Hydrodynamic Models of Classical Novae and Type I X-Ray Bursts

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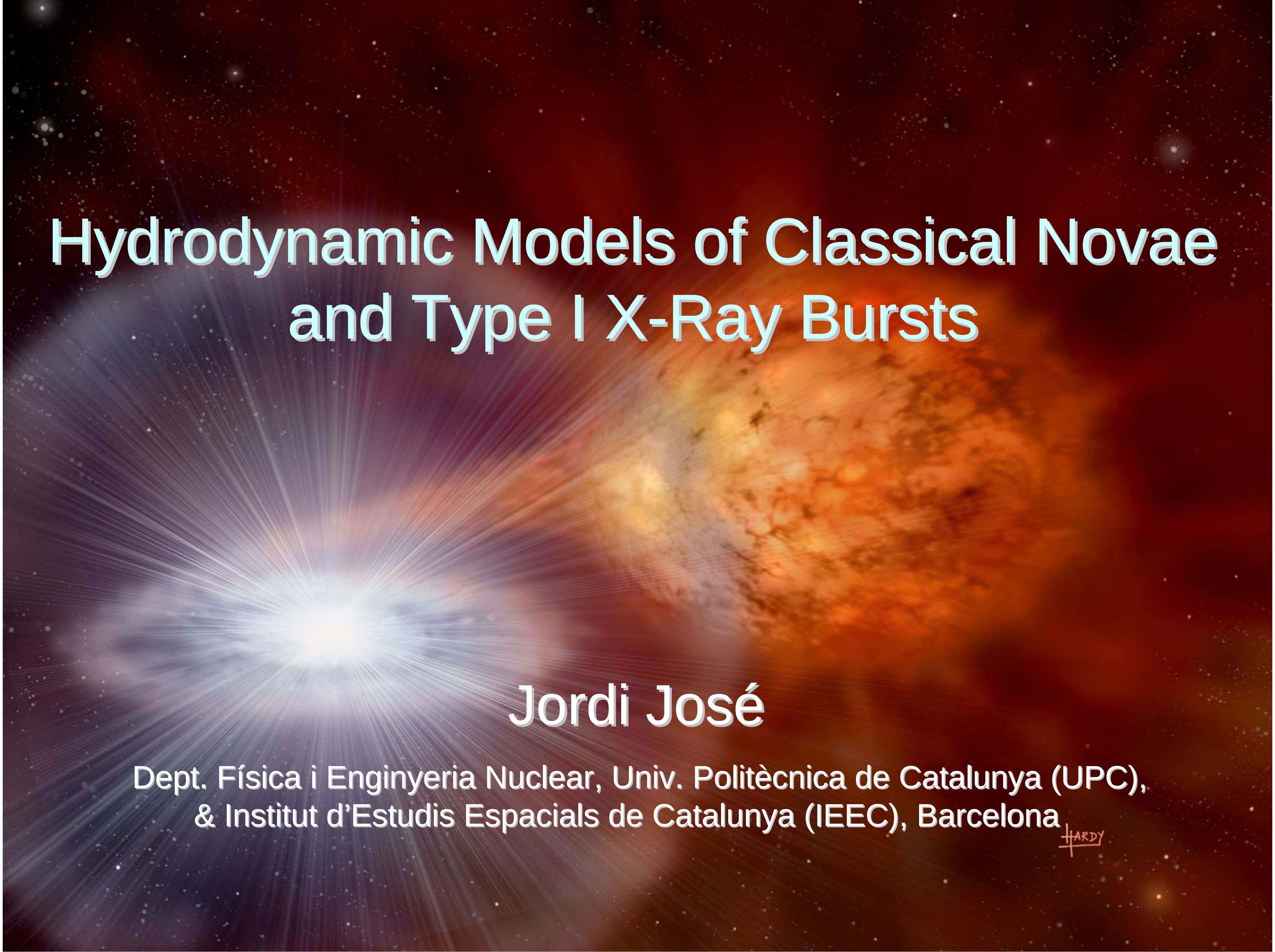


I. *Stellae Novae*: An Introduction

G. B. Riccioli, *Almagestum Novum* (1651), lib. 2, pp. 177-179

↓

14 (im)possible explanations!


AD
MAGNANIMVM PRINCIPEM
HONORATVM II.
MONOECI PRINCIPEM
DVCEM VALENTINVM
PAREM FRANCIÆ
MARCHIONEM BAVCII, COMITEM CARLADESII
BARONEM BVISSII, ET CALVINETI
DOMINVM S. REMIGII &c.
ALMAGESTI NOVI
PARS POSTERIOR
TOMI PRIMI.

I. Newton, *Principia Mathematica* (1726), 3rd ed., book 3, prop. 42:

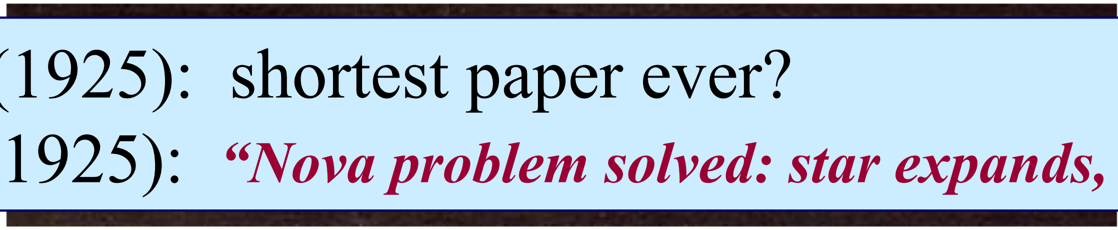
So fixed stars, that … emitted from them for a long time, ma… n this fresh supply of new fuel those old stars, acquiring new splendor, may pass for new stars

Old stars accreting (fuel) material!

Observational & Theoretical Breakthroughs

Observations

* **Huggins & Miller** perform the first (optical) spectroscopic study of a nova [T CrB 1866]



Hartmann (1925): shortest paper ever?
RR Pic (1925): ***"Nova problem solved: star expands, and bursts"***

Nova-Problem (Telegramm aus Buenos Aires 1925 Nov. 26). Nova-Problem gelöst. Stern bläht sich auf, zerplatzt.
J. Hartmann.

* **Pickering** (1894), **Pike** (1929) and others suggest that the spectral features may be due to ejection of a shell from a star
* **Stratton & Manning** (1939) propose that the minimum in DQ Her light curve is due to dust formation
* **Walker** (1954), **Kraft** (1963, 1964) demonstrate the binary nature of CVs (<u>novae</u>, in particular)

Theory

* **Schatzmann** (1951): outburst triggered by nuclear reactions [^{3}He]

REMARQUES SUR LE PHÉNOMÈNE DE NOVA (IV)

L'onde de détonation due à l'isotope ^{3}He

par Evry Schatzman

Sommaire. — *L'isotope ^{3}He peut s'accumuler en faible quantité dans les étoiles. Une faible concentration de ^{3}He est suffisante pour que puisse se former une onde de détonation, à condition que l'amorçage convenable existe.*

Ann. d'Astroph. (1951) **14**, 294

* See also **Cameron** (1959), **Gurevitch & Lebedinsky** (1957), **Rose** (1968), **Starrfield** (1971a,b)... and many more!

DYNAMICAL MODELS OF NOVAE*

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Received June 26, 1968; revised September 27, 1968

ApJ (1969) **156**, 569

ABSTRACT

The dynamics of a nova outburst are studied by means of a time-dependent hydrodynamics computer program which includes transport of energy by radiation and convection. Two distinct types of ejections which could give rise to novae are identified. The "flash" nova (e g., T CrB) has a very rapidly rising and falling light curve and a rapidly decreasing velocity curve. A strong shock wave which imparts a velocity greater than the escape velocity to the outer layers of the star will produce this behavior. A less rapidly rising and falling light curve and a nearly constant velocity are characteristic of the "ordinary" nova (e.g., GK Per). These features will result when the stellar material is forced outward by a pressure front which is not a shock wave. The pre-maximum halt, which is characteristic of the latter type of nova, results from the temperature dependence of the opacity of neutral hydrogen.

