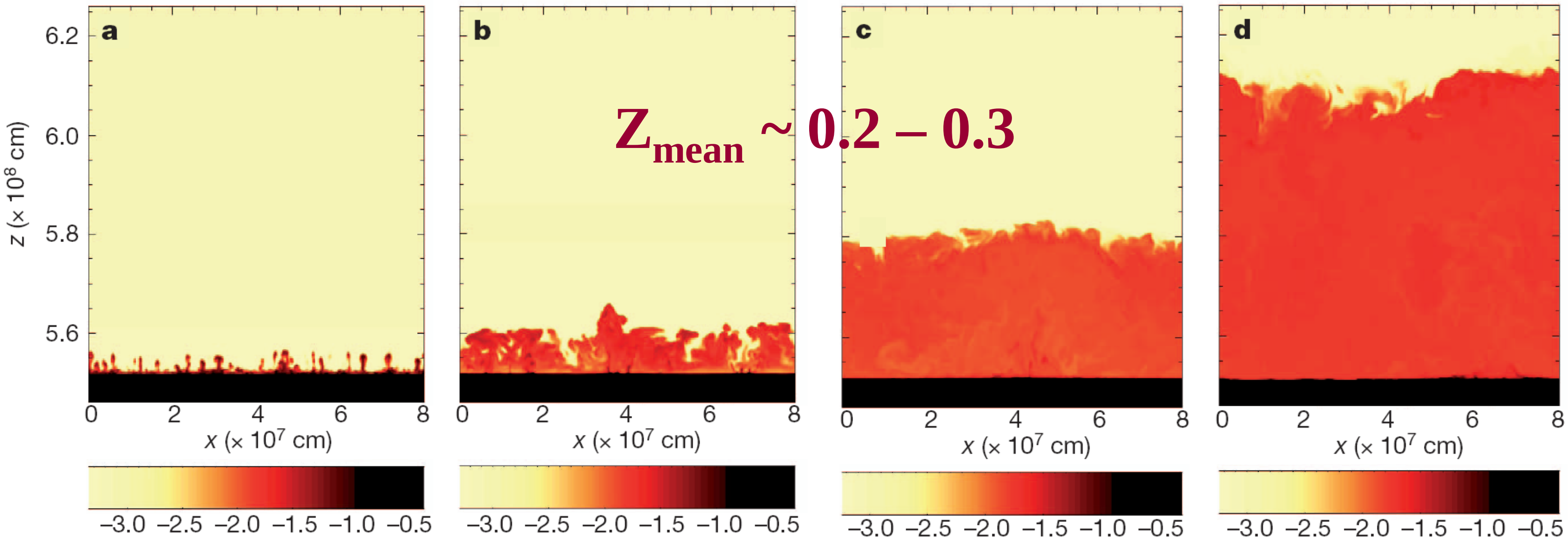


LETTER

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]



$Z_{mean} \sim 0.2 – 0.3$

490 | NATURE | VOL 478 | 27 OCTOBER 2011

MareNostrum II (BSC, 2006), 94.21 Tflops/s, 10,240 processors

MareNostrum III (BSC, Jan. 2013), >1 Petaflop/s, 48,000 processors
[6,000 Intel SandyBridge chips (2,6 GHz), each with 8 cores]

III. Type I X-Ray Bursts

First discovered in **1975** (Grindlay , Heise, et al. 1976) with the **ANS** (also Belian, Conner & Evans 1976: **Vela** satellites)

