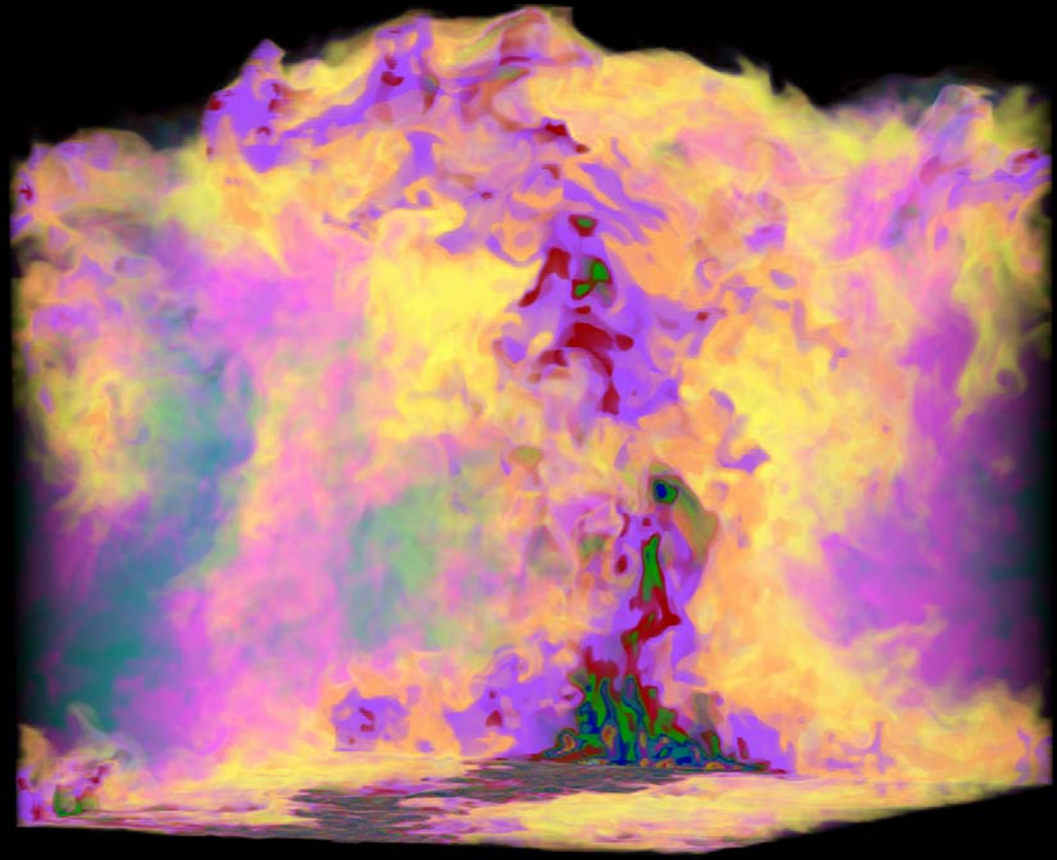
Multidimensional Modeling of Nova Outbursts



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& Institut d'Estudis Espacials de Catalunya (IEEC), Barcelona

Introduction. Theory & Early Models

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

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

See also **Cameron** (1959), **Gurevitch & Lebedinsky** (1957), **Giannone & Weigert** (1967), **Rose** (1968), **Starrfield** (1971a,b), **Prialnik, Shara & Shaviv** (1978), and several others!

DYN

Starrfield's talk, this Conference

969) **156**, 569

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Received June 26, 1968; revised September 27, 1968

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.

Composition of the ejecta

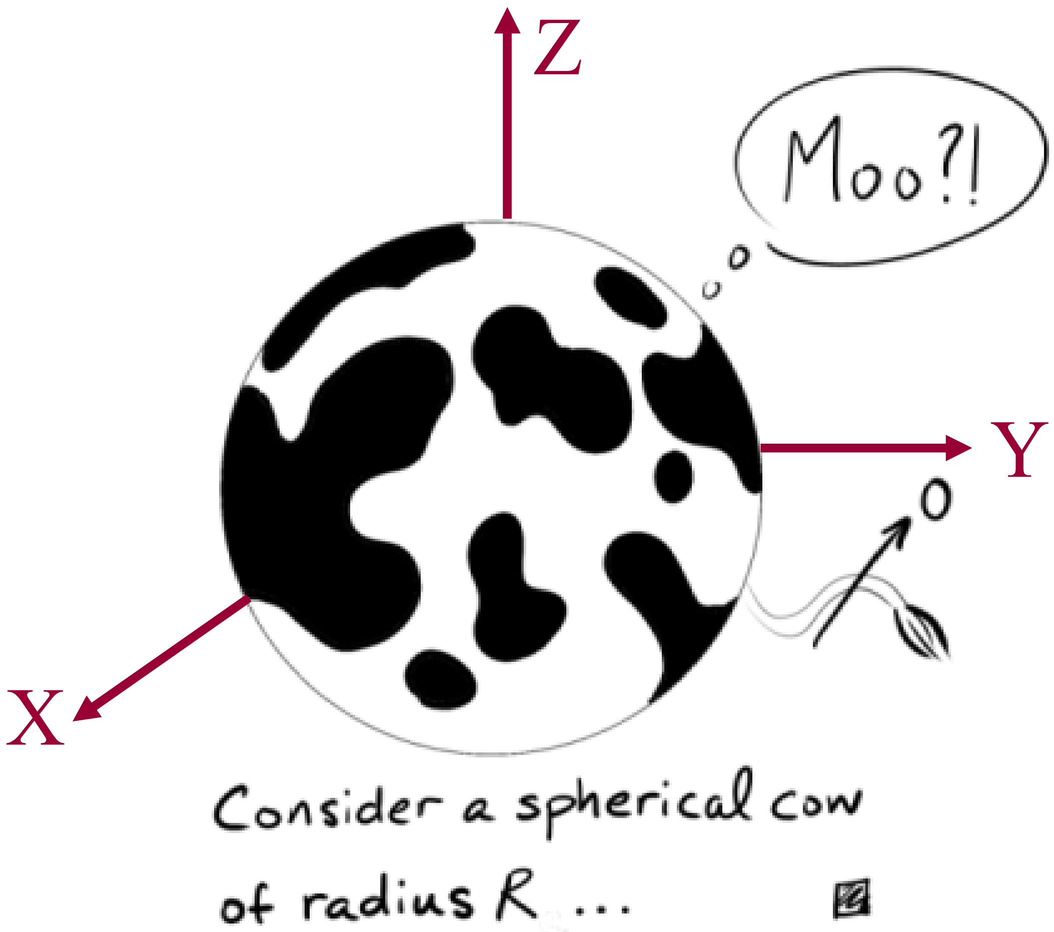
* $Z_{\odot}$ → Z ~ **0.50** (up to **0.86**, for V1370 Aql 1982)? Limited T_{peak}

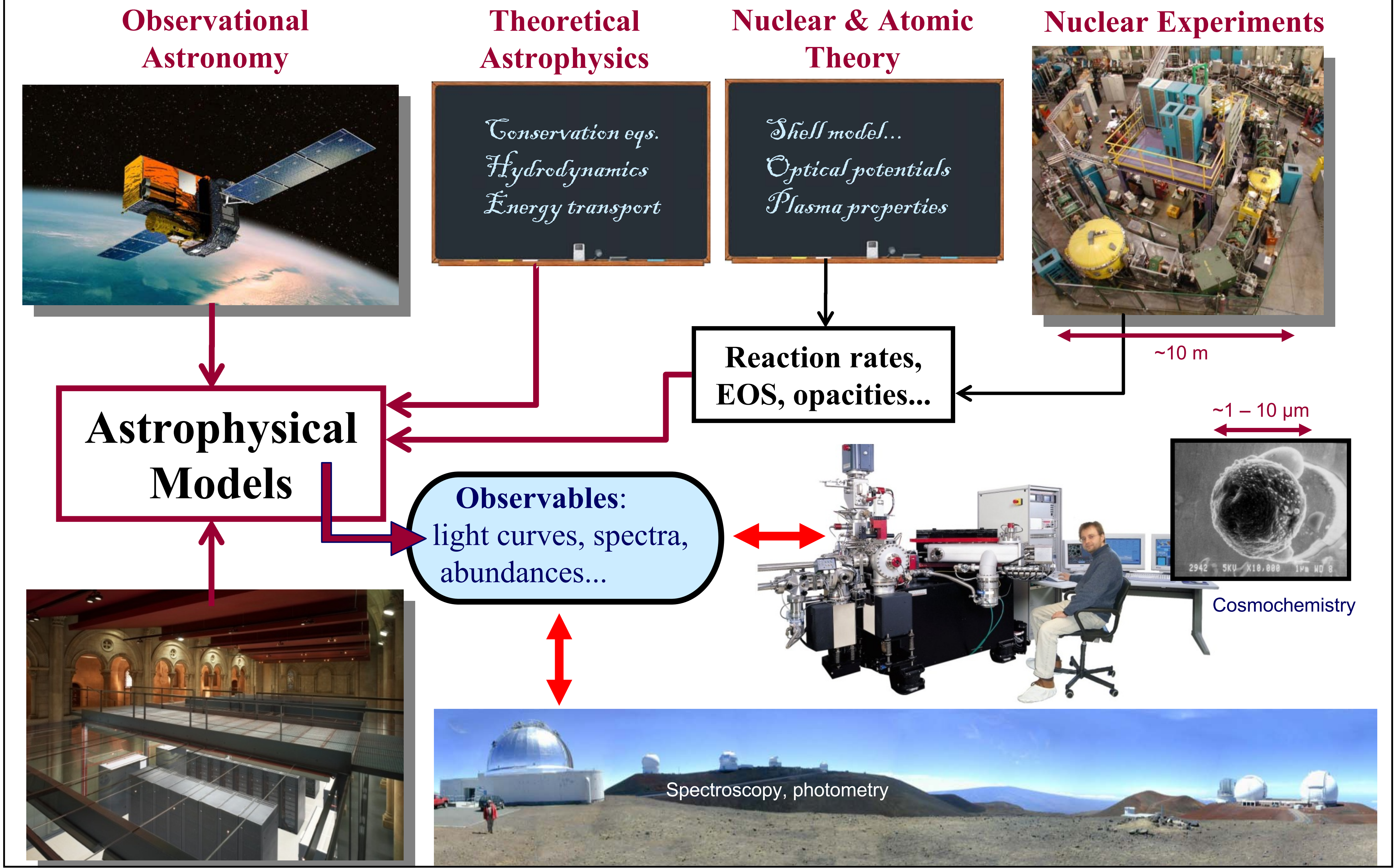
CNO-breakout unlikely! → **Mixing at the core-envelope interface**

The mixing mechanism: the *Holy Grail* of nova modeling

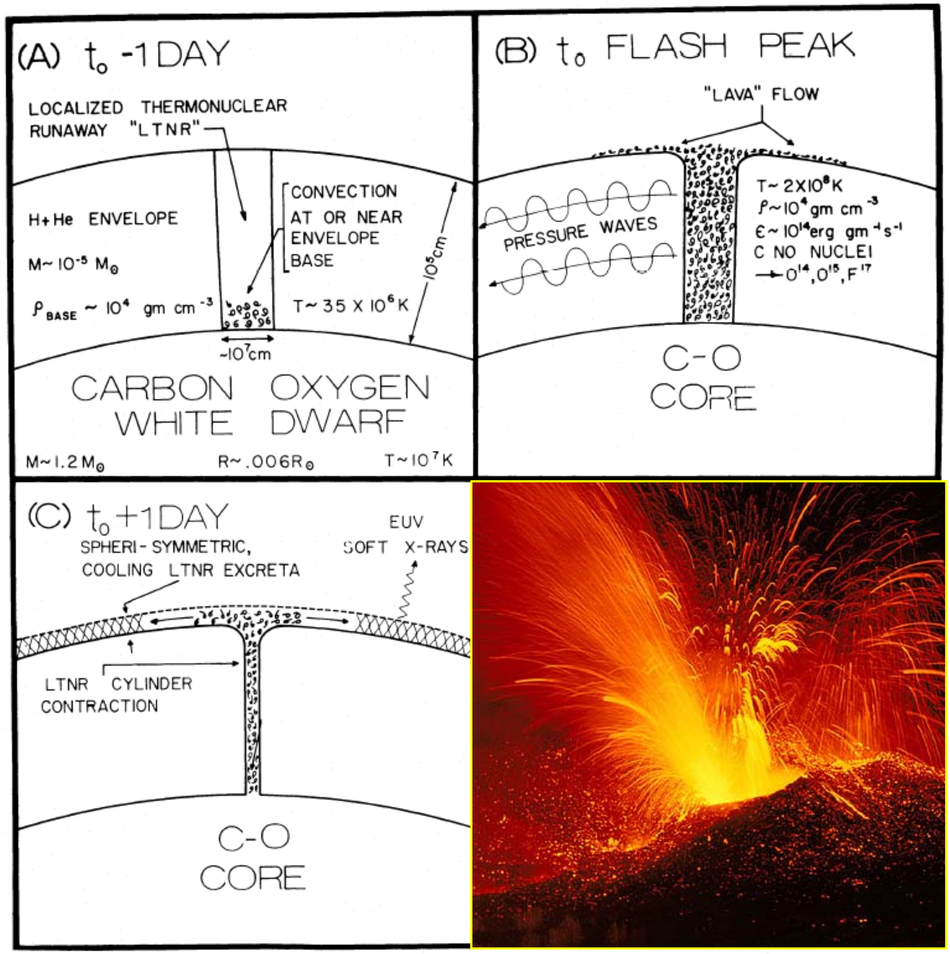
* **Diffusion Induced Convection** [Prialnik & Kovetz 1984; Kovetz & Prialnik 1985; Iben, Fujimoto & MacDonald 1991, 1992; Fujimoto & Iben 1992]
* **Shear mixing** [Durisen 1977; Kippenhahn & Thomas 1978; MacDonald 1983; Livio & Truran 1987; Kutter & Sparks 1987; Sparks & Kutter 1987]
* **Convective Oveshoot Induced Flame Propagation** [Woosley 1986]
* **Convection Induced Shear Mixing** [Kutter & Sparks 1989]

