A new mechanism for Deflagration to Detonation Transition (DDT) in thermonuclear supernovae

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CEA/DSM/Service d'Astrophysique - AIM

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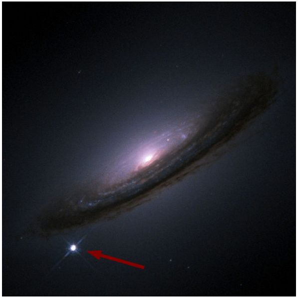
Séminaire LUTH

Outline

Supernovae

Two types of supernovae : Core-collapse and Thermonuclear



High-Z Supernova Search Team
HST/NASA

- 1 Supernova as bright as 1 galaxy
- Visible extremely far away
- Thermonuclear SNe are standardisable candles : $\rightarrow$ distance measurement across the Universe

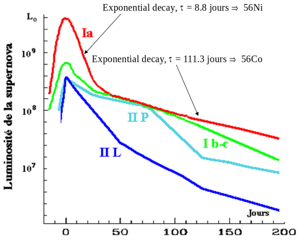
$\Rightarrow$ Revealed the acceleration of the expansion of our Universe (Nobel prize 2011 : Perlmutter, Schmidt et Riess)

Thermonuclear Supernovae (type Ia)

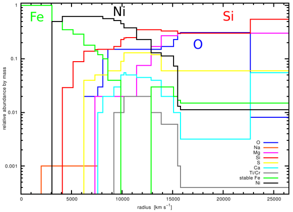
- Spectra :
  - No hydrogen lines
  - Strong silicon lines
- Light curves :
  - Powered by decay of ^{56}Ni :

$$^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$$

- Nucleosynthesis :
  - Stratification of ejecta
  - High velocity IME ($\sim^{28}Si$)



Light curves of different types of supernovae



Abundance stratification inferred by tomography

Diversity and correlation

Inhomogeneities strongly correlated

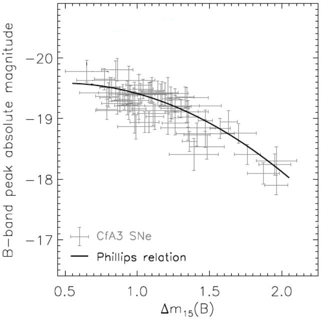
Most SNe Ia are arrangeable in a 1-parameter family according to explosion strength

- weaker explosions :
  - less luminous
  - redder
  - decline faster
  - slower ejecta velocities

Phillips Relation

$$M_{max} = -21.7 + 5.7\Delta m_{15}$$

Δm_{15} is the magnitude decrease after 15 days



Diversity of SNe Ia, correlated through the Phillips relation

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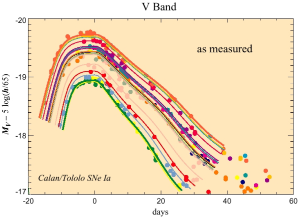


Brighter-slower correlation

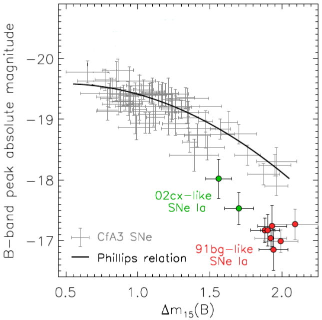
Peculiar supernovae

However, Peculiarity rate of about 30%

- These SNe are outlier compared to phillips relation
- They present spectral differences that make them abnormal

Subluminous (20%) :

- Fainter than Phillips relation
- Two subclasses
  - 91bg like
  - 02cx like or type Iax



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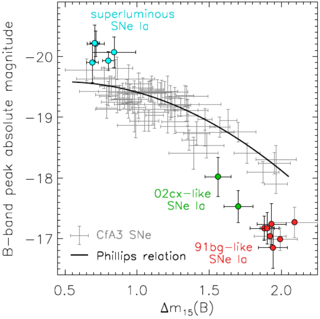
Superluminous (10%) :

- Brighter than Phillips relation



Diversity of SNe Ia, correlated through the Phillips relation

What are thermonuclear supernovae ?

