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Space-time Correlations of an Over-expanded Jet

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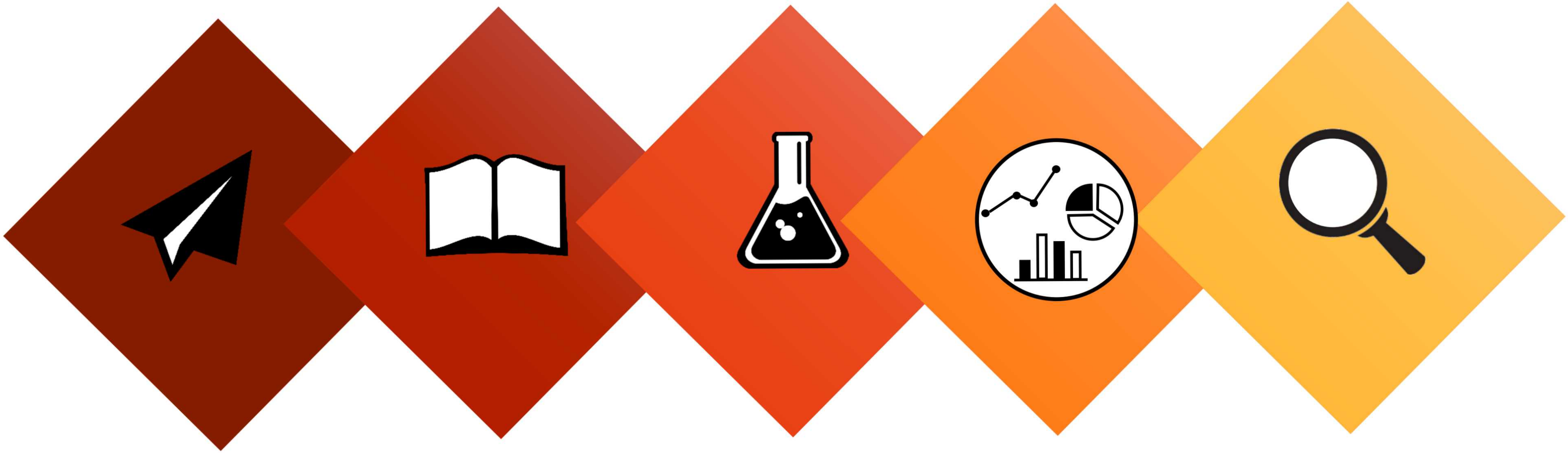
Overview



Motivation

Literature Review

Facility & Technique

Key Results

Future Work & Summary

Motivation

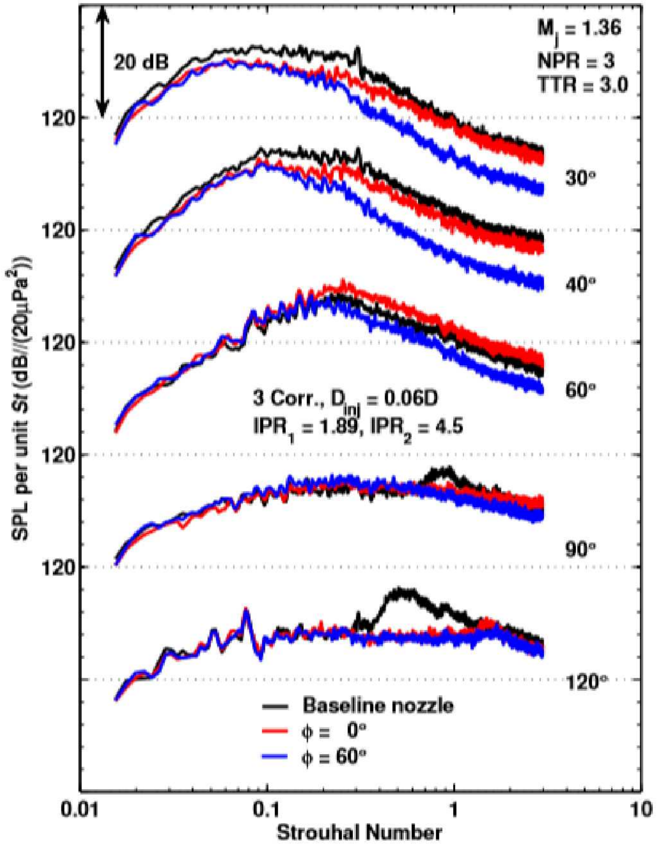
Noise induced hearing loss a real concern for DoD

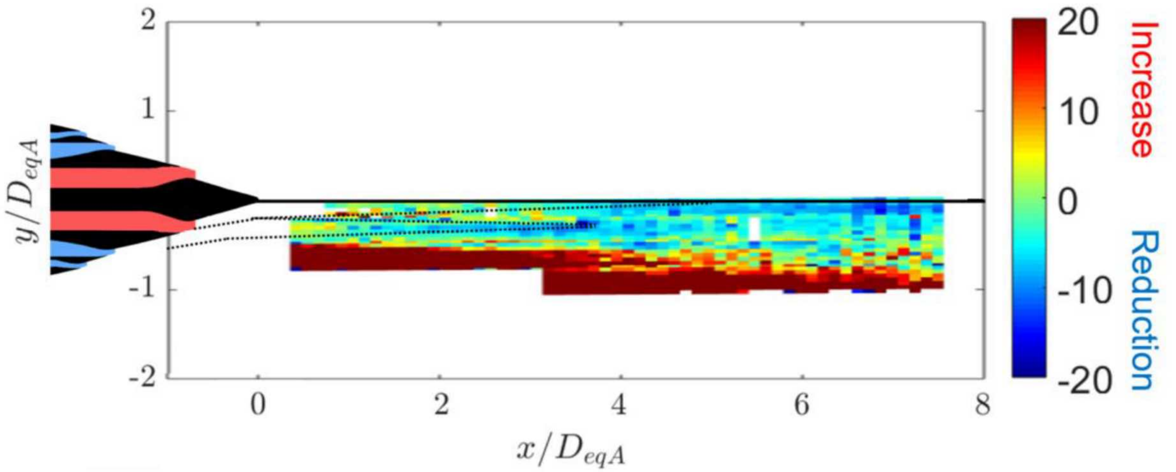
- Noise levels on a carrier decks can exceed 145 dB
- Dept. of Veteran Affairs claims on an exponentially increasing trend

Community noise is also an issue:

- Locality actions to limit F-35 flights
- NASA High Speed project reinvigorating development of supersonic transport

Future Jet Noise Reduction Techniques??





Stuber et al. (2019):

- Reduced U_c in shear layer and along centerline beyond end of potential core

Henderson et al. (2016):

- Up to 8dB reductions along thin side of jet

Powers et al. (2013):

Fluid injections reduce noise from over expanded jets by up to 5 dB OASPL

Shock Noise Source Map

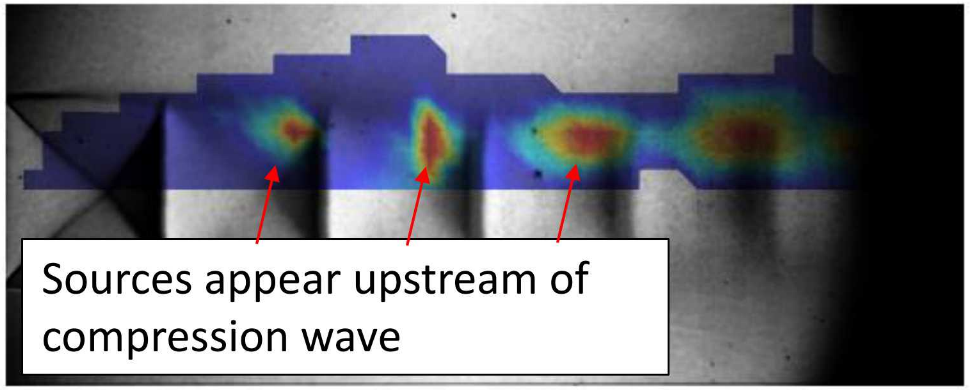
Savarese et al. 2013

- Supersonic under-expanded jets
- Effect of NPR & flight stream velocity on BBSAN
- Simultaneous near-field pressure & 2 component LDV

Create "source map" by integrating over region of interest

$$\alpha_{u,p} = \int_{\Omega} \gamma_{u,p}^2 \, d\Omega$$

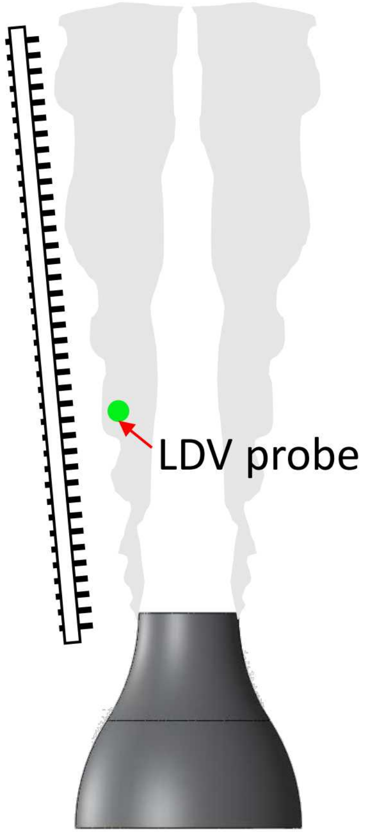
Where Ω represents boundaries in x_{mic}, St

