Complex systems approach to investigate thermoacoustic instability in turbulent combustors

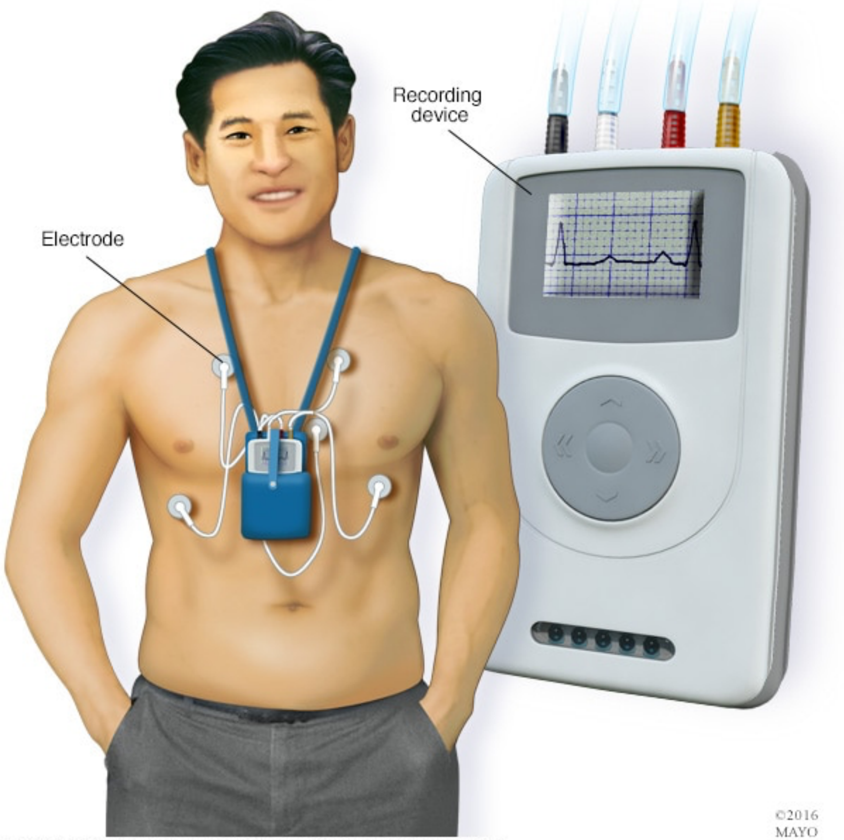
Part 2: Spatiotemporal analysis & directions for future research

R. I. Sujith

Indian Institute of Technology Madras

Nitin George, Abin Krishnan, Vishnu R Unni, Manikandan Raghunathan, Samadhan Pawar, Krishna.

We acknowledge the funding from DST, ONRG, TANGO & IIT Madras


Recording device
Electrode
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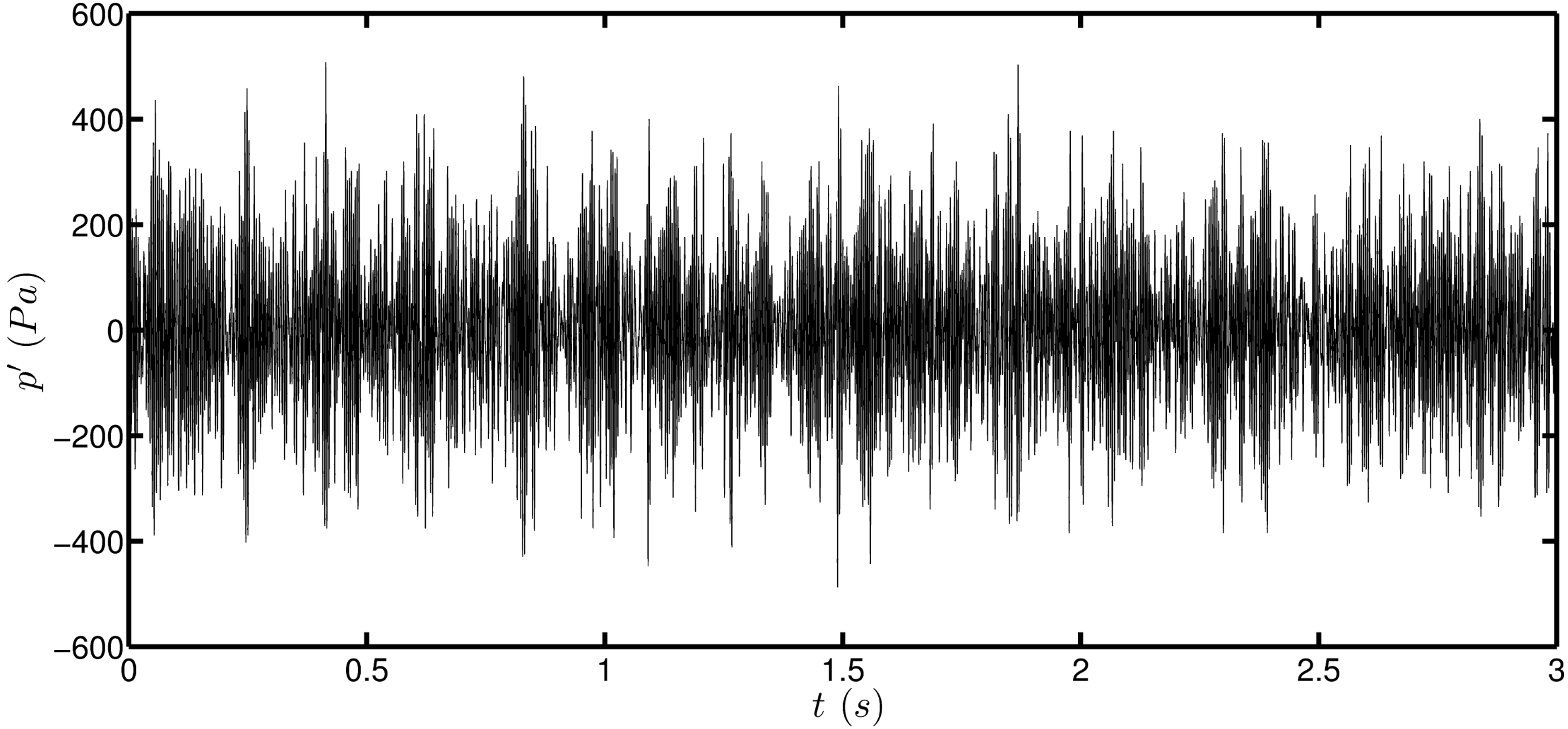
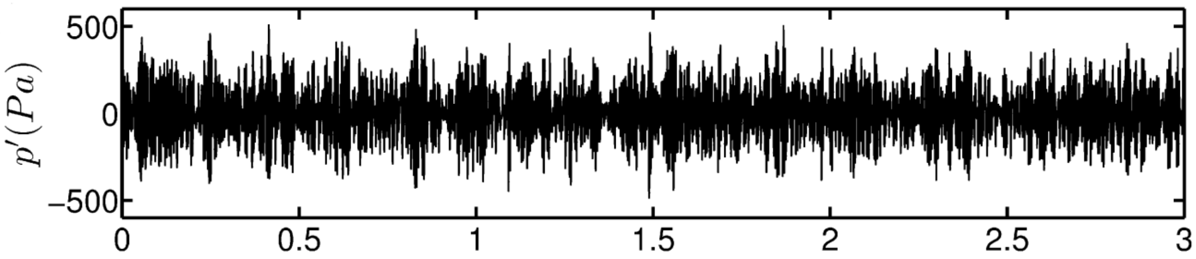
Recap

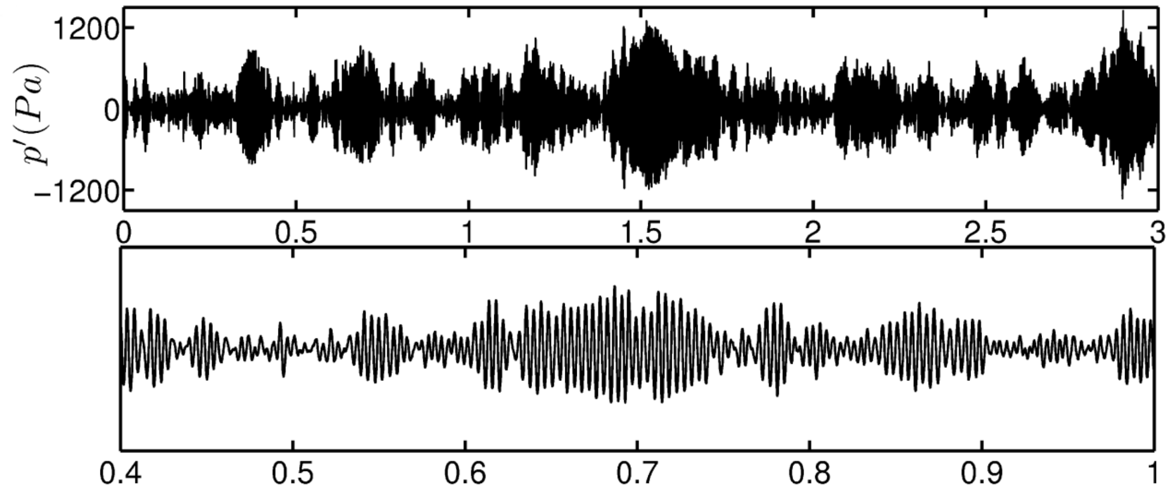
Combustion noise is deterministic chaos



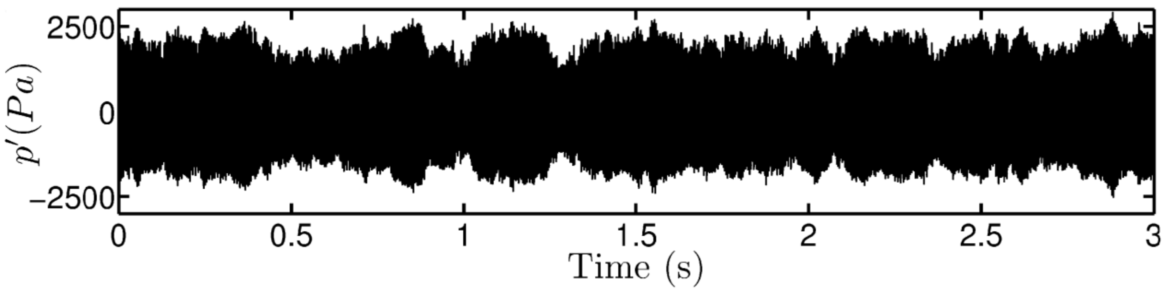
Combustion noise



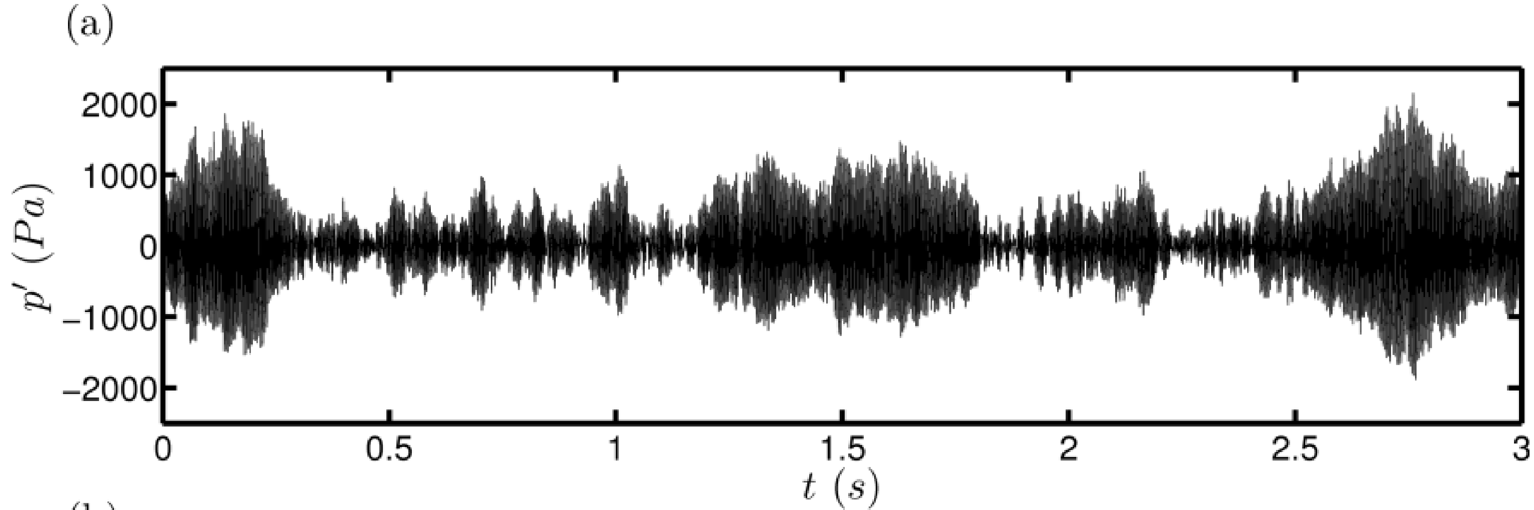
Intermittency



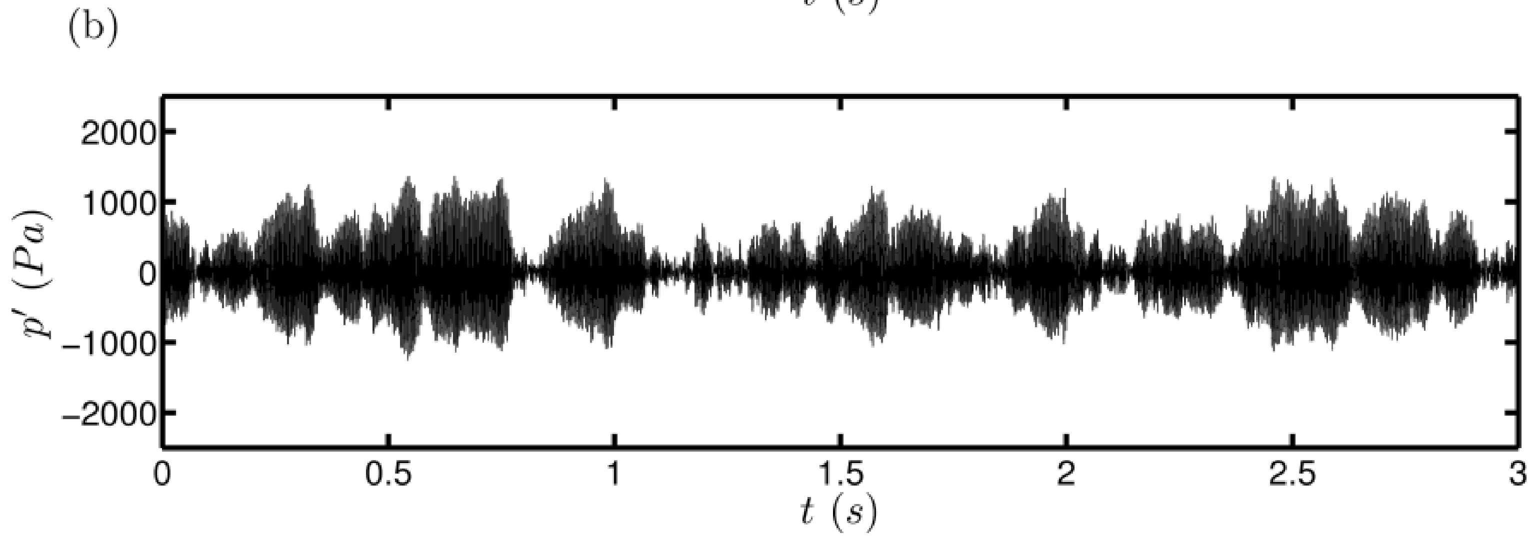
Combustion instability



Intermittency presages the onset of thermoacoustic instability



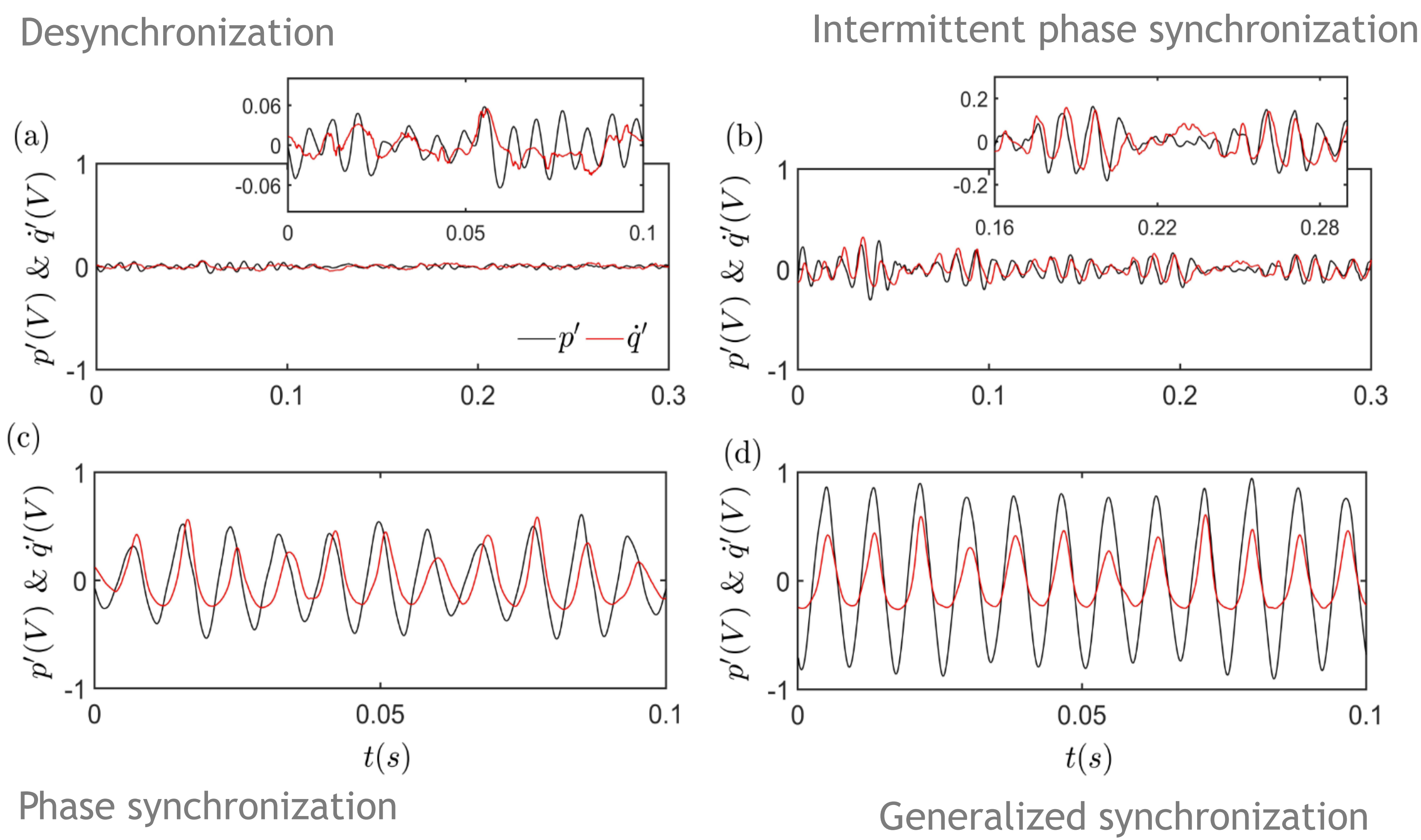
Swirl



Bluff body

Combustion noise → Intermittency → Full blown instability

Time series of acoustic pressure & heat release rate show synchronization transition from stable operation to limit cycle

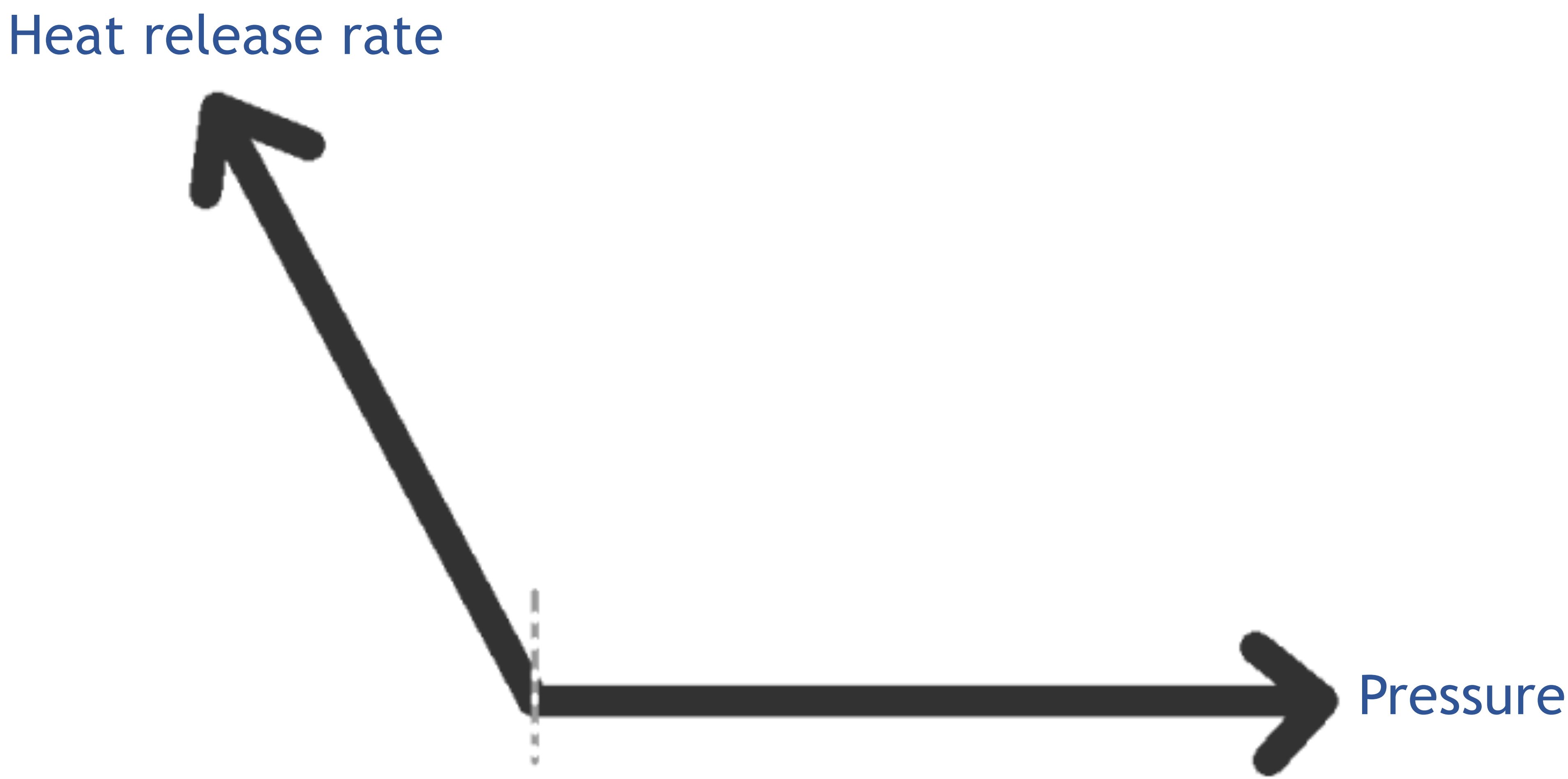


(a) Stable operation; **(b)** Intermittency; Pawar *et al.* (*Journal of Fluid Mechanics*, 2017)

