16th Russbach School on Astrophysics 2019

The Single Degenerate scenario for Type Ia Supernova: the modeller point of view

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Plan of the talk

- Type Ia supernova (SNe Ia): generalities
- The current Zoo of SNe Ia models. SD versus DD scenarios.
- Releasing nuclear binding energy into $\simeq 10^{51}$ ergs of kinetic energy. Explosion models.
- Disentangling the Zoo of models. Example: The issue of single point-like ignitions, - the gravitational confined detonations (GCD)- and the - double-detonation (DDet)- explosion models.
- Final comments.

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Type Ia Supernova

Generalities

- $L_{peak}(t \simeq 20\ days) \simeq 10^{43}$ ergs, mostly in the visible band (T$\simeq$ 6000 K).
- From: $L = 4\pi R^2 \sigma T^4 \longrightarrow R \simeq 10^{15}$ cm
- Expansion velocity: $R/t \simeq 10^9$ cm/s
- The kinetic energy per unit $M_\odot$: $KE = 1/2(M/M_\odot)\, v^2 \simeq 5(M/M_\odot)10^{17}$ ergs

Byrne Observatory at Sedgwick Reserve and the Palomar Transient Factory | LCOGT ... | BJ FULTON

Figure: Type Ia Supernova 2011fe.

Type Ia Supernova:

Generalities

- For a CO-WD, M$\simeq$ 1 M$_\odot$ such KE is similar to their nuclear energy budget $^{12}C \rightarrow ^{56} Fe$
- $t_p \simeq \sqrt{\frac{\kappa M}{c v}} \simeq$ 60 days $\longrightarrow$ M$\simeq$ 1 M$_\odot$ ($\kappa \simeq$ 0.4 cm^2/g) **White Dwarf progenitor**.
- SNe Ia are present in all galaxy types

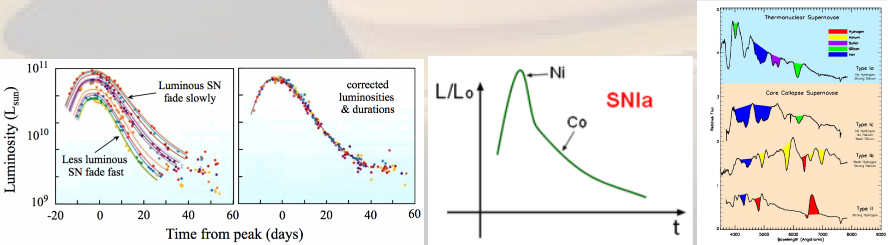
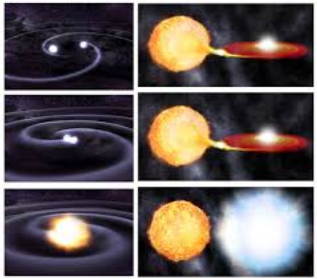


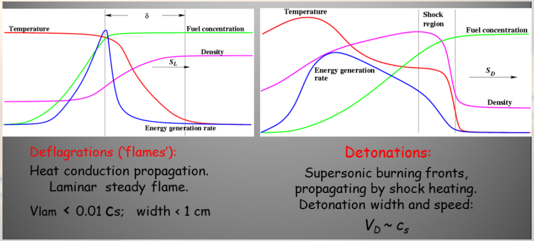
Figure: Type Ia Supernova standarizable light curves and spectra.

Type Ia Supernova:

Basic building bricks

- One/Two degenerate stars ? (SD, DD)





Deflagrations ('flames'):
Heat conduction propagation.
Laminar steady flame.
Vlam < 0.01 Cs; width < 1 cm

Detonations:
Supersonic burning fronts,
propagating by shock heating.
Detonation width and speed:
$V_D \sim c_s$

