# Multi-Scalar Experiments on Turbulence-Chemistry Interaction

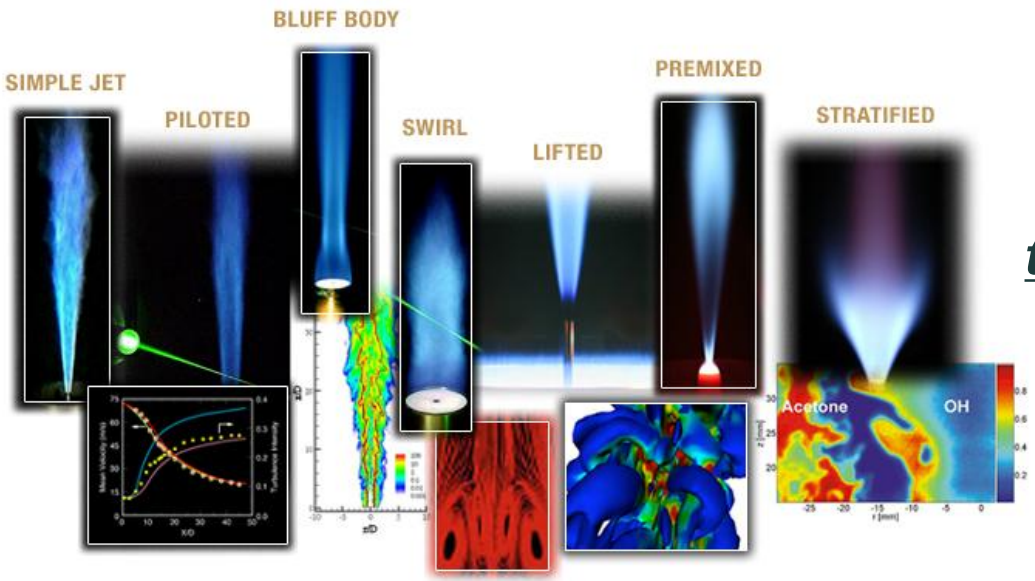
# &

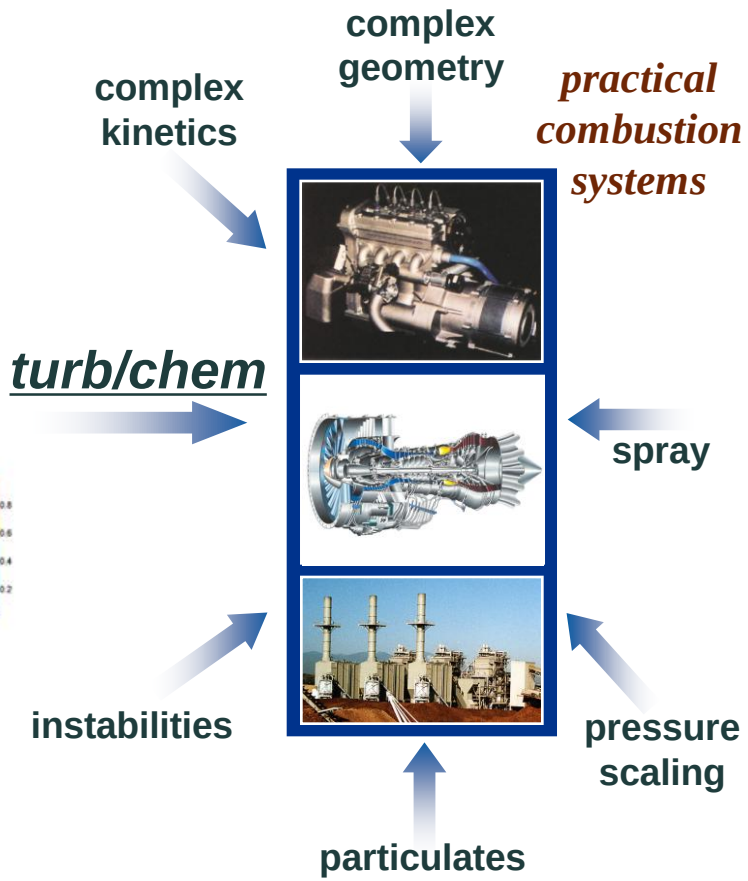
# Multi-Agency Coordination on Turbulent Combustion

**Rob Barlow**

**Supported by DOE/BES**

# Strategy for Validation of Submodels for Turbulence-Chemistry Interaction




- **Progression of well documented flames that address the fundamental science of turbulent flow, transport, and chemistry**

# TNF Workshop Series

- **International Workshop on Measurement and Computation of Turbulent (Non)premixed Flames**
  - Collaboration among experimental and computational researchers
  - Web-based library of validation target flames
  - Framework for detailed comparison of measured and modeled results

- **Systematic progression toward predictive capability**
  - Significant influence on modeling of turbulent nonpremixed flames
  - Increasing emphasis on partially-premixed, stratified, and premixed flames

| Naples | Heppenheim | Boulder | Darmstadt | Delft | Sapporo | Chicago | Heidelberg | Montreal | Beijing | Darmstadt |
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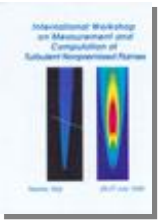
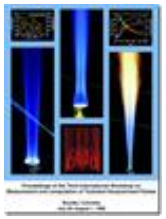
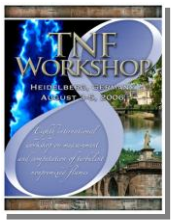
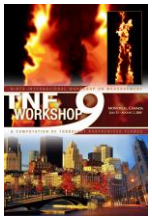
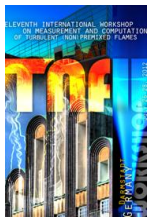
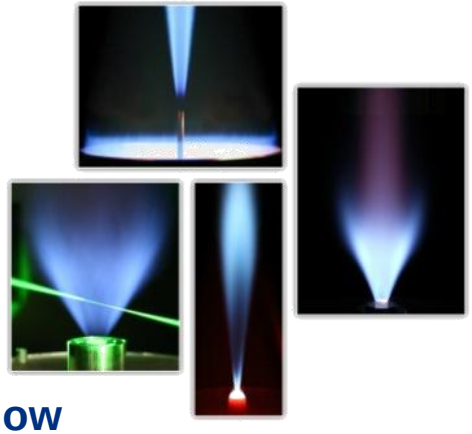
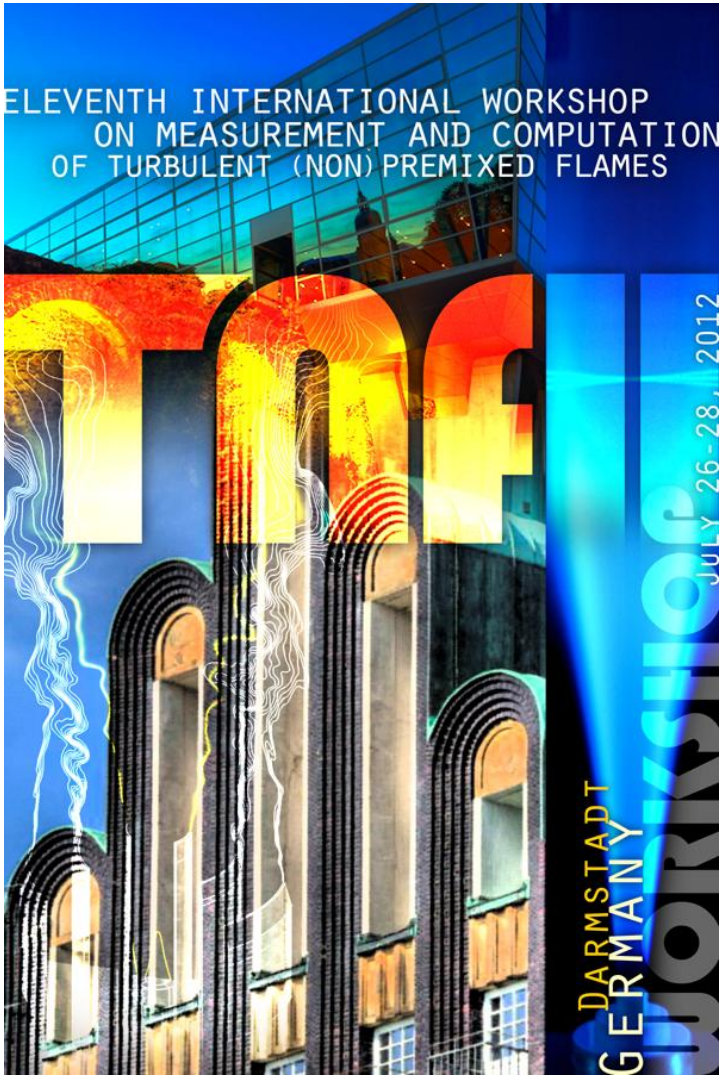
|  | |  | | | | |   |   | |  |
| 1996 | 1997 | 1998 | 1999 | 2000 | 2002 | 2004 | 2006 | 2008 | 2010 | 2012 |

