A New Mechanism for Deflagration to Detonation Transitions

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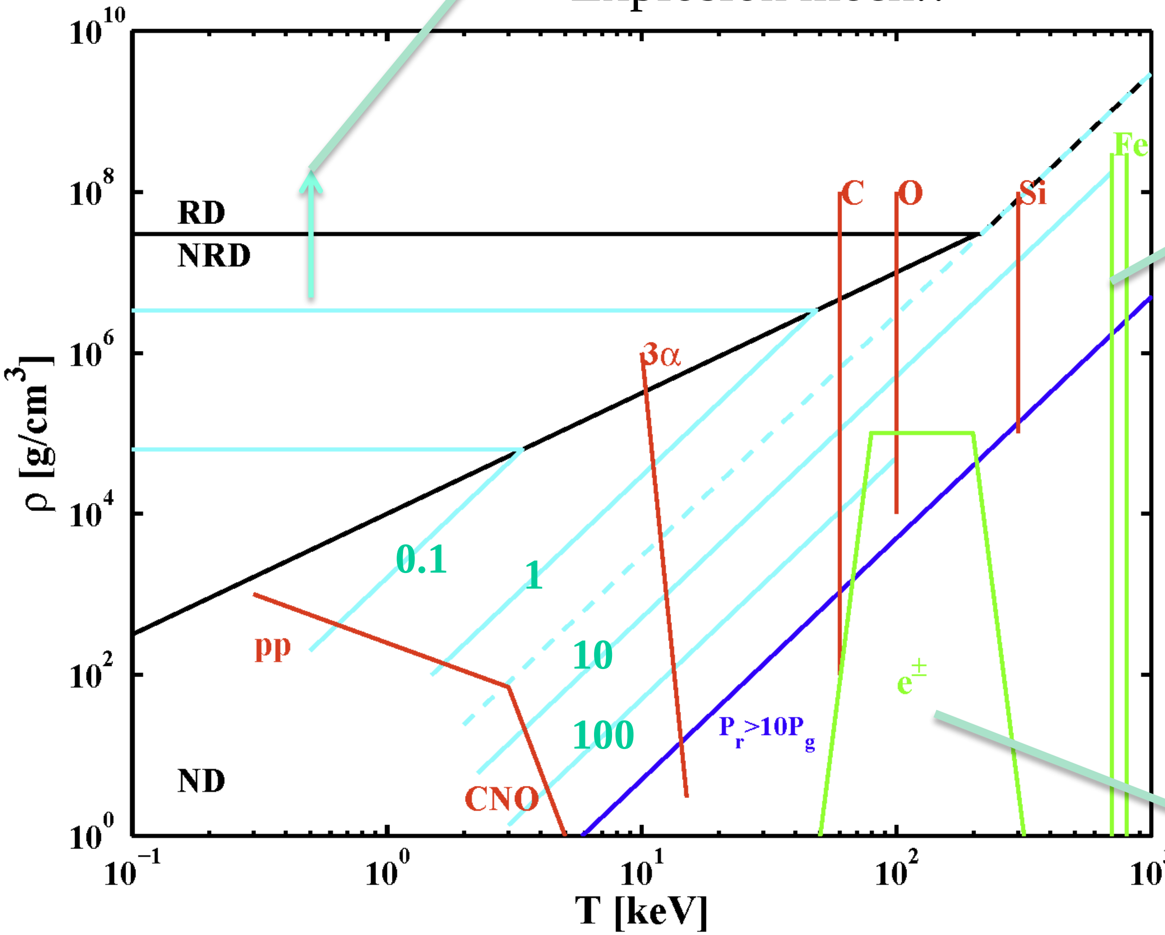
Supernova (SN) types & Open Q's

Ia SNe
- Accretion or Merger induced?
- Explosion mech.?



II, Ib, Ic
Core collapse SNe
- Explode?
- Type II, Ib, Ic- Envelope evolution?

Pair-Instability SN
- Exist?
- Pre-explosion evolution?

Ia's

- The common view
- Ignition of C/O under degenerate conditions (White Dwarf)→ thermonuclear "runaway" → No NS remnant, ~10^{51} erg (1MeV/nucleon=2×10^{51} erg/M_{sun})

[Hoyle & Fowler 60]

