Recent Advances in the Modeling of Type I X-Ray Bursts and Nova Outbursts

Jordi José

Dept. Physics, Technical University of Catalonia (UPC)
& Institute of Space Studies of Catalonia (IEEC), Barcelona

Classical Novae and X-Ray Bursts in a Nutshell

Classical Novae

Moderate rise times (<1 – 2 days)
$L_{Peak} \sim 10^4 - 10^5\ L_\odot$
$E_{output} \sim 10^{45}$ ergs

Mass ejected: $10^{-7} - 10^{-4}\ M_\odot$
($\sim 10^3$ km s^{-1})
Recurrence: $\sim 10^4 - 10^5$ yr
Frequency: $\sim 50\ yr^{-1}$
[Obs. $\sim 10\ yr^{-1}$]

X-Ray Bursts (Type I)

Fast rise times (<1 – 10 s)
$L_{Peak} \sim 10^4 - 10^5\ L_\odot$
$E_{output} \sim 10^{39-40}$ ergs [in 10- 100 s]

Mass ejected?

Recurrence: ~ hrs – days
Sources detected: ~ 100

Novae are XRBs in slow motion…
…XRBs are novae in fast forward

T. Kormpakis' talk

Novae vs. X-Ray Bursts

WD + MS (often, K-M dwarfs)

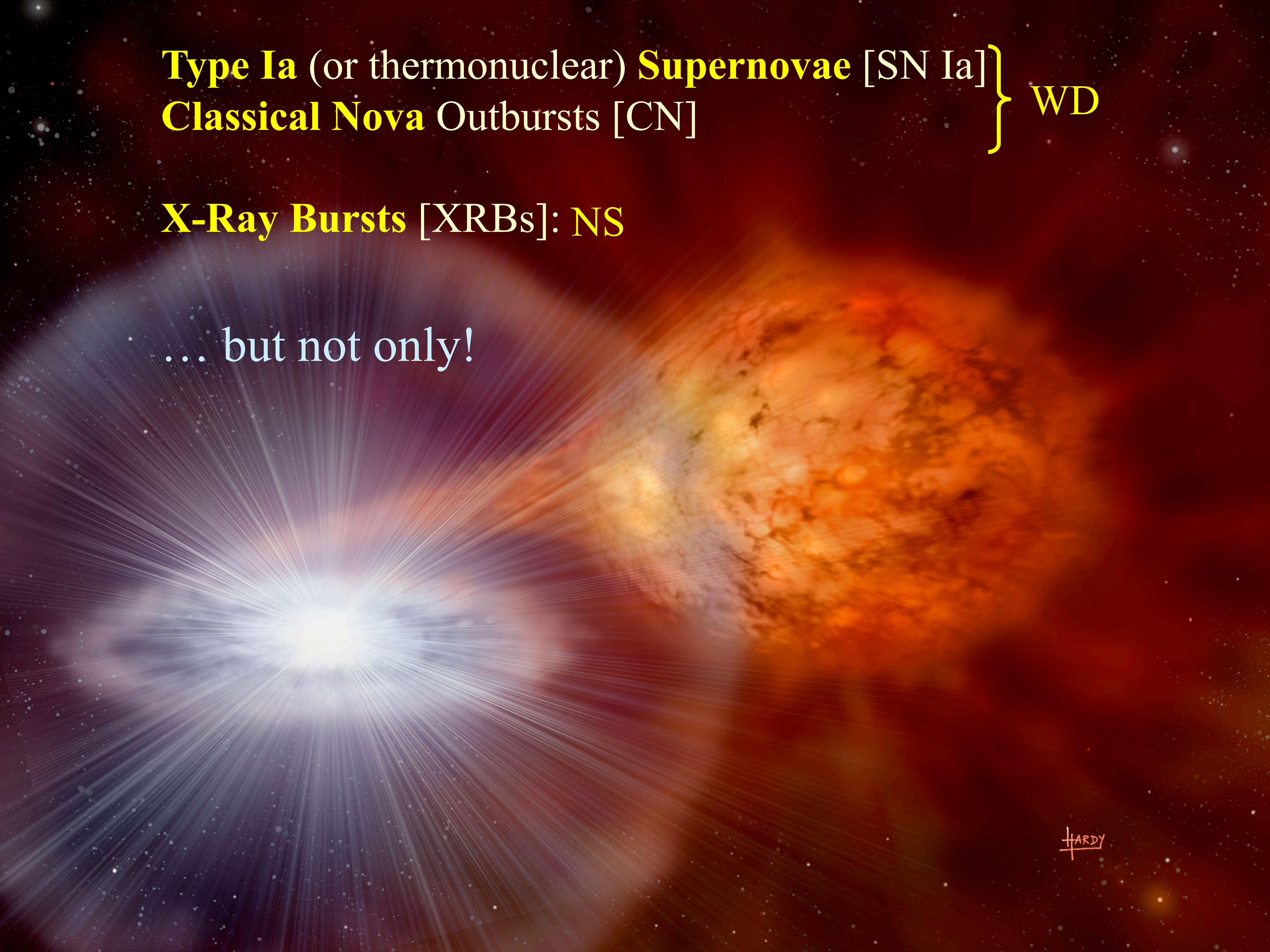
NS + MS

but sometimes more evolved companions (e.g., RG)

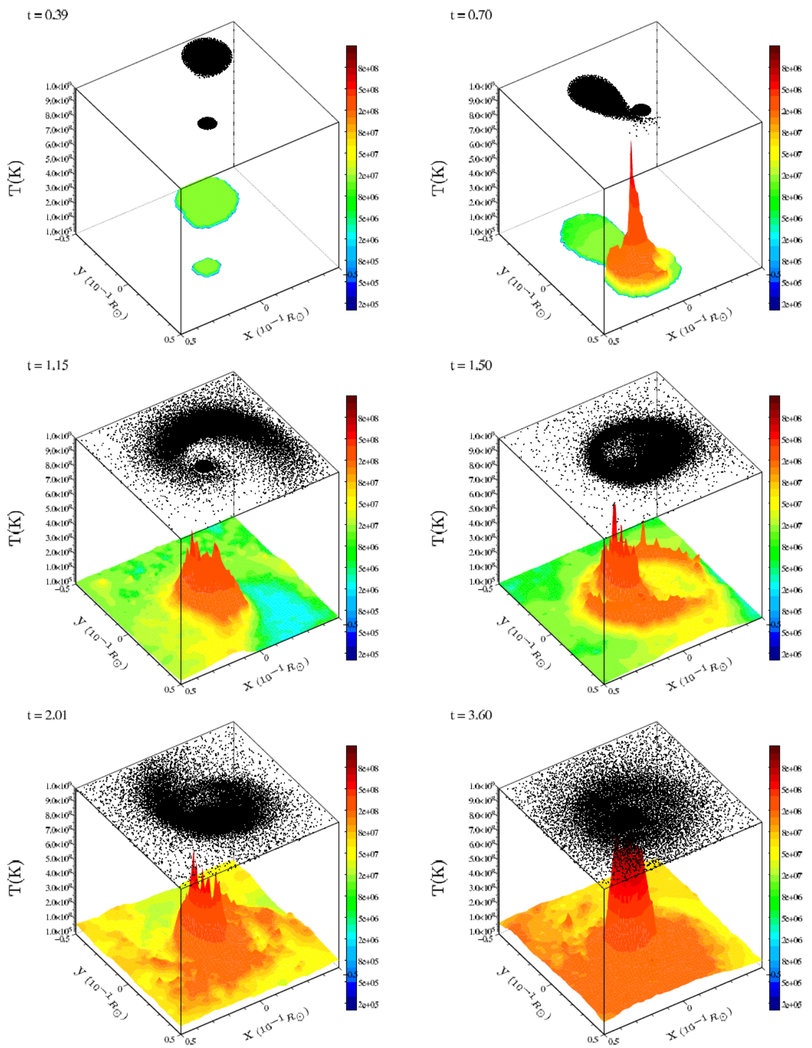
Type Ia (or thermonuclear) **Supernovae** [SN Ia]
Classical Nova Outbursts [CN]
} WD

