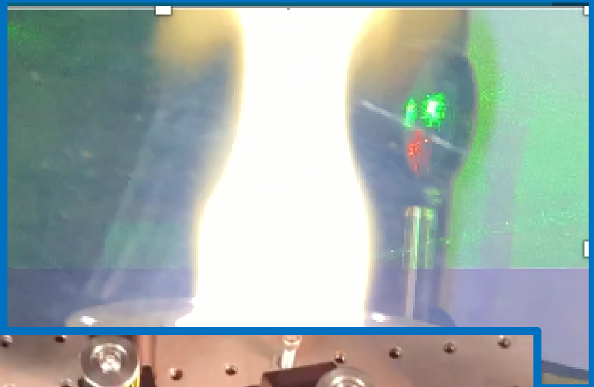
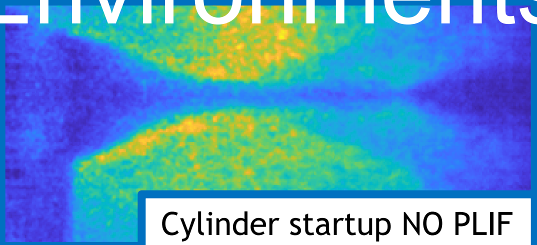
SAND2022-12717C

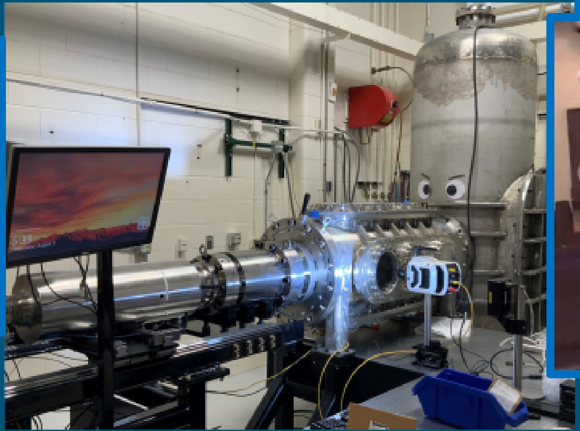
Sandia National Laboratories

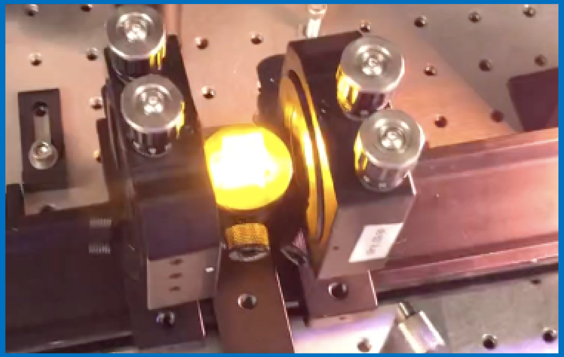
CARS Thermometry and Species Measurements in Extreme-Temperature Environments





Cylinder startup NO PLIF





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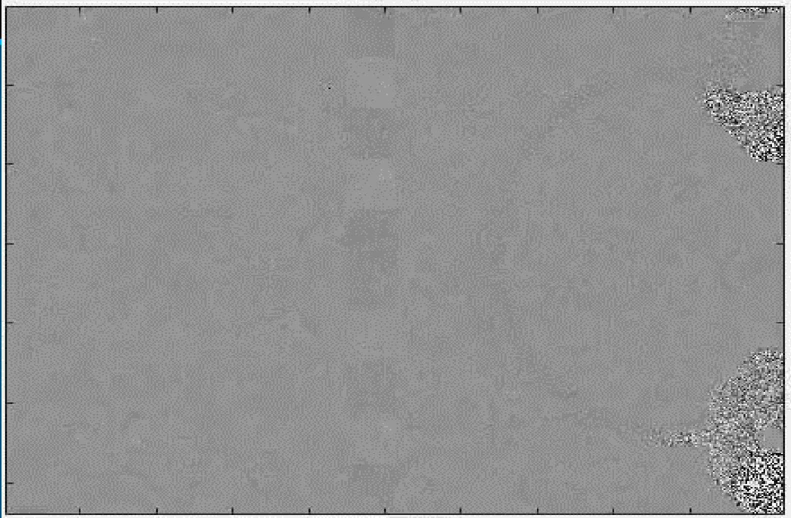
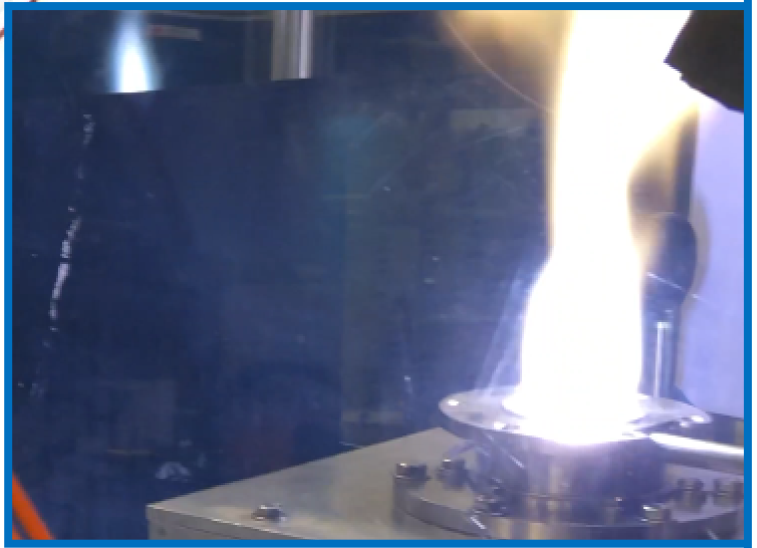
Our Motivation: High Temperature Materials Test Environments

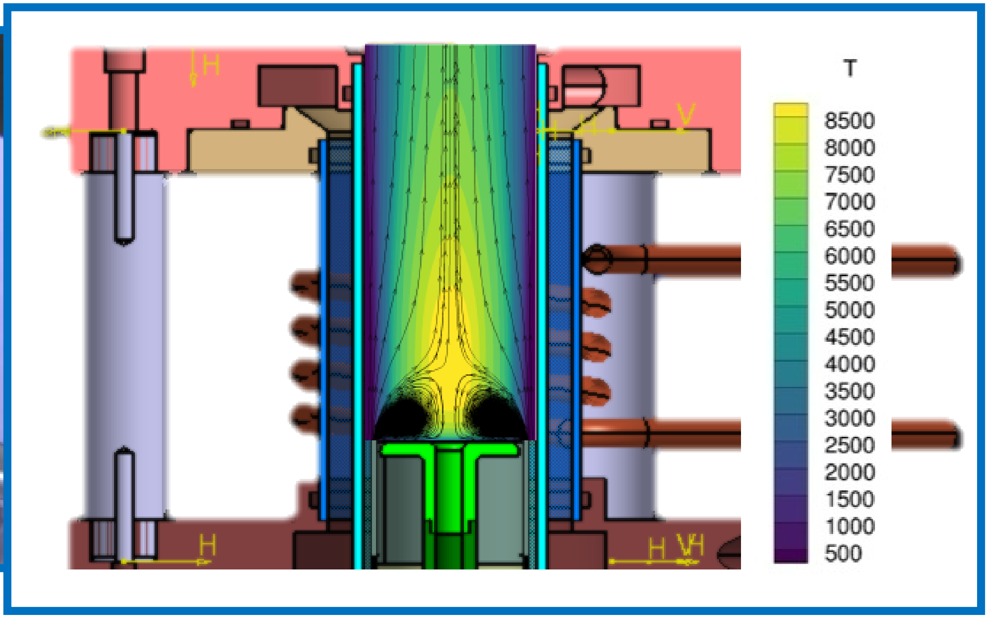
Free-Piston Reflected Shock Tunnel



Inductively Coupled Plasma Torch

N_2 CARS Thermometry in IC Plasma Torch at UT-Austin



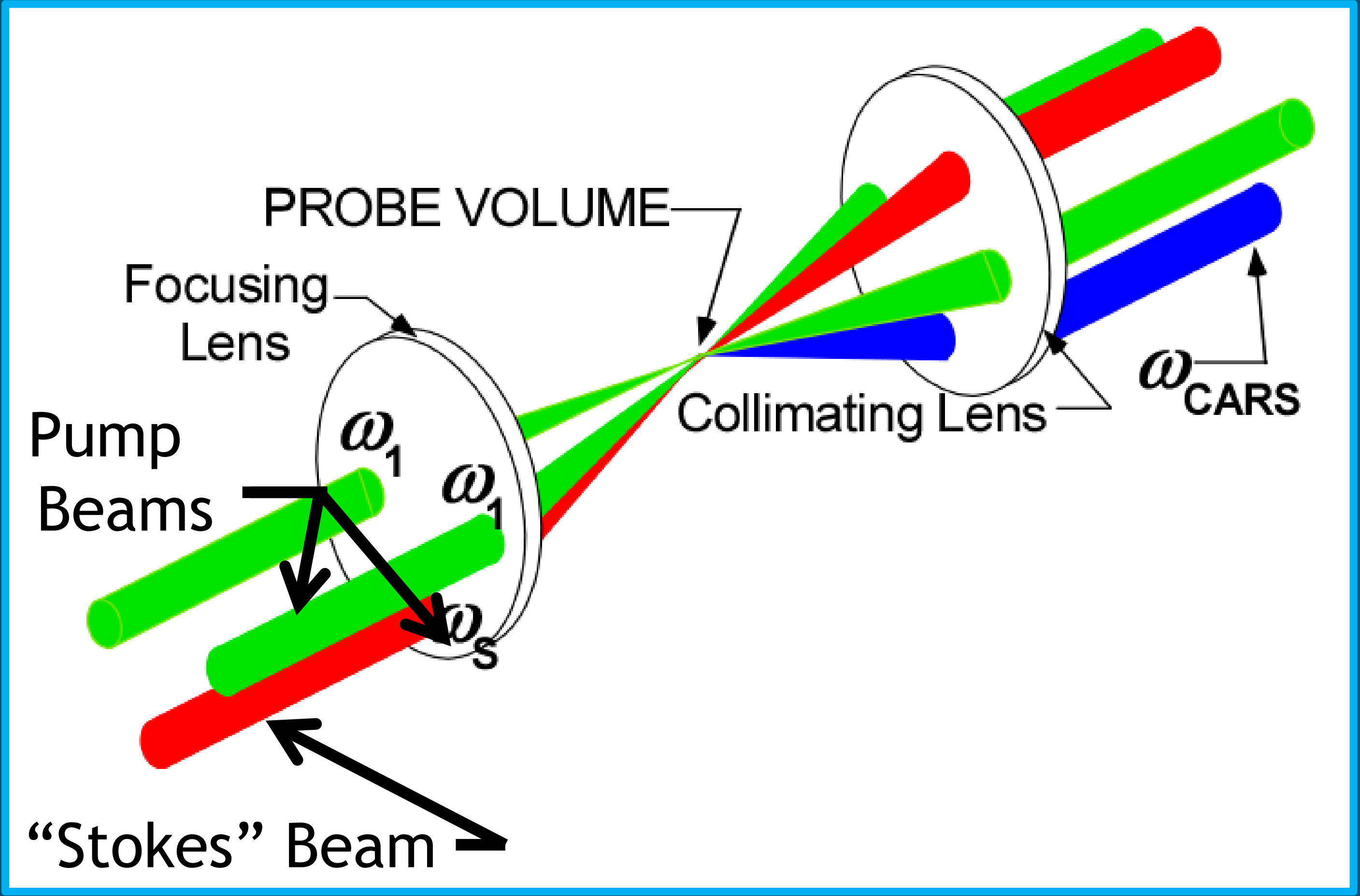


<u>Inductively Coupled Plasma Torch</u>

- Source for testing of hypersonic TPS materials
- “Chemically clean” – electrodes isolated from flow
- Realistic temperatures (T > 6000 K)
- Low flow rate – cannot match flight conditions

Collaboration with DOE/PSAAP Center at UT

Coherent anti-Stokes Raman scattering (CARS)



