SAND2011-5627C

Exploding Stars, Indestructible Flames, Dark Energy, and the Origin of Elements: The Turbulent Mixing Connection

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August 18, 2011

CRF Research Highlight

The U.S. Department of Energy, Office of Basic Energy Sciences, Division of Chemical Sciences, Geosciences, and Biosciences supported this work. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy under contract DE-AC04-94AL85000.

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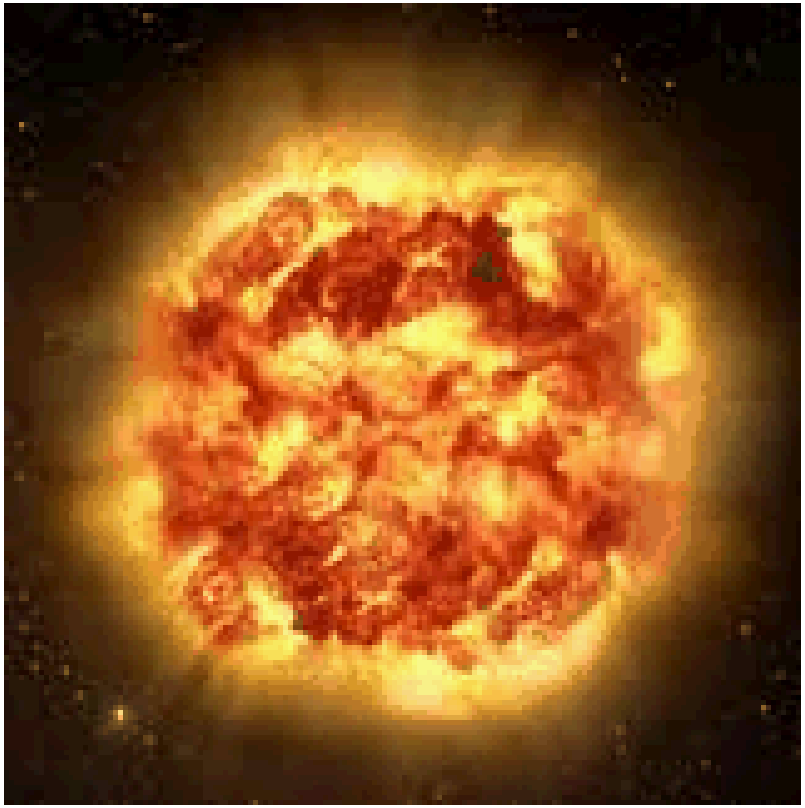
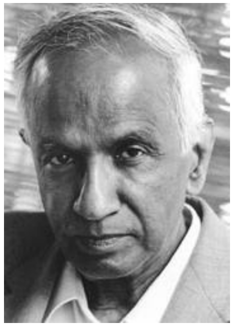
Explaining supernova explosions is a scientific grand challenge with deep implications



- Why is it important?
- Why is it hard?

Supernovae are important from several perspectives



- They confirm the century-old insight of Chandrasekhar that quasi-steady star evolution can be superseded by transient events

- They are the main 'factories' that produced many of the elements, hence shaping our geological and biological environments (including us!)

- Most type 1a supernovae emit roughly the same peak level of radiation and are therefore the 'standard candles' of cosmology, e.g., revealing the existence of 'dark energy'

Observational evidence implies that type 1a supernovae are delayed detonations

- Detonation requires mixing to be faster than reaction to form a zone of reactants mixed with hot products

- Supernova theory and simulations indicate that typical turbulent mixing times at required length scales are too slow

- To initiate the detonation requires rare high-intensity mixing events whose likelihood depends on the statistics of turbulent intermittency

XxXxxxxxXxxxxXxxxxxxxxxxxxxxxxxXxxxxxxxxXxxxxXxxxXxxxxX bang!