The Type I XRB ID Card

Very fast rise times: 2 – 10 s

Short duration: 10 – 100 s

$L_{peak} \sim 10^{38}$ erg s^{-1}

Energy released: $\sim 10^{39}$ erg

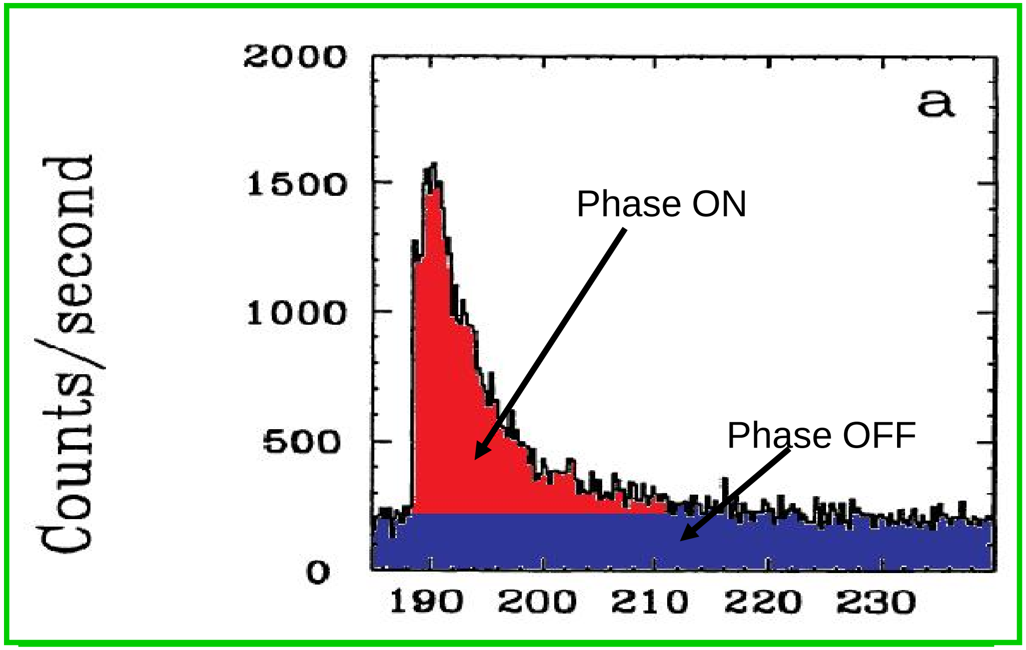
Recurrence time: ~ hours – days

α [E(off)/ E(on)]: 40 – 100

$E_p = G \cdot M_{NS}/R_{NS} \sim 200$ MeV·nucleon^{-1}

$E_b \sim 5$ MeV·nucleon^{-1}

Orbital periods: 1 – 15 hours



Haberl et al. (1987) 4U 1820-30

First models: Woosley & Taam’76; Maraschi & Cavalieri’77; Joss’77

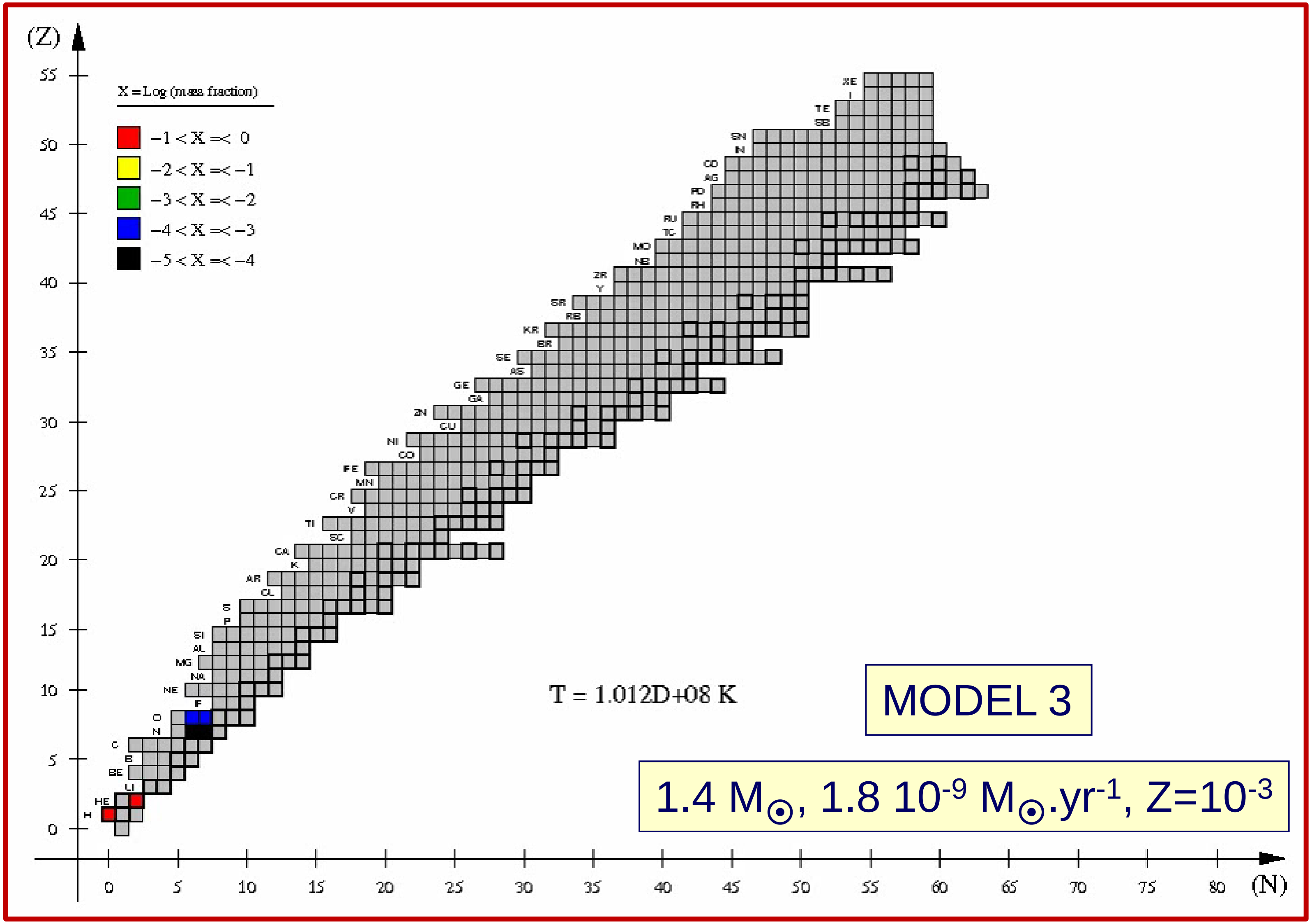
