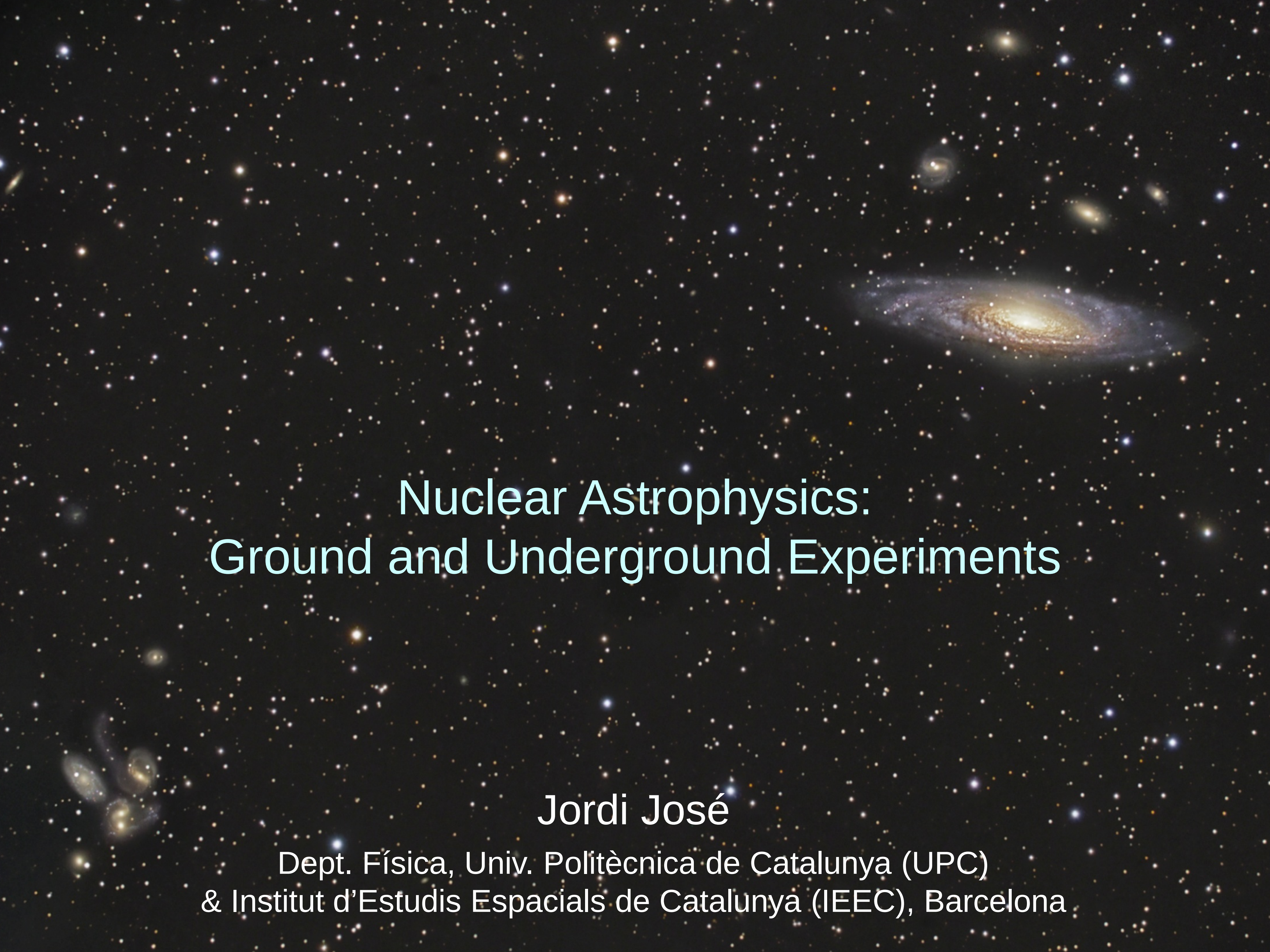
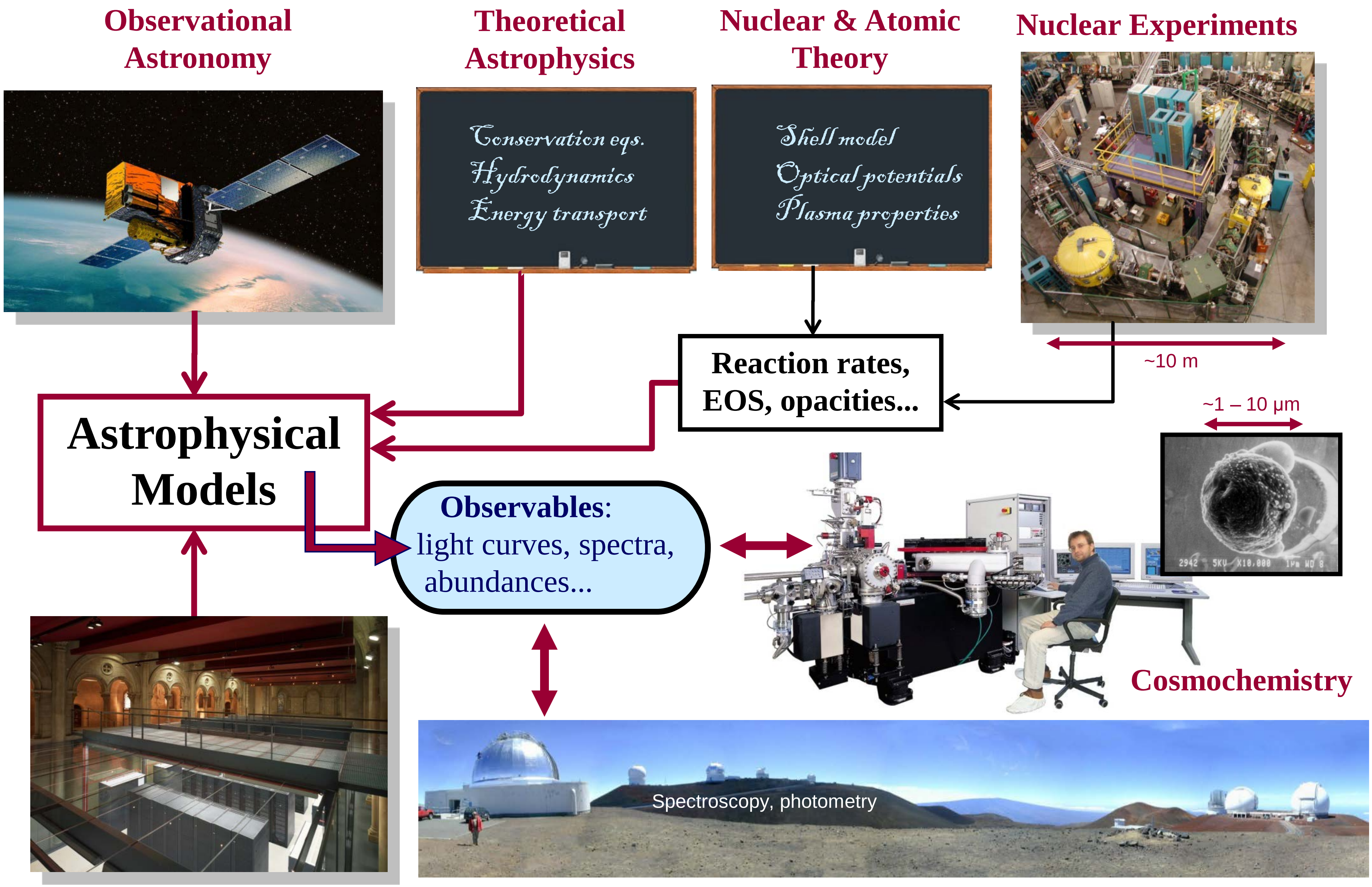


Nuclear Astrophysics:
Ground and Underground Experiments

Jordi José
Dept. Física, 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...

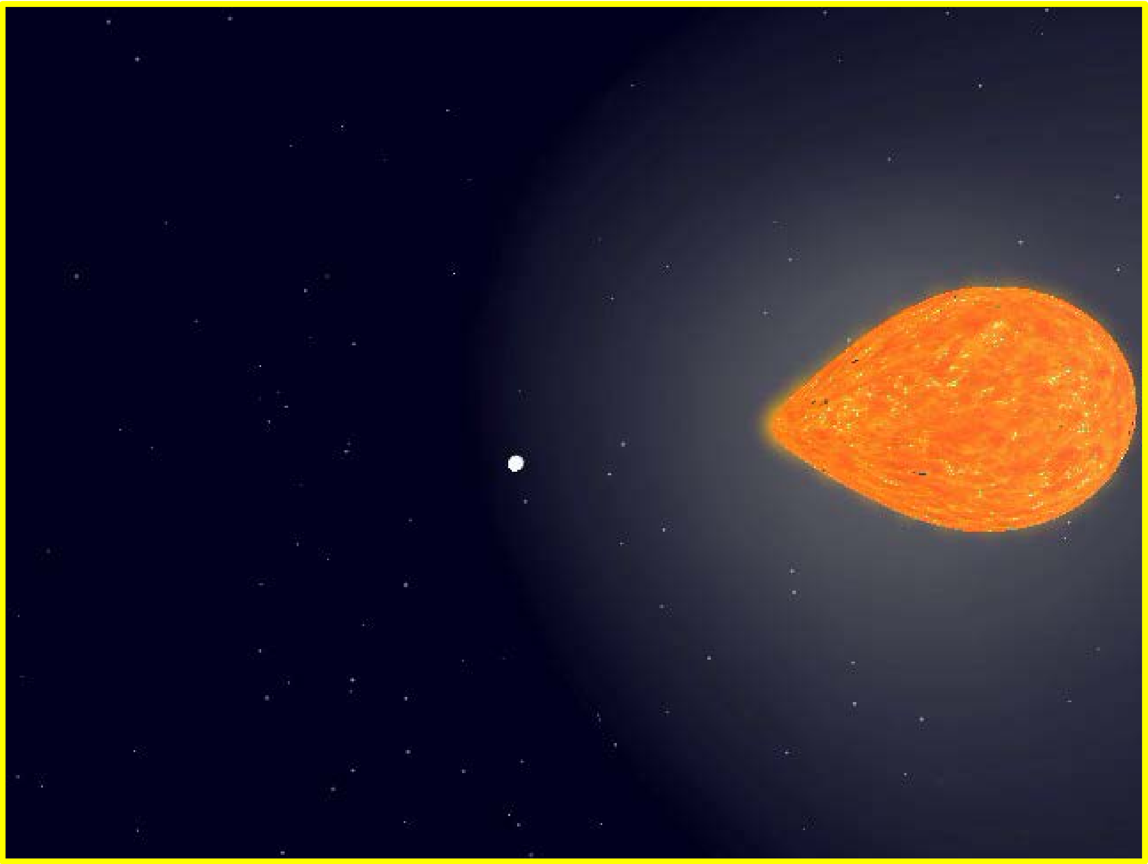
~1 – 10 μm

Astrophysical Models

Observables: light curves, spectra, abundances...

