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Turbulent Premixed Combustion Beyond the Flamelet Regime: An Astrophysical Example

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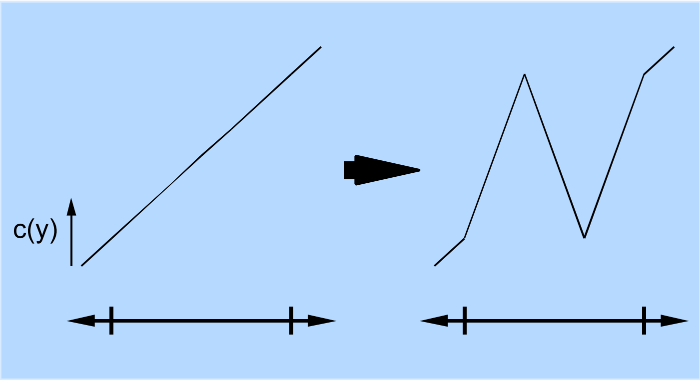
Turbulent premixed flames extinguish when the eddy time scale falls below the chemical time scale

- So there's little empirical information about strongly turbulent premixed flames
- But nuclear flames in exploding supernovae are subject to very strong turbulence, and never extinguish
- ***How do these flames behave?***
- ***Might high-pressure flames resist extinction and behave comparably?***

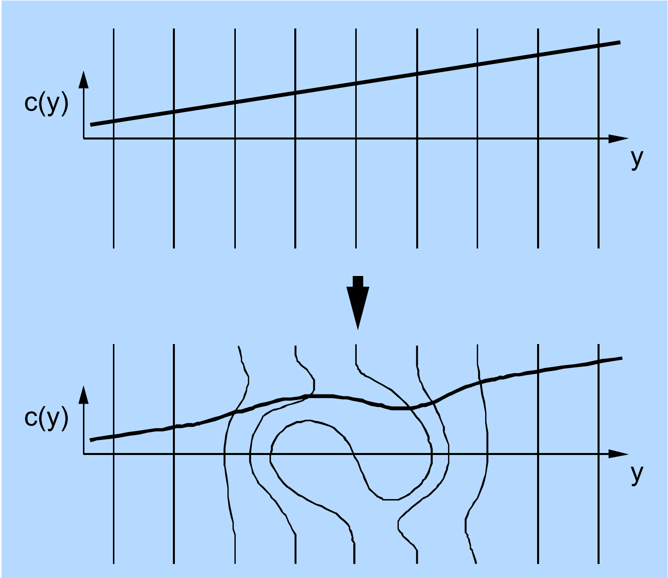
Gathering information about non-flamelet turbulent combustion is difficult

- DNS is costly
- Coarse-grained simulation with subgrid modeling doesn’t reliably capture flame structure
- Here the Linear-Eddy Model (LEM) is used:
  - Captures details of flame structure and evolution in 1D
  - Affordable1D ‘flow simulation’

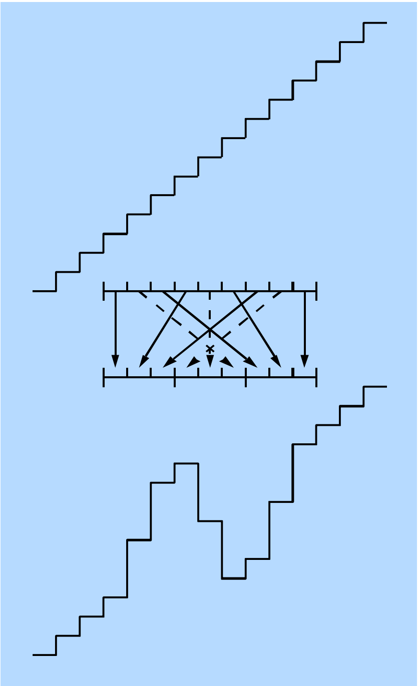
In LEM, advection is modeled as a sequence of *triplet maps*, which preserve desired properties



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



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



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

The triplet map (1D eddy)

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

In LEM, eddy occurrences and properties (size, location) are sampled from fixed distributions

