

## Fire Dynamics: Level 2 Milestone Peer Review

Sean Kearney, 1512, Portfolio Lead and PI  
Task No.: 20.30.11

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# L2 Milestone Language



“Document experimental methodology and results of joint temperature and soot experiments, and determine the spatial resolution and uncertainty of the measurements. Joint statistical results from jet-flame and pool fire measurements. Documentation in Journal article (Combustion and Flame); AIAA conference papers, and conference presentation slides”

## LASER-DIAGNOSTIC MAPPING OF TEMPERATURE AND SOOT STATISTICS IN A 2-m DIAMETER TURBULENT POOL FIRE

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*Submitted to Combustion and Flame*

### Abstract

We present spatial profiles of temperature and soot-volume-fraction statistics from a sooting 2-m base diameter turbulent pool fire, burning a 10%-toluene / 90%-methanol fuel mixture. Dual-pump coherent anti-Stokes Raman scattering and laser-induced incandescence are utilized for simultaneous point measurements of temperature and soot. The research fuel-blend used here results in a lower soot loading than real transportation fuels, but allows us to apply high-fidelity laser diagnostics for spatially resolved measurements in a fully turbulent, buoyant fire of meter-scale base size. Profiles of mean and rms fluctuations are radially resolved across the fire plume, both within the hydrocarbon-rich vapor-dome region near fuel pool and higher within the actively burning region of the fire. The spatial evolution of the soot and temperature probability density functions is discussed. Soot fluctuations display significant intermittency across the full extent of the fire plume for the research fuel blend used. Simultaneous, spatially overlapped temperature/soot measurements permit us to obtain estimates of joint statistics that are presented as spatially resolved conditional averages across the fire plume, and in terms of a joint pdf obtained by including measurements from multiple spatial locations. Within the actively burning region of the fire, soot is observed to occupy a limited temperature range between ~1000–2000 K, with peak soot concentration occurring at 1600–1700 K across the full radial extent of the fire

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5th AIAA Aerospace Sciences Meeting



## Hybrid fs/ps Rotational CARS Temperature and Oxygen Measurements and Soot LII Measurements in a Turbulent C<sub>2</sub>H<sub>4</sub>-Fueled Jet Flame

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We present a detailed set of measurements from a piloted, sooting, turbulent C<sub>2</sub>H<sub>4</sub>-fueled jet flame. Hybrid femtosecond/picosecond coherent anti-Stokes Raman scattering (CARS) is used to monitor temperature and oxygen, while laser-induced incandescence (LII) is applied for imaging of the soot volume fraction in the challenging jet-flame environment at Reynolds number,  $Re \approx 20,000$ . A new dual-detection channel CARS instrument provides the enhanced dynamic range required in this highly intermittent and turbulent environment. LII measurements are made across a wide field of view requiring us to account for spatial variation in the soot-volume-fraction response of the instrument. Single-laser-shot results are used to illustrate the mean and rms statistics, as well as probability densities of all three measured quantities. LII data from the soot-growth region of the jet are used to benchmark the soot source term for one-dimensional turbulence (ODT) modeling of this turbulent flame. The ODT code is then used to predict temperature, oxygen and soot fluctuations within the soot oxidation region higher in the flame.

### 1. Introduction

Radiative heat transfer from accidental fires and sooting flames is often dominated by emission and absorption from soot, making accurate soot modeling essential for fire risk analysis, as well as prediction of soot emission, and the performance of practical power-generation systems. Thermal radiation from sooting flames is generated in high-temperature regions by emission from hot soot. In lower temperature regions, soot can act as an absorber, providing shielding of the surroundings from flame radiation. These effects are captured in heat-transfer calculations through the radiative transfer equation (RTE),

$$\frac{dI_{\lambda}}{ds} + \mu_{\lambda} I_{\lambda}(s) = \mu_{\lambda} I_{\lambda}^{\text{em}}(s) \quad (1)$$

In Eq. 1, the subscript  $\lambda$  indicates the optical wavelength, while  $b$  indicates blackbody conditions at the local temperature,  $T$ .  $I_{\lambda}$  is the radiation intensity,  $\mu_{\lambda}$  is the absorption coefficient of soot, and  $s$  is a spatial coordinate. Eq. 1 is a simple statement that the change in radiation intensity along a line-of-sight path is equal to emission minus absorption (when scattering is neglected).

Reliable, experimentally validated evaluation of Eq. 1 is a requirement for accurate fire risk-assessment modeling and requires knowledge of both the temperatures and the soot concentration (through  $\mu_{\lambda}$ ) fields, which also

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AIAA SciTech Forum  
7-11 January 2017, Grapevine, Texas  
5th AIAA Aerospace Sciences Meeting



## Two-Beam Femtosecond Rotational CARS for One-Dimensional Thermometry in a Turbulent, Sooting Jet Flame

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Single-laser-shot femtosecond rotational coherent anti-Stokes Raman scattering (fs-RCARS) temperature measurements are performed across a 3-mm line in a turbulent, sooting ethylene jet flame to characterize temperature gradients. A 60-fs pulse is used to excite many rotational Raman transitions, and a 160-ps pulse is used to probe the Raman coherence. The spatial resolution of the measurements is 670 μm in the direction of beam propagation, 200 μm in the direction along the LD line, and 50 μm in the transverse direction. Measurements have been performed at multiple locations in the jet flame, and the measured temperature are similar to previously recorded point measurements.

### 1. Introduction

Soot is an important aspect in many combustion applications. Particularly, soot plays a major role in radiators, which can impact engine hardware and combustion performance in boilers, furnaces, and other combustion devices. Additionally, soot had an adverse effect on the environment and human health. To better understand the role of soot, one-dimensional temperature measurements are performed in a canonical, turbulent, sooting ethylene jet flame that has been previously characterized using laser-induced incandescence (LII)<sup>1,2</sup> and point temperature measurements<sup>3</sup>.

Coherent anti-Stokes Raman scattering (CARS) has been used for temperature, pressure, and species-concentration measurements in gas-phase reacting and nonreacting flows for many decades<sup>4,5</sup> and more recently with ultrafast laser systems<sup>6</sup>. Two distinct advantages of ultrashort-pulse CARS are the high peak-energy of the femtosecond (fs) and picosecond (ps) pulses which efficiently drive the Raman excitation process and allow for 1D<sup>7</sup> or 2D<sup>8</sup> measurements, and the stable, near-transform-limited nature of the pulses which greatly reduces shot-to-shot fluctuations in the CARS signal. Several variations and improvements to ultrashort-pulse CARS techniques

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AIAA2017-0031

## Fire Dynamics: Predicting Smoke from Fires

Sean Kearney, 1512, Portfolio Lead and PI, Task No.: 20.30.11

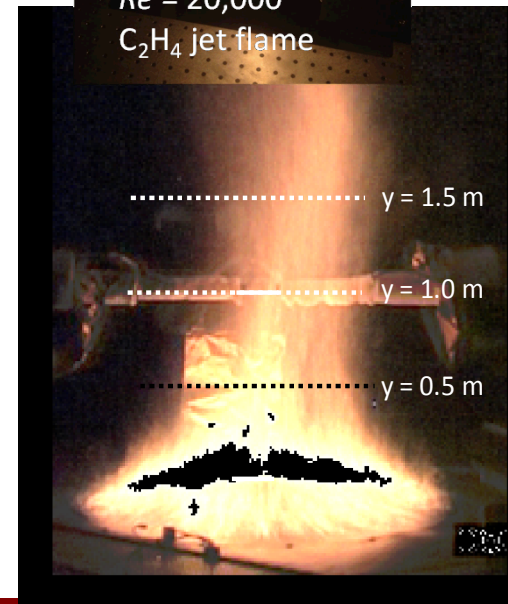
### Current Efforts and Progress

#### Jet Flame

- Soot measurements throughout flame for  $C_2H_4$  and  $C_2H_4/C_3H_6$  mixtures
- Temperature measurements at peak soot load in  $C_2H_4$  flames
- Joint temperature/soot measurements at peak soot load (spatially resolved)

#### Pool Fire

- Performed detailed analysis of existing 2-m pool fire data for joint temperature/soot statistics (coarser spatial resolution)
- Submitted manuscript to Combustion and Flame with T/soot and joint T/soot statistics throughout the fire plume



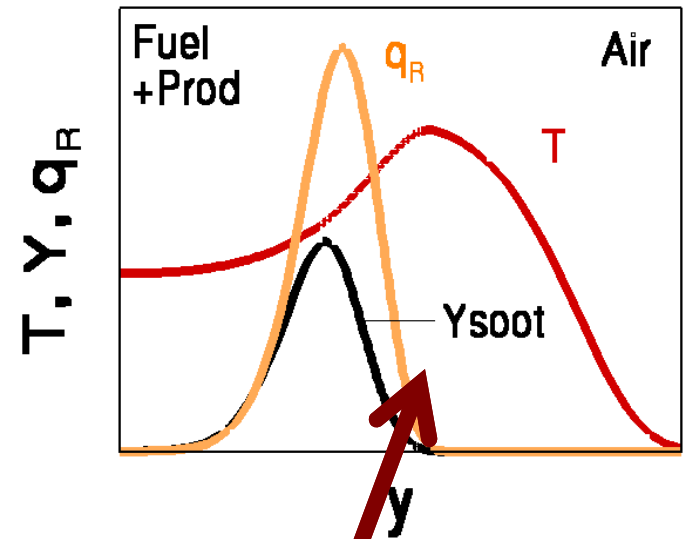
## Radiative Transfer Equation (RTE)

$$\frac{d\overline{I_\lambda}}{ds} = \overline{\mu_\lambda I_{\lambda,b}(T)}_{\text{emission}} - \overline{\mu_\lambda I_\lambda}_{\text{absorption}}$$

$I_{\lambda,b}(T)$  = blackbody at temperature,  $T$

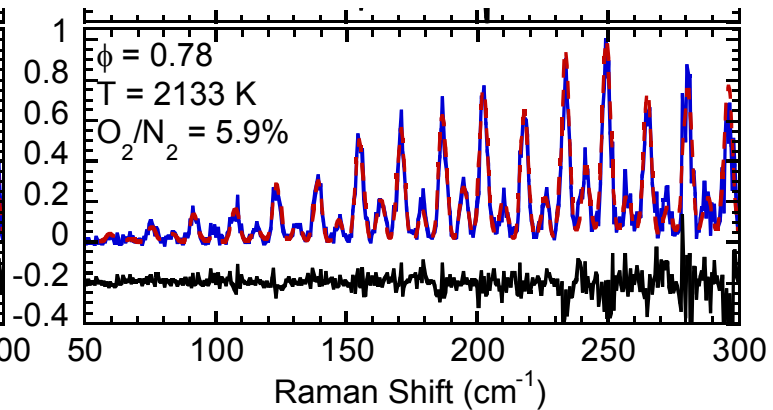
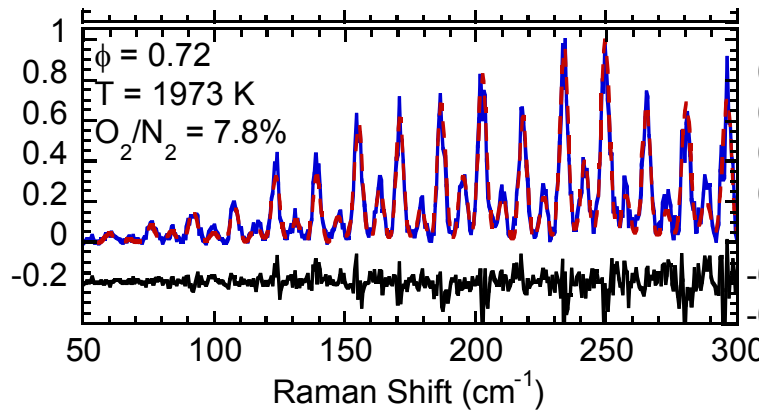
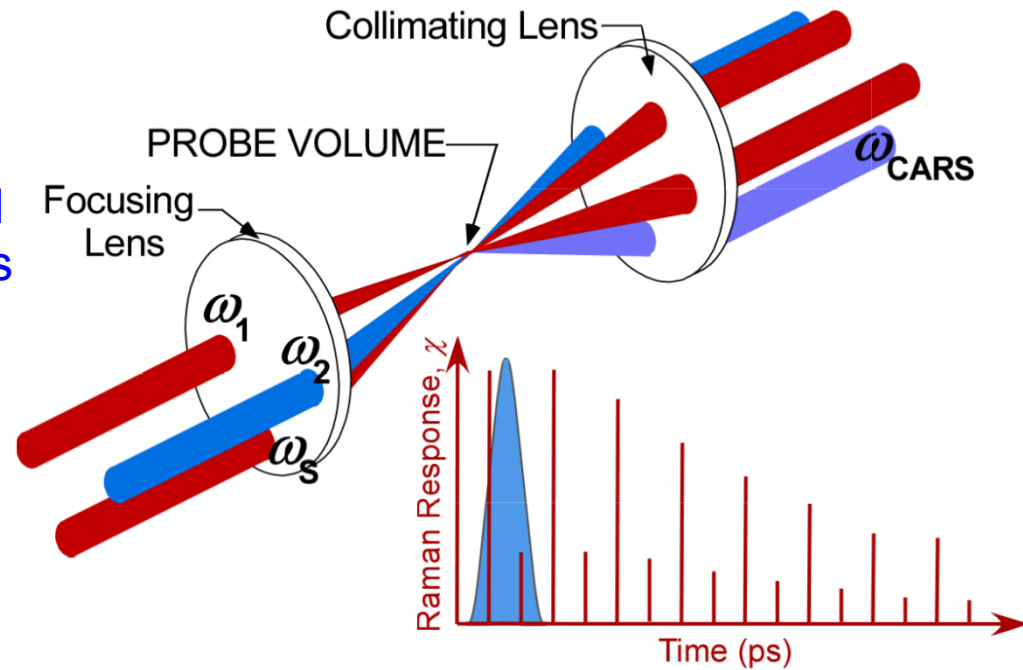
$\mu_\lambda = \frac{f_v}{\lambda} g(n, k)$  = soot absorption coeff.

- Turbulent flame is an assembly of strained and wrinkled flame sheets
- Direct validation of RTE and heat-transfer models require
  - Temperature and soot measurements
  - Time- and space-resolved



# fs/ps Rotational Coherent anti-Stokes Raman scattering

- Temperature/O<sub>2</sub> detection
- High-spatial and temporal resolution
- Developed under RTBF/TRP and now leveraged for measurements on C6/WSEAT
- Distinct advantages for sooting, fuel-rich flames
- Enhanced precision ~ 1%
- Enhanced data rates from 10 Hz to 1 kHz

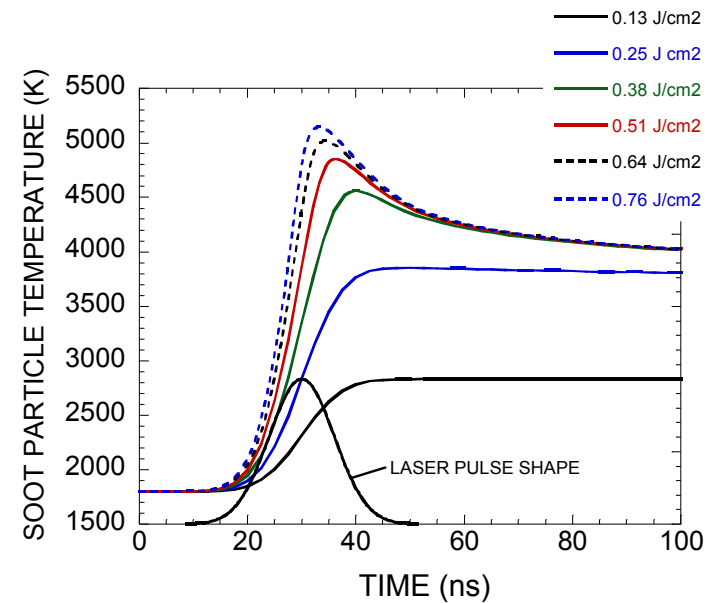
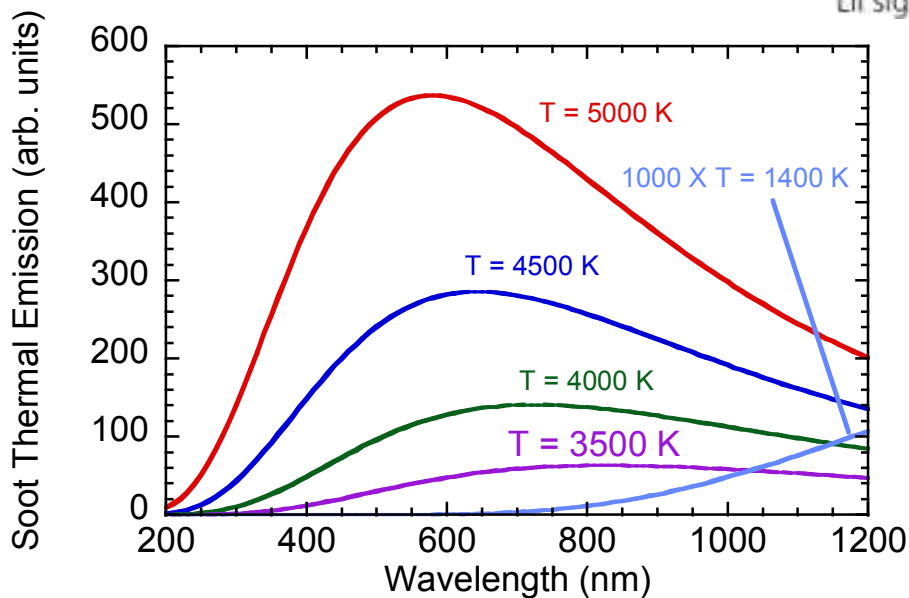
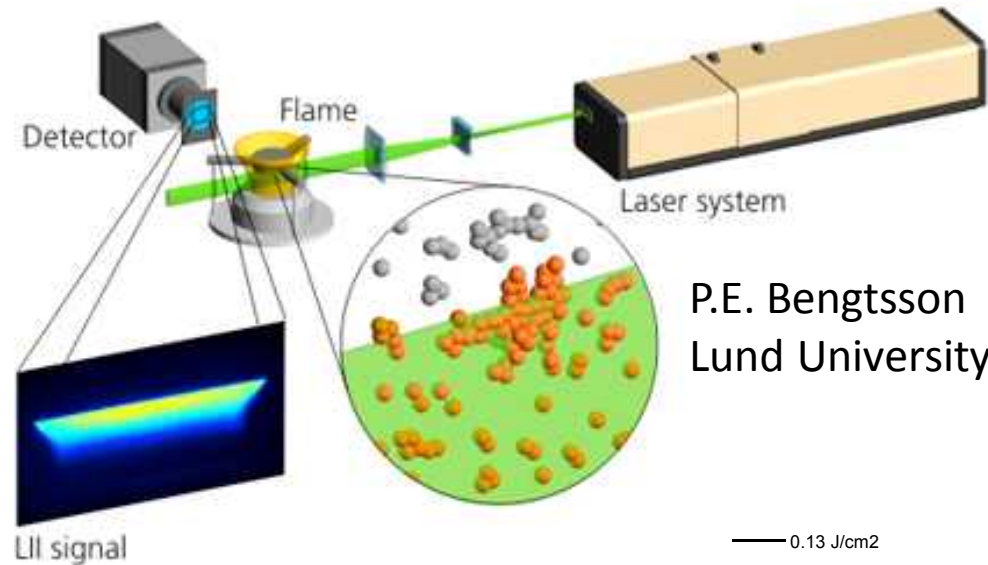


