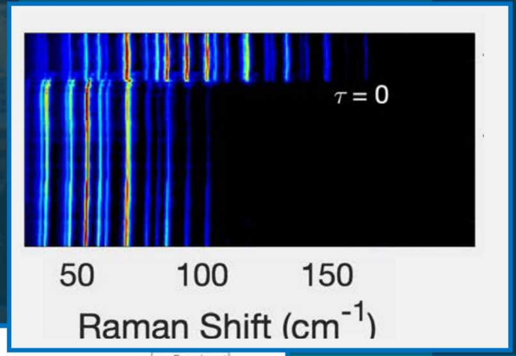
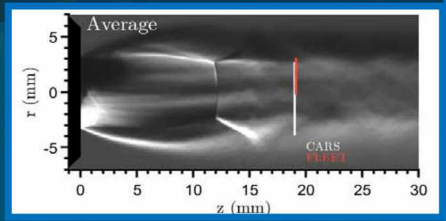
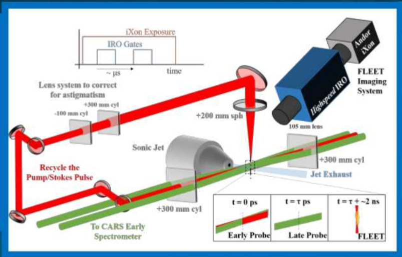
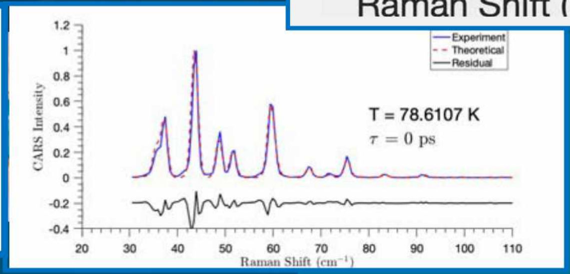
SAND2019-15491C

Simultaneous Temperature/Pressure Monitoring in Compressible Flows using Hybrid fs/ps Pure-Rotational CARS









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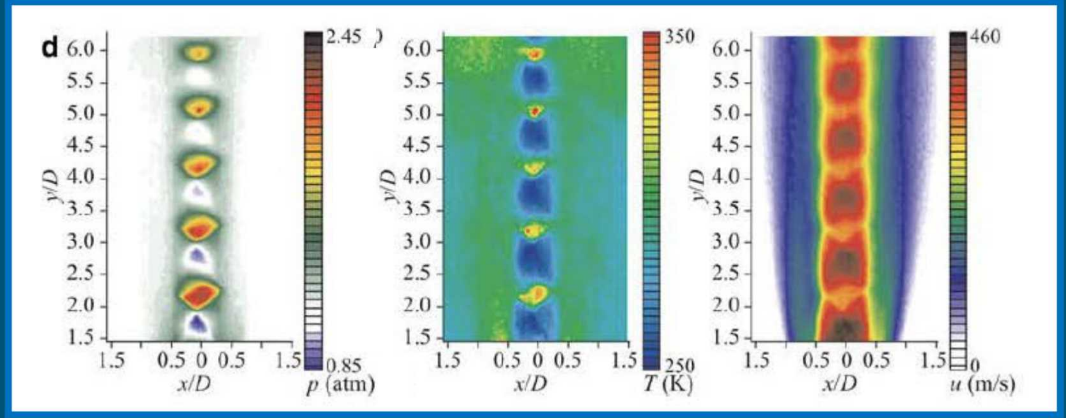
Background

- There is renewed interest in supersonic and hypersonic ground-test facilities
- Cold-flow facilities require measurement of temperature, pressure, velocity, even thermal distribution functions
- Noninvasive tools for temperature/pressure monitoring
  - Laser-induced fluorescence (LIF)
  - Filtered Rayleigh scattering

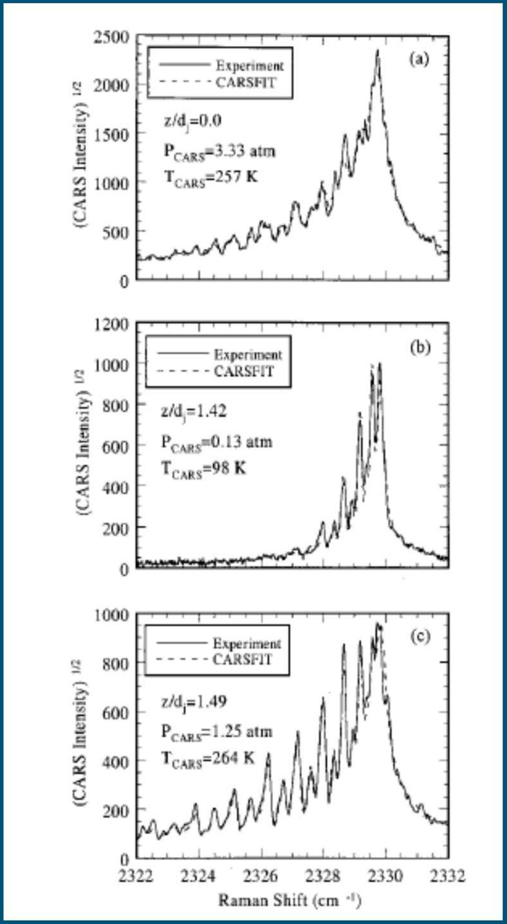
- Two-dimensional imaging
- kHz repetition rate
- May require seed/tracer molecule (LIF)
- Multi-camera, multi-angle detection scheme (Rayleigh)

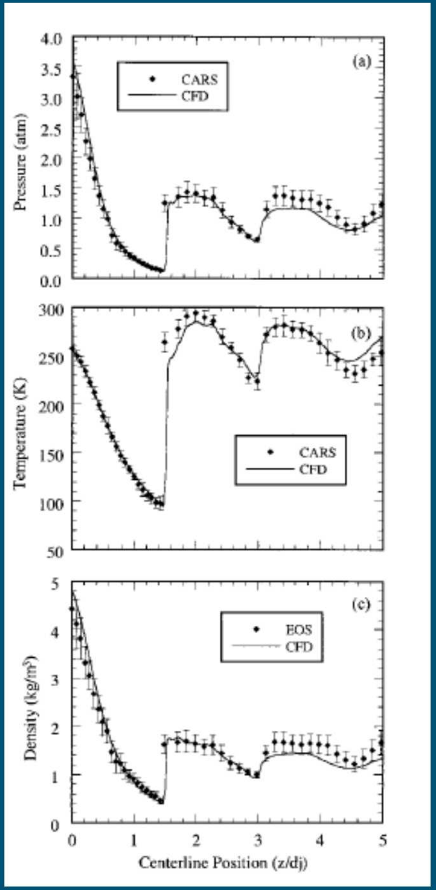


Time-scanned FRS detection of T,P,V
Boguszko and Elliott, *AIAA J.* (2005)

Coherent anti-Stokes Raman Scattering (nanosecond)

- CARS demonstrations for simultaneous T/P measurement
- Nanosecond-duration laser pulses
- High spectral resolution to deconvolve the effects of T and P
  - Temperature from line intensity distribution
  - Pressure from collision-broadened linewidths (Woodmansee et al., Farrow)
  - Density from calibrated signal amplitude (Grisch *et al.*)





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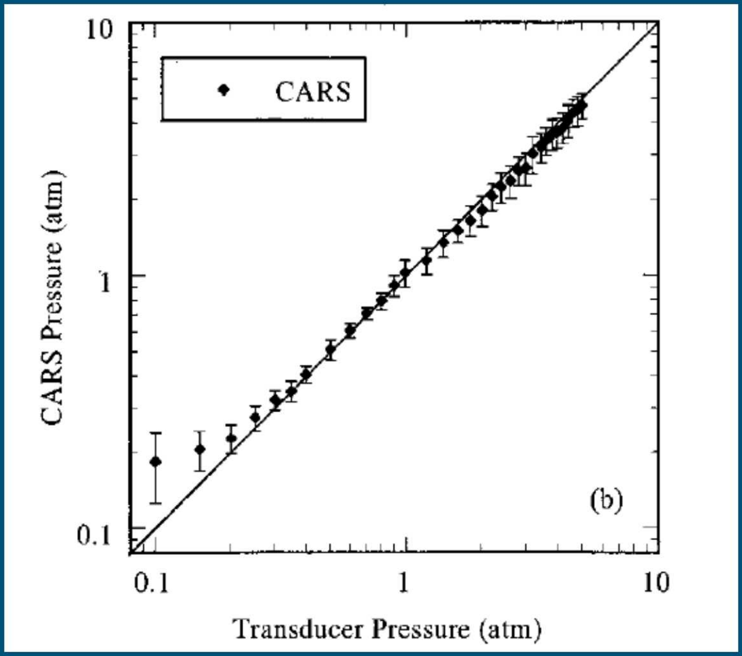
  - Pressure from collision-broadened linewidths (Woodmansee et al., Farrow)
  - Density from calibrated signal amplitude (Grisch *et al.*)
- Spectroscopy of the N_2 *Q* branch
  - Overlapping lines
  - Doppler contributions at P ~ 0.1 atm and below
  - Limited low-pressure sensitivity in ground testing



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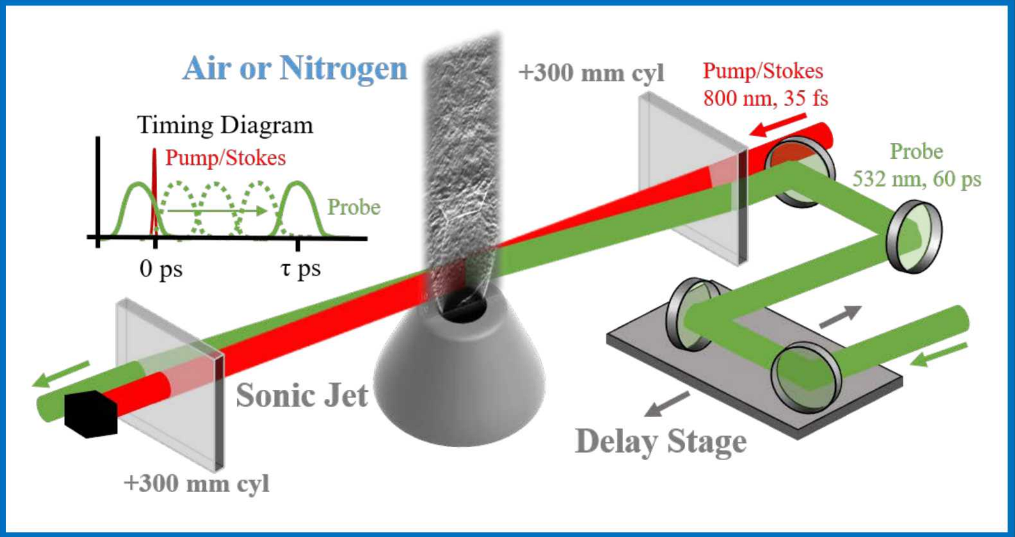
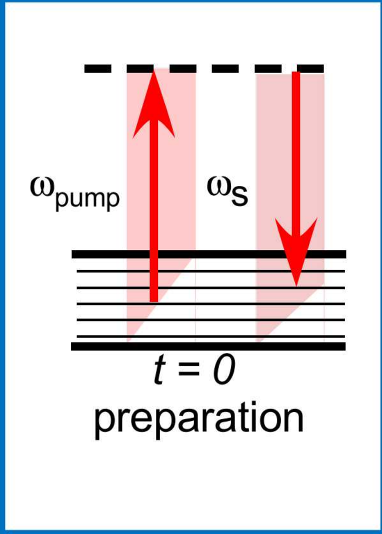
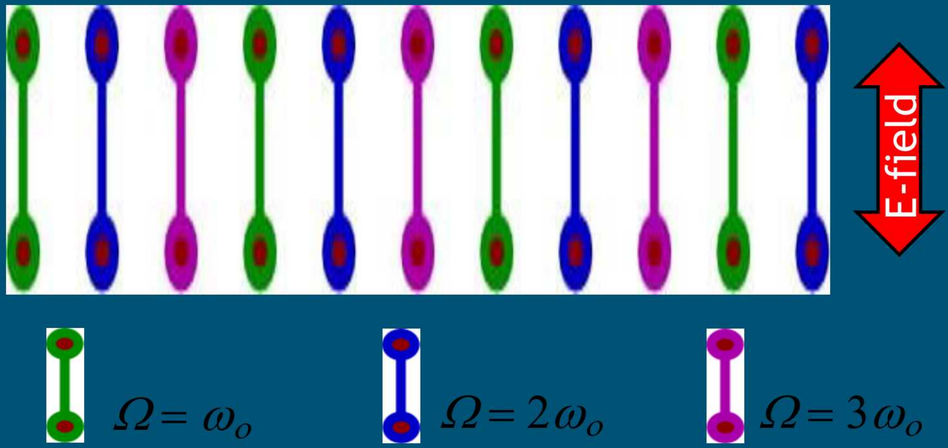
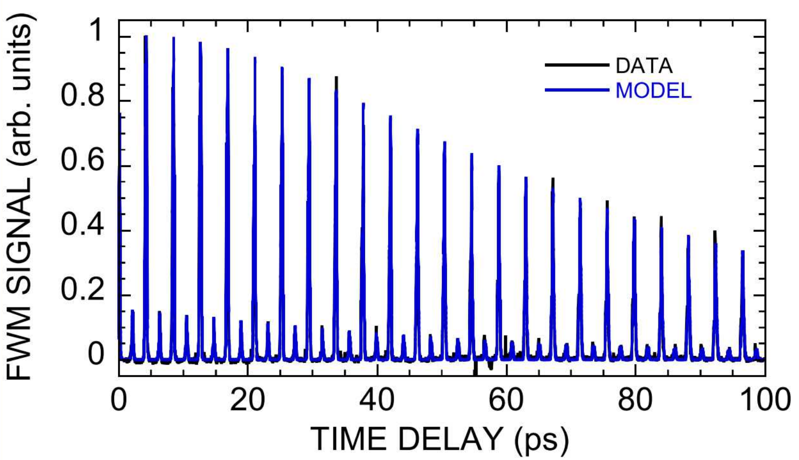
"Hybrid" time- and frequency domain CARS detection