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A crude detonation treatment implies no detonations at the under simulated conditions

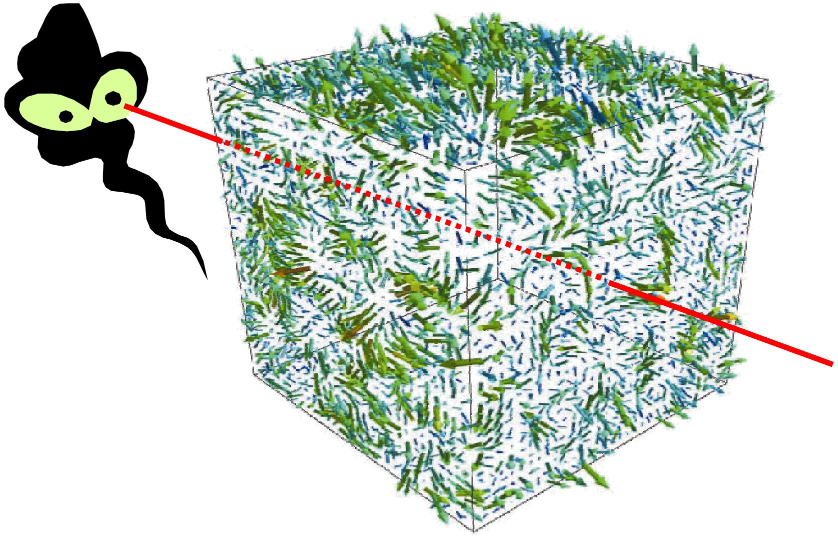
- 3D supernova simulations are under-resolved, so the strongest mixing events and their consequences are inferred by extrapolating to unresolved scales
- This crucial part of the problem is modeled crudely
- Is something better needed to capture the detonation? (audience feedback is encouraged)

Lacking understanding of the detonation mechanism, can we have confidence in the standard-candle hypothesis?

Strategy: Extrapolate the turbulence intermittency but simulate the resulting mixing and chemistry

- 3D simulations cannot affordably capture the relevant combustion regime but are useful for validating …

- a more economical 1D simulation model



What is the *relevant combustion regime*?

Unlike familiar turbulent premixed flames, nuclear flames don't extinguish

- Chemical flames extinguish when the local flow time scale is lower than the chemical time scale …
- so there's little empirical information about strongly turbulent premixed flames …

- but the nuclear burning rate is effectively adiabatic and involves no intermediate species, so nuclear flames never extinguish
- ***What new burning regimes then become possible?***

In principle, the premixed flame regimes are known

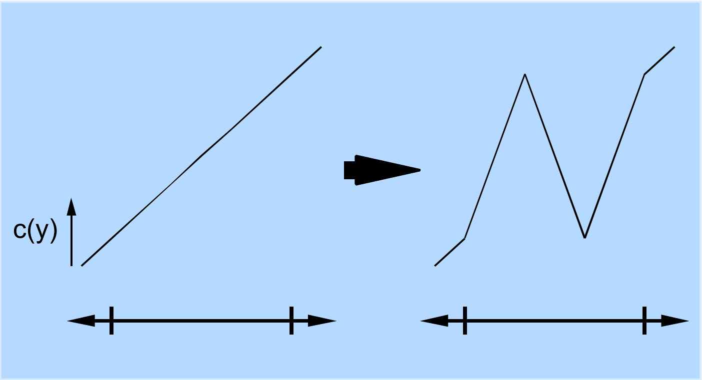
- Chemical time shorter than flow time: thin flamelets

- Chemical time longer than flow time:
  - Small-scale stirring: well-stirred reactor (Damköhler)
  - Large scale stirring: stirred flames (A.K. 2001)

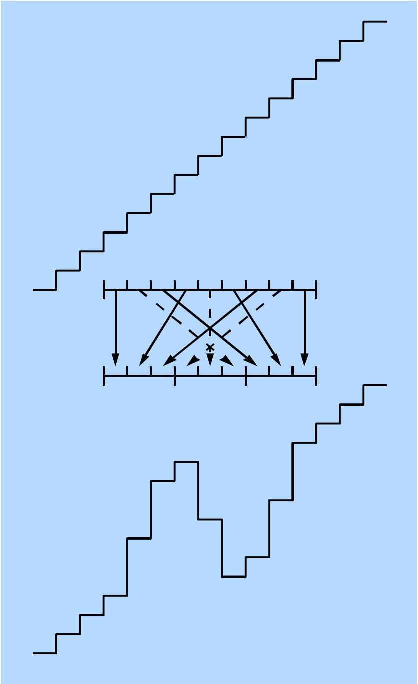
- Tricky part: Turbulence has different time scales at different length scales (short times at small scales) …

- so, small well-stirred reactors within larger-scale heterogeneity?