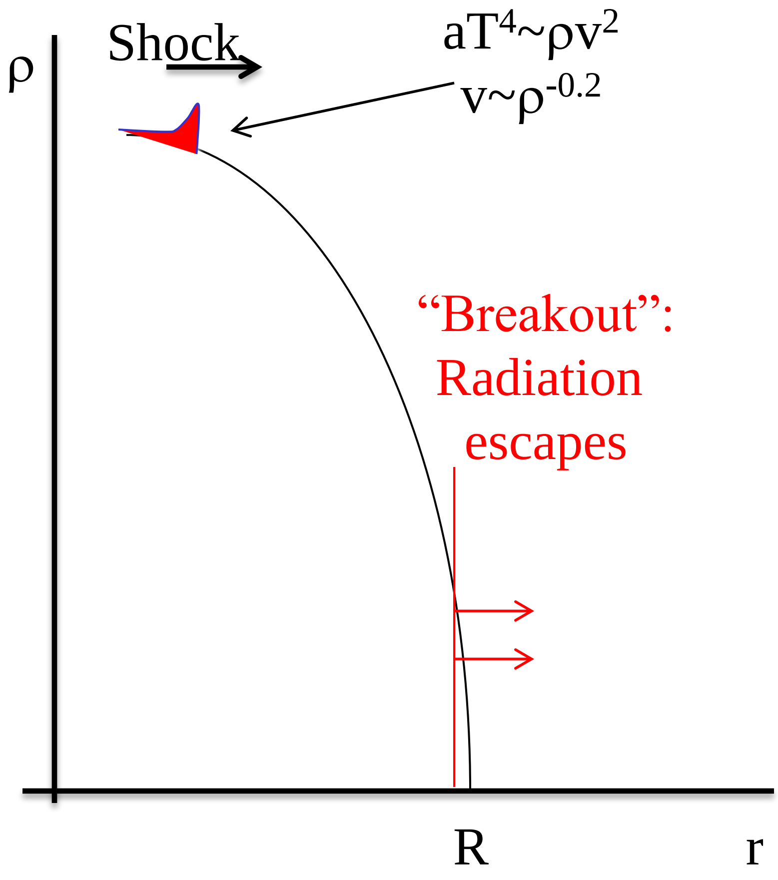
- Support: Composition, v, Light curves (E, v)

- Open Q's
- Progenitors: Accretion/merger?
- How is the explosion triggered?
- How does the burning propagate: Pure deflagration or DDT?
- DDT mechanism?
- Why so uniform?

[eg Hillebrandt & Niemeyer 00]

A recent development

- Wide field surveys (eg PTF): post-Breakout-detection

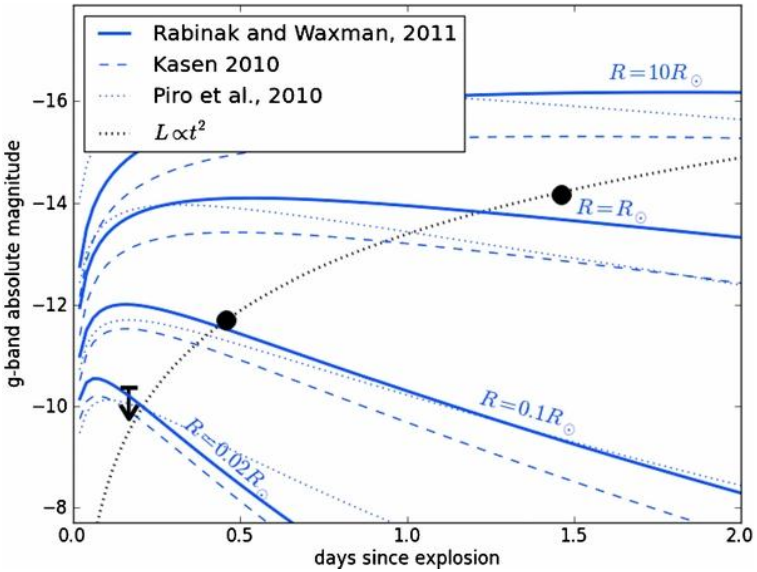


- Ia SN 2011fe early non-detection:

  First direct determination of compact prog. Radius:

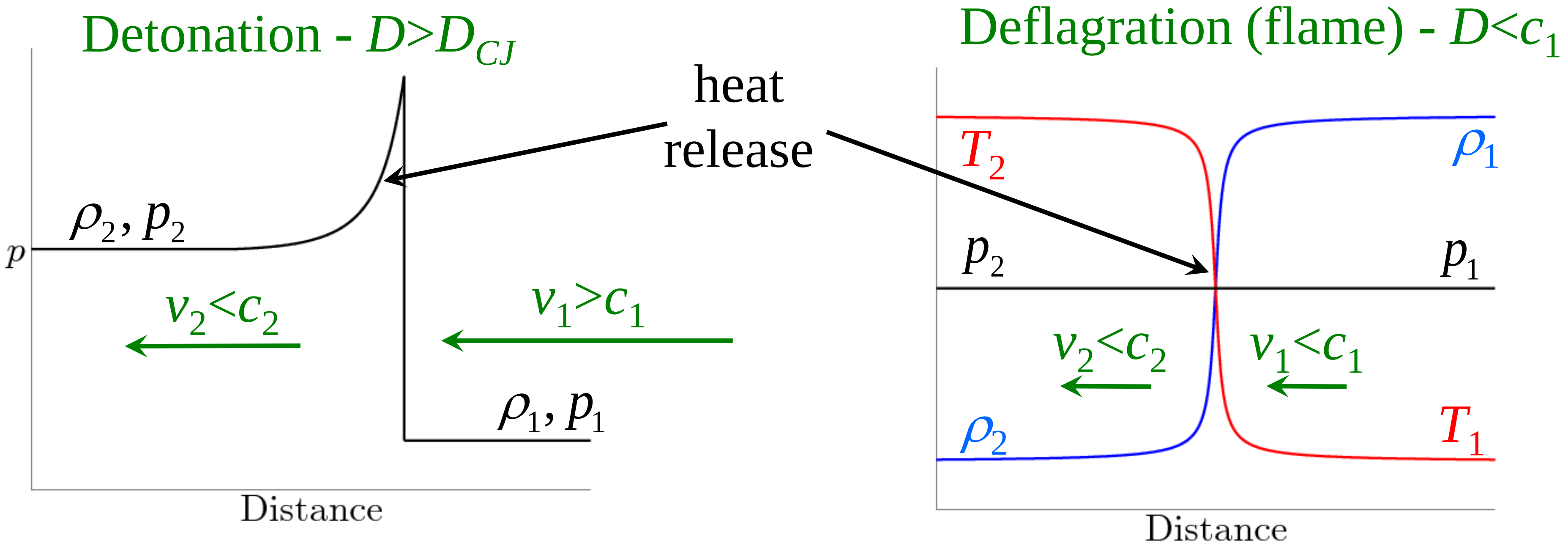
  $R < 10^{10}$cm [Nugent et al 11]

  $R < 10^{9}$cm [Bloom et al 11]



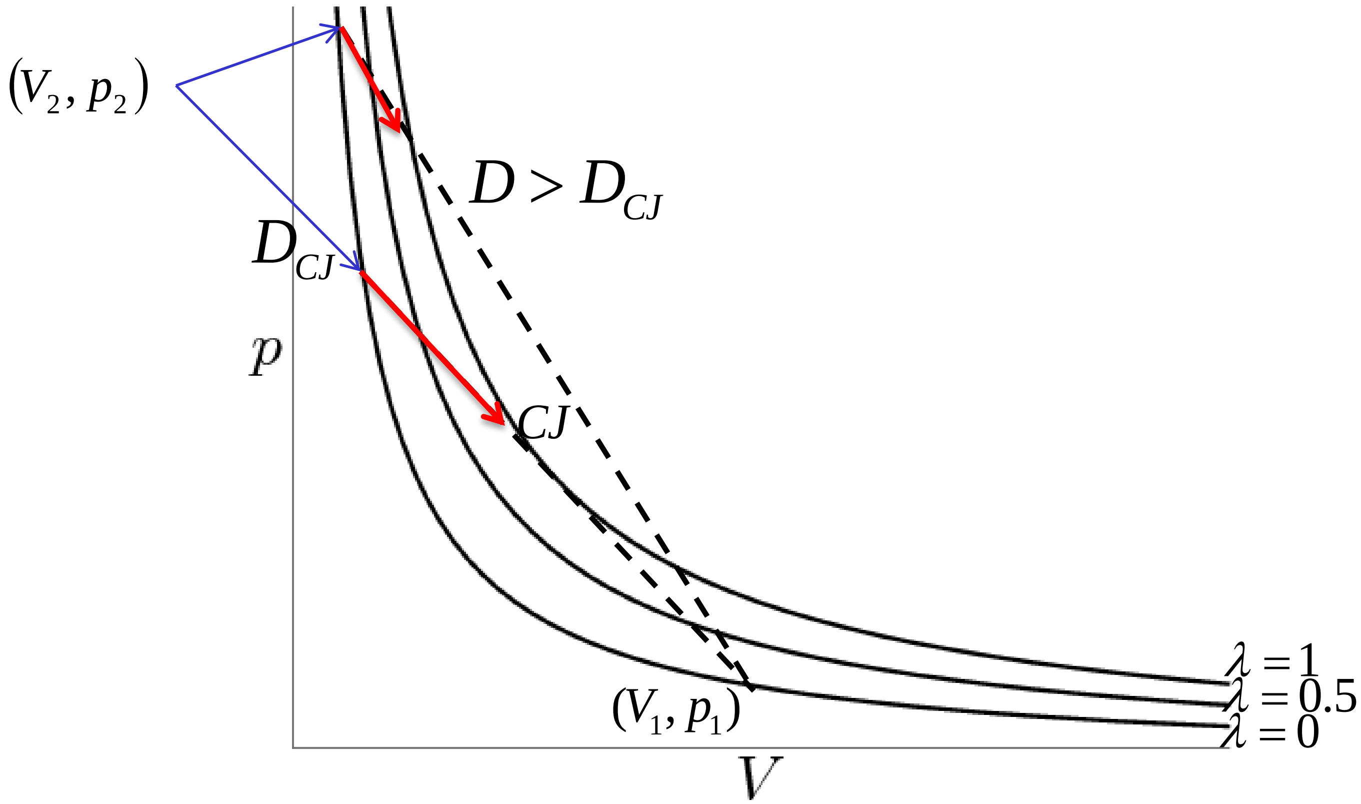
[Bloom et al. 11]