They are thermonuclear explosions of Carbon-Oxygen White Dwarf

SN 2011fe (in M101) has a radius $< 0.02R_\odot$ (Bloom & al 2011)

C+O combustion explains :

- Absence of H and He
- Production of ^{28}Si and ^{56}Ni
- Typical energy of $1.5\,10^{51}$ *erg*

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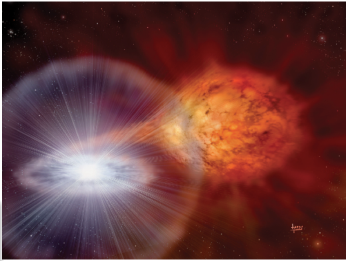
$\Rightarrow$ Necessarily in binary systems



Artist view

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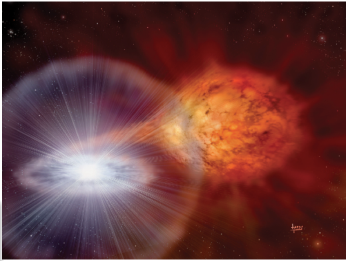

Artist view

However

- Progenitor evolution up to ignition ?
- Combustion mode : deflagration or detonation ?

Physical conditions in White Dwarves

- 1 solar mass in less than an earth radius :

$\Rightarrow$ Very compact object, $\rho_c \gtrsim 10^9\ g.cm^{-3} = 1000\ ton.cm^{-3}$.

- Fully ionized plasma
- Correlated plasma : ions form a liquid
- e^- are extremely degenerate and relativistic ($\epsilon_f > m_e c^2$) :
  - Superconducting plasma : Strong magnetic field
  - Pressure P dominated by degenerate electrons (P_e)
  - Thus P is (mostly) independent of the temperature

No negative feedback on combustion by expansion

$\Rightarrow$ Explosive thermonuclear reactions

Thermonuclear combustion

- 13 α-elements network :
  $^4He(=\alpha)$ and ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ..., ^{52}Fe, ^{56}Ni

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- Including 30 nuclear reactions :
  - Heavy ions : $^{12}C + ^{12}C \rightarrow$ $^{20}Ne + \alpha$ ...
  - α captures : $^{20}Ne + \alpha \rightarrow$ $^{24}Mg + \gamma$ ... , all the way to ^{56}Ni
  - Reverse reactions : photo-disintegration.

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  - Reverse reactions : photo-disintegration.
- Reaction rates :

$$\frac{dn_{Mg}}{dt} = n_{Ne} n_{\alpha} < \sigma v > + \ldots$$

σ is the cross section, v the relative speed, $< \sigma v >$ tabulated in T

Propagation of combustion

Subsonic mode : Deflagration

- Propagate through e^- conduction + radiation
- Unstable to Rayleigh-Taylor and Landau-Darrieus instabilities
- Slow combustion : **the star expands**

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Supersonic mode : Detonation

- Propagated by a leading shock followed by combustion
- Once triggered, disrupt the whole star (**No expansion**)

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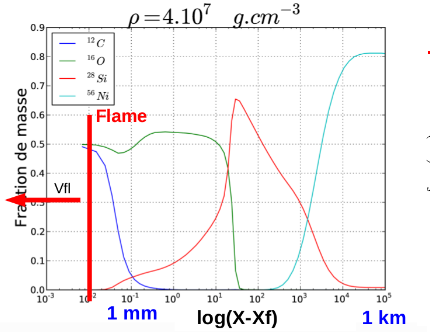
Reaction rates $\propto T^{27} \Rightarrow$ very thin flames ($1\mu m$ to 1cm)

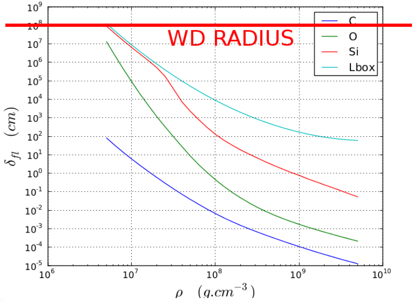
Combustion fronts unresolved (in simulations) $\delta_{fl}/R_{WD} \sim 10^{-10}$

Thermonuclear flames in C+O white dwarfs

High resolution hydro simulations with ASTROLABE (ALE mesh) :



Flame structure



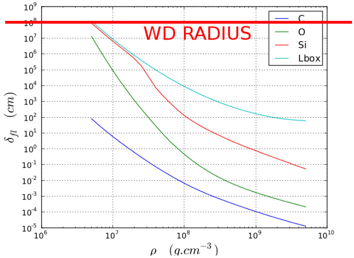
Combustion scales versus density

- 3 burning stages : Carbon, Oxygen , Silicium
- 3 highly disparate reaction lengths
- Incomplete silicon burning at low densities

Nucleosynthesis constraint

Combustion products :

- High densities :
  $\rho \gtrsim 10^8 \ g.cm^{-3} \rightarrow {}^{56}Ni$
- Low densities :
  $\rho \lesssim 5 \ 10^7 \ g.cm^{-3} \rightarrow {}^{28}Si$

