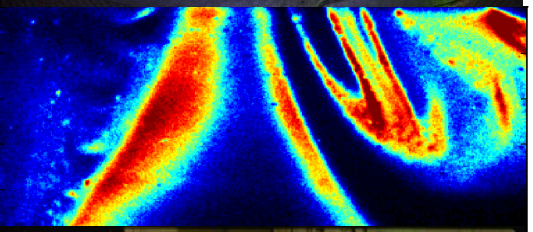
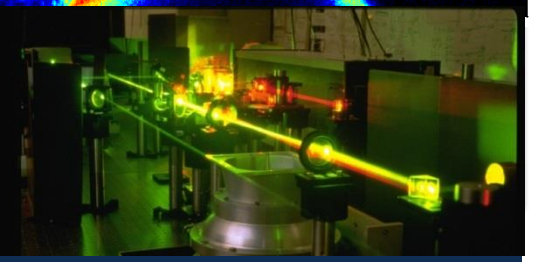




Sandia National Laboratories

*Exceptional service in the national interest*

SAND2013-10023C

# Laser-Diagnostic Mapping of Temperature and Soot Statistics in a 2-m Diameter Turbulent Pool Fire

Sean Kearney

Engineering Sciences Center

Sandia National Laboratories

Albuquerque, NM 87185

(spkearn@sandia.gov)

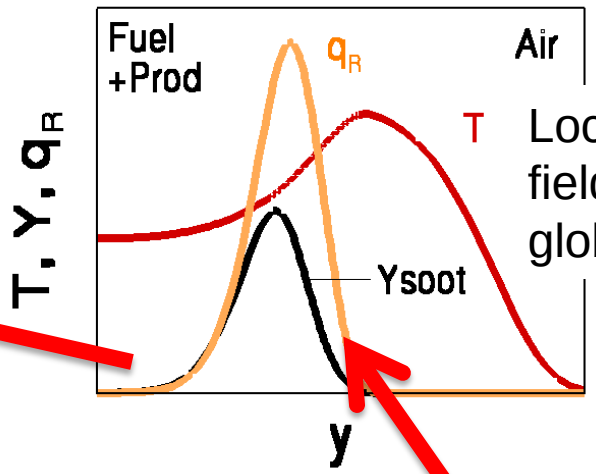
U.S. DEPARTMENT OF ENERGY

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

- Radiative transfer equation

$$\frac{d\overline{I_\lambda}}{ds} = \overline{\mu\lambda\, I_{\lambda,b}(T)} - \overline{\mu\lambda}\;\overline{I_\lambda}$$




Local soot & temp fields add up to global heat flux

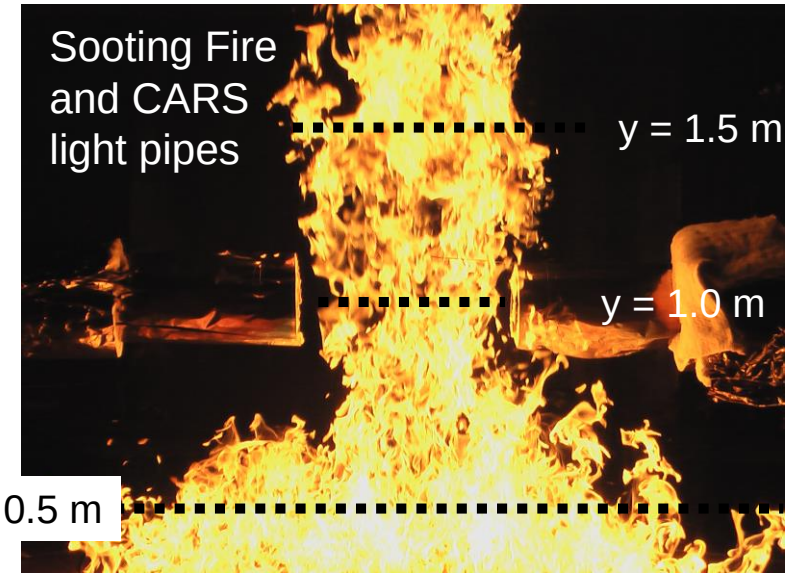
- **Emission term**
- **Temperature**
- **Absorption coeff → soot fv**
- ***Local not path integrated!***
- ***Key measurement challenge!***
- **Measurement approach**
  - **CARS thermometry**
  - **LII soot detection**

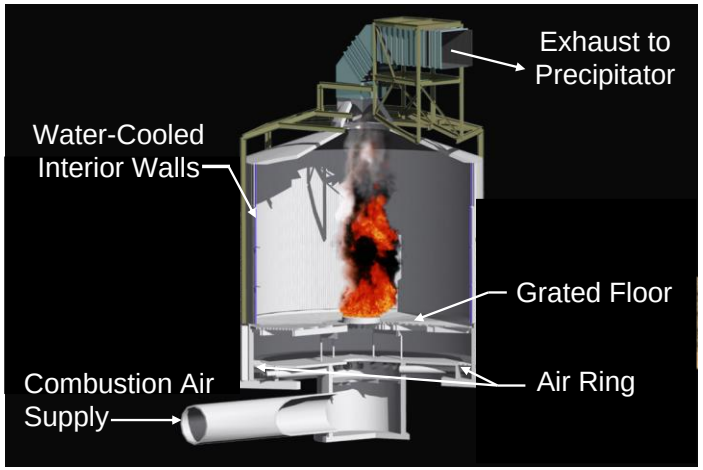

Large-Scale Accident

# FLAME Facility Enables Full-Scale Testing with High-Fidelity Laser Diagnostics

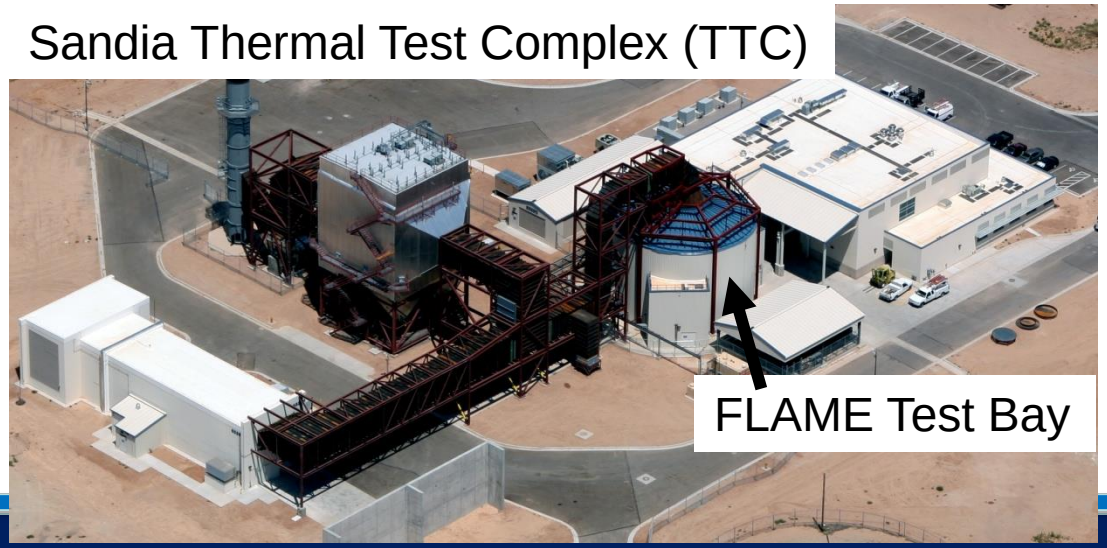
Sandia National Laboratories

- Fire Laboratory for Accreditation of Models and Experiments (FLAME) Facility
- Designed to facilitate deployment of optical diagnostics for full meter-scale fire testing
- Optical Access Ports and Adjacent Lab Space at East,West, and South Positions Around Test Cell
- Liquid and Gas-Fueled Fires up to 3-m in Base Dia.
- Brings Laboratory Control to Full Scale Testing