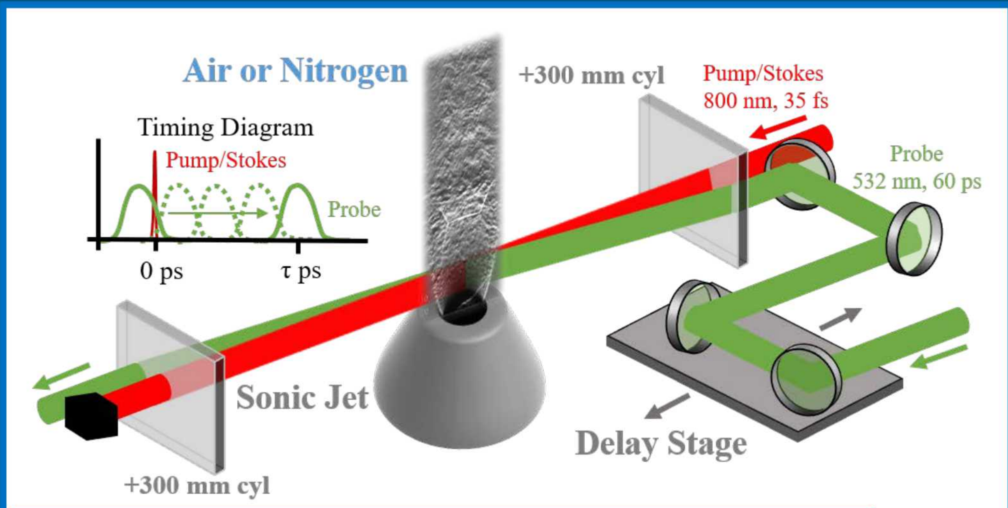
Impulsive pump/Stokes Raman preparation



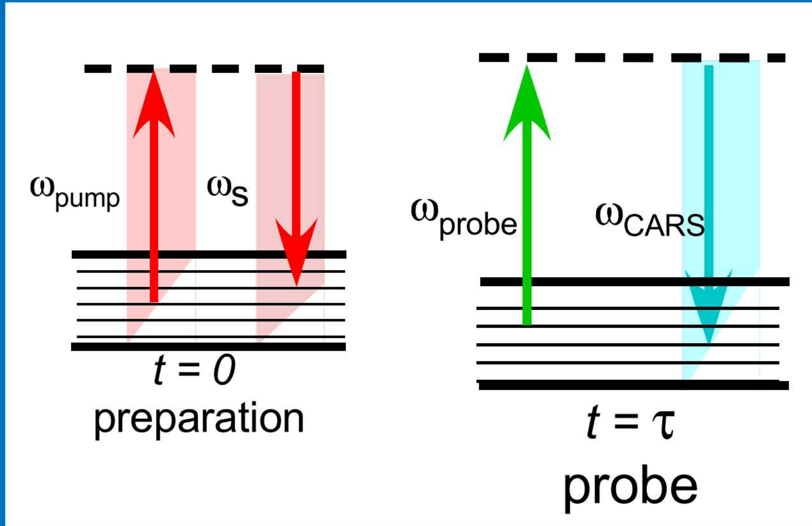


Time Evolution of Raman Coherence

"Hybrid" time- and frequency domain CARS detection

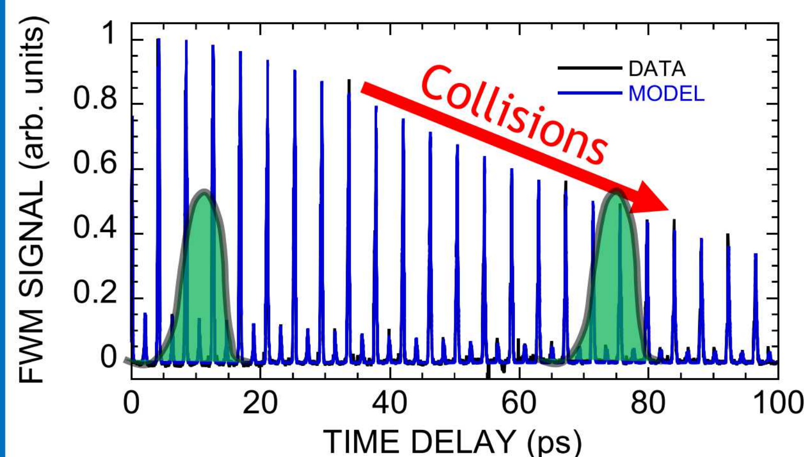


$$\chi = \sum_J W_J \exp\left(i\,\omega_J t\right)\exp\left(-\Gamma_J\, t\right)$$



- Hybrid time/frequency detection decouples effects of T and P
- Pure-Rotational spectroscopy delays onset of Doppler effects to much lower pressure

$$\Delta\omega_D = 2\omega_R\sqrt{\frac{2\log(2)kT}{m}}$$

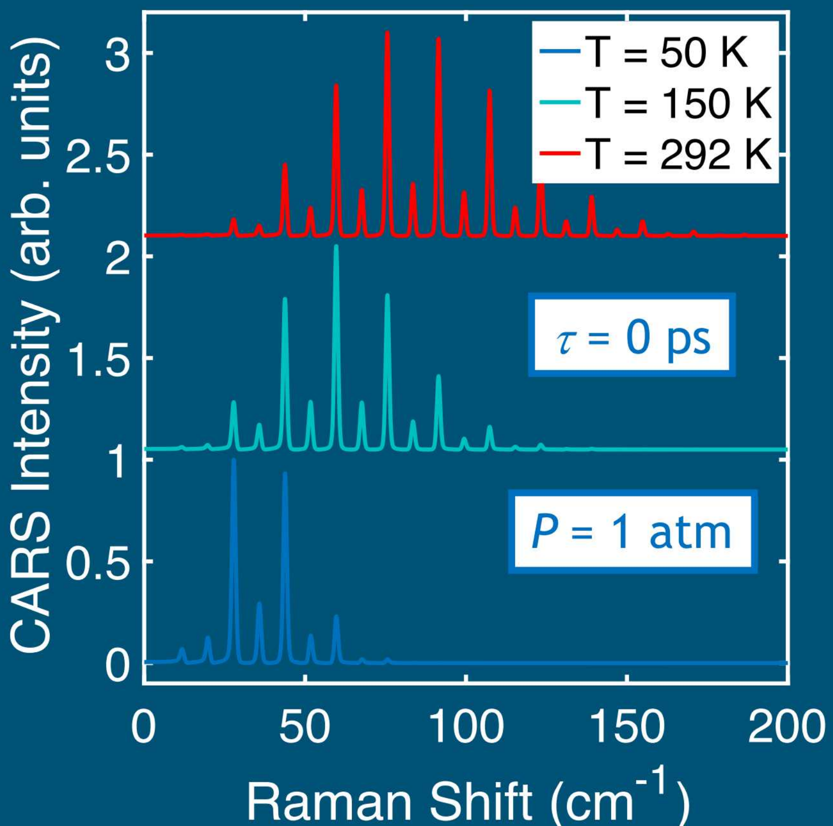


Time Evolution of Raman Coherence

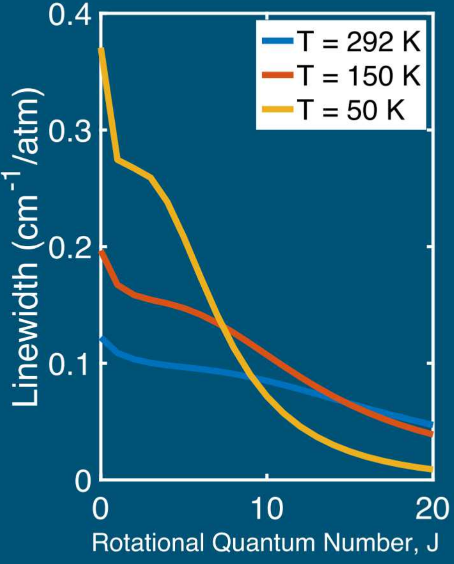
Temperature and Pressure Sensitivity of Hybrid R-CARS Spectra

Step 1: Thermometry at Early Time

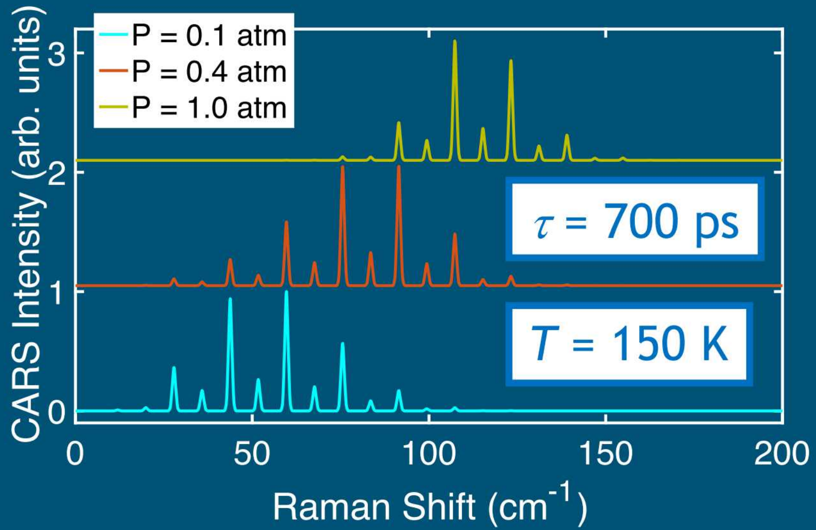
- "Collision-Free" spectra temperature sensitive independent of pressure
- Spectra largely reflect rotational Boltzmann populations



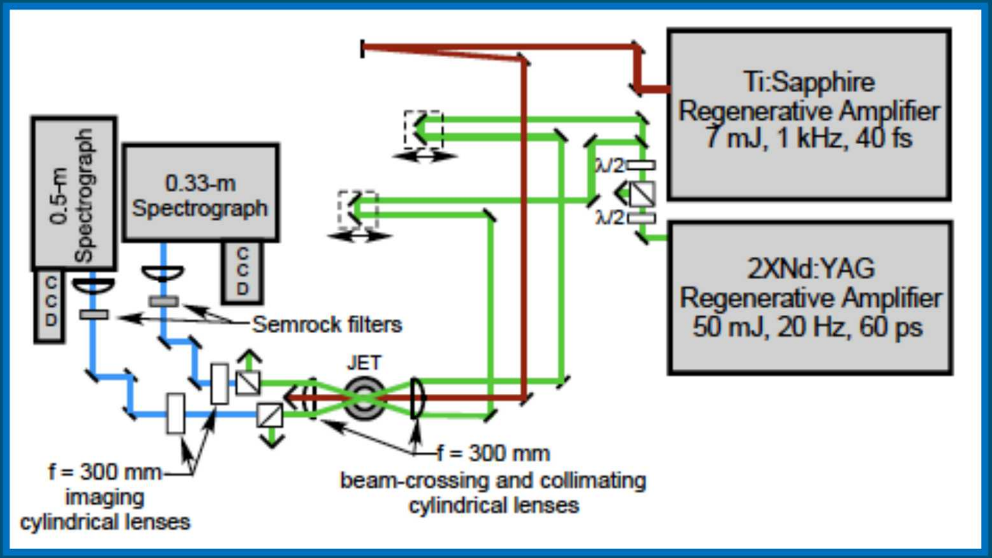
Step 2: Sample late-time collisions for pressure



- Monotonic decrease in Γ with J
- High energy transitions have longer lifetimes
- Spectra look "hotter" with increasing P or delay

