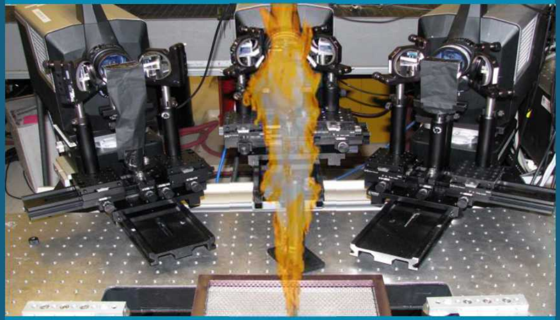
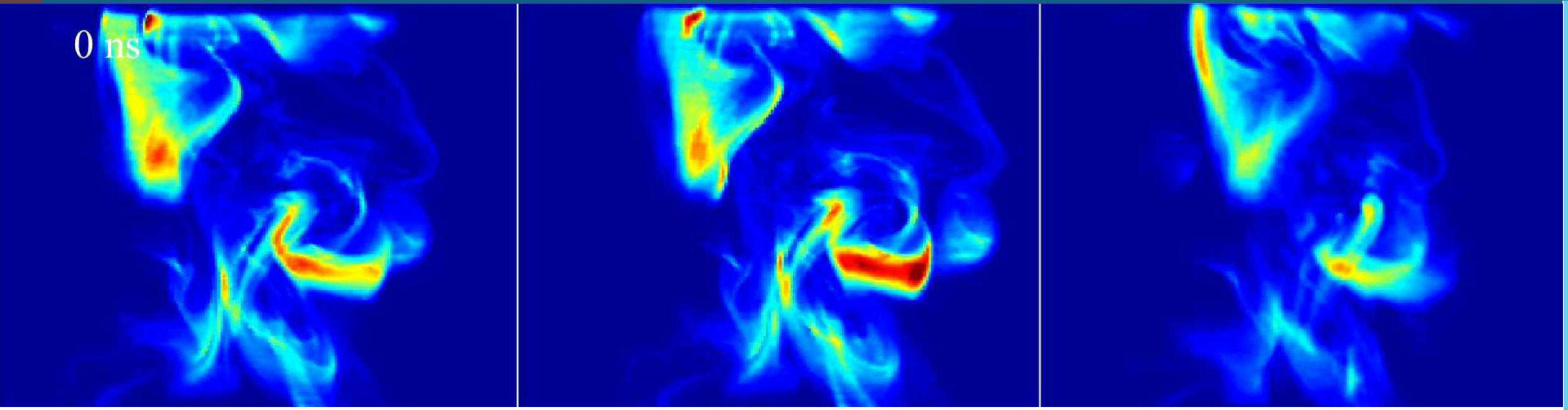
SAND2020-0081C

Tomographic Time-Resolved Laser-Induced Incandescence





Elise M. Hall, Benjamin R. Halls, Daniel R. Richardson, Daniel R. Guildenbecher, Emre Cenker, Megan E. Paciaroni

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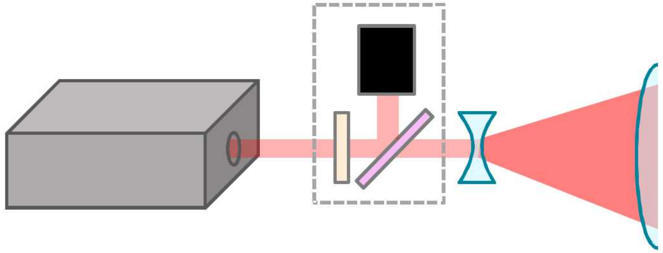
Laser Induced Incandescence (LII)

Radiative emission measured

Signal magnitude correlated with volume fraction (2D image measurements)

Decay rate correlated with particle size (Ti-Re point measurements)



Soot particles heated by a laser

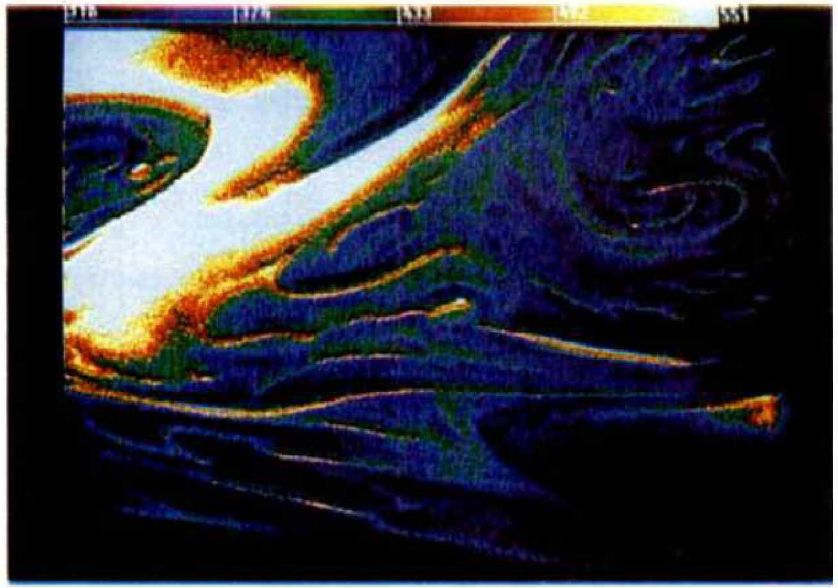
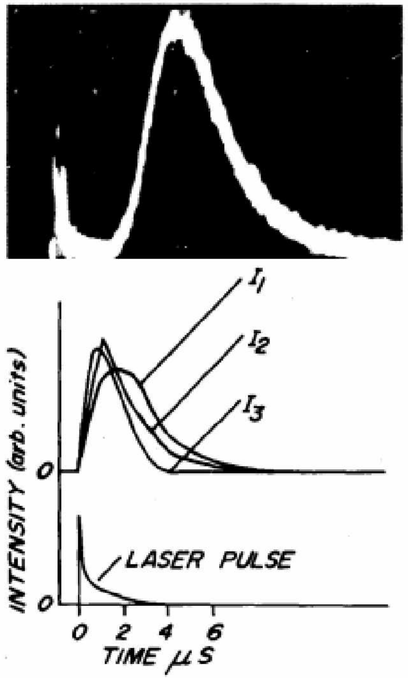


Fig. 9
LII image from a strongly turbulent jet flame

Tait, N.P., & Greenhalgh, D.A. (1993). *PLIF imaging of fuel fraction in practical devices and LII imaging of soot.* Berichte der Bunsengesellschaft fuer Physikalische Chemie, 97(12), 1619-1624.



Weeks, R.W., & Duley, W.W. (1974). *Aerosol-particle sizes from light emission during excitation by TEA CO2 laser pulses.* Journal of Applied Physics, 45(10), 4661-4662.

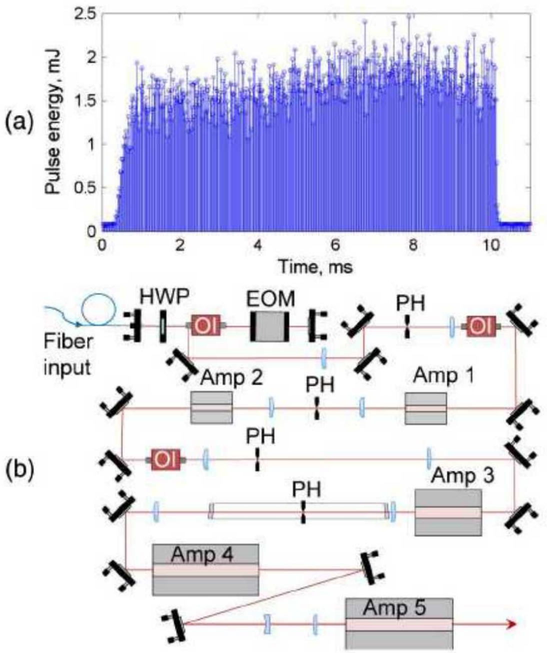
LII towards measuring both signal magnitude and decay rate

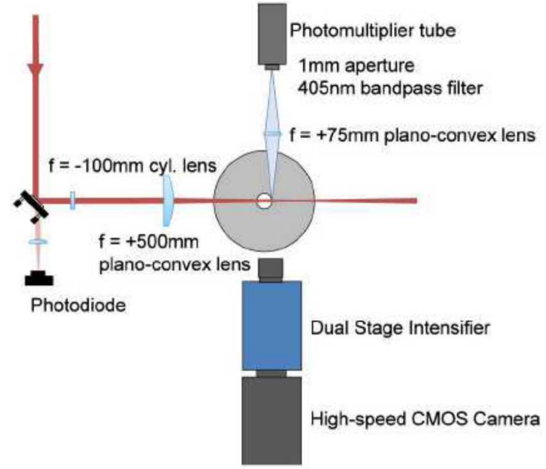
Michael, J.B., et. al., Effects of repetitive pulsing in multi-kHz planar laser-induced incandescence imagining in laminar and turbulent flames (2015)

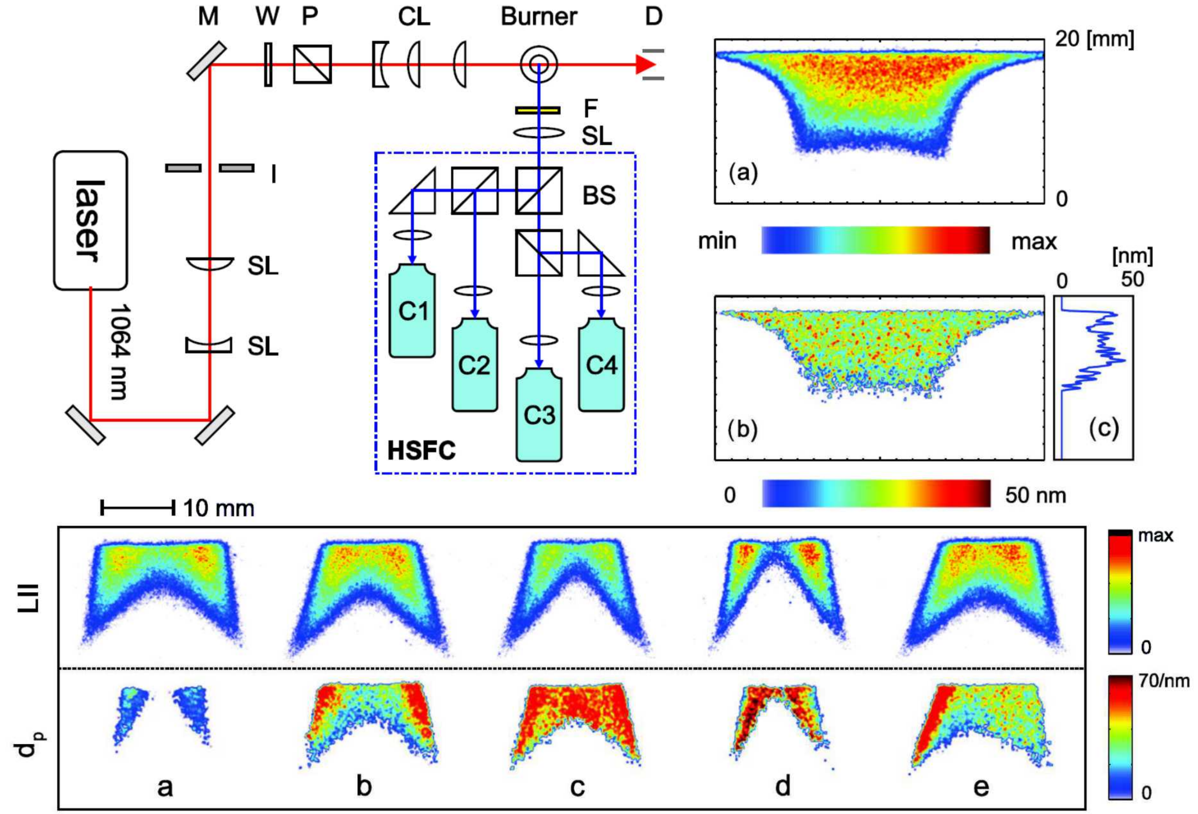
- Burst mode laser and PMT
- Towards increased repetition rate LII

Sun, Z.W. et. al., Single-shot, Time-Resolved planar Laser-Induced Incandescence for soot primary particle sizing (2014)