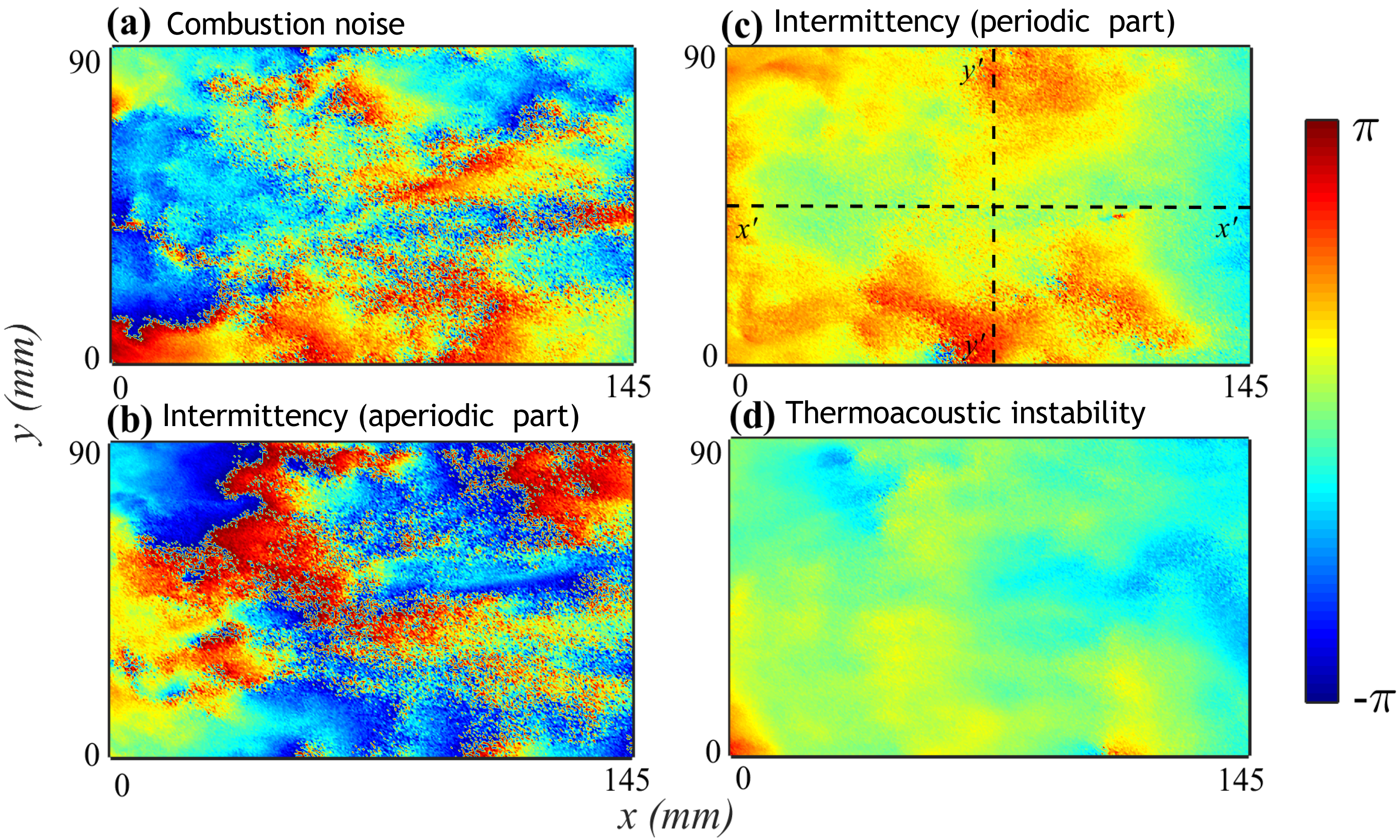
(c) Weakly correlated limit cycle; **(d)** Strongly correlated limit cycle

Desynchronized chaos → IPS → PS → GS

Pawar *et al.* (JFM 2017)

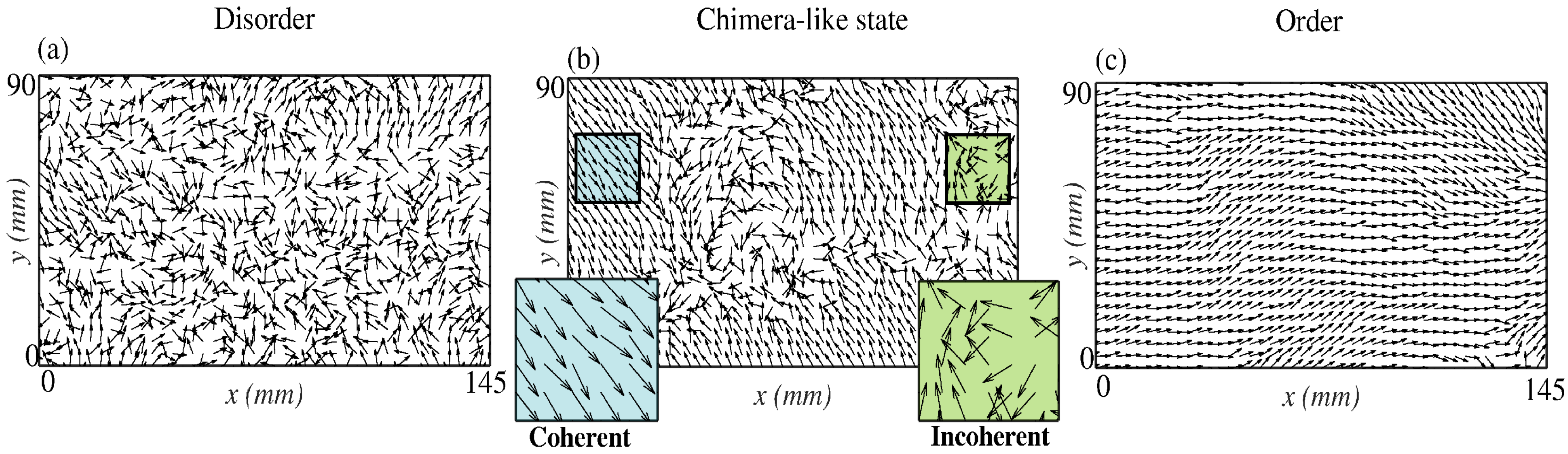

Heat release rate
Pressure

The instantaneous phase fields show interesting patterns during the transition to thermoacoustic



Mondal *et al.*, JFM, 2017

The transition from stable to unstable operation happens via a chimera state



Combustion noise

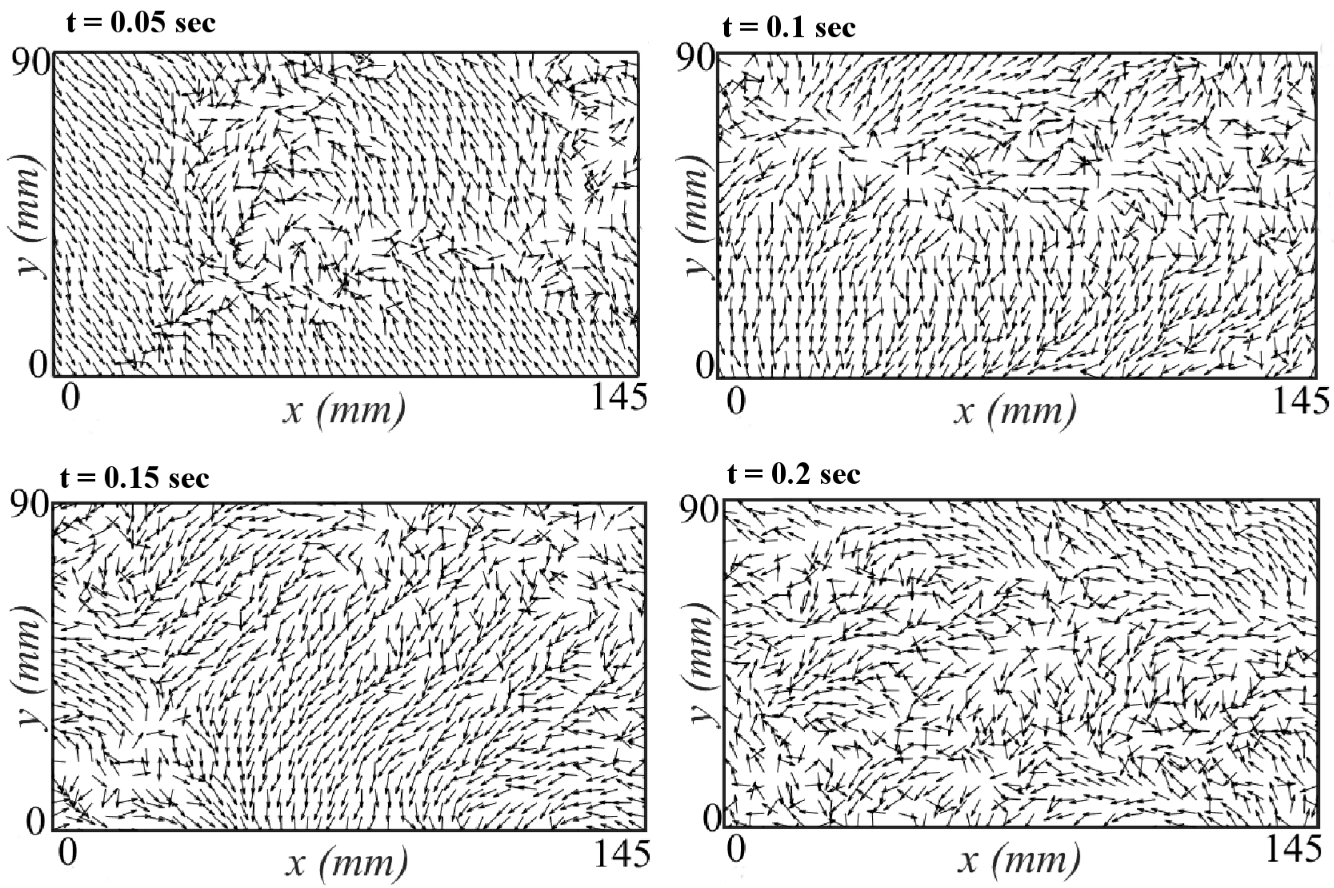
Intermittency

Thermoacoustic instability

Mondal et al. (*JFM*, 2017)

Chimera state: Abrams & Strogatz, 2004

The regions of disordered and ordered phasors change their locations with time



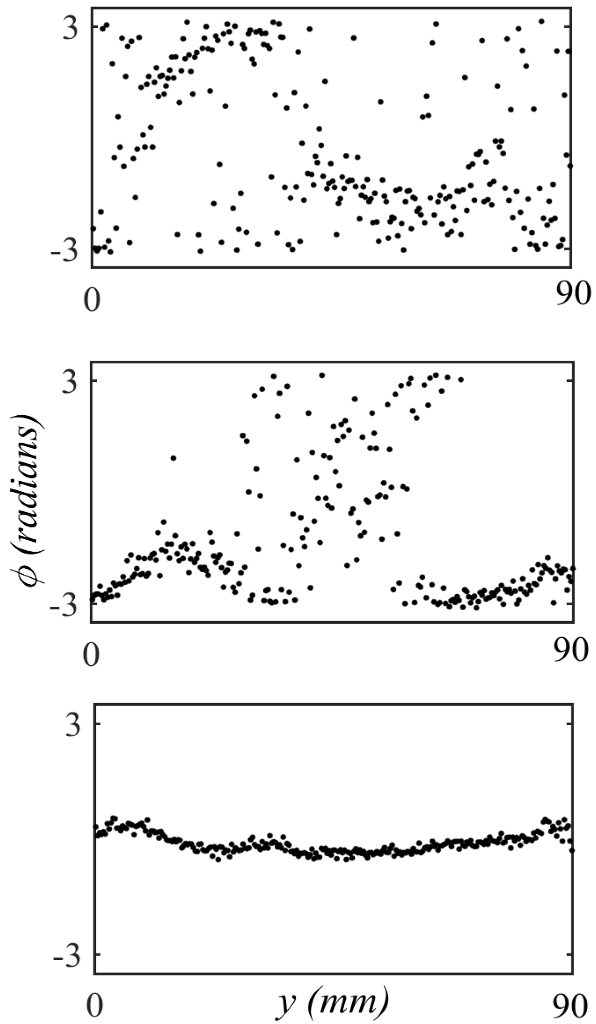
Breathing chimera state

The transition from phase asynchrony to phase synchrony happens via chimera-like state

Combustion noise

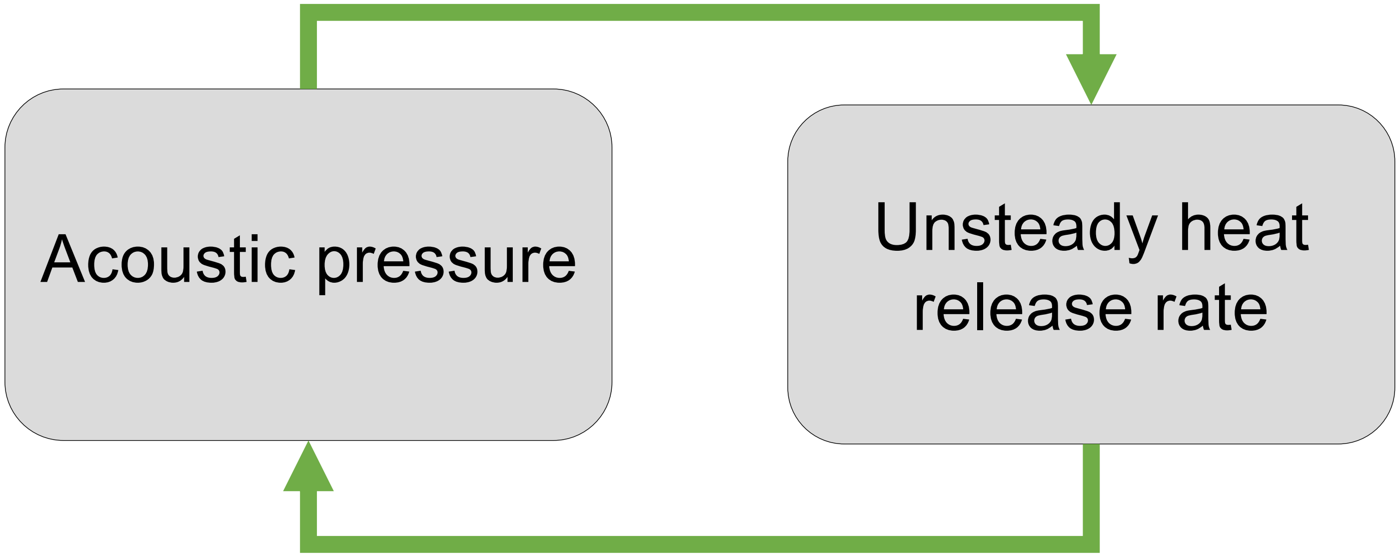
Intermittency

Thermoacoustic instability

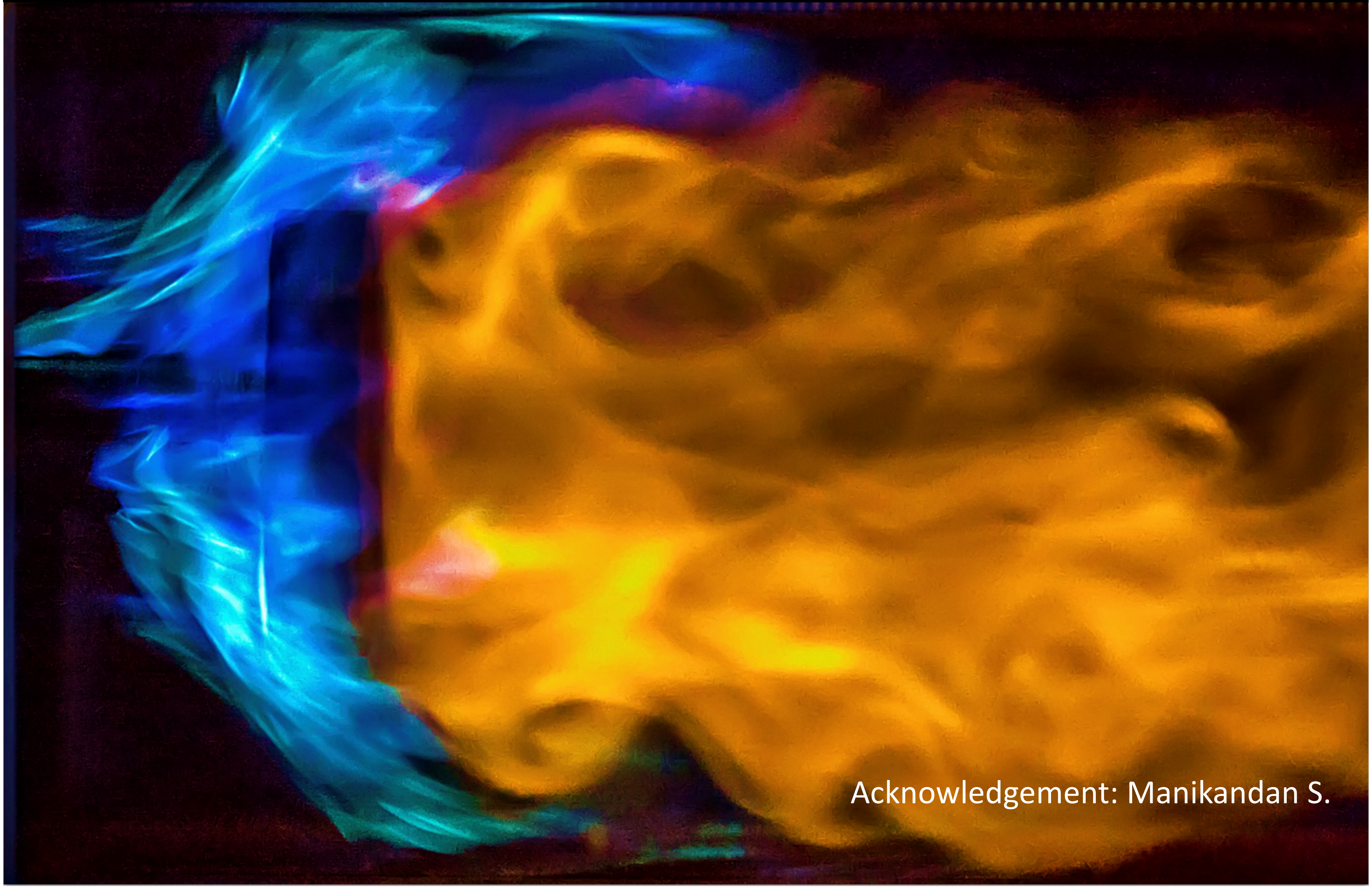


From disordered & incoherent dynamics to ordered & coherent dynamics through pattern formation

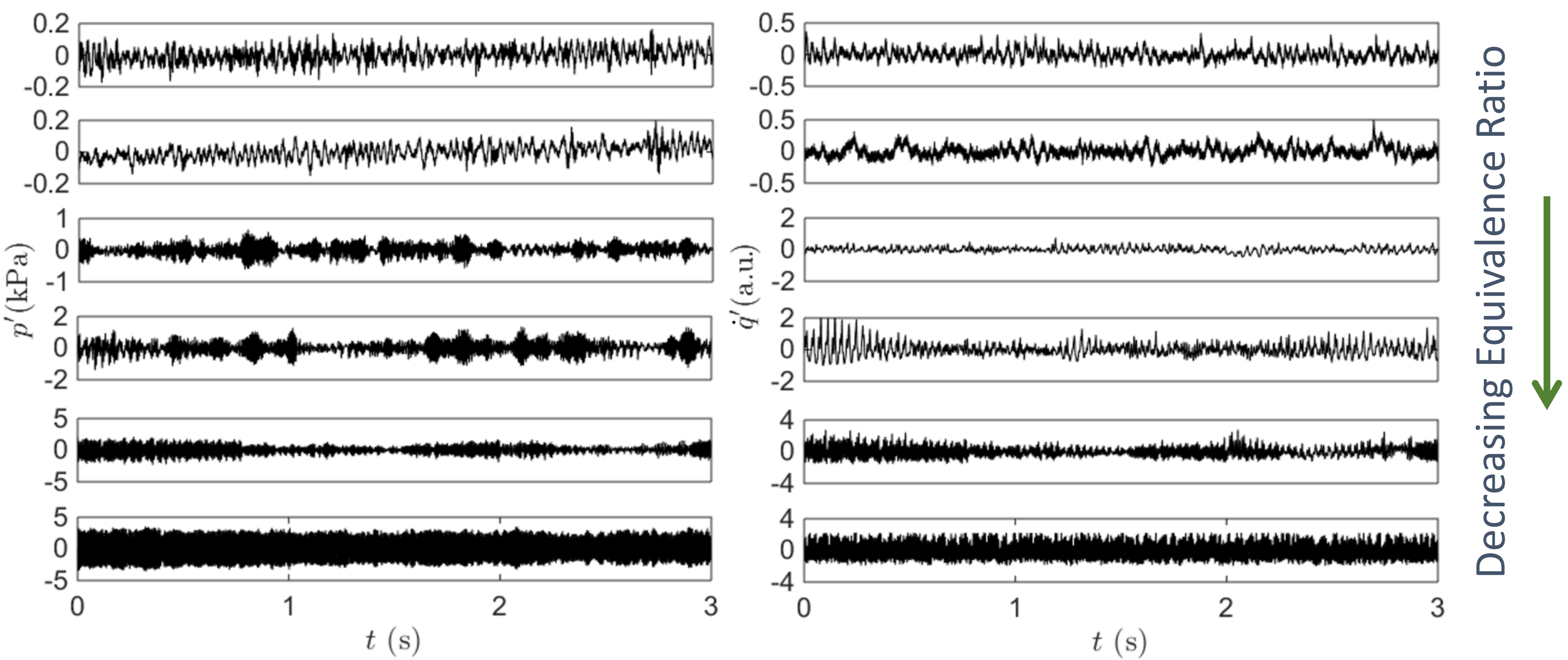
Thermoacoustic instability caused by positive feedback between acoustic & unsteady heat release rate



