A New Approach to the Transition Deflagration to Detonation (TDD) in Thermonuclear Supernovae

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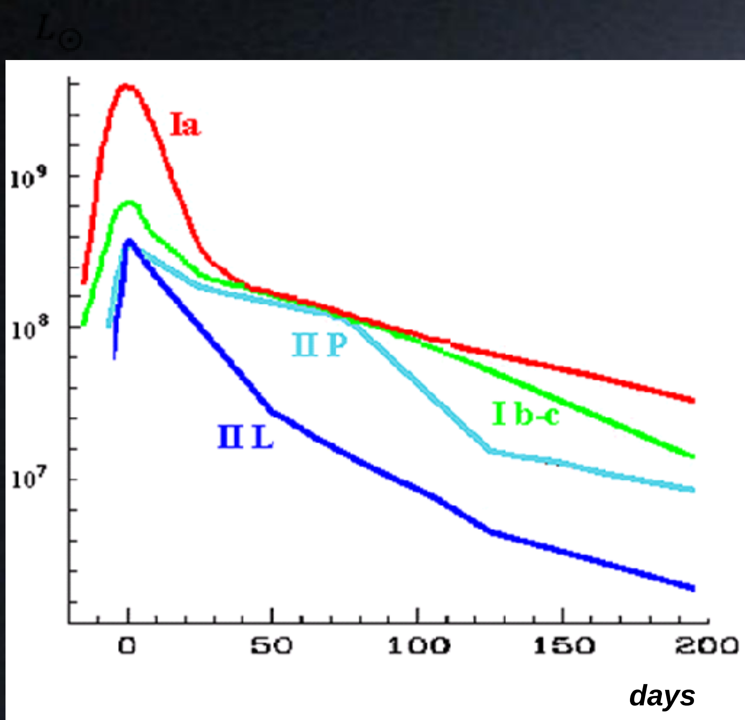
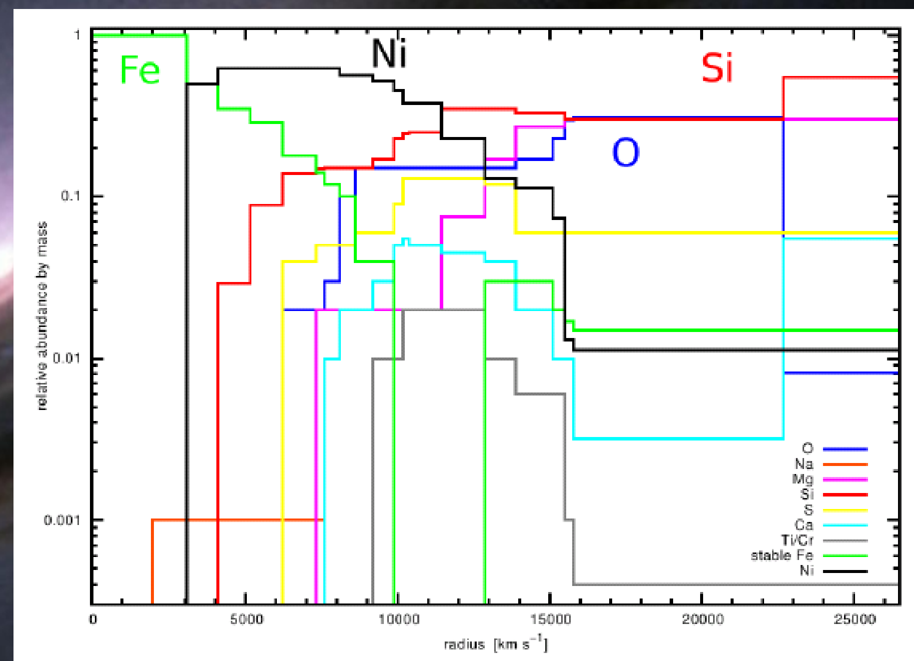
What are Thermonuclear Supernovae ?

Two types of supernovae : Core-collapse and Thermonuclear

- SN Ia have similar light curves, powered by $^{56}Ni \longrightarrow {}^{56}Co \longrightarrow {}^{56}Fe$ decays.
- SN Ia: no H in spectra, ^{28}Si and IME lines
  SNIb, SNIc, SNII : H lines in spectra.