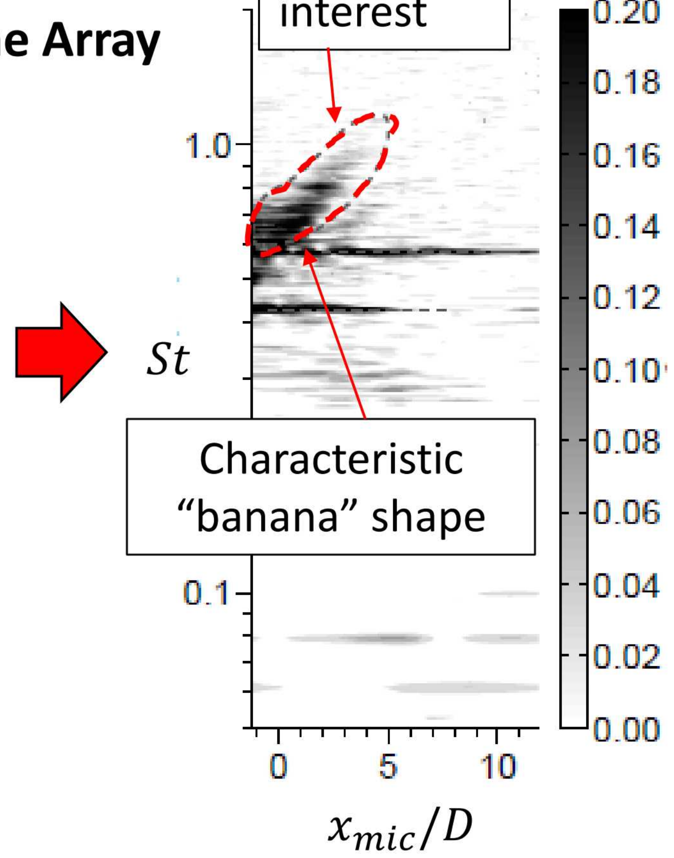


(a) $\alpha_{u,p}$ map

Space-frequency Coherence Maps $\gamma_{u,p}$

- Coherence between:
  - u' at LDV probe point
  - p' at points in nearfield array





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Experimental Conditions

Jet Conditions

Over Expanded Jet

- $NPR_{jet} = 2.6$
- $NPR_D = 3.7$

Heated Jet

- $TTR = 2$

Noise Sources Present

Mach Waves

- $M_c \approx 1.1$
- Mach waves at shallow downstream angle

Broad band shock associated noise

- Radiates at sideline & upstream directions

Turbulent Mixing Noise

- Temporal evolution & directivity distinct from Mach waves

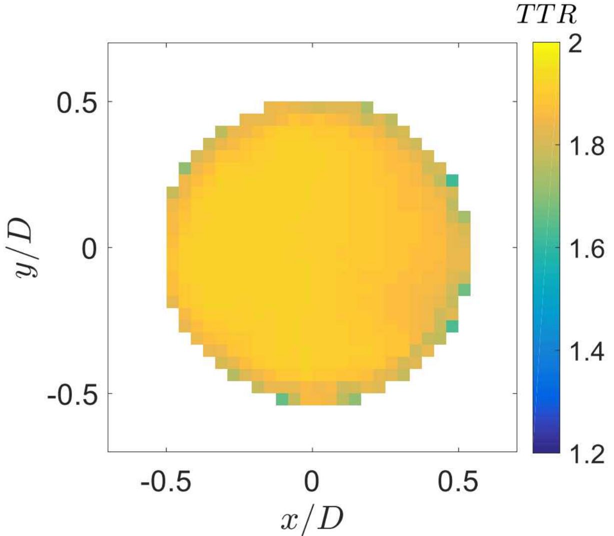
Goal:

Gain physical insight into different noise components

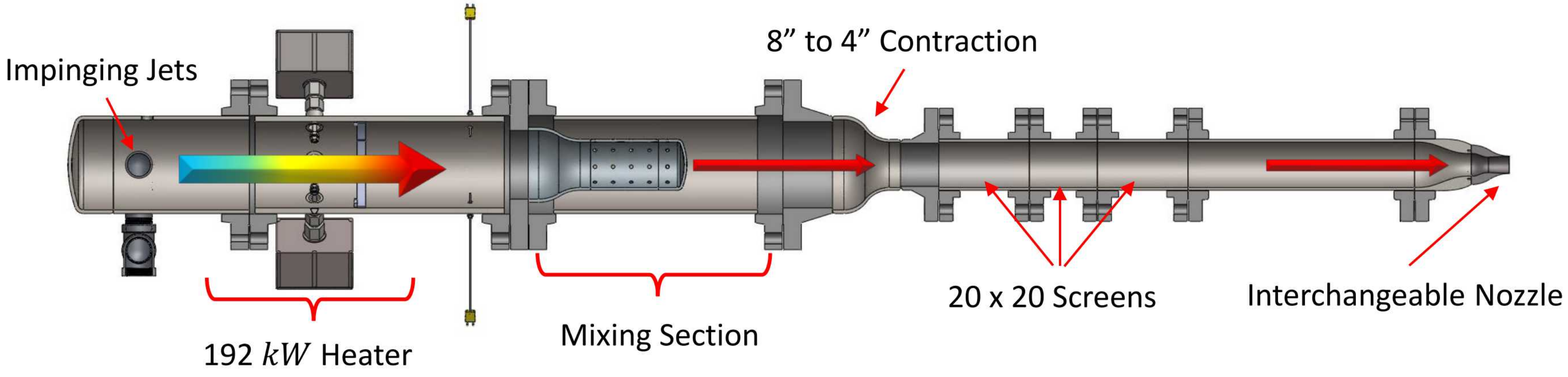
- Examine differences in
  - Directivity
  - Frequency range
  - Temporal evolution

2D space-time correlations of the frequency filtered density near-field

T_0 survey of nozzle exit

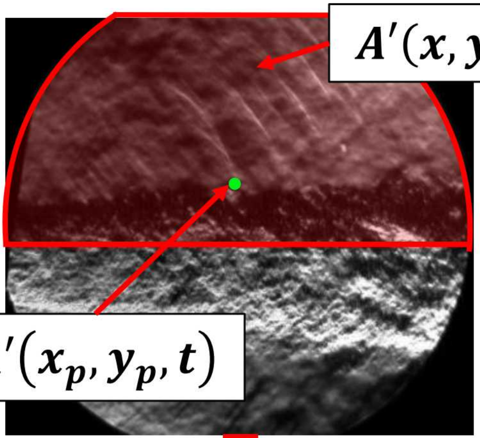


VT Heated Jet Rig



Analysis Techniques

Near-field Schlieren



Visualize temporal & spatial evolution of density waves

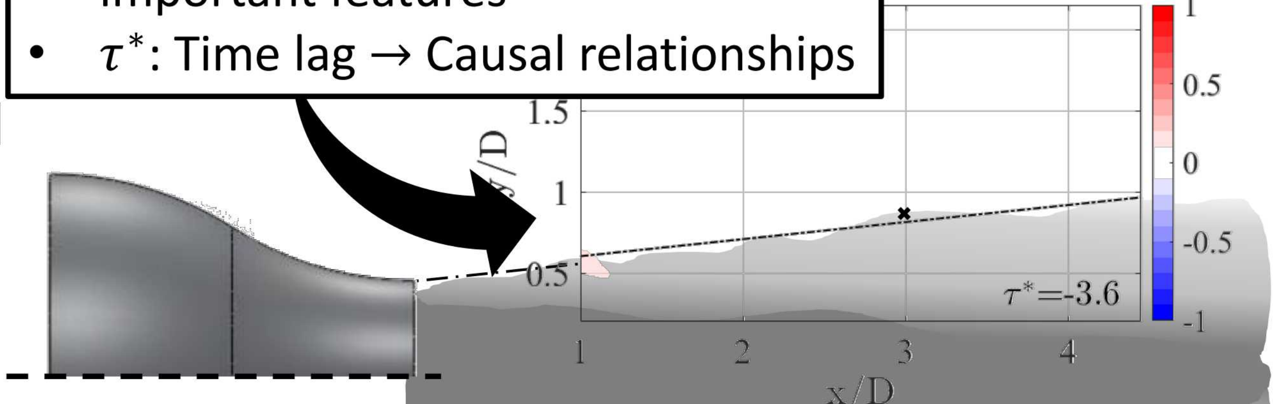
$$R_{AA}(\tau) = E\left[A'\left(x_p, y_p, t\right)A'(x, y, t+\tau)\right]$$

- Provides radial density gradient $\left(\frac{\partial \rho}{\partial r}\right)$
- Resolved in time and space $(f_s = 110\ kHz)$
- Intensity is uncalibrated

Captures temporal & spatial evolution of density waves

Physical Significance:

- Statistical structure of acoustically important features
- τ^*: Time lag → Causal relationships



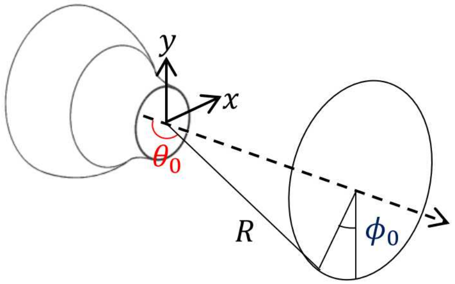
Goal:

Gain physical insight into different noise components

- Examine differences in
    - Directivity
    - Frequency range
    - Temporal evolution

- Space-time correlations of frequency filtered schlieren images
- What frequency range matters?