# Laser-Induced Incandescence (LII)

- Nd:YAG laser at 1064 nm
- Rapid heating of soot particles above background
- For nm-scale soot primary particles

$$S_{LII} \sim d_p^3$$

- Detection w/ICCD 30-ns gate
- Direct imaging of soot  $f_v$

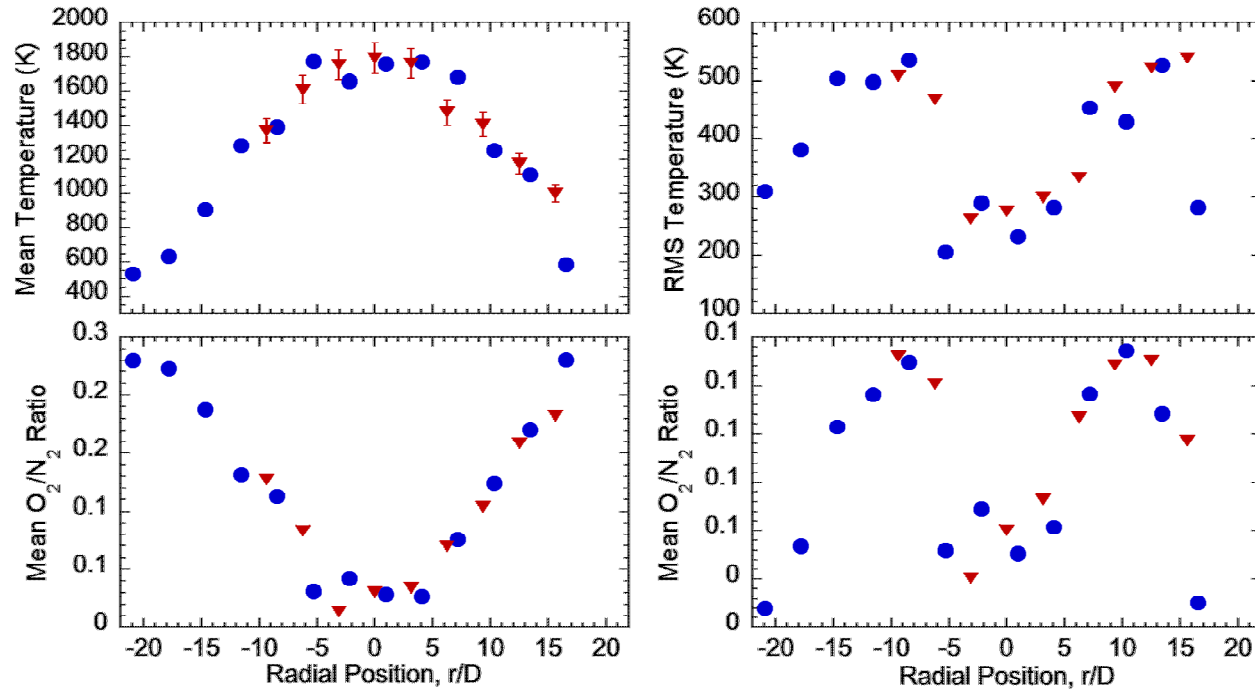


# Sooting Ethylene Jet Flame at $Re = 20,000$

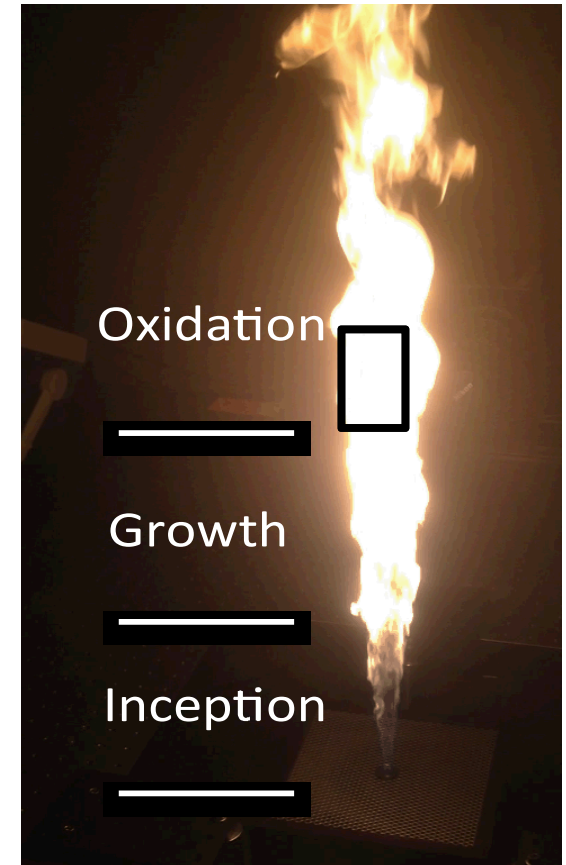
- *Sandia CRF design (Shaddix)*
- *Pilot-stabilized canonical turbulent jet flame:  $Re = 20,000$*
- *Soot/smoke yield can be varied by vitiation, dilution, or fuel type*
- *Baseline case  $\rightarrow$  pure  $C_2H_4$  fuel*
- *Also investigating 25% and 50%  $C_3H_6$  addition*
- *LII measurements have been performed by Shaddix et al. (SAND2010-7178)*
- *Max soot  $f_v \sim 0.55$  ppm, jet-fuel pool fire is  $\sim 1$  ppm*



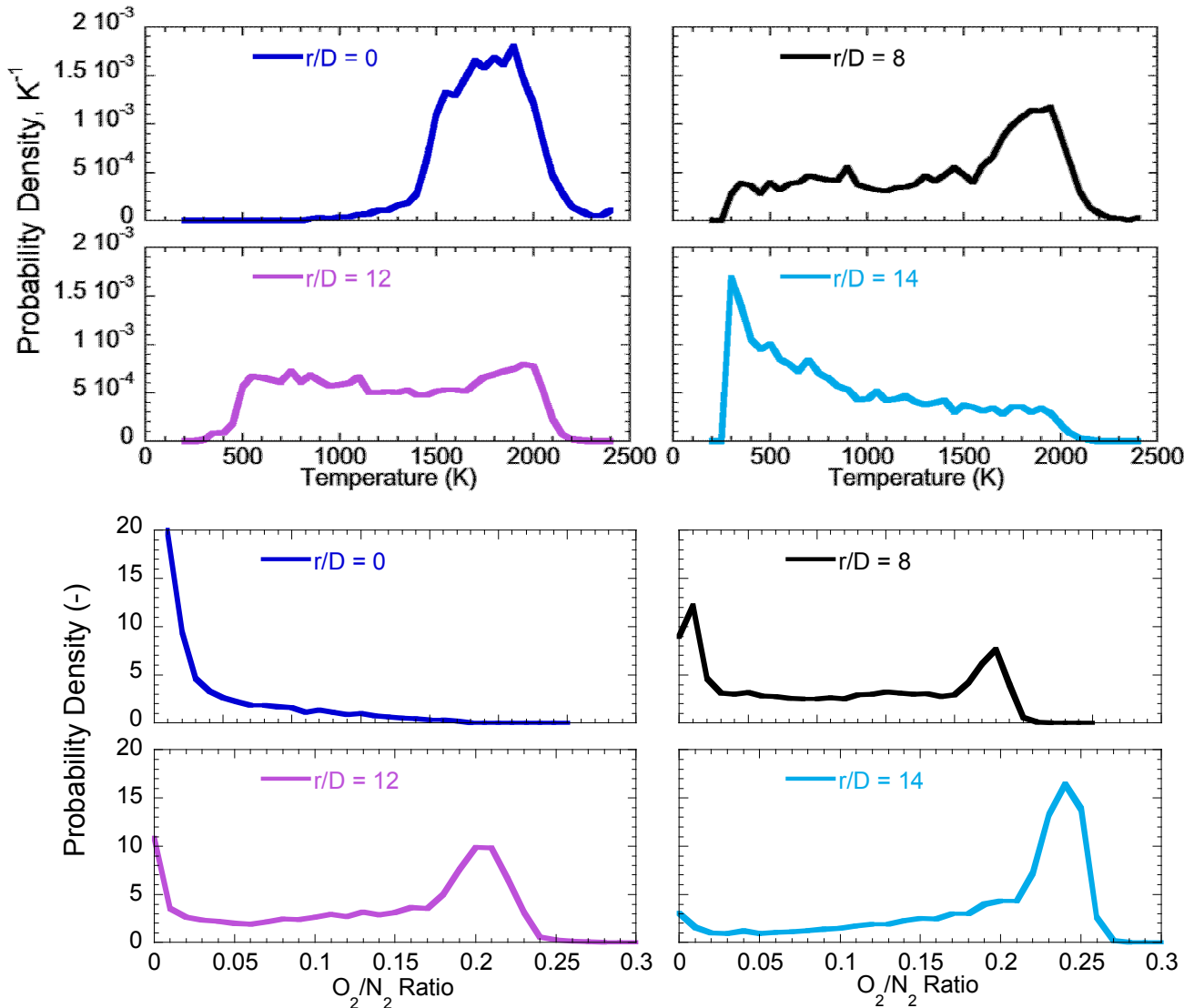
# Rotational CARS Mean and RMS Temp./O<sub>2</sub> Profiles



- Data from separate days spaced over 1 month apart
- Results obtained in 1-cm ( $z/D = 3.1$ ) vertical increments
- Soot oxidation zone  $z/D = 127-175$  investigated
- Little vertical variation in profiles

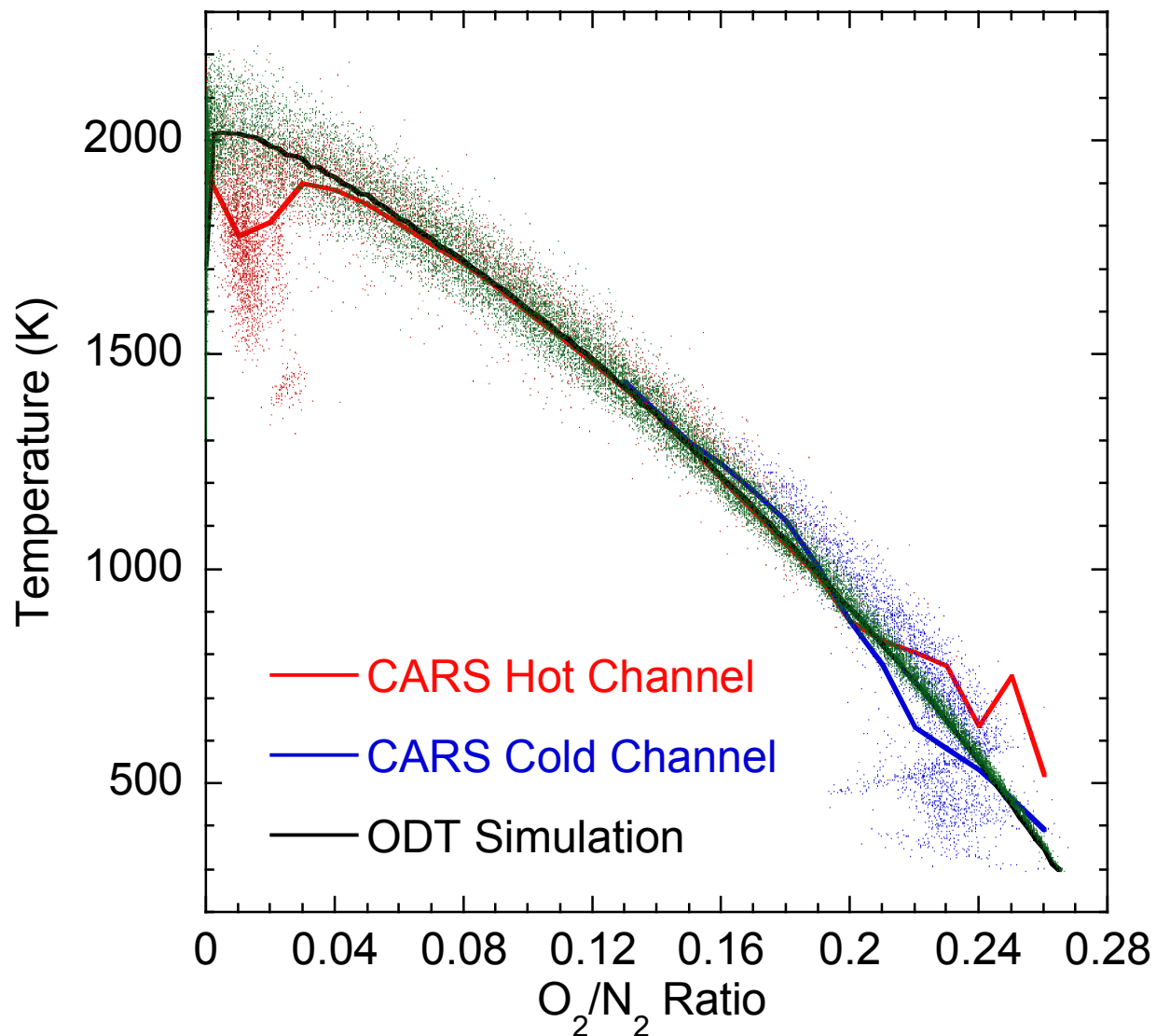


# Temperature/O<sub>2</sub> Probability Densities—Radial Dependence



- Centerline  $T \sim 1400-2200$  K
- Transitions to uniform distribution in peak mixing zone
- Intermittent  $T$  fluctuations at jet edges – “clipped” pdf
- Intermittent O<sub>2</sub> fluctuations at jet centerline
- Transitions to bi-modal pdf w/ uniform region in peak mixing zone
- Intermittent O<sub>2</sub> fluctuations at jet edges