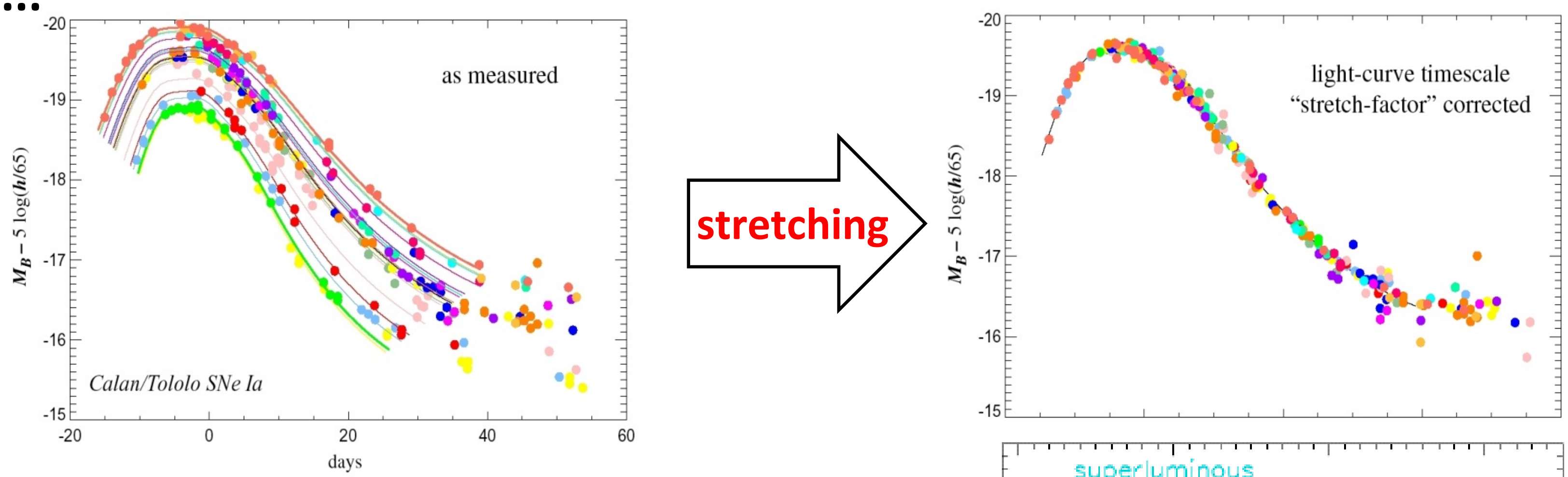




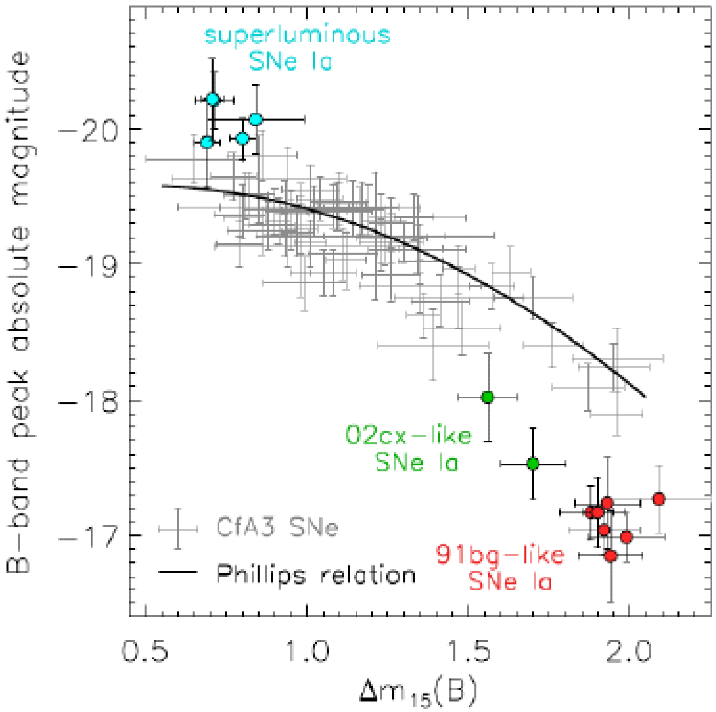
Spectrotomography of a SN Ia
Hachinger et al. 2012

SNIa empirical specificity

- **SN Ia light curves are 'standardizable' …**



- **… with exceptions :**



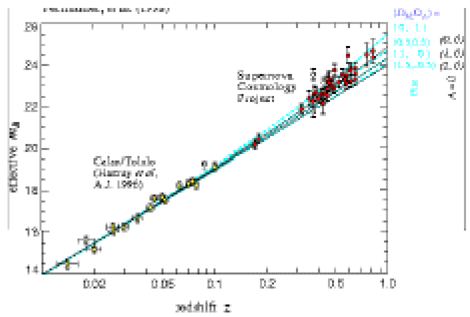
when « anomalous » SN Ia are excluded, the dispersion of the Philipps relation :

$$M_{max}(B) = -21.7 + 2.7\Delta m_{15}(B)$$

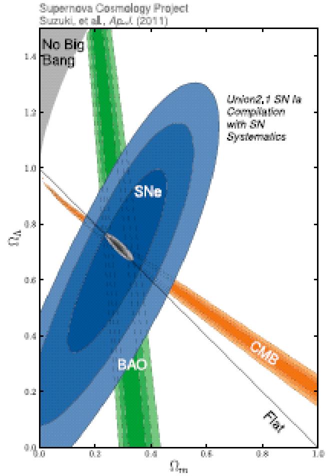
reduces to $\sigma = 0.11$

SNIa and cosmology

- **SN Ia revealed the acceleration of the expansion of the Universe Perlmutter, Schmidt & Riess Nobel Prize 2011**



