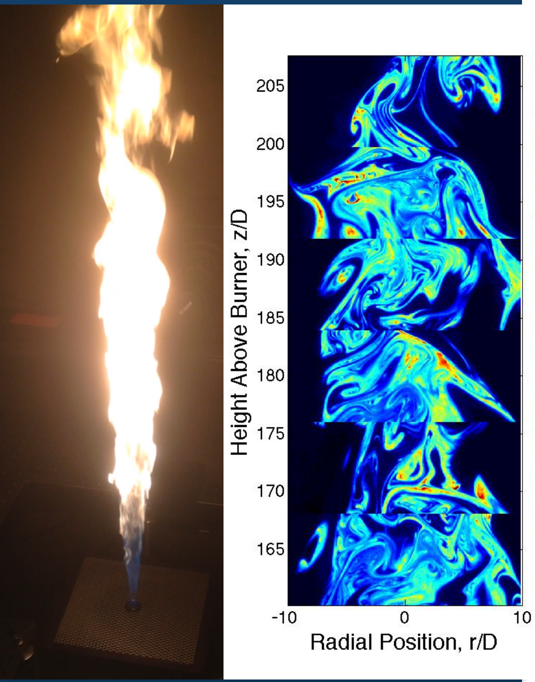
SAND2016-2512C

Hybrid fs/ps Rotational CARS Temperature/Oxygen Measurements and Soot LII Measurements in a Turbulent C_2H_4-fueled Jet Flame



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Exceptional service in the national interest

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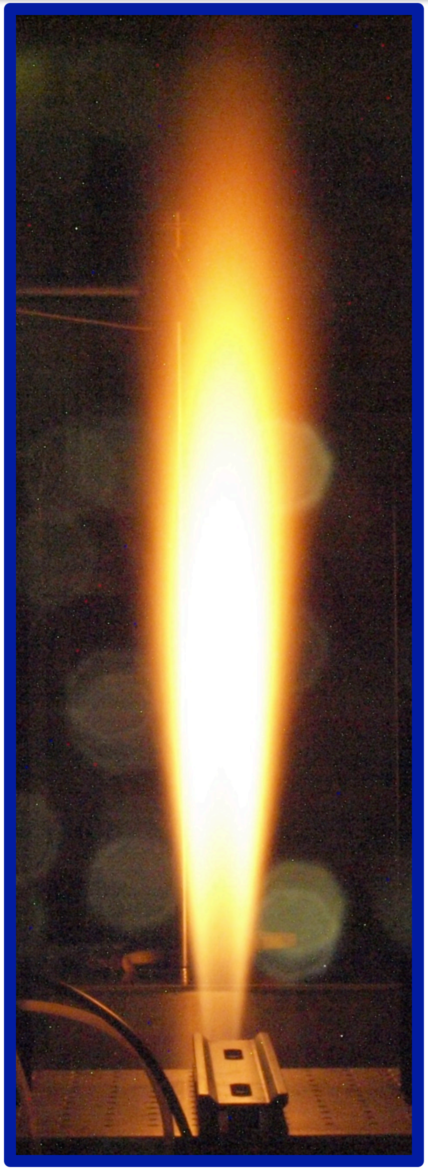
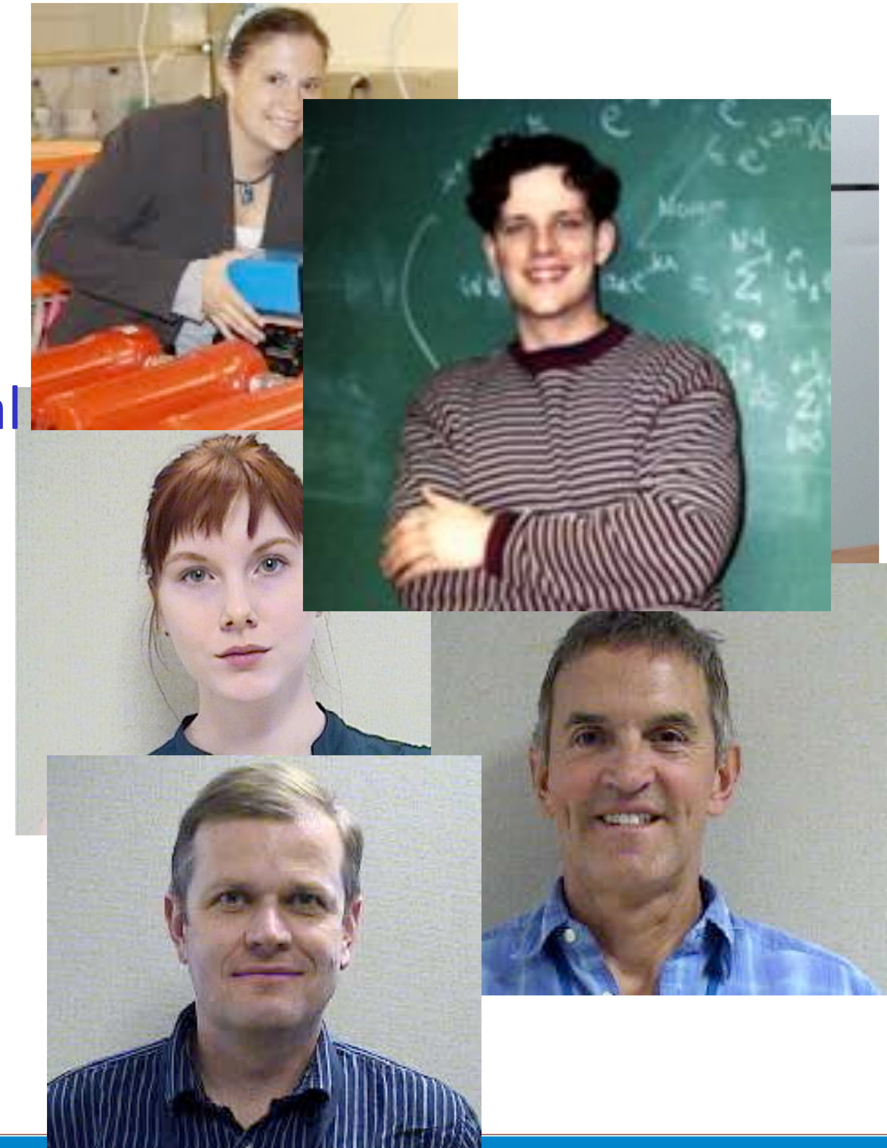
Preview

- Motivation
  - Fire thermal radiation problem
  - Laser Diagnostics
- Experiments
  - Sandia/CA piloted jet-flame burner
  - Hybrid fs/ps CARS
  - Laser-induced incandescence
- Results and Discussion
  - Mean and RMS statistics
  - Probability densities
  - Comparison to one-dimensional turbulence (ODT) simulations
- Summary, conclusions, and future work



Contributions from .....

- Kate Hoffmeister: Soot LII Measurements
- Dan Guildenbecher: Soot LII Measurements
- Caroline Winters: CARS spectral fitting
- Tom Grasser: Burner Construction/LII setup
- John Hewson: ODT Modeling



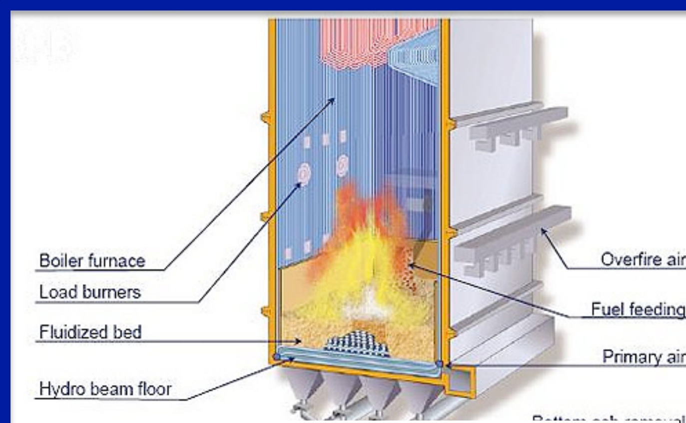
Soot impacts a wide variety of engineering applications

- ***Soot formation impacts a wide variety of combustion systems***
- ***Fire is a dominant safety threat***
- ***Propulsion and power generation systems***
- ***Emissions/environment/health***
- ***Heat transfer equipment***
  - ***Furnaces, boilers***


hydrocarbon fire safety

http://abcnews.go.com/Technology/Travel/wireStory?id=3529012


energy.sandia.gov



tubeih.com/powerstation-boiler

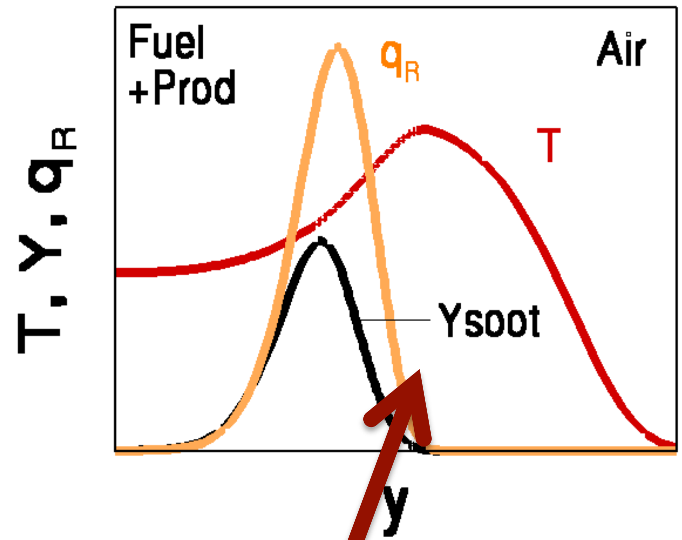
Soot radiative heat flux is the dominant risk driver in fire environments

Radiative Transfer Equation (RTE)

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

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

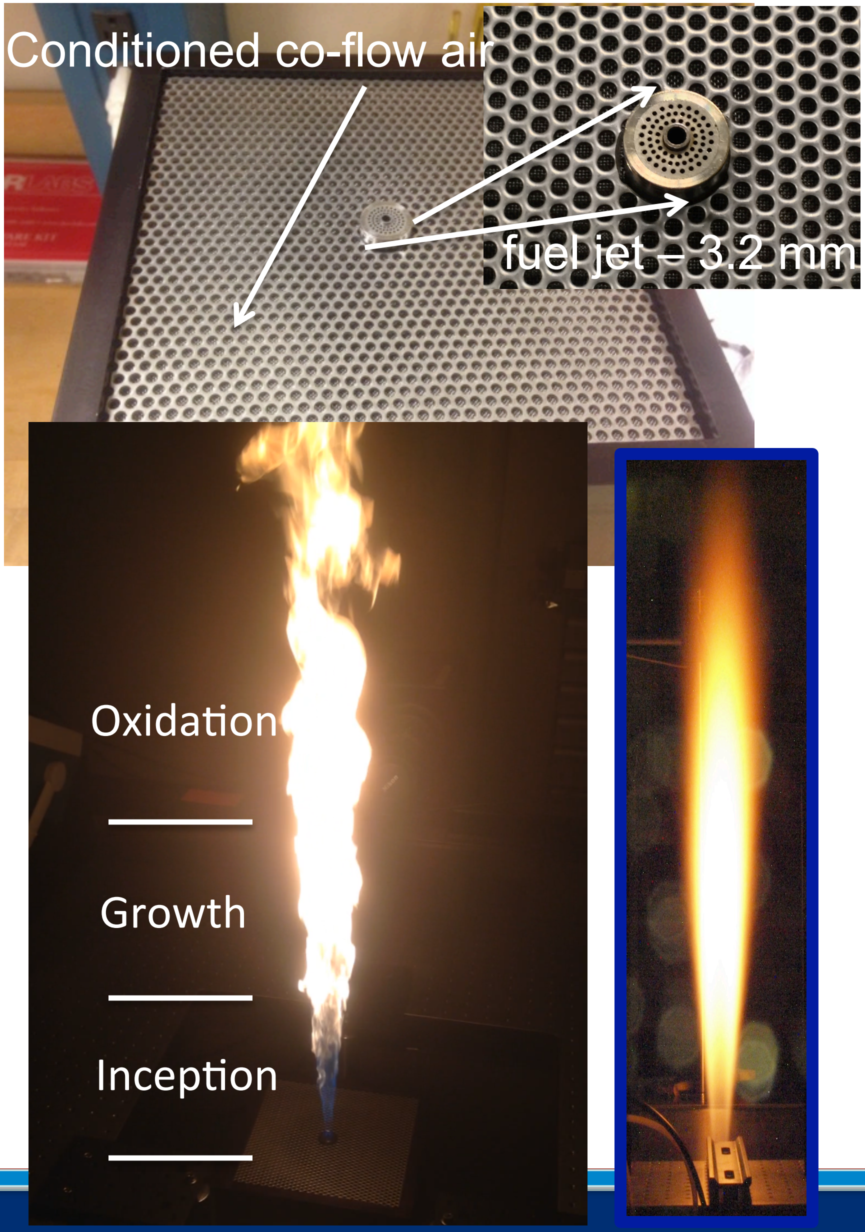
$\mu_\lambda = \dfrac{f_v}{\lambda} g(n,k)$ = soot absorption coeff.



