From early convective phases to ignition: the convective Urca process

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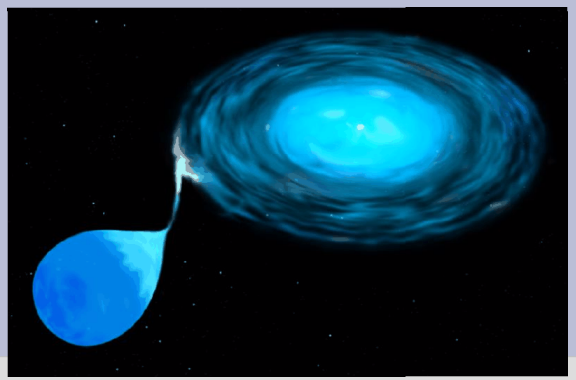
Motivation

- Big surveys **SNFactory**, **SNLS**, **SNAP ...**
- Pskovsky-Phillips relations ⇒ Cosmology
- <u>Links:</u> host galaxy ⇔**progenitors ⇔ ignition conditions** ⇔ explosion models ⇔ light curves and spectra

The computation loop is now closed

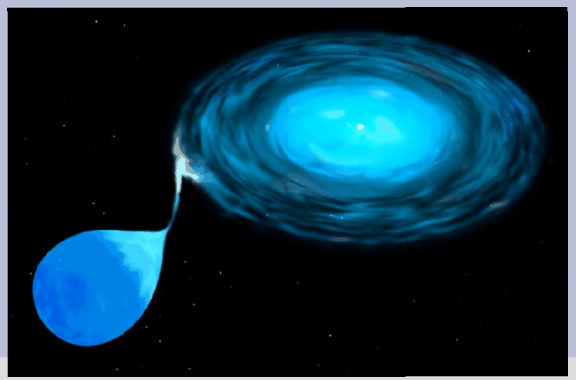
Path to the supernova: initial conditions



Single Degenerate Channel :

- a C/O White Dwarf of mass $\mathbf{M_{WD}}$ is born as the warm heart of an AGB star
- it has a metallicity **Z**, so has its companion
- the companion Roche-Lobe overflows at time **T** which corresponds to the Main sequence life time of its *mass* ; it also determines the WD *cooling time*
- the WD accretes C/O at a rate $f(M_{WD})$ given by the Hachisu (1996) wind model and the efficiency of conversion H -> He -> C/O

Path to the supernova: accretion phase



Neutrino cooling time : t_ν

Convective turnover time : t_c

Carbon fusion time : t_f

- $t_c < t_\nu < t_f$ **C burns mildly** ; neutrino cooling gets rid of energy generation
- $t_c < t_f < t_\nu$ **C flash** : convection sets in ; convective core grows fast due to temperature sensitivity of fusion and electron degeneracy
- $t_f < t_c < t_\nu$ **C ignition** : a flame front builds up

Stellar evolution code : FLASH_THE_TORTOISE

- **STAR (Eggleton 1971)** with a new moving mesh algorithm (Dorfi&Drury 1986)

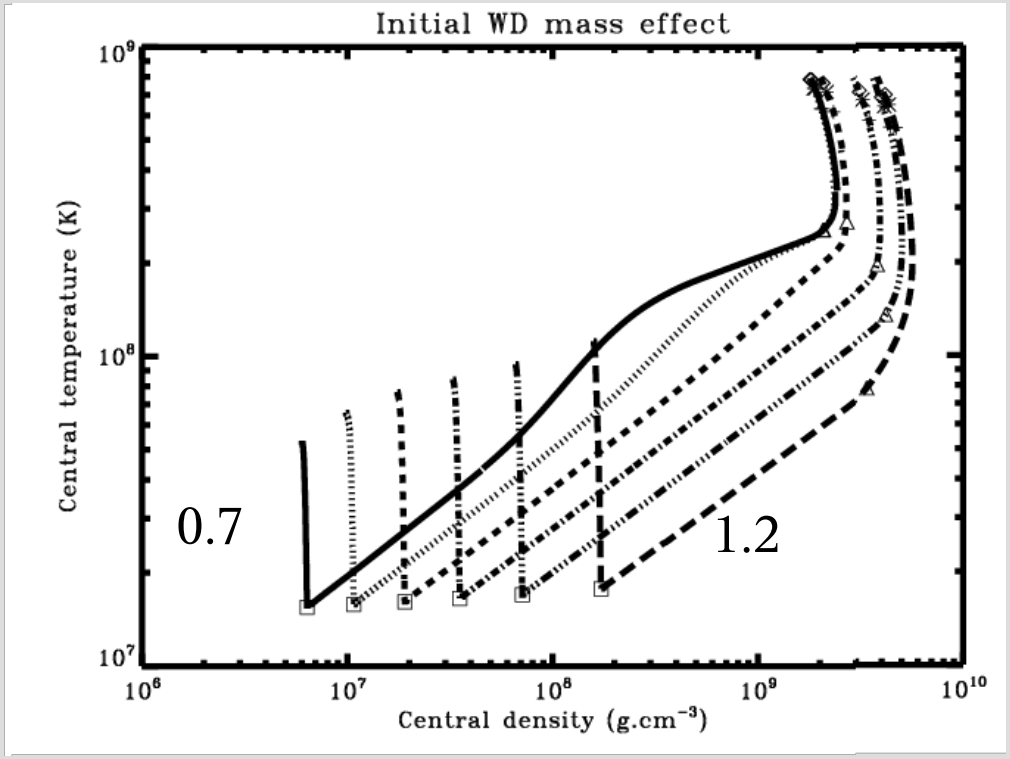
- A **staggered mesh** for small steps *stability*