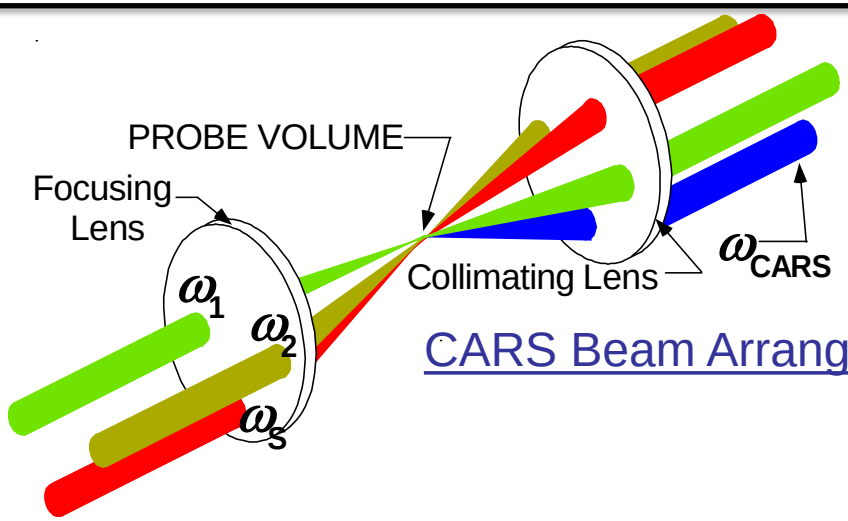




Sandia Thermal Test Complex (TTC)



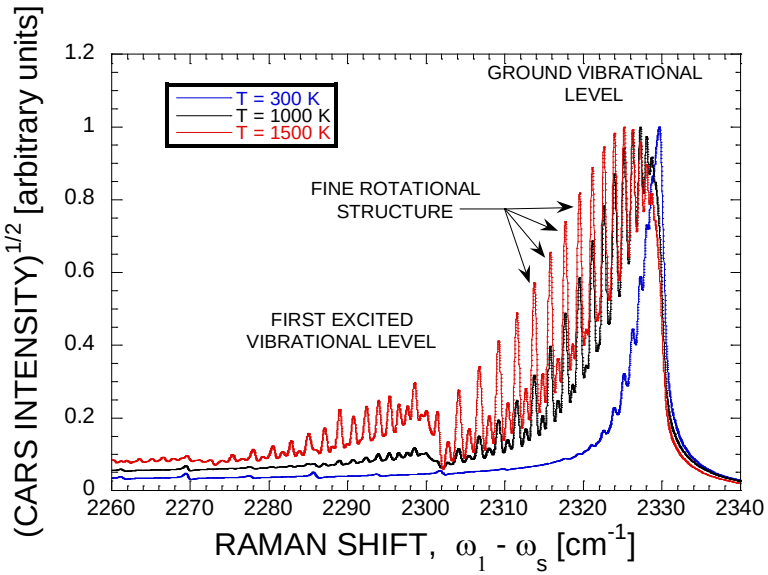
# *Dual-Pump* CARS Approach for Sooting Flame Temperature *and* Species

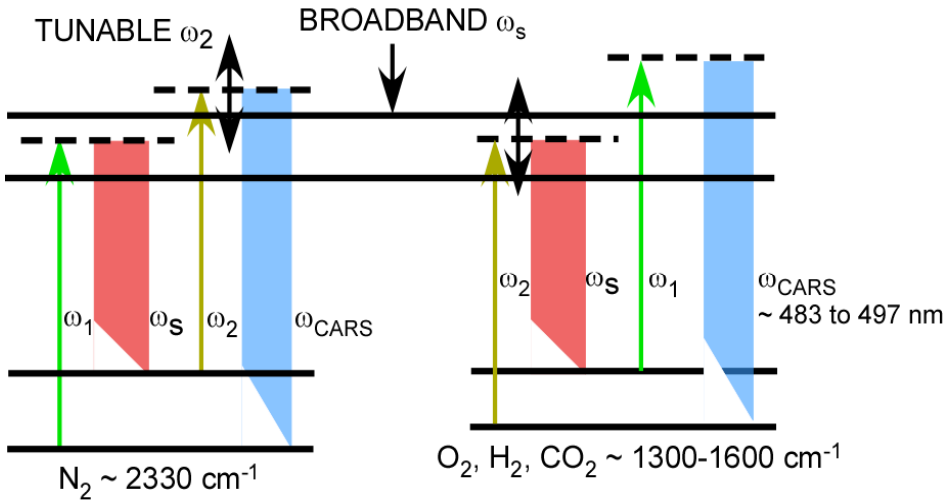
- Coherent laser-like signal with rotational/vibrational Raman information
- Soot and optical interferences well-handled
- Readily coupled to optical fibers for large facility applications