Cosmochemistry

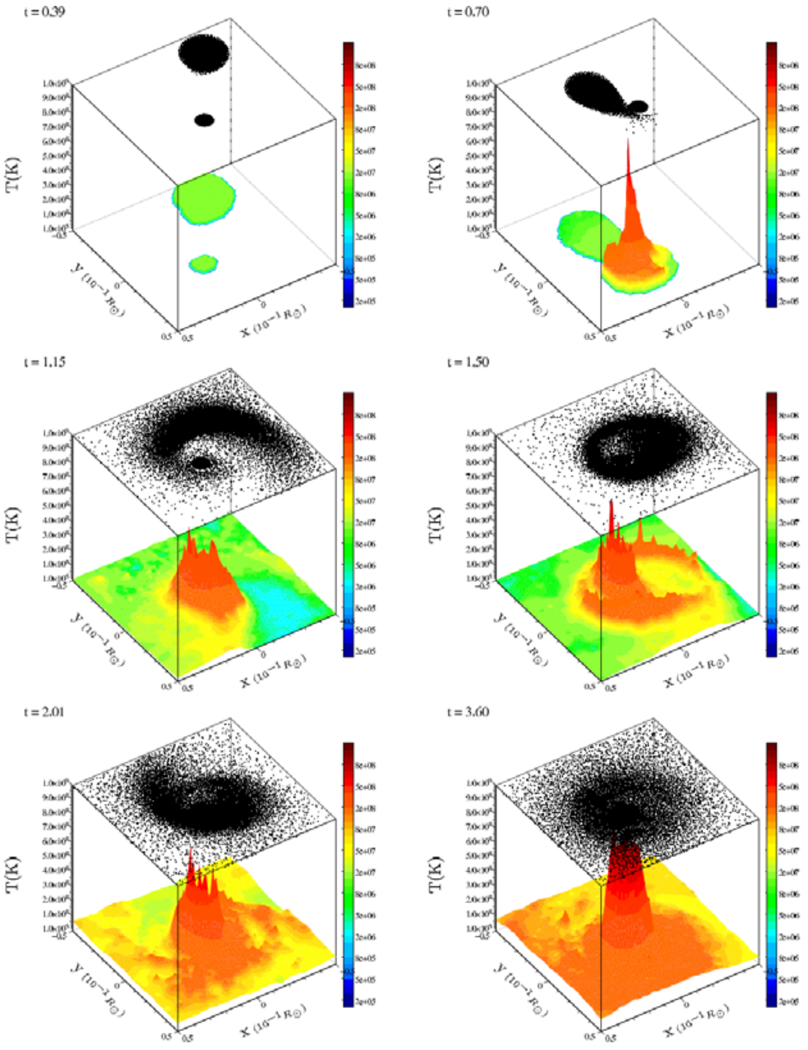
Spectroscopy, photometry



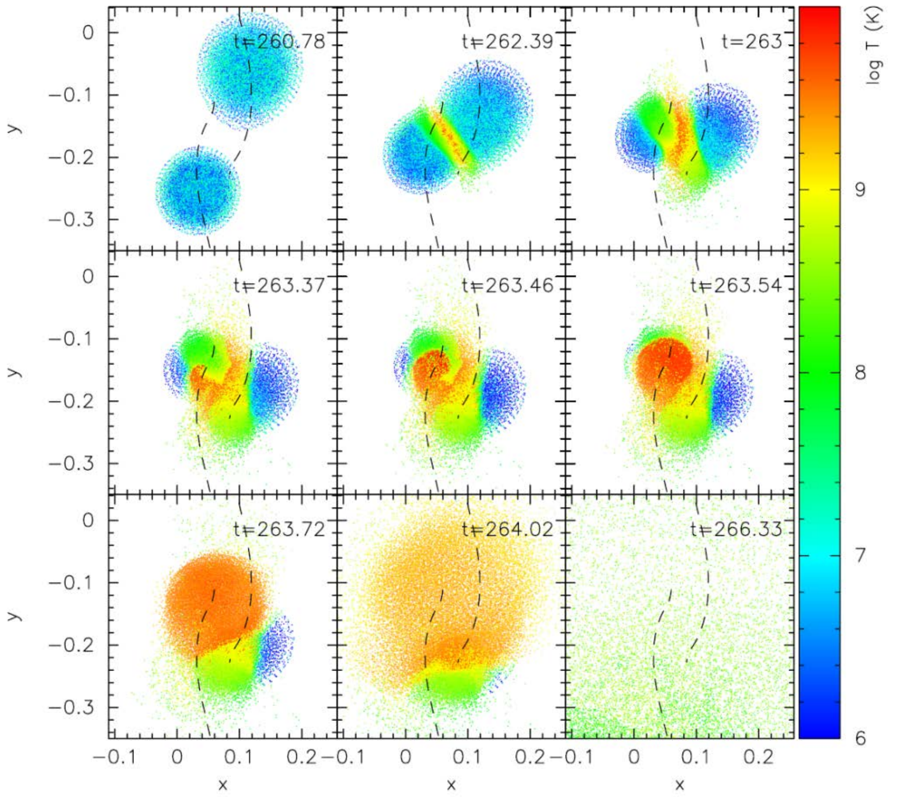
Type Ia (or thermonuclear) **Supernovae** [SN Ia]
Classical Nova Outbursts [CN]
} WD

X-Ray Bursts [XRBs]: NS

Stellar Mergers and Collisions



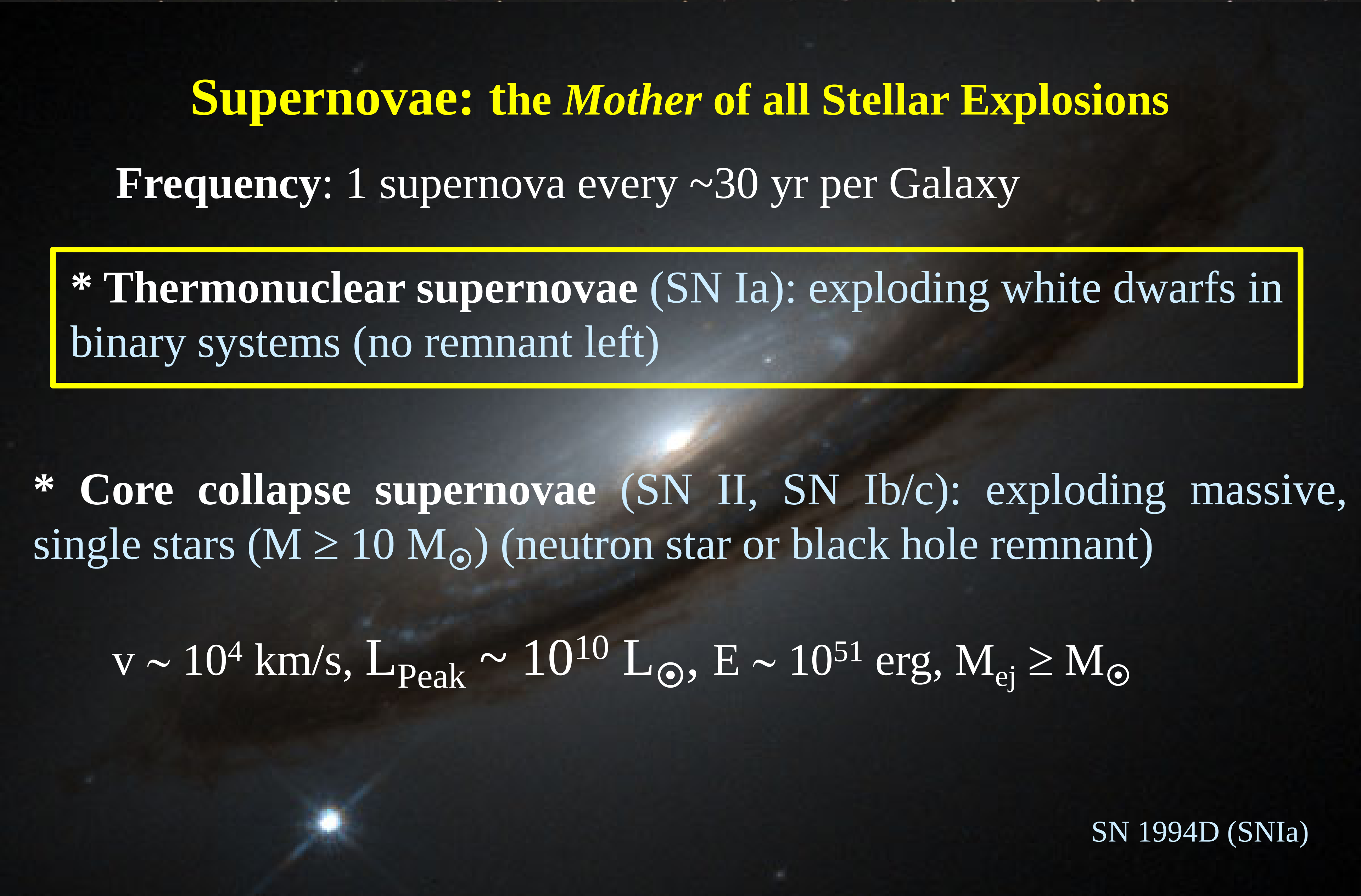
Guerrero, García-Berro & Isern, A&A (2004)