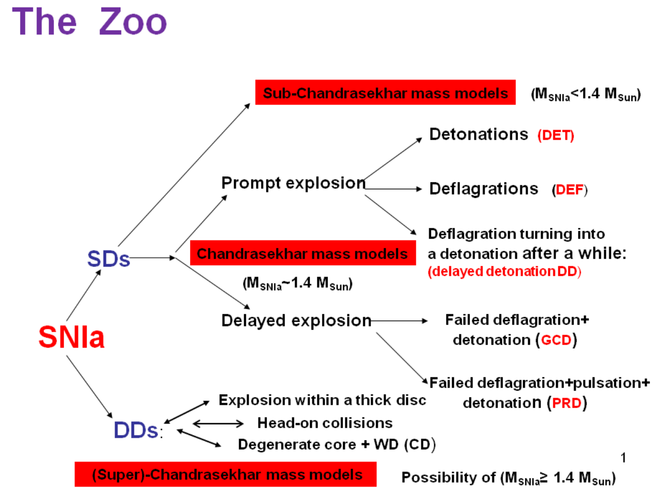
- Mass of the white dwarf/s ?
- WD chemical composition ? (C+O/He, or both)
- Explosion mechanism ? (deflagrations/detonations or both)

Type Ia Supernova:

+ … Lack of knowledge of the initial conditions

- How and when the explosion starts ? (in both SD and DD)
- Role played by the angular momentum (in DD and maybe in some SD).
- Detailed initial composition and model input physics/resolution issues.

Type Ia Supernova:



The Zoo

SNIa

SDs

DDs:

Sub-Chandrasekhar mass models (M_{SNIa}<1.4 M_{sun})

Prompt explosion

- Detonations (DET)
- Deflagrations (DEF)
- Deflagration turning into a detonation after a while: (delayed detonation DD)

Chandrasekhar mass models (M_{SNIa}~1.4 M_{sun})

Delayed explosion

- Failed deflagration+ detonation (GCD)
- Failed deflagration+pulsation+ detonation (PRD)

DDs:

- Explosion within a thick disc
- Head-on collisions
- Degenerate core + WD (CD)

(Super)-Chandrasekhar mass models Possibility of (M_{SNIa}≥ 1.4 M_{sun})

1

Type Ia Supernova: The SD channel

Some PROS of the SD scenario

- Several Chandrasekhar and Sub-Chandrasekhar mass models are able to reproduce the gross features of the explosion (Hillebrandt et al. 2013).
- A good fit of the X-ray spectra of Kepler SNR was obtained by Badenes et al (2006) with a Ch-mass Def-Det explosion. The hard X-ray spectra of the 3C 397 SNR is consistent with e-captures during high-density combustion (Yamaguchi et al. 2014)
- Transient UV and X-ray features before maximum, observed in PTF14atg, could be caused by the presence of a nearby companion star (Cao et al. 2015)
- Observed Supersoft X-ray sources are interpreted as H-accreting WDs with high $\dot{M}_H$ (van den Heuvet et al. 1992).

Type Ia Supernova: The SD channel

Some CONS of the SD scenario

- Unsuccessful identification of the remnant of the companion star in historical SNR (Lapuente et al. 2018) .
- No traces of the stripped H from the companion in the nebular spectra (Botyánski et al. 2018).
- Predicted rates and the delay-time-distribution favors the DD against the SD channel (Maoz et al. 2014).
- Difficult to induct a detonation in a high-density C+O mixture.

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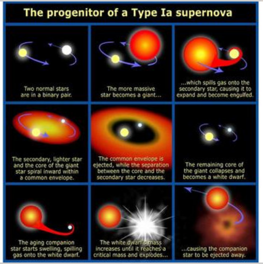
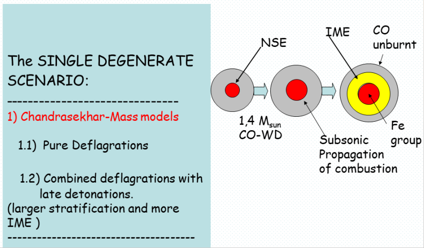
Type Ia Supernova: The SD channel

The Modelling of the Explosions. (Example: Ch-mass models -1-)

- Near $\rho_{c9} \simeq 2$ ($M_{wd} \simeq 1.36 M_\odot$, $R \simeq 2000$ km): $v_{cond} \simeq 100$ km/s; $v_{det} \simeq 5000$ km/s) $\Longrightarrow v_{cond}$ too slow (expansion instead explosion) but v_{det} too fast (^{28}Si is underproduced)
- Combustion begins laminar (a nuclear flame) but soon accelerates because of hydrodynamic instabilities.
- The star expands but not too much. After a while, the defl. may turn into a deto.