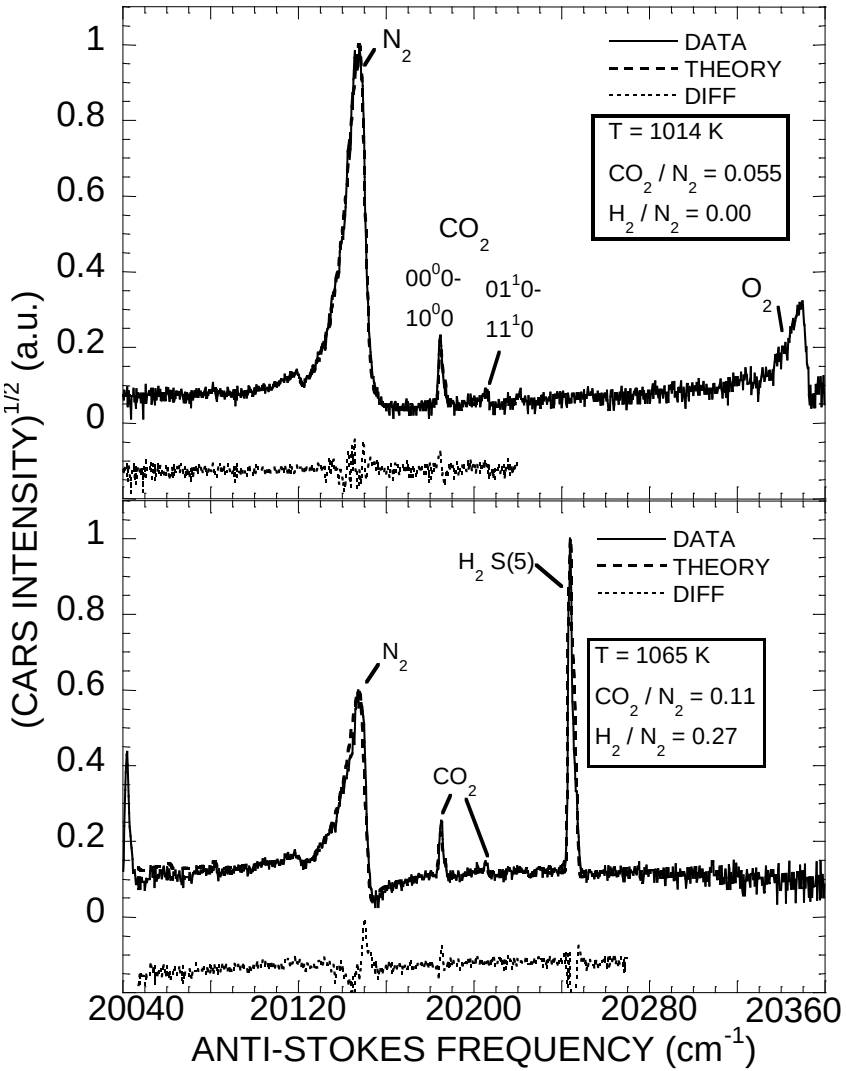

CARS Beam Arrangement

$$\omega_{CARS} = (\omega_1 - \omega_s) + \omega_2$$

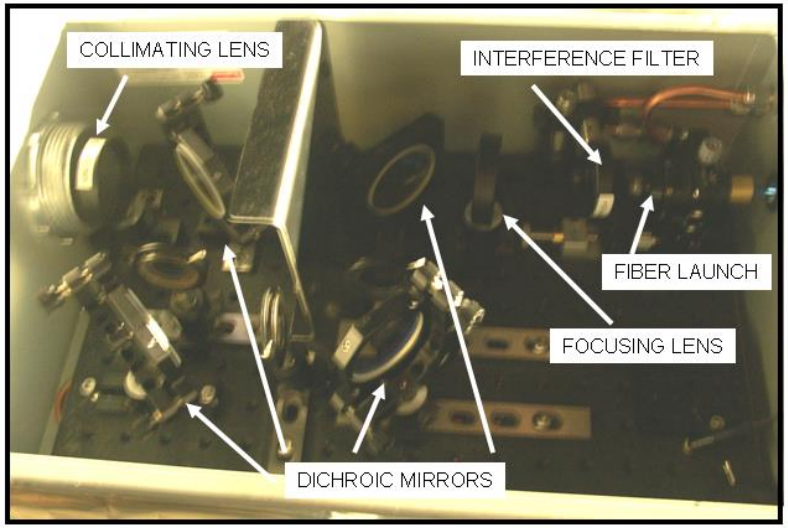


# Dual-Pump CARS Instrument at FLAME

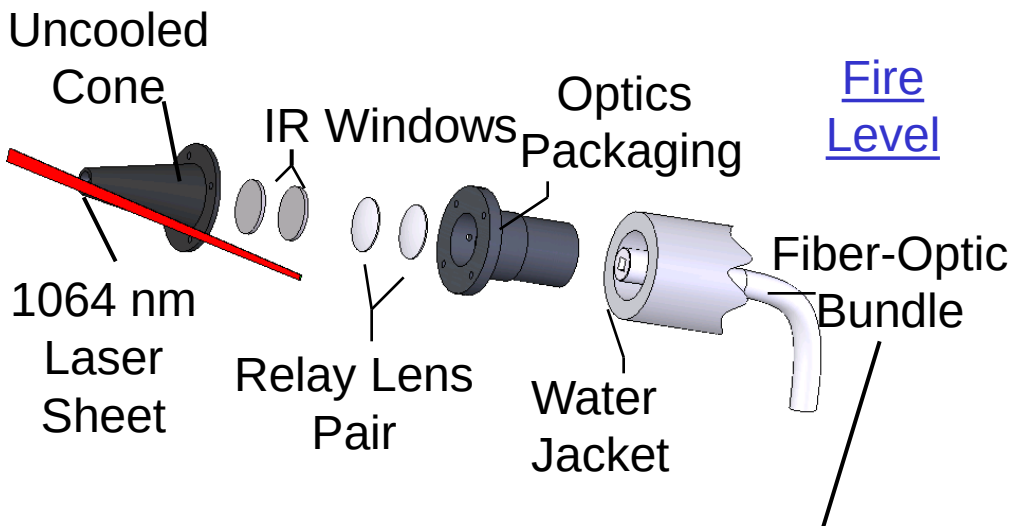


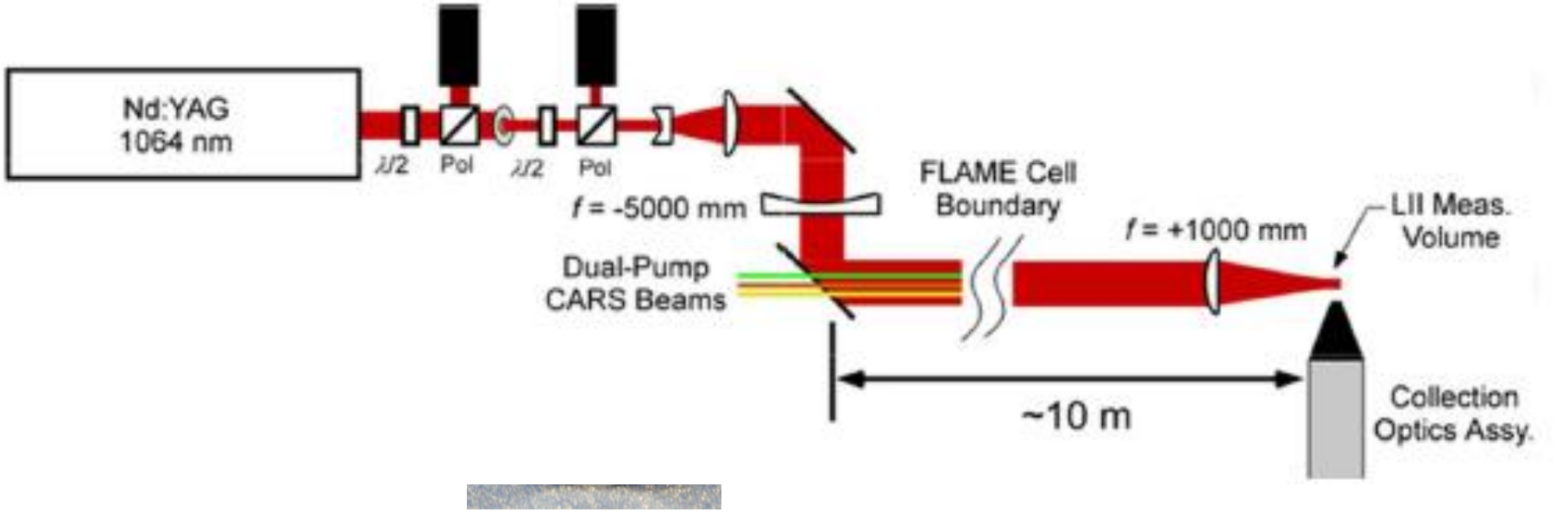




# Laser-Induced Incandescence Instrument at FLAME

- Toluene/Methanol blended fuel, ranging from 10/90 to 30/70 ratio, higher sooting propensity than pure methanol
- 1064nm laser sheet, fluence ~ 1.14 J/cm$^2$
- LII probe, water-cooled jacket, 200mm achromatic relay lens pair, 1cm$^2$ fiber-bundle (10 μm) couples signal to ICCD camera
- Four stage automated translation system to position probe and adjust focus
- Signal is filtered using IR-reflecting window gating reduces background emission from fire

