Thermoacoustic Oscillations in Aeronautical Gas Turbine Combustors

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National Colloquium on Sustainable Aviation
UTIAS, 23/06/2017

Institute for Aerospace Studies
UNIVERSITY OF TORONTO

The Team


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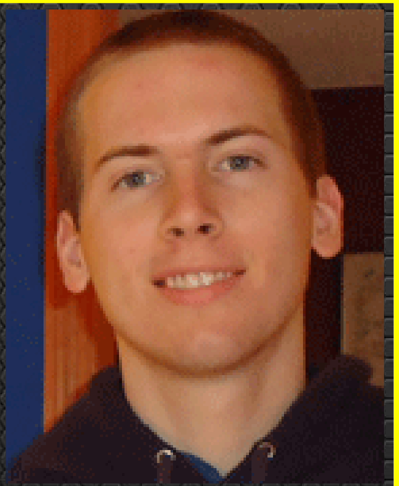
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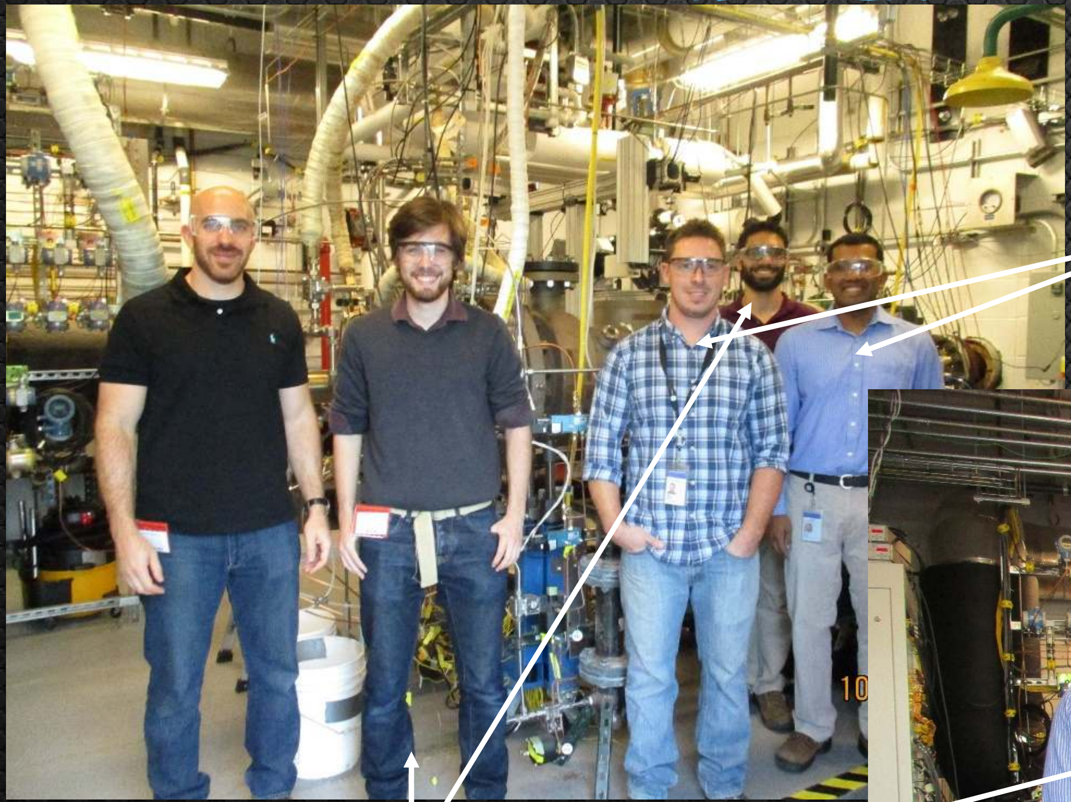
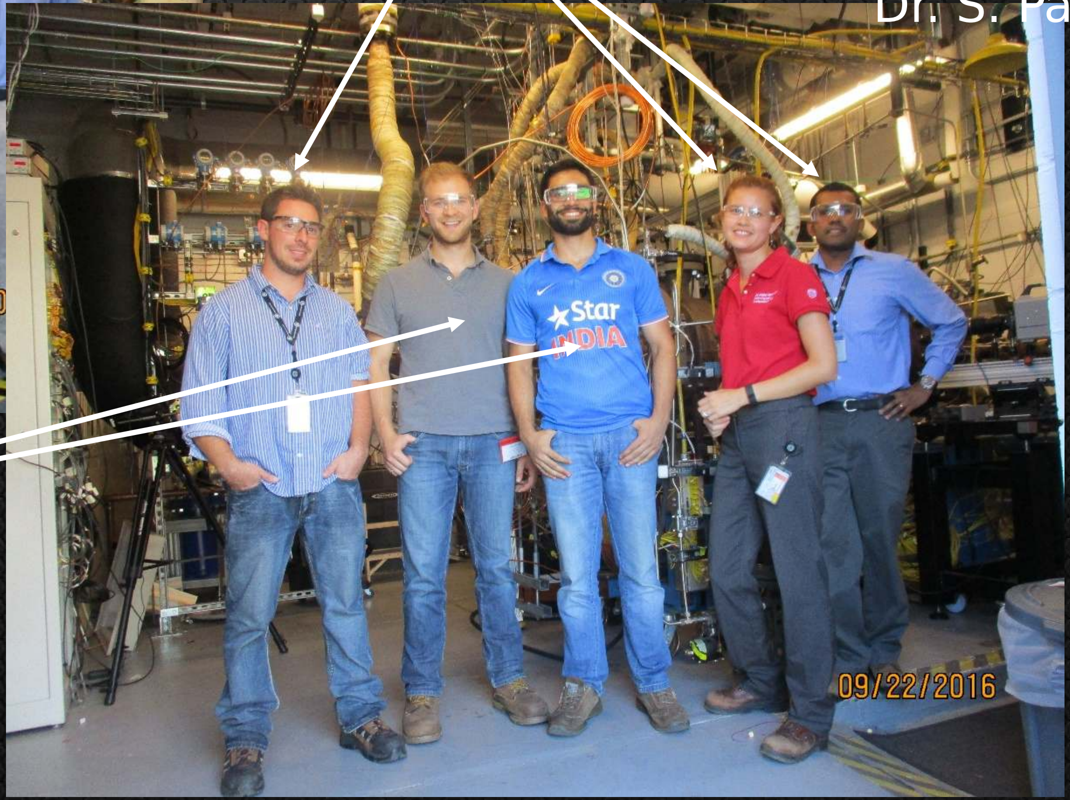
The Team: GE Global Research Centre





GE Staff

Students

Dr. F. Han
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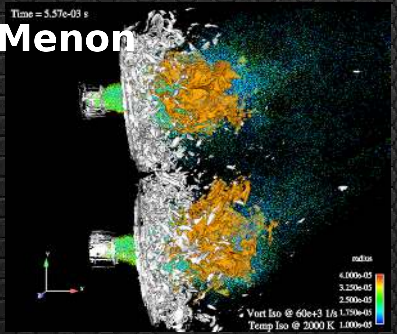
Dr. M. Benjamin
Dr. K. Kim
Dr. S. Pal

Gas Turbine Combustor R&D Landscape

Turbulent Reactive Flows

- High Ka combustion
- Rare events
  - Ignition, extinction, flashback
- Chemistry of real fuels
- …

Evolutionary Brayton Cycle

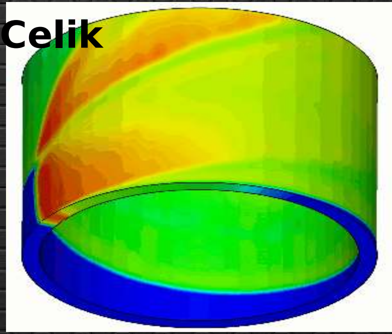


- Engineering improvements to combustor architectures
- Reduced design/ development costs
- …

Novel Brayton Cycle

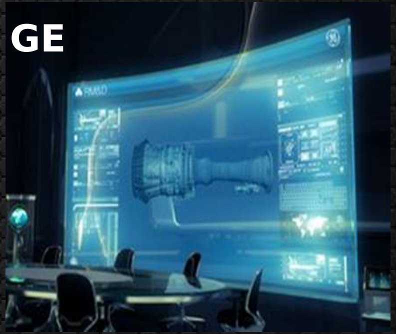
- New combustor architectures for Brayton cycle
  - TAPS
  - Multi-point LDI
- Reduced design/ development costs
- …

Non-Brayton Cycle



- Pressure gain combustion
  - Rotating detonation combustors
- …

Digitalization



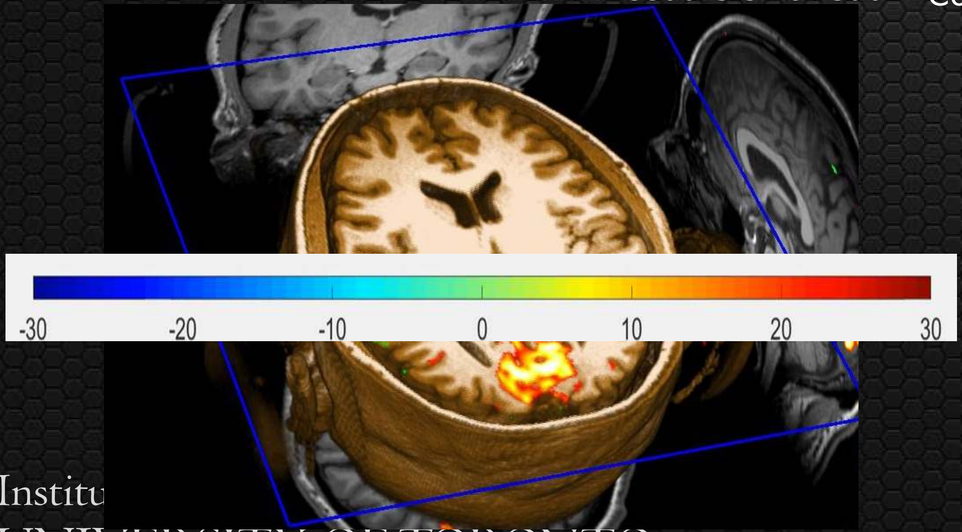
- Digital twins
- Real-time monitoring
  - Sensor networks
  - ANN
- …