Detonations in WD dynamic interactions

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

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**

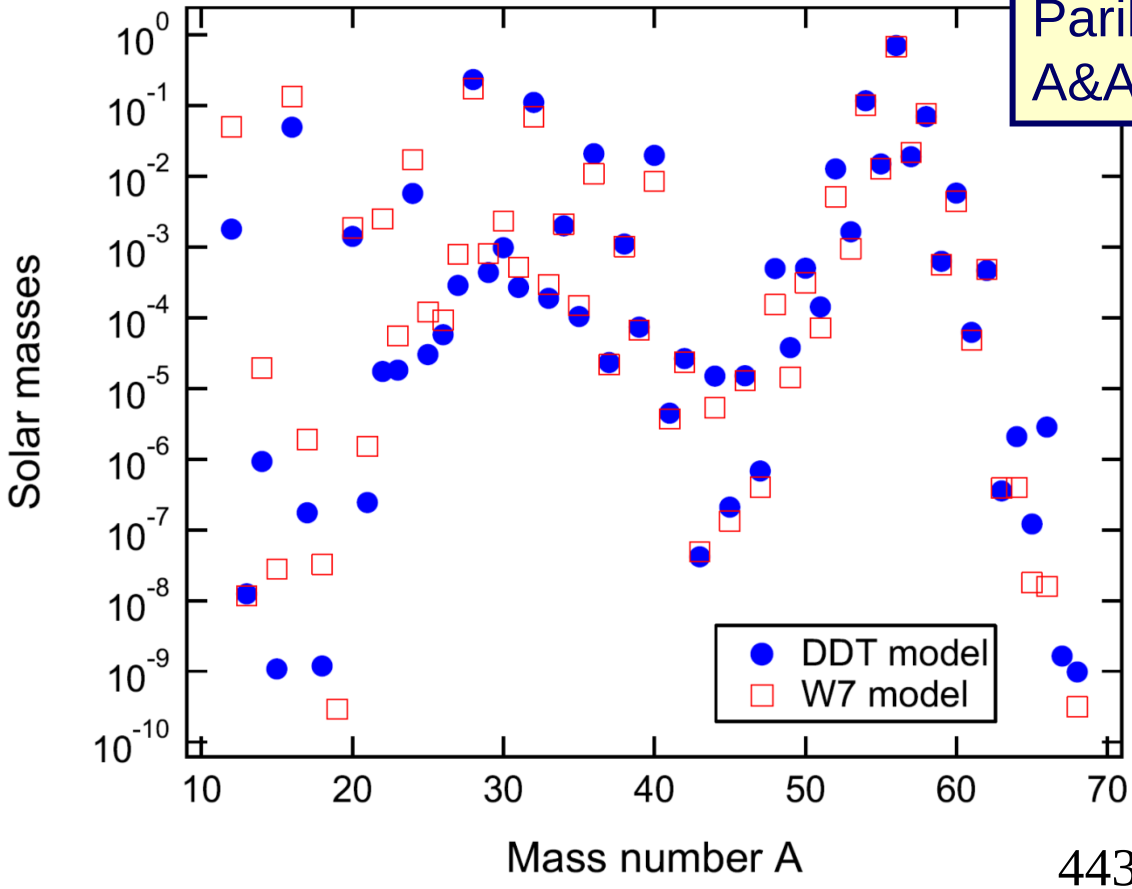
* SN Ia: main **Fe factories** in the Universe (> SN II)

* Scenario: not fully understood

- Single degenerate scenario: **WD + 'Normal' companion**
  (H or He accretion)
- Double degenerate scenario: **WD + WD**
  (He or C-O accretion)

Thermonuclear Supernovae: Nucleosynthesis

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



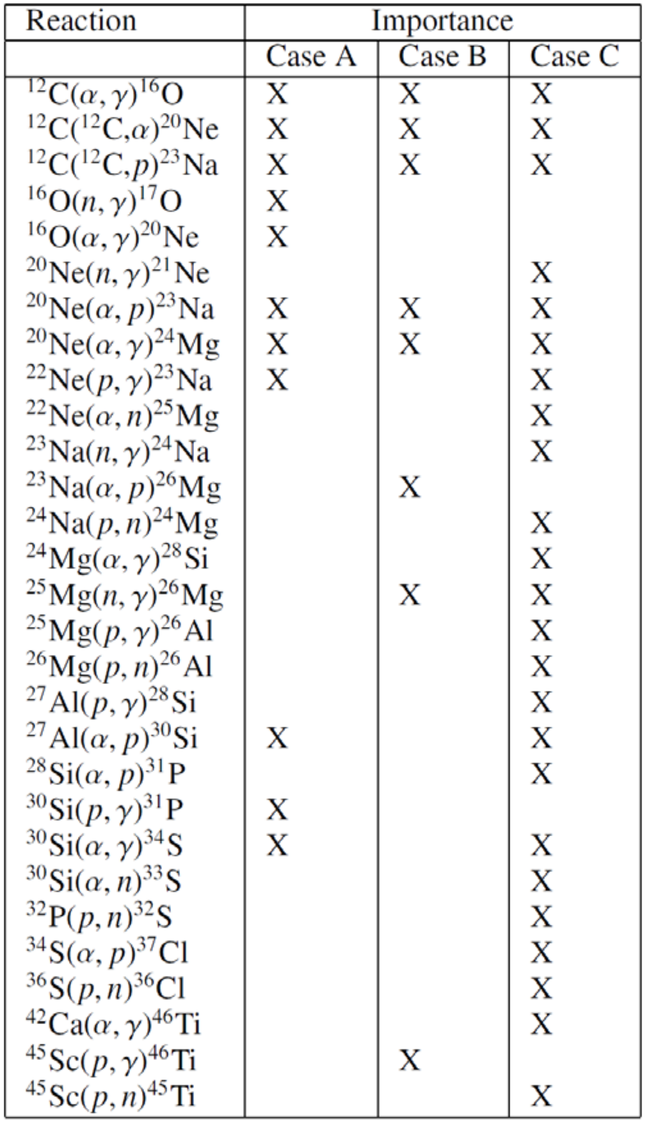
Parikh, JJ, Seitenzahl & Röpke, A&A (2013)

443 isotopes (H − Kr); 5267 links

Nuclear Uncertainties

After **several million** individual post-processing calculations

W7 **DDT** **W7+DDT**



Reaction	Importance		
	Case A	Case B	Case C
^{12}C(α,γ)^{16}O	X	X	X
^{12}C(^{12}C,α)^{20}Ne	X	X	X
^{12}C(^{12}C,p)^{23}Na	X	X	X
^{16}O(n,γ)^{17}O	X		
^{16}O(α,γ)^{20}Ne	X		
^{20}Ne(n,γ)^{21}Ne			X
^{20}Ne(α,p)^{23}Na	X	X	X
^{20}Ne(α,γ)^{24}Mg	X	X	X
^{22}Ne(p,γ)^{23}Na	X		X
^{22}Ne(α,n)^{25}Mg			X
^{23}Na(n,γ)^{24}Na			X
^{23}Na(α,p)^{26}Mg		X	
^{24}Na(p,n)^{24}Mg			X
^{24}Mg(α,γ)^{28}Si			X
^{25}Mg(n,γ)^{26}Mg		X	X
^{25}Mg(p,γ)^{26}Al			X
^{26}Mg(p,n)^{26}Al			X
^{27}Al(p,γ)^{28}Si			X
^{27}Al(α,p)^{30}Si	X		X
^{28}Si(α,p)^{31}P			X
^{30}Si(p,γ)^{31}P	X		
^{30}Si(α,γ)^{34}S	X		X
^{30}Si(α,n)^{33}S			X
^{32}P(p,n)^{32}S			X
^{34}S(α,p)^{37}Cl			X
^{36}S(p,n)^{36}Cl			X
^{42}Ca(α,γ)^{46}Ti			X
^{45}Sc(p,γ)^{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)

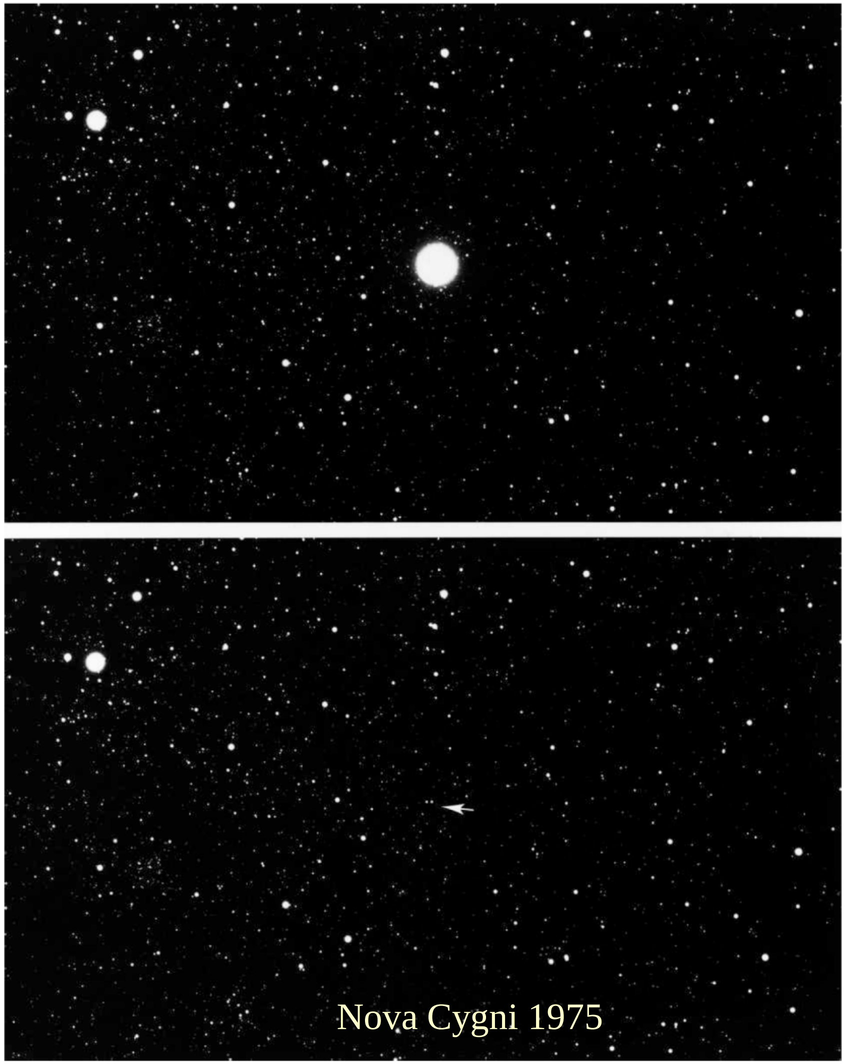
Recurrence time: ~ 1 - 10 yr (RNe) – 10^5 yr (CNe)

