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Laser-Diagnostic Probing of Radiative Flux Generation in Hydrocarbon Pool Fires

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Sandia's Motivation for Fire Research

• Fire is a dominant source of risk to Sandia/DOE strategic systems, and US civilian and commercial infrastructure

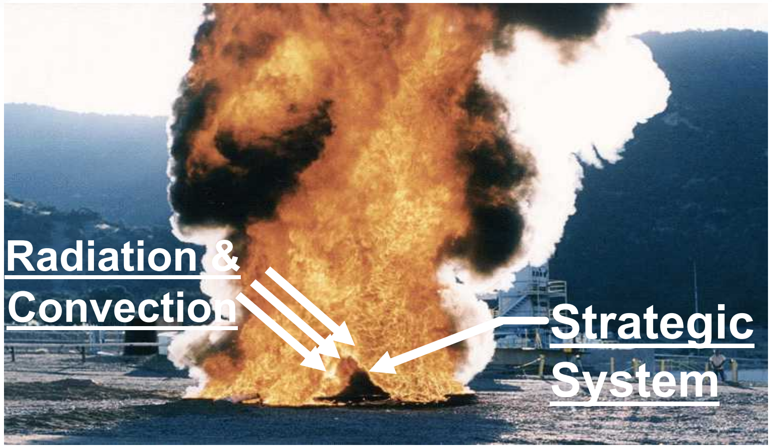
• The heat flux from fires to objects is critical for engineering risk analysis

•Validation and verification of fire-simulation tools such as ASC-FUEGO requires high-fidelity experimental data

• Temperature, soot, mixture fraction, fuel regression rate, velocity….

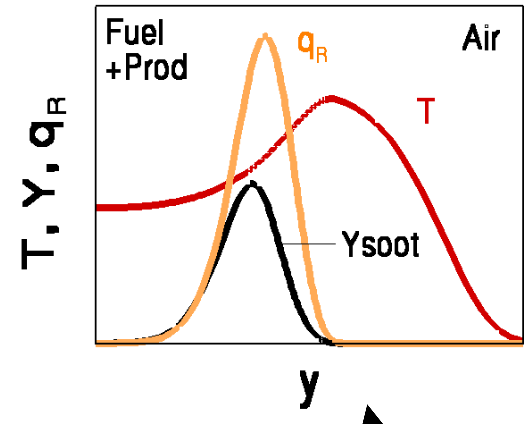
• The meter-scale and large-scale turbulent fluctuations of realistic fire testing makes high-fidelity experiments extremely challenging!

• Fire testing typically low-cost robust instrumentation, but improved multi-parameter diagnostics are needed.

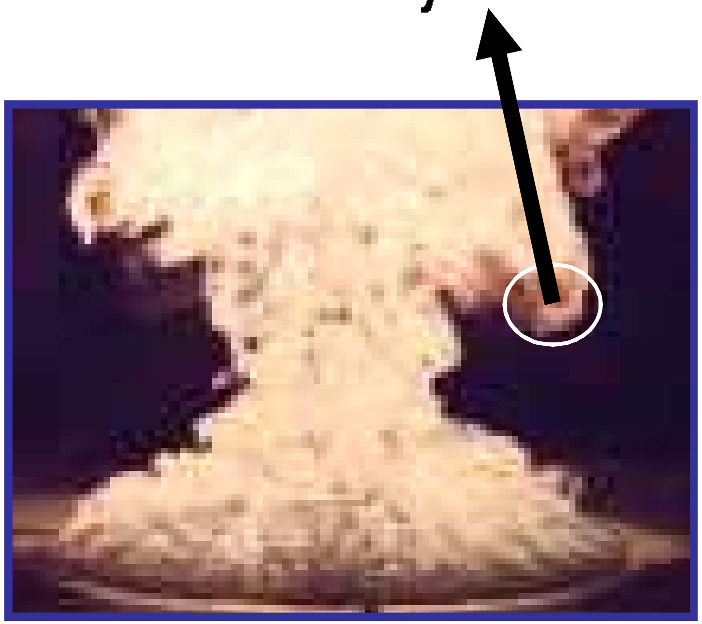


Radiative Transport Equation

$$\int s \bullet \nabla I(s)ds = \int \left(\underbrace{\frac{\langle \alpha \sigma T^4 \rangle}{\pi}}_{Emission} - \underbrace{\langle \alpha \rangle I(s)}_{Absorption} \right) ds$$

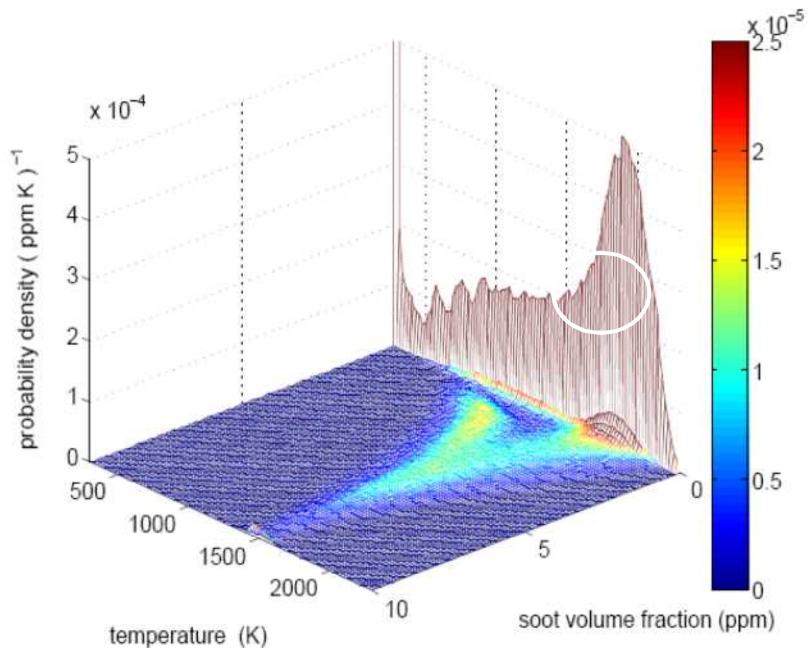


- RTE (neglecting scattering) requires knowledge of
  - Product αT^4 for emission
  - Absorptivity, α, related to Y_{soot}.
- In CFD codes these are spatially filtered for practical purposes of engineering simulations
- But the source of radiative emission occurs at length scales comparable to the local soot layers!
  - Below the computation grid
  - Must be modeled



Approach: Spatially Resolved Laser Diagnostics

- **Objective:** Obtain fundamental data for development of next-generation fire heat-flux models
- **Experimental Approach: Laser Diagnostics**
  - **Coherent anti-Stokes Raman Scattering (CARS) → Temperature, Gas Mole Fractions**
  - **Laser-Induced Incandescence (LII) → Soot Volume Fraction**
  - **Joint temperature/soot statistics reveal subgrid radiative production**



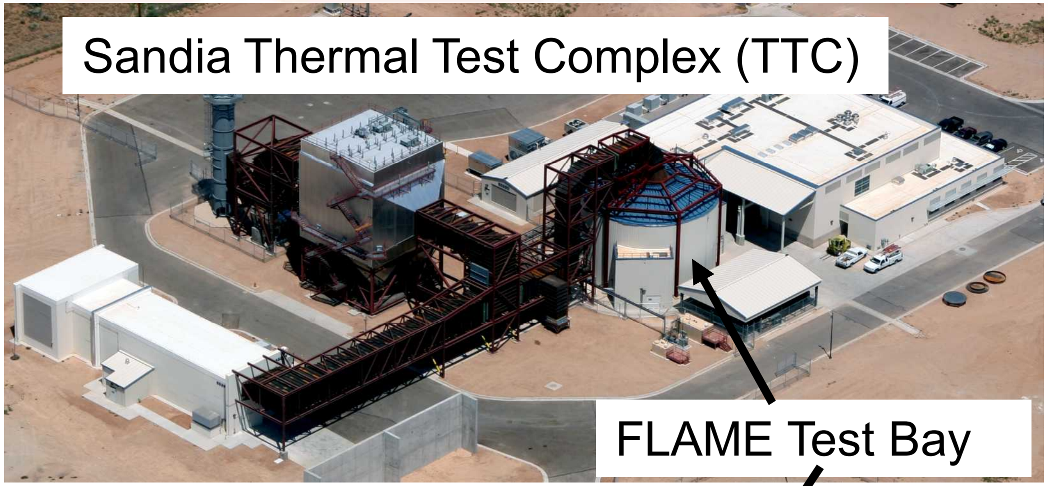
$$P(T, f_v \mid Z; \vec{\mathbf{x}}, t)$$

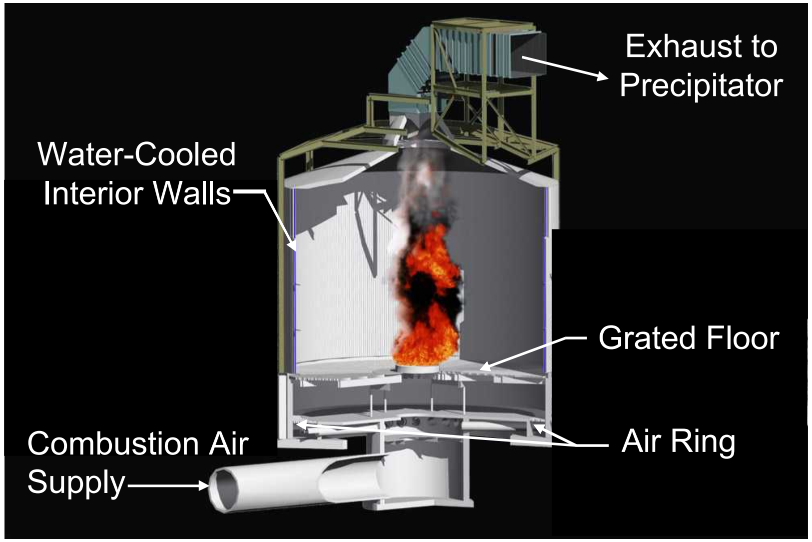
Joint Temperature/Soot pdf

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

Thermal Test Complex and FLAME Facility

- Thermal Test Complex (TTC) brings laboratory control and diagnostics to meter-scale fire testing
- FLAME facility provides canonical wind-free fire plumes
- Designed with access for laser diagnostics in mind