Far-field Acoustics: Identify BBSAN



Presented Data:
100D arc $\theta_0 = 70°: 10°: 160°$

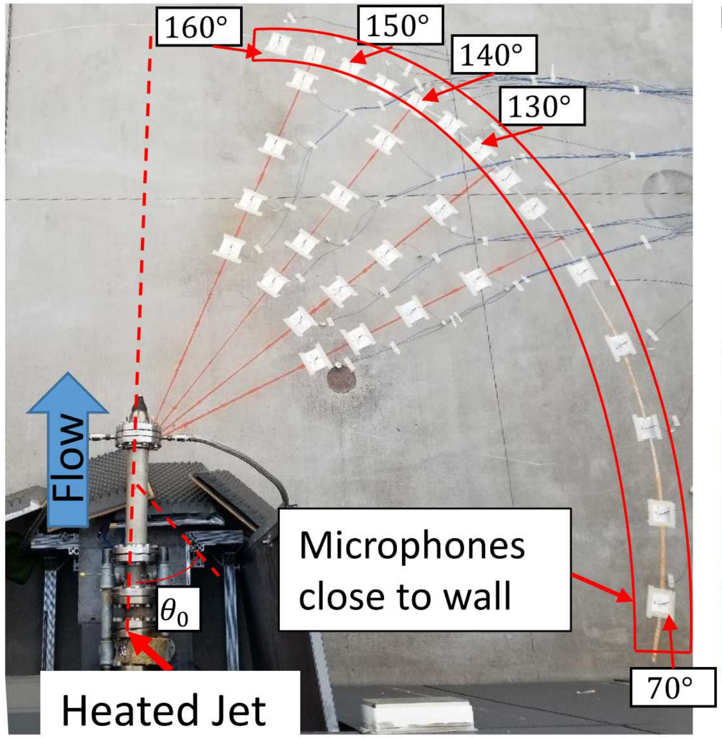
Far-field Narrowband Spectra indicate presence of BBSAN

1. Dominates angles upstream of $\theta_0 = 90°$
2. Occurs at frequencies $St > 0.4$

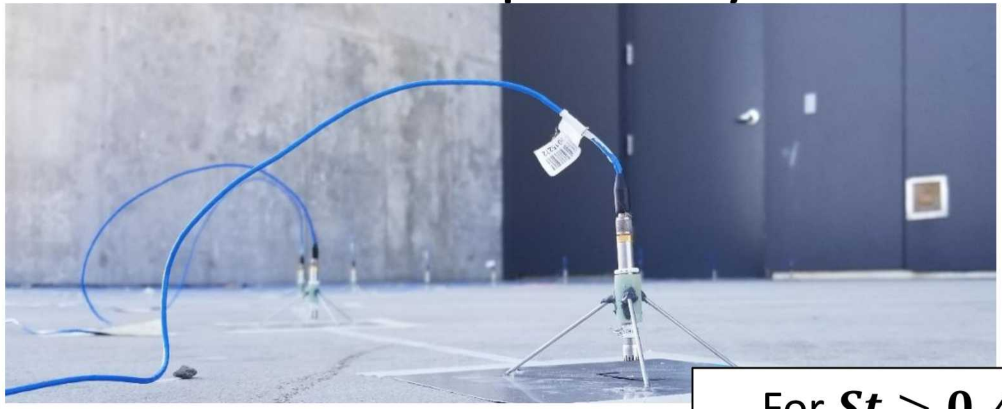
Note: Waviness in spectra at low θ_0 due to reflections from wall

Use $St = 0.4$ as cutoff frequency

Birds Eye View

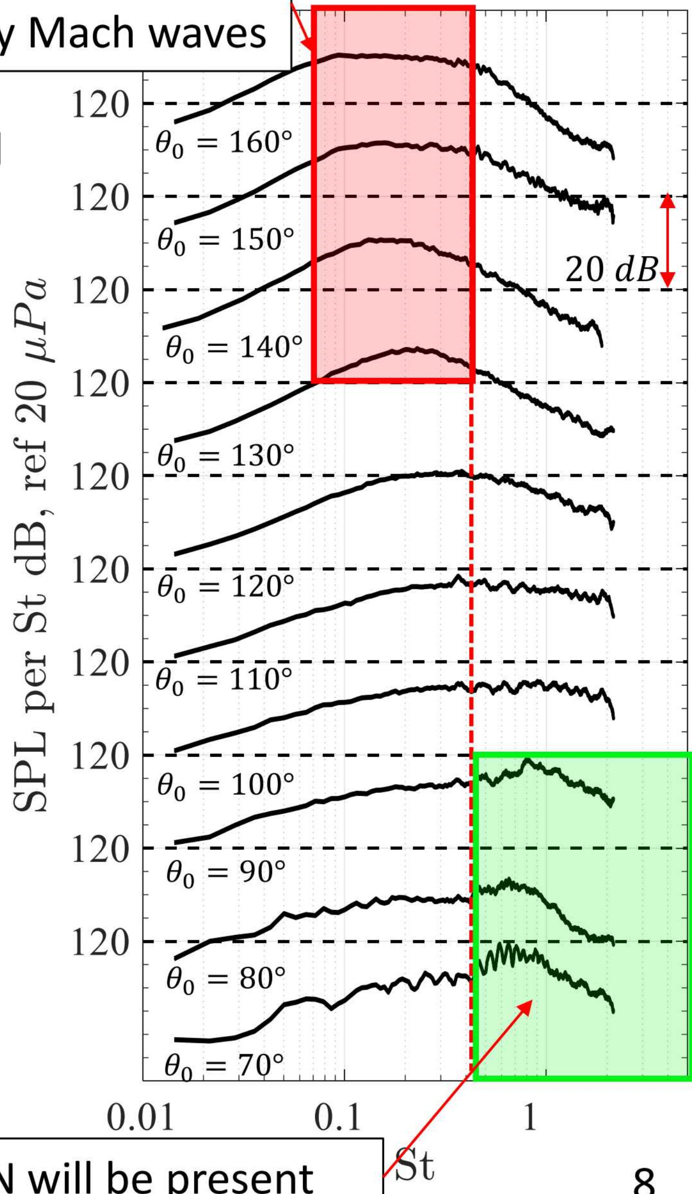


Ground Microphone Array



Method follows SAE standard AIR 1672B

For $\boldsymbol{St} < \mathbf{0.4}$ will be dominated by Mach waves



For $\boldsymbol{St} > \mathbf{0.4}$ BBSAN will be present

Analysis Techniques

Far-field Narrowband Spectra indicate presence of BBSAN

1. Dominates angles upstream of $\theta_0 = 90°$
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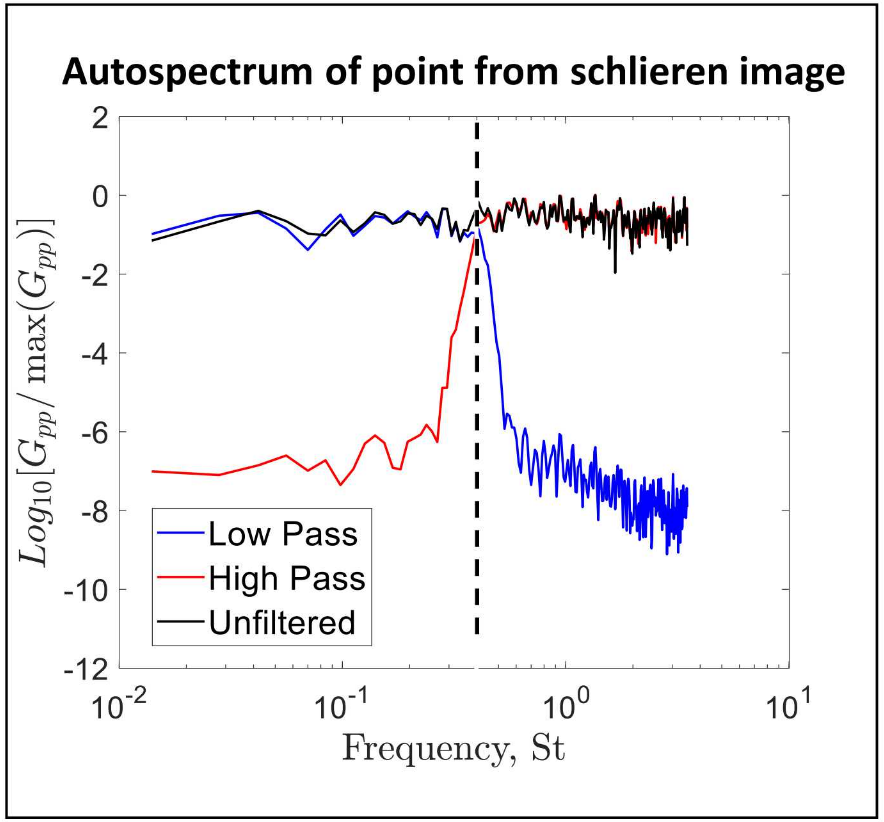
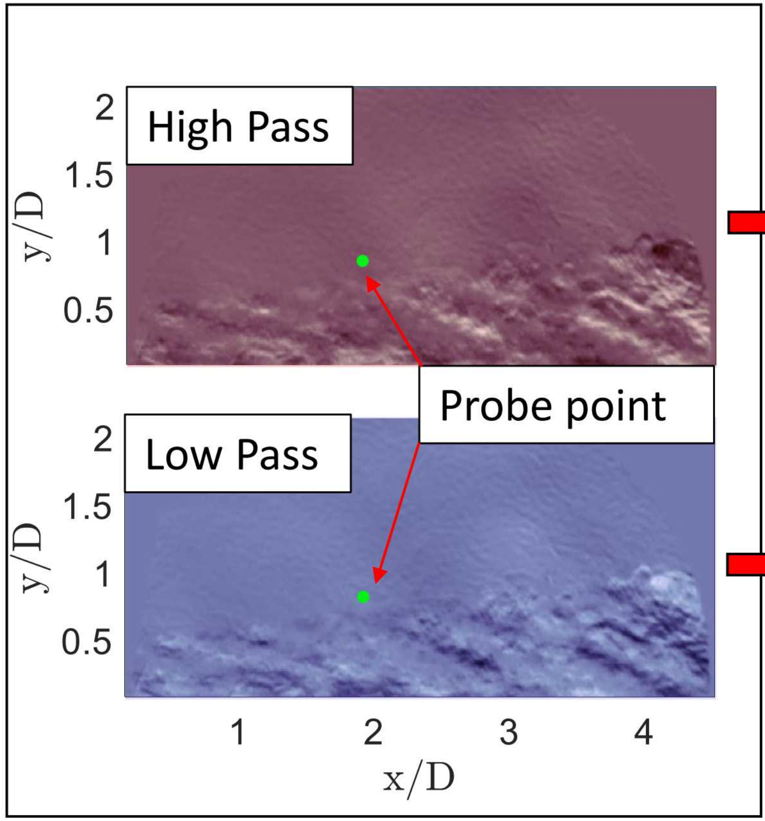
Separate Mach waves and BBSAN by frequency filtering schlieren data