But the coupling is spatiotemporal since a flame is spatially extended



Intermittency is a gradual emergence of temporal patterns en route to thermoacoustic instability



A pattern is any regularly repeated arrangement

Patterns are ubiquitous in nature


https://www.dreamstime.com/stock-photos-yellow-blue-striped-fish-image1911383

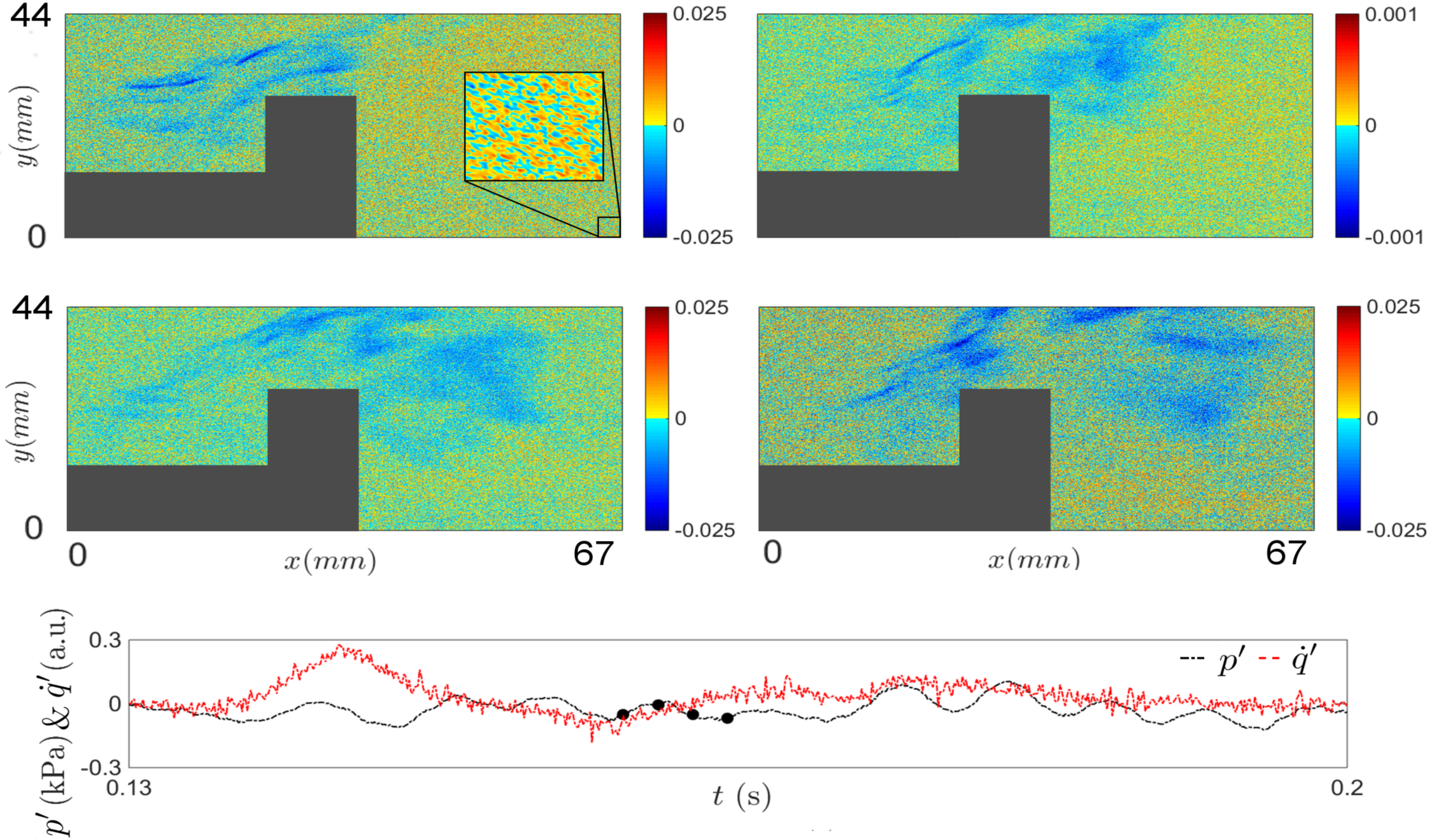
http://animals.howstuffworks.com/mammals/zebra-stripes1.htm

Belousov Zhabotinsky reaction

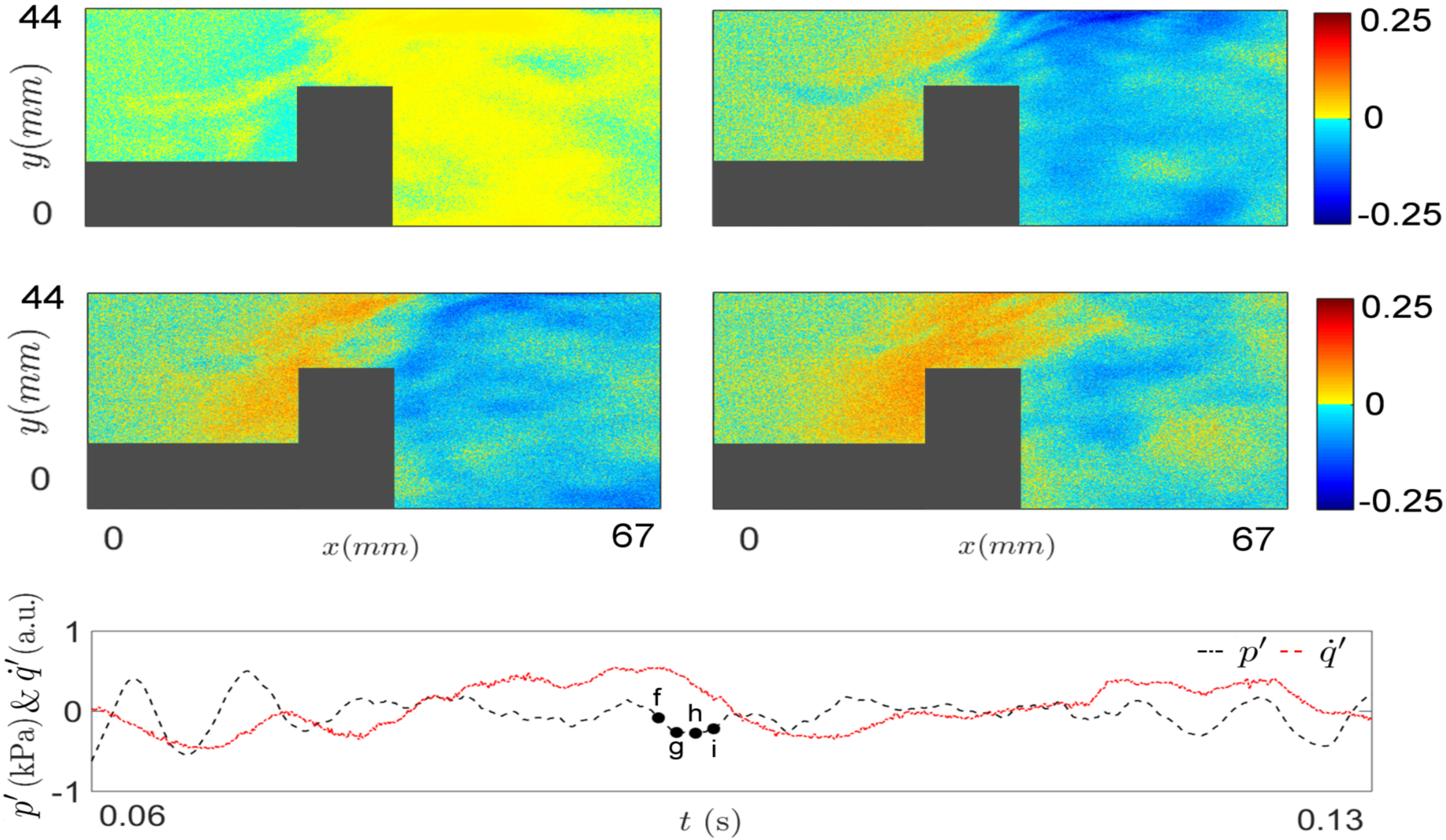
https://www.flickr.com/photos/nonlin/3572095252

Are there spatial patterns in a turbulent thermoacoustic system?

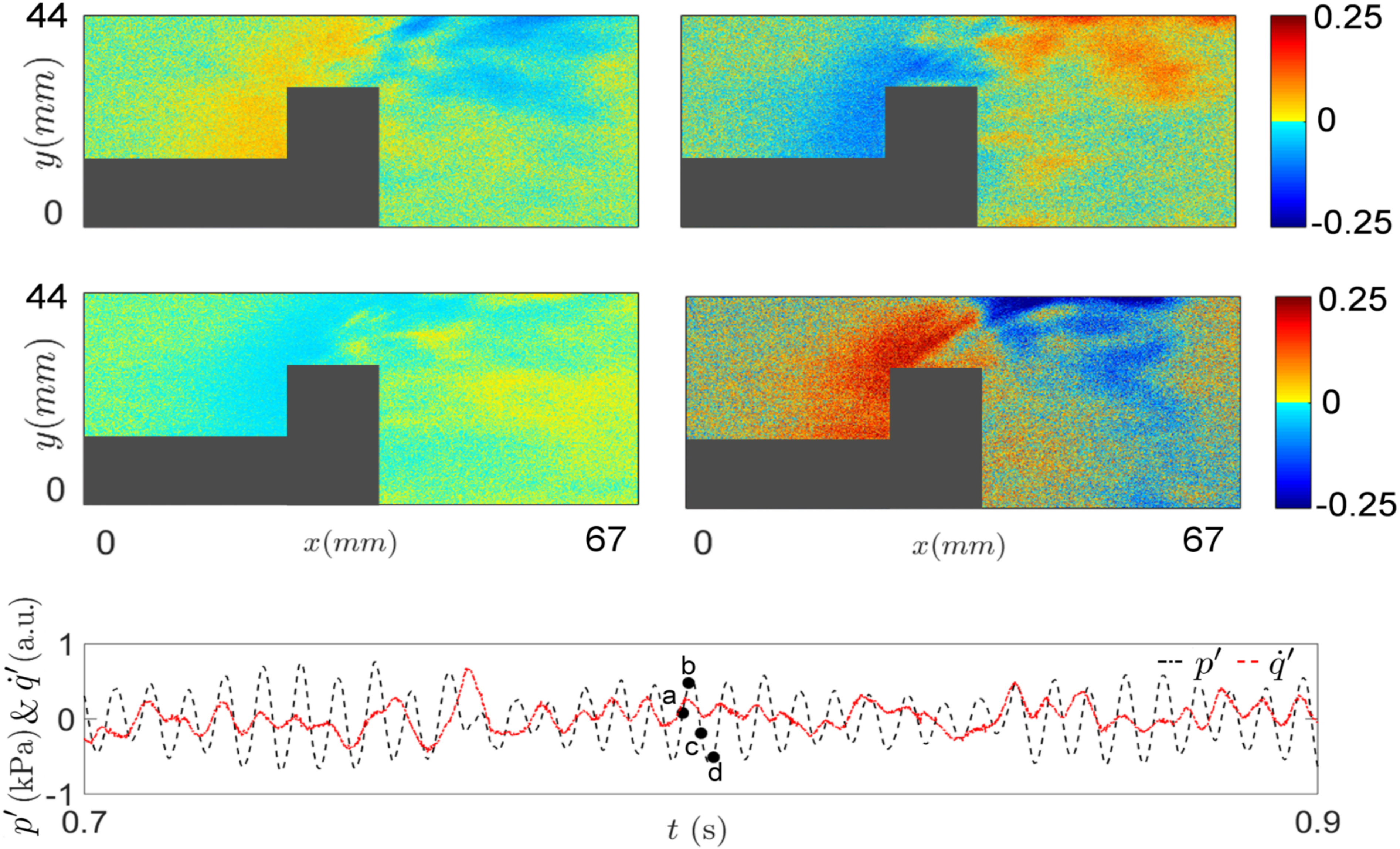
Incoherence in the spatial dynamics of the flame is present during combustion noise



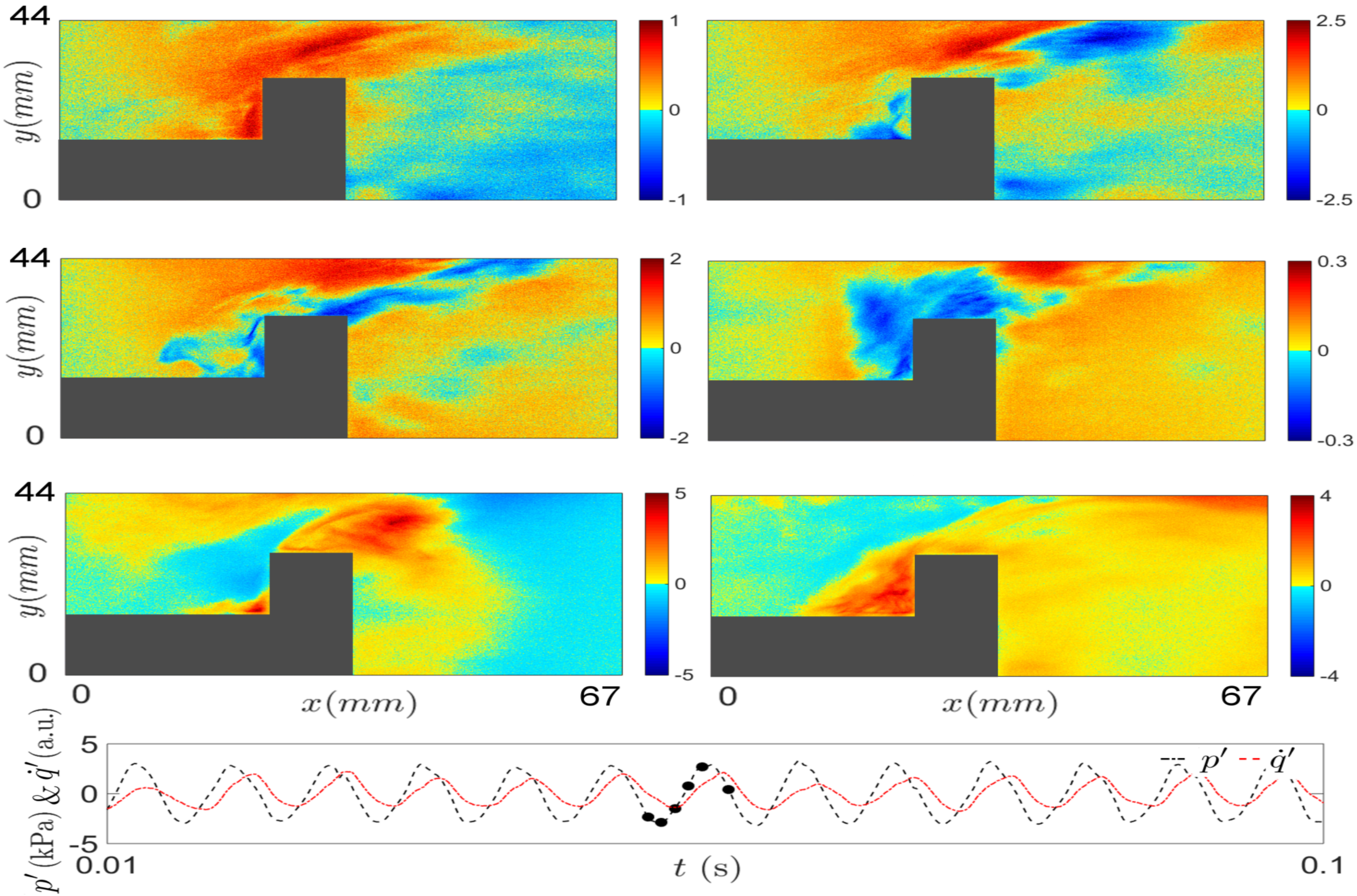
Incoherence in the spatial dynamics of the flame is present during the aperiodic epoch of intermittency



An emergence of coherence occurs during the periodic epoch of intermittency

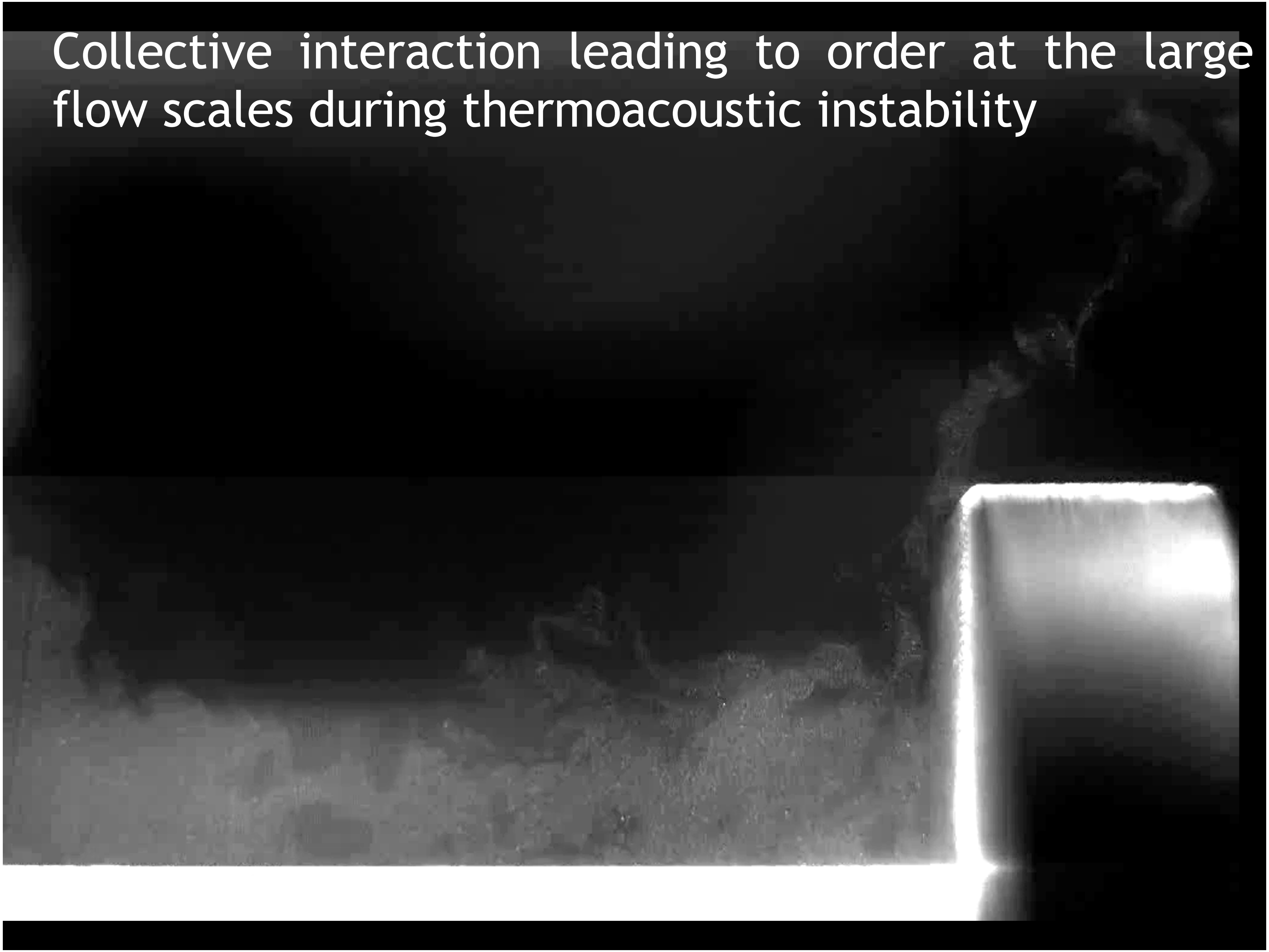


The regions of spatial coherence increase in size and strength during thermoacoustic instability

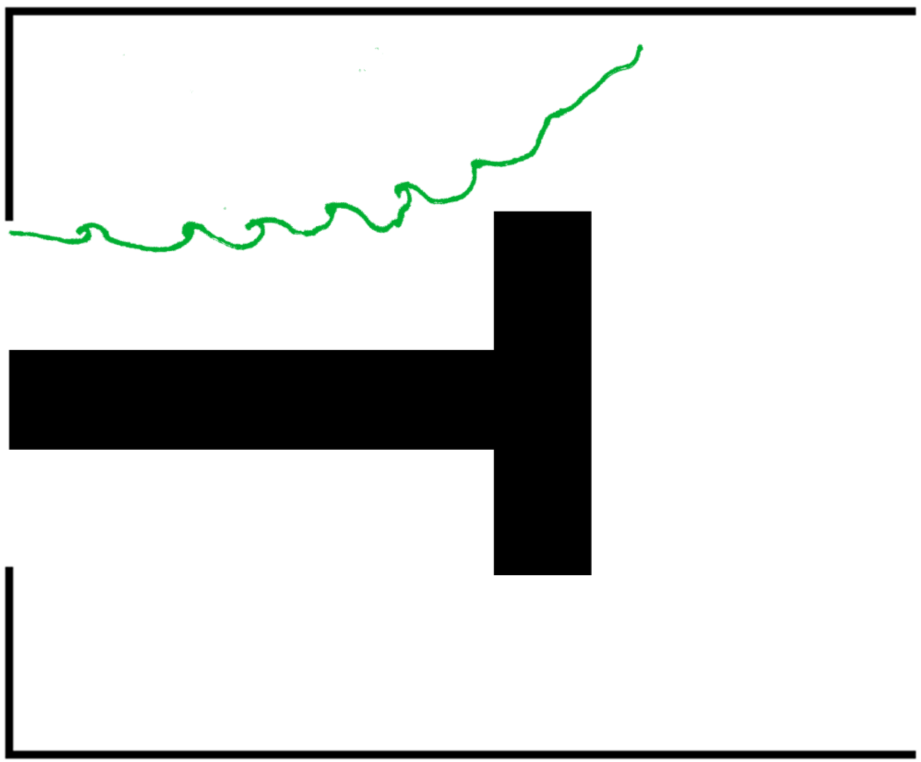


Disordered emergence of small scale vortices occurs in the flow field during combustion noise