- **SN Ia provide complementary constraints to BAO and CMB for ΛCDM models**



- **But the determination of the Hubble constant from SN Ia** (Riess et al., 2009)

$$H_0 = 72.4 \pm 3.4\ km\, s^{-1} Mpc^{-1}$$

is in tension with the value obtained by Planck :

$$H_0 = 67.3 \pm 1.2\ km\, s^{-1} Mpc^{-1}$$

What are Theoretical Thermonuclear Supernovae ?

- **Thermonuclear supernovae result from the thermonuclear explosions of a Carbon-Oxygen white dwarf**

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

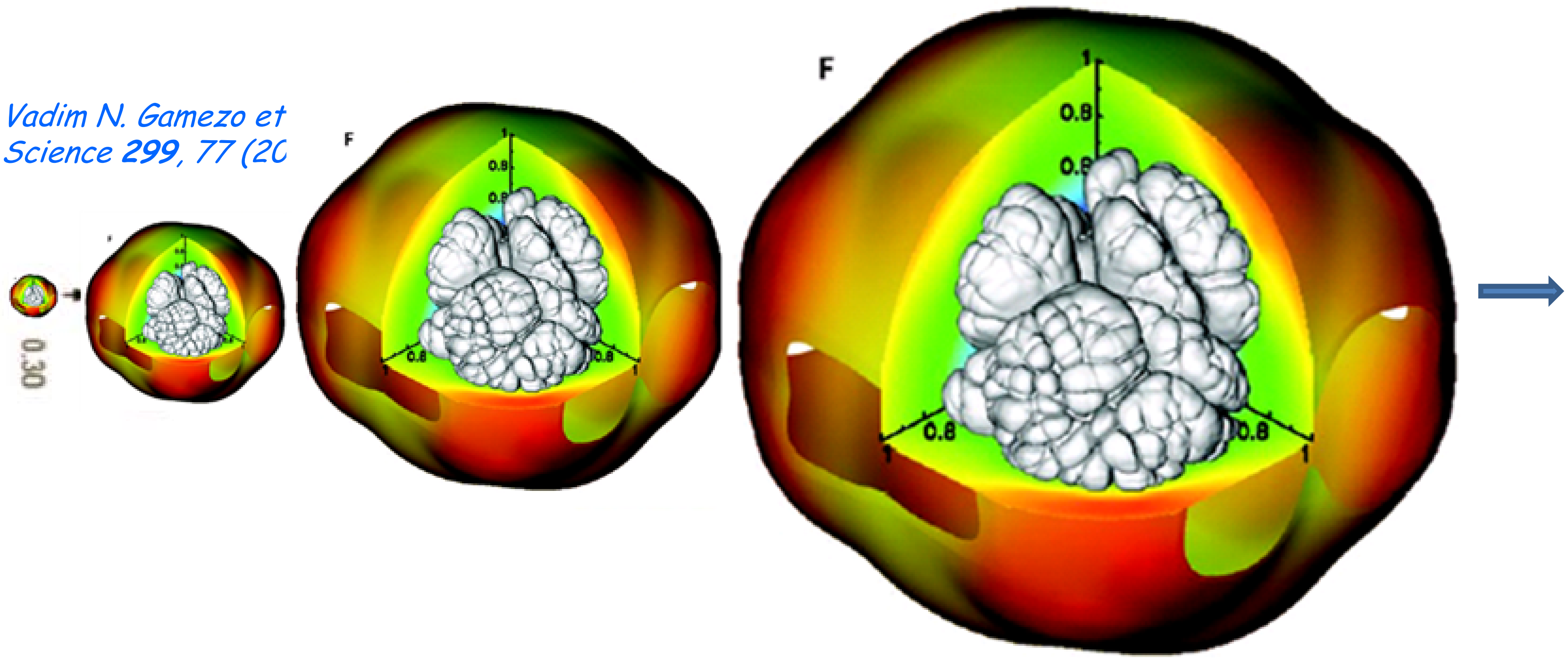
- **Despite considerable numerical efforts, even the actual combustion regime is still uncertain** ***(Calder et al. 2013)***