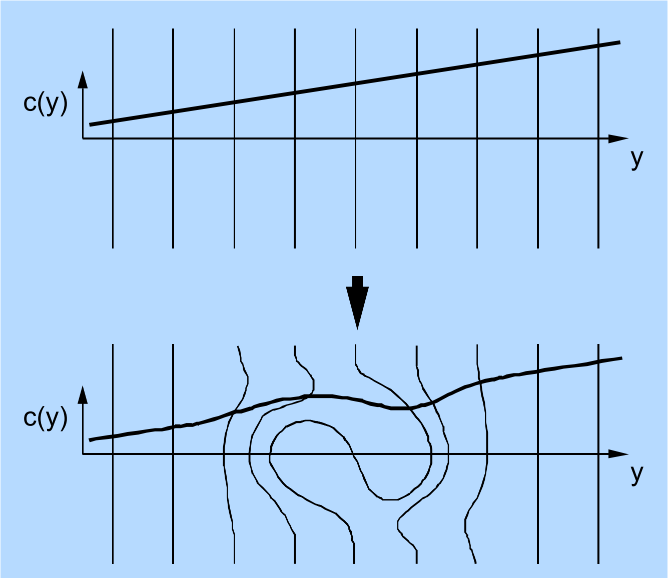
In 1D, advection is modeled as a sequence of *triplet maps*, which preserve desired properties



The triplet map captures compressive strain and rotational folding effects, and causes no property discontinuities



The triplet map is implemented numerically as a permutation of fluid cells (or on an adaptive mesh)



This procedure imitates the effect of a 3D eddy on property profiles along a line of sight

The triplet map (1D eddy)

- moves fluid parcels without intermixing their contents
- conserves energy, momentum, mass, species, etc.
- Reduces fluid separations by at most a factor of 3 (optimal in this respect)

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Eddy occurrences and properties (size, location) are sampled from fixed distributions

- Eddies (instantaneous maps) punctuate continuous-in-time advancement of molecular-diffusive transport, chemistry, etc. For example:

$$\theta_t = \kappa\theta_{yy} + \text{‘eddies’}$$

- Goal: Predict thermochemical evolution based on the turbulent state represented by the parameters of the sampling distributions

Linear Eddy Model (LEM) - A.K. 1988

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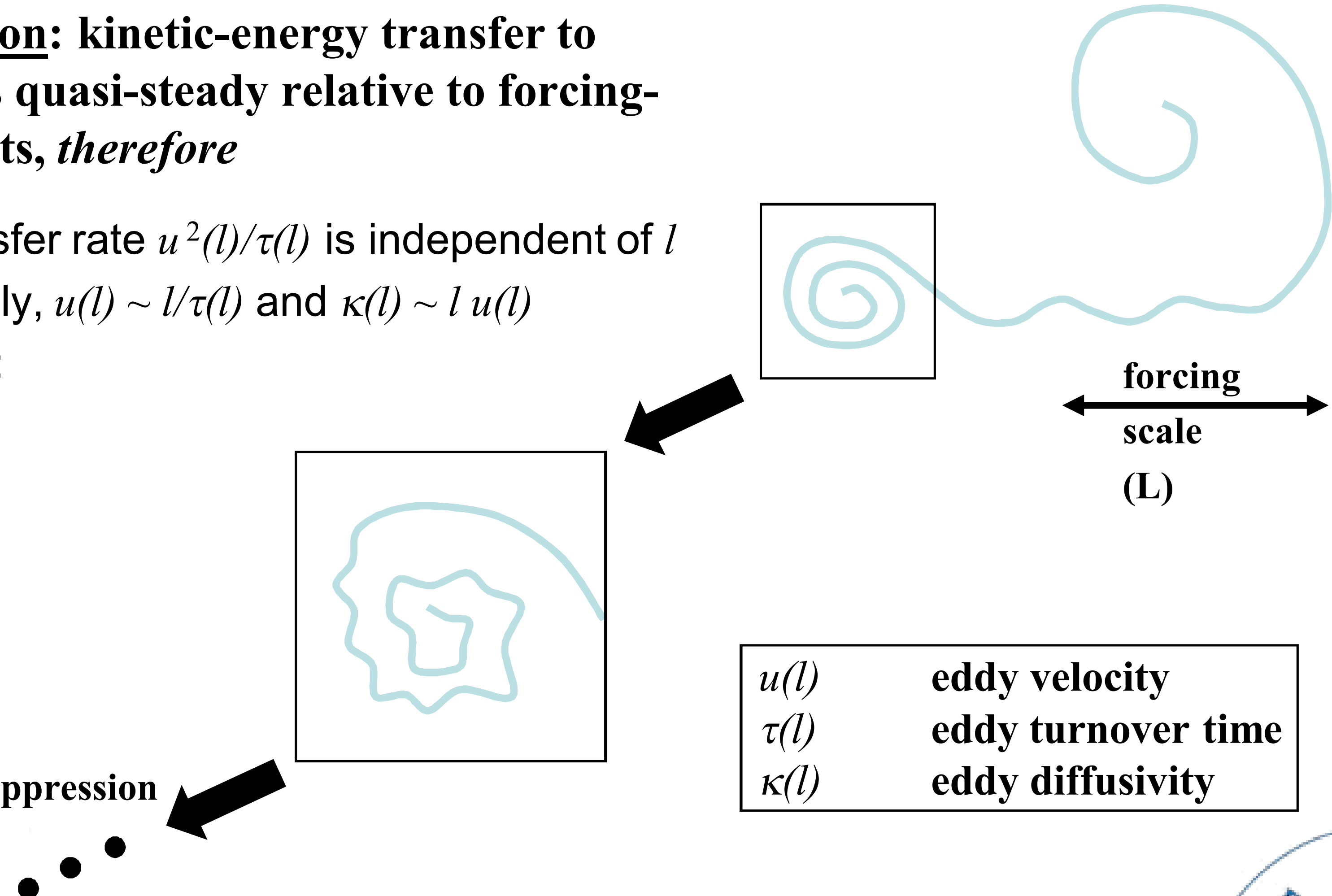
Turbulent cascade phenomenology guides LEM formulation