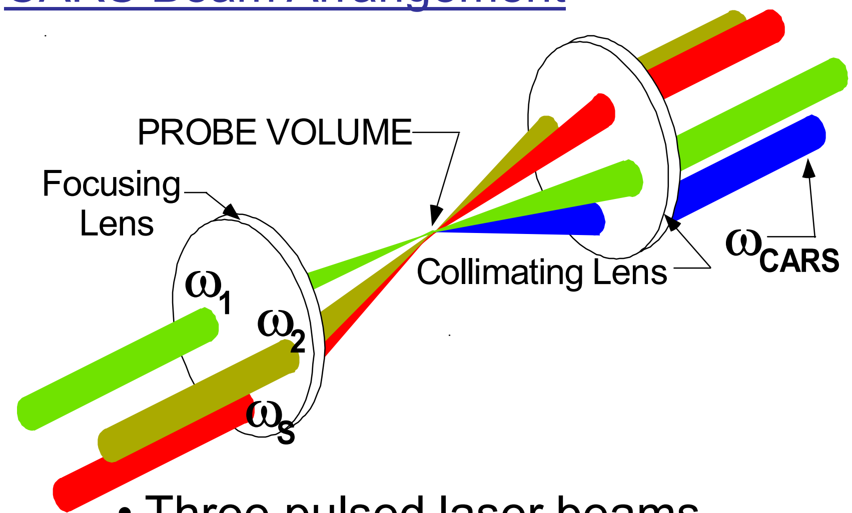




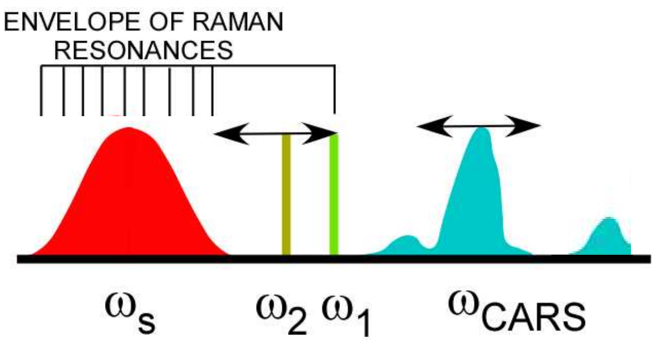
CARS THERMOMETRY

Coherent Anti-Stokes Raman Scattering (CARS)

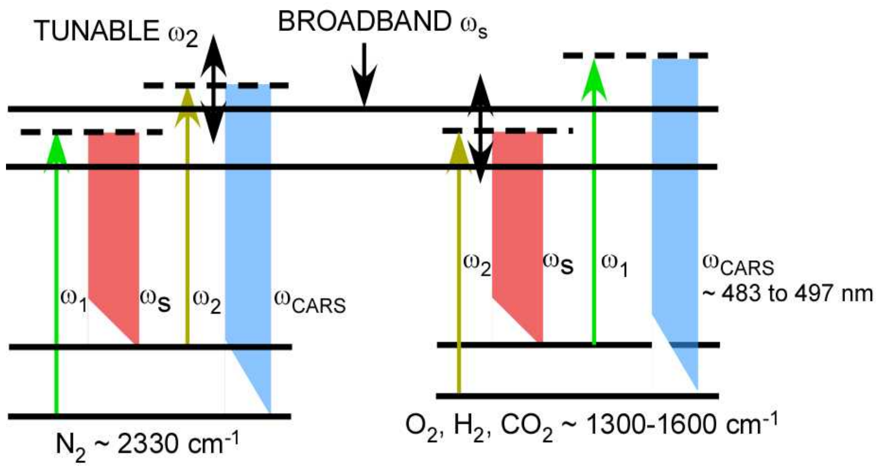
CARS Beam Arrangement



- Three pulsed laser beams (pump #1, pump #2, Stokes) crossed at a common focus
- Pump-Stokes tuning at $\omega_1 - \omega_s$ and $\omega_2 - \omega_s$ drives Raman polarizations (dipole) in N_2 and selected combustion gases
- The Raman polarizations scatter the remaining pump photons; a blue-shifted laser-like signal emerges.



Spectra of pump/Stokes/CARS Beams



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

Energy Level Diagrams

N_2 is Used as a "CARS Thermometer"

- Shape of the N_2 CARS spectrum reflects partitioning among vibrational and rotational states

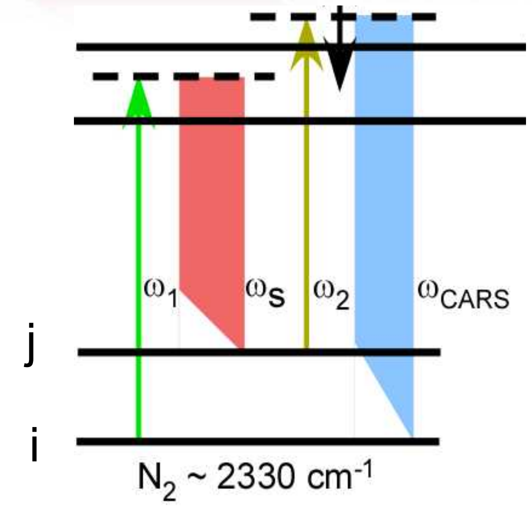
- For a Raman transition from level i to level j, the CARS signal the reflects the population difference

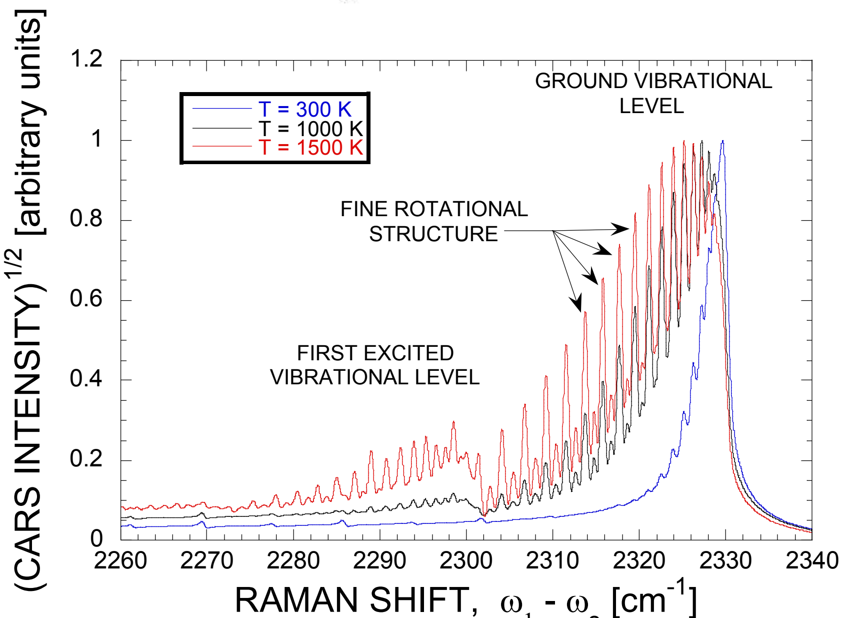
$$I_{CARS} \sim \left(\frac{N_i - N_j}{\omega_{ij} - (\omega_1 - \omega_s) + i\Gamma} \right)^2$$

- Boltzmann distribution defines a temperature in terms of this partitioning of states

$$\frac{N_i}{N} = \frac{g_i \exp(-\varepsilon_i / kT)}{\sum_i g_i \exp(-\varepsilon_i / kT)}$$

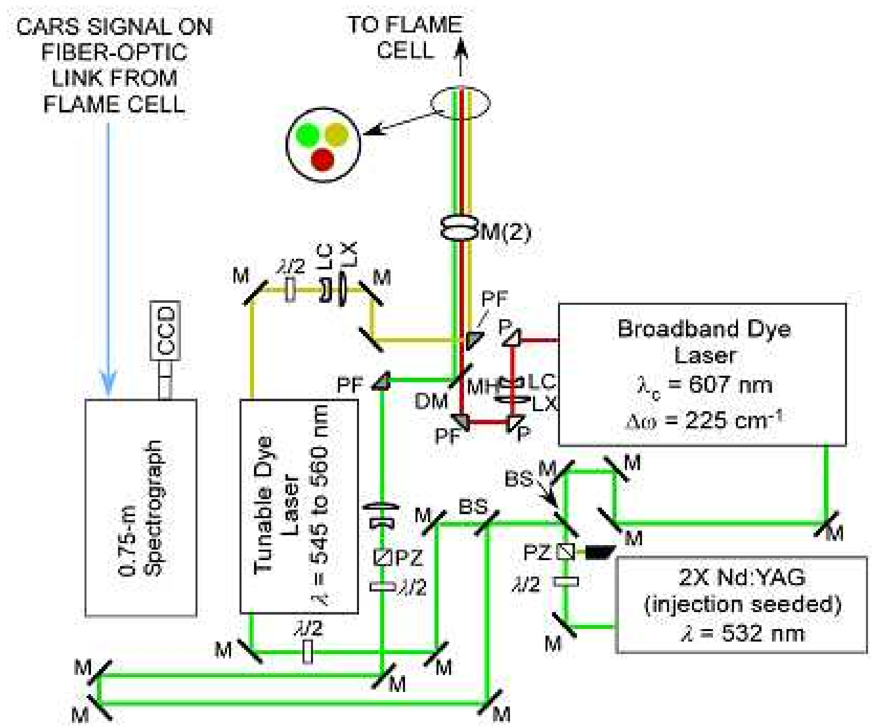
- Temperatures are inferred by least-squares fitting to theoretical spectra