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

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

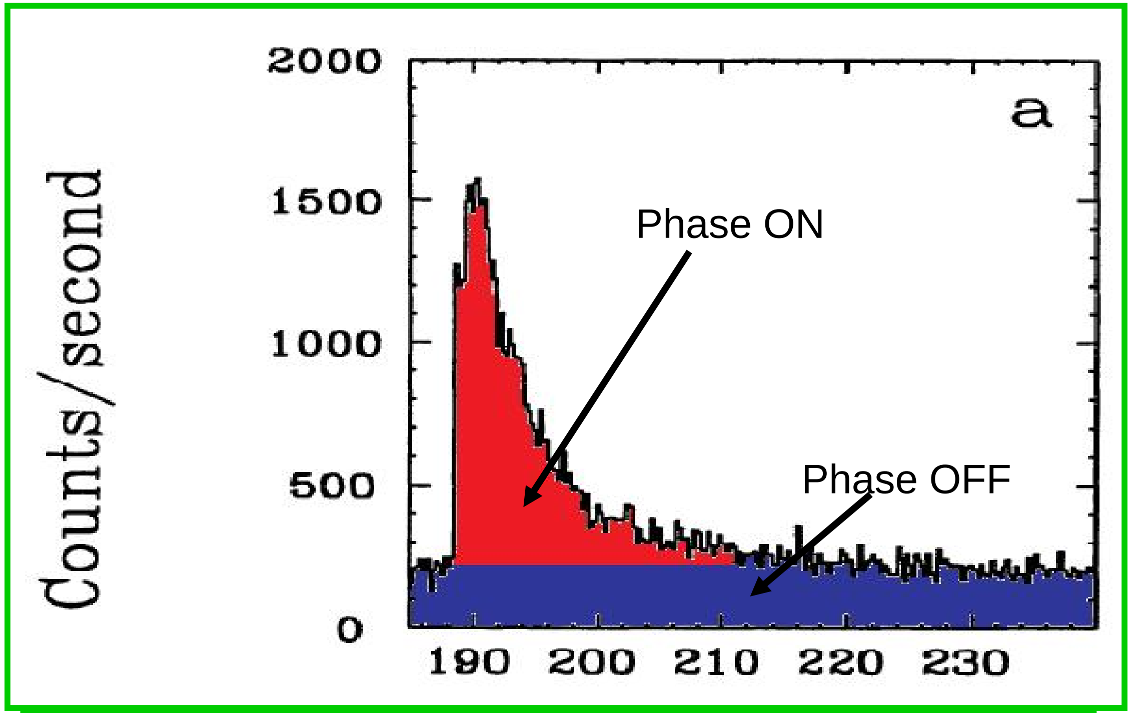
Recurrence time: ~ hours – days

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



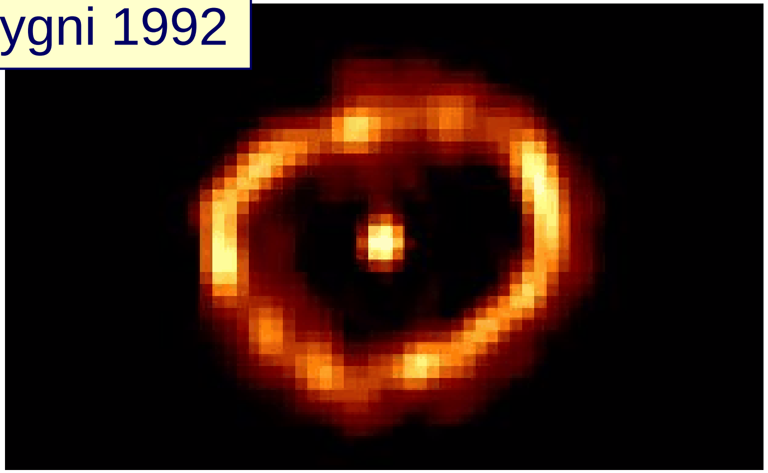
Haberl et al. (1987) 4U 1820-30

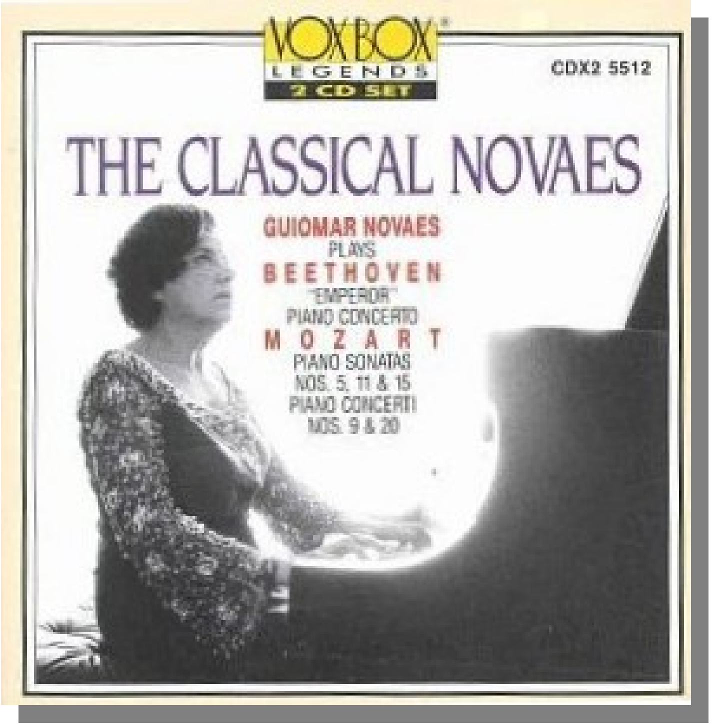
First models: Woosley & Taam'76; Maraschi & Cavalieri'77; Joss'77

II. The Nuclear Symphony

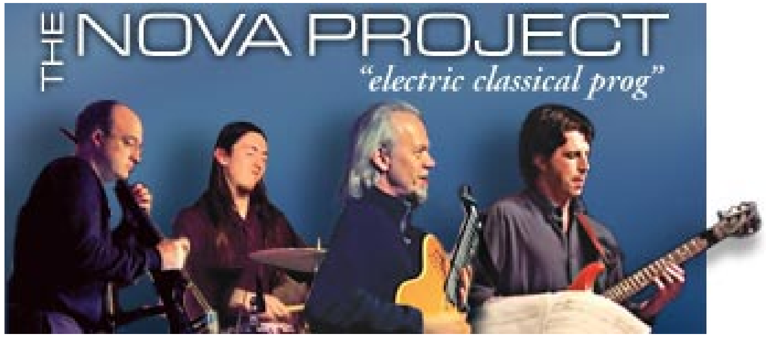
Classical Novae: ~**100** relevant isotopes **(A<40)** & a **(few) hundred** nuclear reactions **(T_{peak} ~ 100 – 400 MK)**

