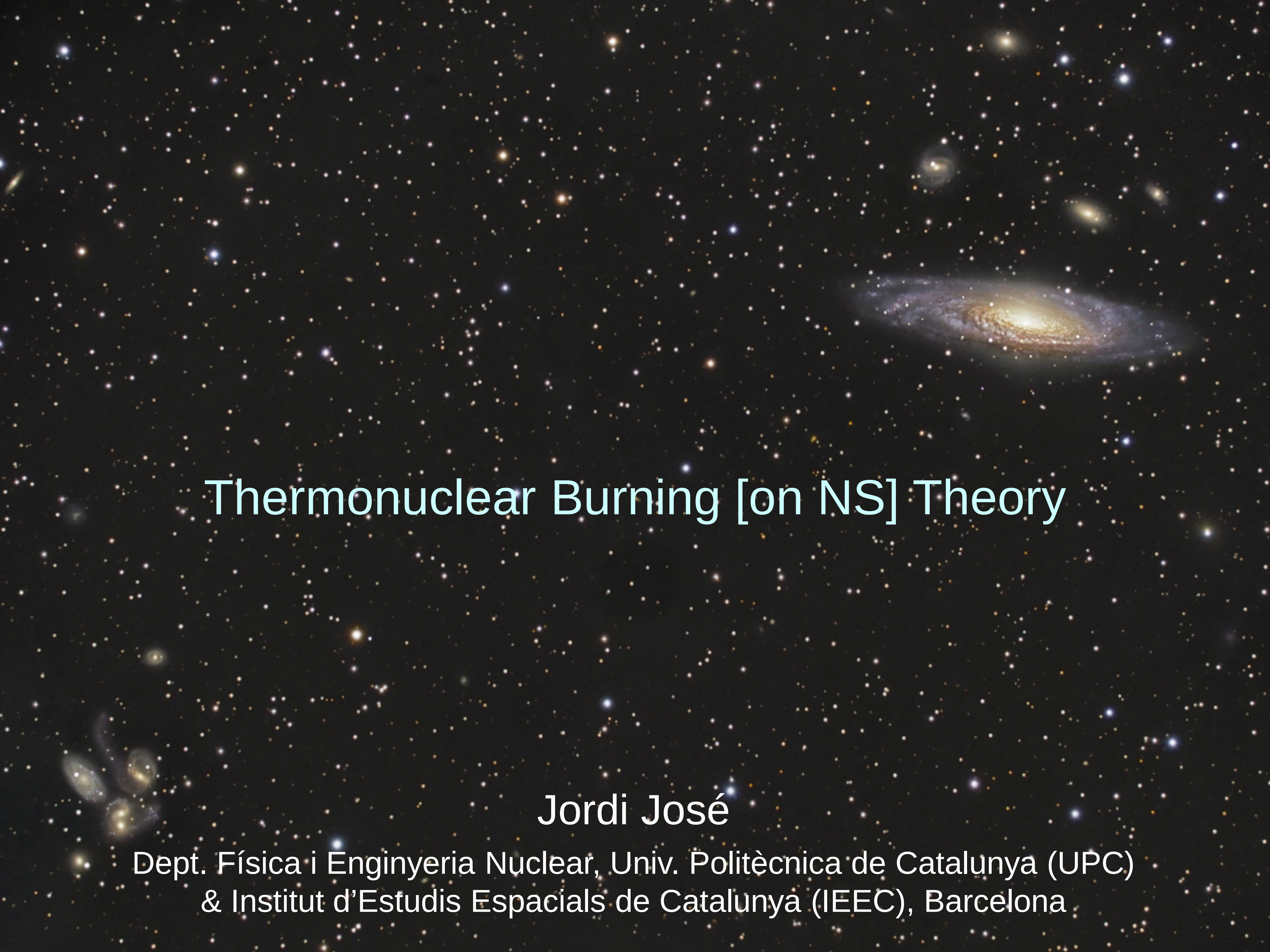

Thermonuclear Burning [on NS] Theory

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I. Introduction

Discovery of pulsars and X-ray sources, interpreted as spinning NS accreting mass from a stellar companion

* Rosenbluth et al. (1973): **first estimates of the energy released** from accretion and fusion of H–rich material piled up onto a NS
* Van Horn and Hansen (1974, 1975) pointed out that **nuclear burning** on the surface of NS may actually be **unstable**.

→ The **link** between **TNRs** driven by **unstable nuclear burning and XRBs** was independently suggested by Woosley and Taam (1976) (He– or C–burning driven bursts), and Maraschi and Cavaliere (1977) (H–burning bursts)

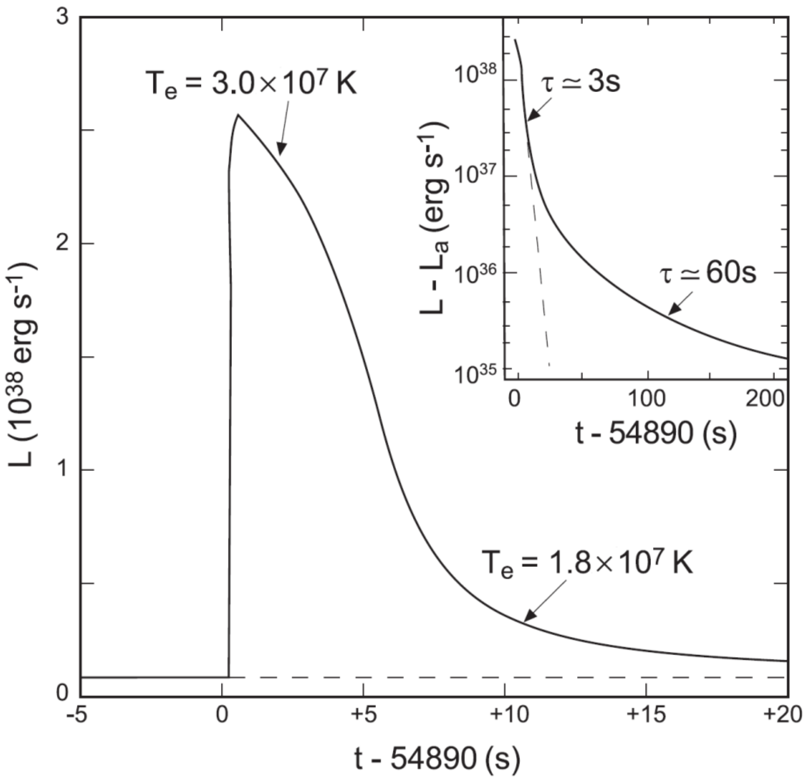
II. X-Ray Fireworks. Modeling the Burst

XRBs driven by accreting NS were first explored by means of semi–analytical models by Joss (1977), and Lamb and Lamb (1978), built on the basis of Hansen and Van Horn's models.

➡ **$L_{peak} \sim 10^{37}$ erg s^{-1}**, light curve **rise times** of ~ 0.1 s, **burst durations** ≥ 10 s, an overall **energy release** of 10^{39} erg per burst, and ratios of persistent over burst luminosities about **$\alpha \geq 100$**, in good agreement with observationally-inferred values.

