Perry Fest 2004
Queen's University, Kingston

Dominant spanwise Fourier modes in the log and wake regions of the turbulent boundary layer

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Department of Aerospace Engineering and Mechanics
University of Minnesota

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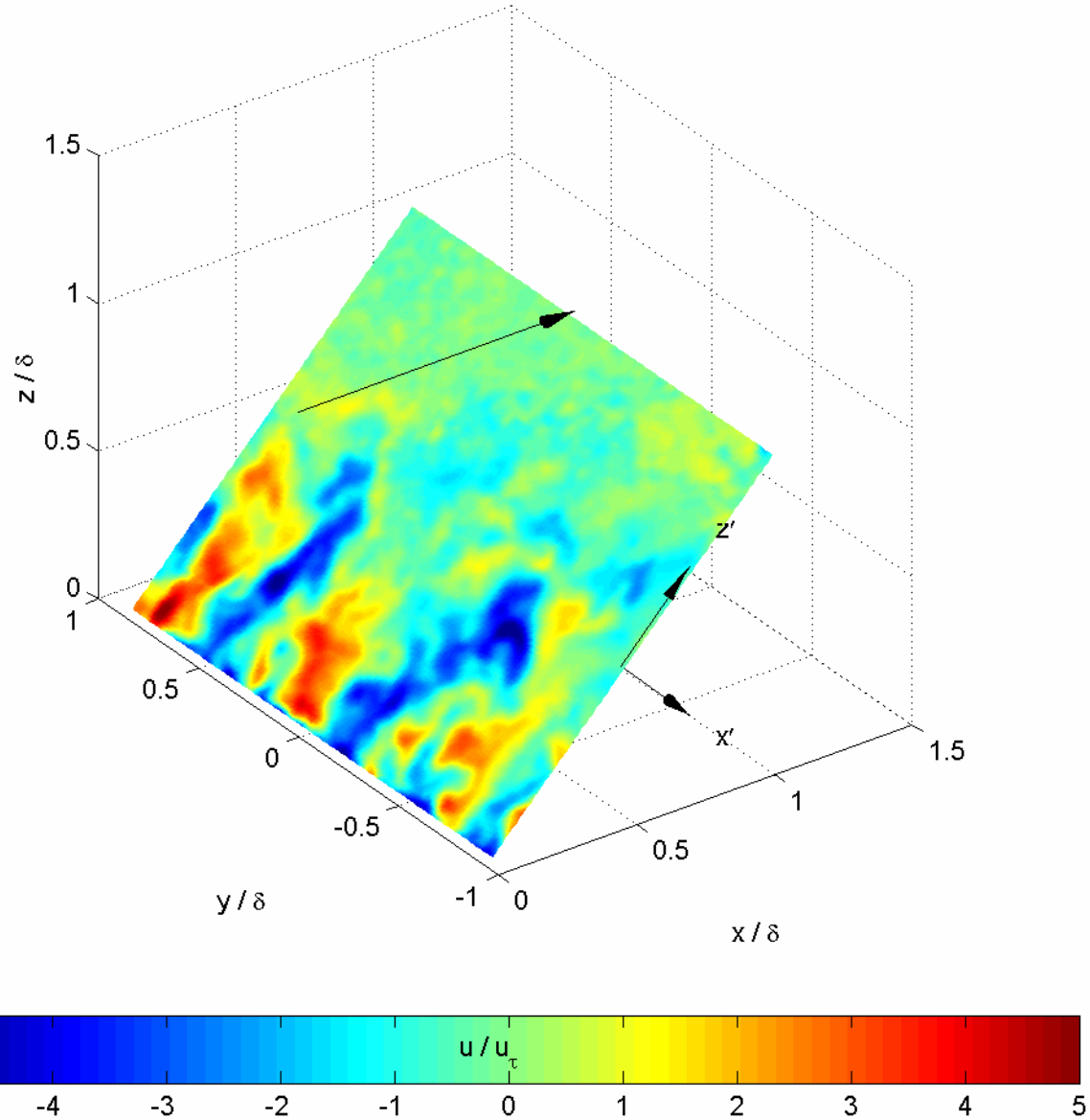
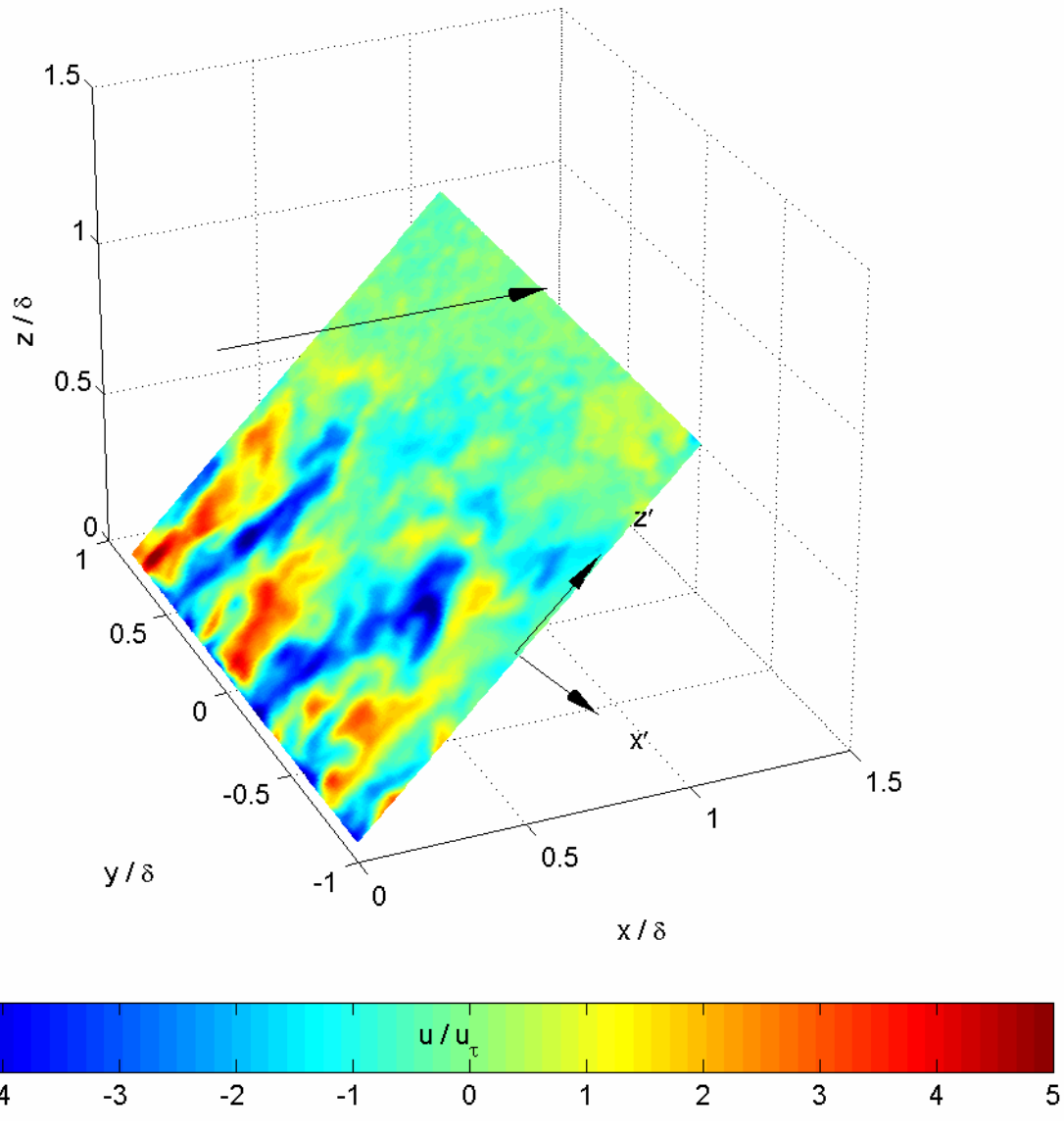
David and Lucile Packard Foundation