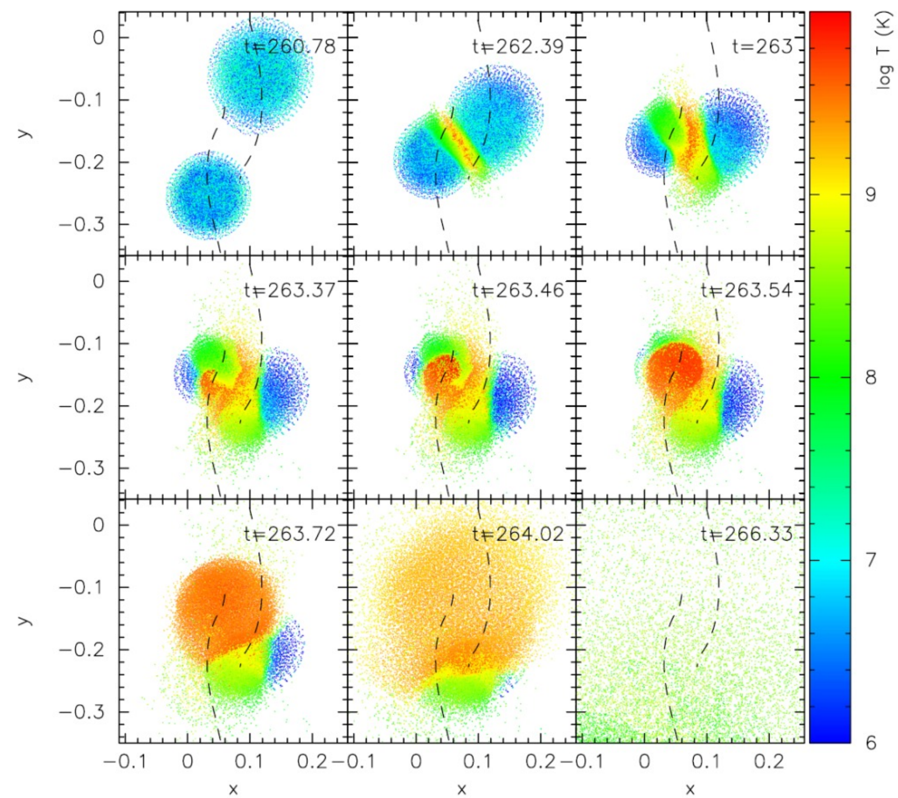
X-Ray Bursts [XRBs]: NS

… but not only!



Stellar Mergers and Collisions

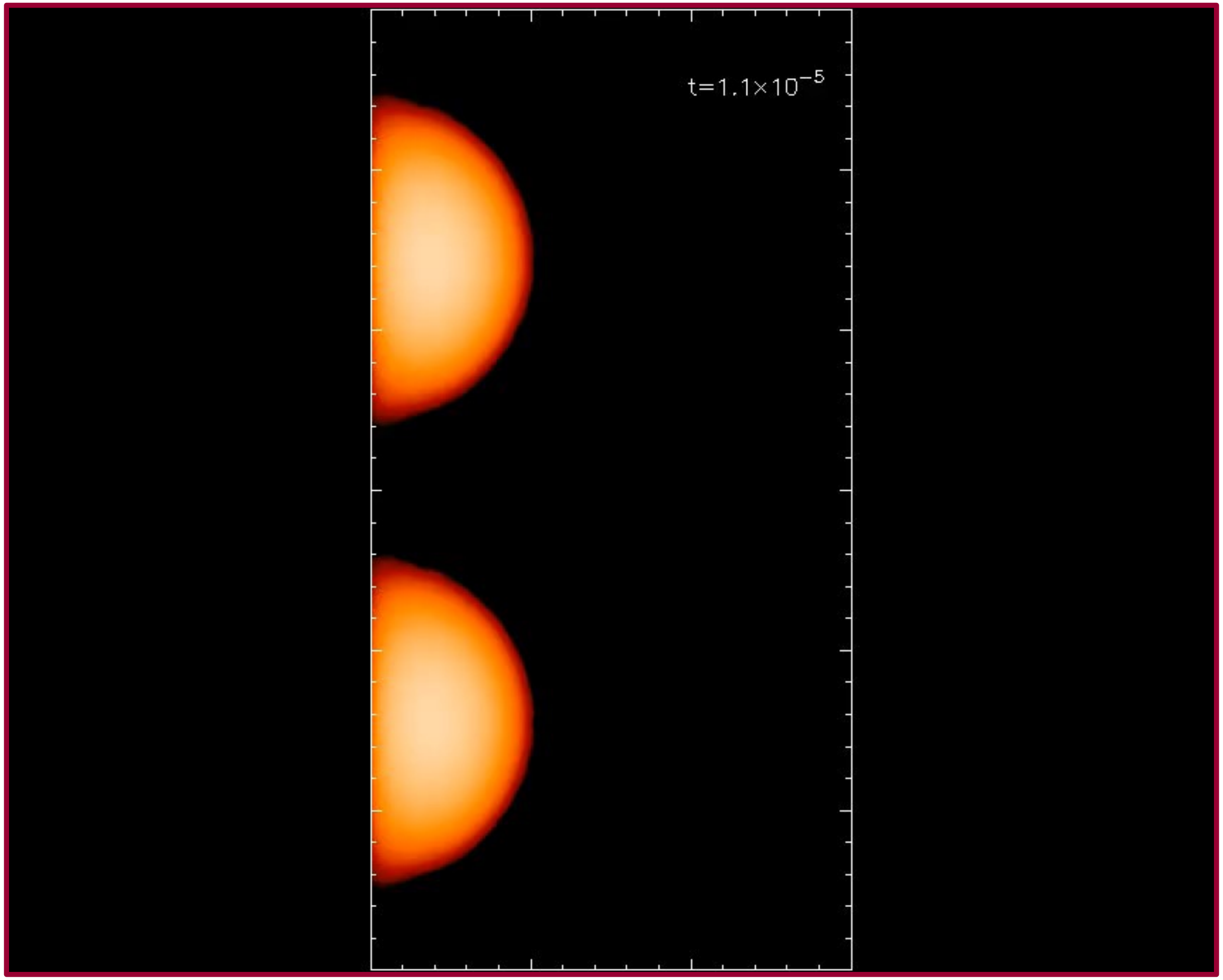




Detonations in WD dynamic interactions
Aznar-Siguán, García-Berro, Lorén-Aguilar, JJ & Isern, MNRAS (2013)

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

frequency ~ f(type Ia SNe)



Head-on collision of two neutron stars
(R. Cabezón, D. García-Senz et al., UPC Barcelona)