→ Likely **fuel**: **He** (and **C**)

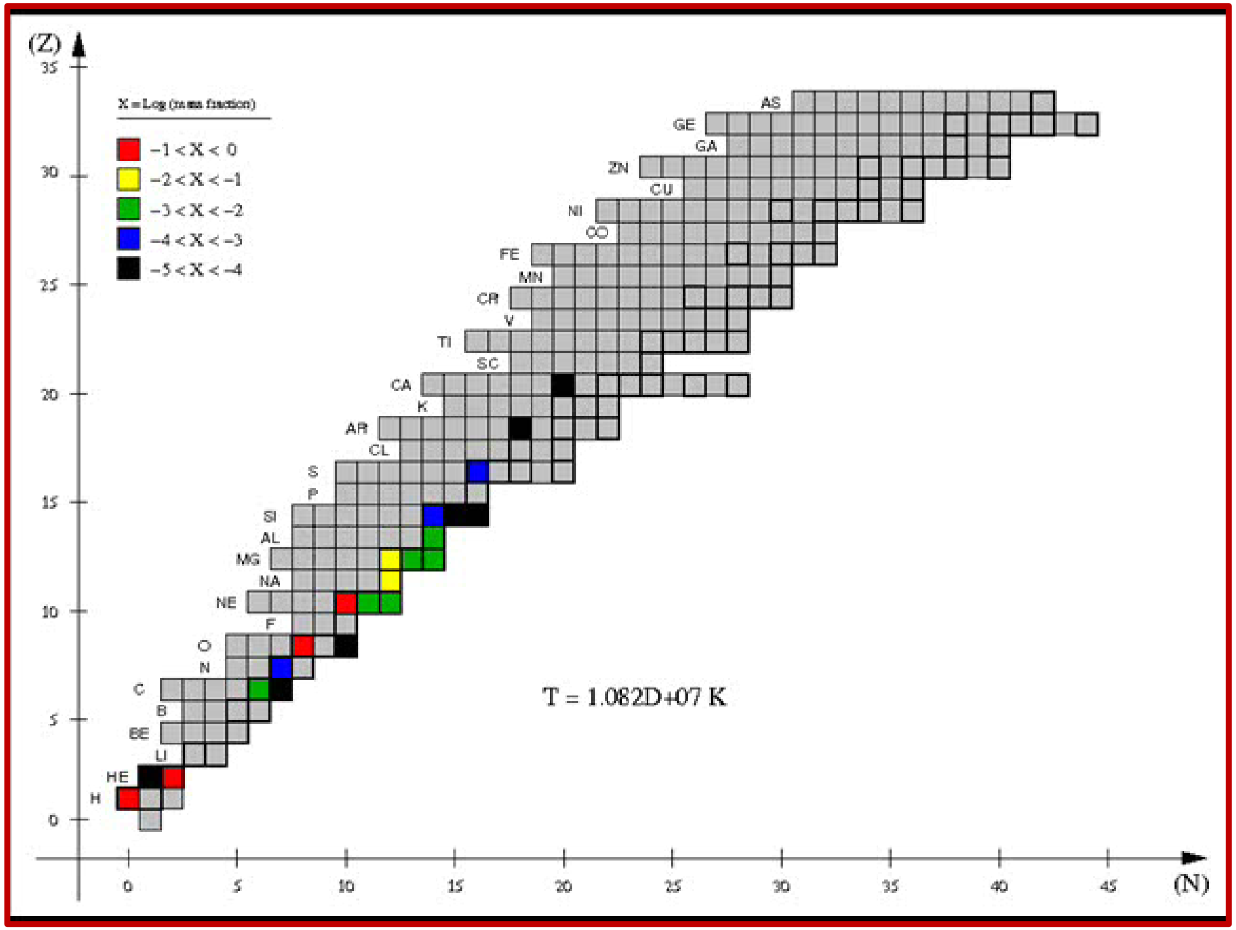
First detailed hydro **simulations** by Joss (1978): for different mass–accretion rates, and NS central temperatures



Joss (1978)

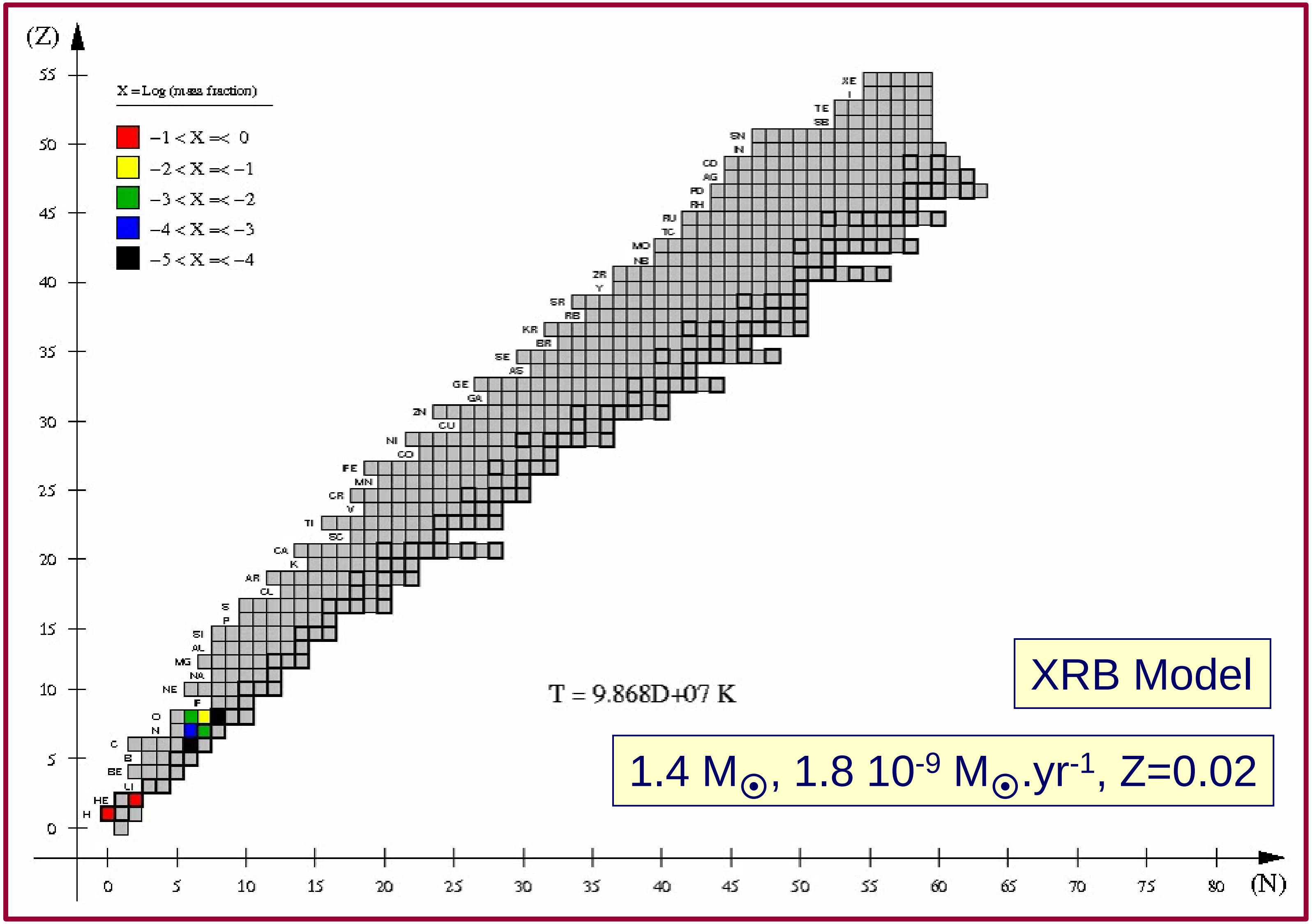
→ unstable He–burning can account for **XRB light curves** (i.e., peak luminosities, rise and decay times, the presence of low–energy tails...), **total energies, spectral features,** and **recurrence times.**

→ first claim that **nuclear fuel gets virtually consumed** (into Fe-peak nuclei); energy preferentially released in **X-rays**



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

Classical nova model: JJ (2015), in prep.