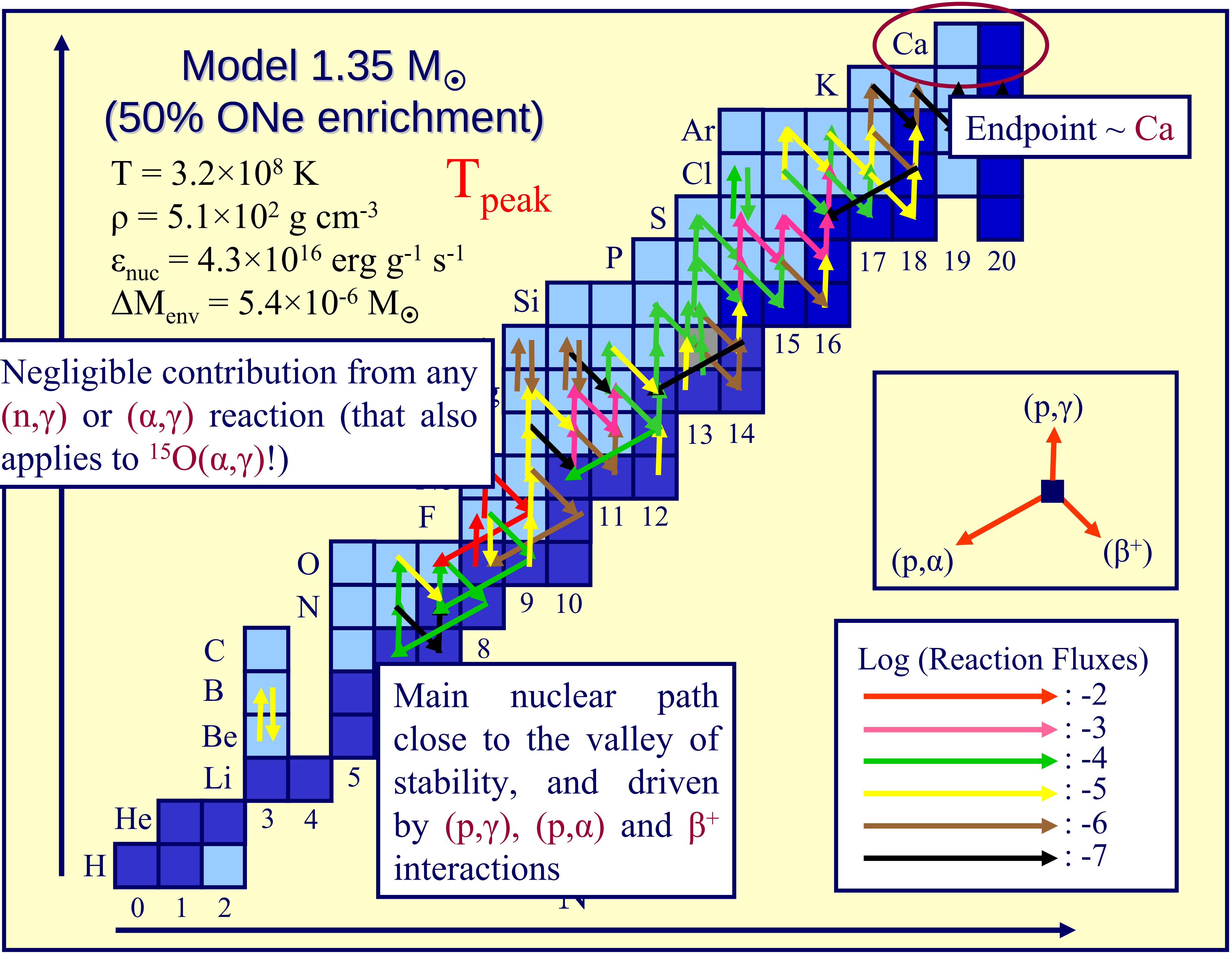
Nova Cygni 1992



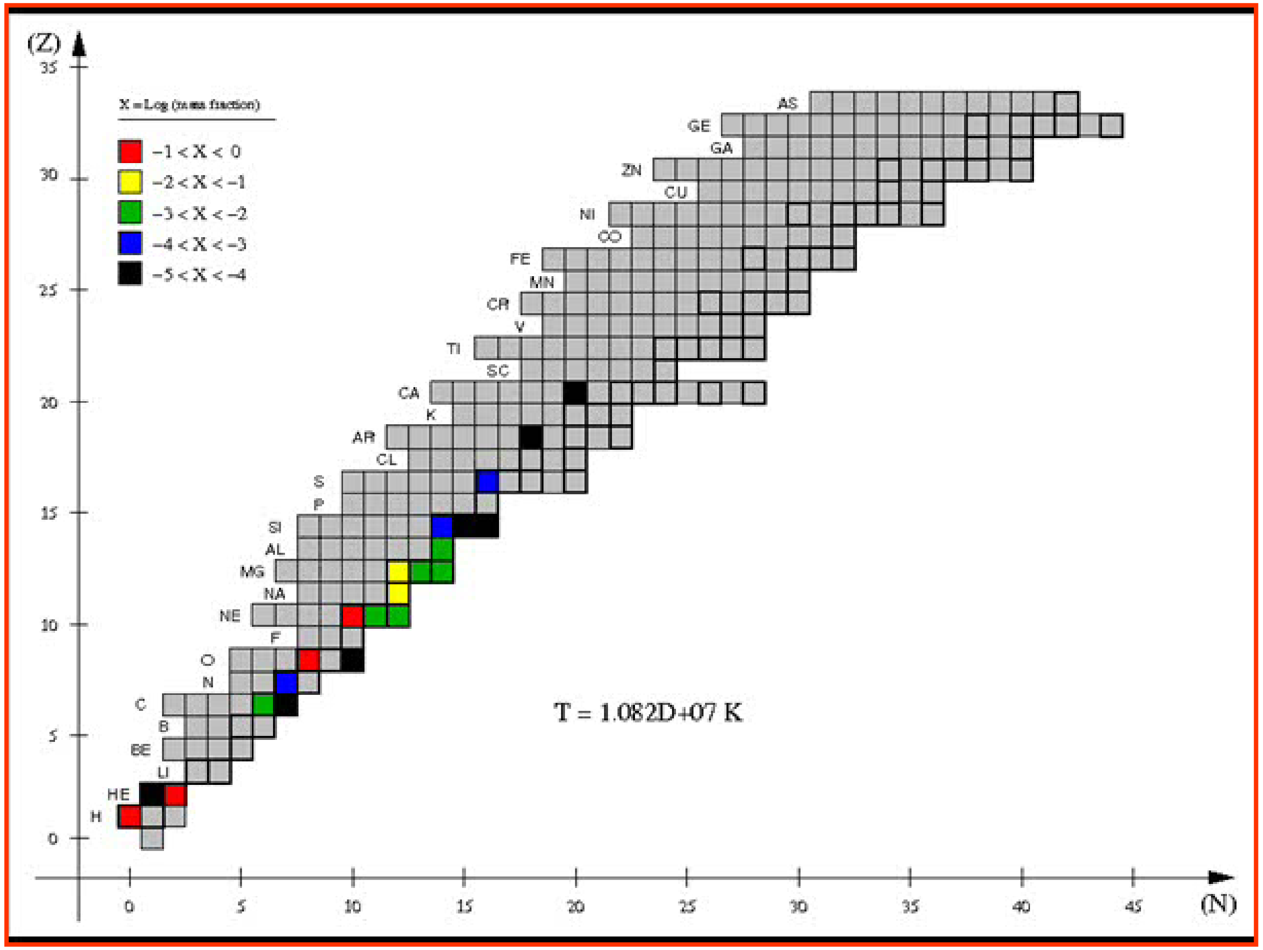


Novae as **unique stellar explosions** for which the nuclear physics input is (will be) primarily based on experimental information (JJ, Hernanz & Iliadis, Nucl. Phys. A 2006)





Model 1.35 M⊙
(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⊙
T_peak
Negligible contribution from any (n,γ) or (α,γ) reaction (that also applies to 15O(α,γ)!)
Main nuclear path close to the valley of stability, and driven by (p,γ), (p,α) and β+ interactions
Endpoint ~ Ca
H
He
Li
Be
B
C
N
O
F
Si
P
S
Cl
Ar
K
Ca
0
1
2
3
4
5
8
9
10
11
12
13
14
15
16
17
18
19
20
N
(p,γ)
(p,α)
(β+)
Log (Reaction Fluxes)
: -2
: -3
: -4
: -5
: -6
: -7



1.35 $M_{\odot}$, 2 10^{-10} $M_{\odot}.yr^{-1}$, Z=Solar (+50% pre-enrichment)

Classical Novae: JJ, Hernanz, Coc & Iliadis (2011), in prep.