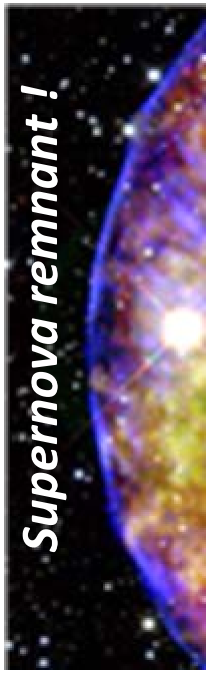
- **We propose a new mechanism as a contribution to the long-lasting problem of the transition from the delagation to the detonation (DDT) combustion regimes.**

Deflagration (or Flame)

- Propagates through efficient electronic conduction and radiation
- Very subsonic ($\Delta P/P \ll 1$) ⇨ Inflation of the star ⇨ Synthesis of IME
- Unstable against Rayleigh-Taylor, etc. ⇨ Generation of acoustic energy

Vadim N. Gamezo et Science ***299****, 77 (20*





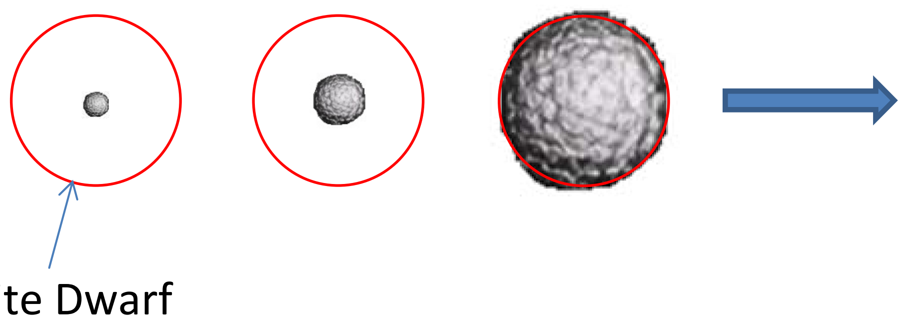
Two Combustion Regimes

Detonation

- Supersonic : Propagates as a shock wave $(\Delta P/P > 1)$, followed by combustion
- No inflation of the star

