Imaging of Eddy-Flame Interactions in Turbulent Flames

to assess concepts of Damköhler

to measure subgrid flame stretch rate (K) needed for LES

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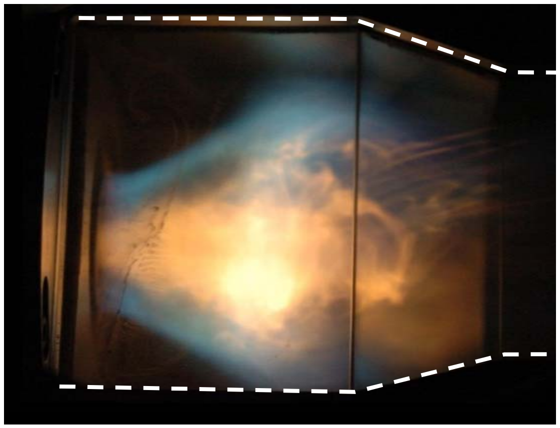
Motivation = need LES submodel of turbulent flames



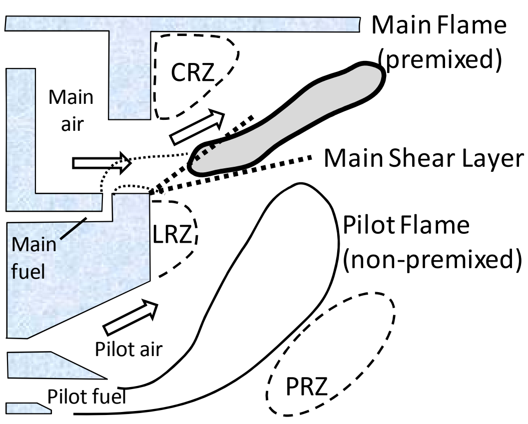
Michigan –General Electric
Lean-Premixed –Pre-vaporized Gas Turbine Project

5 atm, Jet-A, lifted jet-in-cross-flow premixed flame
Ultra low NOx GE-TAPS injector
Used in GEnx engine for Boeing 787

- premixed flame provides lower NOx,
- shorter flame
- creates “growl” – how to avoid instabilities ?

-Need for a design LES to model unsteadiness

-But submodel of M. Ihme requires
experimental information



Outline

Task #1: Develop methods to image eddies:

Cinema-stereo PIV movies at 1100 frames/sec

Task #2: Image eddies:

"Damköhler wrinkling" seen in fully turbulent flames

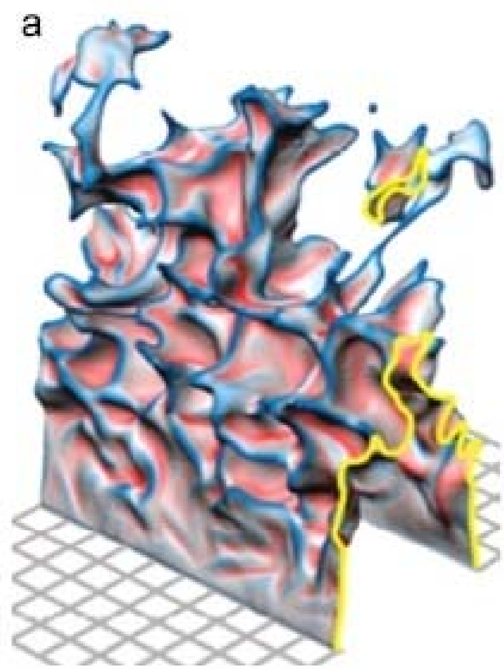
Landau hydrodynamic instability observed

Task #3: Measure Subgrid Flame Stretch Rate (K) - for LES

Task #1: Develop Methods to Image Eddies

Michigan –Turbulent
Slot Bunsen Burner

DNS of our turbulent
flame by Bell et al. LBL



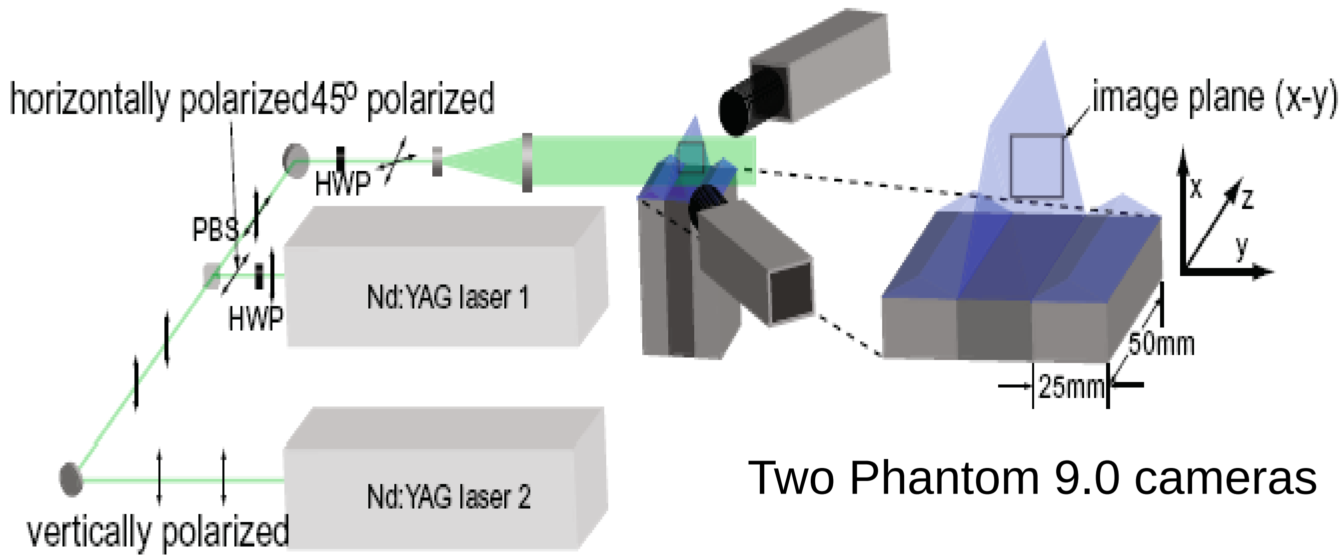
Co-flowing hot products
to prevent air entrainment

Methane-air,
$\phi = 0.7$

"fully-turbulent" $u'/S_L = 3.0$
$S_T/S_L = 2.5$

Task #1: Develop method to image eddies

Cinema-stereo PIV   Adam Steinberg, U. of Michigan



Two Clark ORC YAG lasers
Pulsed at 1100 pulses/sec

Taylor scale = 1.0 mm

Two Phantom 9.0 cameras

1100 velocity images/second
Scheimpflug stereo PIV optics

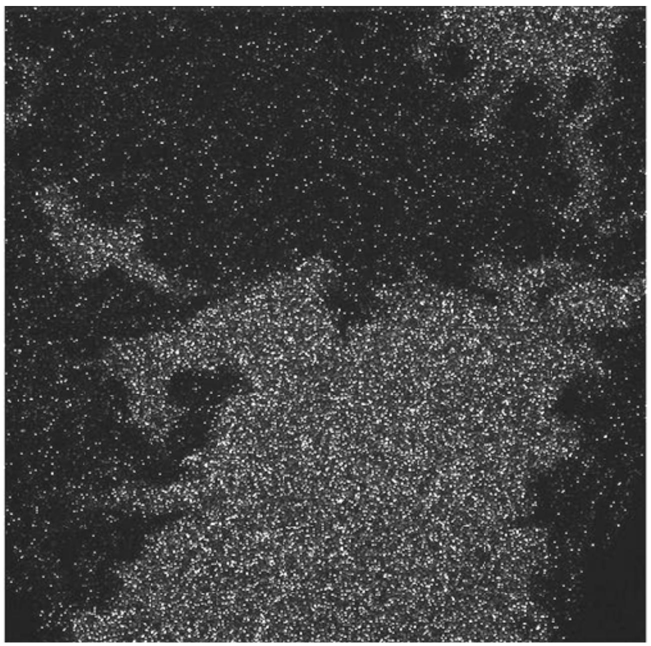
Small field of view 8 x 11 mm
Spatial resolution = 140 microns
Time resolution 0.9 ms