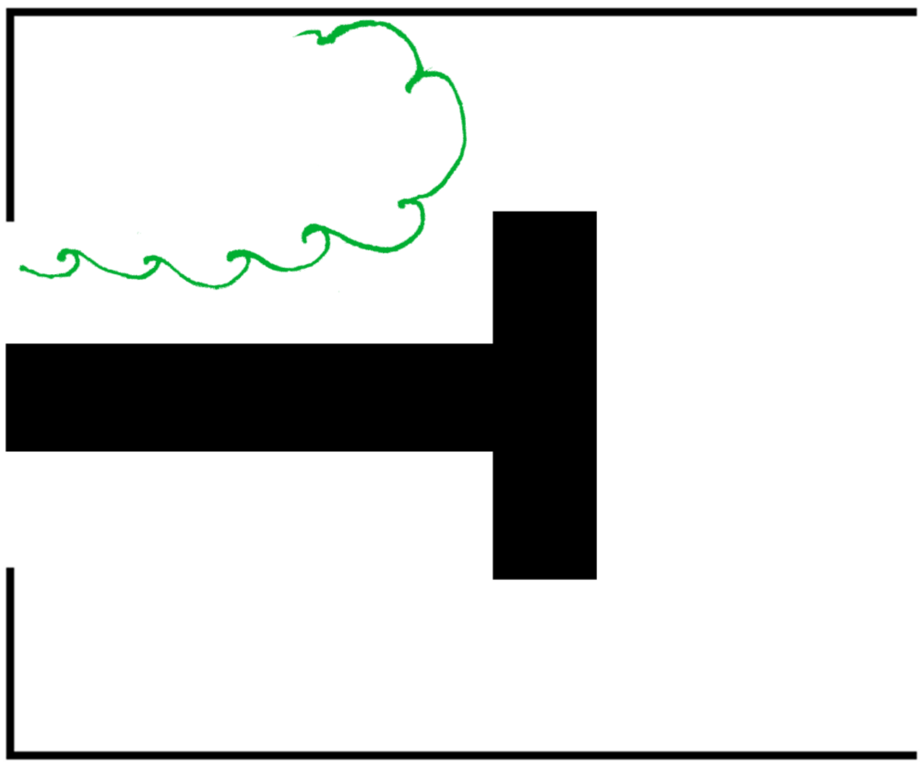
Collective interaction leading to order at the large flow scales during thermoacoustic instability



Interactions at the small scales causing self-organization at the large scales in the flow field

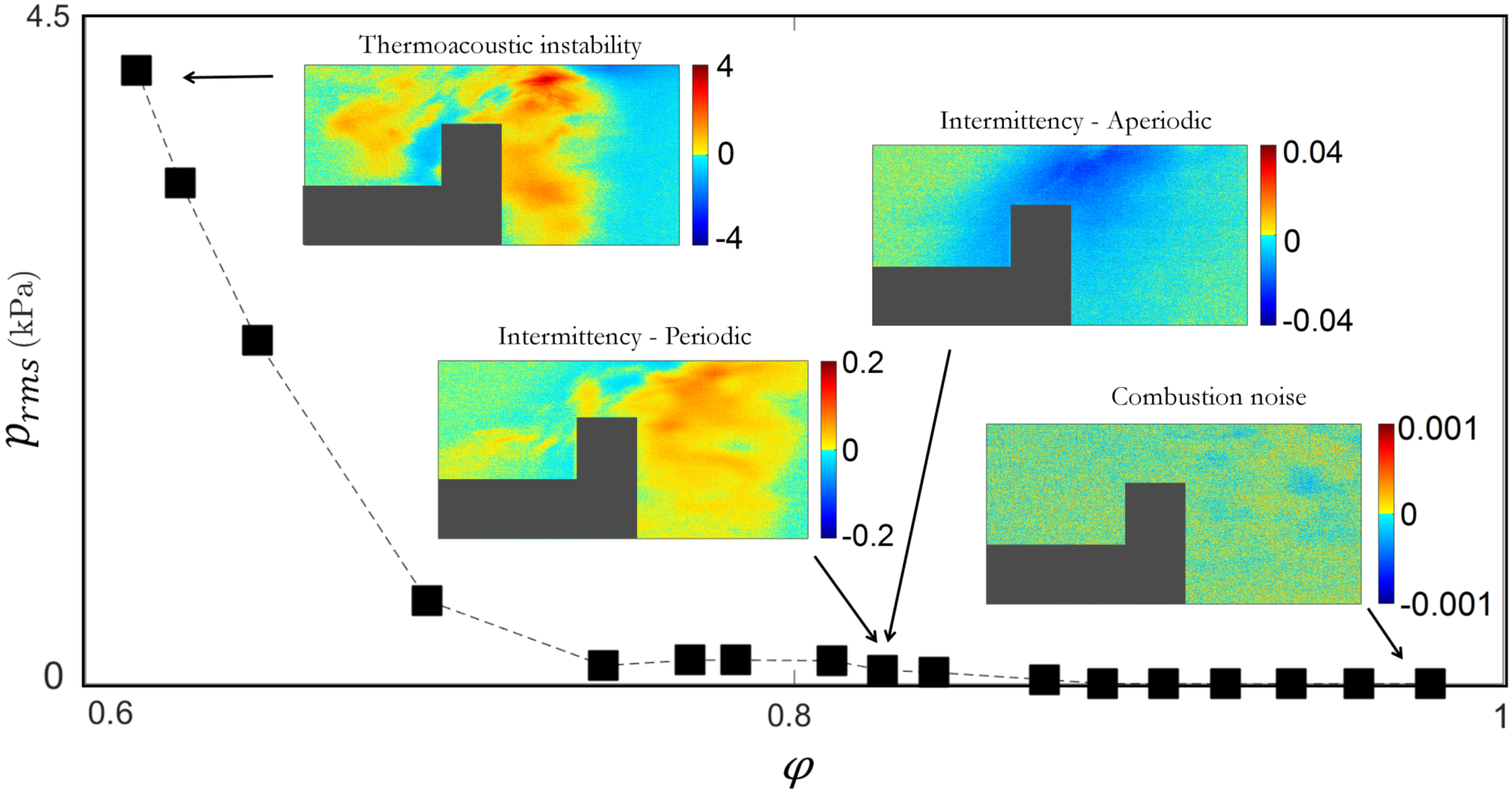


Combustion noise

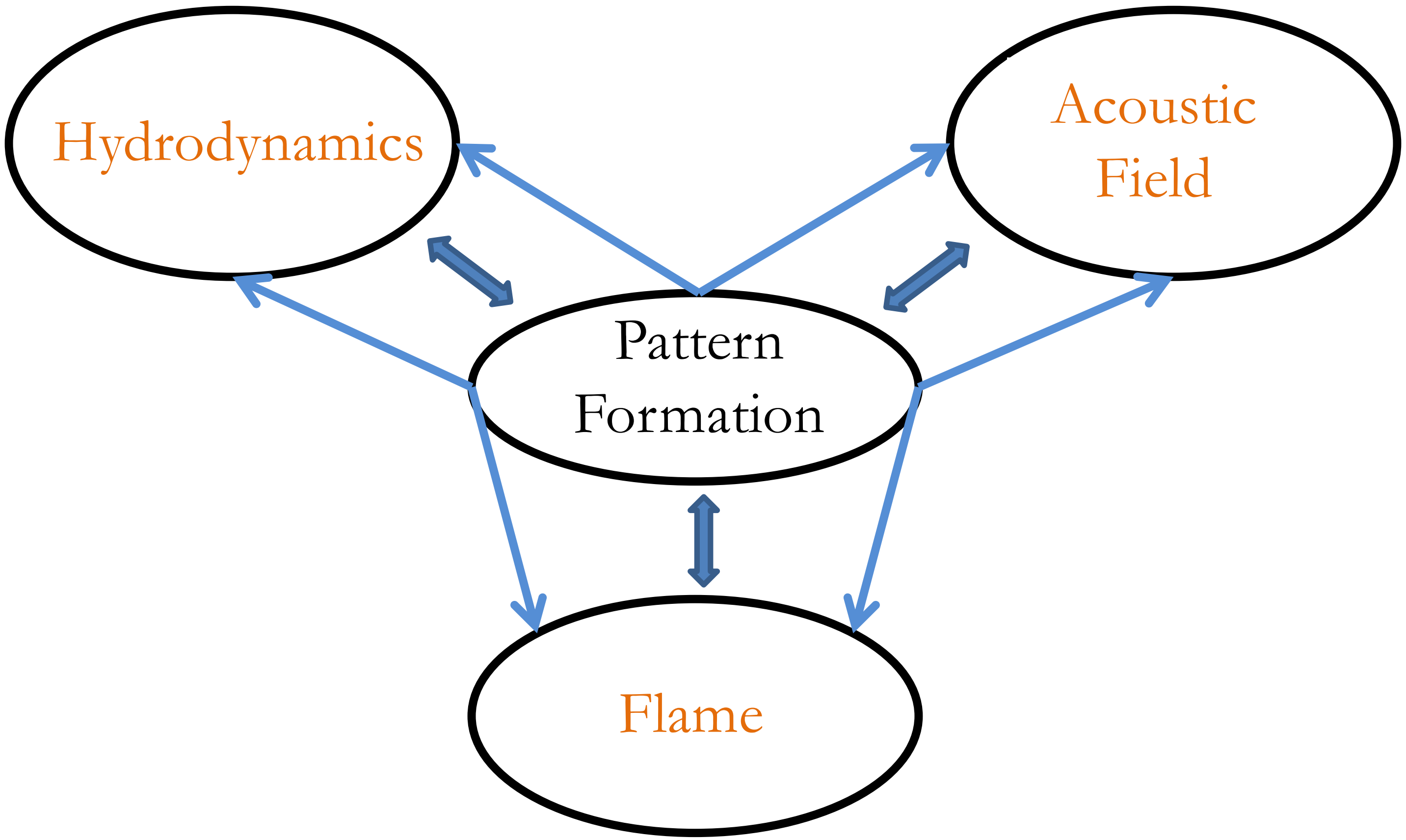


Thermoacoustic Instability

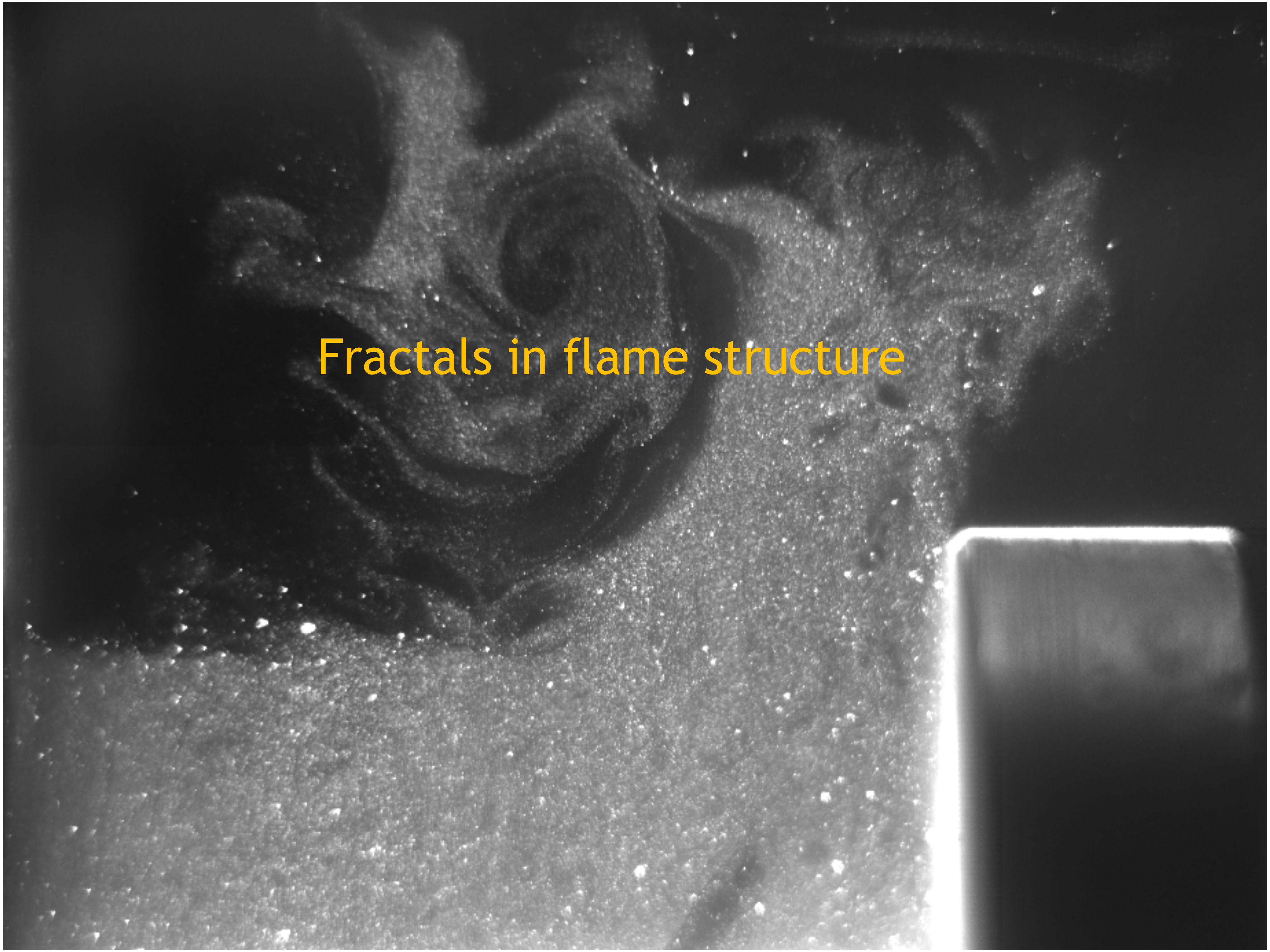
The onset of thermoacoustic instability is the onset of pattern formation



Thermoacoustic instability is the result of coupling between hydrodynamics, flame and acoustic field

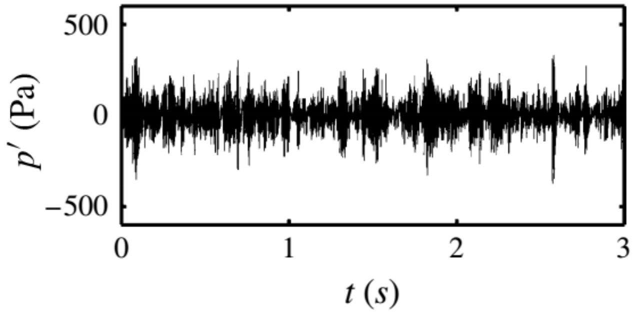


Intertwined & highly intricate interactions between wide spatio-temporal scales in flame, flow & acoustics are through pattern formation.

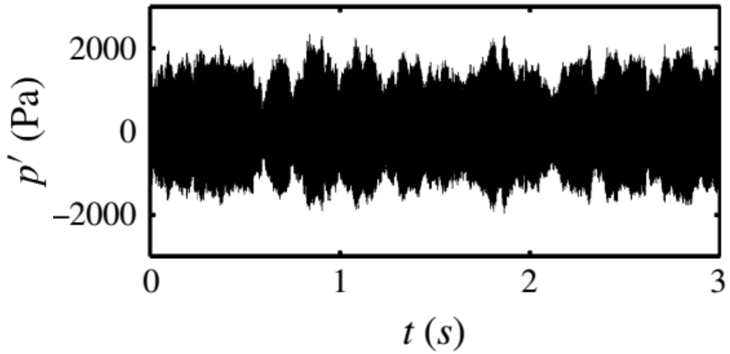

Fractals in flame structure

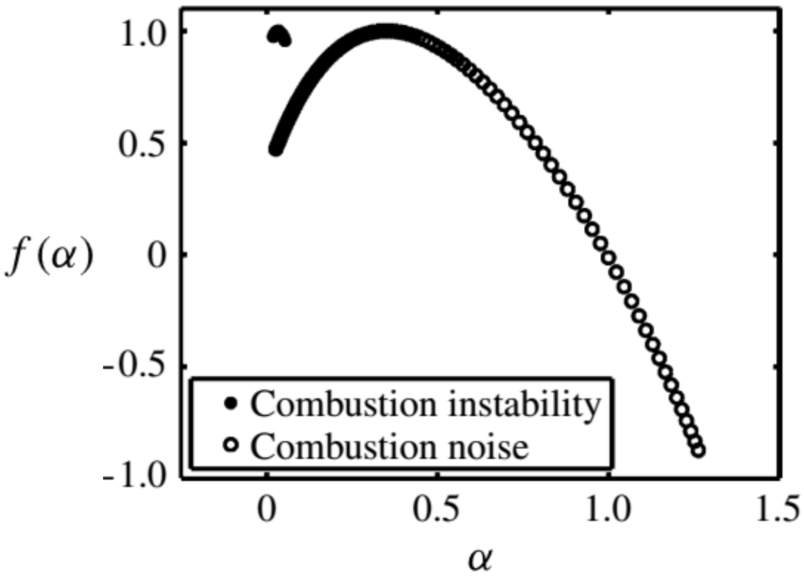
We observe loss of multifractality in pressure oscillations at the onset of thermoacoustic instability

Combustion noise



Combustion instability

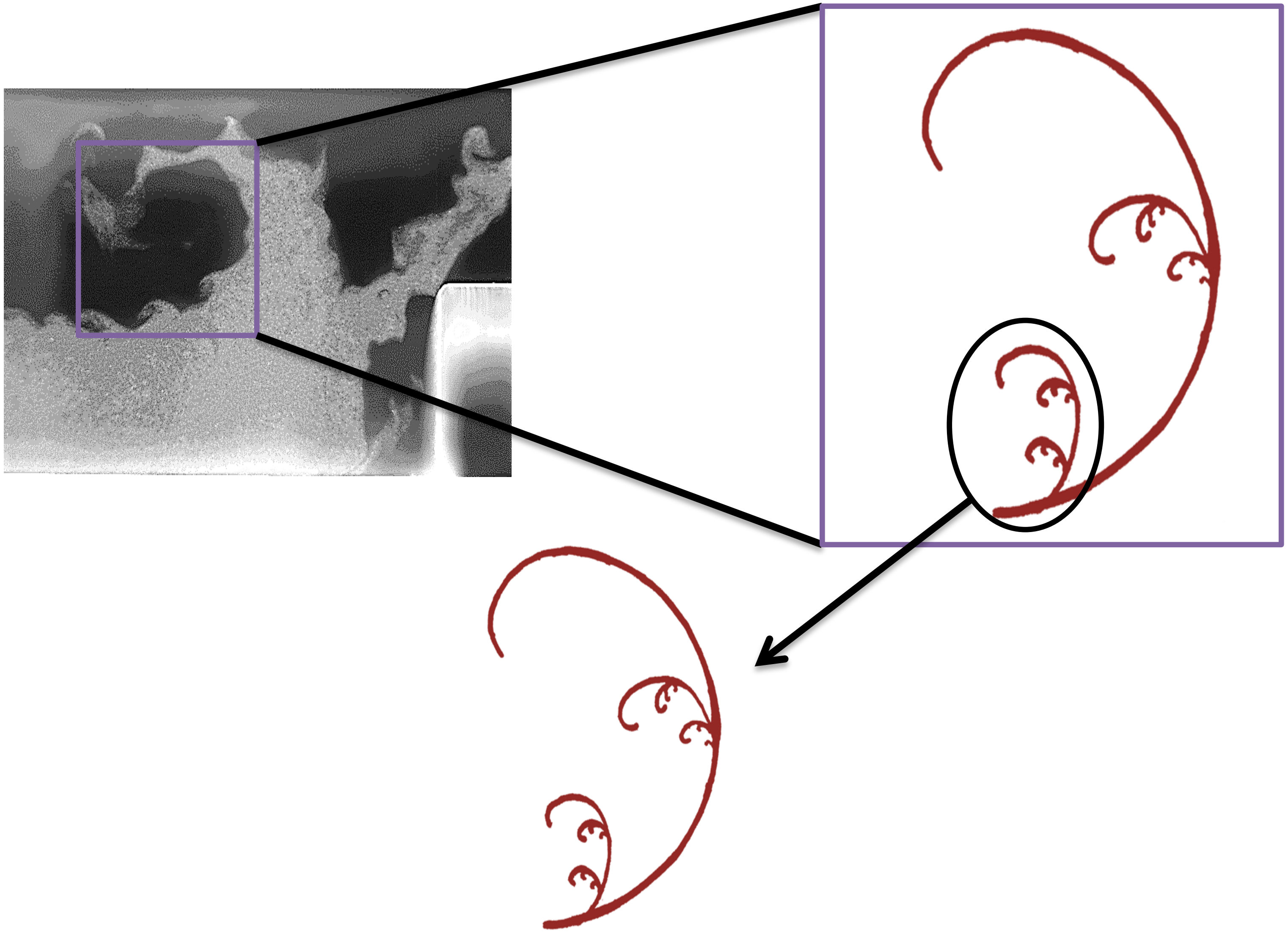




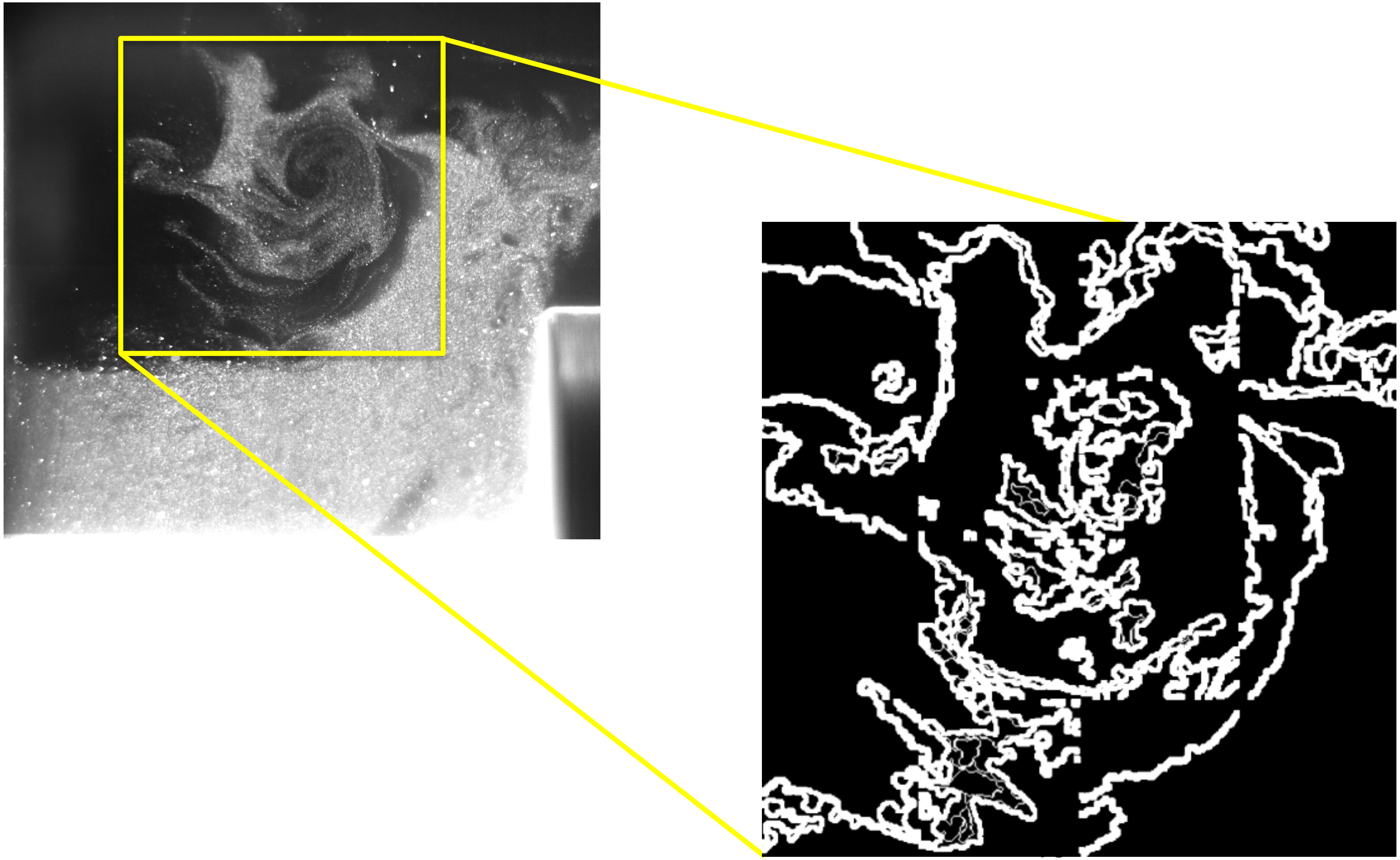
Nair & Sujith (2014, JFM)

Is there multifractality in turbulent flame topology?