  ⇒ High density nucleosynthesis ⇒ most material incinerated to ^{56}Ni

- Weak cellular instabilities



Deflagratons & Detonations vs. Observations

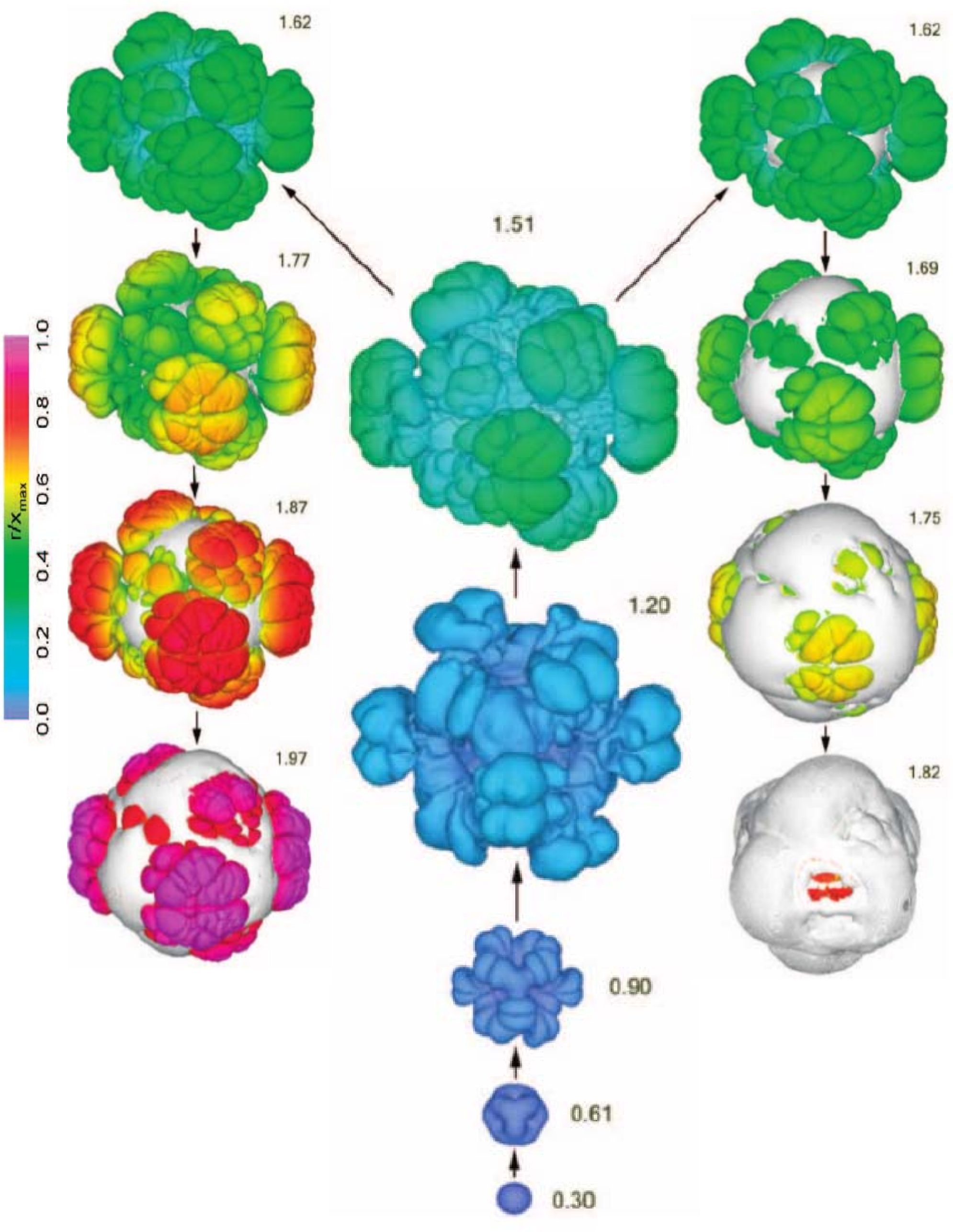
Detonations

- ⬀ Complete combustion $(10^{51} erg)$
- ⬀ « Brighter-Slower » light curve correlation
- ⇩ Synthesis of 1,4 M_{sol} $\{Fe\}_{ENS}$
- ⇩ No intermediate mass elements {Mg, Si, S, Ar, Ca}

Deflagrations

- ö Nucleosynthesis :
  internal layers {Fe} – intermediate {Mg-Ca } – external {Ø}
- ⇩ « Brighter-Faster » light curve correlation
- ⇩ Slow velocity of the IME layers : 10 000 km/s vs. 25 000 km/s obs.

Delayed Detonation Models



Combining ...

- A **deflagration** to expand the star
- A **detonation** to incinerate the remaining fuel

Consistent with nucleosynthesis and energetics if

- $\rho_{DDT} \sim 2 \times 10^7 g\ cm^{-3}$

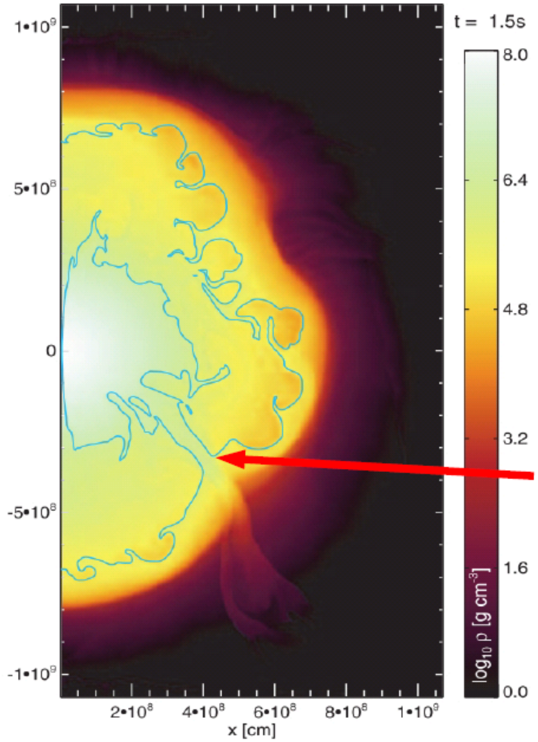
But ...

The physical mechanism for Deflagration to Detonation Transition is still unknown !

Models to Get a 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
- ...



They all rely on the Zel'dovich indiction time gradient mechanism ...

But on widely unresolved scales

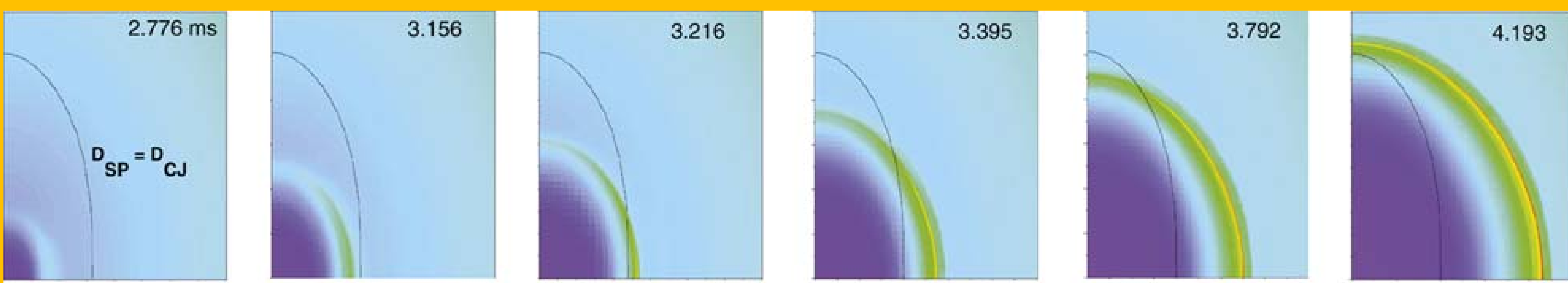
Unconfined DDT ?