XRB Model

1.4 M$_\odot$, 1.8 10^{-9} M$_\odot$.yr^{-1}, Z=0.02

JJ, Moreno, Parikh & Iliadis (2010), ApJS

Degeneracy
At the very early stages of accretion, the envelope is mildly degenerate. As in CNe, a small increase in T is enough **to lift degeneracy** in XRBs.

A simple estimate: for a chemical mixture characterized by Z/A ~ 0.5, and a density of 10^5 g cm^{-3} (close to ρ_{max}), **degeneracy is lifted** (i.e., the thermal energy of the electrons becomes comparable to the Fermi energy) at **$T \geq 1.8\times10^8$ K** (~ 0.1 Tpeak)

NS → $M_{NS} \sim 1.4\ M_\odot$, $R_{NS} \sim 10$ km → $v_{esc} = \sqrt{2G\ M_{NS}/R_{NS}} \sim$ **190,000 km s^{-1}**

WD → $M_{WD} \sim 1\ M_\odot$, $R_{WD} \sim 6000$ km → $v_{esc} \sim$ **7000 km s^{-1}**

➡ **XRBs are halted by fuel consumption** (due to efficient CNO–breakout reactions) rather than by expansion → nearly **constant pressure** at ignition depth

The modeling of TNRs on accreting NS experienced a *burst* during the 1980s:

* **semi-analytical models**: Barranco et al. 1980, Buchler et al. 1980, Czerny & Jaroszynski 1980, Ergma & Tutukov 1980, Fujimoto et al. 1981, Paczynski 1983

* **hydrostatic/hydrodynamic simulations in 1-D**: Taam & Picklum 1979, Taam 1980, Joss & Li 1980, Ayasli & Joss 1982, Taam 1982, Wallace et al. 1982, Paczynski 1983, Woosley & Weaver 1984

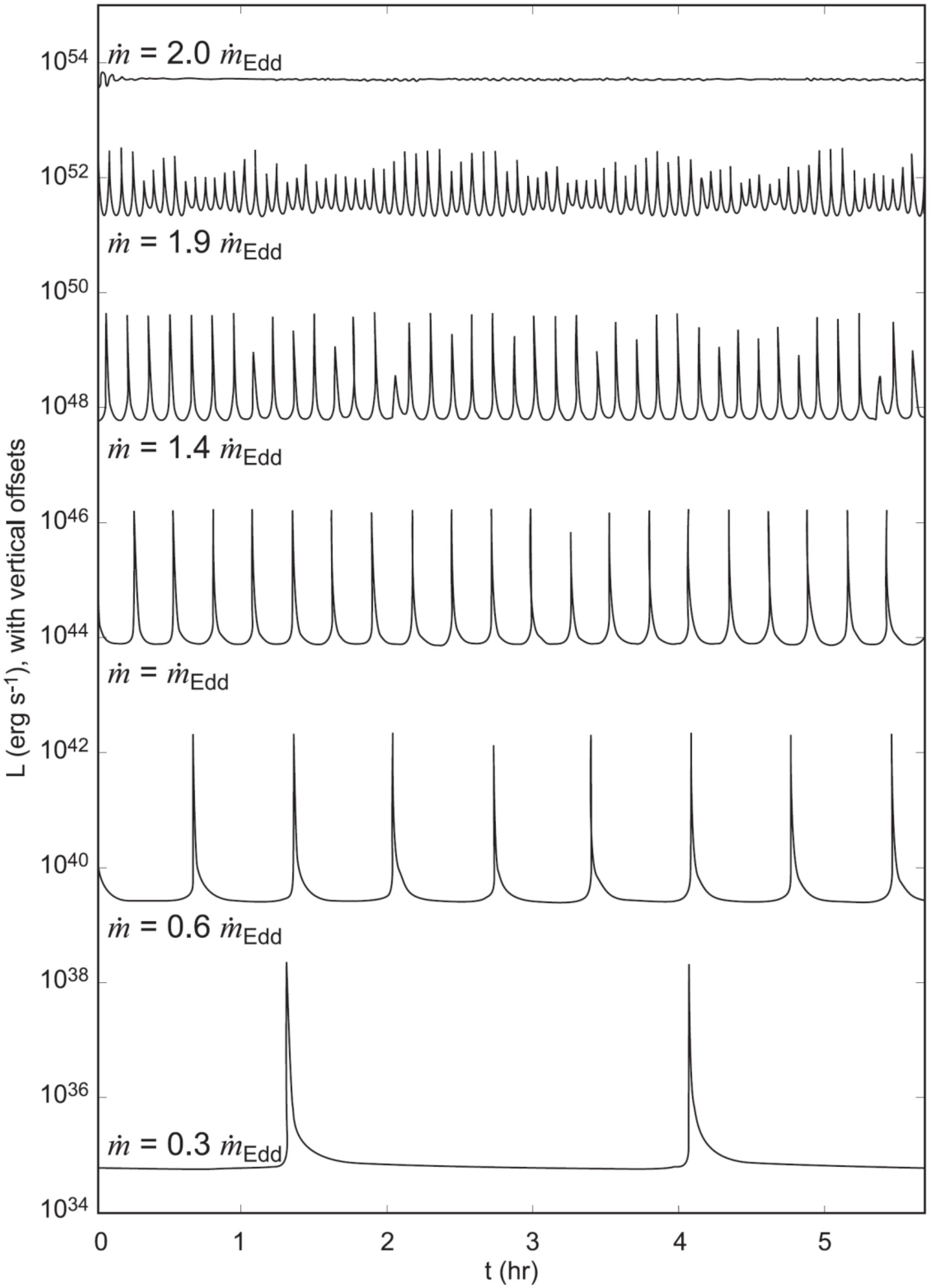
Most **influential parameters**: **mass–accretion rate, NS temperature (luminosity), metallicity of the accreted material** (Ayasli & Joss 1982, who also included GR corrections)

Dependencies:

- e.g., an increase in the mass–accretion rate translates into bursts of shorter duration and recurrence (with a **stable burning** regime obtained for high mass–accretion rates)
- a reduction of the overall metallicity of the accreted material delays the burst, increasing the amount of mass piled up on top of the star, and in turn, the strength of the explosion

Major drawbacks: shared by ALL models from 1980s

- use of reduced nuclear reaction networks to limit the computational load
- results exclusively based on a single burst, because of computational constraints → major step forward: modeling of full series of bursts (properties of the first burst may be affected by the initial conditions): **XRBs vs CNe**



Zamfir, Cumming & Niquette (2014), MESA

Simulations predict that the **transition between stable and bursting regimes** (Taam 1981) **occurs at about 10 times higher mass–accretion rates than observed** (Keek et al. 2014, Zamfir et al. 2014)

Attempts to reconcile theoretical and observed values include **variations of key nuclear reaction rates** (e.g., the 3α reaction, ^{15}O(α, γ)^{19}Ne, and ^{18}Ne(α, p)^{21}Na (Keek et al. 2014) or the **inclusion of a base heating flux** in models of accreting neutron stars (Zamfir et al. 2014).

Marginally–stable nuclear burning (close to transition) → **oscillations** in the XRB light curve (Cumming & Bildsten 2000, Heger et al. 2007) identified with the mHz quasi–periodic oscillations discovered in NS accreting H–rich matter at rates in the range 0.05 M_{Edd} – 0.5 M_{Edd} (Revnivtsev et al. 2001, Altamirano et al. 2008, Linares et al. 2012).