The SINGLE DEGENERATE SCENARIO:

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1) Chandrasekhar-Mass models

1.1) Pure Deflagrations

1.2) Combined deflagrations with late detonations.
(larger stratification and more IME)

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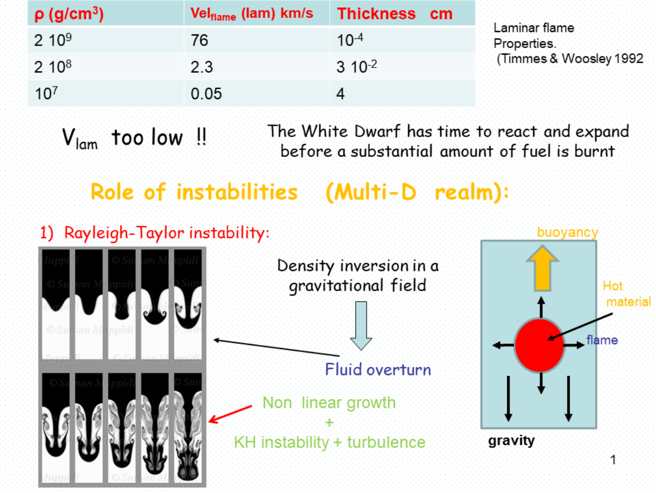
Type Ia Supernova: The SD channel

The Modelling of the Explosions (Example: Ch-mass models -2-)



ρ (g/cm^3)	Vel$_{flame}$ (lam) km/s	Thickness cm
$2\ 10^9$	76	10^{-4}
$2\ 10^8$	2.3	$3\ 10^{-2}$
10^7	0.05	4

Laminar flame
Properties.
(Timmes & Woosley 1992

V_{lam} too low !!

The White Dwarf has time to react and expand before a substantial amount of fuel is burnt

Role of instabilities (Multi-D realm):

1) Rayleigh-Taylor instability:

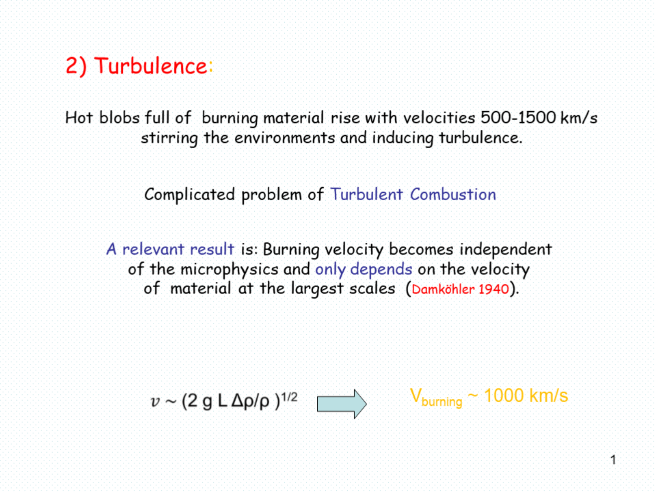
Density inversion in a gravitational field

Fluid overturn

Non linear growth
+
KH instability + turbulence

Type Ia Supernova: The SD channel

The Modelling of the Explosions (Example: Ch-mass models -3-)



2) Turbulence:

Hot blobs full of burning material rise with velocities 500-1500 km/s stirring the environments and inducing turbulence.