* **Multidimensional processes** [Glasner & Livne 1995; Glasner, Livne & Truran 1997, 2005, 2007, 2012; Rosner et al. 2002; Alexakis et al. 2004, Casanova et al. 2010, 2011a,b]




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

The Roadmap for Multidimensional Models



Shara (1982), ApJ

Semianalytic model of **localized**, *volcanic-like* TNRs

Heat transport is **too inefficient** for a flame to spread a localized TNR to the rest of the WD surface

But! The study ignored the major role played by **convection**

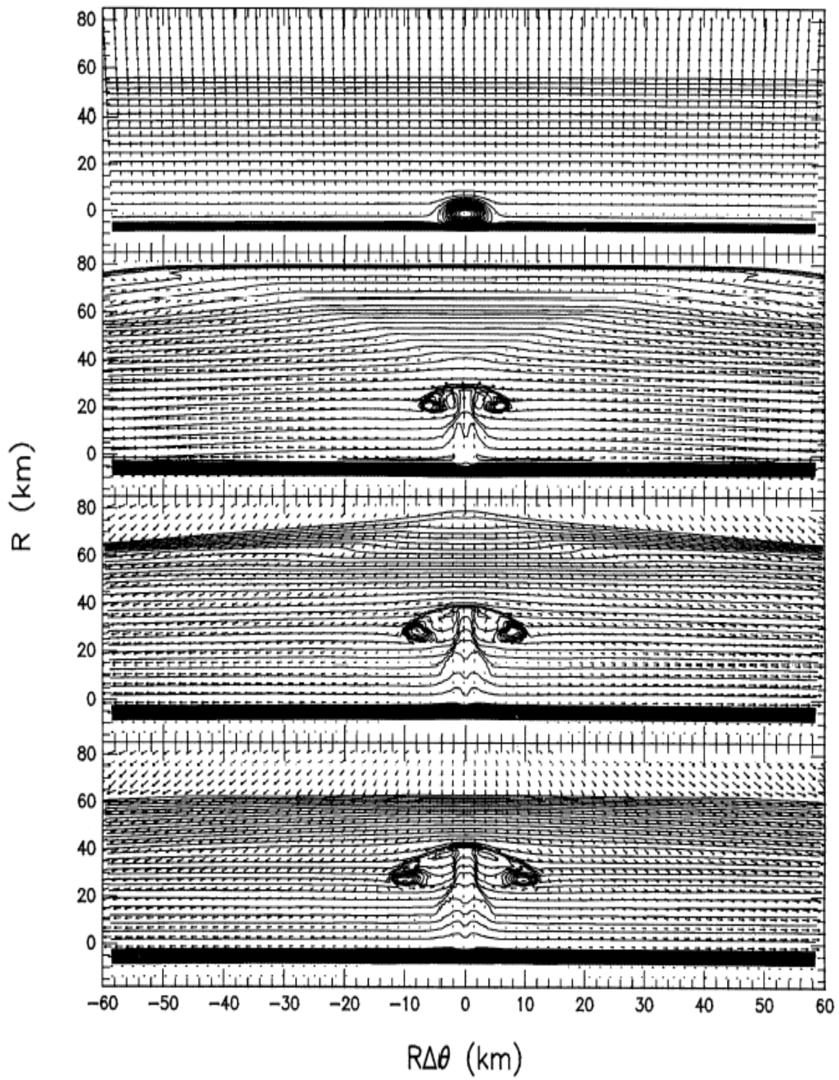
Fryxell & Woosley (1982), ApJ

Study based on dimensional analysis and flame theory: → TNR propagated by **small-scale turbulence**

$$v_{def} \sim (h_p \, v_{conv} \, / \, \tau_{burn})^{1/2} \sim 10^4 \text{ cm s}^{-1}$$

Halfway propagation across the stellar surface in ~**1.3 days**

Shankar, Fryxell & Arnett (1992), ApJ; Shankar & Arnett (1994), ApJ

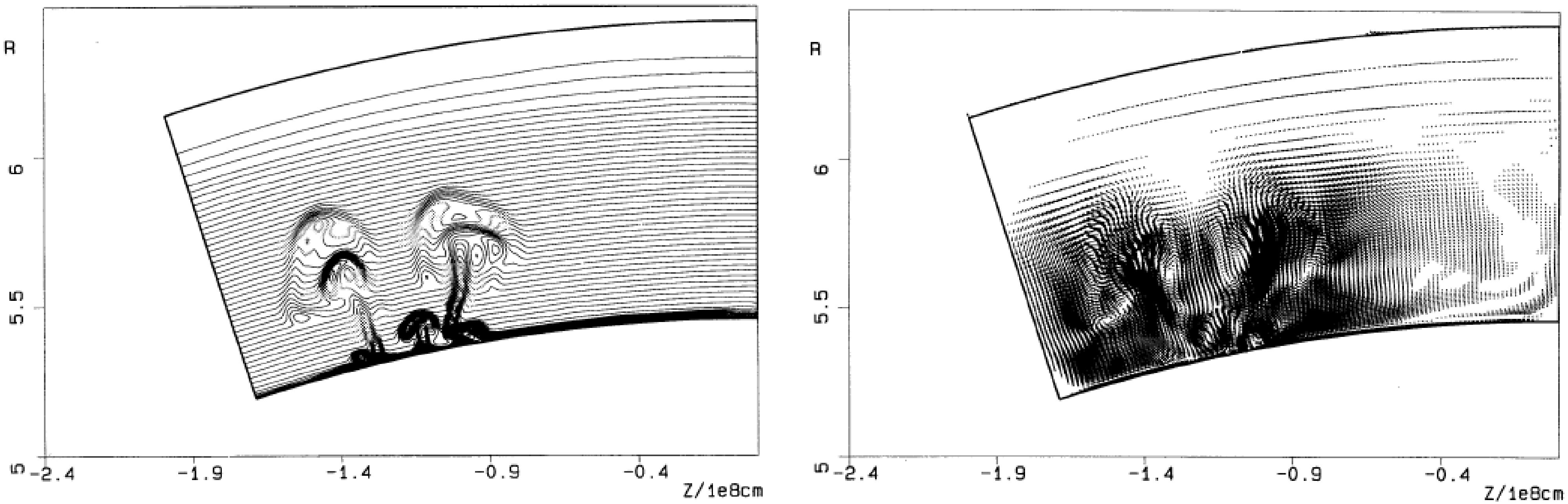


An accreting 1.25 M_o WD (1-D) → mapped into a 2-D domain (polar grid 25×60 km^2). 2-D simulation performed with PROMETHEUS (an Eulerian code). **12 isotope network**

Computed time: 1 sec! T perturbations cause **Rayleigh-Taylor** instabilities. Rapid rise and expansion, τ_{dyn} → halts the lateral spread of the TNR, **favoring localized TNRs.**
But!, **very extreme** (rare) conditions assumed.

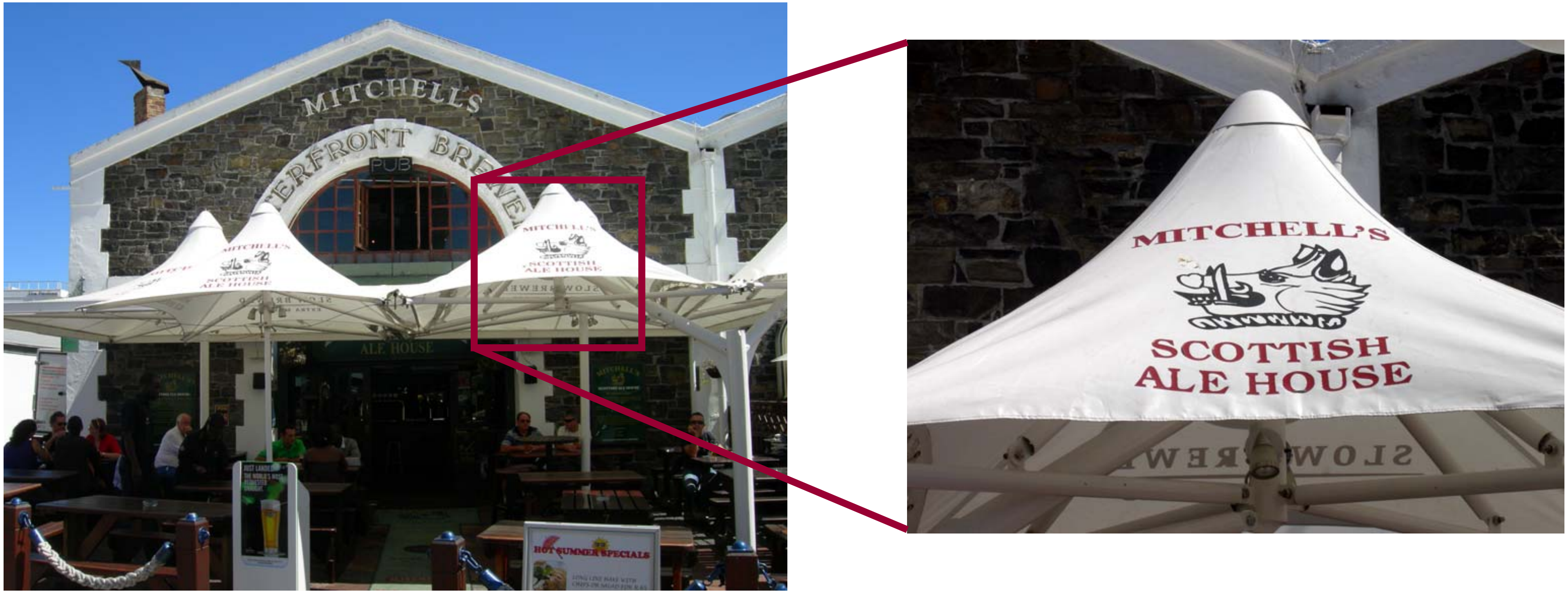
Glasner & Livne (1995), ApJ; Glasner, Livne & Truran (1997), ApJ

An accreting 1.0 M_o CO WD (1-D) → mapped into a 2-D domain at T=10^8 K. 2-D simulation performed with *VULCAN* (ALE code). **Spherical/polar coordinates**, with reflecting boundary conditions. Slice of $0.1\pi^{rad}$, **resolution** 5×5 km^2, 12 isotope network



Glasner & Livne (1995), ApJ; Glasner, L

An accreting 1.0 M_o CO WD (1-D domain at T=10^8 K. 2-D simulatio code). **Spherical/polar coordin** conditions. Slice of $0.1\pi^{rad}$, **resoluti**

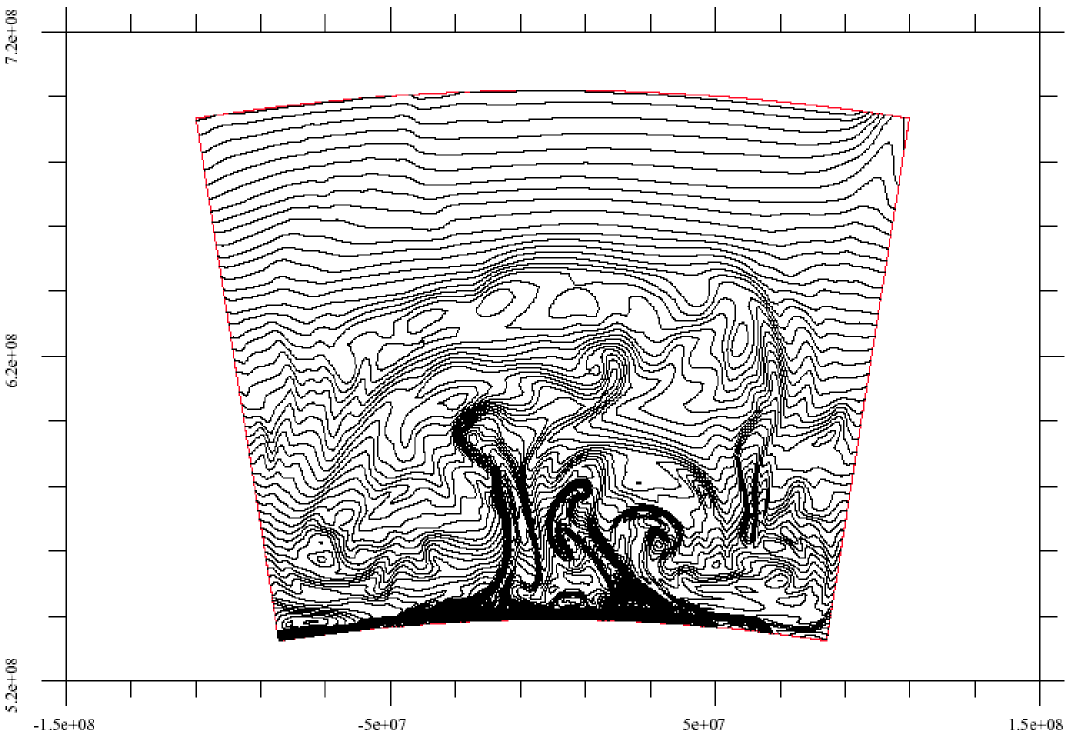


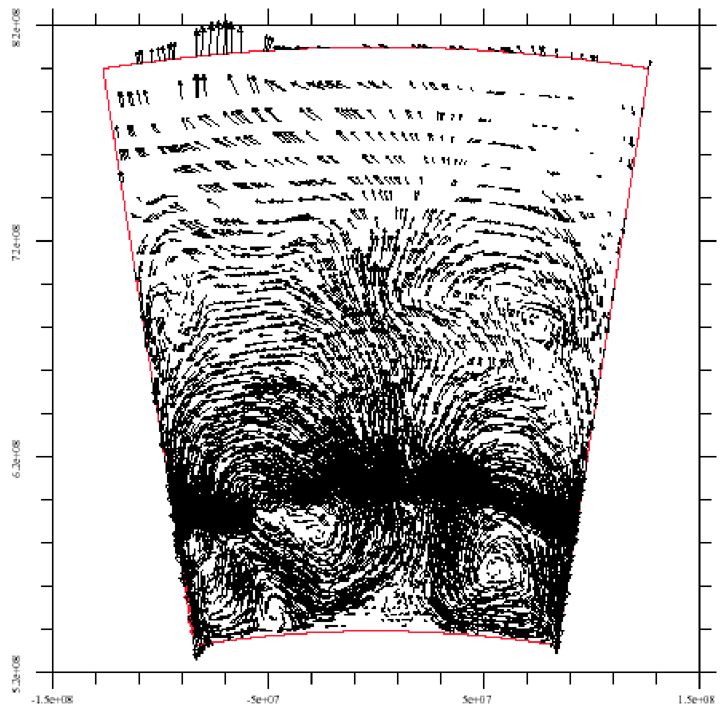
Differences with 1-D simulations:

* TNR initiates as a myriad of irregular, **localized eruptions**

* **Core/envelope interface is now convectively unstable** → mechanism for mixing? (~ convective overshoot, Woosley 1986)

* **Large** convective eddies ($h \sim 2/3\ \Delta z_{env}$)

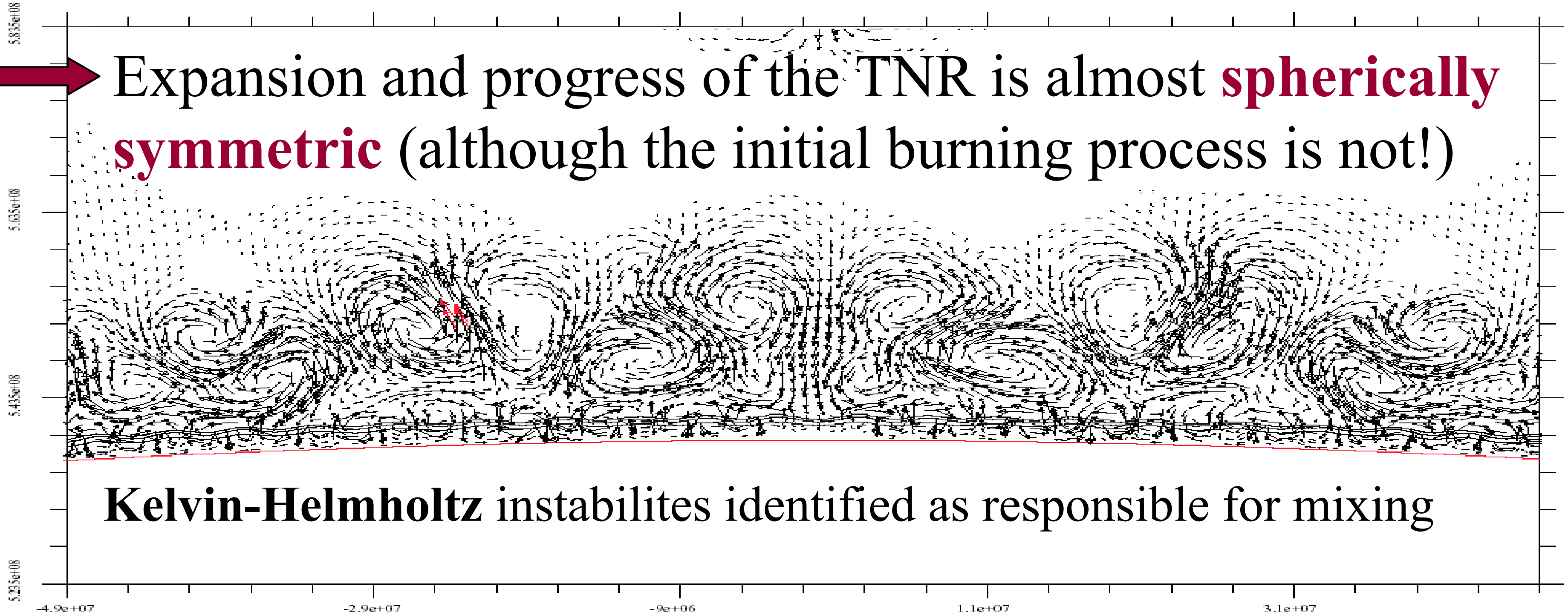




Good agreement with 1-D simulations!

* Role of β^+-unstable nuclei **$^{14,15}O$, ^{17}F (^{13}N)** in the ejection process
* Significant presence of **$^{14,15}N$, ^{17}O (^{13}C)** expected in the ejecta

→ Expansion and progress of the TNR is almost **spherically symmetric** (although the initial burning process is not!)



Kelvin-Helmholtz instabilites identified as responsible for mixing

Glasner, Livne & Truran (1997), ApJ

Kelvin-Helmholtz instabilities

Kercek, Hillebrandt & Truran (1998, 1999), A&A

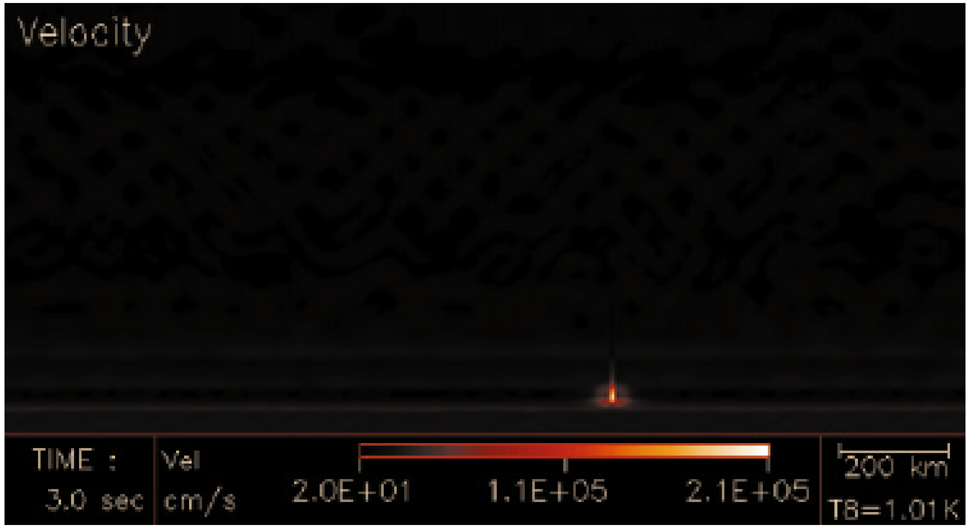
Same initial model than **GLT97** → mapped into a 2-D domain at T=10^8 K. 2-D (3-D) simulations performed with PROMETHEUS, assuming a **Cartesian**, plane-parallel geometry, with periodic boundary conditions

Computational domains: 1800×1000 km^2 (2-D)
1800×1800×1000 km^3 (3-D)
Resolution: 5×5 km^2, 1×1 km^2 (2-D); 8×8×8 km^3 (3-D)

12 isotope network

Multidimensional modeling of nova outbursts

J. José



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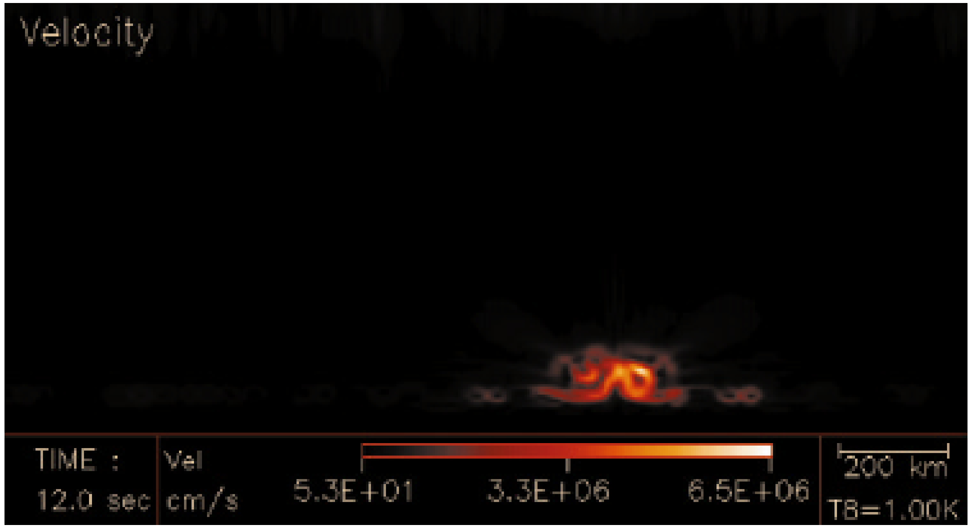
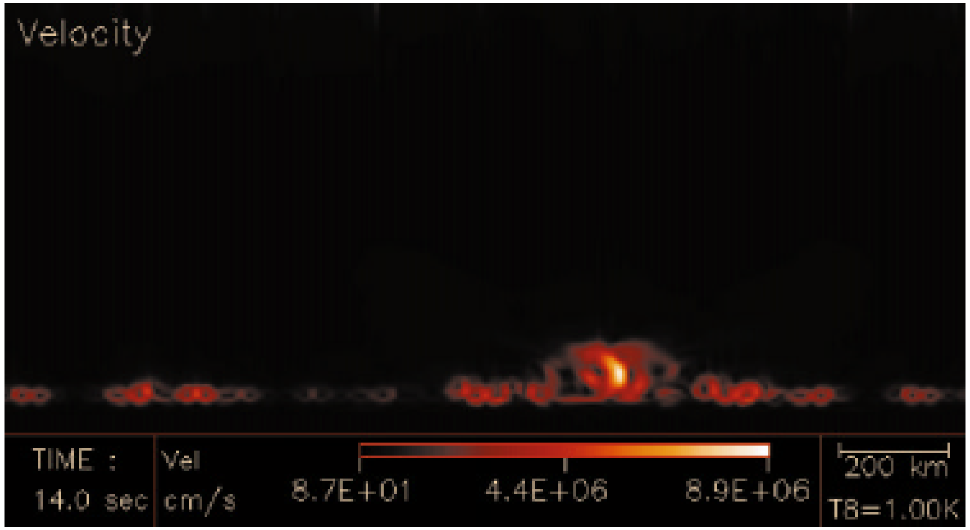


Kercek, Hillebrandt & Truran (1998), 2-D



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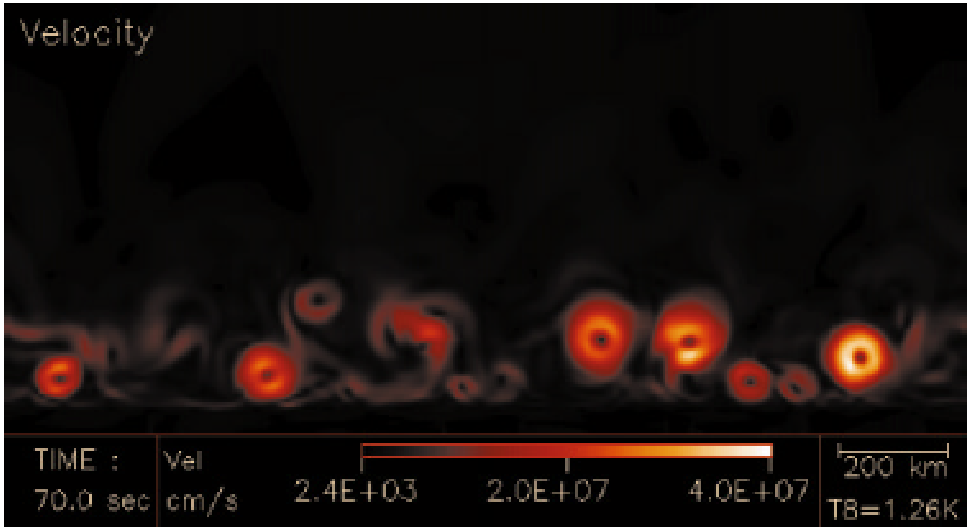

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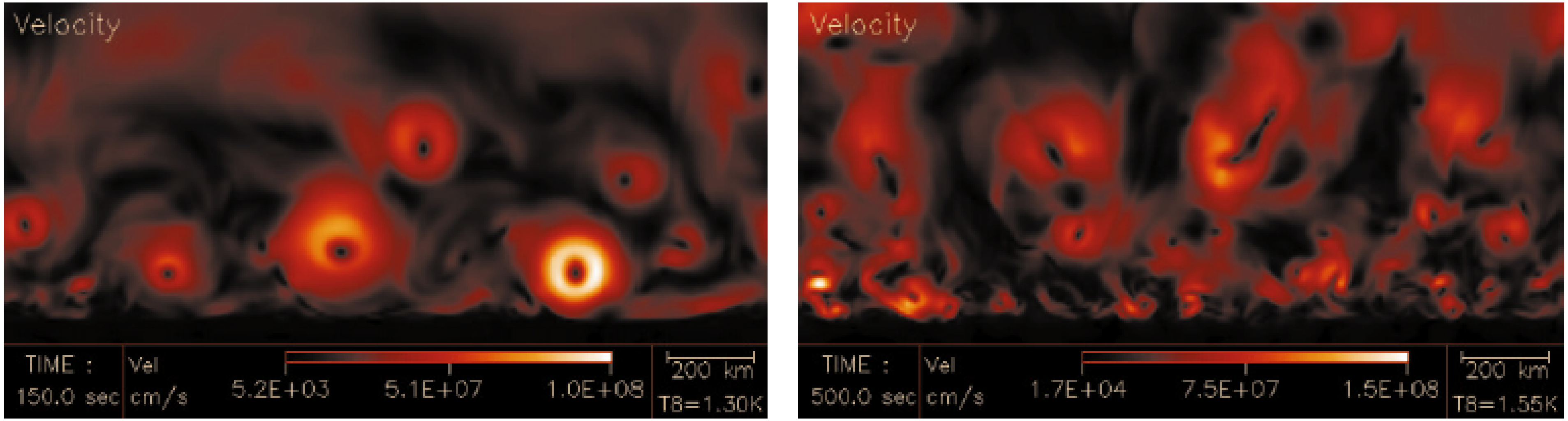