- 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

Turbulent ethylene jet-flame burner

- *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 → 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 ~ 0.55 ppm, jet-fuel pool fire is ~ 1 ppm***

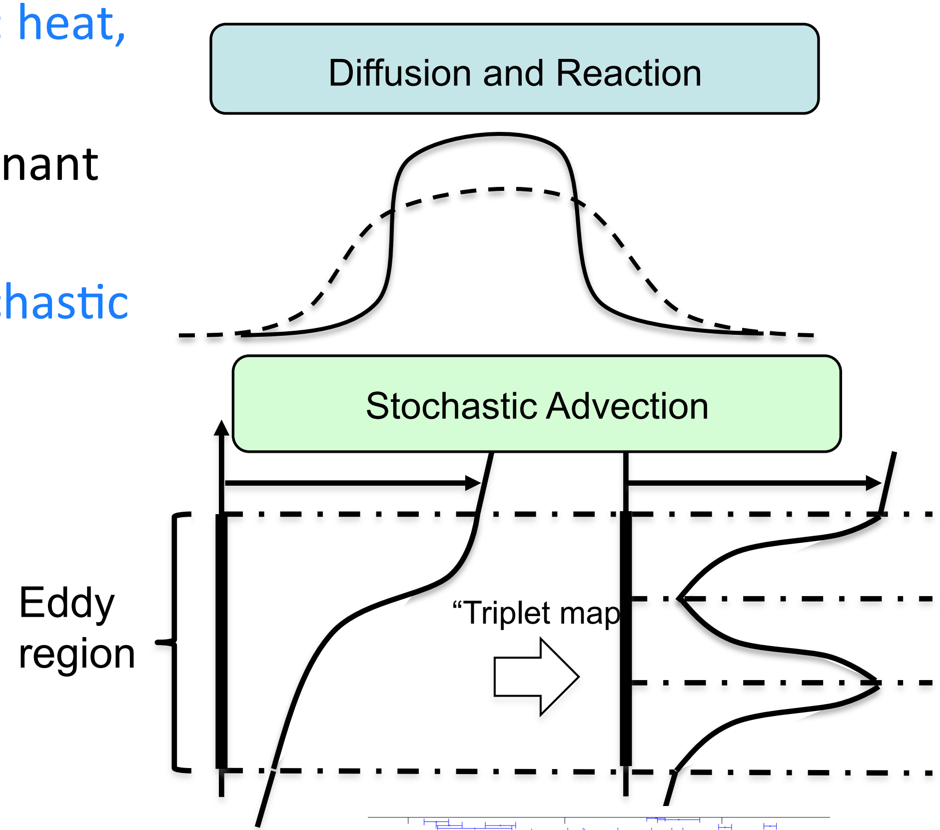


Movie of F

Abercrombie & Fitch
MADE IN USA
Casual wear for the fashionable diagnostics engineer

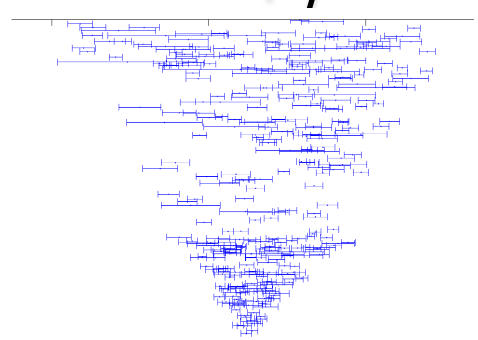
One-dimensional turbulence (ODT)

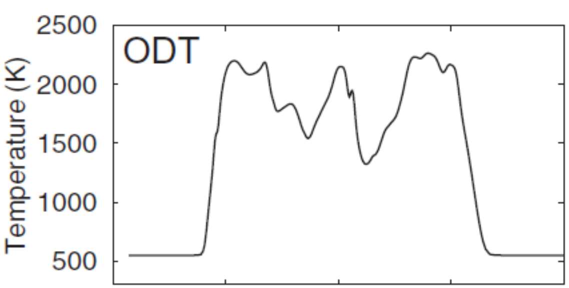
- Resolves diffusive-reactive structures: heat, species, mass, momentum.
- 1-D: line through flame or along dominant gradient
- Turbulent advection modeled via stochastic eddy events.
- Computationally affordable.
  - O(8) hr per realization
  - O(100) realizations for statistics

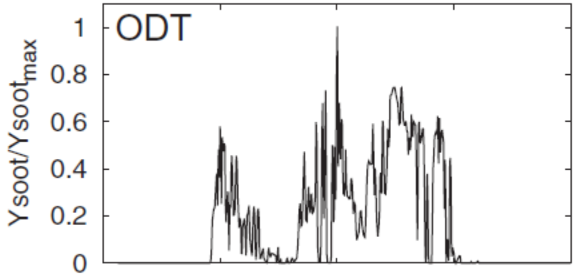


Vary soot production rates to match LII results in soot-growth region

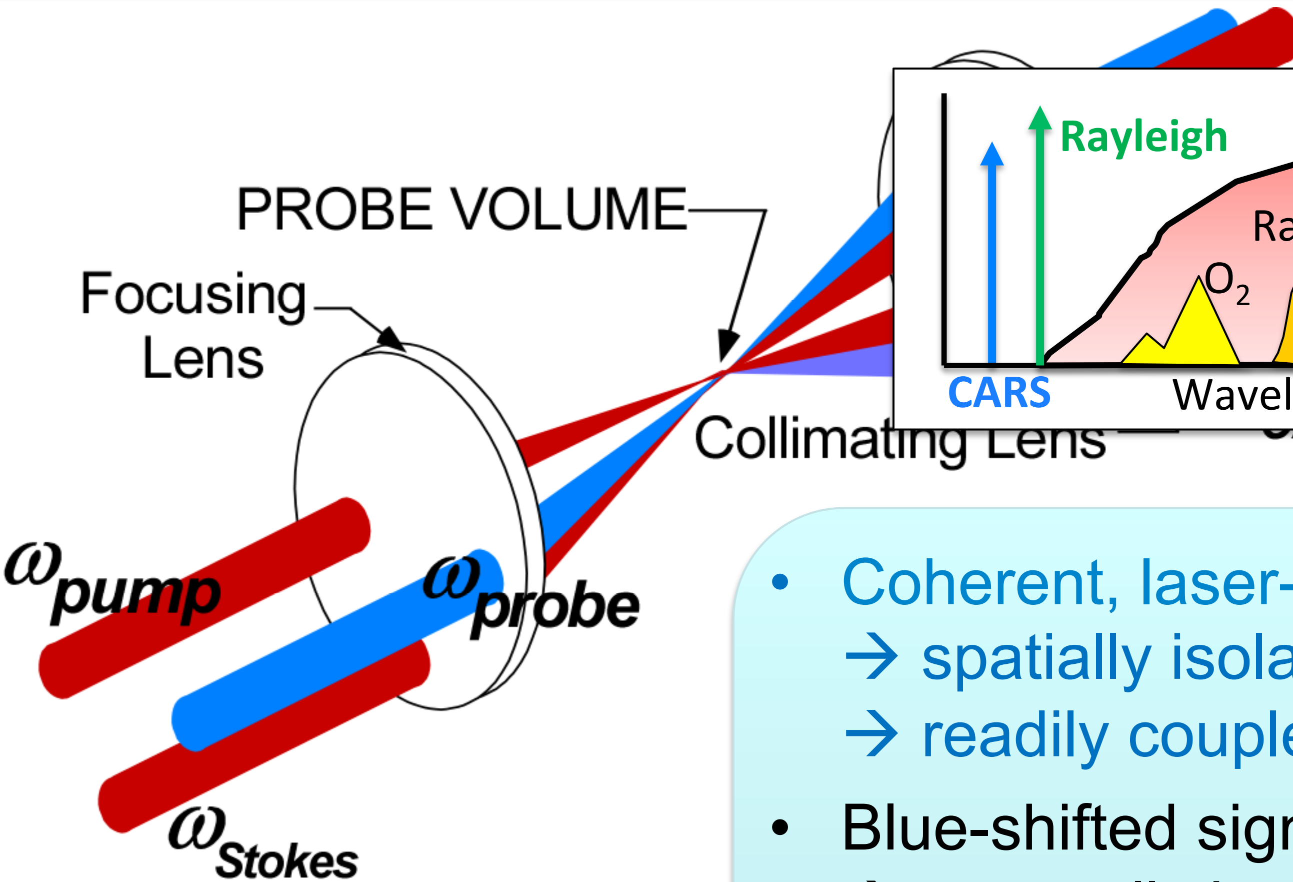
- Leung and Lindstedt soot model

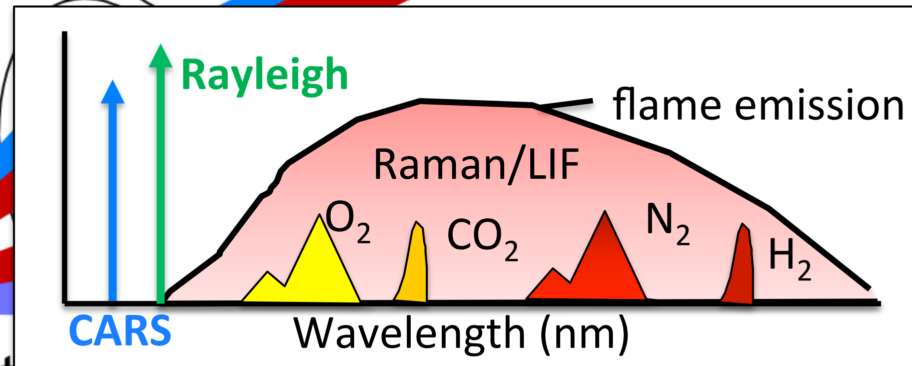






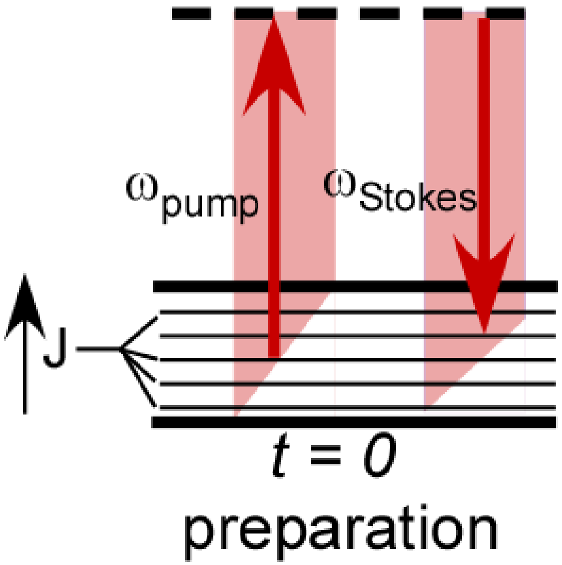
Coherent anti-Stokes Raman Scattering (CARS)