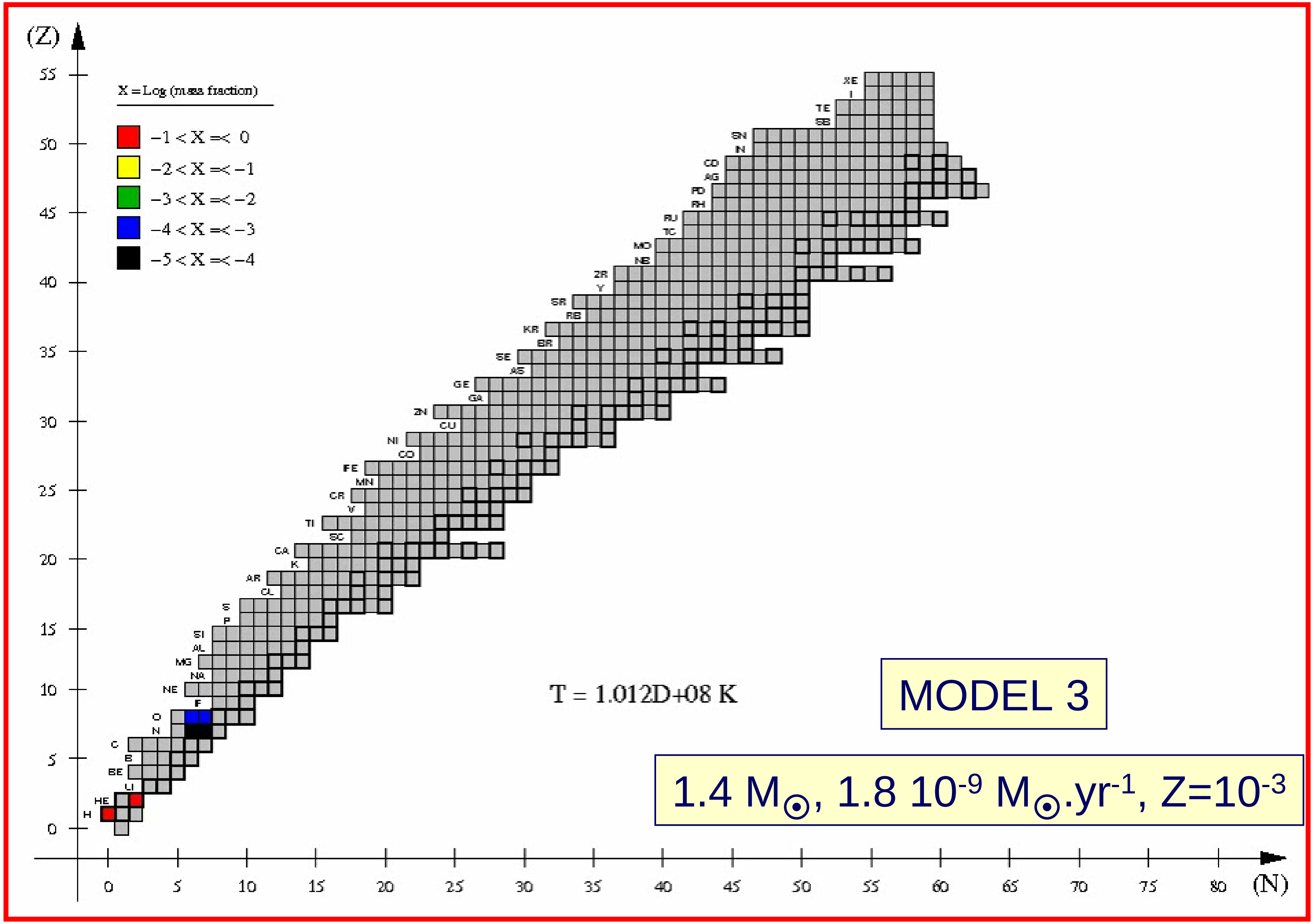
Nucleosynthesis in Type I X-Ray Bursts

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

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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$\approx$7350 nuclear reaction network calculations

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

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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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
$^{12}C(\alpha, \gamma)^{16}O$[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]

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.

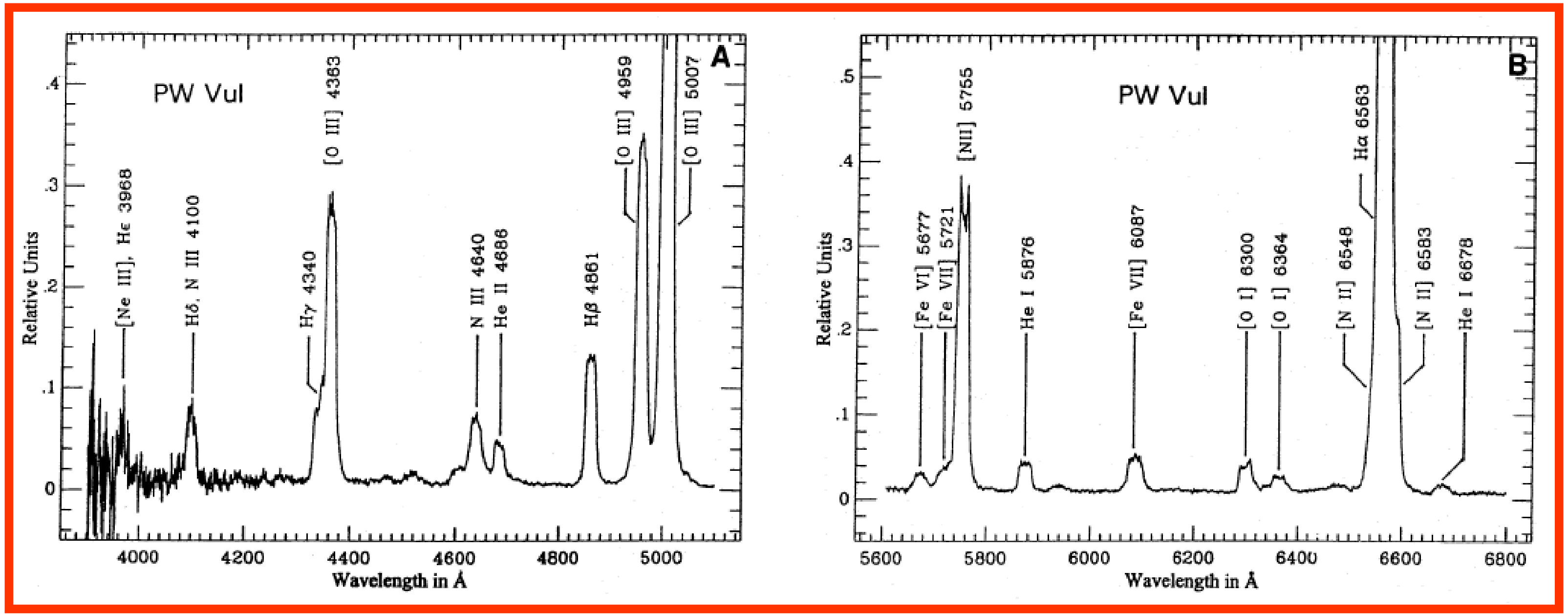
[b] Reaction that affects the total energy generation rate by more than 5% at some time interval in this model, when its rate is varied by a factor of 10 up and/or down. See text and Table 20 for details.

TABLE 20

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

Reaction	Models Affected
$^{15}O(\alpha, \gamma)^{19}Ne$[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

III. 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 and dust

Evidence for **dust formation** (IR) accompanying nova outbursts

Gehrz et al. (1998)

Nova	Year	V_o (km s^{-1})	Types of Dust Formed[b]
FH Ser	1970	560	C
V1229 Aql	1970	575	C
V1301 Aql	1975	...	C
V1500 Cyg[a]	1975	1180	...
NQ Vul	1976	750	C
V4021 Sgr	1977	...	C
LW Ser	1978	1250	C
V1668 Cyg	1978	1300	C
V1370 Aql[d]	1982	2800	C; SiC; SiO_2
GQ Mus	1983	600	No dust
PW Vul	1984 #1	285	C
QU Vul[a]	1984 #2	1–5000	SiO_2
OS And[a,e]	1986	900	C?
V1819 Cyg[a]	1986	1000	No dust
V842 Cen	1986	1200	C; SiC; HC
V827 Her[a]	1987	1000	C
V4135 Sgr	1987	500	...
QV Vul	1987	700	C; SiO_2; HC; SiC
LMC 1988 #1	1988 #1	800	C?
LMC 1988 #2	1988 #2	1500	...
V2214 Oph	1988	500	...
V838 Her	1991	3500	C
V1974 Cyg[a]	1992	2250	No dust
V705 Cas	1993	840	C; HC; SiO_2
Aql 1995[a]	1995	1510	C