Ia: Thermonuclear combustion of C/O WD



ZND Theory

shock $\Rightarrow$ ignition $\Rightarrow$ reaction zone

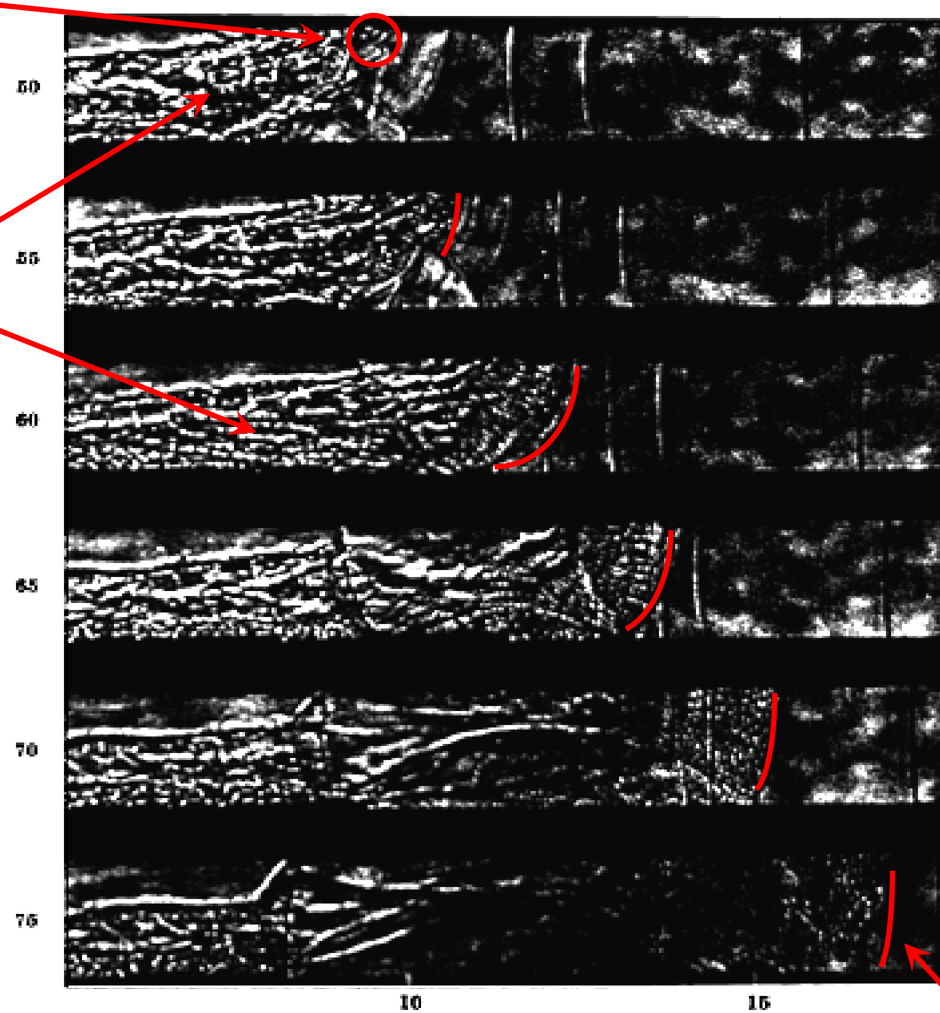


Ia DDT

- Ejecta composition suggests
  Deflagration-to-Detonation-Transition (DDT)

- Pure detonation- complete burning to Fe group
- Sub-sonic deflagration: expansion → lower density burning → intermediate mass elements
- Pure deflagration difficulties: v, mixed composition