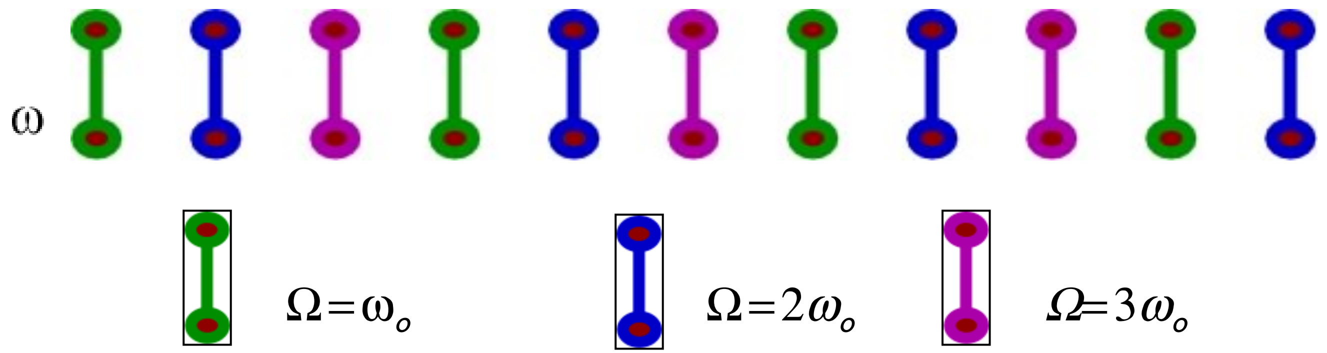




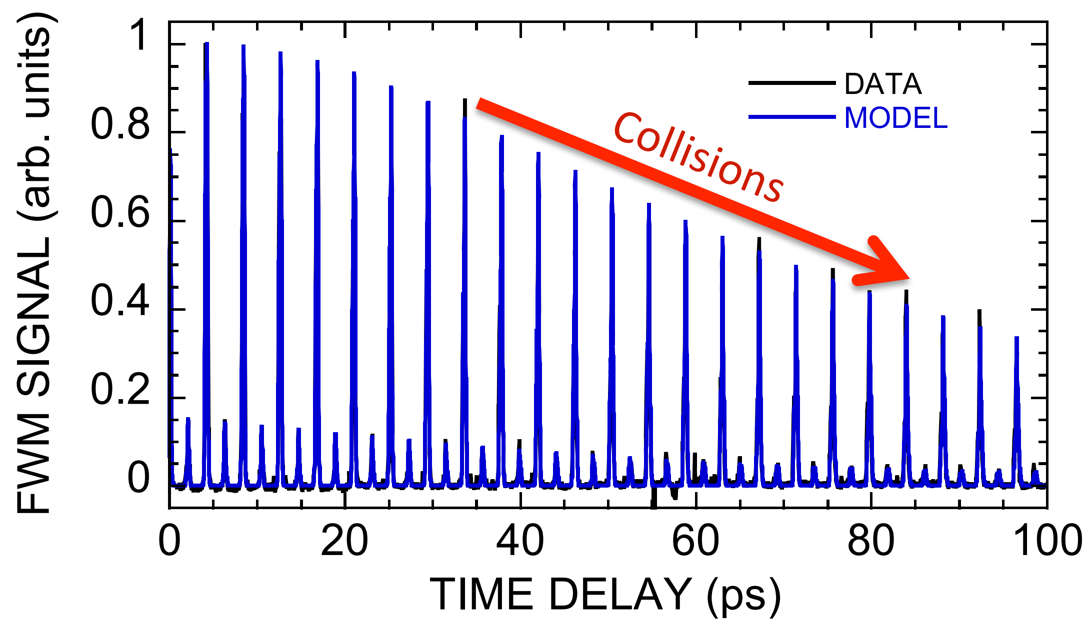
- Coherent, laser-like signal beam
  → spatially isolated
  → readily coupled to fibers
- Blue-shifted signal beam
  → spectrally isolated
- Orders of magnitude stronger than incoherent scattering

fs/ps Rotational CARS processes

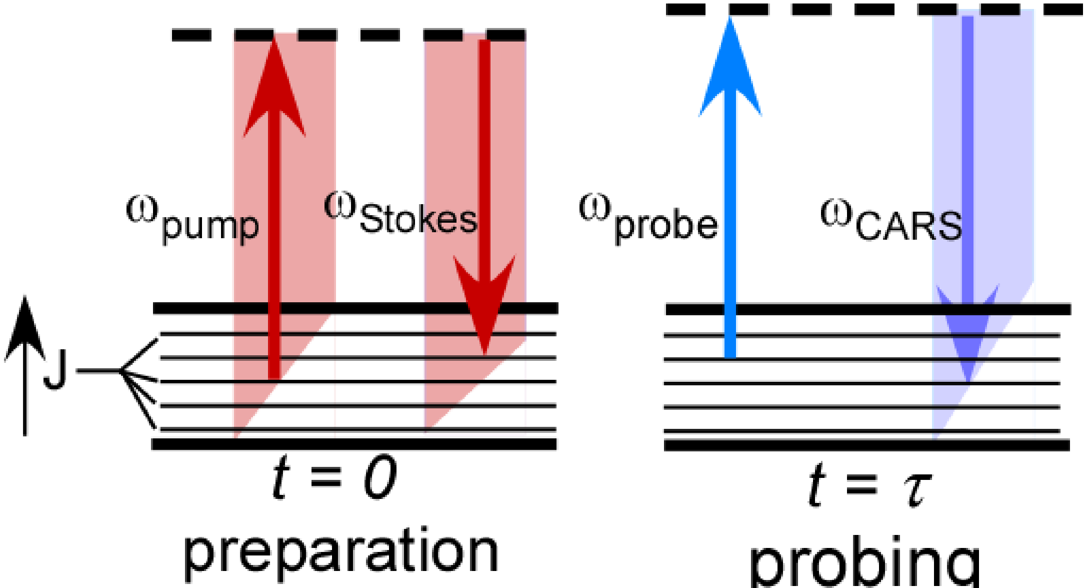


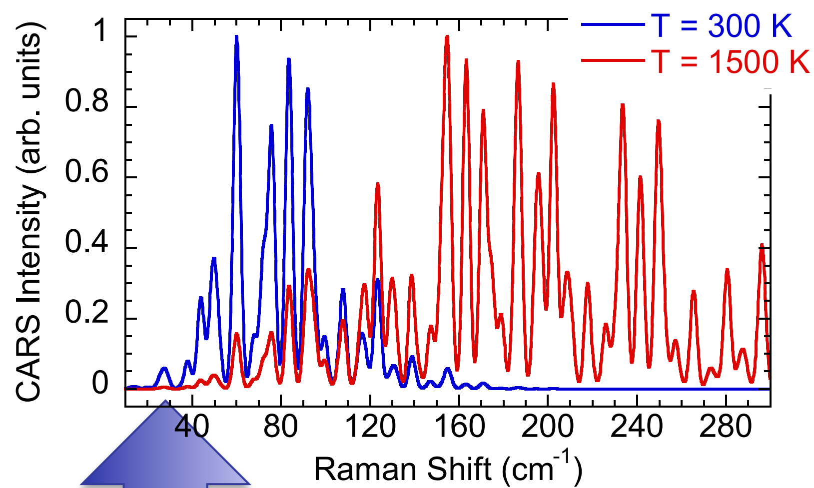


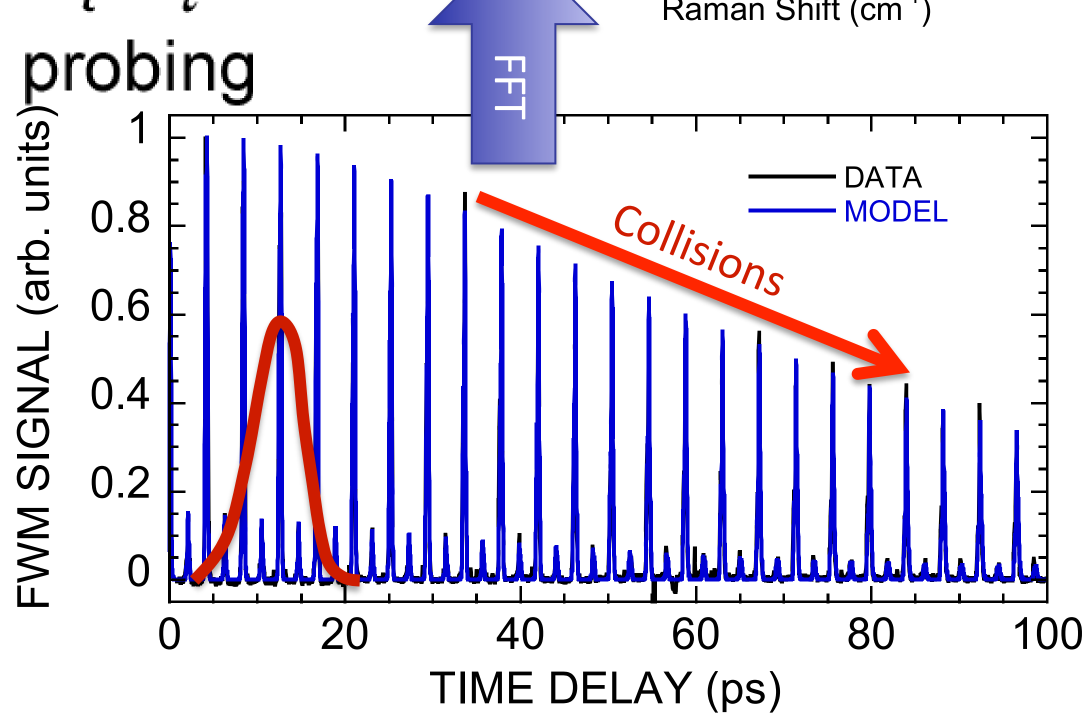
$$\chi = \sum_J W_J \exp(i\,\omega_J t)\exp(-\Gamma_J\, t)$$



fs/ps Rotational CARS processes







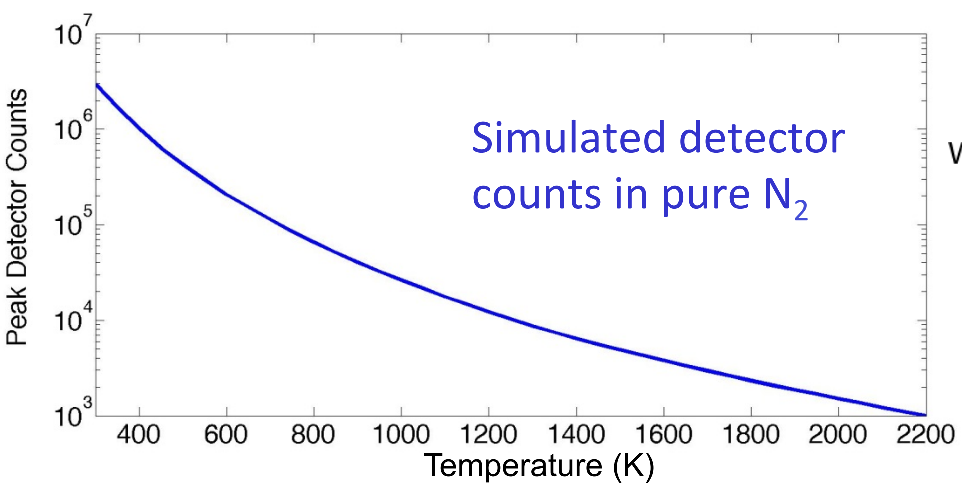
$$\chi = \sum_J W_J \exp(i\omega_J t)\exp(-\Gamma_J t)$$

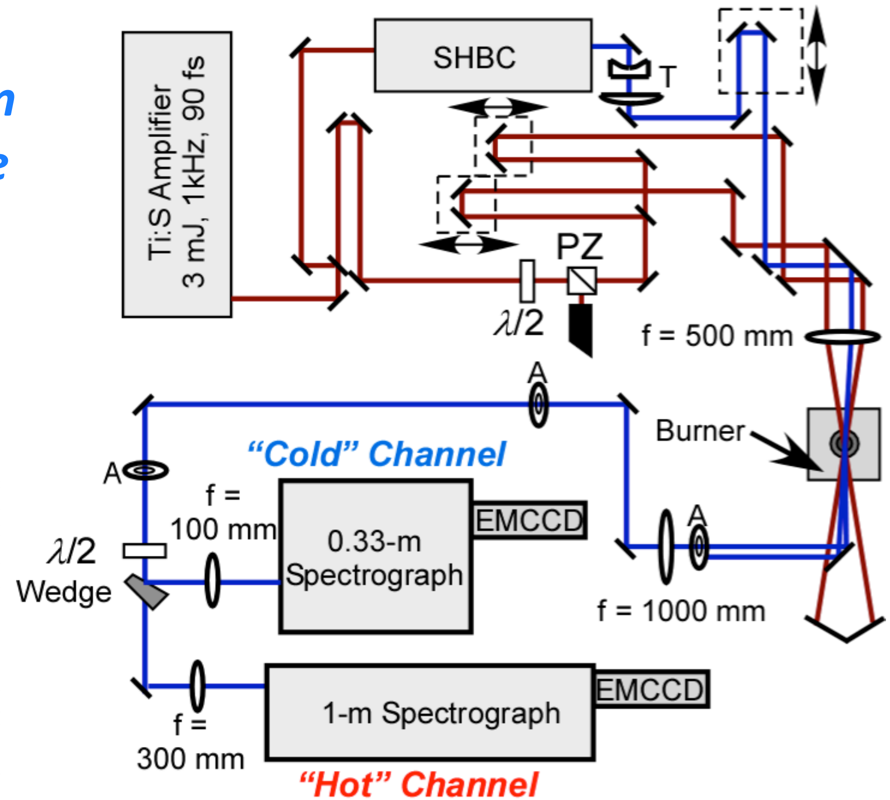
$$E_{CARS}(t-\tau) = E_{probe}(t-\tau)\times\chi(t)$$

$$\boxed{W_J = X\gamma^2 b_{JJ'}(N_{J'} - N_J) \qquad \frac{N_J}{N} \sim \frac{1}{T}\exp(-\varepsilon_J/kT)}$$