45° inclined plane – axis system



45° inclined plane – axis system



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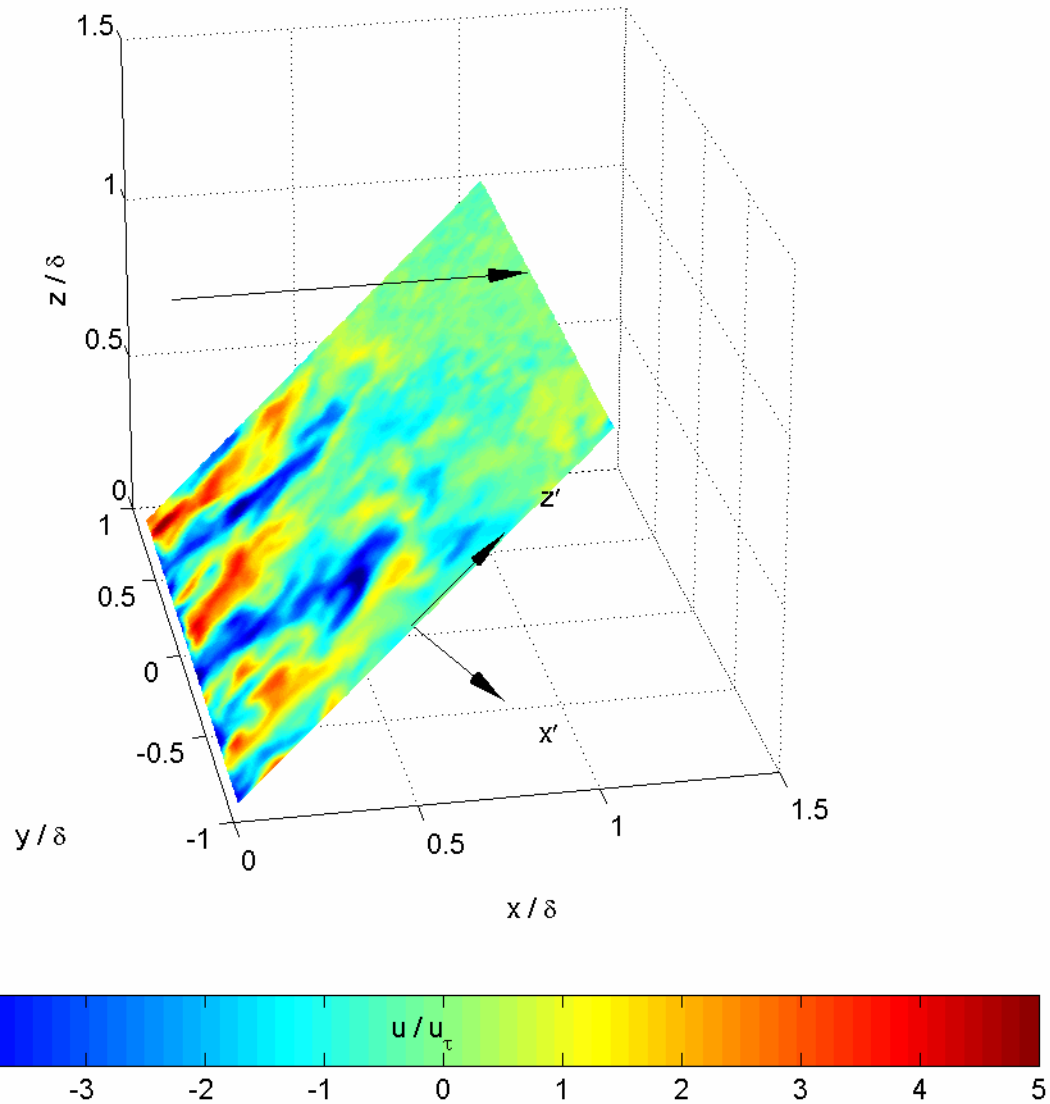
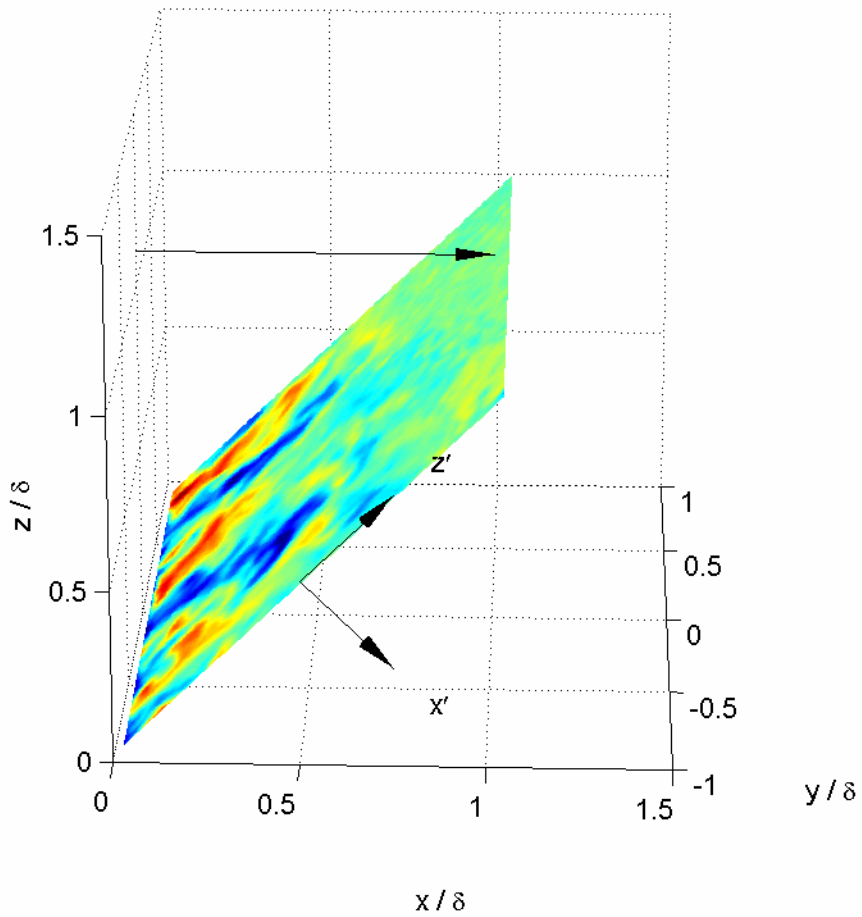
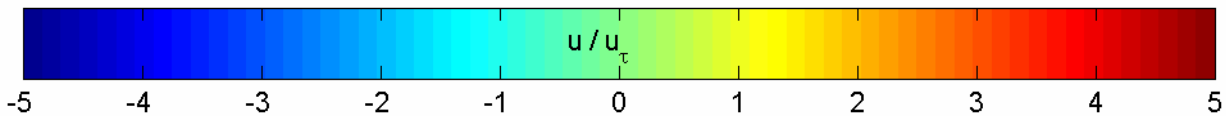