Altamirano, Luy, Strohmayer, this Conference

Transition to stable burning has also been invoked to account for the observed **quenching** of type I X–ray bursts following a superburst (Cumming & Bildsten 2001, Cumming & Macbeth 2004, Kuulkers et al. 2002, Keek et al. 2012)

Dependencies:

- e.g., an increase in the mass–accretion rate translates into bursts of shorter duration and recurrence (with a **stable burning** regime obtained for high mass–accretion rates)
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➡ thermal (Taam 1980) and compositional inertia (Woosley & Weaver 1984)

- **thermal inertia**: role played by the energy released during a burst —and the subsequent heating of the surface layers— on the critical mass required to power the next burst
- **compositional inertia**: burst properties are sensitive to the chemical abundance pattern of the ashes of previous bursts onto which accretion and explosion will occur in the next bursting episode → reduces the influence of metallicity on burst properties.

Some models achieve high pressures and densities at the envelope base → strong bursts, with short periods of **super–Eddington luminosities**, frequently accompanied by the presence of **precursors** in the X–ray light curve, together with mass–loss episodes through **radiation–driven winds**

Radiation–driven winds: the radiation flux that difuses outwards from the burning regions may exceed the local Eddington limit in the outer, cooler layers of the star → hydrostatic equilibrium is broken. Pioneering models: Kato (1983), Ebisuzaki et al. (1983), and Quinn and Paczynski (1985). GR effects were introduced by Paczynski and Proszynski (1986), and Turolla et al. (1986).

More refined treatments of radiative transfer in quasi–static winds from NS (Joss & Melia 1987, Yahel et al. 1987, Nobili et al. 1994, Weinberg et al. 2006) yield $\mathbf{M_{loss} \sim 10^{17} - 10^{20}\ g\ s^{-1}\ (10^{-9} - 10^{-6}\ M_{\odot}\ yr^{-1})}$

Different **regimes of unstable burning** on NS have also been identified, including combined H/He bursts and pure He flashes

→ large spread in burst properties (Fujimoto et al. 1981, Taam 1981, Strohmayer & Bildsten 2006)

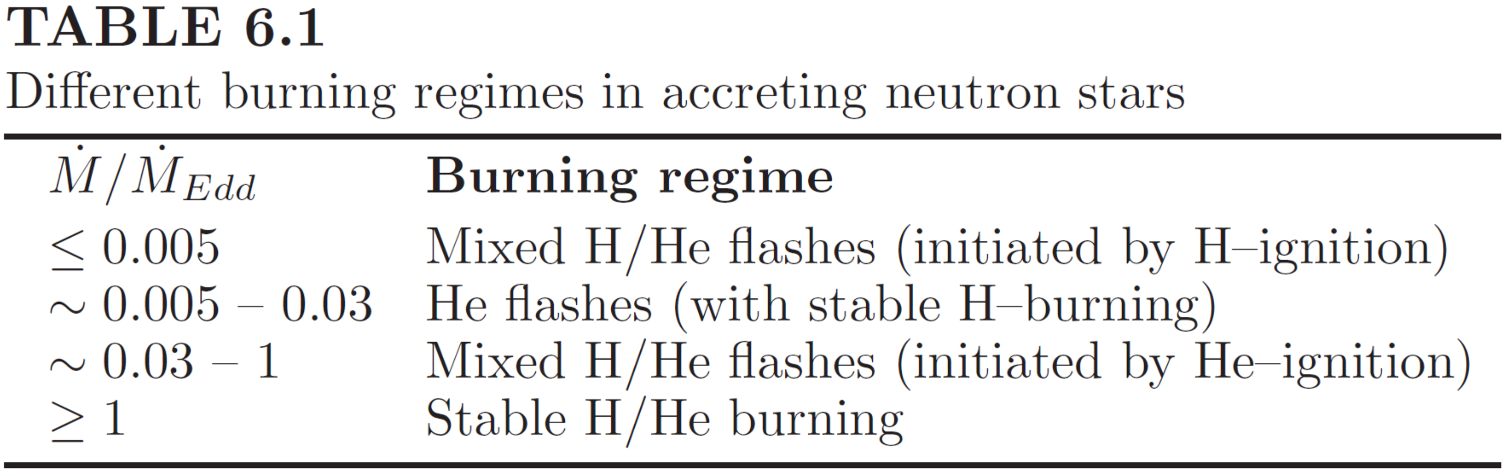


TABLE 6.1

Different burning regimes in accreting neutron stars

$\dot{M}/\dot{M}_{Edd}$	**Burning regime**
≤ 0.005	Mixed H/He flashes (initiated by H–ignition)
$\sim 0.005 - 0.03$	He flashes (with stable H–burning)
$\sim 0.03 - 1$	Mixed H/He flashes (initiated by He–ignition)
≥ 1	Stable H/He burning

Observed spread in burst properties (explained by different fuels and ignition depths)→ **XRB subtypes**: normal and intermediate–duration bursts, and superbursts

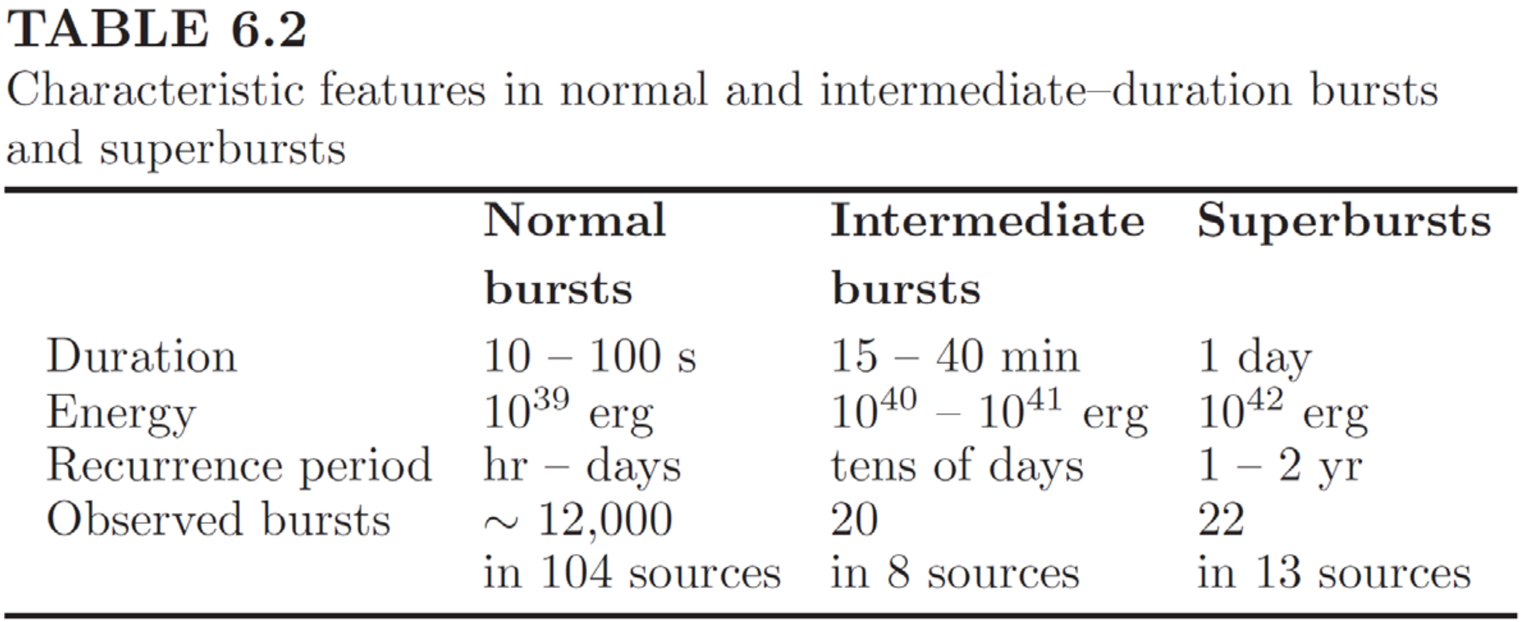


TABLE 6.2

Characteristic features in normal and intermediate–duration bursts and superbursts

	Normal bursts	**Intermediate bursts**	**Superbursts**
Duration	10 – 100 s	15 – 40 min	1 day
Energy	10^{39} erg	10^{40} – 10^{41} erg	10^{42} erg
Recurrence period	hr – days	tens of days	1 – 2 yr
Observed bursts	∼ 12,000 in 104 sources	20 in 8 sources	22 in 13 sources

* **Normal bursts**: burst duration is determined by the characteristic cooling timescale of the burning shell (~ 10 s), which is set by the ignition depth. In the presence of H, ignition occurs at similar depths, but rapid proton captures (**rp–process**) during the decay from peak luminosity can extend the duration of a burst up to ~ 100 s.