DDT in the laboratory



Urtiew, Oppenheim, 1966

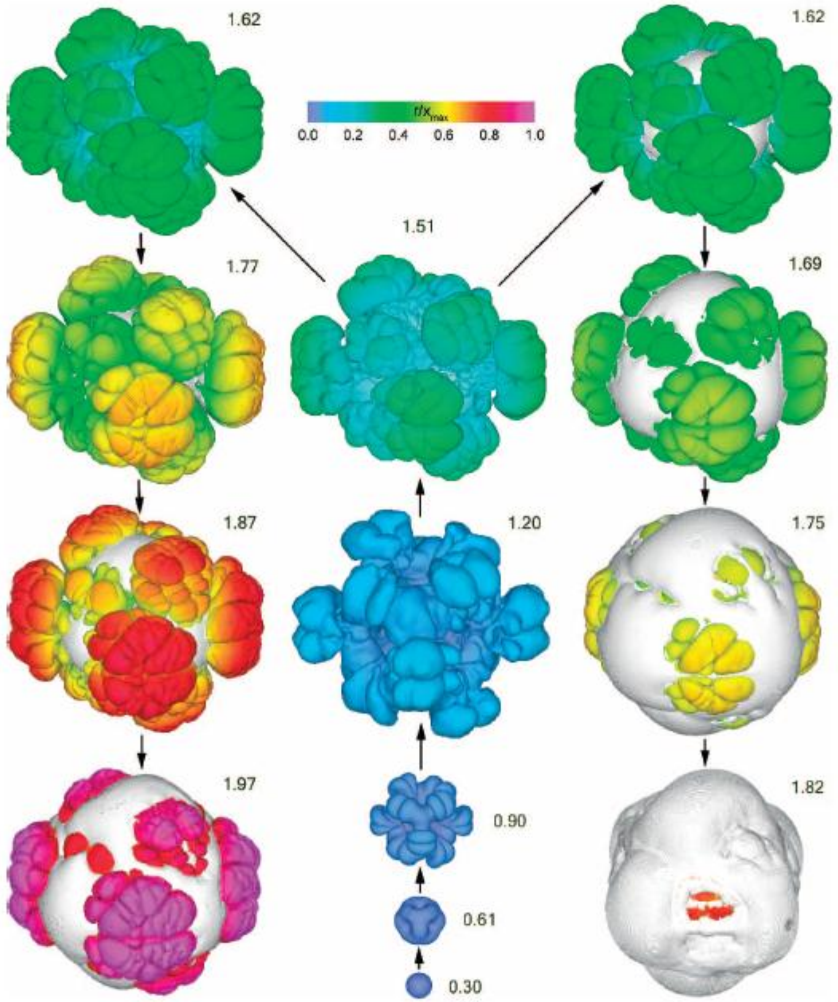
- DDT is an open question in combustion theory.

- Common features of laboratory DDT:
  - turbulent flow field
  - hot spot explosion

DDT in Ia explosions

• Rayleigh-Taylor instability
  → turbulent flame
  →burned/unburned material mix

• Detonation initiated by artificially introducing a Hot spot

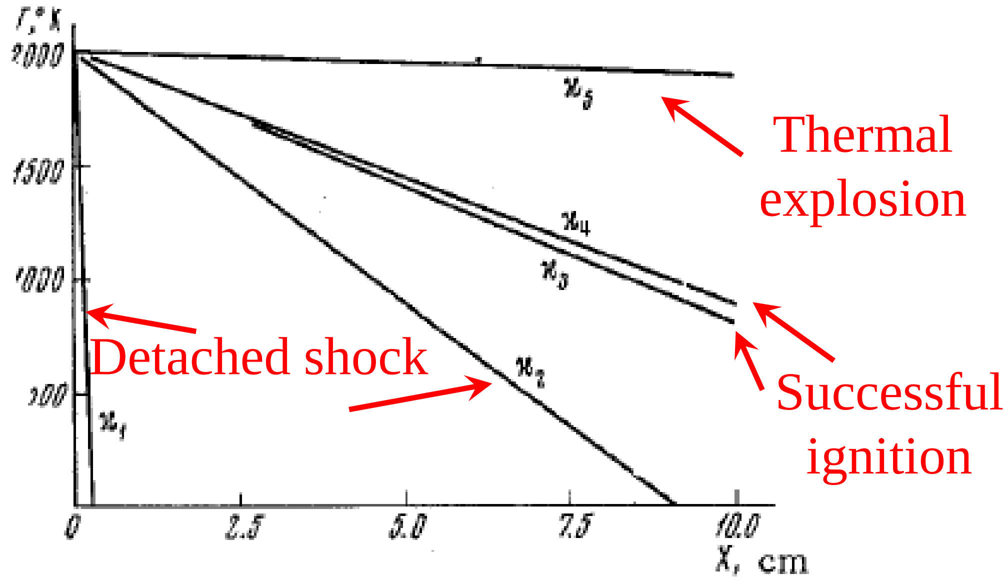


Gamezo et al., 2005

DDT mechanisms: I

- Zel'dovich et al., 1970
  A spatial gradient in chemical induction time
  → A spontaneous reaction wave with $v_p \approx D_{CJ}$.

Initial temperature distributions



?? How gradients are maintained over the critical length?
(10^4—10^5cm @10^7g/cc, Seitenzahl et al. 09)

DDT mechanisms: II

- Our Mechanism:

  - Converging shock waves ignite detonation, provided the radius at which they become strong exceeds R_{crit} (may be tested experimentally).

  - DDT may be due to converging shocks produced by the turbulent deflagration flow, which reaches sub (but near) sonic velocities on scales $\gg R_{crit}$.

?? Are such converging shocks indeed produced in deflagration flows?