Frequency: 30 ± 10 yr^{-1}

Observed frequency: ~ 5 – 7 yr^{-1}

$E \sim 10^{45}$ ergs

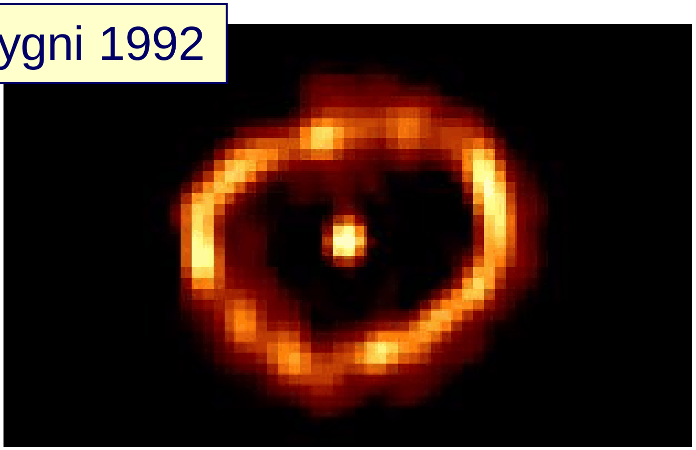
Mass ejected: $10^{-3} – 10^{-7} M_\odot$ ($\sim 10^3$ km s^{-1})

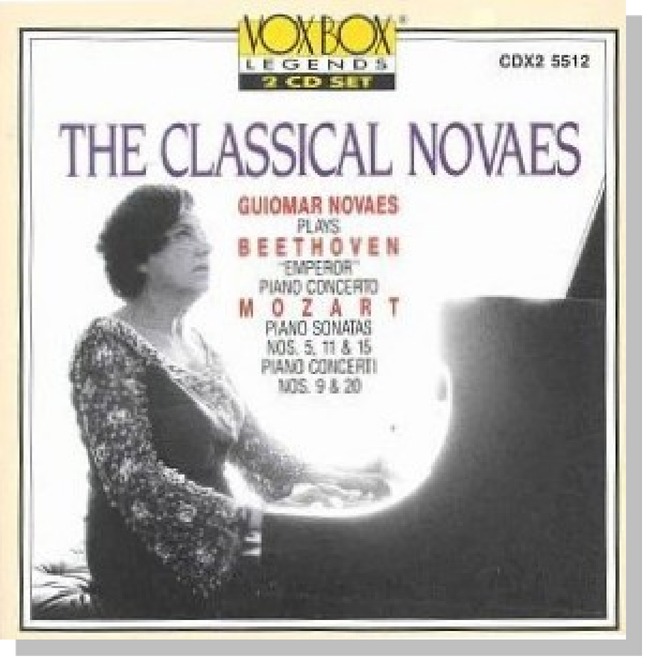

Nova Cygni 1975

The Classical Nova Nuclear Symphony

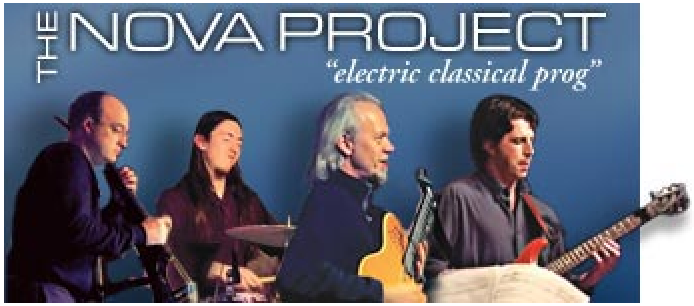
Classical Novae: ~**100** relevant isotopes **(A<40)** & a **(few) hundred** nuclear reactions **(T_{peak} ~ 100 – 400 MK)**

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)

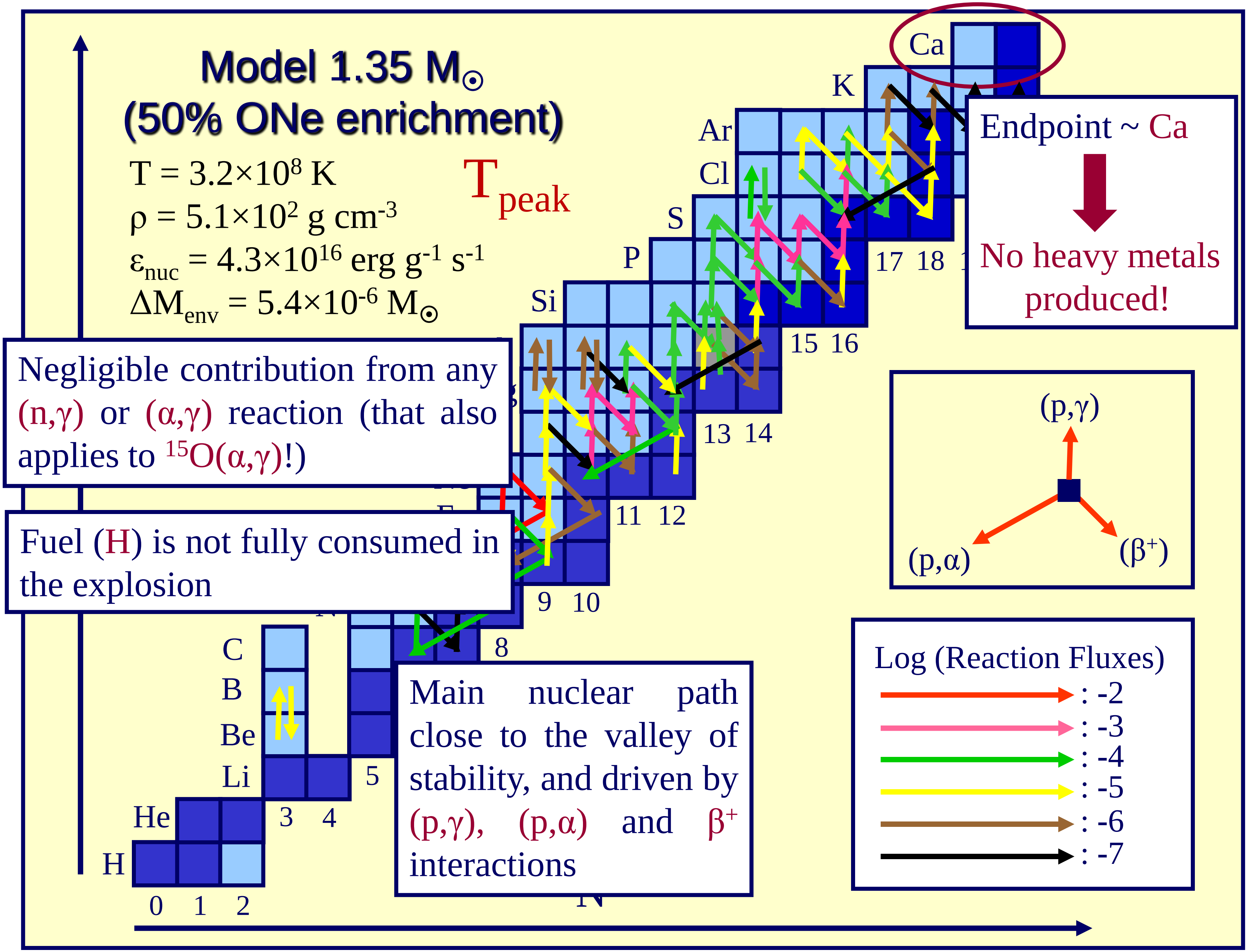
$T = 3.2\times10^{8}$ K

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



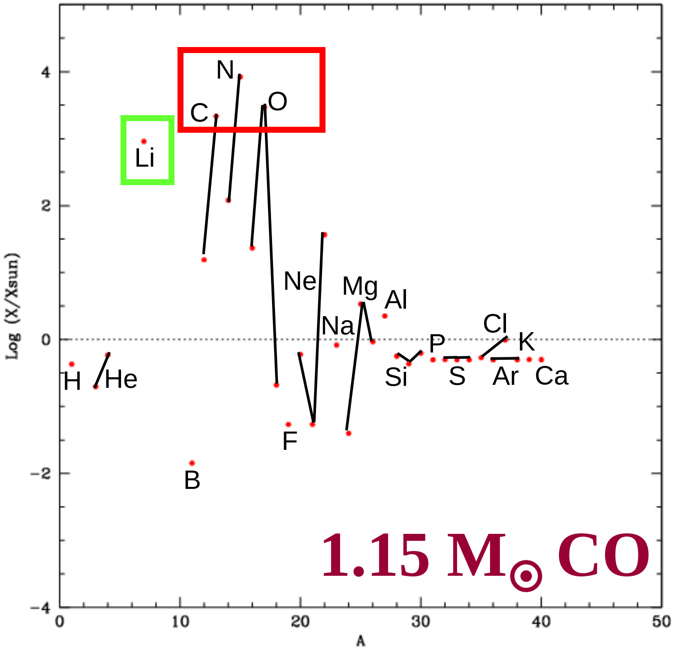
Endpoint ~ Ca

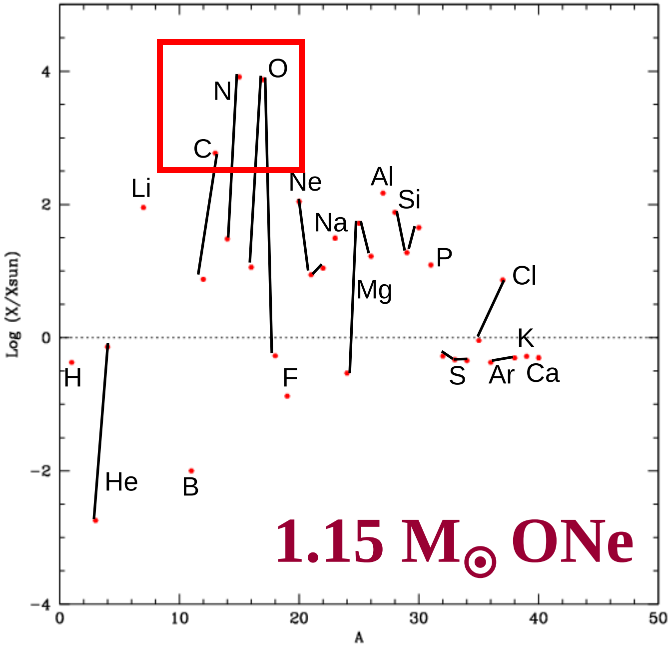
No heavy metals produced!