<u>Key assumption</u>: kinetic-energy transfer to small scales is quasi-steady relative to forcing-scale transients, *therefore*

- Energy-transfer rate $u^2(l)/\tau(l)$ is independent of l
- Dimensionally, $u(l) \sim l/\tau(l)$ and $\kappa(l) \sim l\, u(l)$
- Implications:
  - $\tau(l) \sim l^{2/3}$
  - $u(l) \sim l^{1/3}$
  - $\kappa(l) \sim l^{4/3}$



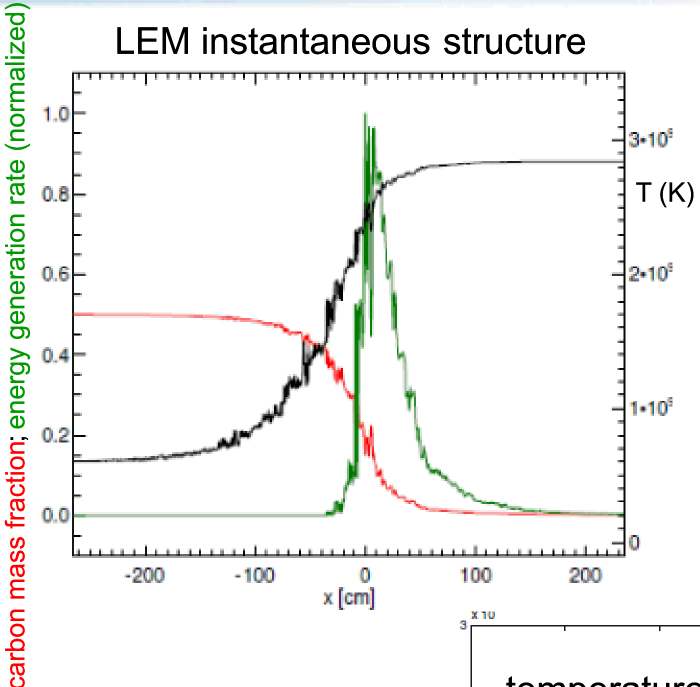
$u(l)$	**eddy velocity**
$\tau(l)$	**eddy turnover time**
$\kappa(l)$	**eddy diffusivity**