- Multiple intensified cameras

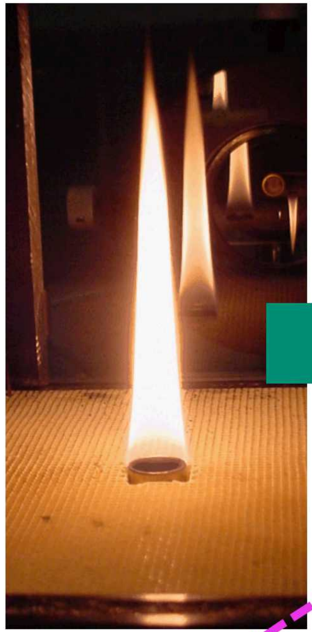


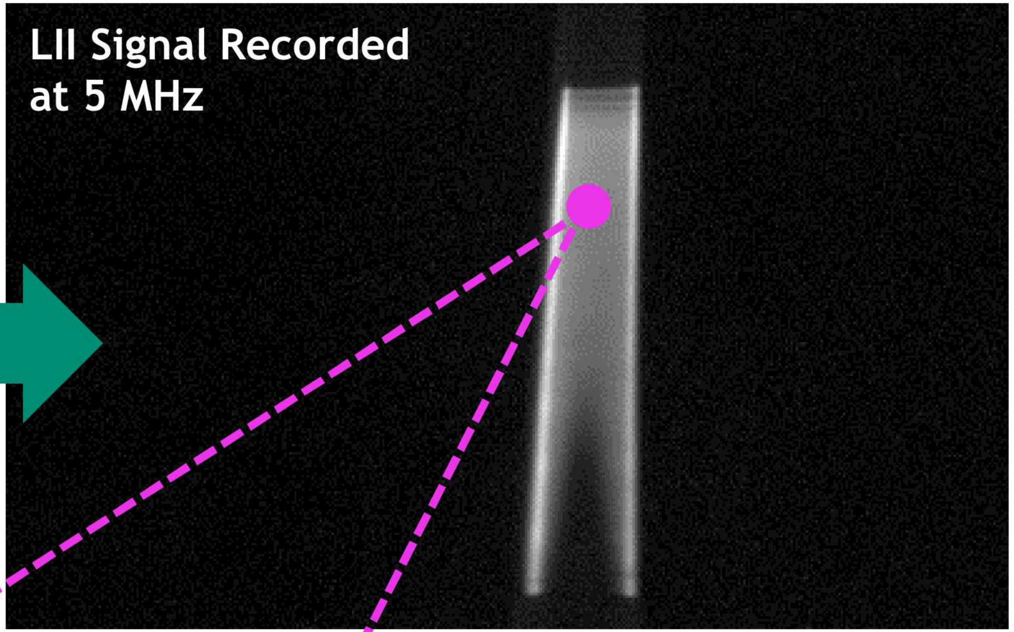


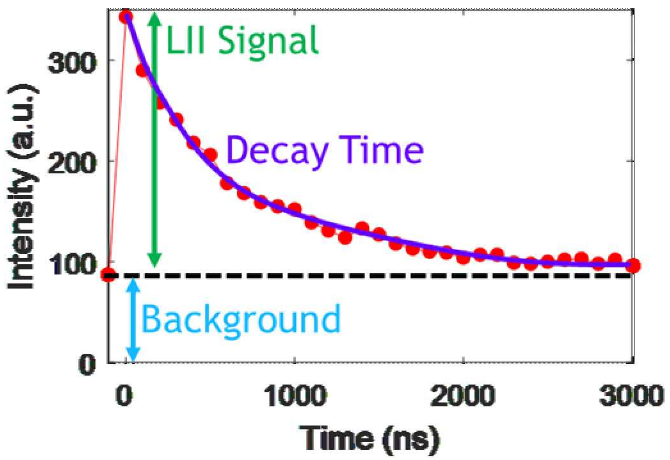


Previous Work: 2D Ti-Re LII

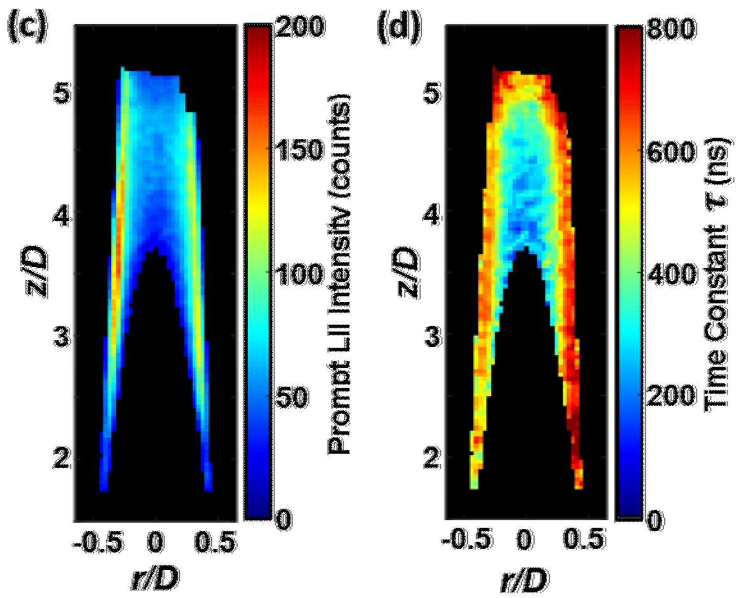
- 2D Ti-Re LII traditionally via:
  - Multiple cameras/laser pulses
  - Photomultipliers
- Single-Camera, Single-shot 2D Ti-Re LII
  - MHz rate camera allowed sufficient speed and intensity





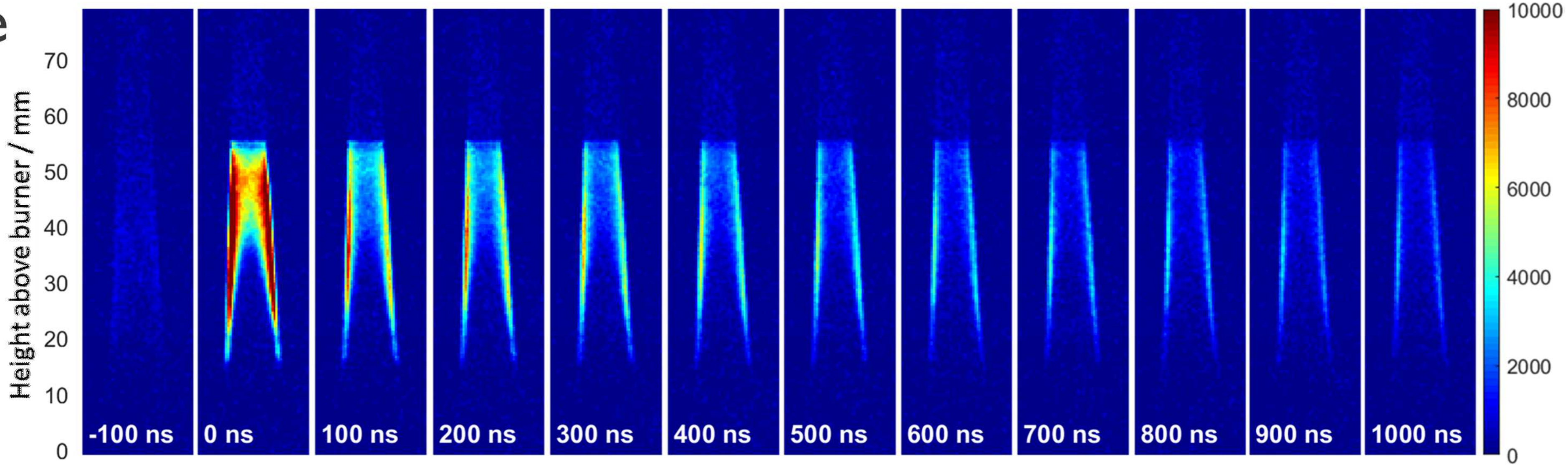


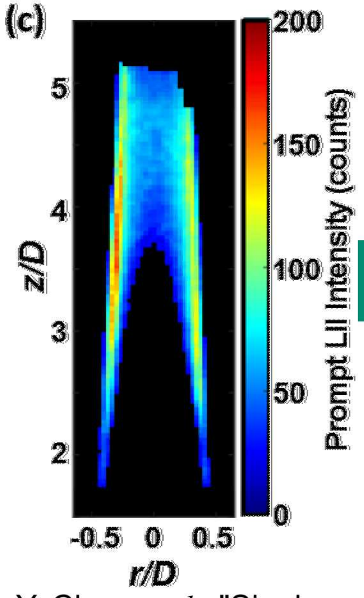
Time- and spatially-resolved LII (Chen *et al* 2018)

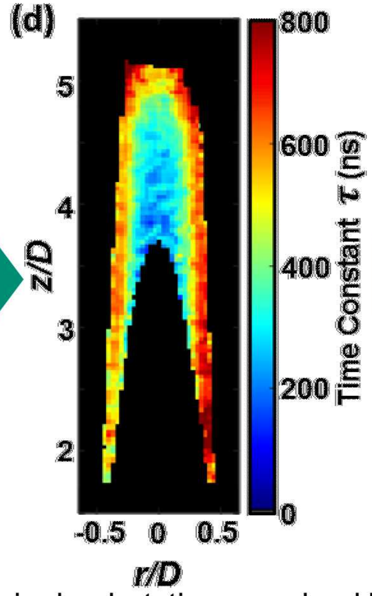


Y. Chen *et al.*, "Single-camera, single-shot, time-resolved laser-induced incandescence decay imaging," *Optics Letters,* vol. 43, no. 21, pp. 5363-5366, 1 November 2018 2018, doi: https://doi.org/10.1364/OL.43.005363.

Previous Work: Particle Size Measurements Validated with Santoro Flame

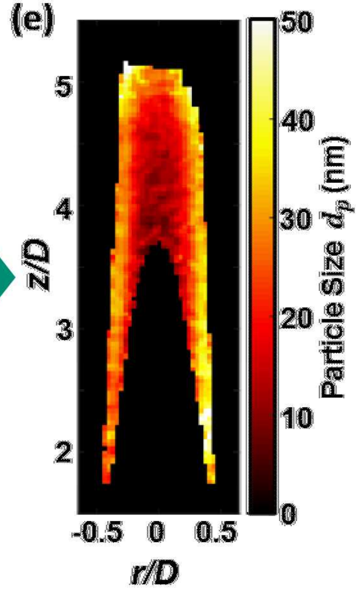


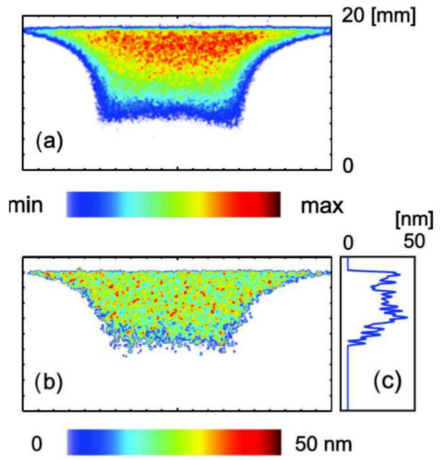




LII model (Emre Cenker):

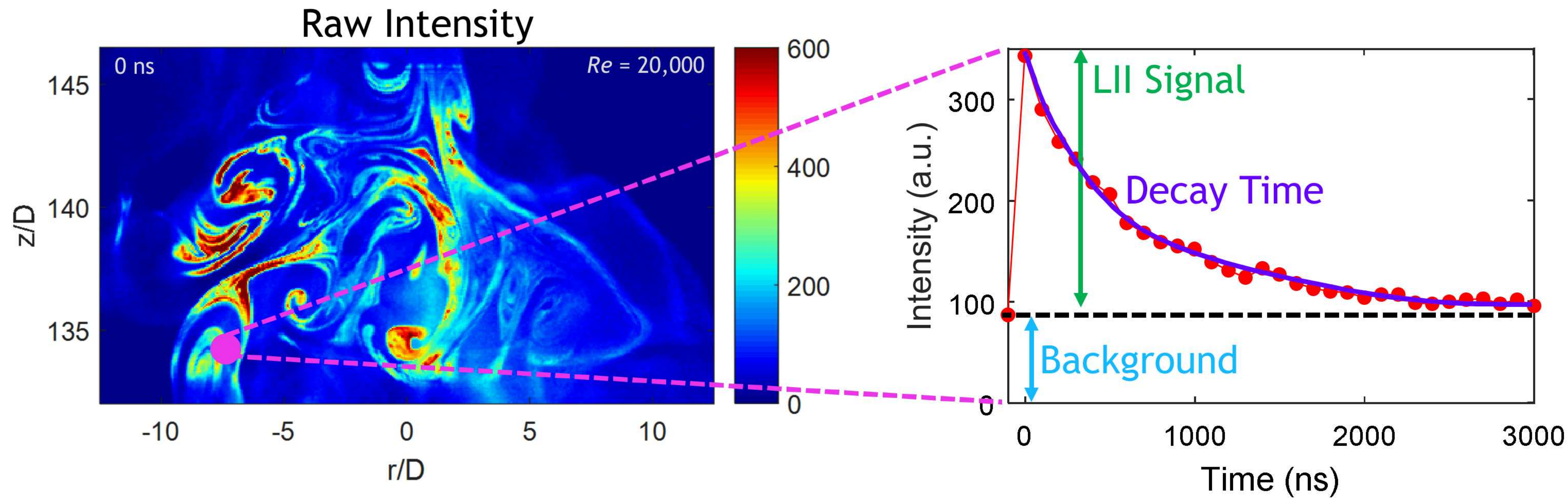
HAB	40 mm
Gas temperature	1850 K (pyrometry)
Pressure	0.84 bar (5000 ft)
Laser fluence	0.08 J/cm^2
E(*m*)	0.4 (literature)
TAC	0.37 (literature)
Aggregate size	60 (TEM)
Time domain	4500 ns (aLaser)
Detection band	603 – 678 nm
Bath-gas heating	On (f_v = 6 ppm)

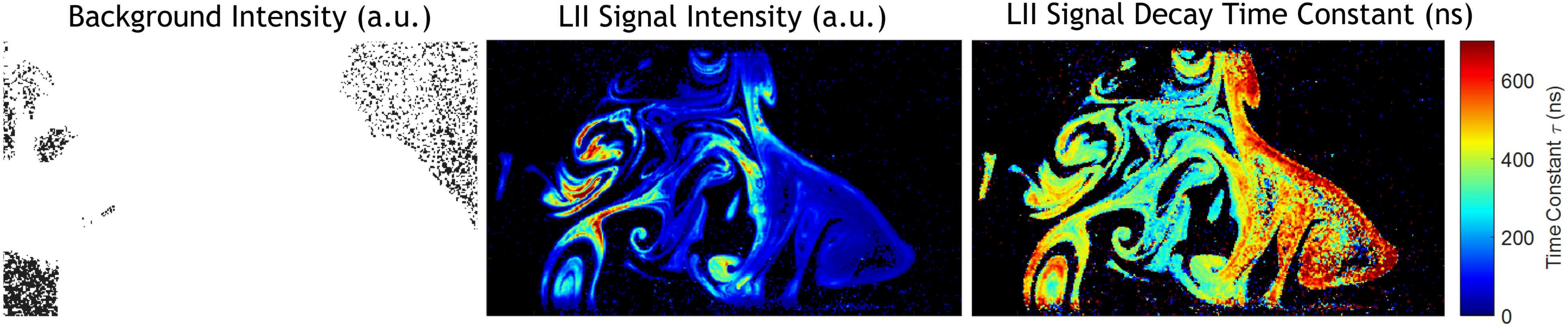




Y. Chen *et al.*, "Single-camera, single-shot, time-resolved laser-induced incandescence decay imaging," *Optics Letters,* vol. 43, no. 21, pp. 5363-5366, 1 November 2018 2018, doi: https://doi.org/10.1364/OL.43.005363.