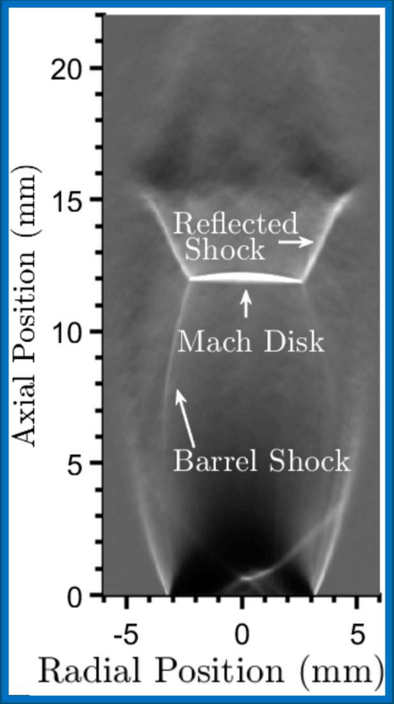


CARS Optical System and Jet Experiment

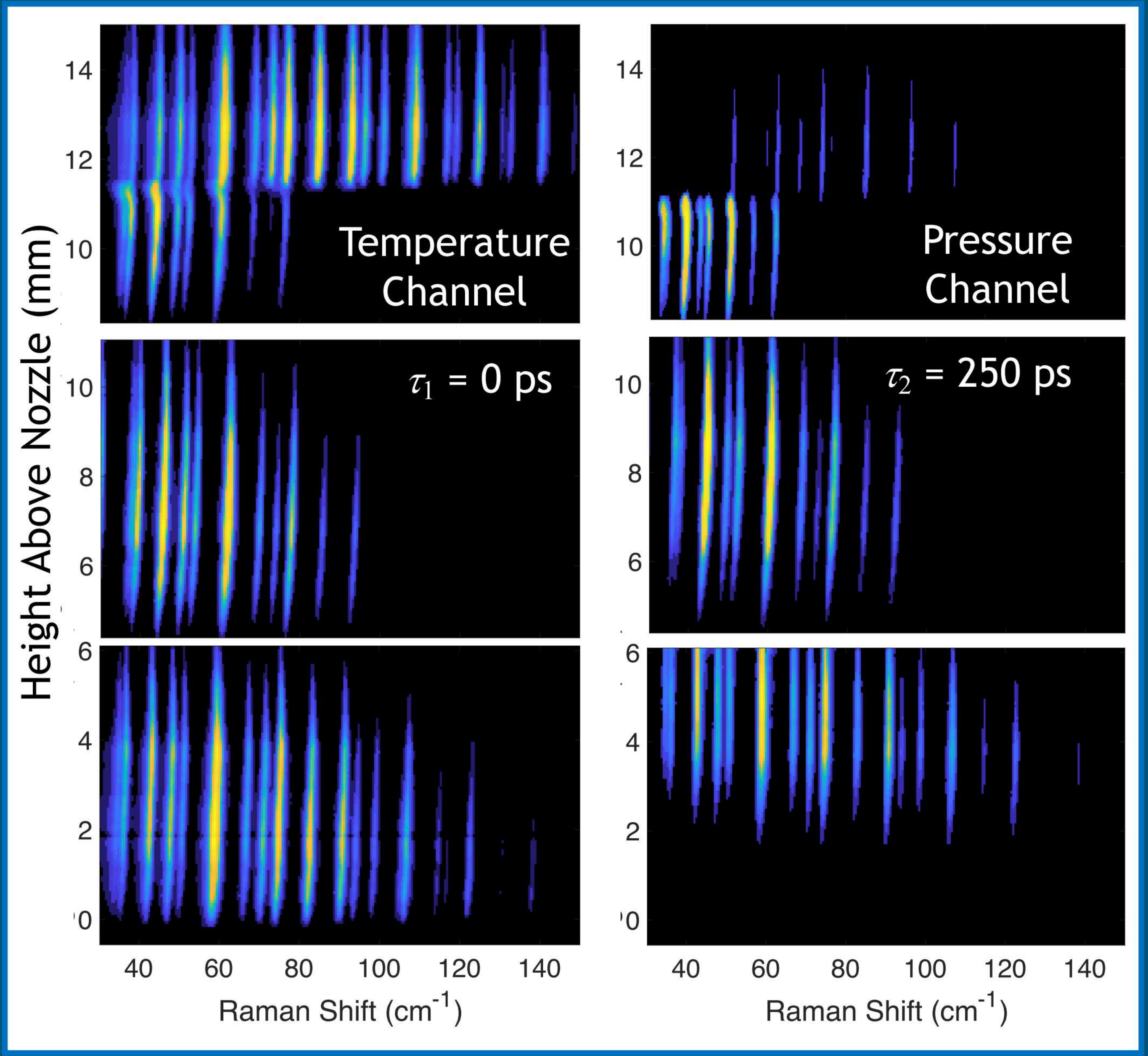


- 1D imaging scheme developed by Bohlin and Kliewer
- Two independent detection channels for early (T) and late (P) measurements
- 50-fs pump, ~250 cm^{-1} bandwidth, 4 mJ
- 60-ps probe near transform limit, 50 mJ
- 6-mm long measurement line
- 1000 μm X 67 μm X 30 μm resolution

- 6.35 mm underexpanded sonic jet
- Po = 7.62 atm, To = 292 K
- Working fluid = air
- 3 independent ROIs required to span jet exit past Mach disk
- 50-laser-shot ensembles at τ_2 probe delay

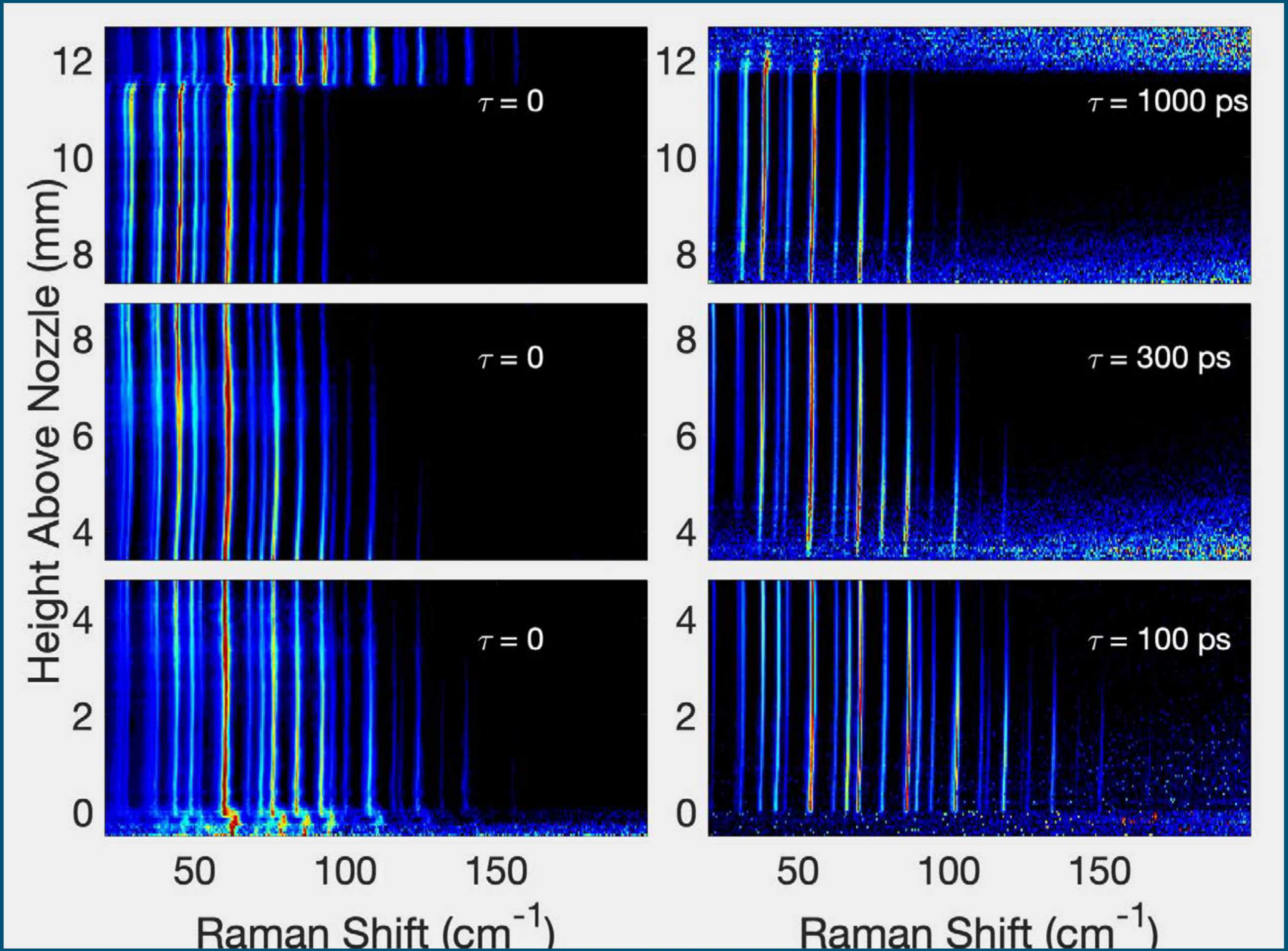


One-dimensional R-CARS Imaging: 50-shot averages



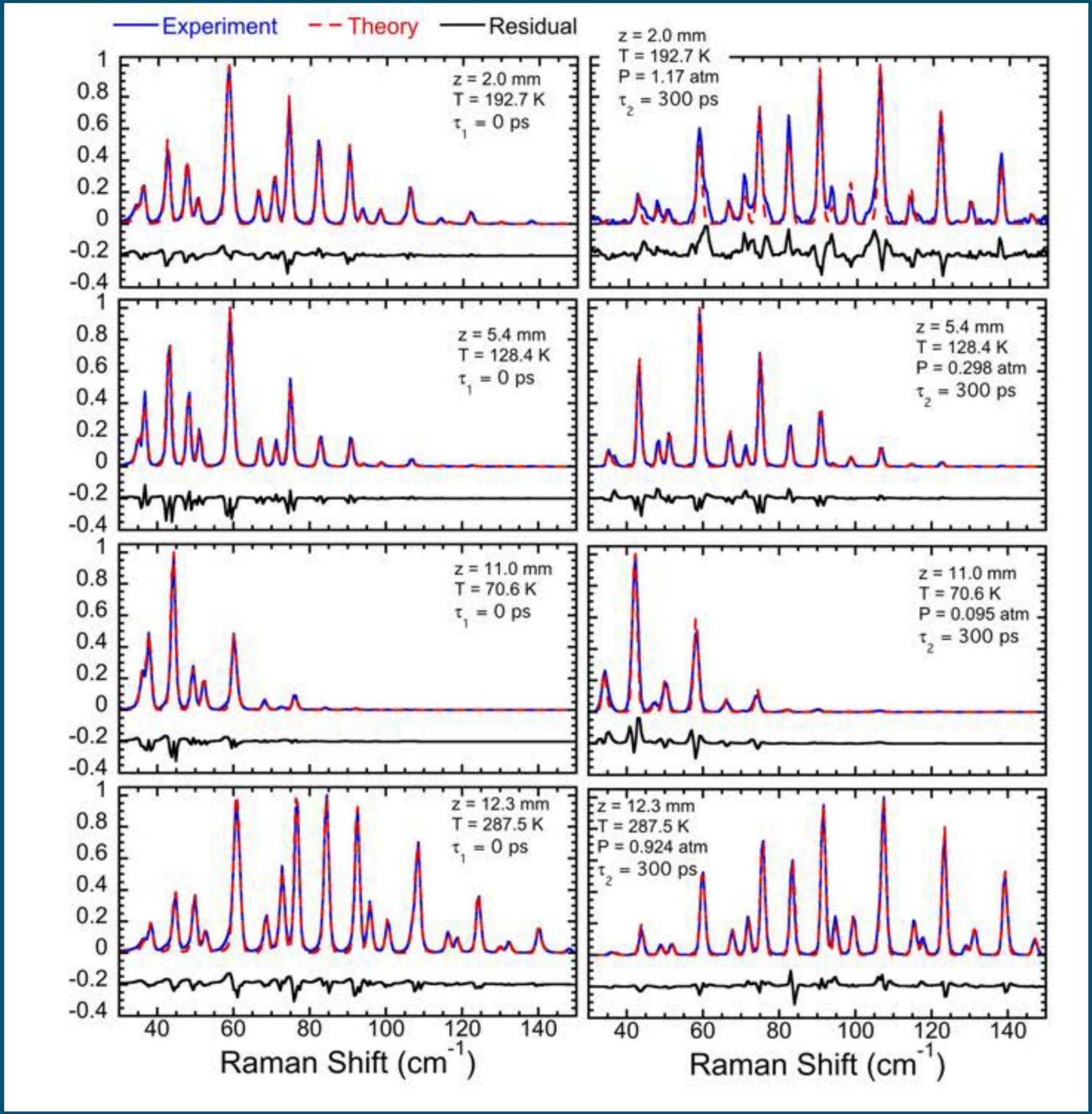
- Pressure challenges dynamic range
- High-pressure regions require low τ
- Low-pressure regions require very long τ (ns!)
- Pressure sensitivity maximized in near-jet and post-shock regions at τ = 250 ps

Single-laser-shot imaging (20 Hz)



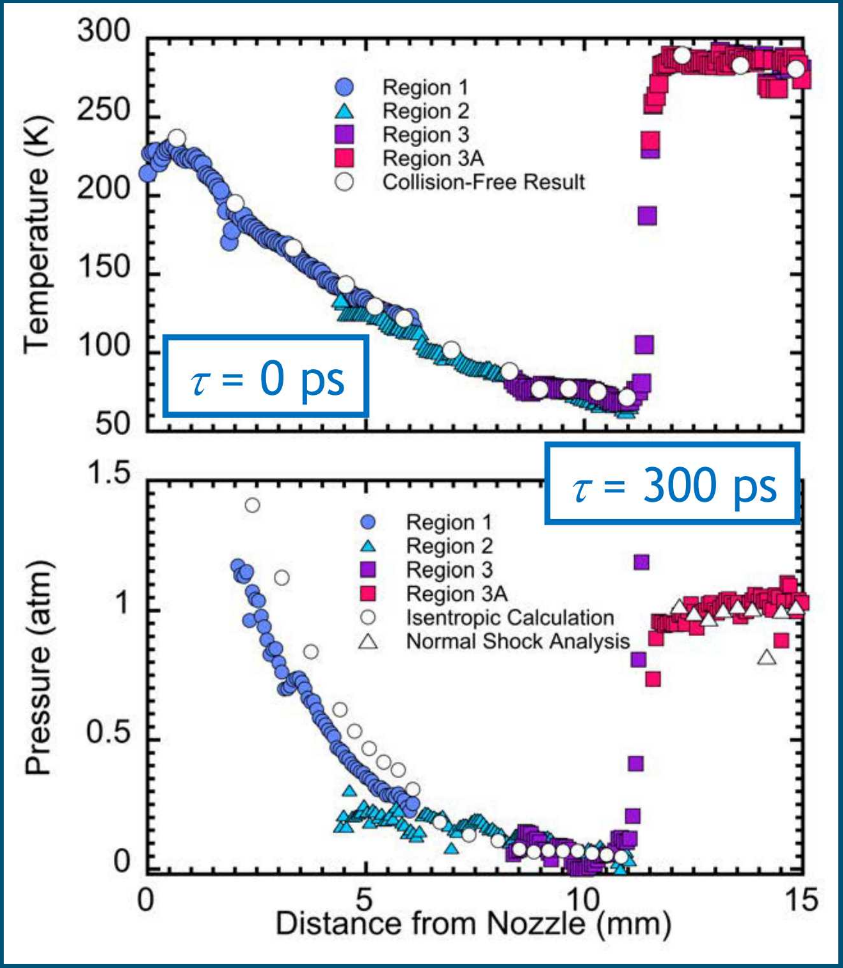
Temperature and pressure dependence of CARS spectra