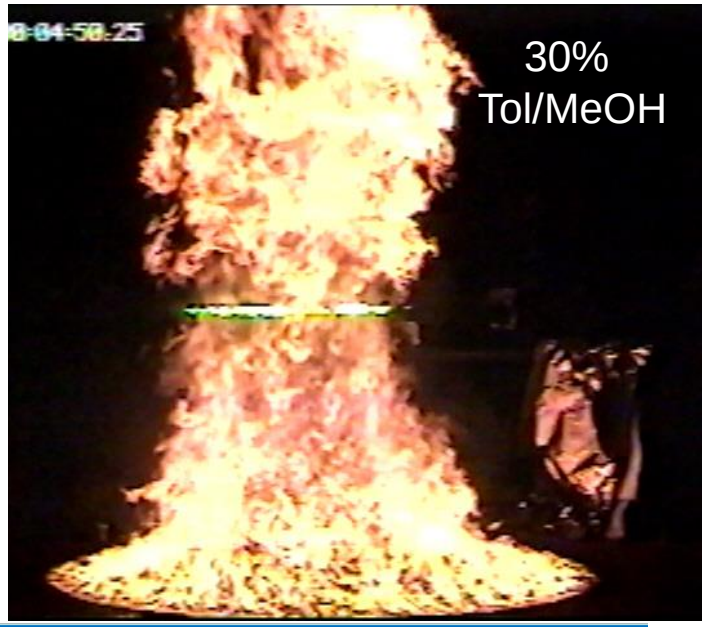


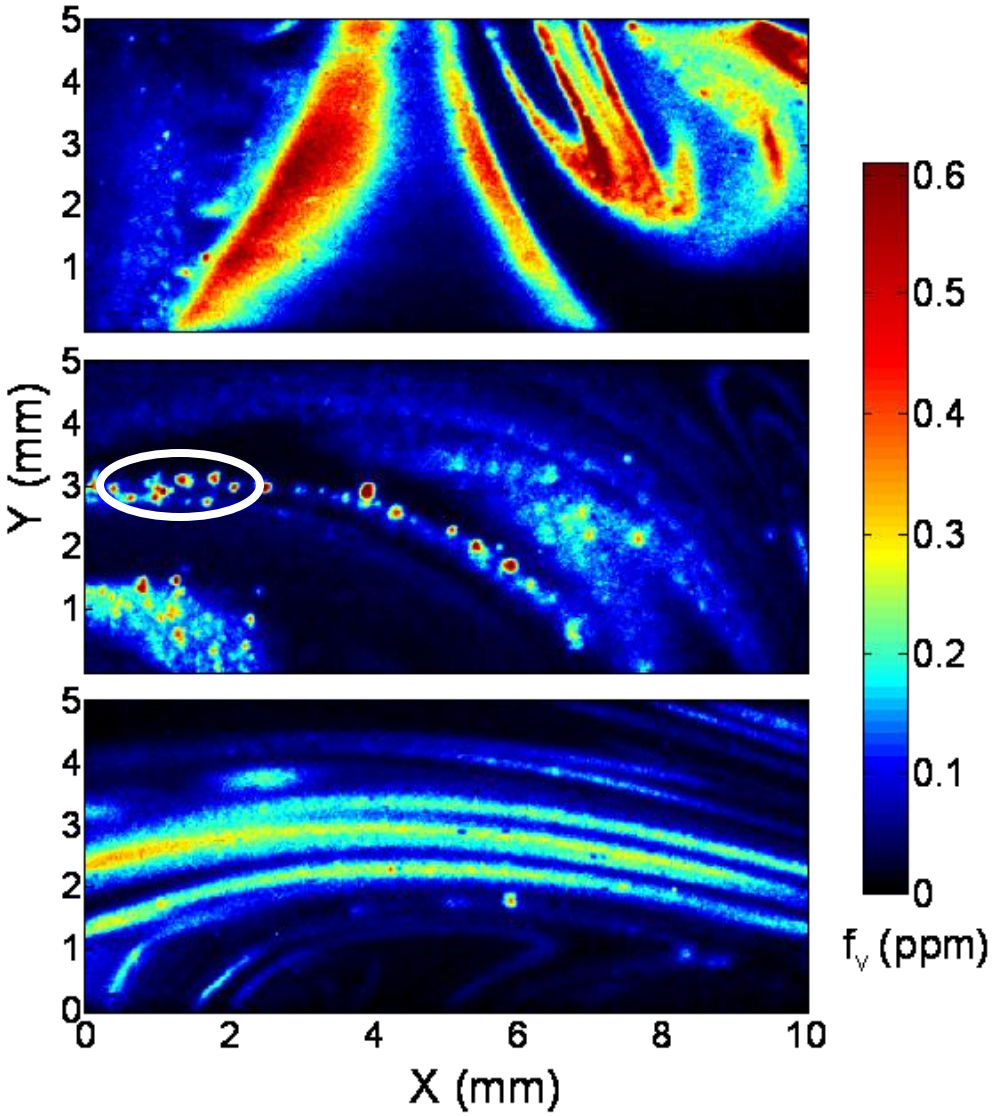




Frederickson and Kearney, *Appl. Opt.* **50,** A49 (2011)