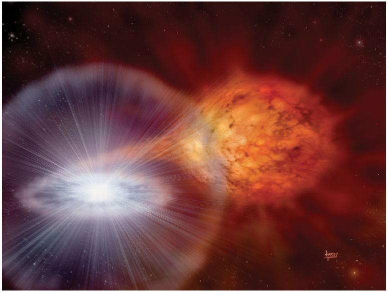


Combustion scales versus density

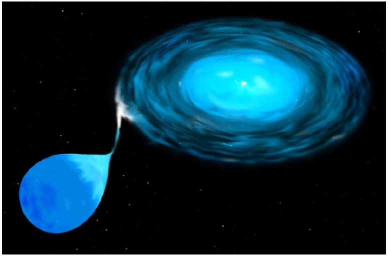
Observations : Both ${}^{56}Ni$ and ${}^{28}Si$ produced

$\Rightarrow$ Combustion has to occur both at low and high densities.

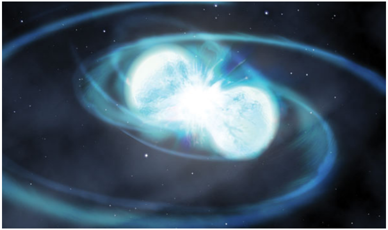
The three main models



Accretion model (Hydrogen)



Accretion model (Helium)



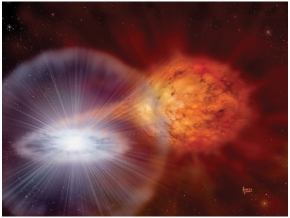
2 WD merger model

Single Degenerate model (SD)

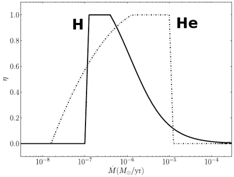
External trigger :

Accretion of Hydrogen up to Chandrasekahr mass

- **Robust ignition mechanism**
  - The WD accretes mass to M_{ch} $\rightarrow$ unstable WD $\rightarrow$ explosion
  - Central ignition as a deflagration



Acretion of H from a giant companion



Retention efficiency

- **But M_{ch} hard to reached**
  - if low $\dot{M}_H$ $\rightarrow$ recurrent novae
  - if strong $\dot{M}_H$ $\rightarrow$ mass loss by winds

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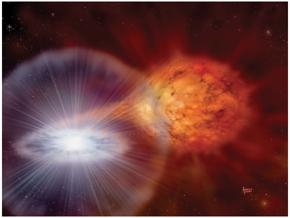

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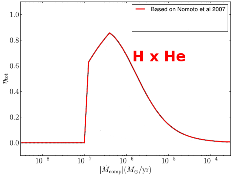

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Pure detonation models (Arnett 1969)

Chandrasekhar mass white dwarfs :

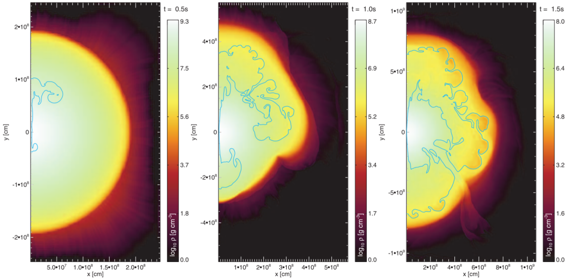
- $M_{ch} \sim 1.4\ M_{\odot}$
- Central densities above $10^9\ g\ cm^{-3}$
- Most of the mass is above $10^8\ g\ cm^{-3}$

This rules out pure detonation models

A detonation propagates supersonically :
$\Rightarrow$ The star has no time to expand
$\Rightarrow$ Combustion at high density, producing only ^{56}Ni

Pure deflagration models

With the most advanced flame model :

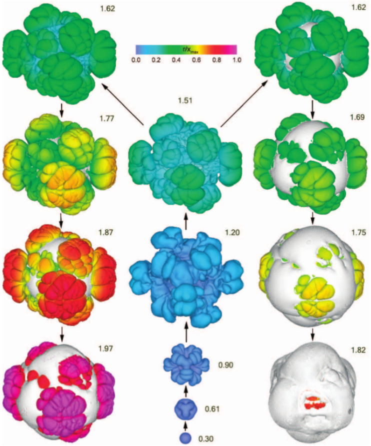


Röpke, Woosley & Hillebrandt 2007

Not enough energy released

- In 2D : The deflagration cannot unbind the star
- In 3D : The outcome depends on the ignition geometry

Delayed detonation models



Gamezo, Khokhlov & Oran 2005

1. Deflagration to expand the star
2. Detonation to incinerate the remaining fuel

- $\rho_{DDT} \sim 2.10^7 g.cm^{-3}$

$\Rightarrow$ correct nucleosynthesis and energetics.