Two-channel CARS instrument for enhanced dynamic range

- ***CARS signal strength varies by ~3 orders of magnitude between room and flame temperatures***
- ***The highly fluctuating temperatures in turbulent flames make dynamic range a challenge***
- ***Two-channel detection system implemented***



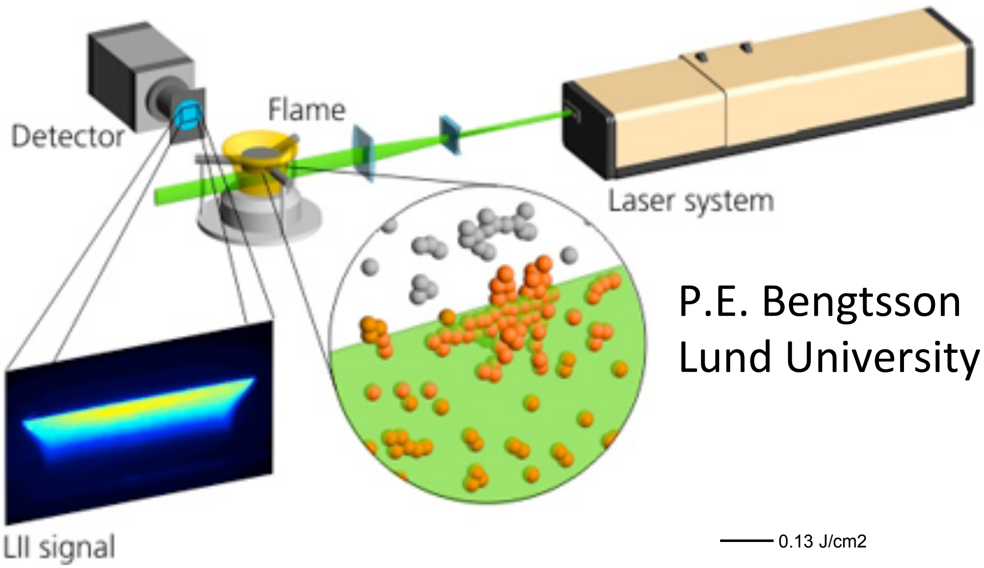


Laser-Induced Incandescence (LII)

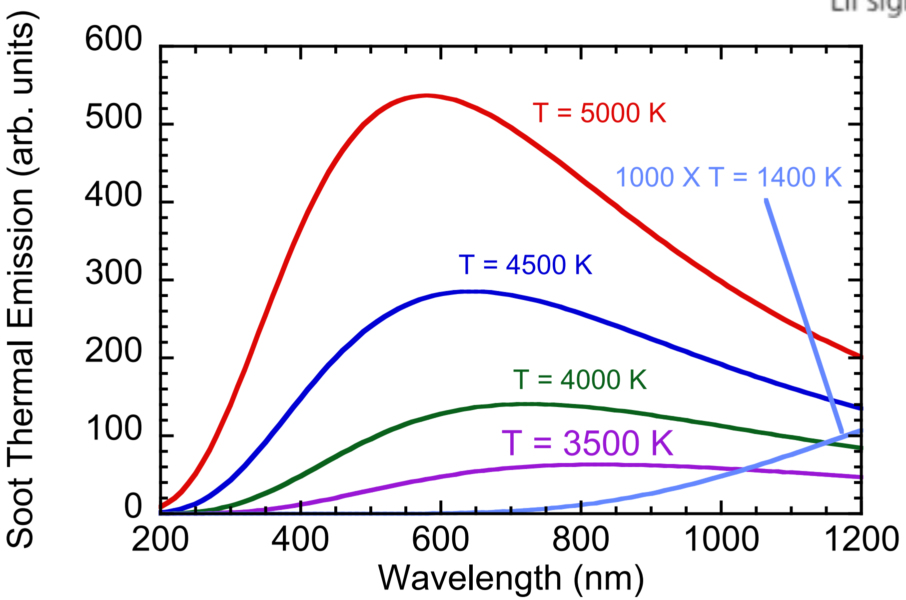
- Nd:YAG laser at 1064 nm
- Rapid heating of soot particles ***above background***
- For nm-scale soot primary particles

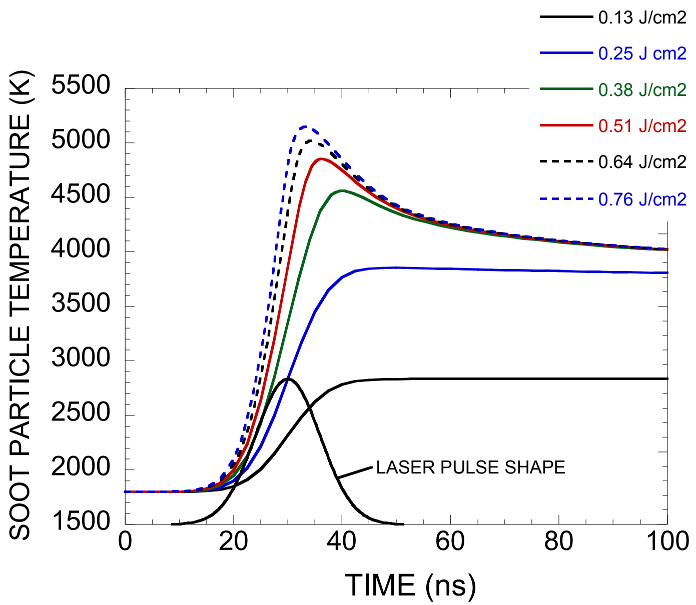
$$S_{LII} \sim d_p^3$$

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



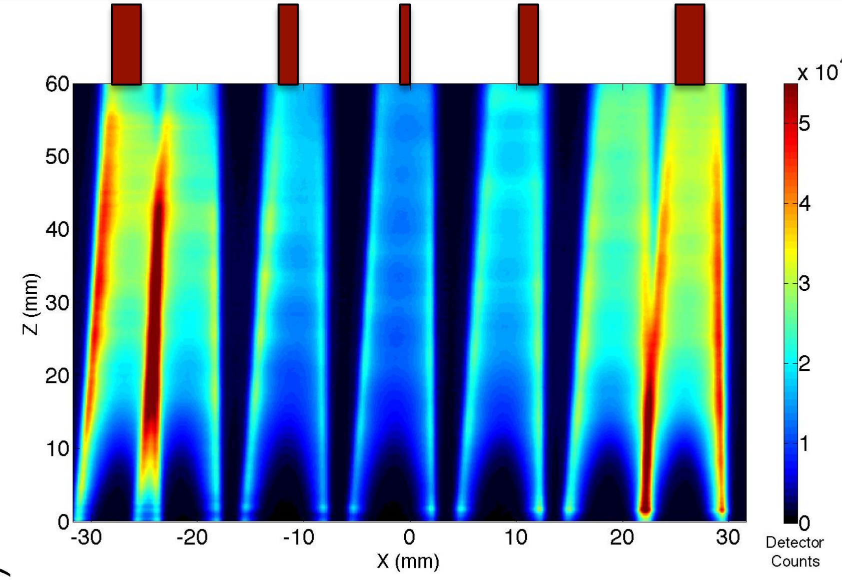
P.E. Bengtsson
Lund University



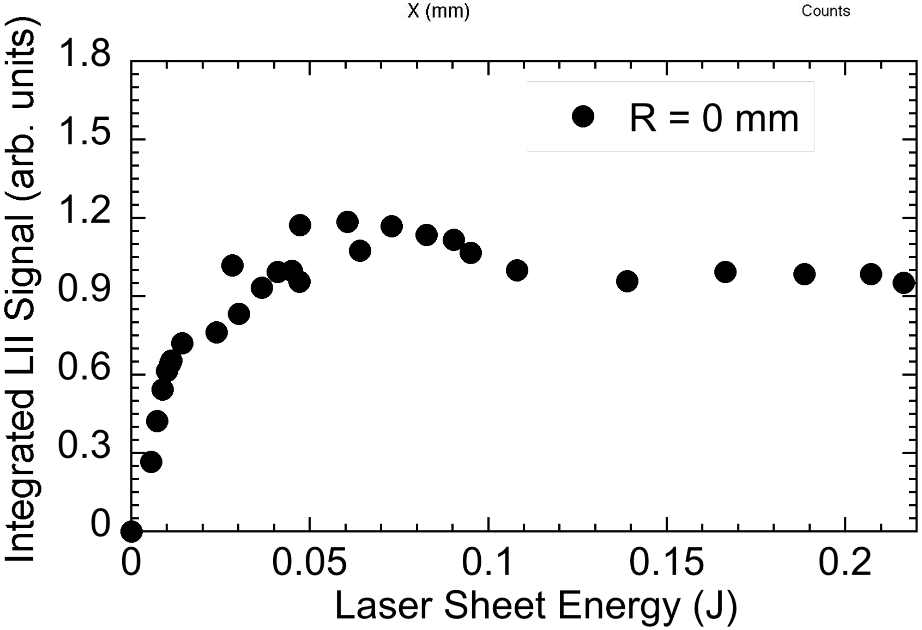


Collection of LII over a wide field of view presents challenges

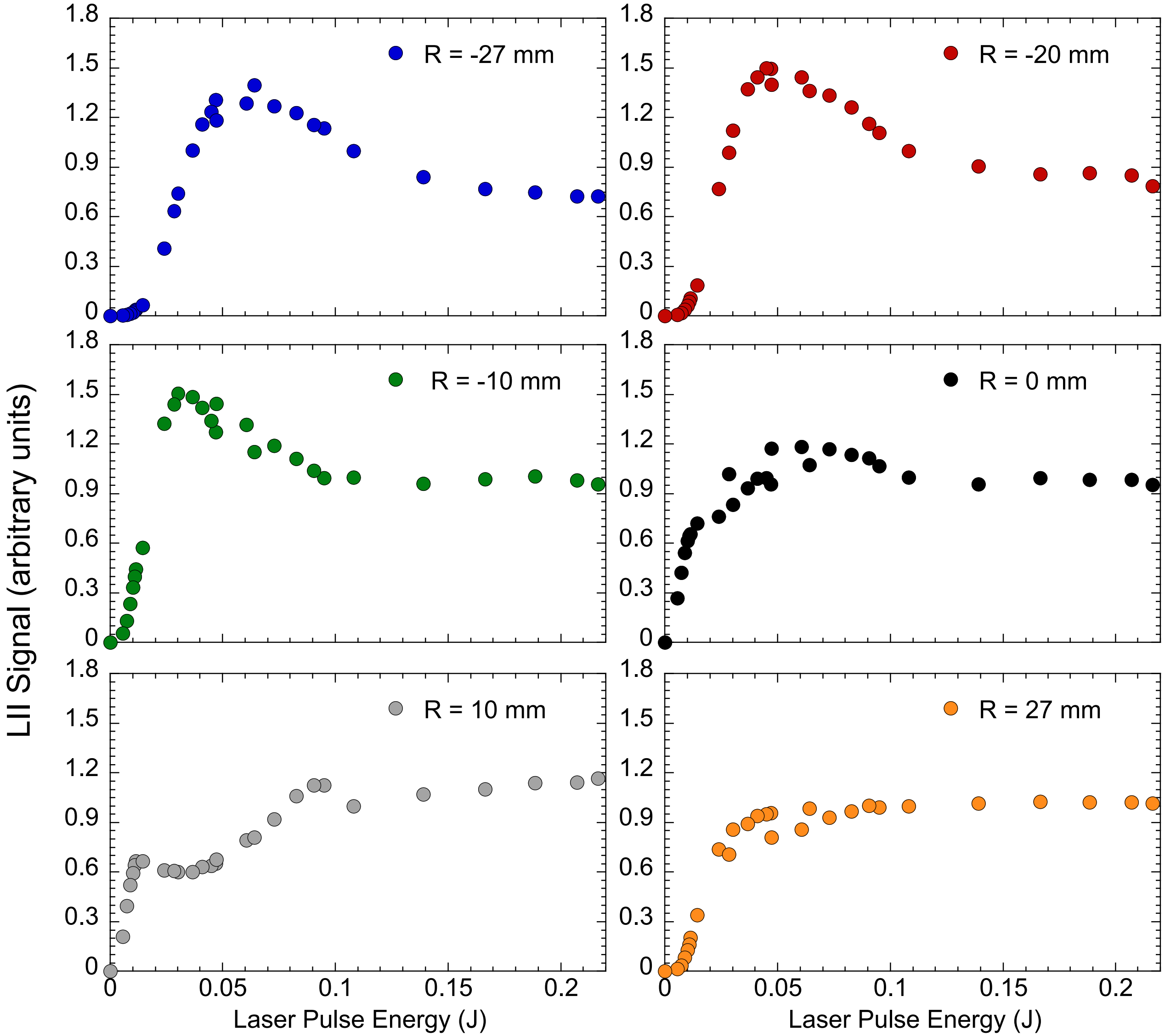
- Jet flame width > 60 mm
- Much larger than beam waist
- Laser sheet thickness varies
    - Measurement volume size
    - Laser sheet fluence (J/cm^2)
    - LII calibration response