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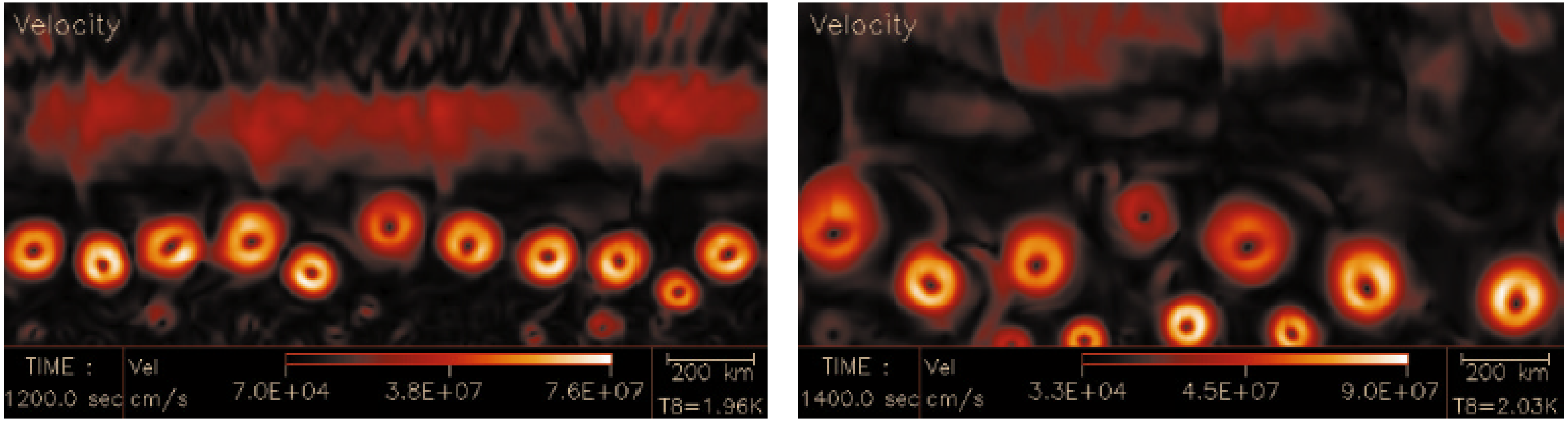
Kercek, Hillebrandt & Truran (1998), 2-D



g h

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

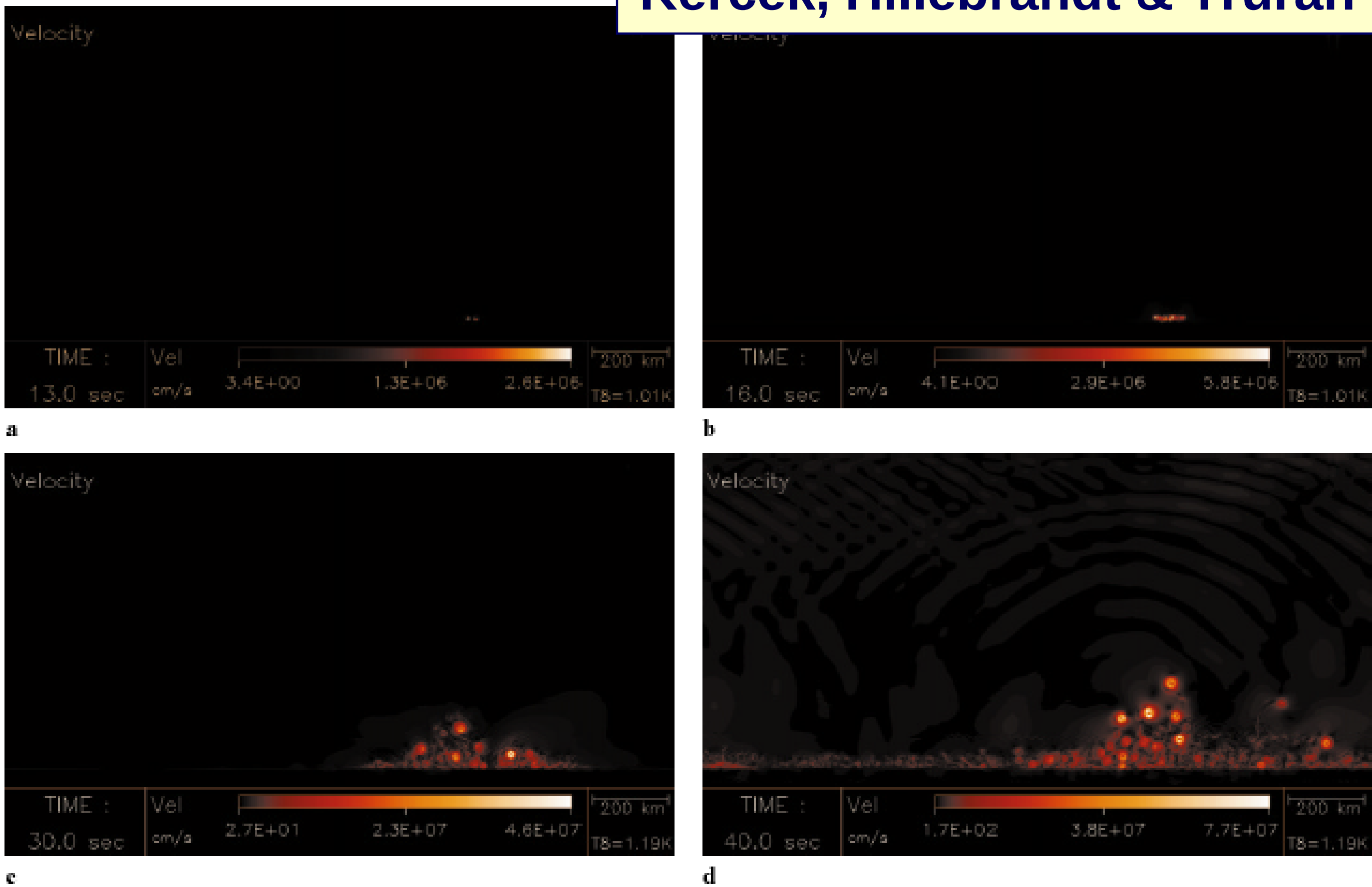
* **2-D:** Qualitatively, similar results than in Glasner, Livne, & Truran (1997), but somewhat **less violent outbursts** (**longer τ_{TNR}, lower T_{peak} & v_{ejec}**) caused by major differences in the convective flow patterns:

few, large convective eddies ⟷ **many, small stable eddies**

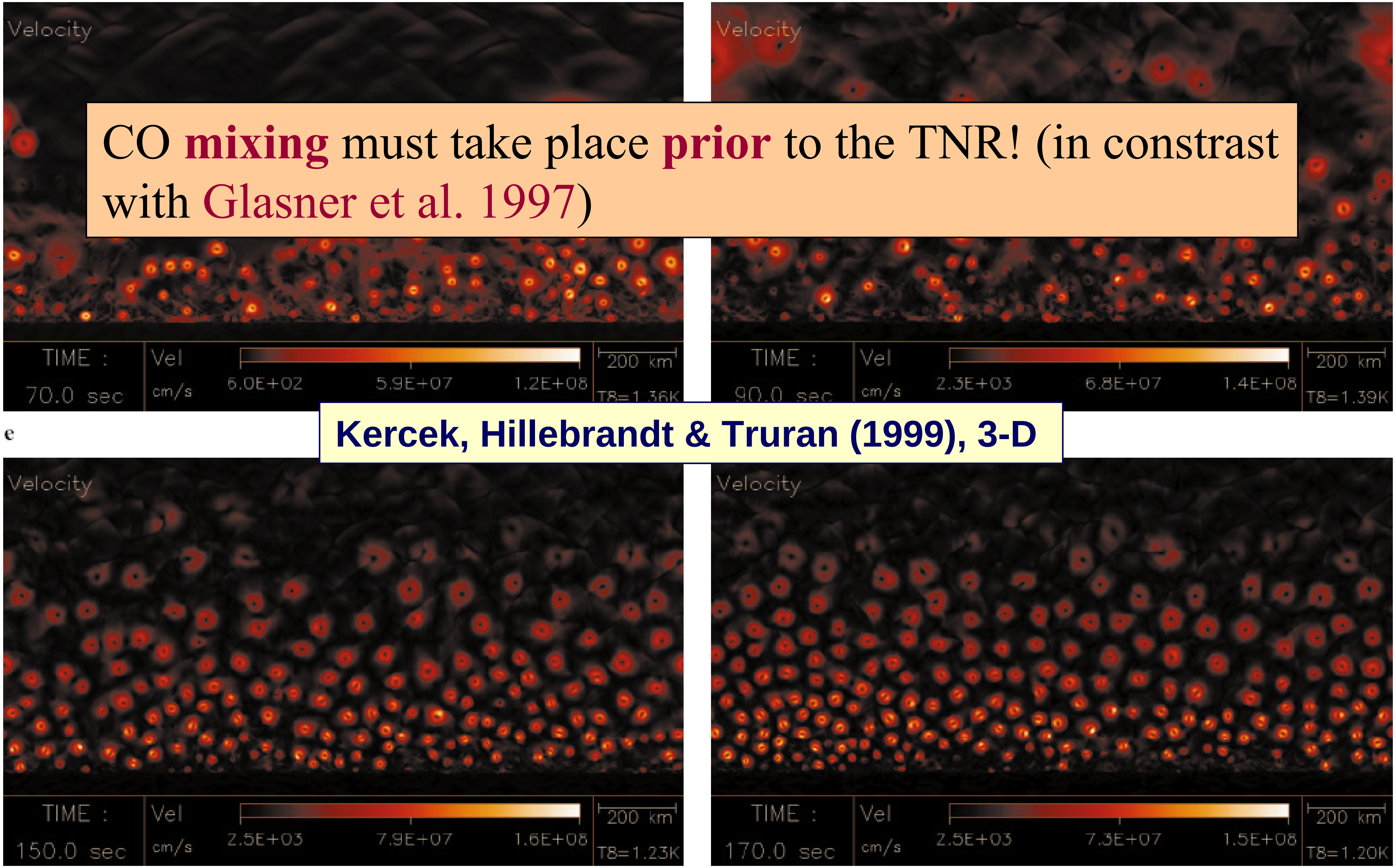
(Glasner et al. 1997) (Kercek et al. 1998)

* **3-D:** Flow patterns are **dramatically different** from those in 2-D. Mixing by turbulent motions on very small scales: **no nova** (i.e., no mass-ejection phase expected) is found!, as a result of a very limited dredge-up and mixing episodes

Kercek, Hillebrandt & Truran (1999), 3-D



CO **mixing** must take place **prior** to the TNR! (in constrast with Glasner et al. 1997)



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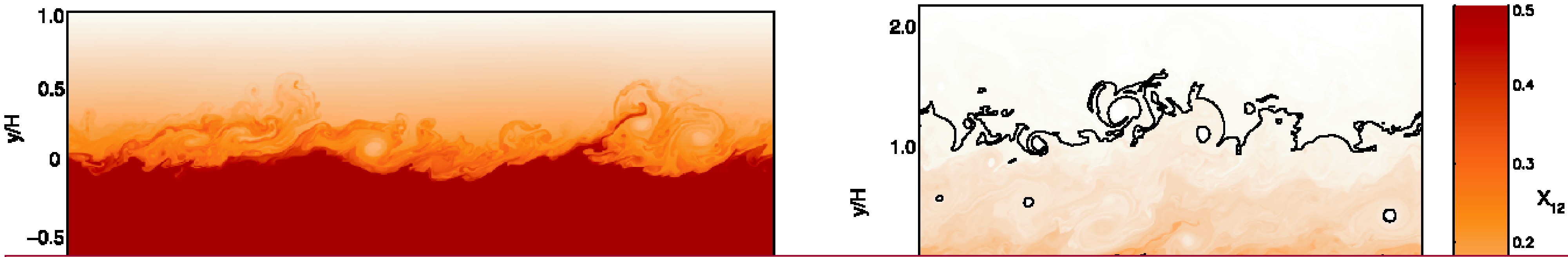
Kercek, Hillebrandt & Truran (1999), 3-D

g

h

I meant ***messy***, not ***Messi***!

* Other multidimensional studies (Rosner et al. 2001; Alexakis et al. 2004a,b) focused on the role of **shear instabilities** in the stratified fluids that form nova envelopes.

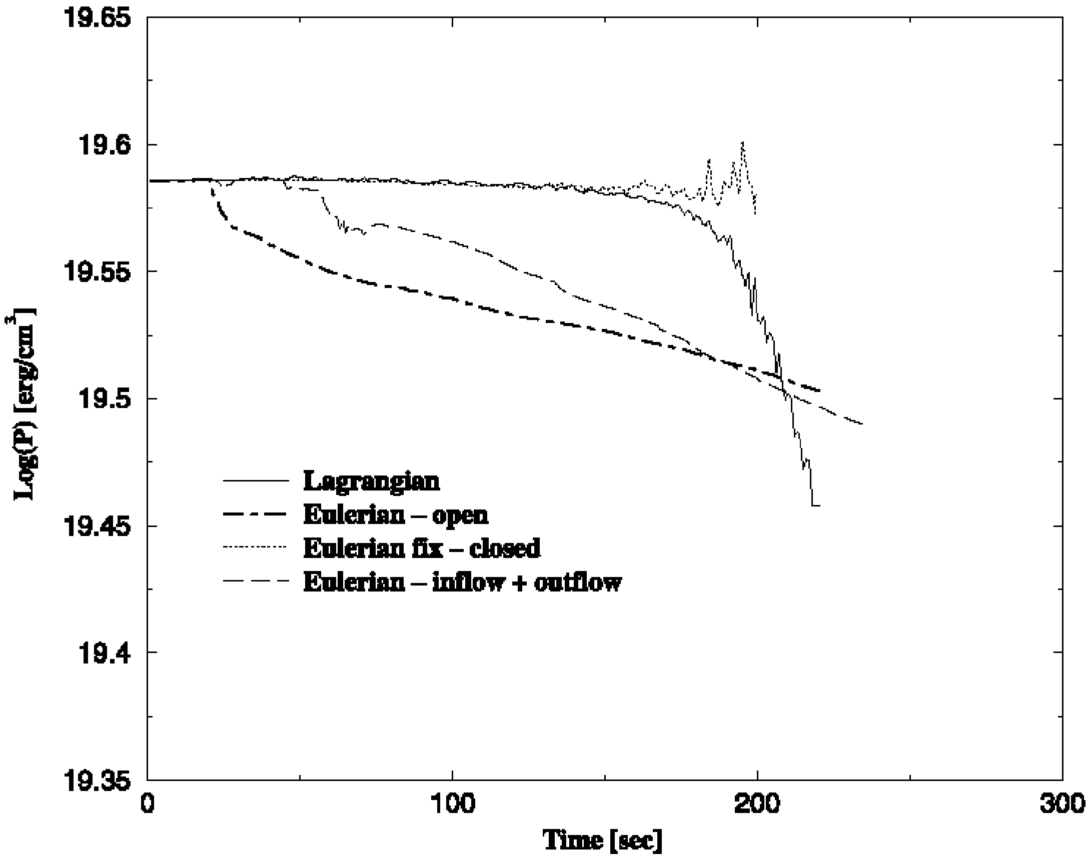


To account for significant mixing, a **very high shear** (with a **specific velocity profile**) had to be assumed.