But...

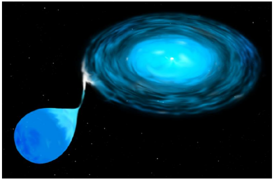
Physical mechanism for DDT still unknown

Sub-M_{ch} double detonation models

External trigger :

Accretion of helium up to ignition of a He-detonation

- The WD accretes Helium
- If sufficiently massive layer forms
  $\Rightarrow$ Helium detonation
- Send a converging shock inward
  $\Rightarrow$ Trigger a carbon core detonation



Helium accretion

Detonation in a sub-Chandrasekahr mass WD

- Less massive WD $\Rightarrow$ Lower central densities
- A pure detonation produces correct nucleosynthesis

Sub-M_{ch} double detonation models

The helium layer problem

- Produces ^{56}Ni in outer layers
  $\Rightarrow$ At odds with observations
- Model discarded in 90s

(Thought to require too massive helium layer : $\sim 0.1 M_{\odot}$)

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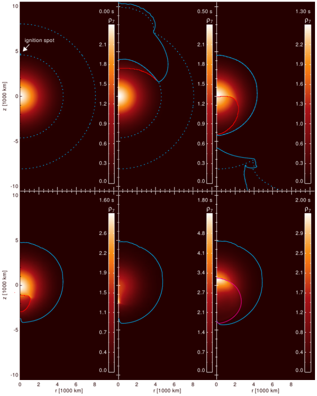
Shock convergence

The convergence of the inner shock allows for lighter helium shell



Fink&al2010

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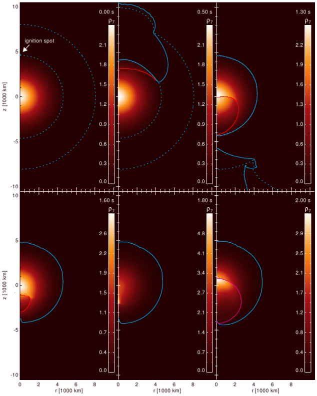
Small helium layer + Mixing

Correct spectra (Kromer & al 2010)

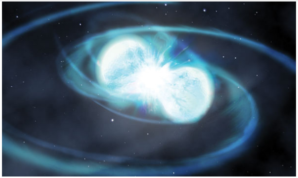


Fink&al2010

Double Degenerate models (DD)

External trigger :

Collision of two C+O white dwarfs



Merger of two CO whites dwarfs

- WD mergers are quite frequent
- Off-center deflagration ignition must be avoided (leading to collapse)

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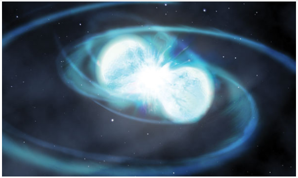

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M_{ch} mergers

- Secondary is disrupted and slowly accreted
- Central deflagration ignition
- DDT ($\Leftrightarrow$ SD scenario)

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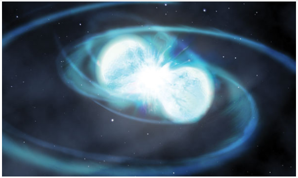

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M_{ch} mergers

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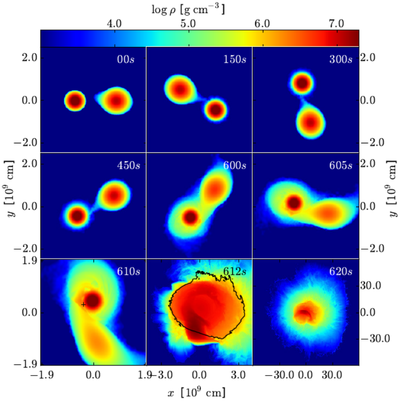
sub-M_{ch} violent mergers

- Violent accretion of secondary
- Off-center detonation
- sub-M_{ch} leads to correct nucleosynthesis

Violent double degenerate mergers



Pakmor & al 2011

Detonation ignition

favourable conditions are met directly during the fast accretion of the secondary

Observables

Spectra from these events can reproduce normal Type Ia

Explosion models, summary :

- Each oh these models can reproduce the main observables :
  - the range of observed luminosities
  - the stratification of ejecta

- 3D modelling of hydro and radiative transfer gives acceptable spectra

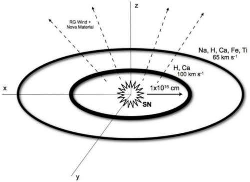
HOWEVER all rely on unresolved physical mechanisms :

- **Delayed detonation :** The DDT mechanism (also in the classical M_{ch} merger)
- **Double detonation :** The helium - detonation ignition
- **Violent merger :** The detonation ignition at contact between the two white dwarfs

Direct Observations

- PTF 11kx : Symbiotic Nova progenitor
  ⇒ incompatible with DD
  (Dilday&al 2012)

- SNR 0509-67.5 : Absence of any companion star
  ⇒ Rules out SD scenario.
  (Schaefer&al 2012)



Dilday & al 2012

No single progenitor path to thermonuclear supernovae

⇒ the question is now, which one contributes most ?