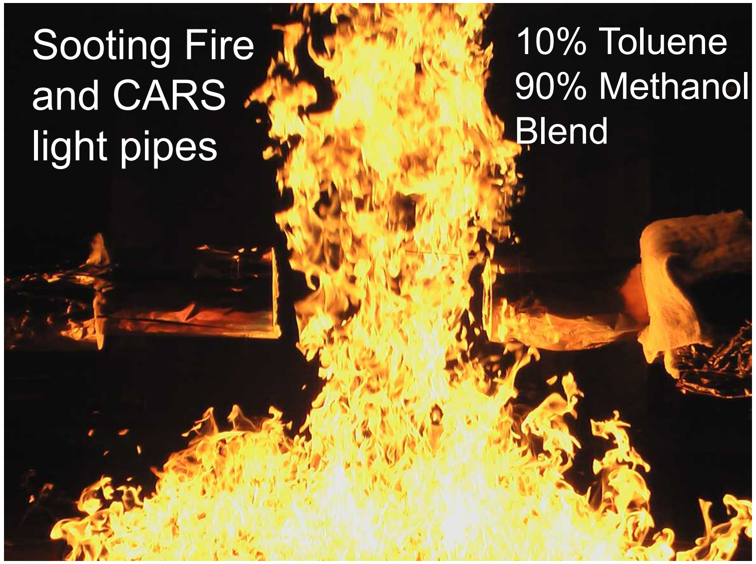




Dual-Pump CARS Instrument at FLAME

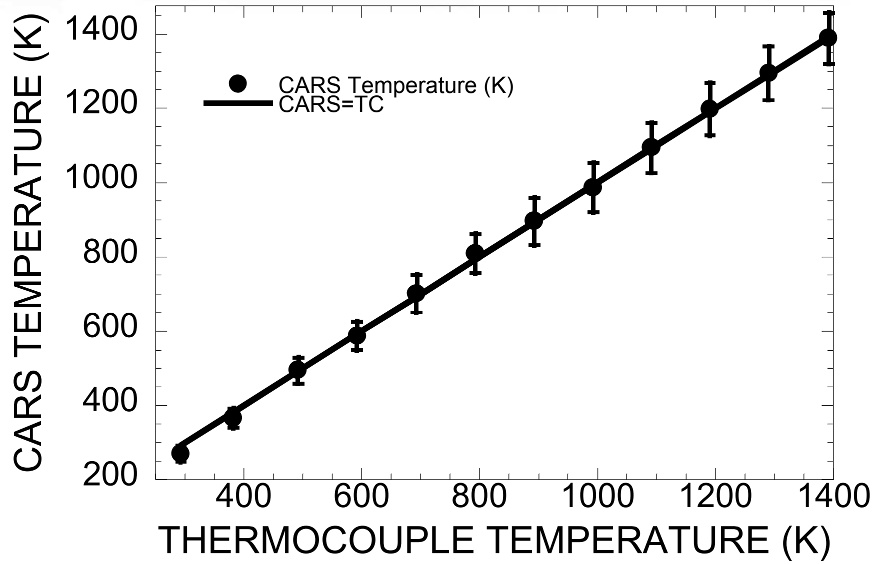
- **First-ever implementation of CARS for large-scale fire testing**
- **Methanol and sooting methanol/toluene blends have been tested to date**
- **Simultaneous mole-fraction measurements have been added to thermometry capabilities**

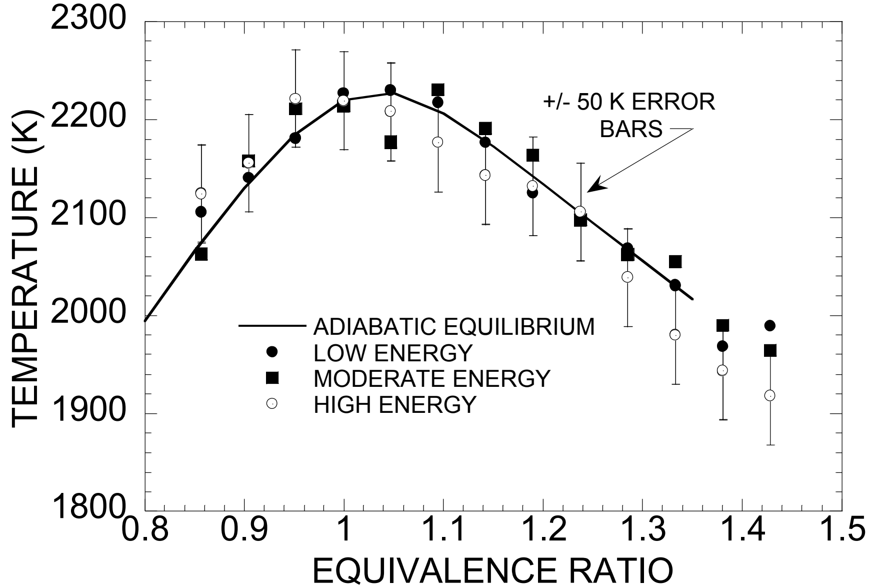




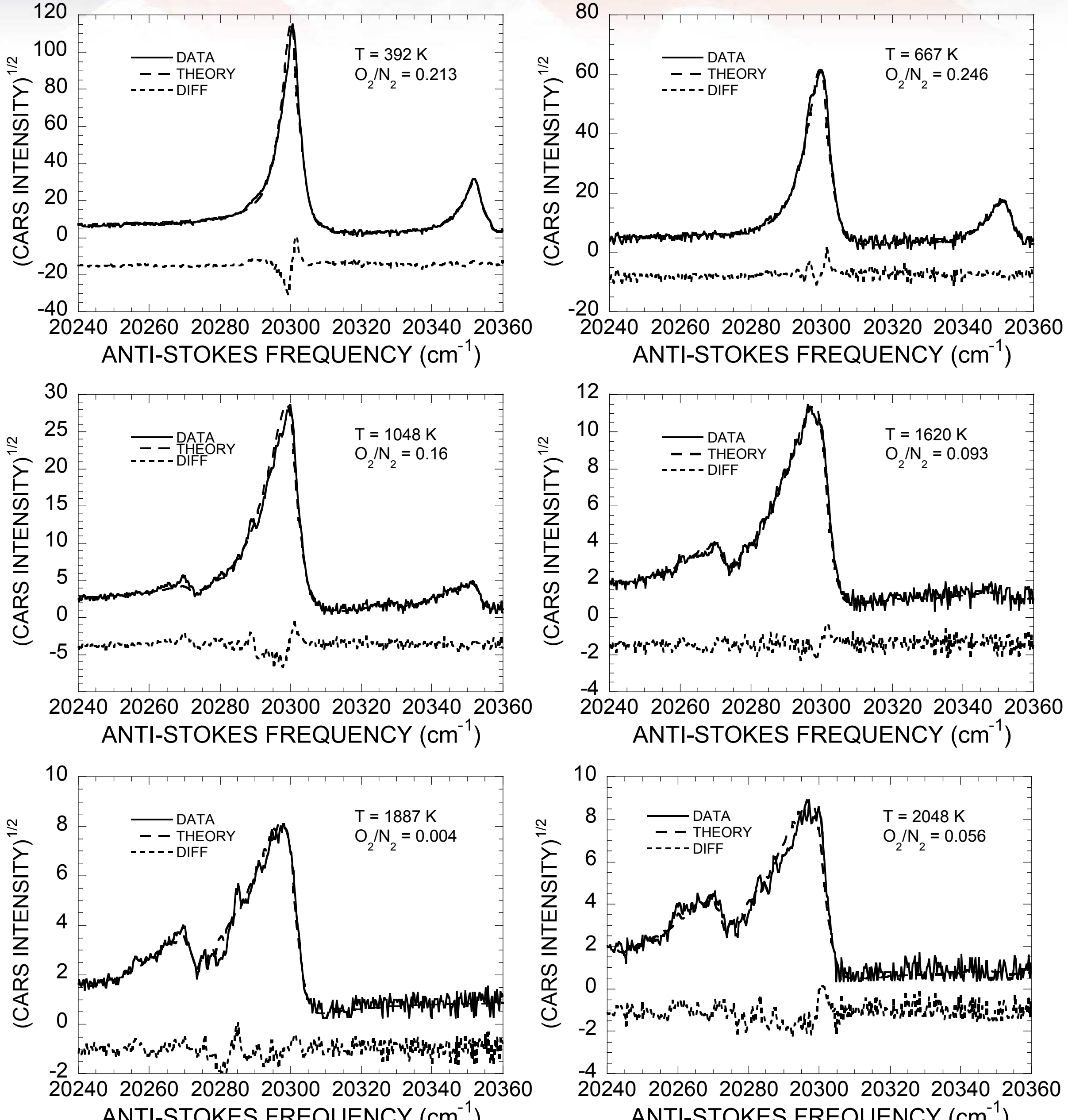
Results – Data Fidelity

- Accuracy and precision of N_2 CARS thermometry assessed with 2 lab standards
  - Tube-furnace → thermocouple
  - Adiabatic flat flame → equilibrium calculated temperature
- Ensembles of single-laser-shot CARS spectra acquired for a given furnace/flame setting
- Accuracy: 5-40 K, within 2% for T> 500 K
- Precision: 5-7%