We observe fractals in the flame topology during the transition to thermoacoustic instability

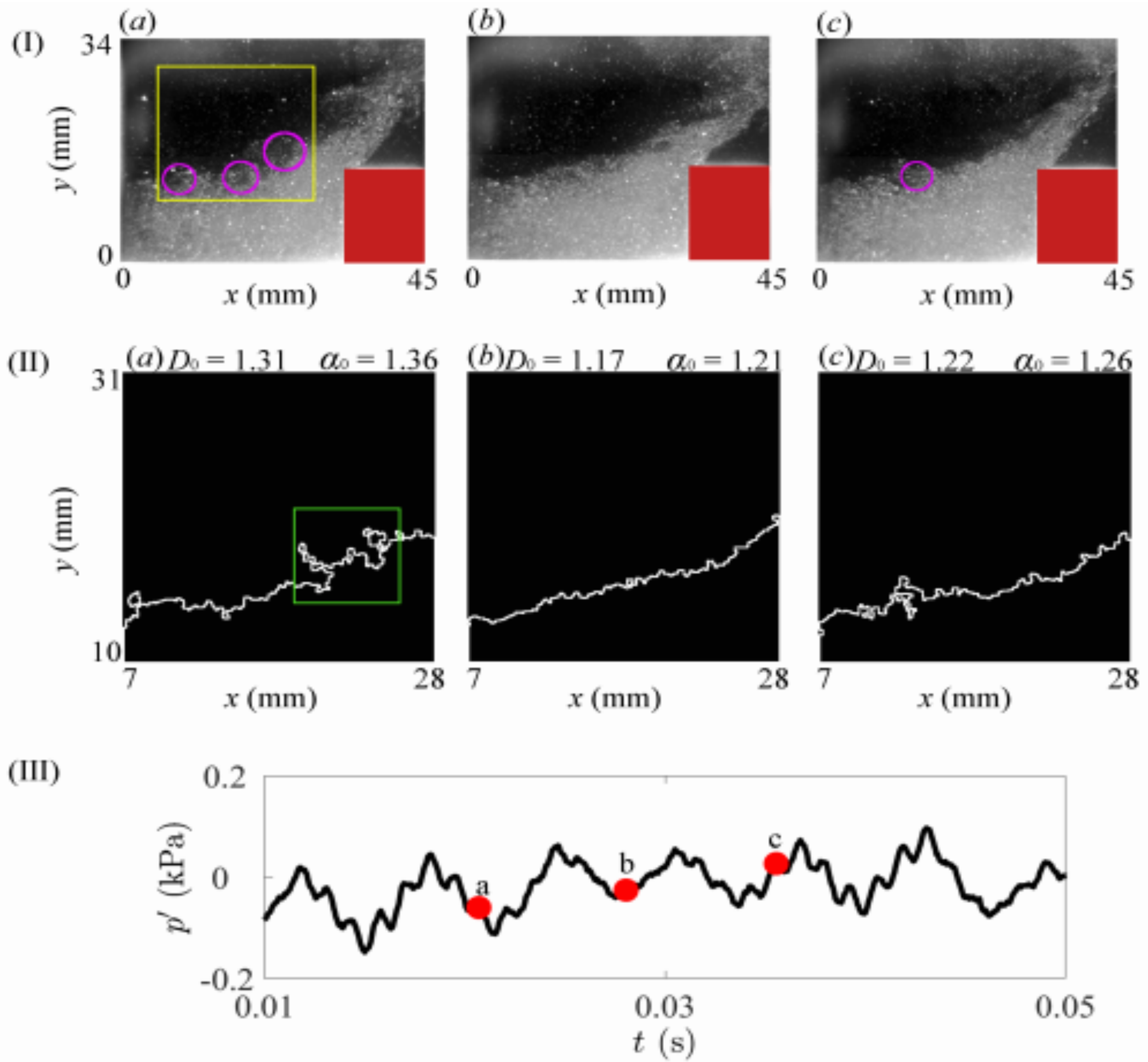


Formation of large-scale coherent structure during thermoacoustic instability

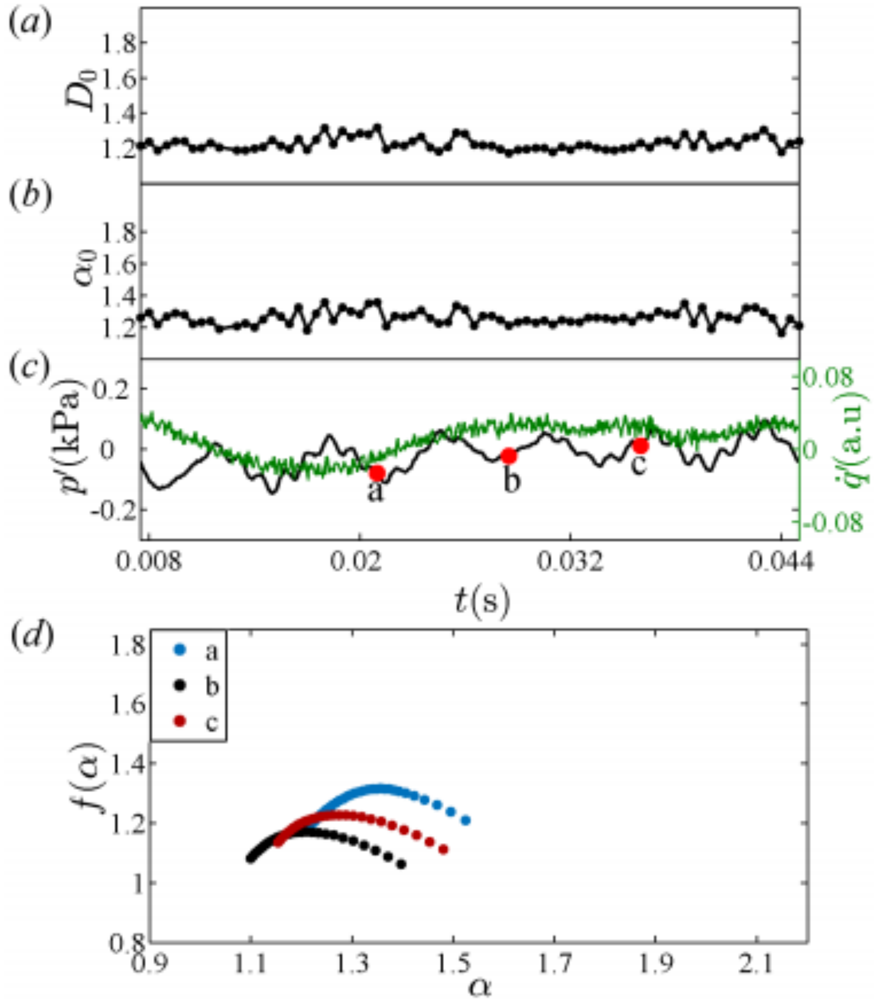


Multifractal analysis of flame dynamics during transition to instability

Small-scale structures are present along the shear layer during combustion noise

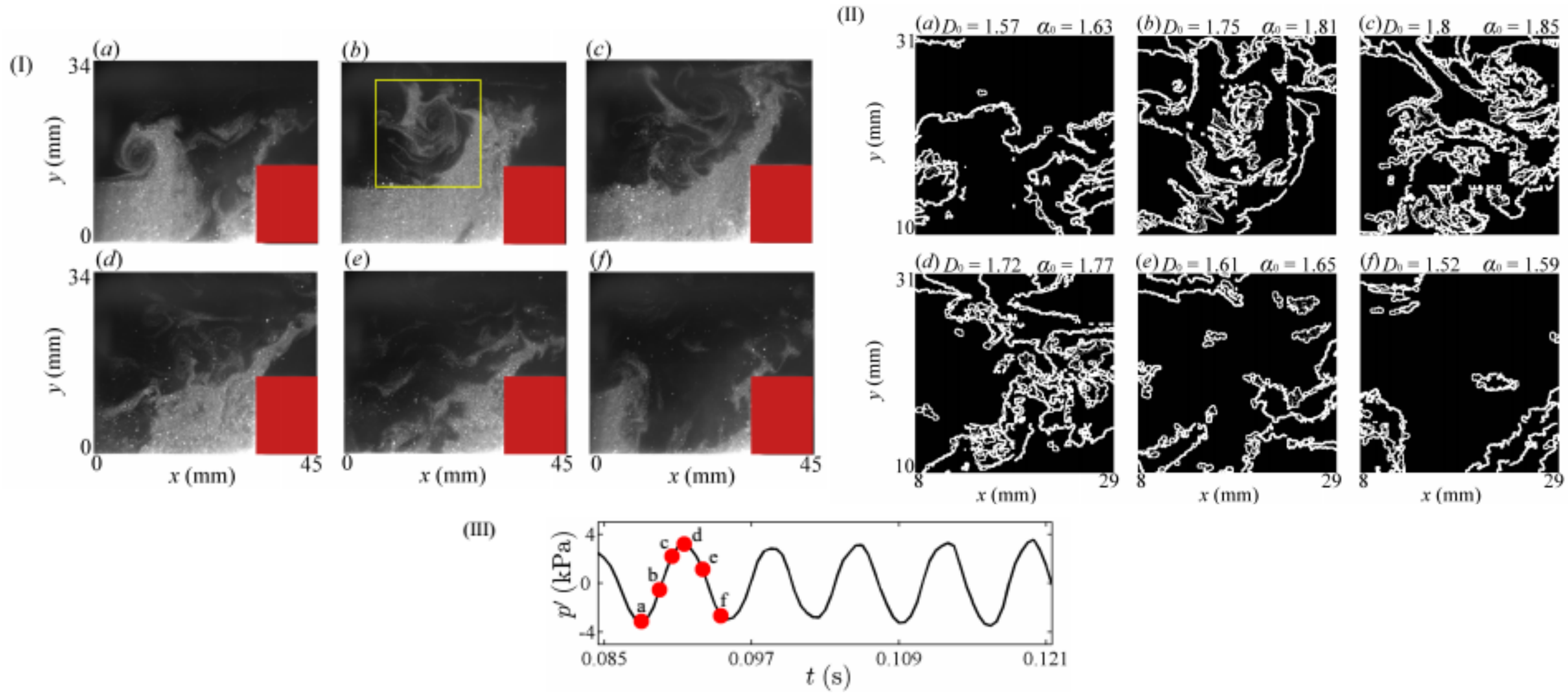


Low value of D_0, close to 1 shows the flame is not space-filling



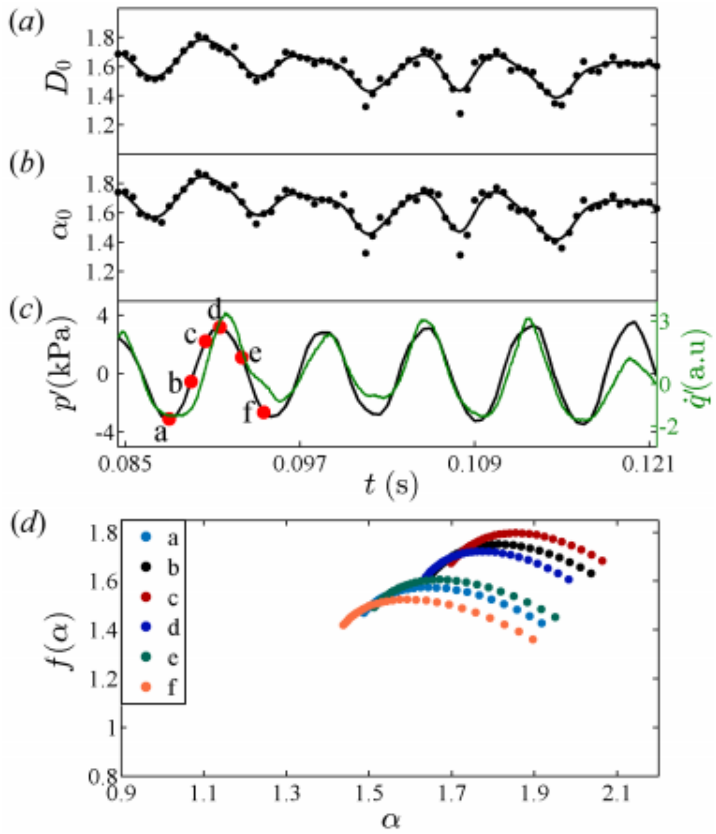
Multifractal spectrum fluctuates in an aperiodic manner

During TAI, within the large-scale roll-up, there are small-scale roll-ups, suggestive of collective interaction



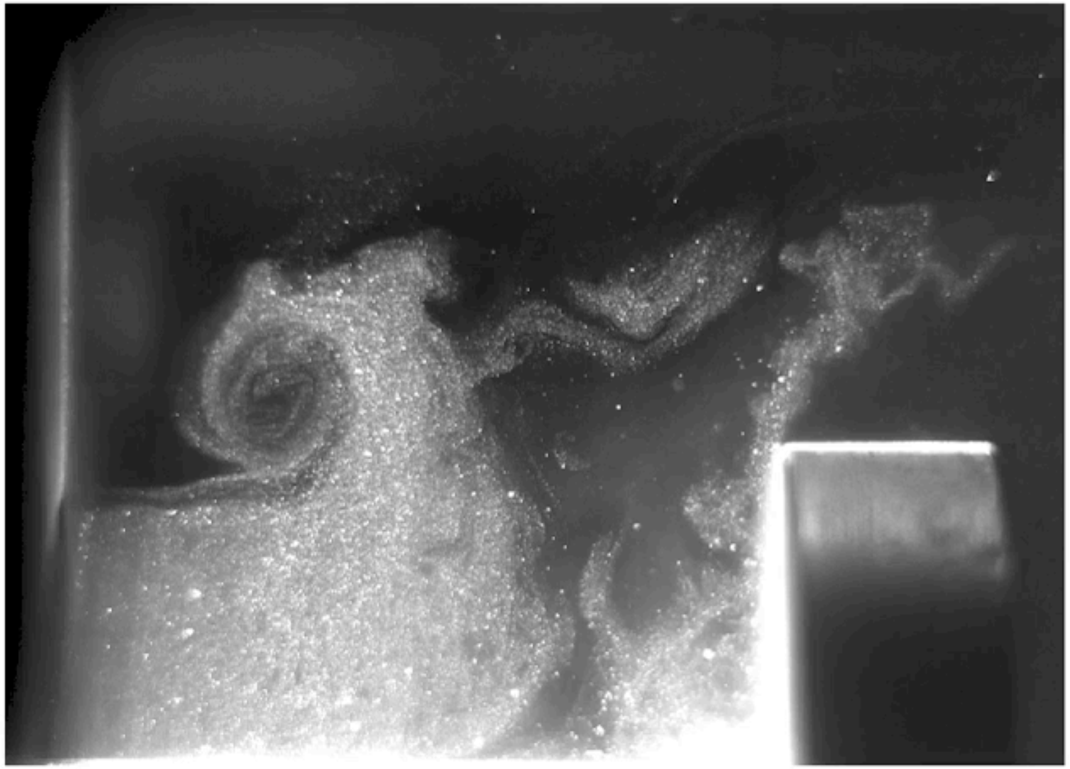
Flame fills space through phenomenon of collective interaction

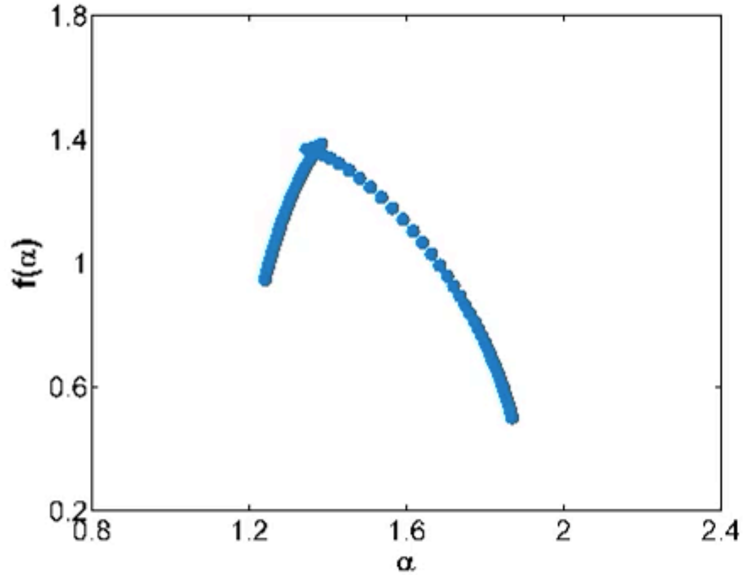
The maximum value of D_0 and α_0 occur just before the impingement of the large-scale coherent structure



Multifractal spectrum oscillates periodically at the time scale of acoustic pressure oscillations

Periodic oscillation of the multifractal spectrum manifests as the periodic oscillations of *p*′ and *q*′





Periodic oscillation of multifractal spectrum possibly results in loss of multifractality in *p*′ during TAI

Spatio-temporal analysis using time varying complex networks

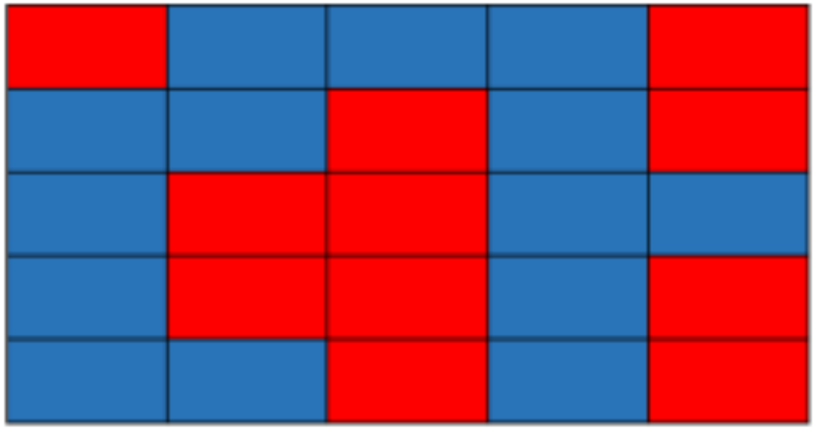
Journal of Fluid Mechanics (2019)

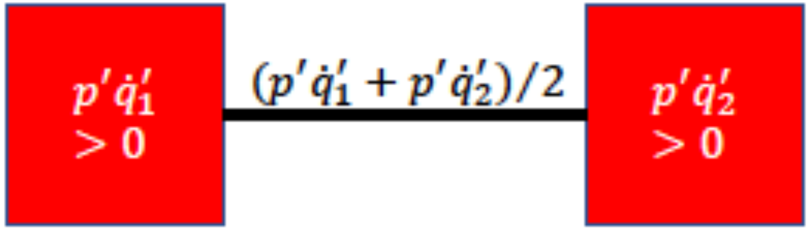
We obtain instantaneous local acoustic power field for different control parameters

+	−	−	−	+
−	−	+	−	+
−	+	+	−	−
−	+	+	−	+
−	−	+	−	+

$p'\dot{q}' > 0$: Acoustic power source
$p'\dot{q}' < 0$: Acoustic power sink

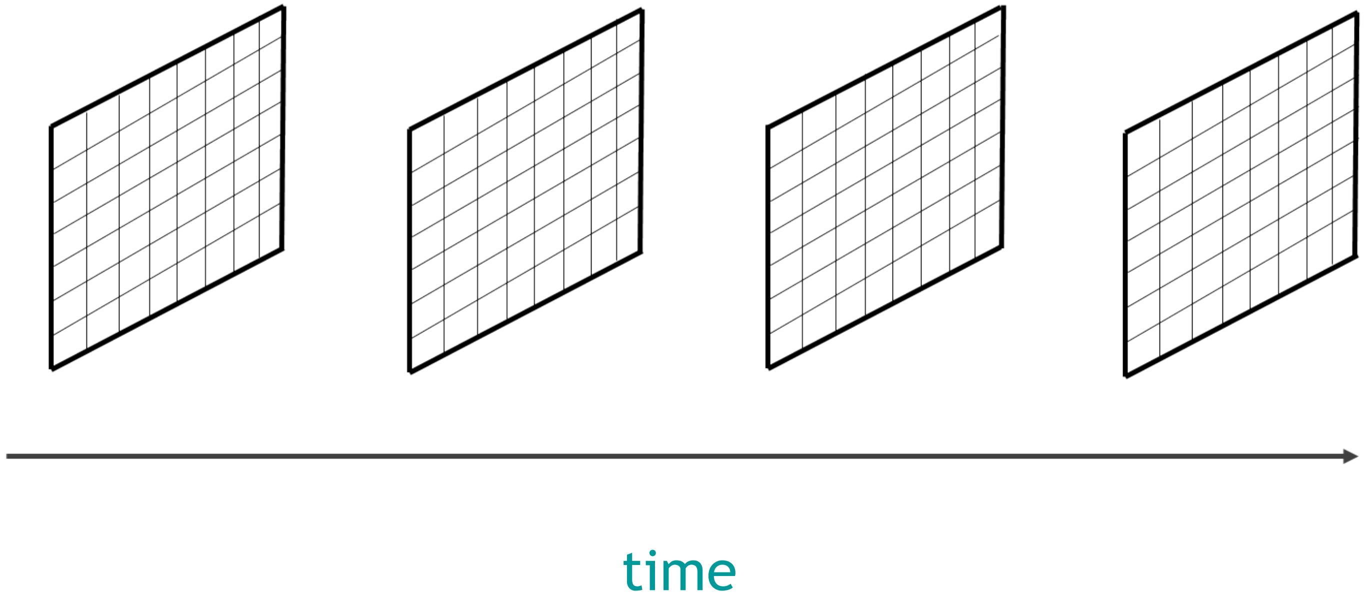
We construct weighted acoustic power network at each instant of time