3D Hydrodynamic Simulations of White Dwarf-Main-Sequence Star Collisions

I. Head-on Collisions

C. J. T. van der Merwe[1,2], S. S. Mohamed[1,2,3,4], J. Jose[5,6], M. M. Shara[8], and T. Kaminski[7]

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[2] South African Astronomical Observatory, P.O Box 9, Observatory, 7935, Cape Town, South Africa.
[3] Department of Astronomy, University of Virginia, Charlottesville, VA 22904, USA.
[4] NITheCS National Institute for Theoretical and Computational Sciences, South Africa.
[5] Departament de Física, EEBE, Universitat Politècnica de Catalunya, c/Eduard Maristany 16, 08019 Barcelona, Spain.
[6] Institut d'Estudis Espacials de Catalunya,c/Esteve Terradas 1, 08860 Castelldefels, Spain
[7] Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, Rabiańska 8, 87-100 Toruń, Poland.
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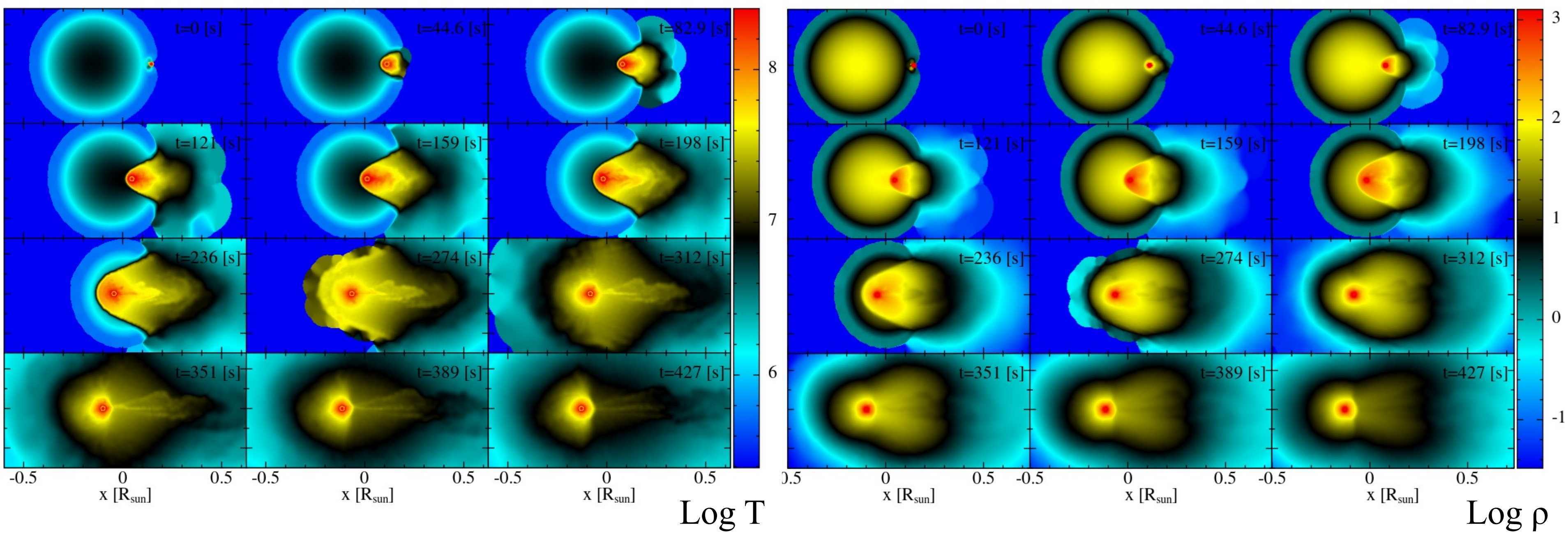
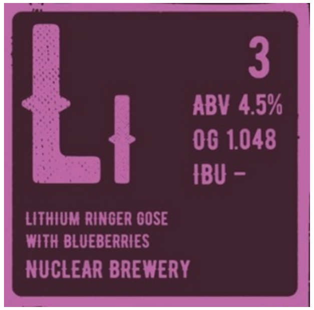
A&A, submitted

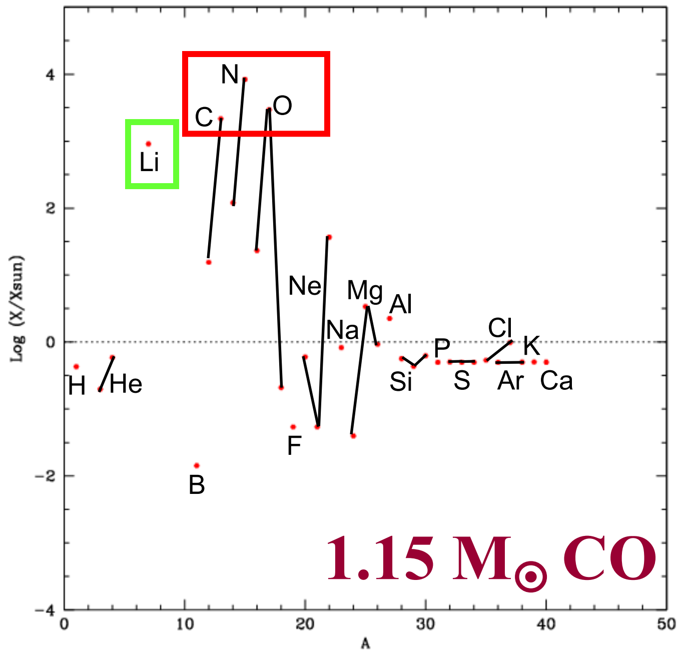



Li
3
ABV 4.5%
OG 1.048
IBU –
LITHIUM RINGER GOSE
WITH BLUEBERRIES
NUCLEAR BREWERY


30-04-19
Lithium
Lithium


12 FL OZ.
4% ALC./VOL.
NOVA
BEACH LAGER
SAN DIEGO, CA
100 CAL
MADE WITH COCONUT WATER


A Flippin Good Beer
TOPSY TURVY
Lake Geneva
Wisconsin
HAZY IPA
STELLAR
NOVA
Bottoms Up!


1.15 M⊙ CO
Log (X/Xsun)
A
H
He
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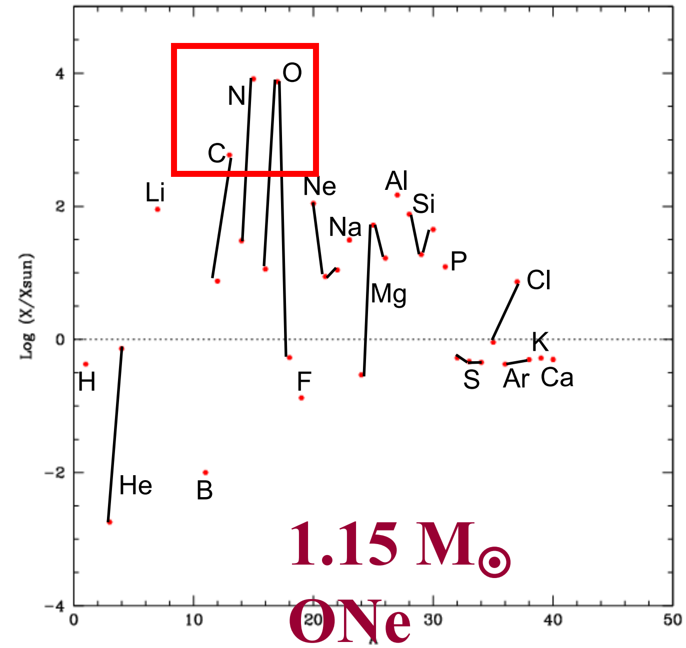
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca


1.15 M⊙
ONe
Log (X/Xsun)
H
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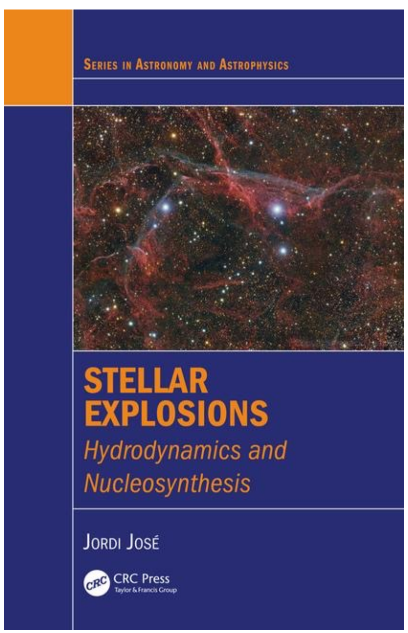
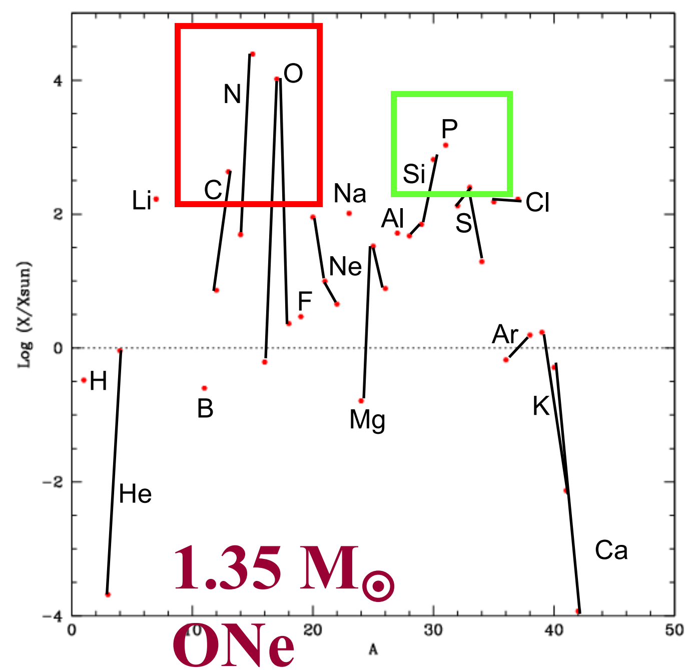

Series in Astronomy and Astrophysics
STELLAR EXPLOSIONS
Hydrodynamics and Nucleosynthesis
Jordi José
CRC Press
Taylor & Francis Group

JJ (2016)


1.35 M⊙
ONe
Log (X/Xsun)
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Si
P
S
Cl
Ar
K
Ca

1D have been successful in reproducing the *gross* observational features that characterize classical novae (e.g., light curves, nucleosynthesis...), but the assumption of spherical symmetry excludes an entire sequence of events → **Multidimensional models**

* The long-term evolution of a nova involves the **interaction** between the ejecta, the disk, and the stellar companion

J. Figueira (PhD thesis 2023)

A&A 613, A8 (2018)
https://doi.org/10.1051/0004-6361/201731545

Astronomy & Astrophysics

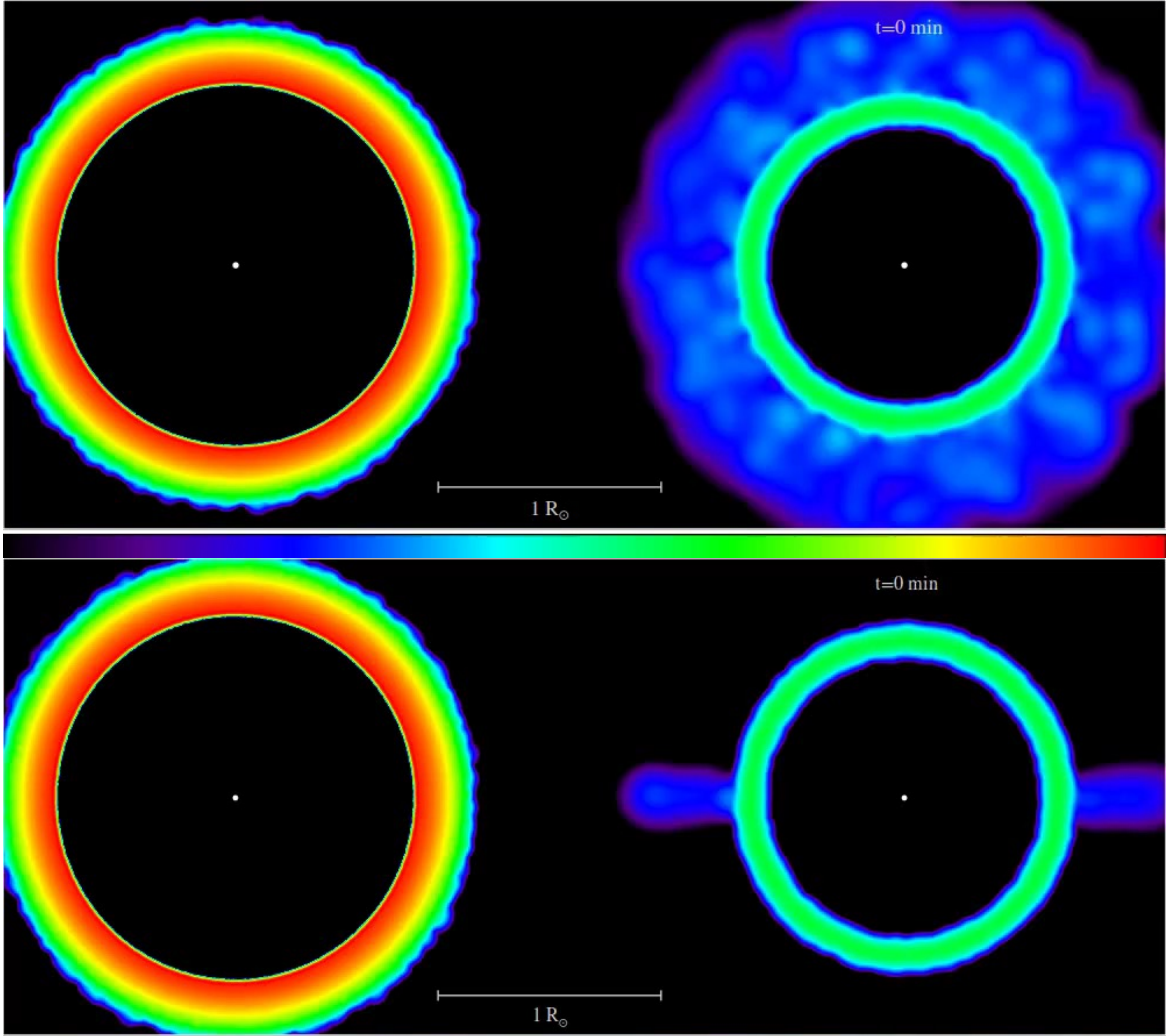
Three-dimensional simulations of the interaction between the nova ejecta, accretion disk, and companion star★

Joana Figueira[1,2], Jordi José[1,2], Enrique García-Berro[2,3], Simon W. Campbell[4,5,6], Domingo García-Senz[1,2], and Shazrene Mohamed[7,8,9]

XY
Plane

$P_{orb} \sim 9$ hr

YZ
Plane



The Recurrent Nova ID Card

- long period binaries: very homogeneous class (WD + RG)
  ex: **RS Oph**
- short period binaries: heterogeneous class (WD + MS)
  → Subclasses: **U Sco, CI Aql, T Pyx** [Anupama 2007]

Recurrence time: 1 – 100 yr

NOT all the accreted material is ejected → **SN Ia progenitors**

Recurrence time: 1 – 100 yr →

$M_{acc} \sim 10^{-7} - 10^{-8}\ M_{\odot}\ yr^{-1}$

M_{WD} close to Chandrasekhar limit

High initial L_{WD}

Hydrodynamic Simulations of the Recurrent Nova T Coronae Borealis (T CrB)

Jordi José[1,2] and Margarita Hernanz[2,3]

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[3] Institut de Ciències de l'Espai (ICE-CSIC), Campus UAB, Camí de Can Magrans s/n, E-08193 Bellaterra, Spain
e-mail: jordi.jose@upc.edu

May 8, 2024

A&A, in prep.