- Special treatment of **Chemical fluxes** for extremely low gradients : allows *physical mixing*

- A **front tracking** algorithm for the interfaces between radiative and convective regions : allows to compute the *ultimate phases* 0.01 s before ignition

Initial M_{WD} effect

Lesaffre, Han, Tout, Podsiadlowski, Martin (2006) MNRAS

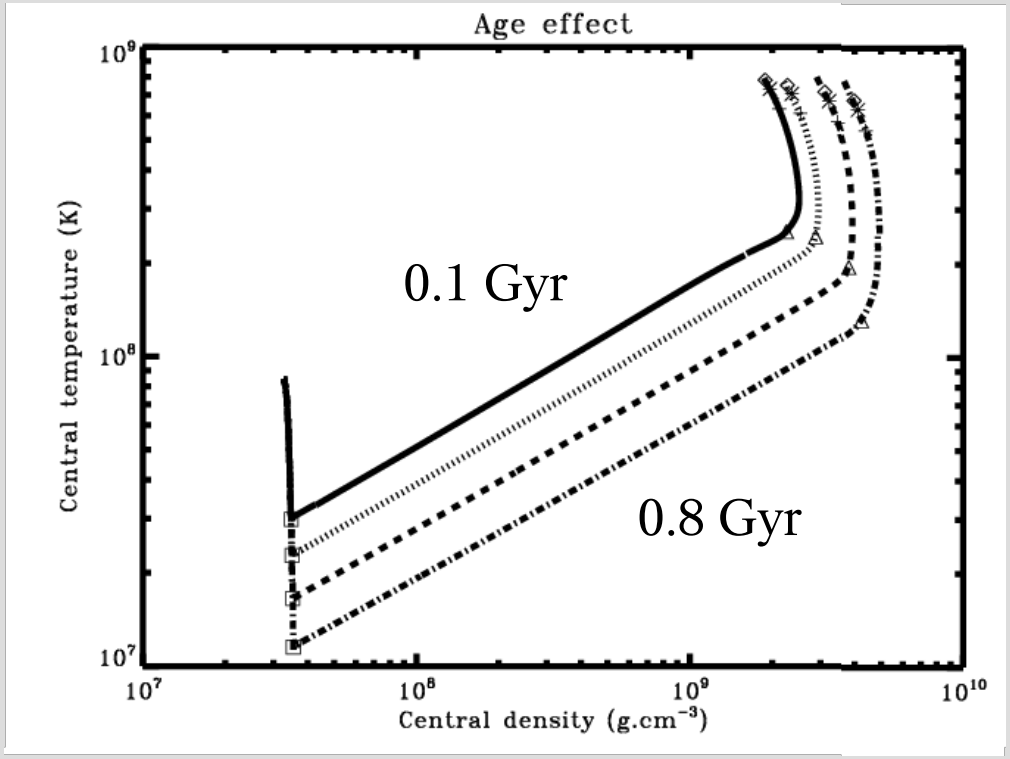


M_{WD} = 0.7 to 1.2 $M_\odot$ for T=0.4 Gyr

- **Higher M_{WD}** start with higher density and lead to **higher ignition density**
- **Small M_{WD}** : thermal diffusion is faster than accretion, all have the **same evolution**
- **High density** : electron screening effects in the burning rates **fix ignition density**