We only consider neighbouring acoustic power sources for network construction

We construct time-varying weighted acoustic power network for a given control parameter



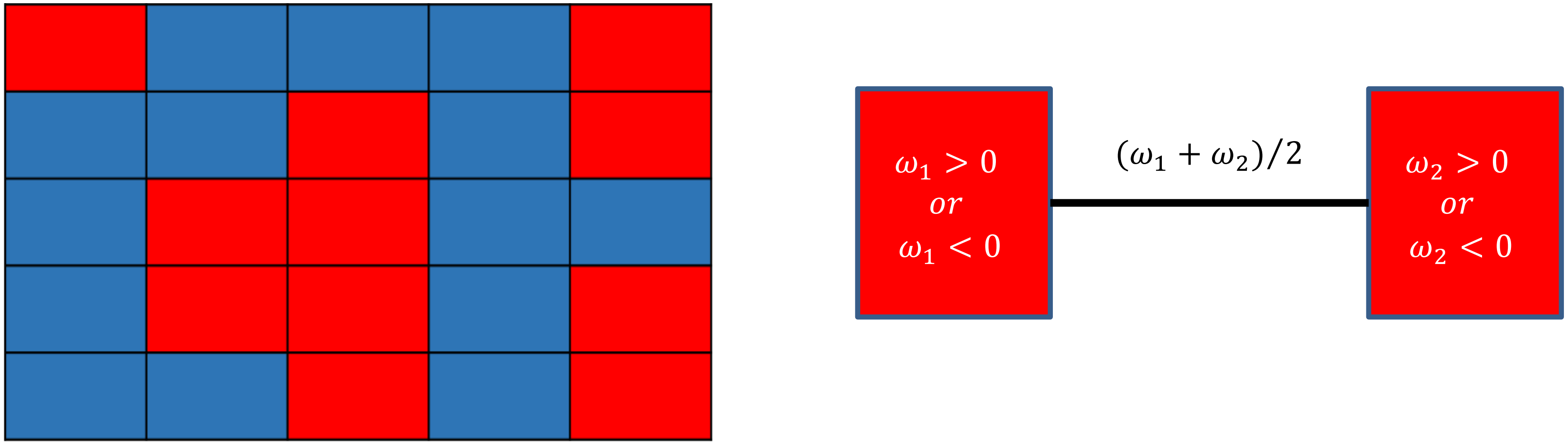
We also construct time varying vorticity network

We obtain instantaneous vorticity field from PIV for different control parameters

+	−	−	−	+
−	−	+	−	+
−	+	+	−	−
−	+	+	−	+
−	−	+	−	+

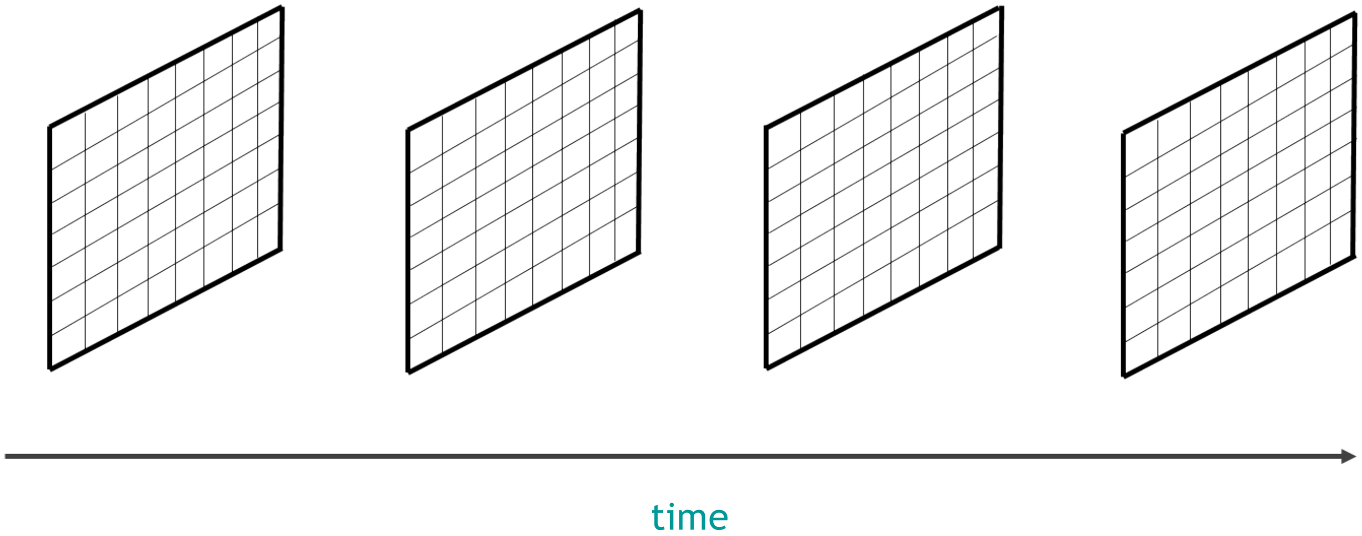
$\omega > 0$: Counter clockwise vorticity
$\omega < 0$: Clockwise vorticity

We construct weighted vorticity network at each instant of time



We only consider neighbouring nodes with positive (negative) vorticity for network construction

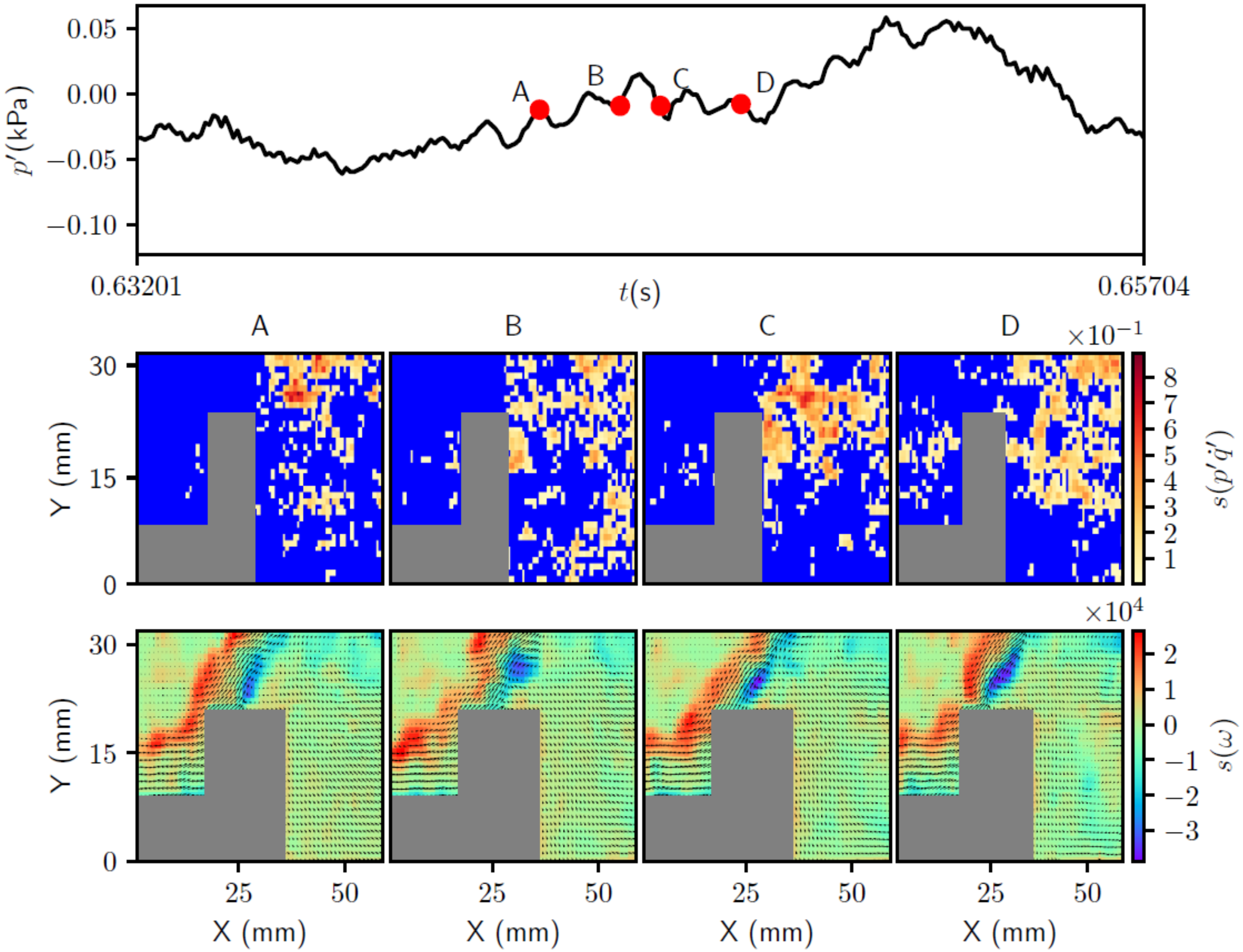
We construct time-varying weighted vorticity network for a given control parameter



During combustion noise, acoustic power production occurs in small fragmented clusters

power

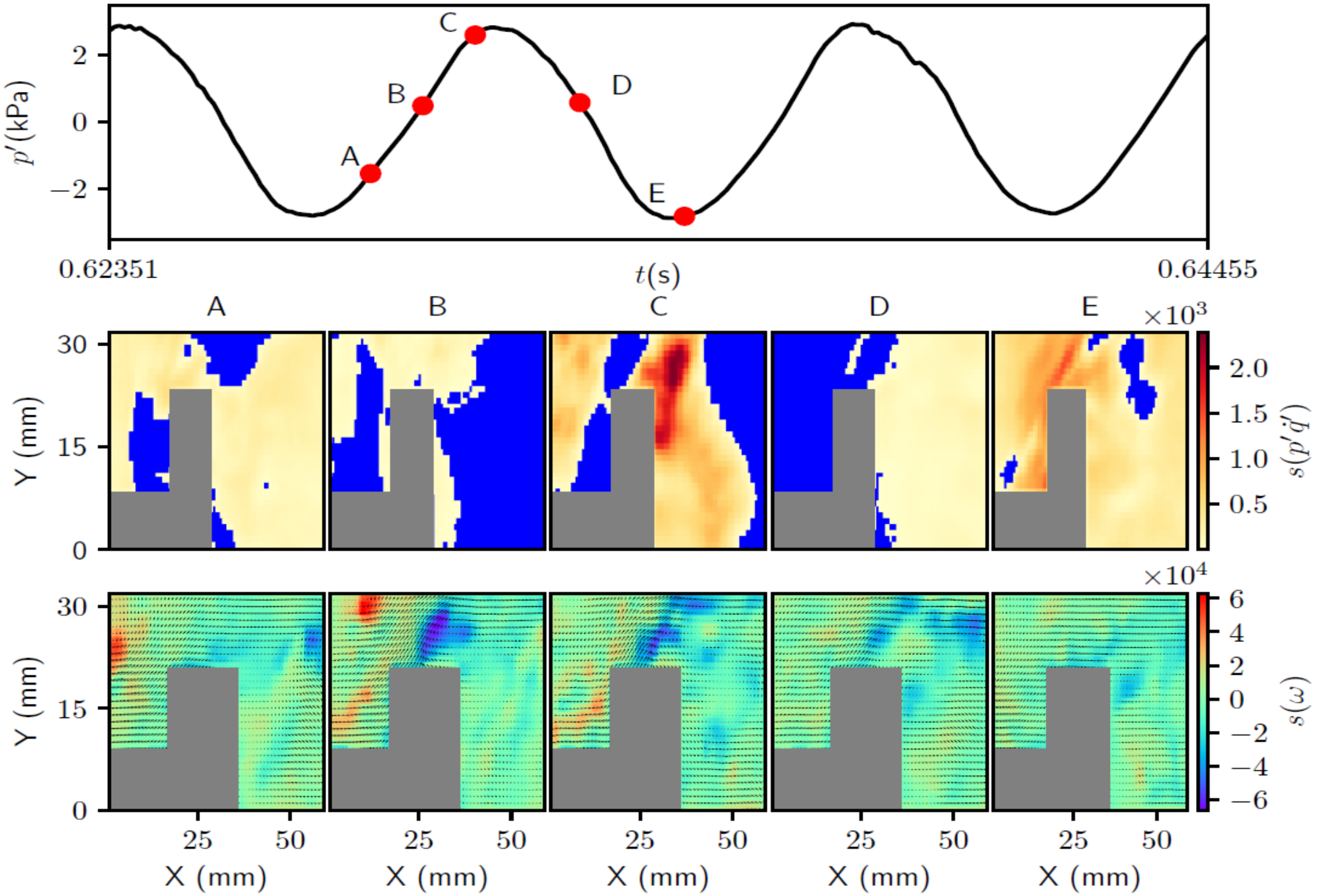
vorticity



During thermoacoustic instability, acoustic power production occurs in large clusters

power

vorticity

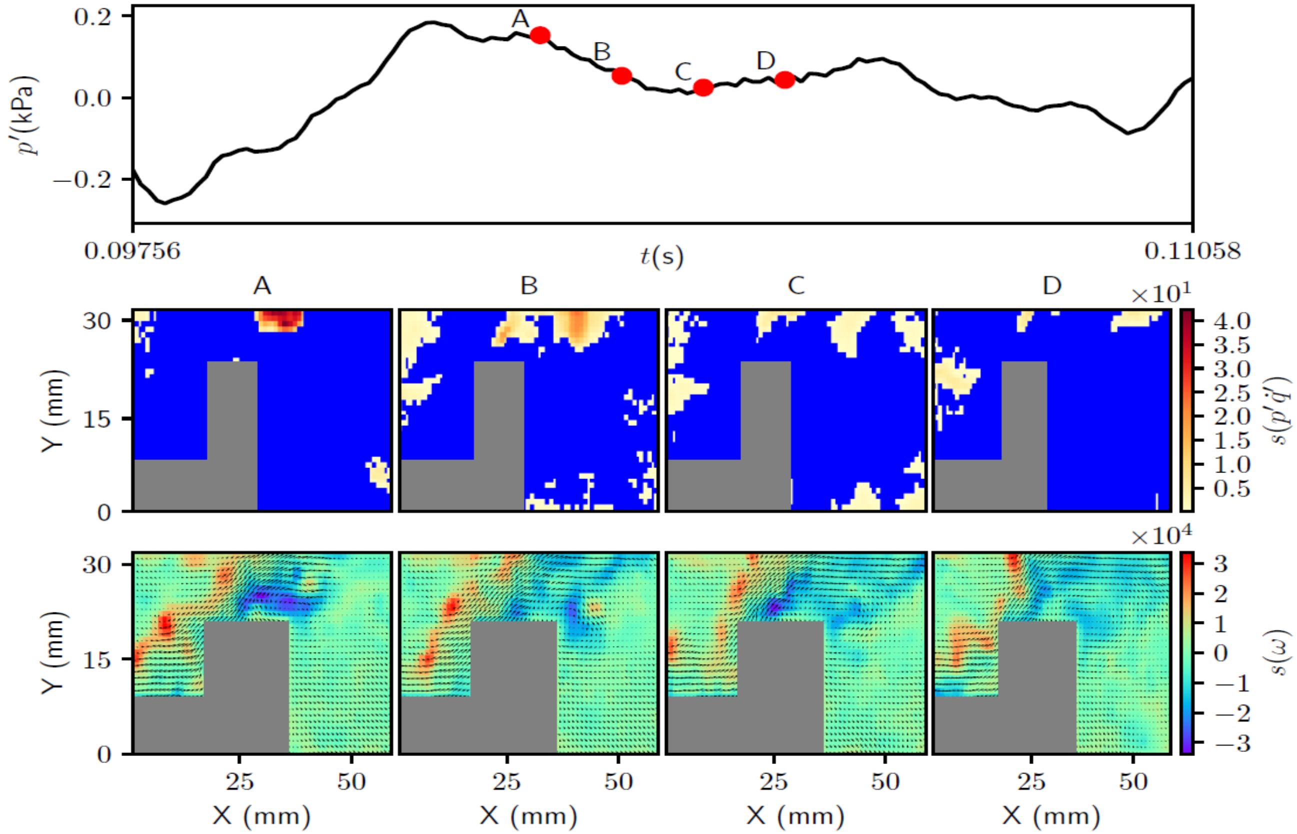


What happens during intermittency?

During aperiodic epochs of intermittency, acoustic power production occurs in small fragmented clusters

power

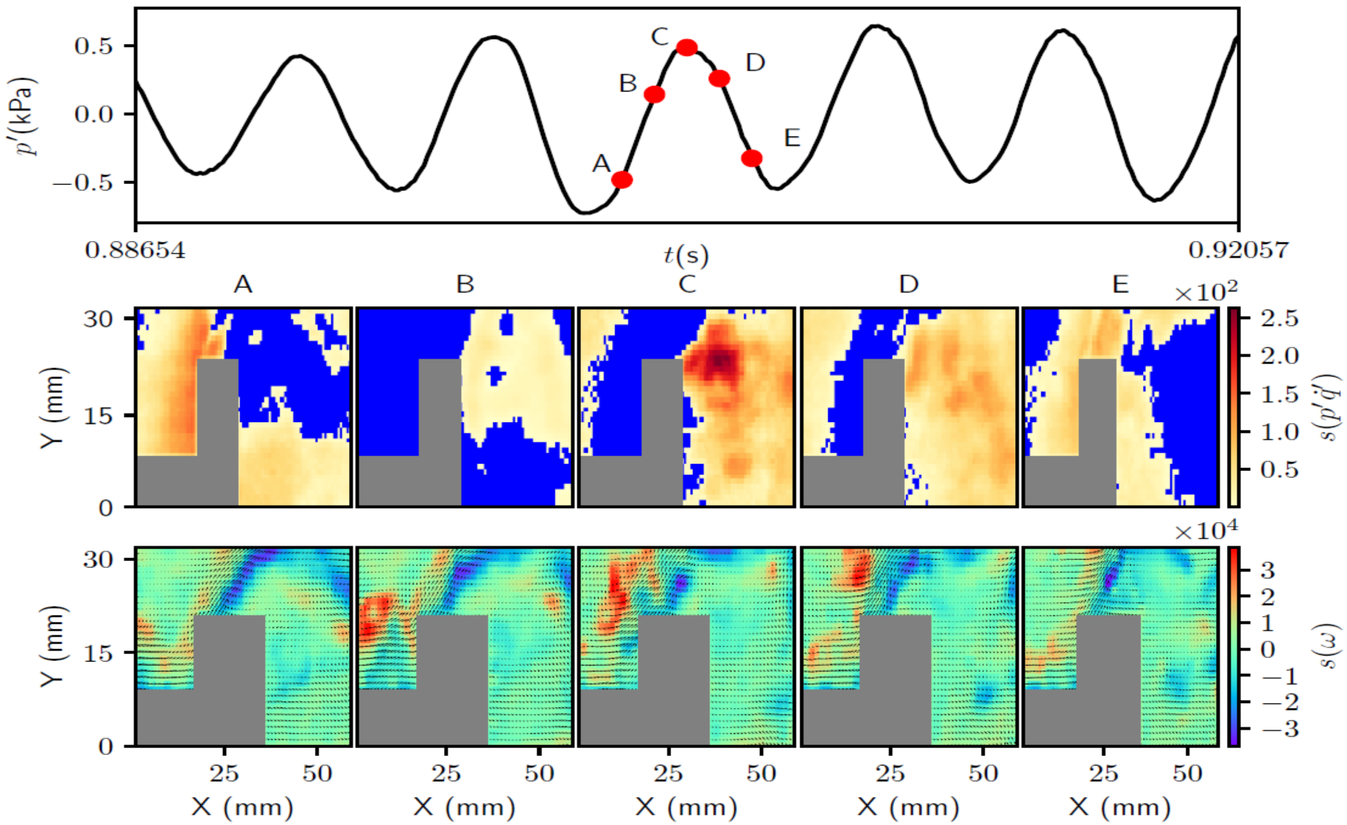
vorticity



During periodic epochs, power production occurs in not so large clusters as that during TA instability