Previous Work: LII Signal Decay Time Constants in 2D



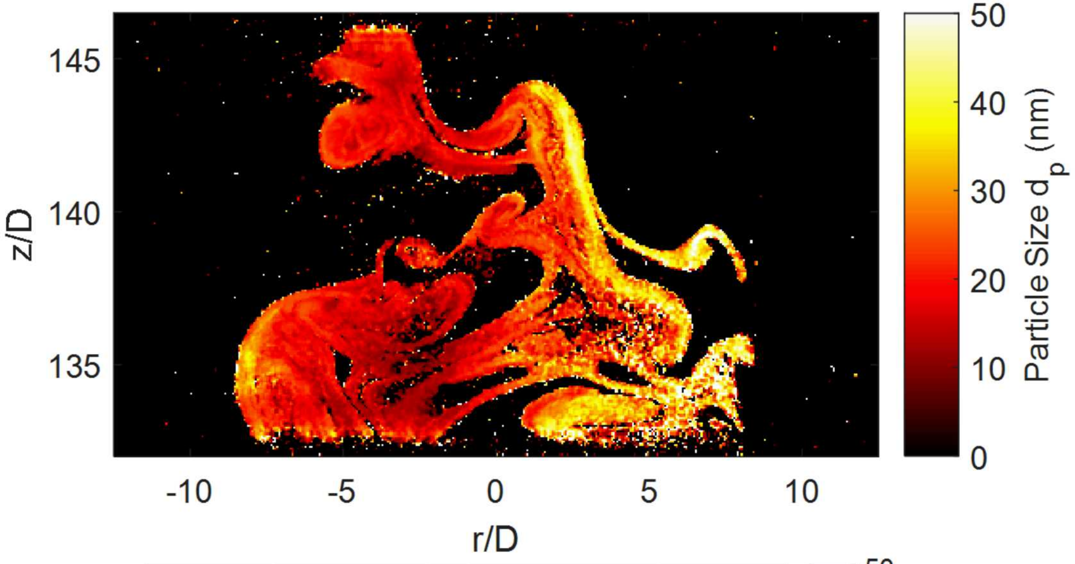


Background, LII signal, and signal decay time constants show different patterns

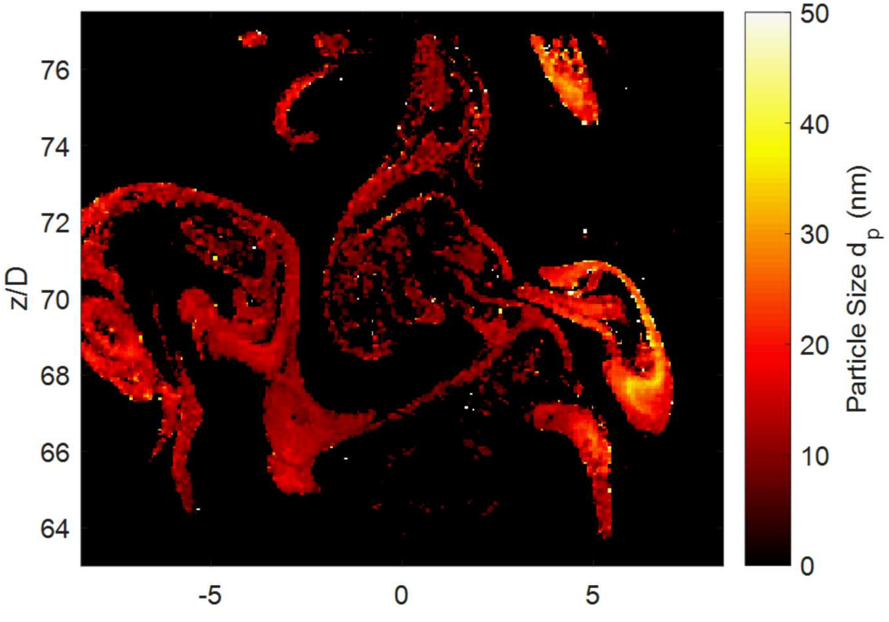
Y. Chen *et al.*, "Single-camera, single-shot, time-resolved laser-induced incandescence decay imaging," *Optics Letters,* vol. 43, no. 21, pp. 5363-5366, 1 November 2018 2018, doi: https://doi.org/10.1364/OL.43.005363.

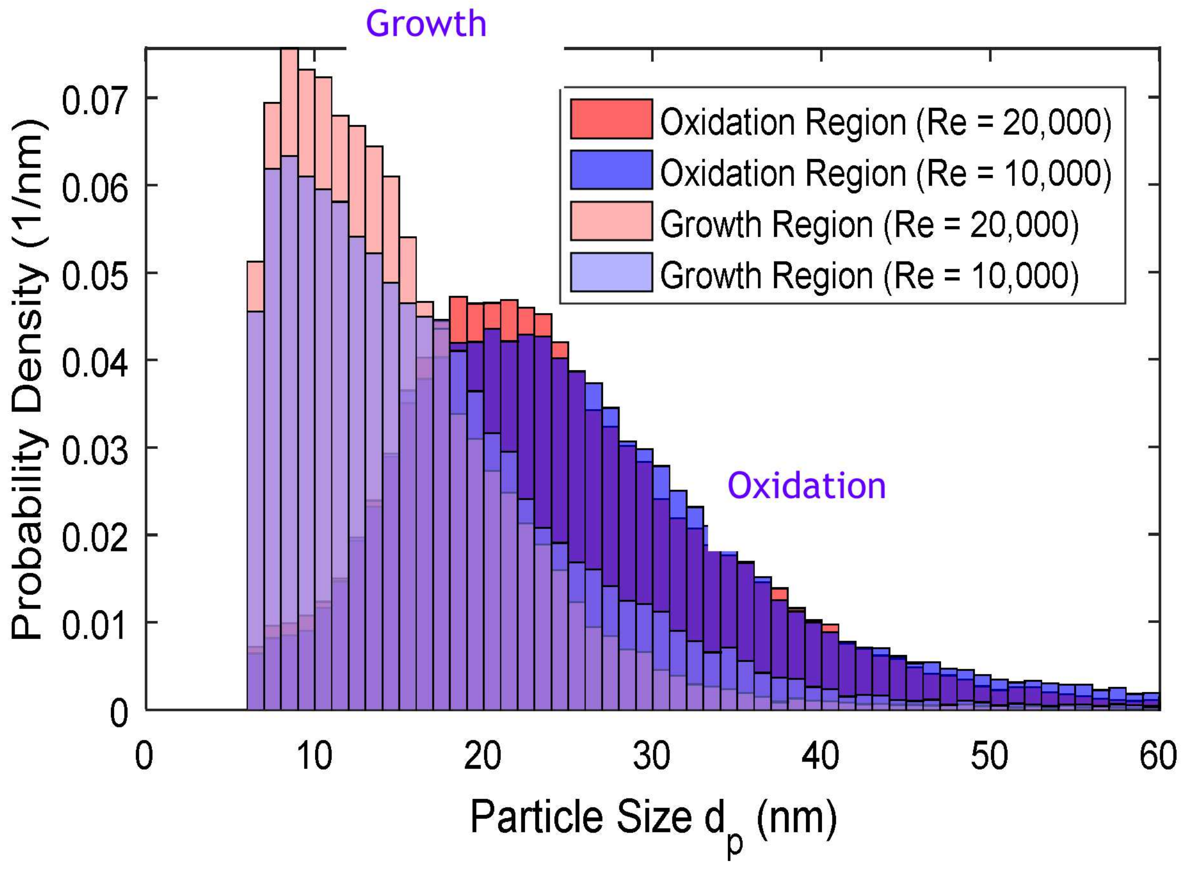
Previous Work: 2D TiRe LII

Oxidation Region



Growth Region

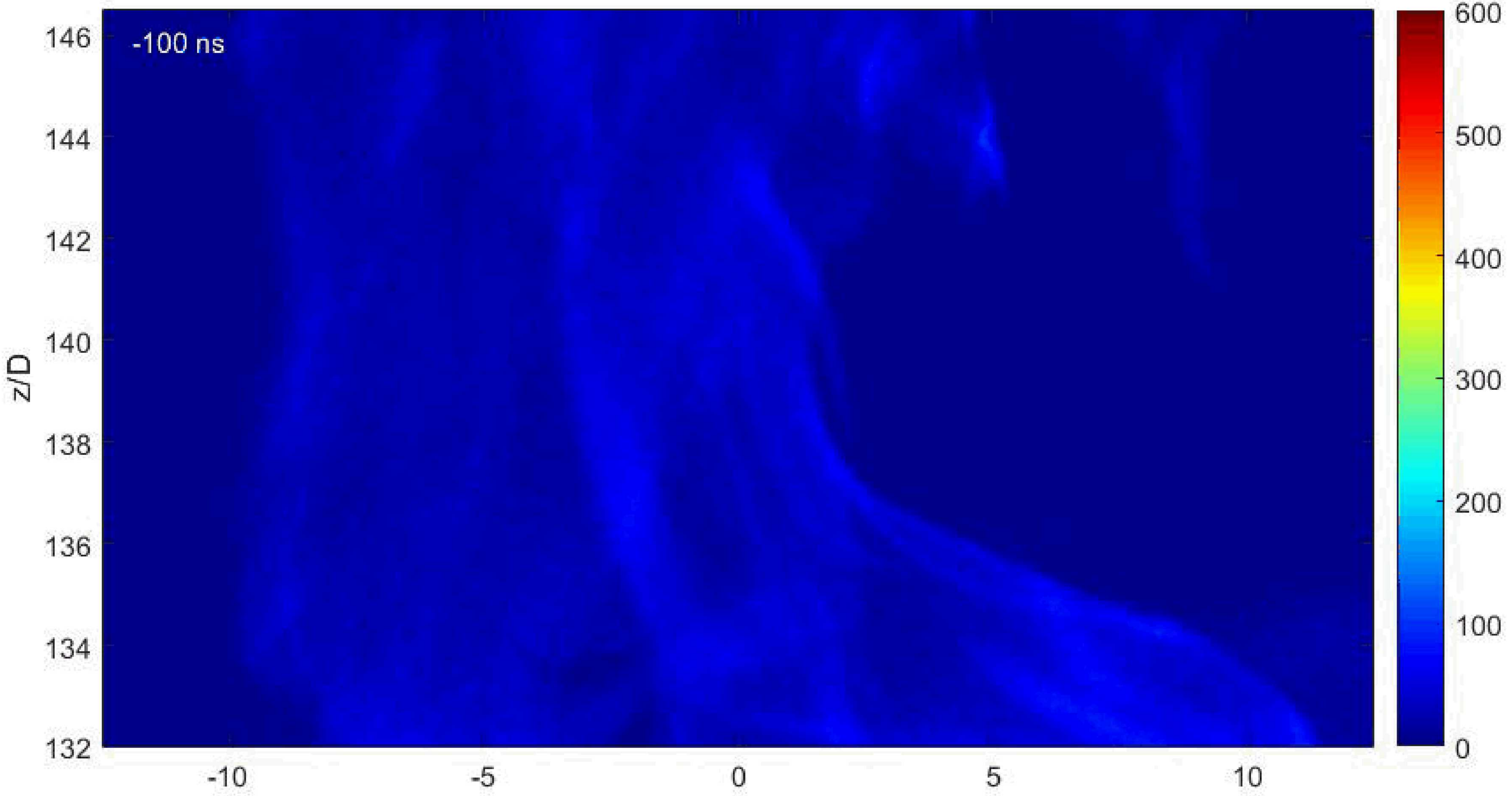




- Ultra-high speed cameras (Shimadzu at 5 to 10 MHz) can be used to <u>capture the LII signal decay without the use of image intensifiers.</u>

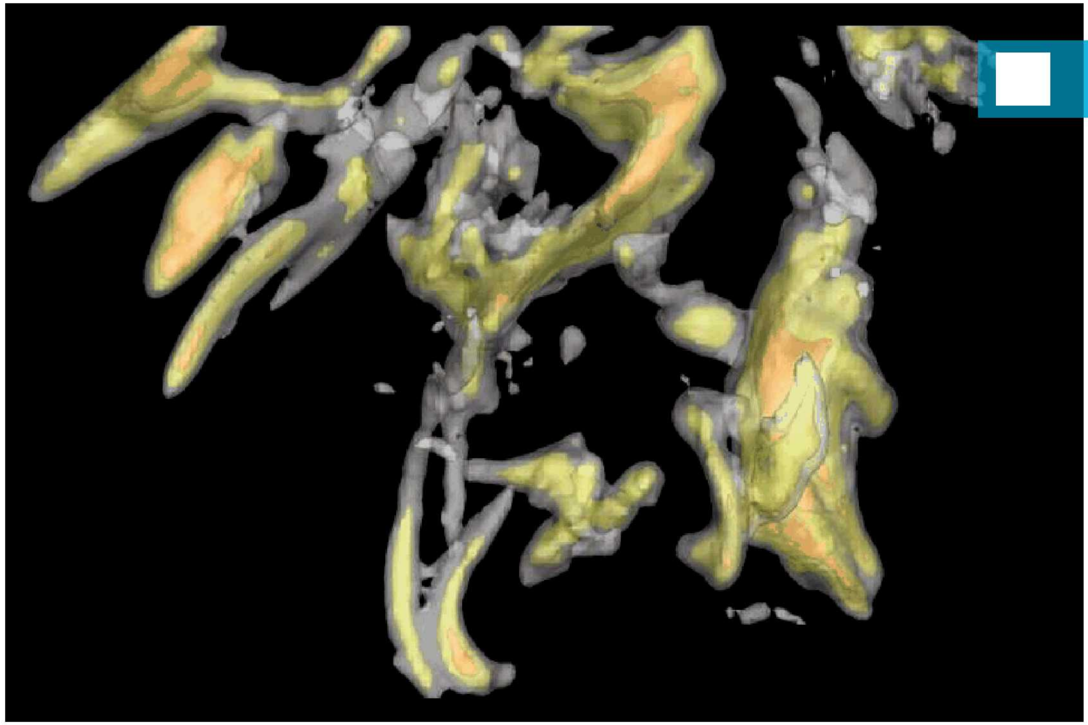
Y. Chen *et al.*, "Single-camera, single-shot, time-resolved laser-induced incandescence decay imaging," *Optics Letters,* vol. 43, no. 21, pp. 5363-5366, 1 November 2018 2018, doi: https://doi.org/10.1364/OL.43.005363.

Previous Work: 2D Ti-Re LII → the limitation: soot evolves in 3D

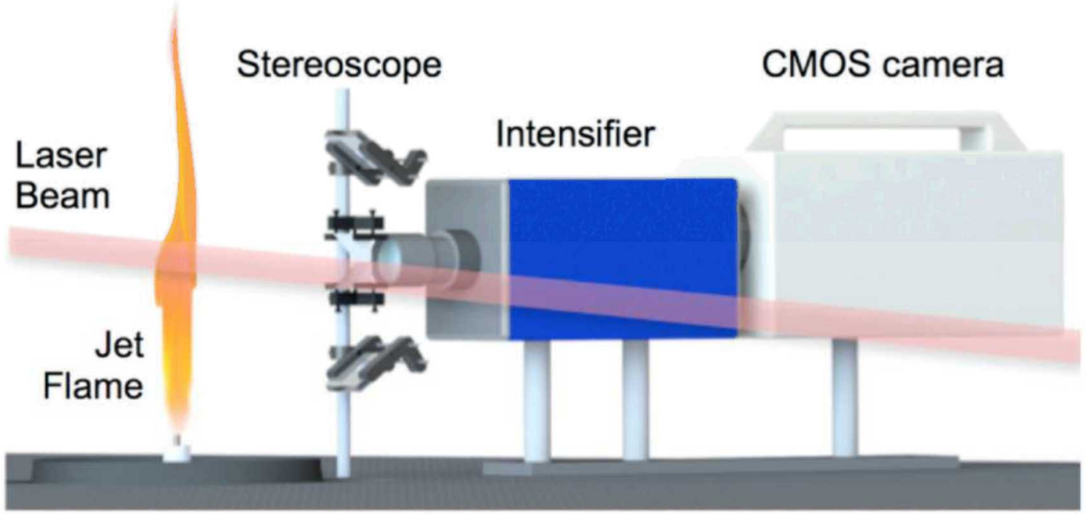


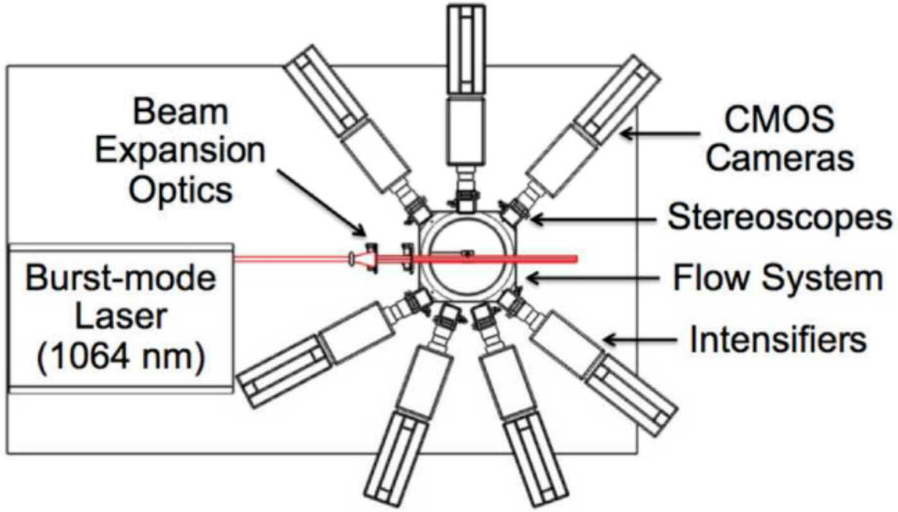
Y. Chen *et al.*, "Single-camera, single-shot, time-resolved laser-induced incandescence decay imaging," *Optics Letters,* vol. 43, no. 21, pp. 5363-5366, 1 November 2018 2018, doi: https://doi.org/10.1364/OL.43.005363.