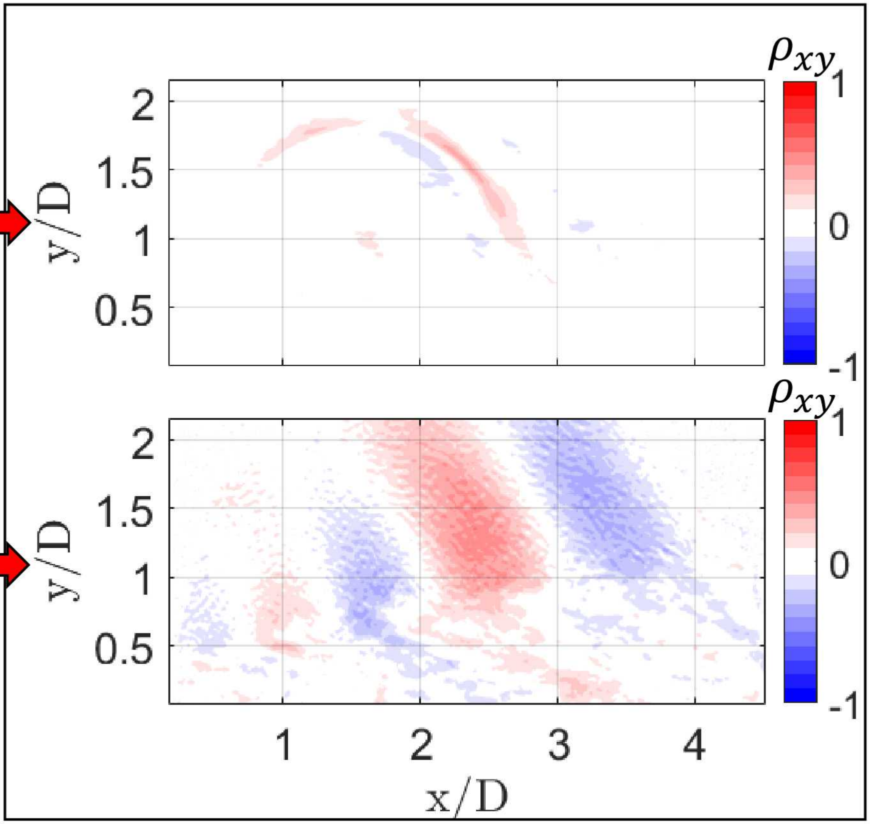
1. Filter Schlieren with cutoff frequency of $St = 0.4$ using FFT filter



2. Perform Space-time correlations on filtered schlieren data



3. Examine differences in filtered space-time correlations



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Filtered Space-time Correlations

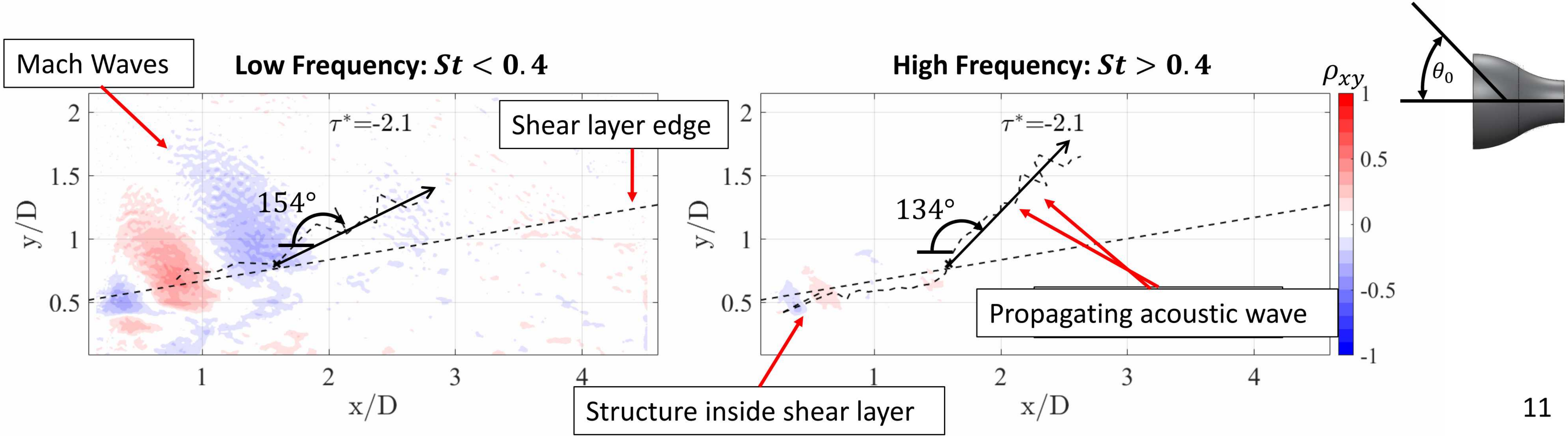
Frequency filtering separates Mach waves and turbulent mixing noise

- Low frequency: Mach waves
- High frequency: turbulence mixing noise
  - Distinct from Mach waves
  - Correlation structure inside shear layer at $\tau^* < 0$
  - Propagating acoustic wave in near-field for $\tau^* > 0$

Structures radiate with different directivities

- Mach waves: $\theta_0 \approx 154°$
- Turbulent mixing noise: $\theta_0 \approx 134°$

Results support observations of Liu et al. 2016
Differences in directivity between Mach wave radiation & L-S mixing noise



Filtered Space-time Correlations

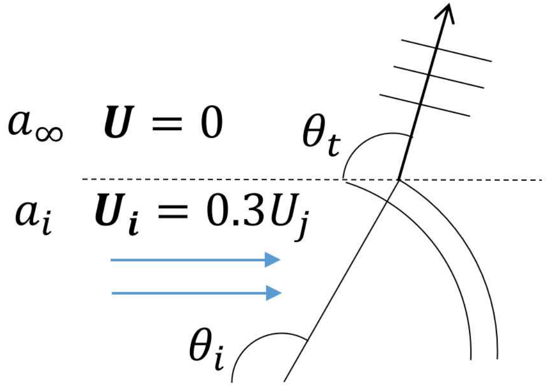
Mach wave directivity:

- Typically in high subsonic/supersonic jets
$$\frac{U_c}{U_j} = 0.7$$
- Estimated Dominate Mach waves at:
$$\Theta_M = \pi - \cos^{-1}(1/M_c) = 160°$$

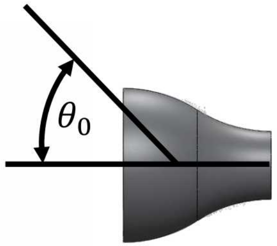
- Estimated directivity roughly agrees with observed
- Note: Θ_M increases with U_j (moves upstream)

L-S Turbulence Directivity:

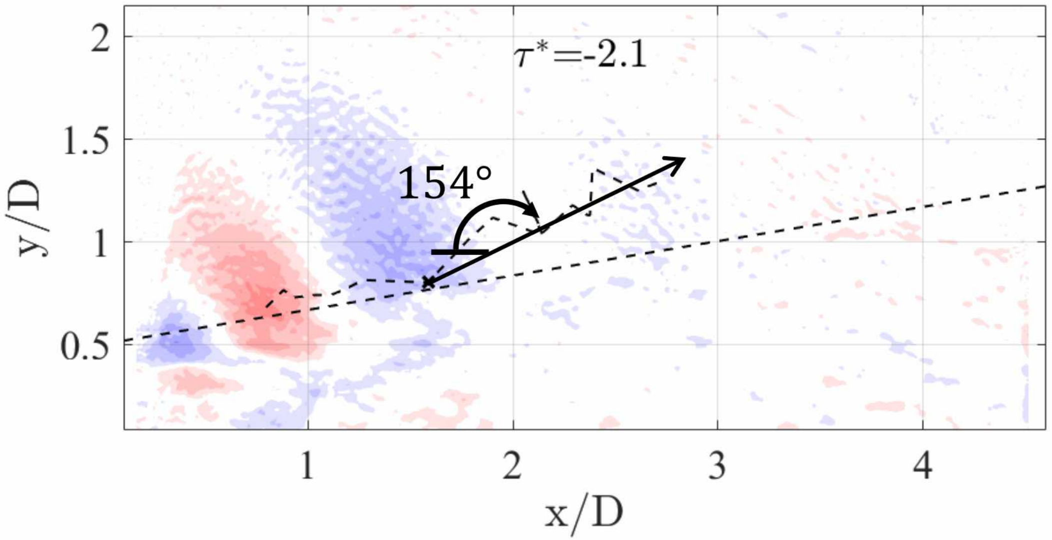
- Structure in shear layer may represent acoustic waves
- Shear layer will refract waves
- Estimate transmission angle using:
$$\cos\theta_t = \frac{a_\infty}{\frac{a_i}{\cos\theta_t} - U_i} \rightarrow \theta_t = 126°$$