Age effect

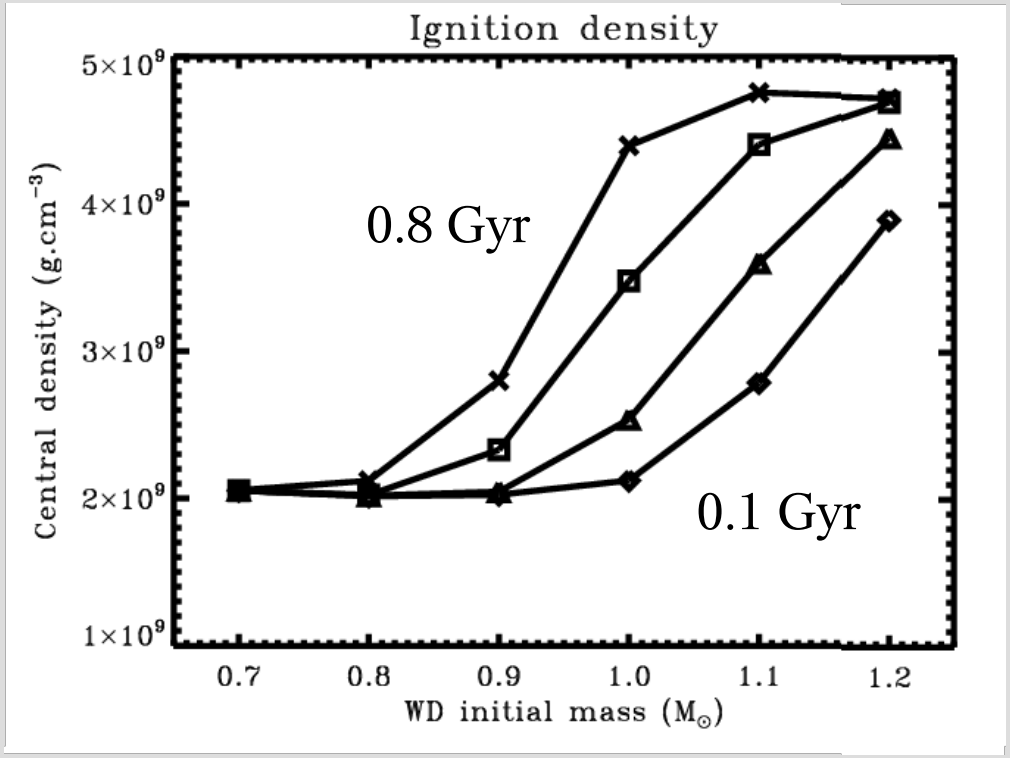
Lesaffre et al (2006) MNRAS



- **Younger systems** start at higher temperature and ignite at **smaller density**
- For **old age** and high initial mass, Coulomb screening effects yield **same ignition density**

$M_{WD} = 1\ M_\odot$ for T= 0.1, 0.2, 0.4 and 0.8 Gyr.