# TNF11 Darmstadt, Germany (July 2012)

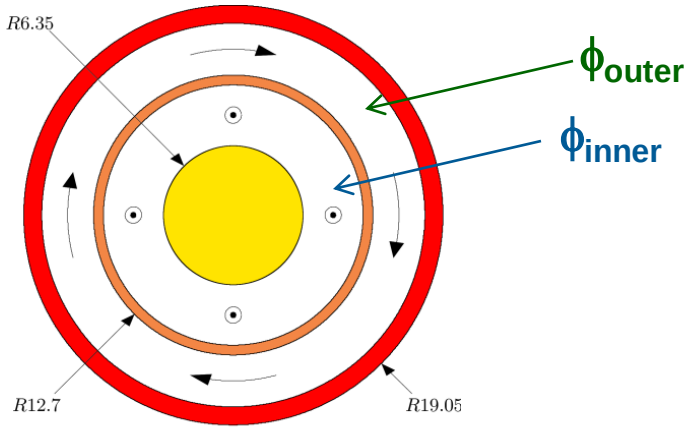


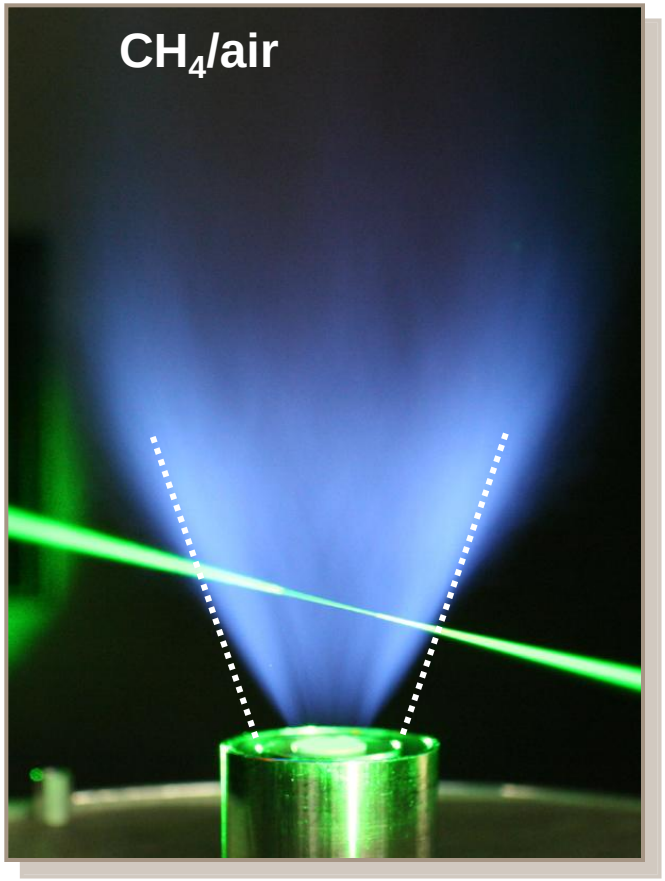
- **FOCUS TOPICS**
  - Stratified flames
  - Lifted flames in hot coflow
  - Piloted Premixed Jet Burner
  - Turbulent opposed jet flames
  - DME diagnostics and piloted DME flames
  - LES/DNS quality and best practice
- **Organizing Committee**
  - R Barlow, J-Y Chen, A Dreizler, J Janicka A Kempf, P Lindstedt, A Masri, J Oefelein, H Pitsch, S Pope, D Roekaerts, L Vervisch



# Cambridge/Sandia Stratified Swirl Burner

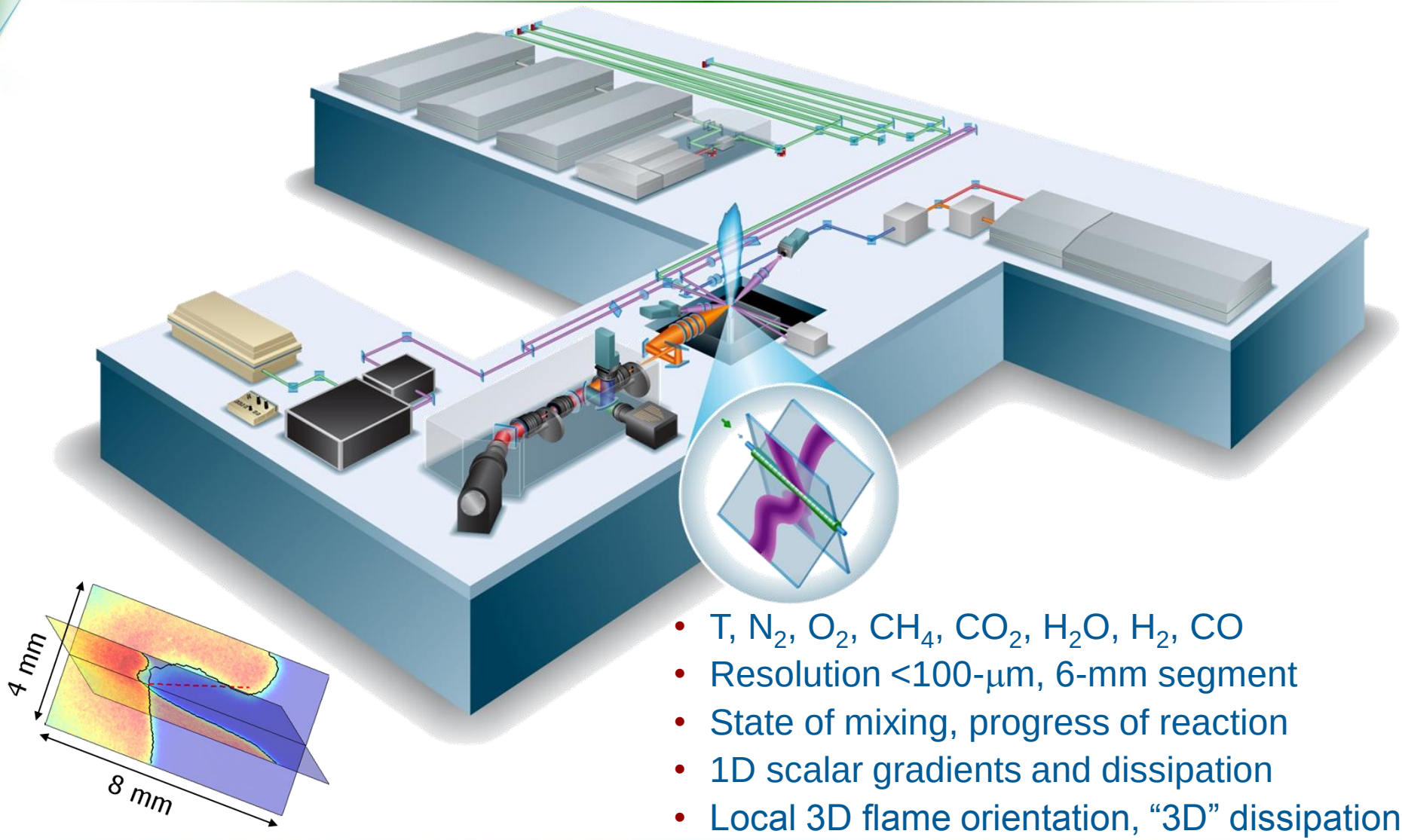
**Top View**




- Double annular construction
- Ceramic center body, 12.7-mm diameter
- Variable swirl in outer annular flow
- Isolate effects of mixture stratification on flame structure
- Include recirculation, shear, swirl
- Collaboration with Mark Sweeney, Simone Hochgreb, Matt Dunn