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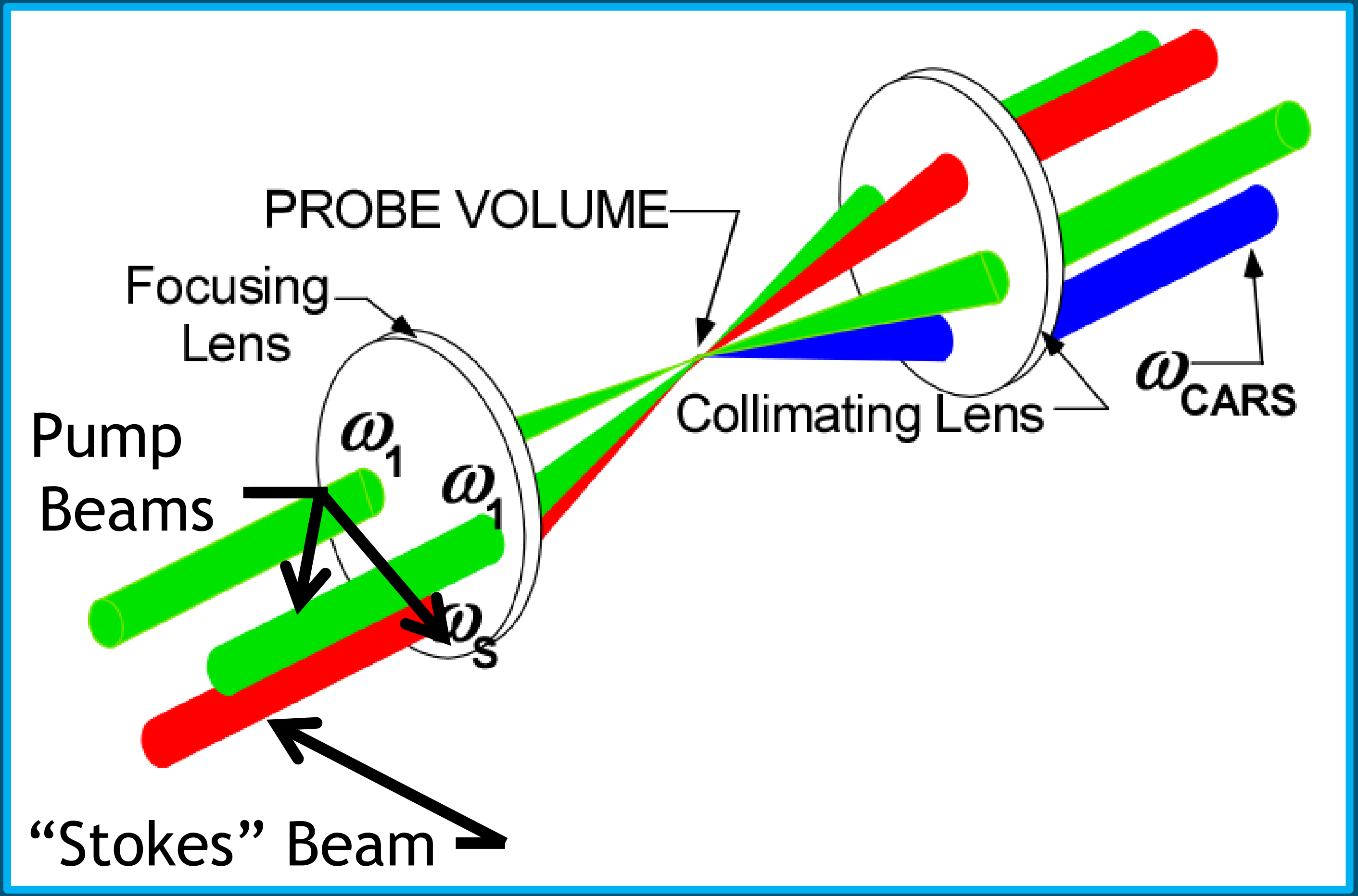
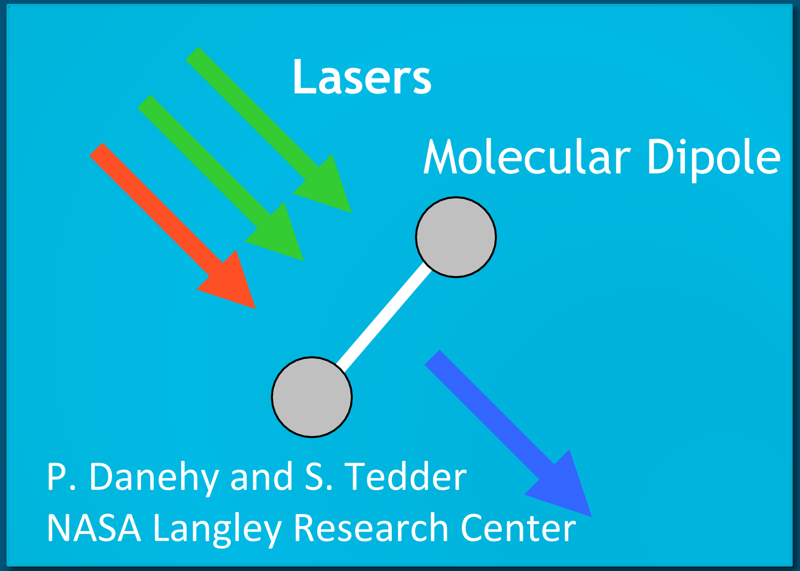
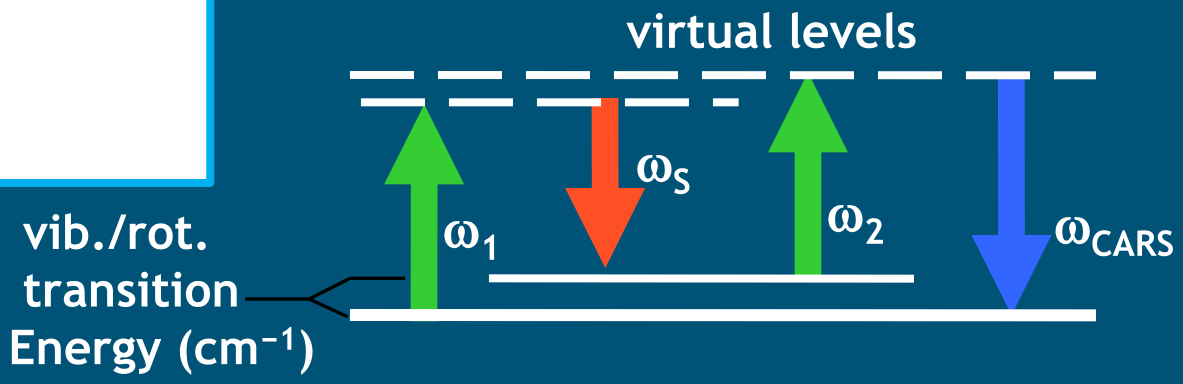
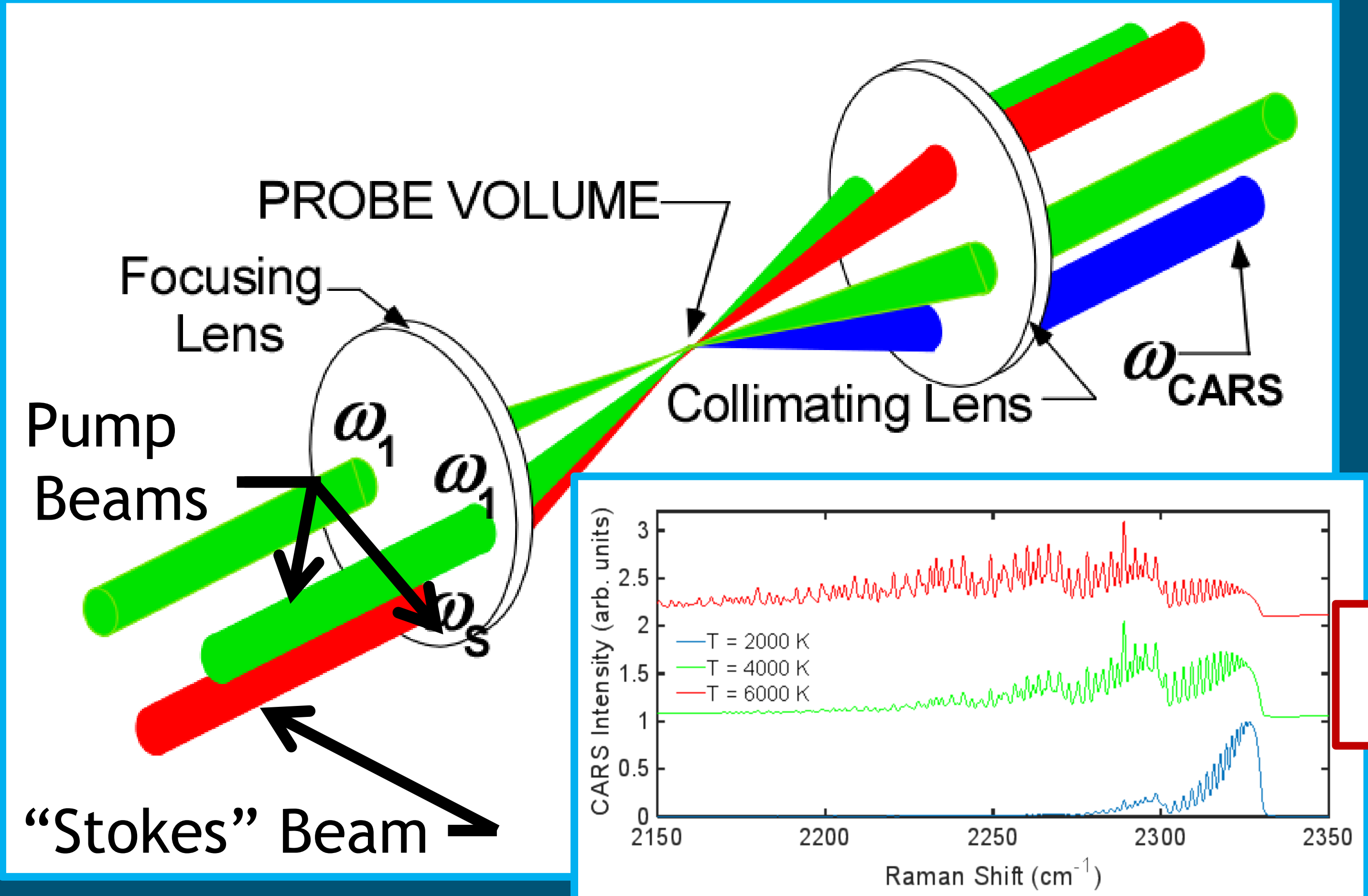




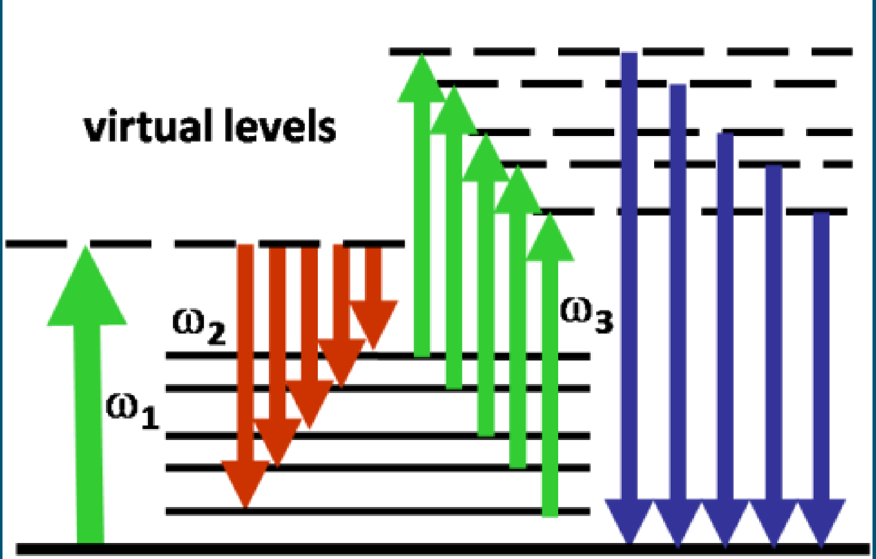
Coherent Anti-Stokes Raman



Coherent anti-Stokes Raman scattering (CARS)



Calculated N_2 CARS Spectra

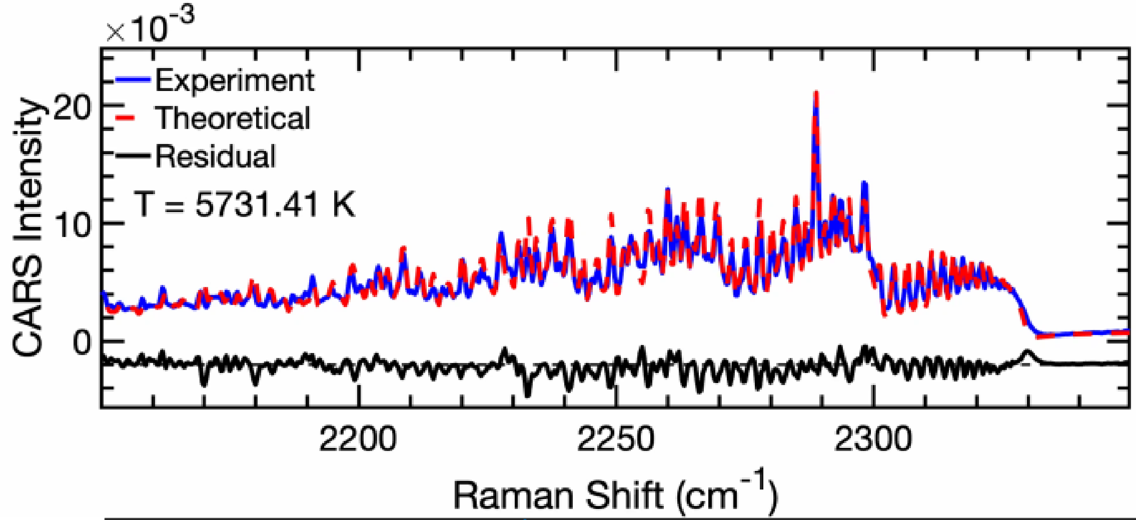


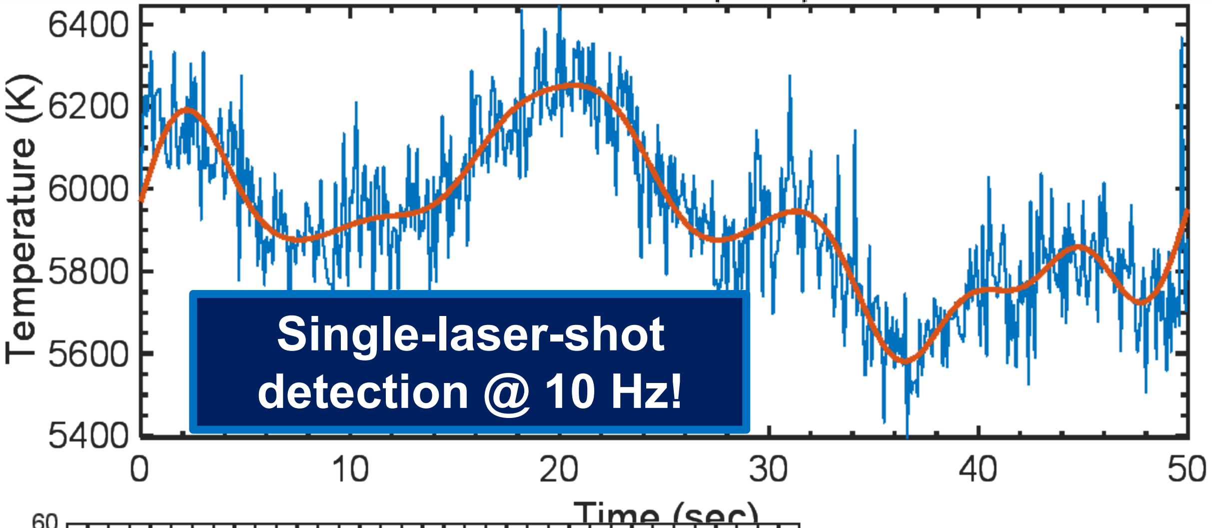
Broadband Stokes Source Pumps Multiple Raman transitions simultaneously