THE ASTROPHYSICAL JOURNAL, 203:490–496, 1976 January 15

GRAINS OF ANOMALOUS ISOTOPIC COMPOSITION FROM NOVAE

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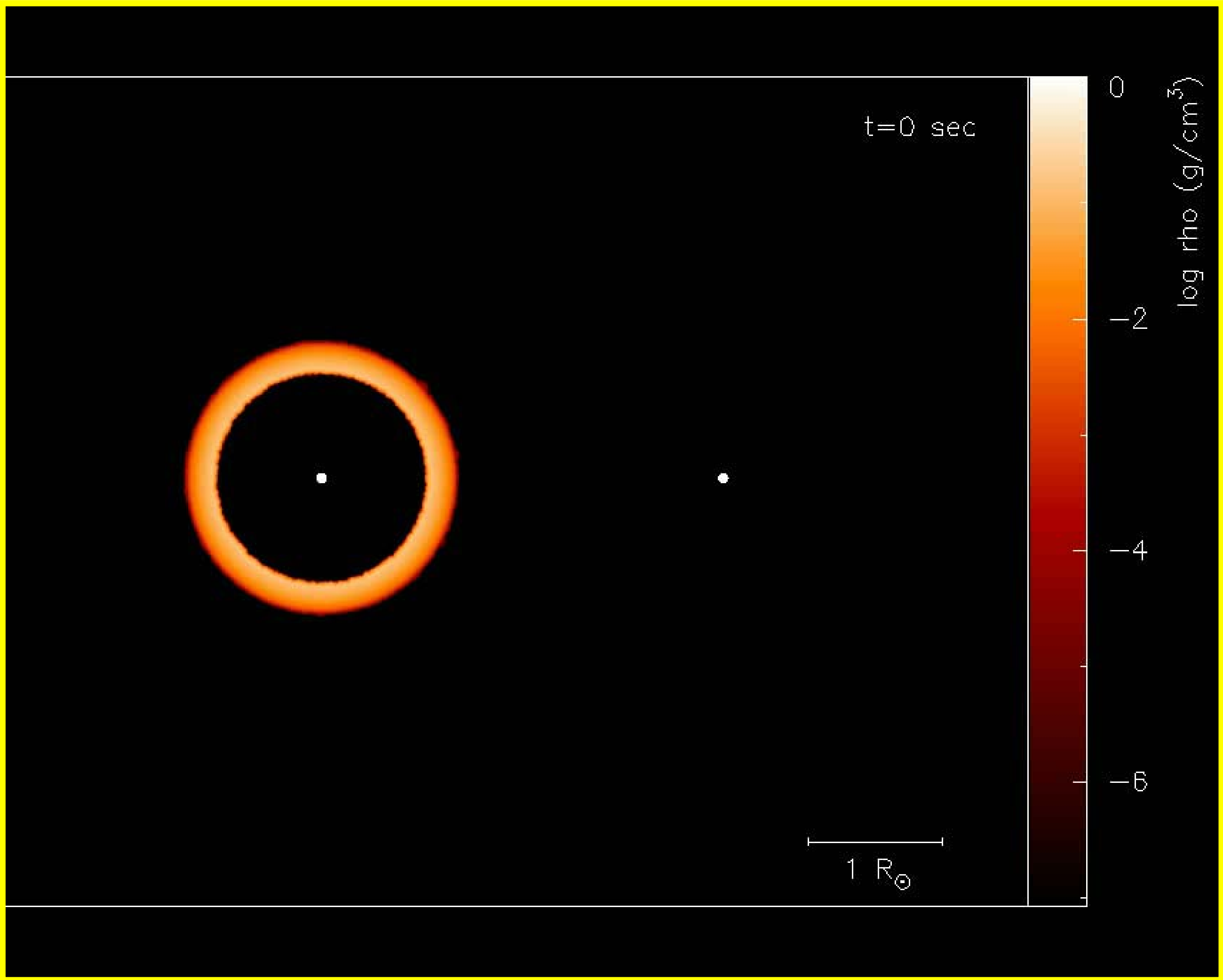
Department of Space Physics and Astronomy, Rice University
Received 1975 April 28; revised 1975 June 26

Isotopic peculiarities: ^{13}C, ^{14}C, ^{18}O, ^{22}Na, ^{26}Al, ^{30}Si

A very preliminary **3-D SPH** simulation of the interaction between the nova ejecta and the stellar companion

Campbell, JJ, Cabezón & García-Berro, NIC XI (2011)



To-Do List:

* Simulations of the **interaction** between the nova ejecta and the accretion disk

* **Contamination** of the **MS star** and effect on the next CN?

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

Main contributor to the prompt gamma-ray emission

* Main reaction paths: $^{16}O(p,\gamma)^{17}F$
  - → $^{17}F(p,\gamma)^{18}Ne(\beta^+)^{18}F$
  - → $^{17}F(\beta^+)^{17}O(p,\gamma)^{18}F$

* Destruction channel: $^{18}F(p,\gamma)^{19}Ne$ and $^{18}F(p,\alpha)^{15}O$

* Nuclear uncertainties: $^{18}F(p,\gamma)^{19}Ne$, **$^{18}F(p,\alpha)^{15}O$**, $^{17}O(p,\gamma)^{18}F$, $^{17}O(p,\alpha)^{14}N$

[Hernanz, JJ, Coc, Gómez-Gomar, Isern 1999; Coc, Hernanz, JJ, Thibaud 2000]

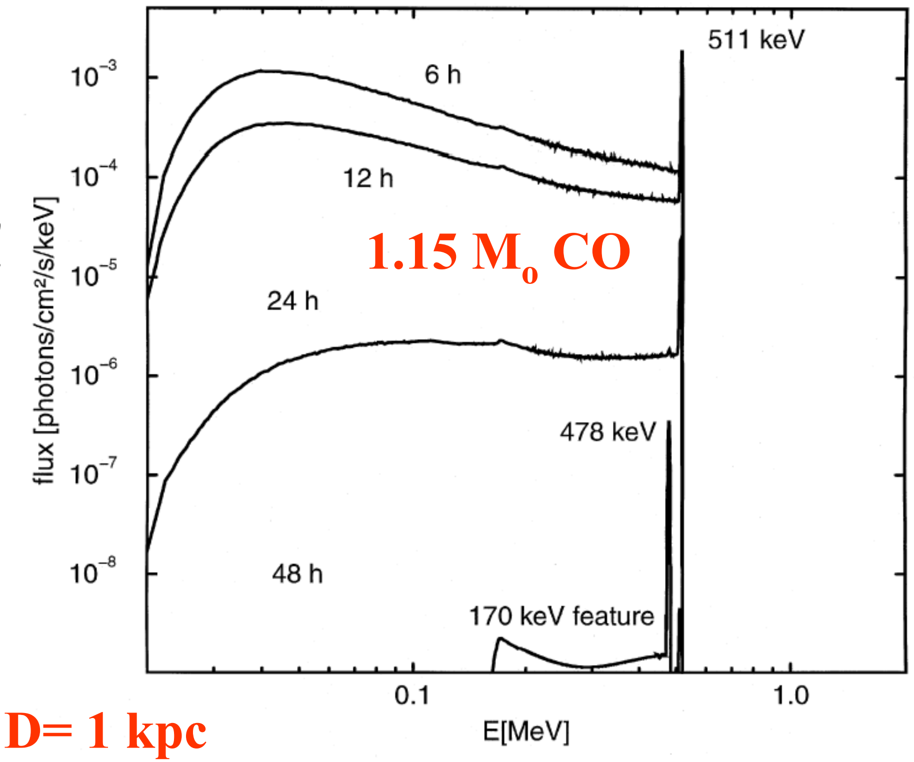
→ Recent improvements:

$^{18}F(p,\alpha)^{15}O$: Beer et al. (2011), de Séréville et al. (2009), Adekola et al. (2011), Murphy et al. (2009)...

$^{17}O(p,\alpha)$, $^{17}O(p,\gamma)$: Fox et al. (2005), Chafa et al. (2007), Moazen et al. (2007), Newton et al. (2010)...

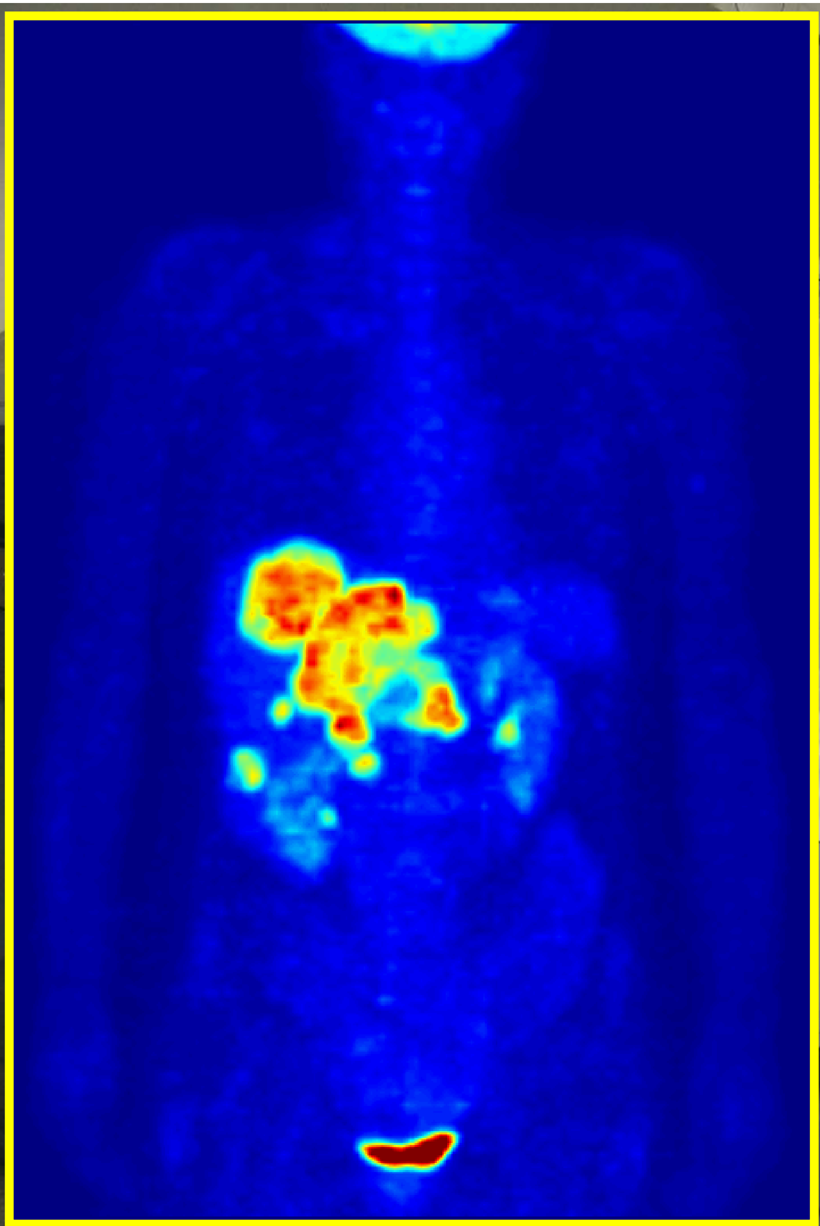
* **γ-ray signature**: **^{18}F** decay (**τ ~ 158 min**) provides a source of gamma-ray emission at **511 keV and below** (related to electron-positron annihilation).