Measurement is Key

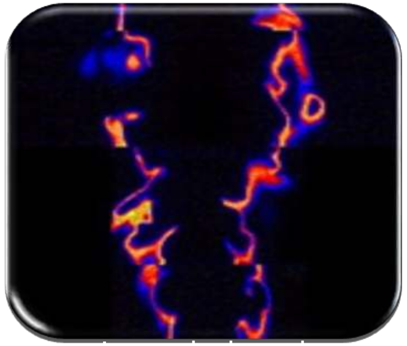
Wa wake interactions in highly-loaded transonic turbomachines

www.vital-temp.com

www.cedars-sinai.edu

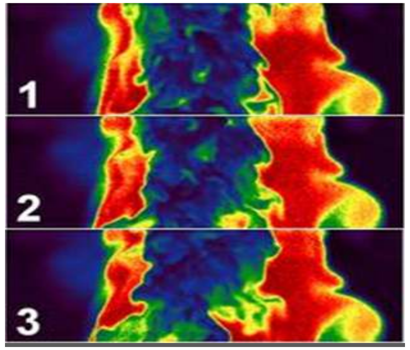


Steinberg et al. *PCI* (2011)



2D distribution of minor species
Indicators of thermo-chemistry

Papageorge et al. *App. Phy. B* (2014)



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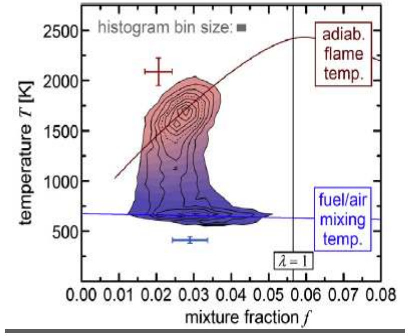
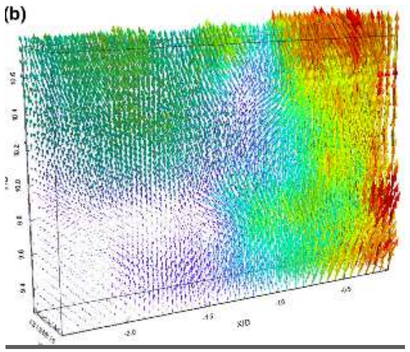


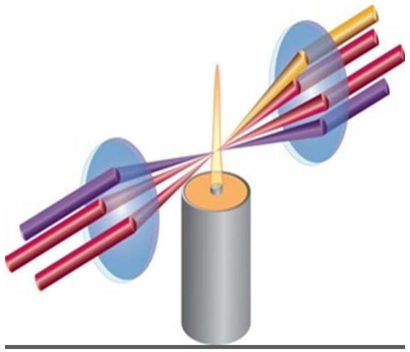
0D major species and temperature
Detailed chemical state

Coriton et al. *Exp. Fluids* (2014)



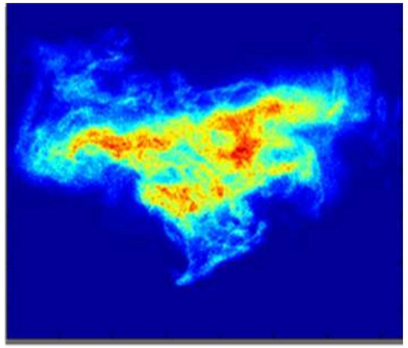
Velocity fields by tracking particles
2D, 3D, 4D

Image from J. Gore (Purdue)



Temperature, pressure, density
Highly accurate

An et al. *CnF* (2016)



Heat release rate
Fuel air ratio

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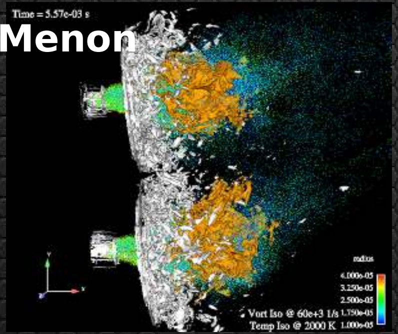

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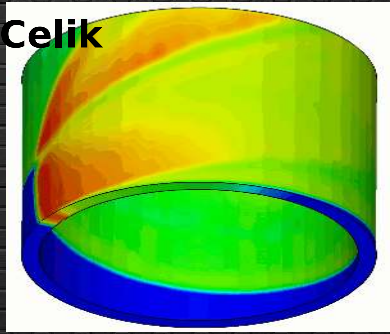

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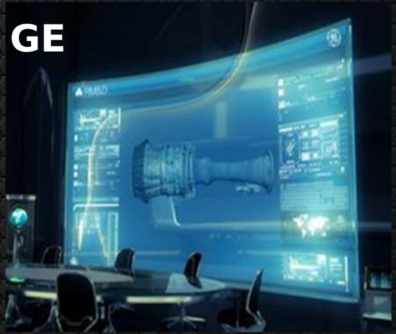
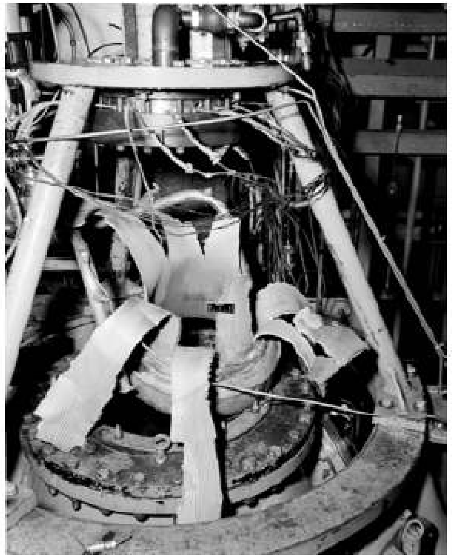
Digitalization



- Digital twins
- Real-time monitoring
  - Sensor networks
  - ANN
- …

Thermoacoustic Instabilities



Liquid rocket engine (NASA 1957)

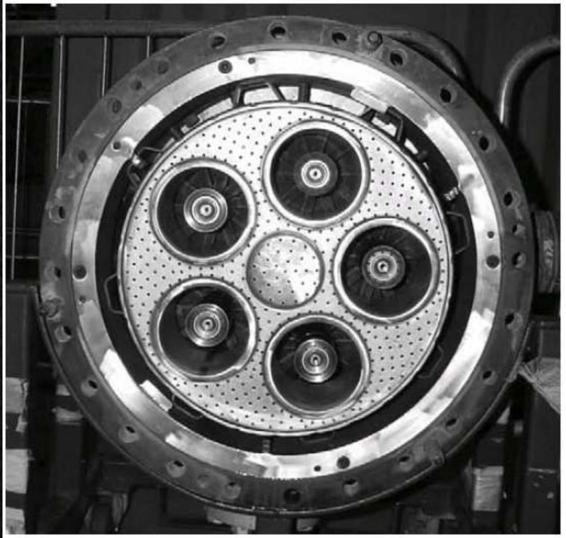
Liquid rocket engine (NASA 1963)

Calpine: Equipment Failures From Siemens Turbines

February 24, 2005: 15:43 p.m. EST

SAN FRANCISCO -(Dow Jones)- Calpine Corp.'s (CPN) unexpected costs due to equipment failure in the fourth quarter were related almost entirely to turbines purchased from Siemens AG (SI), a Calpine executive said Thursday in a conference call with Wall Street analysts.

Calpine reported a fourth-quarter net loss of $172.8 million, compared with net income of $119.6 million in the final quarter of 2003. The company, which has built its huge fleet of natural gas-fired power plants in the U.S. over the past several years, said equipment-failure costs of $45.3 million were a significant part of the downturn in results. The fourth-quarter loss of 39 cents a share surprised Wall Street analysts, who had been expecting a loss of 14 cents on average, according to First Call.



Goy *et al.*, AIAA (2005)

Thermoacoustic Instabilities

$\psi_s > 0$: Positive forcing

$\psi_s < 0$: Negative forcing

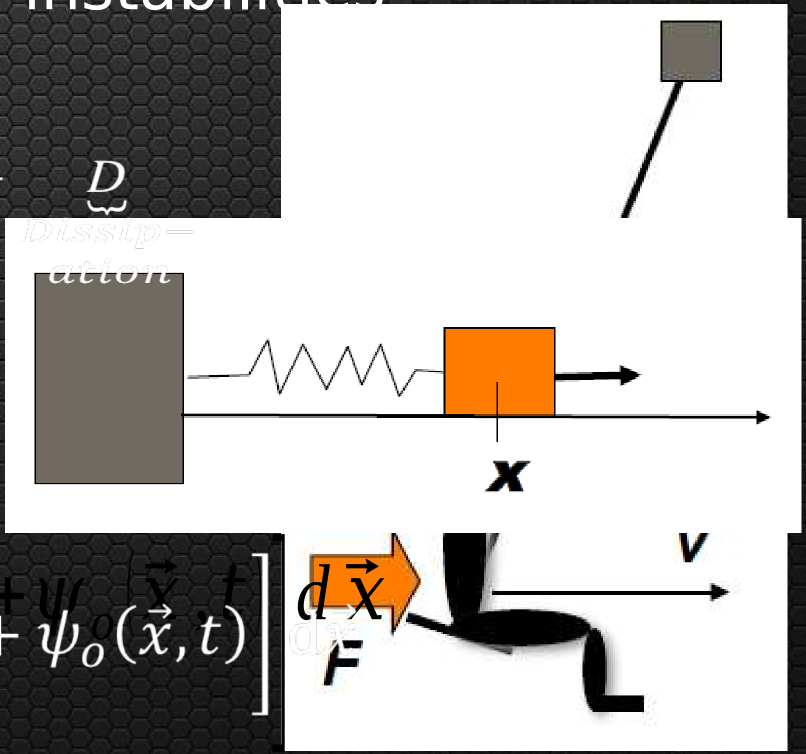
- All combustors can exhibit thermoacoustic instabilities

$$\frac{\partial \overbrace{e(\vec{x},t)}^{Acoustic\ energy}}{\partial t} + \underbrace{\nabla \cdot [p'(\vec{x},t)\vec{u}'(\vec{x},t)]}_{Flux} = \underbrace{\frac{\gamma-1}{\gamma\bar{p}} p'(\vec{x},t)\dot{q}'(\vec{x},t)}_{Source/sink} + \underbrace{D}_{Dissipation}$$

$$\frac{1}{2}m\dot{x}^2 + \frac{1}{2}kx^2 = E_0 + \int_0^t f\dot{x}\,dt'$$

$$\Theta = \underbrace{\int_v e(\vec{x})\,d\vec{x}}_{Total\ energy} \propto \int_v \int_0^t \underbrace{p'(\vec{x},t)\dot{q}'(\vec{x},t)}_{Forcing}\,dt\,d\vec{x}$$