ICL
Soluble fertilizer
for fertigation
Nova
Calcium
15.5-0-0(+26.5CaO)
15.5-0-0(+19 Ca)
Calcium Nitrate
Net Weight 25 kg

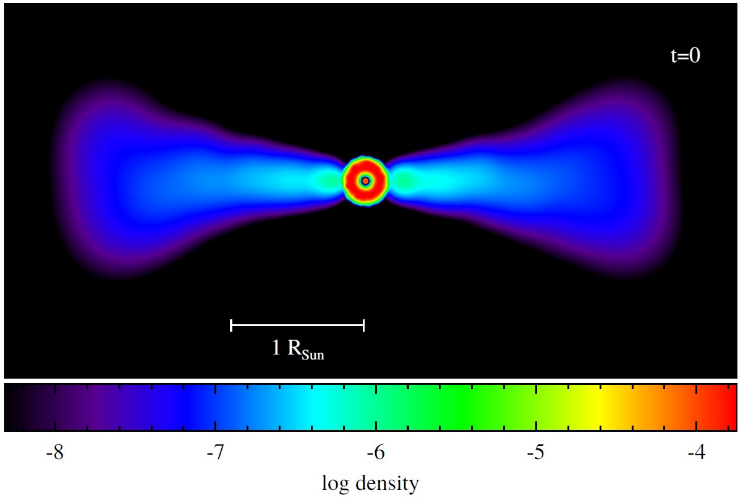
Interaction Between the Ejecta, the Accretion Disk, and the Secondary Star in the Recurrent Nova System U Sco

Joana Figueira[1,2], Jordi José[1,2], Rubén Cabezón[3], and Domingo García-Senz[1,2]

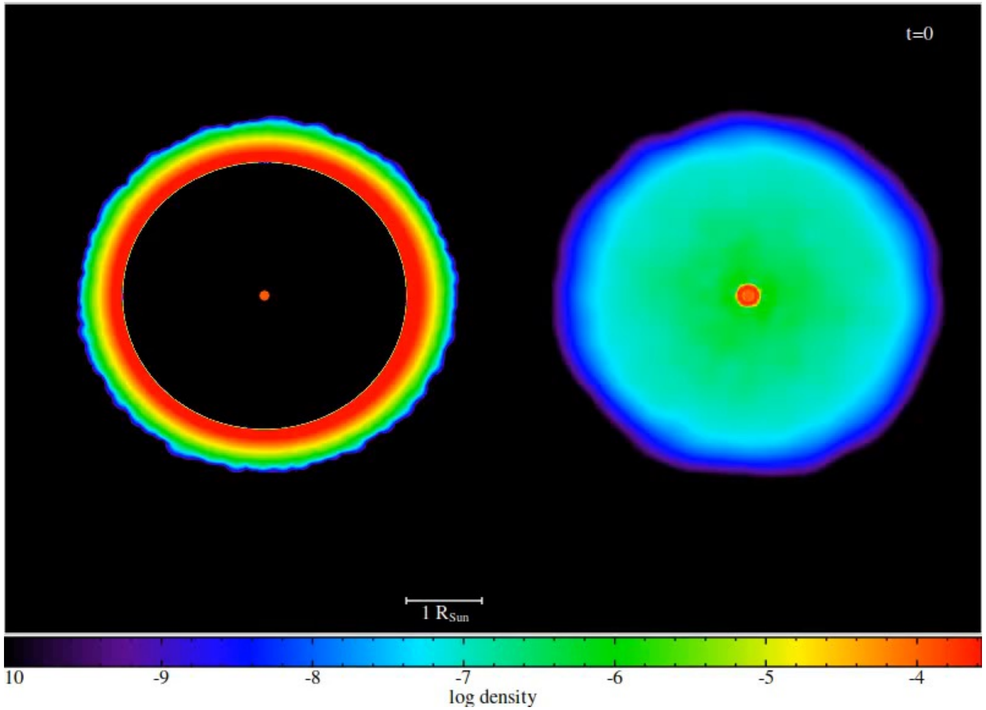
A&A, submitted

12000 ± 2000 pc from Earth

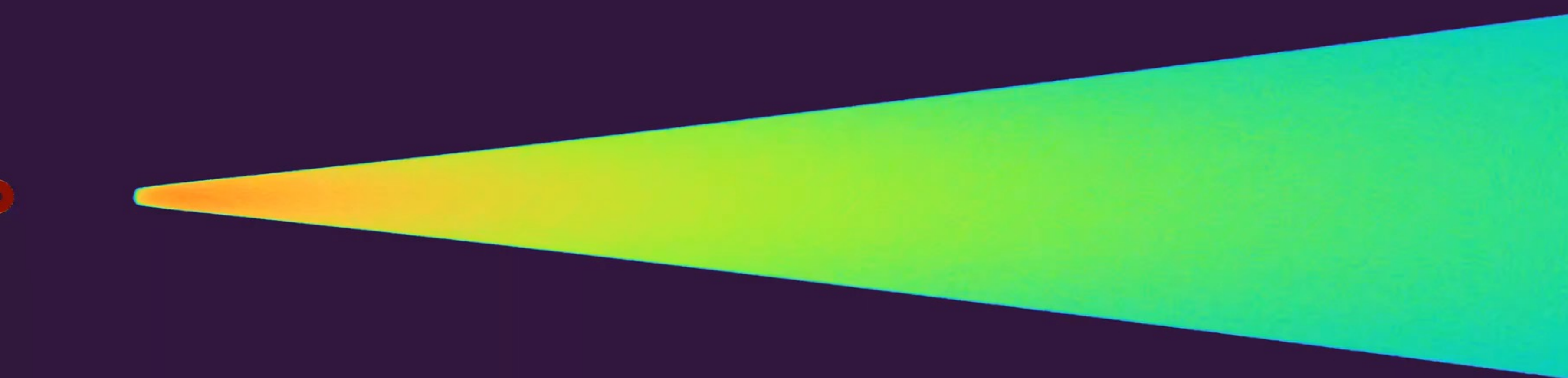
Seen in outburst in 1863, 1906, 1936, 1945?, 1969?, 1979, 1987, 1999, 2010… and **June 6, 2022**



9.77×10^6 SPH particles
(disk ~ 2000 p.; ejecta ~3900 p.)