45° inclined plane – axis system





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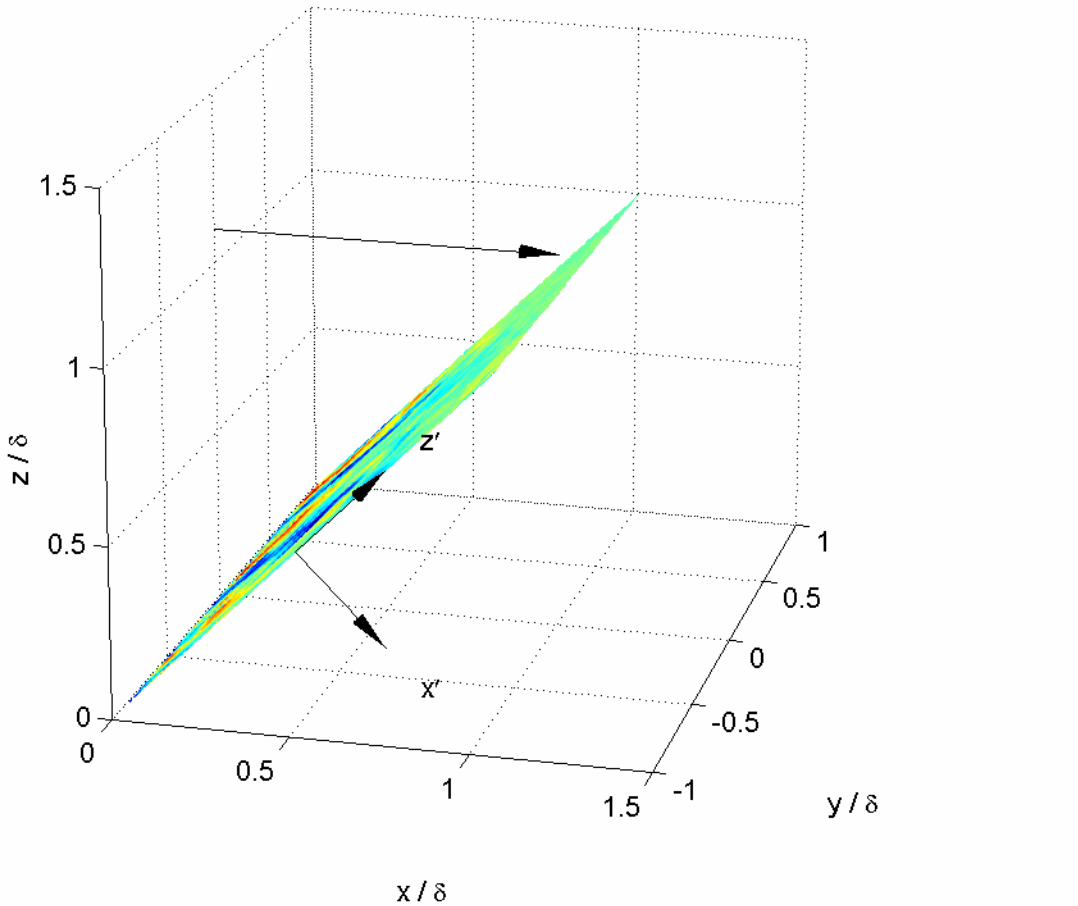