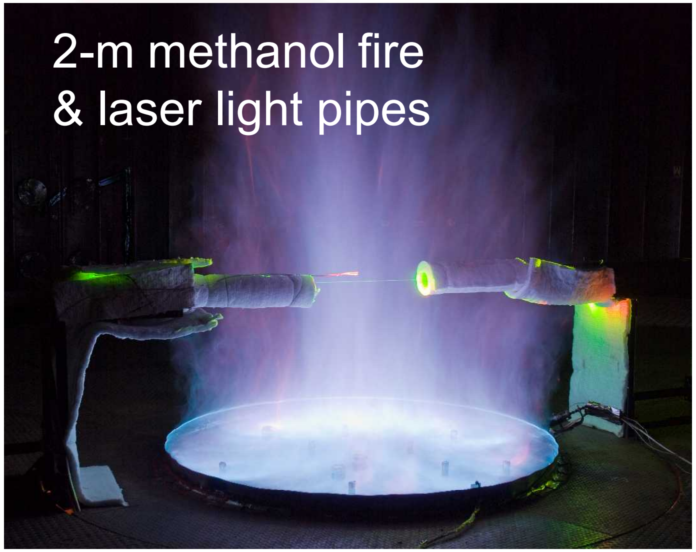


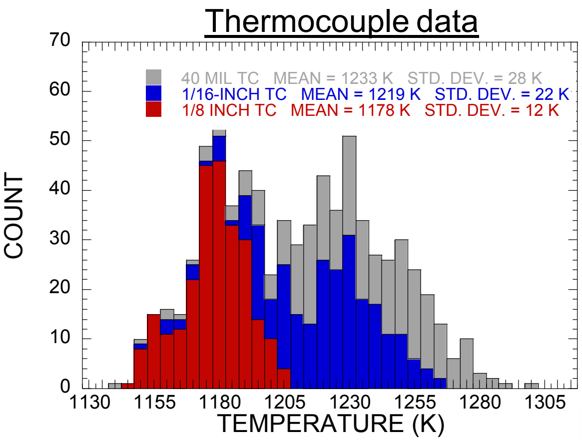
Single-Shot Dual-Pump CARS Spectra from a Methanol Pool Fire

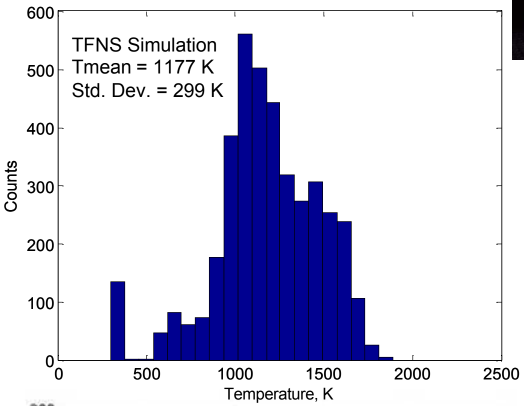


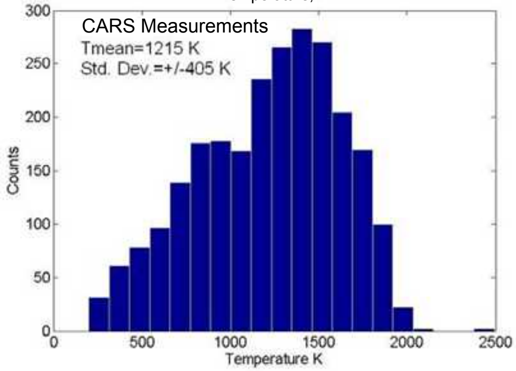
Results – Temperature and O_2 Data from a Methanol Pool Fire

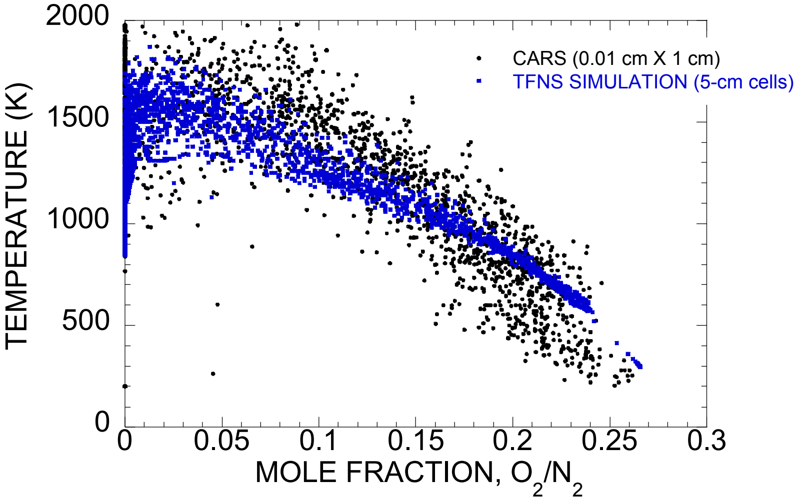
- First experiments conducted in methanol fire
- Nonsooting fuel is simpler starting point for diagnostic development
- Temperature and simultaneous O_2 data extracted
- Nearby thermocouples cannot follow turbulent fluctuations











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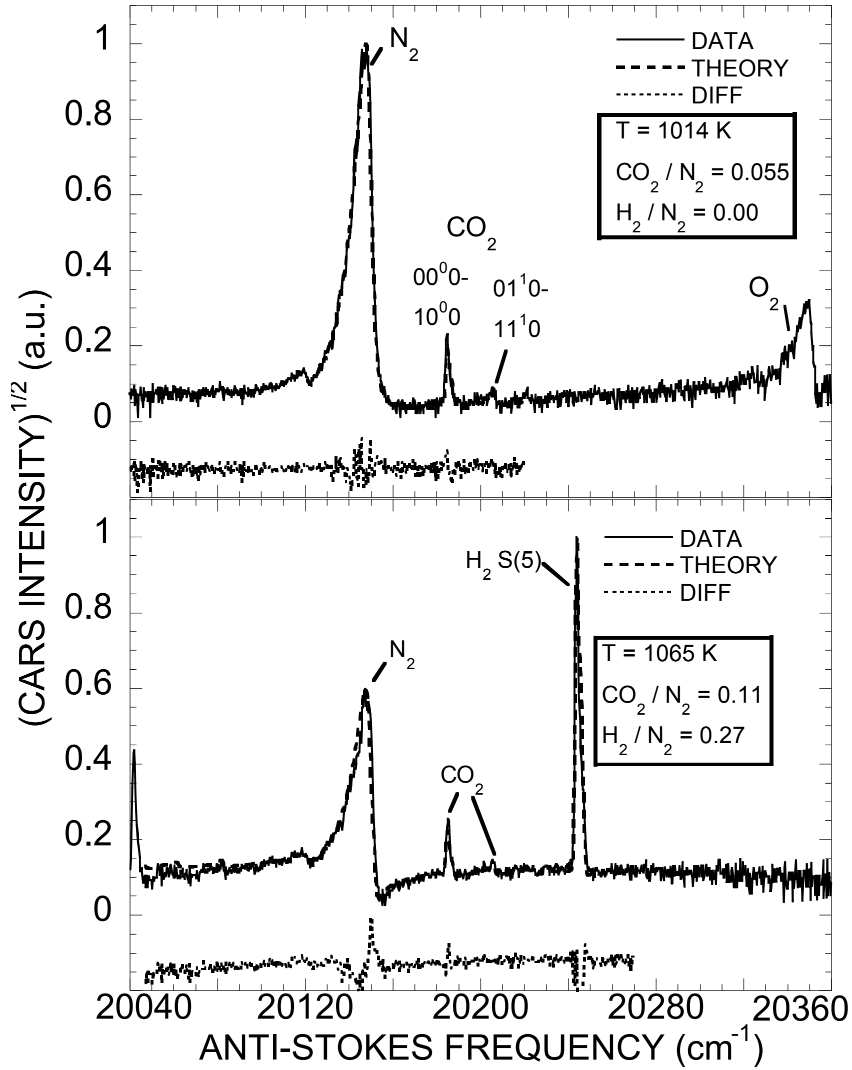
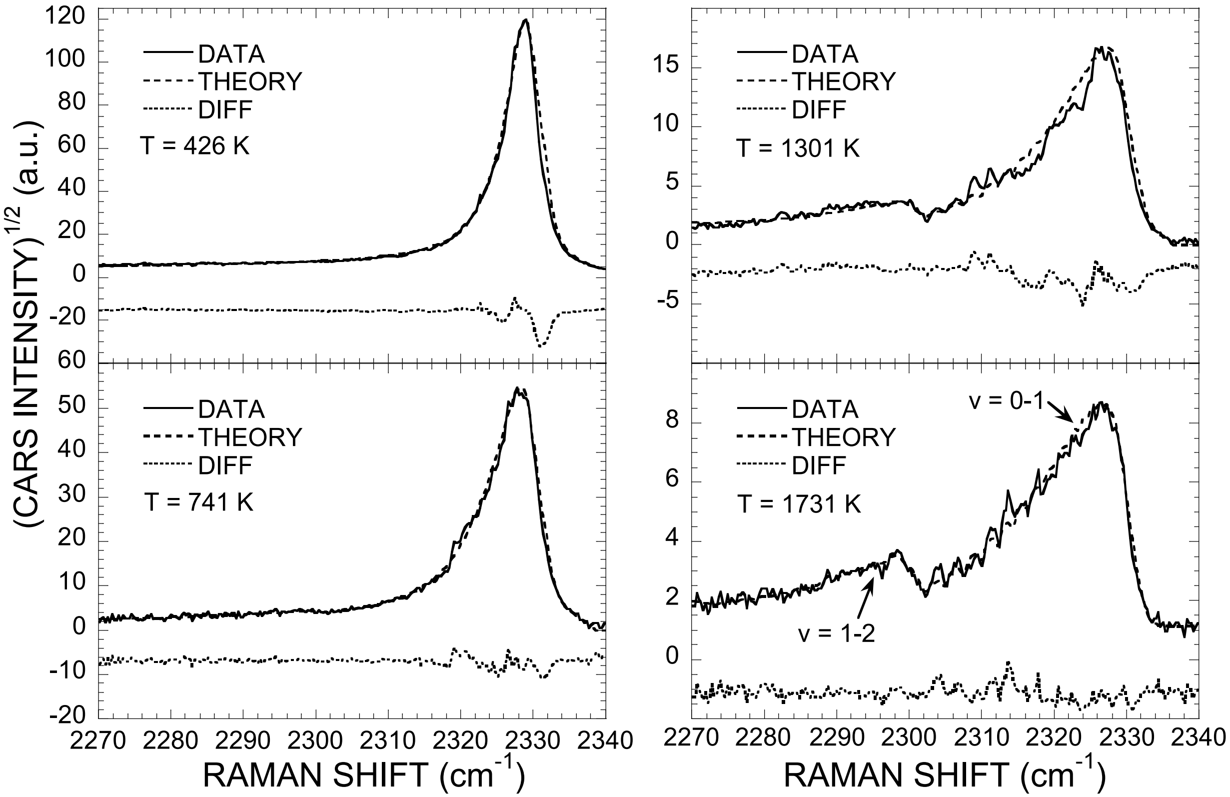
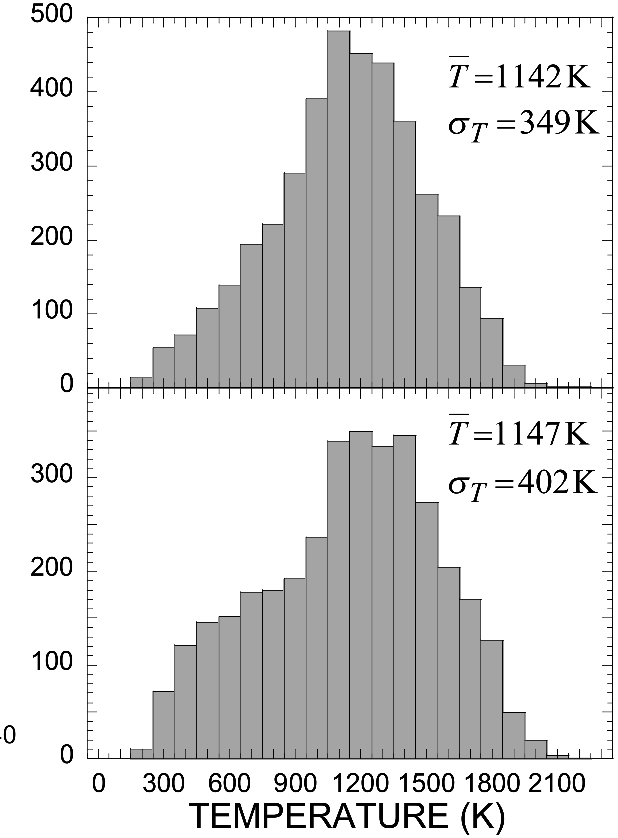
Single-Shot Spectra Provide Simultaneous Temperature/Species Information in Sooting Fire