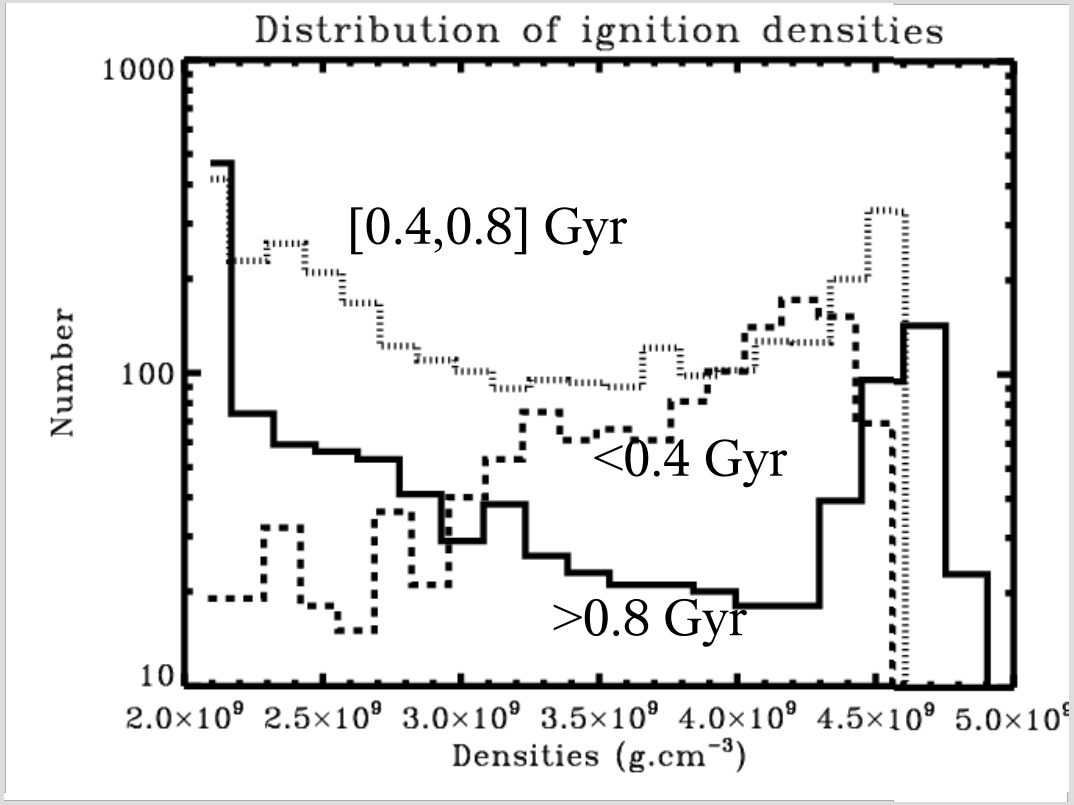
Ignition conditions: Central Density



Diamonds, triangles, squares and crosses correspond to ages T= 0.1, 0.2, 0.4 and 0.8 Gyr.

- **A range of ignition density**
- The **minimum density** corresponds to the global thermal equilibrium
- The **maximum density** corresponds to screening effects on the ignition curve
- Note: these high densities require the **treatment of electron captures** (cf. Urca process, not yet included)

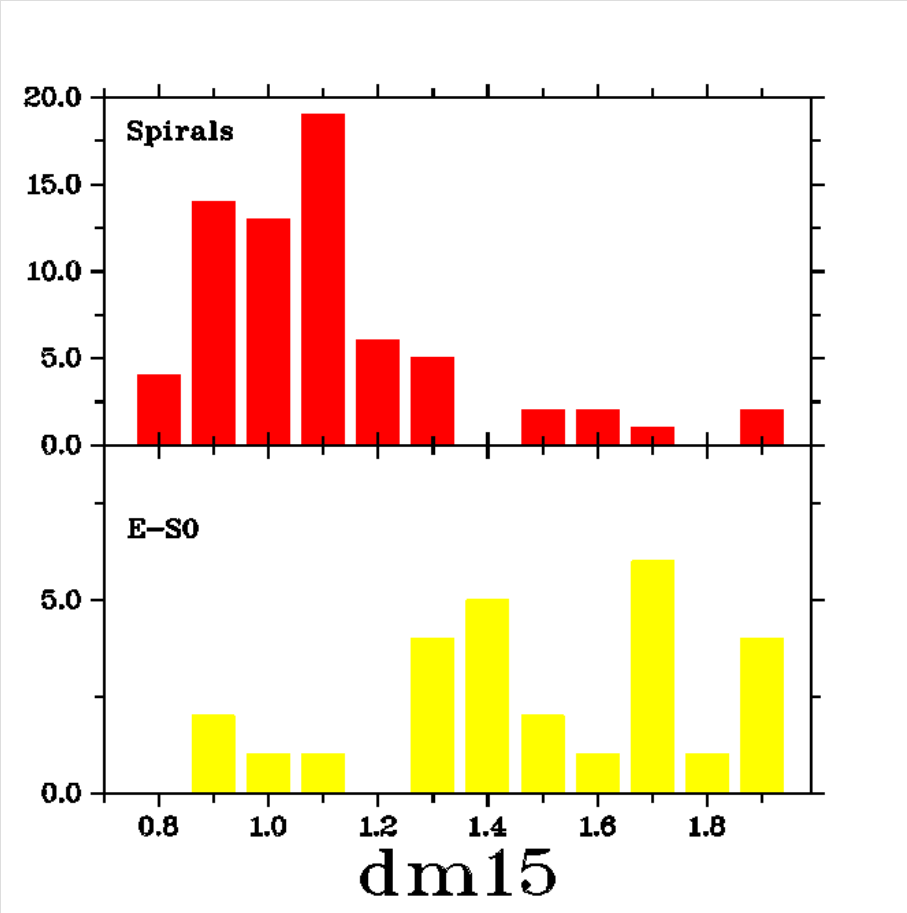
Ignition conditions Distributions



Solid: T > 0.8 Gyr
Dotted: 0.4 Gyr < T < 0.8 Gyr
Dashed: T < 0.4 Gyr

- **Population synthesis by Z.Han**
- **Bimodal distribution**
- **Young systems** ignite at **higher density**
- **Density ⇔ Luminosity ?**