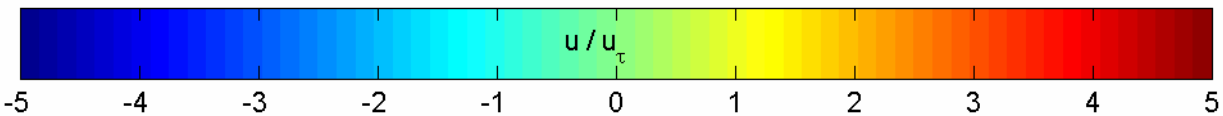

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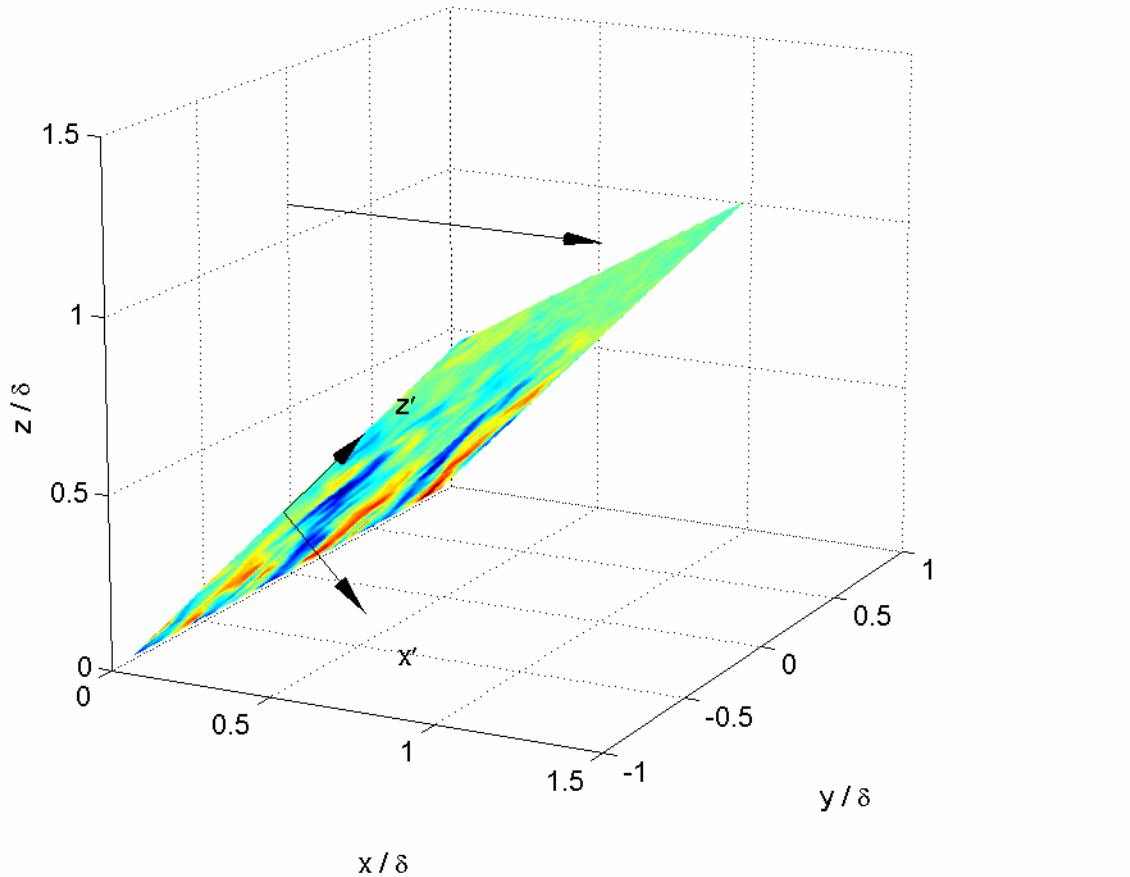
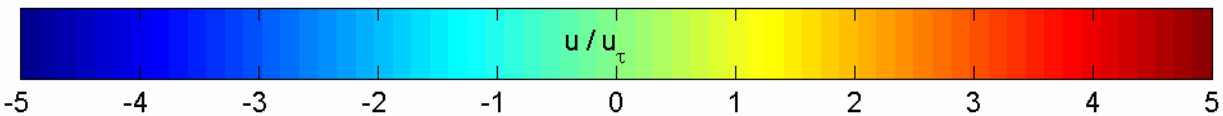
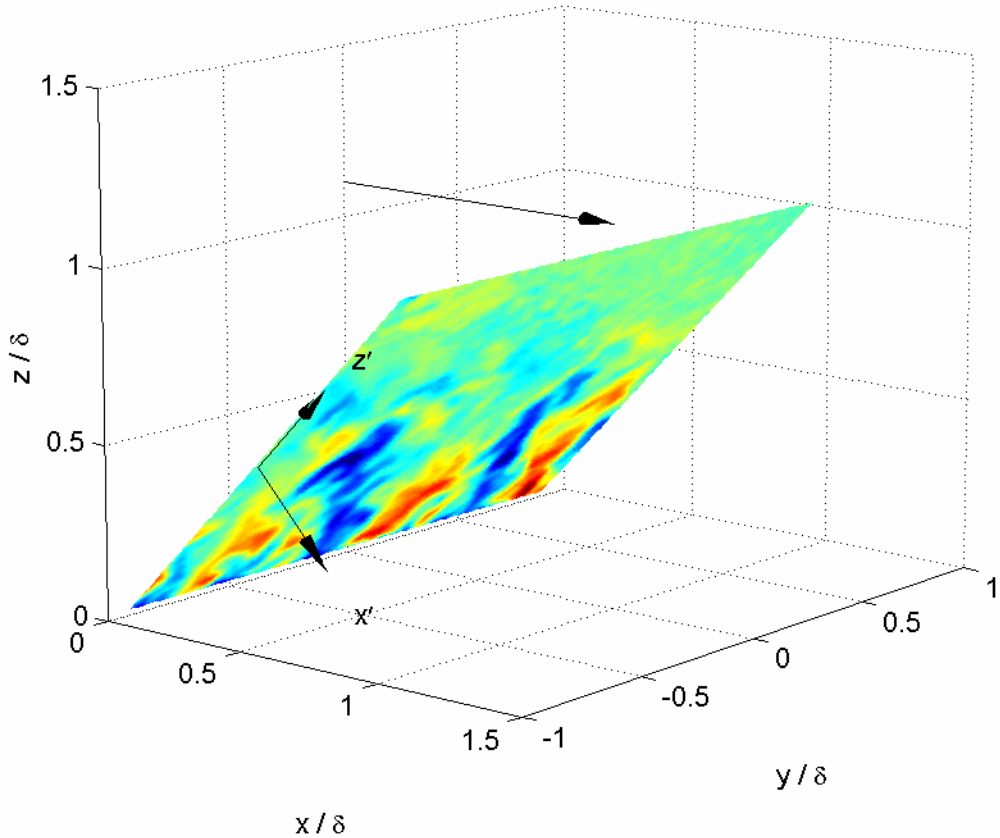
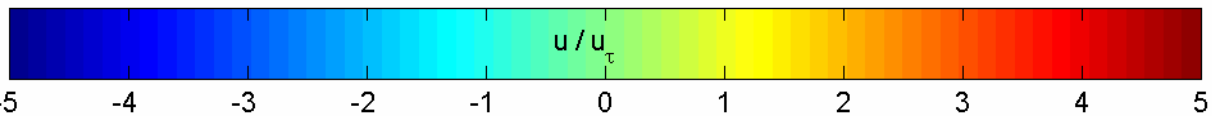