Temperature Measurements in Sooting Pool Fire



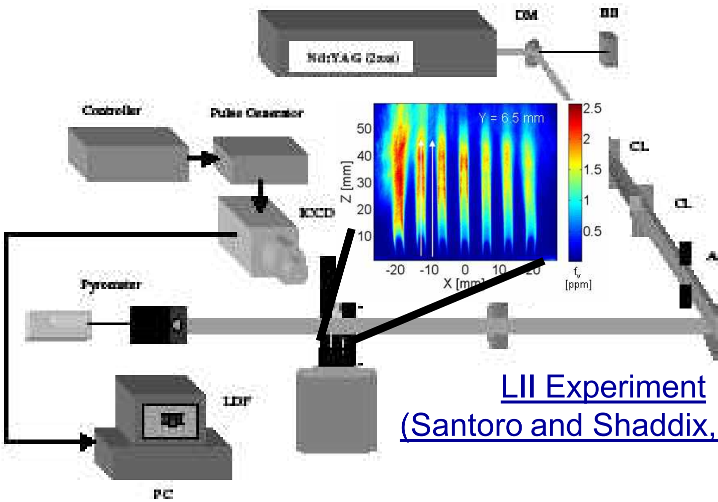
Single-Laser-Shot Spectra and Theoretical Fits



Temperature PDFs from 2 Separate Methanol/Toluene Burns

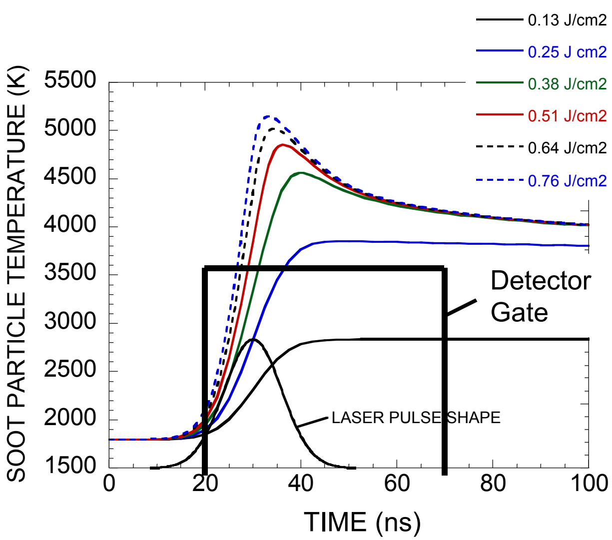
LII MEASUREMENTS OF SOOT VOLUME FRACTION

Laser-Induced Incandescence (LII)

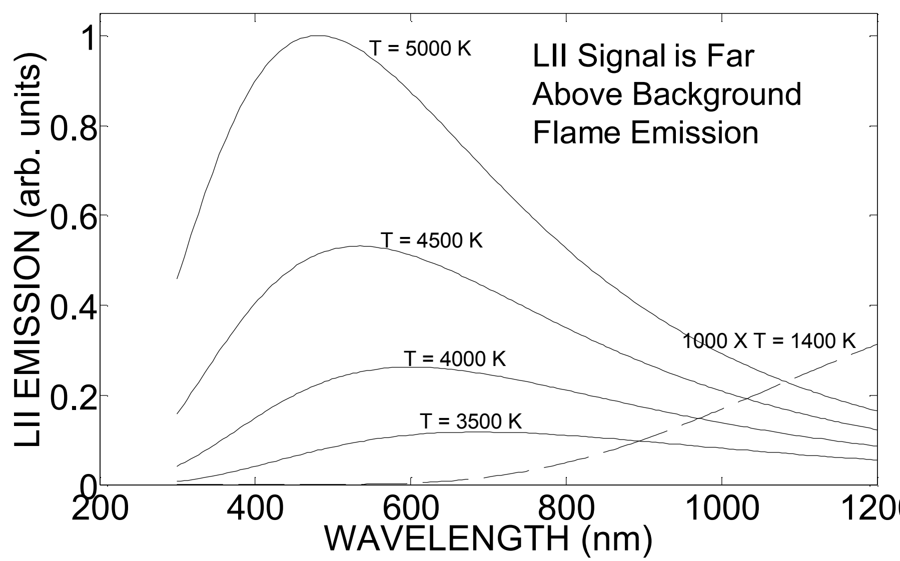


LII Experiment
(Santoro and Shaddix, 2002)

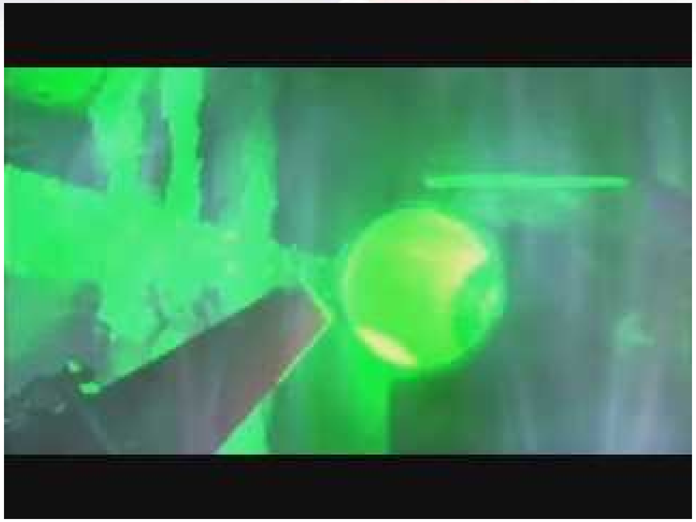
- Soot particles heated to vaporization point (4000-5000 K) by absorption of laser radiation
- Thermal emission from soot is monitored during and/or after laser pulse
  - Laser-heated soot emits in excess of background
  - Total emission ~ soot volume
- 2-D imaging
  - ns time resolution
  - 50 μm X 500 μm spatial resolution
- Calibration against light extinction or extractive sampling required