* **Intermediate–duration bursts and superbursts:** ignition at larger depths (higher pressures) →

- Intermediate–duration bursts: ignition in thick He layers on cold NS (direct/indirect He–accretion; Fujimoto et al. 1981, Wallace et al. 1982, Cumming 2003, in’t Zand et al. 2005, Cumming et al. 2006, Cooper & Narayan 2007, Peng et al. 2007)

- superbursts: likely driven by C-burning → thicker envelopes required to account for the longer duration of these bursts

Keek, this Conference

III. Nucleosynthesis in Type I XRBs

Santa Fe, NM

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

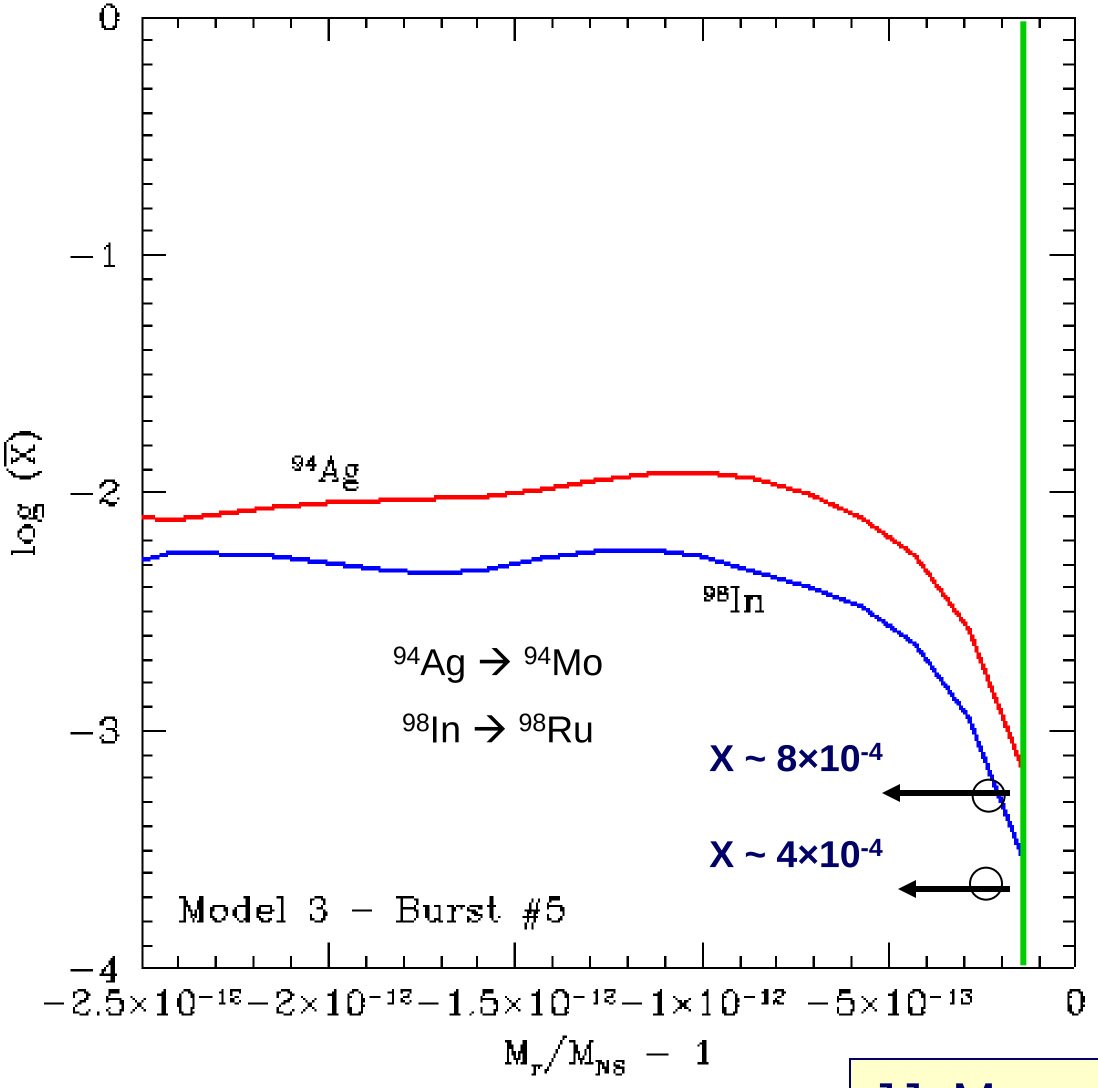
Detailed nucleosynthesis studies require **hundreds of isotopes**, up to **SnSbTe** mass region (Schatz et al. 2001) or beyond (the flow in Koike et al. 2004 reaches ^{126}Xe), and thousands of nuclear interactions

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)

The potential impact of XRB nucleosynthesis on **Galactic abundances** is still a matter of debate:

Ejection from a NS **unlikely** because of its large **gravitational potential** (ejection from the surface a NS of mass *M* and radius *R* requires GMm_p/R ~ 200 MeV/nucleon, whereas only a few MeV/nucleon are released from thermonuclear fusion)

However, it has been suggested that **radiation-driven winds** during photospheric radius expansion may lead to the ejection of a tiny fraction of the envelope (Weinberg et al. 2006a). Indeed, it has been suggested that XRBs might account for the Galactic abundances of the problematic light ***p-nuclei*** (Schatz et al. 1998)



^{94}Ag → ^{94}Mo

^{98}In → ^{98}Ru

X ~ 8×10^{-4}

X ~ 4×10^{-4}

Solar abundances:

^{94}Mo = 5.5×10^{-10}

^{98}Ru = 8.6×10^{-11}

$^{94}\mathrm{Mo} / (^{94}\mathrm{Mo})_\odot \approx 10^6$

$^{98}\mathrm{Ru} / (^{98}\mathrm{Ru})_\odot \approx 10^6$

Far from the ***f*** required to account for the Galactic values

JJ, Moreno, Parikh & Iliadis (2010), ApJS

If XRBs likely do not contribute to the Galactic abundances, what their associated nucleosynthesis is important for?