- 50 laser-shot average spectra
- τ_1 channel (left) indicates temperature nearly independent of pressure
- τ_2 = 300 ps delay on pressure channel
- τ_2 delay results in pressure sensitive intensity to higher cm^{-1} (shown at right)
- Pressure sensitivity optimized near P = 1atm for τ_2 = 300 ps
- Improved P sensitivity at low P for longer τ_2



Time-mean temperature/pressure results (MEG)

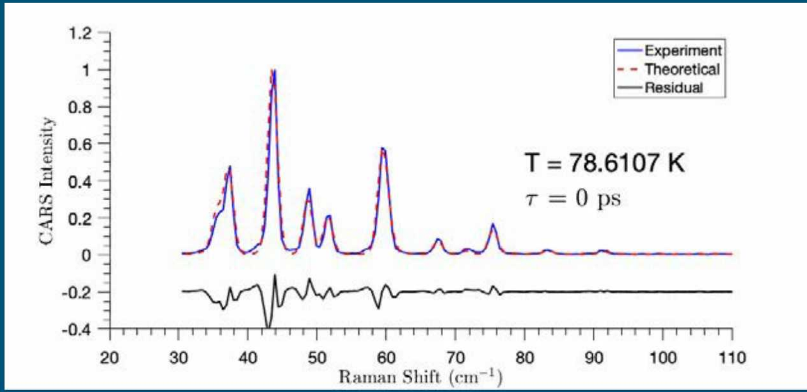
- Profiles spliced together from 4 different 6.7-mm line images
- Each image averaged for 50 laser shots
- Pressure data reported for τ = 300 ps probe delay
- Dynamic range across the shock captured using two images with different filter settings
- Reduced sensitivity at lower pressures → need delays in excess of 1 ns.
- Poor signal at P > 1.2 atm → need delays of 100 ps or less
- Near-jet temperature consistent with sonic nozzle exit
- T/P across shock consistent with M = 3.8

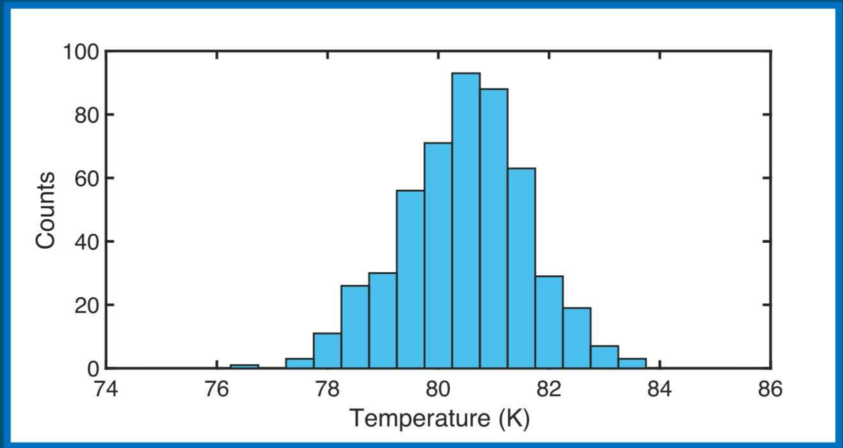


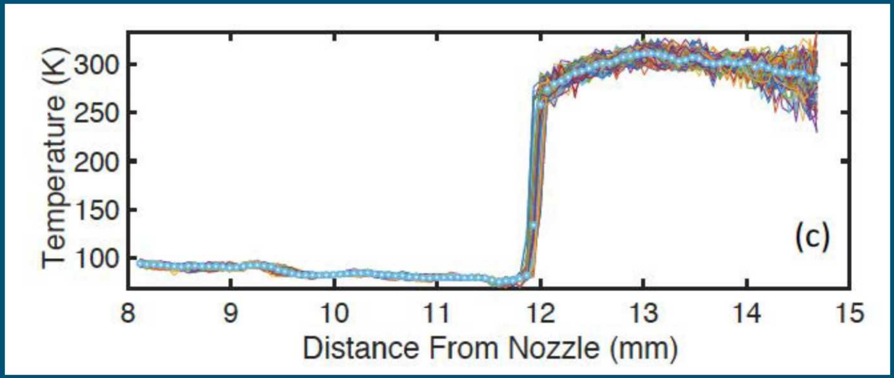
Pressures consistently lower than isentropic predictions!

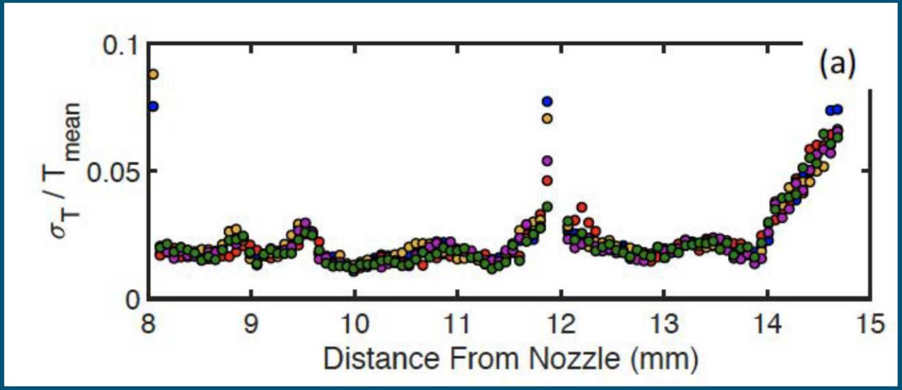
Single-laser-shot precision: Temperature

- Signal-to-noise and measurement precision are very good for thermometry at $\tau = 0$
- σ_T/T evaluated within steady barrel-shock region upstream of Mach disk along jet centerline
- σ_T/T is 1—2% upstream of Mach disk
- This high precision persists downstream of Mach disk
- Shock front appears to be resolved within 130—200 μm (1—3 data pts)







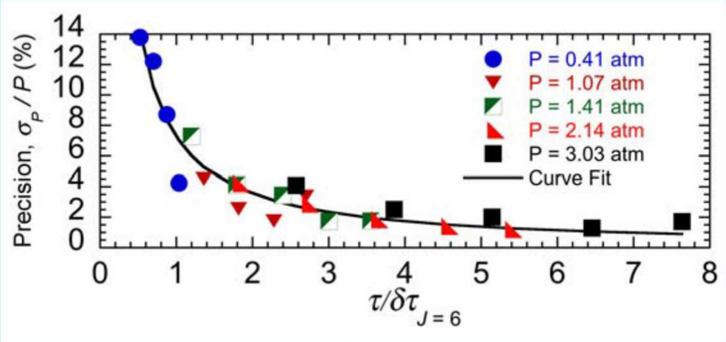


Single-laser-shot precision: Pressure

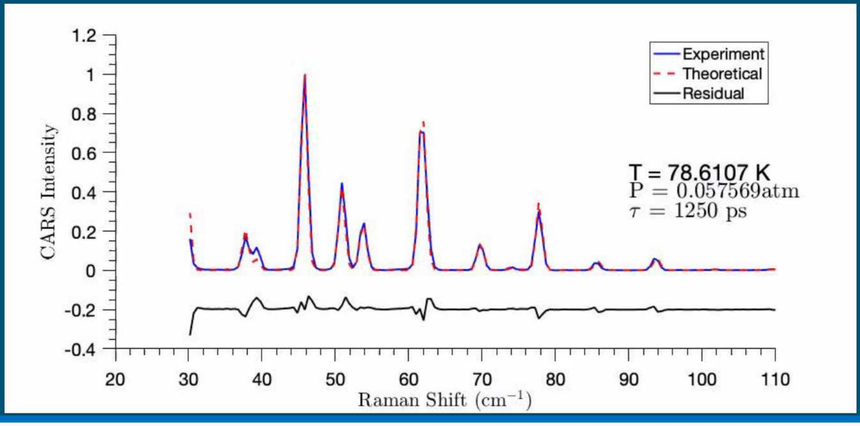
- Tradeoff between SNR and sensitivity with increasing probe delay
- "Raman lifetime"

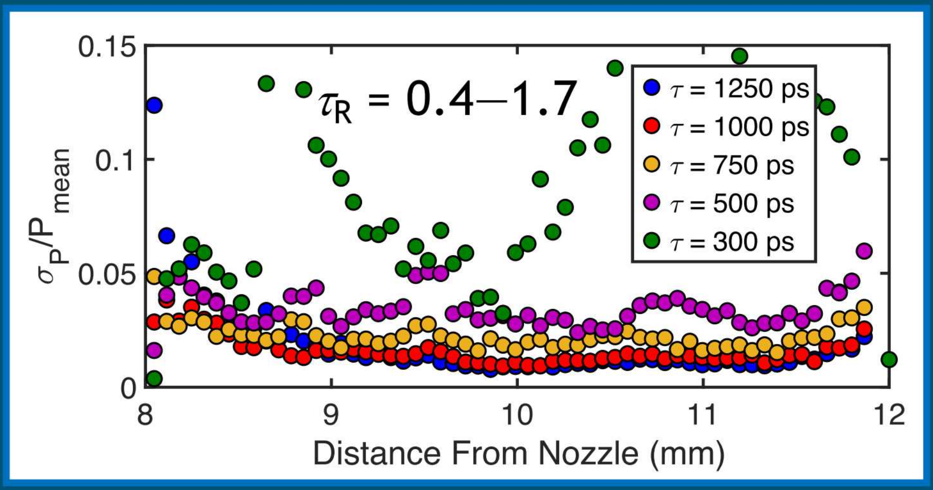
$$\tau_R = (P \pi c \Gamma)^{-1}$$

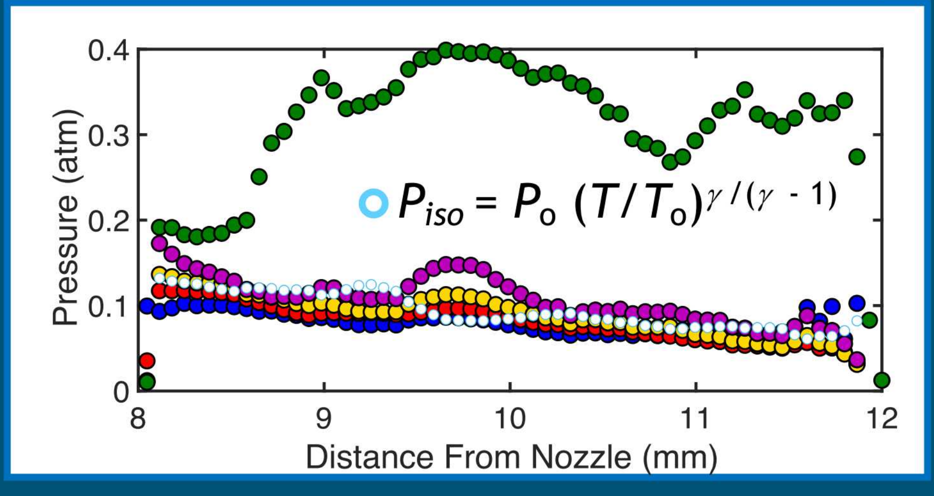
- Room-temperature data suggest $\tau \sim 2.5$—$3\,\tau_R$ for optimal precision
- sP/P optimized at 1-3% at $\tau \sim 1$—$1.7\,\tau_R$ in low (T,P) region of jet
  - T = 75—100 K, P = 50-75 Torr



Kearney and Danehy, *Opt. Lett.* (2015)

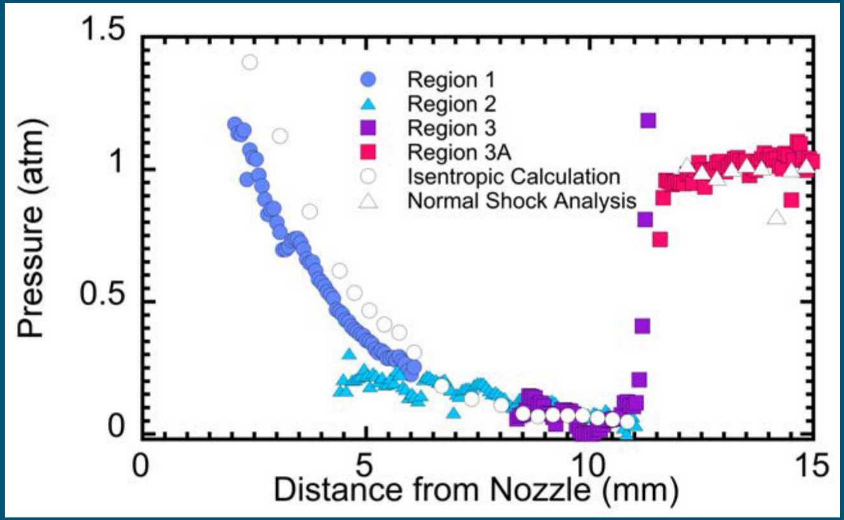






Low-temperature Raman Linewidths (motivation)