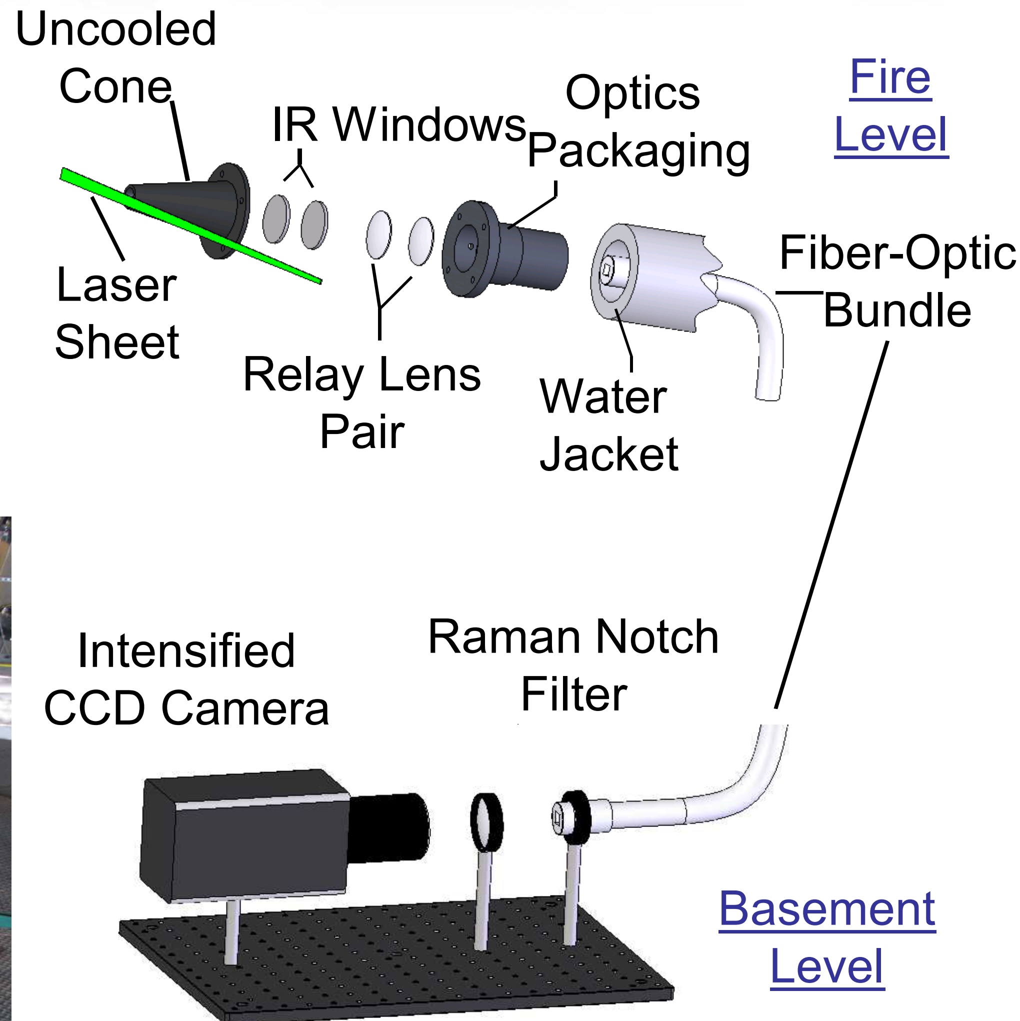


Laser-Heated Soot Particle Histories



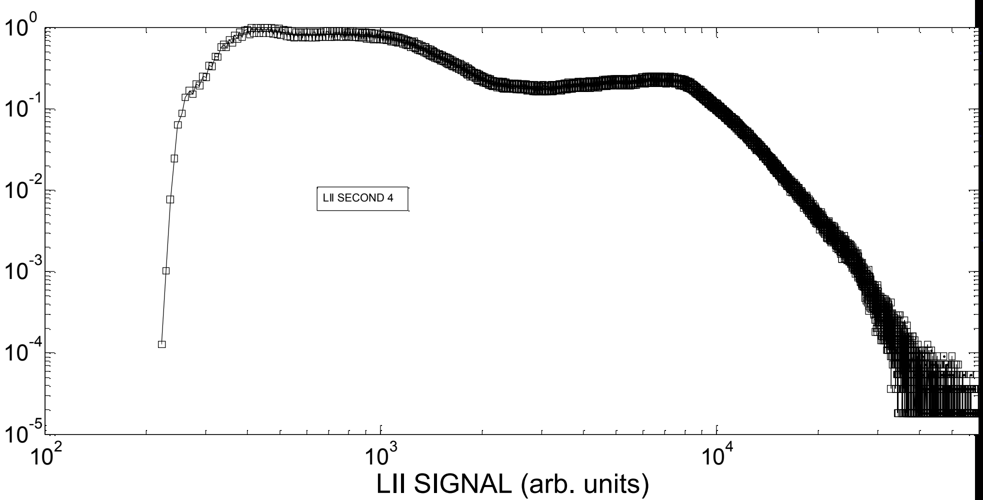
Detail of LII Laser-Sheet Imaging Probe at FLAME

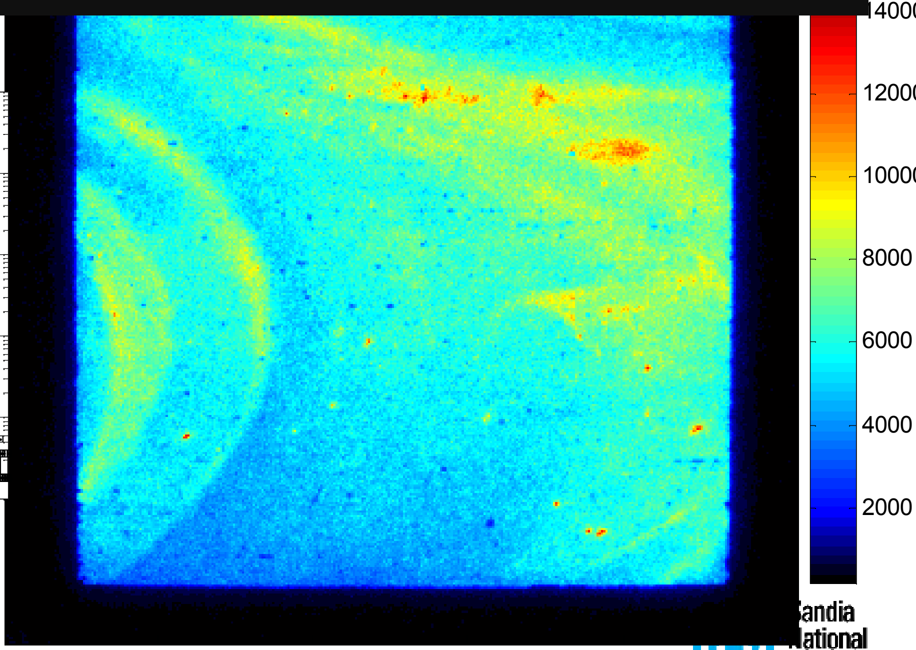




LII Data from a Methanol/Toluene Pool Fire

- LII signal is proportional to volume fraction of soot
- 50-ns exposure using intensified CCD camera
- 1-cm × 1-cm field of view coupled from center of pool fire through optical fiber bundle to detector at FLAME basement level
- Spatial resolution is ~50 μm × 50 μm × 300 μm



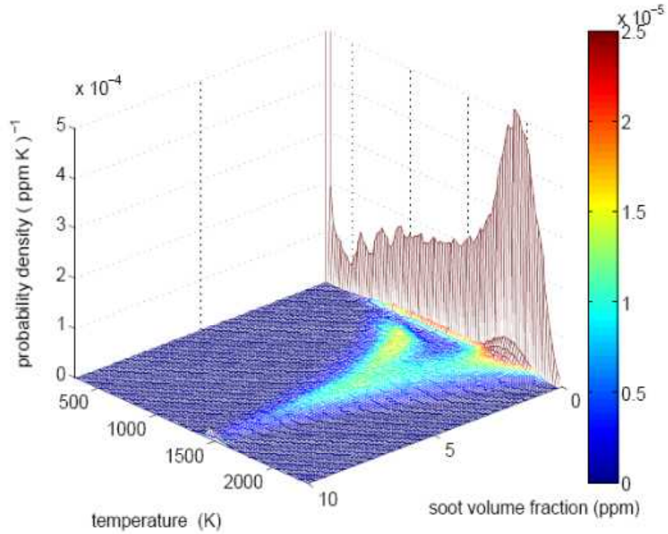


Summary and Conclusion

- The correlation between temperature and soot is dominates thermal emission from fire
- Laser diagnostics offer required mm- and ns-scale resolution and can map multiple parameters simultaneously
- A CARS diagnostic has been fielded to measure temperature (and species) pdf's at a point with ~100 μm X 5 mm X 10 ns resolution
- An LII probe has been implemented for 2-D imaging of soot with ~500 μm X 50 μm X 10 ns resolution
- We are working to combine the two measurement approaches to provide a canonical data set
- New project focuses on <u>femtosecond</u> CARS to extend capability to propellant-fueled environments

Provide experimental data

For model development: <u>joint temperature/soot pdf is needed</u>



$$P(T, f_v \mid Z; \vec{\mathbf{x}}, t)$$

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

Relevant Publications

1. 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.

2. Blanchat, T.K., T.J. O'Hern, S.P. Kearney, A.J. Ricks, and D.A. Jernigan, "Validation Experiments to Determine Radiation Partitioning of Heat Flux to an Object in a Fully Turbulent Fire," *Proceedings of the Combustion Institute* **32**, 2511-2518, 2009.

3. Kearney, S.P. and M.N. Jackson, "Dual-Pump Coherent Anti-Stokes Raman Scattering Thermometry in Heavily Sooting Flames," *AIAA Journal* **45**(12), 2947-2956, 2007.