A. Sanz (PhD thesis)

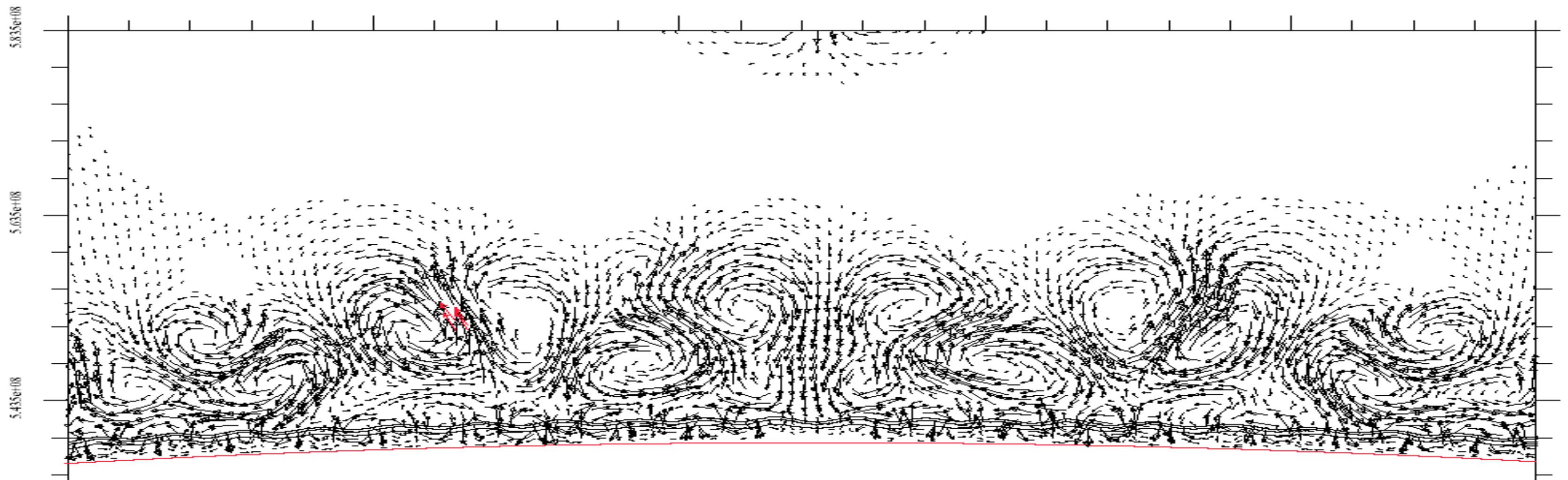


Day 1 00:00

Sanz, García-Senz & JJ (2024, in preparation)

10^6 SPH particles (2D axisym.) → **10^9 particles (3D)**

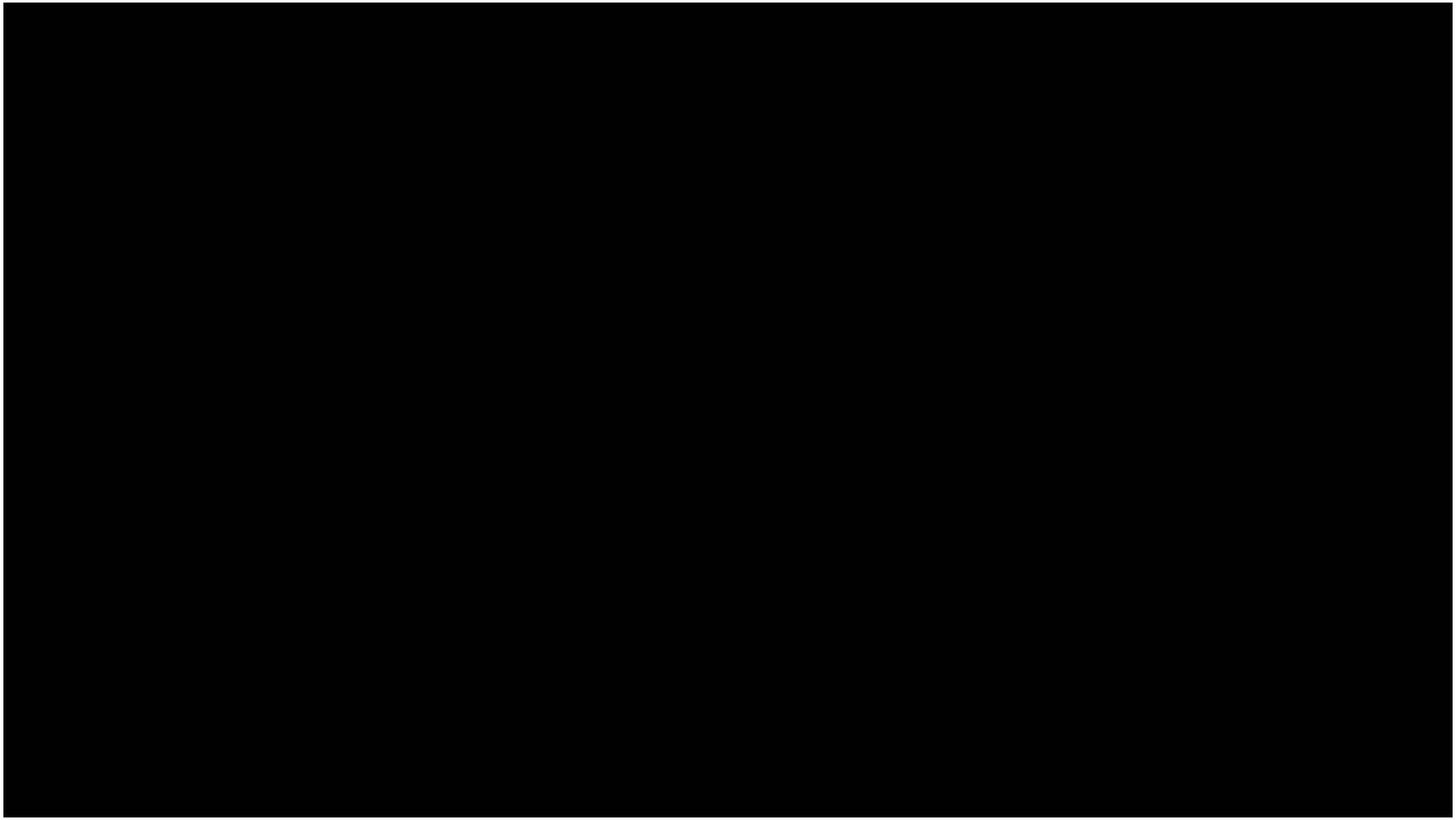
* Ignition and Front Propagation



Glasner & Livne 1995; Glasner, Livne, & Truran 1997, 2005, 2007, 2012

The build-up of **convective eddies** at the envelope's base (2-D) 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

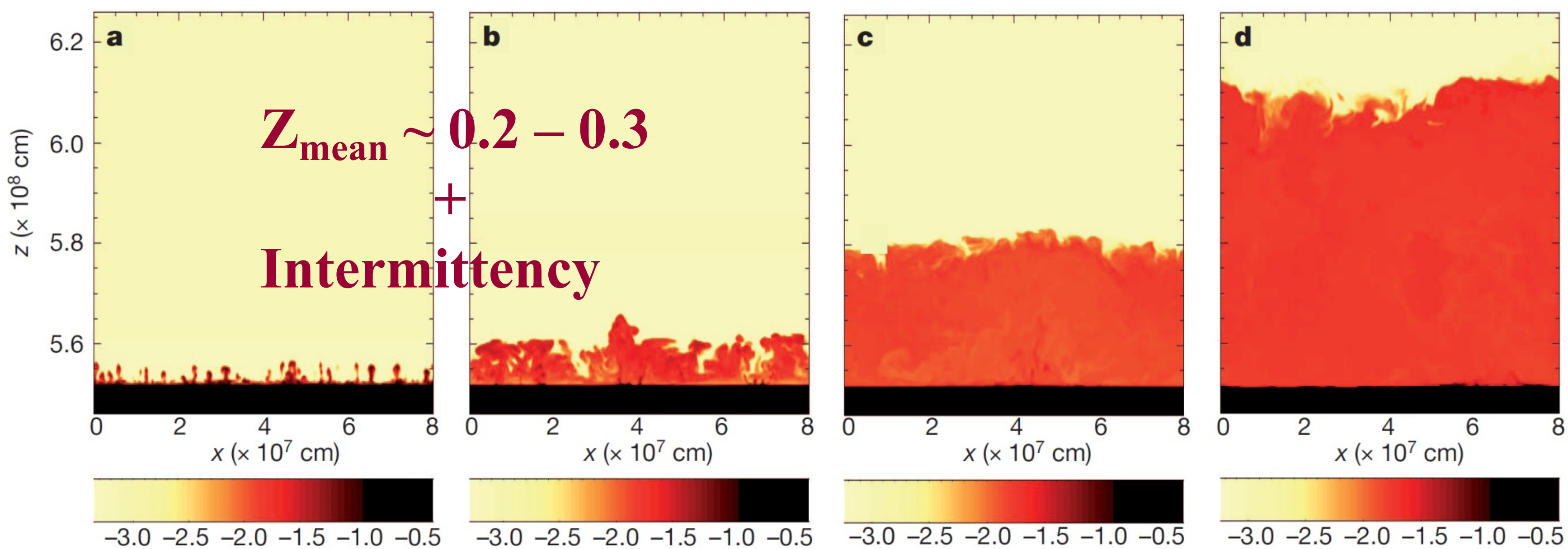
Casanova, JJ, García-Berro, Shore & Calder (2011), Nature