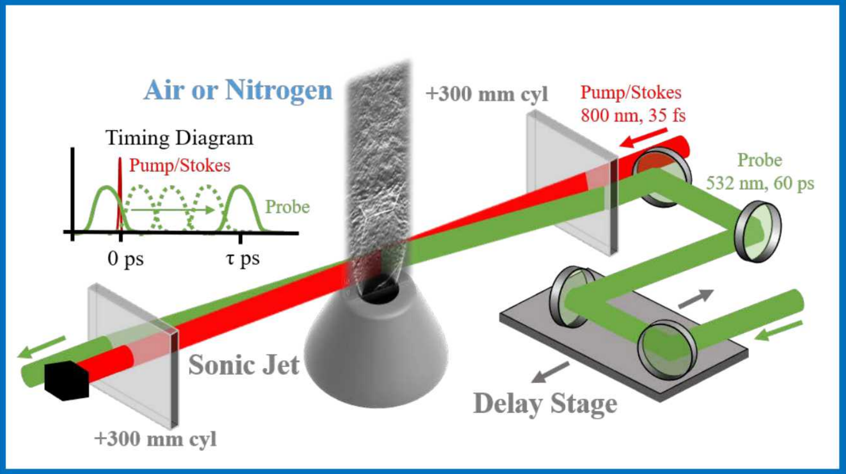
- The ***Modified Exponential Gap (MEG)*** model has been used to compute Raman linewidths
- Developed using *Q-branch* linewidth measurements for T = 292—2200 K
- Extrapolation to low-temperatures is precarious
- Different line-broadening mechanisms
  - Isotropic Q branch
  - Anisotropic rotational transitions
- CARS pressure measurements fall below isentropic predictions based on measured T in the near field



Solution

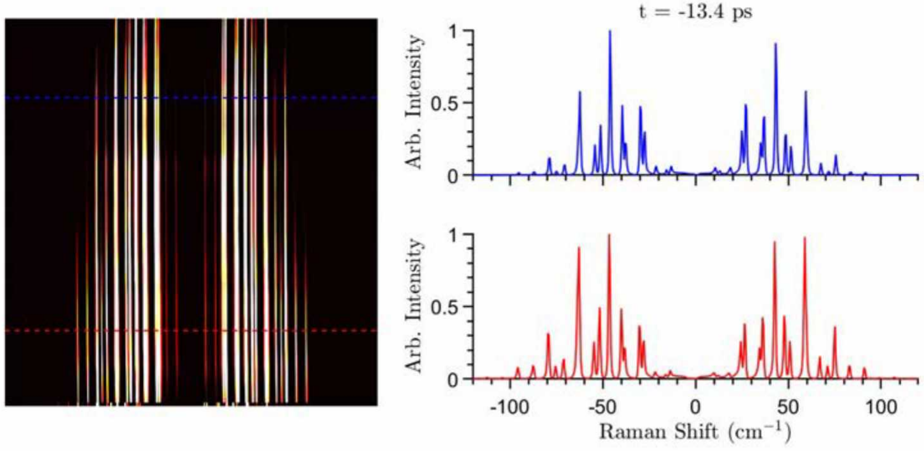
- Use (collision-free) CARS-measured temperatures on jet centerline
- Compute $P_{iso} = P_o\,(T/T_o)^{\gamma/(\gamma\ -\ 1)}$
- Measure the lifetime, $\tau_{CARS,J} = \tau_R/2$, via probe delay scans
- Compute T- and J-dependent linewidths, $\Gamma_J = (2\pi c\,\tau_{CARS,J})^{-1}$

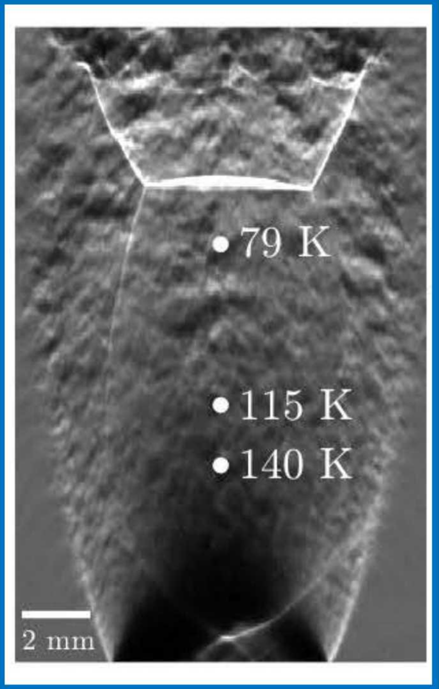
Low-temperature Raman Linewidths (apparatus and methods)



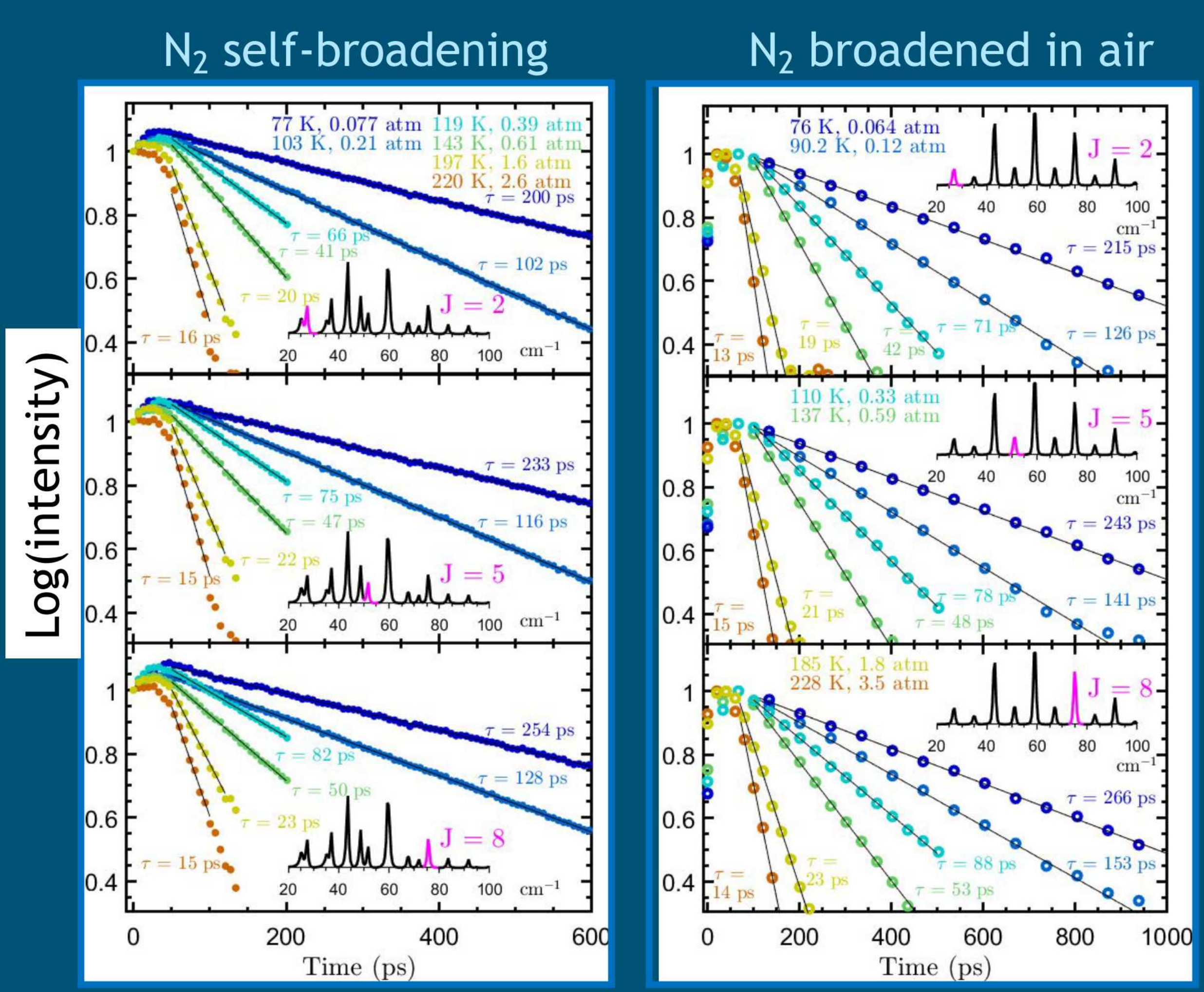
- Probe time-delay mechanically scanned
- Jet centerline measurements within barrel shock region
- Decay of N_2 examined in both air and pure N_2

Probe Time Delay Scan in Air Jet





Low temperature Raman Linewidths (time-domain fits)



- N_2 Coherence decay shown for T = 77—220 K, P = 0.08—2.6 atm
- Rotational levels up to *J* = 10 measured at low-T
- Results for O_2 complicated by $^3\Sigma$ ground state (not shown here)
- Slower decay times with increasing *J*

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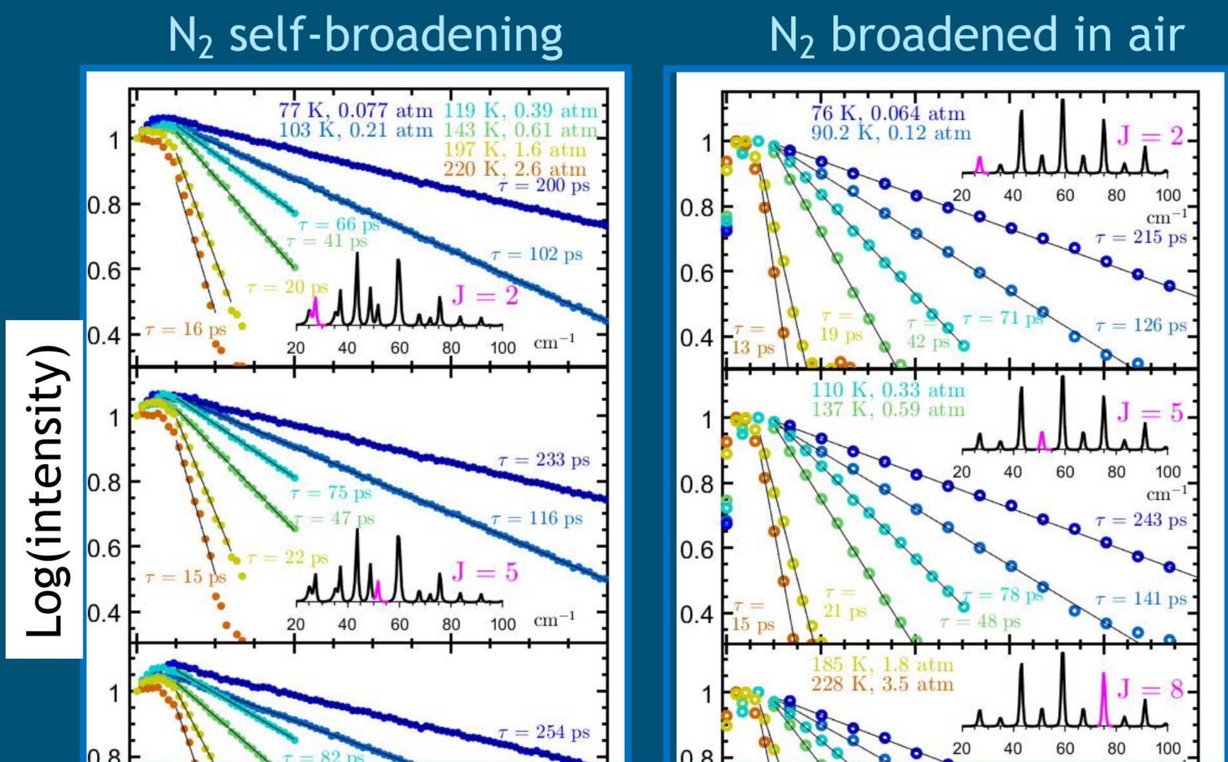