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

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

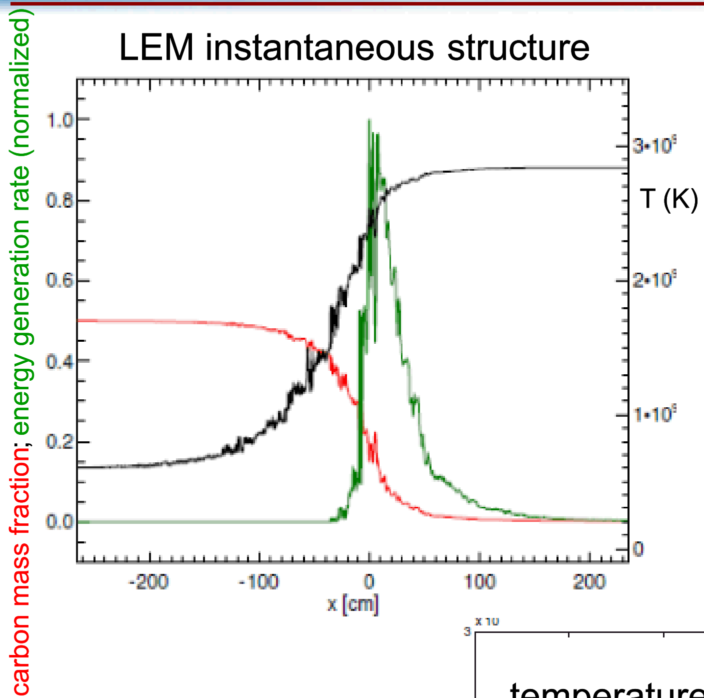
- LEM predicts thermochemical evolution based on the turbulent state represented by the parameters of the sampling distributions

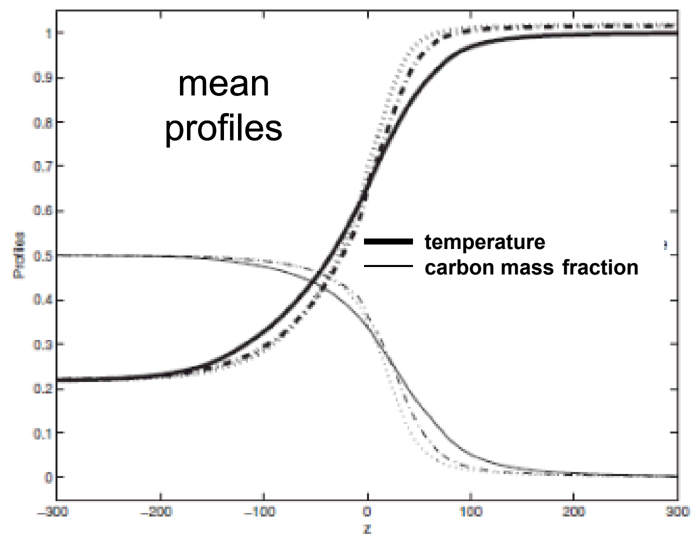
In LEM, the distribution of eddy sizes obeys inertial-range scalings

- The map distribution is spatially uniform (homogeneous turbulence)
- Map size ranges from smallest (η) to largest (L) turbulence scale
- In this range, the known (power-law) dependence of turbulent dispersion 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