3D Models of Mixing

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]




MareNostrum II (BSC, 2006) 94 Tflops, 10 240 cores
MareNostrum III (BSC, 2013) 1 Pflops, 48 000 cores
MareNostrum IV (BSC, 2017) 14 Pflops, 165 888 cores
MareNostrum V (BSC, 2023) 314 Pflops, 680 960 cores
[Pre-exascale HPC; 8th in the TOP500 Supercomputers]

12321 Models

A&A 634, A5 (2020)
https://doi.org/10.1051/0004-6361/201936893

Astronomy & Astrophysics

123–321 models of classical novae

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e-mail: jordi.jose@upc.edu
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Received 11 October 2019 / Accepted 17 December 2019

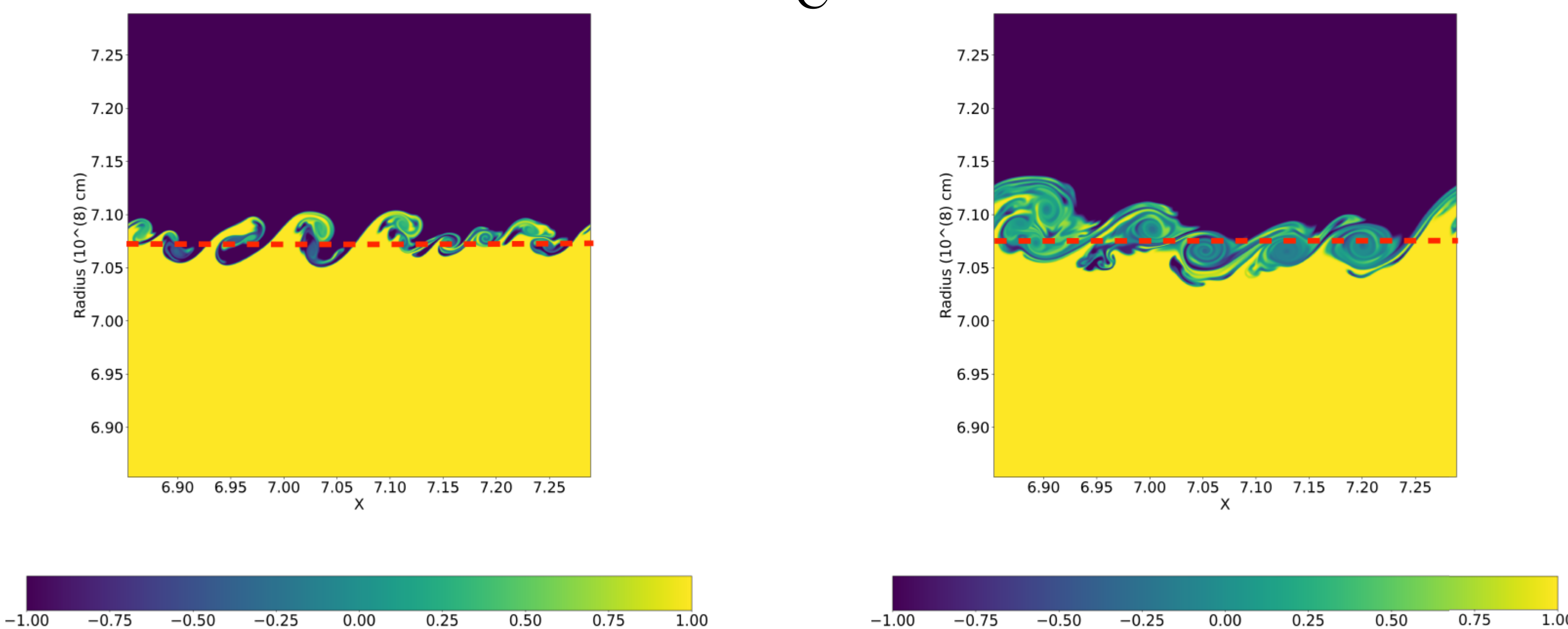
When mixing is treated "the best we can",
the **WD mass decreases**

Hydrodynamical shear mixing in subsonic boundary layers and its role in the thermonuclear explosion of classical novae

Marco Bellomo[1,2], Steven N. Shore[2,3], and Jordi José[4]

A&A, submitted

^{12}C



S. Scaringi's talk

Micronovae [e.g., TV Columbae, EI Ursae Majoris, ASASSN-19bh]

→ Accretion flow **funneled by the magnetic field** of the white dwarf (localized TNR)

Article
Nature | Vol 604 | 21 April 2022 | 447

Localized thermonuclear bursts from accreting magnetic white dwarfs

https://doi.org/10.1038/s41586-022-04495-6
Received: 4 October 2021
Accepted: 1 February 2022
Published online: 20 April 2022

S. Scaringi[1✉], P. J. Groot[2,3,4], C. Knigge[5], A. J. Bird[5], E. Breedt[6], D. A. H. Buckley[3,4,7], Y. Cavecchi[8], N. D. Degenaar[9], D. de Martino[10], C. Done[1], M. Fratta[1], K. Iłkiewicz[1], E. Koerding[2], J.-P. Lasota[11,12], C. Littlefield[13,14], C. F. Manara[15], M. O'Brien[1], P. Szkody[14] & F. X. Timmes[16,17]

Nova explosions are caused by global thermonuclear runaways triggered in the


PICO
NOVA
ALCOHOL FREE
Brussels Beer Project
Alc. 0.3%vol. – Zero West Coast IPA – 33cl


Soulcraft
BREWING
Salida.CO
X-RAY
IPA
12 FL. OZ.
7% ALC. BY VOL.
REAL CHICKEN 1st INGREDIENT
LOVE them like family. TREAT them like family.™
BLUE
Bursts
Crunchy!
Creamy
With Paw-Lickin' CHICKEN
Treats for Cats
Net Wt. 5 oz. (141 g)

Mass Ejection

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 $GMm_p/R \sim 200$ MeV/nucleon, whereas only a few MeV/nucleon are released from thermonuclear fusion)

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

The Astrophysical Journal Supplement Series, 189:204–239, 2010 July doi:10.1088/0067-0049/189/1/204

HYDRODYNAMIC MODELS OF TYPE I X-RAY BURSTS: METALLICITY EFFECTS

Jordi José[1,2], Fermín Moreno[1], Anuj Parikh[3], and Christian Iliadis[4,5]
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[2] Institut d'Estudis Espacials de Catalunya (IEEC), Ed. Nexus-201, C/ Gran Capità 2-4, E-08034 Barcelona, Spain
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https://doi.org/10.1051/0004-6361/202346190

Astronomy & Astrophysics

Mass-loss and composition of wind ejecta in type I X-ray bursts

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e-mail: herrera@ice.csic.es

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Y. Herrera's talk

XRB Model with 1.4 M_{sun}, 13.1 km NS; $Z_{acc} = 0.02$, and $M_{acc} = 1.75\times10^{-9}$ M_{sun} yr^{-1}) → $\mathbf{M_{ejec} = 3.1\times10^{-14}\ M_{sun}}$!