IC Plasma Torch N_2 Thermometry

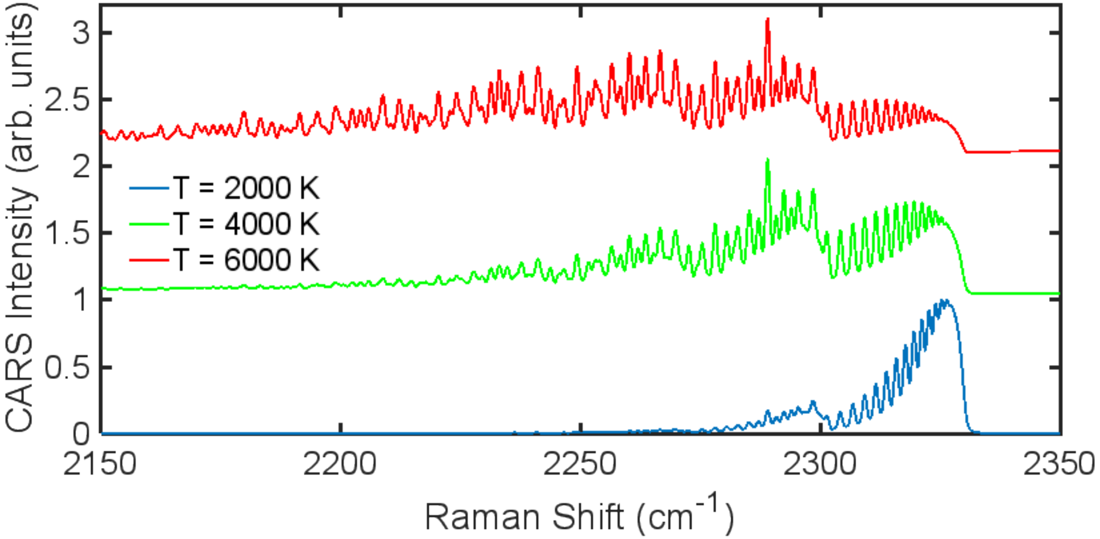
<u>"Conventional" CARS Instrument</u>
- ~10-ns laser pulses at 10-Hz
- Broadband dye laser for Stokes source

<u>Key technical challenges</u>
- Very high background luminosity
- Extreme temperatures, <u>*some of the highest ever measured with this technique*</u>

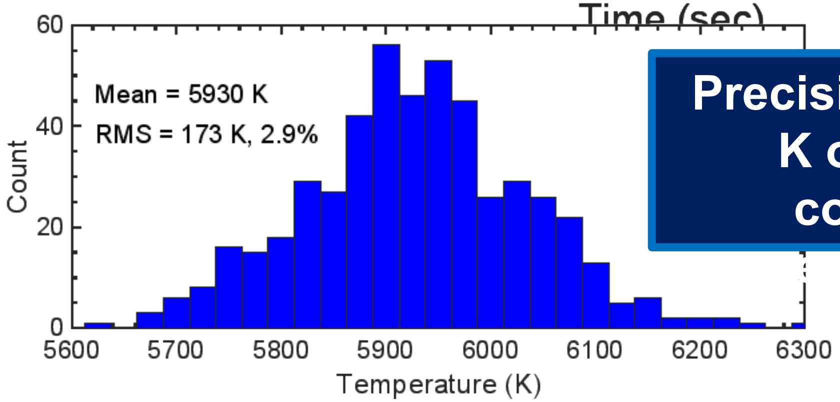




Single-laser-shot detection @ 10 Hz!