4. Frederickson, K., S.P. Kearney, T.W. Grasser, and J.N. Castaneda, "Joint Temperature and Soot-Volume-Fraction Measurements in Turbulent Meter-Scale Fire Plumes, AIAA paper 2009-1264, *47th Aerospace Sciences Meeting and Exhibit*, Orlando, FL; Jan. 2009.

5. Frederickson, K., S.P. Kearney, A.Luketa, J.C. Hewson, and T.W. Grasser, "CARS Temperature/Oxygen Measurements in a 2-m Methanol Pool Fire and Comparison to Numerical Simulations," *Combustion Science and Technology (submitted)*, 2009.

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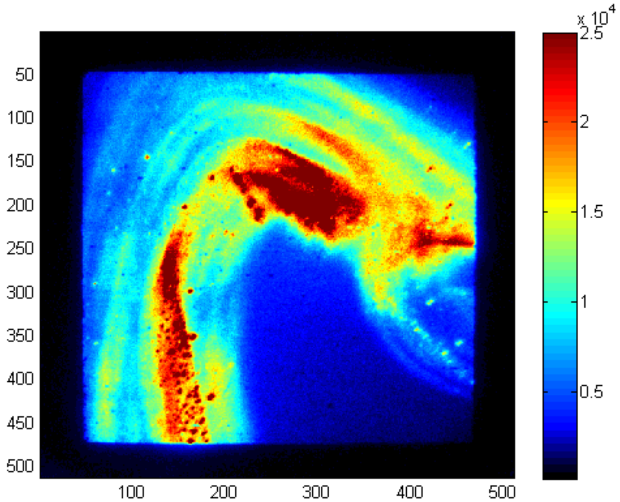
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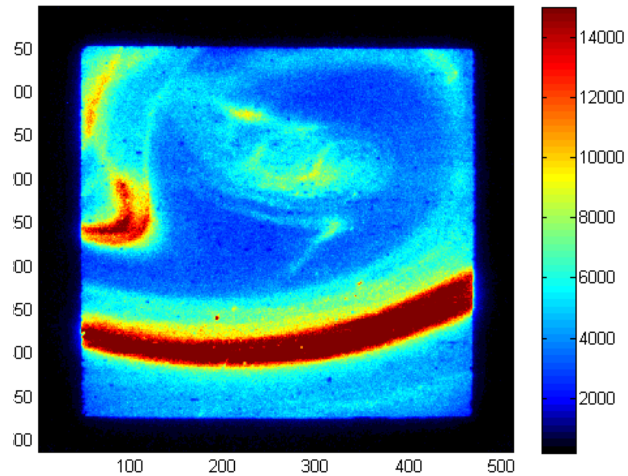
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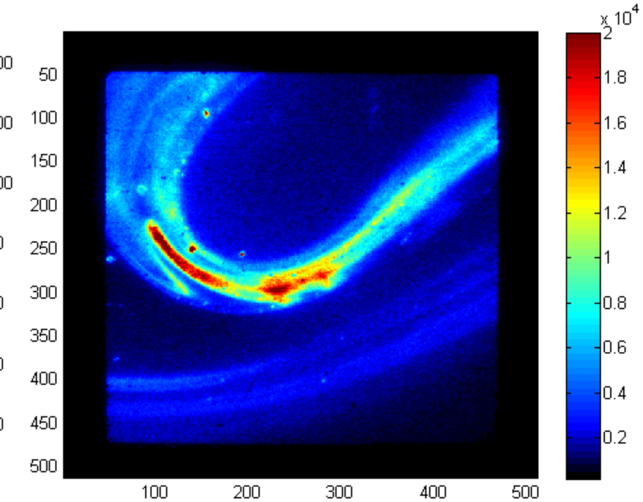
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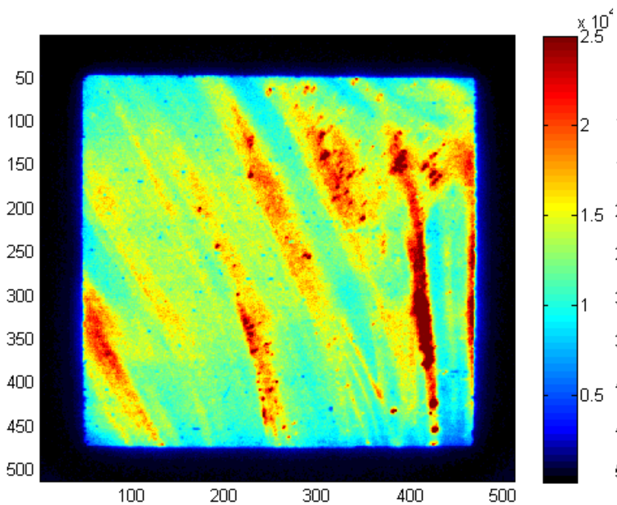
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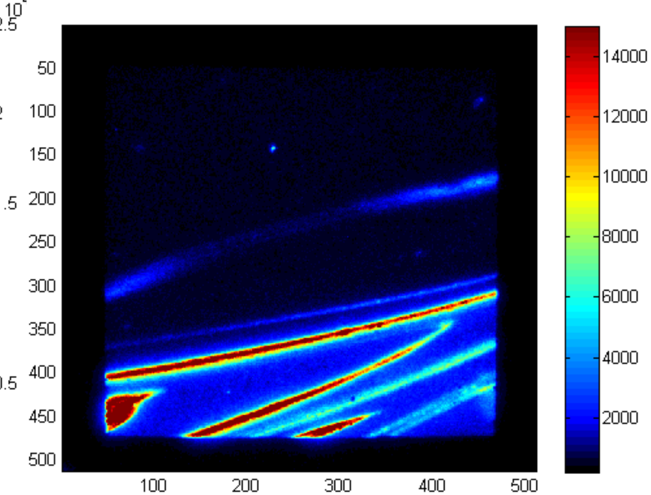
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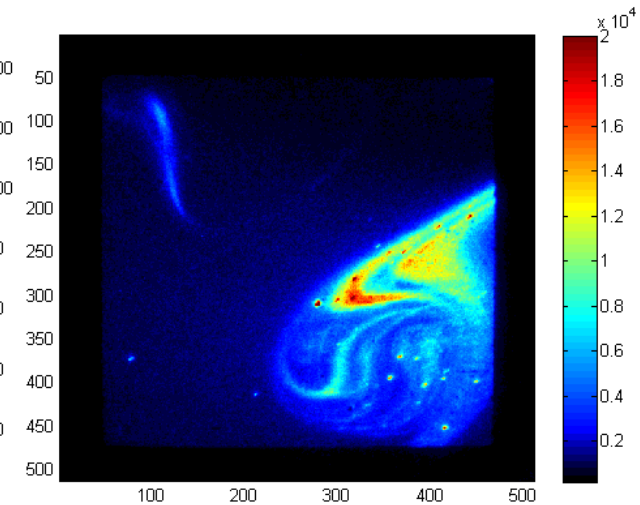
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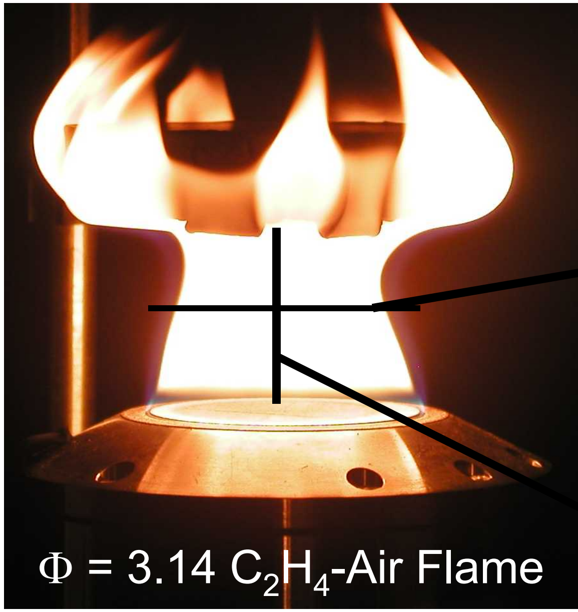
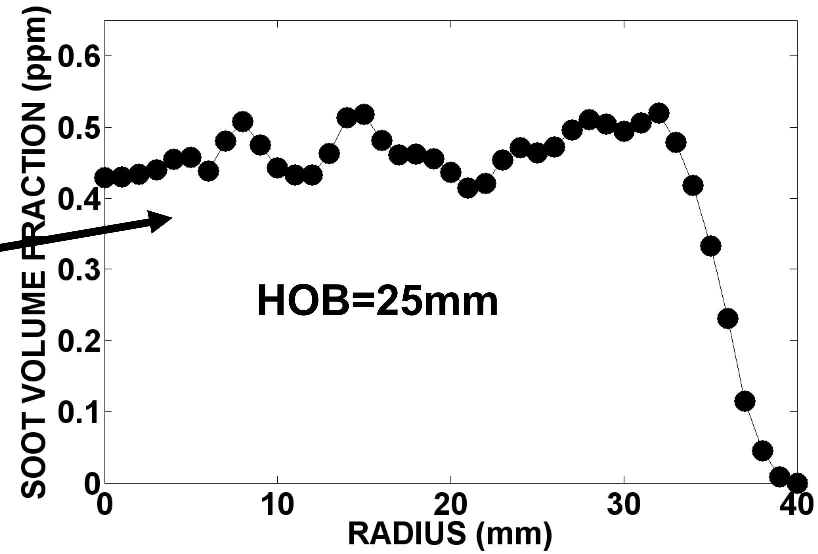
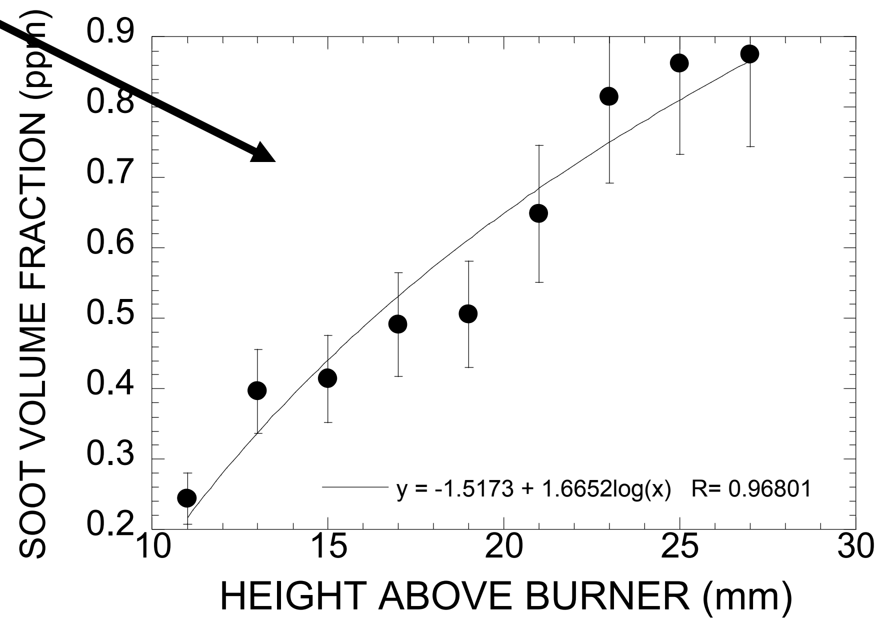
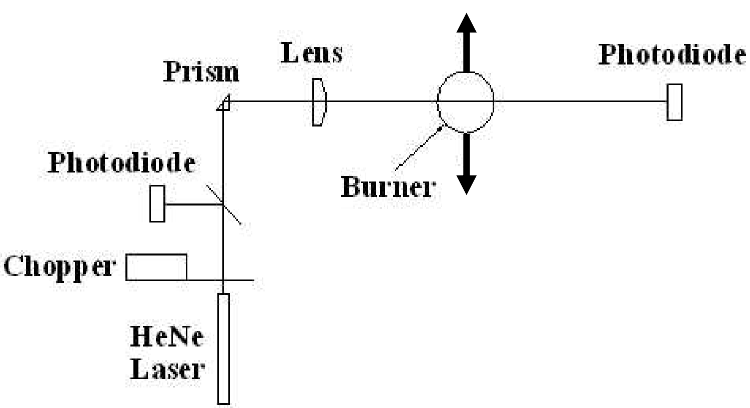
Light-Extinction Data for LII Calibraton