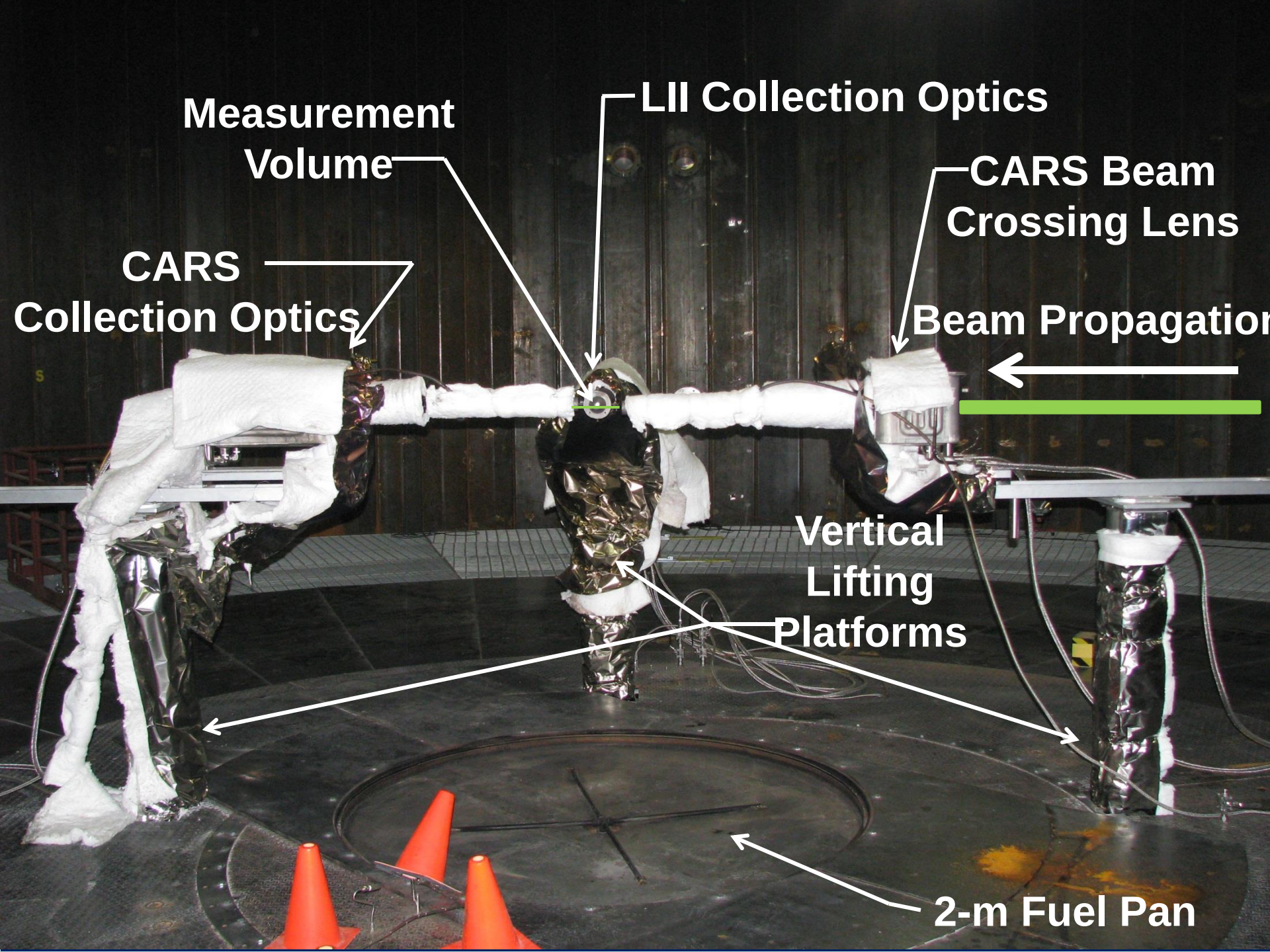
# LII Soot Imaging Results from a Turbulent Pool Fire

- Fires last for 20-30 minutes
- Few thousand single-laser-shot LII images
- Highly resolved soot layer structure in wide variety of orientations; parallel to laser sheet probe to perpendicular
- Thickness of soot layer ~ 0.5-1 mm
- Large-scale features observed in many images for higher sooting fuels