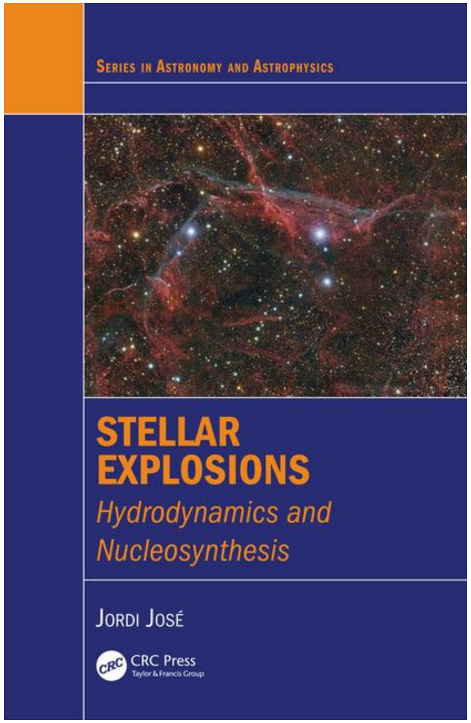
Negligible contribution from any (n,γ) or (α,γ) reaction (that also applies to $^{15}O(\alpha,\gamma)$!)

Fuel (H) is not fully consumed in the explosion

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







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STELLAR EXPLOSIONS

Hydrodynamics and Nucleosynthesis

Jordi José

CRC Press
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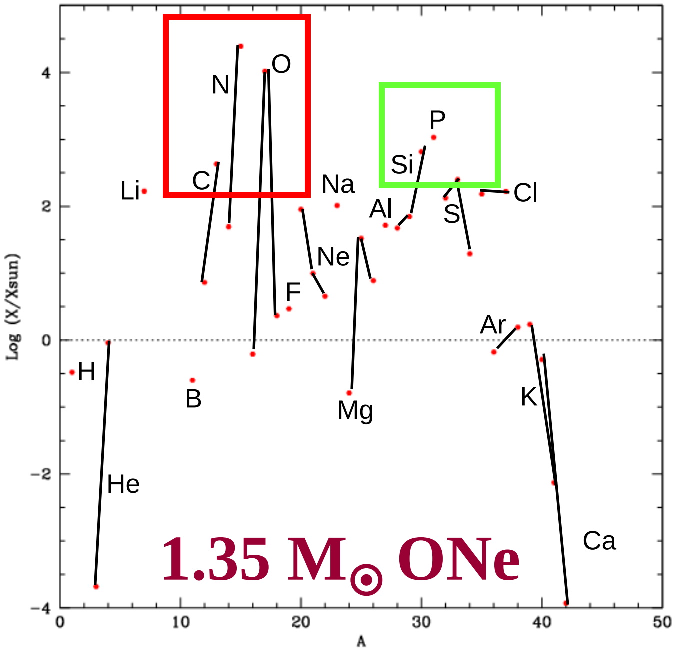
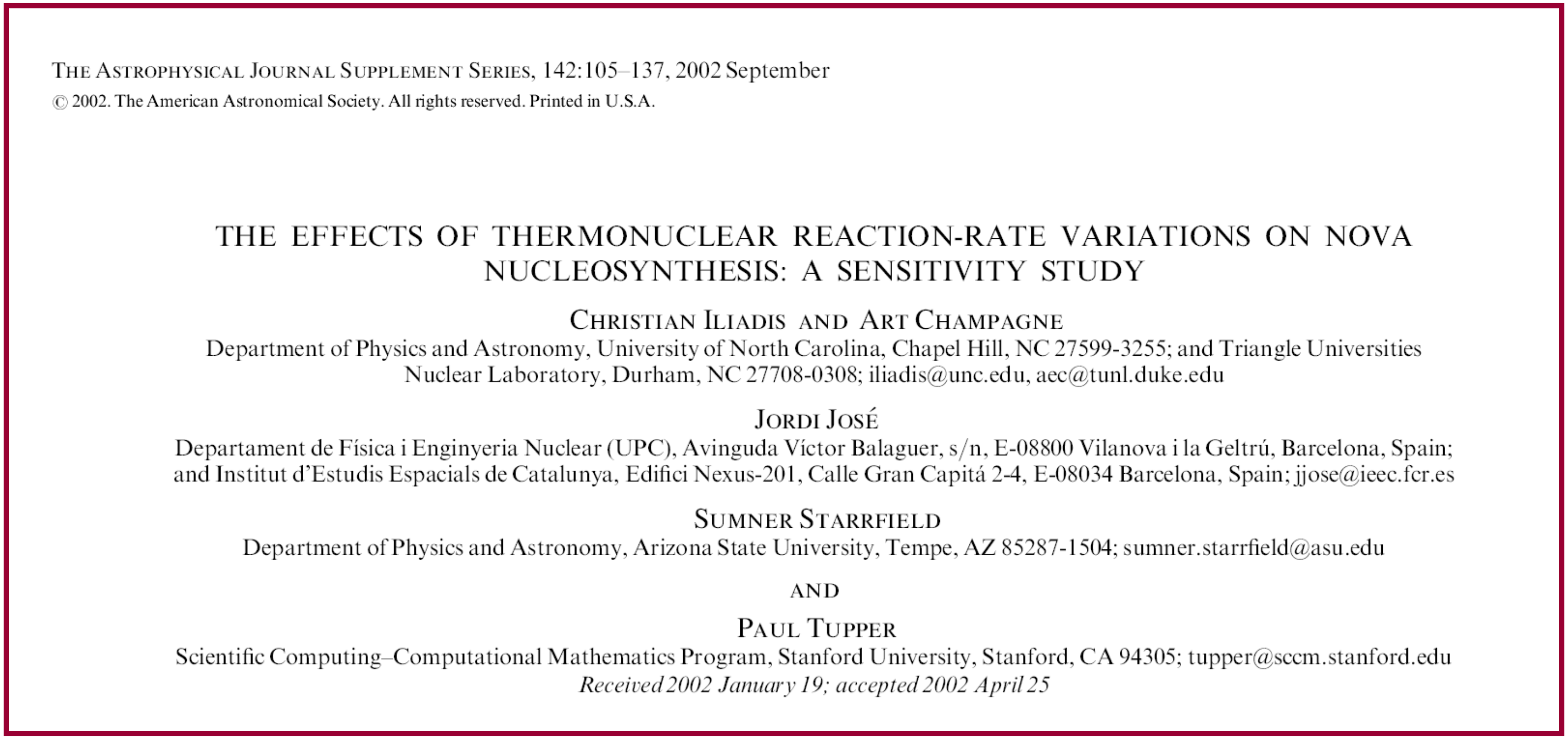
JJ 2016



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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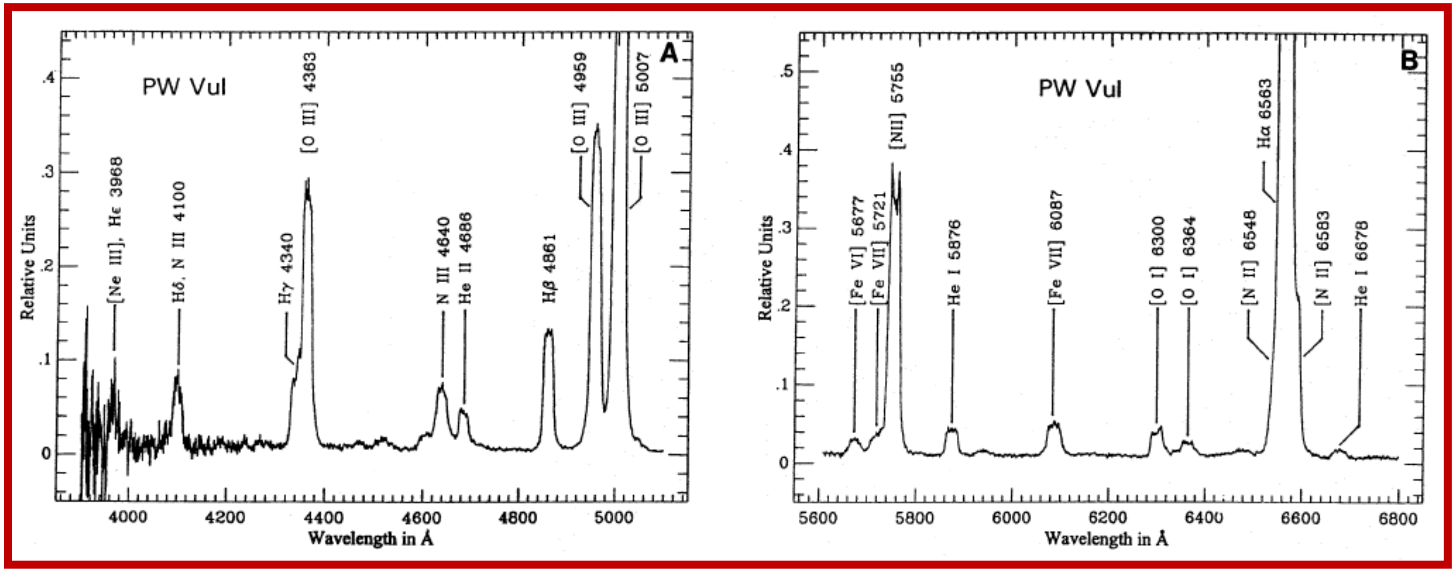
Received 2002 January 19; accepted 2002 April 25

$\approx$7350 nuclear reaction network calculations

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

Observational Constraints

In situ observations (highly risky...)