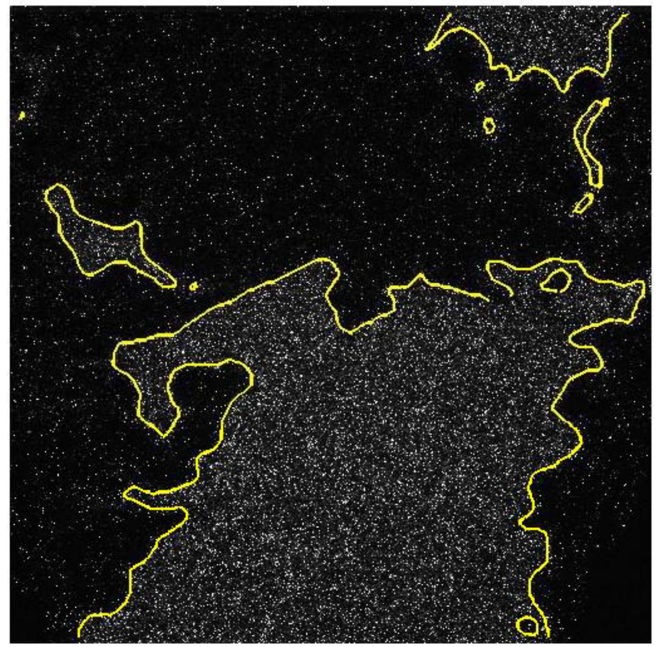
- Achieve good time resolution, spatial resolution (Taylor scales)

- Measure all three components of the velocity field
    - Measure in-plane components of strain, vorticity
    - Did not measure gradients in z-direction

Method to track Flame Front

- Flame front = maximum gradient in PIV particle density





Method to Measure Stretch Rate

$$K = \frac{1}{A}\frac{dA}{dt} = -\hat{n}\cdot(\hat{n}\cdot\nabla)\vec{u} + \underbrace{\nabla\cdot\vec{u}}_{0} + (\nabla\cdot\hat{n})\,S_L$$

1. Measure Stretch Rate (K) of the Flame Surface Area

2. Strain Rate of Flame Surface

3. Curvature of Flame Surface

4. Vorticity Field (eddies)

$$\omega_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

5. Fluid Strain Rate of the Reactants

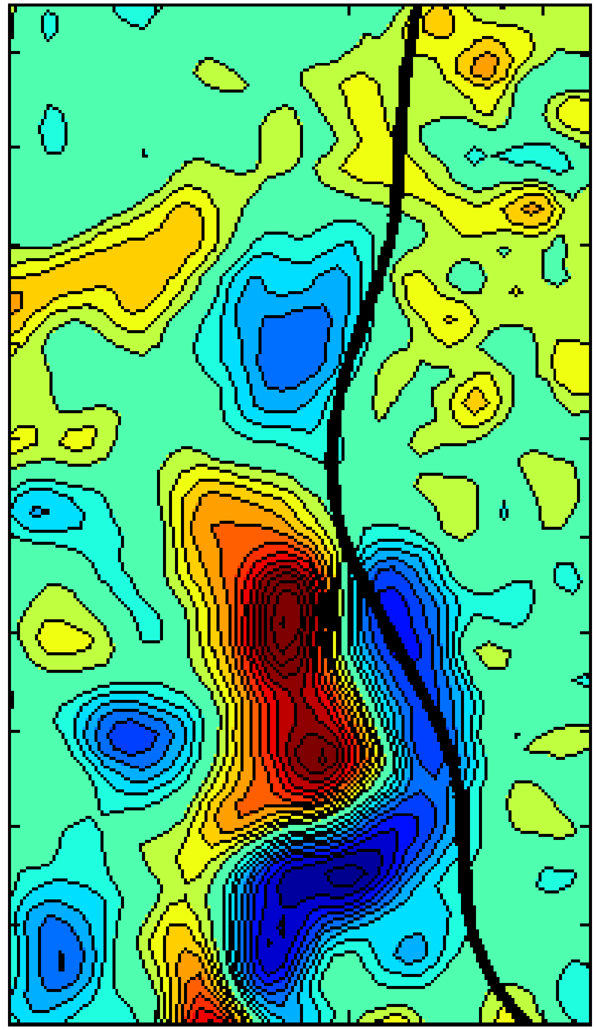
$$S_{xy} = \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)$$

Task #2: Image eddies - interacting with flame

Colors = Vorticity (ω_z) ; -700 s^{-1} (blue)
and 700 s^{-1} (red)

Field of view = 6 mm x 10.5 mm,
Δt = 0.9 ms

1. **Initial Vortex Pair**
2. **Vortex Pair Disappears**
3. **Wrinkle in Flame Appears**



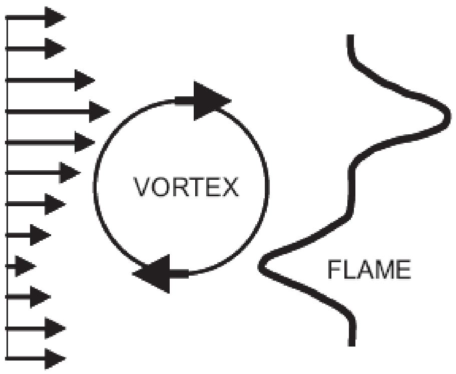
Reactants Products

Hypothesis #1: Single Vortex - increases flame area

Why do turbulent flames burn faster ?

Damköhler /Schelkin:

- Vortex increases flame area
- Reaction rate /area unchanged ?
- Burning velocity ~ flame area



Eddy-flame interaction = “fundamental building block of turbulent combustion”

Good LES submodel - must capture physics of real eddy-flame interactions

Need to - measure properties of eddy-flame interactions

Hypothesis #2: Vortex Pair Stretches Flame

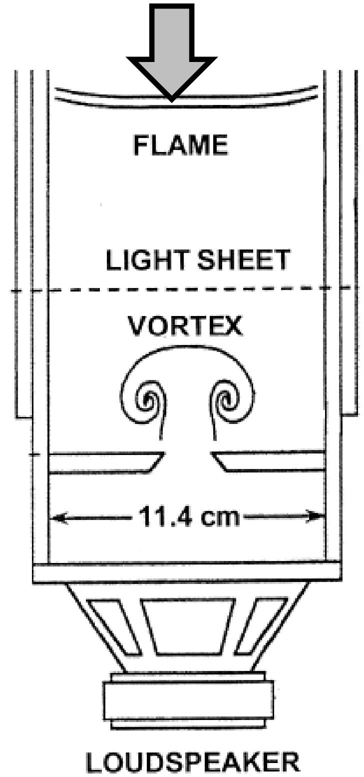
: Meneveau / Poinsot

- Assume that turbulence = ensemble of vortex pairs

  - all aligned exactly to exert positive stretch

  -perform DNS of "canonical" vortex pairs
  -take average over many vortex sizes
  -compute Stretch Efficiency Function Γ_K