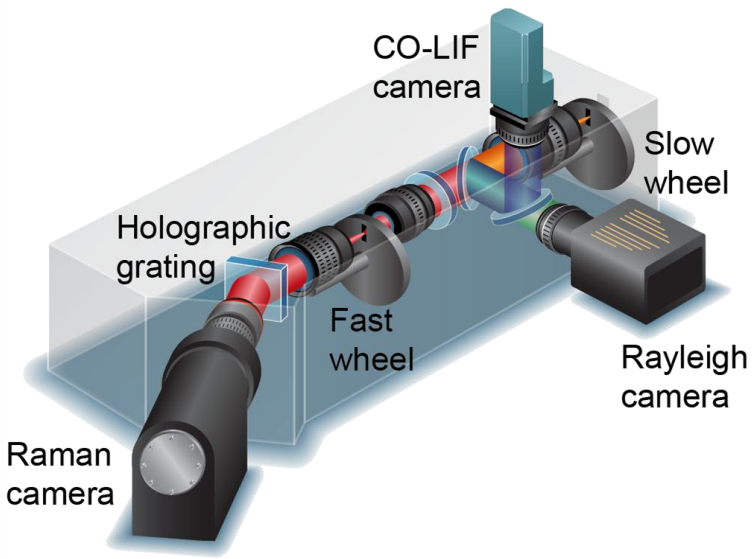
# Raman/Rayleigh/CO-LIF Line Imaging & Crossed Planar Imaging (OH PLIF or Rayleigh)




- T, $N_2$, $O_2$, $CH_4$, $CO_2$, $H_2O$, $H_2$, CO
- Resolution <100-μm, 6-mm segment
- State of mixing, progress of reaction
- 1D scalar gradients and dissipation
- Local 3D flame orientation, “3D” dissipation

# Raman/Rayleigh/CO-LIF Diagnostics: Progress on Precision and Spatial Resolution

- **Compare to data from 1995-2000 (e.g., Sandia piloted Flame D)**
  - **Line imaging vs. point**
  - **Factor ~30 smaller volume of gas**
  - **3-4 times better precision**




| Air (294 K) | 750 μm* | new detection system 100 μm† | denoised† |
|---|---|---|---|
| $Y_{N2}$ | 90 | 400 | 700 |
| $Y_{O2}$ | 30 | 125 | 210 |
| $T_{Ray}$ | 400‡ | 410‡ | 430‡ |

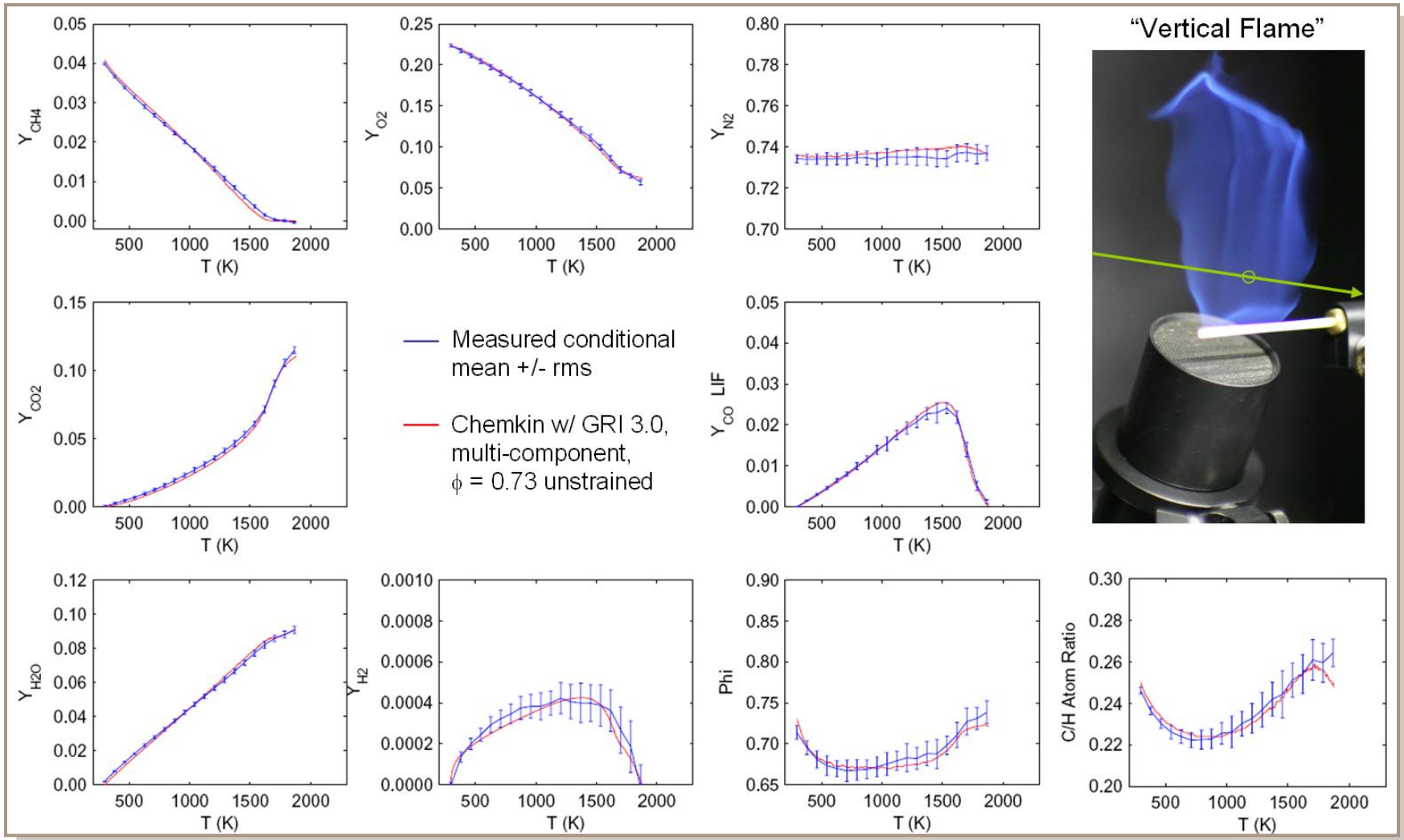
| $CH_4$/air flat flame (2050 K, $\phi$ = 1.28) | | | |
|---|---|---|---|
| $Y_{N2}$ | 50 | 130 | 190 |
| $Y_{H2O}$ | 20 | 50 | 88 |
| $Y_{CO2}$ | 15 | 29 | 45 |
| $Y_{CO_LIF}$ | 17 | 16 | 23 |
| $Y_{H2}$ | 6 | 17 | 24 |
| $T_{Ray}$ | 100 | 150 | 200 |
| phi | 20 | 65 | 86 |