- Absorption of laser sheet energy by soot could be 25% or more
- ***<u>"Plateau-level" LII</u>*** is required!
- Dependent on beam profile
    - Vaporization losses @center
    - Increased contribution from edges



A plateau level response was confirmed across the full field of view



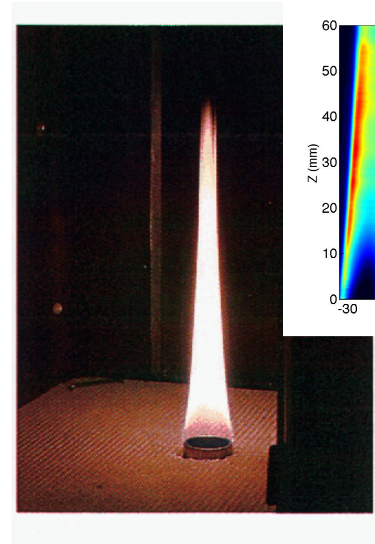
LII signal was calibrated to soot f_v in a laminar diffusion flame

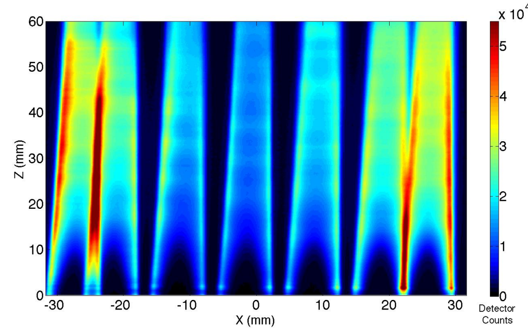
- Santoro-type C_2H_4 laminar flame
- Light extinction measured @1064 nm using apertured laser sheet
- Compared to LII signal monitored simultaneously

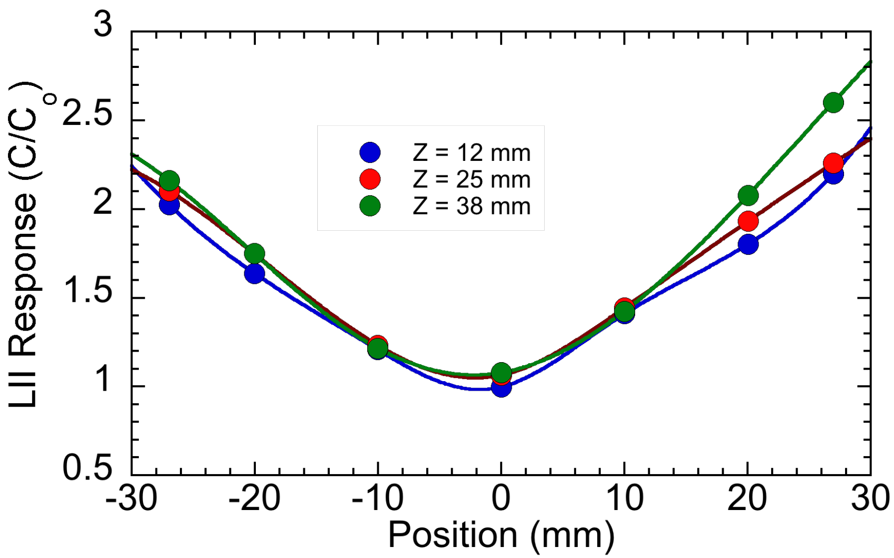
$$\frac{I}{I_o} = \exp\left(-\frac{K_e f_v}{\lambda} L\right) \qquad f_v = C\, S_{LII}$$

$$\boxed{C = -\frac{\lambda}{K_e} \frac{\log\left(I/I_o\right)}{\int_0^L S_{LII}(x)\,dx}}$$

- Translate burner to find spatial dependence of *C*







ging Results

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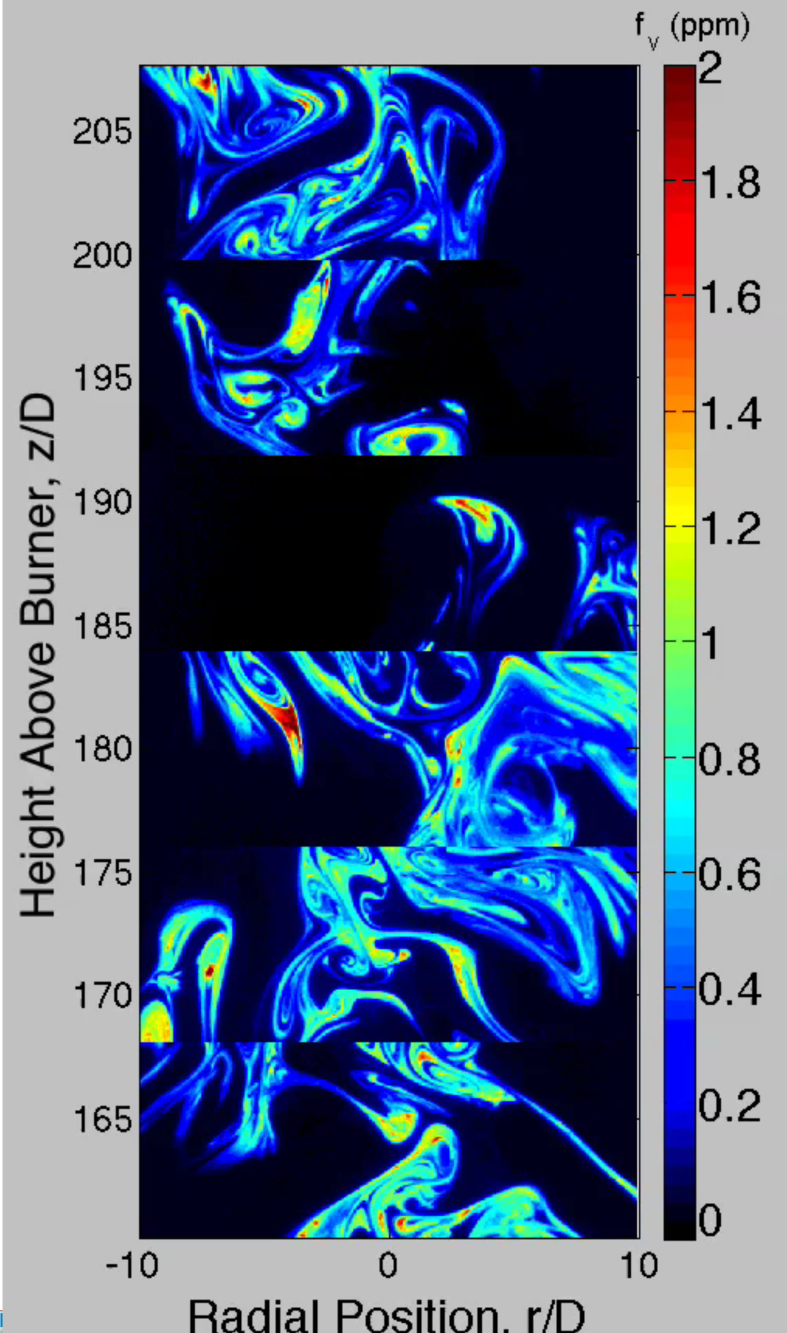
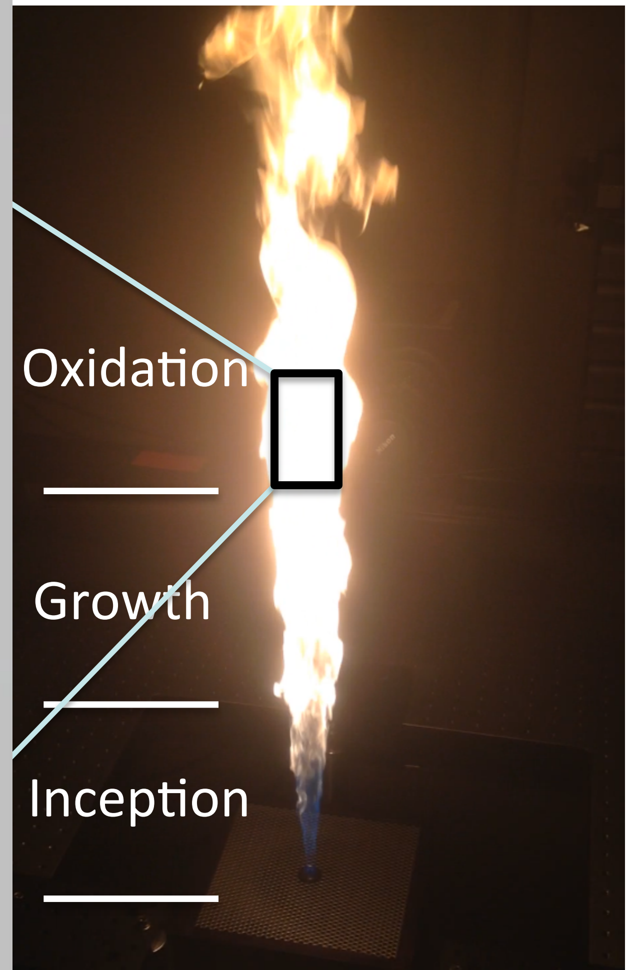
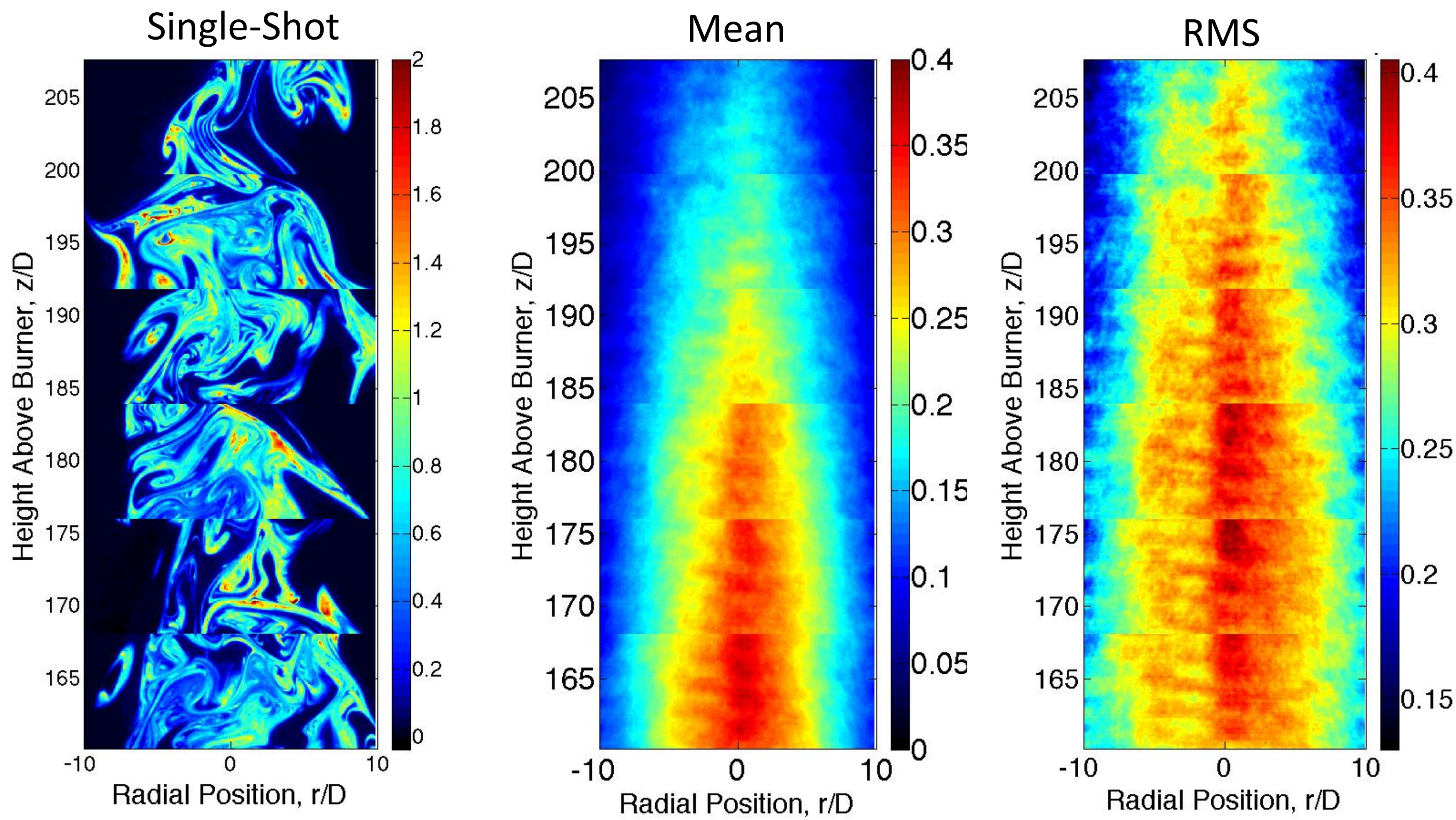