Luminosity
Observed Distributions



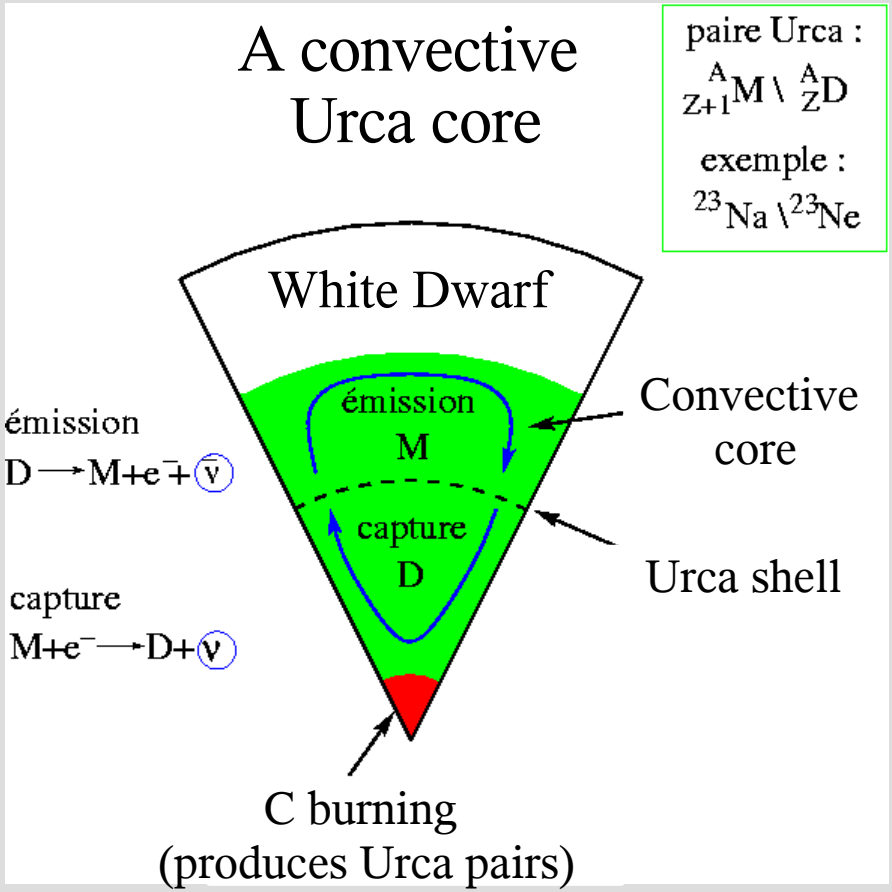
Enrico Cappellaro

- Suggests that **density increases luminosity ?**
- **But** quantitatively incorrect:
  - ages ratio incorrect
  - number ratio inverted
  - bimodal distribution shows up at intermediate ages
- Work in progress...

Ignition Conditions
Partial summary

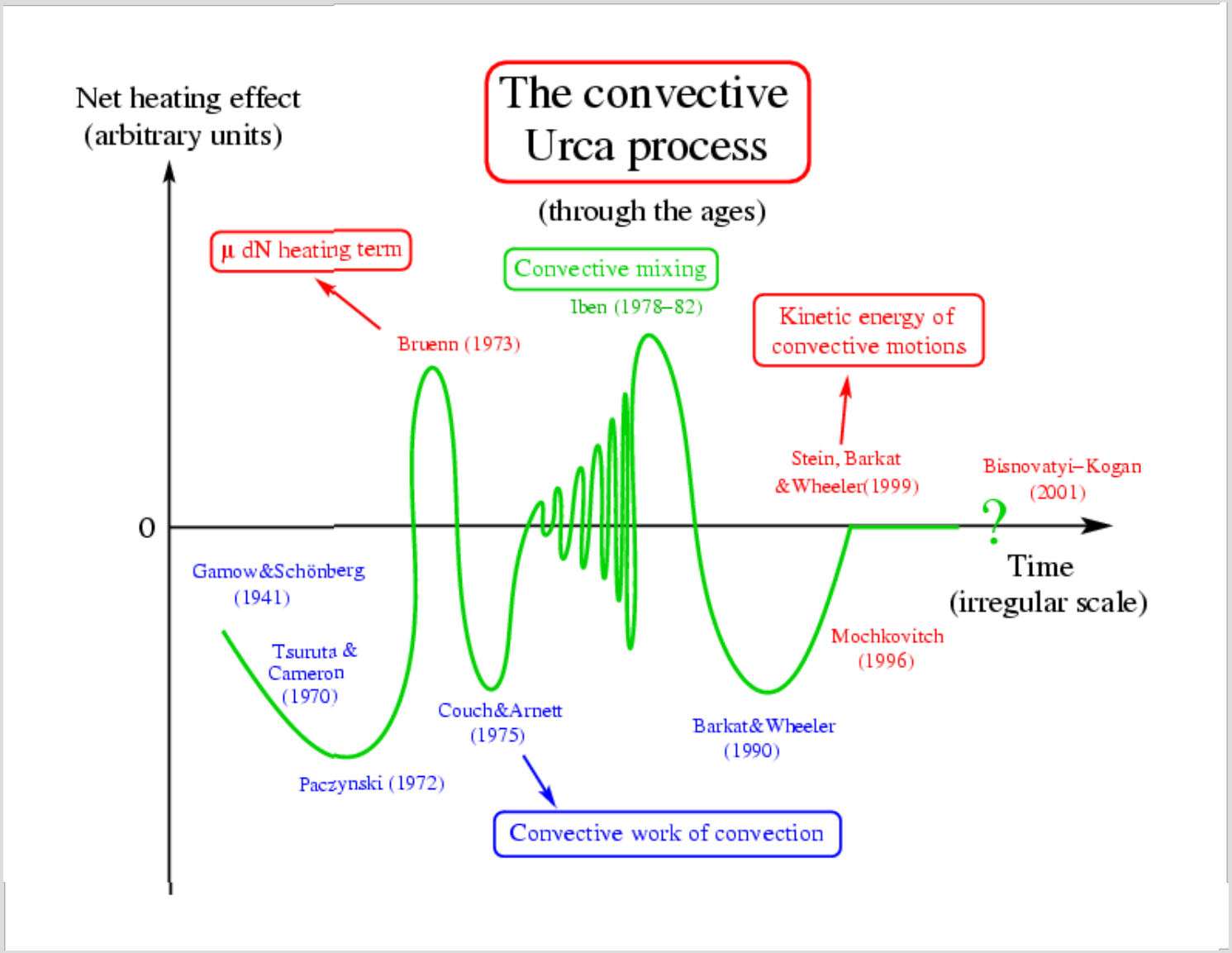
- Age and WD mass determine ρ
- All parameters at ignition (but Z, C/O) are correlated to ρ
- => Two independent parameters:
  - **central density ρ** at ignition (1st ?)
  - **metallicity Z** of the progenitor stars (2nd ? cf. Mazzali & Podsiadlowski 2006)
- Distribution of ρ <=> **luminosity function** of SNIa ?