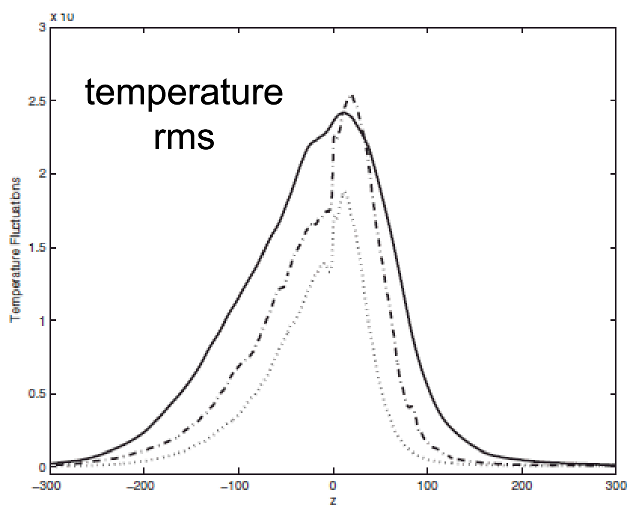


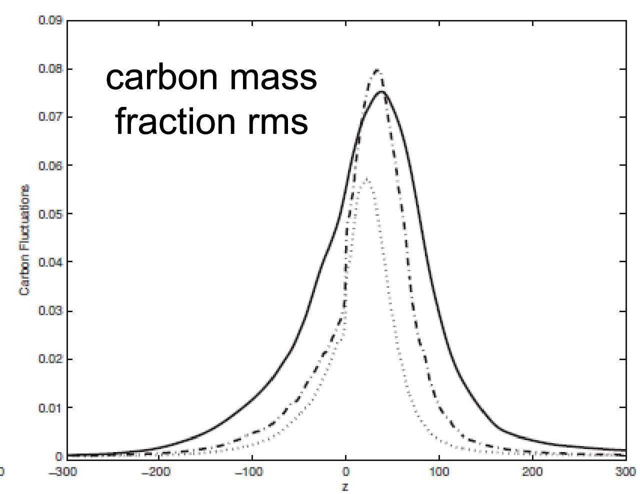


Two LEM parameters were tuned to fit DNS profiles and turbulent burning velocity (one-step kinetics)

DNS (LBNL group)
LEM best fit
LEM excursion

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





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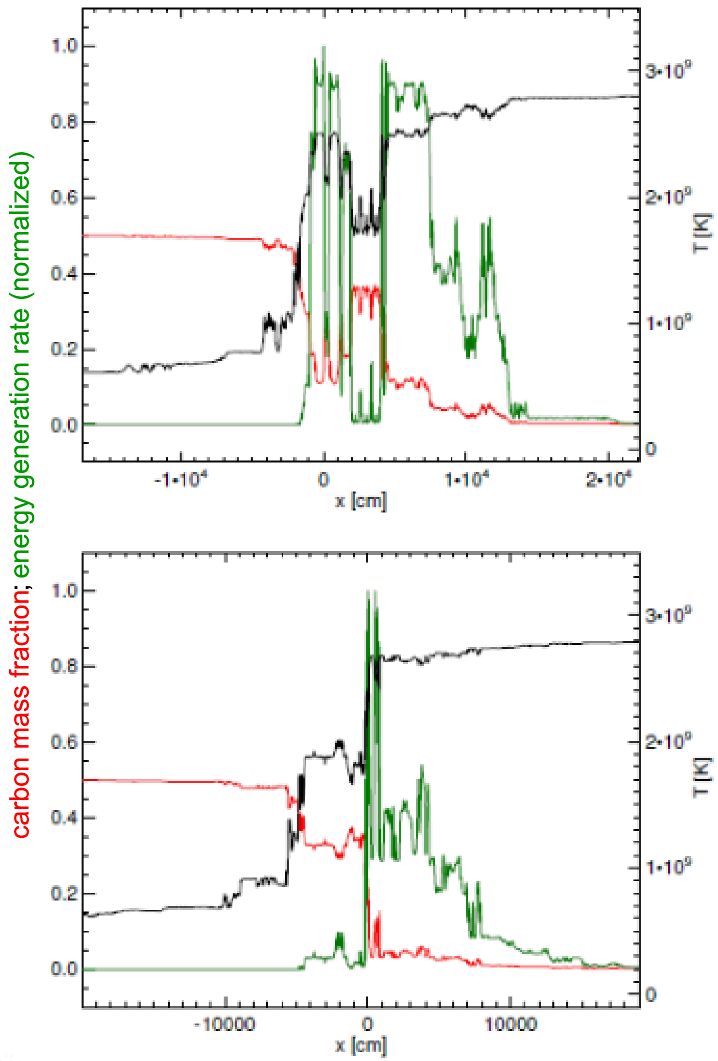
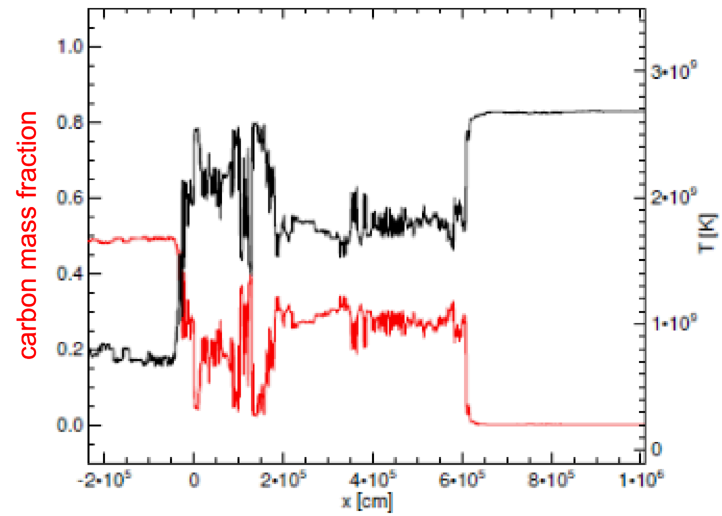
LEM, but not DNS, can reach the 'stirred-flame regime' between flamelet and WSR limits