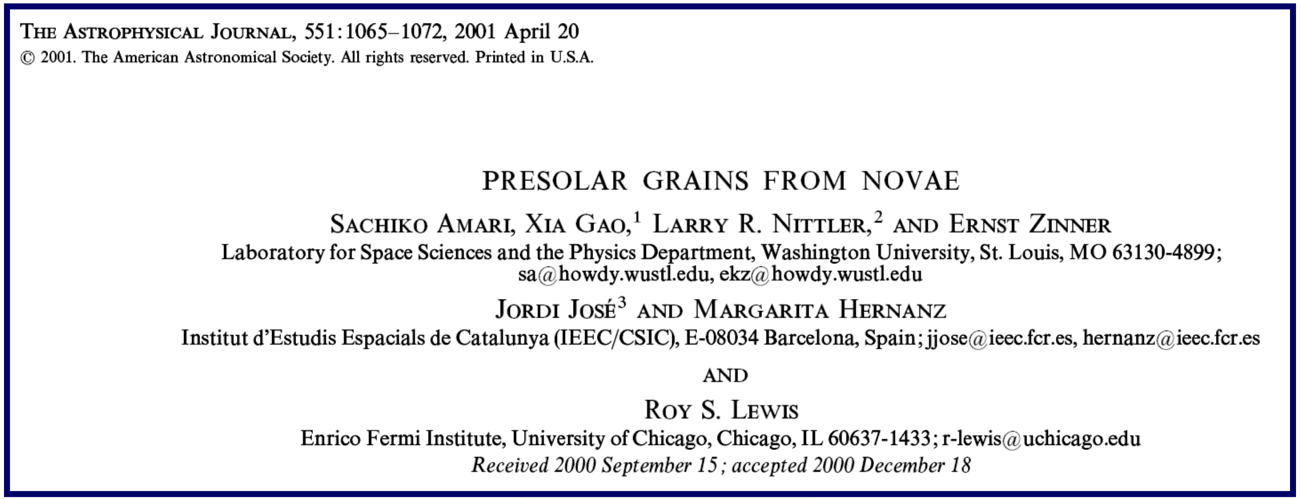
Andrëa et al. (1994)

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)

Presolar Grains



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

PRESOLAR GRAINS FROM NOVAE

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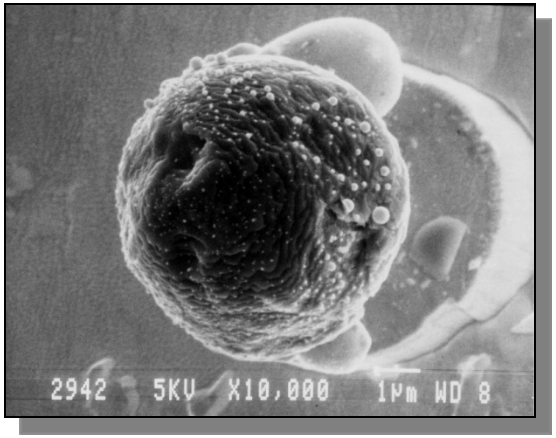
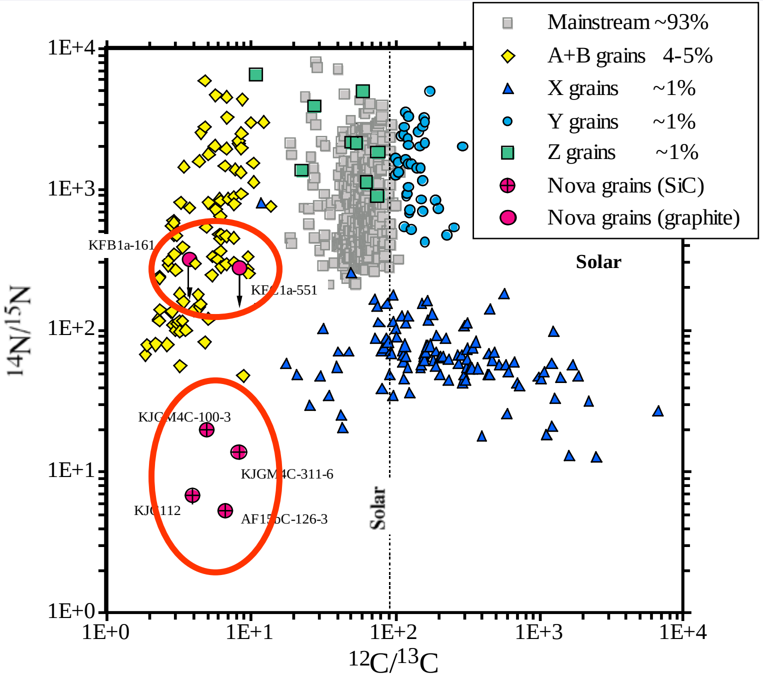
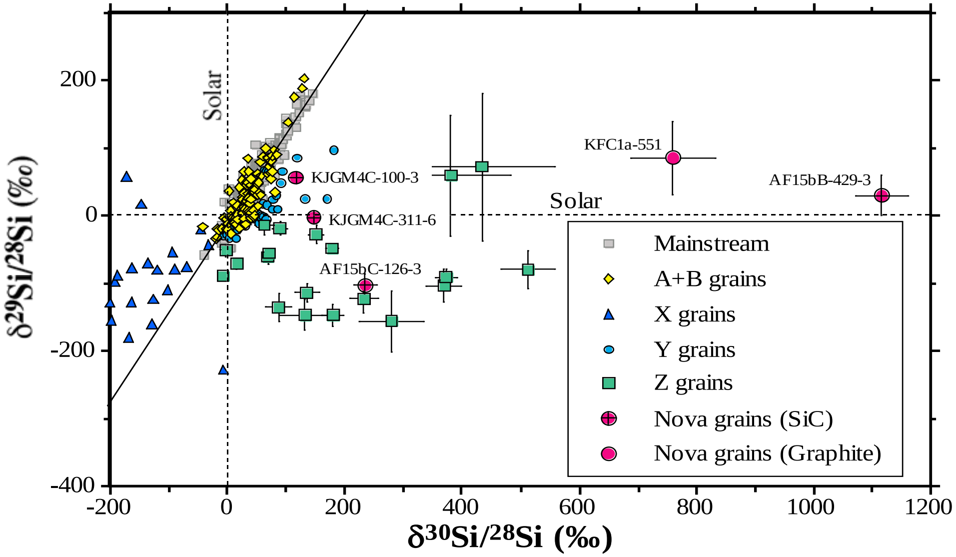






γ-Ray Emission from Classical Novae

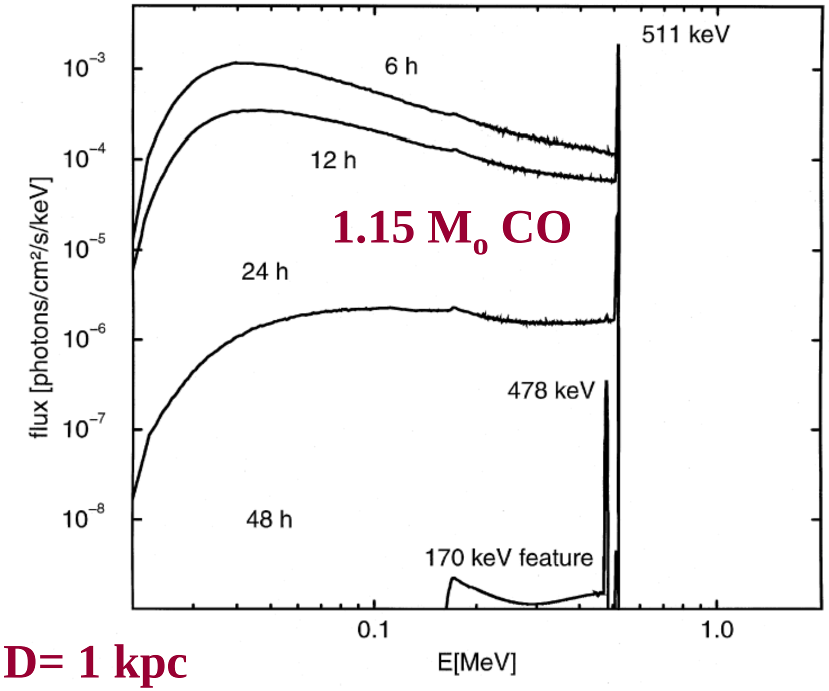
Isotope	Lifetime	Disintegration	Nova type
^{17}F	93 sec	β^+-decay	CO & ONe
^{14}O	102 sec	β^+-decay	CO & ONe
^{15}O	176 sec	β^+-decay	CO & ONe
^{13}N	862 sec	β^+-decay	CO & ONe
^{18}F	158 min	β^+-decay	CO & ONe
^{7}Be	77 day	e^--capture	CO
^{22}Na	3.75 yr	β^+-decay	ONe
^{26}Al	1.0 Myr	β^+-decay	ONe

* ^{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).

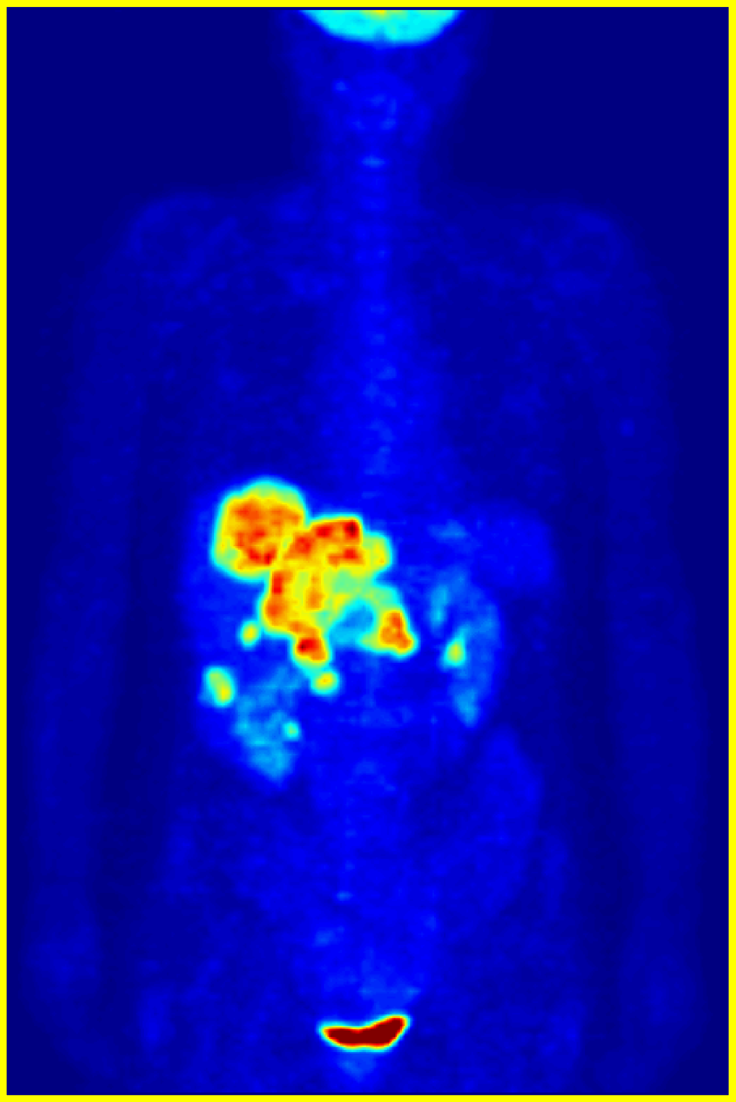
But! **Uncertainties** in the rates translate into a factor **~ 5 - 10** uncertainty in the expected fluxes!