# T/O<sub>2</sub>: Comparison to ODT Simulation

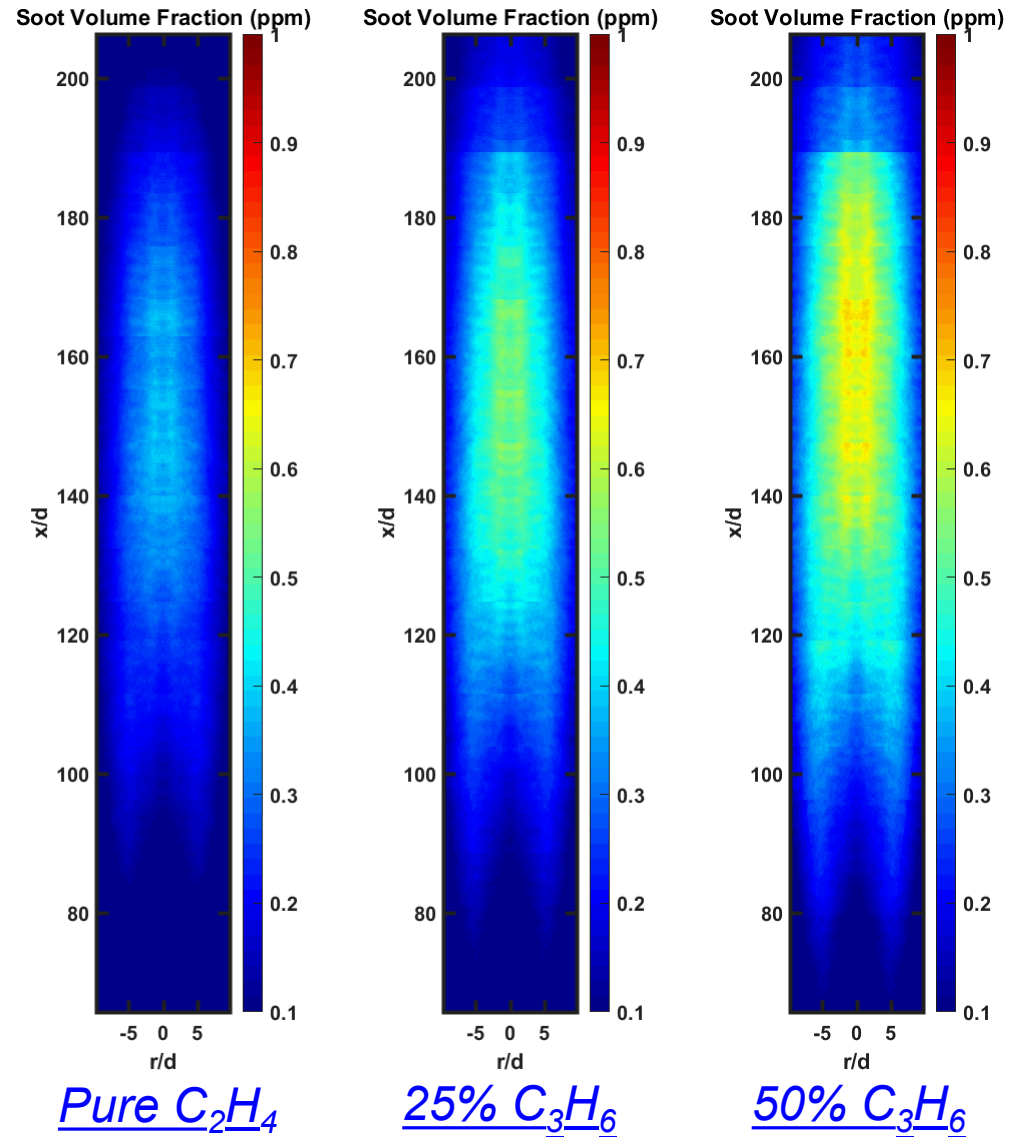


- Results for  $z/D = 175$  (soot oxidation zone)
- Taken near jet centerline
- Scatter points = single realizations
- Lines = mean temperature conditioned on O<sub>2</sub>/N<sub>2</sub>
- Mean of ODT within 1-2% of CARS measurements for O<sub>2</sub>/N<sub>2</sub> = 6-20%
- O<sub>2</sub> detection limit is O<sub>2</sub>/N<sub>2</sub> about 3%
- Hot- and cold-channel data temperatures agree to 1-2% for O<sub>2</sub>/N<sub>2</sub> = 12-20%

# Mean soot-volume-fraction results

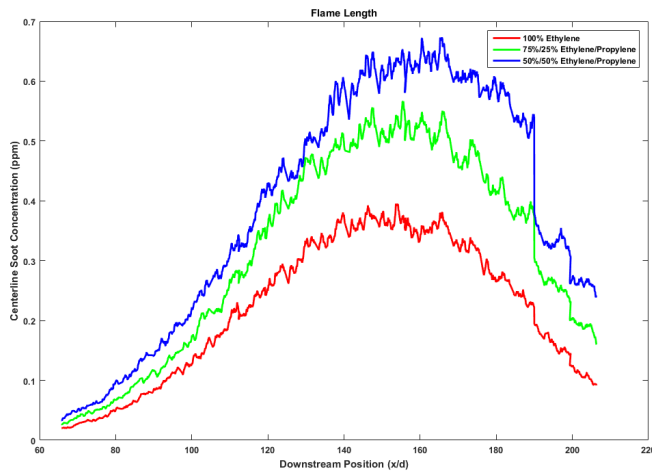
- At request of Sandia modeling community, additional fuel blends were added for LII soot measurement
- Mass flow held constant ( $Re \sim \text{const.}$ )
- Fuel 1:  $C_2H_4$  (base condition)
- Fuel 2: 25%  $C_3H_6$  by mass
- Fuel 3: 50%  $C_3H_6$  by mass

***While useful, these data provide details of temperature and soot concentration alone. The joint statistics are required to model the soot radiation source term!***

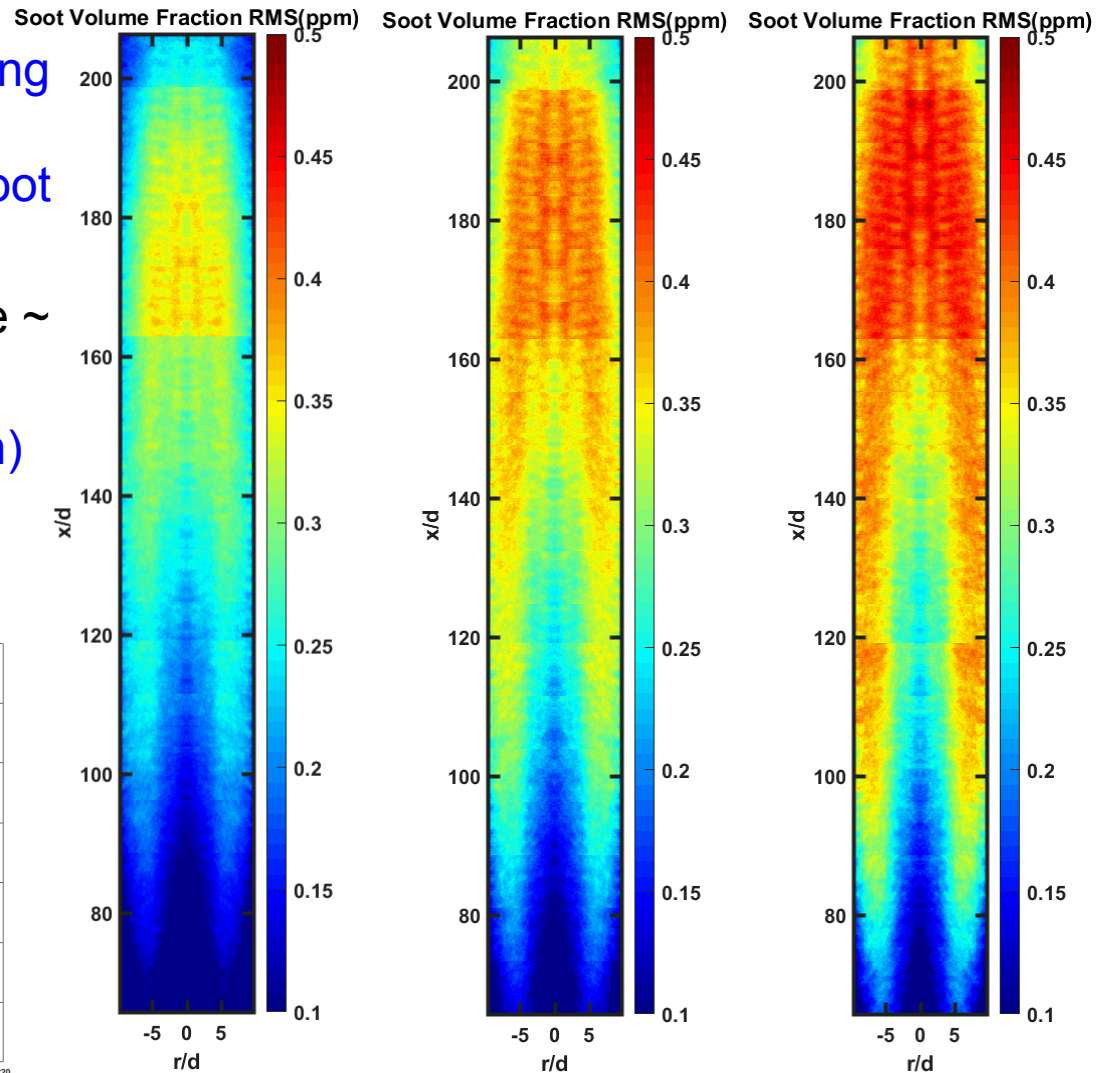


# Soot fluctuations

- At request of Sandia modeling community, additional fuel blends were added for LII soot measurement
- Mass flow held constant ( $Re \sim \text{const.}$ )
- Fuel 1:  $C_2H_4$  (base condition)
- Fuel 2: 25%  $C_3H_6$  by mass
- Fuel 3: 50%  $C_3H_6$  by mass



Centerline Soot Concentration



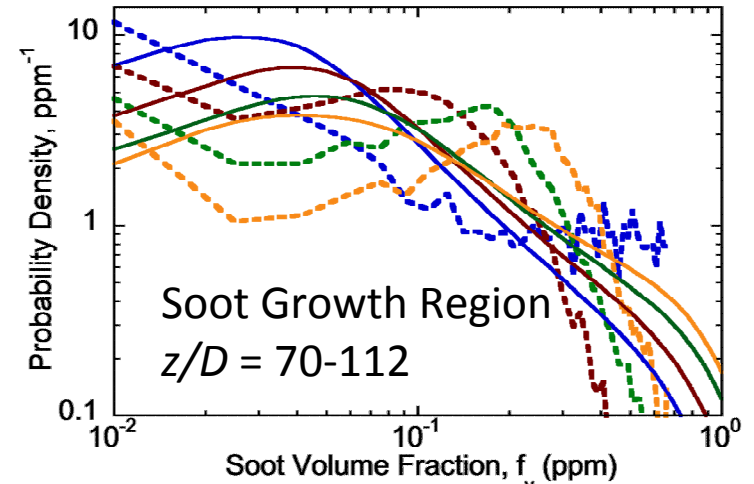
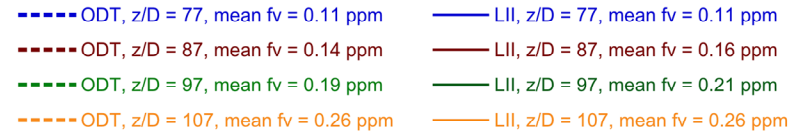
Pure  $C_2H_4$

25%  $C_3H_6$

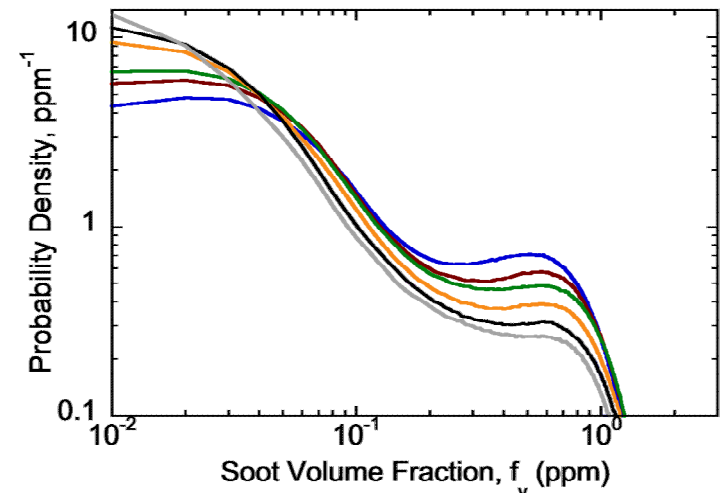
50%  $C_3H_6$

# Soot Probability Densities

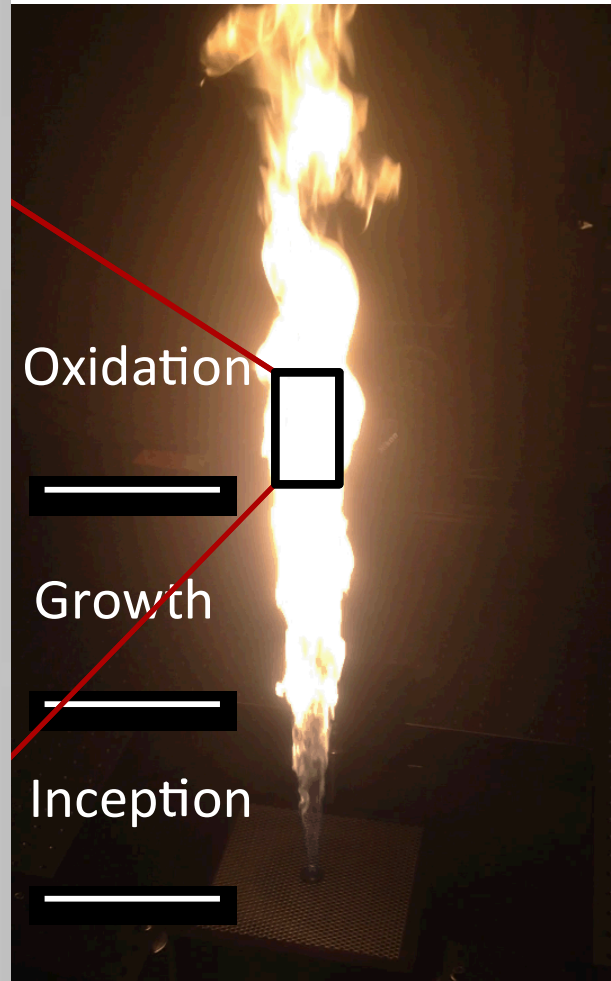
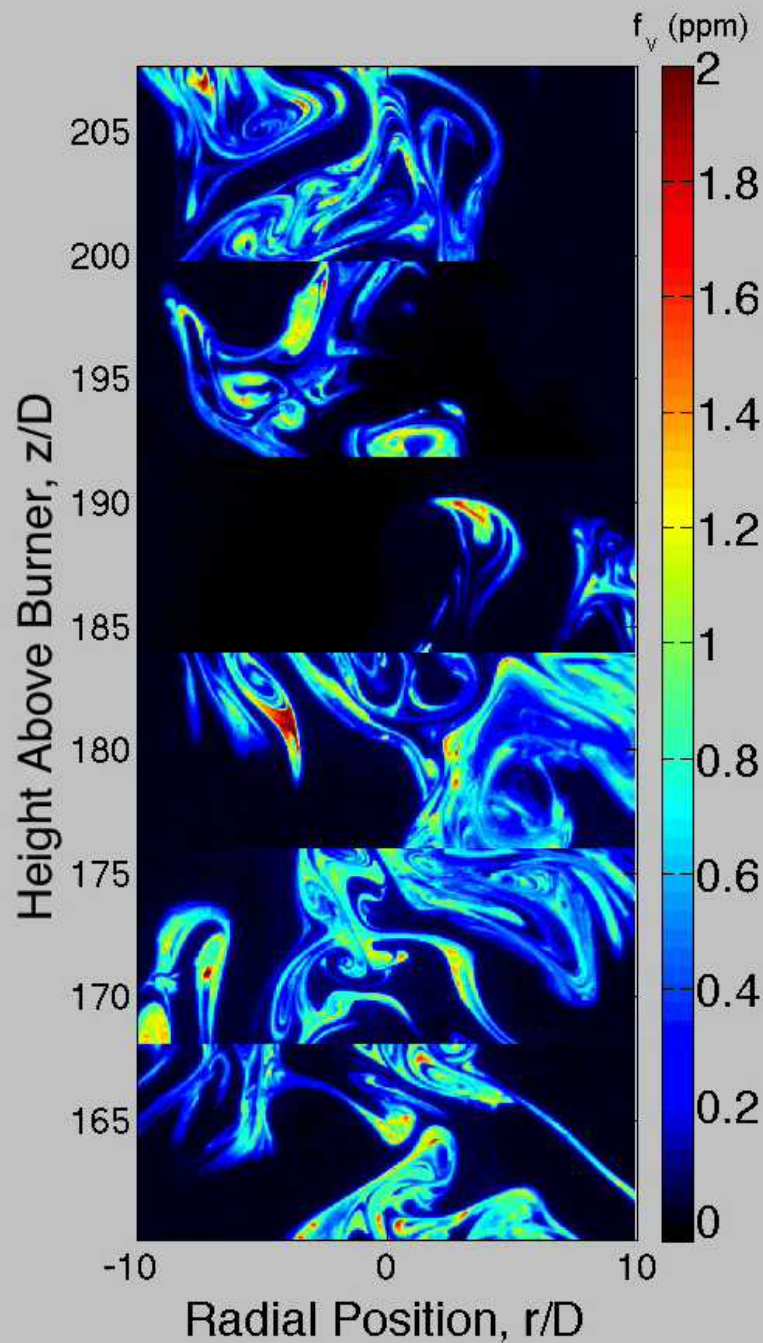
- Additional LII measurements conducted in soot growth zone
- ODT soot production term calibrated to growth-zone LII



- “Clipped” pdfs: Peak at zero from high soot intermittency
- Secondary maxima in ODT results at 500-750 ppb
- ODT results exhibit soot growth for z/D up to 200
- Taller flame in ODT simulation