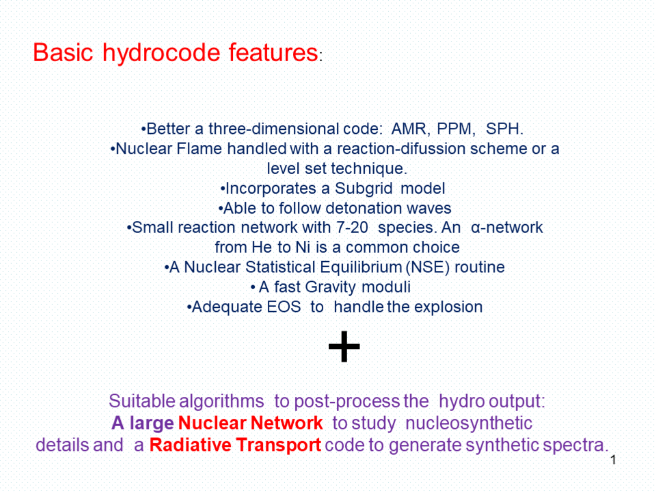
Complicated problem of Turbulent Combustion

A relevant result is: Burning velocity becomes independent of the microphysics and only depends on the velocity of material at the largest scales (Damköhler 1940).

$$v \sim (2\,g\,L\,\Delta\rho/\rho)^{1/2} \Longrightarrow V_{burning} \sim 1000 \text{ km/s}$$

Type Ia Supernova: The SD channel

The numerical modelling of the explosions



Basic hydrocode features:

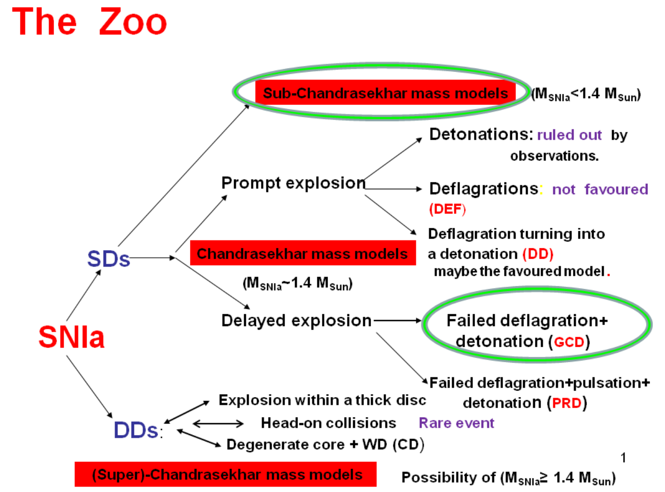
•Better a three-dimensional code: AMR, PPM, SPH.
•Nuclear Flame handled with a reaction-difussion scheme or a level set technique.
•Incorporates a Subgrid model
•Able to follow detonation waves
•Small reaction network with 7-20 species. An α-network from He to Ni is a common choice
•A Nuclear Statistical Equilibrium (NSE) routine
• A fast Gravity moduli
•Adequate EOS to handle the explosion

+

Suitable algorithms to post-process the hydro output:
A large Nuclear Network to study nucleosynthetic details and a **Radiative Transport** code to generate synthetic spectra.

1

Type Ia Supernova: Disentangling the diagram



The Zoo

SNIa

SDs

Sub-Chandrasekhar mass models (M_{SNIa}<1.4 M_{sun})

Chandrasekhar mass models (M_{SNIa}~1.4 M_{sun})

Prompt explosion

- Detonations: ruled out by observations.
- Deflagrations: not favoured (DEF)
- Deflagration turning into a detonation (DD) maybe the favoured model.

Delayed explosion

- Failed deflagration+ detonation (GCD)
- Failed deflagration+pulsation+ detonation (PRD)

DDs:

- Explosion within a thick disc
- Head-on collisions Rare event
- Degenerate core + WD (CD)

(Super)-Chandrasekhar mass models Possibility of (M_{SNIa}≥ 1.4 M_{sun})[1]