The convective Urca process



- At high densities, **electron captures** enter into play
- The **neutrino losses** associated to them plays a complex rôle as we shall see..

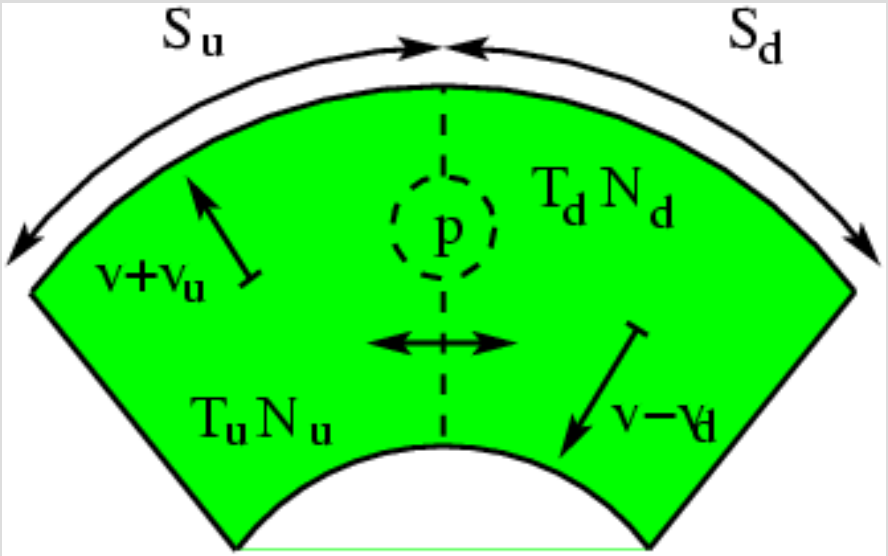
The convective Urca process through the litterature



Convection
Two-streams formalism

(Lesaffre, Podsiadlowski, Tout, 2005)

Inputs:
- spherical RHD
- no viscosity
- an MLT model for horizontal exchanges



Outputs:

- **Correct Energy and Chemical budget**
- **Differential reactivity**
- Ledoux criterion and convective velocities **depend on chemistry**
- Time-dependent model
- Handles convective velocity asymetries, hence potentially overshooting
- Handles interactions with mean flow

To the 1-stream limit: a Self-consistent MLT

Energy equation:

$$\frac{\mathrm{D}e}{\mathrm{D}t} + p\frac{\mathrm{D}}{\mathrm{D}t}\left(\frac{1}{\rho}\right) = \epsilon - \frac{\partial L_{\mathrm{tot}}}{\partial m} + \boxed{W_{\mathrm{conv}}}$$