- Suggests structure inside shear layer represents acoustic wave
- Emphasizes directivity difference in Mach waves & turbulent mixing noise



Low Frequency: $St < 0.4$



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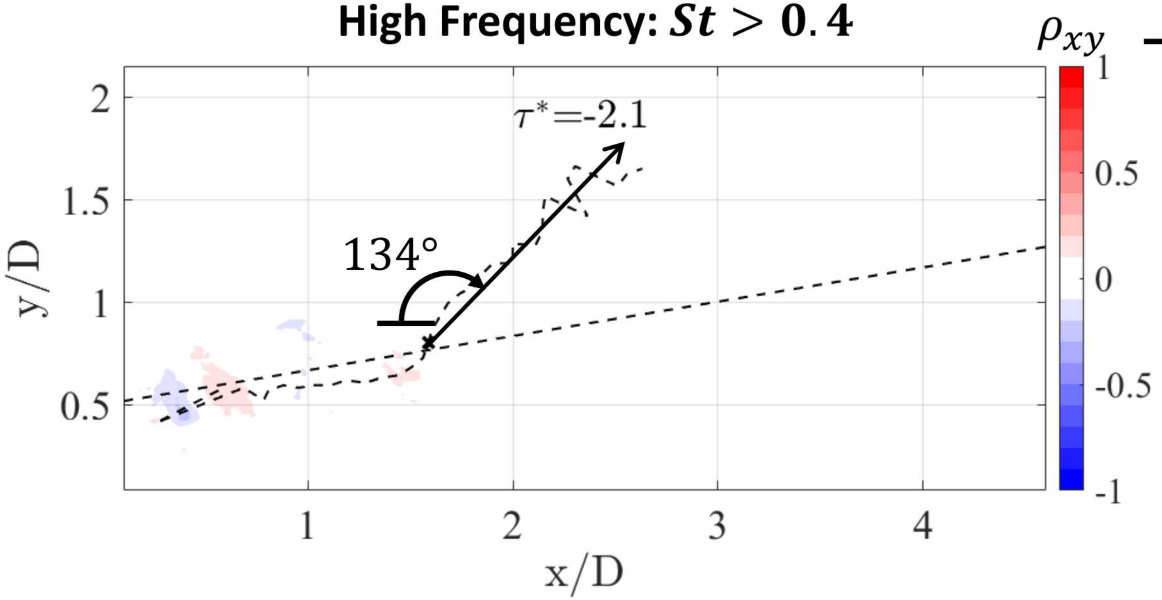

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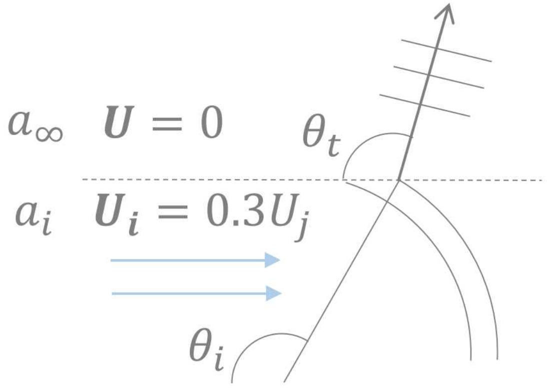

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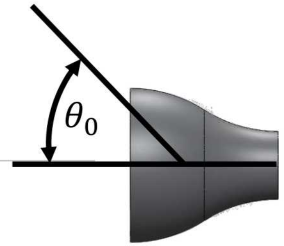
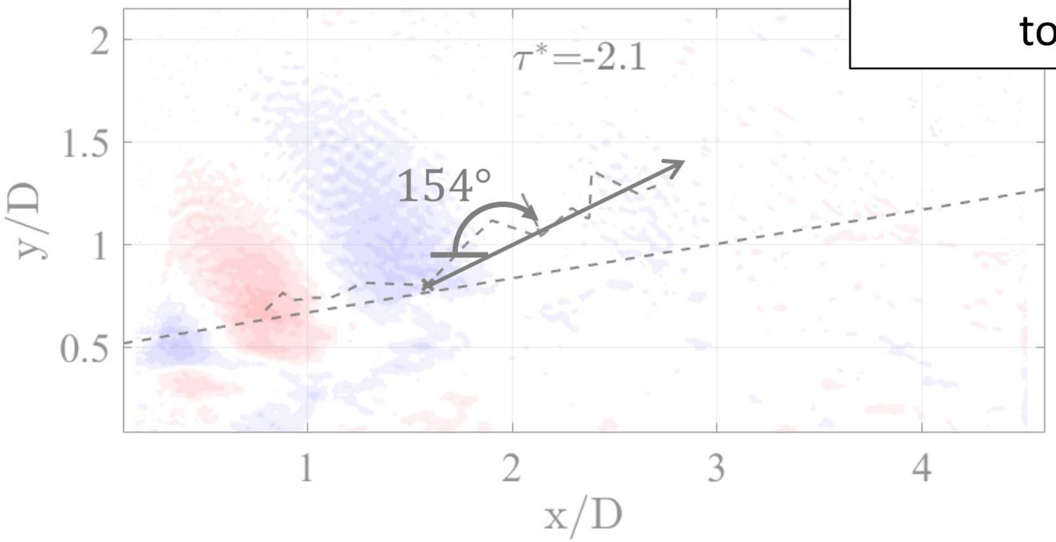
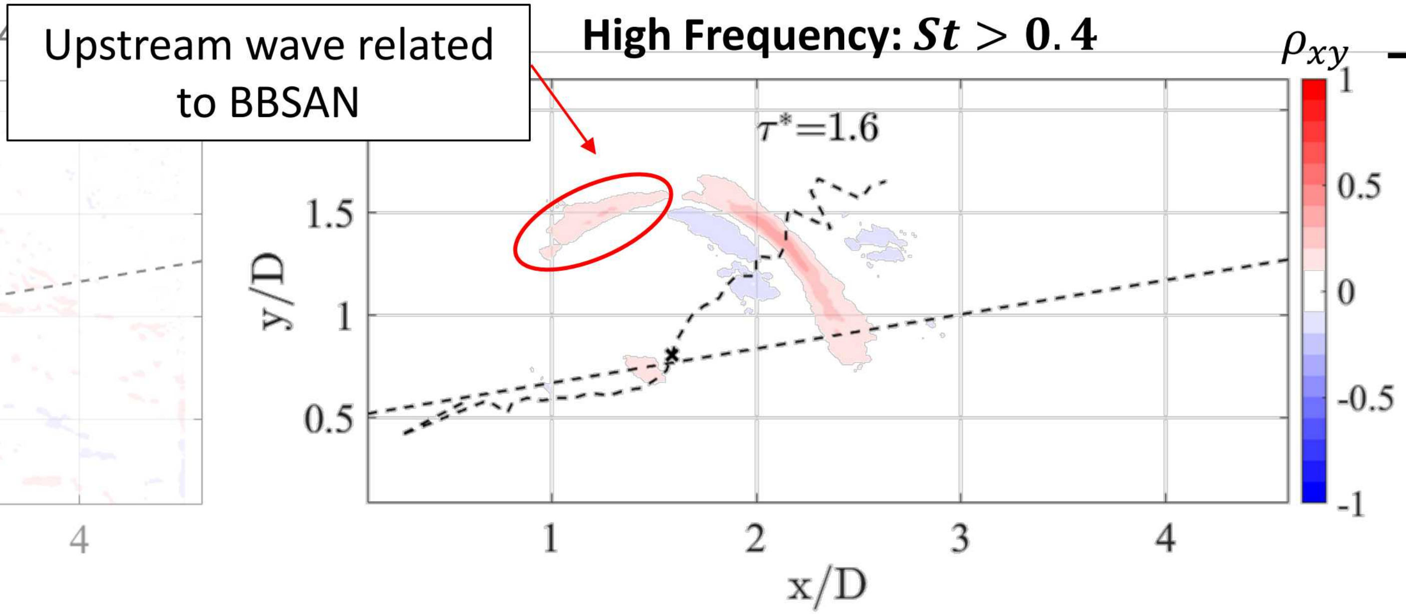