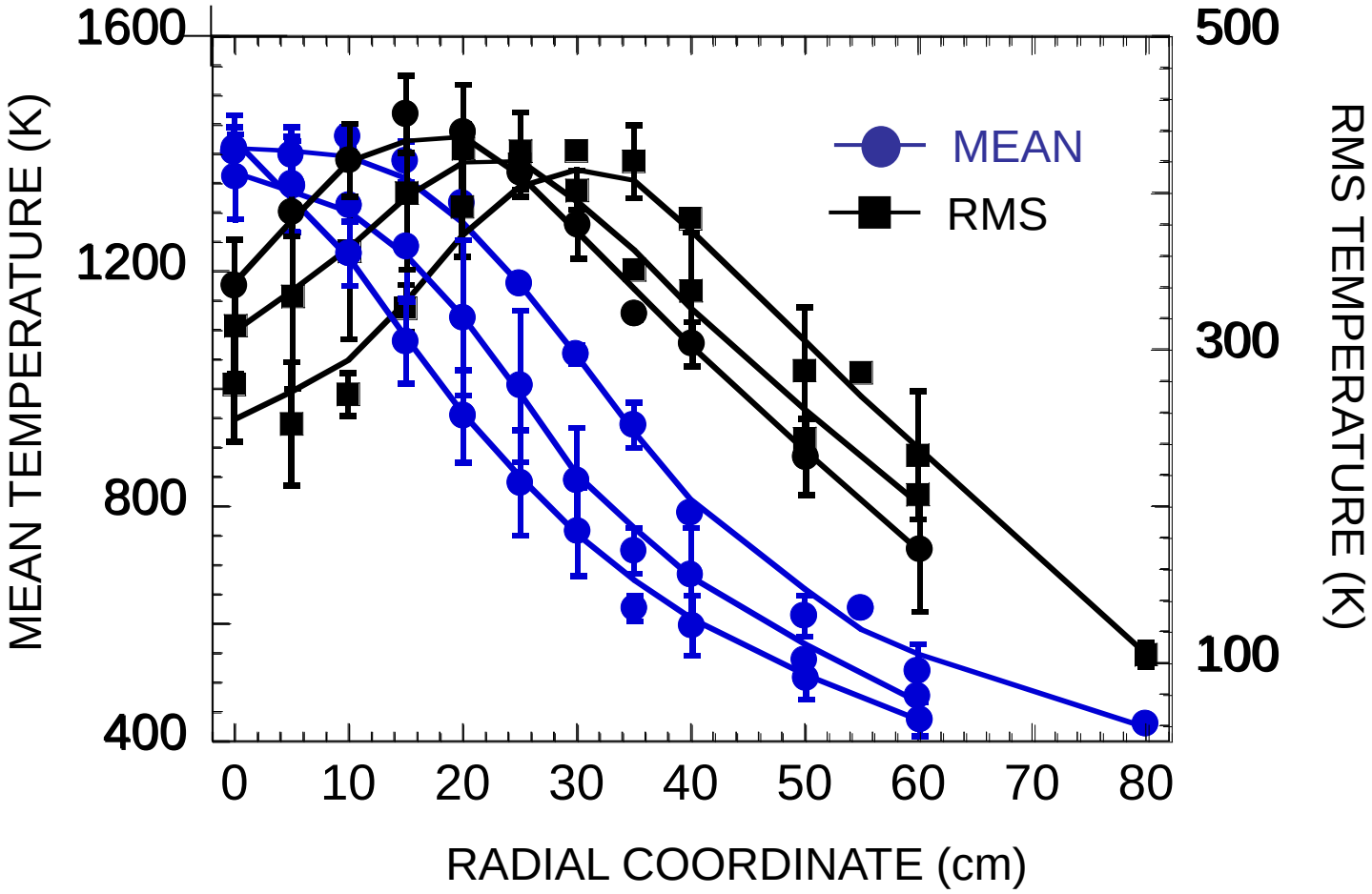


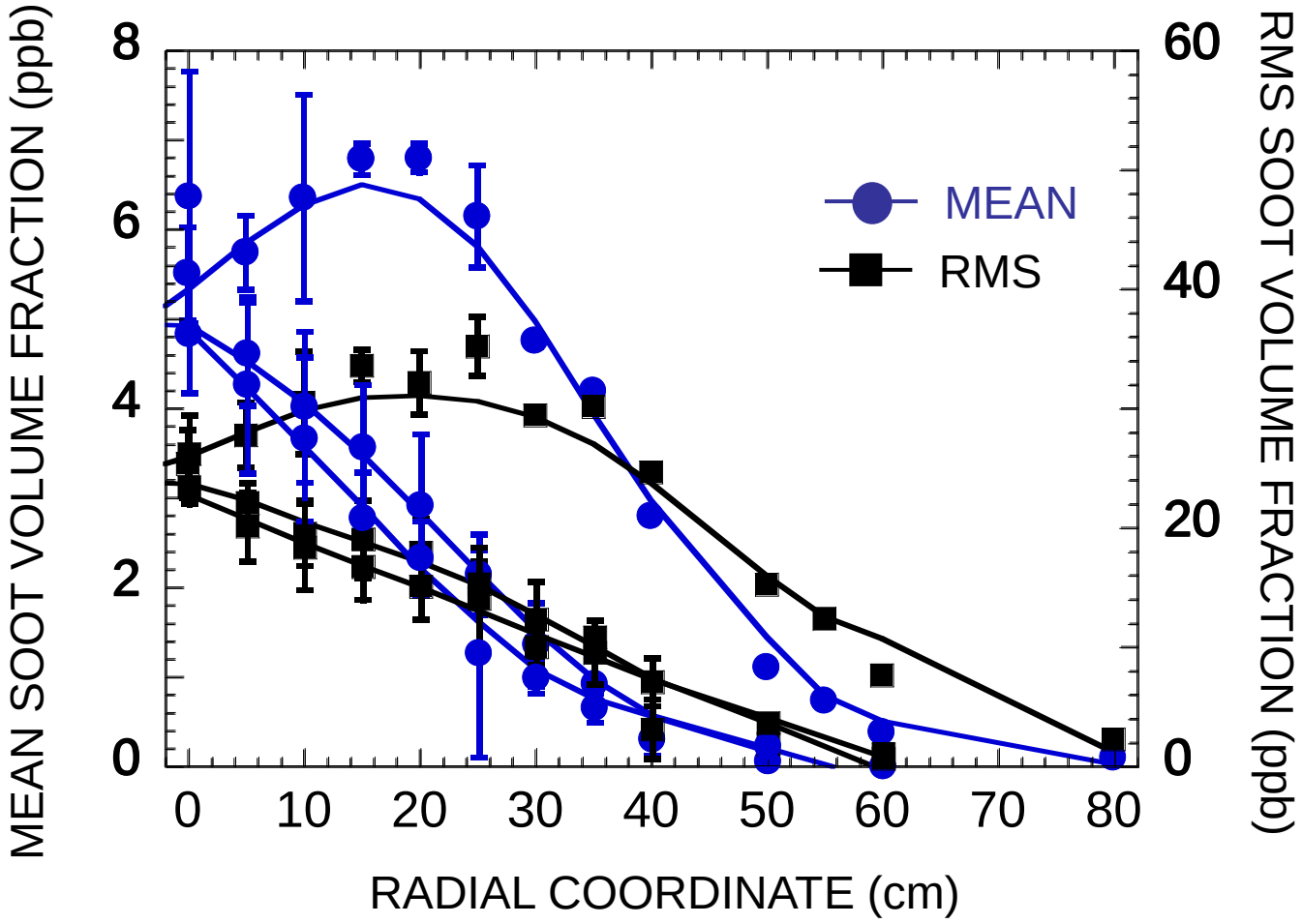

Kearney and Pierce, *Combust. Flame* **159,** 3191 (2012)


Measurement Volume
LII Collection Optics
CARS Beam Crossing Lens
CARS Collection Optics
Beam Propagation
Vertical Lifting Platforms
2-m Fuel Pan

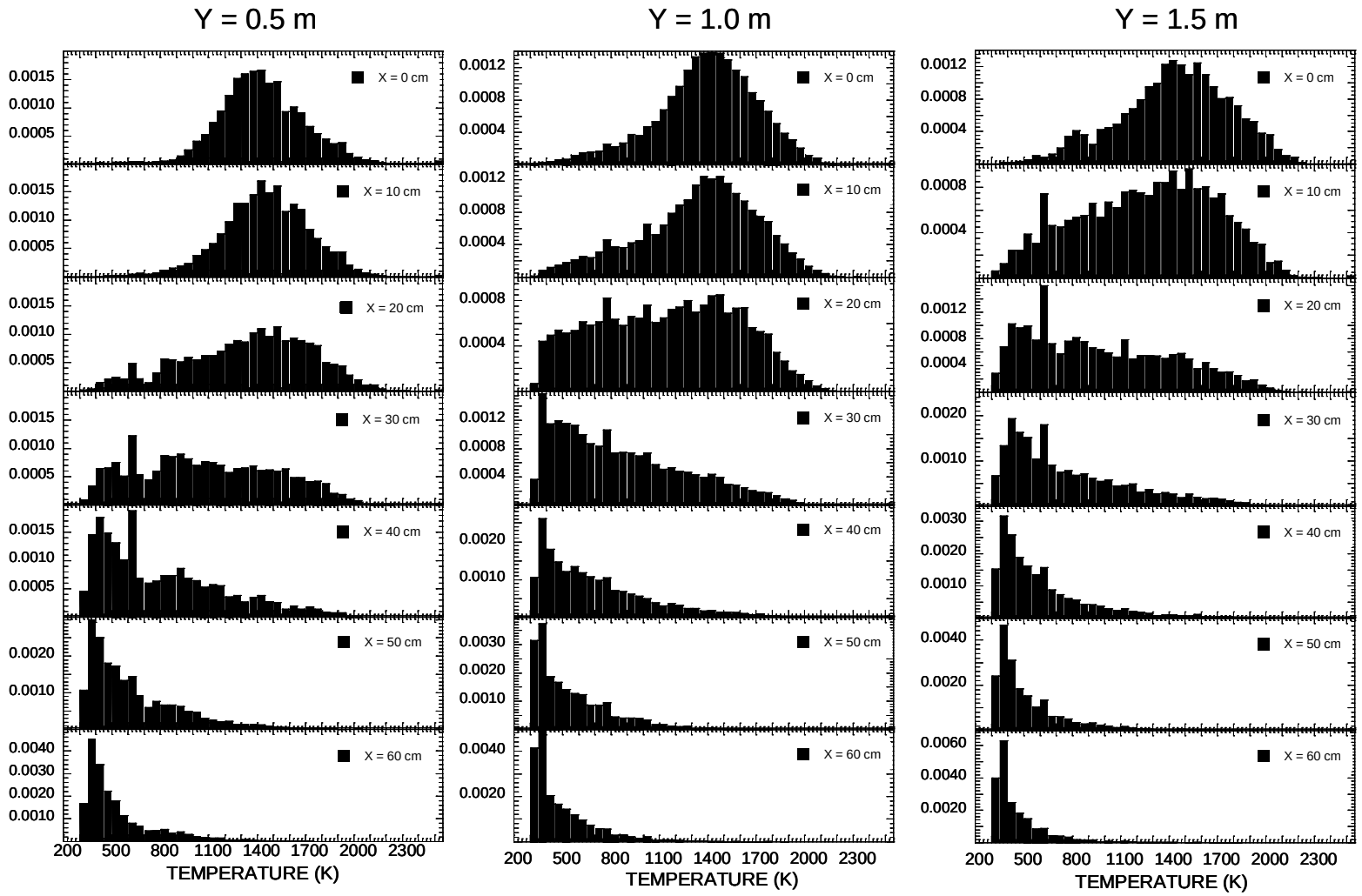
# Radial Temperature Profiles – Sooting Pool Fire