[Kushnir & EW 11]

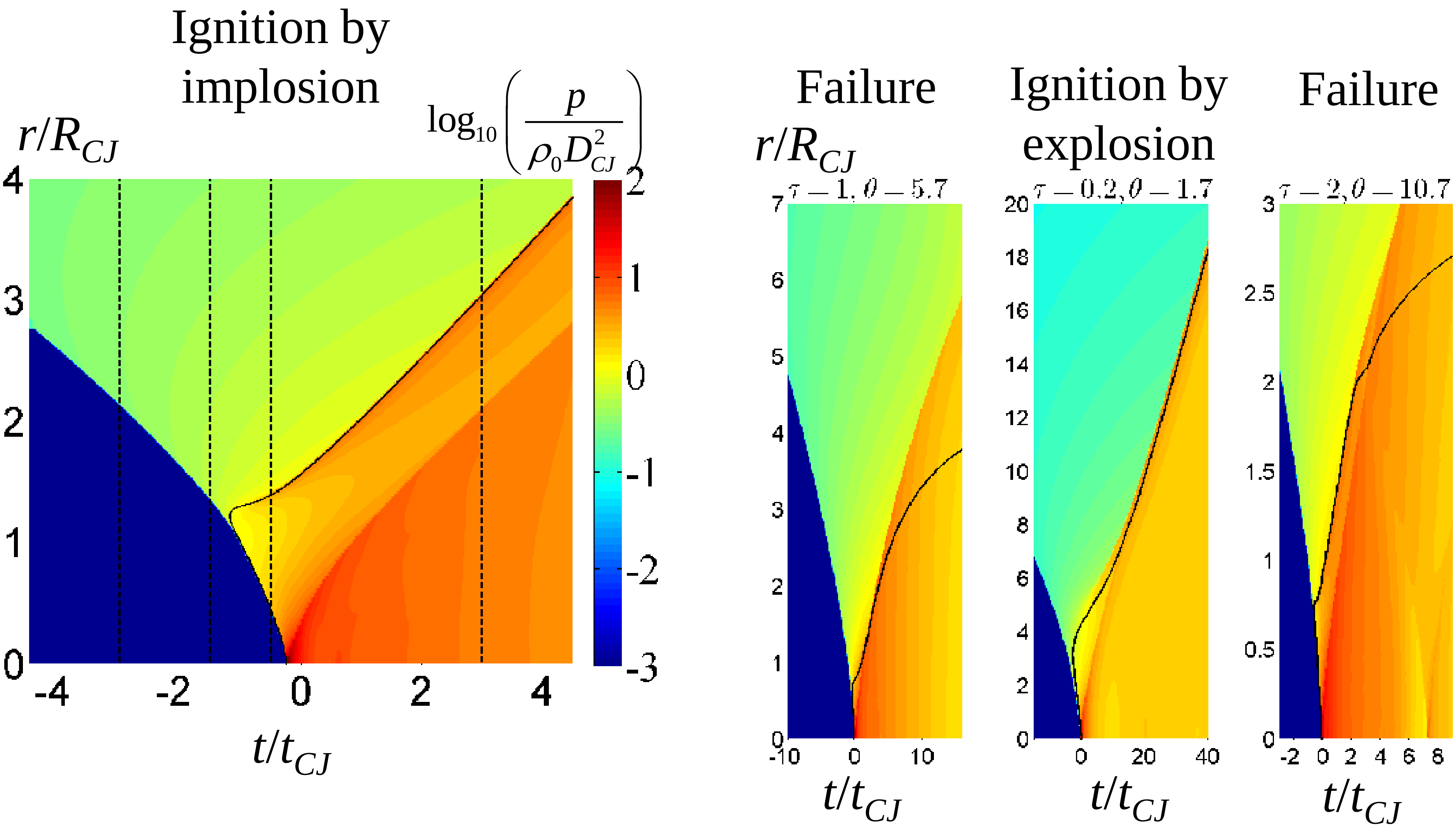
A simple model

- EOS: $$\varepsilon(p,V,\lambda) = \frac{pV}{\gamma - 1} - \lambda Q$$
- Burning: $$\frac{d\lambda}{dt} = \kappa \left(\frac{\rho}{\rho_0} \right)^n (1-\lambda)^m e^{-(p_A/\rho_0)/(p/\rho)}$$
- Initial conditions: Converging shock
$$\dot{R} = -D_{CJ} \left(\frac{R}{R_{CJ}} \right)^{\delta}, \qquad D_{CJ} = \sqrt{2Q(\gamma^2 - 1)}$$
- 5 dimensional parameters (ρ_0, D_{CJ}, R_{CJ}, κ, p_A)

  → fully determined by 2 dimensionless parameters:
$$\tau \equiv \frac{p_A}{\rho_0 D_{CJ}^2}, \quad \text{and } \theta \text{ (TBD).}$$

  (+ γ, n, m).