45° inclined plane – axis system





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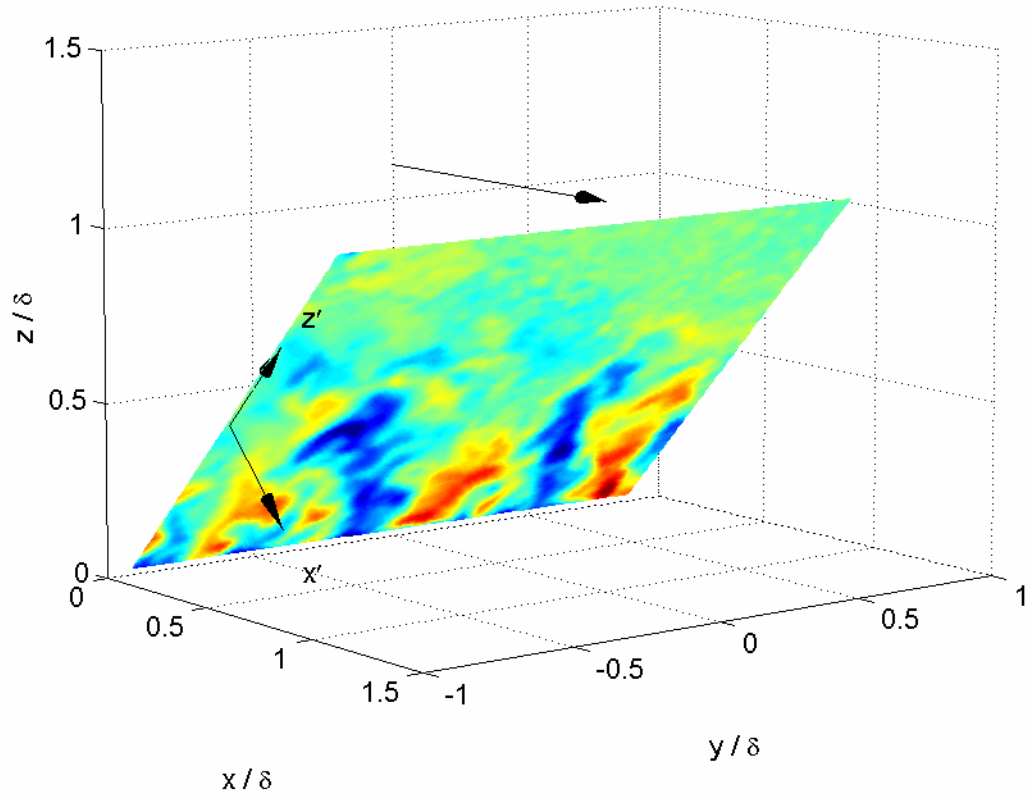

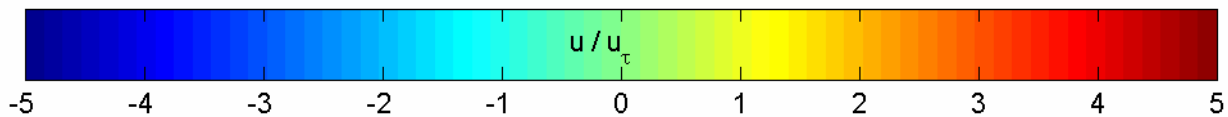

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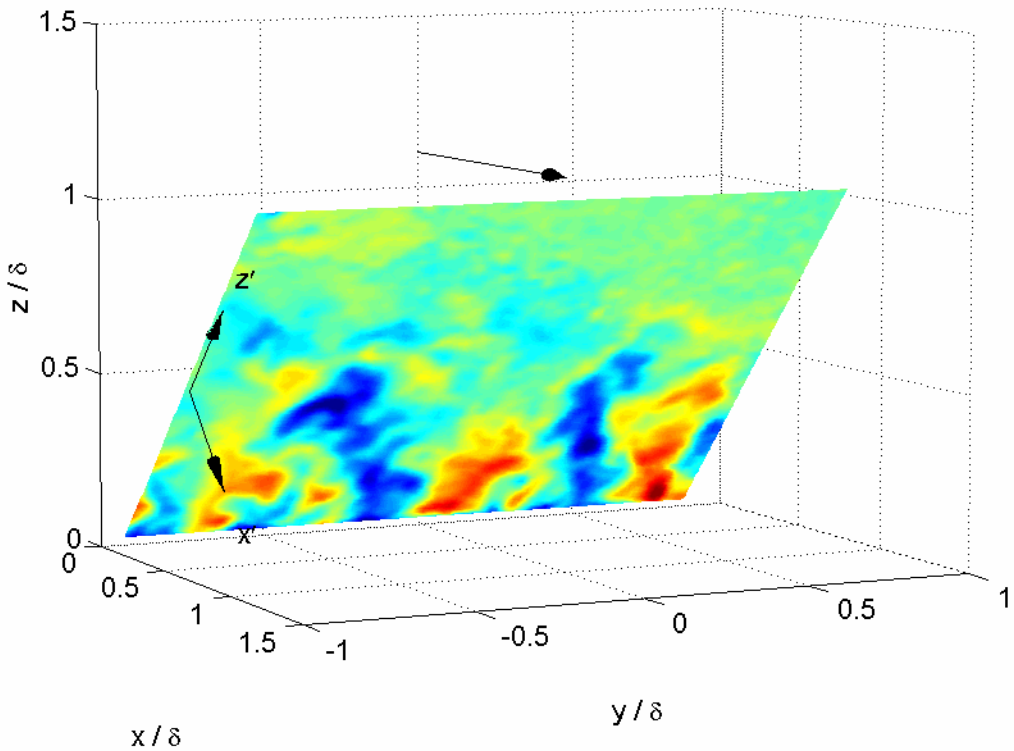