Mixing from the **resonant interaction** between large-scale shear flows in the accreted envelope and gravity waves at the core-envelope interface.

Glasner, Livne & Truran (2005), ApJ

Sensitivity of multidimensional nova calculations to the **outer boundary conditions**



Solutions obtained from **Lagrangian simulations,** where the envelope is allowed to expand and mass is being conserved, are **consistent with spherically symmetric solutions**. In **Eulerian schemes**, which utilize an outer boundary condition of free outflow, the **outburst can be artificially quenched**

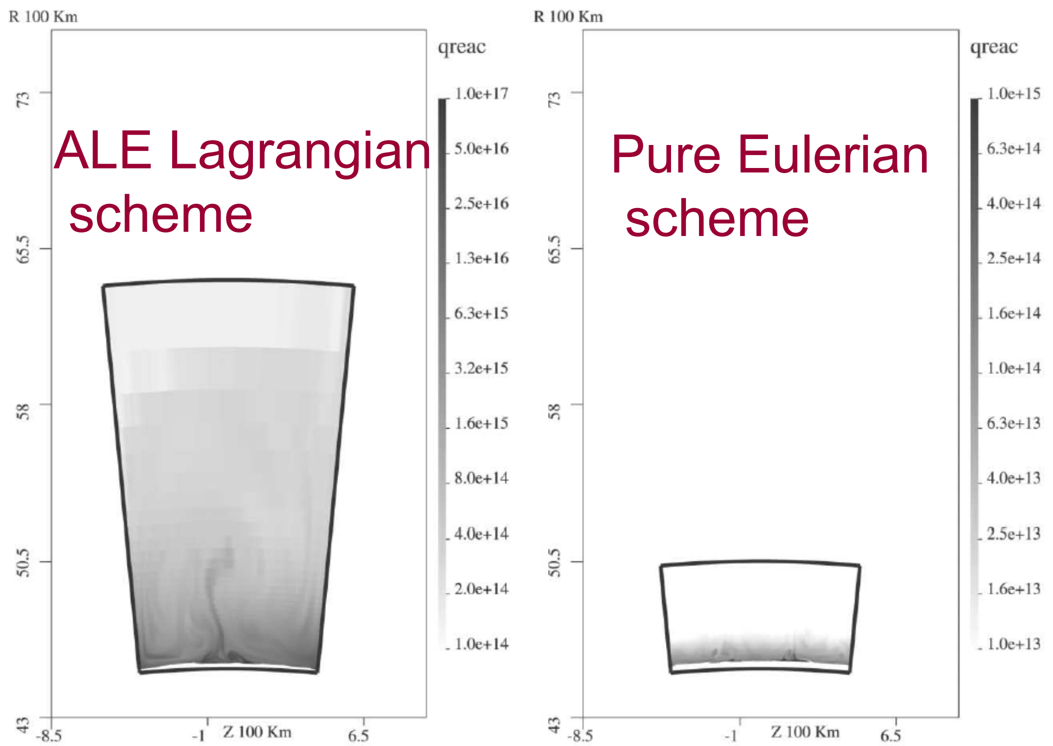
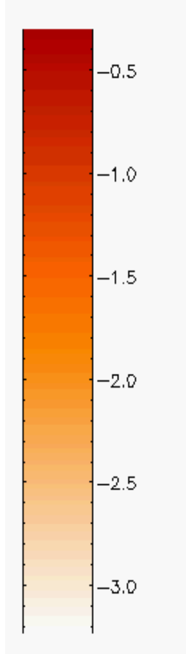


FIG. 3.—Color map of the thermonuclear energy production rate at $t = 100$ s for the pure Eulerian case (*right*) and the ALE Lagrangian scheme (*left*). The spatial coordinate is in units of 100 Km. The energy production rate is in ergs g^{-1} s^{-1}. The rate scale is different in the two cases (see scale to the right of each model; see text).

Jordi Casanova
now post-doc at
UNCS, North Carolina

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

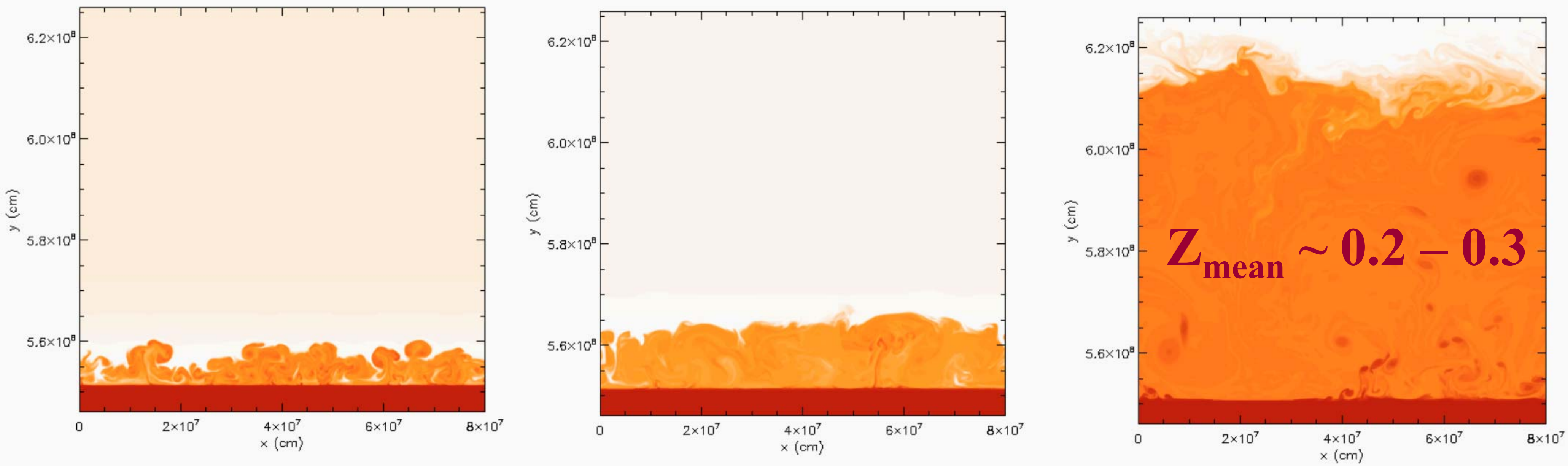
* 2-D Simulations



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]



WARNING!
Table coming...

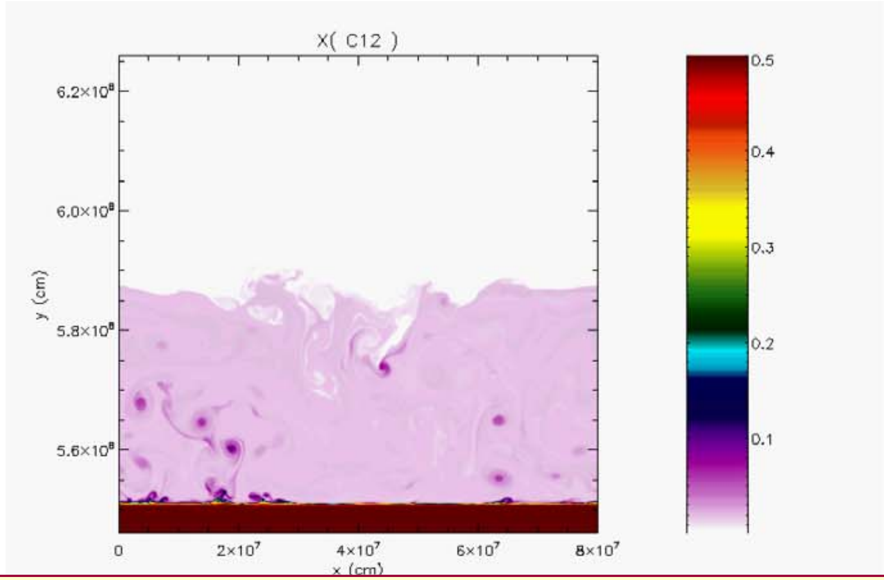
A&A 527, A5 (2011)
DOI: 10.1051/0004-6361/201015895

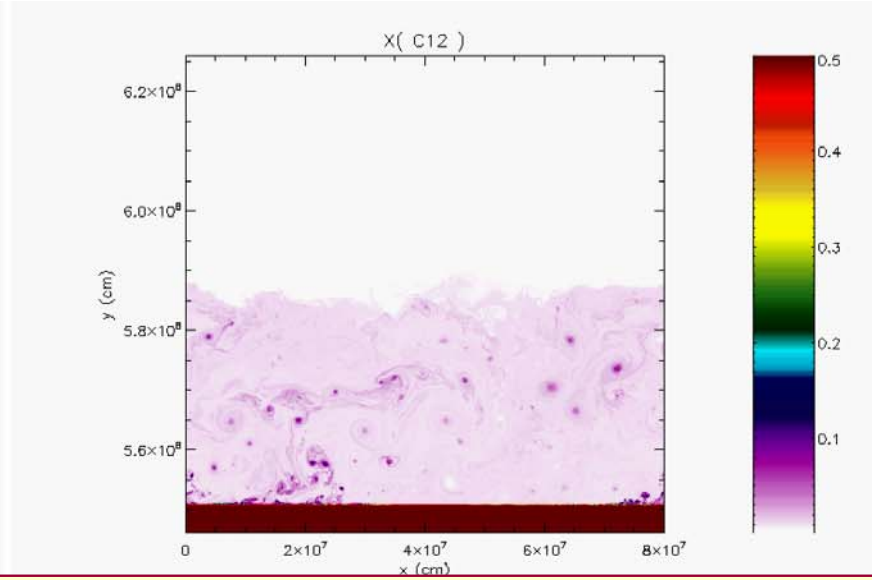
Astronomy & Astrophysics

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

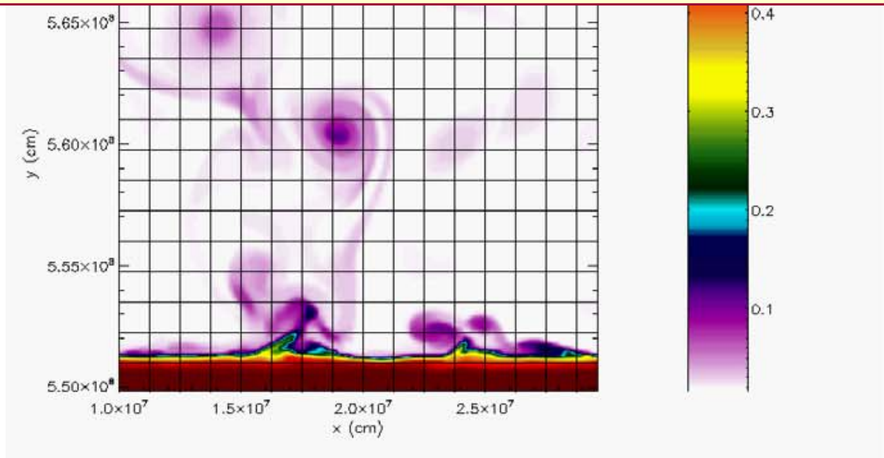
J. Casanova[1,2], J. José[1,2], E. García-Berro[3,2], A. Calder[4], and S. N. Shore[5]

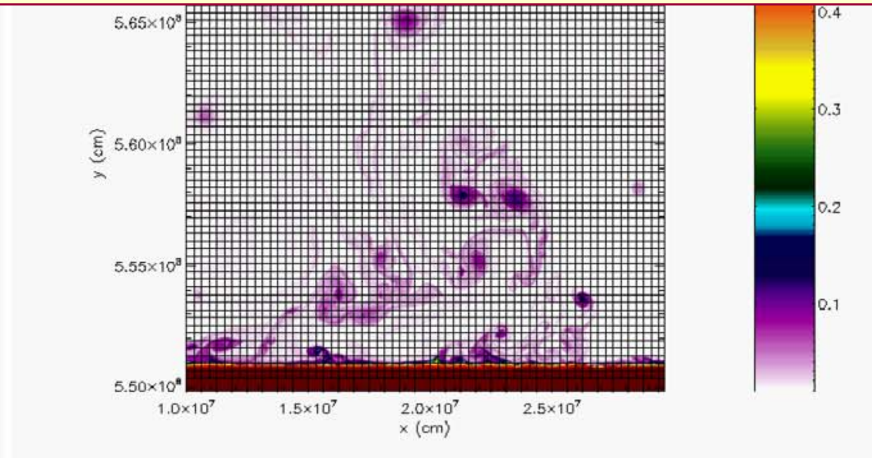
Model	H (km)	$R_x \times R_y$ (km)	δT	δt (s)	Resolution (km)	Computational Domain (km)	t_{KH} (s)	t_Y (s)	Z
A	0	1 × 1	5%	10^{-10}	1.56 × 1.56	800 × 800	155	496	0.224
B	0	1 × 1	5%	10	1.56 × 1.56	800 × 800	28	347	0.212
C	0	1 × 1	0.5%	10^{-10}	1.56 × 1.56	800 × 800	155	493	0.209
D	5	1 × 1	5%	10^{-10}	1.56 × 1.56	800 × 800	154	496	0.235
E	5	5 × 5	5%	10^{-10}	1.56 × 1.56	800 × 800	156	486	0.209
F	0	2 × 1	5%	10^{-10}	1.56 × 1.56	1600 × 800	151	493	0.206
G	0	1 × 1.25	5%	10^{-10}	1.56 × 1.56	800 × 1000	156	526	0.291
H	0	1 × 1	5%	10^{-10}	1 × 1	800 × 800	162	584	0.201
I	0	1 × 1	5%	10^{-10}	0.39 × 0.39	800 × 800	268	893	0.205