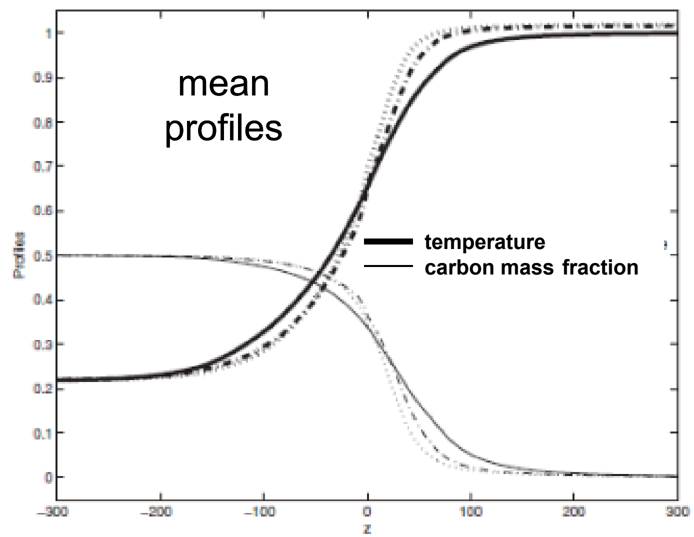
In LEM, the distribution of eddy sizes obeys inertial-range scalings

- The map distribution is spatially uniform (homogeneous turbulence)
- Map size ranges from smallest (η) to largest (L) turbulence scale
- In this range, the known 4/3-power dependence of the eddy diffusivity on the scale of motion determines the map size PDF
- Need an input value of the turbulent diffusivity to set the overall map frequency, and empirical determination of the range of map sizes

In the well-stirred-reactor (WSR) limit, the flame is relatively featureless

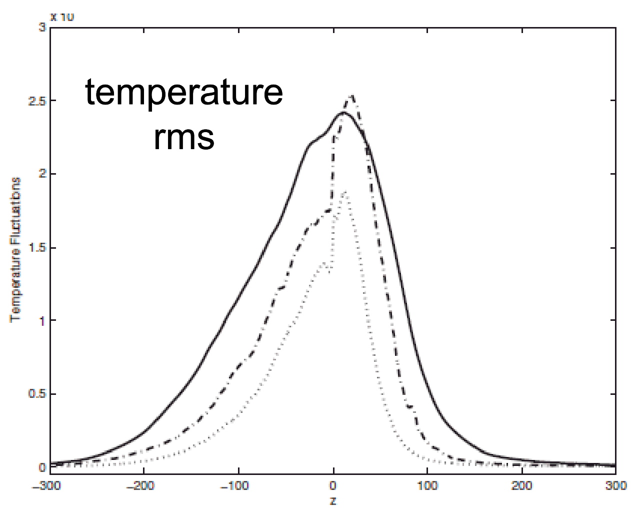
LEM instantaneous structure

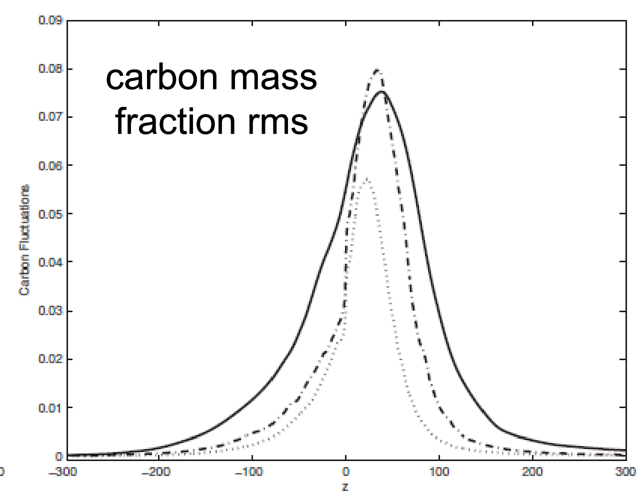




Two LEM parameters were tuned to fit profiles and turbulent burning velocity from 3D simulations (one-step kinetics)