* 750 μm values from Barlow & Frank (1998) using 1.2 J/pulse

† Representative SNR from 100-shot files using 1.8 J/pulse

‡ SNR for $T_{Ray}$ limited by accuracy of laser energy measurements

# Laminar Unstrained Premixed Flame ($\phi$ = 0.73) Compares Well with Chemkin Calculation



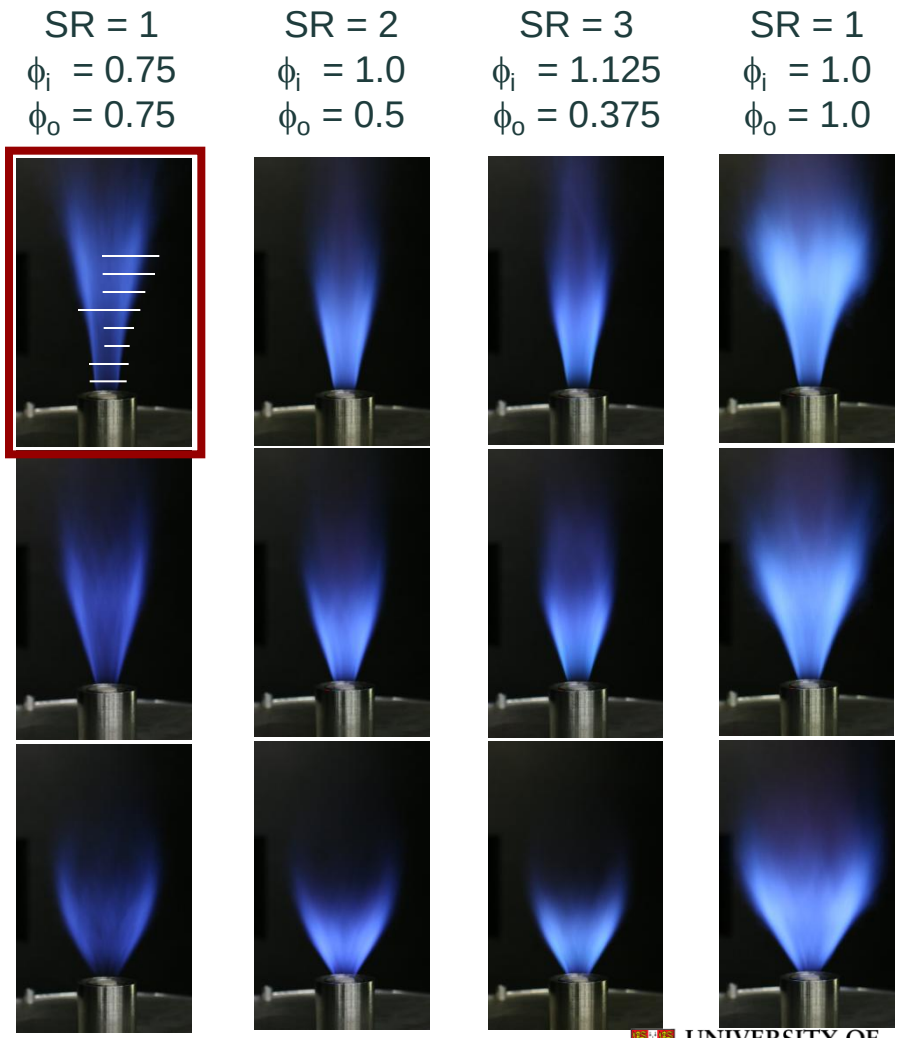
# Cambridge/Sandia Stratified Swirl Burner

$U_i$ = 8.3 m/s  $U_o$ = 18.7 m/s  $U_{cf}$ = 0.4 m/s

$Re_i$ = 5,960  $Re_o$ = 11,540

Vary stratification ratio and swirl

- **Radial profiles**
  - z = 10, 20, 30, … mm
  - 300 shots at each location, 1500 in flame brush
  - 103 μm data spacing
- **Long records**
  - crossing of flame & mixing layer
  - 30,000 shots
  - 20 μm data spacing
  - Wavelet denoising
- **Velocity (at Cambridge)**

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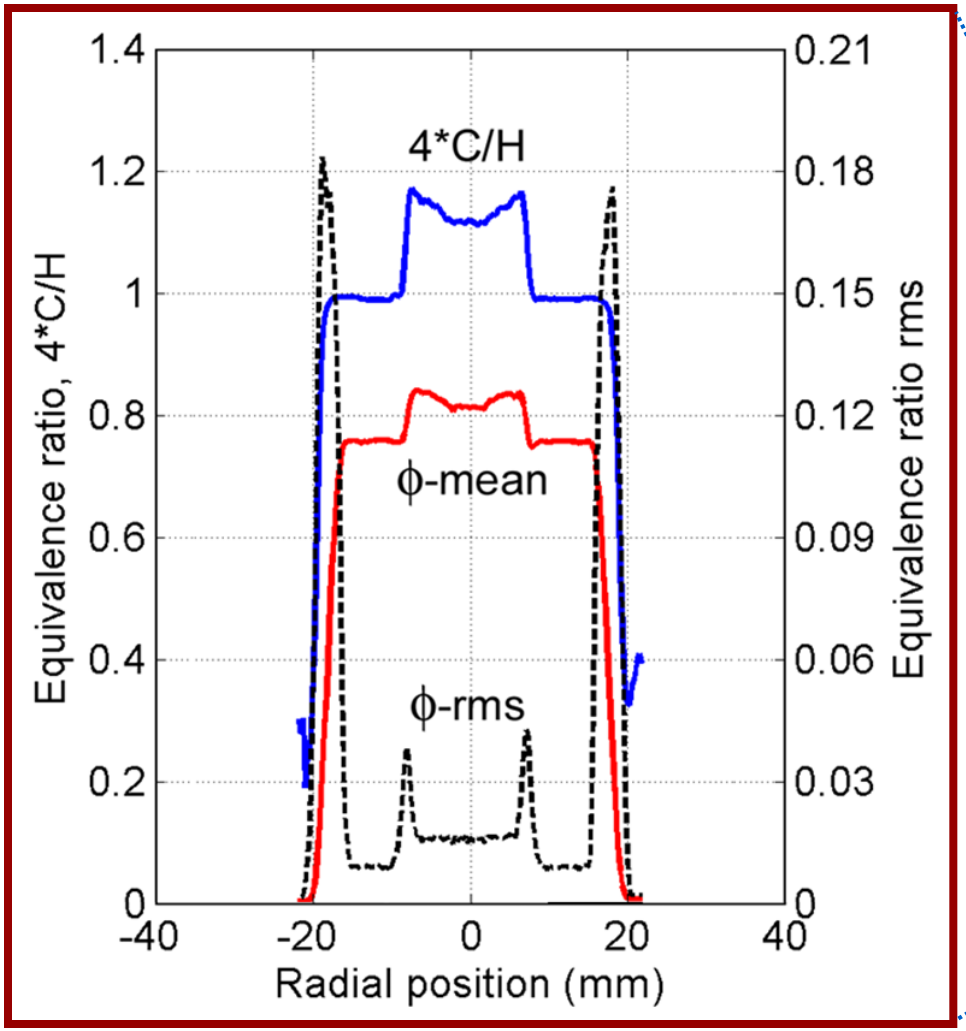
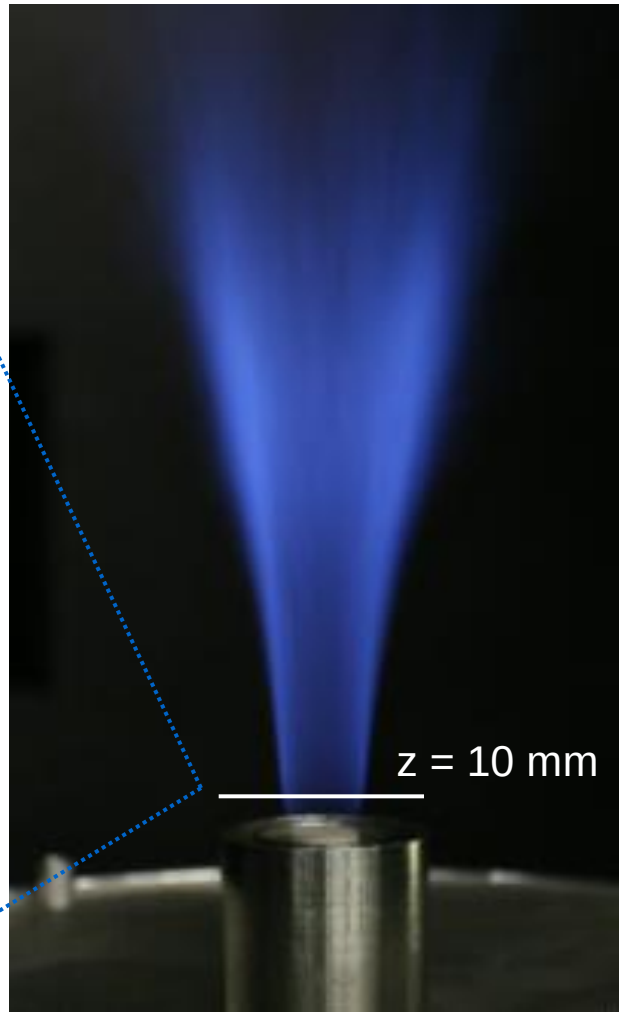
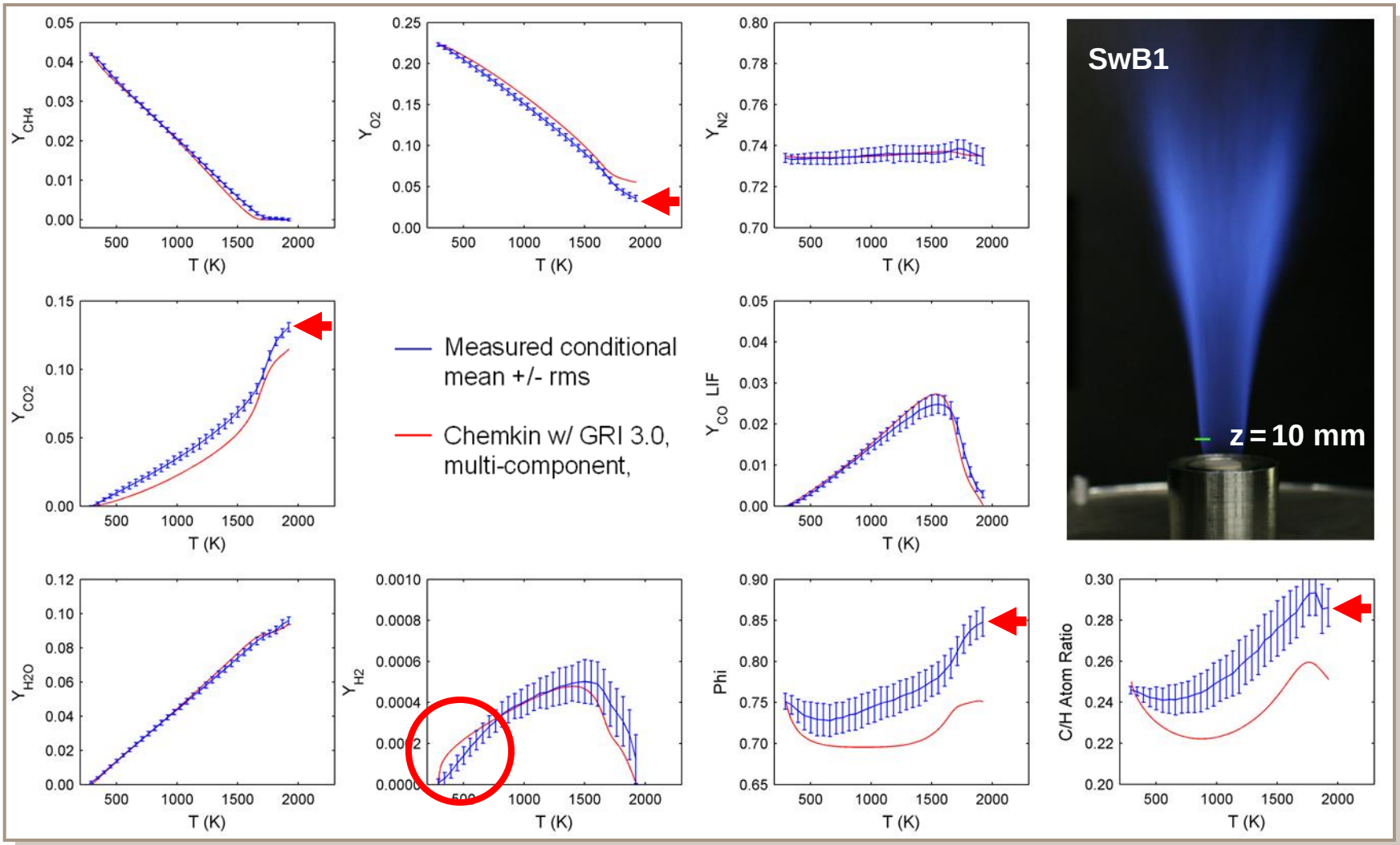
# Equivalence Ratio and Atom Balances NOT Conserved from Reactants to Products