Several **thermal** (Miralda-Escudé, Paczynski, & Haensel 1990; Schatz et al. 1999) and **electrical** properties (Brown & Bildsten 1998; Schatz et al. 1999) of NS depend critically on the specific chemical composition of the envelope

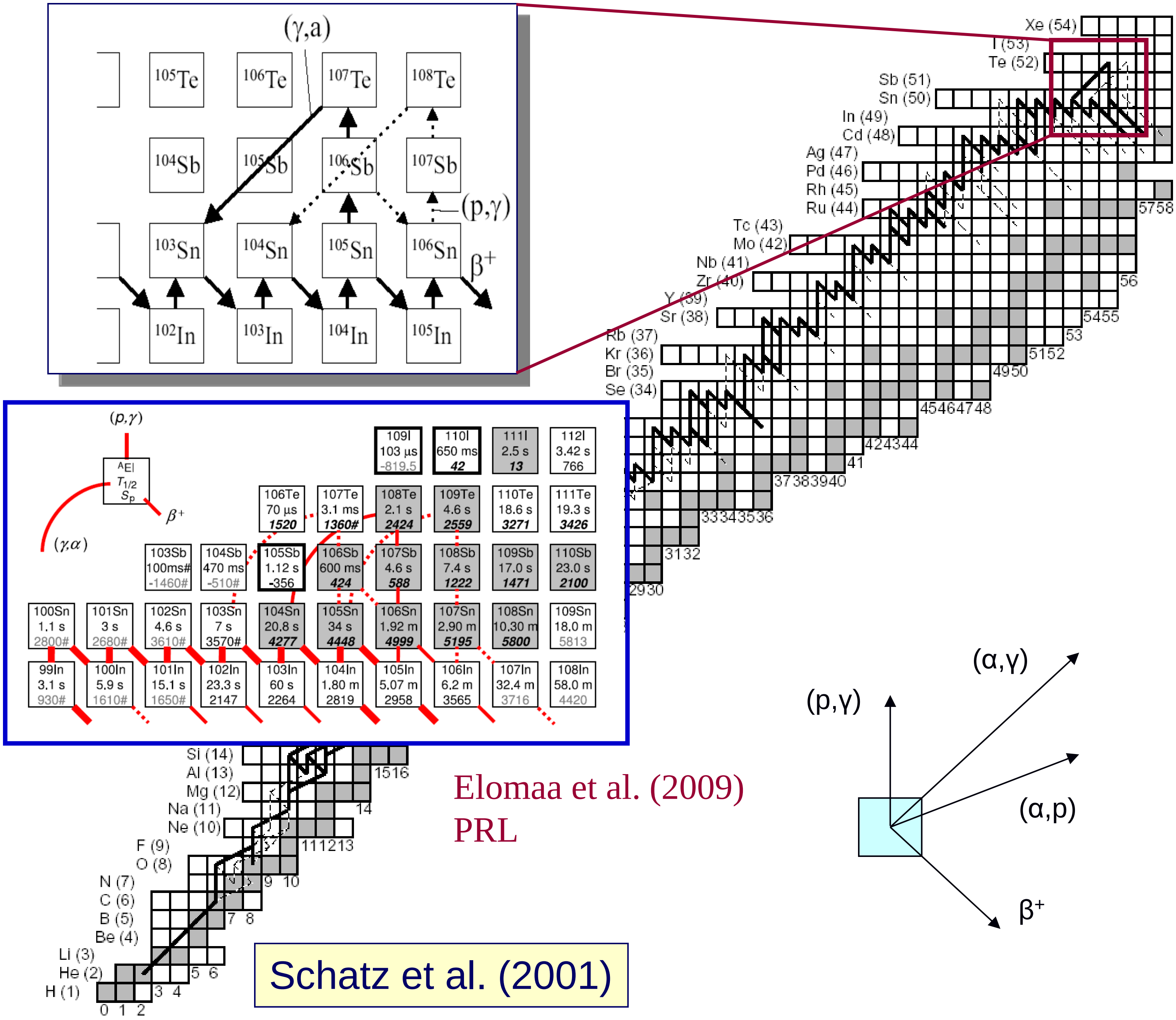
Ashes may provide characteristic **signatures** such as gravitationally redshifted atomic absorption lines from the NS surface that may be identified through **high-resolution X-ray spectra**

→ Cottam, Paerels, & Mendez (2002); Bildsten, Chang, & Paerels (2003); Chang, Bildsten, & Wasserman (2005); Chang et al. (2006); Weinberg, Bildsten, & Schatz (2006)

Computational limitations: → studies of XRB nucleosynthesis using **limited** nuclear reaction networks

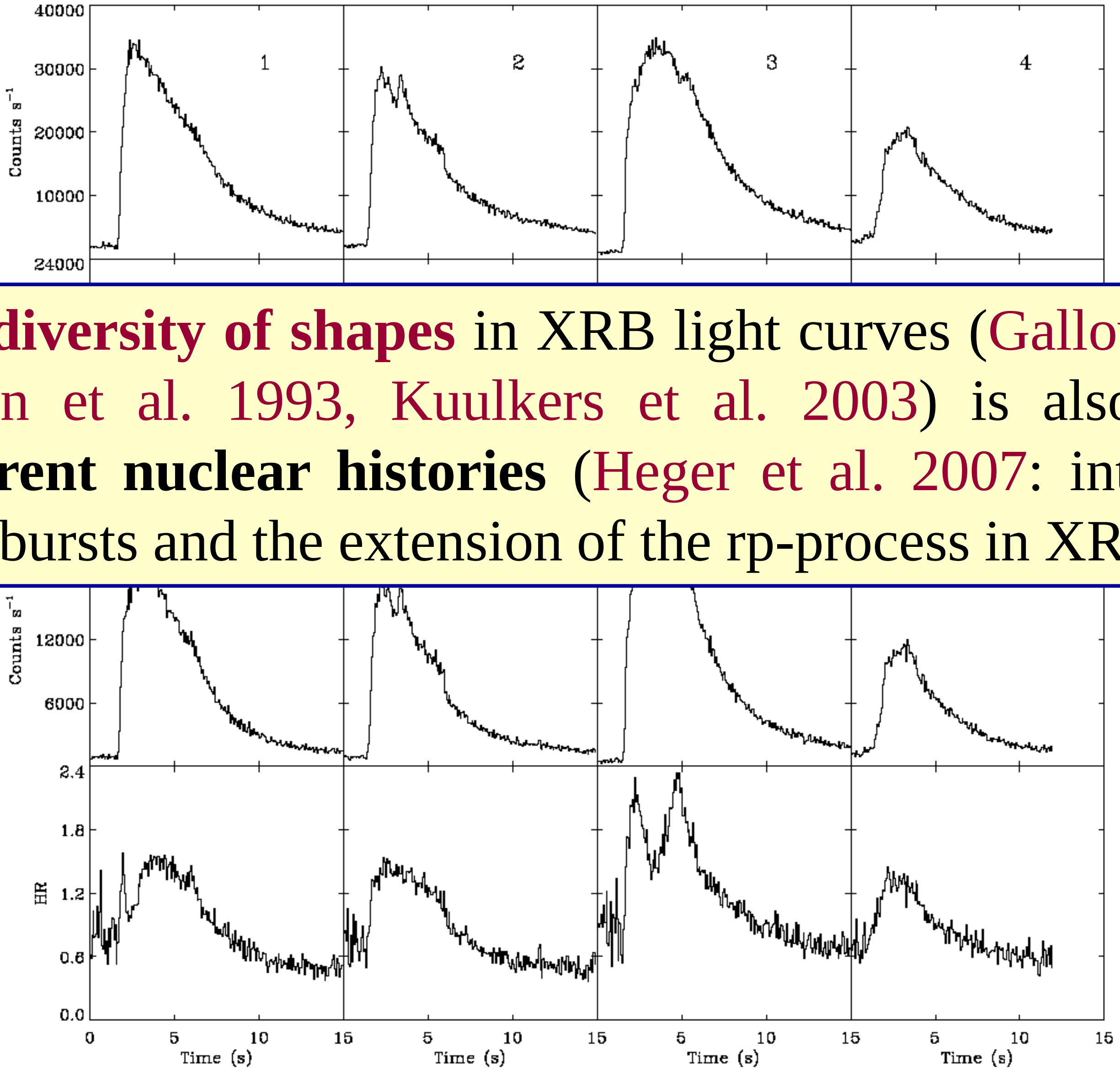
* Up to **Ni** (Woosley & Weaver 1984; Taam et al. 1993; Taam, Woosley, & Lamb 1996 –all using a **19-isotope network**)
* **Kr** (Hanawa, Sugimoto, & Hashimoto 1983 –**274 isotope-network**; Koike et al. 1999 –**463 nuclides**)
* **Cd** (Wallace & Woosley 1984 –**16-isotope network**)
* **Y** (Wallace & Woosley 1981 –**250-isotope network**)