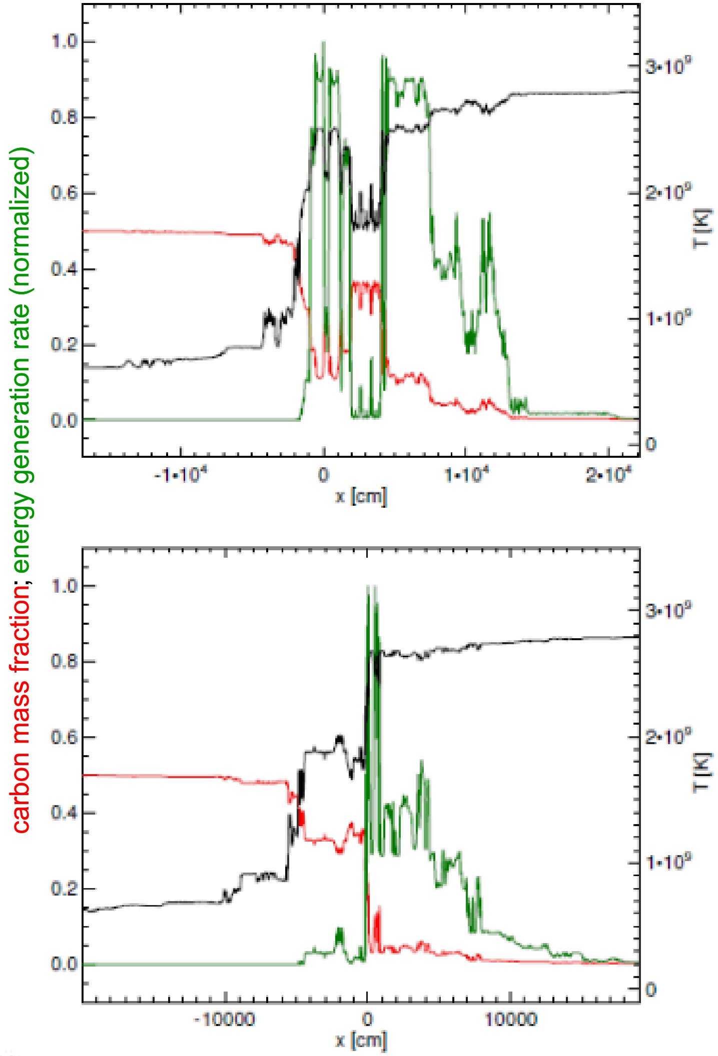
- 3D (LBNL group)
- LEM best fit
- LEM excursion



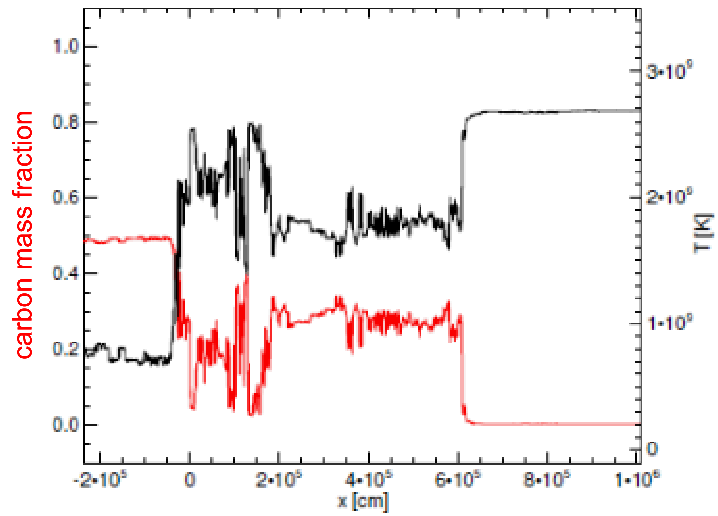


Woosley, Kerstein, Sankaran, Aspden, and Roepke (2009)