In this context :

- Homogeneity is an argument in favour of SD
- This model is the most mature
- It still lacks a major piece of physics :

The DDT mechanism

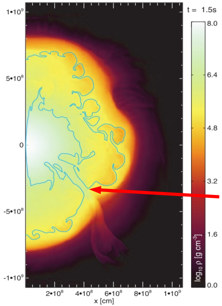
Studying and understanding this transition is still important

(This transition is also needed in the classical M_{ch} DD scenario)

Models to get a delayed detonation :

Several models have been designed to obtain a detonation after an initial phase of deflagration and expansion :

- Turbulence induced DDT (Khokhlov 1997)
- Gravitationally confined detonation (Plewa & al 2004)
- Pulsational detonation
- ...



All rely on the Zel'dovich's gradient mechanism

But on VERY unresolved scales

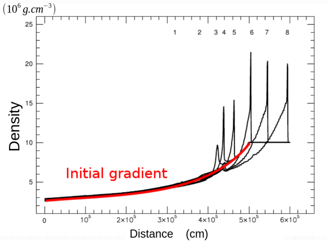
Zel'dovich gradient mechanism

- Rely on an induction time (τ_i) gradient :
  - τ_i is the time needed to burn half of the carbon
  - A spontaneous combustion wave propagates from short τ_i to long τ_i

- If the gradient is sonic :

$$\nabla \tau_i = \frac{1}{Cs}$$

Overpressure accumulates at the wave front



Khokhlov & al 1997

If the gradient is sonic and large enough

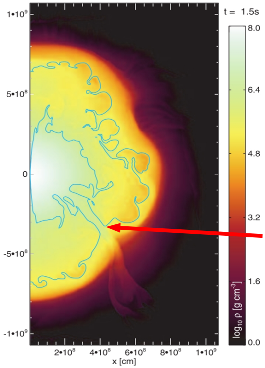
P_{CJ} can be reached $\Rightarrow$ self-sustained detonation

Global models

- Gravitationally confined detonation
- Pulsational detonation

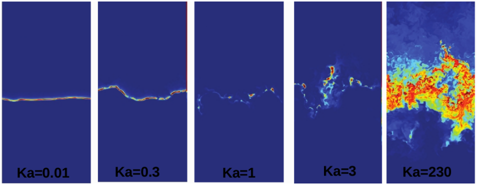
1. Ignition studies with resolved combustion scales :
   → Critical conditions
2. If a cell meet those conditions :
   → Detonation

⇒ Rely on the global flow to reach critical values at the grid scale
(Collision of two plumes or re-contraction of the whole structure)



Turbulence induced DDT

- Rayleigh-Taylor and Kelvin-Helmholtz$\Rightarrow$ Turbulence :
  - $V_{RT} \sim 100\ km.s^{-1}$ on scale $L_{RT} \sim 10$ km
  - Cascade down to Kolmogorov scale
  - $\eta \ll \delta_{fl} \ll L_{RT} \Rightarrow$ Interaction with the flame
- If intense enough, can penetrate the flame : (Distributed burning)



Aspden, Bell & Woosley, 2008,2010

Distributed regime reached at $\rho \sim 3\ 10^7\ g.cm^{-3}$

Correspond to the ρ_{DDT} inferred from observation. Coincidence ?

Requirement for the Zel'dovich mechanism in supernovae

- Woosley & al (2009) obtained a DDT in one dimensional turbulence simulations
- DDT actually occurred in the distributed regime
- Require high turbulence intensity (20% of sound speed)

Is such a level of turbulence realistic ?