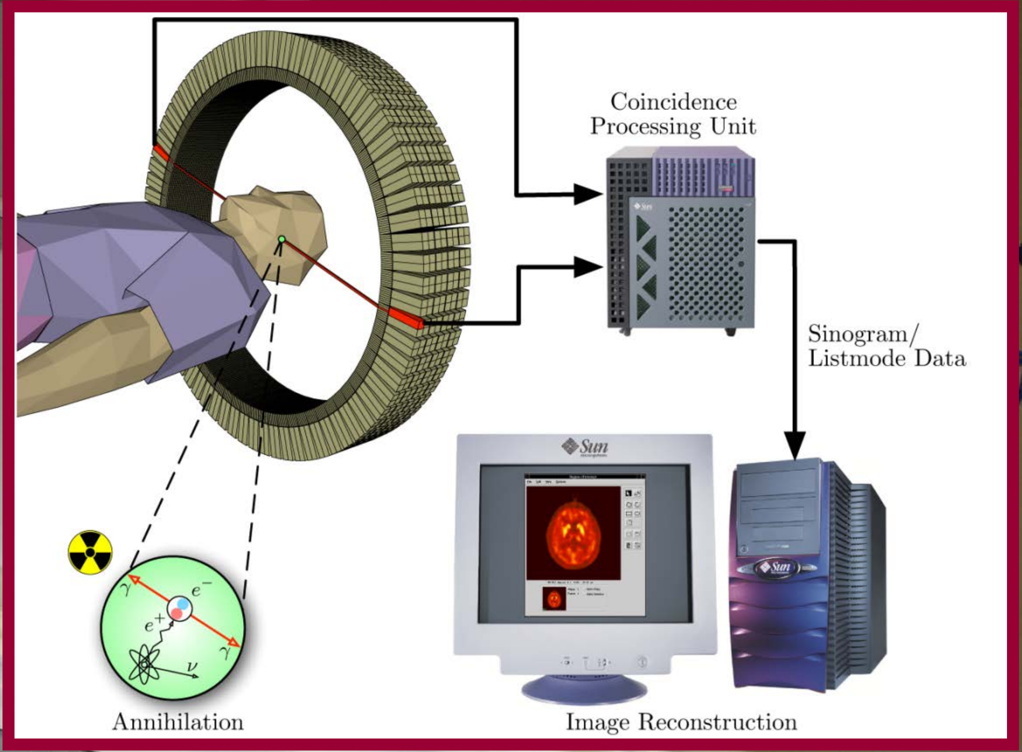


1.15 M_o CO

D= 1 kpc

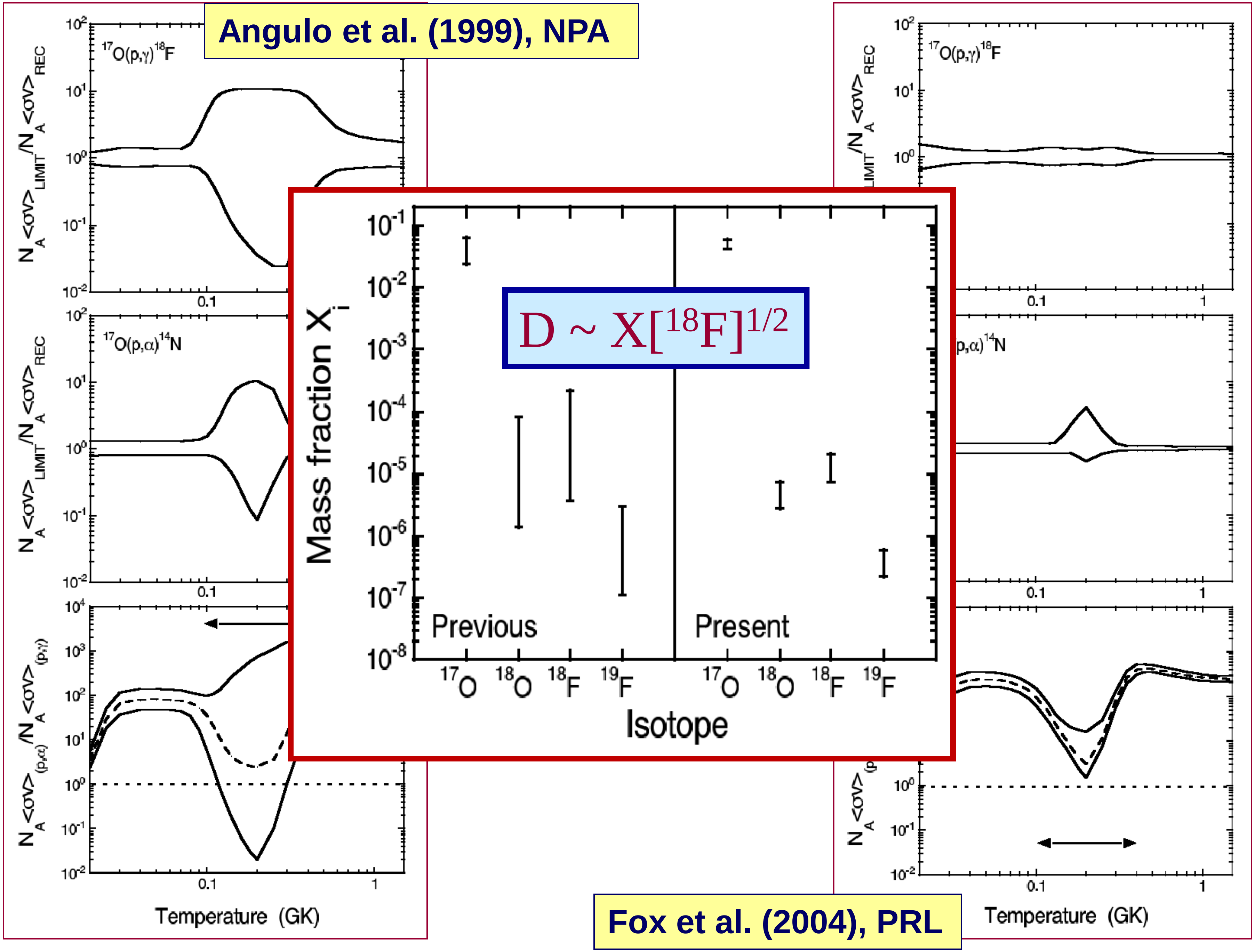
Gómez-Gomar, Hernanz, JJ, & Isern (1998), MNRAS





Positron Emission Tomography (**PET**)

Angulo et al. (1999), NPA



$D \sim X[^{18}F]^{1/2}$

Fox et al. (2004), PRL

III. Type I X-Ray Bursts

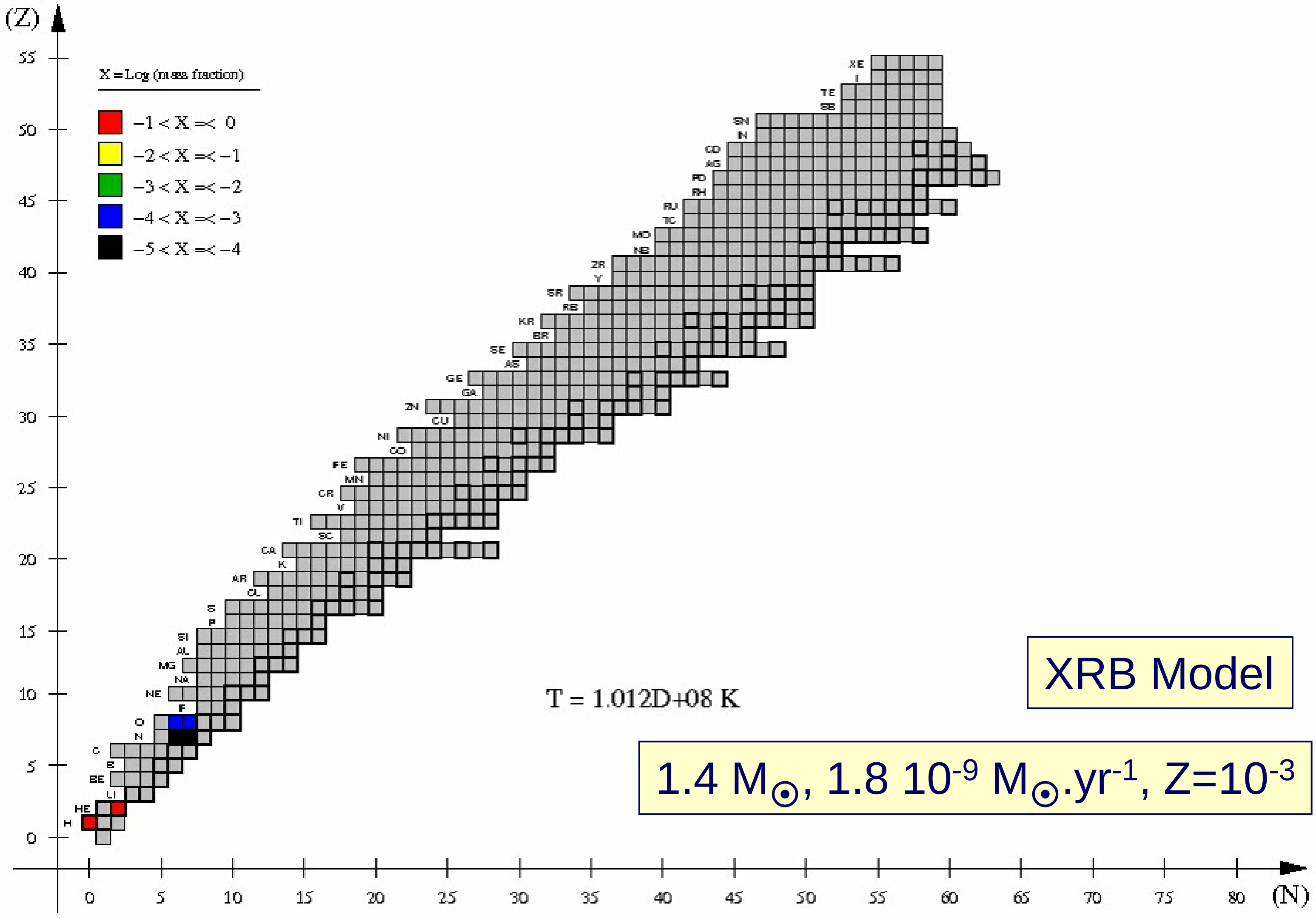
Nucleosynthesis in Type I X-Ray Bursts

Santa Fe, NM

NS $\longrightarrow$ $T_{peak} > 10^9$ **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