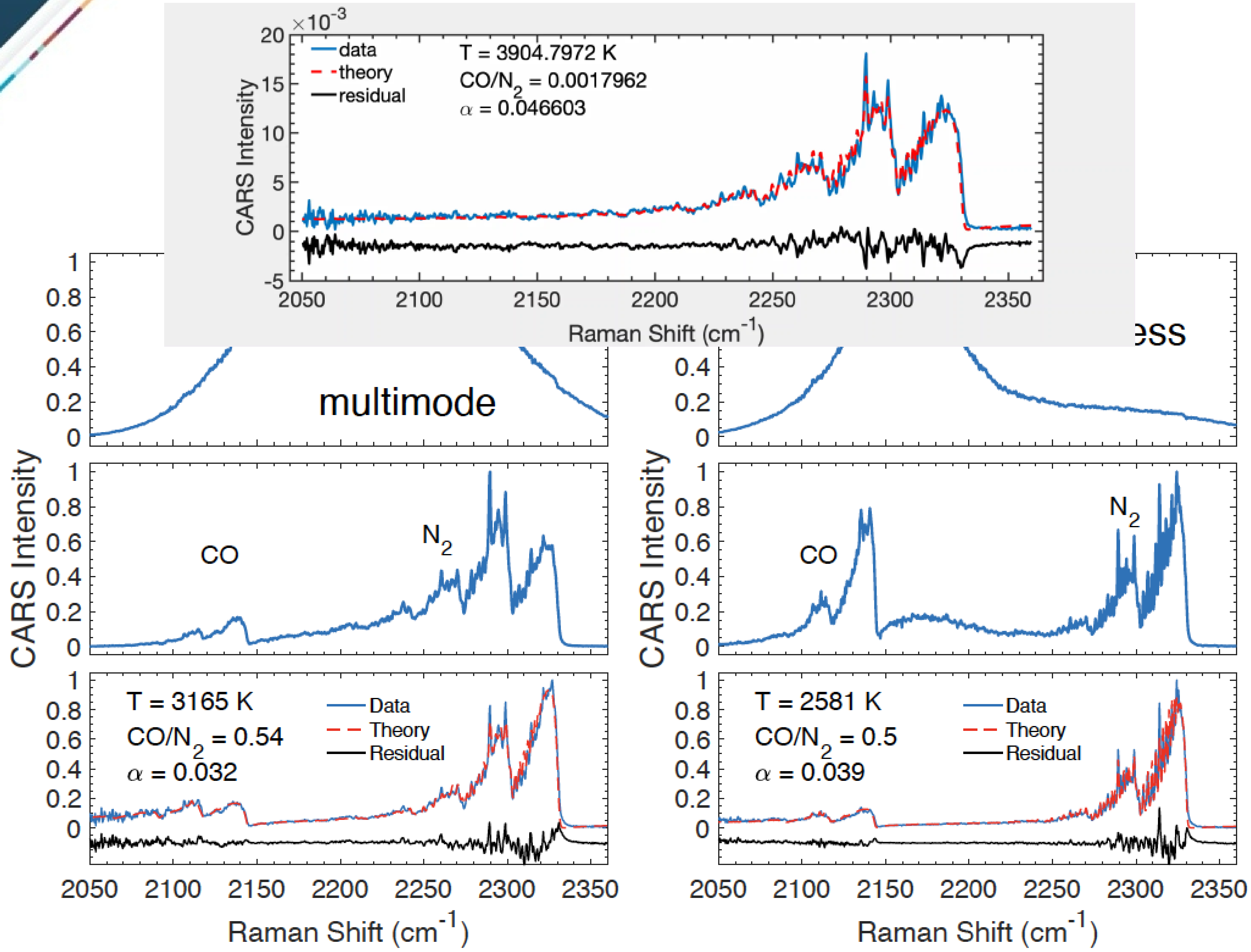


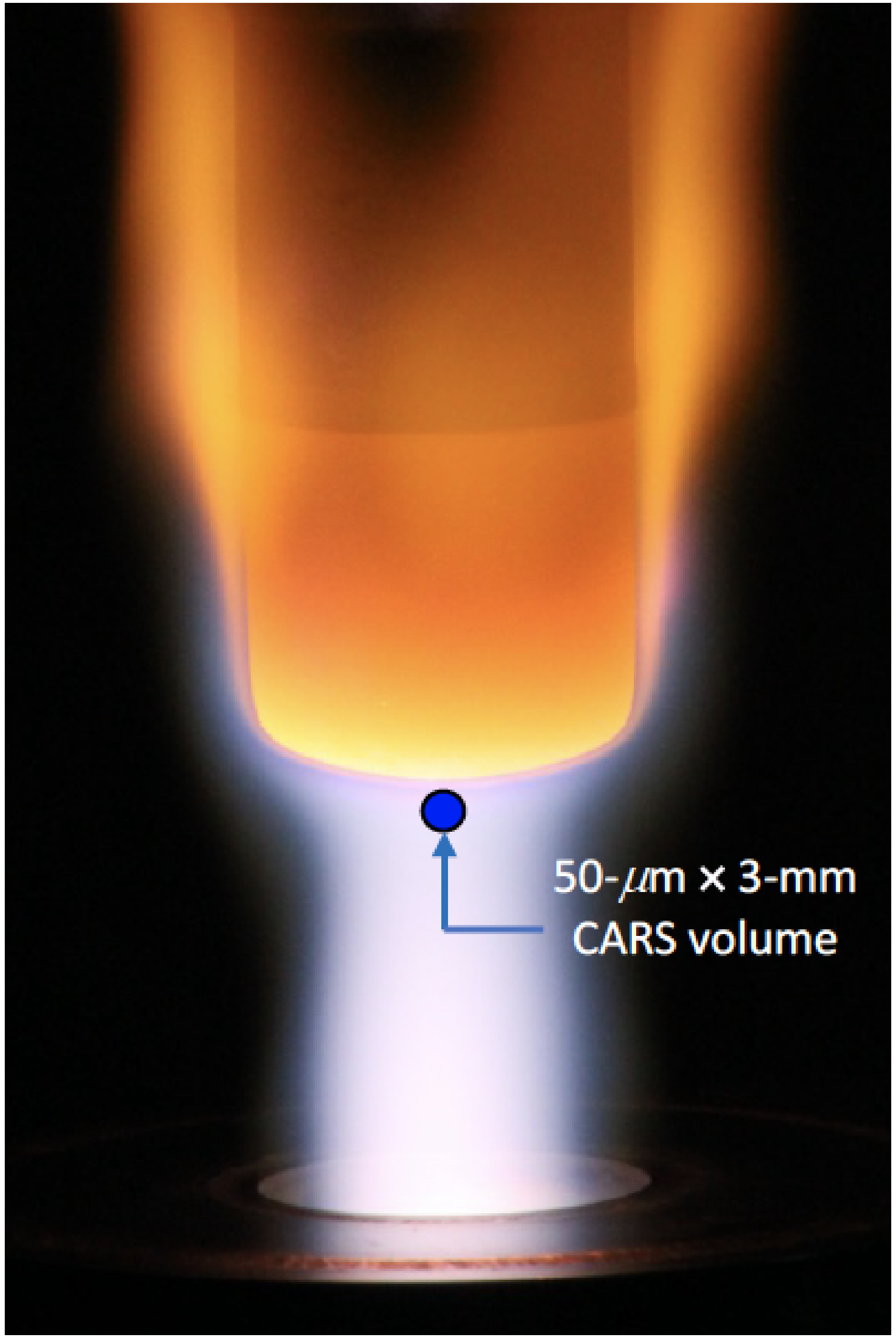
<u>Calculated N_2 CARS Spectra</u>



Precision at T = 5900 K on par with combustion

CO/Temperature Measurements in High-T Reaction Layer





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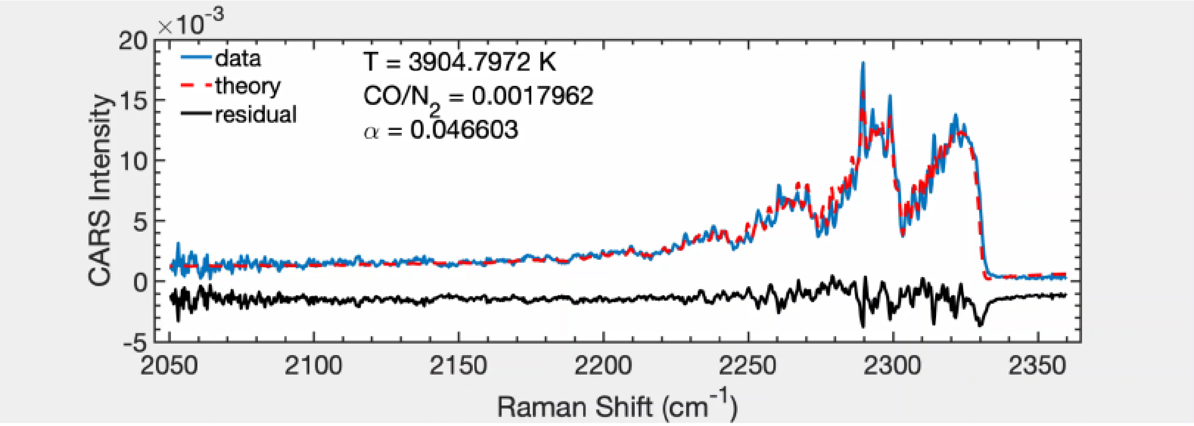
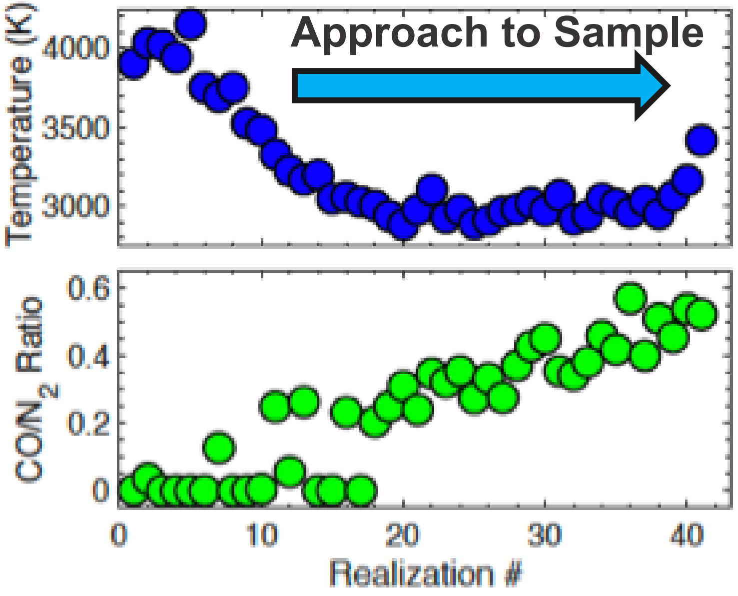
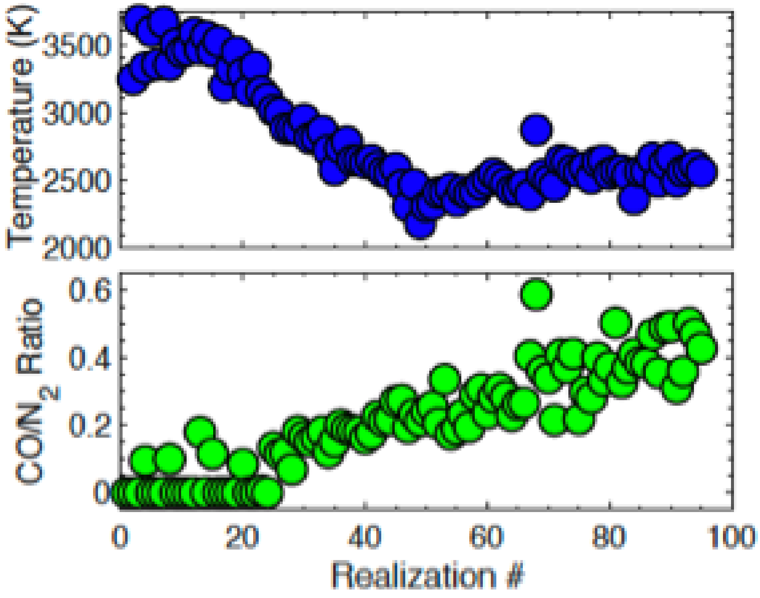
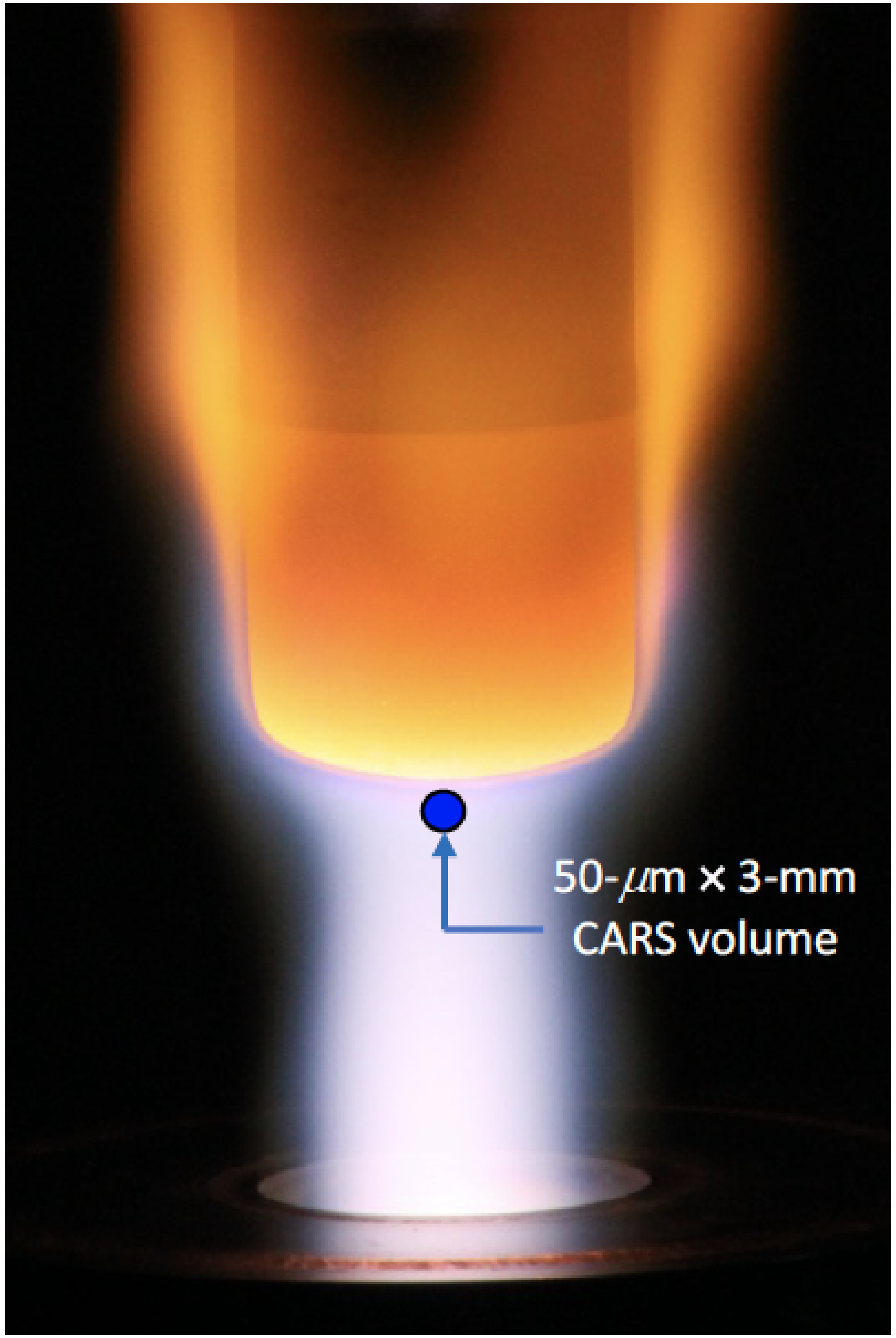
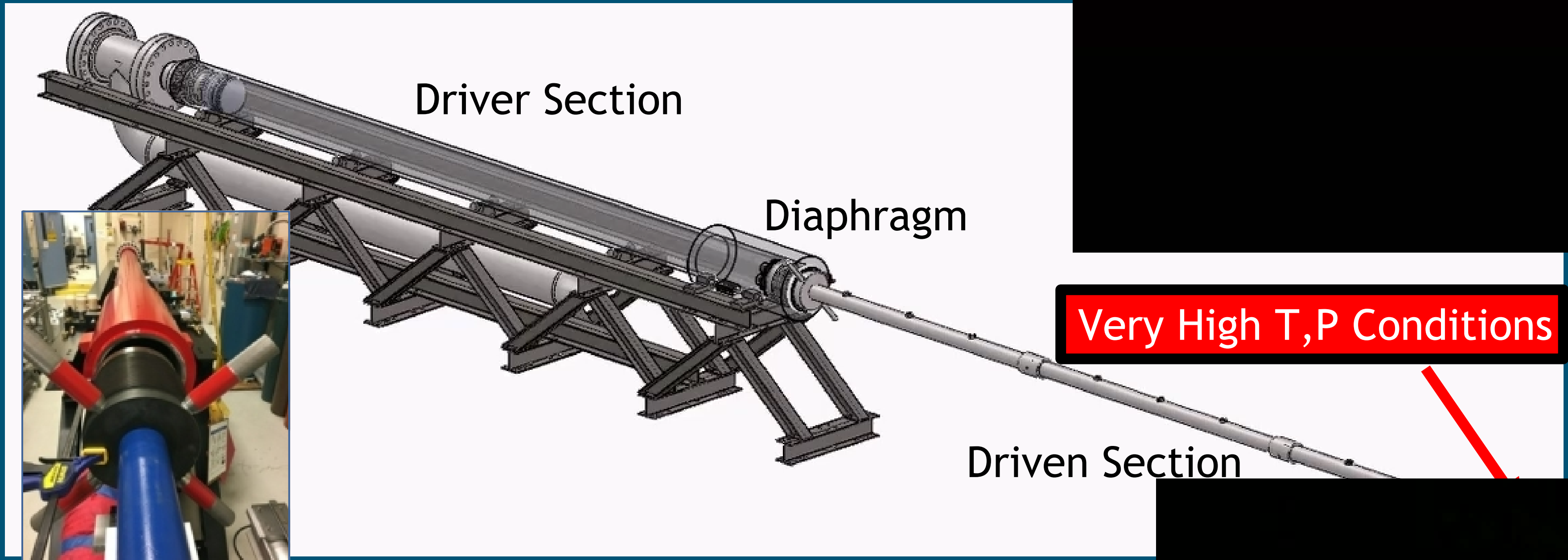


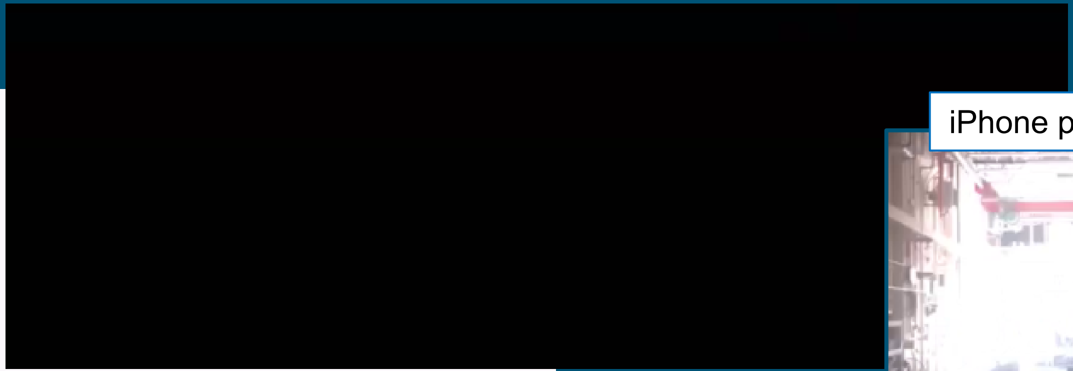






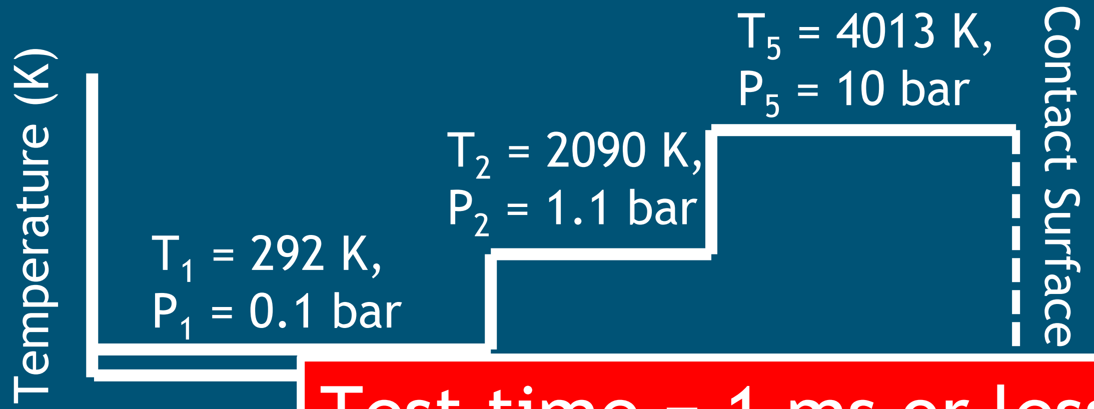
Sandia Free-Piston-Driven High-Temperature Shock Tube (HST)