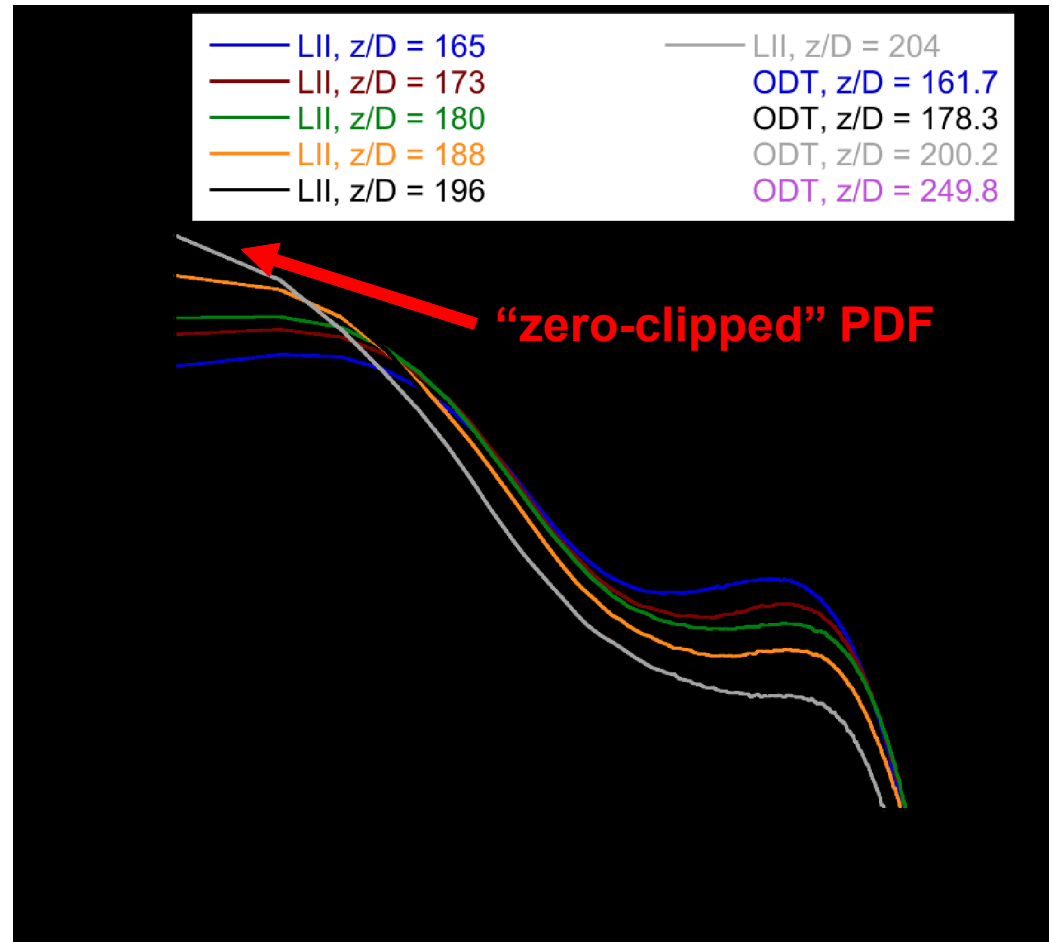
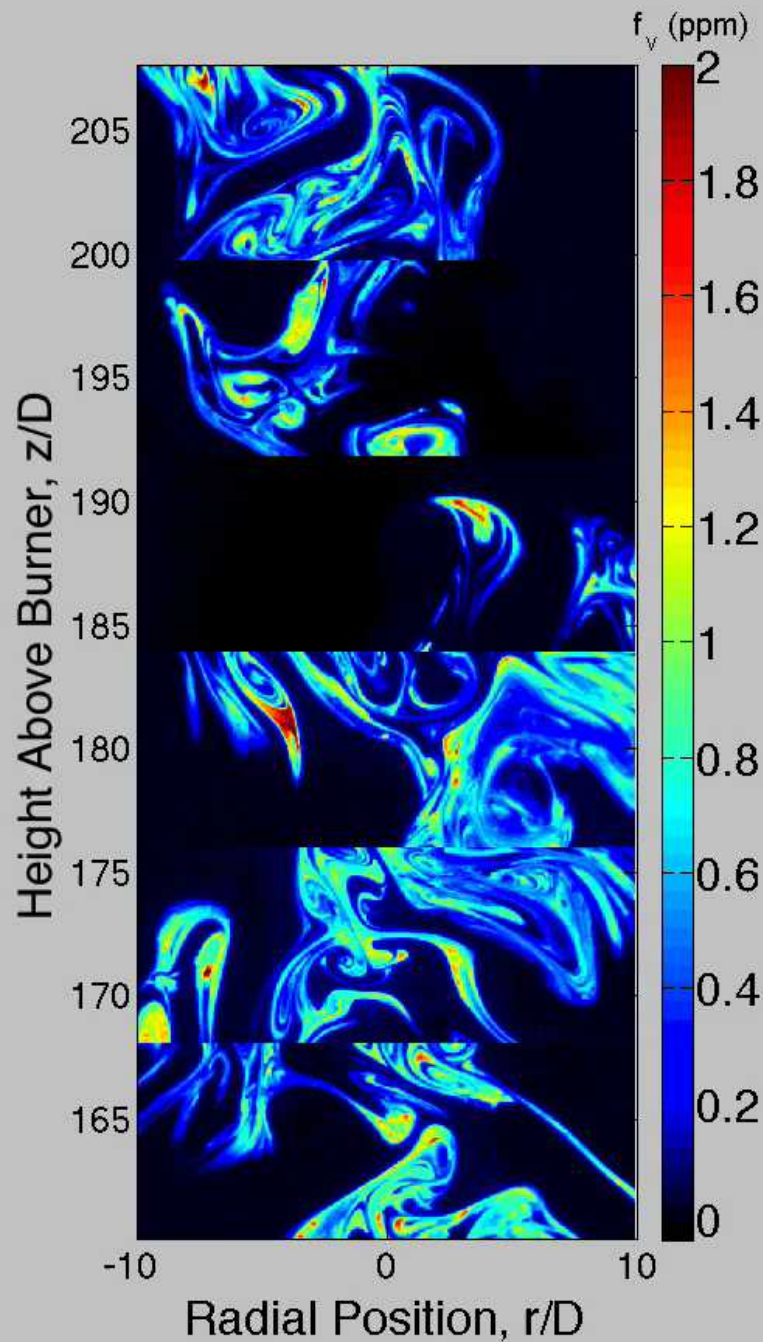


# mittent quantity

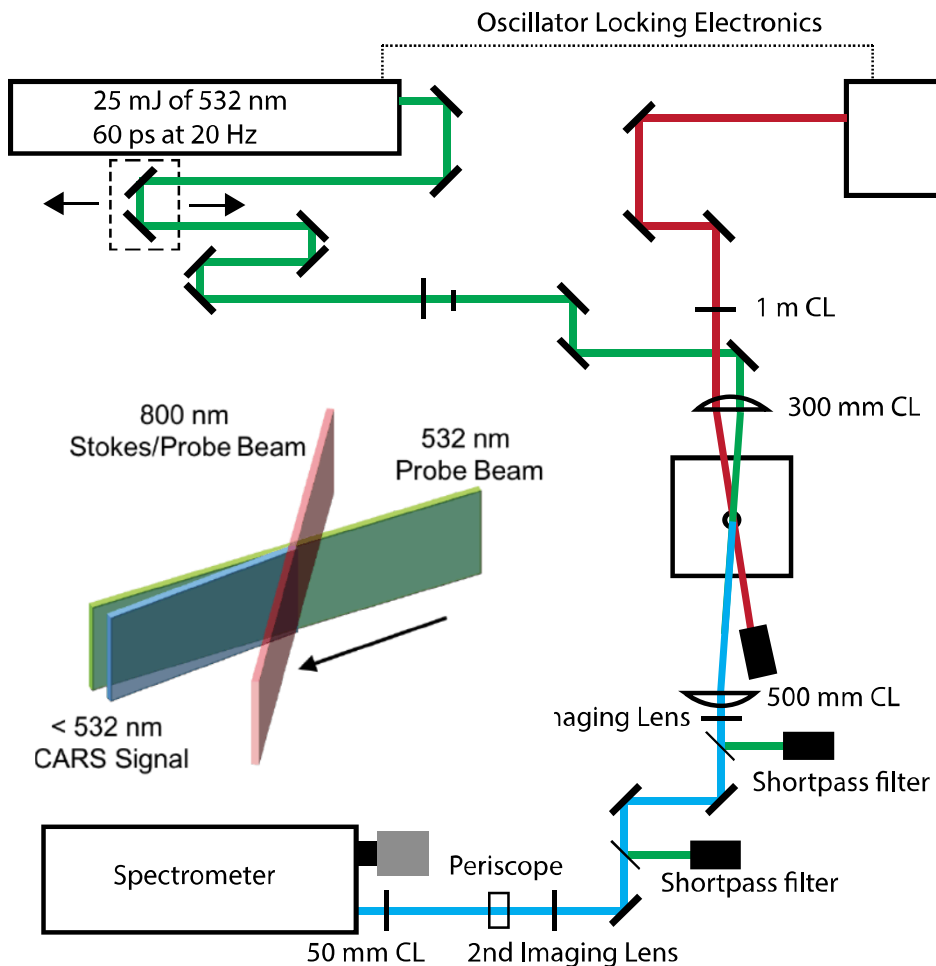


- 2000 single-shot images
- 6 panels each  $7.7D$  in height
- In-plane resolution =  $124 \mu\text{m}$
- Out-of-plane resolution  $\sim 200\text{-}450 \mu\text{m}$
- **Intermittent** turbulent fluctuations
- High probability of zero soot (black)
- Peak fluctuations of 1-3 ppm

# mittent quantity



# 1-D Line CARS imaging system

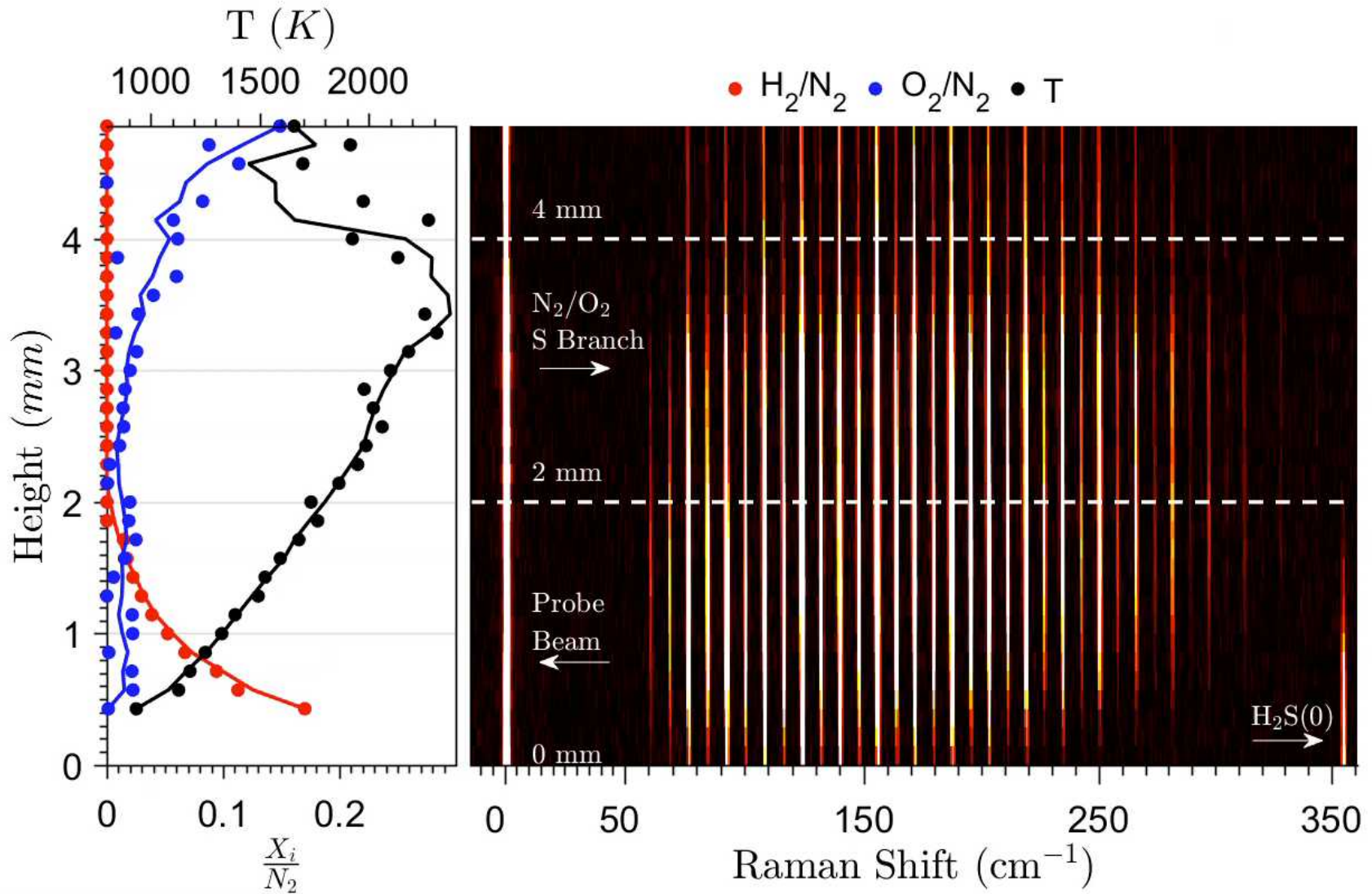


- 1-D imaging scheme developed by Kliewer and Bohlin

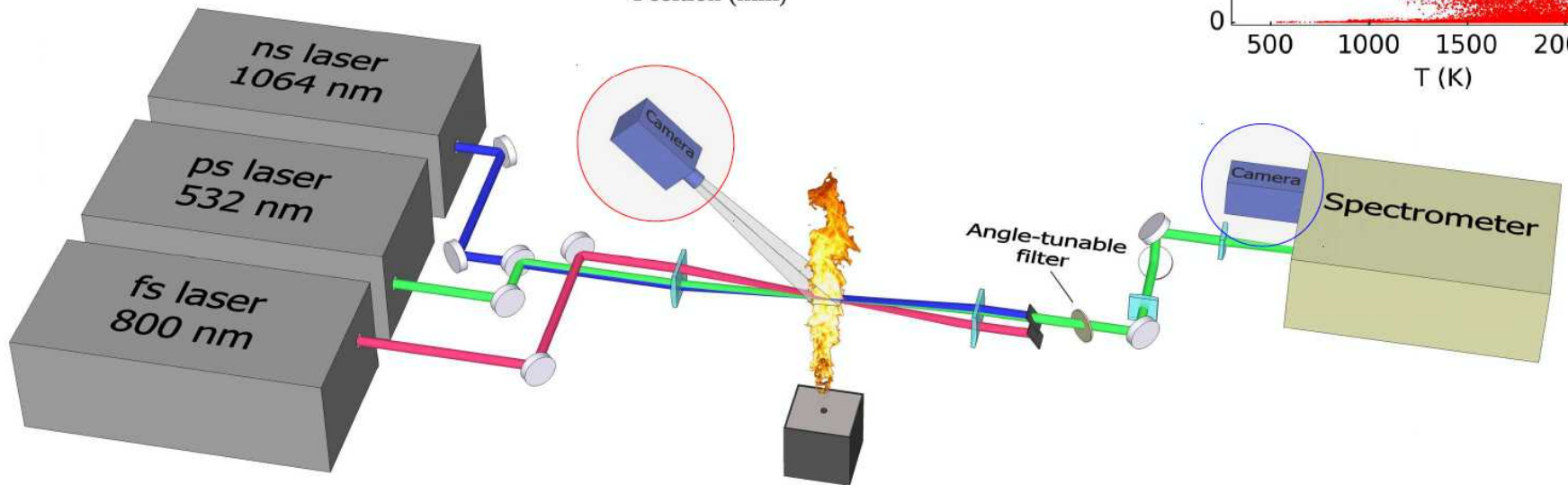
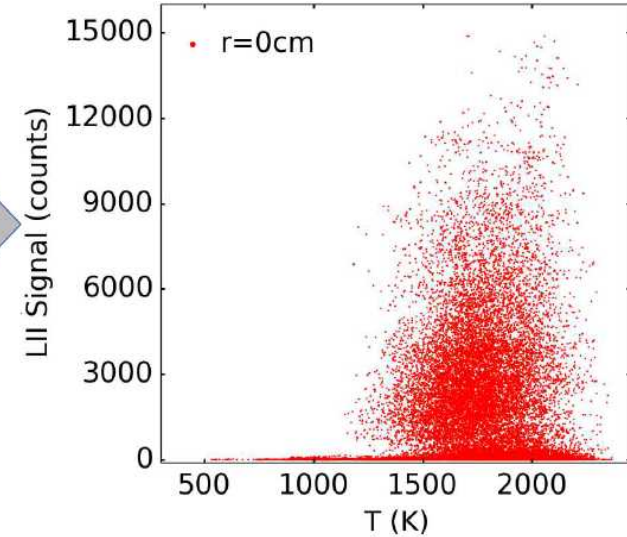
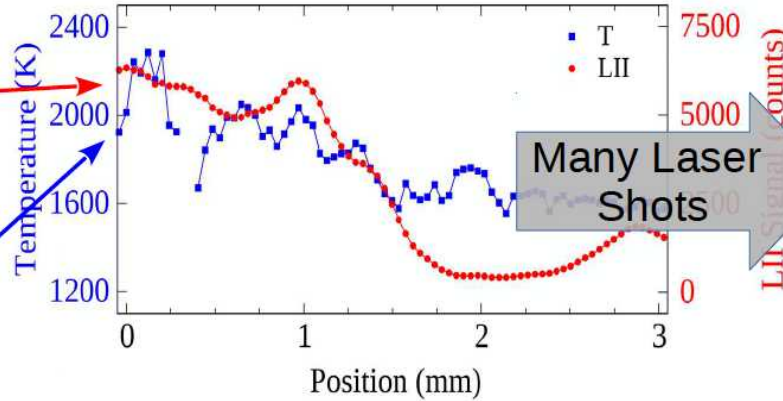
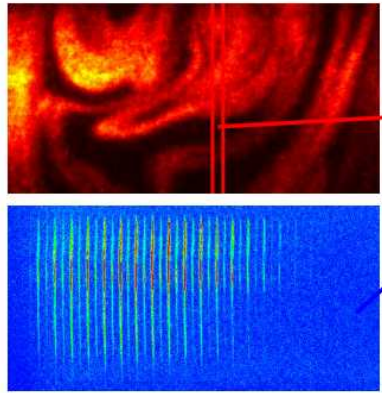
- Two-beam, arbitrarily phase-matched configuration
- 4-mJ, 50-fs,  $\sim 250 \text{ cm}^{-1}$  pump pulse at 800 nm
- 57 mJ, 60-ps,  $\sim 0.48 \text{ cm}^{-1}$  probe pulse @532 nm
- RF locking of seed sources
- Image measurement volume to spectrometer slit
- $\sim 6\text{-mm}$  long line
- **$400 \mu\text{m} \times 130 \mu\text{m} \times 50 \mu\text{m}$  spatial resolution**