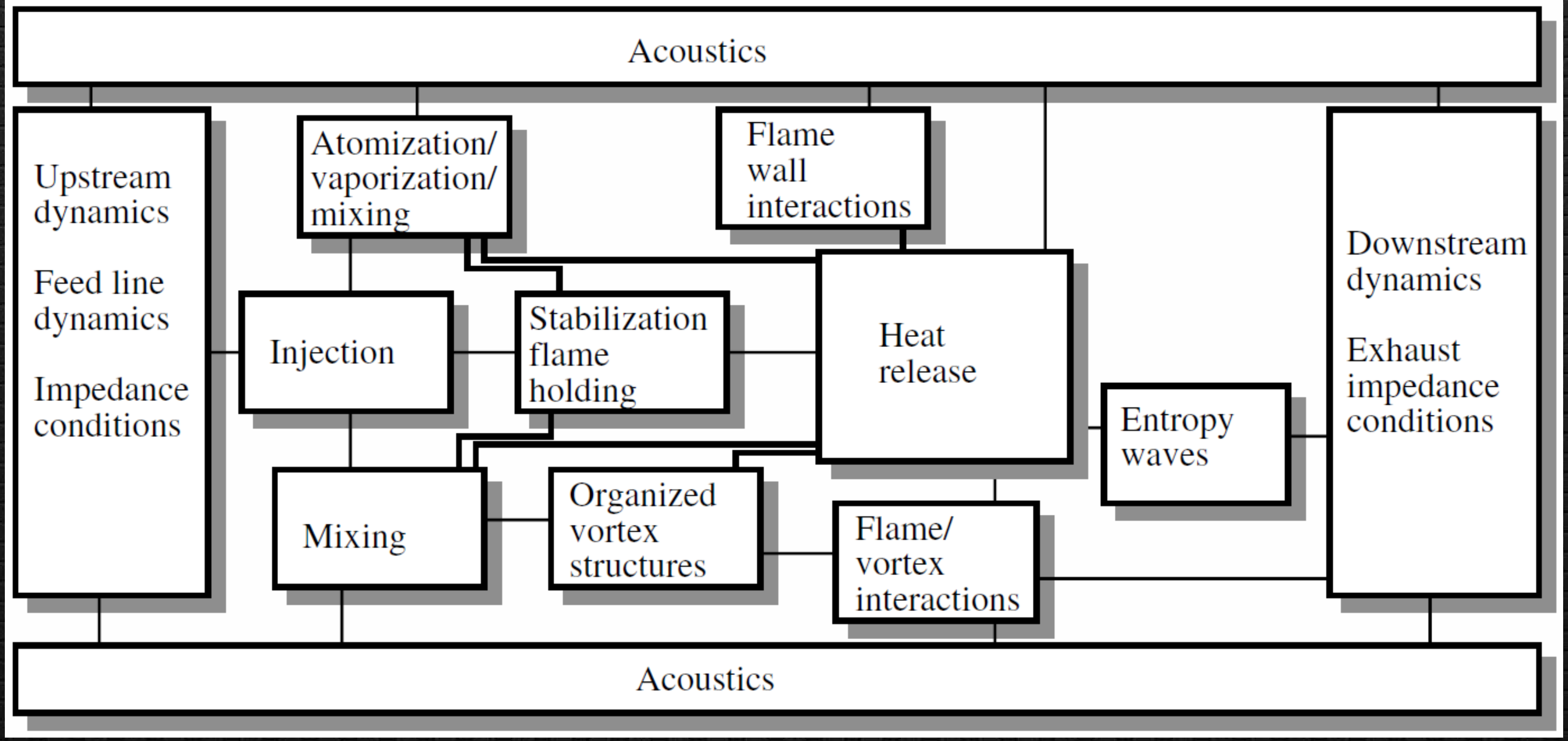
$$\Psi(t) = \int_v \psi(\vec{x},t)\,d\vec{x} \propto \int_v \left[\underbrace{\tilde{p}(\vec{x},t)\tilde{q}(\vec{x},t)\cos\left(\Delta\phi_{pq}(\vec{x},t)\right)}_{\psi_s(\vec{x},t)} + \psi_o(\vec{x},t) \right]$$



- Combustion methods that reduce emissions (NO_x, particulates) increase the chance of thermoacoustic instabilities

Thermoacoustic Instabilities

- All combustors can exhibit thermoacoustic instabilities

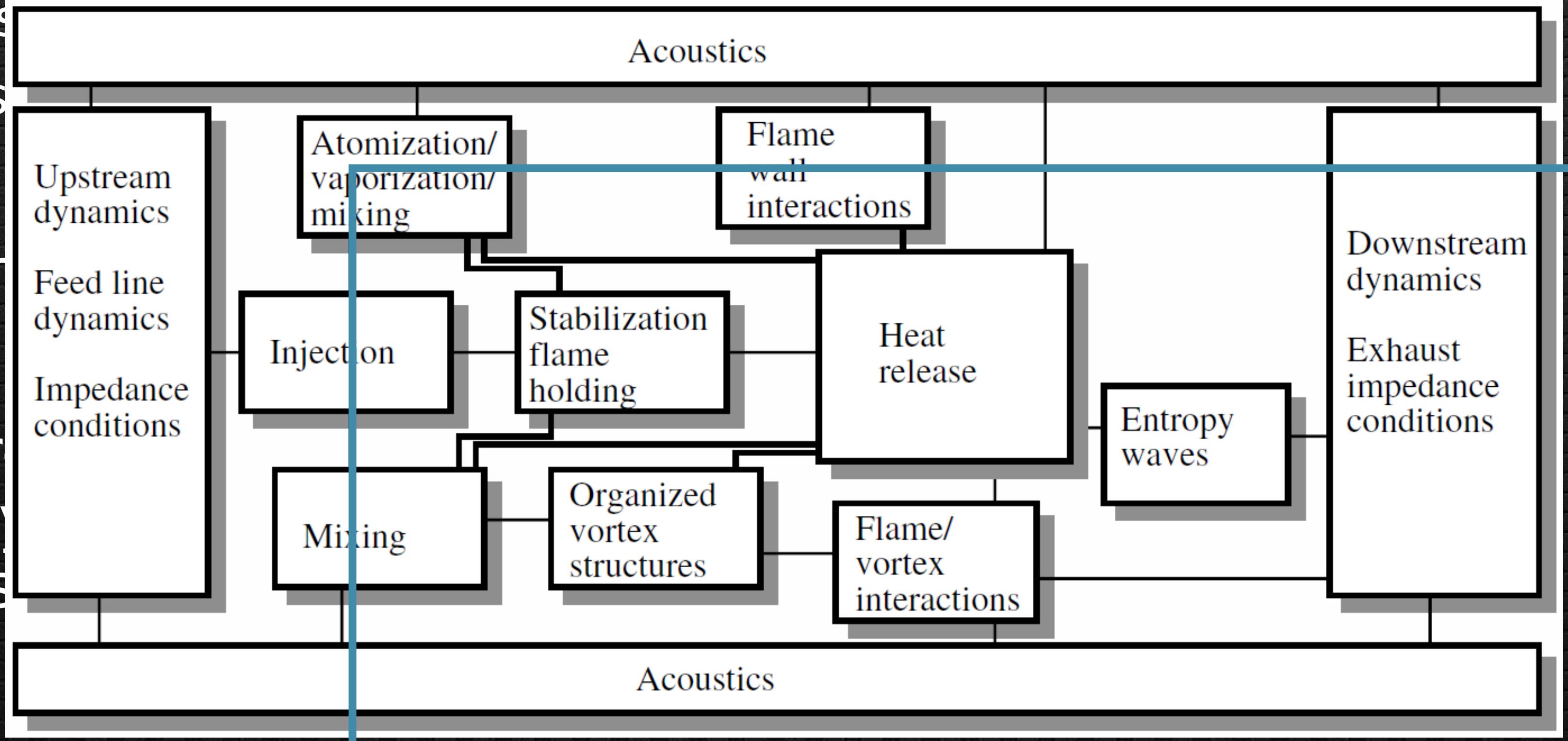


Candel, 2002

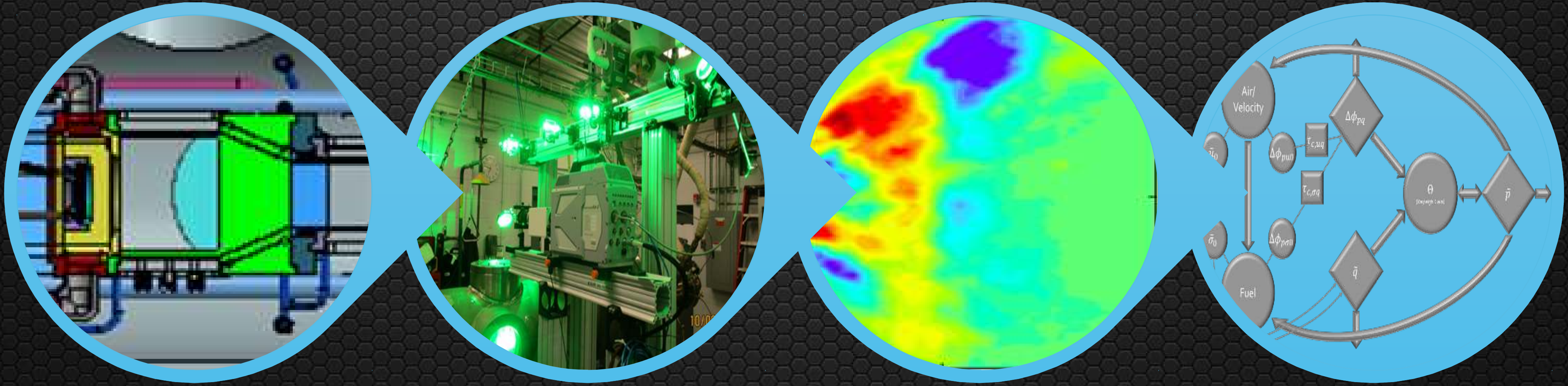
- Combustion methods that reduce emissions (NO_x, particulates) increase the chance of thermoacoustic instabilities