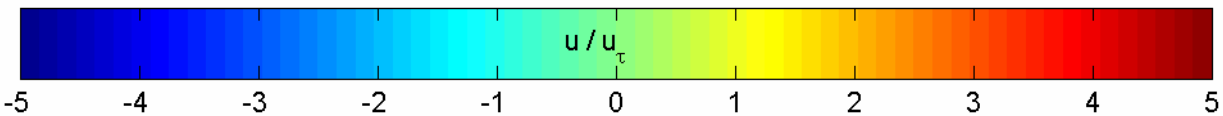

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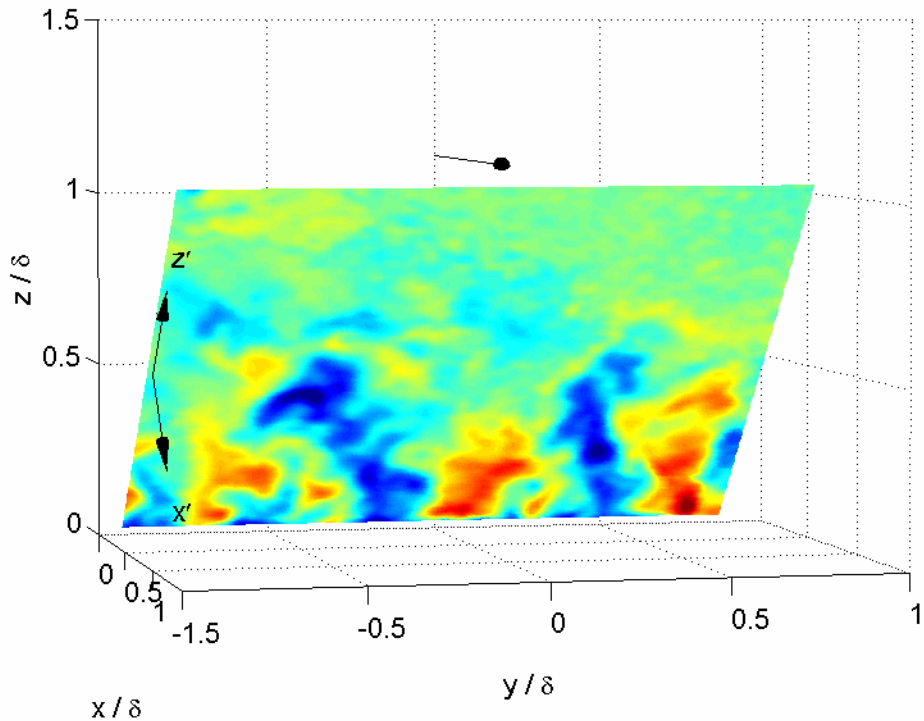
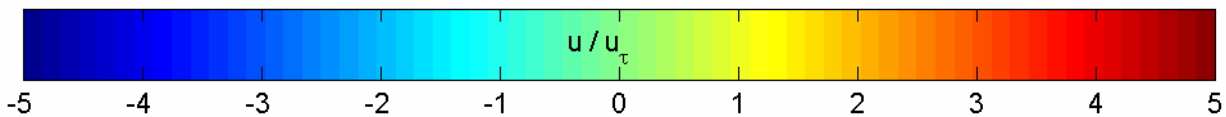
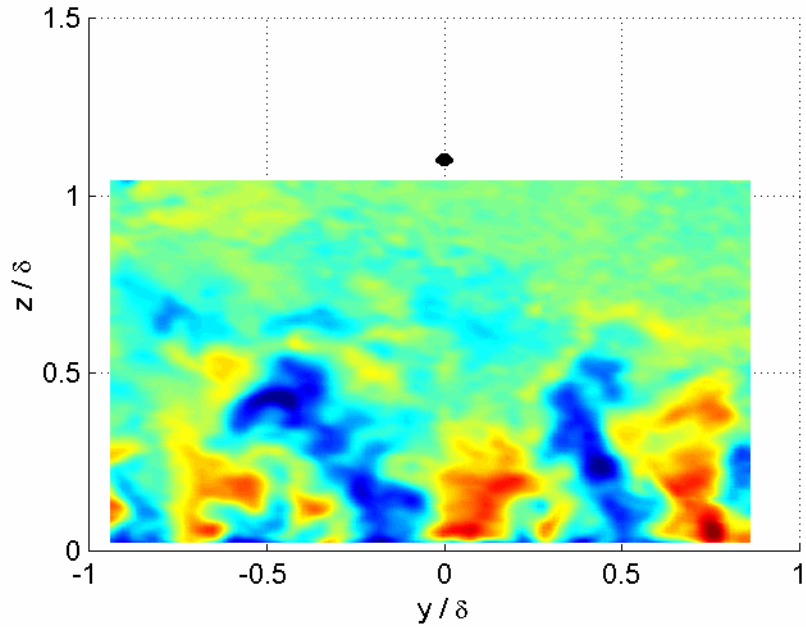
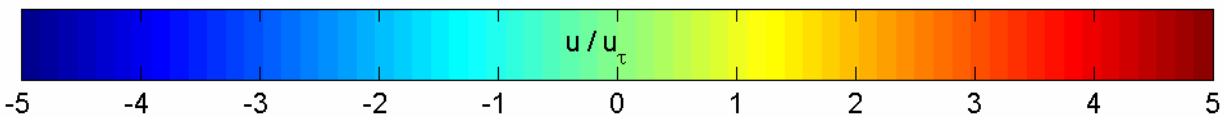