Low Frequency: $St < 0.4$



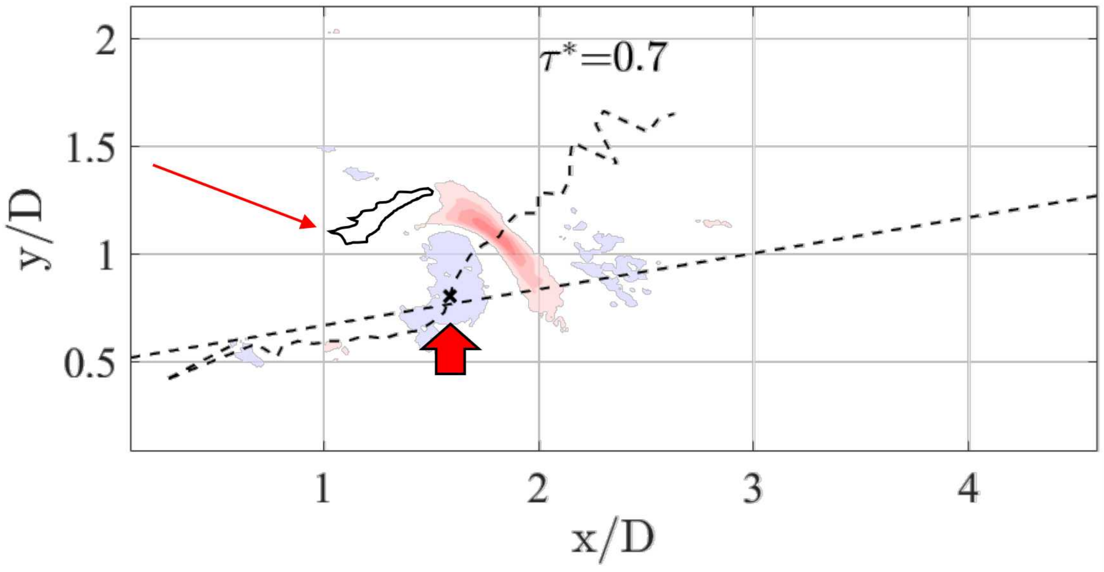
High Frequency: $St > 0.4$

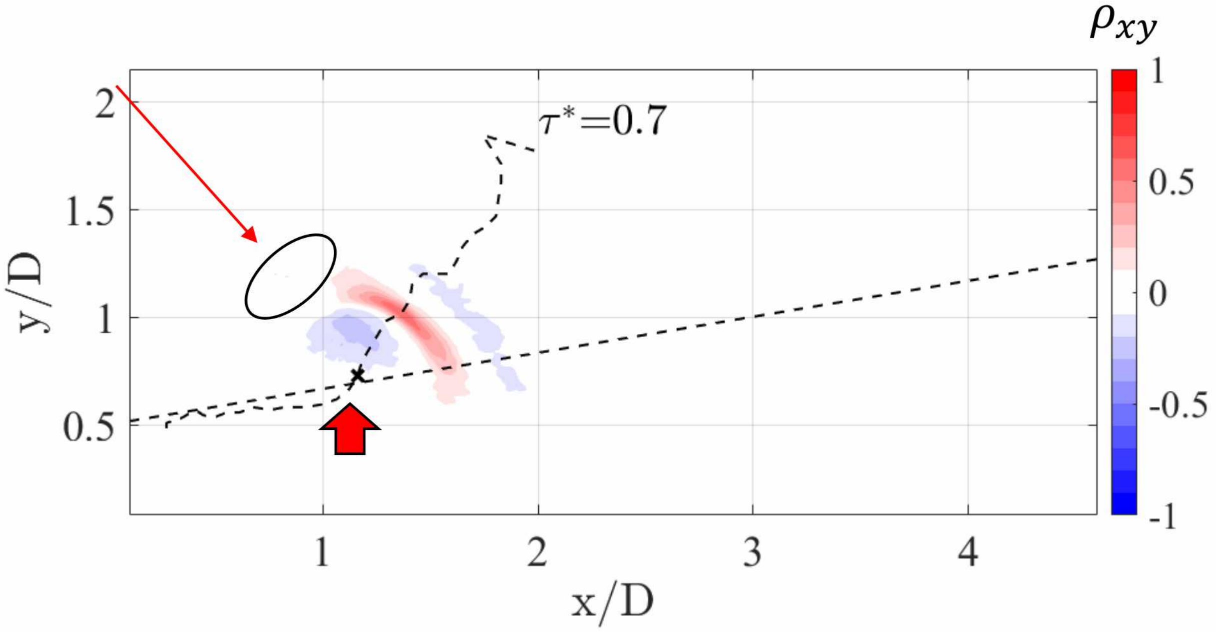


High-pass Correlations

Correlation captures upstream propagating structure
- Upstream wave likely represents BBSAN

Are upstream correlation structure sensitive to axial probe location ?
- Move probe point upstream by ~0.5D





Correlation strength of upstream wave dependent on probe location

Strength of upstream structure dependent on relative location to shock cell

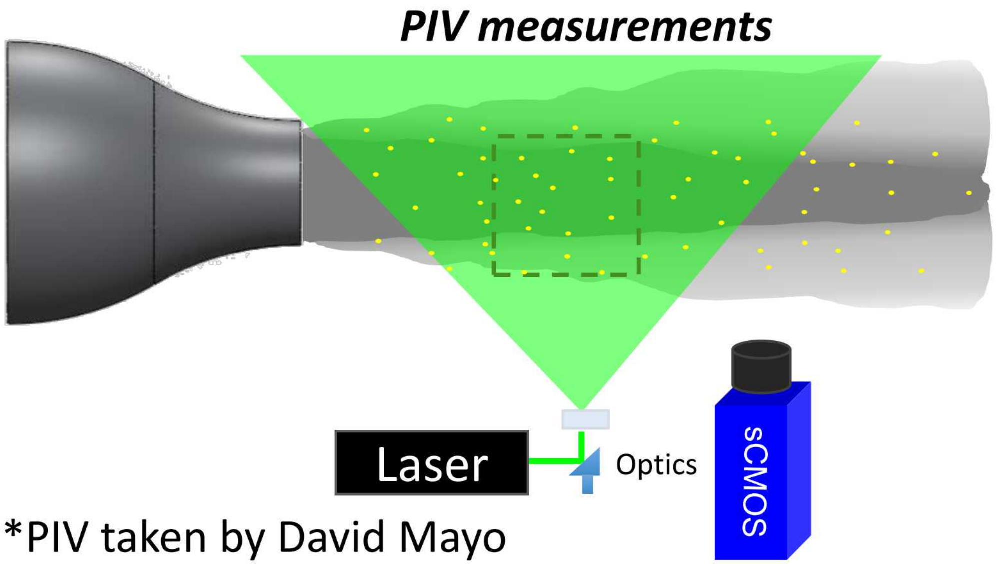
Probe Point Selection

Choose probe points with locations relative to shock cells

Use PIV to determine location of shock cells

Probe points that are:

- Points directly above shock tip (P1, P4)
- Points in between shock tips (P3, P6)
- Points just downstream of shock tips (P2, P5)