Our Approach to Thermoacoustics

- Measure this…
  - With as
  - As clos
- Optical measur techniq
- High-pr optically combus

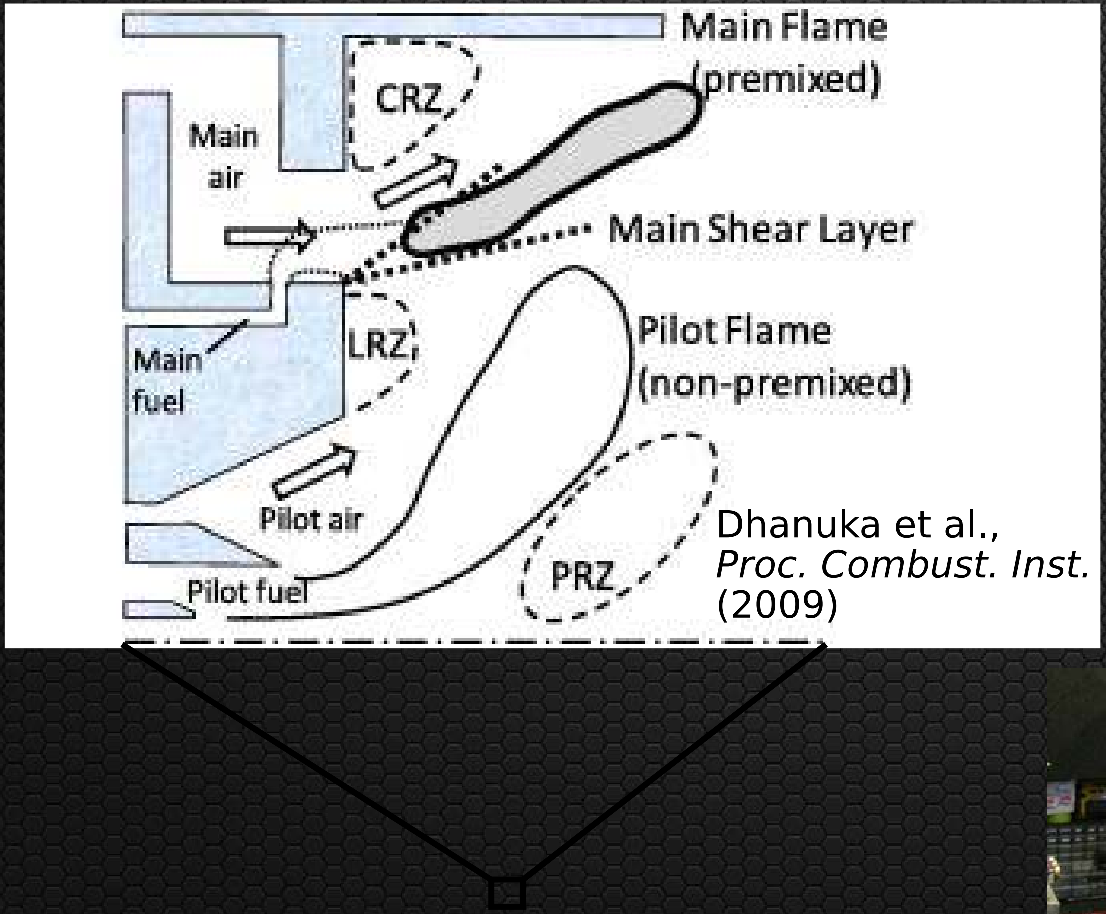


Outline for Next ~15 Minutes



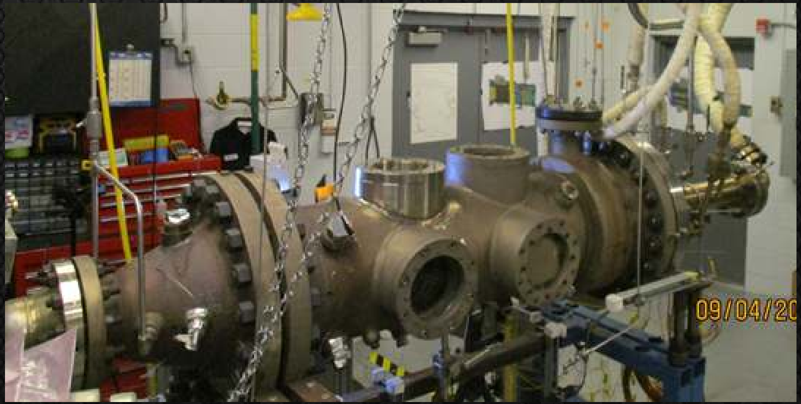
- Experiment
- Diagnostics
- Intermittent thermoacoustic oscillations
- Predictability

Experimental Setup

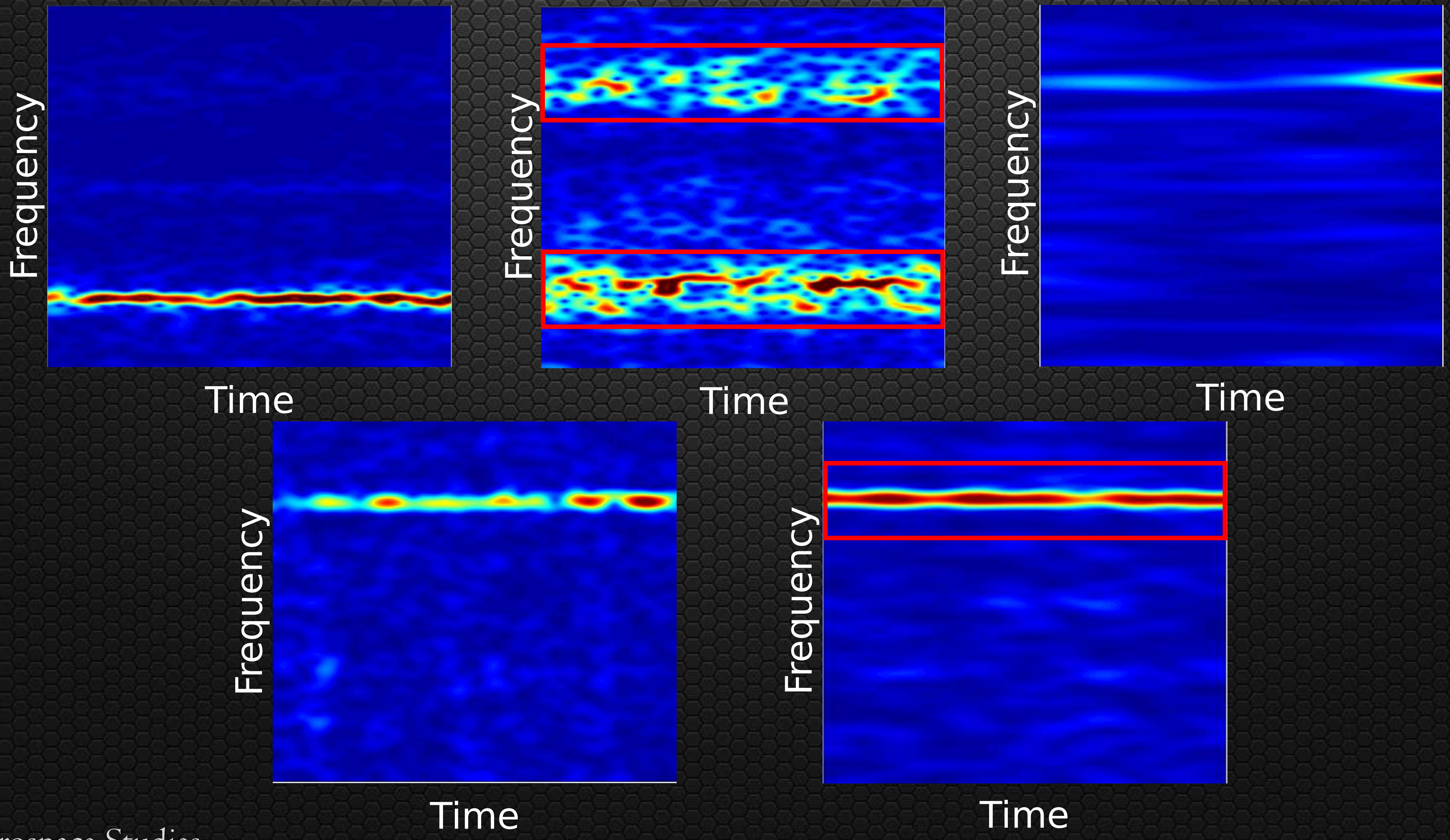


Dhanuka et al., *Proc. Combust. Inst.* (2009)

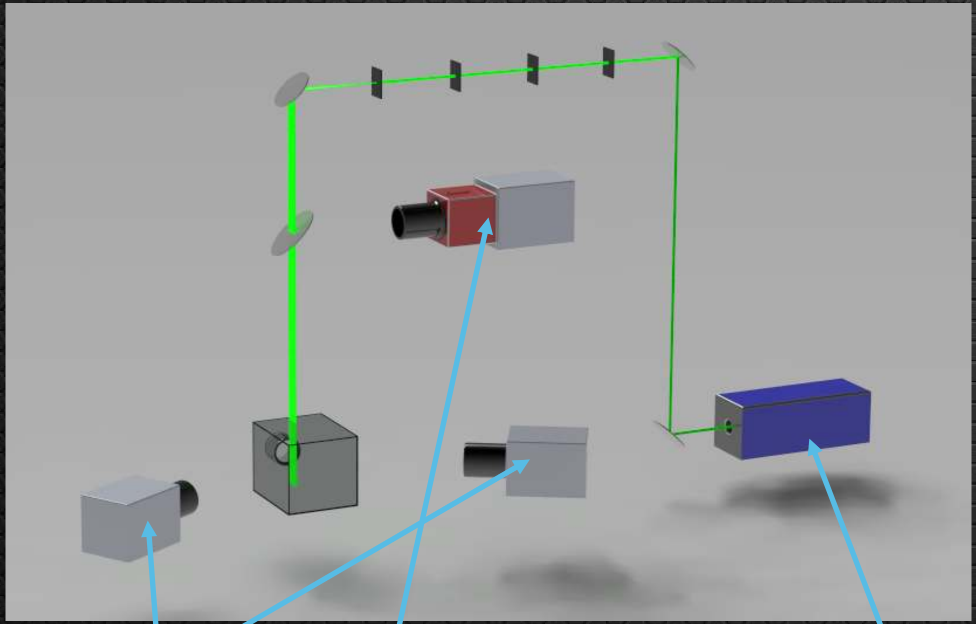
- Experiments at GE Global Research Center (Niskayuna, NY)
- Model injector for N+1/N+2 hardware
- p ~ 10 atm
- P_{th} ~ 700 kW
- Jet-A fuel
- Many different cases