Some numerical examples



Approximate analytic results

- Ignition criterion:

$$\frac{Q}{t_q}\min\left[t_q, t_h\right] > f\ Q_h = f\,\frac{2}{(\gamma+1)^2}\dot{R}^2 \qquad \text{for some } R,$$

$$\text{where} \quad t_q^{-1} \equiv \frac{d\ln\lambda}{dt},\ t_h^{-1} \equiv \frac{d\ln R}{dt}.$$

- Translates to:

$$\theta > f\ g(\xi) \quad \text{for some } \xi > \left[\frac{8(\gamma-1)}{\gamma+1}\right]^{-1/2\delta},$$

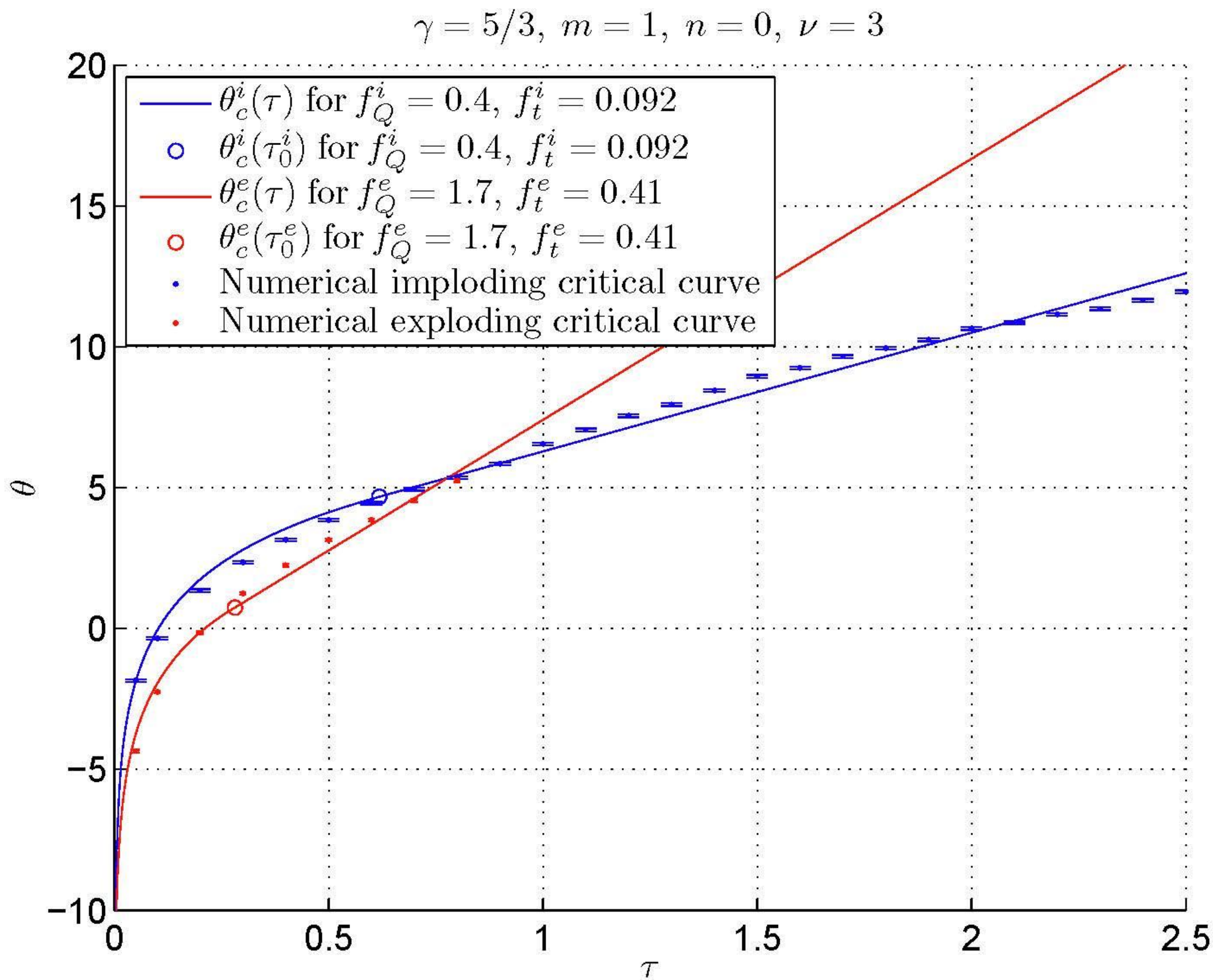
$$\text{where} \quad \xi \equiv R/R_{CJ}\ ,$$

$$g(\xi) = \eta\xi^{-2\delta} - (1-3\delta)\ln\xi,$$

$$\theta \equiv \ln\left(\frac{\kappa R_{CJ}}{(1-\delta)D_{CJ}}\right) + n\ln\left(\frac{\gamma+1}{\gamma-1}\right) + 2\delta\ln\left(\frac{4(\gamma-1)}{\gamma+1}\right).$$

→ $\theta > \theta_c(\tau)$, i.e. R_{CJ} should exceed a critical value.