Previous Work: Tomographic LII



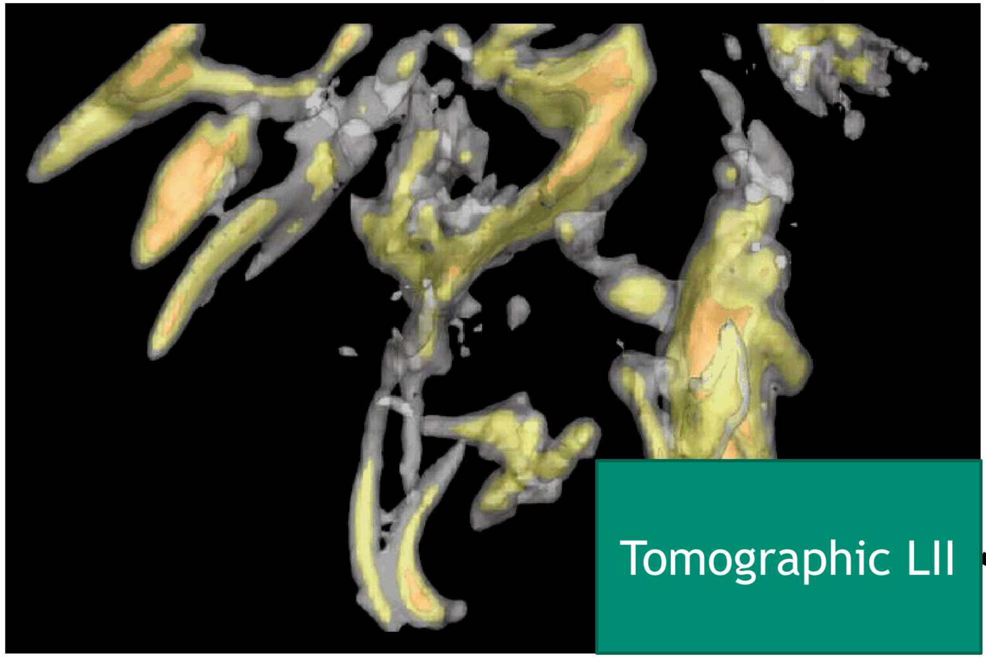
- Up to seven kHz rate intensified cameras (up to 14 views)
  - As few as 6 views produce reasonable reconstruction
- Burst-mode Nd:YAG laser
- ***High-speed 3D measurement of soot volume fraction***



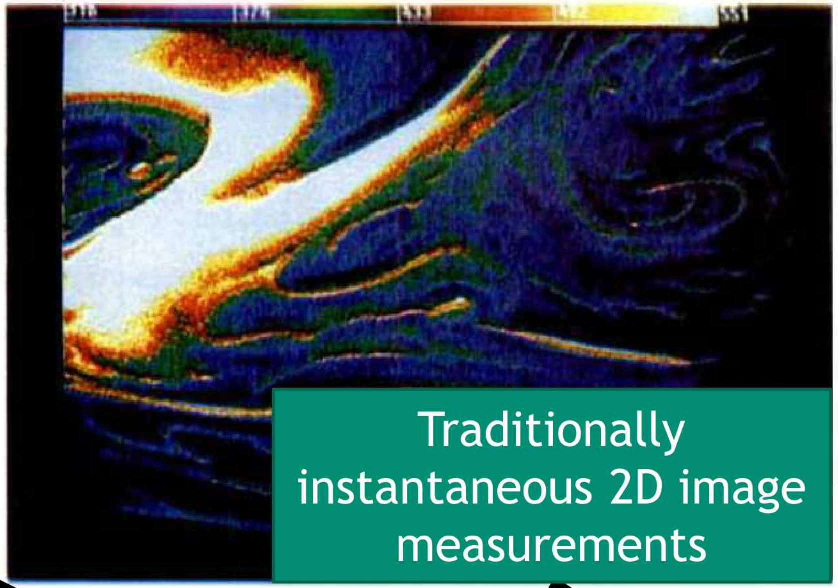


High-speed, three-dimensional tomographic laser-induced incandescence imaging of soot volume fraction in turbulent flames (Meyer, Halls, Jiang, Slipchenko, Roy, and Gord, 2016)

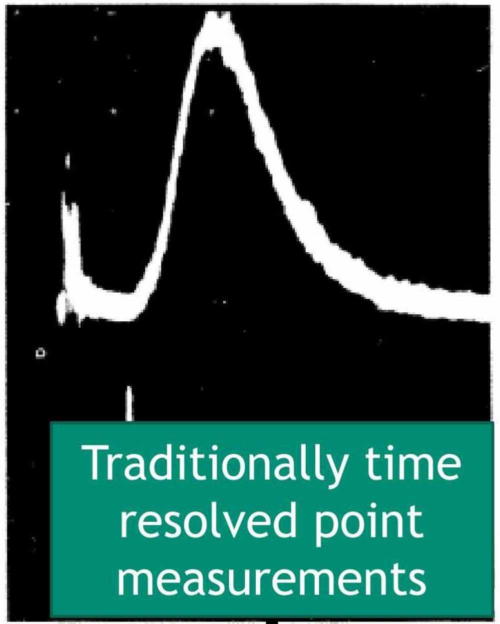
Current Work: Tomographic Time-Resolved LII



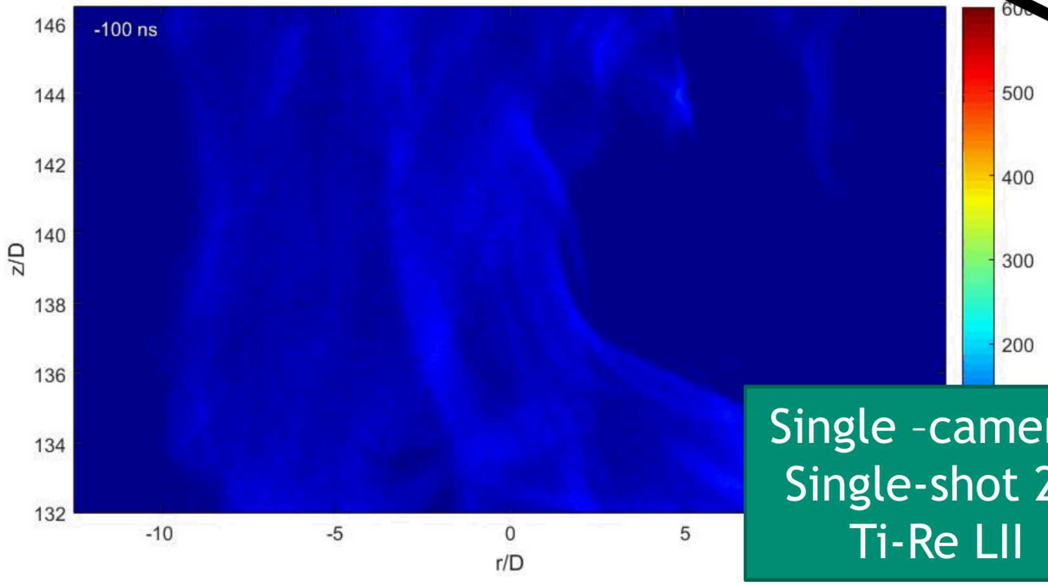
Tomographic LII



Traditionally instantaneous 2D image measurements



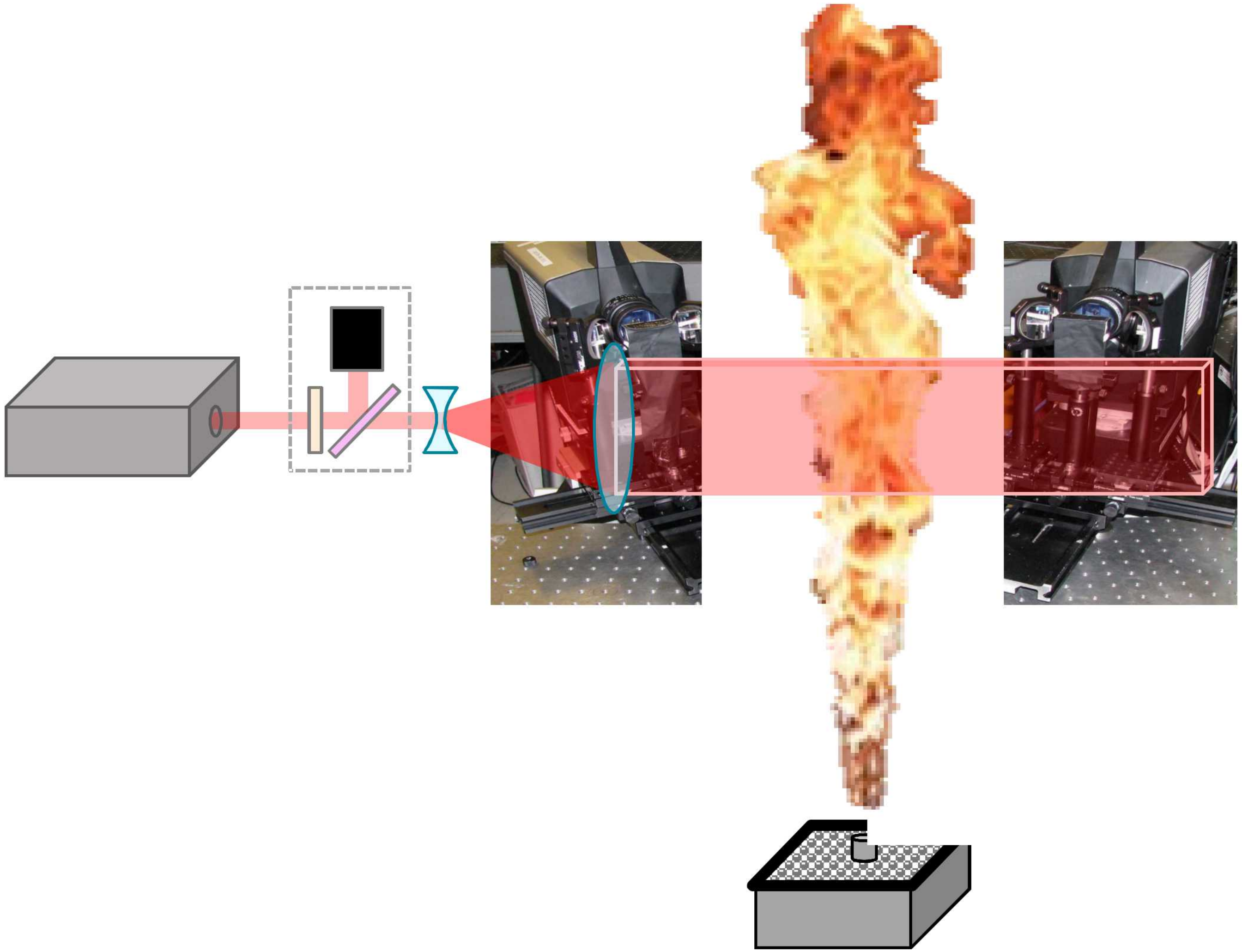
Traditionally time resolved point measurements