wherever strain = +, curvature = -

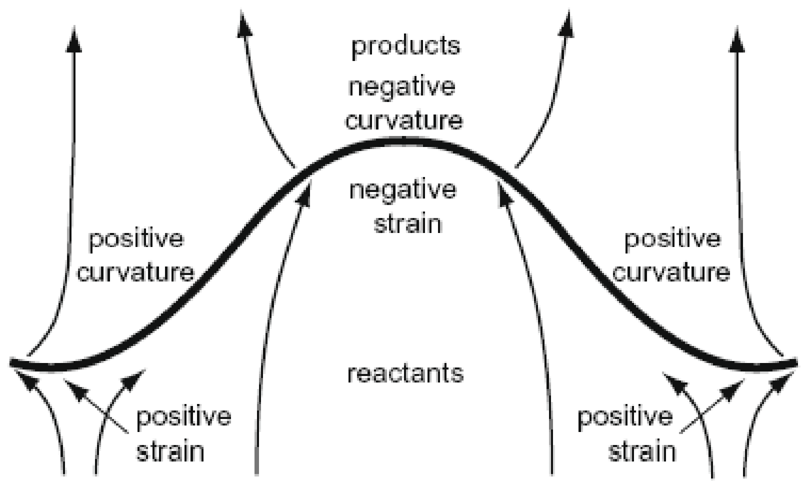


Hypothesis #3: Landau-Darrieus Hydrodynamic Instability also increases flame area

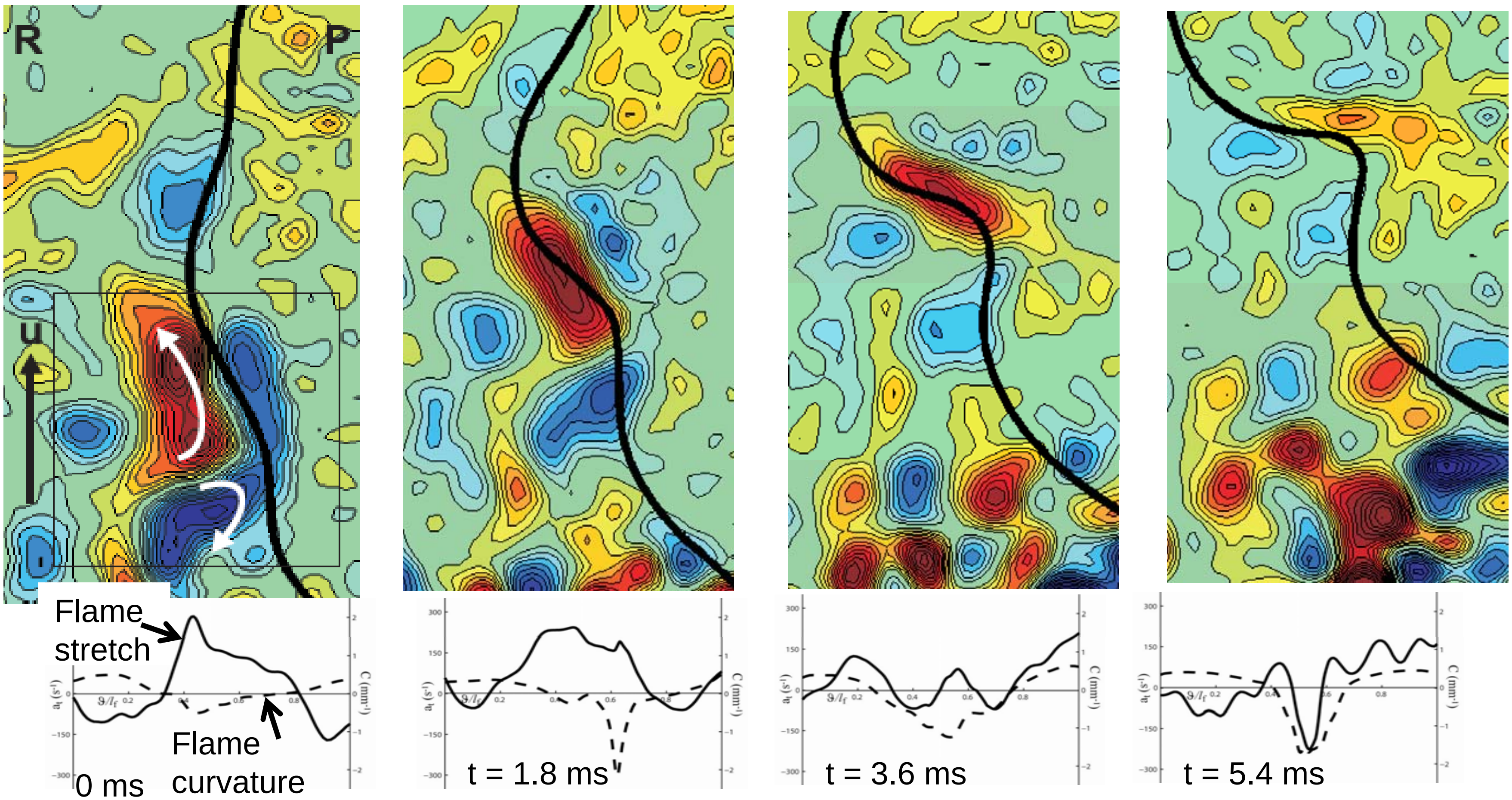
(see text by Forman Williams)

area increases in the absence of vortices

wherever strain = +, curvature = +



Stretch rate and Curvature - are negatively correlated at early times
- are positively correlated at later times

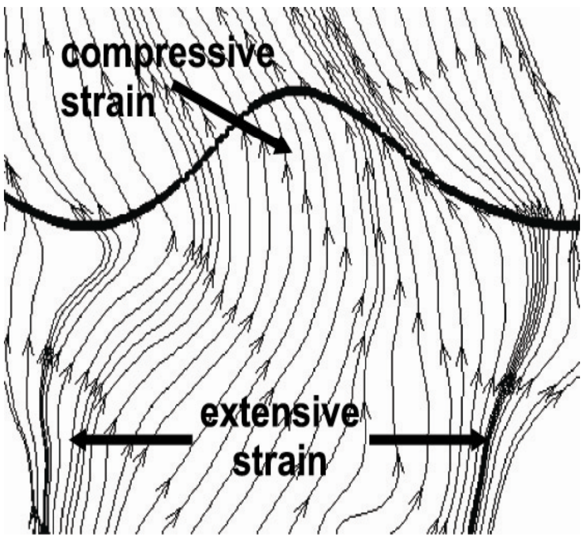


← Damköhler wrinkling →

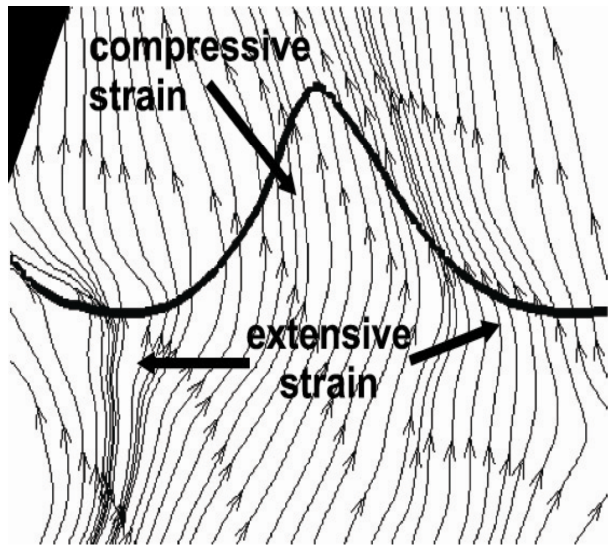
← Landau Hydrodynamic Instability →

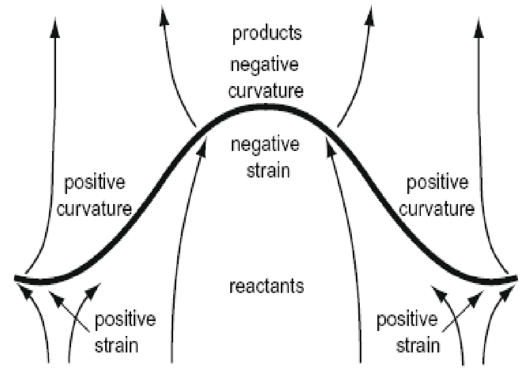
Hydrodynamic Instability Observed

t = 6.3 ms



t = 12.6 ms





Landau theory

Measured streaklines

- Eddy first creates a small wrinkle
- Measured pattern of diverging streaklines agree with theory
- Cause expected strain rate pattern
- Wrinkle eventually forms cusp due to hydrodynamic instabilility