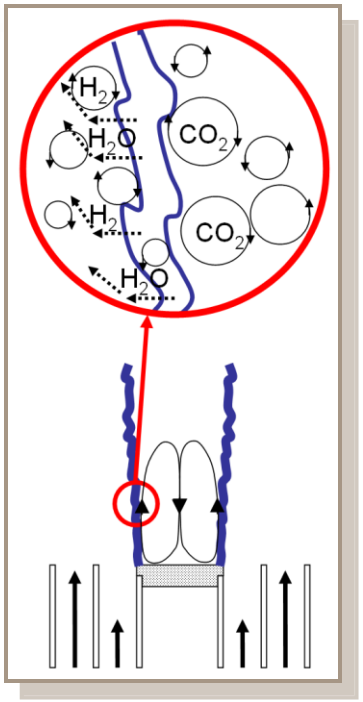


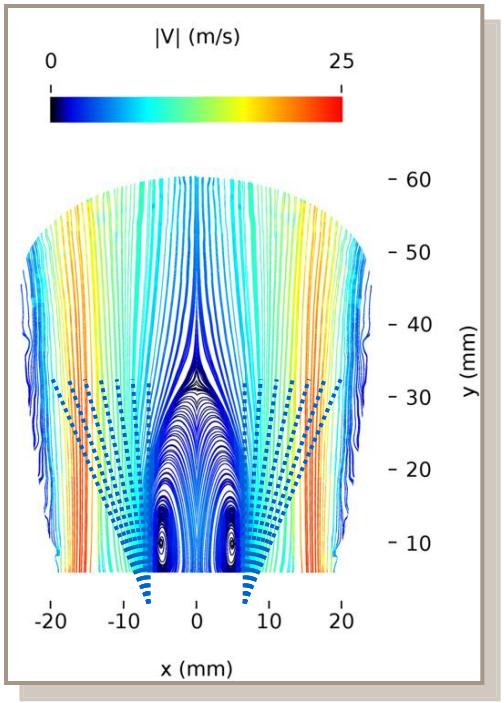



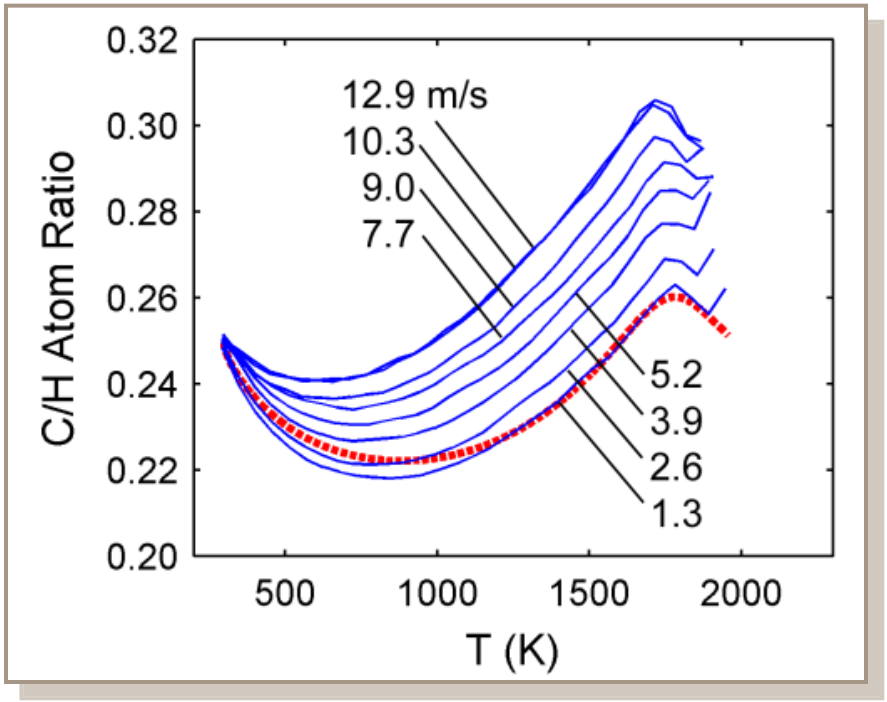
# Turbulent Premixed Flame ($\phi$ = 0.75): Conditional Means from 1500 Shots



# Physical Mechanisms




- **Combination of preferential transport, high shear, and a strong recirculation zone that amplifies the transport effects**