Schatz et al. (1999, 2001) carried out very detailed nucleosynthesis calculations with a network **>600 isotopes** (up to **Xe**), but using a one-zone approach [see Koike et al. (2004) for other one-zone nucleosynthesis calculations, with T-ρ profiles from 1-D calculations, and a **1270-isotope network** up to **Bi**]



Elomaa et al. (2009) PRL

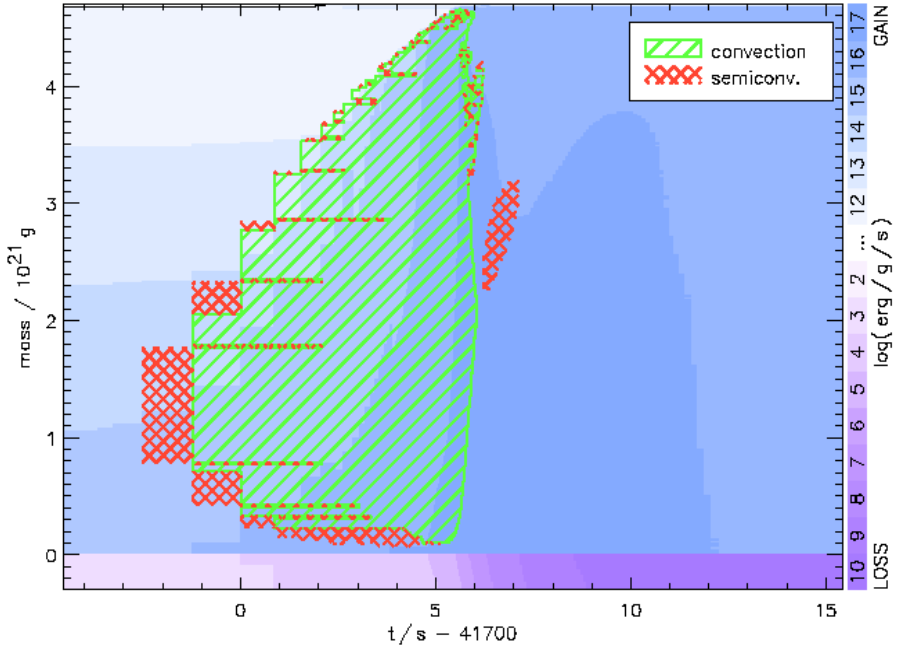
Schatz et al. (2001)

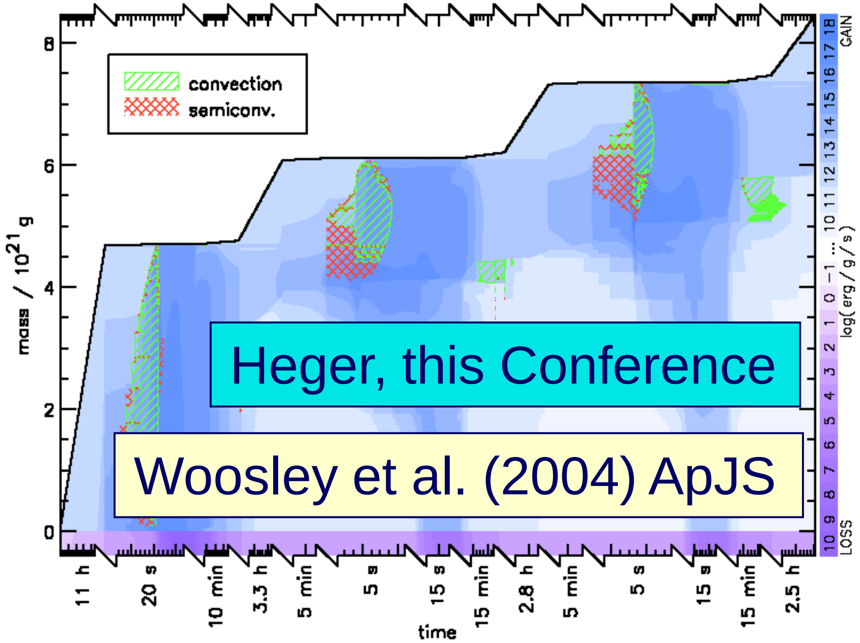


The **diversity of shapes** in XRB light curves (Galloway et al. 2007, Lewin et al. 1993, Kuulkers et al. 2003) is also likely due to **different nuclear histories** (Heger et al. 2007: interplay between long bursts and the extension of the rp-process in XRBs)

Strohmeyer & Bildsten (2002)
4U 1728 –34, RXTE

Recent attempts to couple **1-D hydrodynamic calculations** and **detailed nuclear networks** include Fisker et al. (2004, 2006, 2007, 2008) and Tan et al. (2007) (using networks of **~300 isotopes**, up to **^{107}Te**), JJ et al. (2006, 2010) (using a network of **2640 nuclear reactions**, and **478 isotopes**, up to **Te**) and Woosley et al. (2004), Heger et al. (2007) (using up to **1300 isotopes** with an adaptive network)