Retter, Elliott, and Kearney, AIAA2017-0028

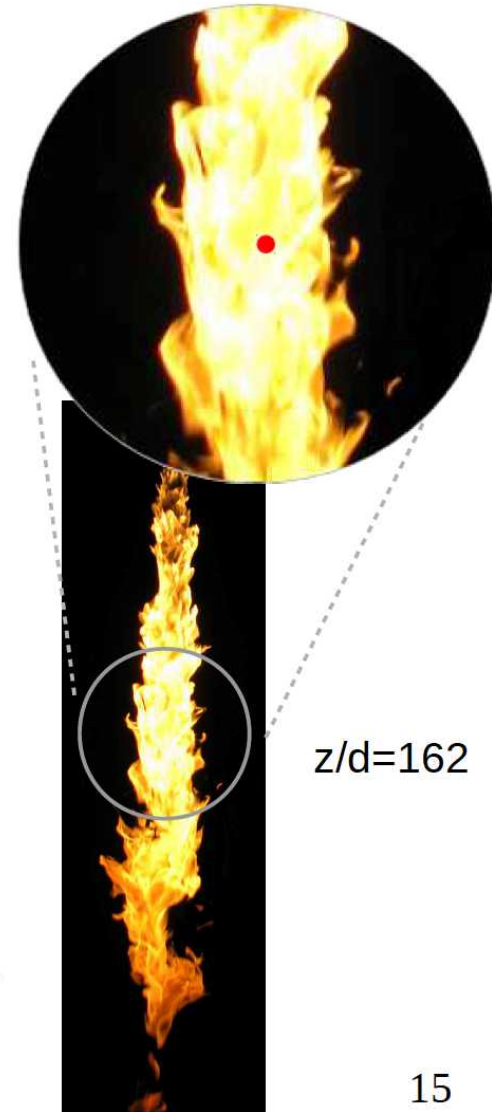
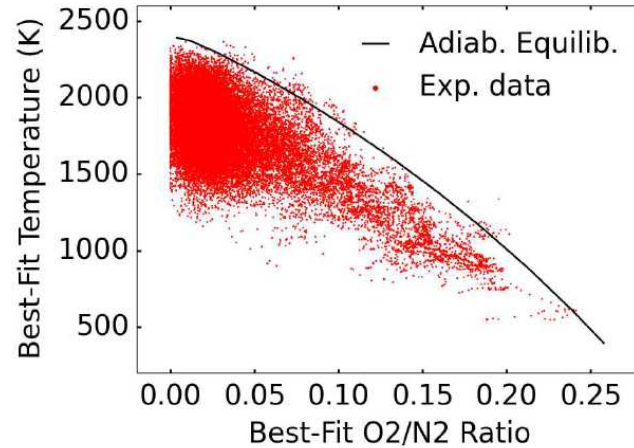
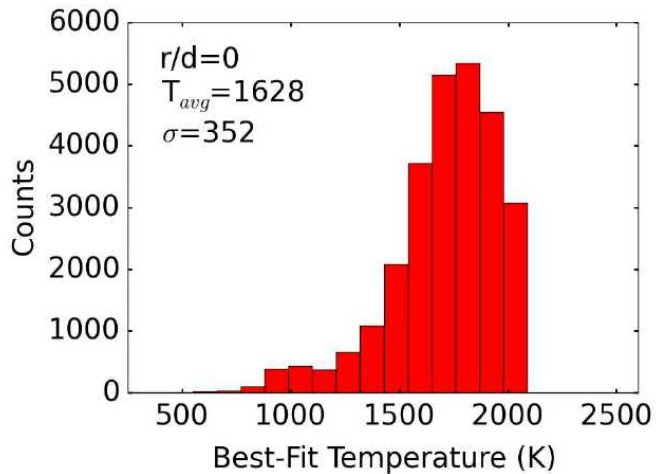
# Line CARS imaging results -- H<sub>2</sub> flame



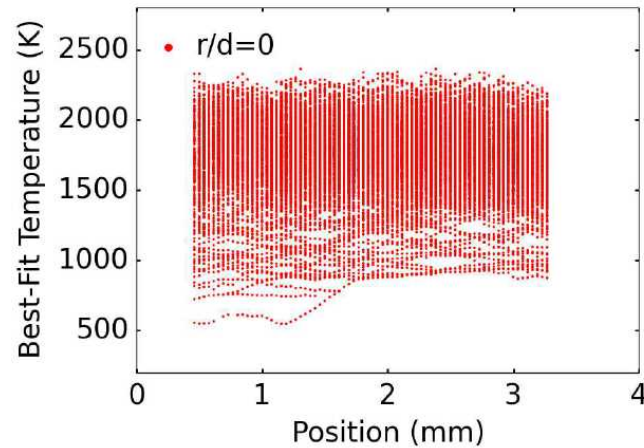
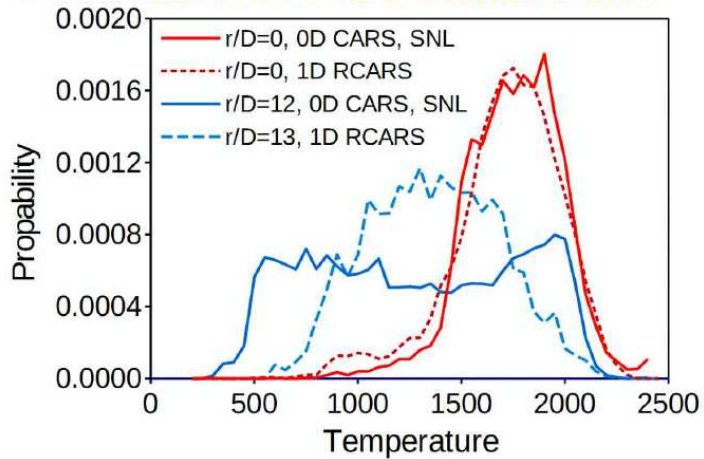
# Spatially resolved *joint* $T/f_\nu$ measurements



# Line CARS imaging at WPAFB



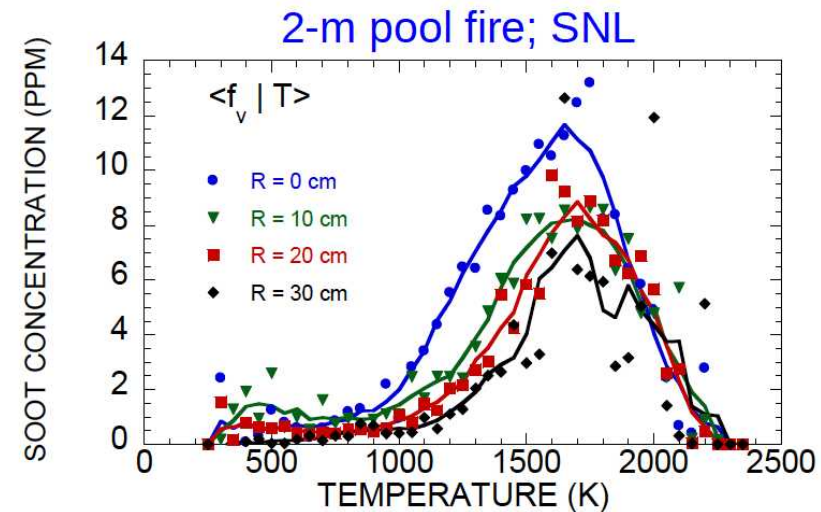
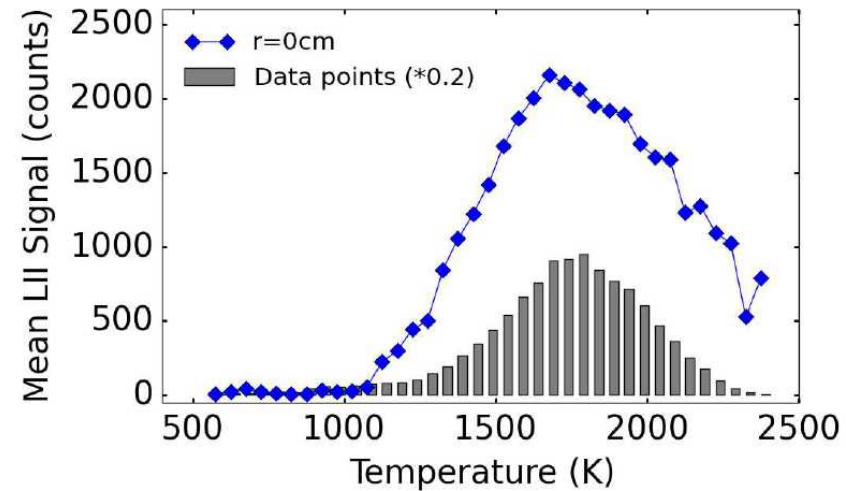
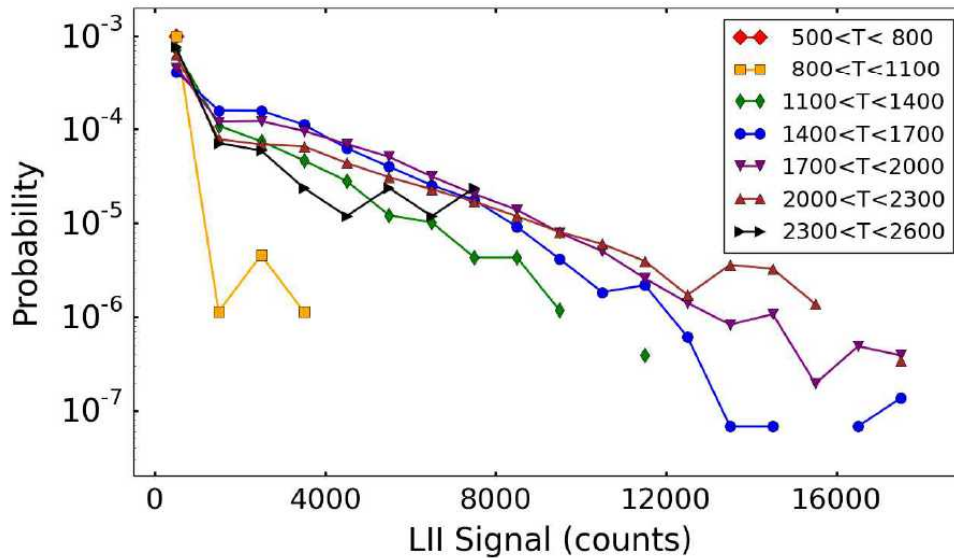
## 0D RCARS data from SNL



# Joint CARS/LII Temperature/Soot Data

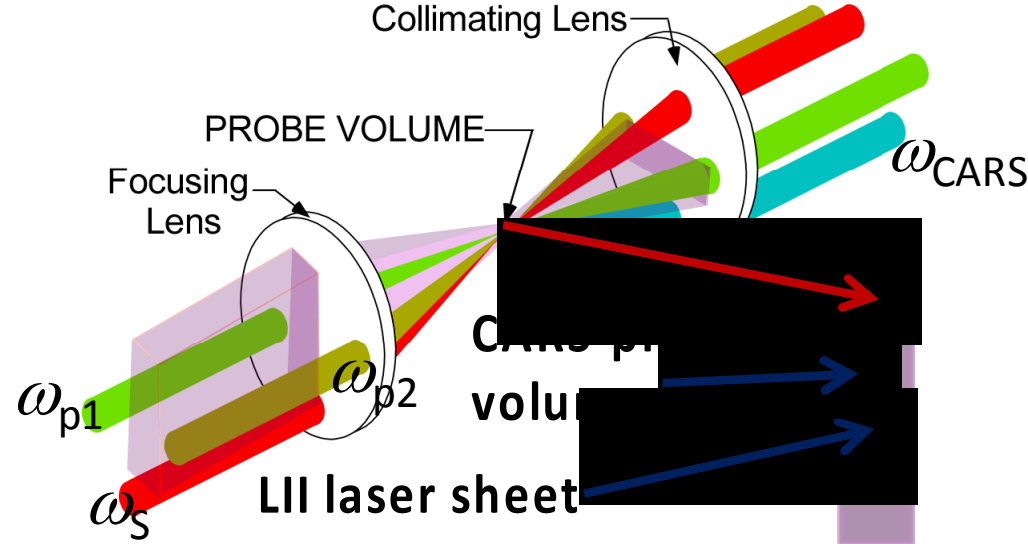
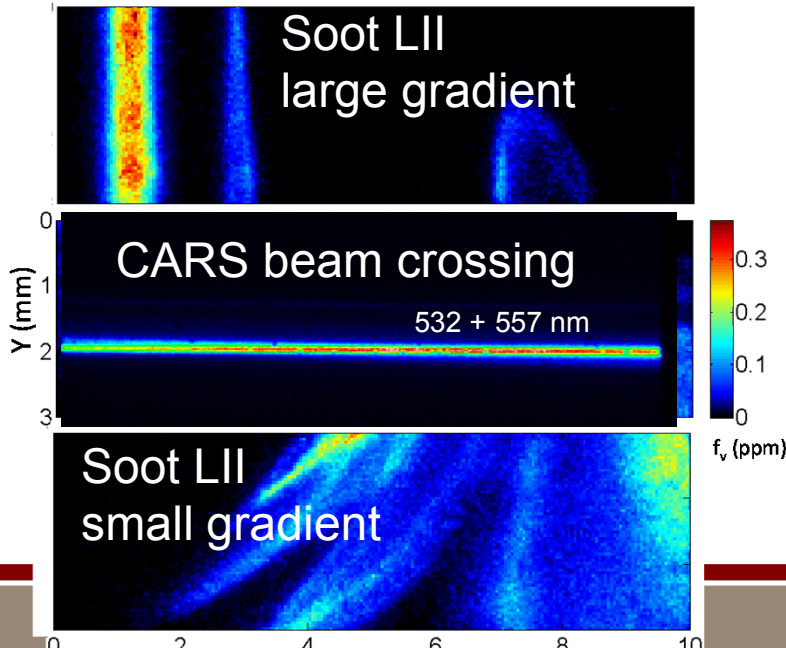
## Joint statistics of soot, T:

- Conditional averages
- Comparison to 0D RCARS data from SNL
- Temperature-filtered PDF of soot