→ Maybe through intermittency (Röpke 2007)

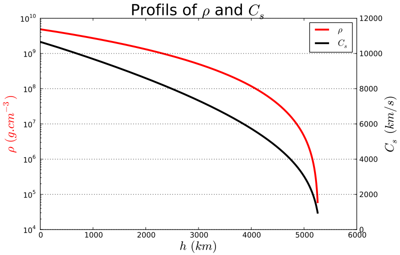
⇒ **In this context we propose a novel approach...**

non local DDT

We considered another original approach :

Sound waves :

- Energy carried :
  $F = \frac{1}{2}\rho u^2 C_s$
- Flux conservation :
  $u(h) = u_0 \sqrt{\frac{\rho_0 C_{s,0}}{\rho C_s(h)}}$



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1. Perturbations are produced in the flame,

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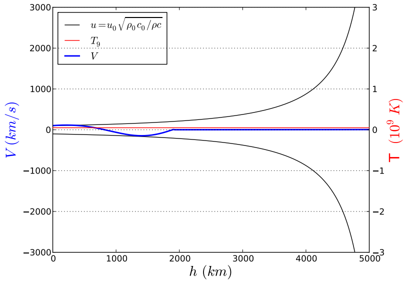

non local DDT

We considered another original approach :

1. Perturbations are produced in the flame,
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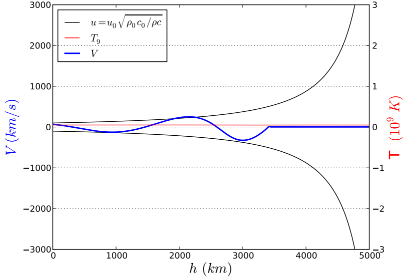

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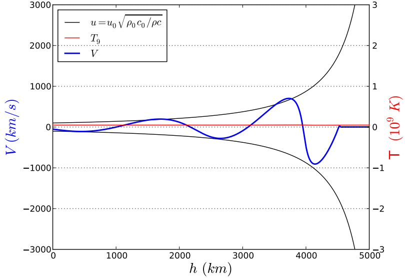

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We considered another original approach :

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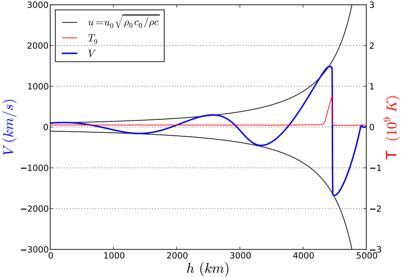

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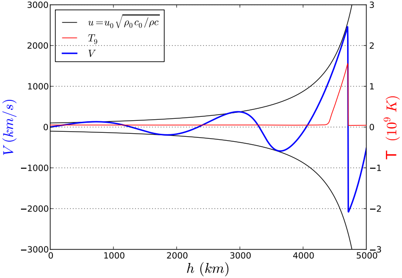

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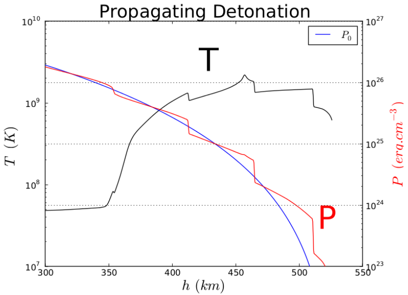

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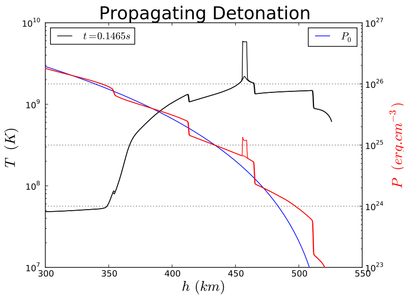

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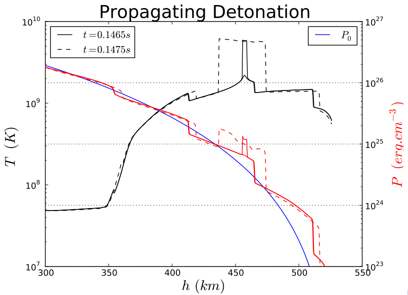

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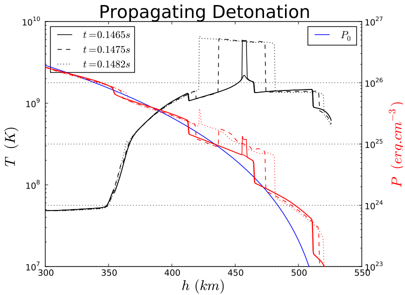
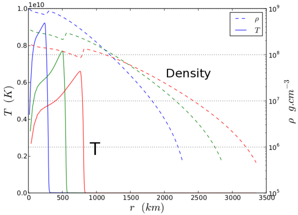


Application to supernovae

1. **A self-gravitating white dwarf :** Geometrical effects

$$F = \frac{1}{2}\rho u^2 C_s r^2, \; u(r) = u_0\sqrt{\frac{\rho_0 C_{s,0}}{\rho C_s(r)}} \times \frac{r_0}{r} \Rightarrow \text{weaker shocks.}$$

2. **Taking into account the initial deflagration phase :**
   - A thickened flame model to pre-expand the star...
   - Allowing for studies at decreasing densities (shallower gradients) :
     - $\rho_{fl} \sim 10^9$: $M \geq 0.02$
     - $\rho_{fl} \sim 3\ 10^8$: $M \geq 0.03$
     - $\rho_{fl} \sim 10^8$: $M \geq 0.05$



Where these perturbations come from ?