- 2000 single-shot images
- 6 panels each 7.7*D* in height
- In-plane resolution = 124 μm
- Out-of-plane resolution ~200-450 μm
- ***Intermittent*** turbulent fluctuations
- High probability of zero soot (black)
- Peak fluctuations of 1-3 ppm

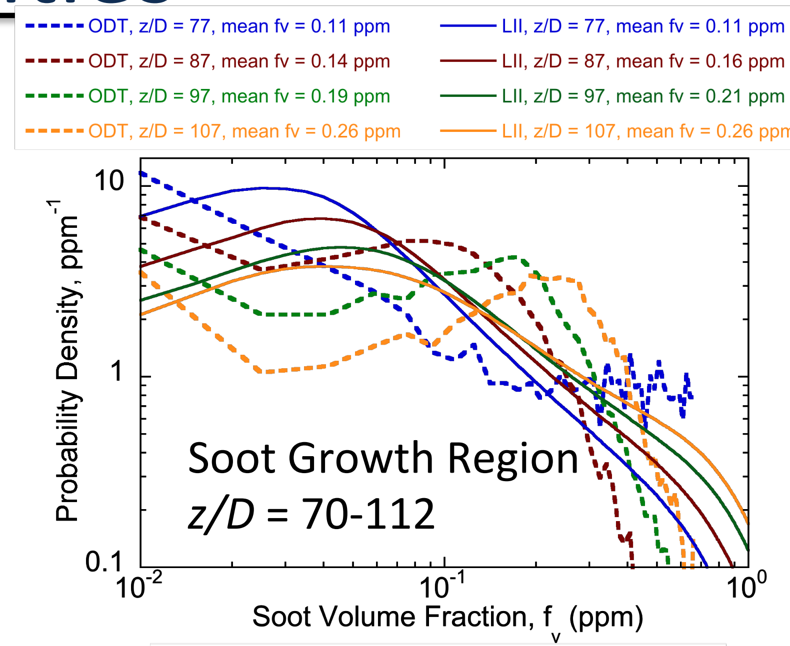
2-D Soot f_v Imaging Results



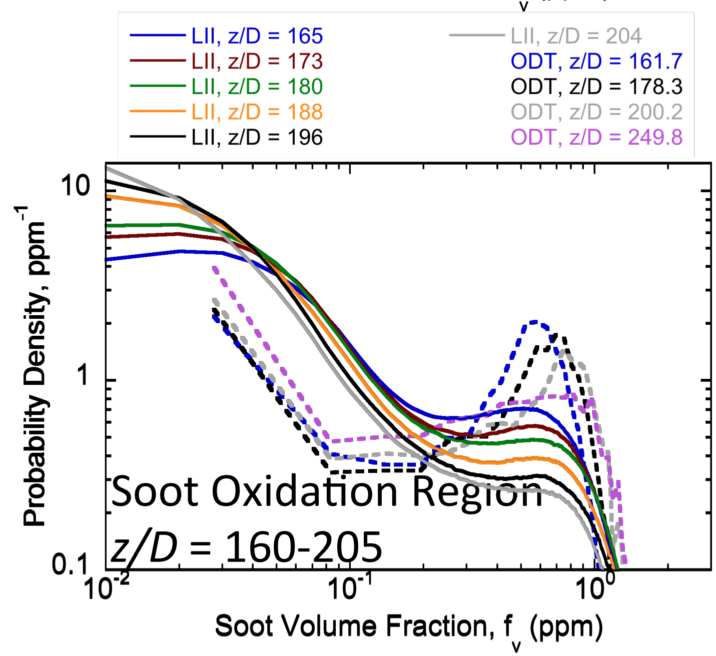
- Peak centerline mean f_v = 0.35-0.37 ppm
  - 20% lower than measured by Shaddix *et al.*
  - Signal trapping correction to be made (~12%)

Soot Probability Densities

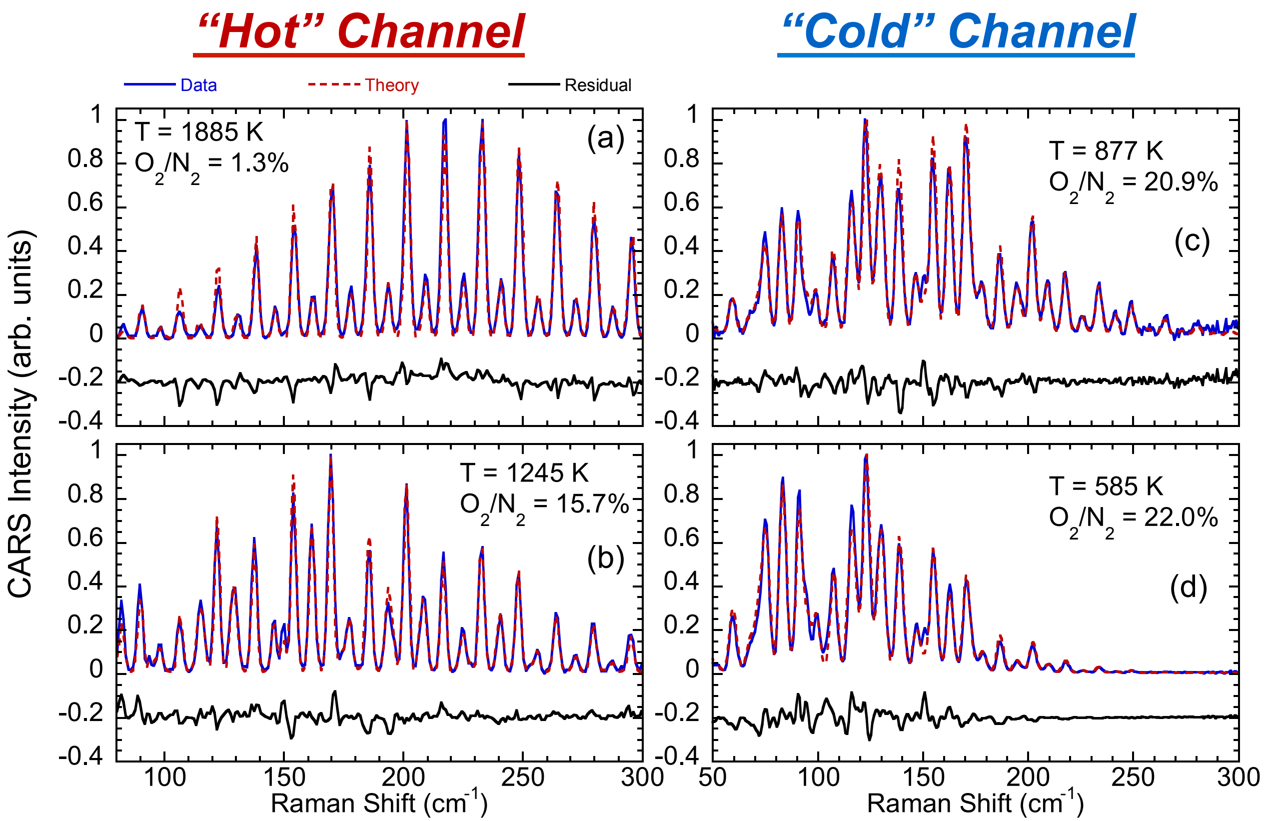
- Additional LII measurements conducted in ***<u>soot growth</u>*** zone
- ODT soot production term calibrated to growth-zone LII



- "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



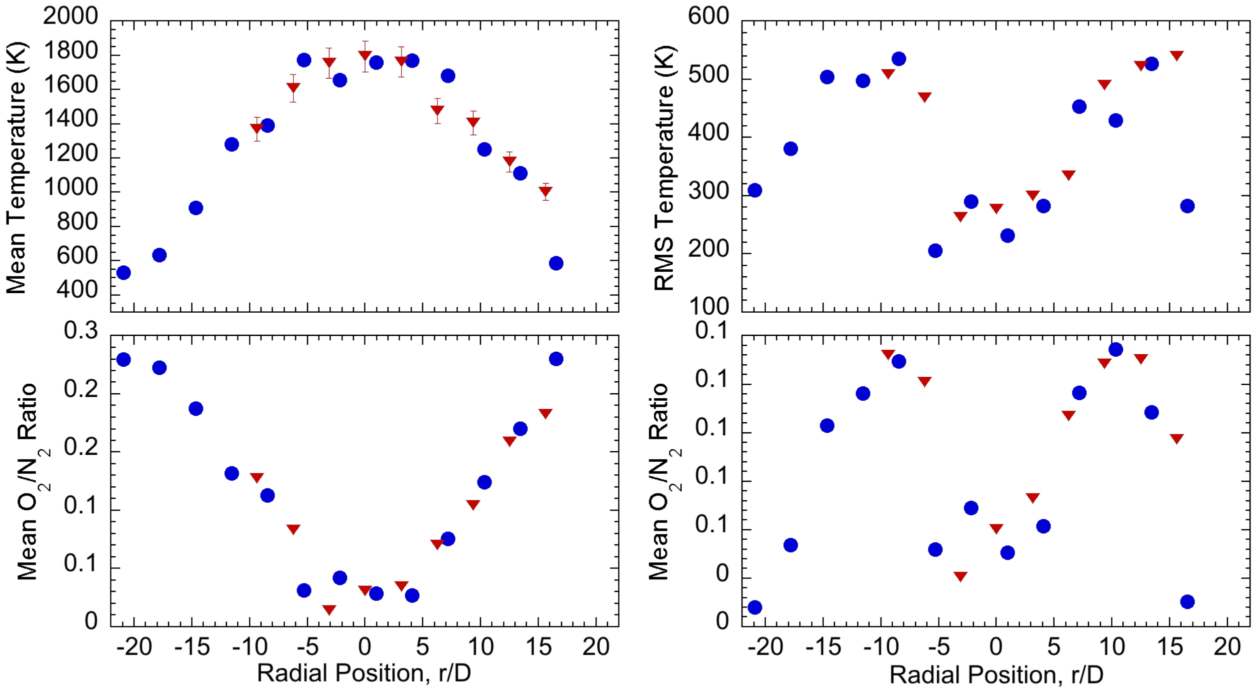
fs/ps CARS spectra at jet centerline

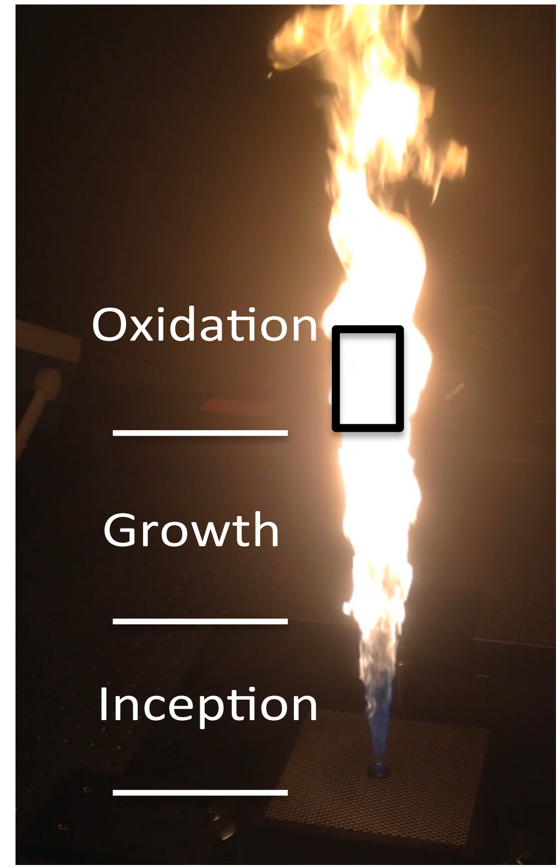


Single-Laser Shot Spectra

- Mean soot volume fraction at centerline, f_v = 0.35-0.5 ppm
- Fluctuations in excess of 1 ppm
- Challenging hydrocarbon-rich, sooting environment for diagnostics
- Fraction of ***valid spectra*** generally 96% or greater