0.1% of the envelope is ejected per burst (^{60}Ni, ^{64}Zn, [^{68}Ge], & ^{58}Ni)

Type I XRB Models with Rotation

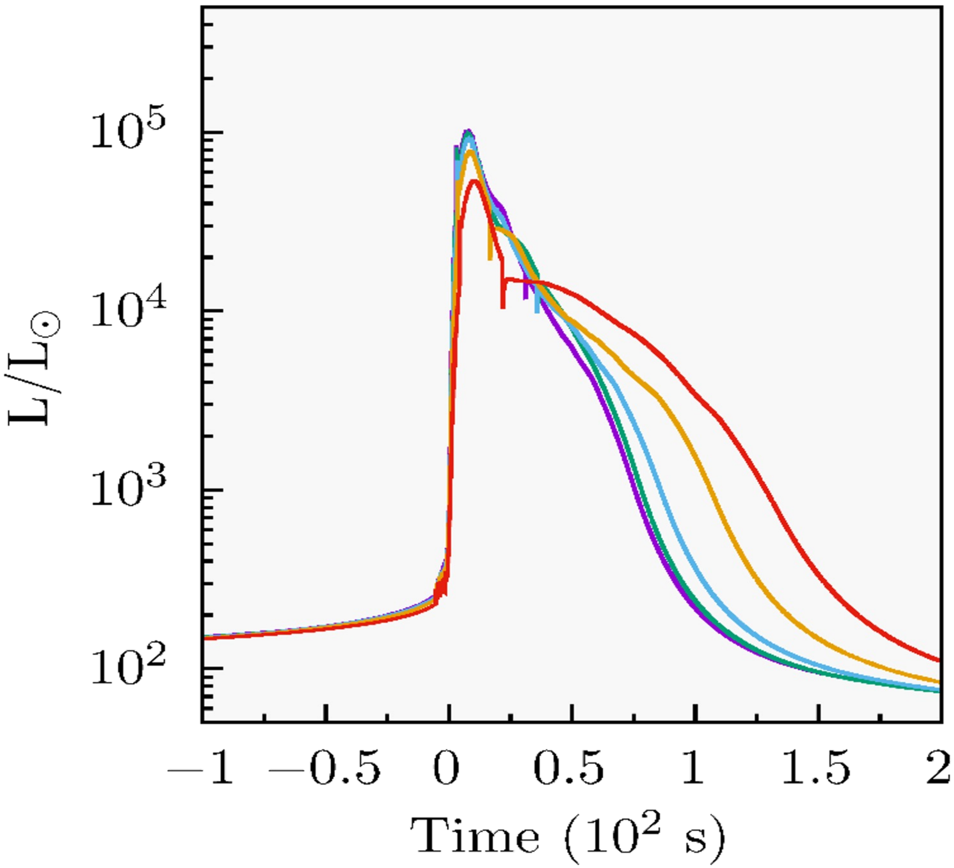
First models with rotation!

Study of the effect of (**shellular**) **rotation** on type I X-ray burst properties

D. Martin
(PhD Thesis 2023)

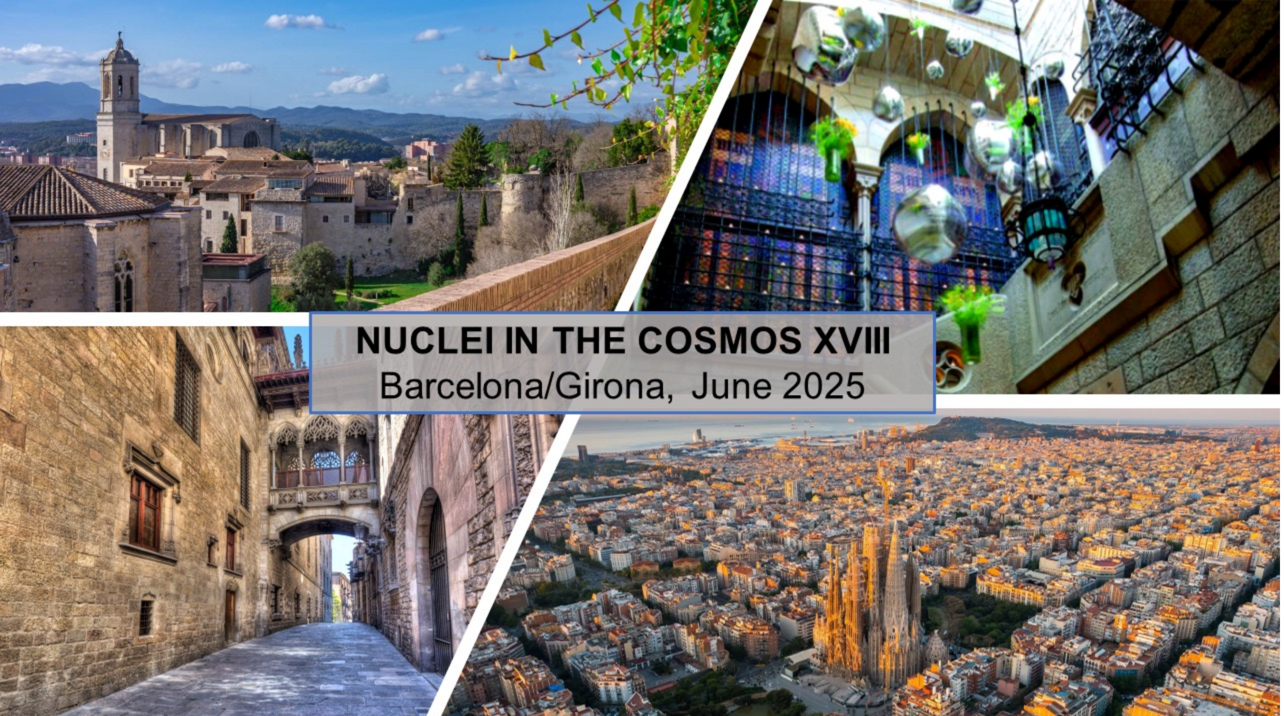
- **Pressure-lifting effect** caused by rotation: maximum density and pressure at the base of the envelope decrease as the angular velocity of the envelope increases
- The **size** of the **envelope shows a significant growth** with the increase of the angular velocity (up to 66% for the fastest rotation model considered)
- Bursts with **higher angular velocities have smaller recurrence times**

Brightest bursts are those with smallest angular velocity Ω_0 (bursts with high rotation rates have long decays [increase up to 45%] and broad light curves)



$$P_{crit} = \frac{G\ M_{NS}}{4\pi\ R_{NS}^4}\ \Delta M_{acc}$$

Martin & JJ, in prep.



Local Organizing Committee (LOC)

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Yuri Cavecchi (UPC)
Margarita Hernanz (ICE-CSIC, IEEC)
Jordi Isern (RACAB, ICE-CSIC, IEEC)
Jordi José (UPC, IEEC), **Chair**
Jordi Llorca (UPC)
Kelsey Lund (NCSU, LANL)
Marina Martínez (UAB)
Arnau Rios (UB, ICC-UB)
Glòria Sala (UPC, IEEC)
Aldo Serenelli (ICE-CSIC, IEEC)
Laura Tolós (ICE-CSIC, IEEC), **Vice-Chair**
Josep M. Trigo-Rodríguez (ICE-CSIC, IEEC)

Anna Bertolín (IEEC)
Pilar Montes (IEEC)

Thank you for your attention!

Jordi José

Recent Advances in the Modeling of Type I X-Ray Bursts & Classical Novae

The X-Ray Mysteries of Neutron Stars and White Dwarfs, ESAC, June 5 – 7, 2024