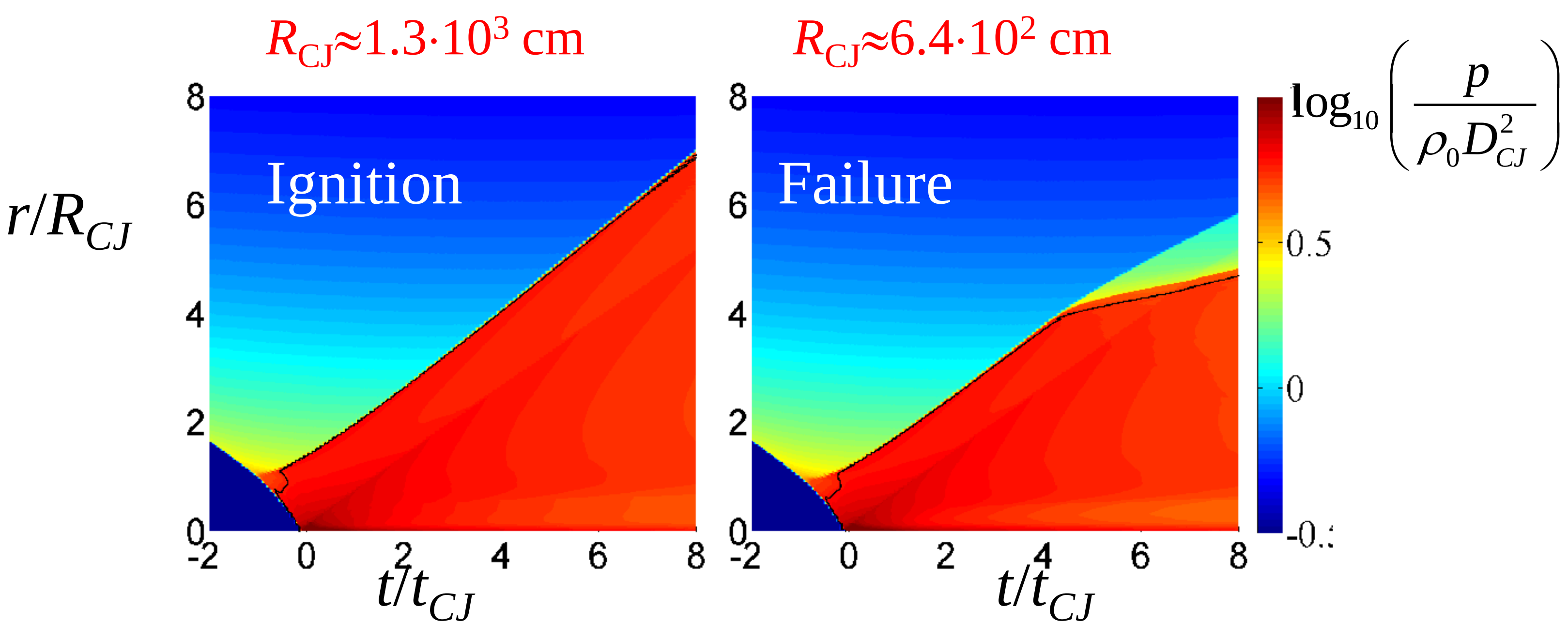
Critical radii: Analytic vs. Numeric



Critical radii: Lab & Ia's

- Laboratory stoichiometric acetylene-air experiments:
  - R_{CJ}~5μ, $R_{M=2}$~100μ.
  - R_{CJ} too small to be resolved (numerically), $R_{M=2}$<<channel diameter

- Ia's: Velocity fluctuations ≃10^8cm/s ($\mathcal{M}$≈1.2) on 10 km scale,
  ρ_0 ≃10^7g/cc
  - Preliminary: R_{CJ} too small to be resolved, $R_{M=2}$~0.1km<<10km



Summary

- Converging shock waves ignite a detonation provided the radius at which the shock becomes strong exceeds R_{crit}.
- $R_{crit} \approx 1$ mm for typical acetylene-air experiments and $R_{crit} \approx 10^4$ cm for the pre-detonation phase of WD in delayed-detonation scenarios of SNIa explosions.
- We suggest that the DDT observed/inferred in these systems may be due to converging shocks produced by the turbulent deflagration flow, which reaches sub (but near) sonic velocities on scales $\gg R_{crit}$.
- Under progress: Evolution of multidimensional perturbations during shock implosion does not suppress the ignition of detonation;
  Ia's: Realistic EOS & nuclear reaction network.
- In order to determine whether our suggested mechanism is indeed responsible for DDT, a detailed analysis of the turbulent flow is required.