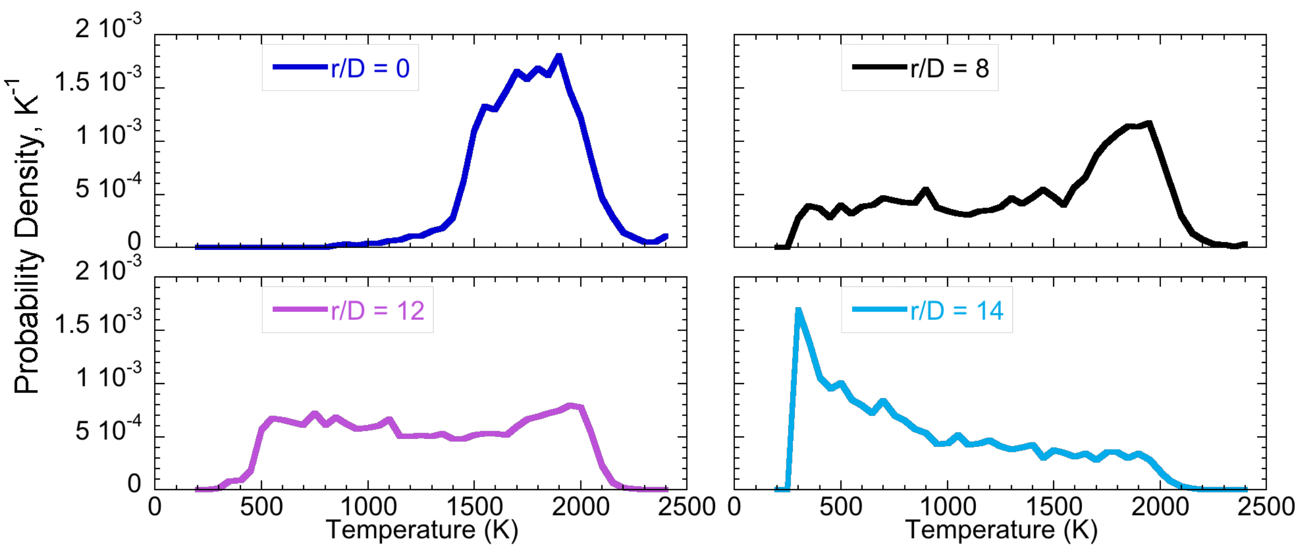
Rotational CARS Mean and RMS Temp./O_2 Profiles



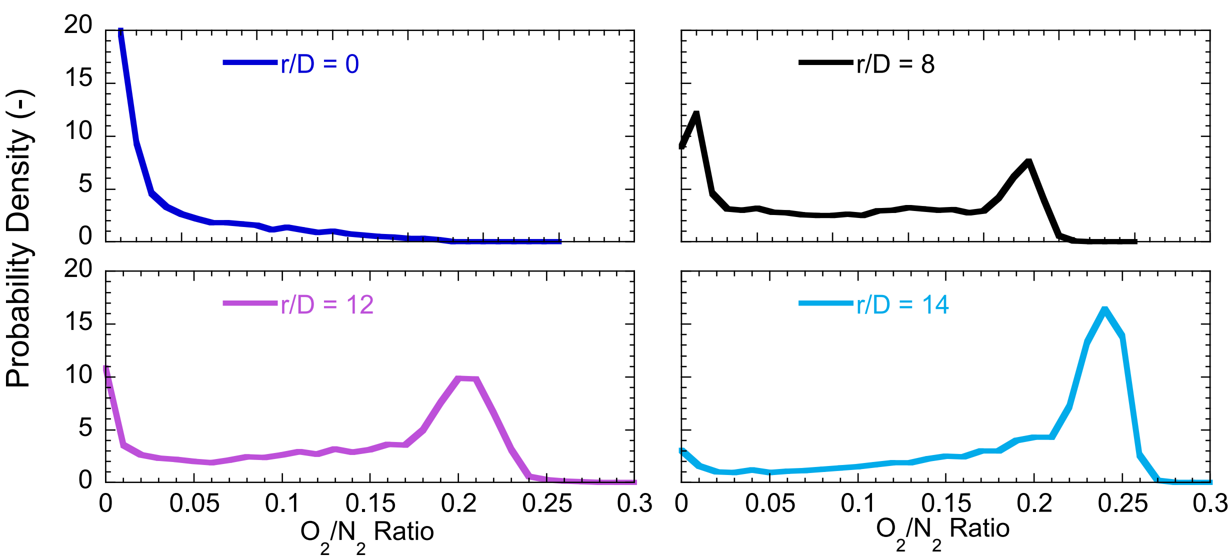


- Data from separate days spaced over 1 month apart
- Results obtained in 1-cm (z/D = 3.1) vertical increments
- Soot oxidation zone z/D = 127-175 investigated
- Little vertical variation in profiles

Temperature/O_2 Probability Densities—Radial Dependence

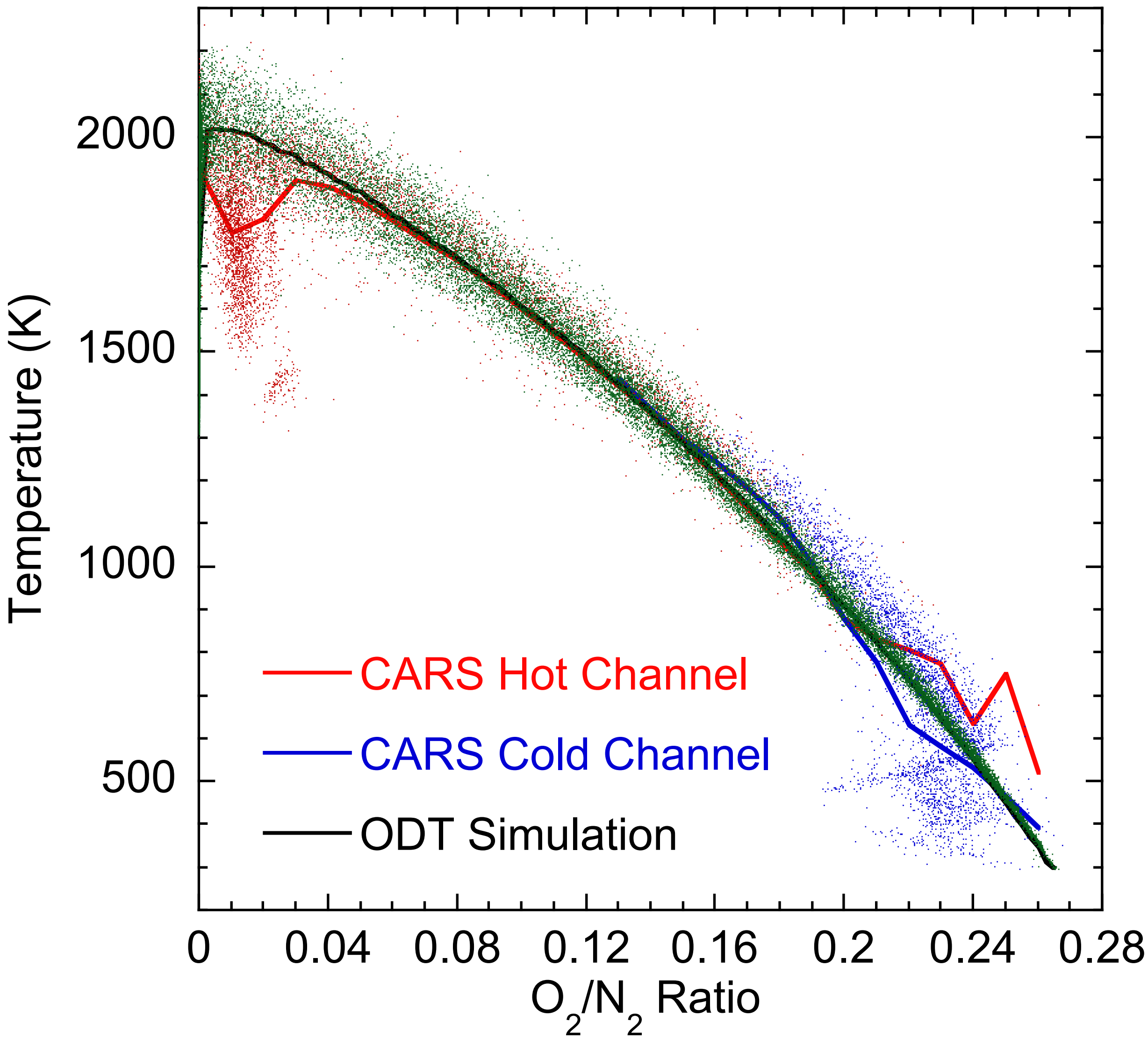


- Centerline T ~ 1400-2200 K
  - Transitions to uniform distribution in peak mixing zone
- Intermittent T fluctuations at jet edges – "clipped" pdf



- Intermittent O_2 fluctuations at jet centerline
  - Transitions to bi-model pdf w/ uniform region in peak mixing zone
- Intermittent O_2 fluctuations at jet edges

T/O_2: 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_2/N_2
- Mean of ODT within 1-2% of CARS measurements for O_2/N_2 = 6-20%
- O_2 detection limit is O_2/N_2 about 3%
- Hot- and cold-channel data temperatures agree to 1-2% for O_2/N_2 = 12-20%

Summary and Conclusions

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- We are currently measuring $T/O_2/f_v$ in a canonical sooting turbulent jet flame

Measurement Science

- A two-channel fs/ps rotational CARS instrument has been successfully implemented for extended dynamic range
  - Generally 96% or more valid laser shots in intermittent, turbulent environment
  - Limited systematic error between two detection channels
- LII soot imaging has been implemented over a wide field of view
  - Plateau-level response achieved throughout
  - Spatial variation of LII response accounted for

Combustion Science and Code Validation

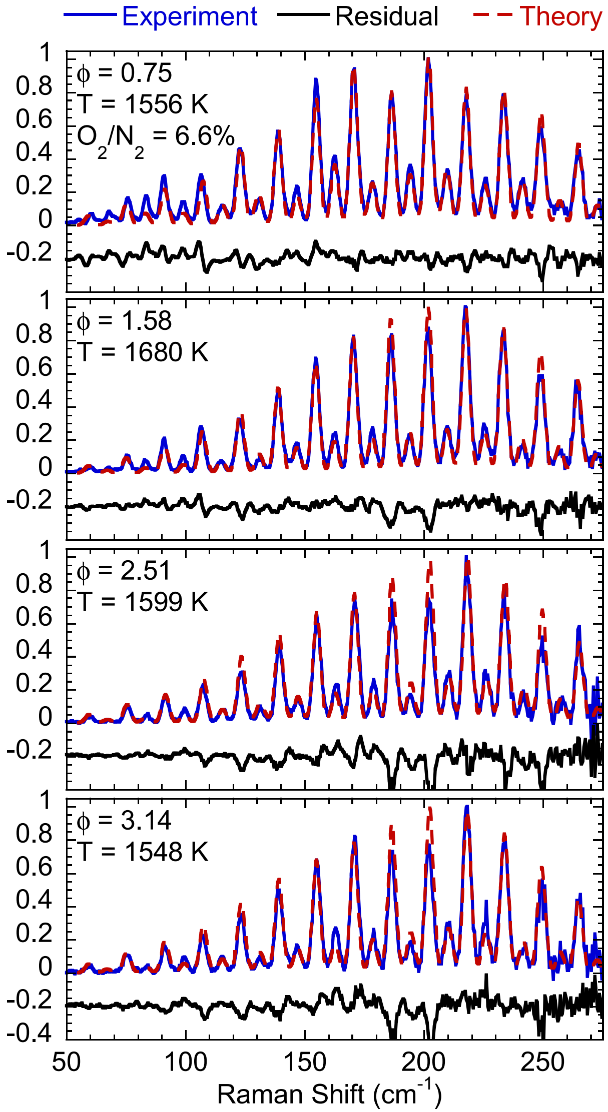
- Multi-parameter data obtained in soot-oxidation region of the jet flame
  - Mean, rms, pdf results presented here
  - ODT simulations calibrated to soot-growth-region LII measurements
  - ODT T/O_2 correlation predicted by ODT to 1-2% over a wide range of O_2/N_2
  - ODT soot f_v ~25% greater in soot oxidation region

What’s next?