power

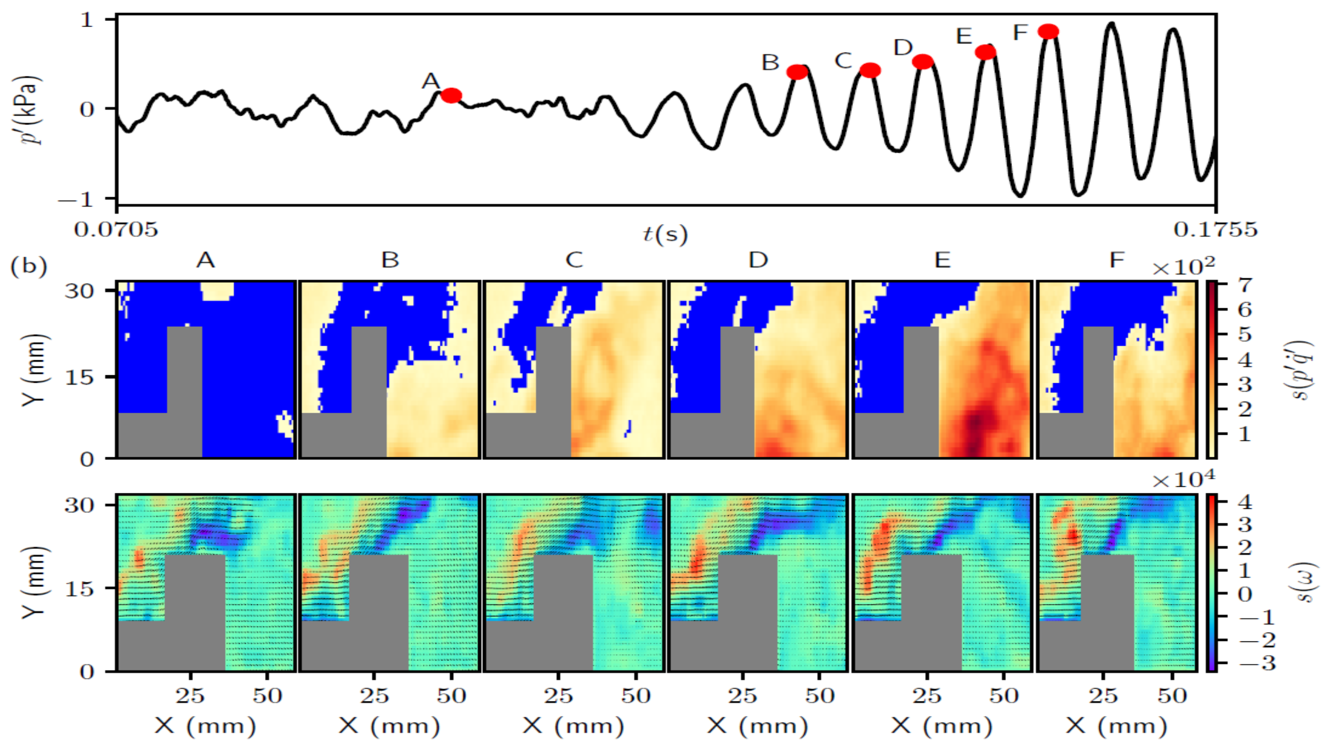
vorticity



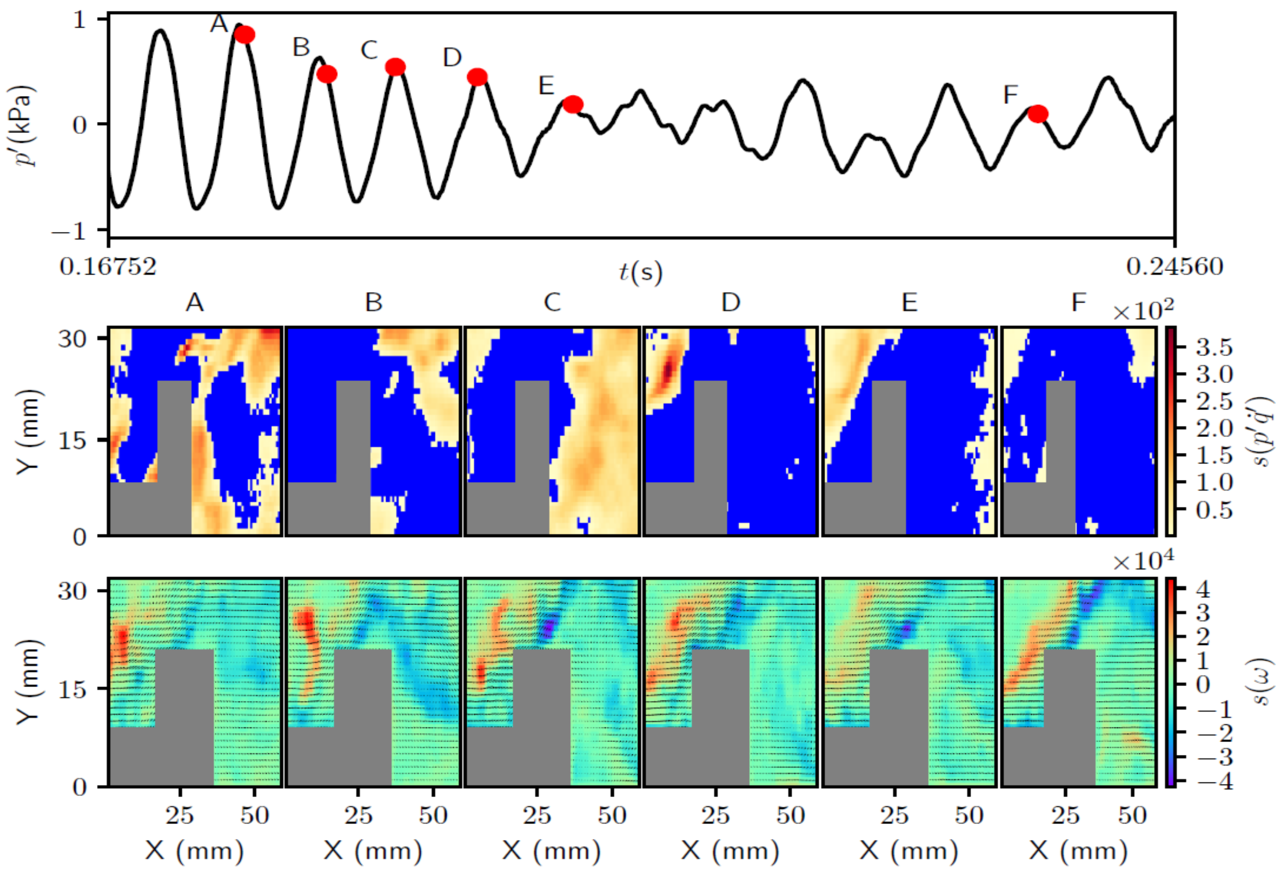
During the growth of oscillations, we see nucleation, coalescence and growth of acoustic power sources

power

vorticity



During decay of oscillations, we see disintegration of large clusters into small fragmented clusters



power

vorticity

We examine the statistics of clusters of acoustic power sources

Link density

Quantifies the number of locations at which acoustic power production happens

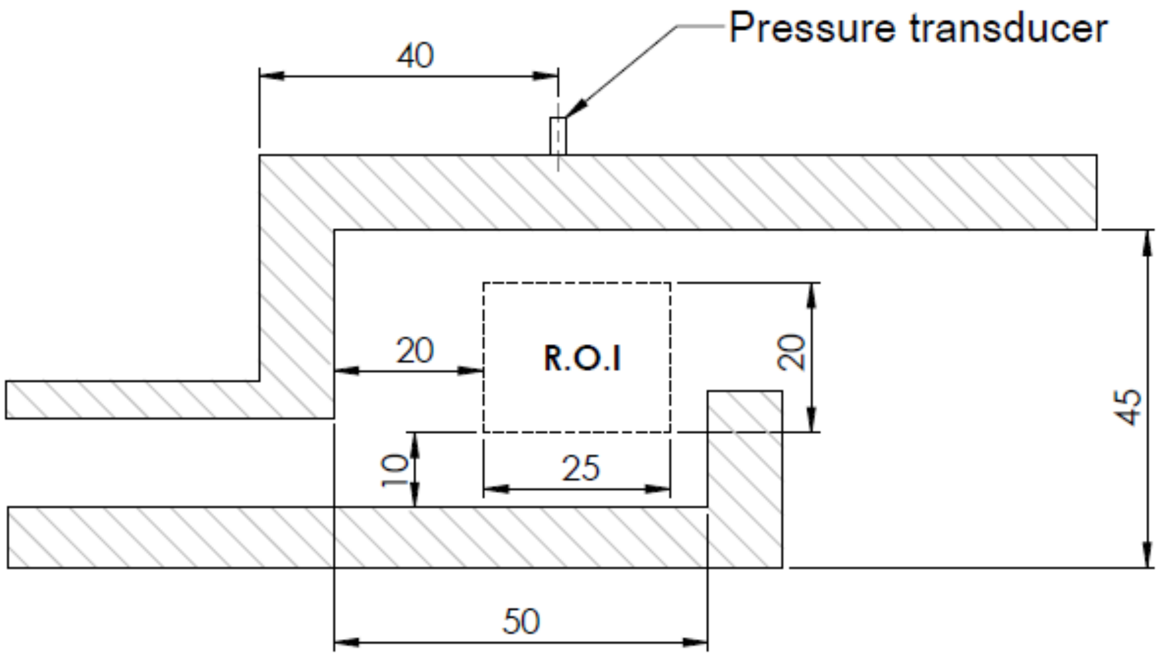
Size of the giant cluster

Quantifies the extend of spatial coherence of acoustic power production

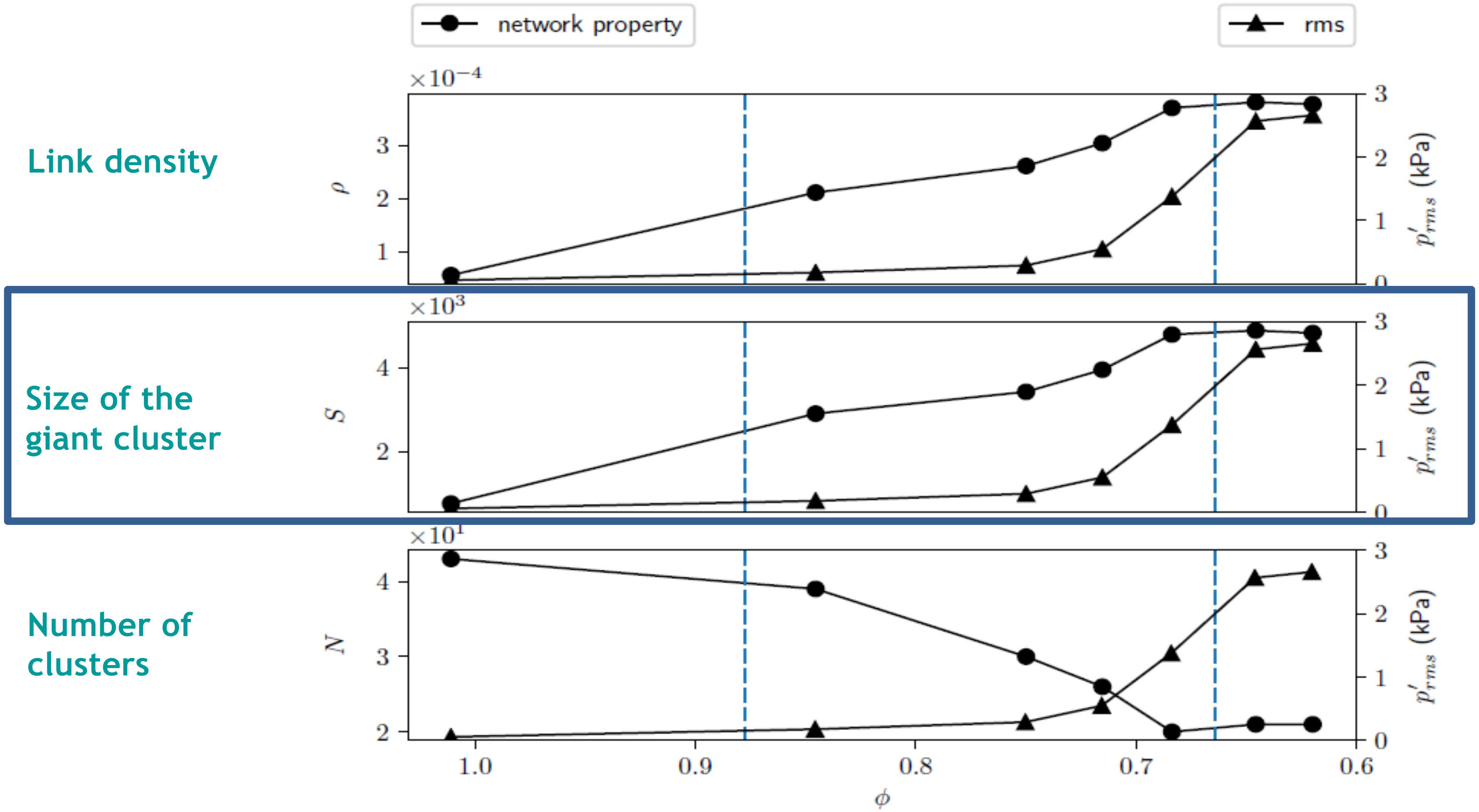
Number of clusters

Quantifies the spatial coherence of acoustic power production

We choose a region of interest upstream of the bluff body for the calculation of the statistics



We see nucleation, coalescence and growth of acoustic power sources



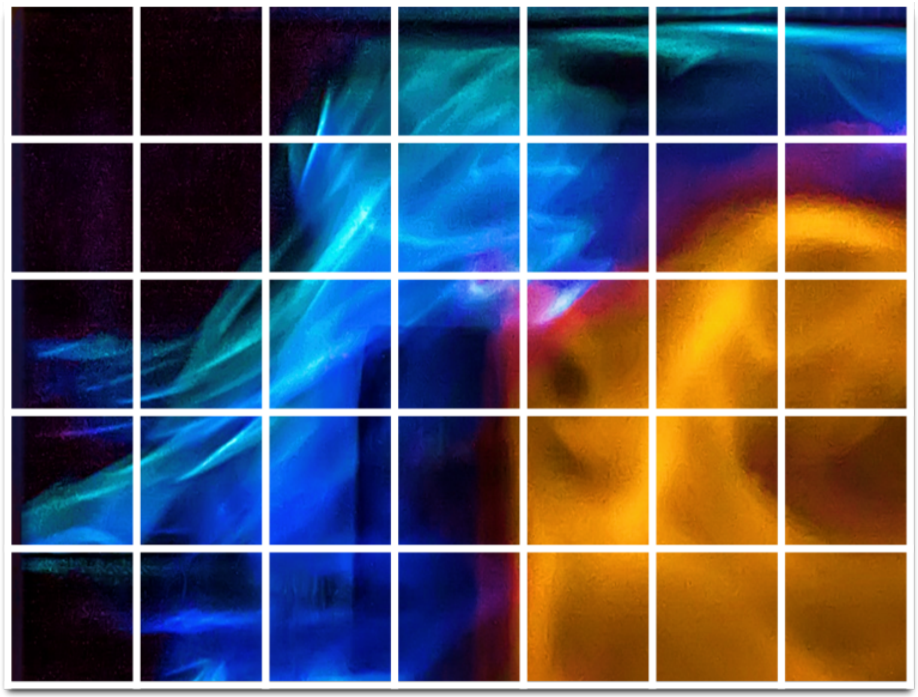
Onset of thermoacoustic instability can possibly be viewed as a percolation-like phase transition

Smart passive control

Patent pending; Unni et al. (Chaos 2018); Krishnan *et al.* (EPL, 2019)

Spatial weighted correlation network from the velocity field

The turbulent reactive flow field is divided into grids in the analysis of Particle Image Velocimetry



Each of these cells is a node of the network

We construct spatial correlation networks using Pearson's correlation

$$R_p = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

- Two nodes are connected if the correlation coefficient is above a threshold of 0.5
- The correlation coefficient is considered as the weight of the link

Network centrality measures

Node strength

Measures the strength of interactions of a node with the neighbours

$$s_i = \sum_{j=1}^{N} w_{ij}$$

A node with high node strength has a strong influence on the functioning of the network

Weighted local clustering coefficient

Measures the heterogeneity in the interaction strength of the neighbours of a node

$$\widetilde{C}_i = \frac{\sum_{j,k} w_{ij} w_{jk} w_{ki}}{\max(w) \sum_{j,k} w_{ij} w_{ki}}$$

Node strength and weighted local clustering coefficient are used to estimate the spatial organization of the correlation field

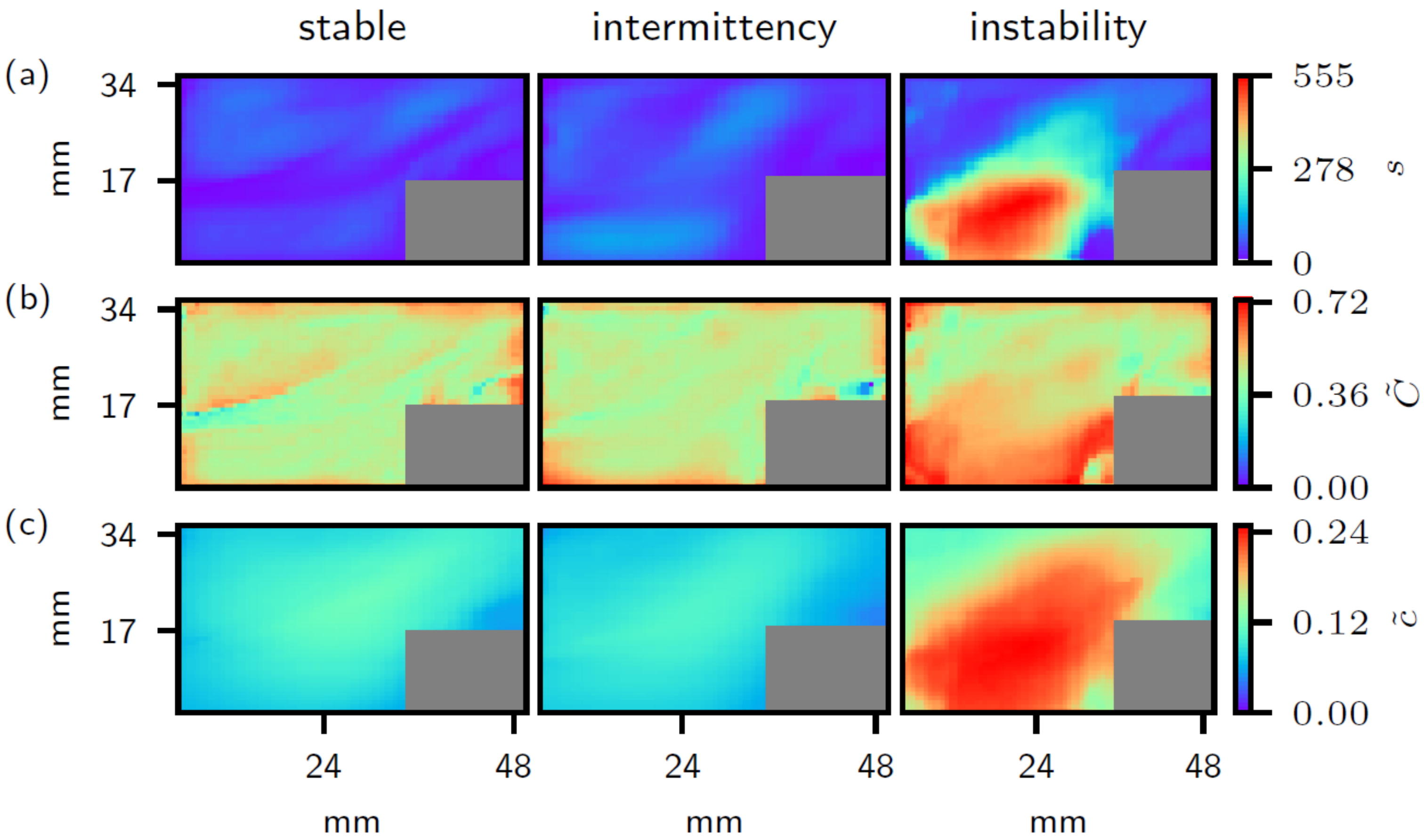
Weighted closeness centrality

Measures the speed of information propagation through the least costly path

$$\tilde{c}_i = \sum_j 2^{-d_w(i,j)}$$

Higher the values of Pearson's correlation coefficient, the quicker the disturbances can travel to all other nodes in the network

The region on top of the bluff body shaft emerges as the critical region during thermoacoustic instability



(Krishnan *et al.*, EPL, 2019)

Control of thermoacoustic instability

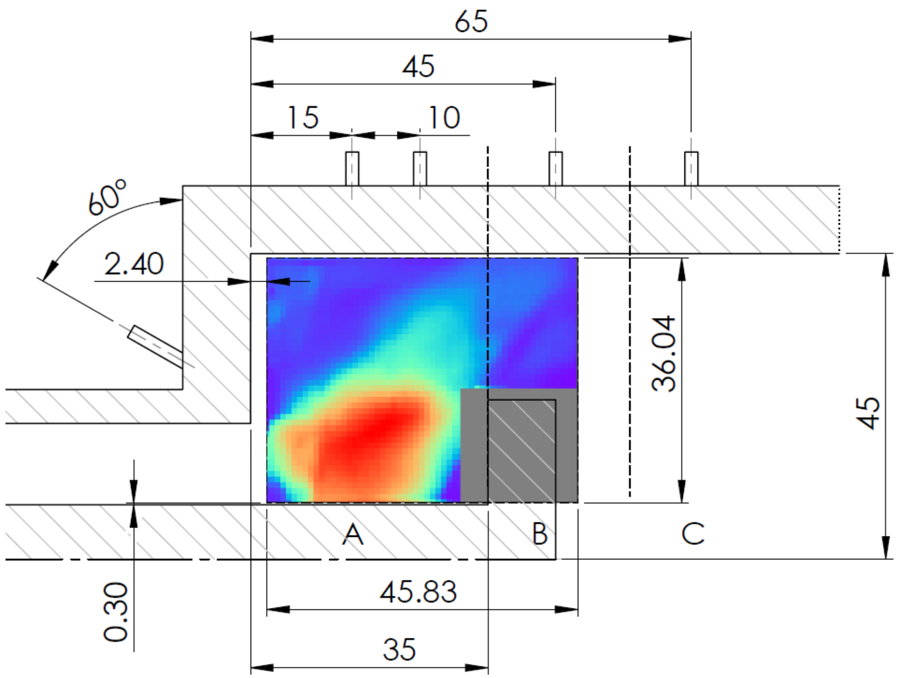
Active Control

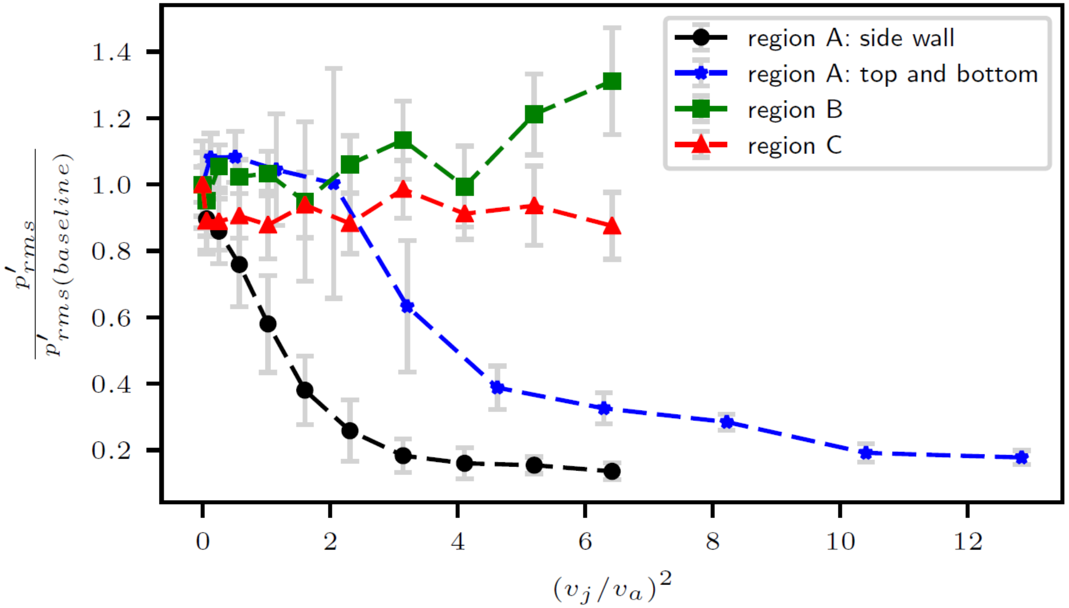
Passive Control

Passive control: usually by trial & error


Sree
CINEMA

We inject air-jets at different locations to suppress thermoacoustic oscillations