LEM, but not 3D methods, can reach the stirred-flame regime



Regions of relatively uniform mixing are seen



These cases used a multistep nuclear reaction mechanism

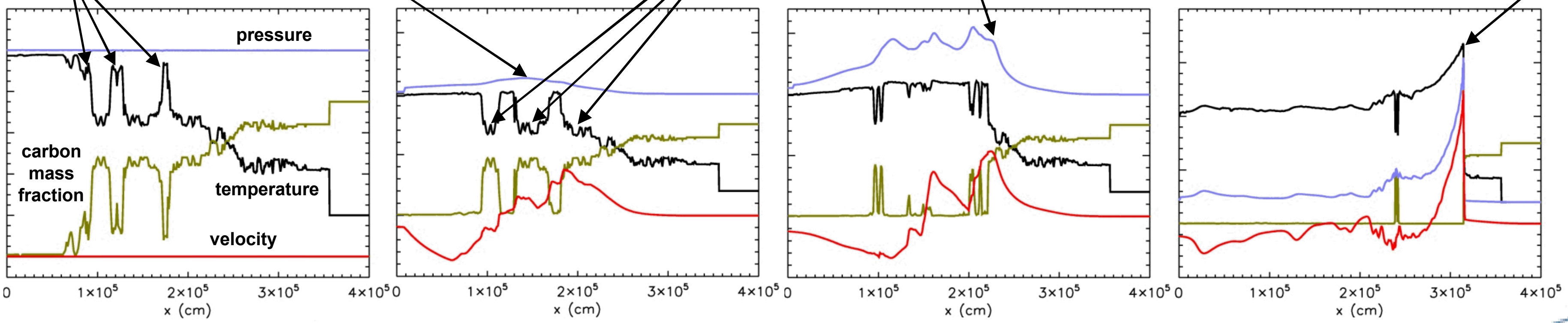
LEM flow states were used to initialize compressible hydro simulations that suggest a new DDT pathway

Prior status: Observations require a 'delayed' deflagration-to-detonation transition (DDT), but nuclear and fluid physics seemed to preclude this.

New insight: The deflagration-detonation transition (DDT) in a supernova could result from the sequential interaction of several distinct mixture states, analogous to a pyrotechnic (igniter, primer, main charge), but in this case unconfined.

Caveats: 1D implies effective confinement. No stirring during hydro advancement.

These burn first, generating pressure that helps burn these. A compression wave propagates rightward, sharpening to a detonation.



initial state **(vertical scale of each property is different on each plot)**

LEM parameters were set based on 'best-case' turbulence

Step-like property profiles are central to this picture – but are they real?

- Step-like structure is well known, e.g., as shown below.
- Proposed explanations invoke details of turbulence dynamics.
- Its occurrence in LEM implies a more general mathematical origin. <u>This will be investigated.</u>

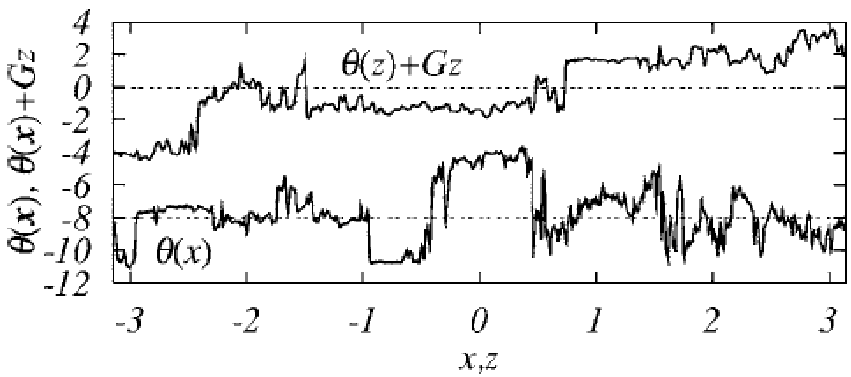


FIG. 4. One-dimensional profile of $\theta+Gz$ (upper) and θ (lower) along the directions of $e_\parallel$ and $e_\perp(=e_x)$ obtained from case G, respectively. The lower curve is shifted by −8 for clarity. Horizontal dot lines denote the zero levels.

DNS of passive scalar mixing:

Watanabe & Gotoh, 2006

Subtle details of turbulent fluctuations might be crucial to supernovae, hence to life as we know it

- The flow states and the mixing-reaction response to flow that are required for detonation might both be sensitive to particular details of turbulence intermittency
- This inference is speculative, but is the basis of a plausible scenario (which was previously lacking)
- A recent LEM study (Woosley et al. 2011) suggests another pathway: Fast burning of carbon preconditions the flow such that subsequent slower burning of oxygen transitions to detonation
- 3D simulation of premixed H2 combustion (Aspden et al. 2011) indicates resistance to extinction, hence relevance of the stirred-flame regime
- 1D turbulent flow modeling, though idealized, can give a first glimpse of otherwise inaccessible combustion phenomena