Regions of relatively uniform mixing are seen



These cases used a multistep nuclear reaction mechanism

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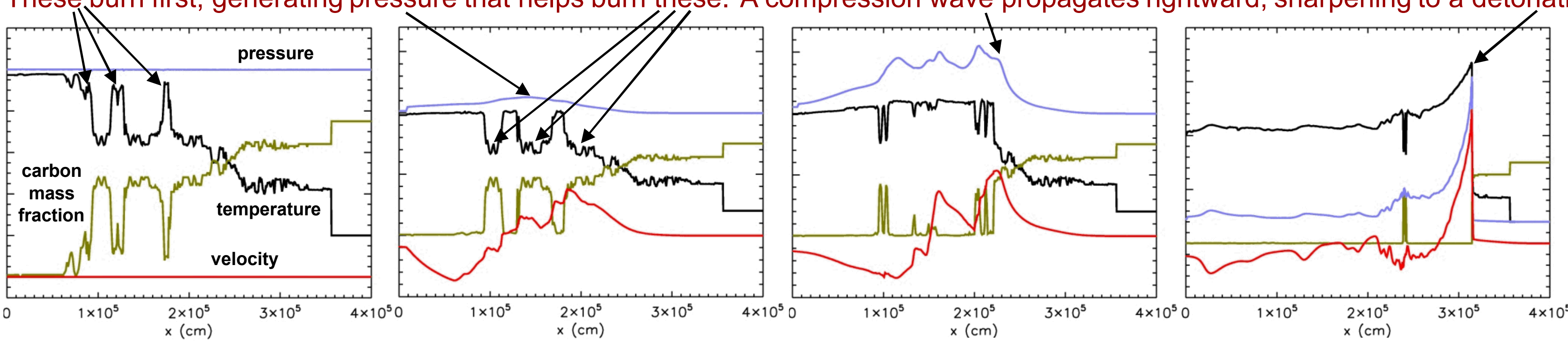
LEM flow states were used to initialize compressible hydro simulations that indicate a new DDT pathway

Context: New physics (e.g., dark energy) is implied if type 1A supernovae are 'standard candles' – but are they?

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

New insight: 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.

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)

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>

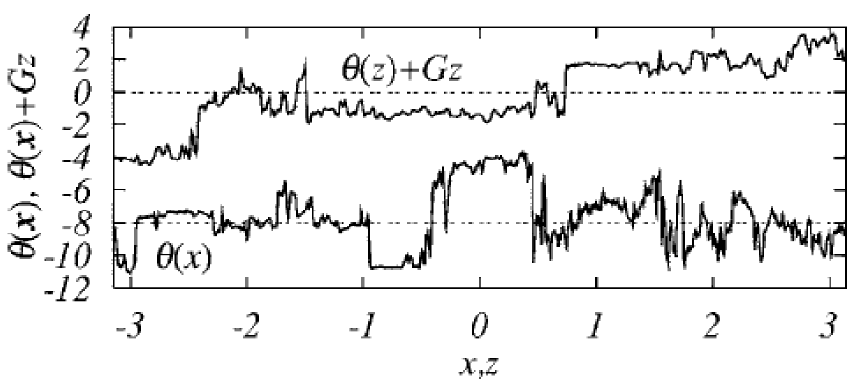


FIG. 4. One-dimensional profile of $\theta+Gz$ (upper) and θ (lower) along the directions of $e_{\parallel}$ and $e_{\perp}(=e_x)$ obtained from case G, respectively. The lower curve is shifted by -8 for clarity. Horizontal dot lines denote the zero levels.

DNS of passive scalar mixing:

Watanabe & Gotoh, 2006

LEM can probe new regimes qualitatively, but it must be combined with other methods to model combustors

Possible approaches:

- RANS-LEM3D
- LES-LEM
- Offline LEM to build tables for RANS or LES closure