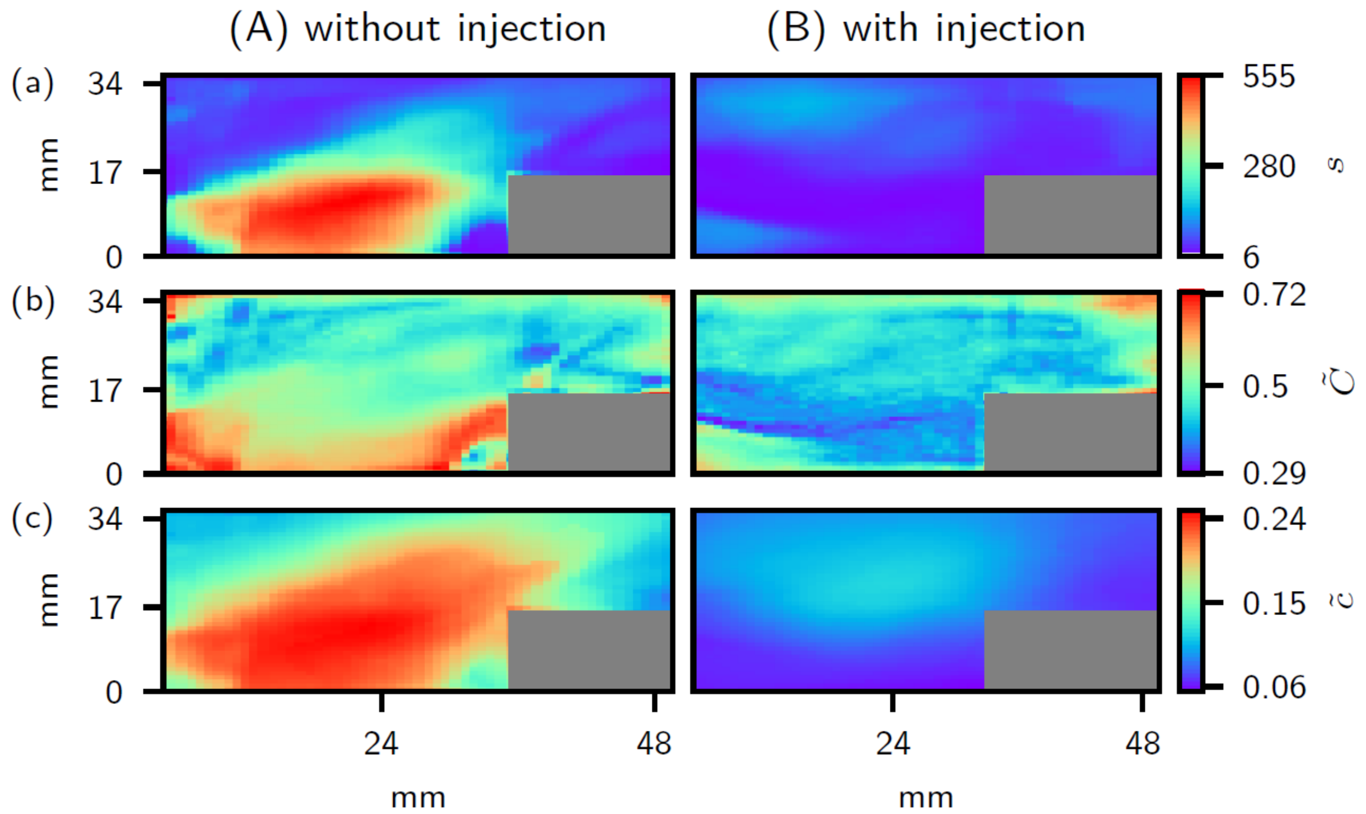




Critical region is the optimal location for implementing control strategies

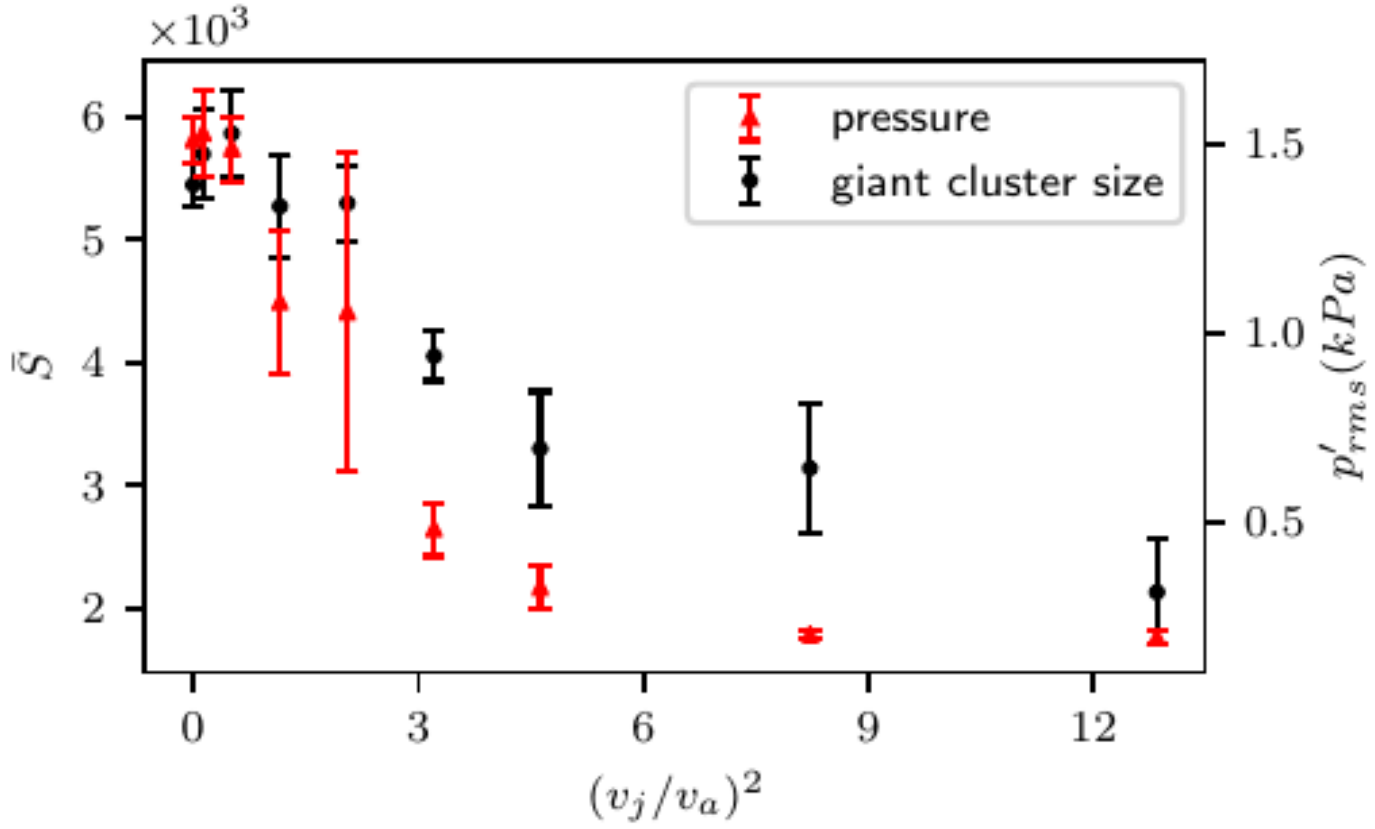
(Krishnan *et al.*, EPL, 2019; U.S. patent appl. no. 16/287, 248)

The critical region disappears with suppression of thermoacoustic oscillations



(Krishnan *et al.*, EPL, 2019)

TAI oscillations are suppressed when coherent acoustic power production over large clusters ceases

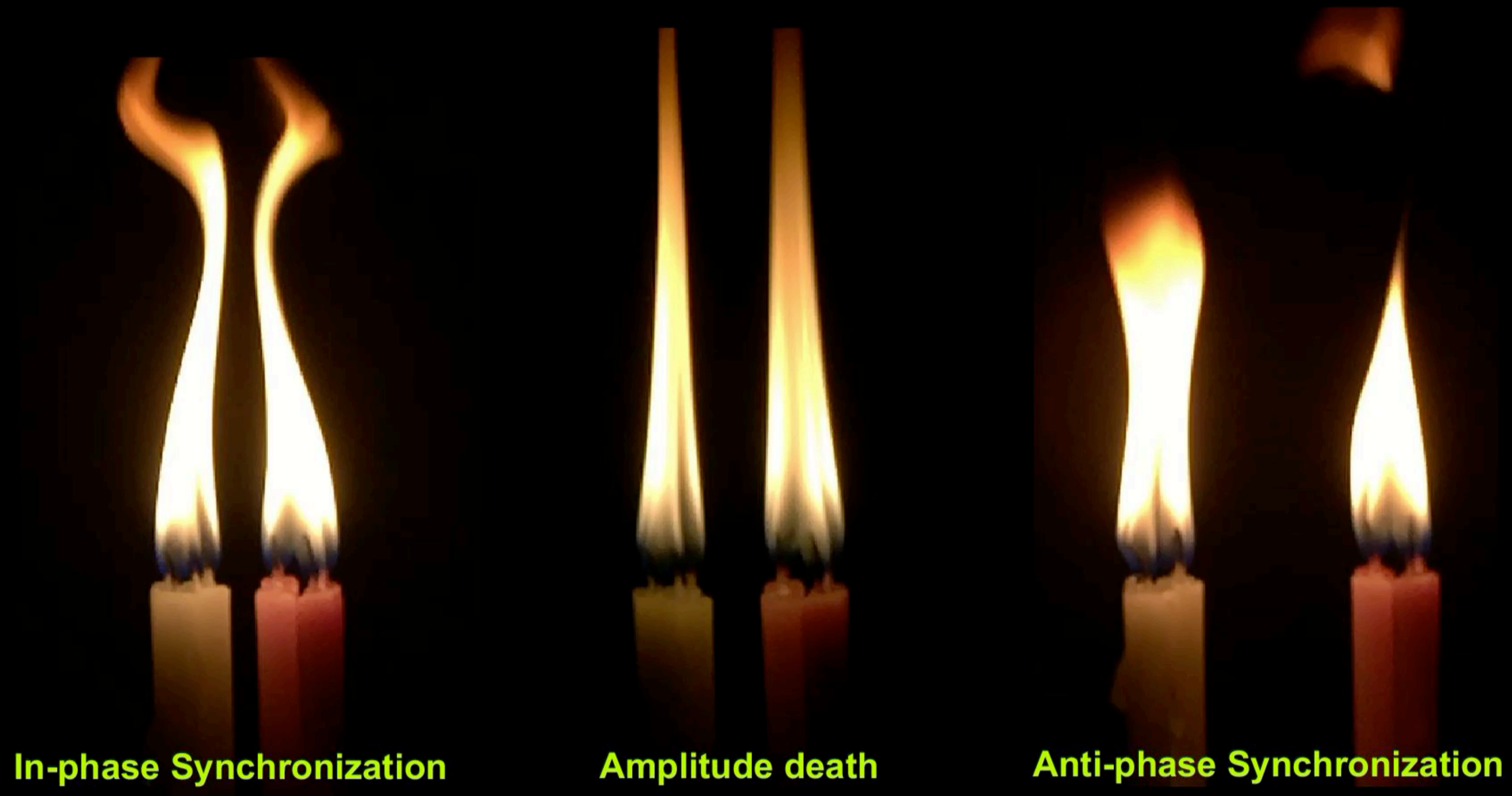


(Krishnan *et al.*, EPL, 2019)

Cardiac ablation

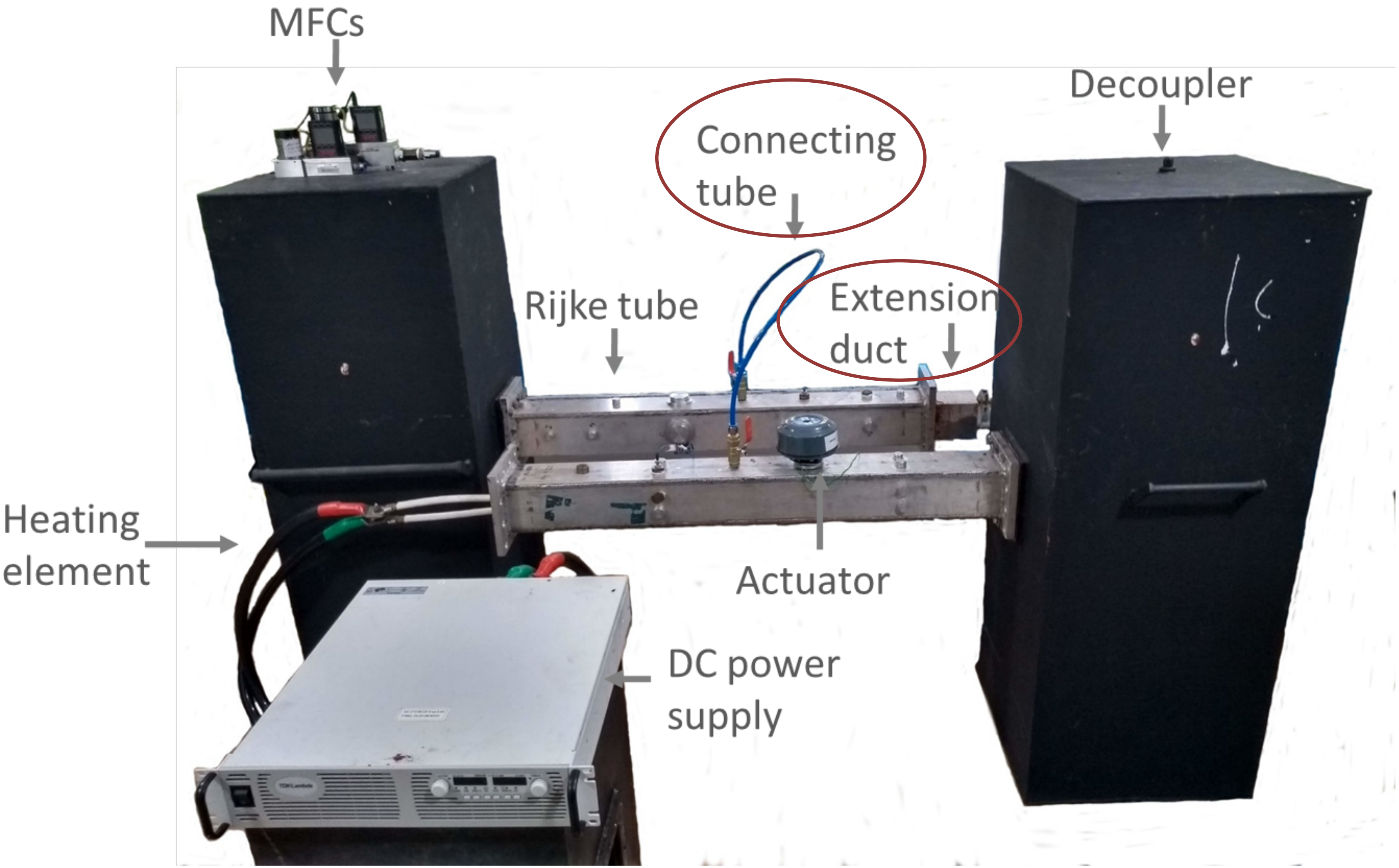
Amplitude Death

Synchronization of Candle Flames



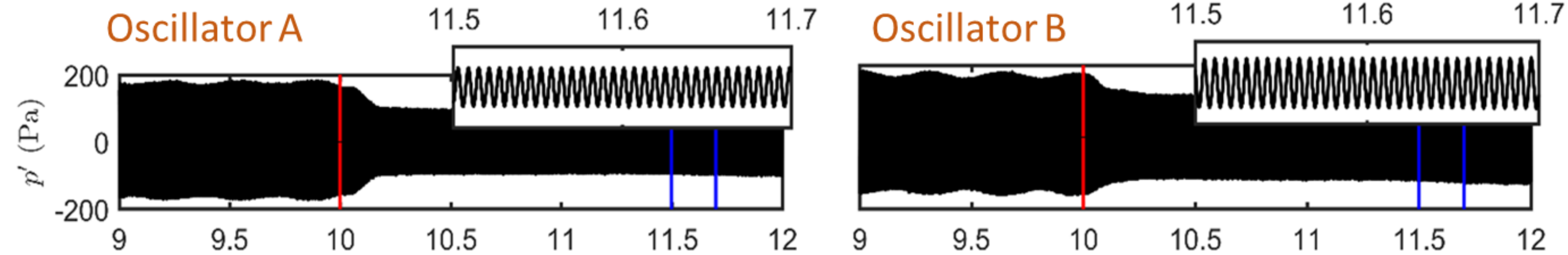
Manoj et al. (PRE 2019)

Quenching of thermoacoustic instabilities in coupled Rijke tube systems via Amplitude Death

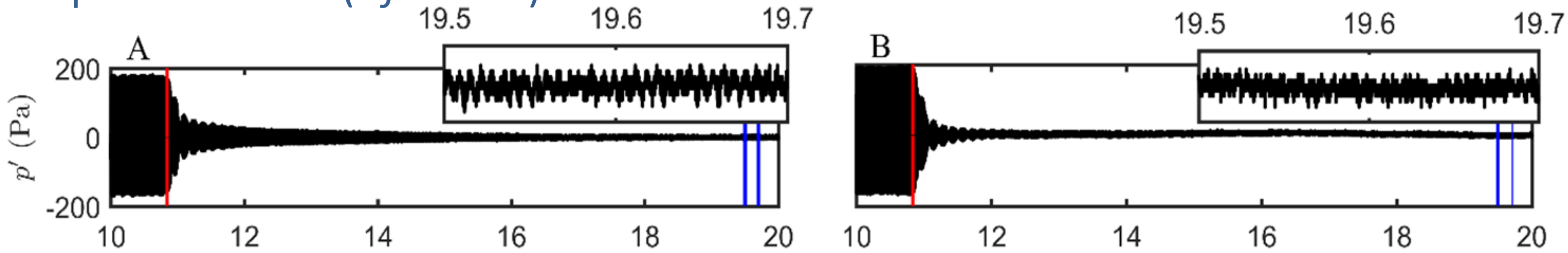


We can get AD and Partial AD, depending on the coupling

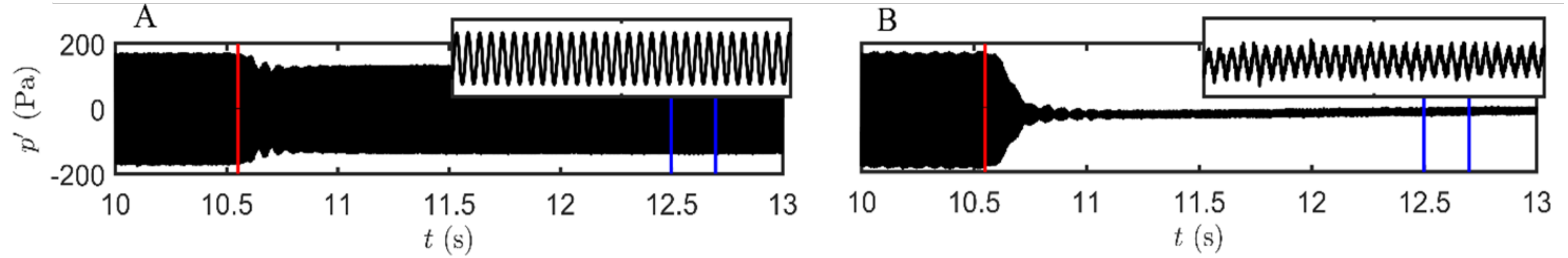
Suppression (Δf = 0)



Amplitude death (Δf = 7 Hz)



Partial amplitude death (Δf = 15 Hz)



Summary, challenges & the way forward

- A beginning has been made to study the spatio-temporal dynamics of thermoacoustic systems using the frameworks of
  - (1) synchronization theory
  - (2) complex networks
  - (3) fractal and multi- fractal analysis
  - (4) pattern formation.

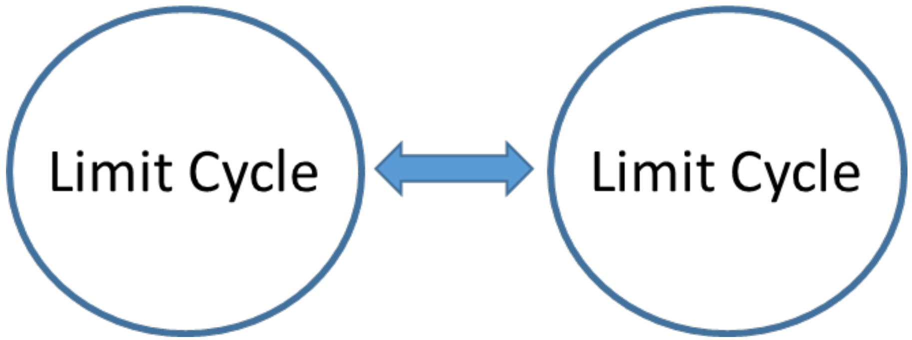
- The study of the spato-temporal dynamics is indeed the next frontier.

Complexity, chimera, collective interaction…

- Complex systems are known to display pockets of order amidst disorder.
  - During intermittency, we find bursts of high amplitude periodic oscillations which correspond to pockets of order, scattered amidst epochs of low amplitude aperiodic fluctuations, which correspond to pockets of disorder.
- Synchronization theory reveals that during the occurrence of intermittency, we see chimera states, where pockets of order co-exist with disorder.
- During the emergence of order, large coherent vortices emerge from the collective interaction of small vortices.

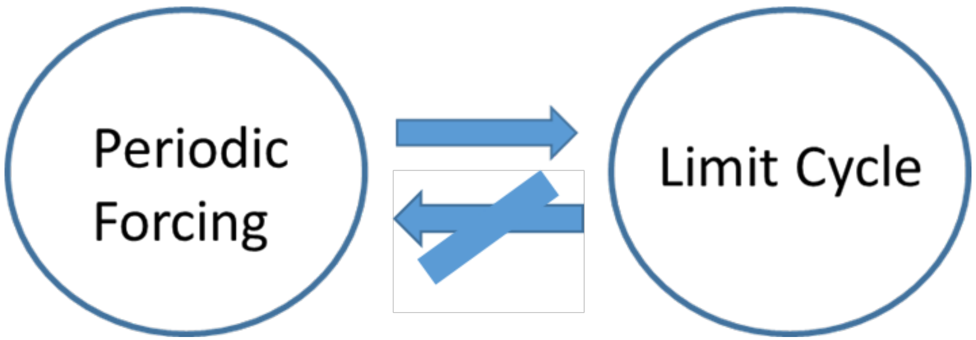
Help mitigate thermoacoustic instability

Amplitude death



Precursors

Asynchronous quenching



Chaos, 28, 033119 (2018) (Editor's pick)
Chaos, 28, 093226 (2018)
Chaos, 29, 093135 (2019)

JFM, 864, 73-96 (2019)
JFM, 884, A2 (2020)

Smart passive control

EPL 128 (1), 14003

Transcending the boundaries between math, physics and engineering

- Improving our understanding of thermoacoustic instabilities & controlling them will require the application of the latest advances in complex systems theory.
- To achieve this, groups that do laser diagnostics and groups that do LES need to work together with researchers who work with complex system theory.
- We also face a new frontier in translating the lessons learnt from complex systems approach into design and engineering practices.

Fasten your seat belt: exciting times are ahead

- The real test for complex systems theory is its ability to provide something useful to the designer to mitigate thermoacoustic instability and to the engineer on the field to evade it.

- Complex systems theory itself needs to be advanced to accommodate the complexities of turbulent flow; this is indeed an exciting prospect.