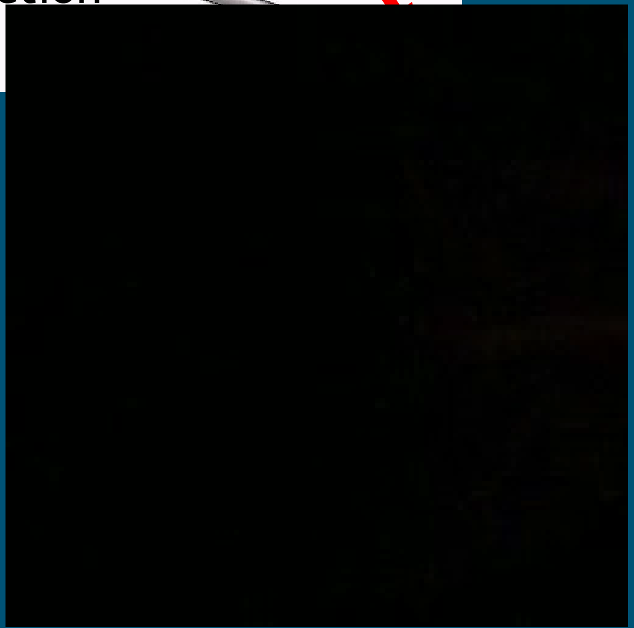


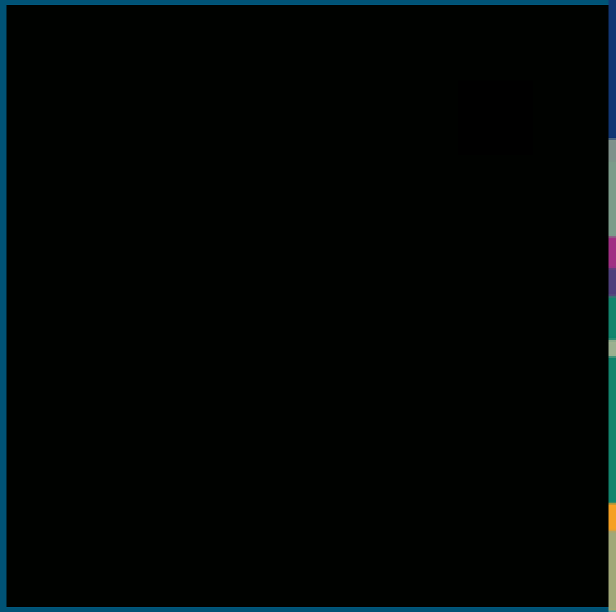
iPhone photo

Very High T,P Conditions



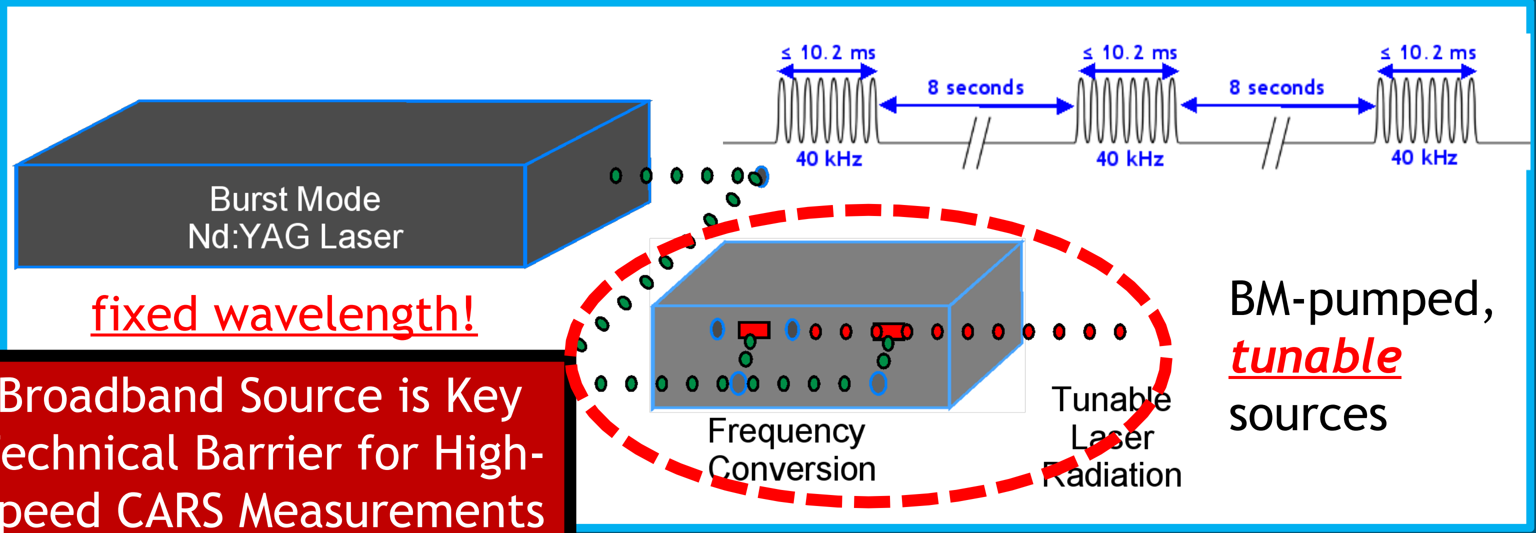
Test time = 1 ms or less!





Picosecond Pulse-Burst CARS at 100 kHz for HST Application

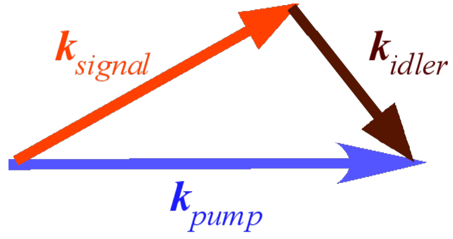
- Burst-mode lasers have allowed experimentalists to access high-speeds (10s to 100s of kHz)
- While powerful, these systems are not wavelength tunable—this prohibits application of ***chemically specific*** imagi[ng] and spectroscopic tools



Broadband Source is Key Technical Barrier for High-Speed CARS Measurements

Broadband Picosecond Optical Parametric Generator/Amplifier (OPG/OPA)

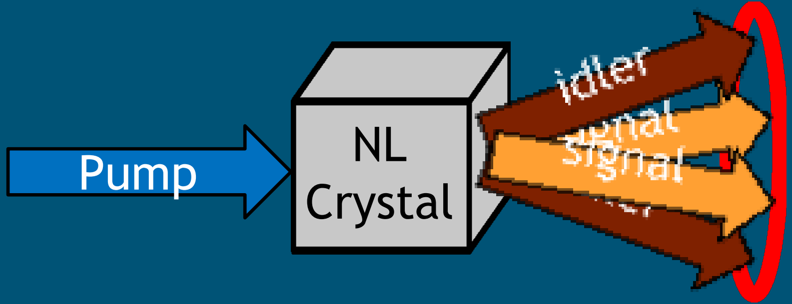
Phase Matching Requirements



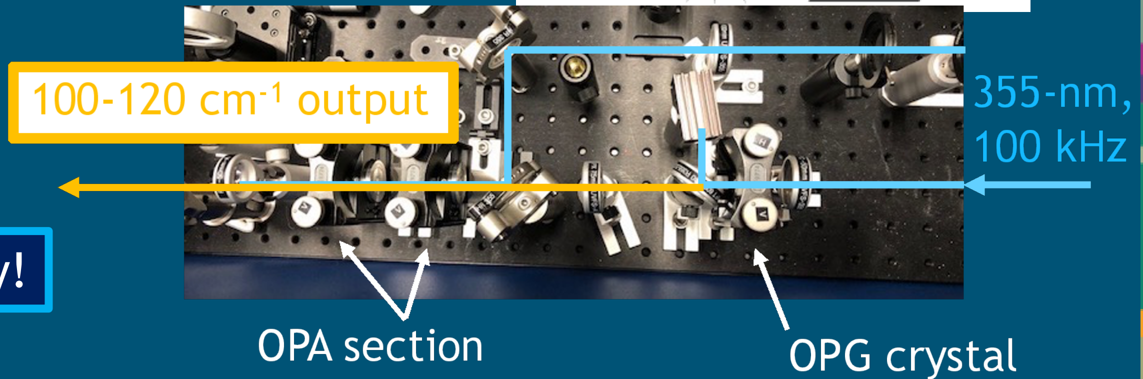
$$\mathbf{k}_{pump} = \mathbf{k}_{signal} + \mathbf{k}_{idler}$$

$$\omega_{pump} = \omega_{signal} + \omega_{idler}$$

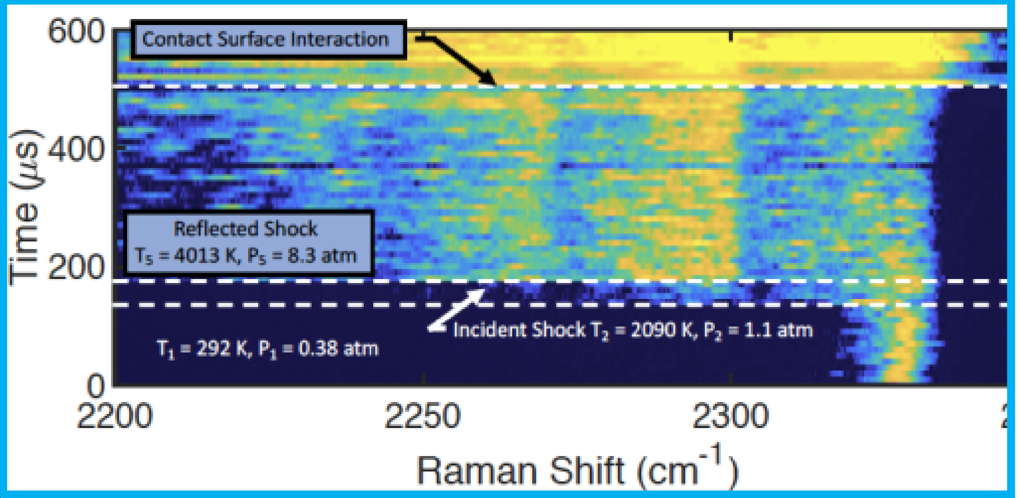
$$|k| = 2\pi/\lambda\ ,\ \omega = 1/\lambda$$