In unconfined media a DDT could be triggered through the Zel'dovich gradient mechanism (Zel'dovich & al. 1970)

A suitable gradient of induction time of thermonuclear reactions requires well shaped gradients of temperature, density or composition.

Spontaneous Combustion Wave with velocity $D_{sp} = 1/\nabla\tau_i$

small τ_i → **large τ_i**



Oran & Gamezo 2007

Turbulence would create in some places the appropriate gradients.

Unconfined DDT ? The Zel'dovich Gradient Mechanism

Woosley (2009) obtained a DDT in 1D Linear Eddy Model simulation and concluded that the level of turbulence needed shouldbe **20%** of sound speed.

Is such a level of turbulence realistic ?

Maybe through intermittency (Röpke 2007)

But strong turbulence may destroy the gradient itself ... before the induction time.

In this context we propose a novel approach...

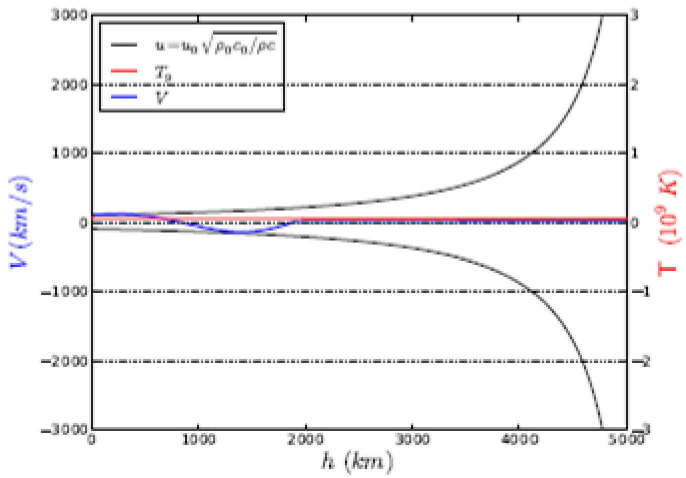
Acoustic wave amplification in a density gradient

We considered another original approach :

1. Perturbations are produced in the flame,

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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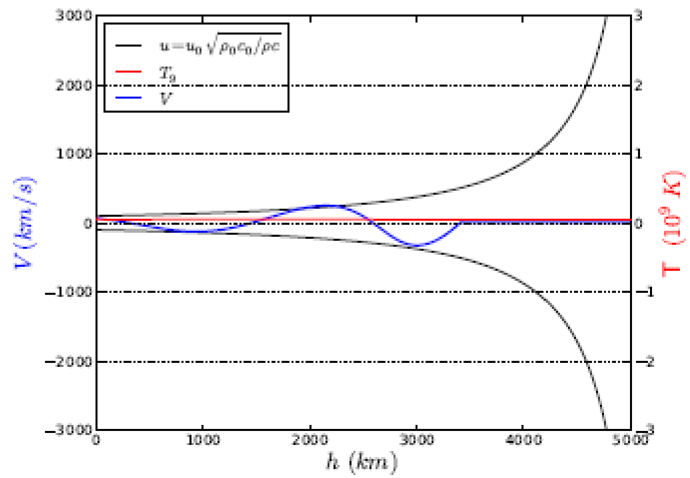

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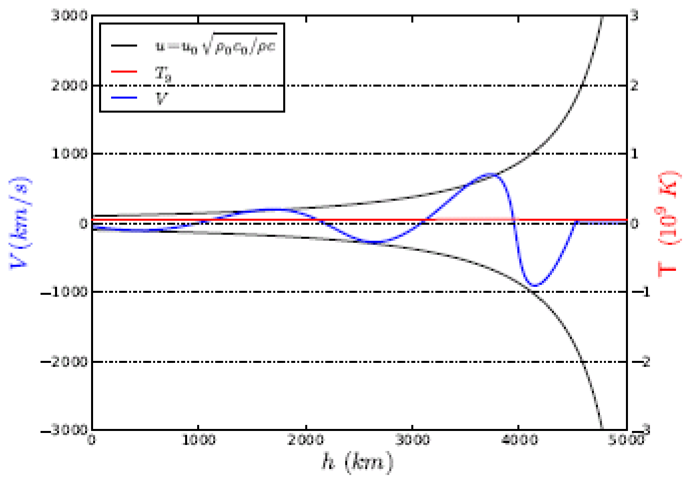