Observed Time History of the Eddy-Flame Interactions

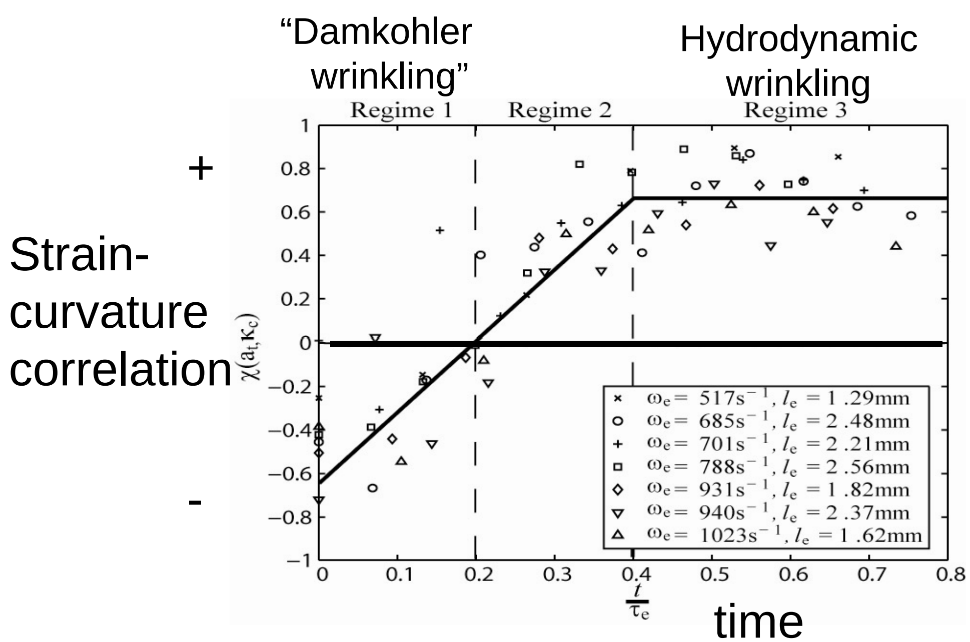
- **Early times: observe "Damkohler-like** "wrinkling sometimes

  Strain & curvature are <u>negatively</u> correlated as predicted

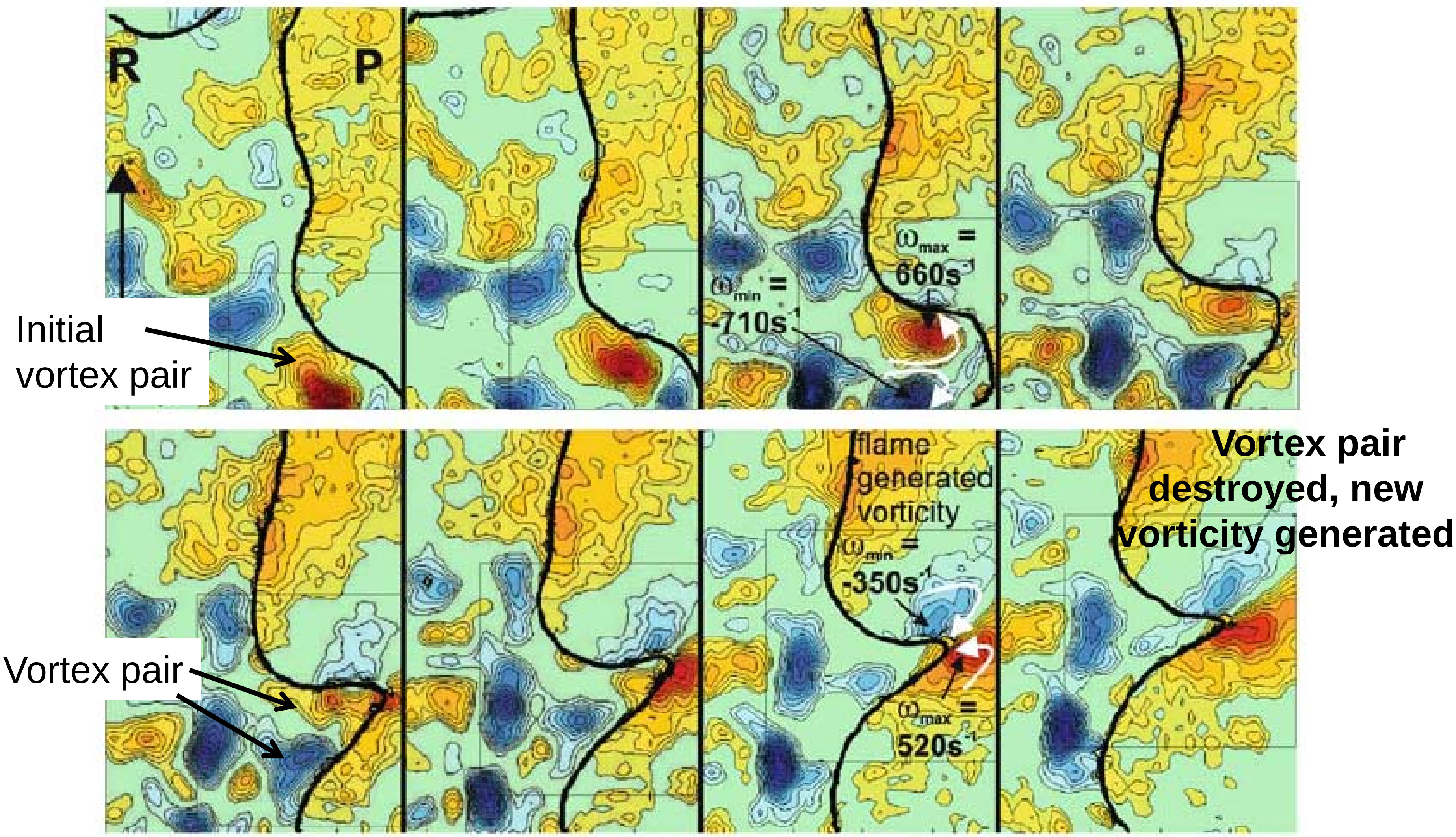
- **Later times: observe that Landau hydrodynamic instability**