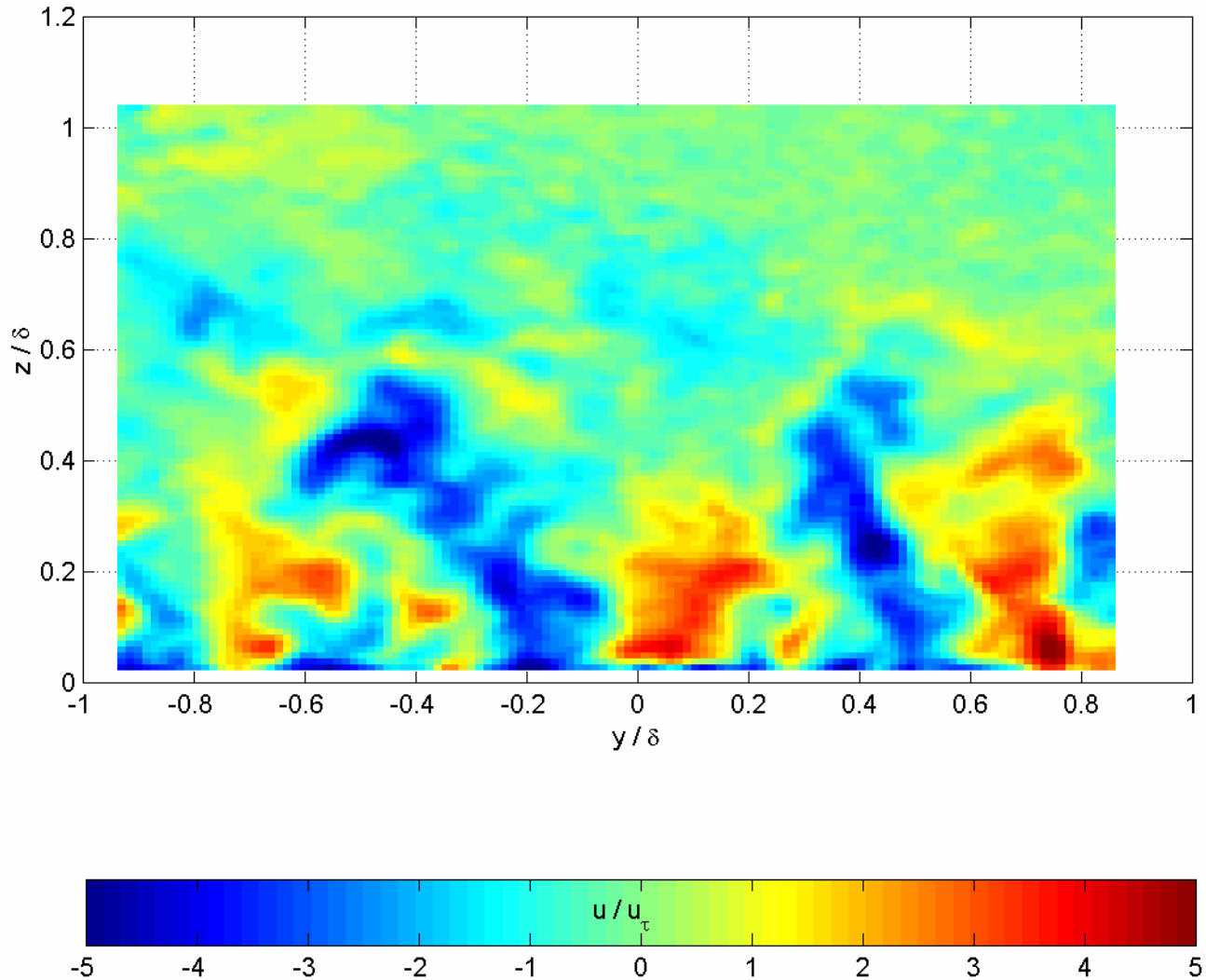


45° inclined plane – axis system

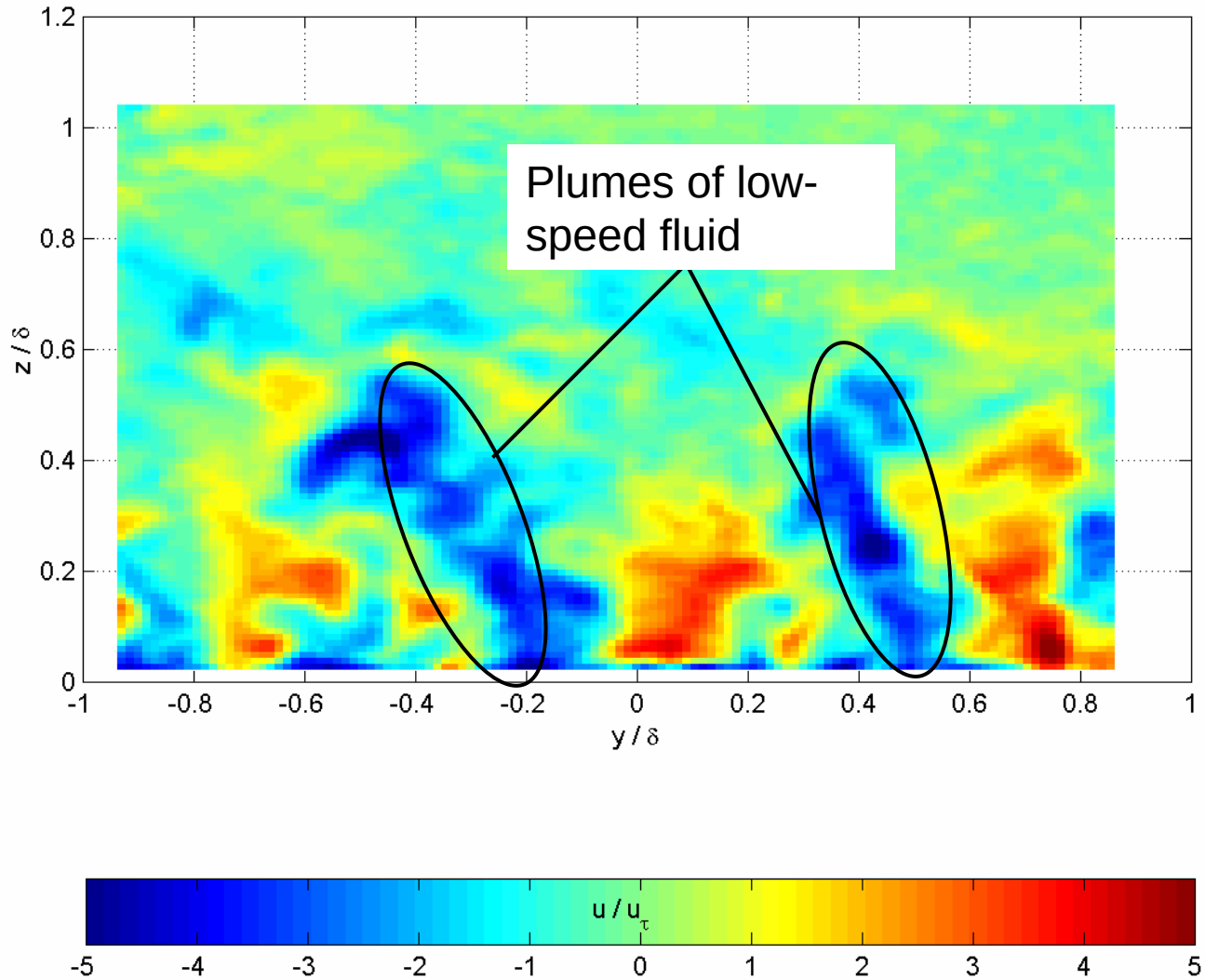