Chemistry equation:

$$\frac{\mathrm{D}\mathbf{N}}{\mathrm{D}t} = \mathbf{R} - \frac{\partial}{\partial m}\mathbf{F}_{\mathrm{tot}}$$

with

$$W_{\mathrm{conv}} = -u^3/\lambda,$$

$$L_{\mathrm{tot}} = L_{\mathrm{rad}} + \frac{1}{2}S\rho u\left[\frac{u}{u+u_0}(\nabla - \nabla_a) - \boxed{\boldsymbol{\mu}.\nabla_{\mathrm{N}}}\right]$$

and

$$\mathbf{F}_{\mathrm{tot}} = \mathbf{F}_{\mathrm{diff}} - S\rho u\,\boldsymbol{\mu}.\boldsymbol{\nabla}_{\mathrm{N}}$$

where the convective velocity:

$$u \simeq c_s\sqrt{\delta(\nabla - \nabla_a) - \boxed{\boldsymbol{\mu}''.\boldsymbol{\nabla}_{\mathrm{N}}}}.$$

Additional features (to MLT):

- **Convective work**
- **Chemical dependence of the convective luminosity**
- **Chemical dependence of the convective velocity**

However, numerical difficulties are extreme…

Buoyancy Forces

Ice cubes floating on Umeshu

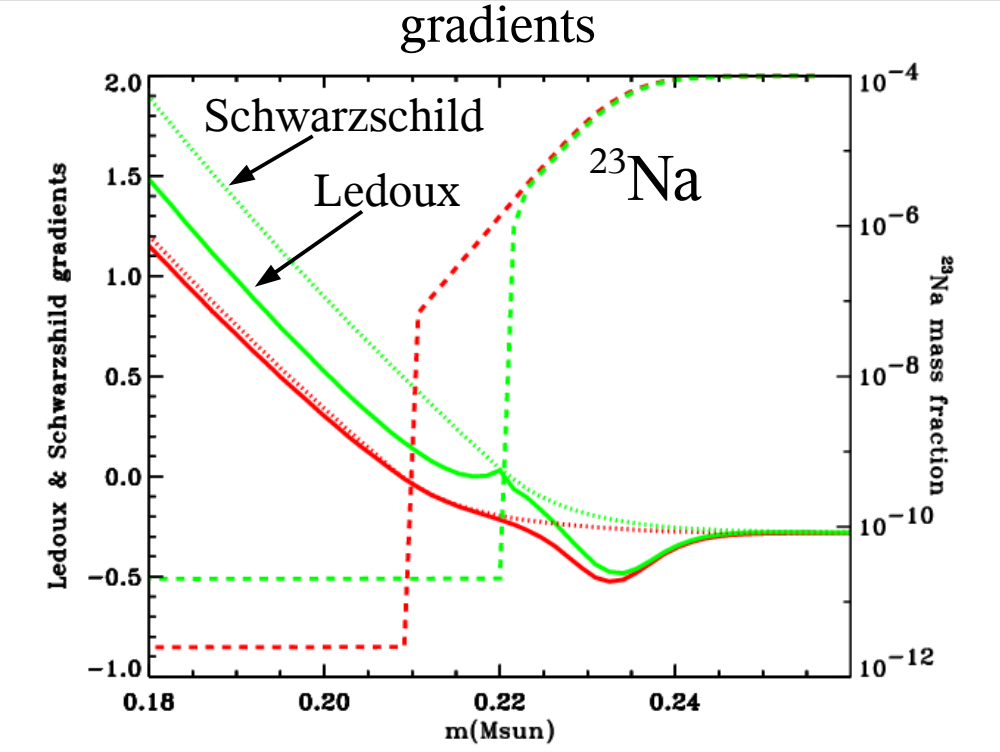
- Ice cubes sink in classical stellar evolution codes...
- **Density** is what matters
- In *degenerate matter*, density depends little on T and a lot on **electron fraction**
- **=> Urca reactions slow down convective motions** (Lesaffre, Podsiadlowski, Tout 2005)
- a rough estimate shows that **C burning wins** over electron captures when :