Type Ia Supernova: The SD channel

The Gravitational Confined Detonation (GCD) Model

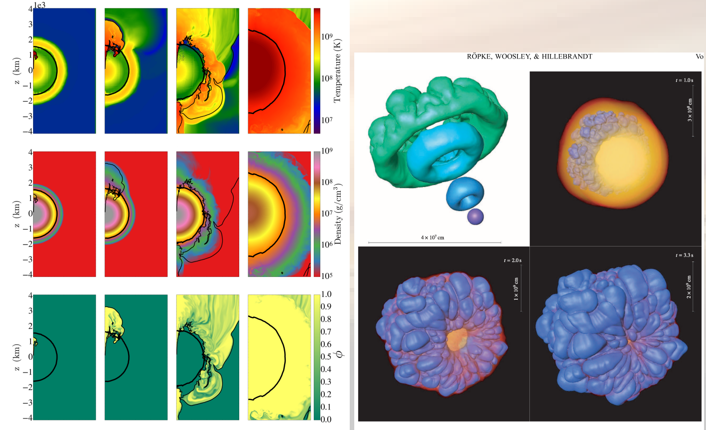
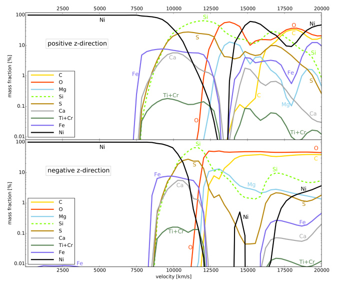
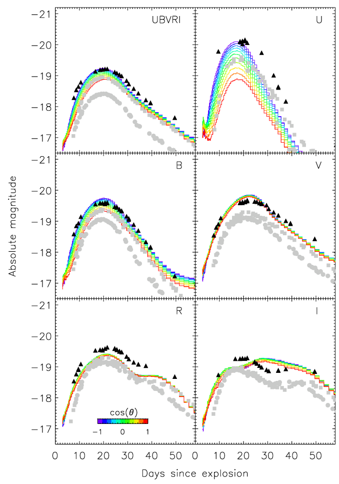


Figure: Calculation of a GCD by Dave et al. 2017. (2D) and Ropke te al. 2007 (3D)

Type Ia Supernova: The SD channel

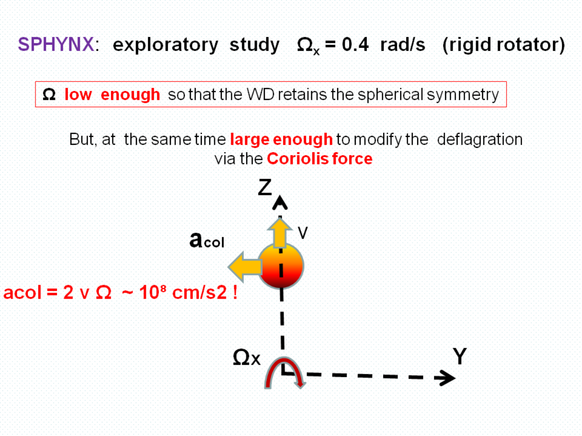
The GCD Model: Nucleosynthesis & LC (Seitenzhal et al. 2016), comparison to SN1991T.





Type Ia Supernova: The SD channel

The GCD Model in a **rotating** WD calculated with the hydrocode SPHYNX (Cabezón et al. 2017).



SPHYNX: **exploratory study $\Omega_x = 0.4$ rad/s (rigid rotator)**

Ω **low enough** so that the WD retains the spherical symmetry

But, at the same time **large enough** to modify the deflagration via the **Coriolis force**

acol = 2 v Ω ~ 10^8 cm/s2 !