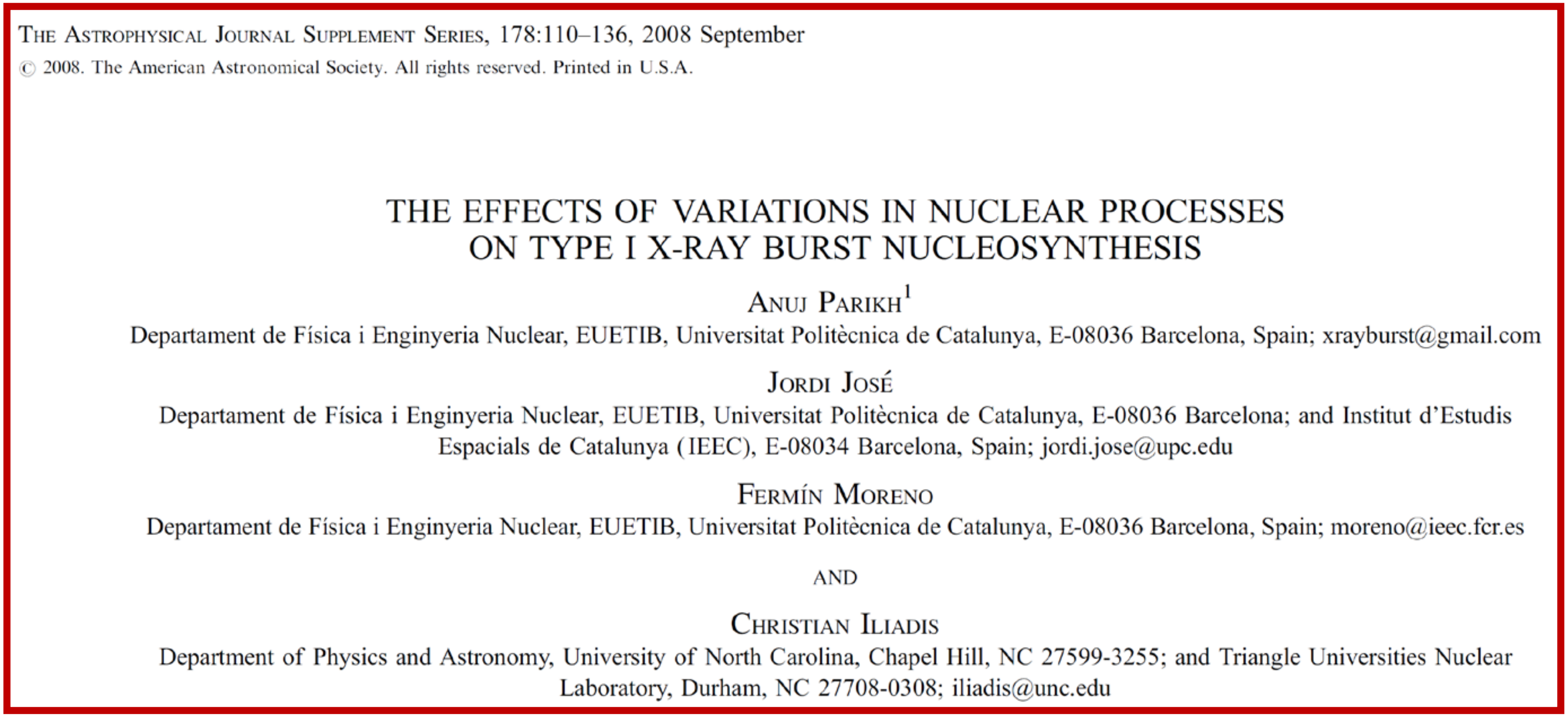
H/He mixed bursts: Main nuclear reaction flow driven by the *rp-process* (rapid p-captures and β^+-decays), the 3α-reaction, and the *αp-process* (a sequence of (α,p) and (p,γ) reactions), and proceeds away from the valley of stability, merging with the proton drip-line beyond **A = 38** (Schatz et al.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



XRB Model

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

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

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

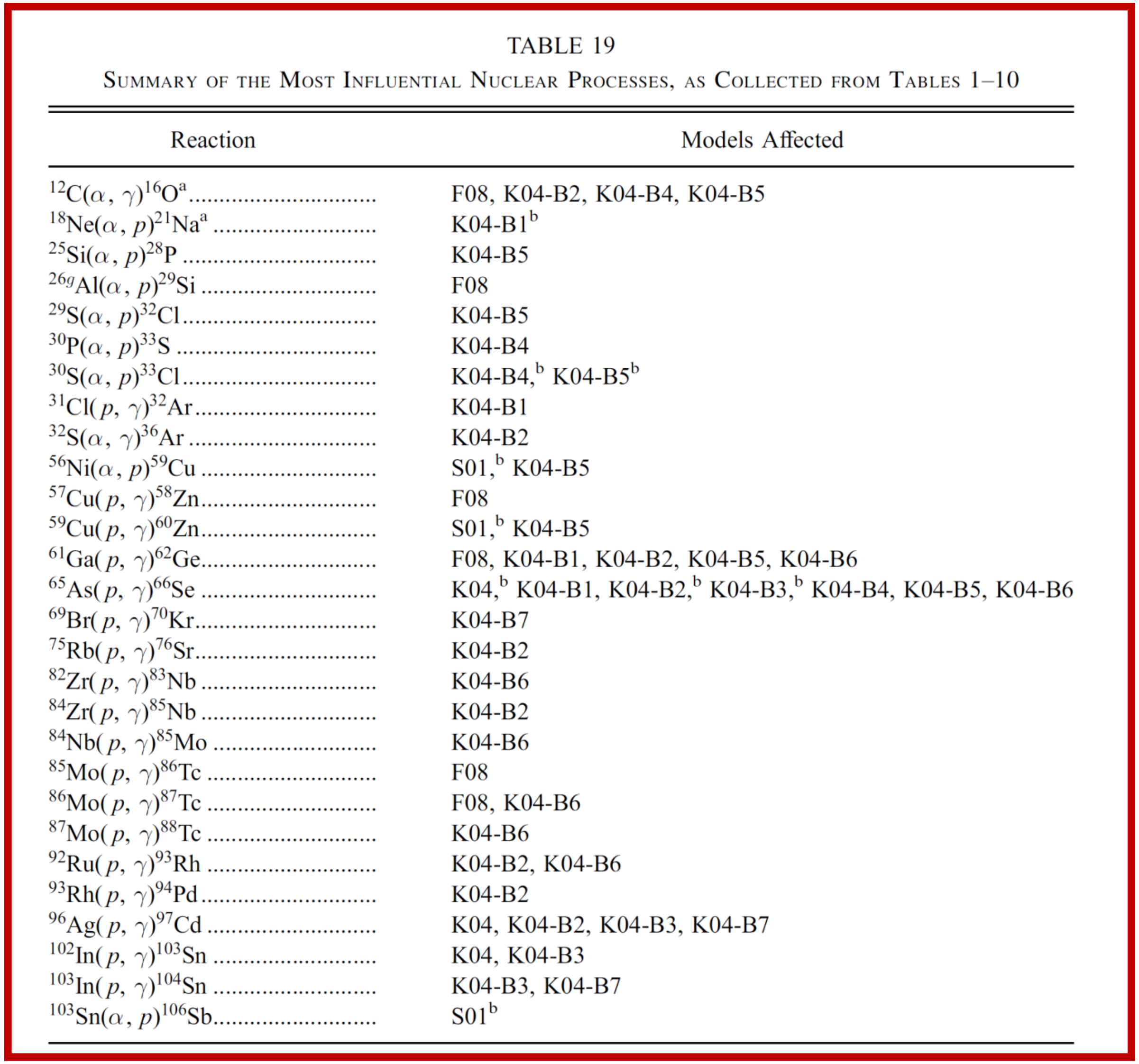

TABLE 19

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

Reaction	Models Affected
^{12}C(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]

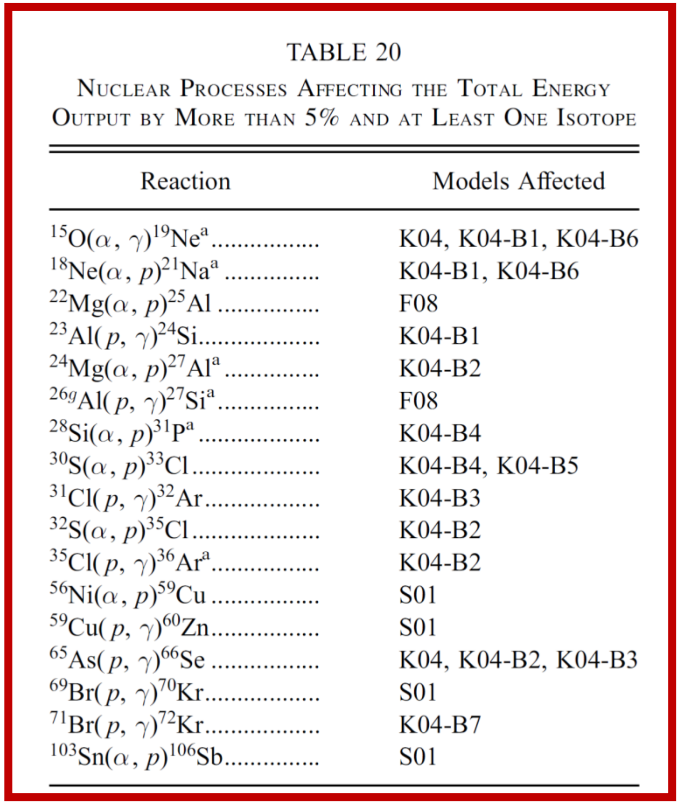

TABLE 20

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

Thank you for your attention!

Nuclear Astrophysics at the Canfranc Underground Laboratory
2nd CUNA Workshop
Canfranc Estación (Spain), Feb 29 – Mar 1, 2016