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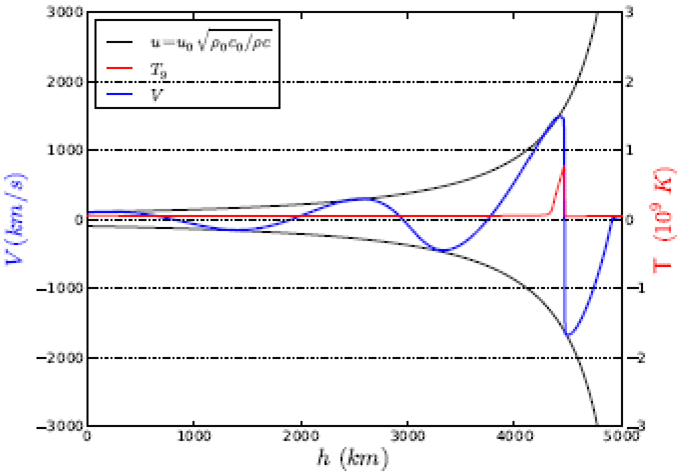

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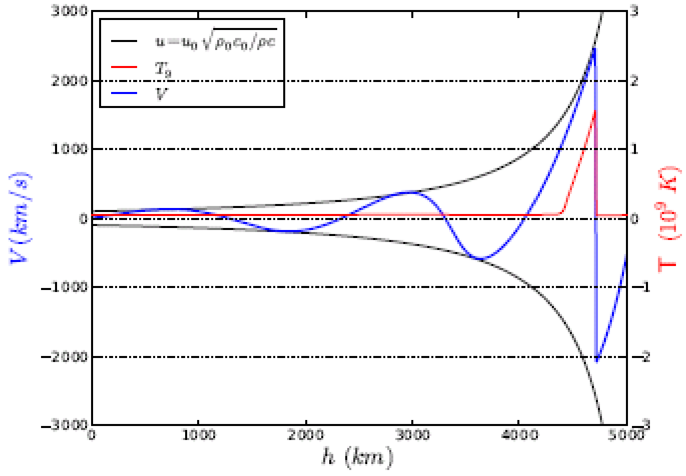

Successful Detonation

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4. If strong enough : a detonation can be ignited (well ahead of the flame $\Rightarrow$ non local DDT)

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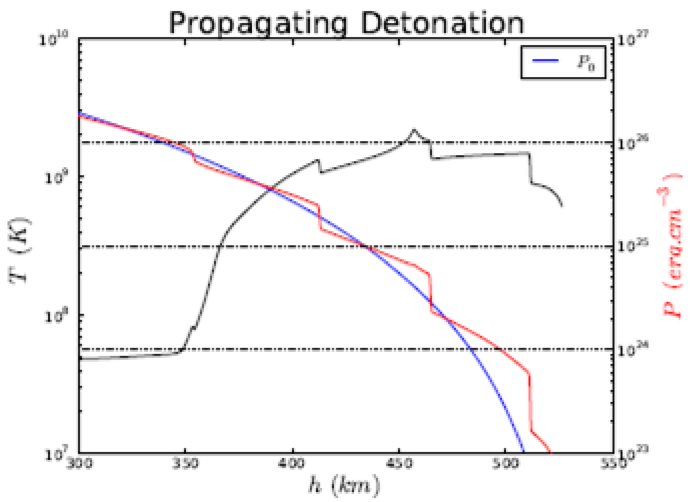

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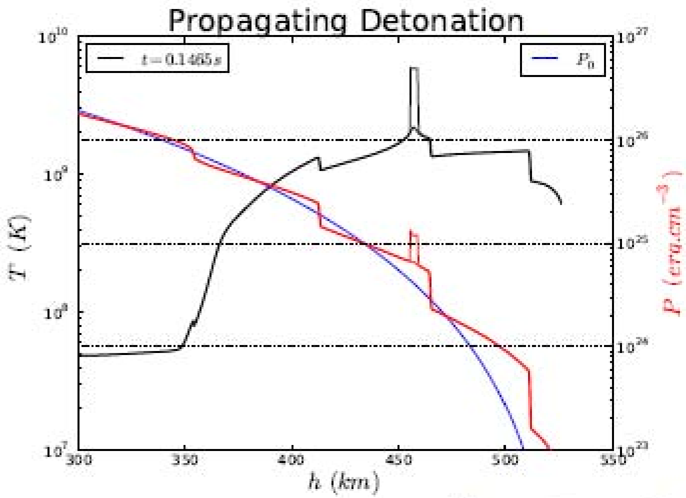