Type Ia Supernova: The SD channel

The GCD Model in a **rotating** WD. Detail of the collision at the WD antipodes

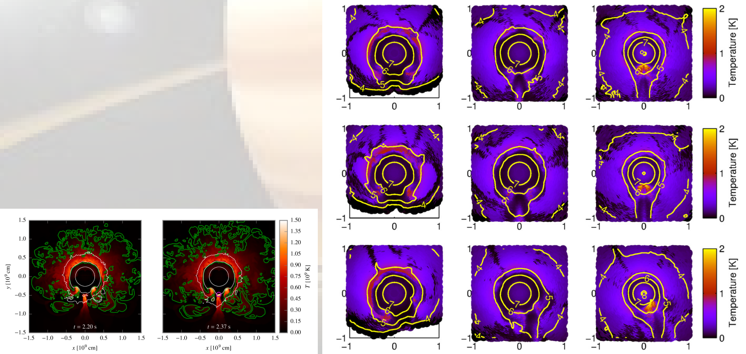
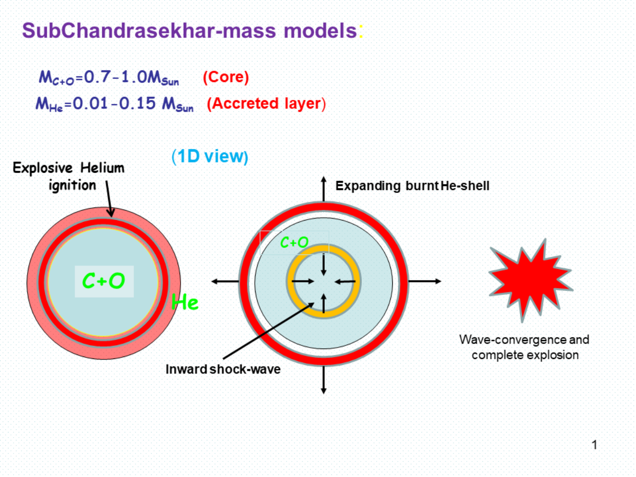


Figure: $\Omega = 0$ (left and upper row), $\Omega_z = 0.4\,s^{-1}$, $\Omega_x = 0.4\,s^{-1}$ (central and lower rows).(Seitenzhal et al. 2016, Garcia-Senz et al. 2016).

Type Ia Supernova: The SD channel

The Sub-Chandrasekhar-mass models: 1D

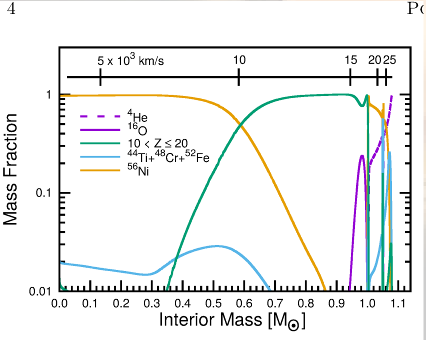


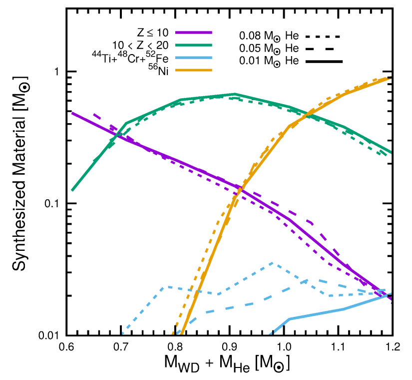
SubChandrasekhar-mass models:

M_{C+O}=0.7-1.0M_{Sun} (Core)
M_{He}=0.01-0.15 M_{Sun} (Accreted layer)

Type Ia Supernova: The SD channel

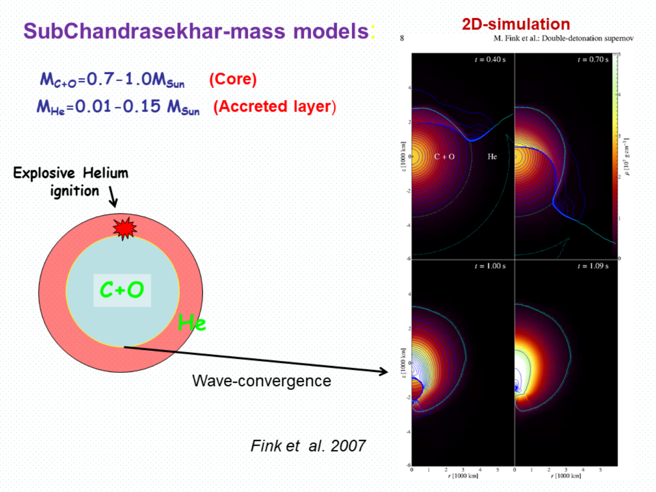
The Sub-Chandrasekhar-mass models:Nucleosynthesis (Polin et al. 2018)





Type Ia Supernova: The SD channel

The Sub-Chandrasekhar-mass models in 2D



SubChandrasekhar-mass models:

$M_{C+O}=0.7-1.0M_{Sun}$ (Core)

$M_{He}=0.01-0.15\ M_{Sun}$ (Accreted layer)

Explosive Helium ignition

Wave-convergence

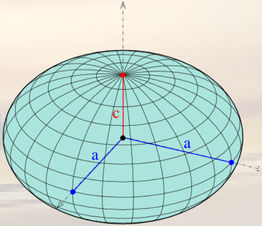
Fink et al. 2007

2D-simulation

Type Ia Supernova: The SD channel

Another twist: SubCh-mass explosion in a fast spinning WD

- Rotating WDs: CO core with 0.8-1.0 $M_\odot$ + He-shell 0.05-0.11 $M_\odot$ + $\Omega \simeq 0.5\,s^{-1}$ (García-Senz et al. 2019).



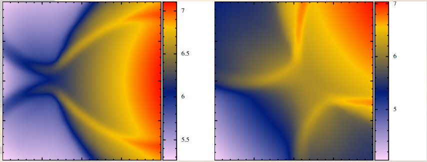
- He-detonation moving on a deformed substrate.
- $L_{equator} = 2\pi a$; but $L_{meridian} = 2\pi\sqrt{0.5(a^2+c^2)}$ → asynchronicity in the wave arrival at the antipodes.

Video: SubCh-mass explosion of a rotating WD

Type Ia Supernova: The SD channel

Another twist: SubCh-mass explosion in a fast spinning WD

- Asynchronicity is actually seen (compare polar -left panel- and meridian right-panel views) but the core detonation is not avoided. **The explosion mechanism is robust**.

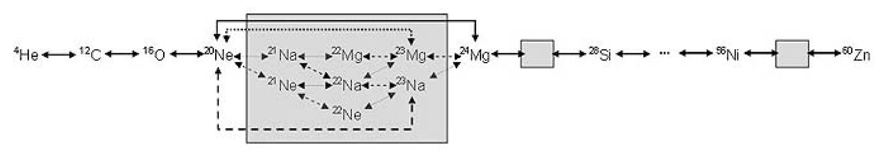


- Minor changes in the nucleosynthetic yields with respect the non rotating models.
- A more asymmetrical explosion increases the polarization of the emitted light.

Type Ia Supernova: The SD channel

The Nuclear Network in 3D simulations with SPHYNX.

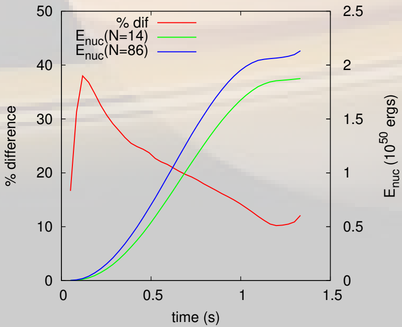
- An α-chain + binary $^{12}C +^{12} C$; $^{12}C +^{16} O$; $^{16}O +^{16} O$ reactions (14 species, **Net14**).
- Implicit simultaneous solution for Y_i and temperature T ⟶ able to follow the NSE and freeze-out consistently .
- Recent implementation of a 86 nuclei network (**Net86**, implicitly coupled to T (Cabezón et al. 2004).



Type Ia Supernova: The SD channel

Checking Net86 in current 3D simulations with SPHYNX: Detonation of the He-shell in SubCh-mass models

- Net86 (including p,n,α): Around 20% **more released energy** than Net14.
- More detailed nucleosynthetic yields.