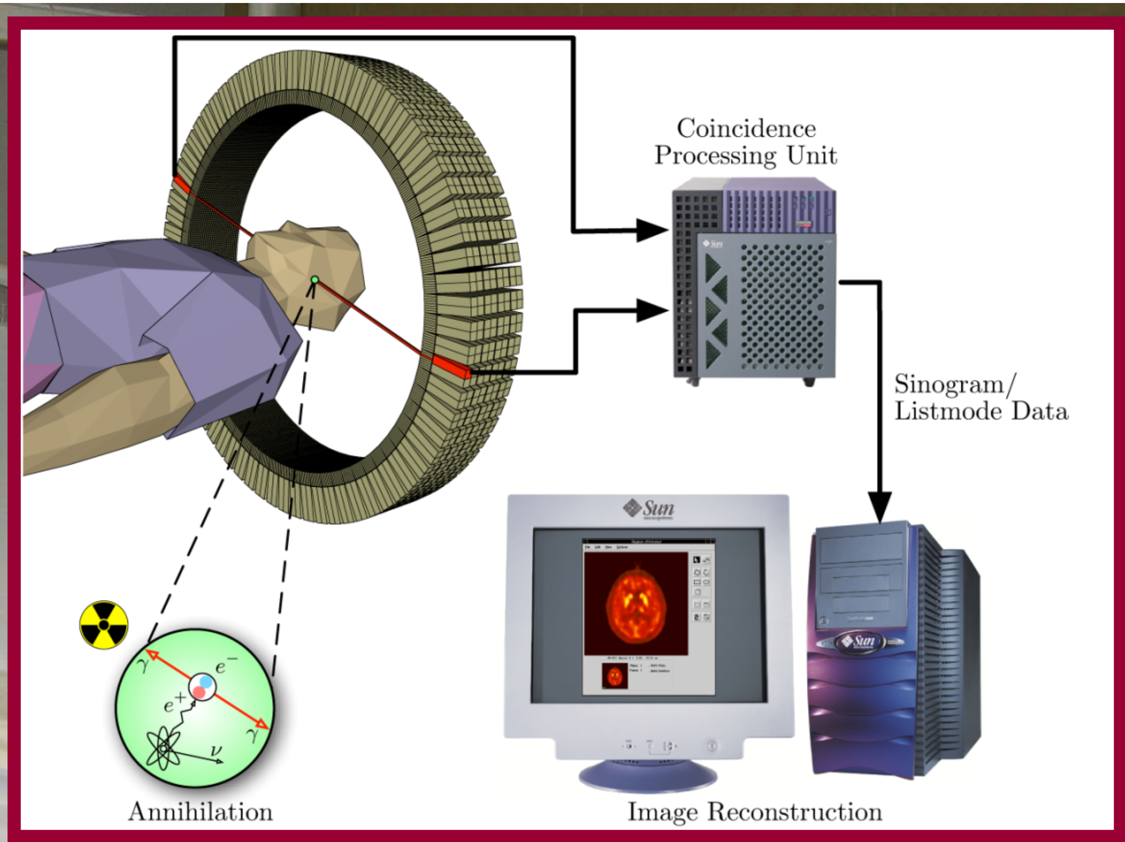
But! **Uncertainties** in the rates translate into a factor ~ **5 - 10** uncertainty in the expected fluxes!



D= 1 kpc

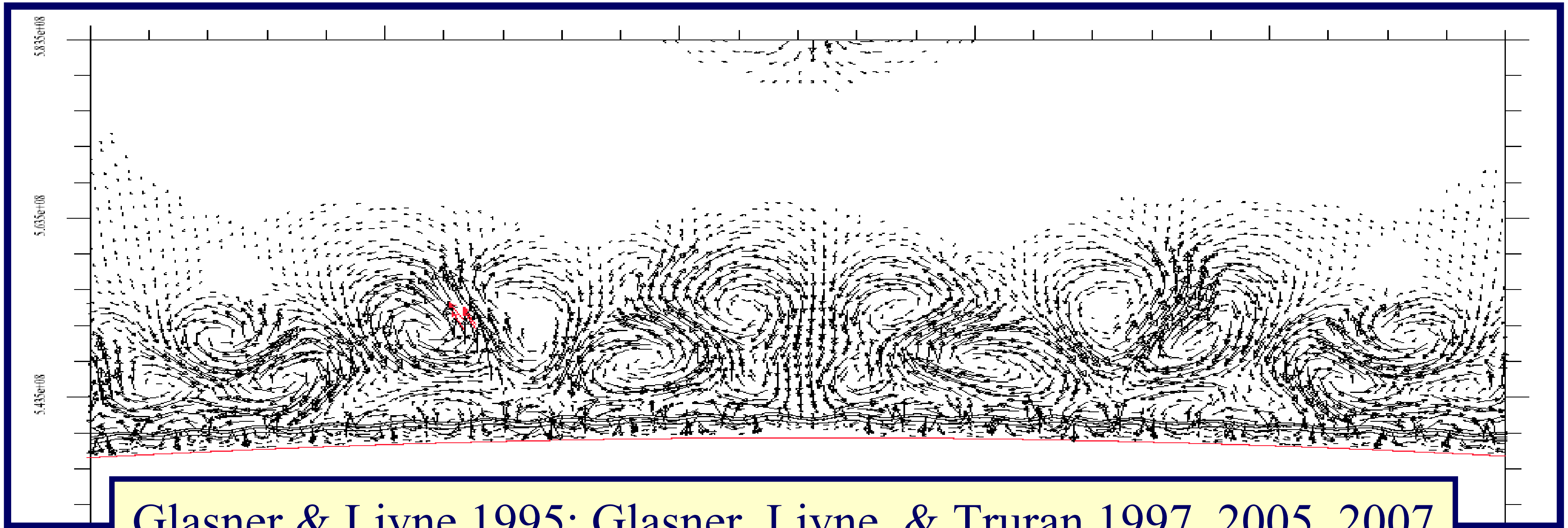
Gómez-Gomar, Hernanz, JJ, & Isern (1998), MNRAS





Positron Emission Tomography (**PET**)