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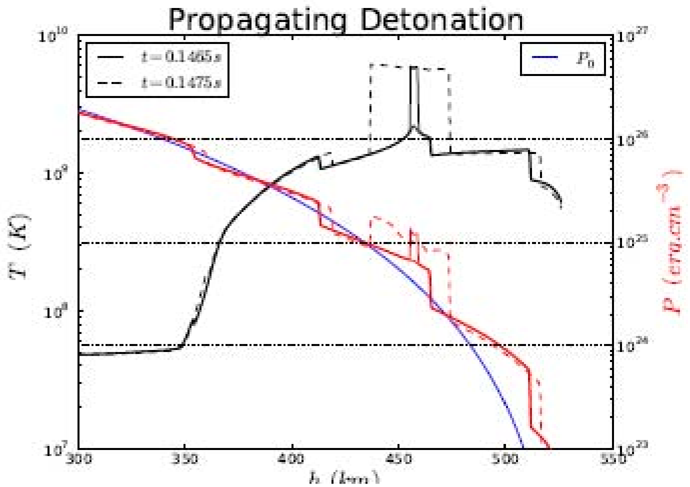

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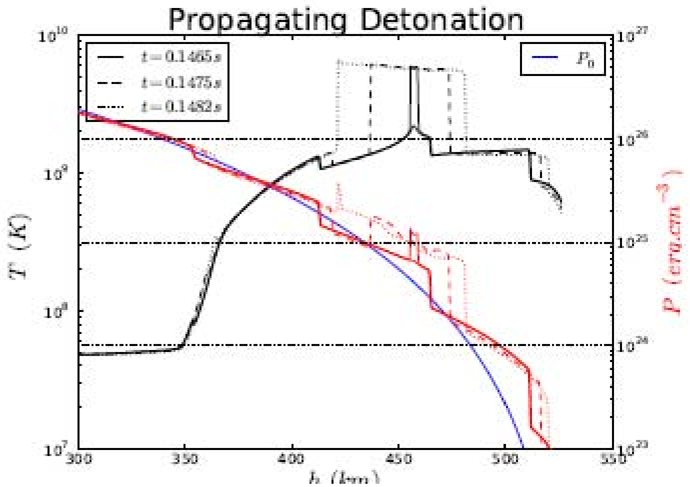
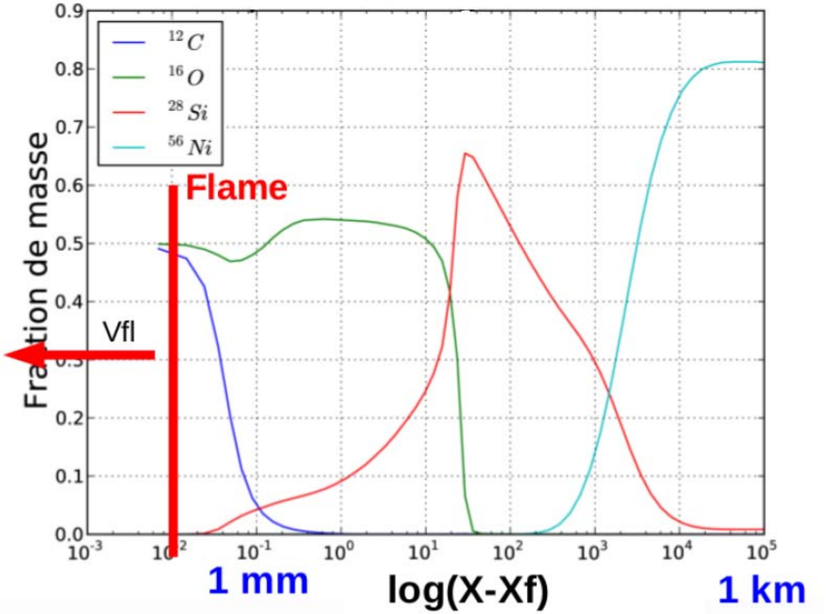


Successful Detonation

High resolution (few μm) HD simulation with ASTROLABE (ALE)



3 Burning stages :
Carbon – Oxygen– Silicium burning

3 well separated reaction lengthes
C: 1 cm – O: 1 m – Si: 1 km

Ignition of the non local TDD is confirmed by a very high resolution calculation

Conclusion

- **We propose a new process able to initiate a detonation from a deflagration, based on the amplification of low amplitude acoustic waves in the density gradient of a white dwarf.**

- **A major input for this process is the spectrum and level of the acoustic noise produced by the turbulent flame.**

- **The non-local nature of this process may generate specific signatures in the SN Ia light curves, and may partly account for the diversity of these events.**

Thank you !