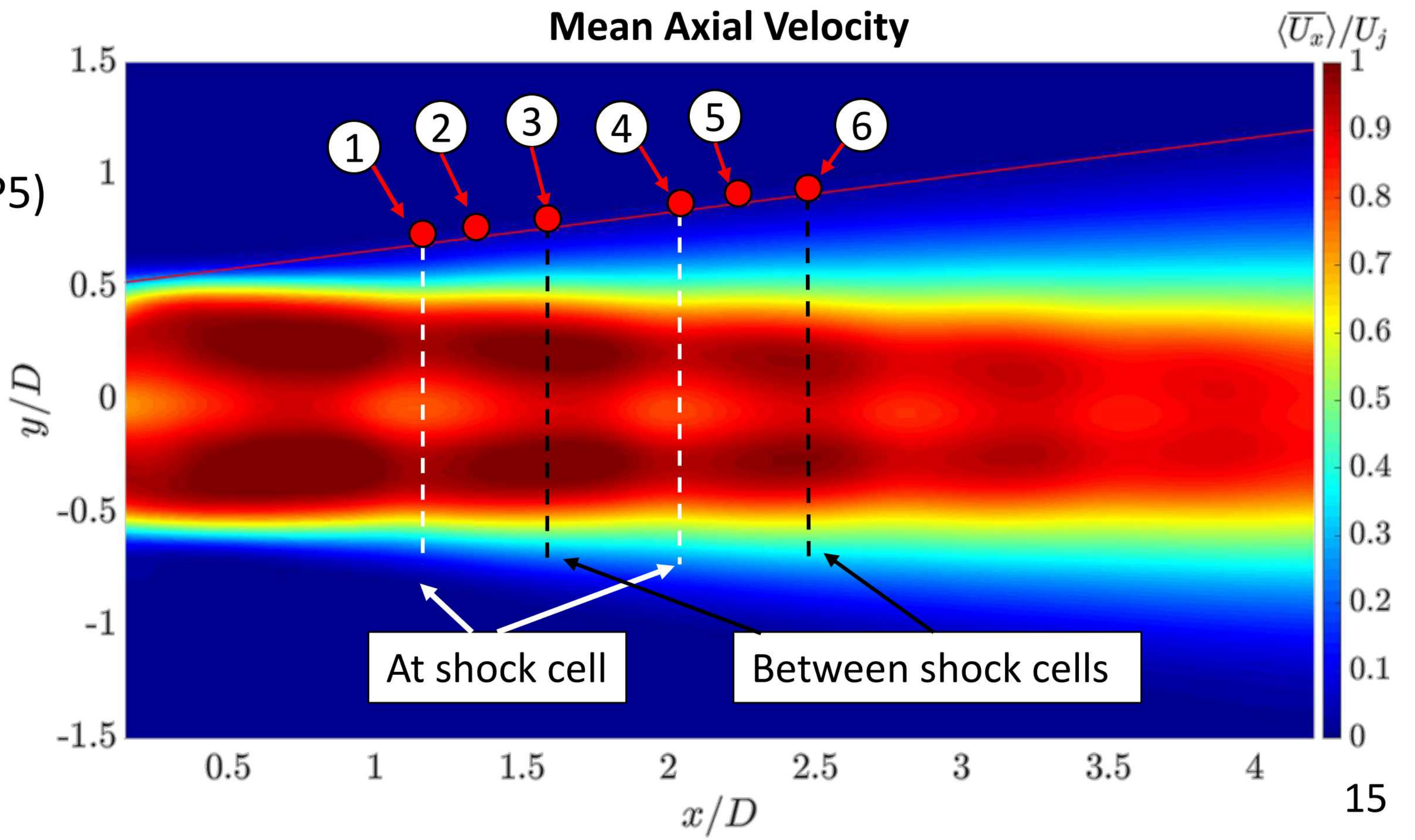


*PIV taken by David Mayo

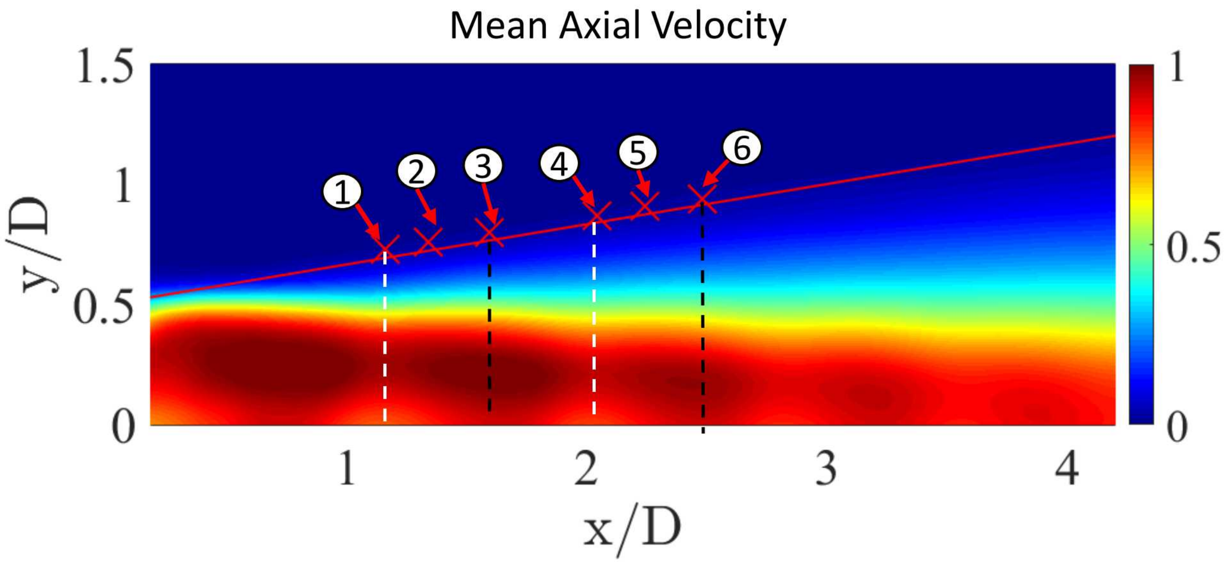
1. Take probe point coordinates in PIV

2. Space-time correlations of schlieren with same probe points locations

Probe points **just upstream** of shock cells will have stronger BBSAN signature.



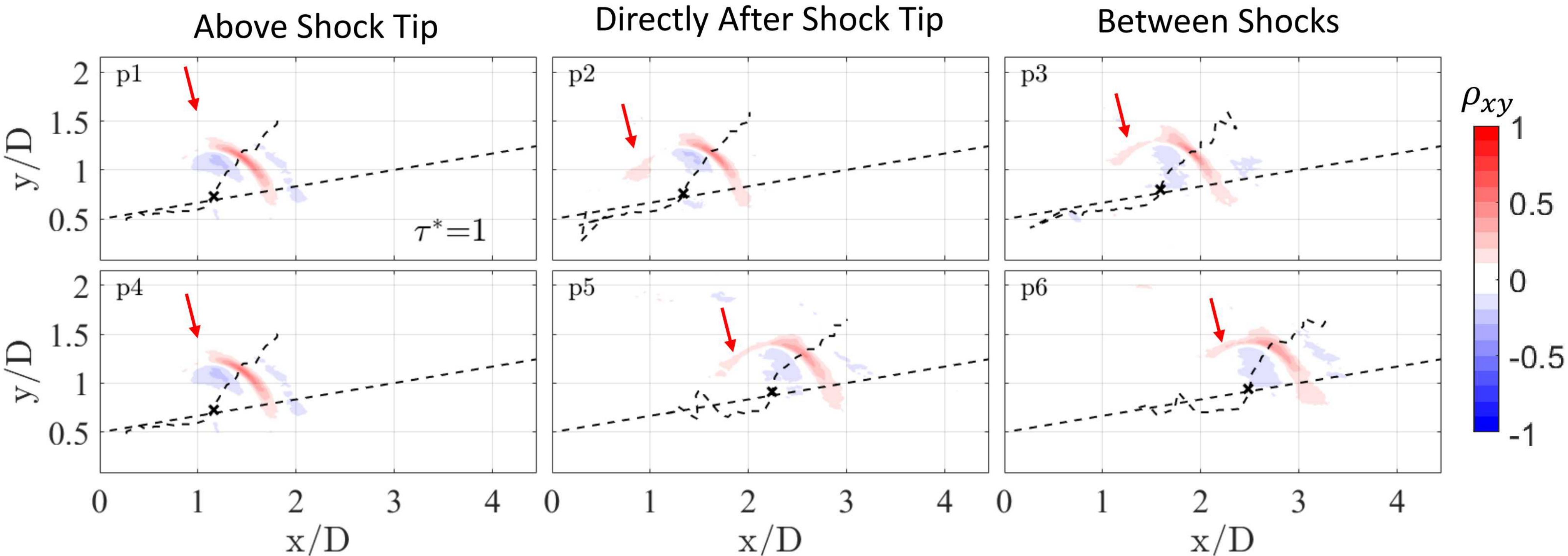
Variation in BBSAN Strength



Strength of upstream structure dependent on relative location or probe point to shock structure

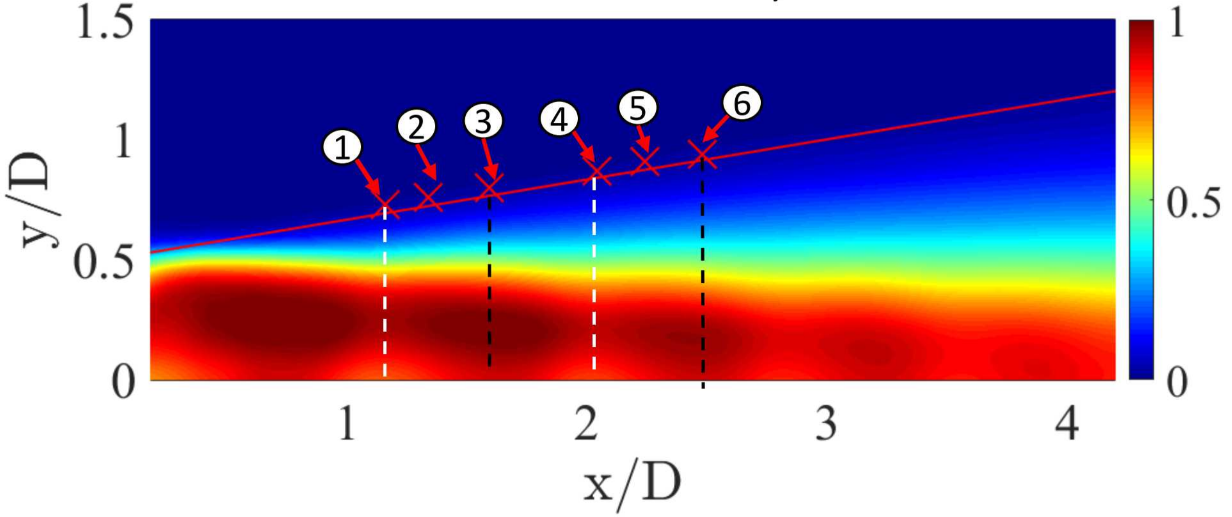
Probe points directly **above** shock cell
⬇
Weak upstream correlation