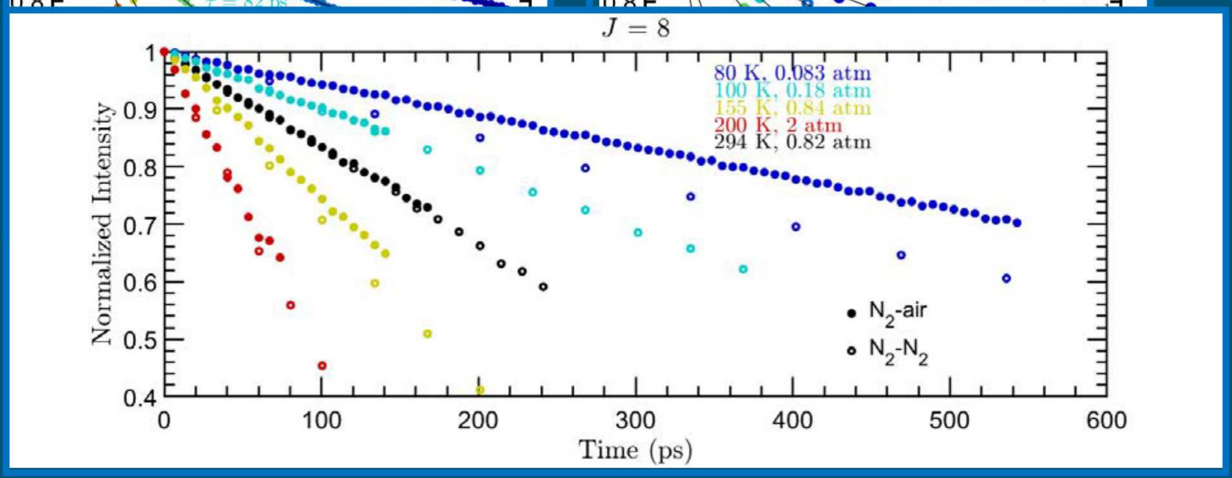

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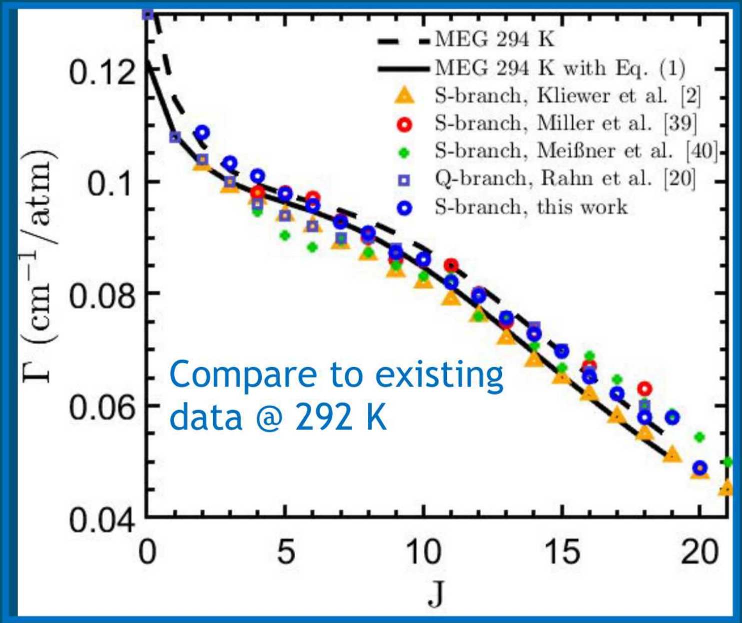
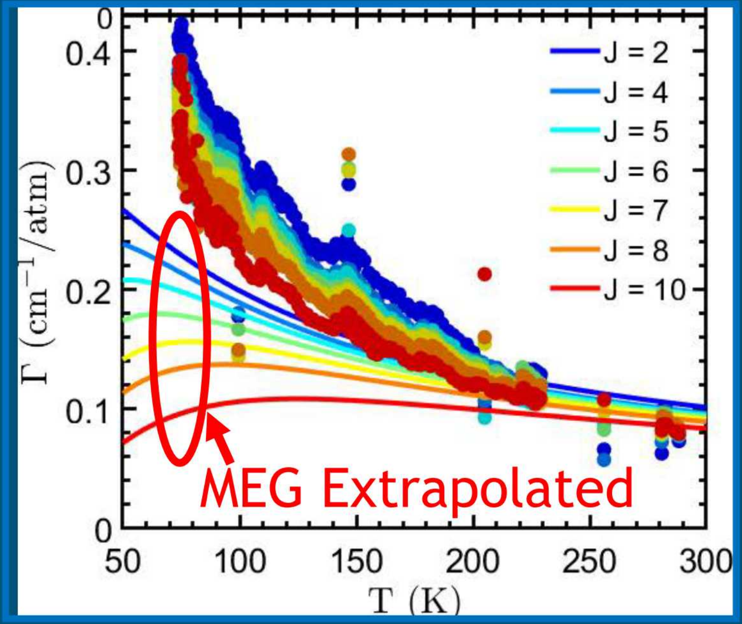
Slower decay times with increasing J

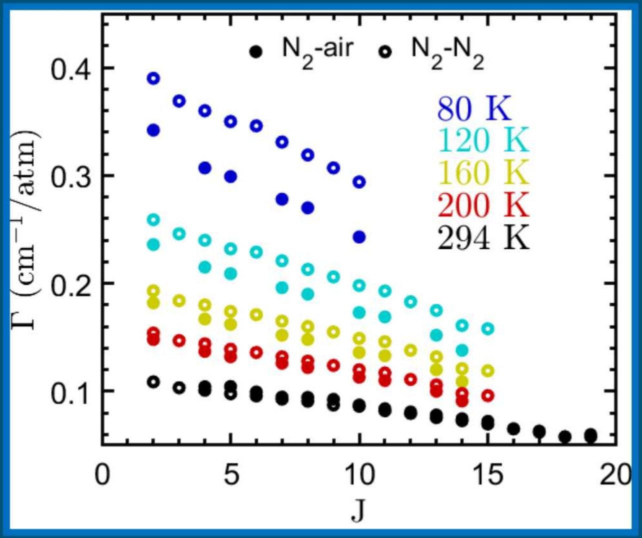
N_2 dephases more rapidly in air below T = 292 K

Low-temperature Raman linewidths: Results I





- Current facility provides data consistent with previous measurements at T = 292 K
- Measured linewidths depart significantly from MEG at low T
- Pressure measurements are sensitive to the *J dependence* of Γ—not the magnitude



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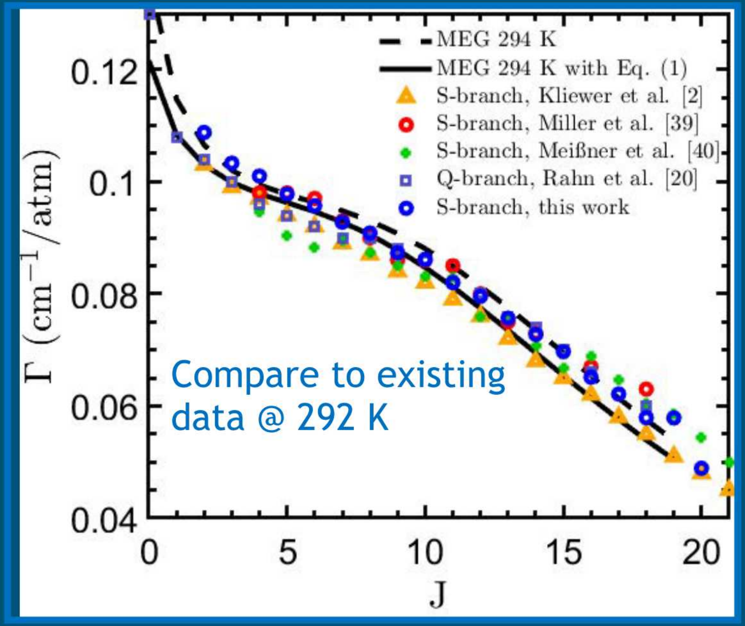

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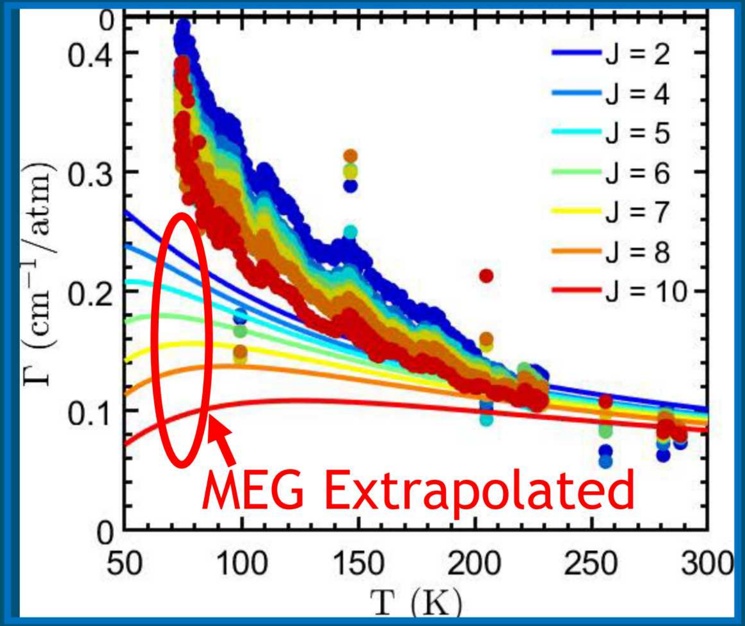
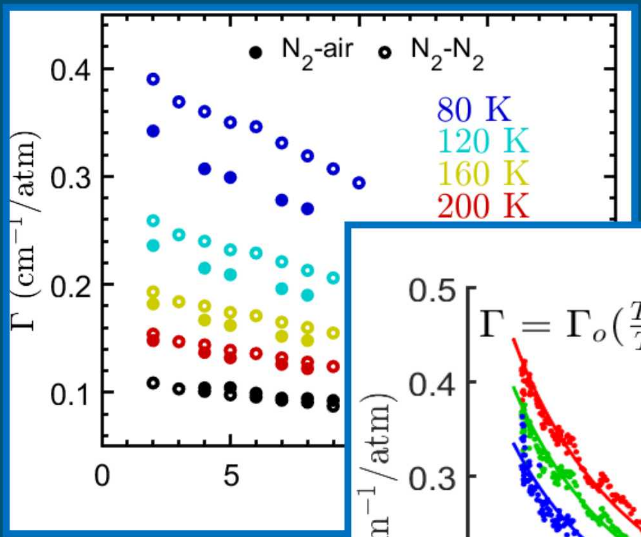
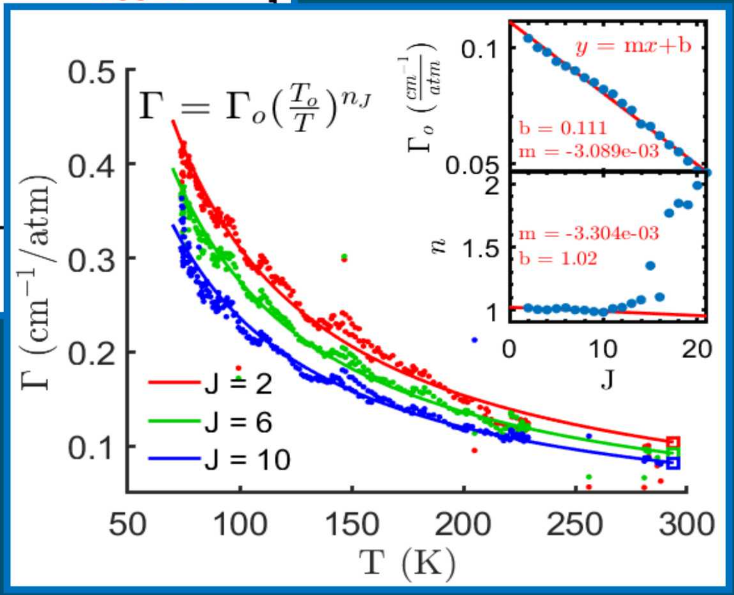


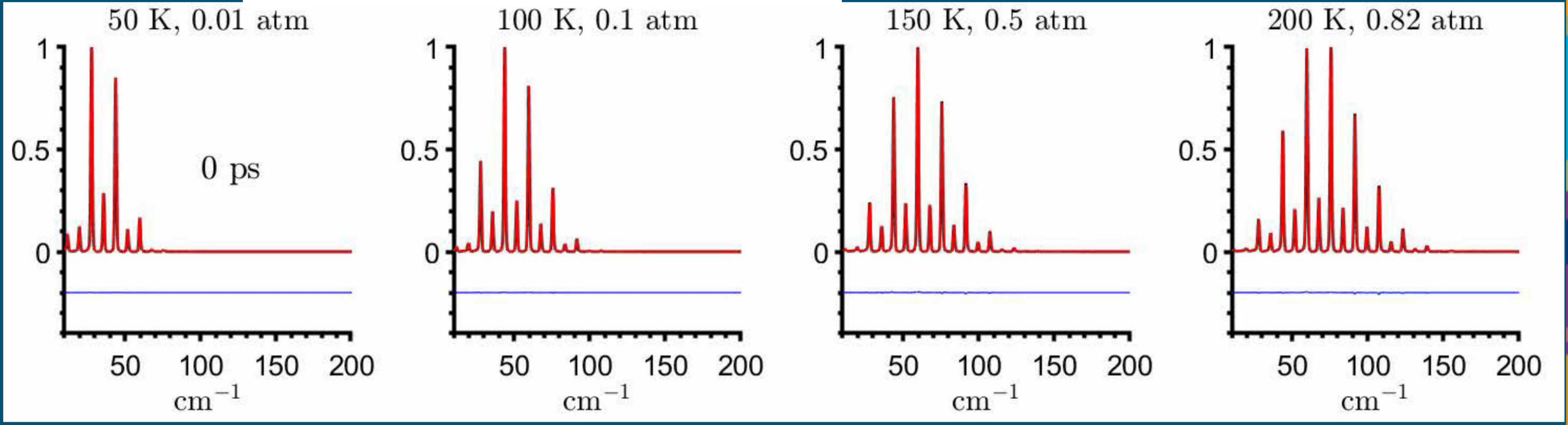


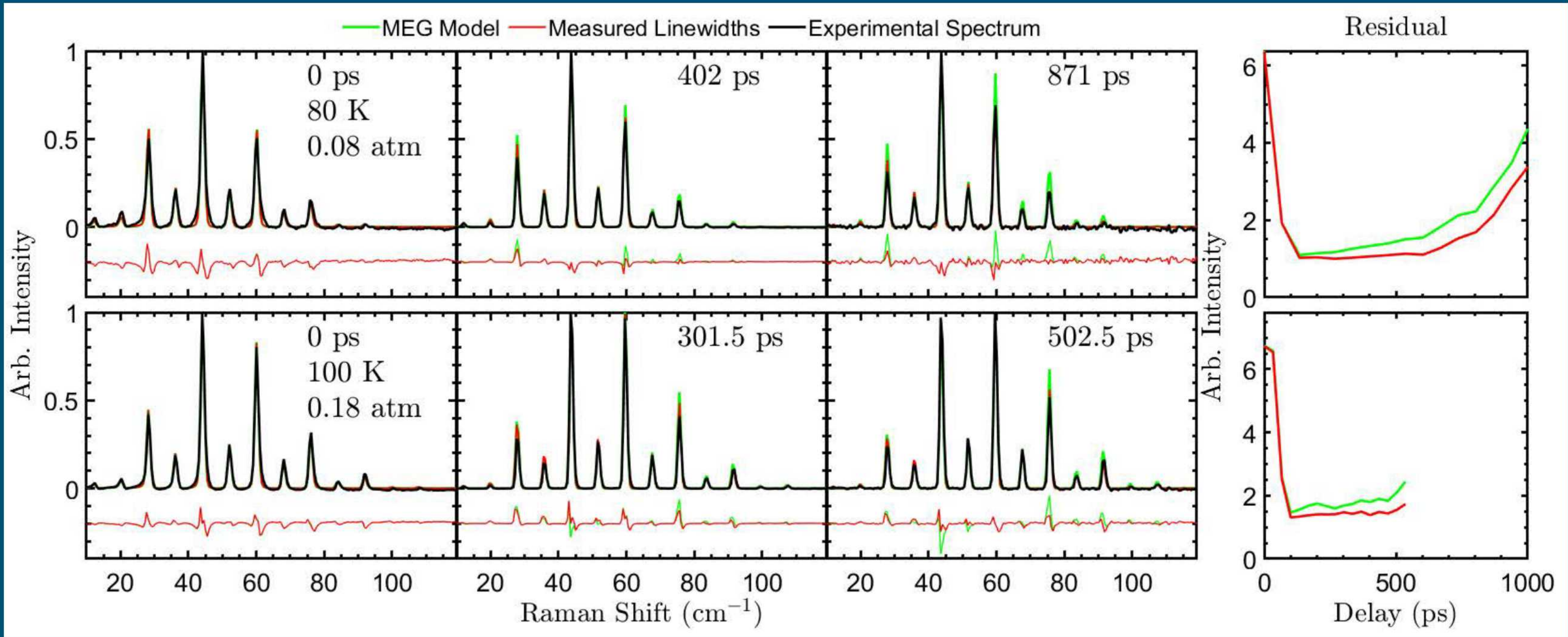
T dependence of Γ correlated by power-law expression