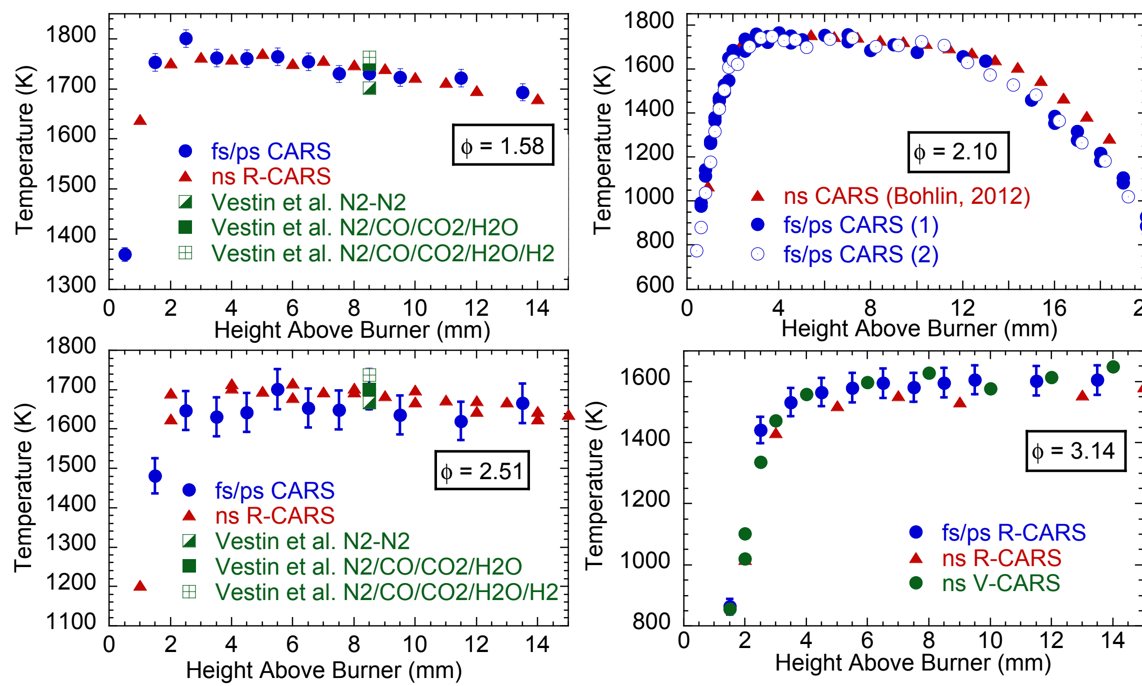
- ***Whats next?***
  - Pressure measurements—monitor collisions on ps scales
  - Vibrational fs/ps measurements for propellants
  - Rocket motor plumes
  - 2-D CARS imaging w/ soot LII

C_2H_4/air McKenna flame results

Single-Shot at 1 kHz



- ***Spectra acquired for fuel-lean to rich sooting flames***
- ***High-quality fits observed for f < 1***
- ***Systematic bias toward "underfit" of isolated lines for fuel-rich flames***
- ***Fitted temperature appears to be robust***
- ***Reliable spectra obtained in sooting regions of the flame***



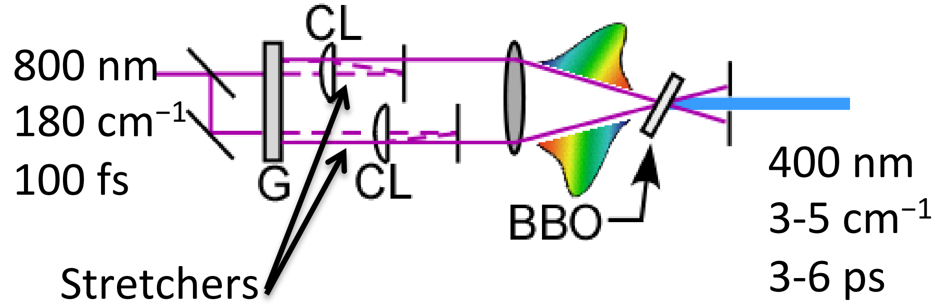
Second-Harmonic Bandwidth Compression (SHBC)

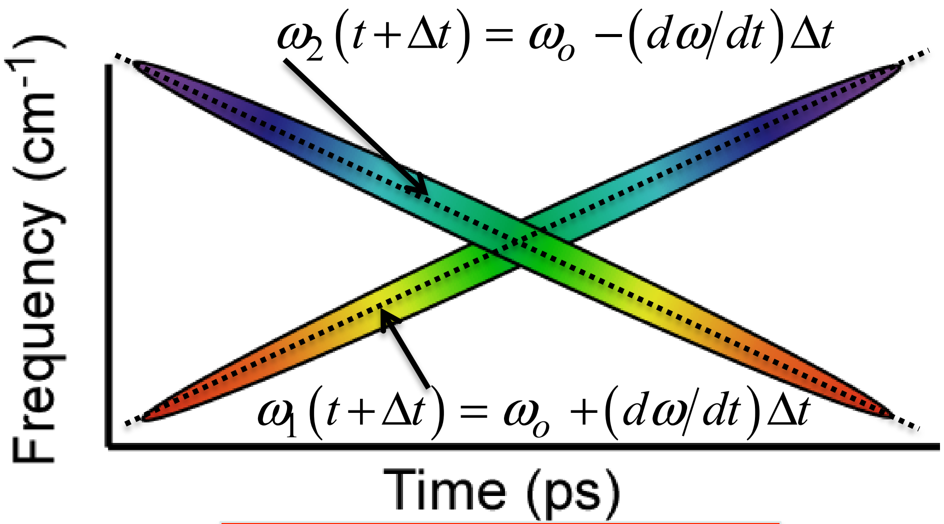
- Commercial device (Light Conversion)
- Converts fs radiation at 800 nm to ps radiation at 400 nm
- Grating pulse stretchers
- **<u>Phase-conjugate</u>** temporal chirps imparted upon broadband fs pumps
- Sum-frequency generation in BBO
- Output linewidth 3.5-4.0 cm^{-1}

$$\Delta\omega_{sfg} \sim d\omega/dt$$

$$\Delta\omega_{sfg} \sim (\Delta t)^{-1}$$

- Conversion efficiency: 35-50%!
- Output pulse energy: 1-1.4 mJ!





$$\omega_{sfg} = \omega_1 + \omega_2 = 2\omega_o$$

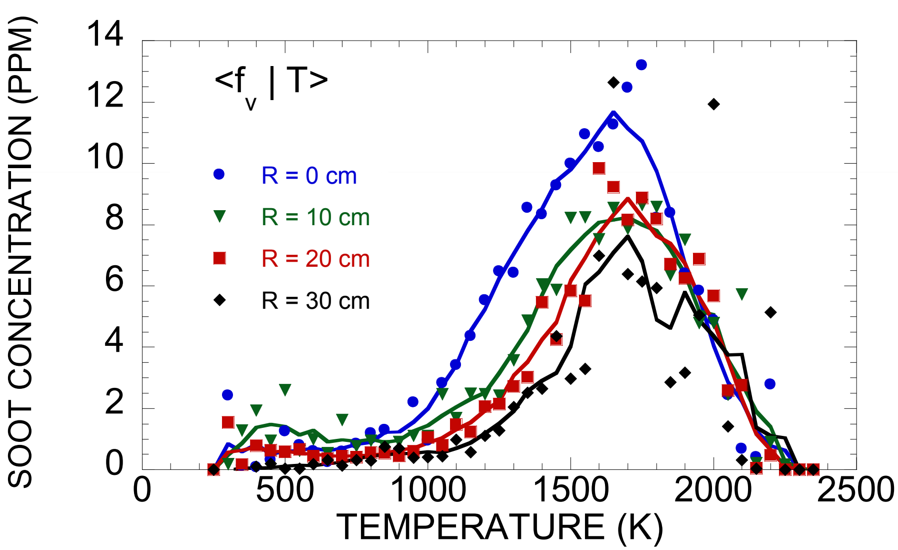
Joint/Temperature Soot Statistics for Emission

Radiative Transfer Equation

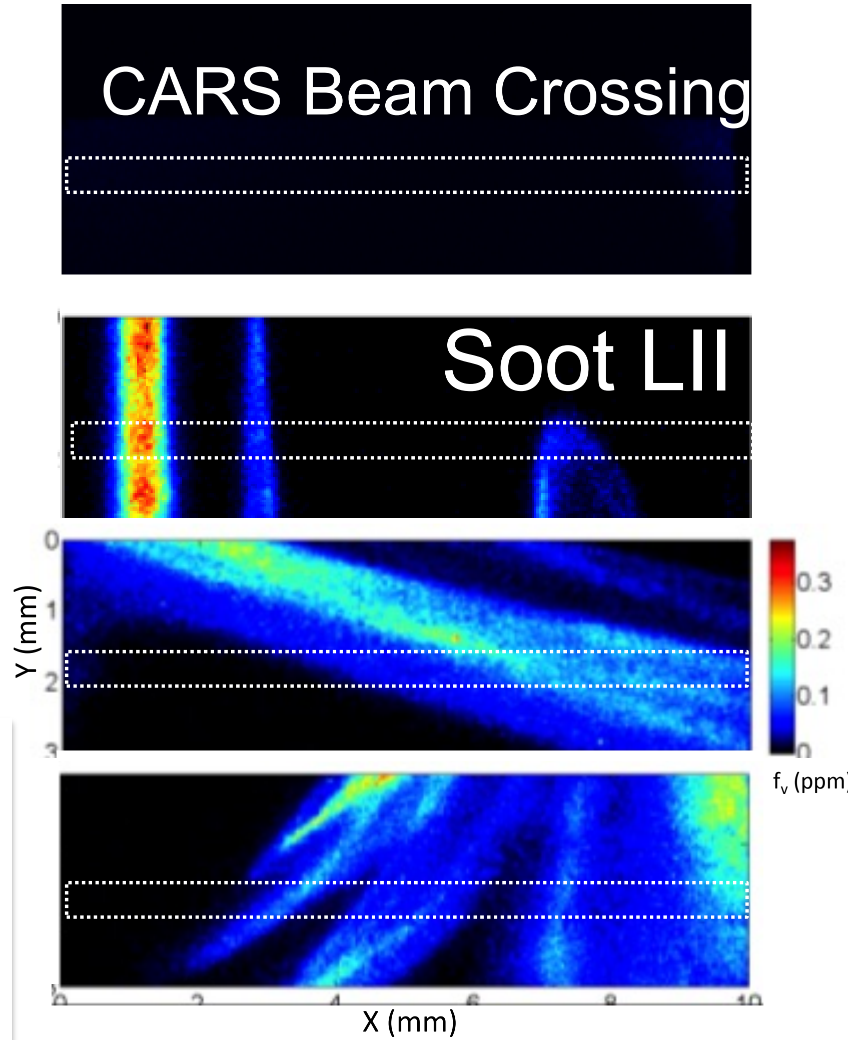
$$\frac{d\overline{I_\lambda}}{ds} = \overline{\mu_\lambda I_{\lambda,b}(T)} - \overline{\mu_\lambda}\,\overline{I_\lambda}$$

Joint Temp. Soot Statistics Desired

- CARS system combined with LII soot detection
- Average soot in 10^{-5} cc CARS volume correlated with enthalpy-pooled temperature



Mean Soot Conditioned on Temperature



Frederickson and Kearney, Appl. Opt. **50** (2011)
Kearney and Pierce, Combust. Flame **159** (2012)