Nucleosynthesis in Type I X-Ray Bursts


Santa Fe, NM

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

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

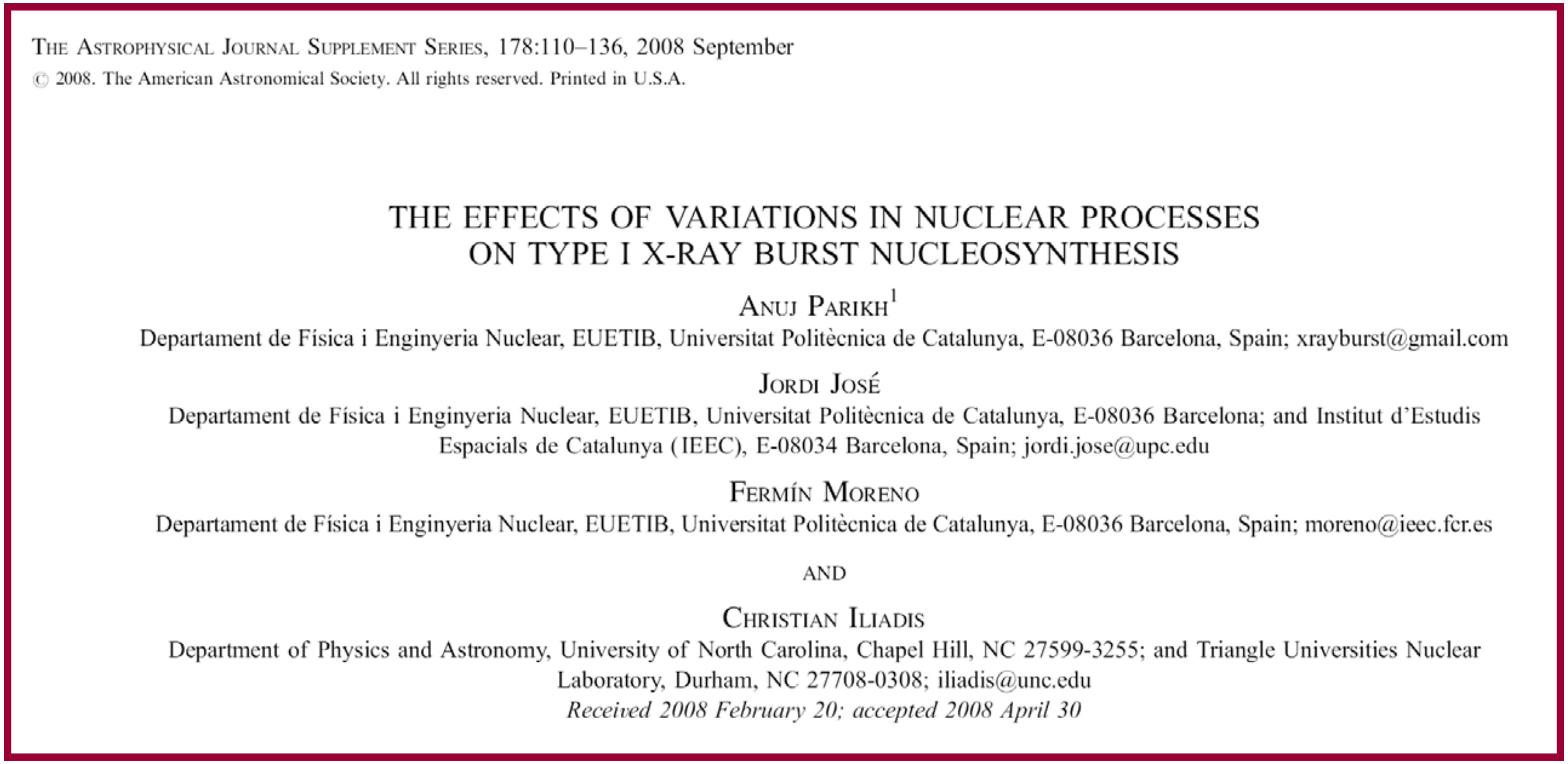
Main nuclear reaction flow driven by the *rp-process* (rapid p-captures and β^+-decays), the 3α-reaction, and the *αp-process* (a sequence of (α,p) and (p,γ) reactions), and proceeds away from the valley of stability, merging with the proton drip-line beyond **A = 38** (Schatz et al. 1999)