# Radial Soot-Volume-Fraction Profiles

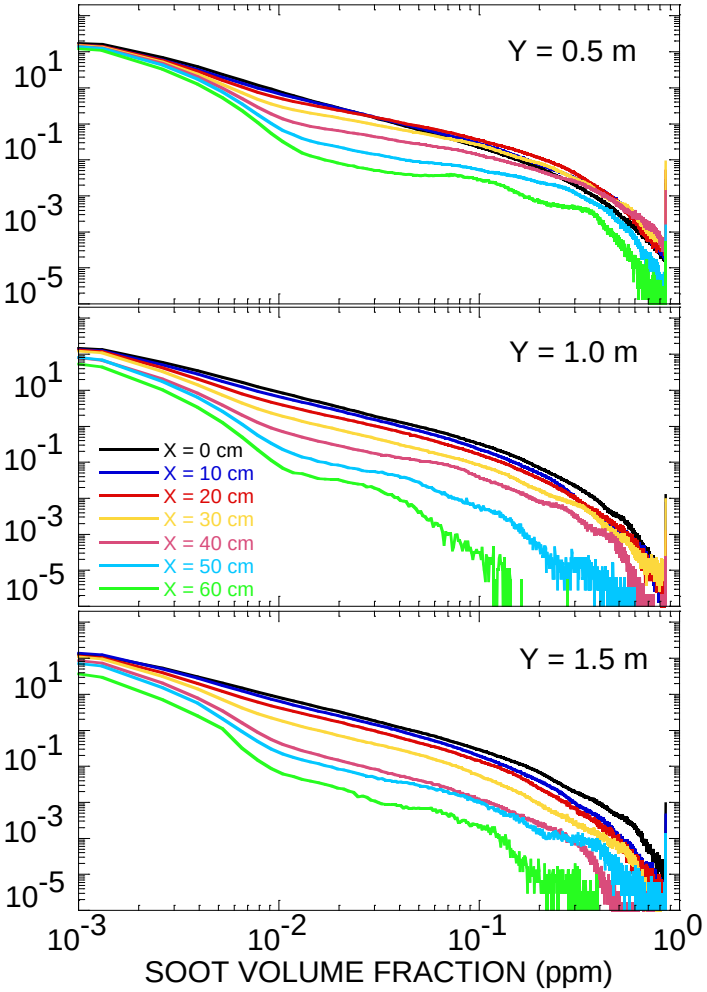


# Temperature PDF – Sooting Pool Fire



# Soot-Volume-Fraction PDF

- PDF Shape exhibits logarithmic decay at locations of high $f_v$
- Sparsely populated soot fields
- Similar log-normal or “clipped” pdf shape observed in:
  - 15-cm JP-8 Pool Fire (Henriksen et al., 2009)
  - 7-cm buoyant $CH_4$ and $C_2H_4$ flames (Xin and Gore, 2005)
- Soot pdf shapes appear different in meter scale JP-8 experiments
  - 2006 2-m JP-8 pool fire (Murphy and Shaddix 2006)
  - 5-m JP-8 pool fire (Gritzo et al., 1998).
  - Spatial resolution? Fuel?



# Joint/Temperature Soot Statistics for Emission

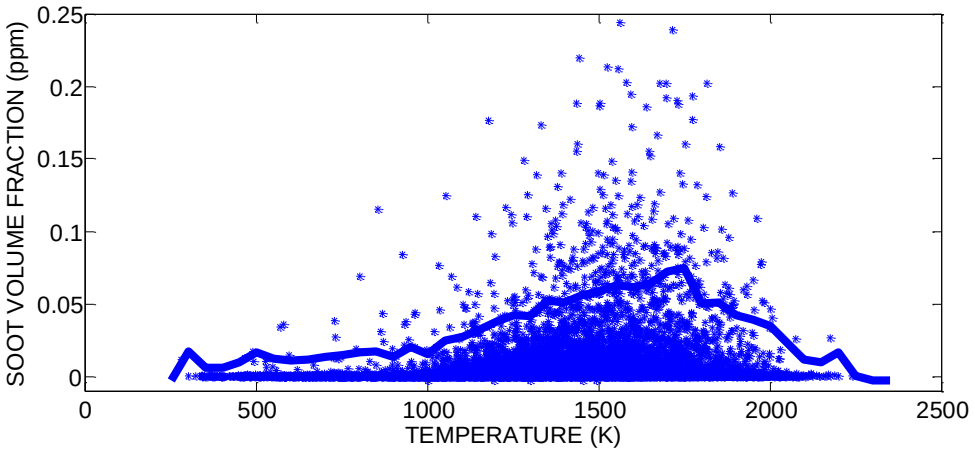
Sandia National Laboratories

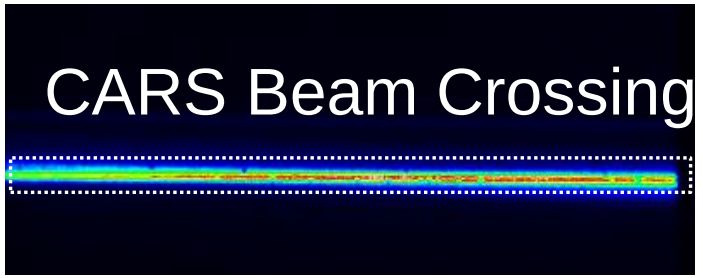
## Radiative Transfer Equation

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

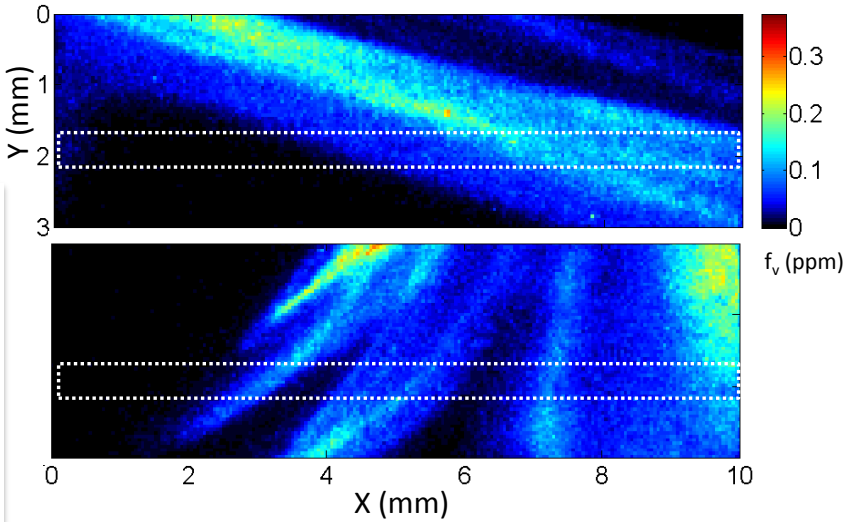
Joint Temp. Soot Statistics Desired

- LII optics for soot measurement "stare" at CARS temperature measurement beam crossing.
- LII soot from region of interest bounding CARS measurement volume is averaged and correlated with CARS temperature.