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**





LETTER

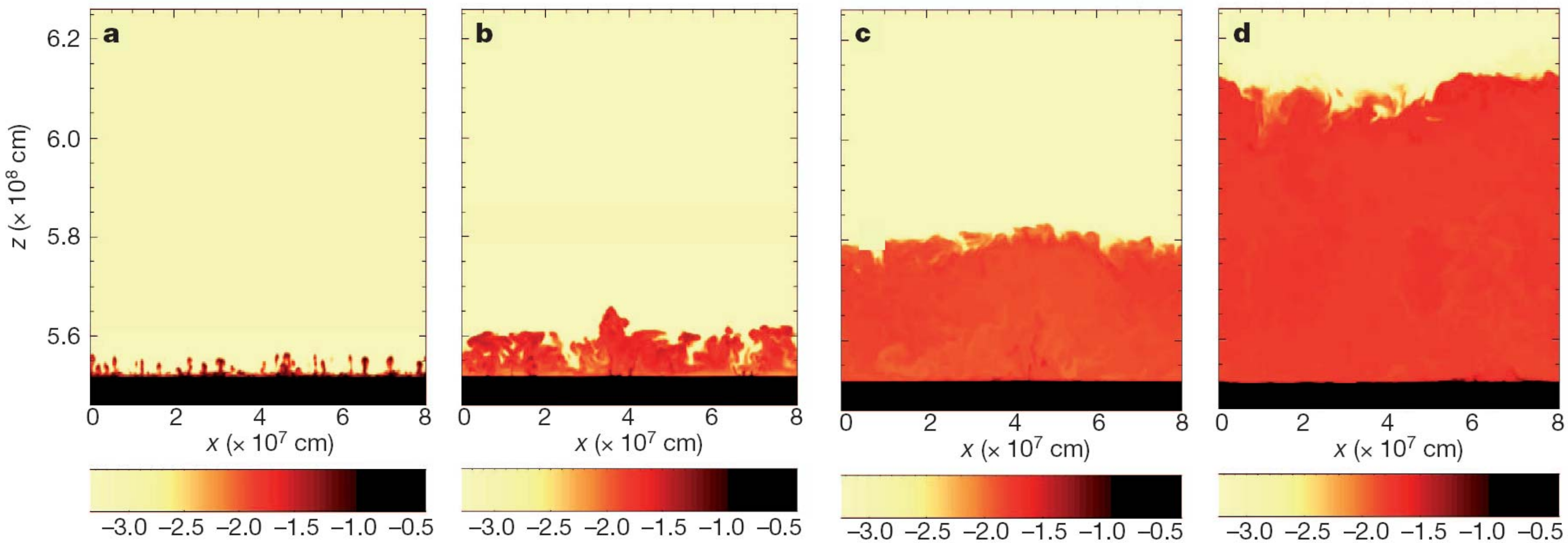
*** 3-D Simulations**

doi:10.1038/nature10520

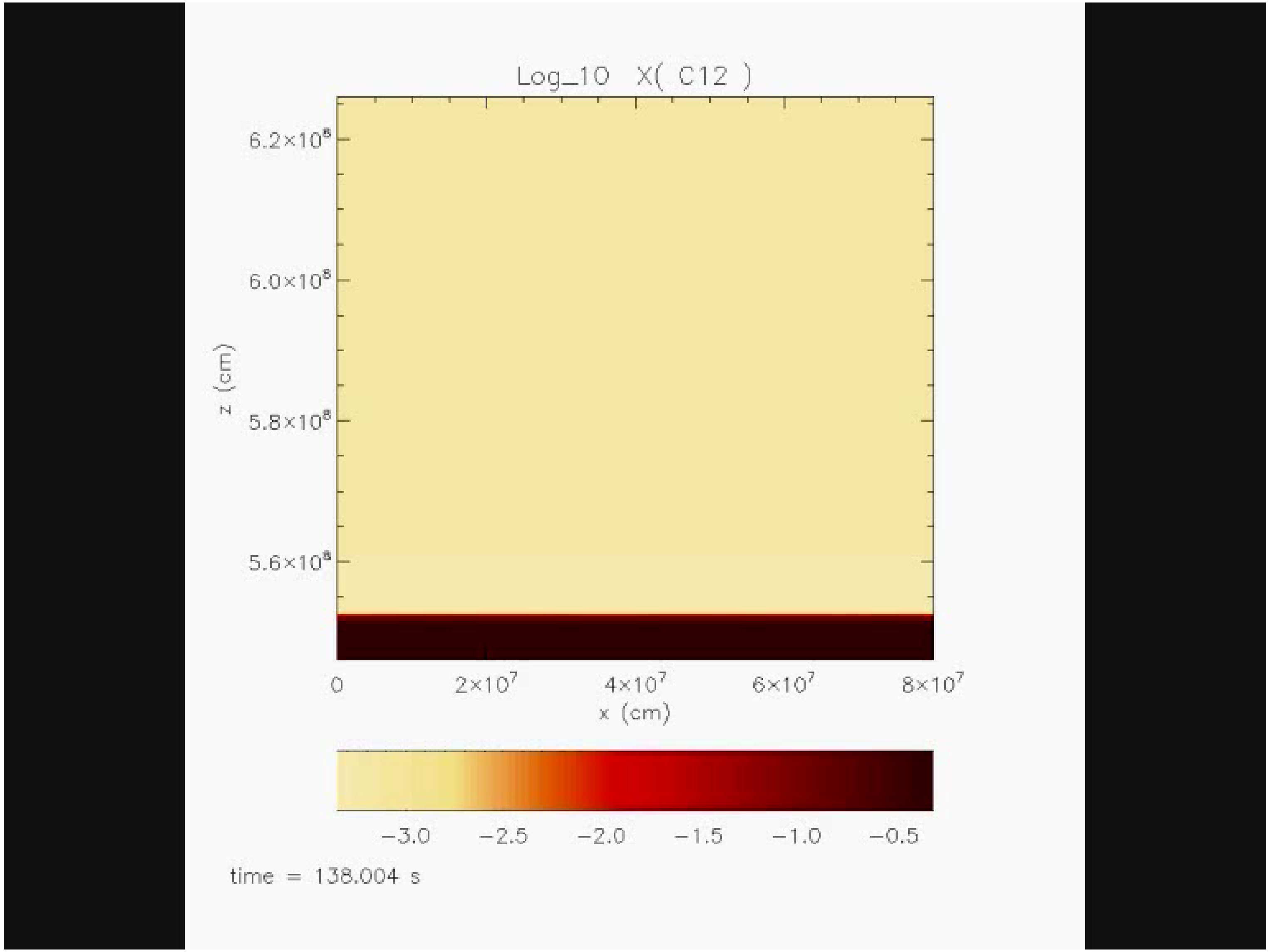
Kelvin–Helmholtz instabilities as the source of inhomogeneous mixing in nova explosions

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

$Z_{mean} \sim 0.2 – 0.3$

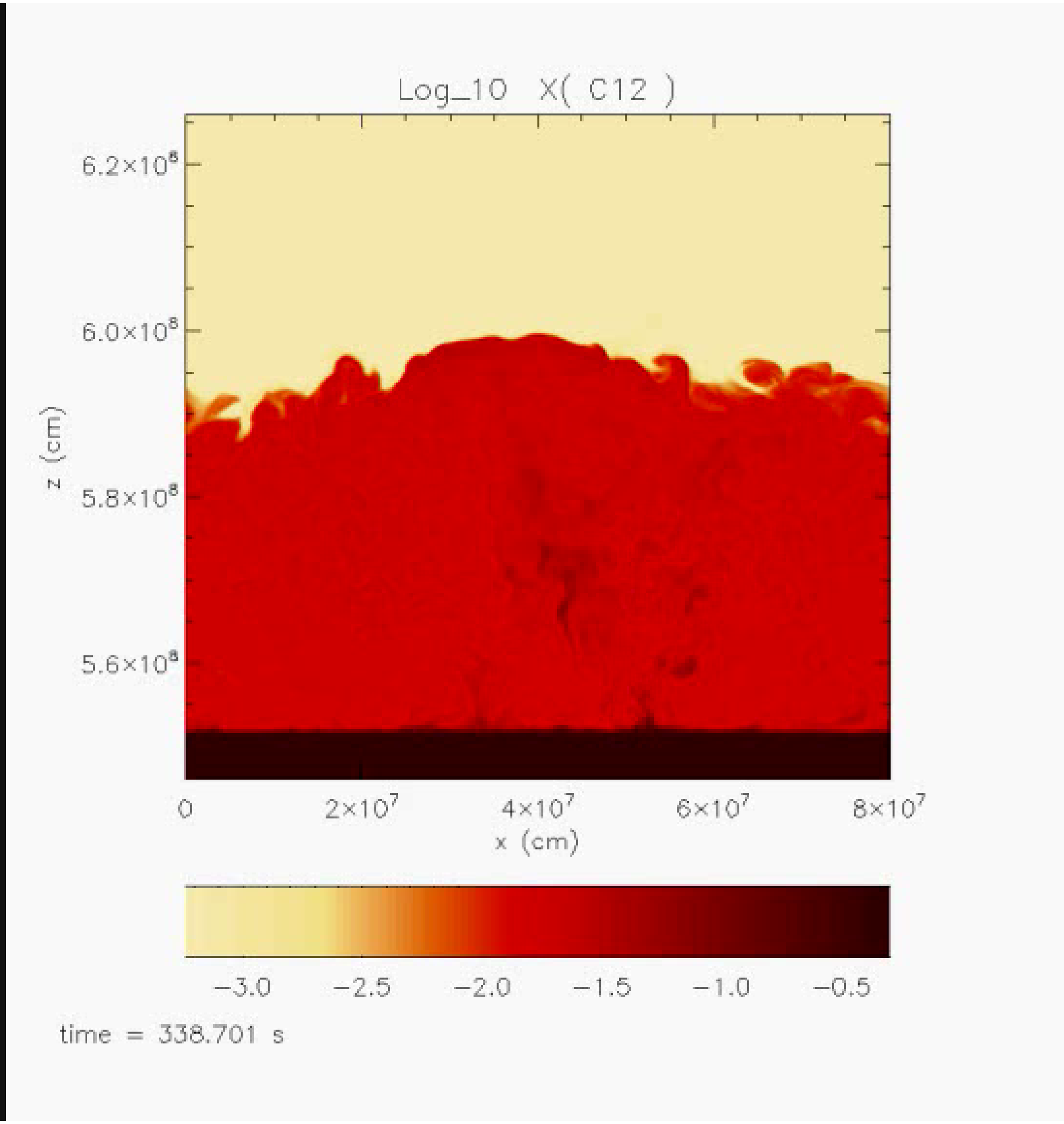


3-D Hydro Simulations with the FLASH Code



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

3-D Hydro Simulations with the FLASH Code




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]

For many problems in the theory of the stellar interior the speed of numerical integrations by hand is entirely sufficient. A person can usually accomplish more than twenty integration steps per day for a set of differential equations [...] Thus for a typical single integration consisting of, say, forty steps less than two days are needed. Correspondingly, if, for example, a set of models is to be determined and if these models are to be constructed of a one-parameter family starting from the surface and a one-parameter family starting from the core, and if each of these two families can be represented with sufficient accuracy by, say, six individual integrations, then the entire numerical work for this fairly typical case can be accomplished by one person in one month. However, if extensive evolutionary model sequences including a variety of physical complications are to be derived, then numerical integrations by hand may become prohibitive and the advantage of large electronic machines will be incontestable.

Martin Schwarzschild, *Structure and Evolution of the Stars* (1958)

Glasner, Livne & Truran (2012), MNRAS

2-D simulations for a wide range of possible compositions of the layer underlying the accreted envelope: **non-carbon cases**

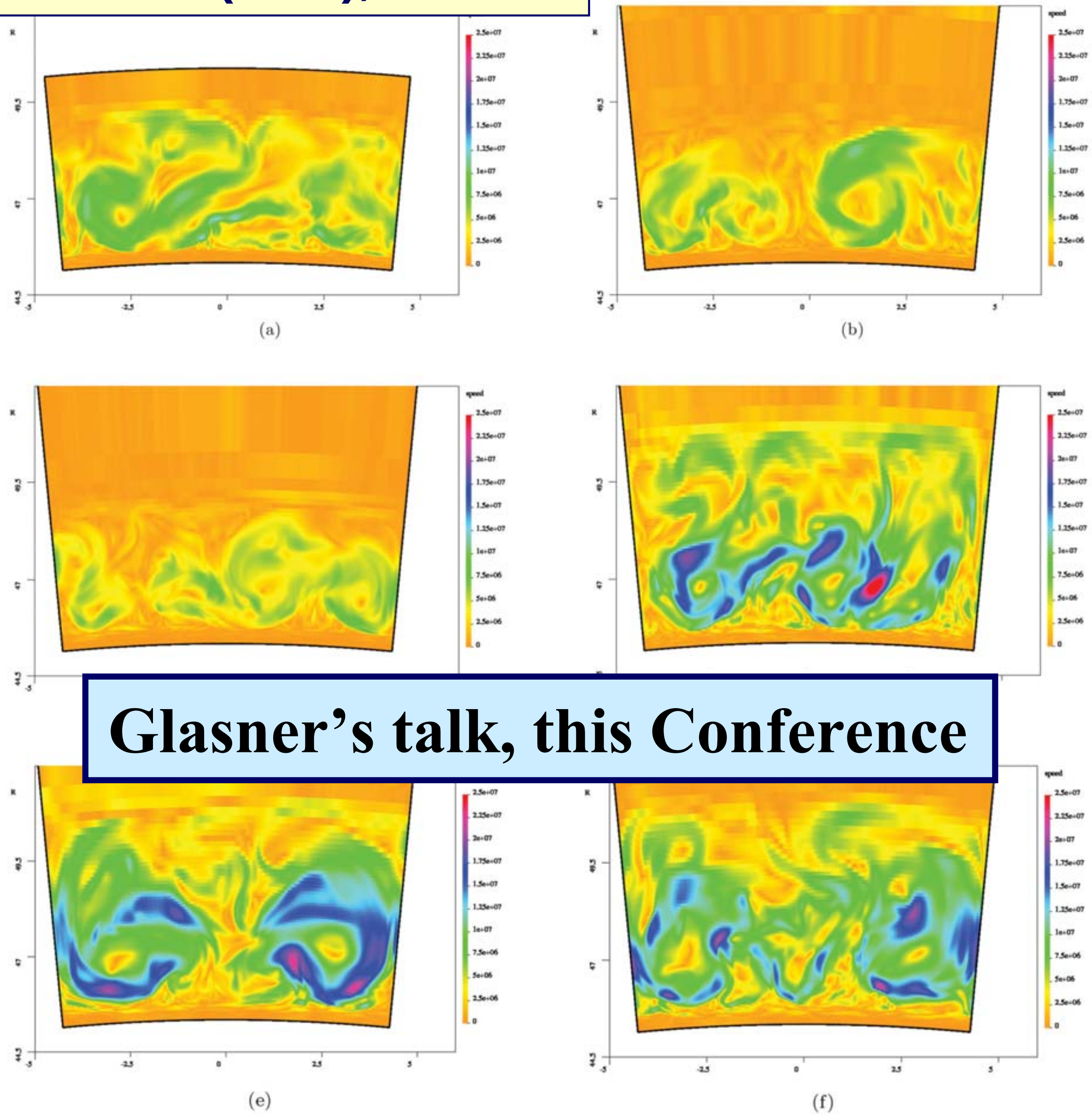
Computational domain: $0.1\pi^{rad}$, as in GLT97
Resolution: 1.4×1.4 km^2