Impact on CARS spectra and pressure measurements

MEG Measured Residual





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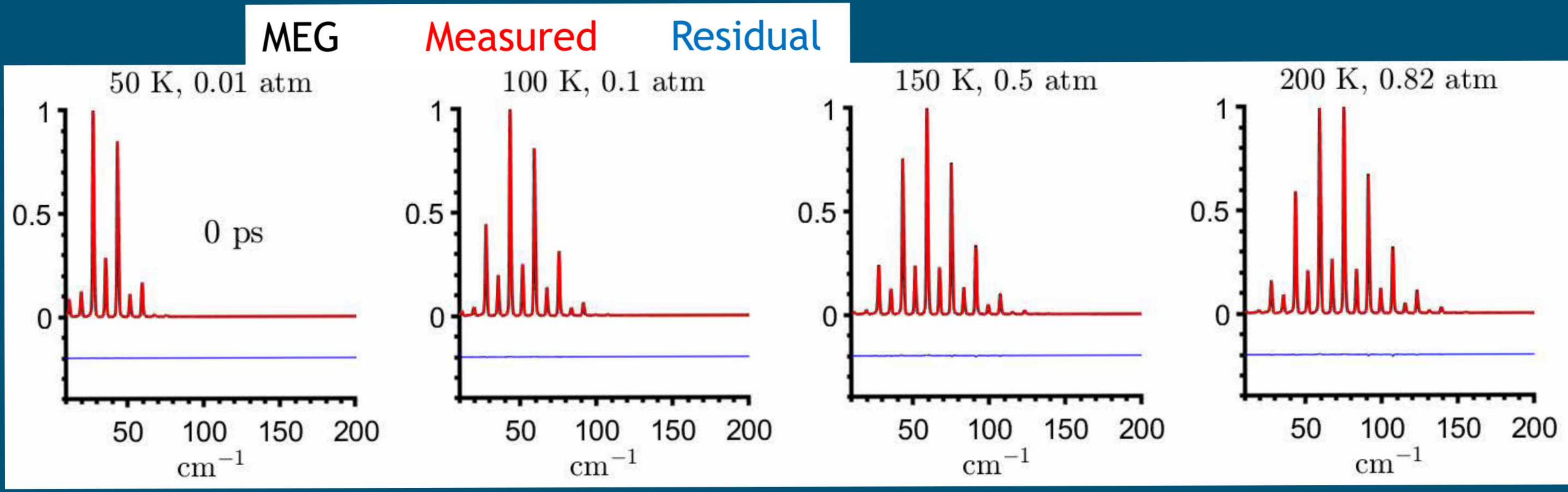
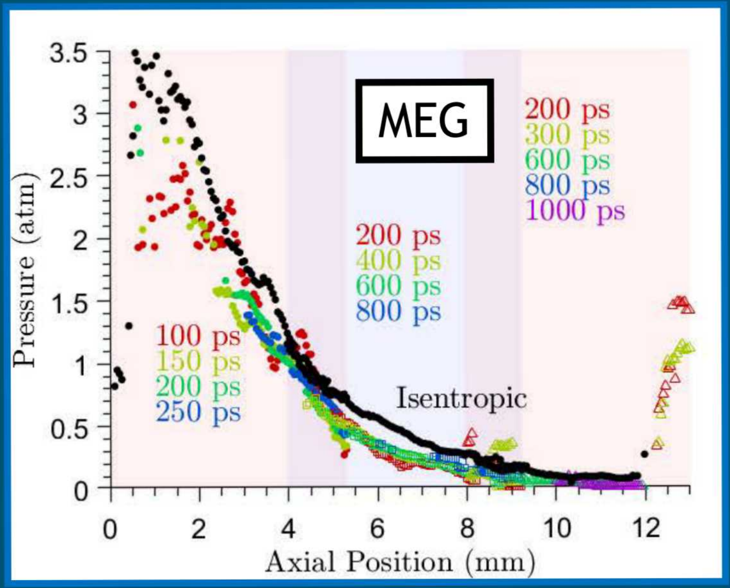
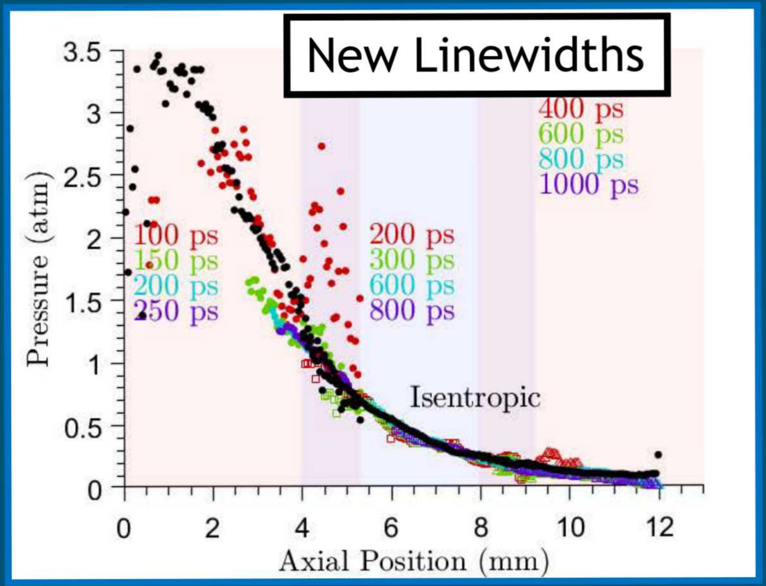
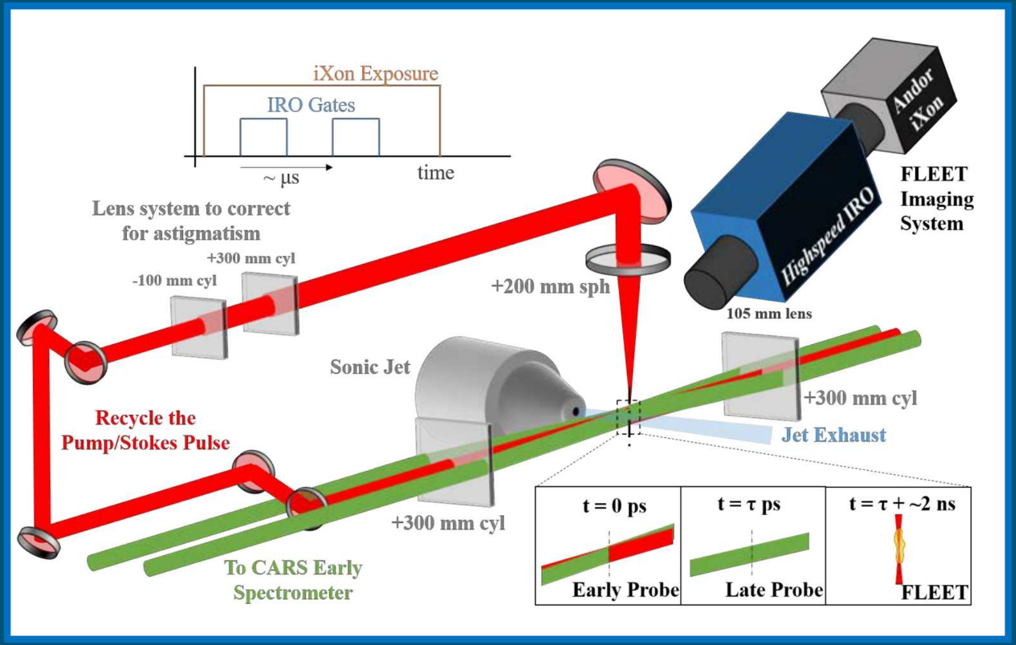






Addition of FLEET Velocimetry



- CARS pump beam "recycled" for FLEET molecular-tagging measurement
- FLEET line oriented radially across the jet
- Simultaneous CARS/FLEET for T/P/V measurement
- FLEET "*t* = 0" line written coincident with CARS beam crossing

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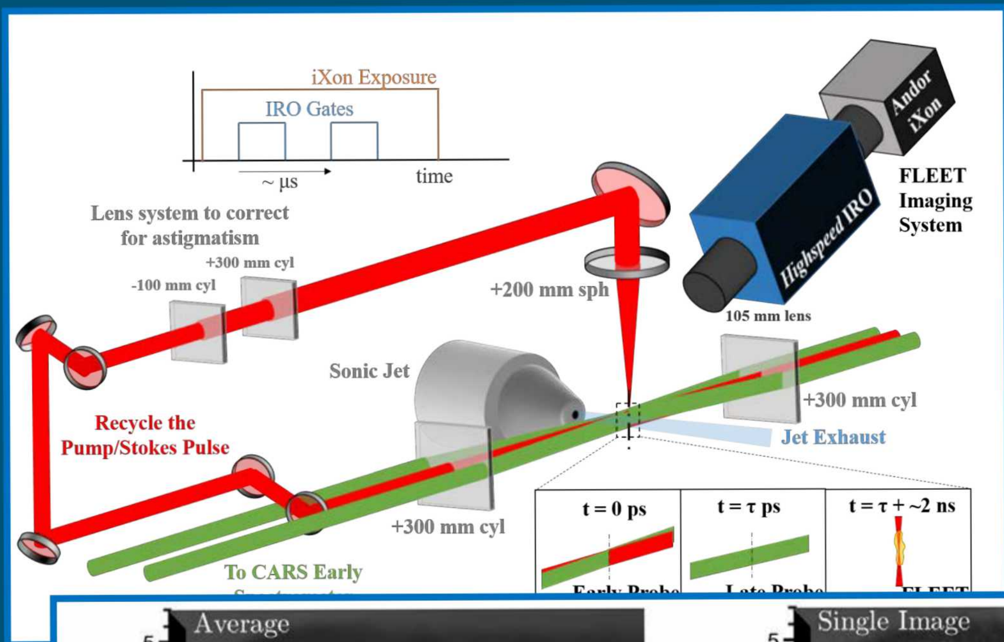