MODEL 3

$1.4\ M_{\odot}$, $1.8\ 10^{-9}\ M_{\odot}.yr^{-1}$, $Z=10^{-3}$

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

Anuj Parikh[1]
Departament de Física i Enginyeria Nuclear, EUETIB, Universitat Politècnica de Catalunya, E-08036 Barcelona, Spain; xrayburst@gmail.com

Jordi José
Departament de Física i Enginyeria Nuclear, EUETIB, Universitat Politècnica de Catalunya, E-08036 Barcelona; and Institut d'Estudis Espacials de Catalunya (IEEC), E-08034 Barcelona, Spain; jordi.jose@upc.edu

Fermín Moreno
Departament de Física i Enginyeria Nuclear, EUETIB, Universitat Politècnica de Catalunya, E-08036 Barcelona, Spain; moreno@ieec.fcr.es

and

Christian Iliadis
Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599-3255; and Triangle Universities Nuclear Laboratory, Durham, NC 27708-0308; iliadis@unc.edu

Received 2008 February 20; accepted 2008 April 30

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

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

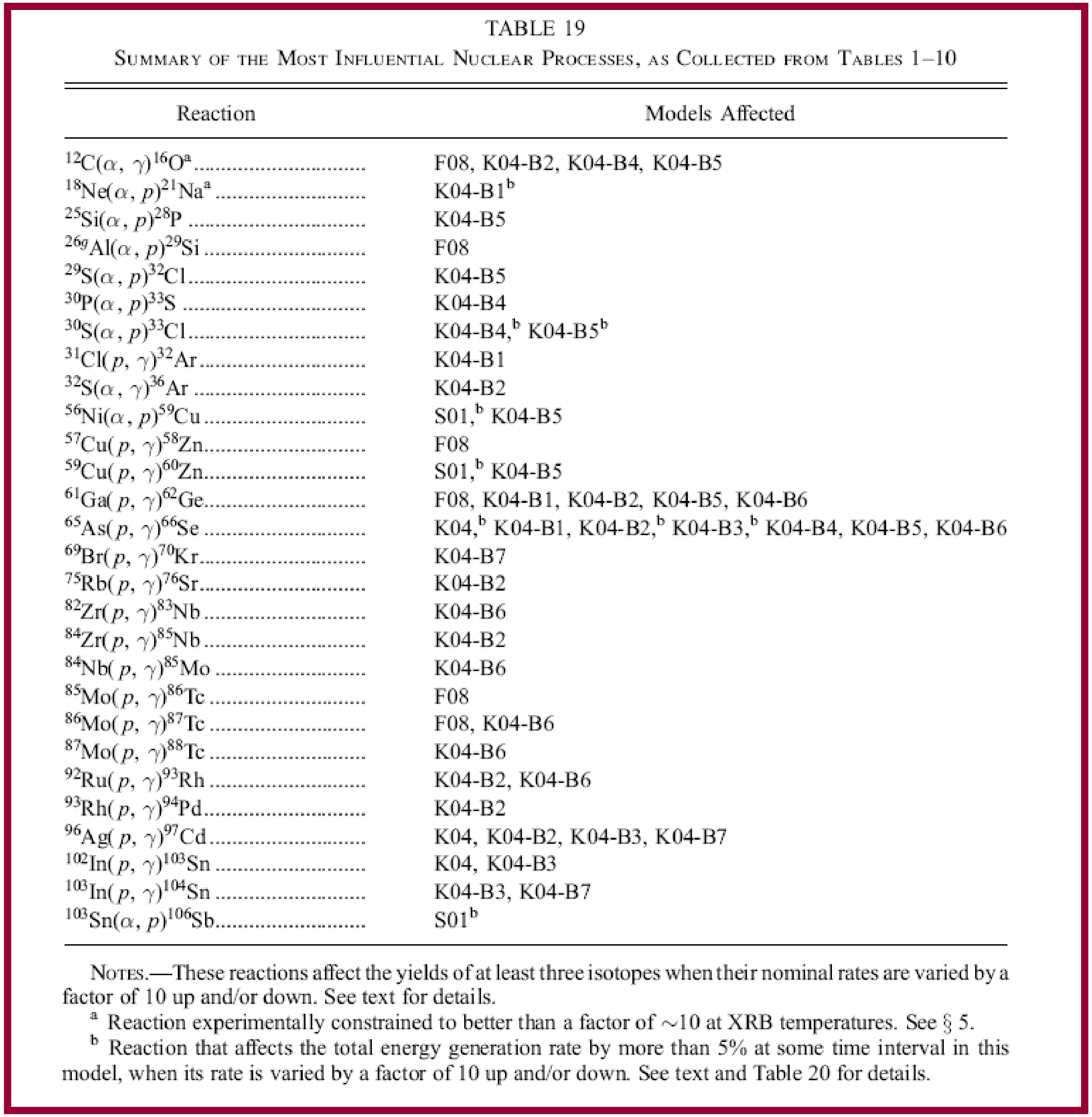


TABLE 19

SUMMARY OF THE MOST INFLUENTIAL NUCLEAR PROCESSES, AS COLLECTED FROM TABLES 1–10

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