  causes additional wrinkling

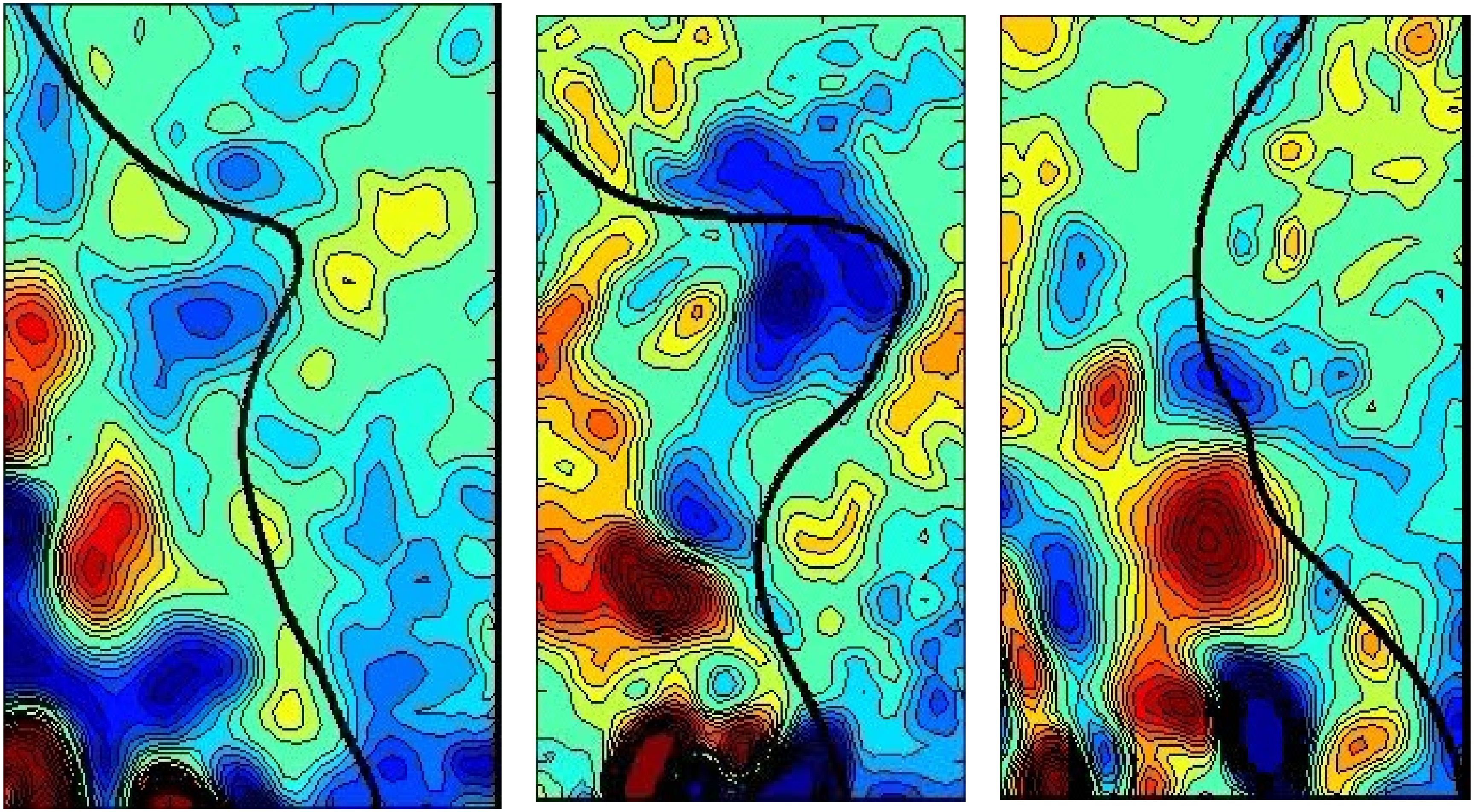
  Then strain & curvature are <u>positively</u> correlated



Flame Generates New Vorticity



Sometimes “non-Damköhler wrinkling is observed



Damköhler wrinkling

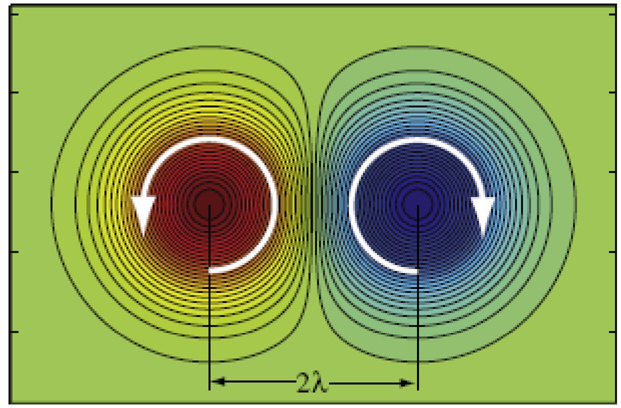
non-Damköhler wrinkling

Is something else important in addition to vorticity ?

Theoretical Burgers vortex pair

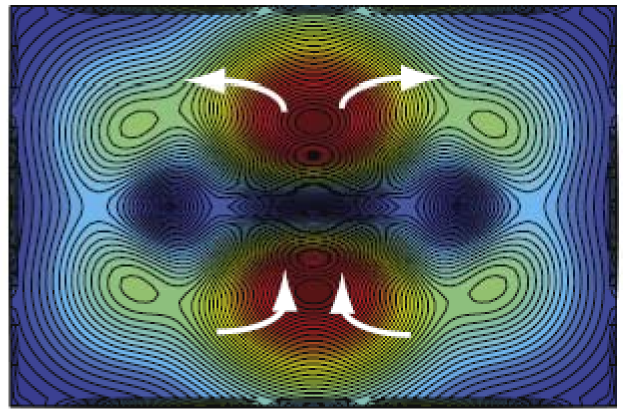
Vorticity and strain structures are at different locations

Maybe we should track the “strain-structures” and not the “vorticity-structures” ?



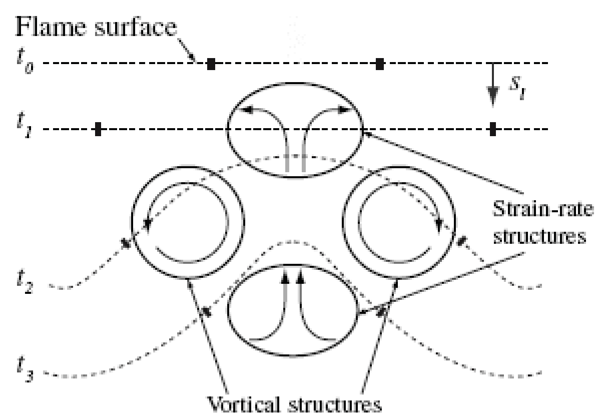
(a) Burgers’ vortex pair. Contours of ω_z.