**Barlow et al., CNF 2012; Dunn & Barlow, ProCI (accepted).**

# Cambridge/Sandia Stratified Swirl Burner

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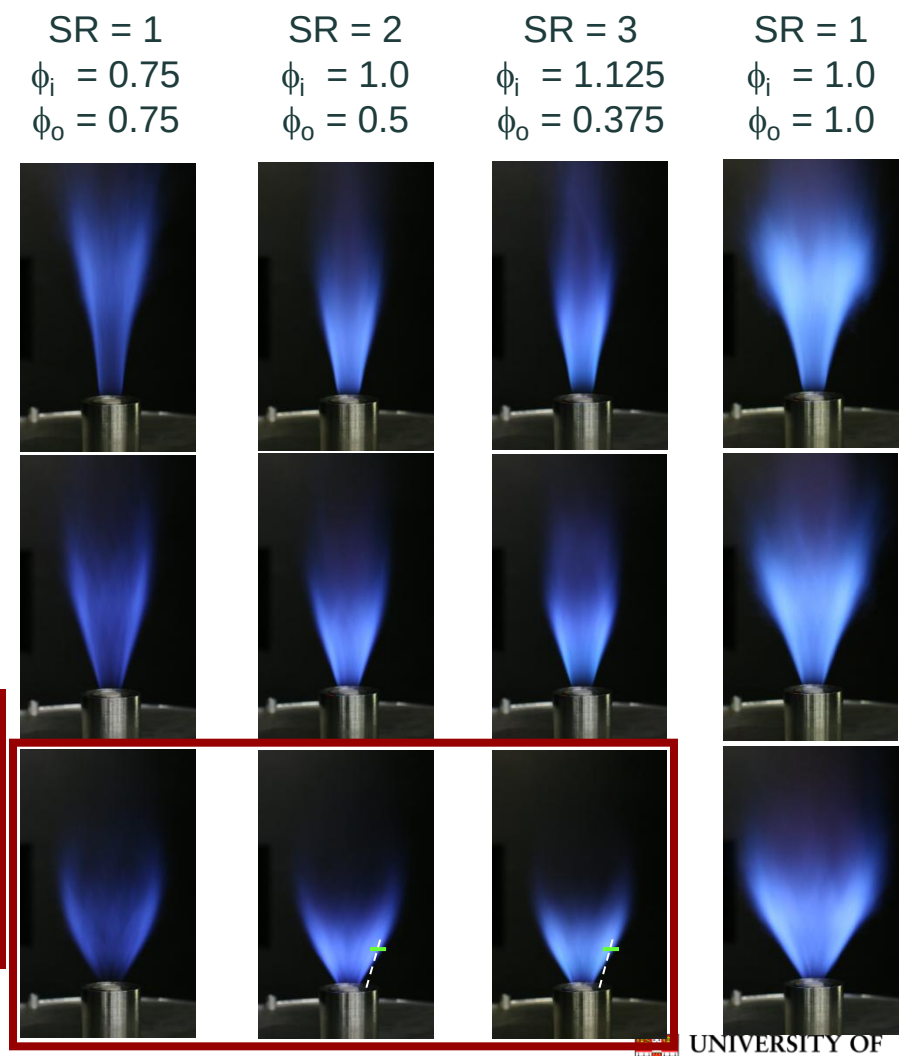


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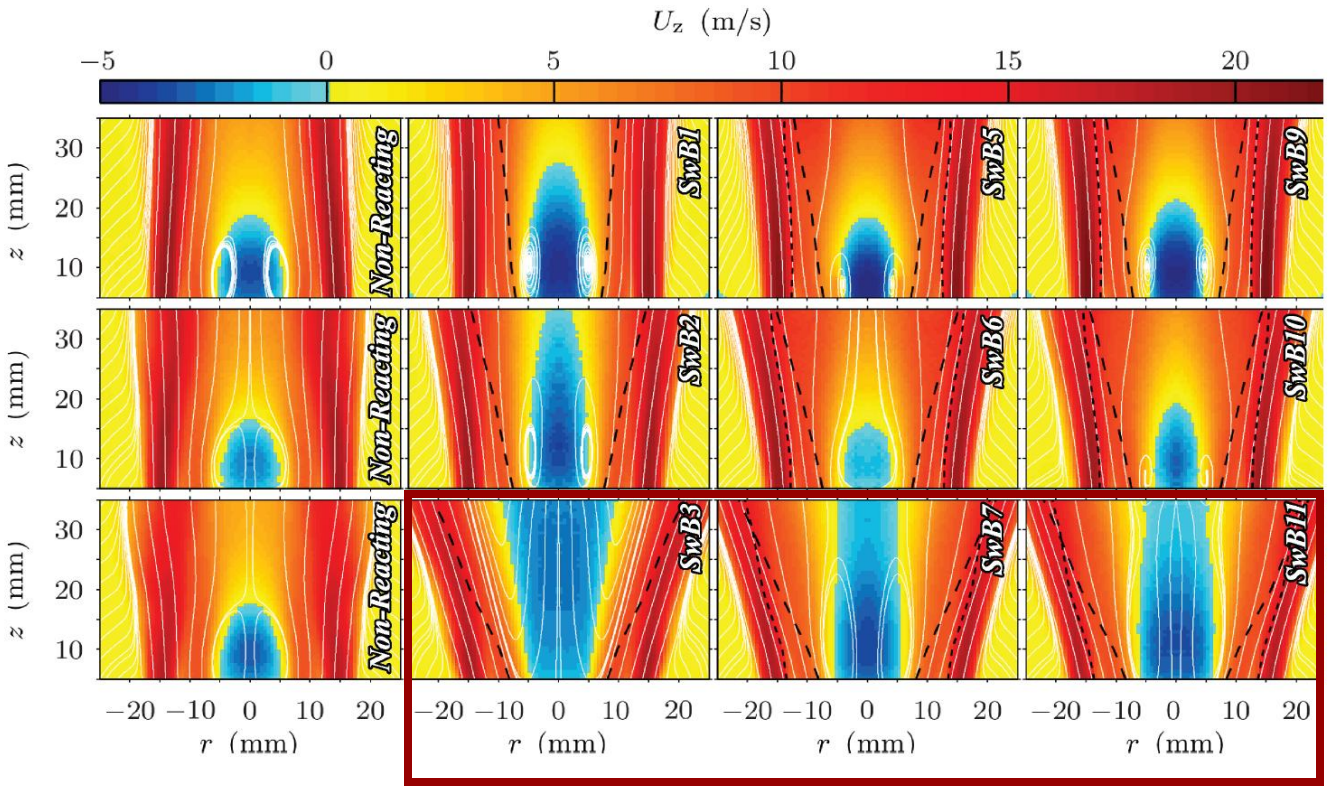
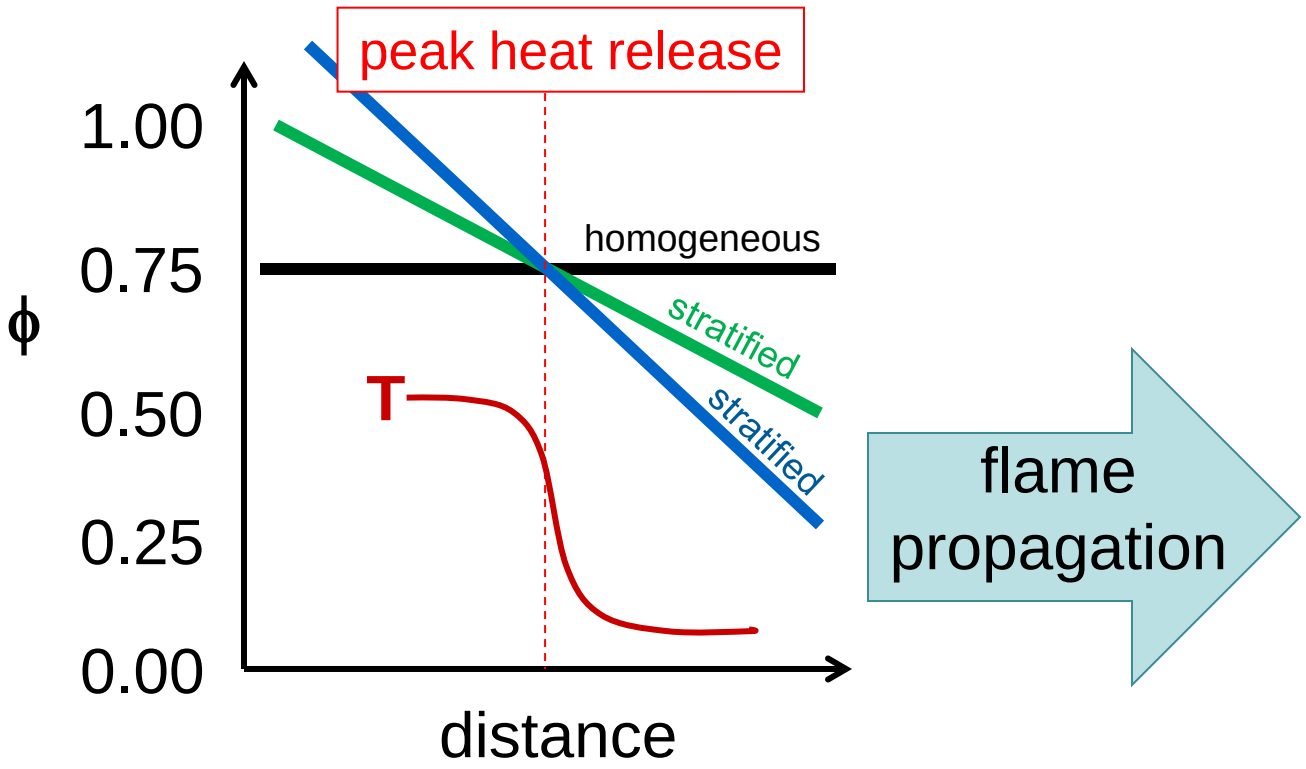
# Mean Axial Velocity from PIV