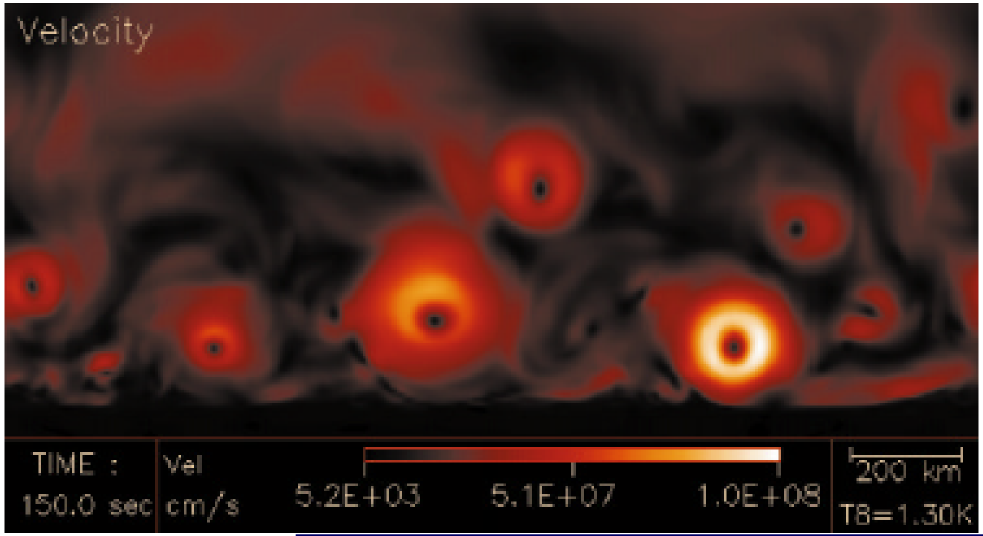
IV. Multidimensional Models

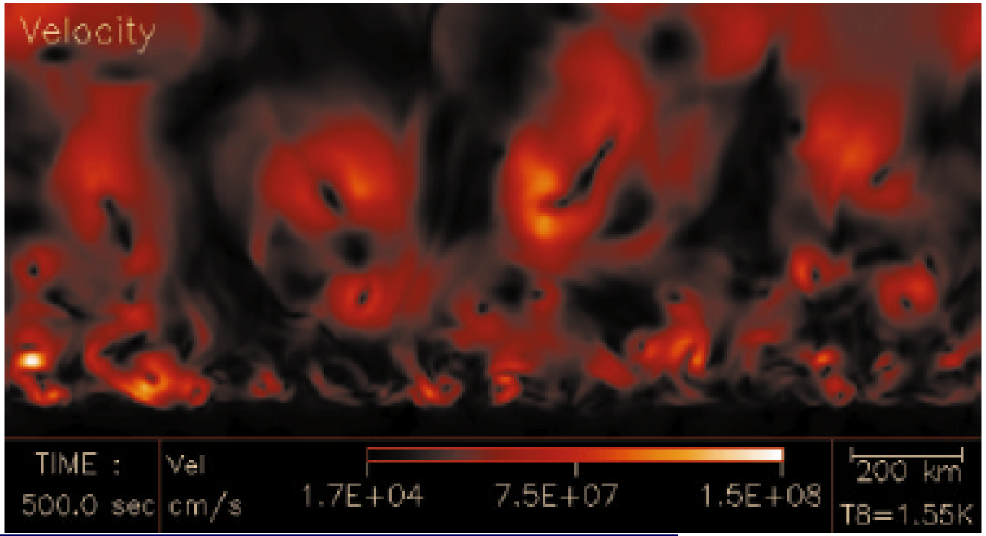


Glasner & Livne 1995; Glasner, Livne, & Truran 1997, 2005, 2007

The build-up of **convective eddies** at the envelope's base causes **shear flow** at the core/envelope interface [**Kelvin-Helmholtz instability**]: pure "solar-like" accreted material can be **enriched** at the late stages of the TNR by some sort of ***convective overshoot*** (Woosley 1986), leading to a powerful nova event!

Kelvin-Helmholtz instabilities





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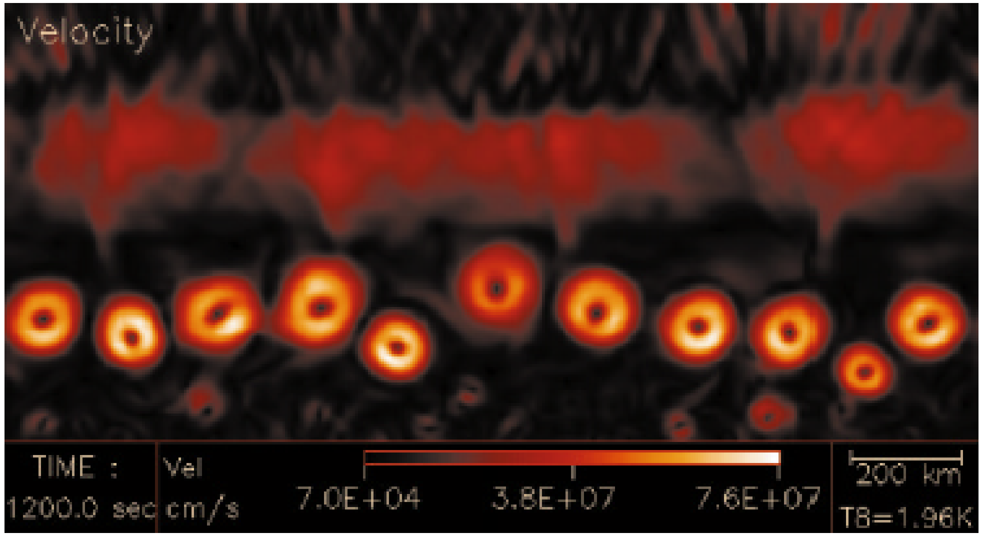
Kercek, Hillebrandt & Truran (1998), 2-D [also 3-D...]



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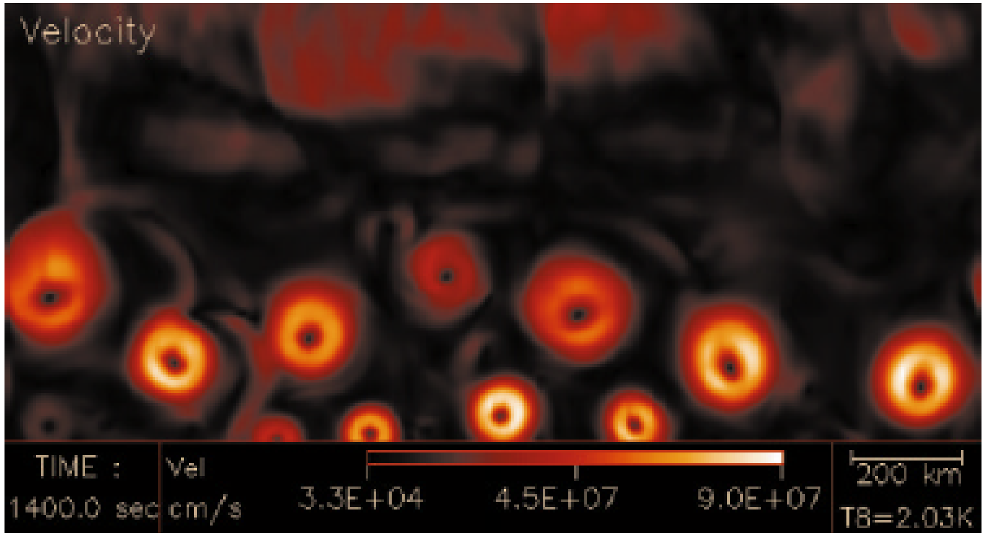

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Very **limited dredge-up** and mixing episodes → **fainter** events!