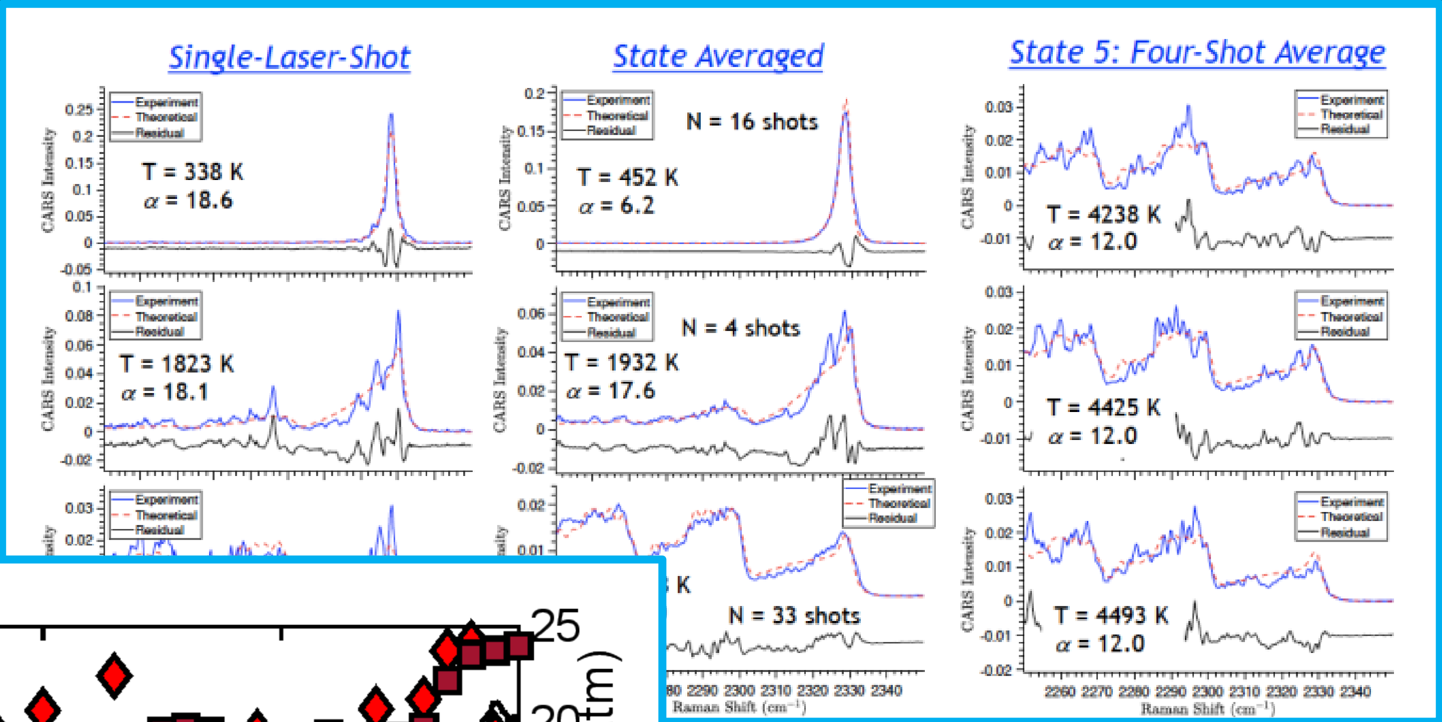


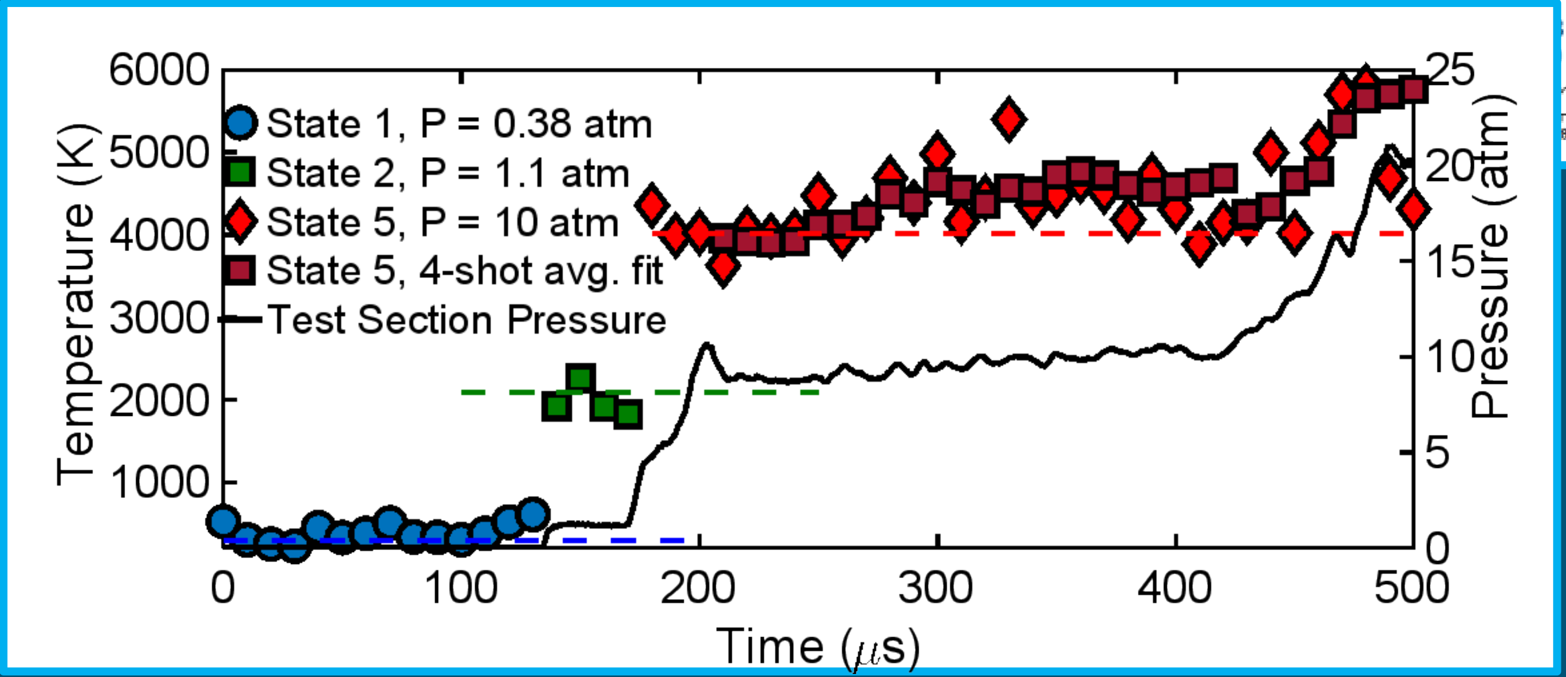
Picosecond OPG = Enabling Technology!



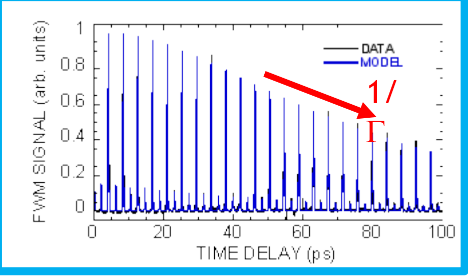
100-kHz Pulse-Burst CARS in the Sandia Free-Piston Shock Tube







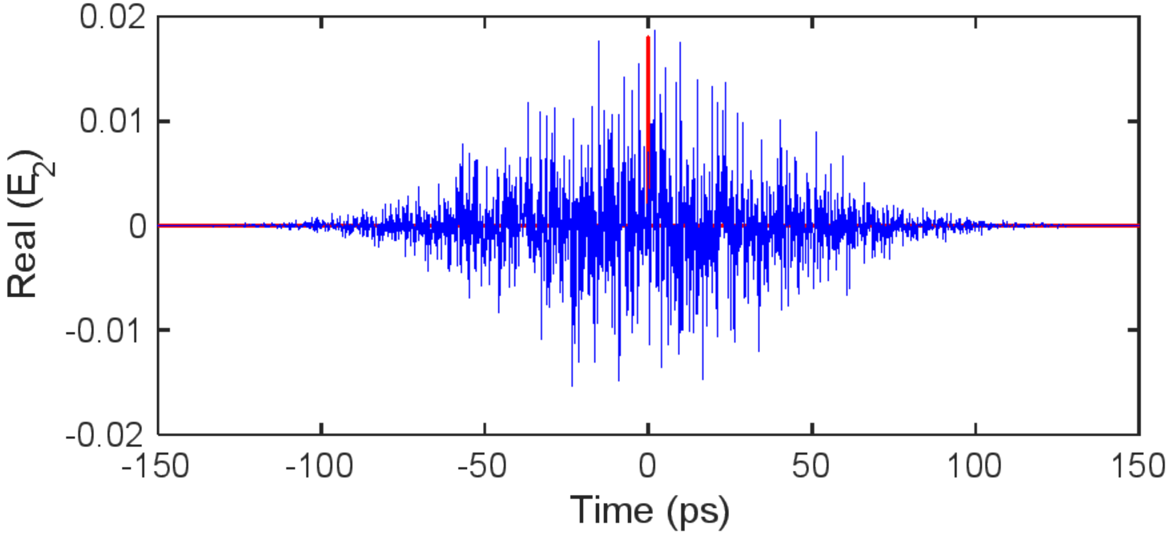
Picosecond CARS comes with a single-shot noise penalty



Dominant source of CARS noise is the quality of the broadband pulse

Time-Bandwidth Product - Fourier-Transform Limit

$$\Delta t\left[\mathrm{ps}\right]\Delta\omega\left[\mathrm{cm}^{-1}\right] \geq 14.67$$



- To achieve sufficient bandwidth for CARS, pulse must exhibit ~150-fs features – inherently noisy!

Picosecond CARS lies between cw and impulsive limits

$\Delta t\ \Gamma$

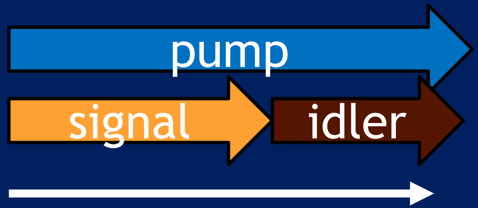
<<1	~1	>>1
fs (impulsive) CARS	ps CARS	ns (cw) CARS
Transform limited (low noise)		Time averaged

- Δt ~ 50-100 ps ~ $1/\Gamma$ → very little averaging in the Raman process

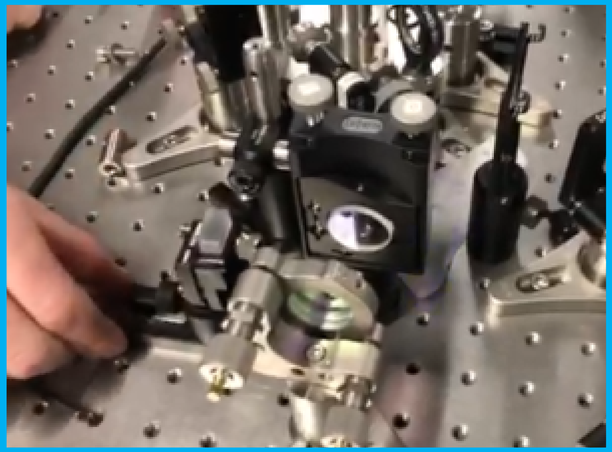
Nanosecond Burst-Mode CARS via *Noncolinear* Optical Parametric Oscillator

Conversion of *low-intensity nanosecond* pulses requires laser-cavity gain

Most OPOs are co-linear to satisfy phase-matching constraint

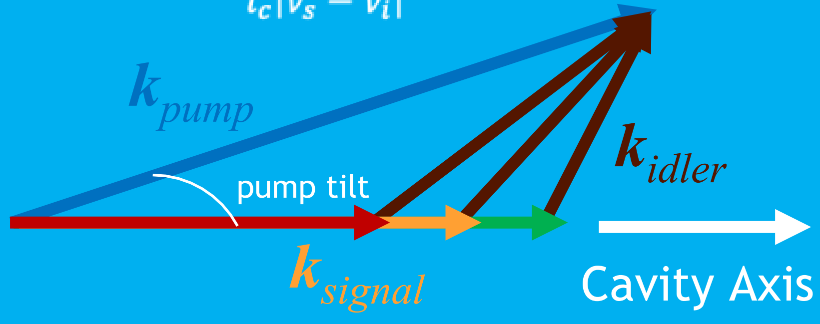


constrained to laser cavity axis



OPO Bandwidth is enhanced by matching group velocities of signal and idler waves

$$FWHM_{OPO} = \frac{c}{l_c|v_s - v_i|}$$



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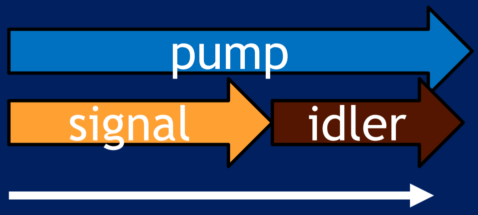
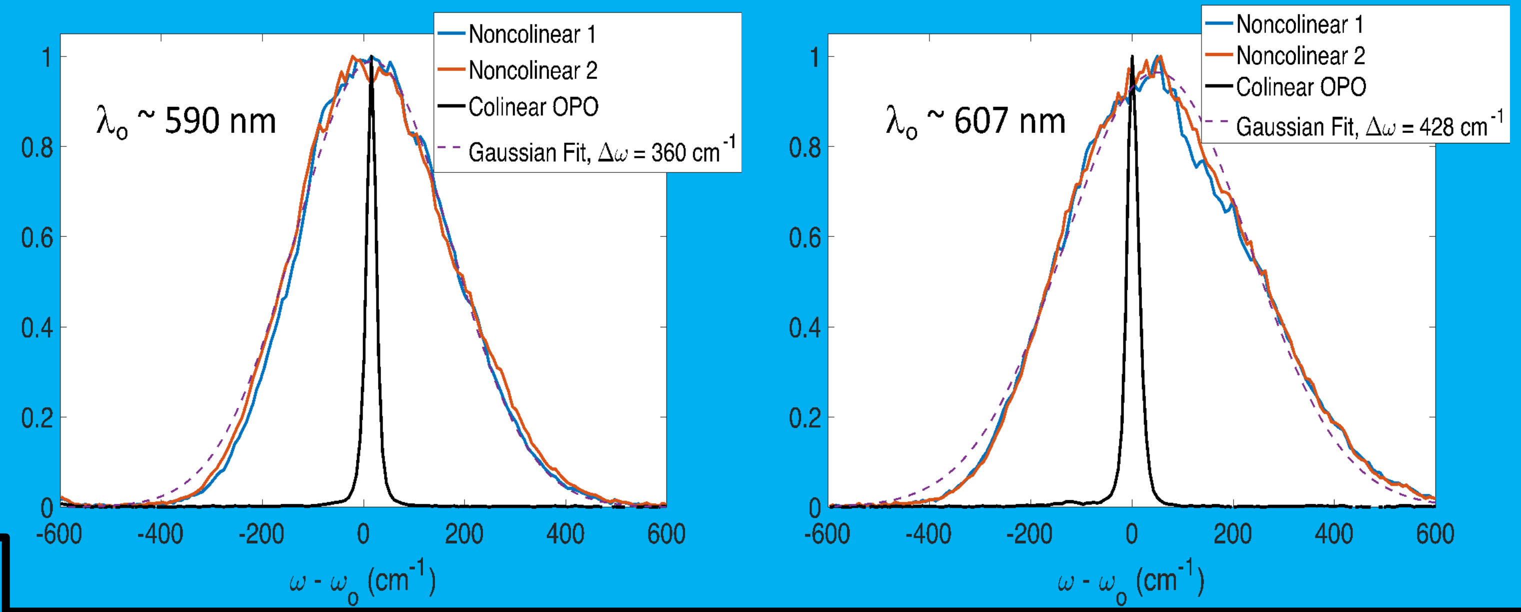