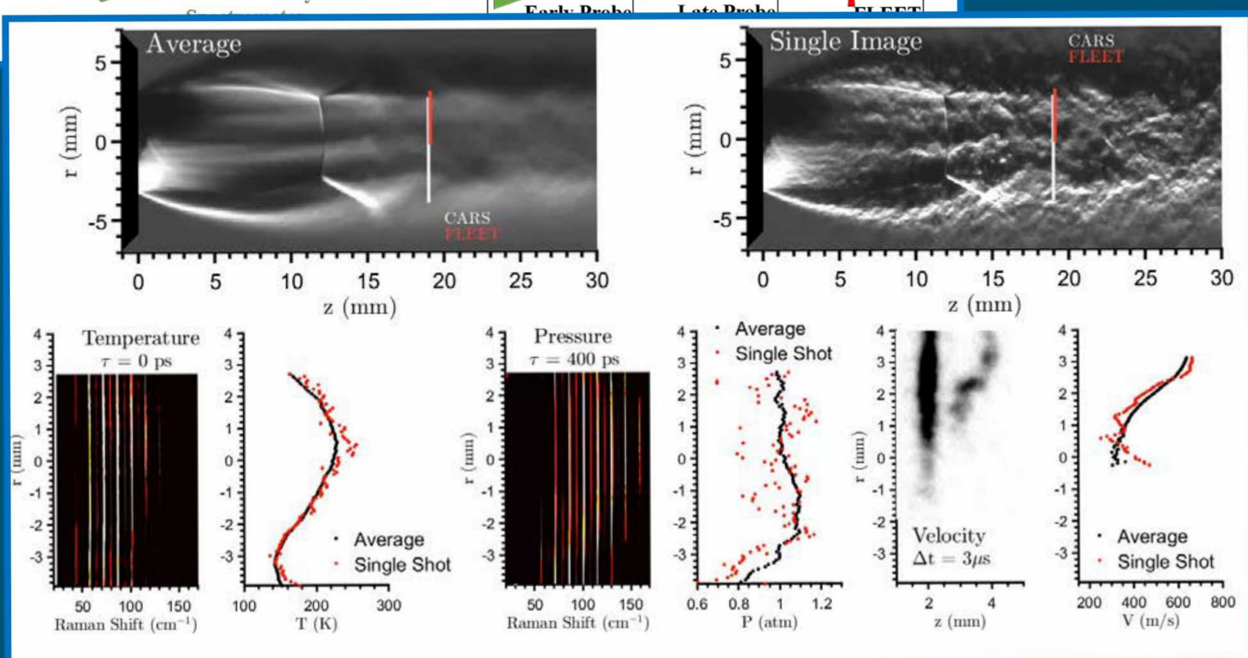

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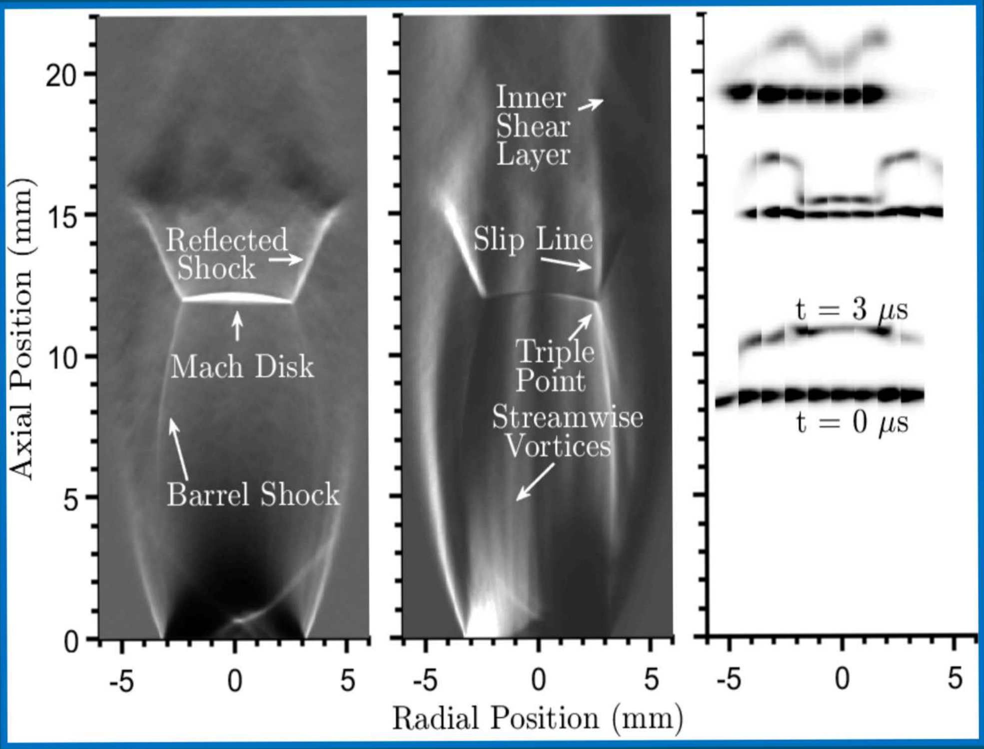
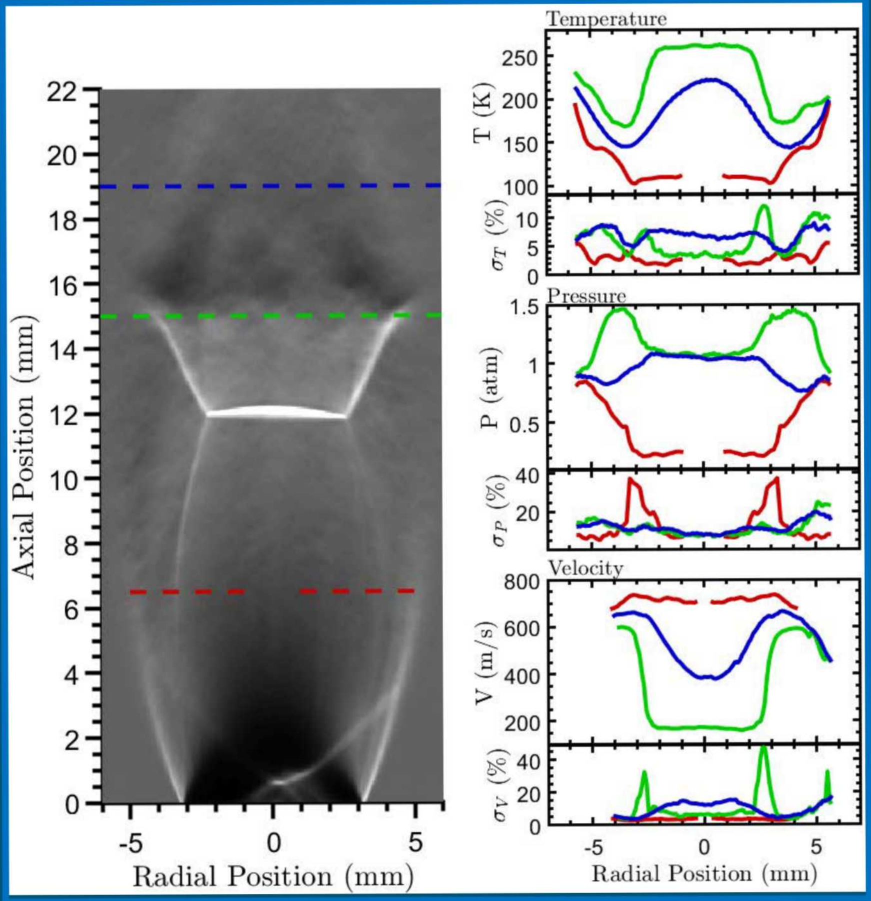
Sample instantaneous CARS/FLEET acquisition and processed T/P/V0 results

Average T/P/V Radial Profiles

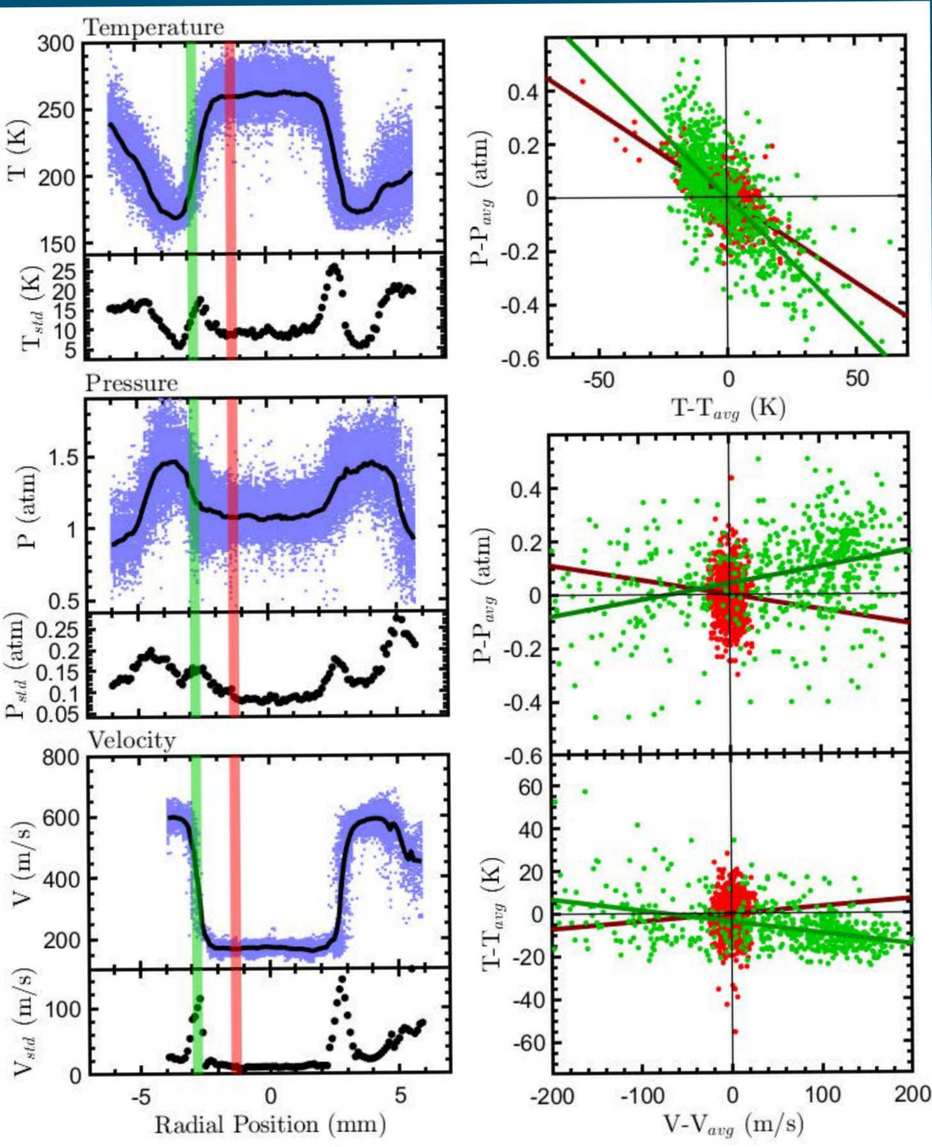
- FLEET velocimetry acquired in multiple segments
- Three axial locations
  - z = 6.5 mm (across barrel shock)
  - z = 15 mm (across slip line)
  - z = 19 mm (turbulent?)



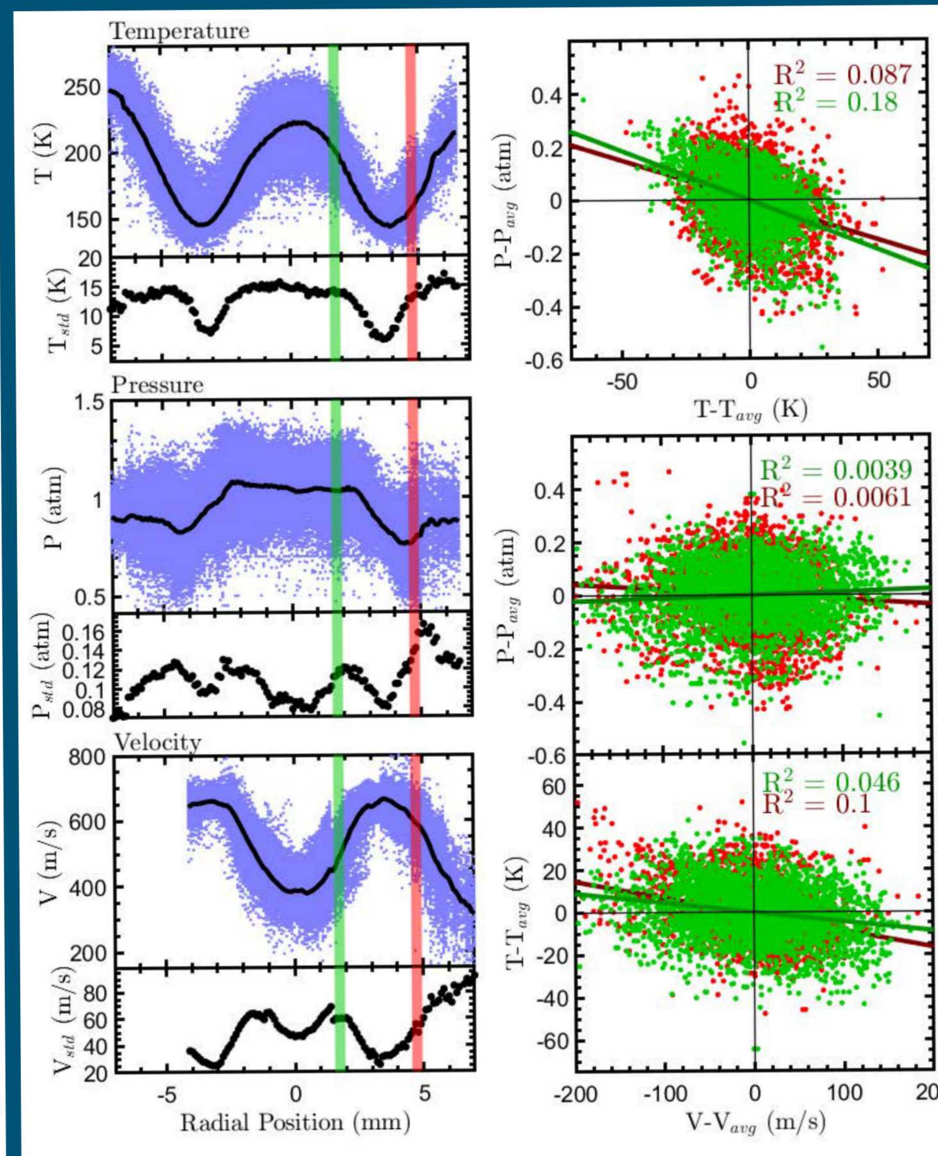


P, T, V Correlations (400 um radial domain)

15 mm



19 mm



Summary and Conclusion

- Hybrid fs/ps *rotational* CARS can be deployed in compressible flows for simultaneous temperature/pressure measurement
- Signal strengths in a sonic jet are sufficient for 1D *line imaging* on single laser shot
  - T = 75—300 K
  - P = 50—800 Torr
- Good dynamic range for thermometry
- Pressure measurements exhibit reduced dynamic range
- Jet measurements exhibit high single-shot precision of 1—3% in both T and P
- Extrapolation of high-temperature MEG linewidths results in underestimated pressure at low T
- New low-temperature *S-branch* linewidths provided based on isentropic jet assumption
- Combination with FLEET velocimetry demonstrated