Probe points **downstream** shock cell
⬇
Stronger upstream correlation



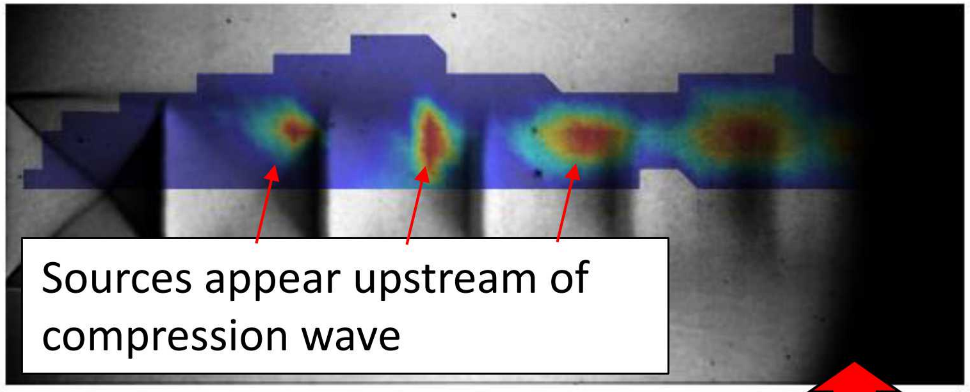
Variation in BBSAN Strength

Mean Axial Velocity



$$\alpha_{u,p} = \int_{\Omega} \gamma_{u,p}^2 \, d\Omega$$

Where Ω represents boundaries in x_{mic}, St

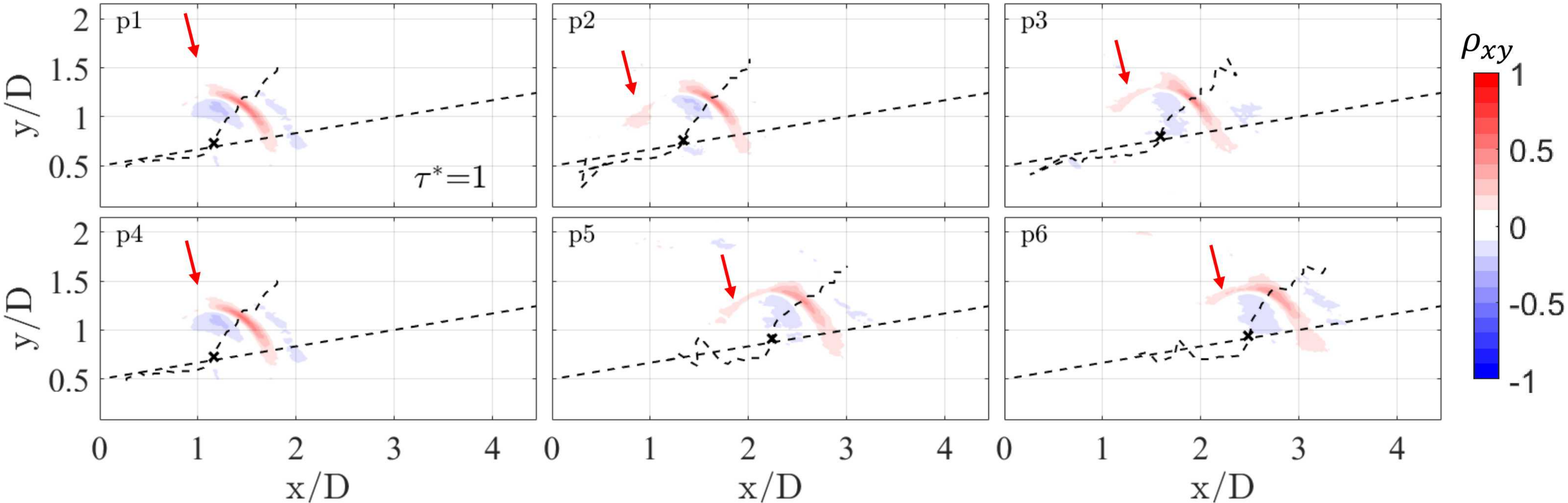


(a) $\alpha_{u,p}$ map

Results similar to 'source maps' from **Savarese et al. 2013**

Above Shock Tip

Directly After Shock Tip



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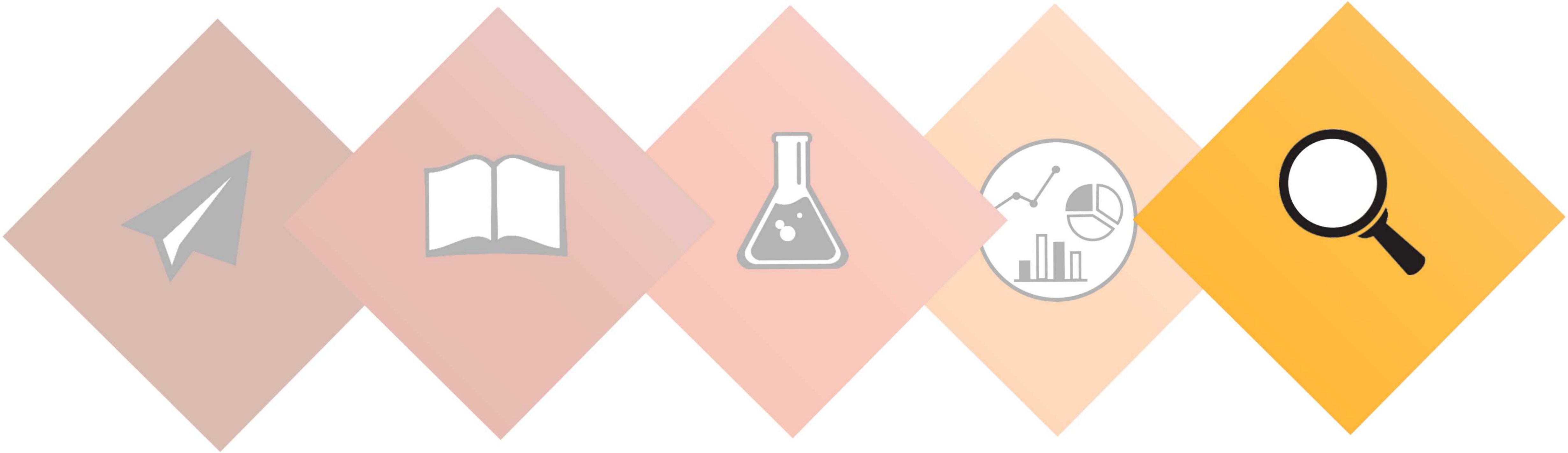

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Future Work

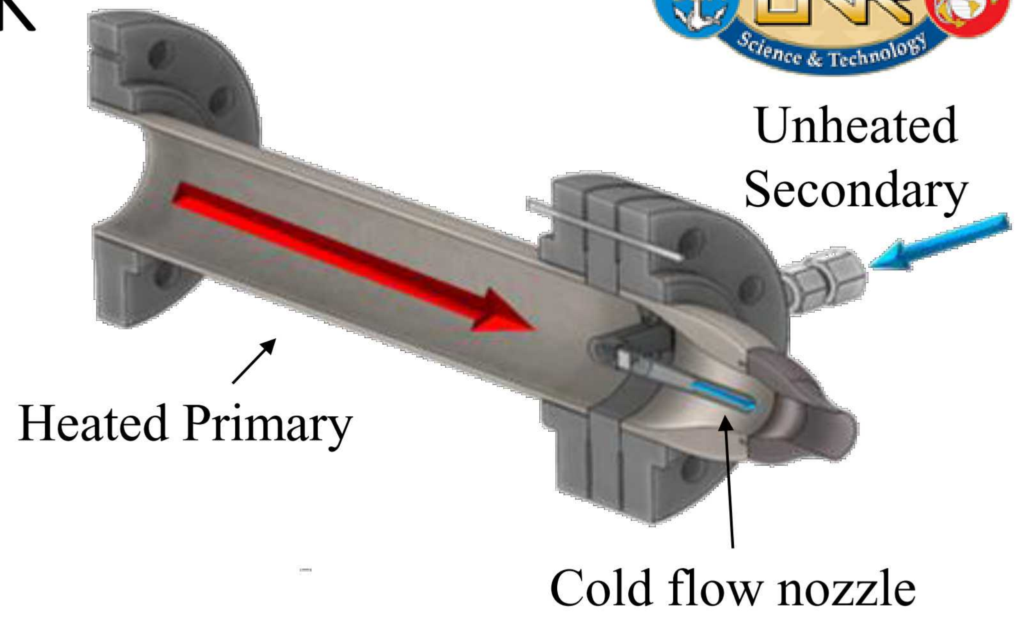
Space time correlations of over-expanded jets with **thermal non-uniformity**

Open Questions:

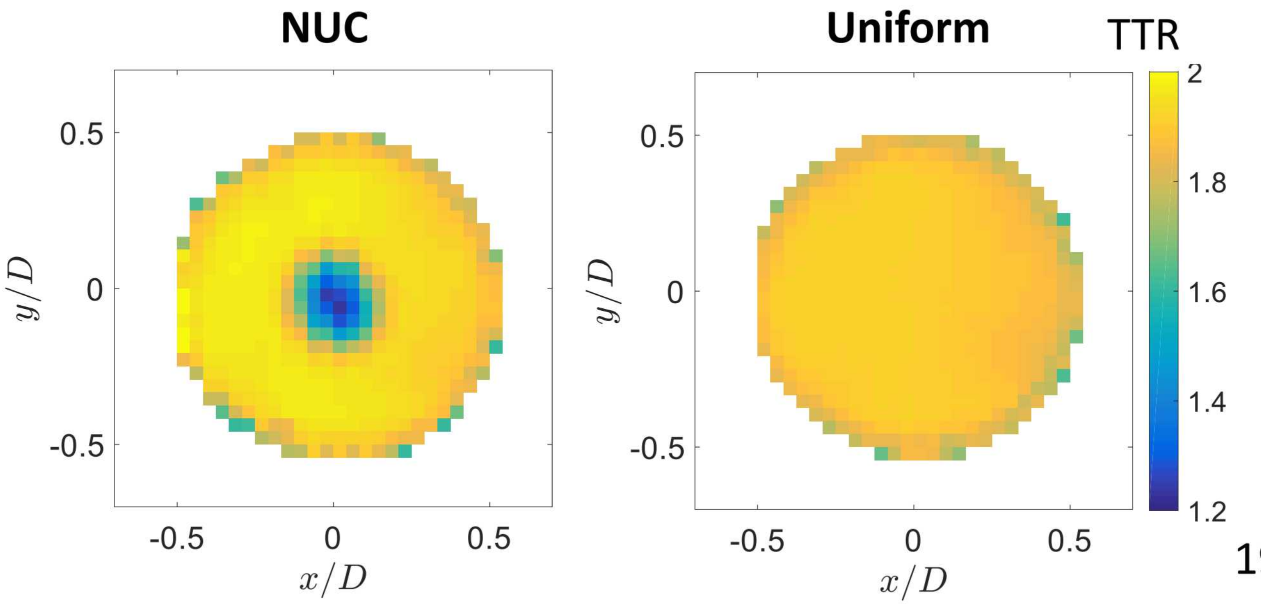
- How does NUC driven perturbations impact BBSAN?
- At what axial location do perturbations mix out?

Other Work

- Additional insight from PIV



T_0 survey of nozzle exit



Conclusion

- **Frequency filtered space-time correlations indicate distinct features**
  - Mach waves dominating **low** frequencies
  - BBSAN and turbulent mixing noise at **high** frequencies

- **Measured difference in Mach wave & turbulent mixing directivity**
  - Mach waves radiate close to angles predicted with u_c
  - Peak angle of turbulent mixing noise similar to angle predicted by shear layer refraction

- **Strength of BBSAN emission dependent on location relative to shock cell**
  - Stronger upstream correlation structures observed with probe points directly downstream of shock cells