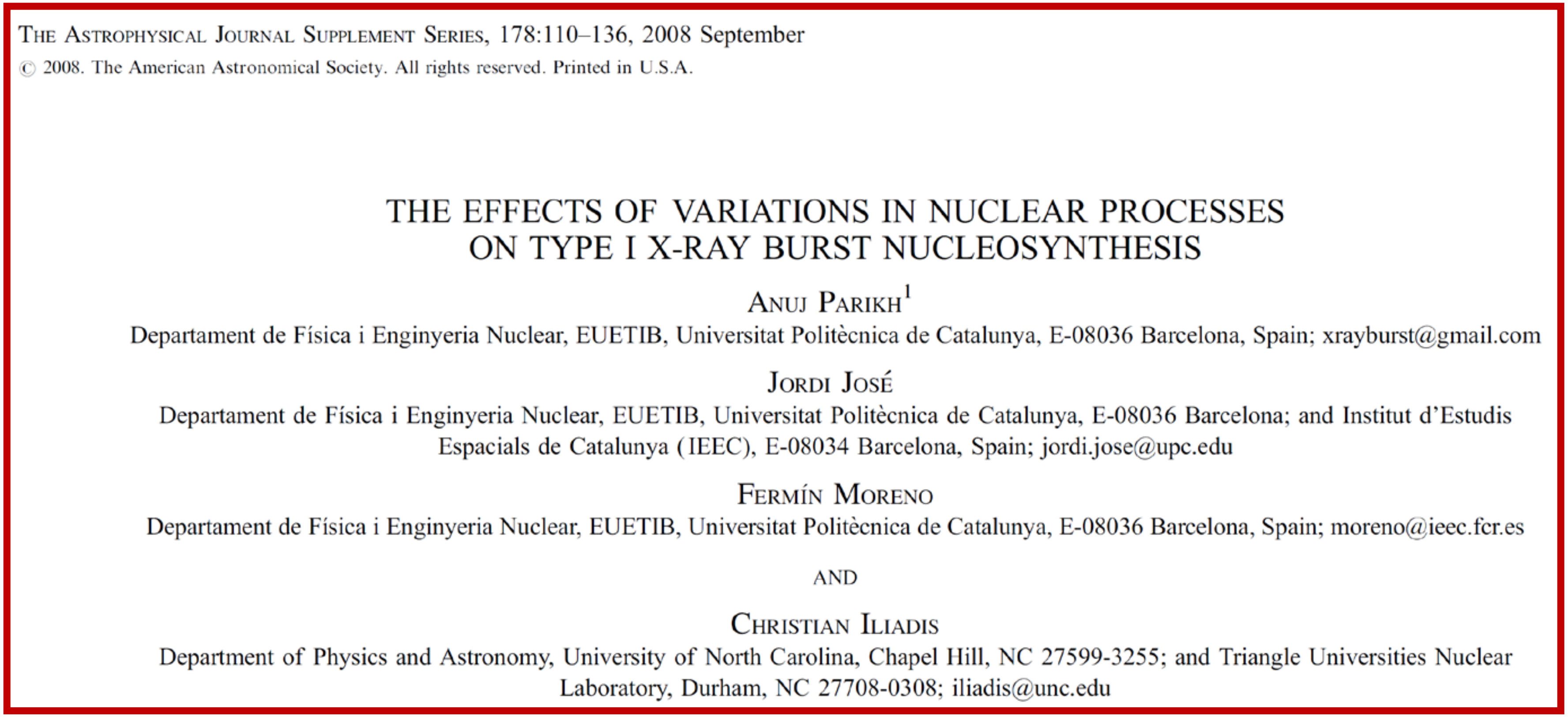


Heger, this Conference

Woosley et al. (2004) ApJS

Nuclear Uncertainties

Cyburt, this Conference



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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

IV. Multidimensional Models

No self–consistent multidimensional full simulation of an XRB, for realistic conditions, has been performed, neither in 2–D nor in 3–D.

Efforts have focused:

- analysis of **flame propagation** on the envelopes accreted onto neutron stars
- **convection–in–a–box** studies aimed at characterizing convective transport during the stages prior to ignition

Pioneering studies of thermonuclear flame propagation on neutron stars, in the framework of XRBs, were performed by Shara (1982) → while localized runaways on WD yield volcanic–like eruptions rather than deflagrative spreads, a localized ignition on a NS would likely propagate as a deflagration front, incinerating the whole envelope in a timescale of ~ 100 s.

Fryxell and Woosley (1982a): two different propagation regimes are actually possible.

- ignition deep inside the envelope, at $\boldsymbol{\rho \sim 10^8}$ **g cm**$^{\boldsymbol{-3}}$: a detonation front propagating at v ~ 9000 km s^{-1} will likely occur.
- if the density is $\boldsymbol{\rho < 10^7}$ **g cm**$^{\boldsymbol{-3}}$ a subsonic front (i.e., a deflagration) will ensue (v ~ 5 km s^{-1}) → the front would horizontally spread, with a characteristic timescale for a halfway propagation across the envelope of about 8 s.

* Fryxell & Woosley (1980b): pioneering 2–D hydro simulations of the propagation of a detonation front in a thick envelope on top of a neutron star, during ~ 50 ms. **Unrealistic** XRB conditions (GRBs)

* Zingale et al. (2001): 2–D simulation of the propagation of a Chapman–Jouguet detonation (v ~ 10^9 cm s^{-1}). Again, **unrealistic** XRB conditions.

The dicotomy between detonations and deflagrations was subsequently explored, for different ignition densities, in 2–D by Simonenko et al. (2012a, b).

Inclusion of rotational effects in flame propagation has been considered by Cavecchi et al. (2013, 2015), through the analysis of the role of a constant and a latitude–dependent Coriolis force in meridional flame propagation → flame propagation strongly depends on the angular velocity and heat conductivity of the fluid.

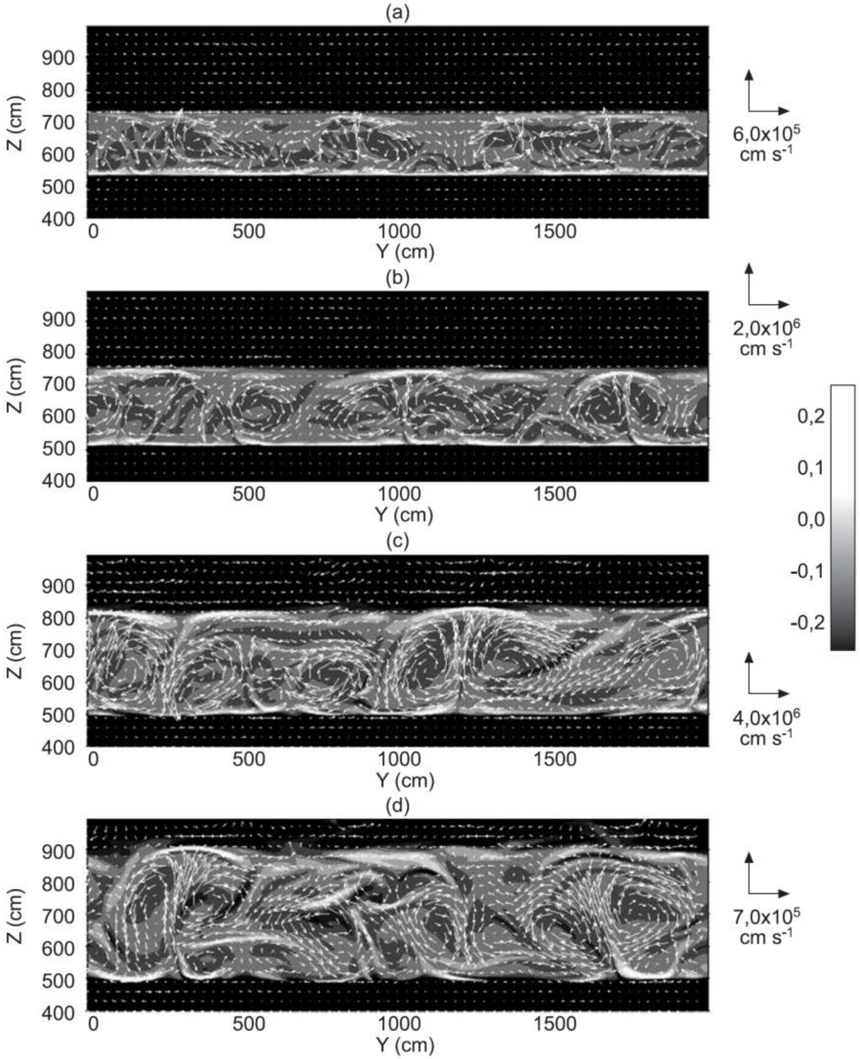
Spitkovsky, Cavecchi, Chakraborty, this Conference

The early development of the **convective stages preceding thermonuclear ignition** in XRBs:

- can a fully–turbulent convection actually modify the expected nucleosynthesis?
- can convection dredge-up ashes enriched in heavy elements to the neutron star photosphere? (Bhattacharyya et al. 2010, in’t Zand & Weinberg 2010)

Pioneering efforts in 2–D by Lin et al. (2006).

2– and 3–D turbulent convection studies by Malone et al. (2011, 2014) and Zingale et al. (2015): similar peak temperatures and Mach numbers, but different convective velocity patterns, with evidence of the **energy cascade** that characterizes 3–D convection.



Lin, Bayliss & Taam (2006)

Thermonuclear Burning Theory

40 Years of X-Ray Bursts: Extreme Explosions in Dense Environments

Madrid (Spain), June 17 – 19, 2015