Thermoacoustic Behaviors



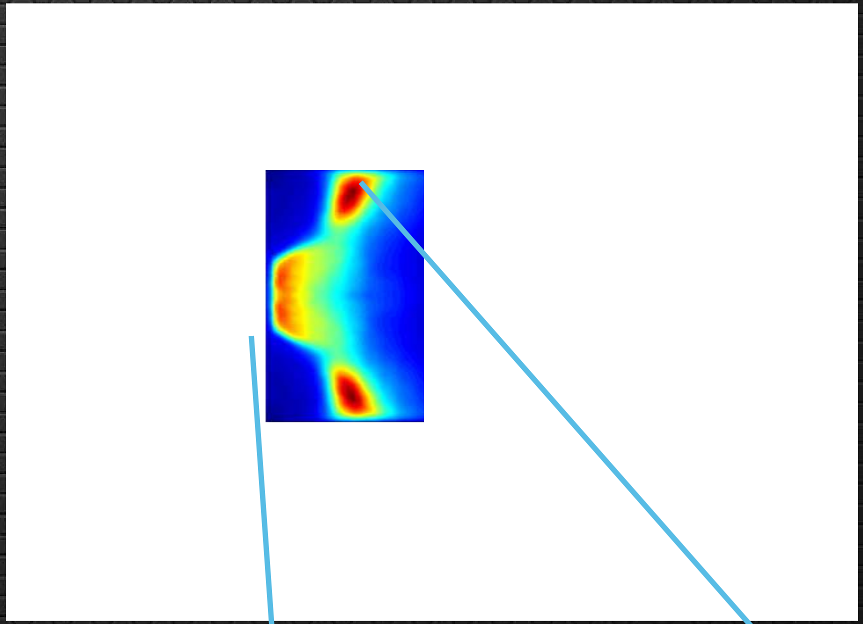
Diagnostic Configuration

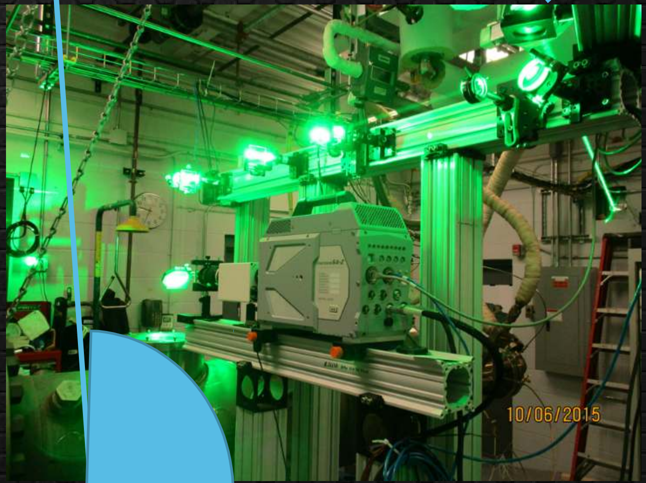


S-PIV cameras

Intensified OH* CL camera

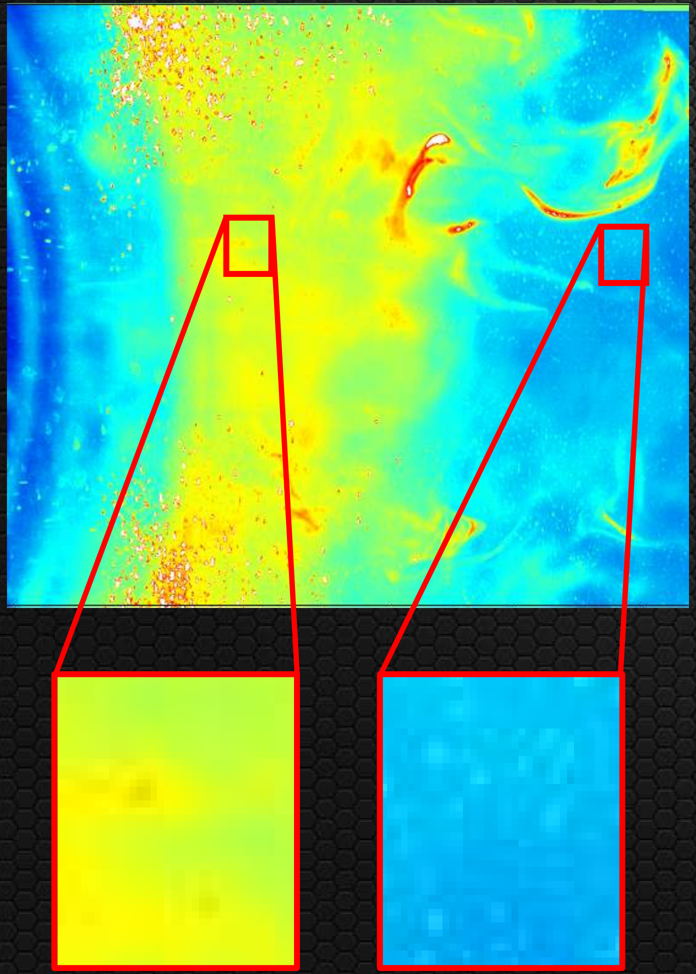
S-PIV Laser (in separate room)

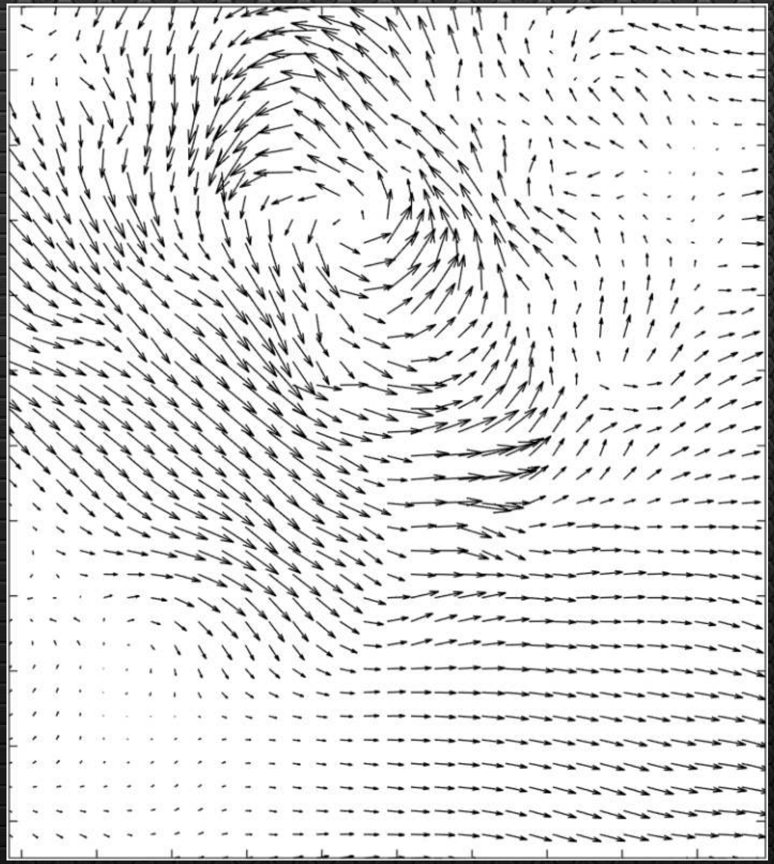




- 5 kHz stereoscopic particle image velocimetry
- 5 kHz stereoscopic droplet image velocimetry
- 10 kHz OH* chemiluminescence