15 isotope network [up to ^{17}F]

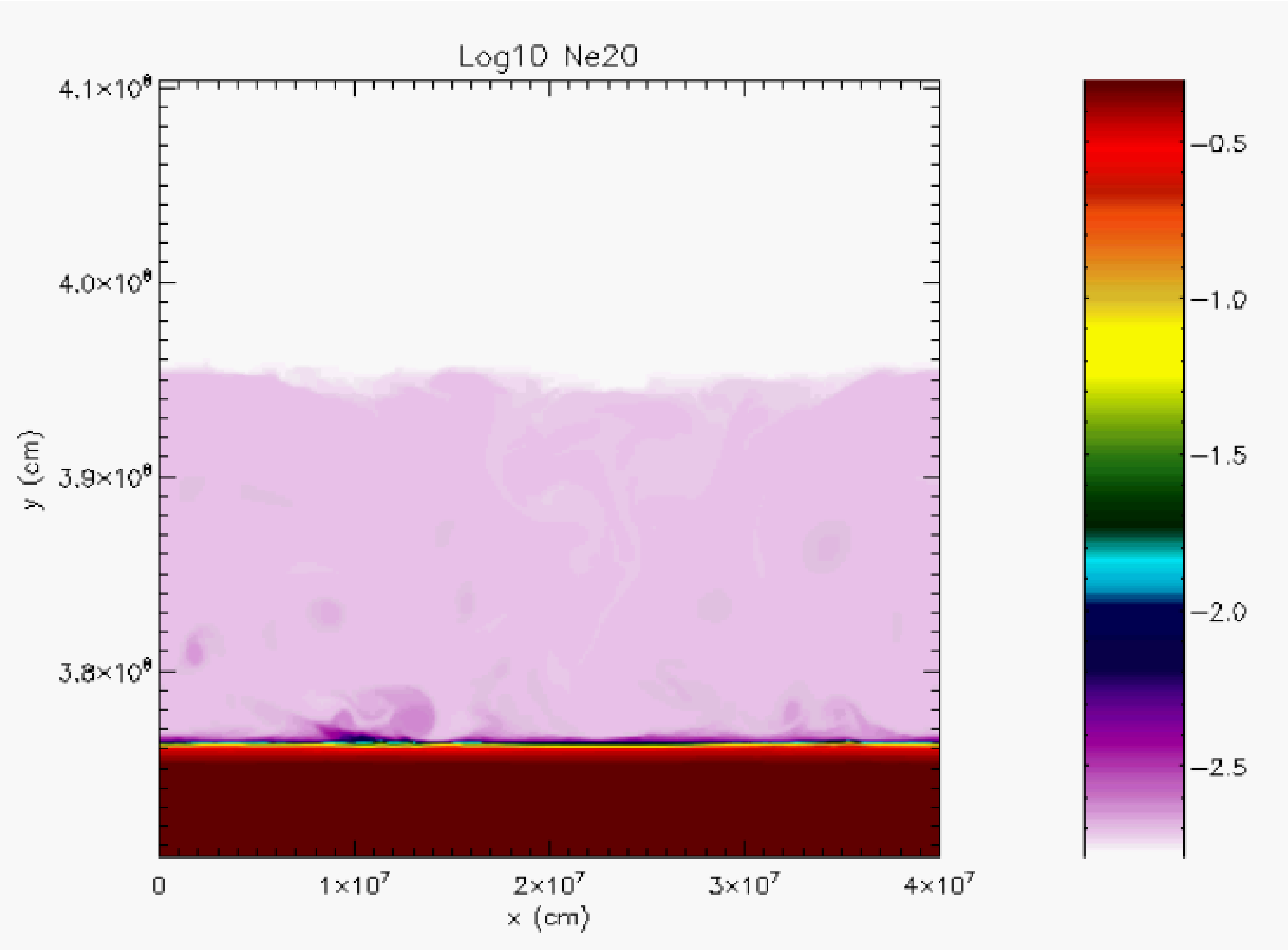
All simulations involve a 1.147 M$_o$ WD, with different substrates:

* CO
* He [recurrent novae]
* ONe → pure ^{16}O
* pure ^{24}Mg

Glasner, Livne & Truran (2012), MNRAS



Glasner's talk, this Conference



Casanova et al. (2013), in preparation

At this stage, **multiD models** can provide the **required inputs** for state-of-the-art, 1-D simulations with large nuclear reaction networks

The Astrophysical Journal, 762:8 (10pp), 2013 January 1
doi:10.1088/0004-637X/762/1/8

MESA MODELS OF CLASSICAL NOVA OUTBURSTS: THE MULTICYCLE EVOLUTION AND EFFECTS OF CONVECTIVE BOUNDARY MIXING

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Denissenkov's talk, this Conference

THE ASTROPHYSICAL JOURNAL, 662: L103–L106, 2007 June 20

THE FIRST NOVA EXPLOSIONS

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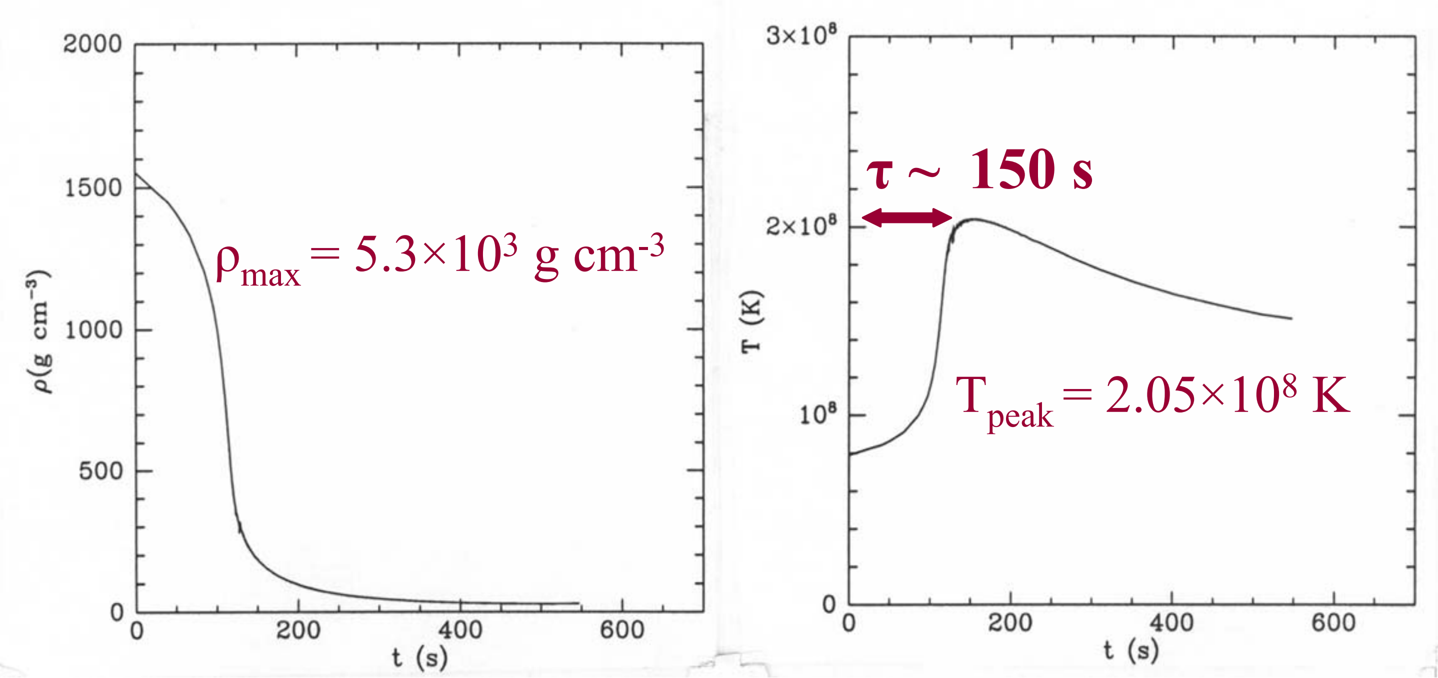
1-D simulations with **input from multiD models** [convective transport; Glasner et al. 1997]

↓

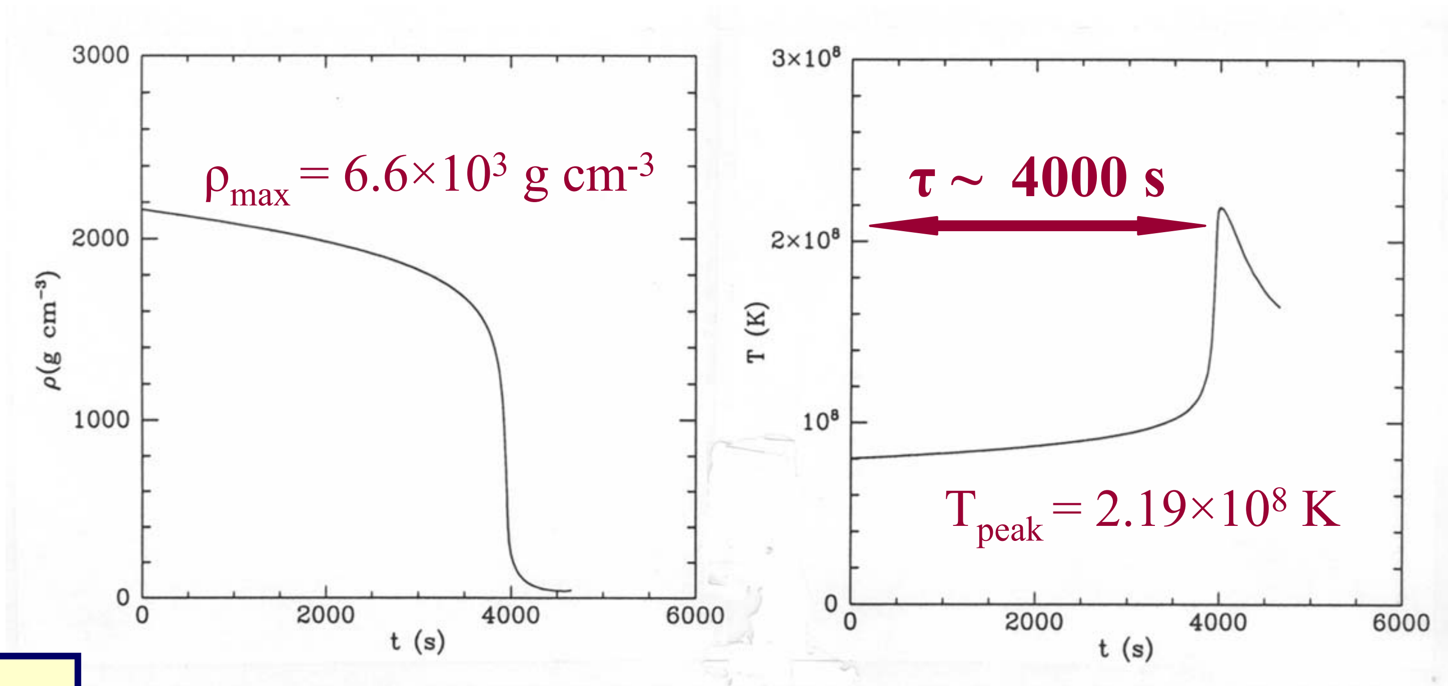
Effect on Nucleosynthesis?