$$\delta R_C/R_U >\sim 1$$

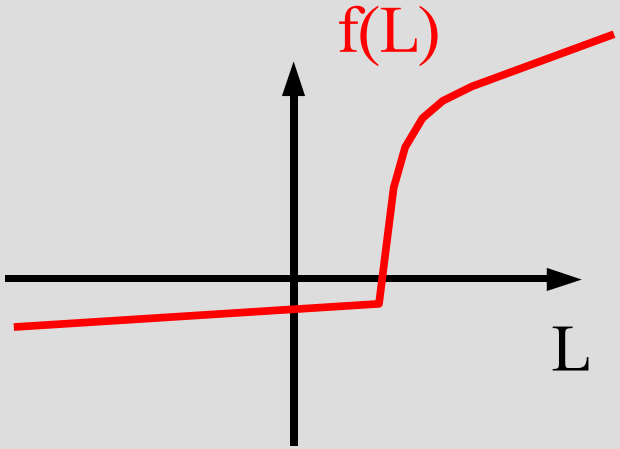
1D simulations

2 snapshots of a 1D simulation by FLASH_THE_TORTOISE

Ledoux (solid) and Schwarzschild (dotted) gradients

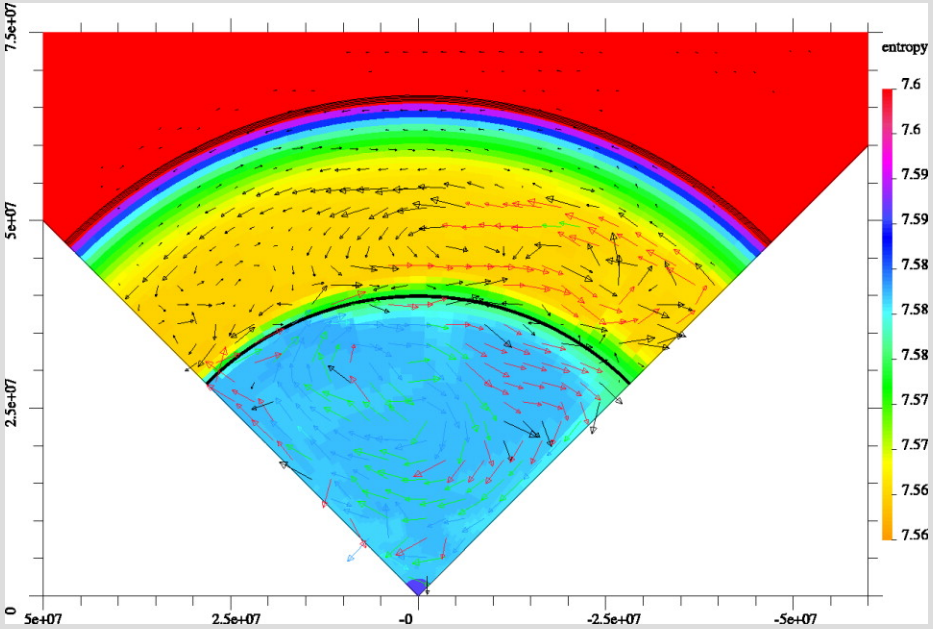


- Regions where the Ledoux criterion is nearly zero want to form when approaching the Urca shell
- Newton-Raphson has a hard time...



2D simulations

Stein & Wheeler (2006)
Code DWARF



Entropy & velocity field

- <u>Code Features :</u>
  - 2D **implicit-pressure** scheme
  - Chemical *rates rescaled*
- <u>Results:</u>
  - Urca reactions **slow down convective motions**
  - Convective core confined yields **higher rate of increase** for the **entropy**
- C burning rates eventually should win ?

A simple model & Cosmological implications

Podsiadlowski, Mazzali, Lesaffre, Wolf, Förster (astro-ph/0608324)

- **Budget of electron captures** on the path to explosion
  - **H burning:** the CNO cycle converts C,N and O to ^{14}N via **(β+)**
  - **He burning:** $^{14}N(\alpha,\gamma)^{18}F$**($\beta$+)**$^{18}O(\alpha,\gamma)^{22}Ne$
  - **C burning:** $^{22}Ne(p,\gamma)^{23}Na(p,\gamma)^{24}Mg(p,\gamma)^{25}Al$**($\beta$+)**$^{25}Mg(p,\gamma)^{26}Al$**($\beta$+)**$^{26}Mg$
  - **total:** from **2 to 4 captures** depending on the convecive Urca efficiency and completeness of ^{22}Ne burning **(Förster confirms)**
- I then deduce the **neutron excess at ignition = f(Z)**
- Assuming fast combusion as in **Timmes, Brown & Truran (2003)**, I deduce from explosive nucleosynthesis **X(^{56}Ni) = f(Z)**
- We finally use the simple light curve models from **Mazzali & Podsiadlowski 2006** to deduce the **drift of luminosity-width relations with respect to the metallicity Z.**

Conclusions

- Urca processes yield complex interactions between **convection and chemistry**
- A simple model illustrates the potential **sensitivity of cosmological measures**
- The convective Urca process **must** be included in our models...
- *End of the loop:* explosion models, nucleosynthesis, light curves

Prospects

- Models **FLASH** with electron captures (F. Förster)
- **2D-3D Explosions** (Iapichino, Röpke)
- Nucleosynthesis (C. Travaglio)
- **Light curves** (S. Blinnikov)