Single –camera, Single-shot 2D Ti-Re LII

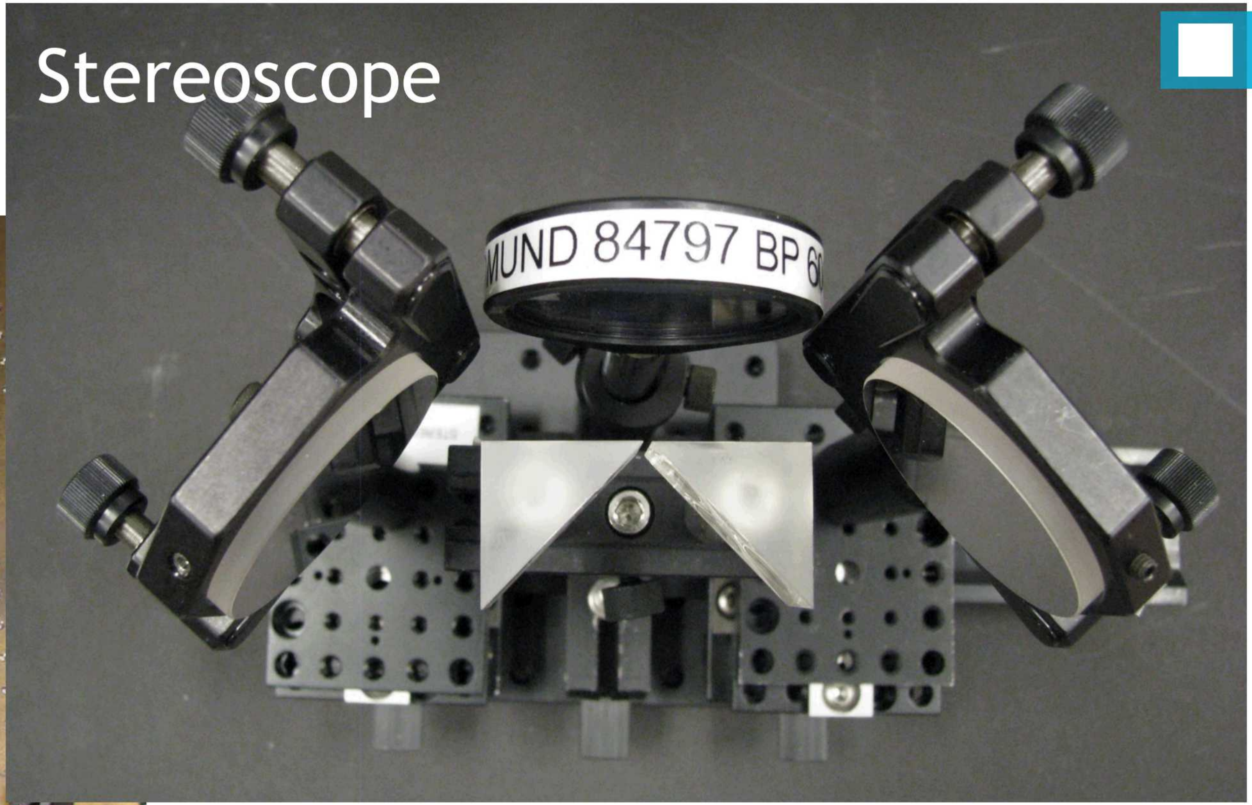
Tomographic Ti-Re LII

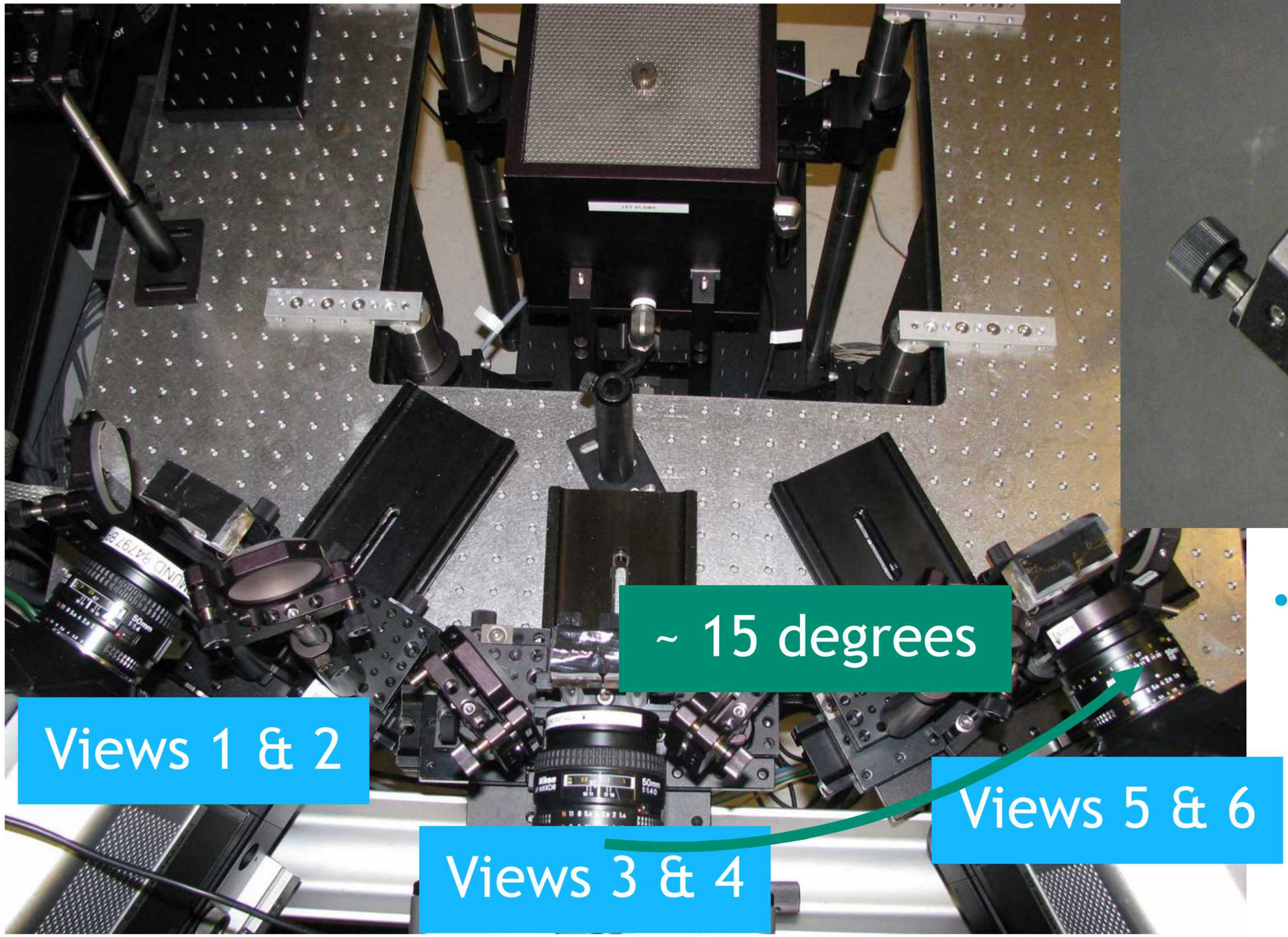
Experimental configuration:



- Turbulent non-premixed ethylene jet flame burner
  - Air co-flow 200 SLPM
  - Ethylene pilot 0.52 SLPM
  - Air pilot 8.4 SLPM
  - Ethylene jet 13.2 SLPM for Re = 10,000
- 1064 nm injection seeded Nd:YAG
  - 10 Hz, 12 ns pulses
  - 48 mm tall × 10 mm thick beam
  - Fluence of 151 mJ/cm^2
- 3 Shimadzu cameras
  - FTCMOS2 sensor (ISO 16,000, 32 μm pixels)
  - 10 bit, 250 ×400 pixels, 256 frames max
  - 5 MHz full frame (110 ns exposure)
  - 10 MHz zig-zag frame (50 ns exposure)
  - Bandpass filter: 600 nm, 50 nm FWHM
  - No image intensifier