- Large scale combustion, driven by the Rayleigh-Taylor instability
- Possible magnetic reconnection after amplification in the flow
- Small scale combustion in very intense turbulence

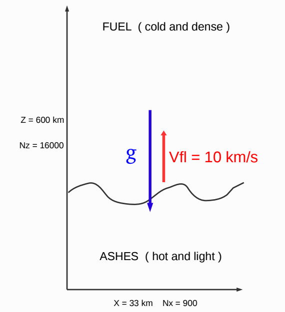
Turbulent combustion and magnetic field

2D Non ideal MHD simulations with OHM (G. Aulanier, LESIA) :

- OHM : A 5th order finite difference MHD code
- ADR flame :

$$\frac{\partial f}{\partial t} + \vec{v}.\vec{\nabla} f = D\Delta f + R(f)$$

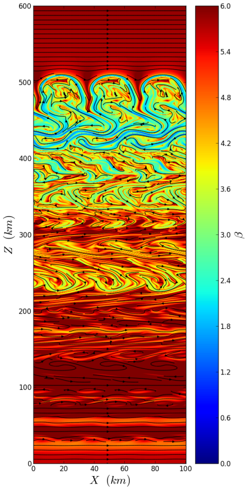
- Initial set-up :
  - Hydrostatic equilibrium
  - Slightly perturbed flame



2D RT driven combustion

2D RT driven combustion : Reconnection

2D RT driven combustion : Reconnection

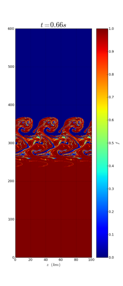


We could not check our hypothesis about magnetic reconnection :

- **Amplification of B**, but not enough for dynamic effects ($\beta \sim 10$)
- **Finite differences scheme**
  $\Rightarrow$ numerical diffusion
  $\Rightarrow$ less amplification

2D RT driven combustion

Acoustic emission :



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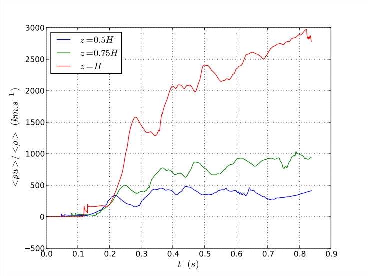


Perturbation of m ∼ 0.05

- A 2D flame can emit enough acoustic perturbations
- Perturbation are associated with large scales. In real 3D combustion, they will likely disappear...

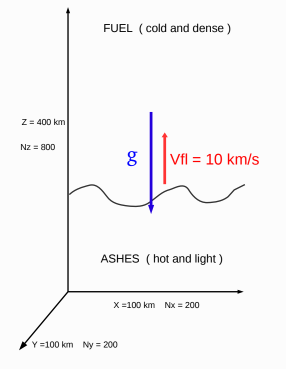
Rayleigh-Taylor driven flame in 3D

Hydro simulations with HERACLES (E. Audit, Maison de la Simulation) :

- HERACLES : A 2nd order Godunov hydro code.
- ADR flame :

$$\frac{\partial f}{\partial t} + \vec{v}.\vec{\nabla} f = D\Delta f + R(f)$$

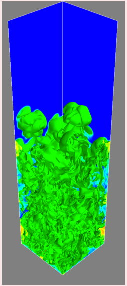
- Same initial set-up



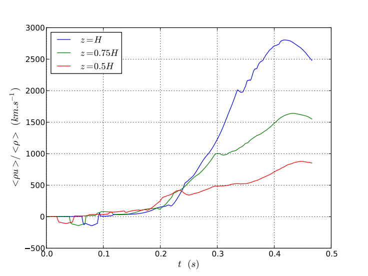
Rayleigh-Taylor driven flame in 3D

3D RT driven combustion

Acoustic emission :



$\Rightarrow$

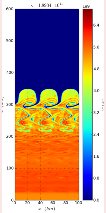


- Not much acoustic emission in 3D
- The magnetic field could prevent the small scale from growing
  $\rightarrow$ Moving the MHD code to 3D

Turbulent Flame : acoustic emission

Conclusion

New DDT mechanism, when density gradients are present :



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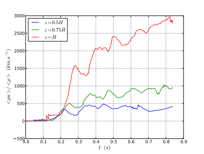

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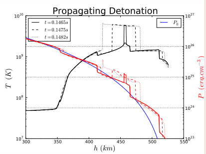


However...