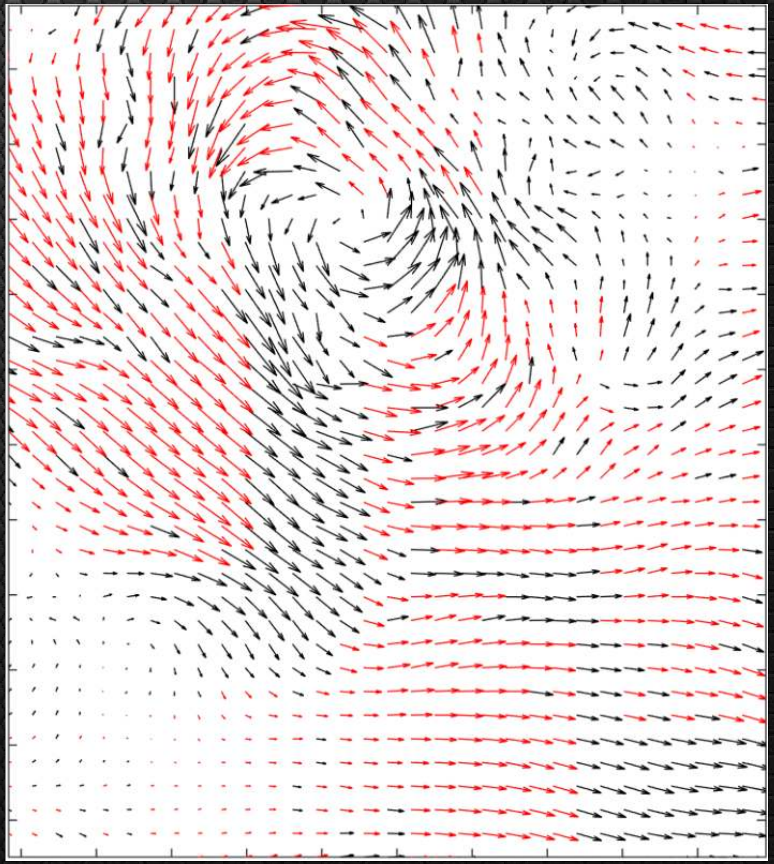
Aside: Managing Noise and Uncertainty





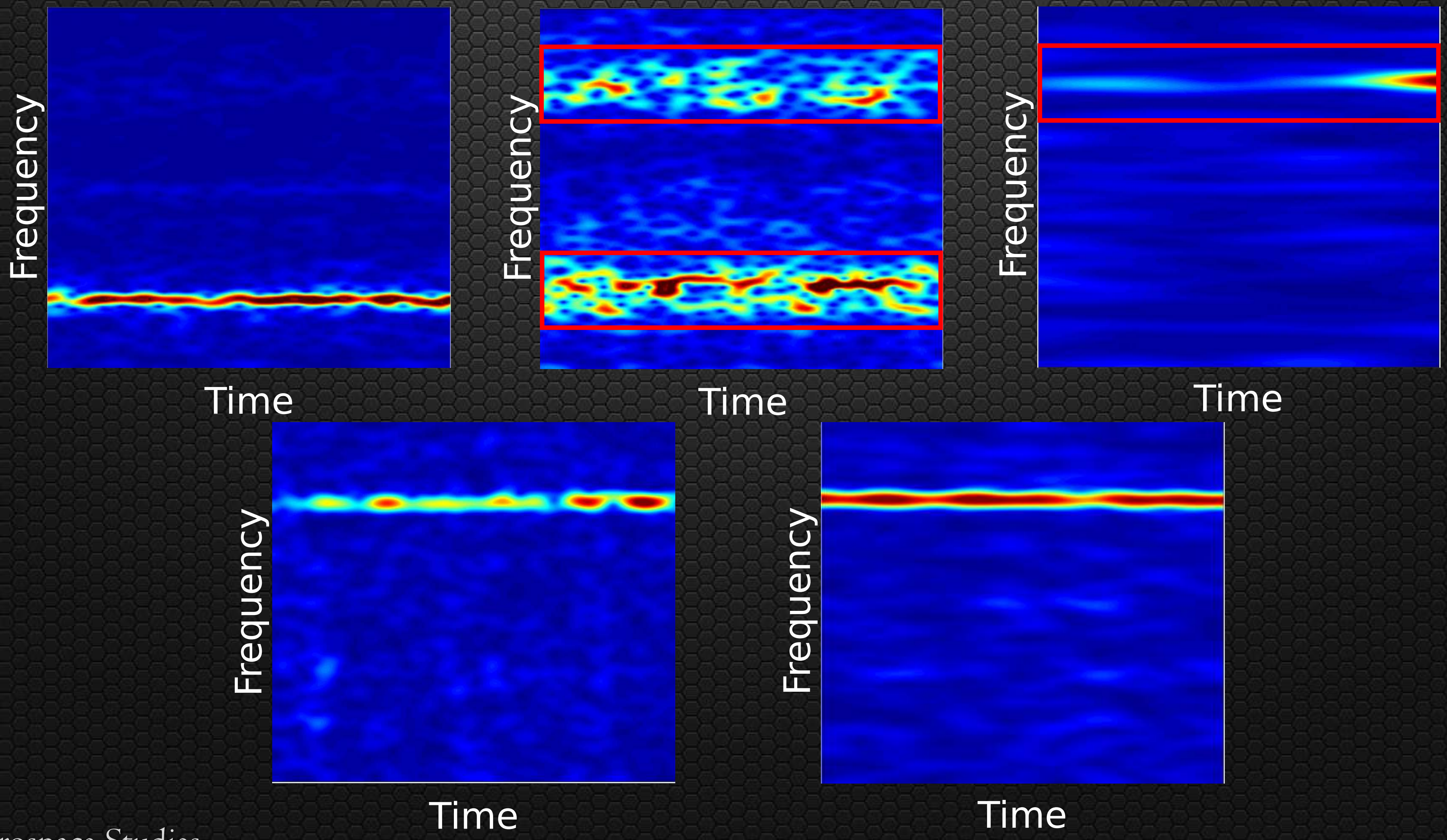
Measurement data with many data points rejected due to noise

Real data



Velocity field deduced using data-driven reconstruction

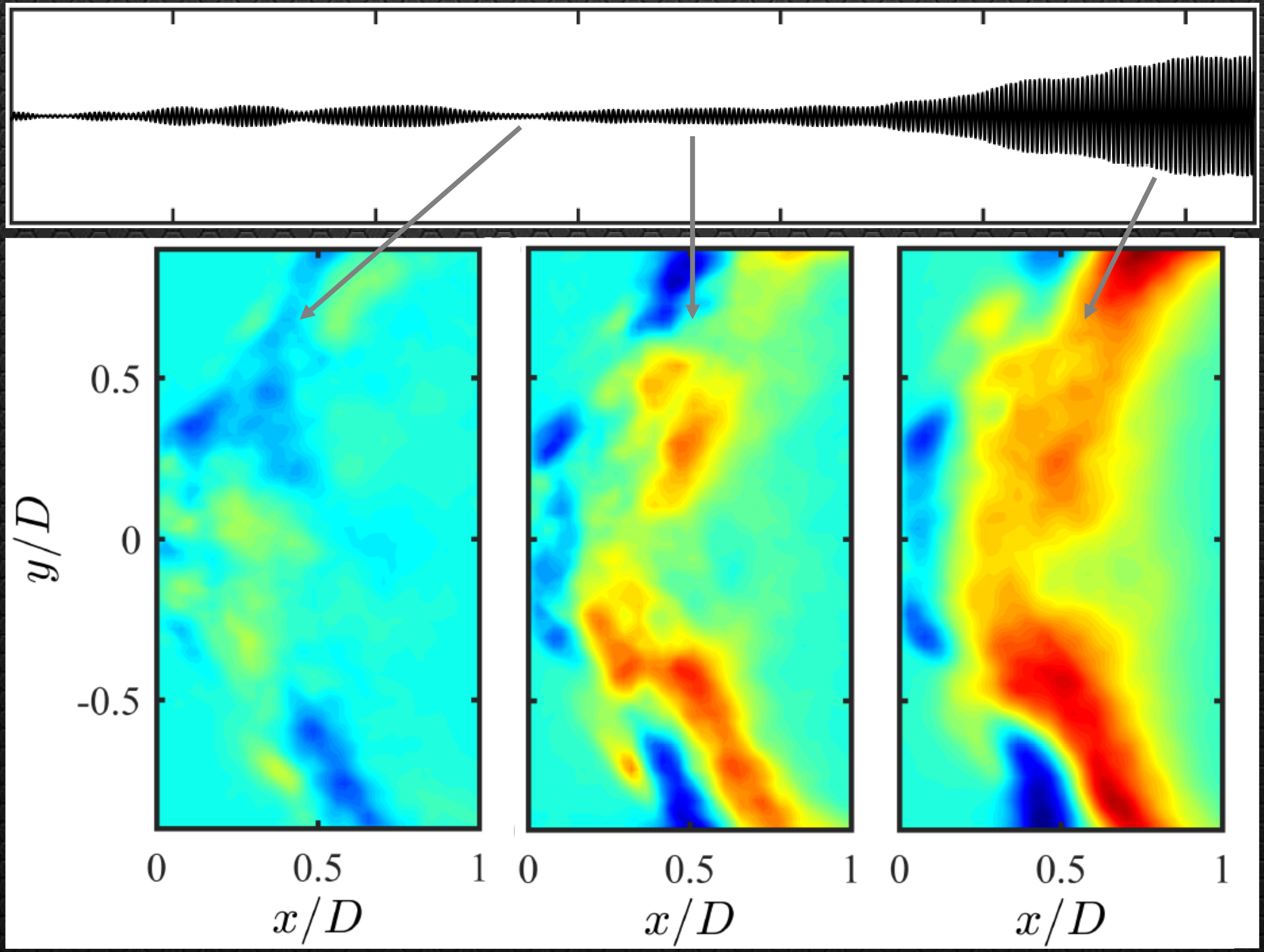
Thermoacoustic Behaviors



Non-Stationary Dynamics

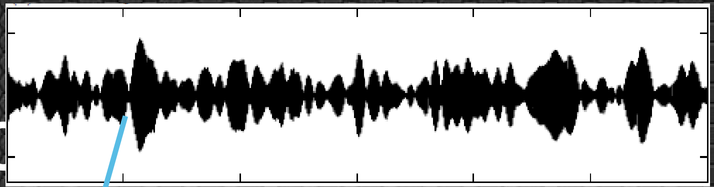
$\psi_s > 0$: Positive forcing

$\psi_s < 0$: Negative forcing



$$\psi_s(\vec{x},t) = \tilde{p}(t)\tilde{q}(\vec{x},t)\cos[\Delta\varphi_{pq}(\vec{x},t)]$$