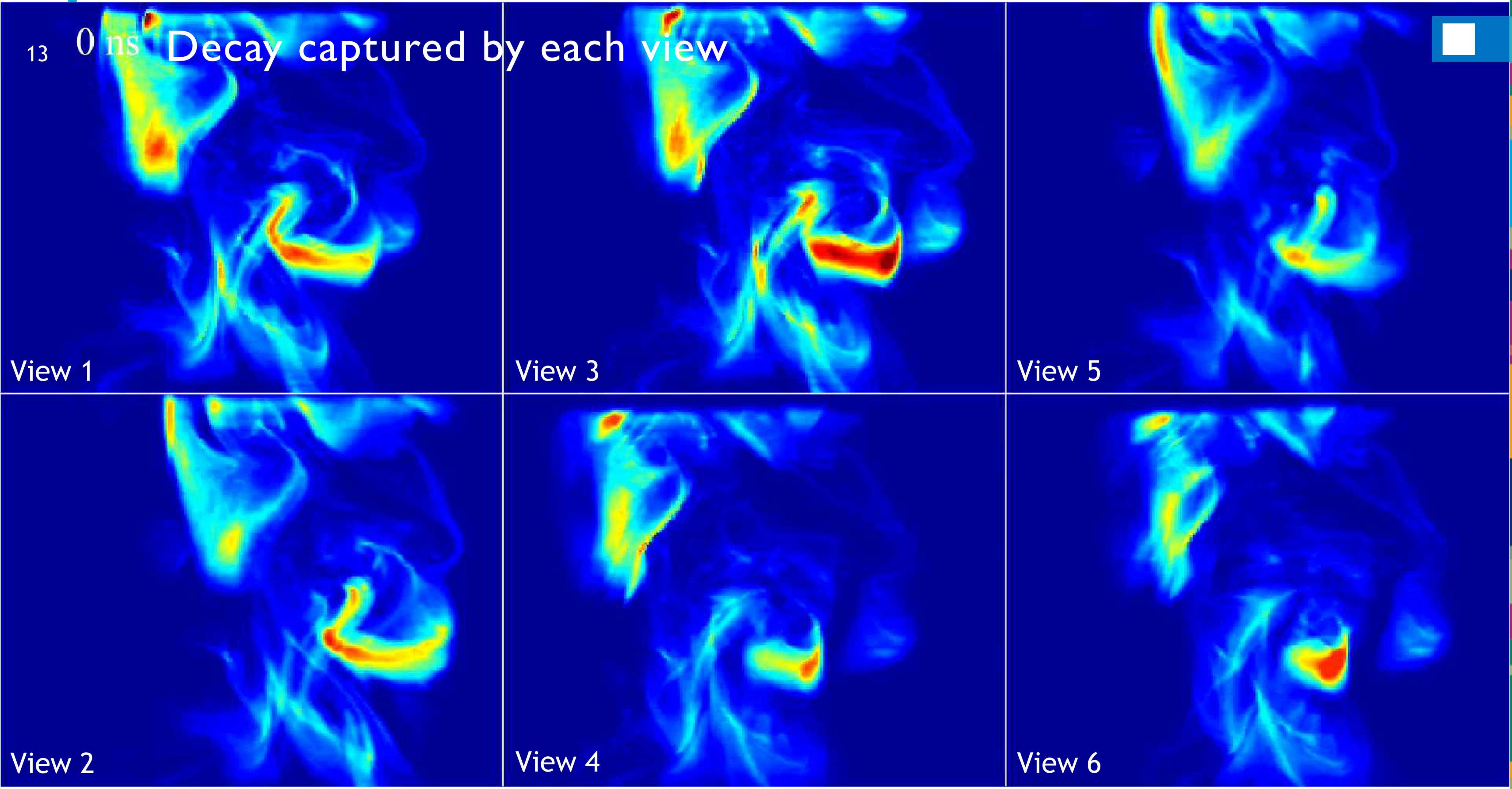
Experimental configuration



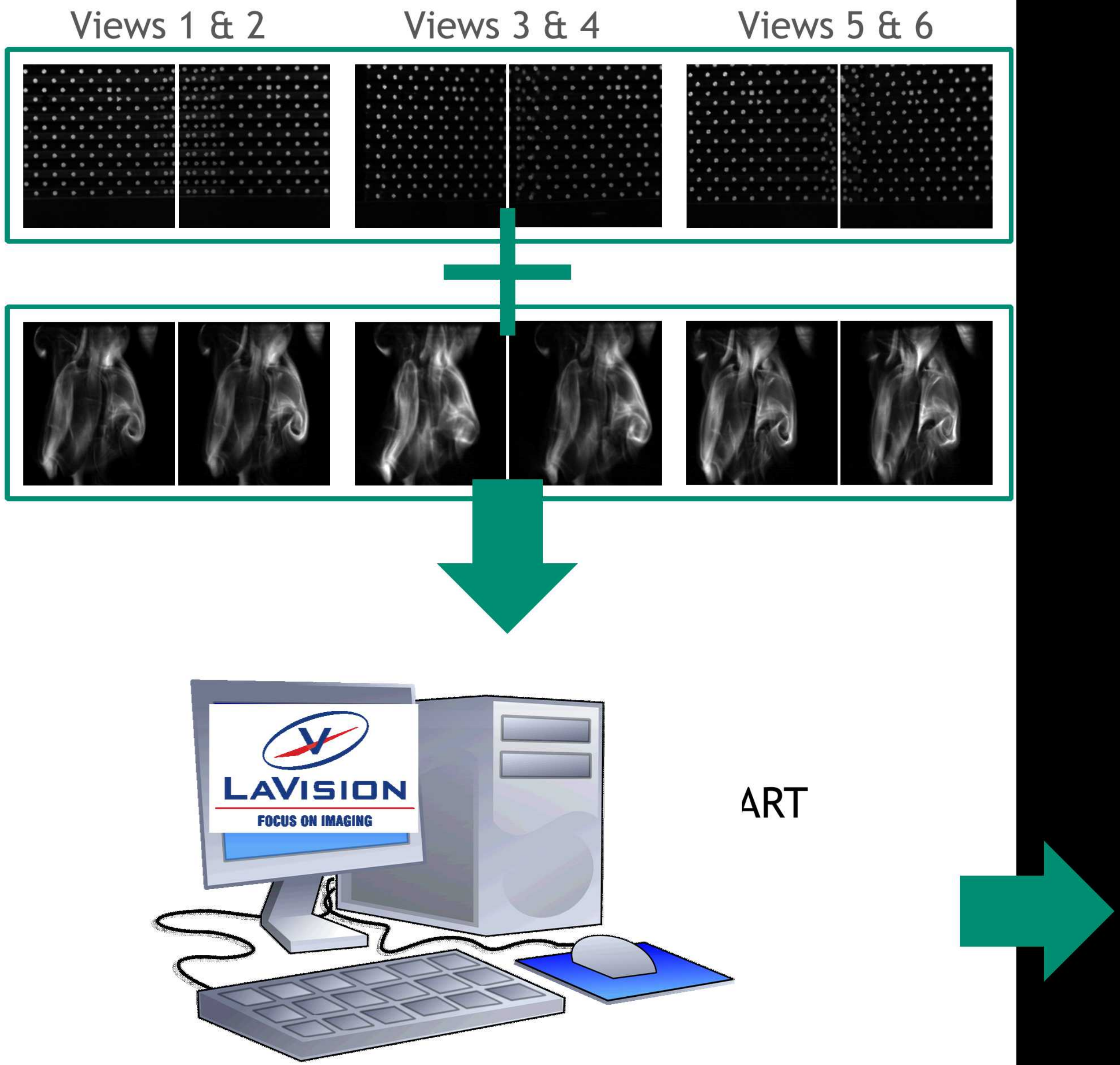


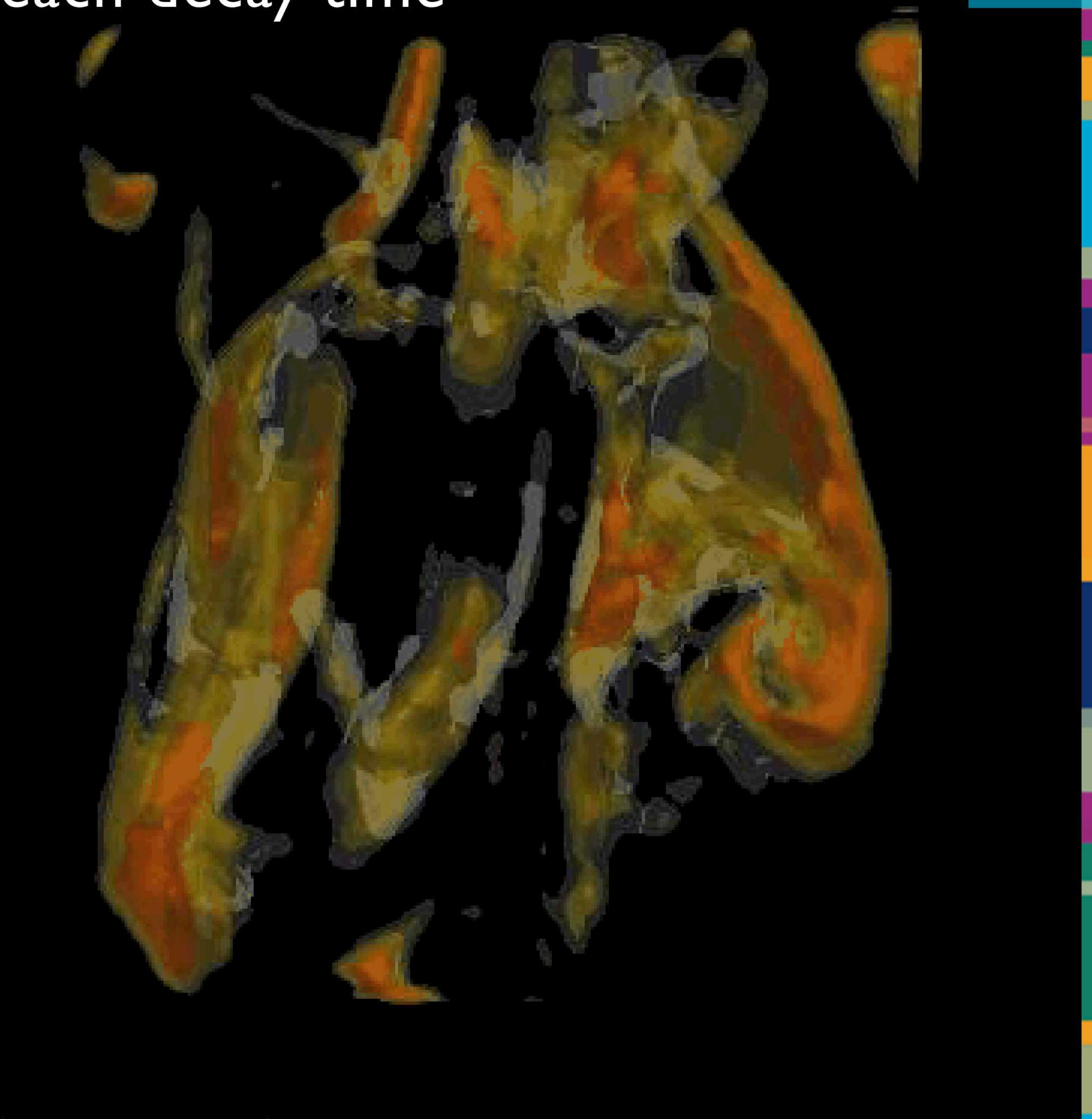
- 3 Shimadzu cameras
  - FTCMOS2 sensor (ISO 16,000, 32 μm pixels)
  - 10 bit, 250 ×400 pixels, 256 frames max
  - 5 MHz full frame (110 ns exposure)
  - <u>10 MHz zig-zag frame (50 ns exposure)</u>
  - Bandpass filter: 600 nm, 50 nm FWHM
  - No image intensifier

Decay captured by each view

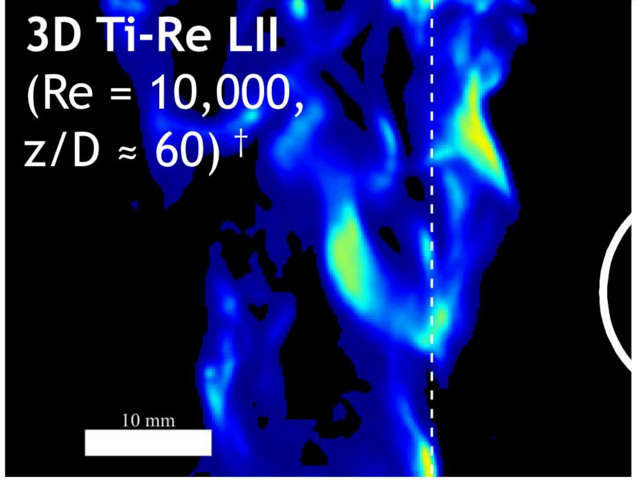


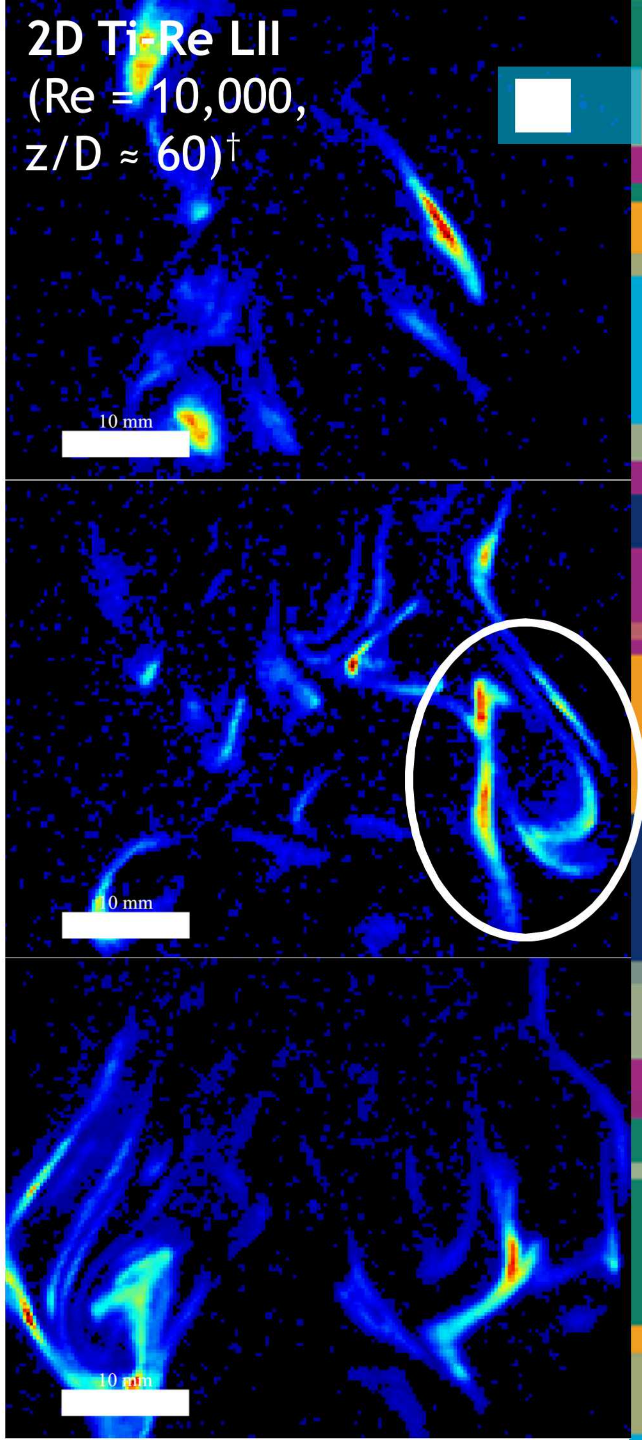
Tomographic reconstruction… at each decay time





3D vs 2D Ti-Re LII



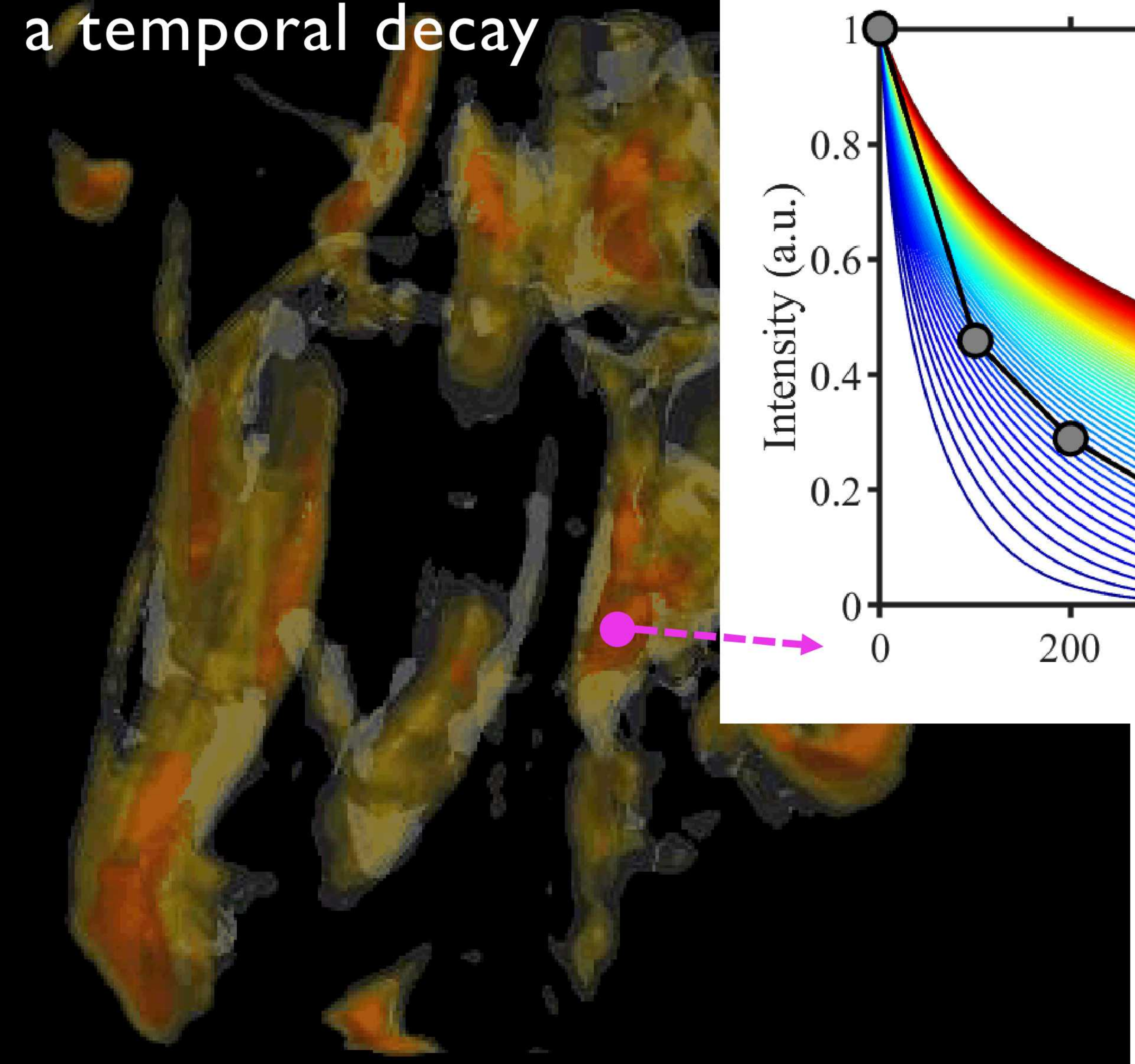


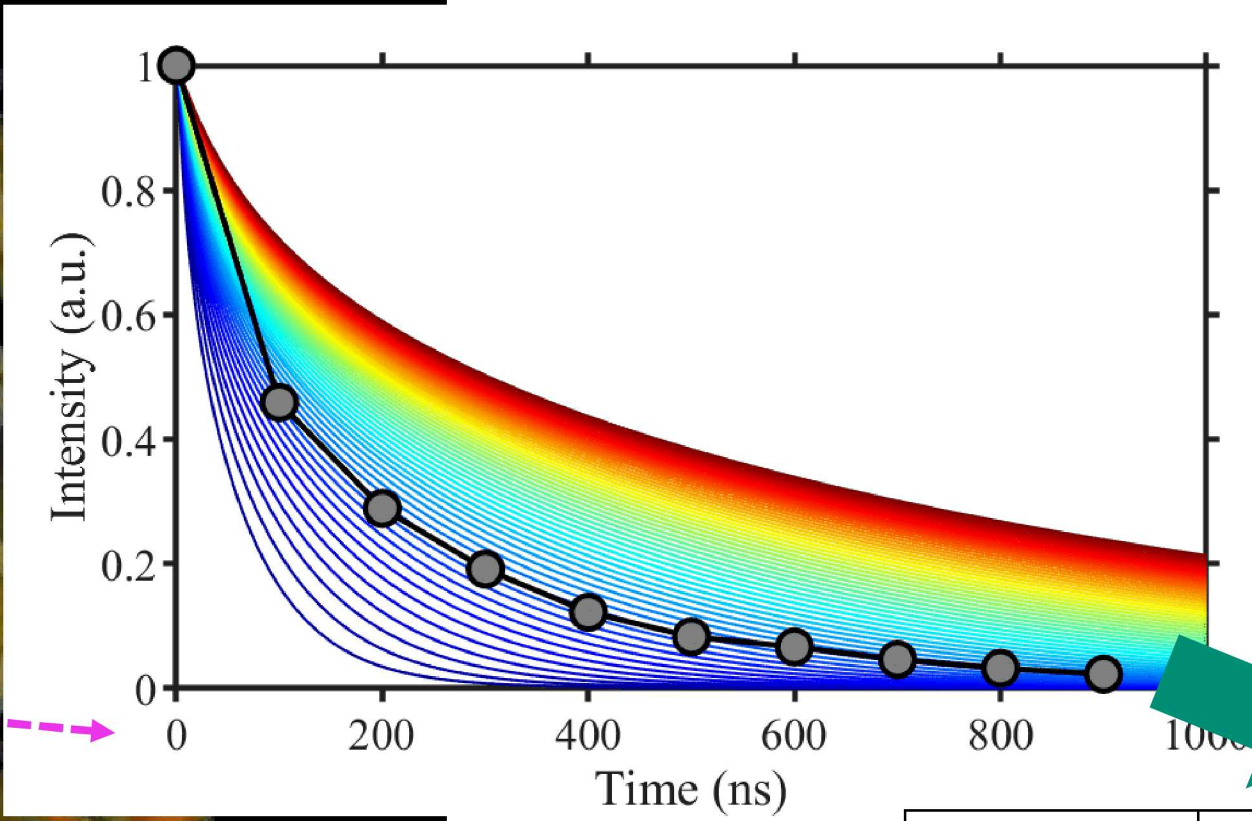
- Reconstructed structures qualitatively match 2D data
  - Rotation in out-of-plane direction
  - Spatial resolution slightly degraded vs 2D
  - Out-of-plane resolution likely inferior to in-plane

†Data uncorrelated and recorded independently

2D data from: Y. Chen *et al.*, "Single-camera, single-shot, time-resolved laser-induced incandescence decay imaging," *Optics Letters,* vol. 43, no. 21, pp. 5363-5366, 1 November 2018 2018, doi: https://doi.org/10.1364/OL.43.005363.