vorticity

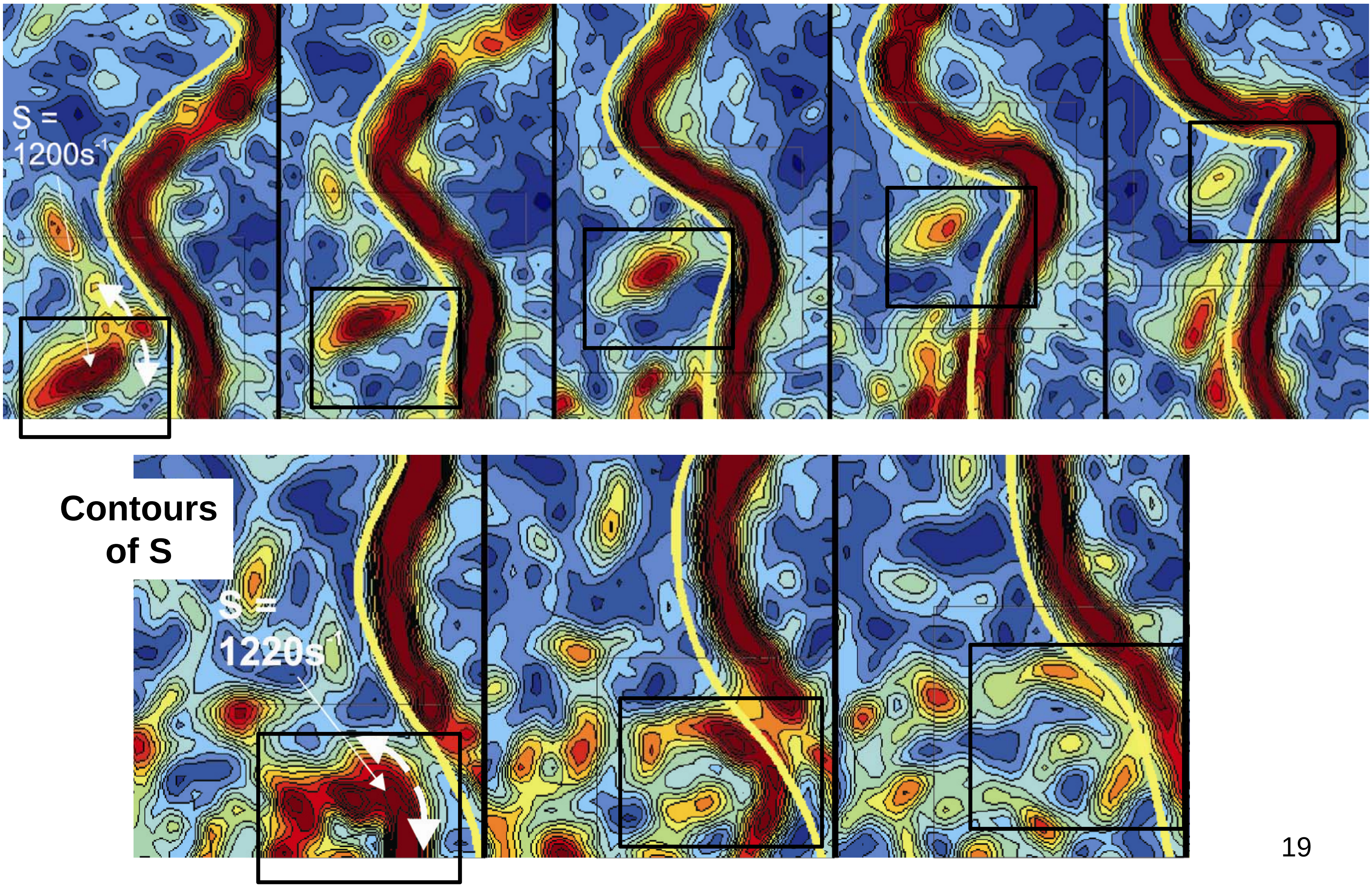


(b) Strain-rate field associated with vortex pair. Contours of $S = (S_{ij}S_{ij})^{1/2}$.

fluid strain rate



Look at the Fluid Strain-Structures (instead of the vorticity)

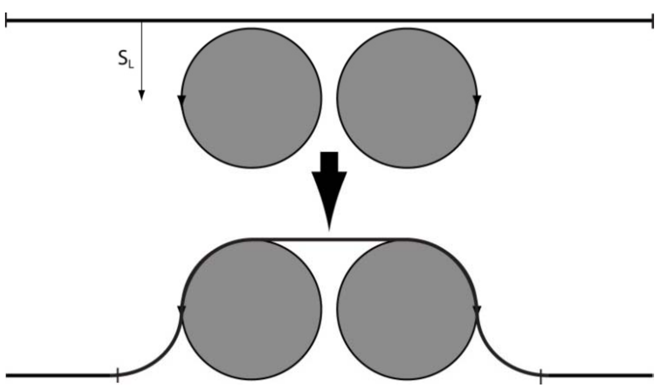


Vorticity - "wrinkles the flame but does not stretch it"
Fluid strain rate - "strains the flame but does not wrinkle it"

Vorticity (no strain-rate)

Solid body rotation

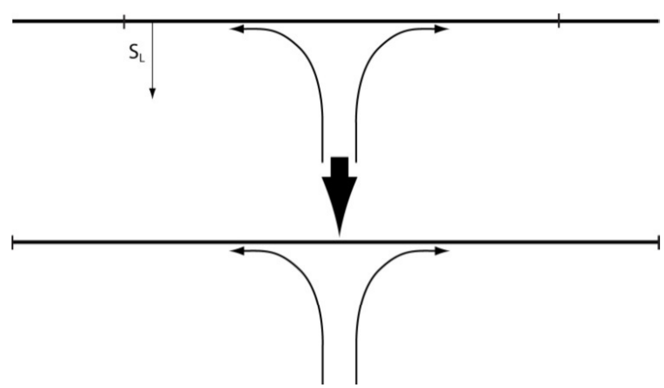
Configure in canonical manner



Strain-rate (no vorticity)

Counter-flow geometry

Laminar flamelet concepts



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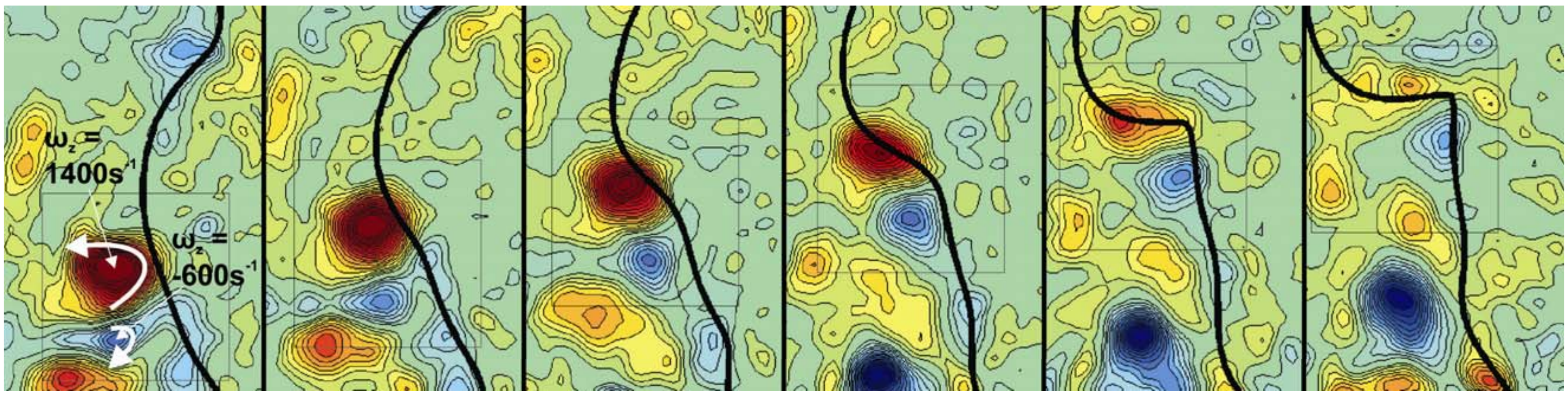
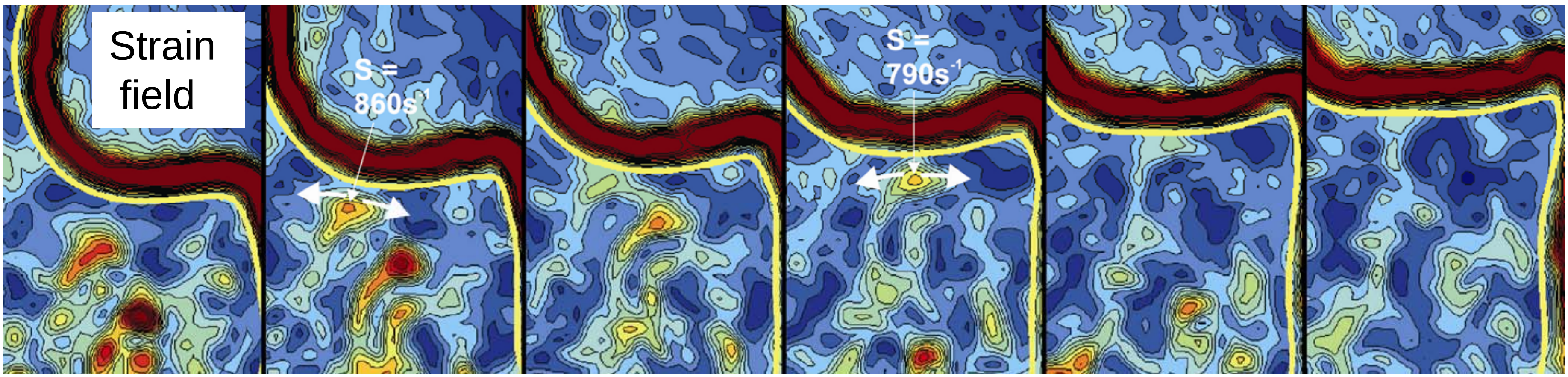