(^{7}Li yields)



1.15 M_o CO

$^7Li/^7Li_\odot \sim 2000$



1.15 M_o ONe

$^7Li/^7Li_\odot \sim 150$

JJ (1996), unpublished

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

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GRAINS OF ANOMALOUS ISOTOPIC COMPOSITION FROM NOVAE

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Received 1975 April 28; revised 1975 June 26

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

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PRESOLAR GRAINS FROM NOVAE

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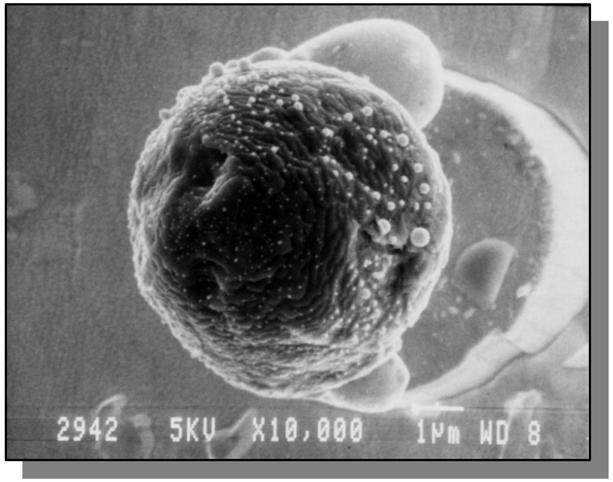
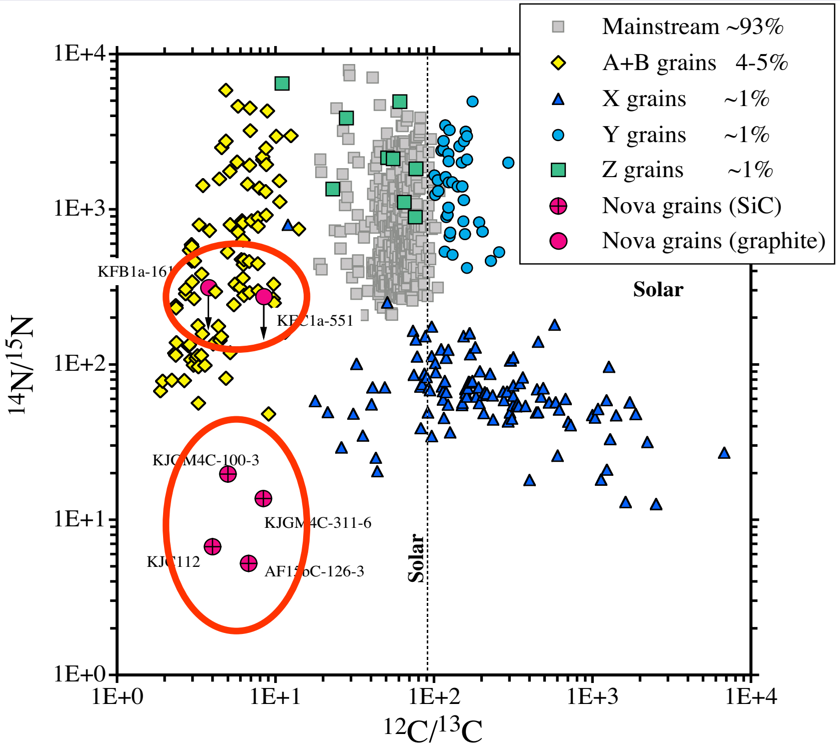
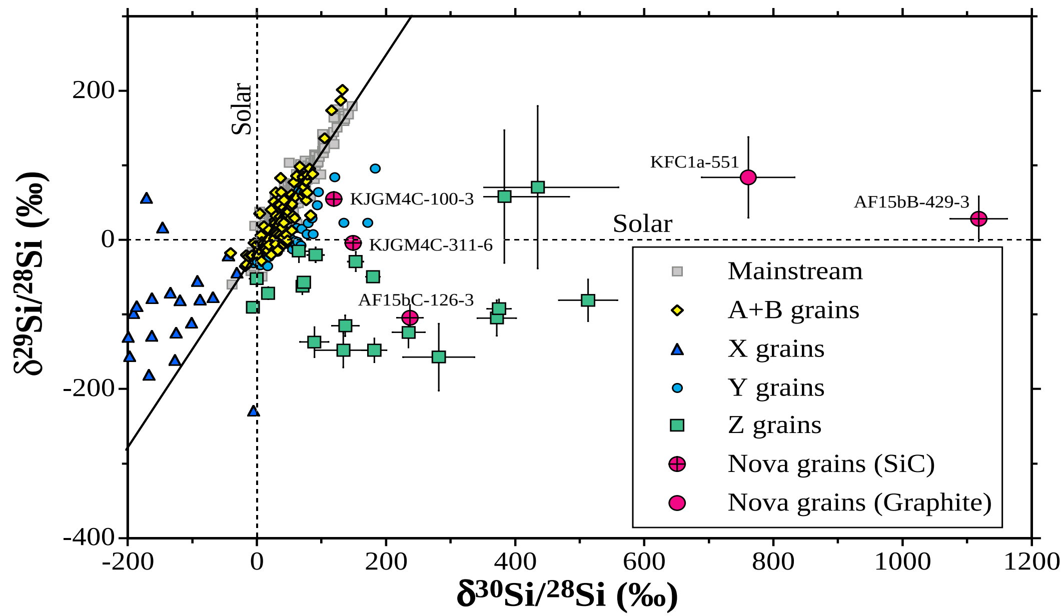






Presolar Nova Grains: *The Magnificent Seven*

Table I. Presolar grains with an inferred nova origin.

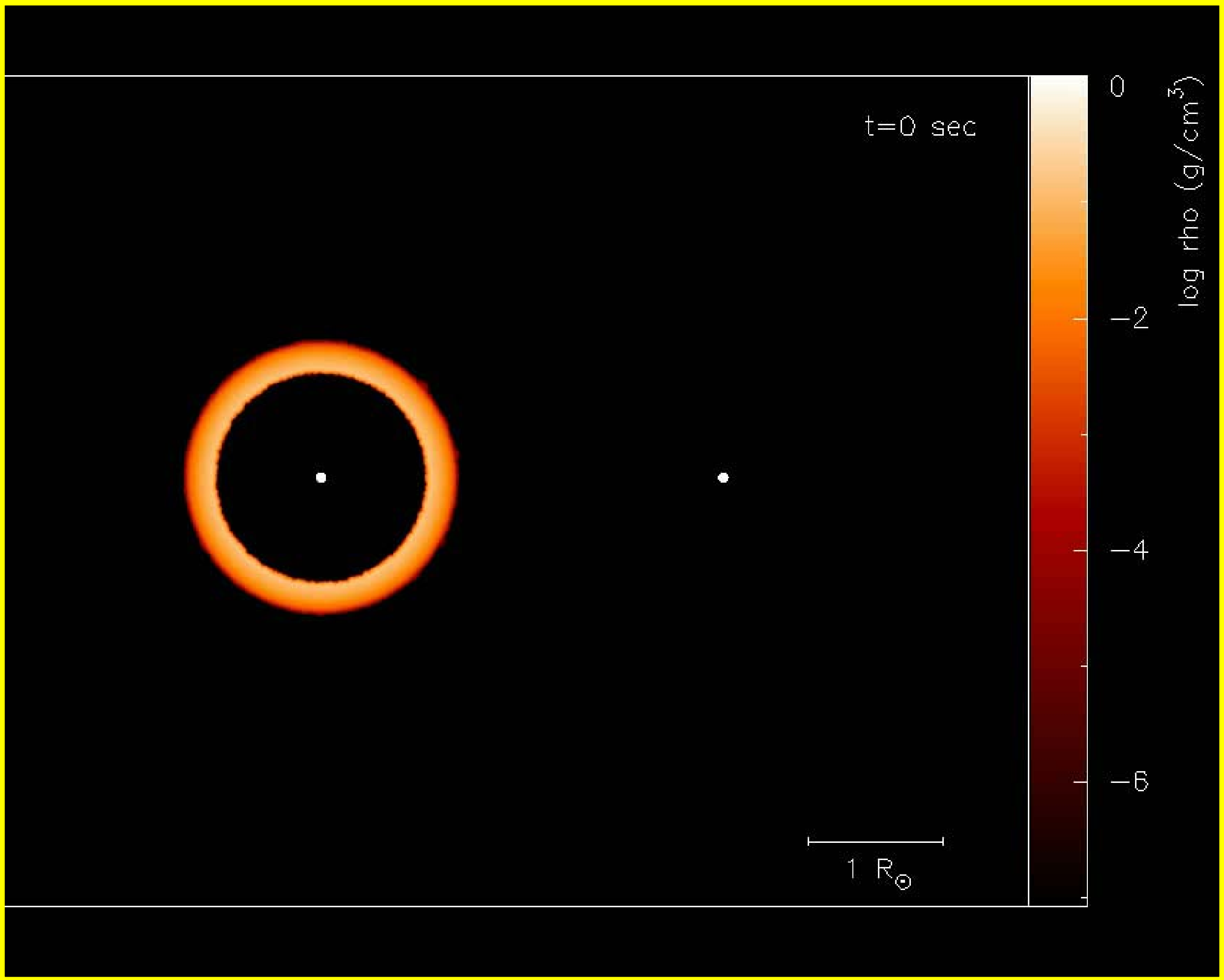
Grain	composition	$^{12}C/^{13}C$	$^{14}N/^{15}N$	$\delta^{29}Si/^{28}Si$	$\delta^{30}Si/^{28}Si$	$^{26}Al/^{27}Al$	$^{20}Ne/^{22}Ne$
AF15bB-429-3	SiC	9.4±0.2	...	28±30	1118±44	...	...
AF15bC-126-3	SiC	6.8±0.2	5.22±0.11	-105±17	237±20	...	...
KJGM4C-100-3	SiC	5.1±0.1	19.7±0.3	55±5	119± 6	0.0114	...
KJGM4C-311-6	SiC	8.4±0.1	13.7±0.1	-4±5	149±6	>0.08	...
KJC112	SiC	4.0±0.2	6.7±0.3	...	...	...	...
KFC1a-551	C	8.5±0.1	273±8	84±54	761±72	...	...
KFB1a-161	C	3.8±0.1	312± 43	-133±81	37±87	...	<0.01
Solar		89	272	0	0	0	14
Nova models		0.2–3	0.1–1900	-950 to 1800	-1000 to 47000	0.01–0.9	0.1–2900

The solar N ratio in the table is that from terrestrial air. Grains AF... are from the Acfer 094 meteorite, whereas grains KJ... and KF... are from the Murchison meteorite (see Amari et al. 2001c and Amari 2002, for details). Errors are 1σ.

Five SiC and **two graphite grains**, whose isotopic ratios point toward a **nova origin**: **low** $^{12}C/^{13}C$ and $^{14}N/^{15}N$ ratios, **high** ^{30}**Si/**^{28}**Si**, and **close-to-solar** ^{29}**Si/**^{28}**Si**. ^{26}**Al/**^{27}**Al** and ^{22}**Ne/**^{20}**Ne** ratios have been determined for some of these grains, with values compatible with nova model predictions ⟶ Dilution with $Z_{\odot}$ material!

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

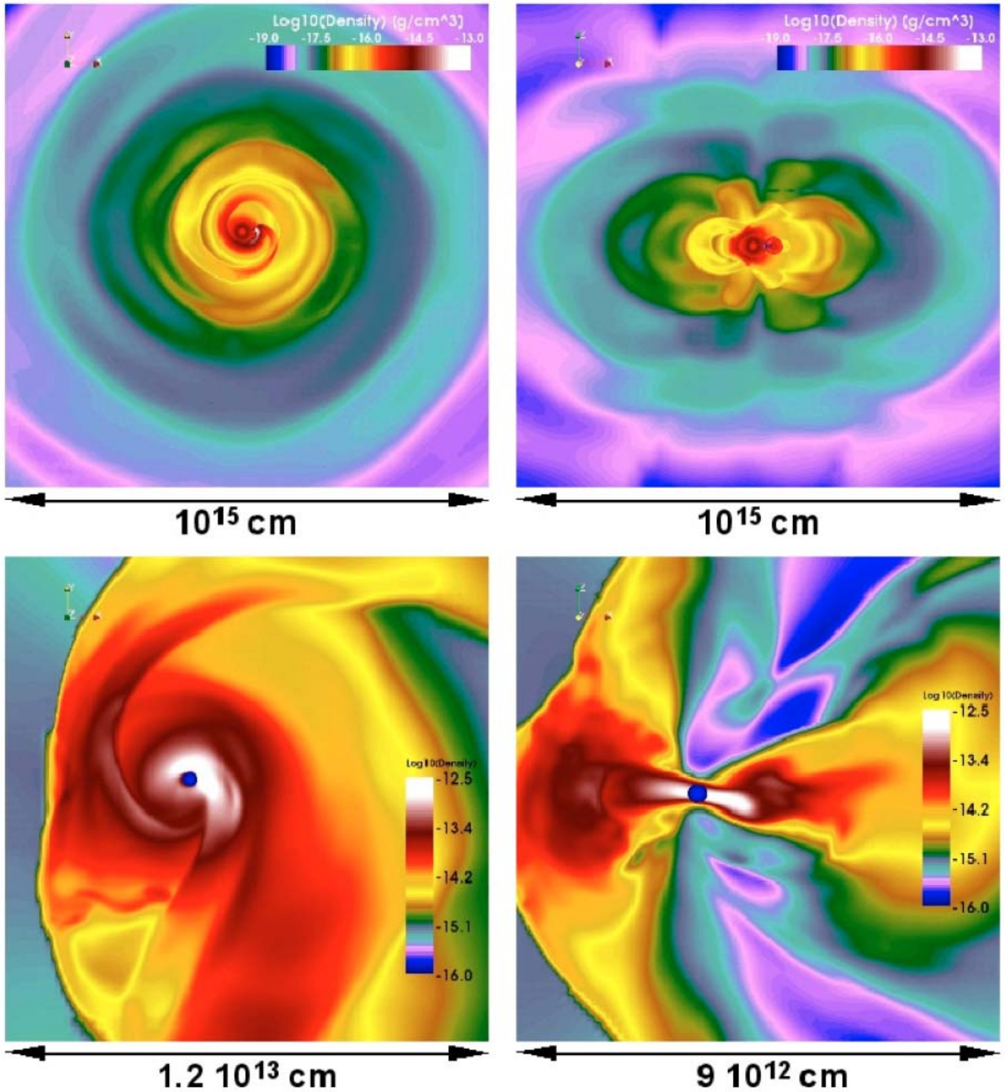
Campbell, JJ, Cabezón & García-Berro, NIC XI (2011)



PhD Thesis by J. Figueira

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

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



* **3-D hydro simulations** of the **quiescent accretion** and the subsequent **explosive phase**

Walder, Folini & Shore (2008), A&A


Thank you for your attention!
Multidimensional Modeling of Nova Outbursts
Stella Novae: Past and Future Decades
Cape Town (South Africa), February 4–8, 2013