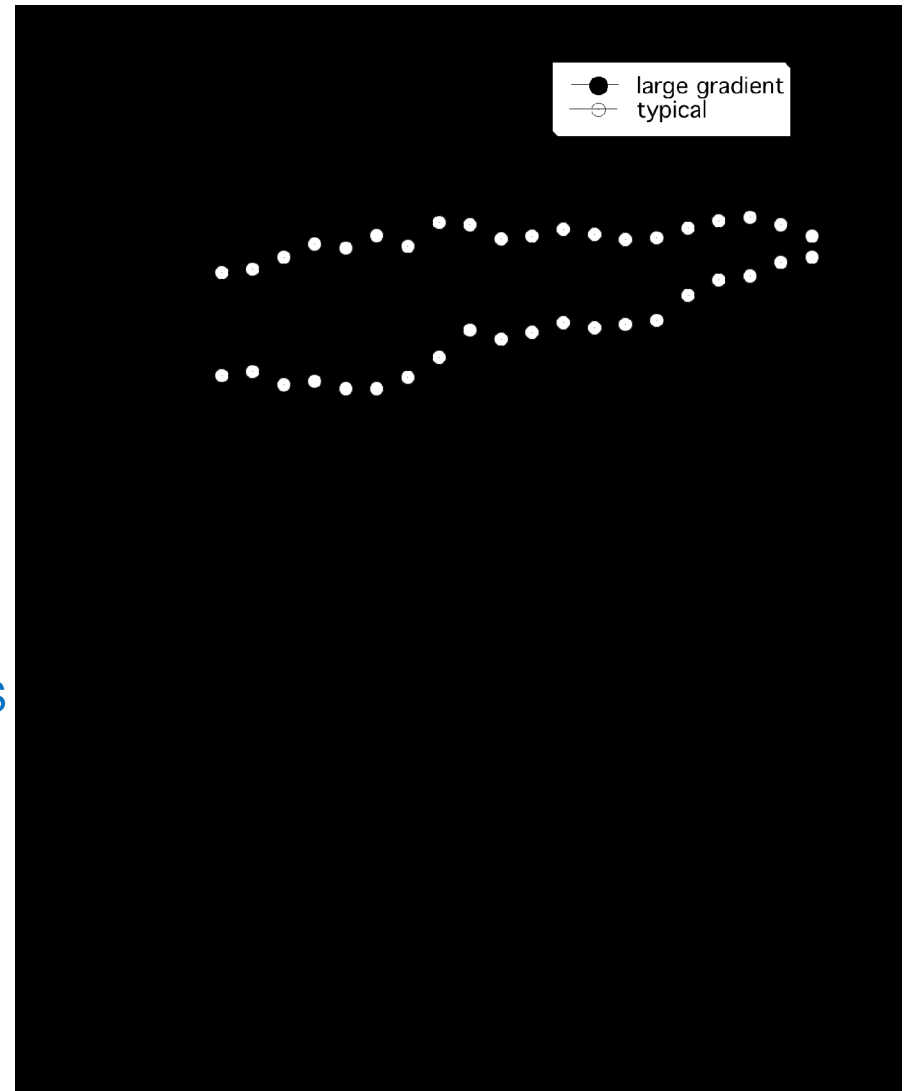
# 2-m Pool Fire Data

- 2011 data campaign
- CARS temperature data at a “point”
- LII soot imaging
- CARS spatial resolution?
  - 10-mm X 0.1 mm
- Realistic fire plume size at 2 m
- Lighter sooting toluene/methanol fuel

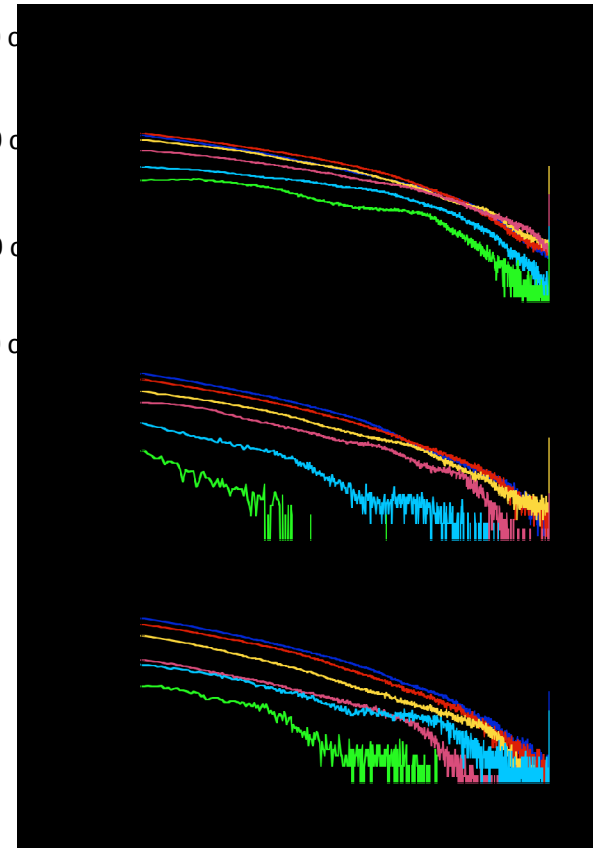
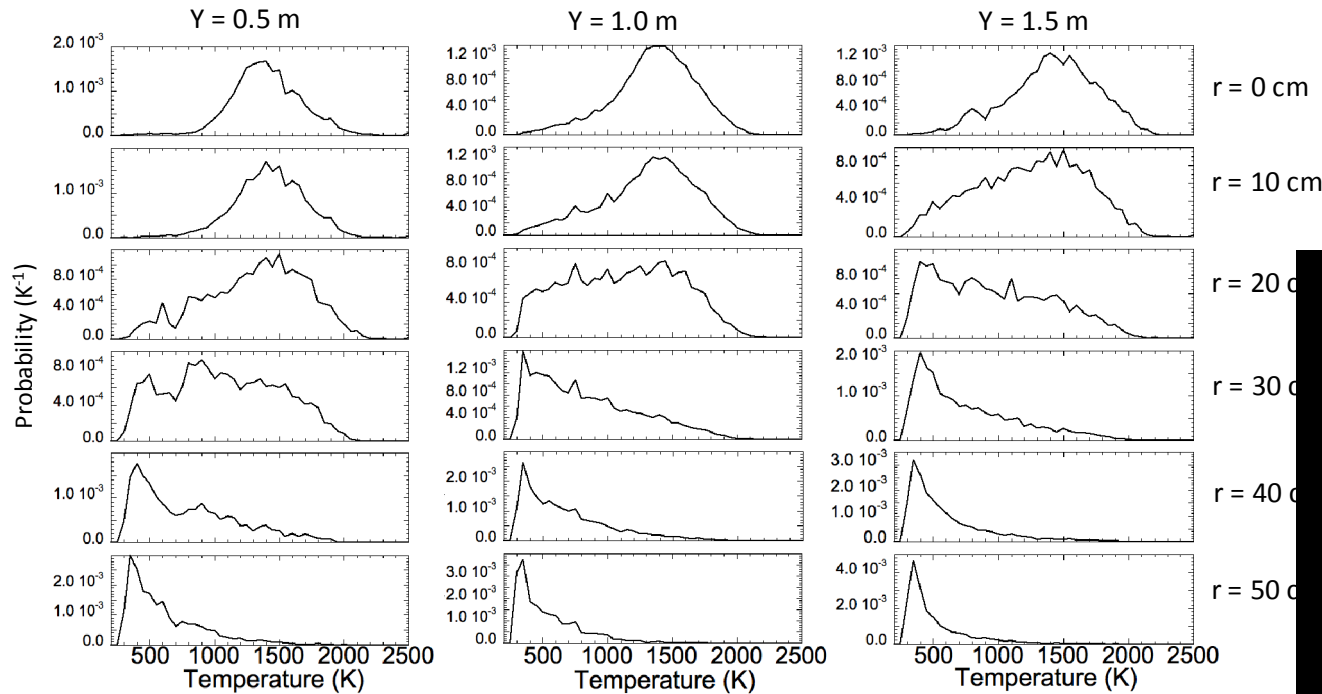


# Effect of finite CARS spatial resolution

- Resolved temperature along CARS volume axis
- Rayleigh scattering in non-sooting methanol fire
- Similar turbulence properties
- Modest gradients in buoyancy driven fire plume
- Literature studies show  $T_{\text{CARS}} \sim T_{\text{thermo}}$  for  $\Delta T < 1000 \text{ K}$

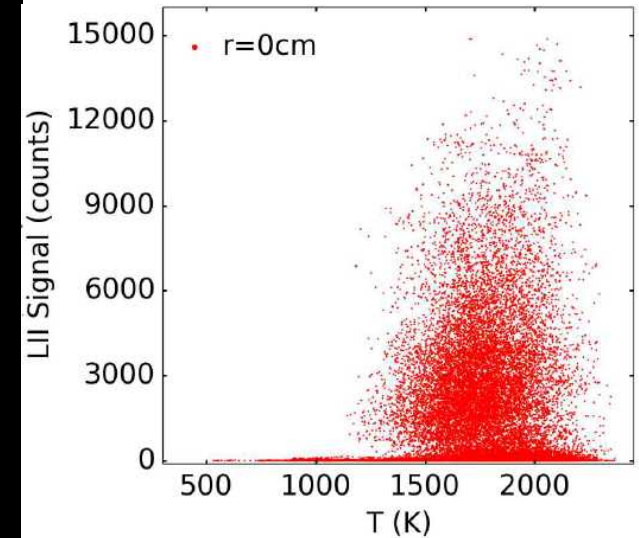
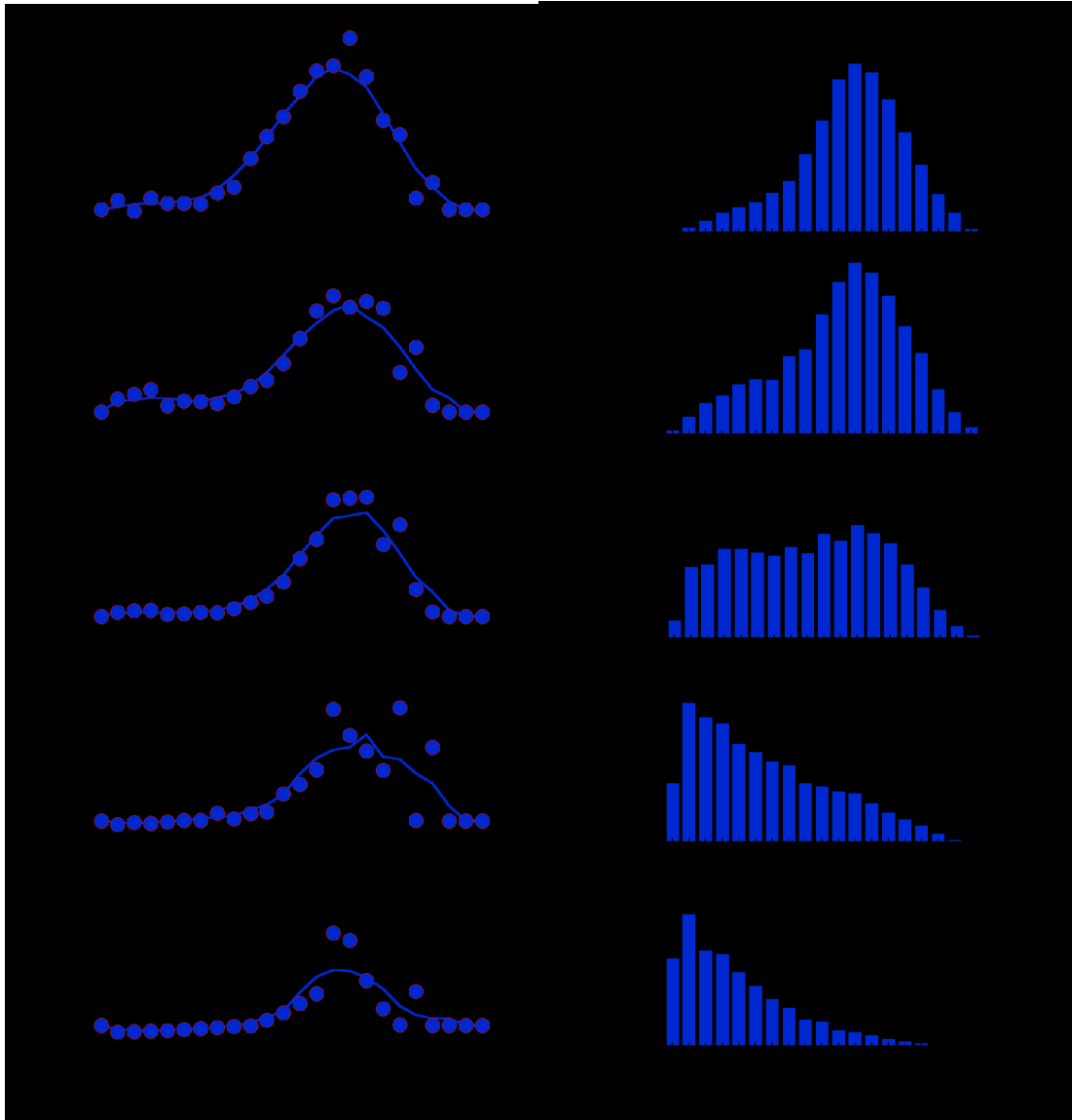


# Pool fire temperature/soot statistics



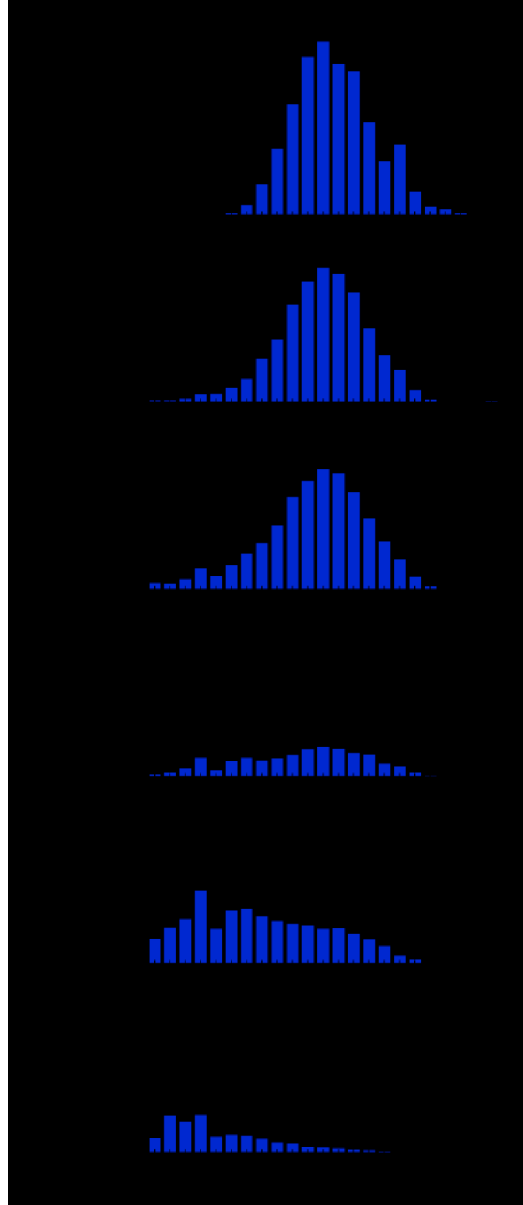
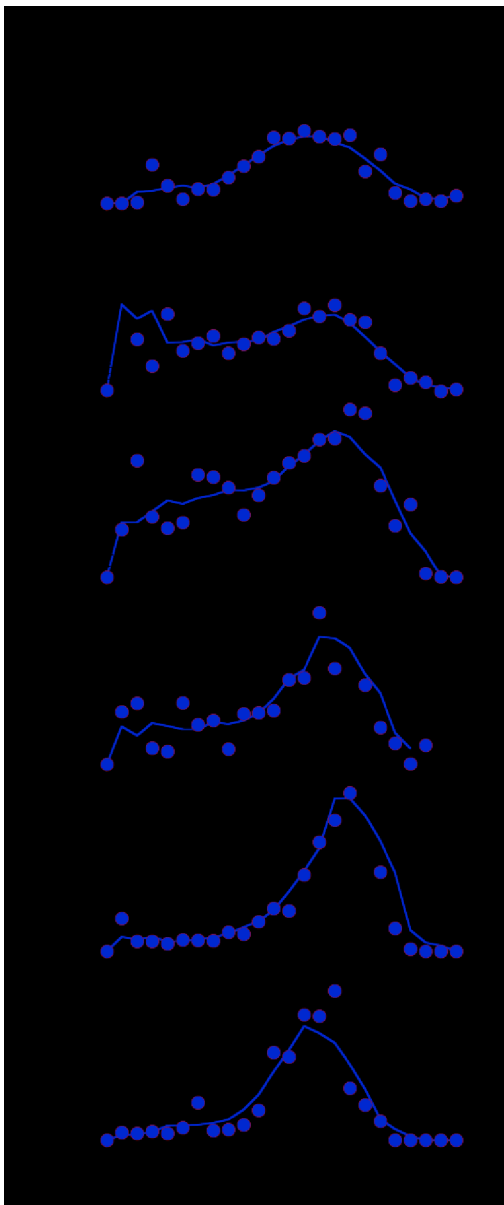
- Several hundred thousand laser shots
- **Individual** pdf results throughout fire
- Soot ***intermittency*** just as in jet flame

# Joint temperature/soot statistics

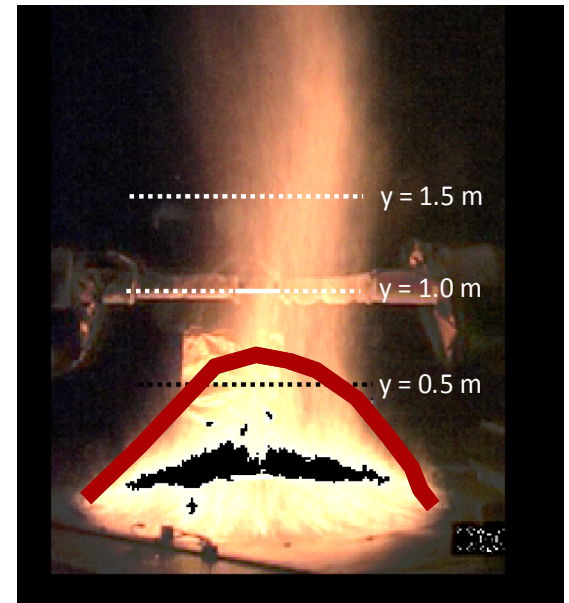


- Average soot concentration in 100-K wide CARS temperature bins
- Y = 1.0 and 1.5 m above fuel pool surface
- Peak soot near 1600-1700 K *across wide range of thermal environments*