NOTES.—These reactions affect the yields of at least three isotopes when their nominal rates are varied by a factor of 10 up and/or down. See text for details.

[a] Reaction experimentally constrained to better than a factor of ~10 at XRB temperatures. See § 5.

[b] Reaction that affects the total energy generation rate by more than 5% at some time interval in this model, when its rate is varied by a factor of 10 up and/or down. See text and Table 20 for details.

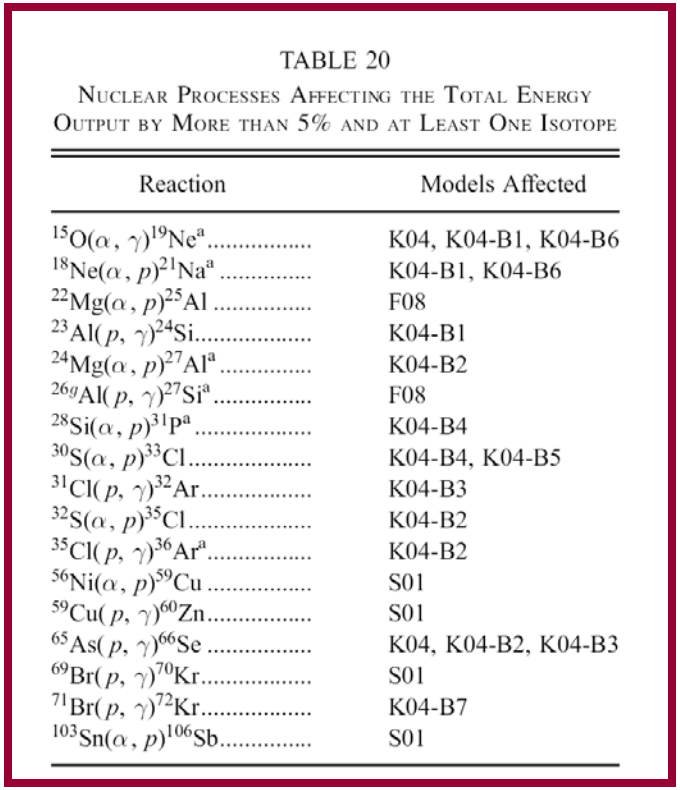


TABLE 20

NUCLEAR PROCESSES AFFECTING THE TOTAL ENERGY OUTPUT BY MORE THAN 5% AND AT LEAST ONE ISOTOPE

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

International Conference

THE ORIGIN OF COSMIC ELEMENTS
Past and Present Achievements, Future Challenges

Barcelona, June 12-15, 2013

Antoni Gaudí's Casa Milà-La Pedrera, downtown Barcelona.

http://www.fen.upc.edu/users/jjose/Conf2.html

Thank you for your attention!

Challenges in Nuclear Astrophysics:

Nucleosynthesis in Type Ia Supernovae, Novae and X-Ray Bursts
IoP High-Energy and Astroparticle Physics Group Meeting,
Liverpool (UK), April 9, 2013