Intermittent Behavio



$\psi_s > 0$: Positive forcing

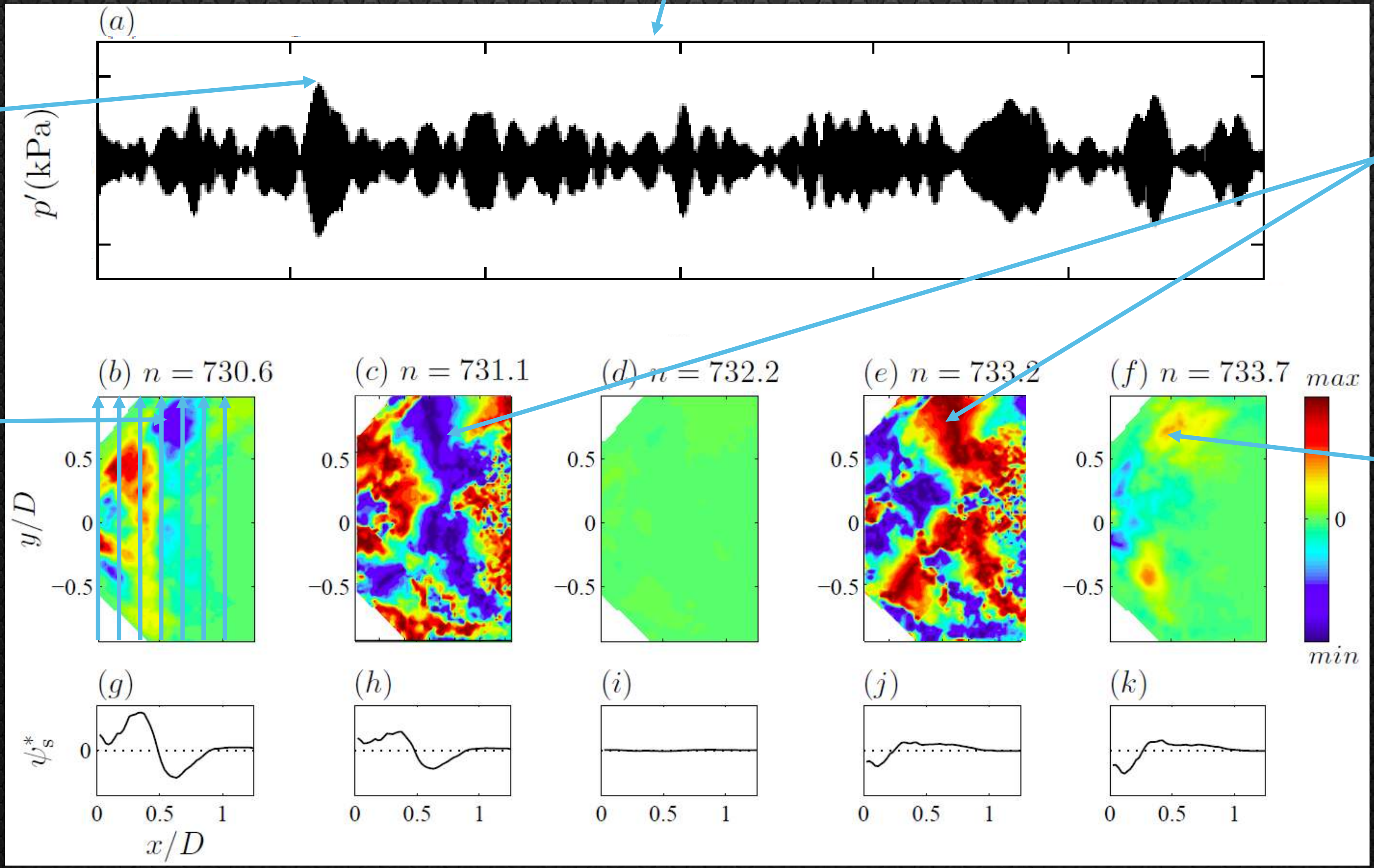
$\psi_s < 0$: Negative forcing

Condition on $\tilde{p}$

Repeat for many 'events'

Condition on $\text{sign}(d\tilde{p}/dt)$

Oscillation attenuation associated with negative downstream forcing (main flame)



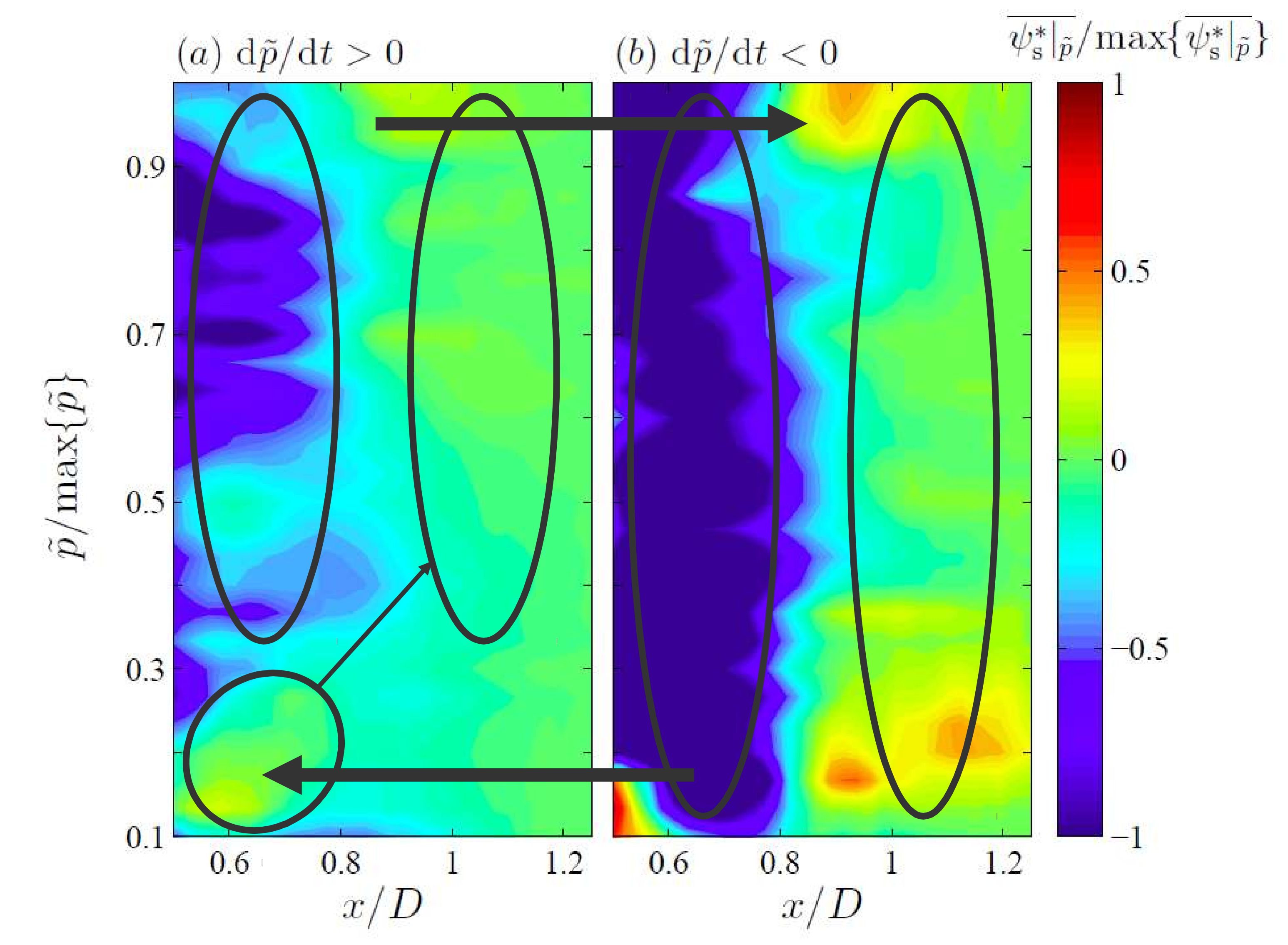
Sudden 180° shift in phase between pressure and heat release rate

Oscillation growth associated with positive downstream forcing (main flame)

$$\psi_s(\vec{x}, t) = \tilde{p}(t)\tilde{q}(\vec{x}, t)\cos[\Delta\varphi_{pq}(\vec{x}, t)]$$

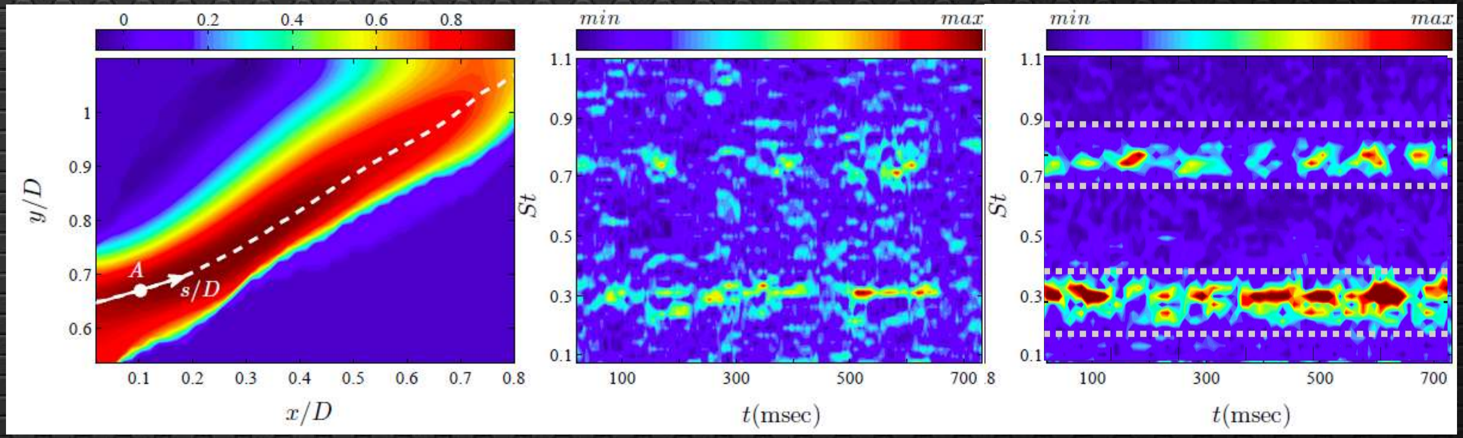
Intermittent Behavior

- Thermoacoustic driving cycles during intermittent oscillations follows a fairly repeatable behavior
- Different axial regions of driving and damping with some transitions



What Wobbles First?