Every voxel measures a temporal decay



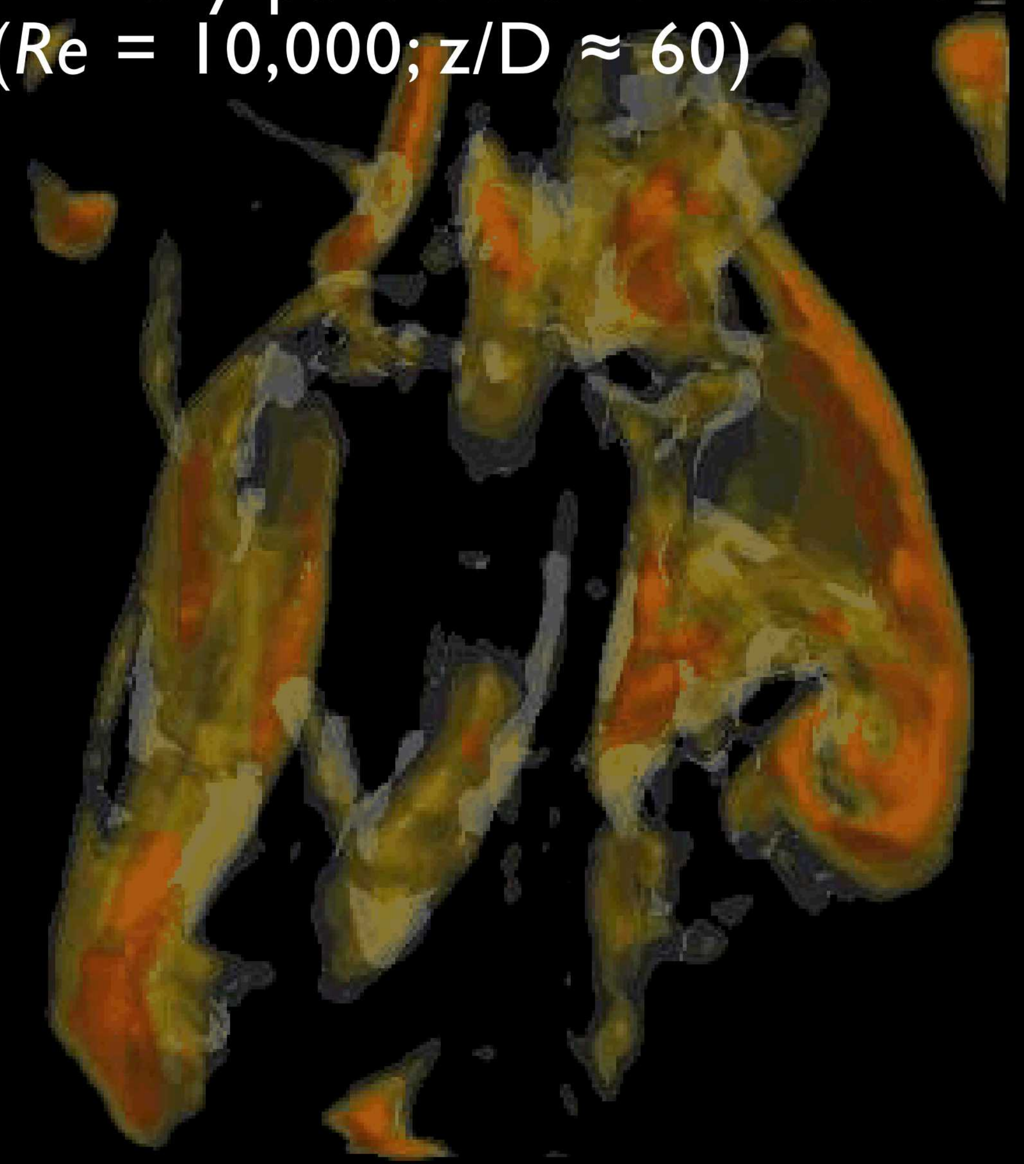


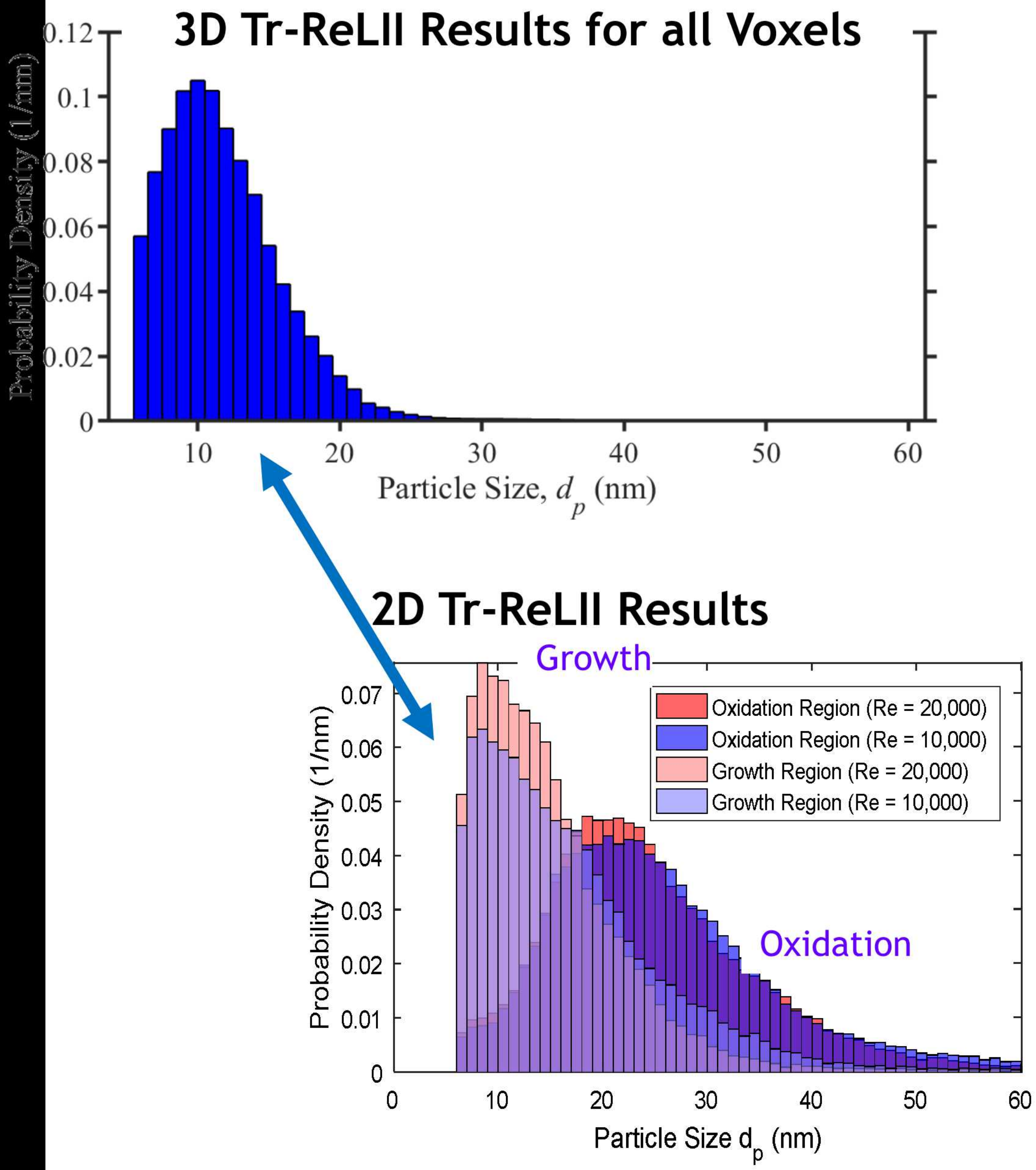
d_p = 16 nm

LII Model

Gas temperature	1550 K
Pressure	0.84 bar (5000 ft)
Laser fluence	0.150 J/cm^2
$E(m)$	0.3
TAC	0.37
Aggregate size	30
Time domain	4800 ns
Detection band	575 – 625 nm
Bath-gas heating	On (f_v = 6 ppm)

Primary particle size measurements (Re = 10,000; z/D ≈ 60)





Future work

Experimental improvements

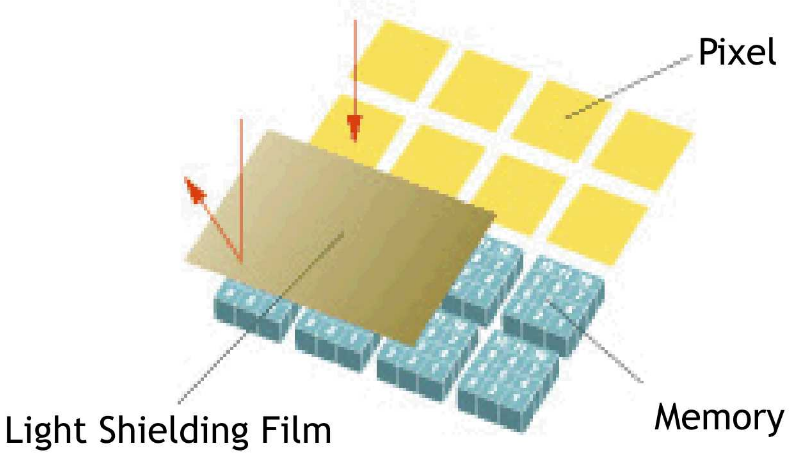
- Resolving camera timing
- Characterization of shot-to-shot laser energy
- Addition of simultaneous planar Ti-Re LII

Parametric study

- Measurement volume at varied flame regions
    - Towards characterization of soot growth and decay
- Variation of Reynolds number
- Variation of laser fluence

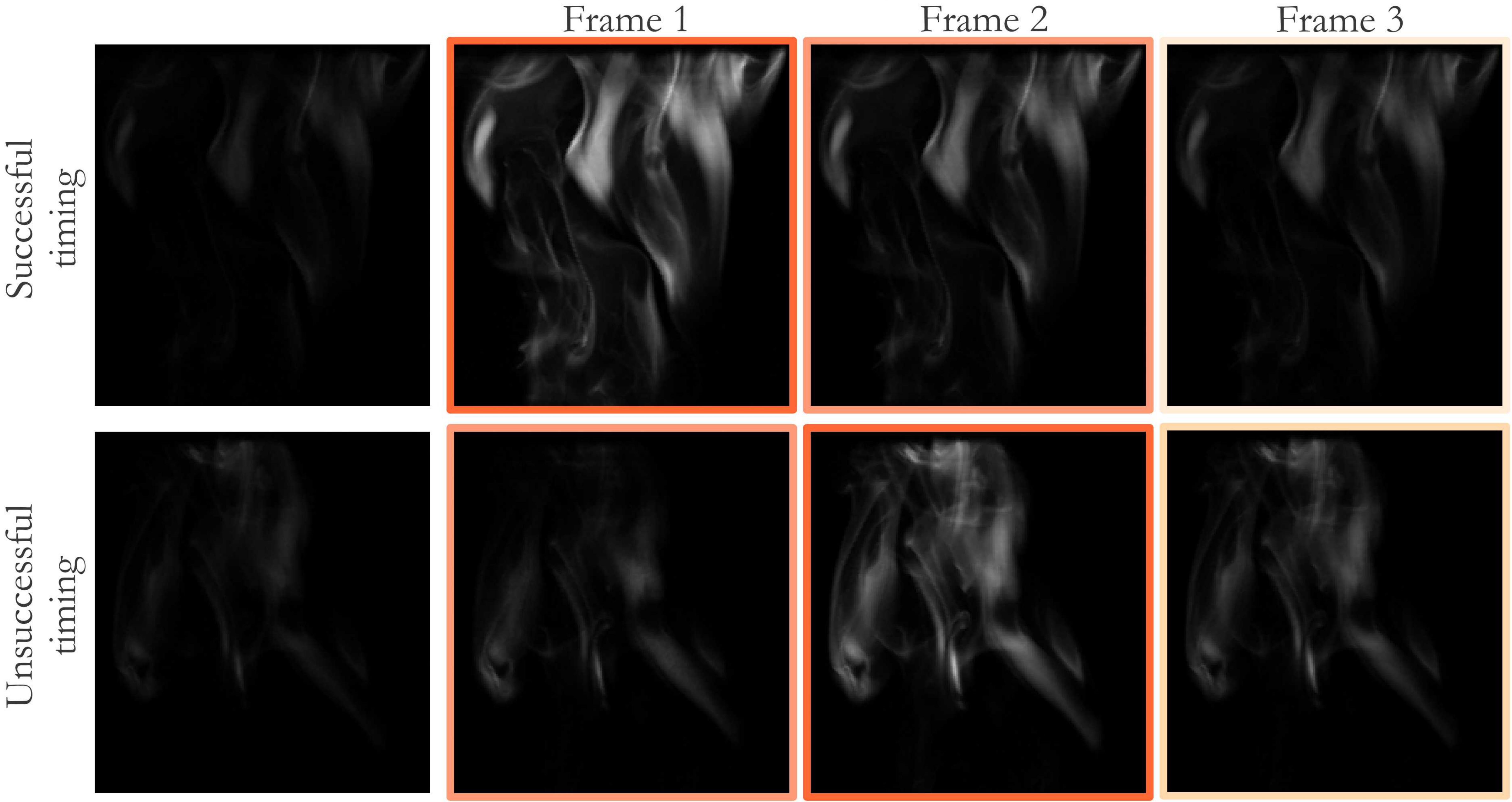
Future work: Resolving Camera Timing

- 3 Shimadzu cameras
  - FTCMOS2 sensor (ISO 16,000, 32 μm pixels)
  - 10 bit, 250 ×400 pixels, 256 frames max
  - 5 MHz full frame (110 ns exposure)
  - <u>10 MHz zig-zag frame (50 ns exposure)</u>
  - Bandpass filter: 600 nm, 50 nm FWHM
  - No image intensifier
- Camera architecture introduces challenges
  - Timing more difficult to control