1. It requires a sufficiently noisy flame
2. At large scales this is not sure
3. At small scales it seems to be the case for highly turbulent flames

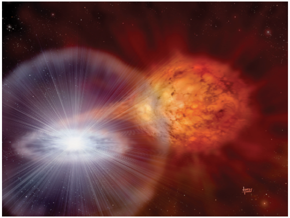
Conclusion

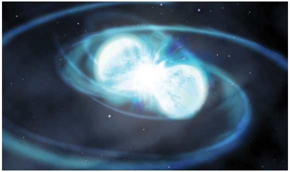
Take away

Thermonuclear SNe are more diverse than we previously thought

- Probably no single progenitor

- Single Degenerate scenario
  - − Rates and delay time distribution
  - − Accretion physics
  - + Robust and well studied ignition
  - ± Physical mechanism for DDT





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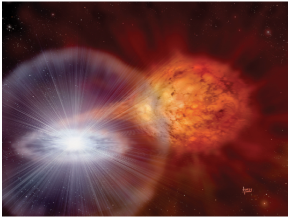

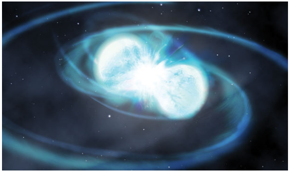

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Peculiar Supernovae : sub-luminous

There are two kinds of subluminous supernovae :

1. 1991bg-like supernovae
   - Low ^{56}Ni mass ($\sim 0.1 M_{\odot}$)
   - ^{28}Si present in most of the ejecta

Detonation at low densities

For example a violent merger of 2 WD of $0.9 M_{\odot}$ (Pakmor & al 2010)

2. 2002cx like or **type Iax supernovae**
   - Low ^{56}Ni mass ($\sim 0.2 M_{\odot}$)
   - Very low expansion velocity
   - Well mixed ejecta

Pure deflagration leaving bound remnant

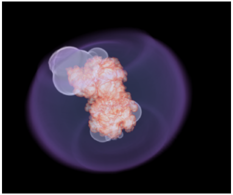
Deflagration naturally explains low kinetic energy and mixed ejecta
Leave a bound remnant : C+O white dwarf with an iron core (Kromer & al 2012)

Peculiar Supernovae : super-luminous

Super-M_{ch} explosions

Such luminosities $\Rightarrow {}^{56}Ni > 1 M_\odot \Rightarrow M_{WD} > M_{ch}$

- Degeneracy pressure cannot support more than M_{ch}
- Centrifugal force could stabilize well above this threshold
- Also rotation will "focus" a deflagration, leaving more fuel for the detonation



Hillebrandt&al2013

Delayed detonation of a rapidly rotating WD

A 2 $M_\odot$ rotating WD could produce 1.5 $M_\odot$ of ^{56}Ni

Constraint on the progenitor system

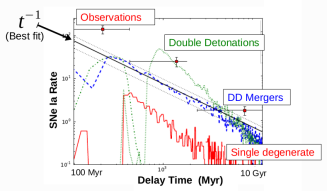
Rates an delay time distribution

- $\nu_{gal} = 0.003\ SNe.yr^{-1}$
- $\nu(t) \propto t^{-1}$

Binary population synthesis studies are parameterized :

- Common envelope
- Accretion efficiency

$\Rightarrow$ Results highly dependent on the group preferred model...



Delay time distribution from Hillebrandt & al 2013

BPS are not yet mature, but

- DD reproduce naturally a t^{-1} DTD ($\tau_{GW} \propto a^{-4}$)
- SD has some problems reproducing the DTD

Unconfined DDT ?

In unconfined media a DDT could be triggered through the Zeldovich's gradient mechanism
$\Rightarrow$ turbulence would create the appropriate conditions.

Flame and turbulence interaction :

- Gibson scale, l_G, defined by $\tau_{turb}(l_G) = \tau_{fl}(l_G)$
  - $\tau_{turb} = l/\delta_v(l)$: Eddy turnover time (at scale l)
  - $\tau_{fl} = l/S_{lam}$: Flame crossing time (at scale l)
- Karlovitz number : $Ka = \sqrt{\frac{\delta_{fl}}{l_G}} = \left(\frac{\tau_{fl}(\delta_{fl})}{\tau_{turb}(\delta_{fl})}\right)^{3/2}$
  - if $Ka < 1$: wrinkled flame regime
  - if $Ka > 1$: distributed regime

DDT in distributed flame ?

Fundamentally different regime $\Rightarrow$ broadened reaction zone