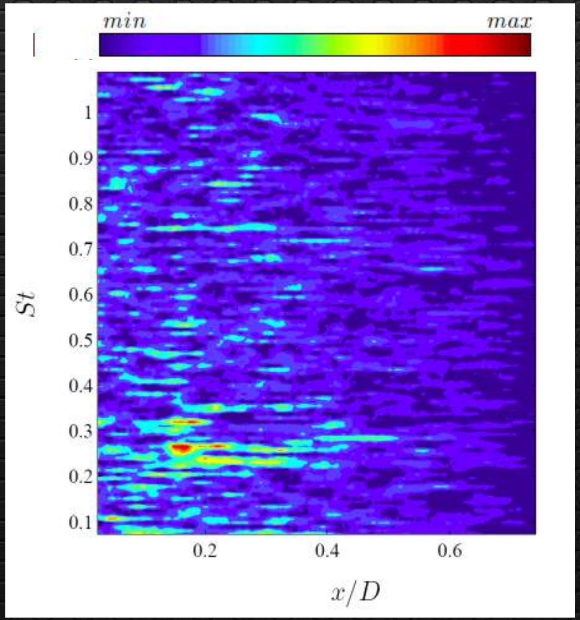
- No <u>detectable</u> oscillations in gas phase velocity at low oscillation amplitudes
- Droplet velocity oscillations shortly after dump plane
  - Same spectral signature as pressure oscillations
- Total droplet scattering oscillations persist downstream
- Amplitude and phase of fuel oscillations linked with pressure oscillations



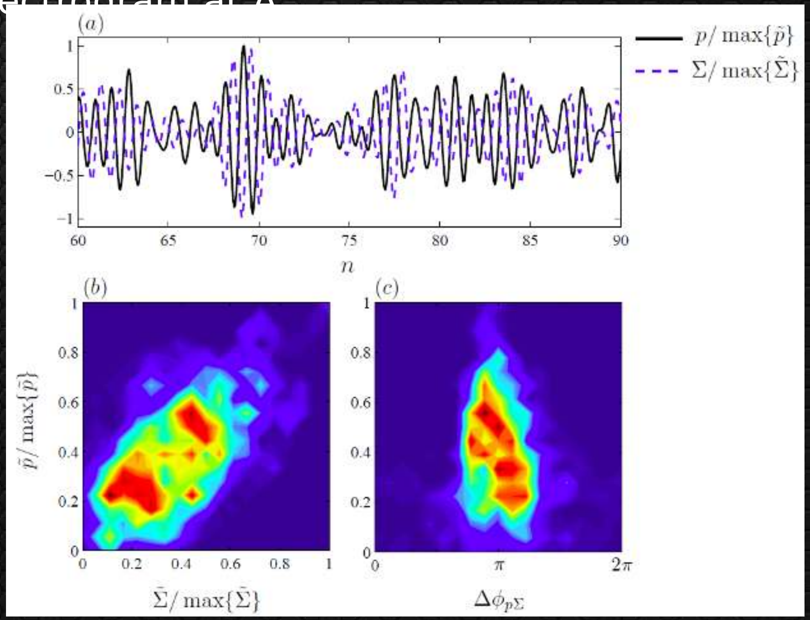
Mean droplet velocity

Droplet velocity spectrogram at A

Pressure spectrogram

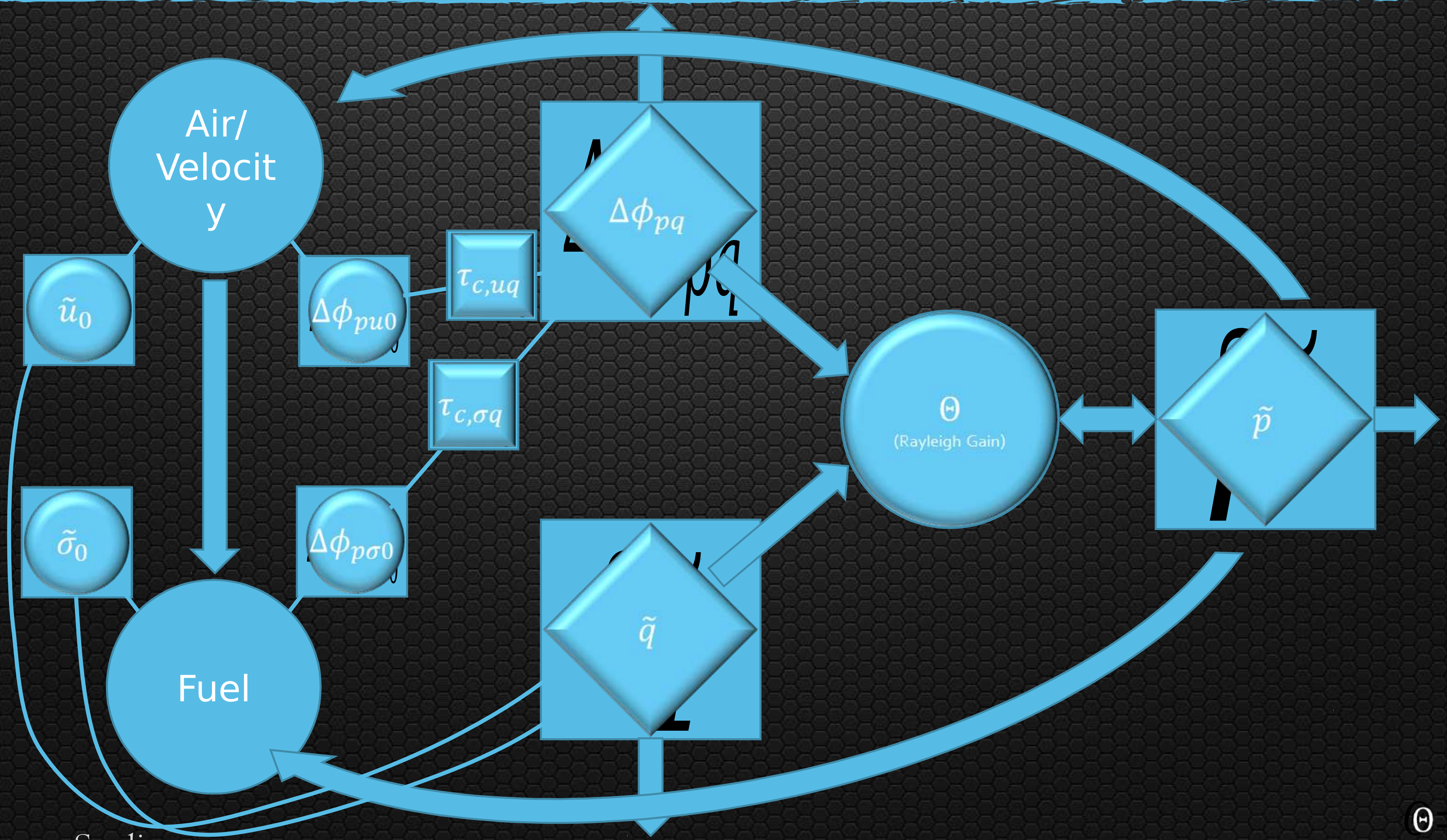


Mie scattering oscillations vs.



Joint behavior of fuel and pressure

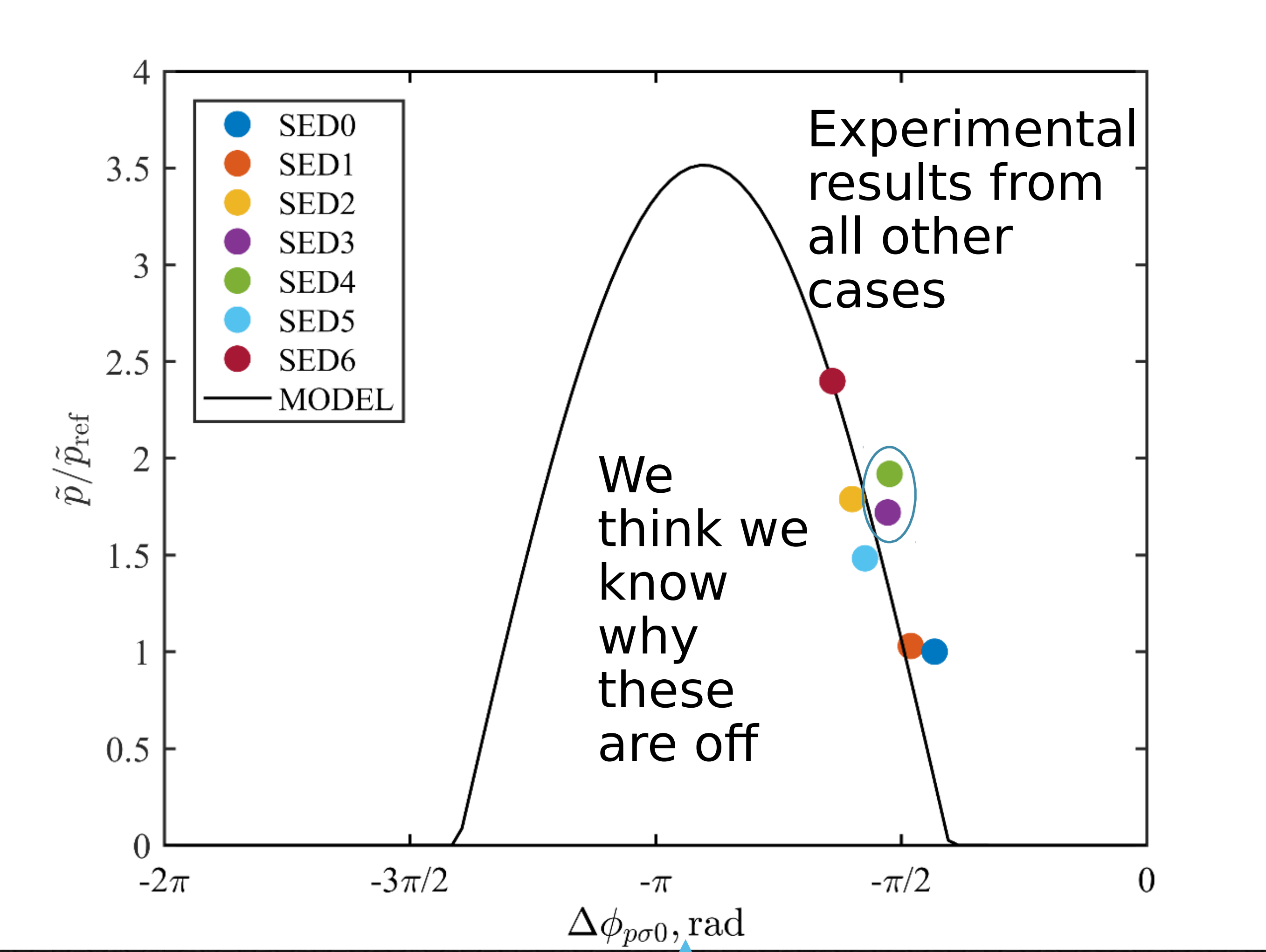
Prediction of Oscillation Amplitudes



$$\Theta = \int_0^{2\pi} p' q' \, \mathrm{d}\phi_p$$

Prediction of Oscillation Amplitudes

- Relatively simple model using algebraic equations for time lags, amplitude responses, etc.
- Predicts saturation thermoacoustic amplitudes as a function of design parameters
- Allows sensitivity studies, design guidance, etc.
- Needs to be retuned for each combustor configuration



Phase shift between fuel droplet oscillations at dome face and

Conclusions

- Laser (and other optical) diagnostics allow for high-fidelity data to be obtained regarding complex dynamic processes in practical hardware at realistic conditions
  - Treatment of uncertain data requires careful consideration
- Provides mechanistic understanding that can be used to
  - Directly aid design and operation
  - Develop best practices for simulations