- **High swirl flames have large recirculation zones (blue) and do not show strong effects of preferential diffusion on product composition**
- **Avoids extra complication in comparing with model results**

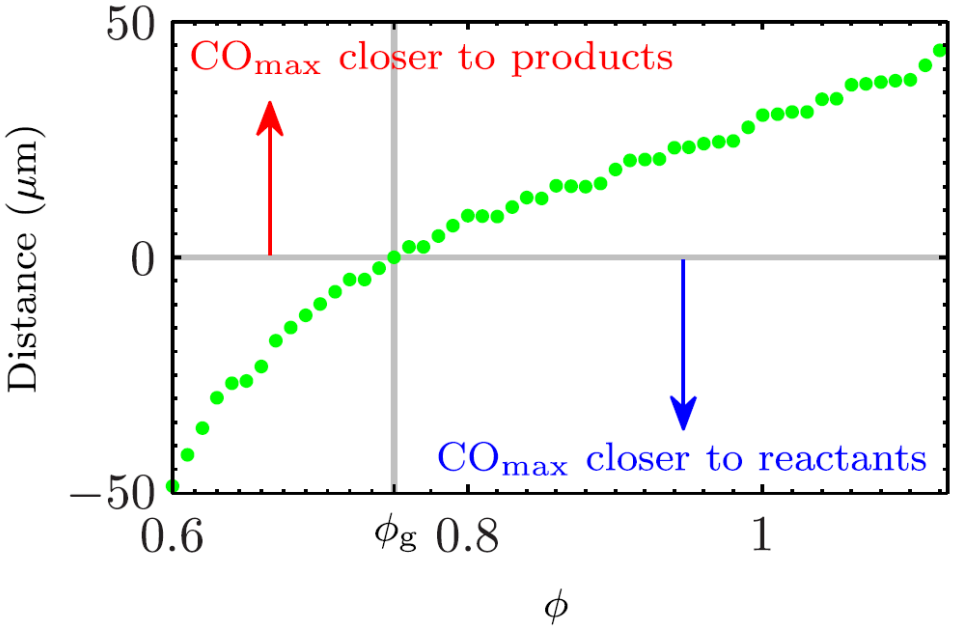
# Question: How is flame structure affected by a gradient in phi



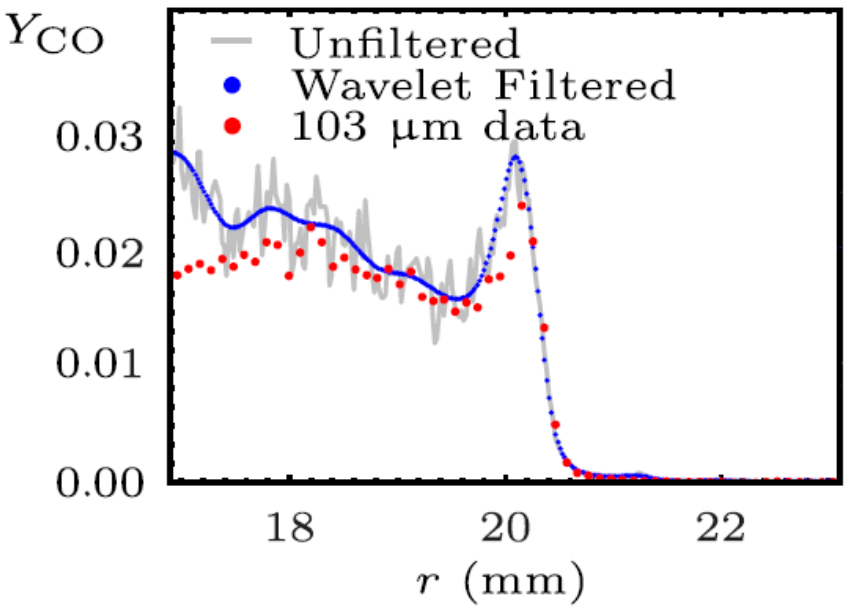

- **Lean, back-supported flames (burn from higher ϕ toward lower ϕ)**
- **Apples vs. apples: Compare when ϕ at the location of peak heat release is the same in homogeneous and stratified flames**