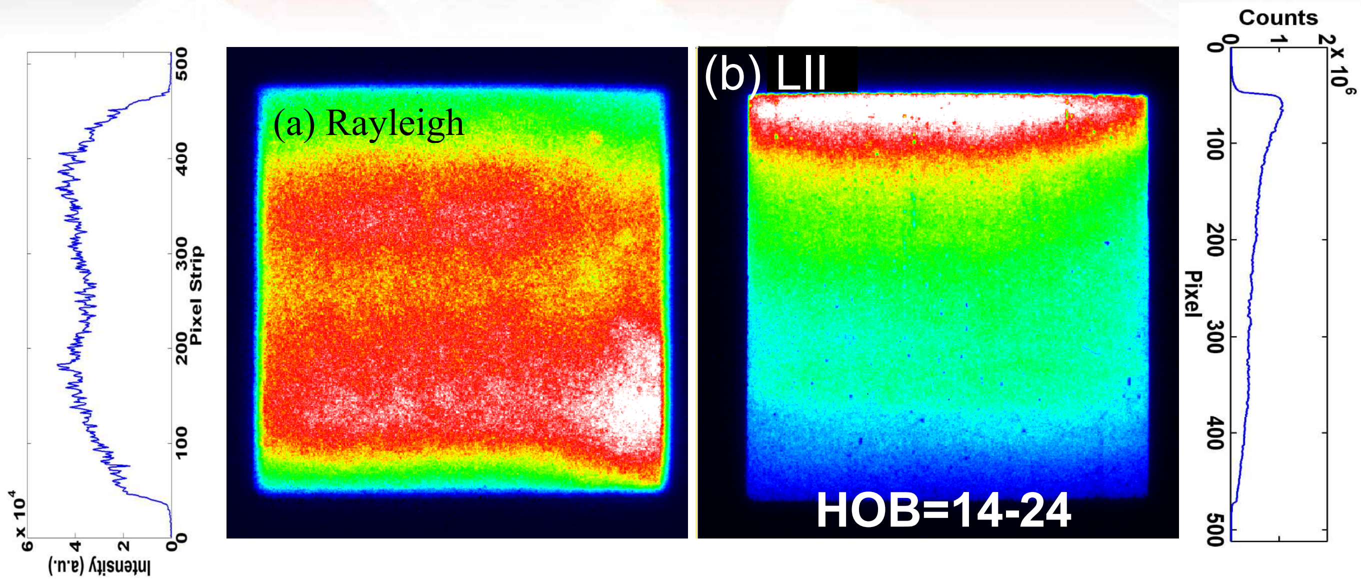


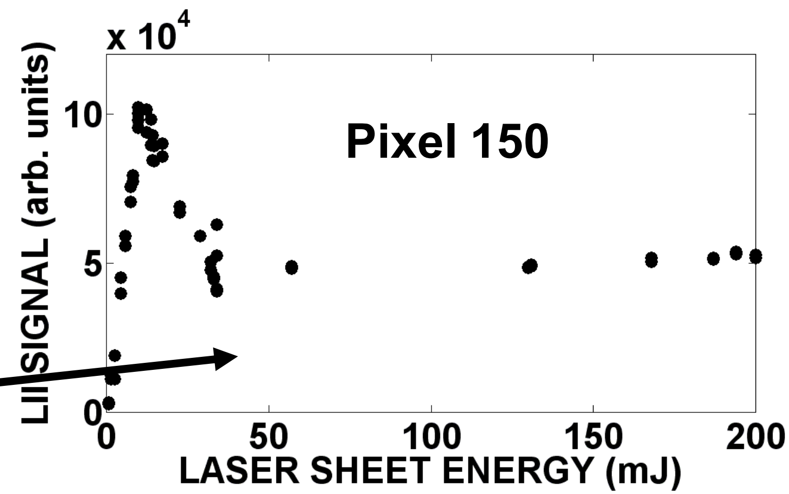






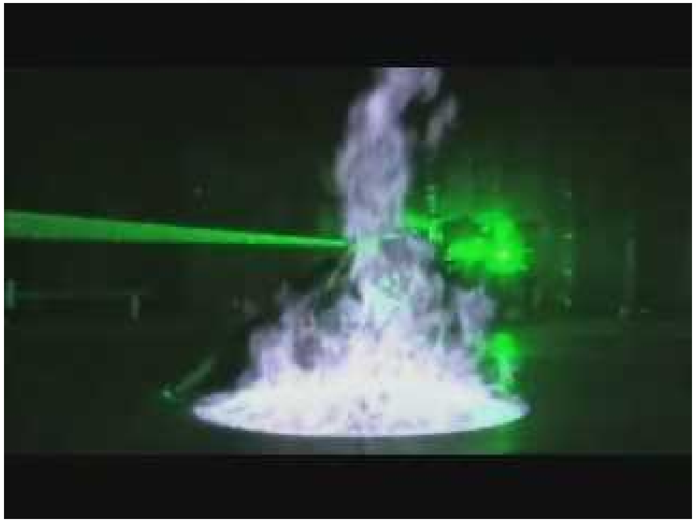
LII Calibration Images from a Premixed Flat Flame

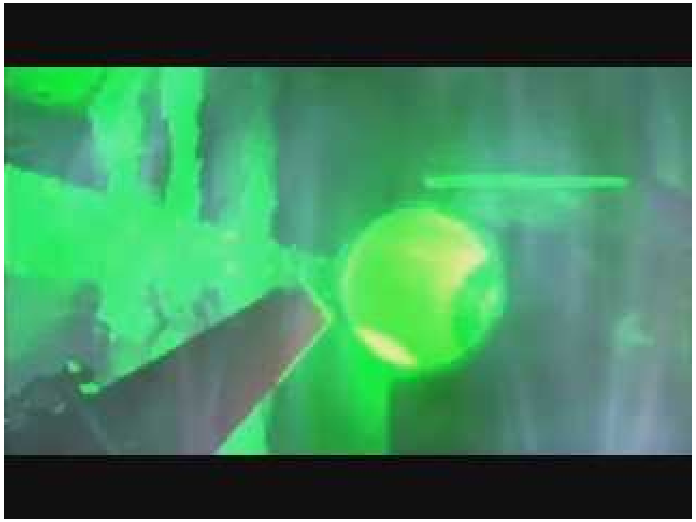




- Sensitivity of LII system calibrated using laser-extinction data
- 6000-10,000 counts/ppm
- Plateau-level response of LII to laser-sheet energy confirmed!
    - Critical for probing light-absorbing sooting fires

Video of LII and Light-Scattering Imaging Laser-Sheet Imaging Experiments





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PDF of LII signals

- LII signal is linear with soot volume fraction
- These plots reveal the shape of the soot volume-fraction pdf at the center of the pool fire
- “Clipped” pdf, low signal, high intermittency
- Must perform calibration measurements against light-extinction data, premixed flame