An example of strong vorticity - but small fluid strain rate

wrinkle is formed but
small stretch rate (K) is measured

Vorticity - "wrinkles the flame but does not stretch it"
Fluid strain rate - "strains the flame but does not wrinkle it"



An example of when the fluid strain is large but vorticity is small

- like a counter-flow flame: flame remains flat but is elongated

Flame stretch rate (K) is important to measure

1. Stretch rate (K) - determines flame area and turbulent burning velocity

2. Stretch rate (K) - determines where flame extinguishes

Flame stretch rate (K) is important (con't)

3. Stretch rate (K) – required in the two main LES subgrid models

LES submodel 1: based on Σ = flame surface density

$$\frac{\partial \Sigma}{\partial t} + \tilde{U}\frac{\partial \Sigma}{\partial x} + \tilde{V}\frac{\partial \Sigma}{\partial y} = v_{\mathrm{T}}\frac{\partial^2 \Sigma}{\partial y^2} + \bar{K}\Sigma - \bar{M} - \bar{Q}$$

⇧ K = Stretch rate of flame area

LES submodel 2: based on G-equation

$$S_T = S_L \left(1 - K \quad Ma\ \alpha\ S_{L0}^{-2}\right)$$

⇧ K = Stretch rate of flame area → needed

Task #3: Measure subgrid flame stretch rate (K)

$$\frac{\partial \Sigma}{\partial t} + \tilde{U}\frac{\partial \Sigma}{\partial x} + \tilde{V}\frac{\partial \Sigma}{\partial y} = \nu_{\mathrm{T}}\frac{\partial^2 \Sigma}{\partial y^2} + \bar{K}\Sigma - \bar{M} - \bar{Q}$$

⇧

Σ = flame surface density

K = Stretch rate of flame area

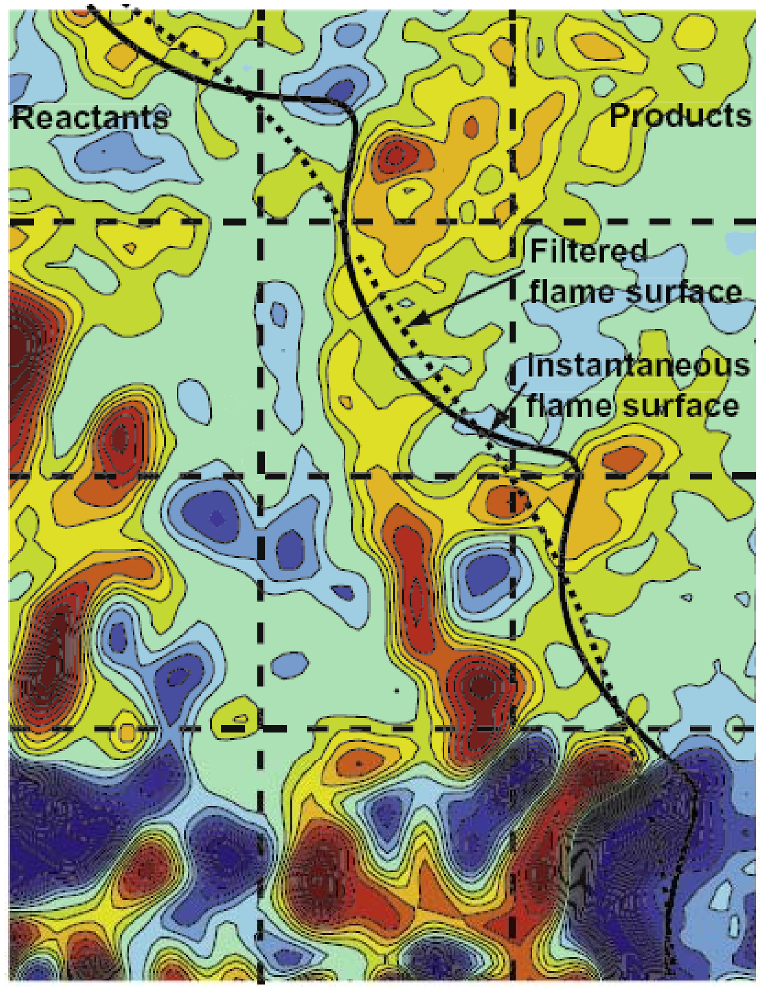
a) Hypothesis of Meneveau/Poinsot $\bar{K} = (u'/\ell)\Gamma_{\mathrm{K}}$

b) Our data suggest that flame area change scales with fluid strain rate S_{xy}

$$\bar{K} = S_{xy}\ \Gamma_s$$

Measure the LES submodel - using standard LES methods

1. Break up the experimental field into **"cells"**
2. **Track eddy motions** in a Lagrangian manner
3. **Perform "filtering"** - both spatial and time averaging over each cell
4. **Correlate** the cell-averaged flame stretch rate with either the cell-averaged (u'/L) (Poinsot) or the fluid strain rate S



Improved LES subgrid model

The rate of flame area change (*K*)

correlates 50% better using the

fluid strain rate S_{xy}

$$\bar{K} = S_{xy} \, \Gamma_s$$

(than with the previously proposed u'/L scaling of Meneveau / Poinsot)

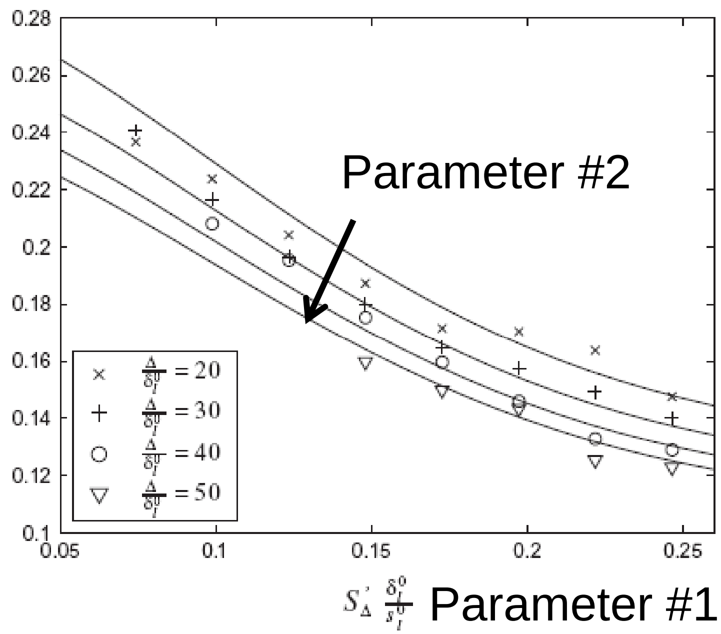
Measurements provide information needed for LES

- Γ_s = Strain Rate Transfer Function
  was measured as a function of two non-dimensional parameters:

  Parameter #1 = $S_\Delta / (S_{L0}/\delta_{L0})$

  Parameter #2 = Δ / δ_{L0}

Strain Rate Transfer Function Γ_s



Parameter #1

$$\bar{K} = S_{xy}\ \Gamma_s$$ ⇨ Stretch rates needed for LES

LES Closure - requires three relations

1. $K = \text{fcn}(S'_\Delta, \Delta)$ from our measurements

K = subgrid flame stretch rate (on the flame surface)

S'_Δ = subgrid fluid strain rate in reactants

2. Standard energy dissipation balance

$$\frac{\nu}{2} (S'_\Delta)^2 = \varepsilon = -\overline{u_i' u_j'} \; \widehat{S_{ij}}$$

3. Standard Smagorinsky relation for Reynolds stresses

$$-\overline{u_i' u_j'} = 2\, C\, \Delta^2 \widehat{S_{ij}} \left| \widehat{S_{ij}} \right|$$

Conclusions

1. A method was developed to make high-speed movies of eddy – flame interactions (Cinema-stereo PIV with flame surface tracking)

2. "Damkohler wrinkling" increases flame area at early times - 20% of time
3. "non-Damkohler wrinkling" occurs > 50% of time, needs further study
4. Eddies destroyed on flame passage but flame generates new vorticity
5. "Landau hydrodynamic instability" increases flame area after eddy gone
6. "Strain-structures" offer better description than vorticity structures
7. Vorticity - "wrinkles the flame but does not stretch it"
8. Fluid strain rate - "strains the flame but does not wrinkle it"

9. Measured Strain Rate Transfer function provided to improve LES models

Future work – “3-D” eddy-flame imaging

Lay the laser sheets horizontal

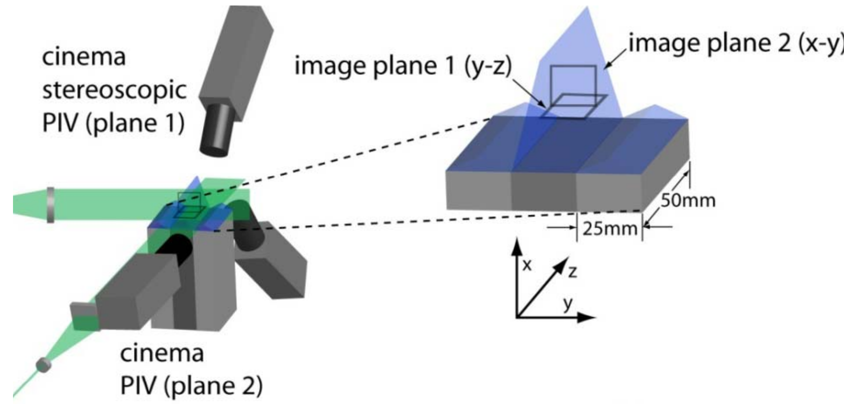
As eddies pass vertically upward through sheets:

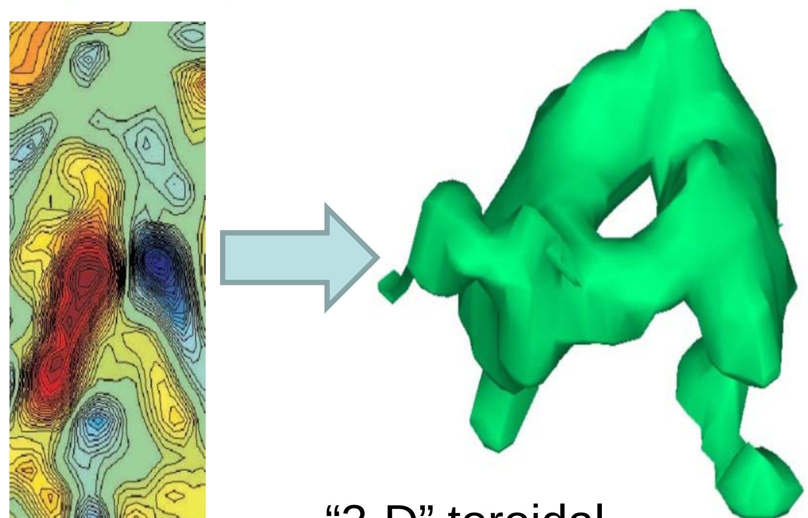
Rapidly image eddies in the horizontal plane

Apply Taylor’s hypothesis

$$\frac{\partial}{\partial x} = \frac{1}{U}\frac{\partial}{\partial t}$$

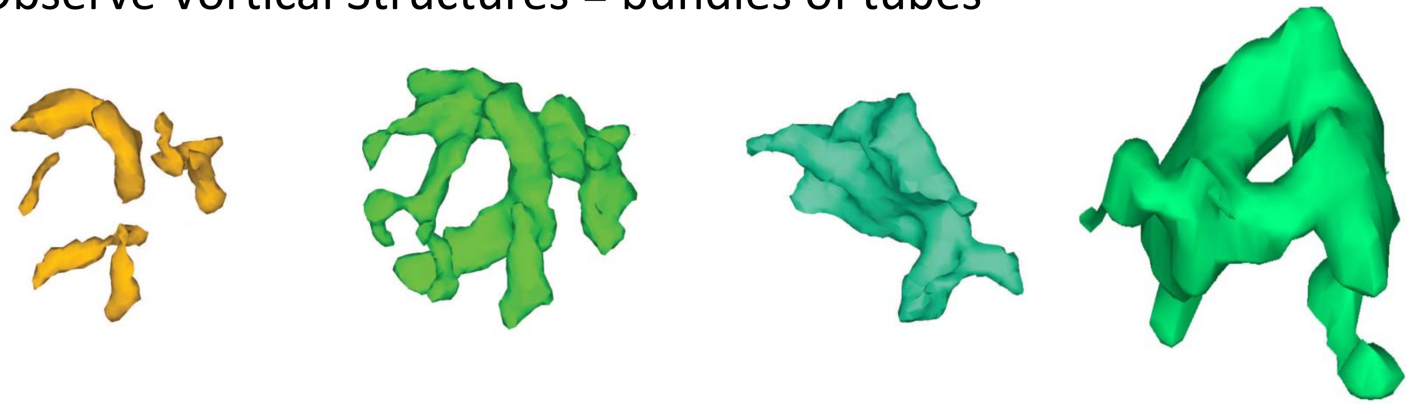
Check Taylor’s hypothesis using one vertical sheet



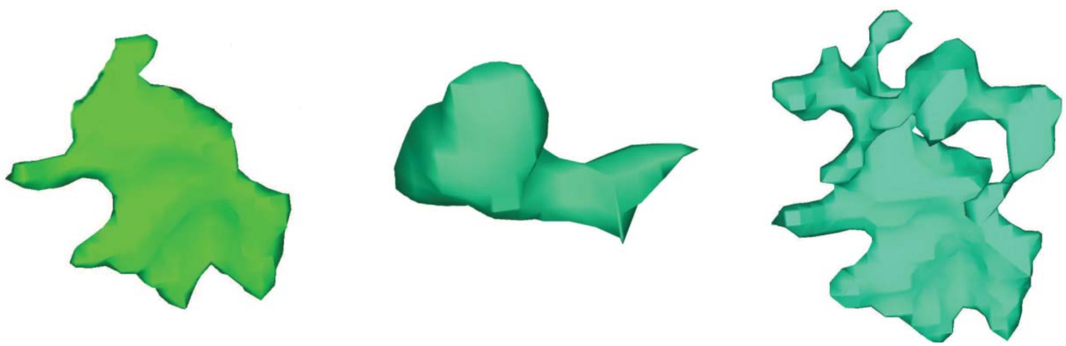


“3-D” toroidal vortex ring

Observe Vortical Structures = bundles of tubes



Observe Strain-Rate Structures - Sheets and Blobs



Questions ?