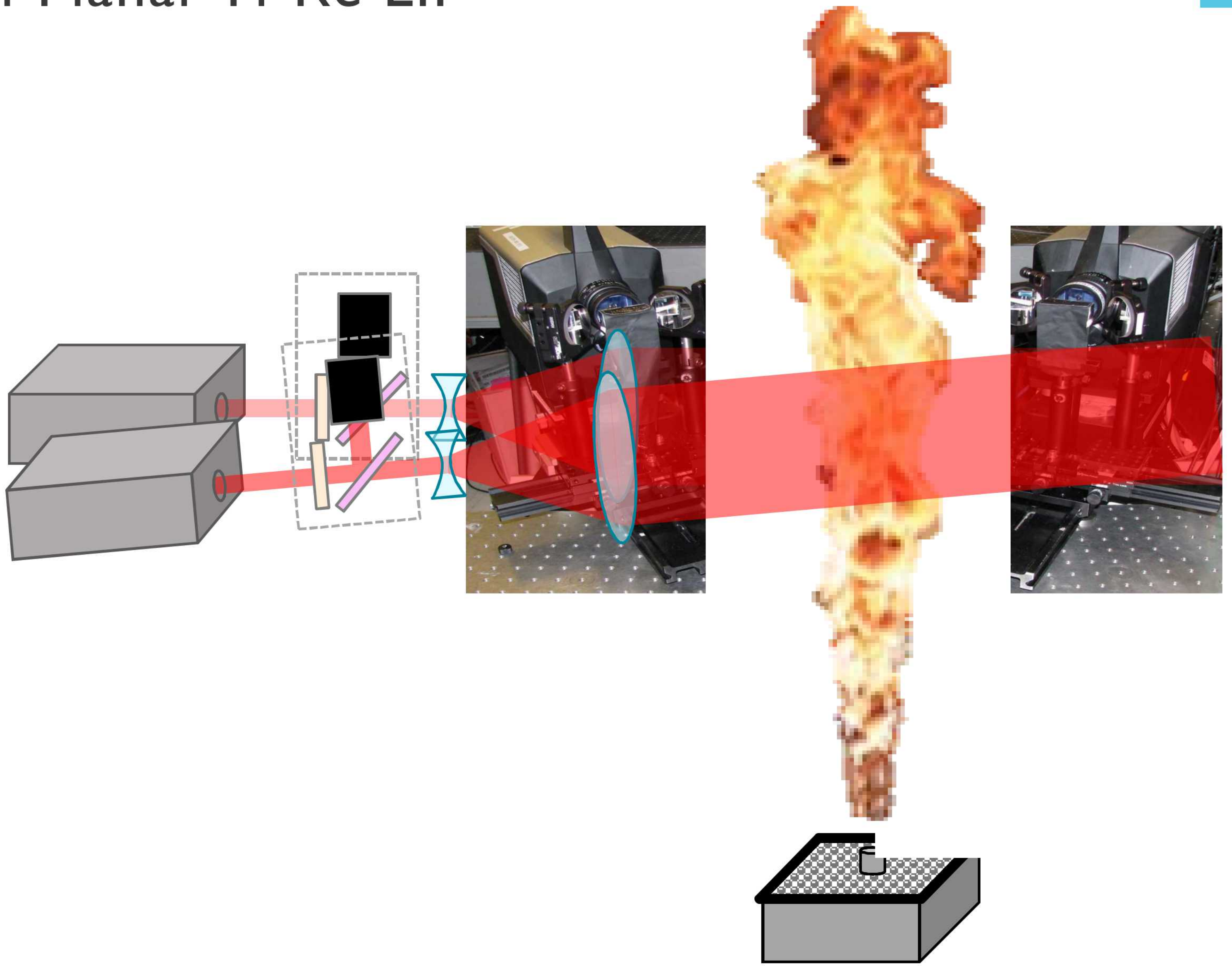
Shimadzu HPV-X2
85 mm lens 1:1.8D

Future Work: Resolving Camera Timing



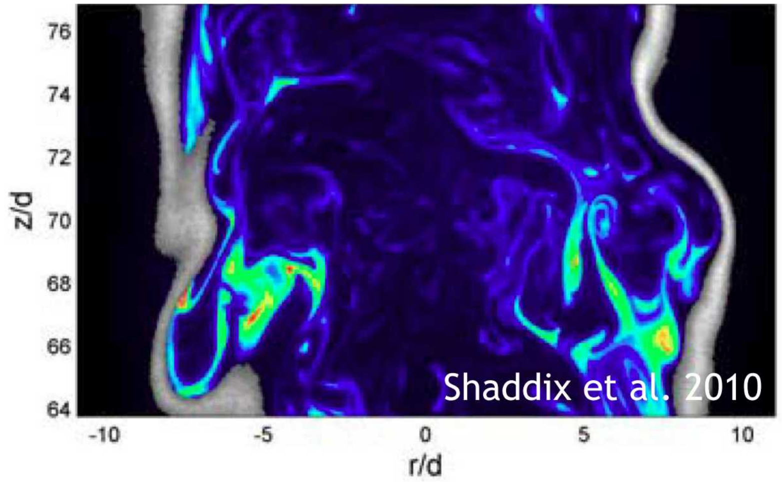
Future Work: Addition of Planar Ti-Re LII

- Each camera captures 256 frames per run, only ~ 10 are used for Tomographic Ti-Re LII
- A second laser pulse could be used to collect 2D Ti-Re LII data immediately before the 3D data collection
- Wider collection angles

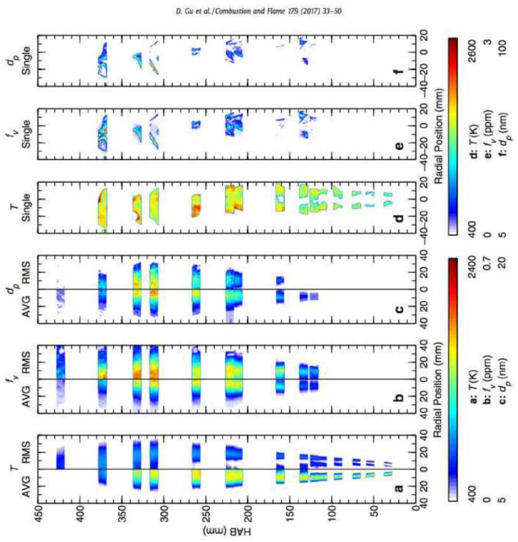


Building a rich data set for this turbulent sooting flame:

OH PLIF and LII

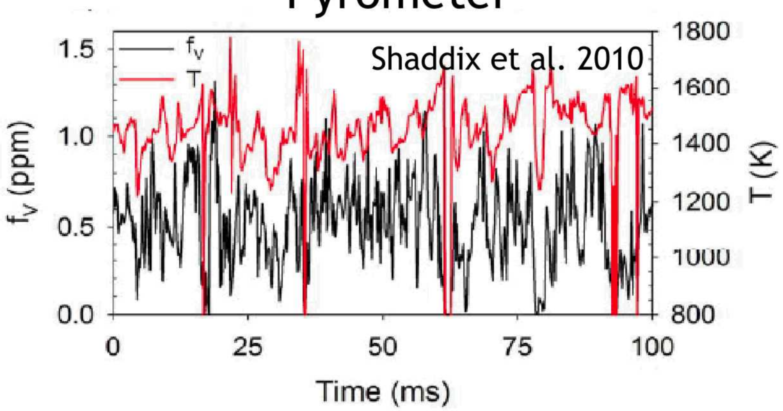


Planar TiRe LII

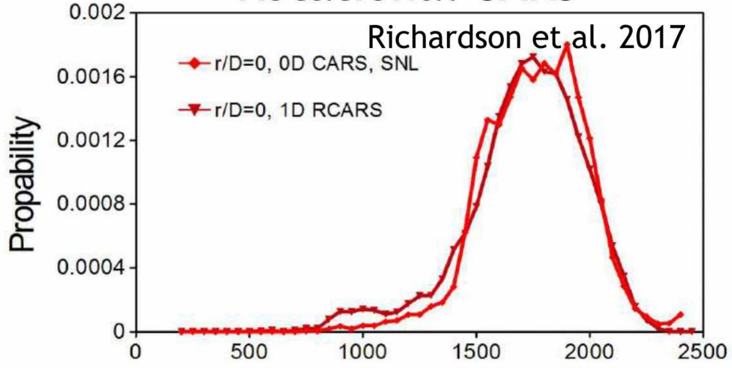


Gu et.al 2017

Pyrometer

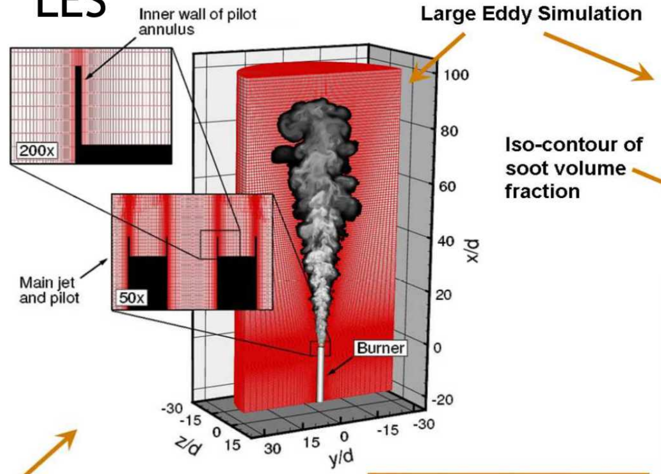


Rotational CARS



LES

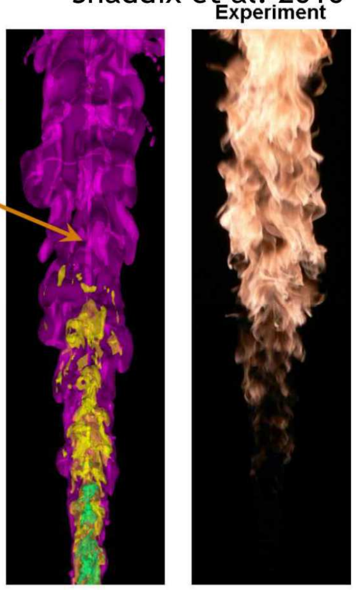
Shaddix et al. 2010



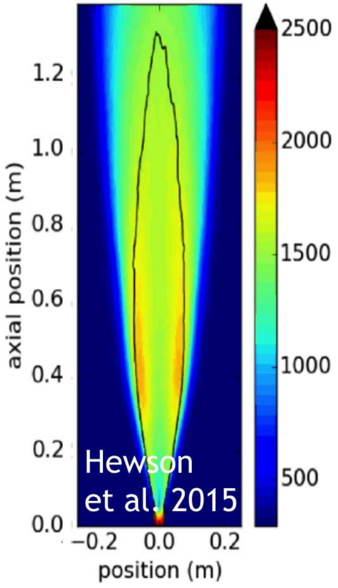
Detailed treatment of burner geometry, pilot, jet boundary layer dynamics and inflow conditions. 12-million cell mesh.

Jet Diameter	3.2 mm
Outer Diameter	19.1 mm
Pilot	C2H4/Air, φ = 0.90
Jet Re	15,000
Jet Velocity	41.0 m/s
Coflow Velocity	0.6 m/s

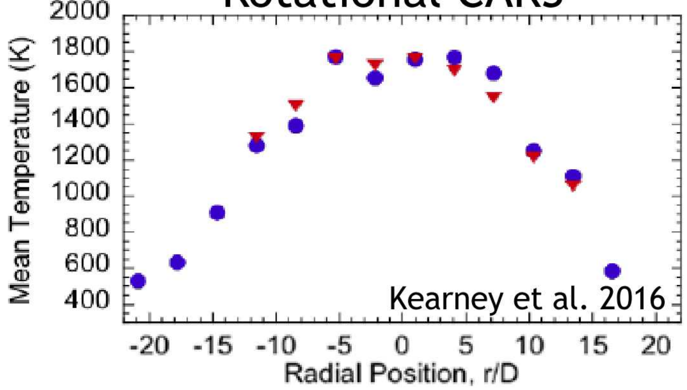
Shaddix et al. 2010



ODT

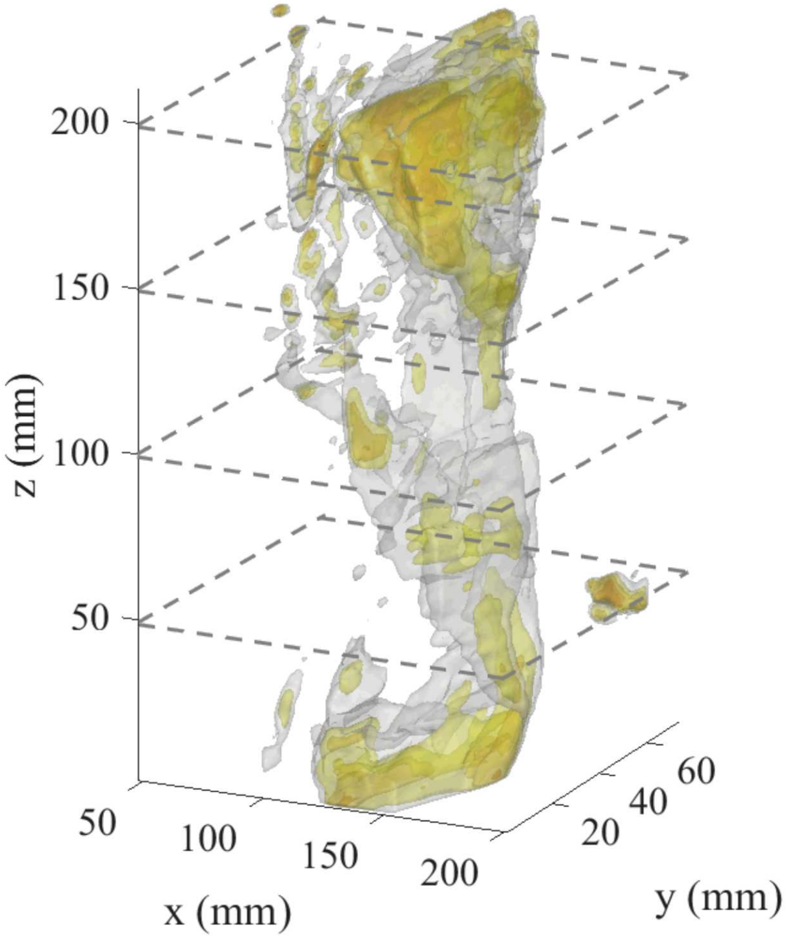


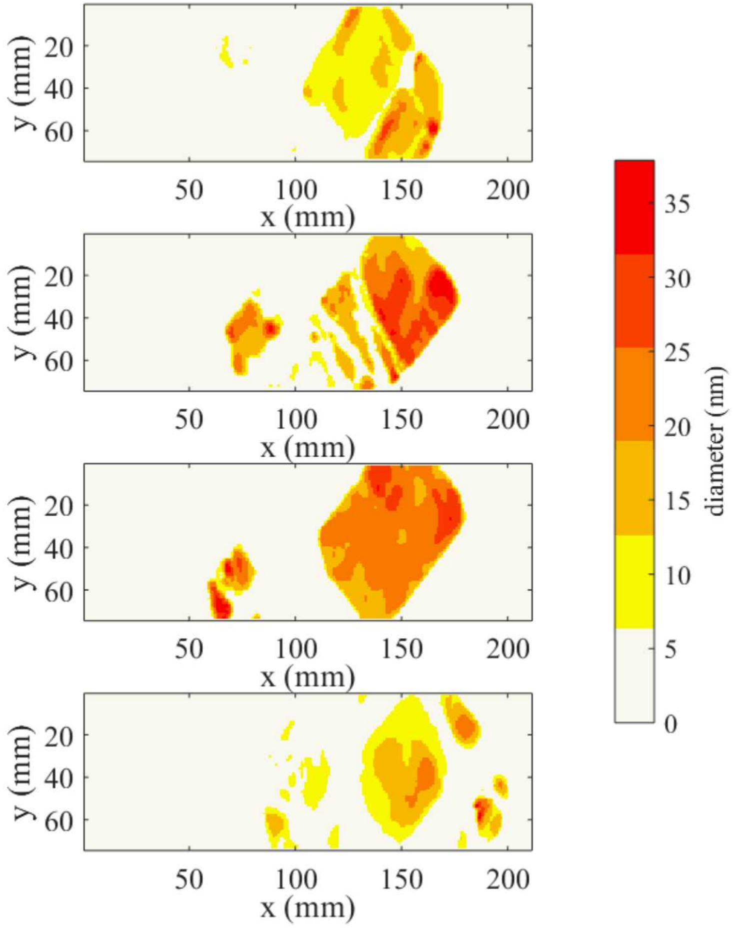
Rotational CARS



Conclusions

- Volumetric determination of soot primary particle sizes has been demonstrated.
- Experimental results agree with several models and the planar results of Chen et al.





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