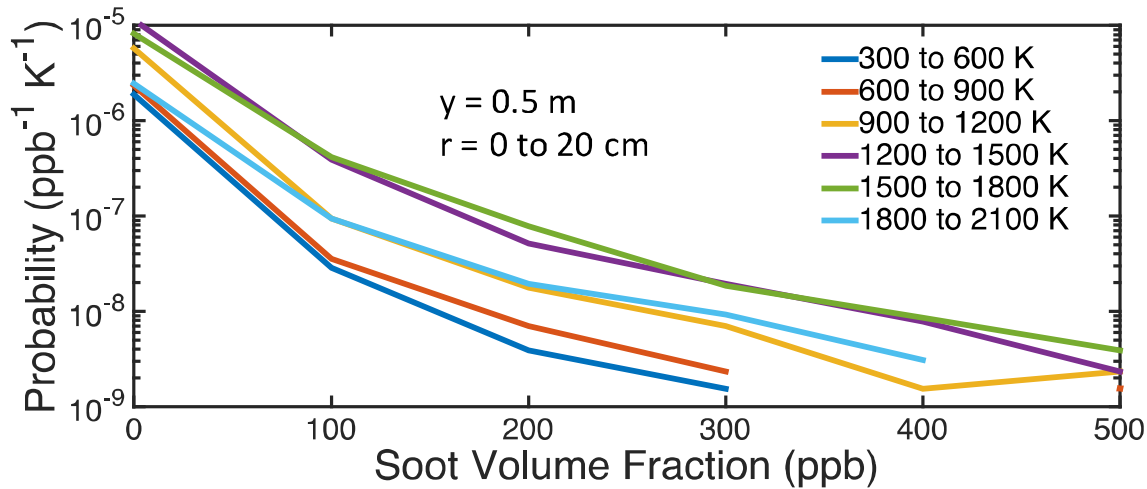
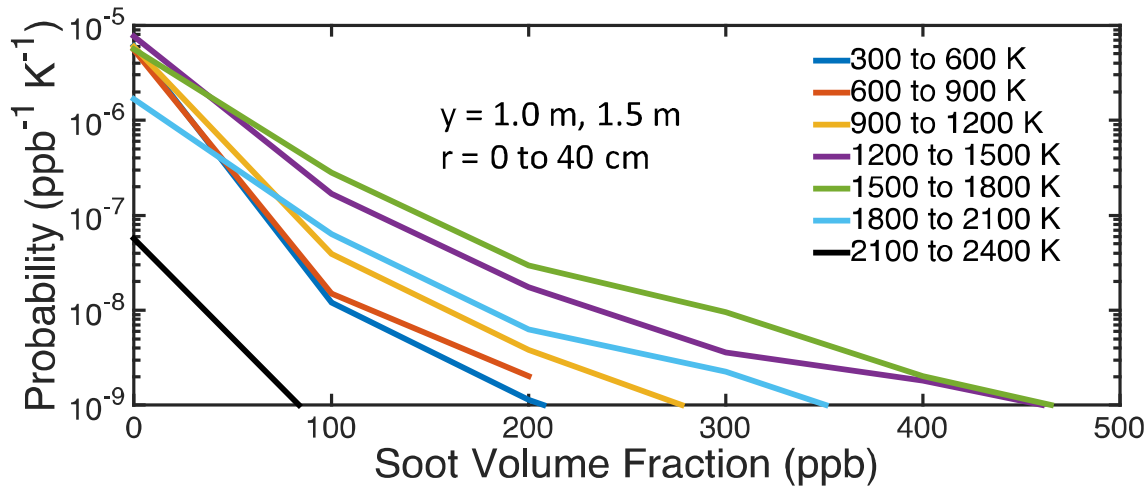
# Joint temperature/soot statistics $Y = 0.5$ m



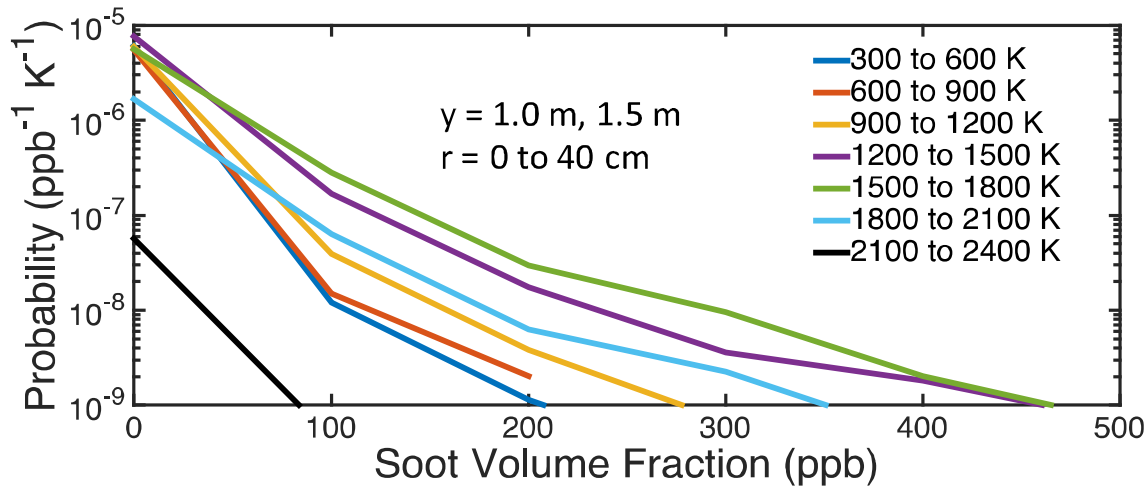
- “Vapor dome” region-- significant unburned hydrocarbons
- Wider range of temperatures observed when soot is detected
- Data scatter, but signal persists into conditional mean for O(100s) of samples



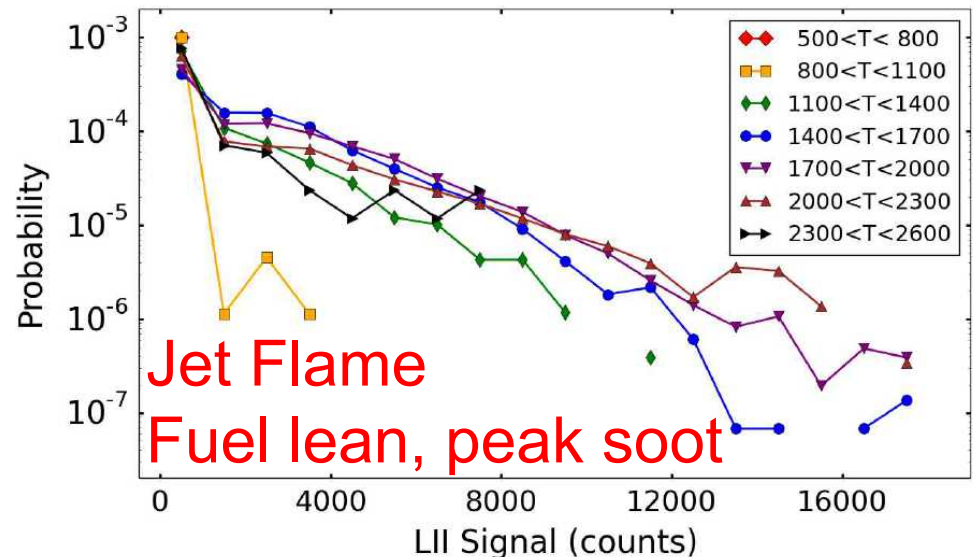
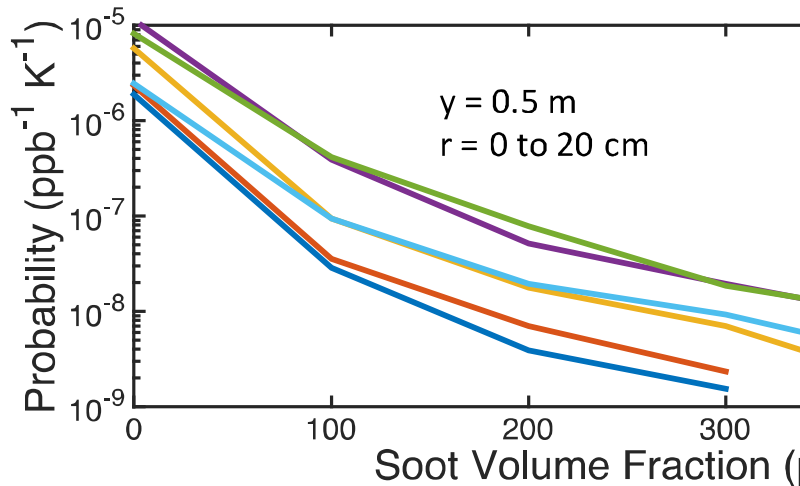
# Joint Probability Density Function



# Joint Probability Density Function

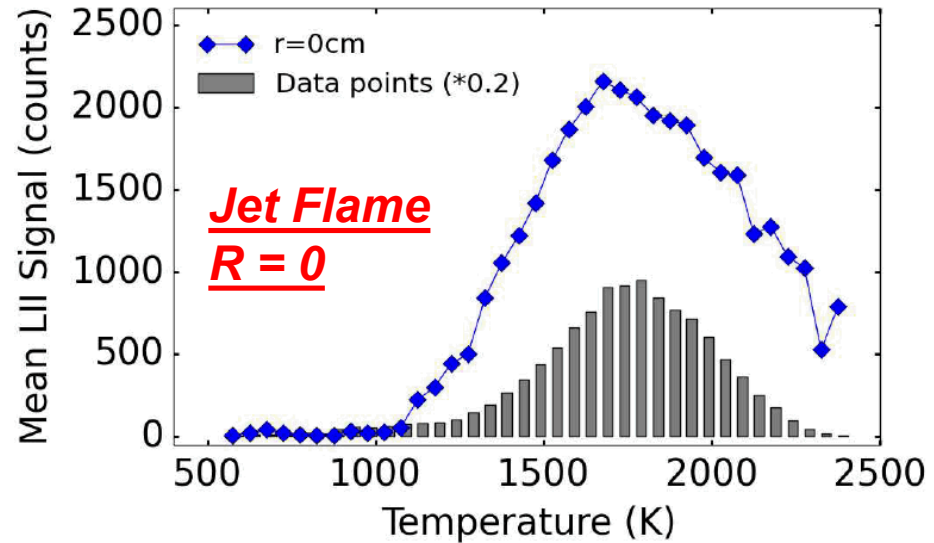
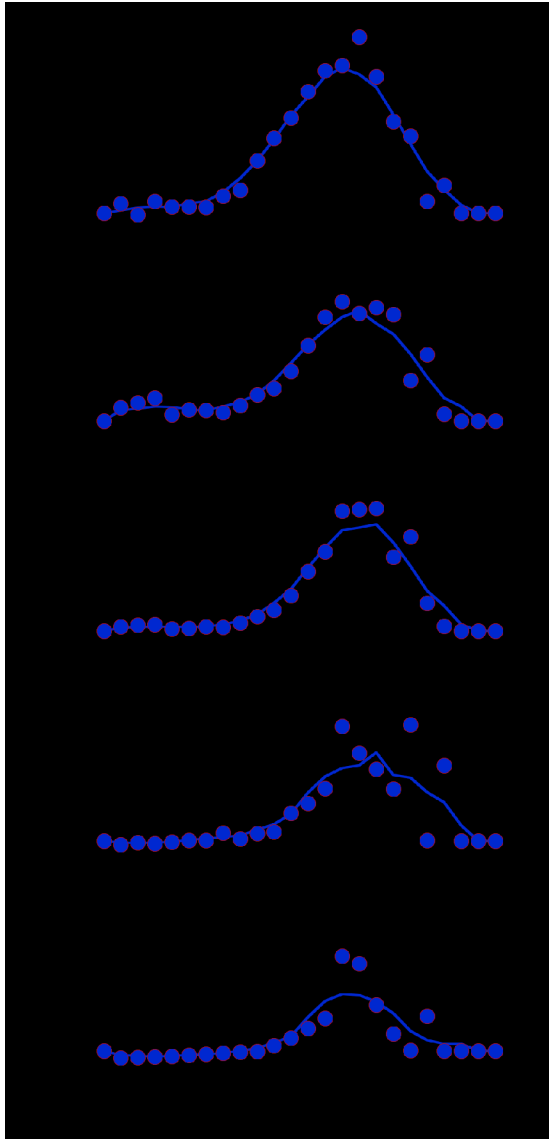


- Intermittent soot fluctuations observed in both pool fire and jet flame
- Soot confined to  $\sim 1000 \text{ K}$  range of temperatures
- Little cold soot or soot at flame temperatures



# Consistency of Soot Conditional Means

## Pool Fire



- Both flames show peak soot near  $T = 1600\text{-}1700\text{ K}$
- Both flames exhibit intermittent soot fluctuations
- Jet flame results away from flame centerline should be analyzed
- Consistency of results despite difference in CARS spatial resolution

# Compare to literature data

- Sivathanu and Faeth, *Combust. Flame* **81**, 150-165 (1990)
- Laboratory buoyant turbulent flames
- Soot pyrometry for Temperature
- Light extinction for soot
- Coarse spatial resolution
  - $0.135 \text{ cm}^3$  ( $10^{-4}$  to  $10^{-5} \text{ cm}^3$  our work)
- Soot temperature “spike” low in flame
- Much broader range of soot temps high in flame

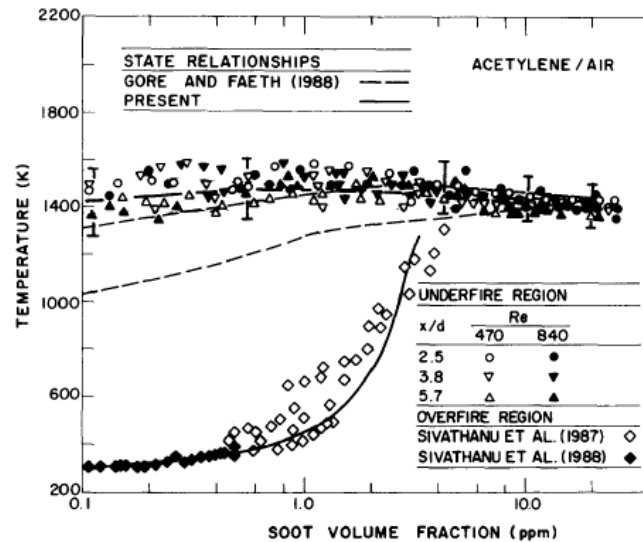
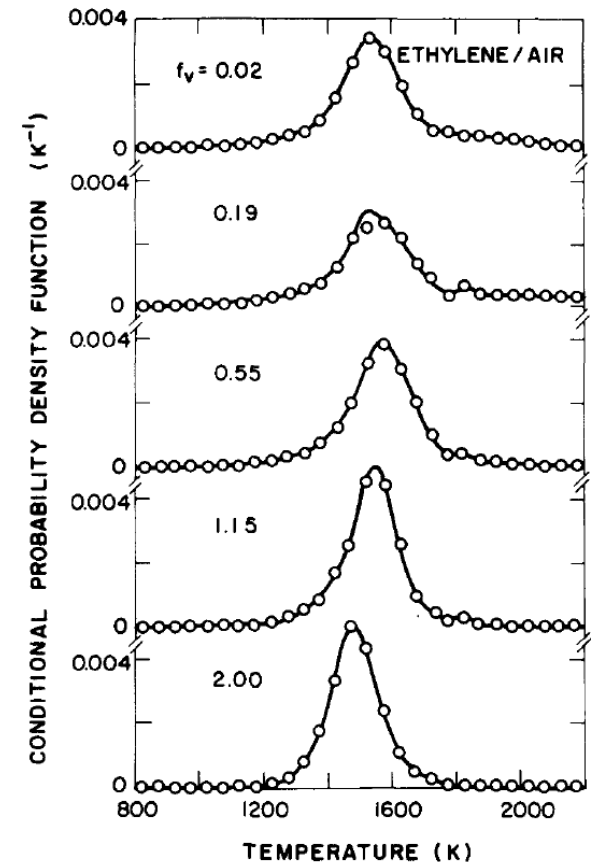


Fig. 8. Correlations between soot volume fraction and temperature for turbulent acetylene/air diffusion flames.