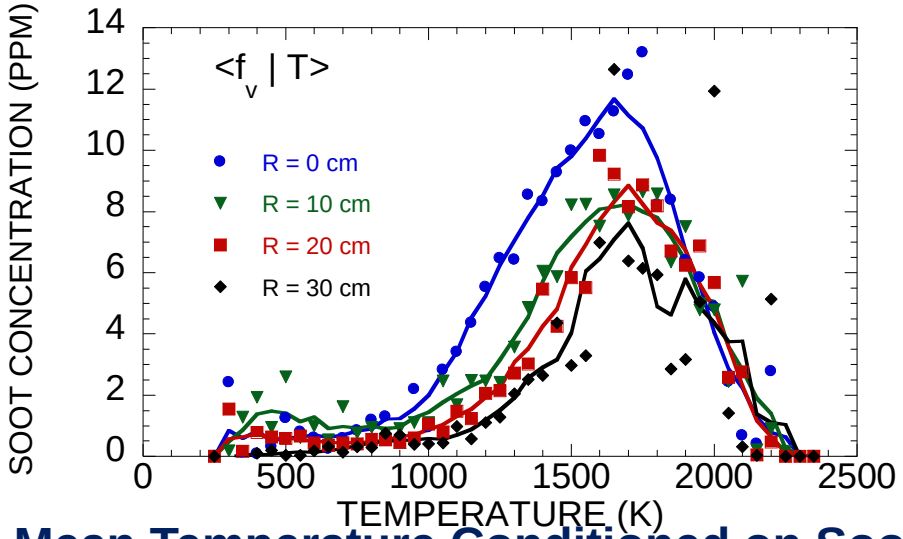


# Soot Profiles Conditioned on Temperature

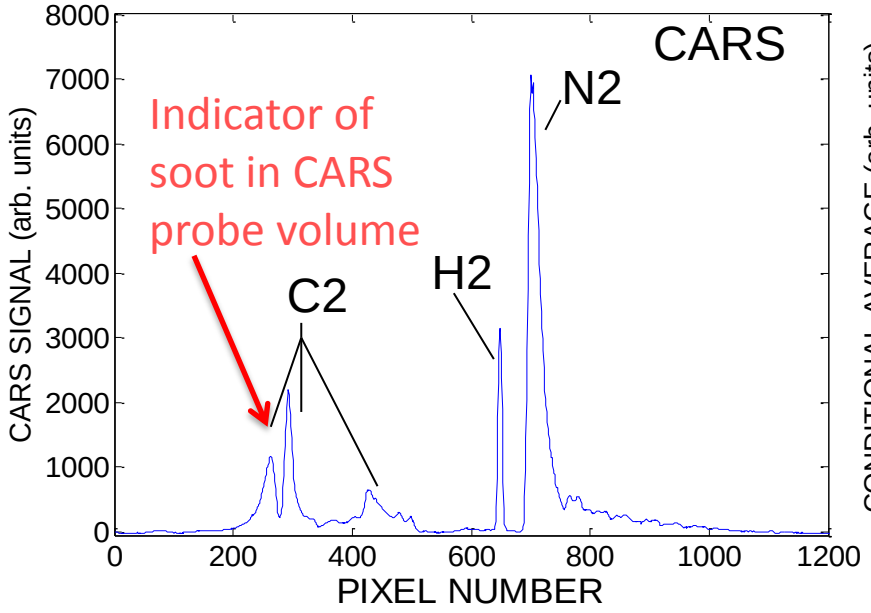
•Additional CARS signal from C2 generated by laser-vaporized soot is an indicator of soot in the temperature measurement volume

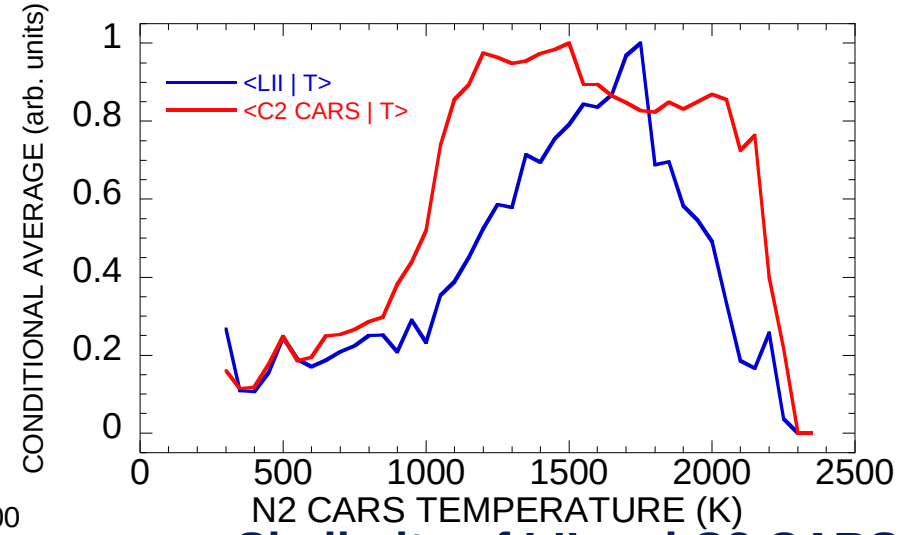
• C2 and LII signals display similar conditional averages

• $<f_v|T>$ peaks near T = 1500 K across the fire plume




**Mean Temperature Conditioned on Soot**

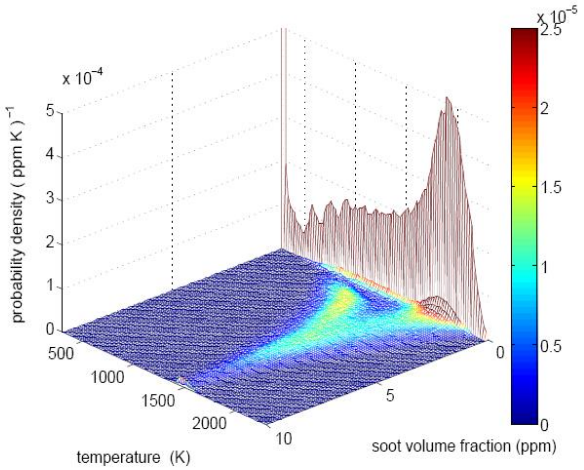



**Similarity of LII and C2 CARS**

# Summary and Conclusions – Fire and Combustion Studies

- Radiative flux from large fires is generated at flame-level length scales below the computational grid
- Laser diagnostics implemented at flame for high spatial and temporal resolution data
- CARS diagnostic measures temperature pdf's at a point with ~100 $\mu$m X 5-10 mm X 10 ns resolution. Accuracy = ±2-3%/precision = ±3.5-5%
- LII probe has been implemented for 2-D imaging of soot with ~500 $\mu$m X 50 $\mu$m X 10 ns resolution. Uncertainty is ±25-50%
- Both measurements have been conducted simultaneously for first estimates of temperature/soot joint statistics in a fire of meaningful size




A. Ricks, Ph.D. Thesis, Purdue University, 2007.