constrained to laser cavity axis



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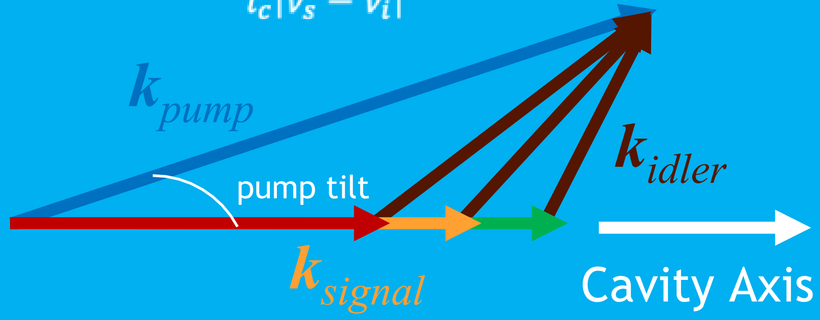
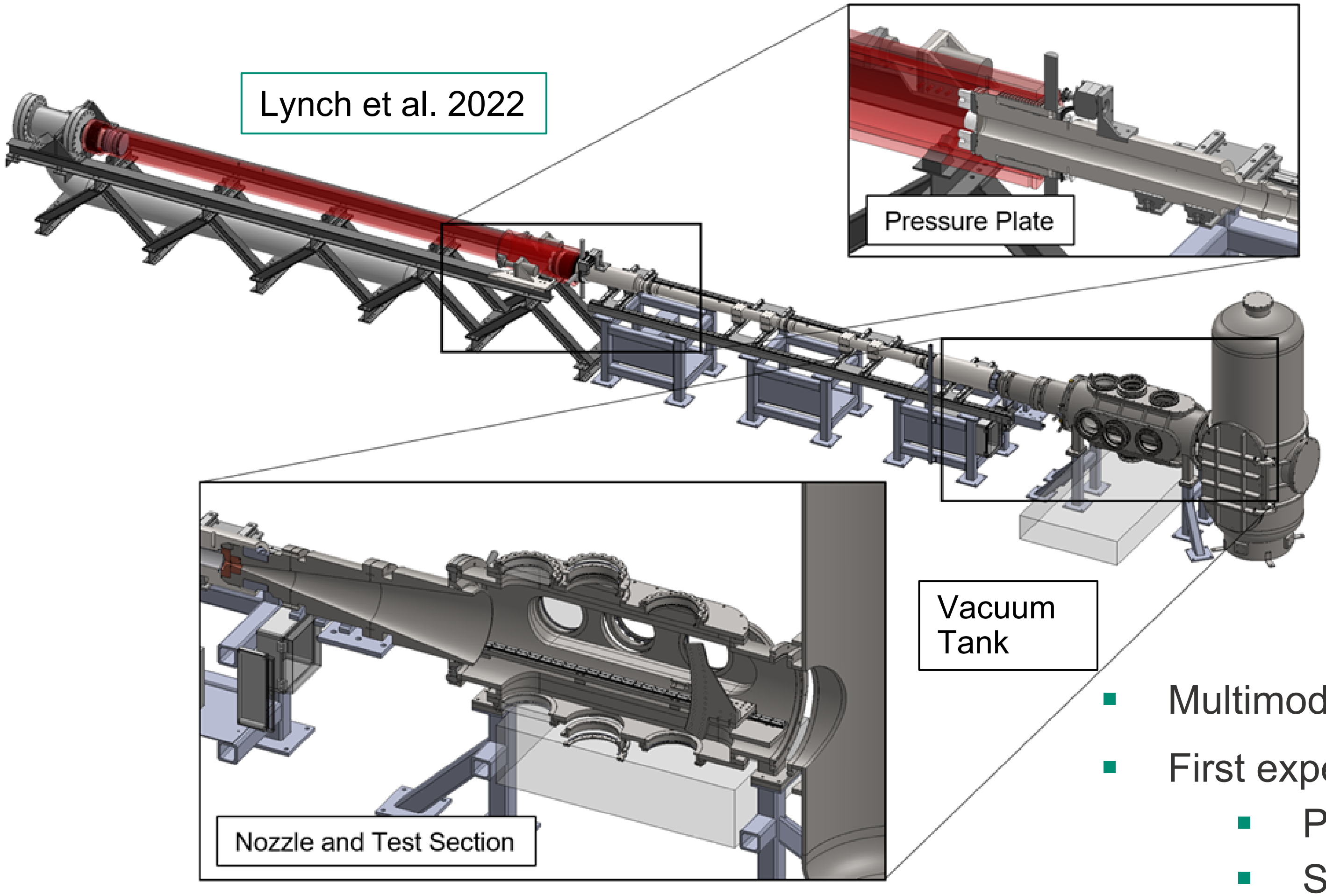
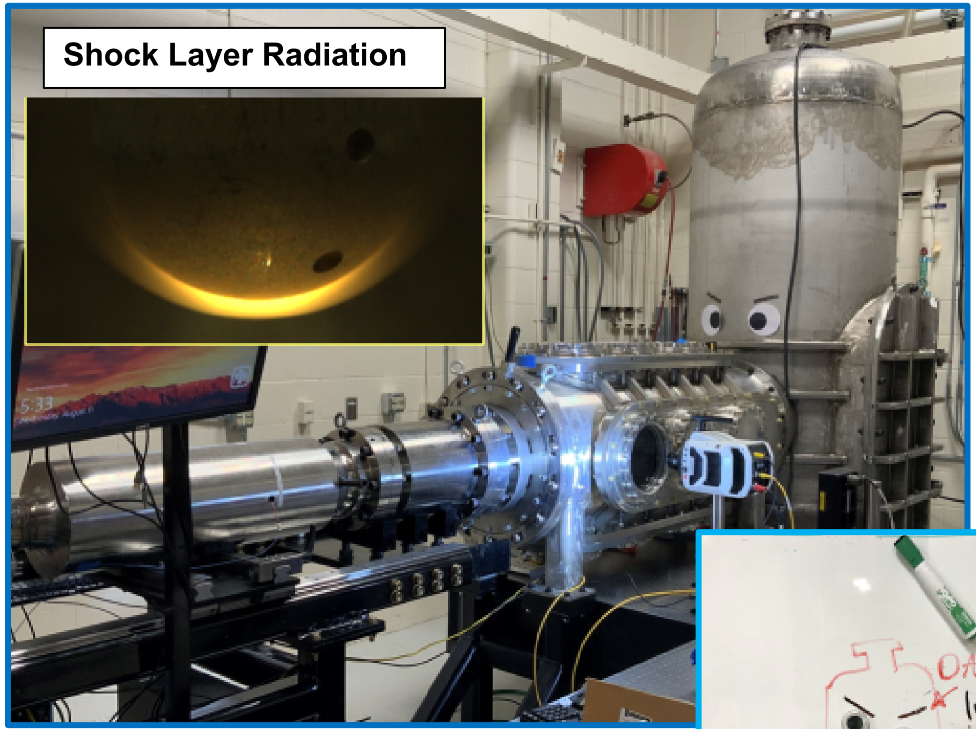
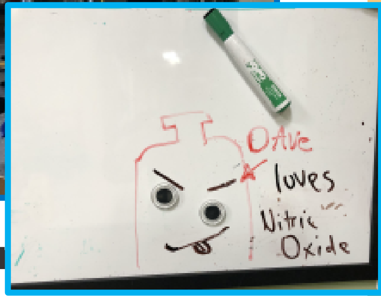


iPhone movie of NOPO spectrum tuning with 10-Hz pump laser

Hypersonic Shock Tunnel (HST) Provides the Reentry Flight Environment



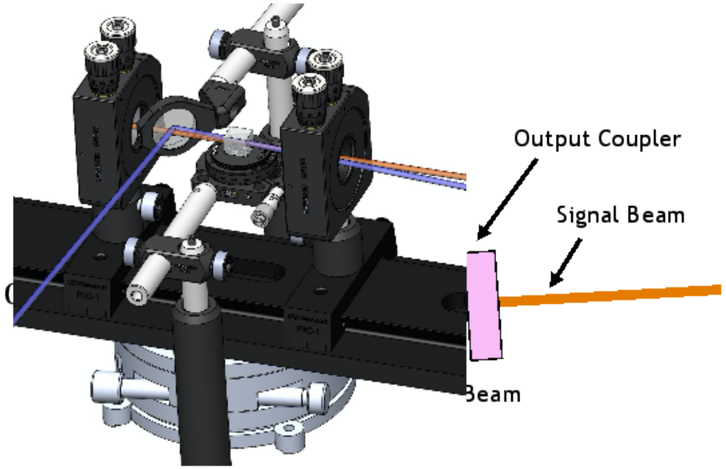


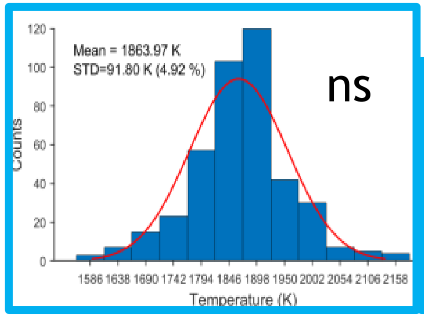


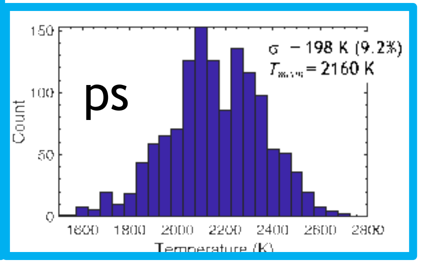
First shot of tunnel in August 2021!

- Multimode: can run as **shock tube or shock tu**
- First experiments at **Mach 8** flight enthalpy
  - Pressure altitude of 42 km (136 kft).
  - Stagnation temperature ≈ 3700 K
- **Research applications:**
  - **Aerothermodynamics including nonequilibrium**
  - **Thermal protection system (TPS) materials**

Improved high-speed thermometry: 100-kHz *nanosecond* CARS



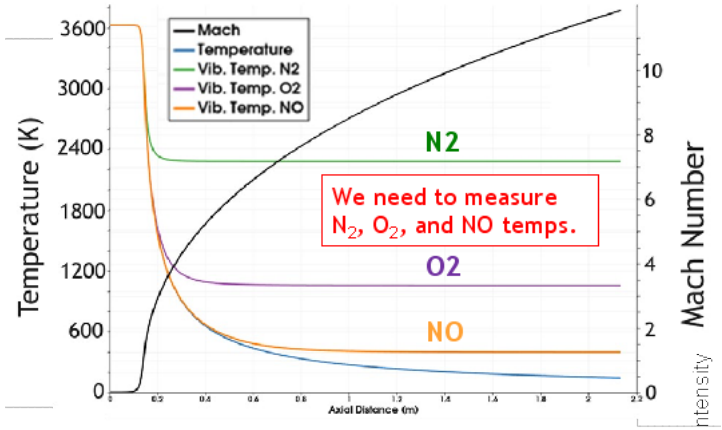




2X reduction in uncertainty!

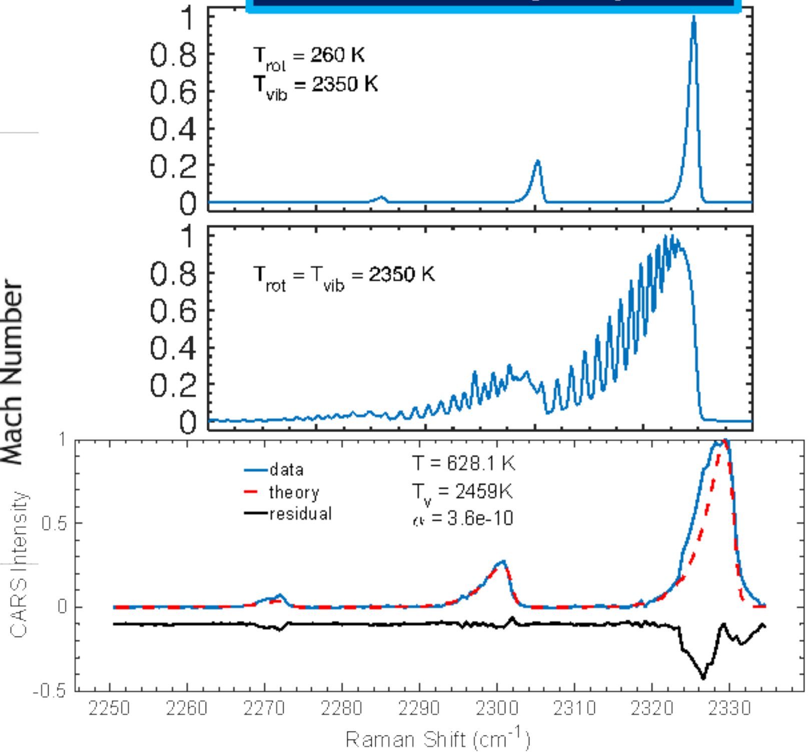
- Short picosecond laser pulses enable high speed but result in noisy data
- We developed longer, nanosecond sources for high-speed CARS thermometry
- Demonstrated in flames
- Applied under nonequilibrium conditions in Sandia shock tunnel

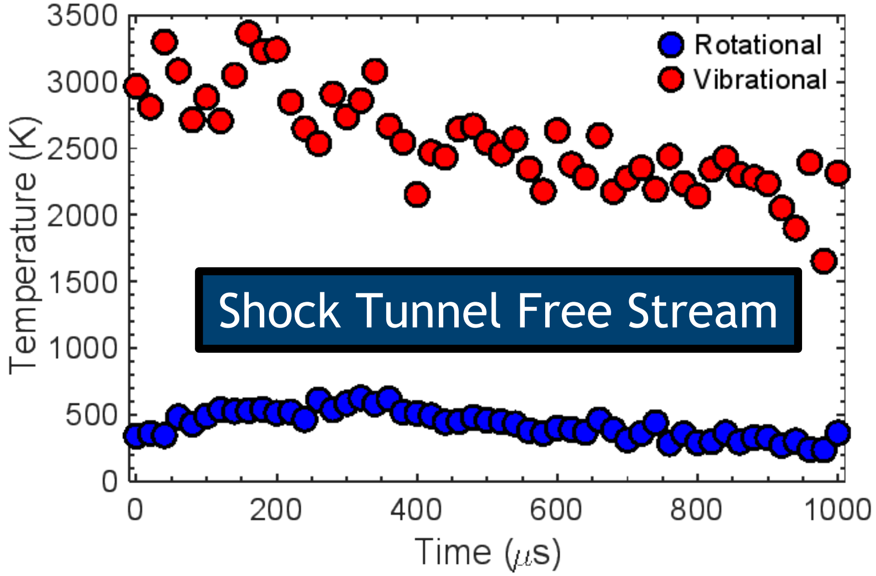
SPARC Calculation of Nozzle Nonequilibrium