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**Our data show 2-3X wider range of soot in soot “spike”**

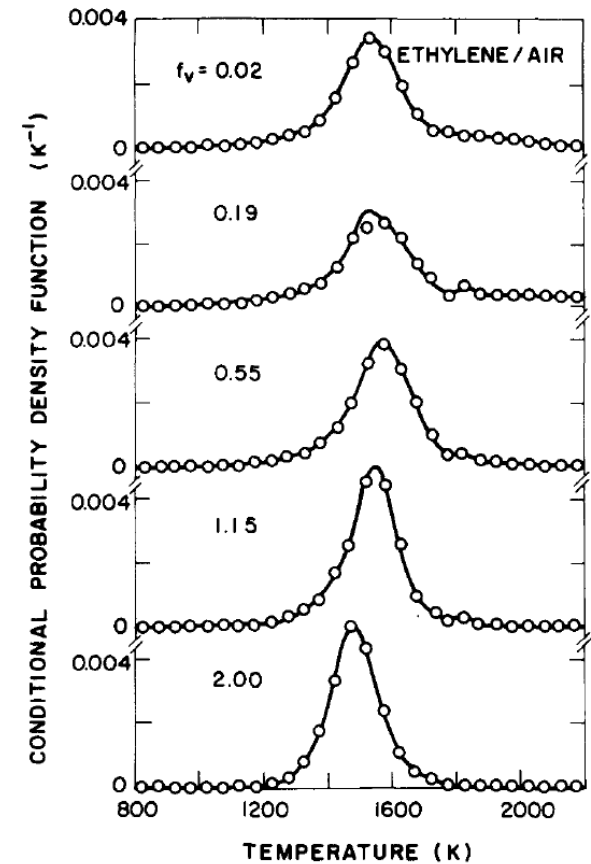
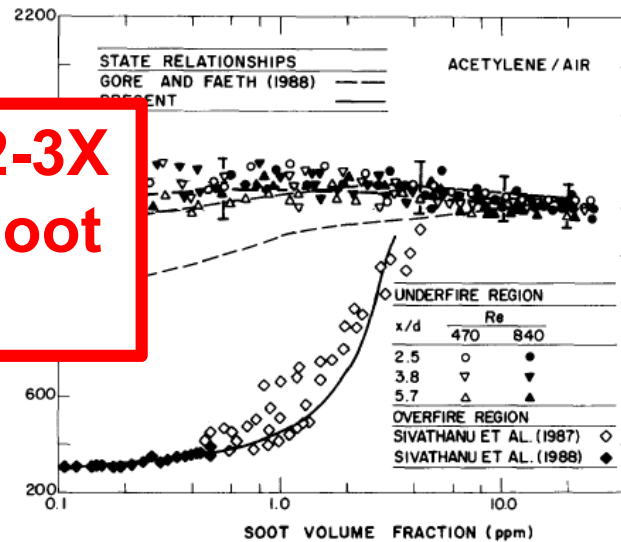
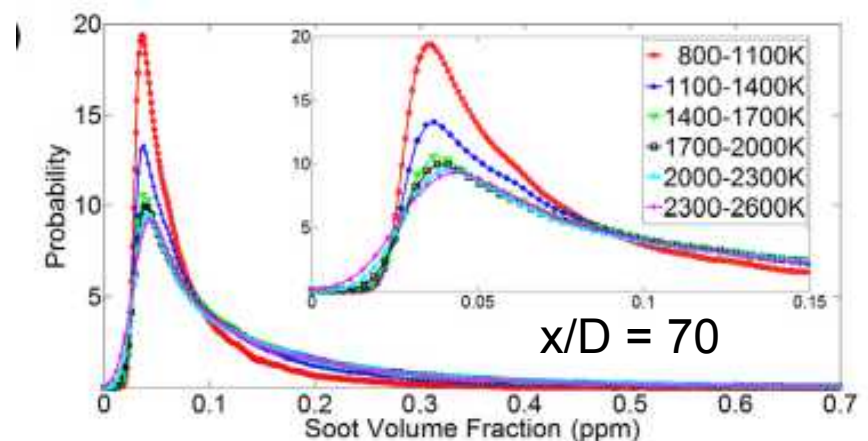
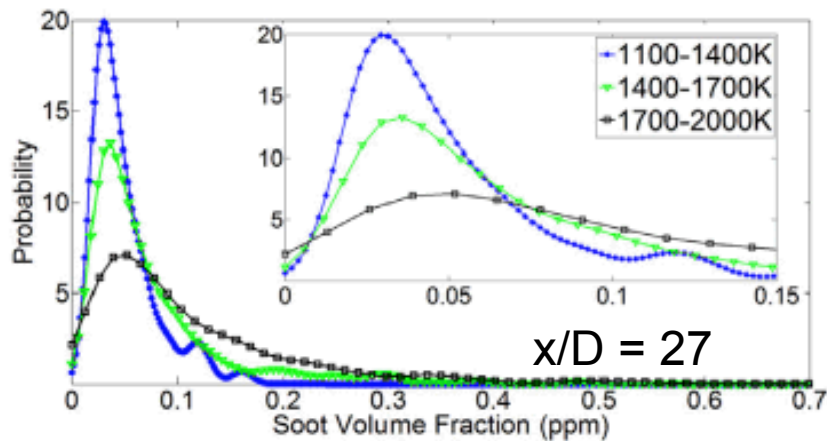
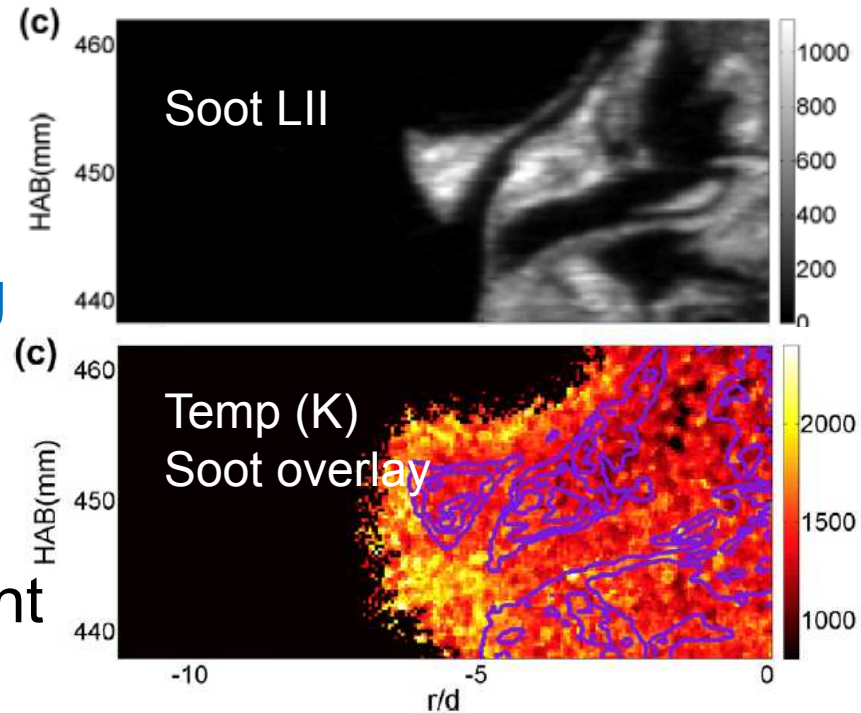


Fig. 8. Correlations between soot volume fraction and temperature for turbulent acetylene/air diffusion flames.

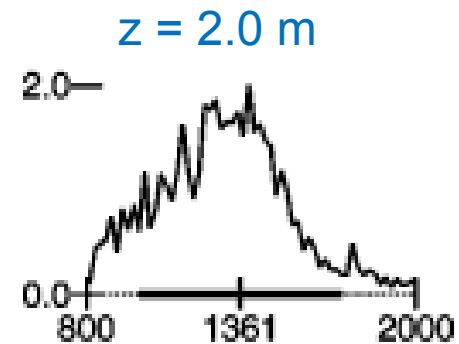
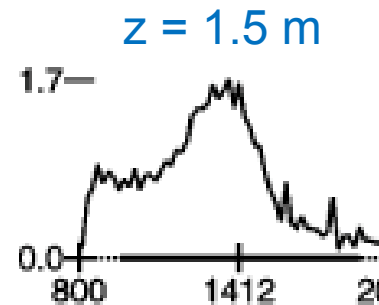
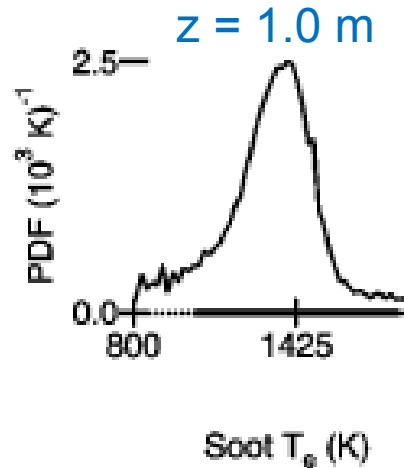
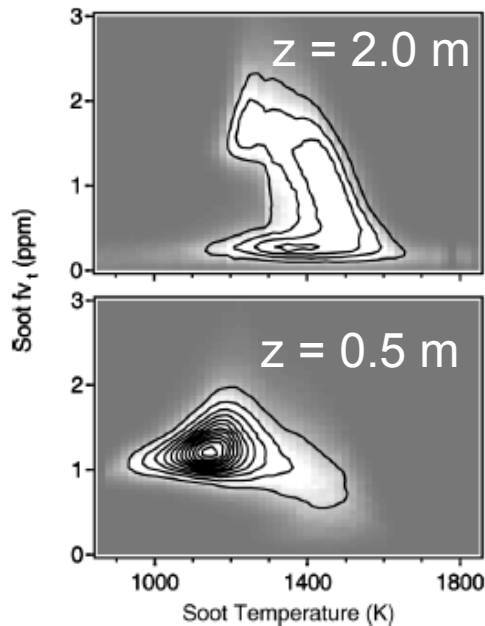
# Compare to literature data

- Mahmoud *et al.*, *Proc. Combust. Inst.* **35**, 1931-1938 (2015)
- Turbulent C<sub>2</sub>H<sub>4</sub>/H<sub>2</sub> jet flame
- Highly spatially resolved imaging (LII/PLIF)
- High soot intermittency
- Low range of soot T low in flame
- Range of soot T grows with height



# Compare to literature data

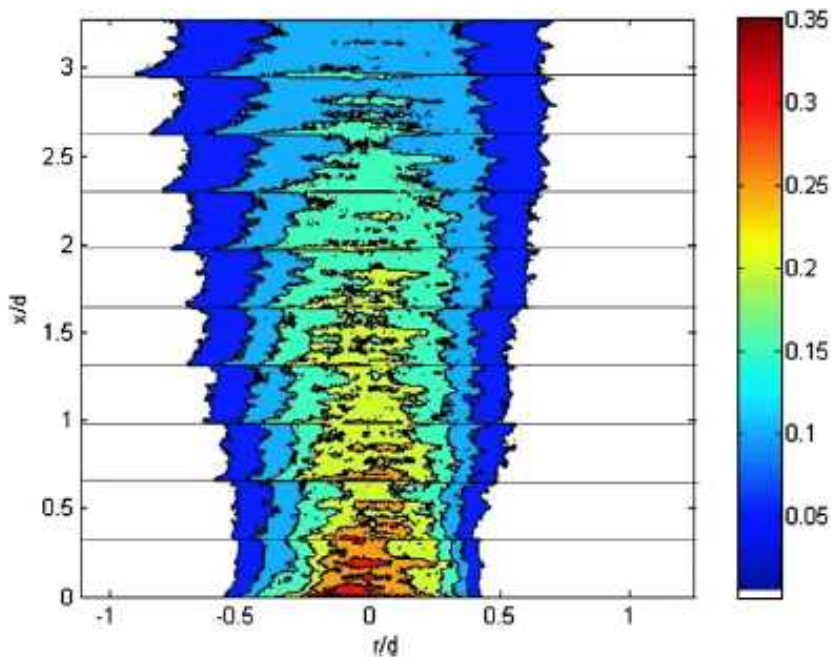
- Murphy and Shaddix, *Comb. Sci. Tech.* **178**, 865-894 (2006)
- Soot pyrometry and light extinction
- 1-m diameter JP-8 pool fire
- Low soot intermittency in fire interior
- High intermittency at radially outward locations
- Increased range of soot temperatures high in fire



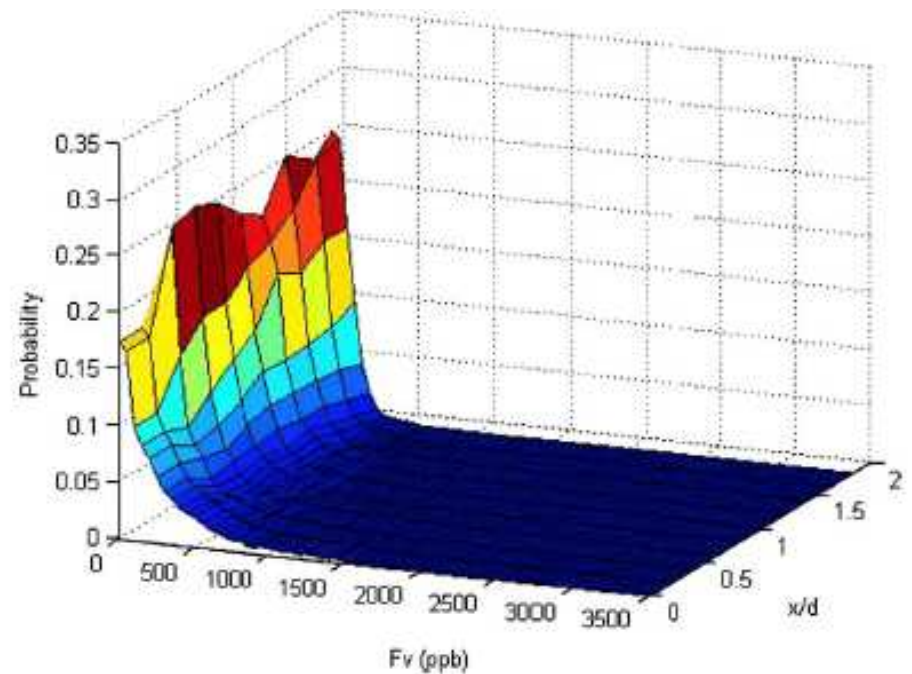
Impact of spatial averaging  
over 2-cm path?!

# Soot intermittency

- Henricksen *et al.*, *Combust. Flame* **156**, 1480-1492 (2009).
- Soot LII in a 15-cm dia. JP-8 Pool Fire
- High soot intermittency
- ***Intermittency depends on both fuel type and fire size!***



Mean Soot fv (ppm)



"Zero-clipped" soot pdf

# Summary and conclusions

- The joint fluctuations of temperature and soot determine radiative emission in fire environments
- We have measured joint soot/temperature statistics in both a 2-m liquid-fueled pool fire and a turbulent  $C_2H_4$  jet flame. The spatial resolution of our measurements is superior to earlier emission/absorption probes!
- Conditional means in both environments show peak soot temperature near 1600-1700 K, with a range of temperatures of about 1000 K
- Similar soot conditional means independent of CARS spatial resolution

# Summary and conclusions

- Our measurements are in the actively burning regions of these flames, lower soot temperatures would be encountered at longer residence times
- Low soot temperatures observed in pool-fire vapor dome
- Soot intermittency is a well-known phenomenon and depends on fire size and fuel sooting propensity
- Intermittency will differ in a large transportation-fuel fire
- Soot pdf will transition from log-normal to “quasi-normal”
- Unclear what the impact on soot temperature will be
- Our methodology for spatially resolved T/soot measurements is well-developed. Would have liked a lot more data from the jet flame!

## ***Joint Statistics***

1. Kearney, S.P. and T.W. Grasser, “Laser-diagnostic mapping of temperature and soot statistics in a 2-m diameter turbulent pool fire, submitted to *Combustion and Flame*, 2017.

## ***Line CARS Thermometry***

1. Retter, J.E., G.S. Elliott, and S.P. Kearney, “Spatially correlated temperature, oxygen, and fuel measurements in a plasma-assisted hydrogen diffusion flame by one-dimensional fs/ps rotational CARS imaging,” AIAA paper 2017-0028, *AIAA SciTech*, Grapevine, TX, January, 2017.

2. Richardson, D., S. Roy, J.R. Gord, and S.P. Kearney, “Two-beam femtosecond rotational CARS for one-dimensional thermometry in a turbulent, sooting jet flame,” AIAA paper 2017-0031, *AIAA SciTech*, Grapevine, TX, January 2017.

# Documentation (cont.)

## *Diagnostic Development and Uncertainty Quantification*

1. Kearney, S.P., “Hybrid fs/ps rotational CARS temperature and oxygen measurements in the product gases of canonical flat flames,” *Combustion and Flame* **162**, 1748-1758, 2015.
2. Kearney, S.P., D.J. Scoglietti, and C.J. Kliwer, “Hybrid fs/ps Rotational CARS Temperature and Concentration Measurements Using Two Different ps-Duration Probe Beams,” *Optics Express* **21**, 12327-12339, 2013.
3. Frederickson, K., S.P. Kearney, and T.W. Grasser, “Laser-Induced Incandescence Measurements of Soot in Turbulent Pool Fires,” *Applied Optics* **50**, A49-A59, 2011.
4. Kearney, S.P., K. Frederickson, and T.W. Grasser, “Dual-Pump Coherent Anti-Stokes Raman Scattering Thermometry in a Sooting Turbulent Pool Fire,” *Proceedings of the Combustion Institute* **32**, 871-878, 2009.