# Data Conditioning to Isolate Effects of Stratification

**Distance between max CO and max heat release**



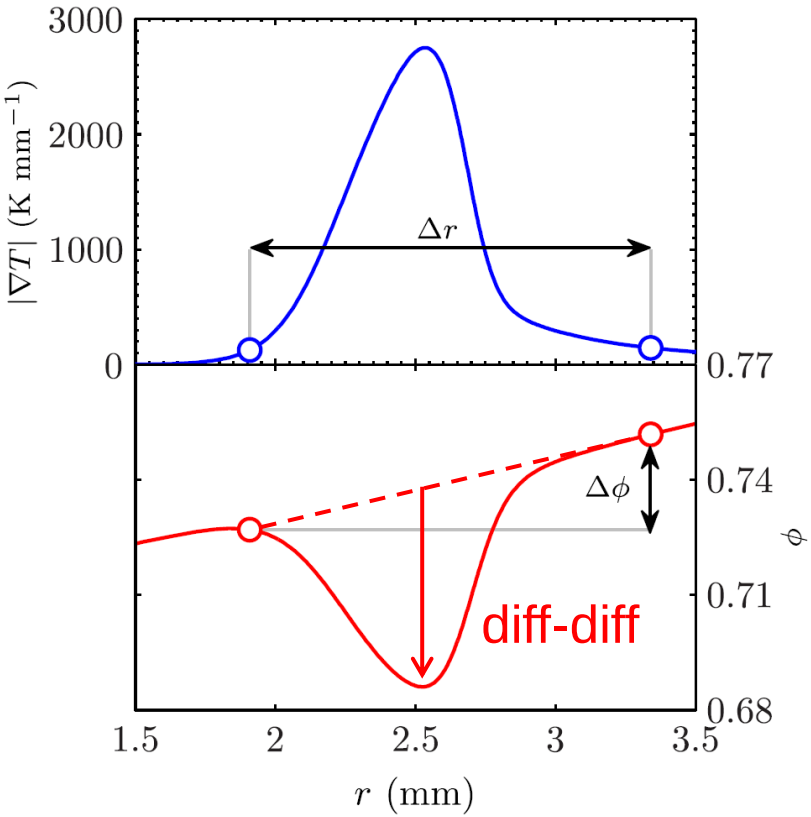

**Single shot profiles**

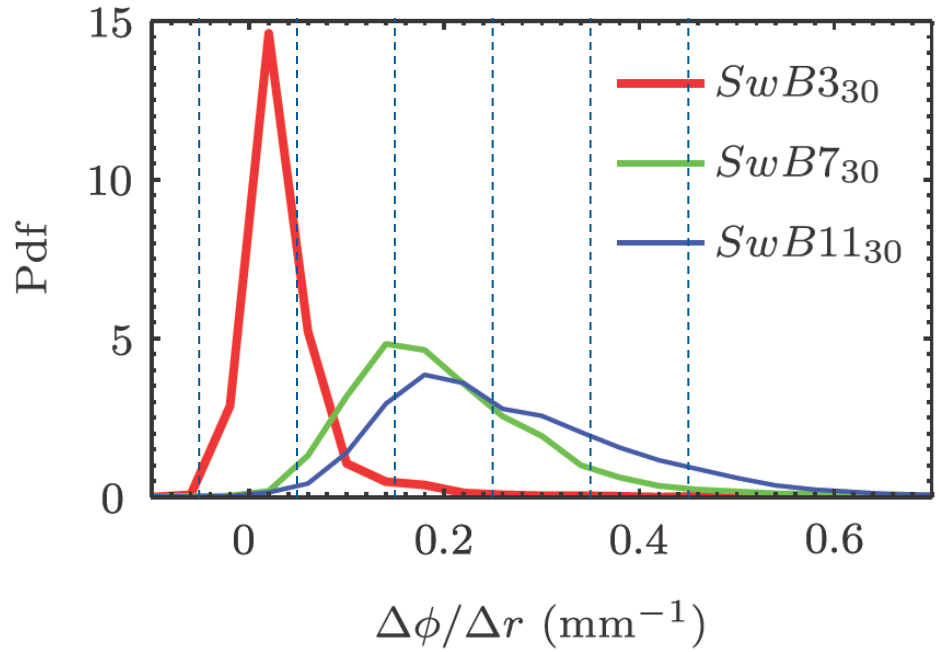



- **Condition each realization on the measured equivalence ratio at the location of maximum CO ($\phi_{CO_max}$ = 0.75 ± 2.5%)**

# Data Conditioning to Isolate Effects of Stratification

- **Condition on change in equivalence ratio across the flame**

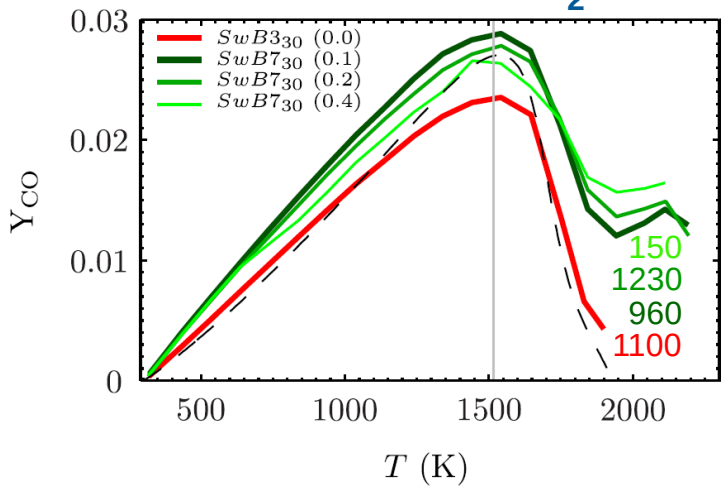


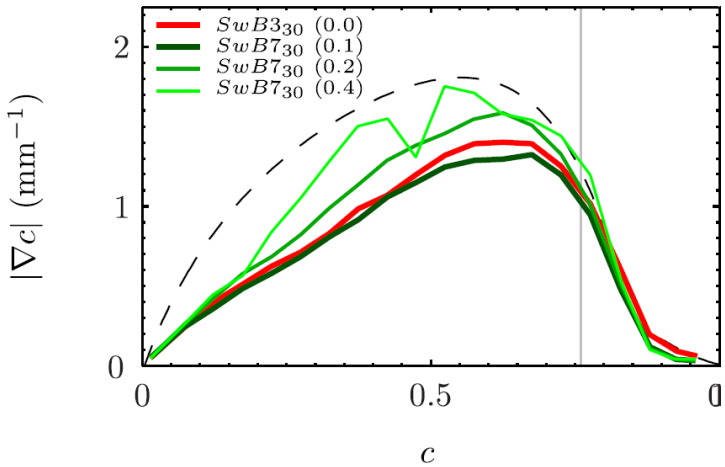

**-0.05 < Δϕ/Δr < 0.05**
**0.05 < Δϕ/Δr < 0.15**
**0.15 < Δϕ/Δr < 0.25**
**0.25 < Δϕ/Δr < 0.35**
**0.35 < Δϕ/Δr < 0.45**

# Doubly Conditioned Results: Effects of Stratification

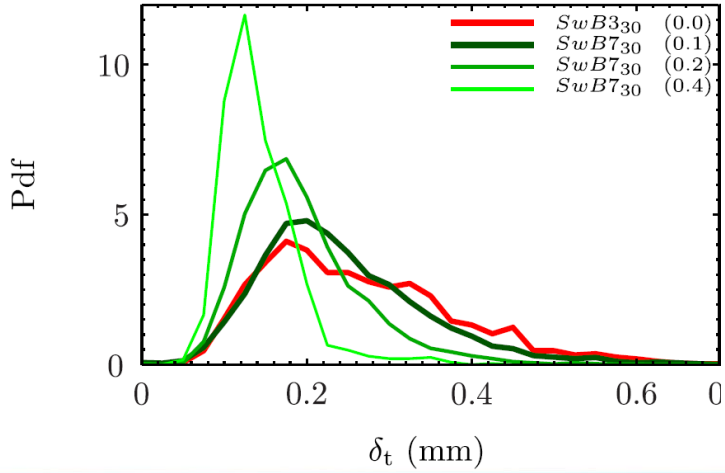
- **Elevated CO and $H_2$**



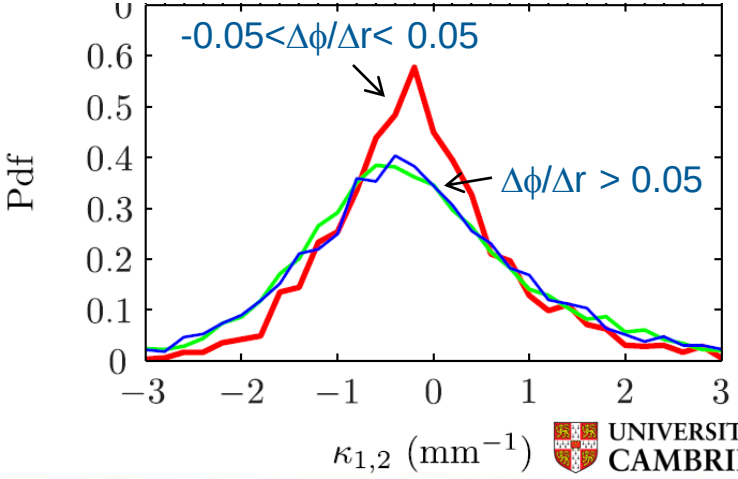

- **Elevated SDF**




- **Reduced flame thickness (3D)**




- **Broader curvature pdf**

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# Summary: Multi-Scalar Experiments on Premixed and Stratified Flames

- **Significant effect of preferential transport on product composition in bluff body stabilized methane/air flames**
  - **Differential diffusion effect amplified by flow recirculation**
  - **May be present in any HC flame with bluff body stabilization**
- **Effects of mixture stratification on turbulent flame structure**
  - **Isolated by conditional averaging**
  - **Are these effects important for modeling?**
- **Experiments designed for model validation can also lead to fundamental scientific discoveries**

*Sweeney et al., CNF, 2012a,b (in press); Sweeney et al. 2012c (accepted)*

# Perspectives on Turbulent Combustion Model Development

- **Development of predictive combustion models depends on availability of validation data sets**
  - **Complementary diagnostics; high data quality**
  - **Well defined boundary conditions**
  - **Burners and phenomena that challenge models in ways relevant to applications**
  - **Target cases that connect across a range of parameters**
  - **Close collaboration between experimenters and modelers**
  - **Still a big gap between fundamental and applied reseach**

# Perspectives on Multi-Agency Coordination on Turbulent Combustion

- **Collaborative workshops (TNF, ECN, Soot, etc.)**
  - **Significant role in coordinating research in focused areas**
  - **Volunteer organizations with little or no direct support**
  - **Require critical mass of people to buy in**

- **Developing and validating predictive models for complex combustion applications (e.g.; gas turbine combustors):**
  - **is beyond the reach of these informal collaborations**
  - **will require multi-agency coordination**
  - **will require better cooperation across government, academia, and industry (precompetitive, cost sharing)**
  - **will require greater investment in the tools of collaboration (infrastructure)**