New SPARC models guide experiment design

CARS spectra can reveal *nonequilibrium* conditions in N_2 and O_2





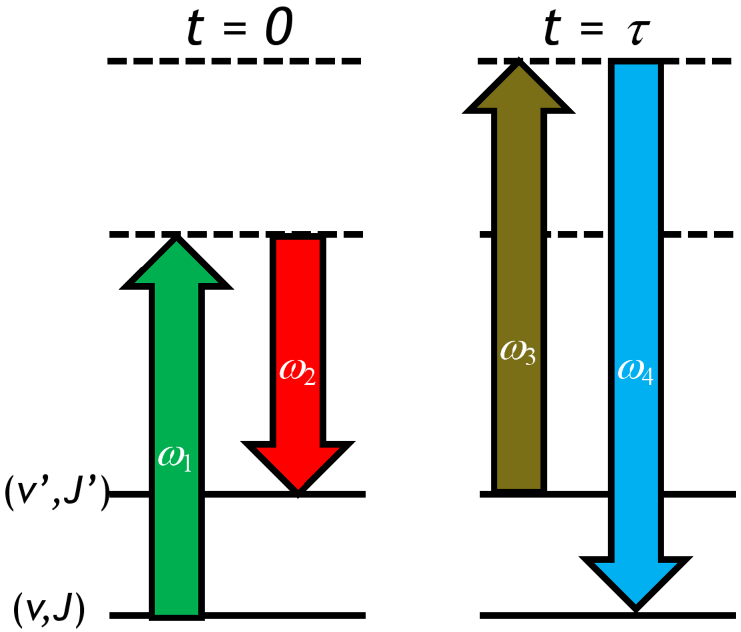
Some Comments re: CARS Spectral Modeling

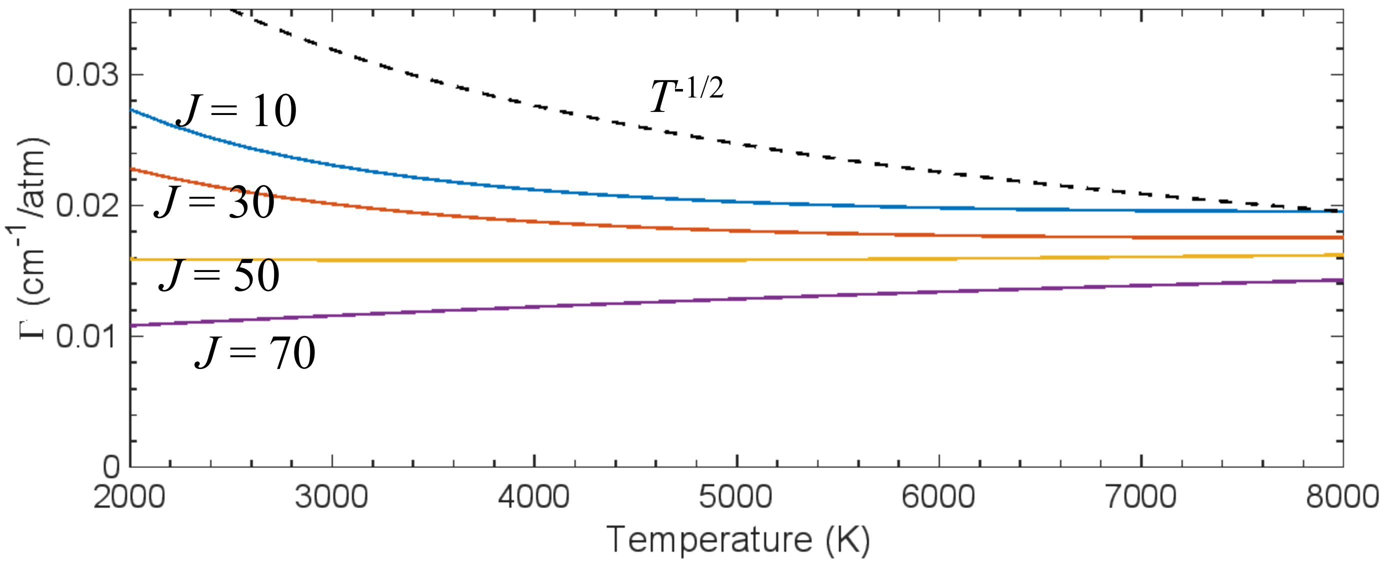
"Generalized Yuratich Equation," Marrocco, *Opt. Lett.* **39**, 4831 (2014)

$$G(\omega;\tau)=\sum_{v,J}\Delta N_{v,J}\left(\frac{d\sigma}{d\Omega}\right)_{v,J}\int_{-\infty}^{\infty}\frac{E_3(\omega_3)e^{i\omega_3\tau}}{\left[\omega_{v,J}-(\omega_3-\omega)\right]-i\Gamma_J/2}d\omega_3$$

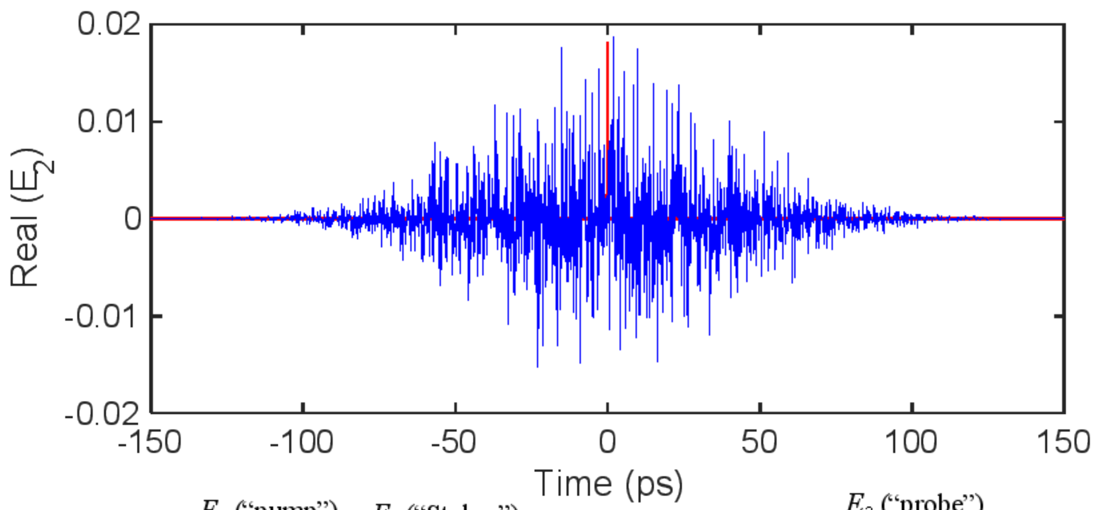
Phase factor (time delay)

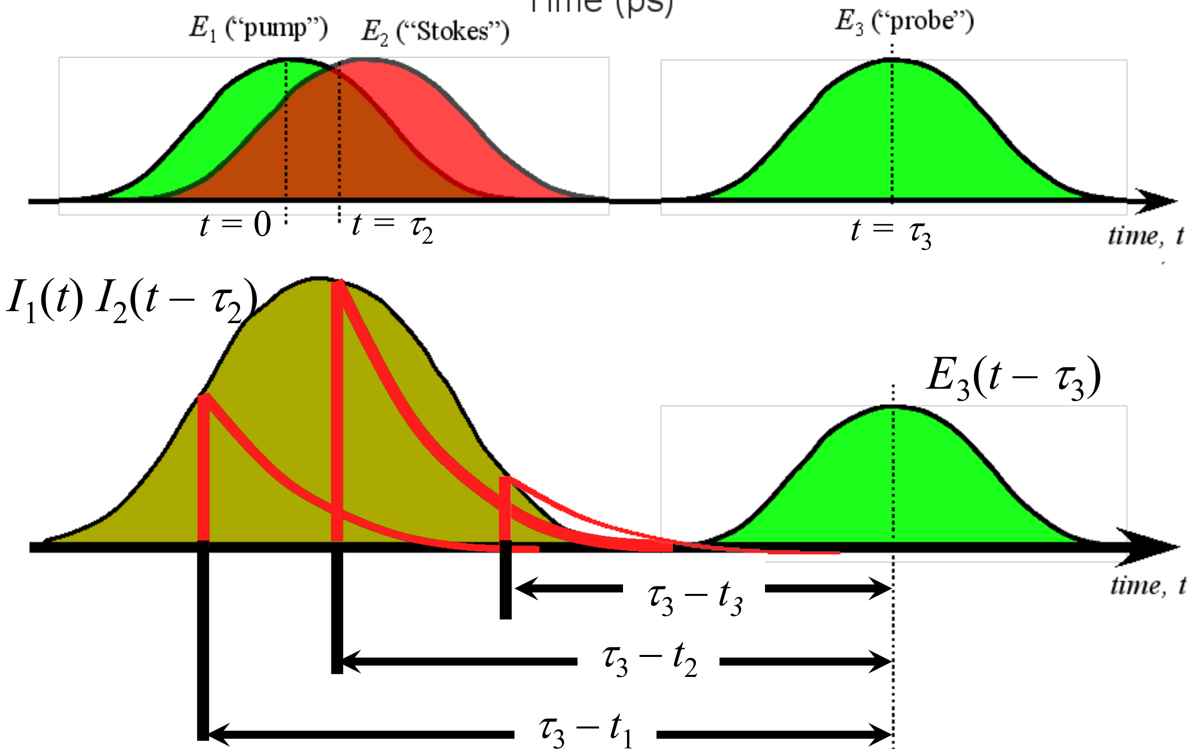
Extrapolate MEG linewidth model to very high T

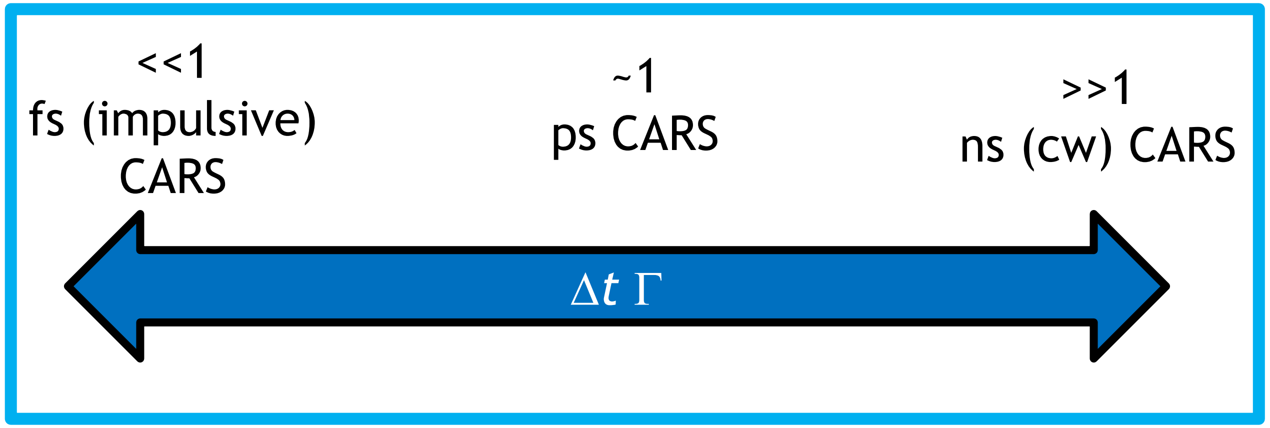




Picosecond CARS calculation







Incoherent Sum of Impulsive Spectra

$$\langle I_4(\omega;\tau_2,\tau_3)\rangle = \int_{-\infty}^{\infty} I_1(t)\, I_2(t-\tau_2) \left\| G(\omega;\tau_3-t) \right\|^2 dt$$

$$G(\omega;\tau) = \sum_{v,J} \Delta N_{v,J} \left(\frac{d\sigma}{d\Omega}\right)_{v,J} \int_{-\infty}^{\infty} \frac{E_3(\omega_3)\, e^{i\omega_3\tau}}{\left[\omega_{v,J} - (\omega_3-\omega)\right] - i\Gamma_J/2}\, d\omega_3$$

Summary and Conclusions

- CARS diagnostics are being applied multiple ground-test facilities to investigate physics of hypersonic flight
  - Extreme gas-phase temperatures (4000-6000 K)
  - Short-duration, impulsive experiments
- CARS thermometry of the N_2 molecule appears to be effective at T as high as ~6000 K
- Pulse-burst lasers can be adapted for CARS thermometry!
  - Picosecond pulses are enabling but noisy
  - Nanosecond pulses can reduce CARS noise
  - Short pulses provide superior performance but not yet ready for burst-mode application (Purdue/SE!)
- We have rigorously developed a new method for treating picosecond CARS spectra