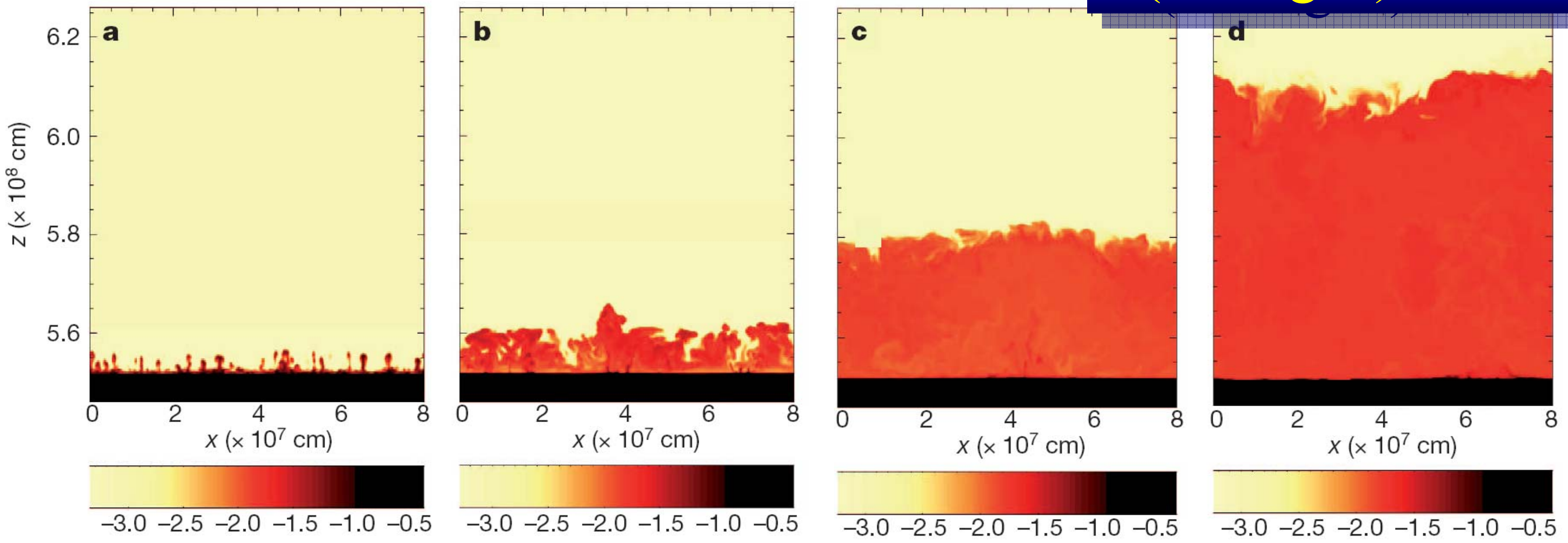
LETTER

doi:10.1038/nature10520

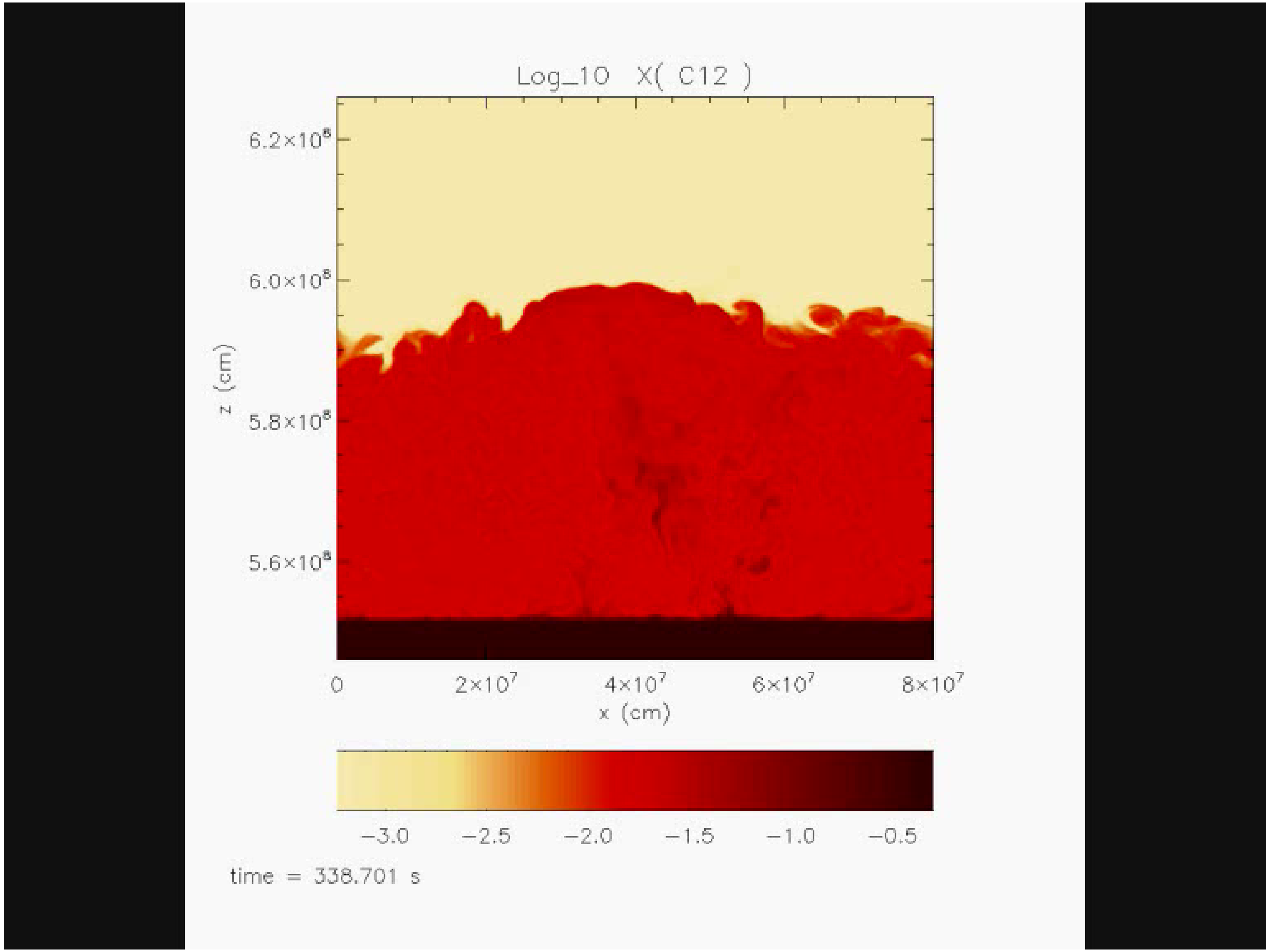
Kelvin–Helmholtz instabilities as the source of inhomogeneous mixing in nova explosions

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

Z(averaged) ~ 0.2 – 0.3



Multi-D Hydro Simulations with the FLASH Code

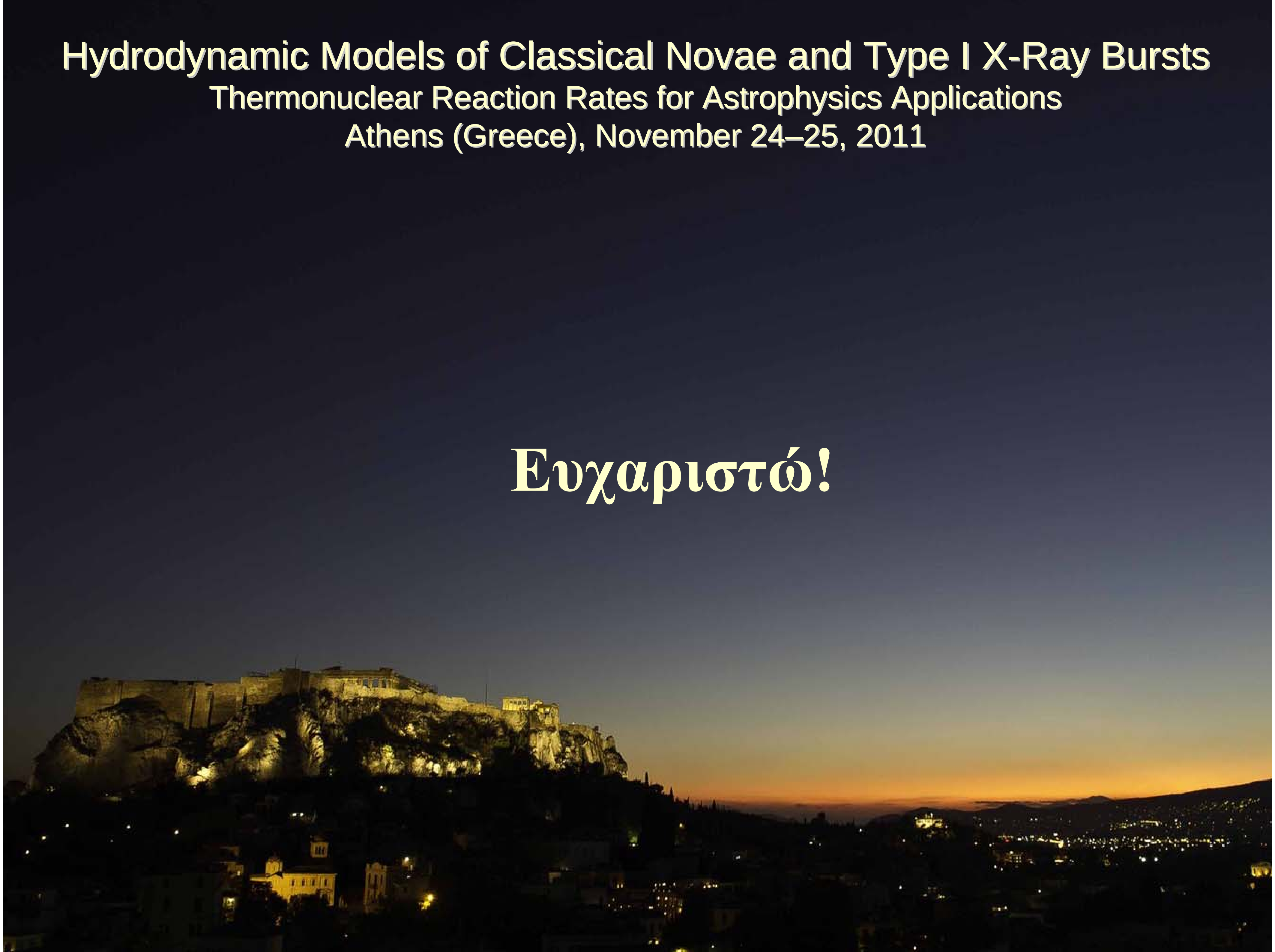


Movie available at: http://www.fen.upc.edu/users/jjose/Downloads.html

Hydrodynamic Models of Classical Novae and Type I X-Ray Bursts

Thermonuclear Reaction Rates for Astrophysics Applications

Athens (Greece), November 24–25, 2011



Ευχαριστώ!