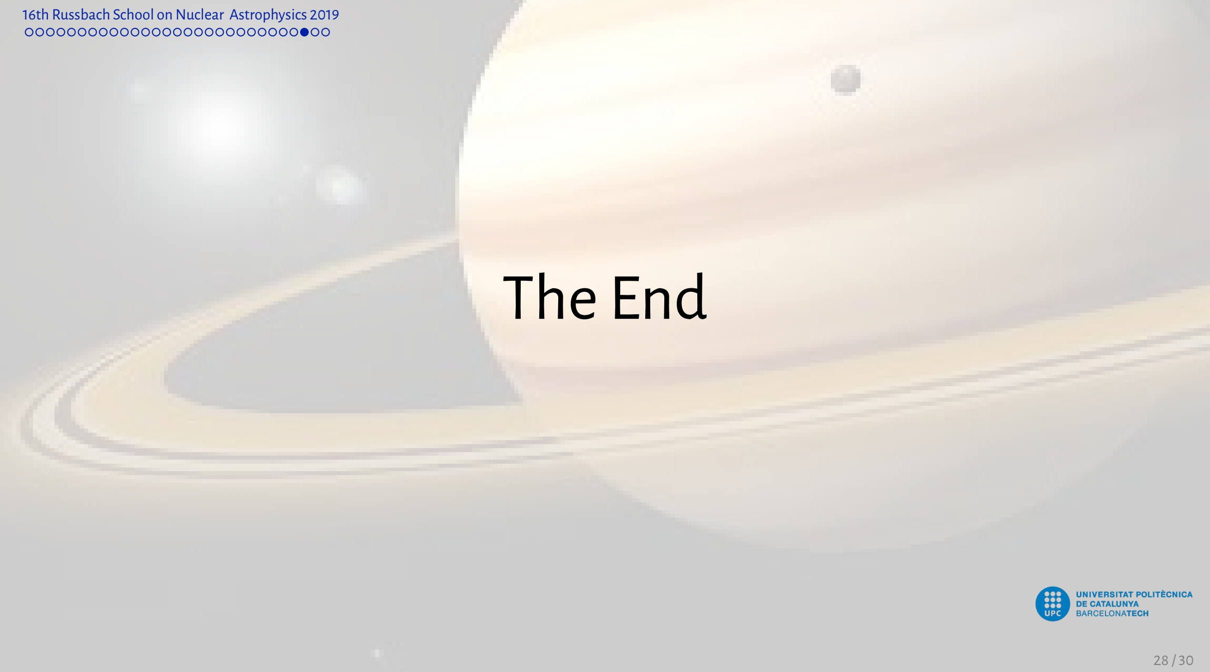


Type Ia Supernova: The SD channel

FINAL COMMENTS

If the SD route to SNe Ia explosions is a viable channel, we ought to discriminate among the many explosion variants:

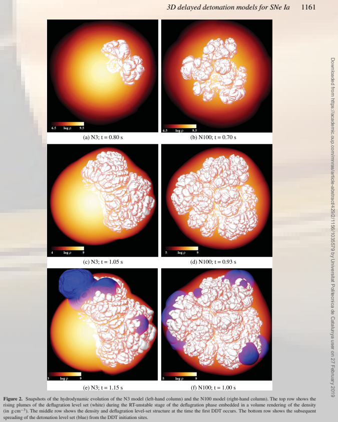
- a) By comparing the predictions of 3D hydro-simulations + Radiative transport with particular, well observed supernova events.
- b) It is necessary to identify the relevant physics in each case and incorporate it into the simulations.For example:
- b1) Rotation is a necessary ingredient to better depict some of the current proposed models.
- b2) Nuclear networks with $logN \simeq 2$ have to be implemented to fill the gap between the small, $\log\ N \simeq 1$ commonly used networks, and the post-processed calculations with $\log N \simeq 3$.



The End

Type Ia Supernova: The SD channel

The Modelling of the Explosions (Example: Ch-mass models)



3D delayed detonation models for SNe Ia 1161

(a) N3; t = 0.80 s (b) N100; t = 0.70 s

(c) N3; t = 1.05 s (d) N100; t = 0.93 s

(e) N3; t = 1.15 s (f) N100; t = 1.00 s

Figure 2. Snapshots of the hydrodynamic evolution of the N3 model (left-hand column) and the N100 model (right-hand column). The top row shows the rising plumes of the deflagration level set (white) during the RT-unstable stage of the deflagration phase embedded in a volume rendering of the density (in $\mathrm{g\,cm^{-3}}$). The middle row shows the density and deflagration level-set structure at the time the first DDT occurs. The bottom row shows the subsequent spreading of the detonation level set (blue) from the DDT initiation sites.

The End