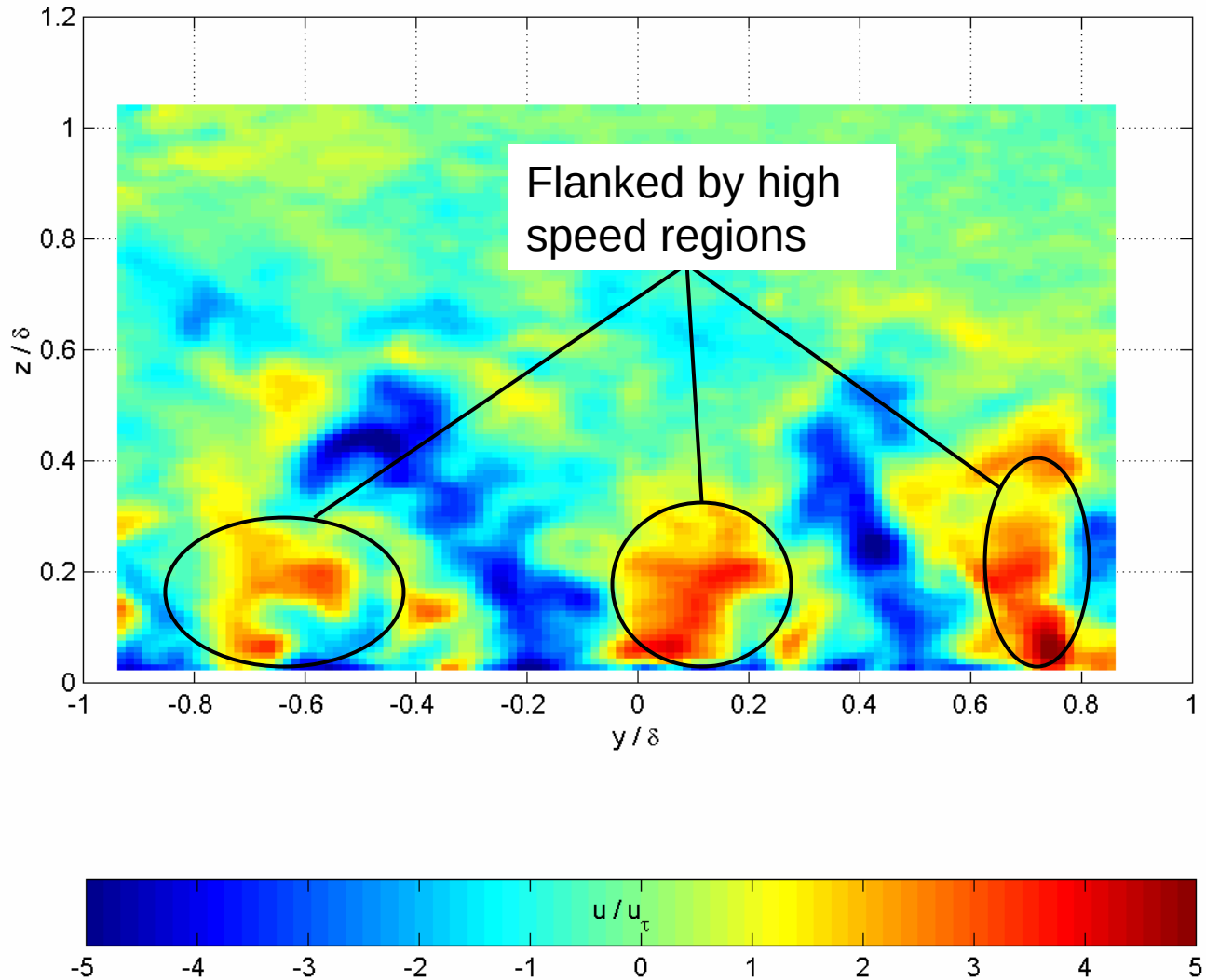
45° inclined plane – typical flow features



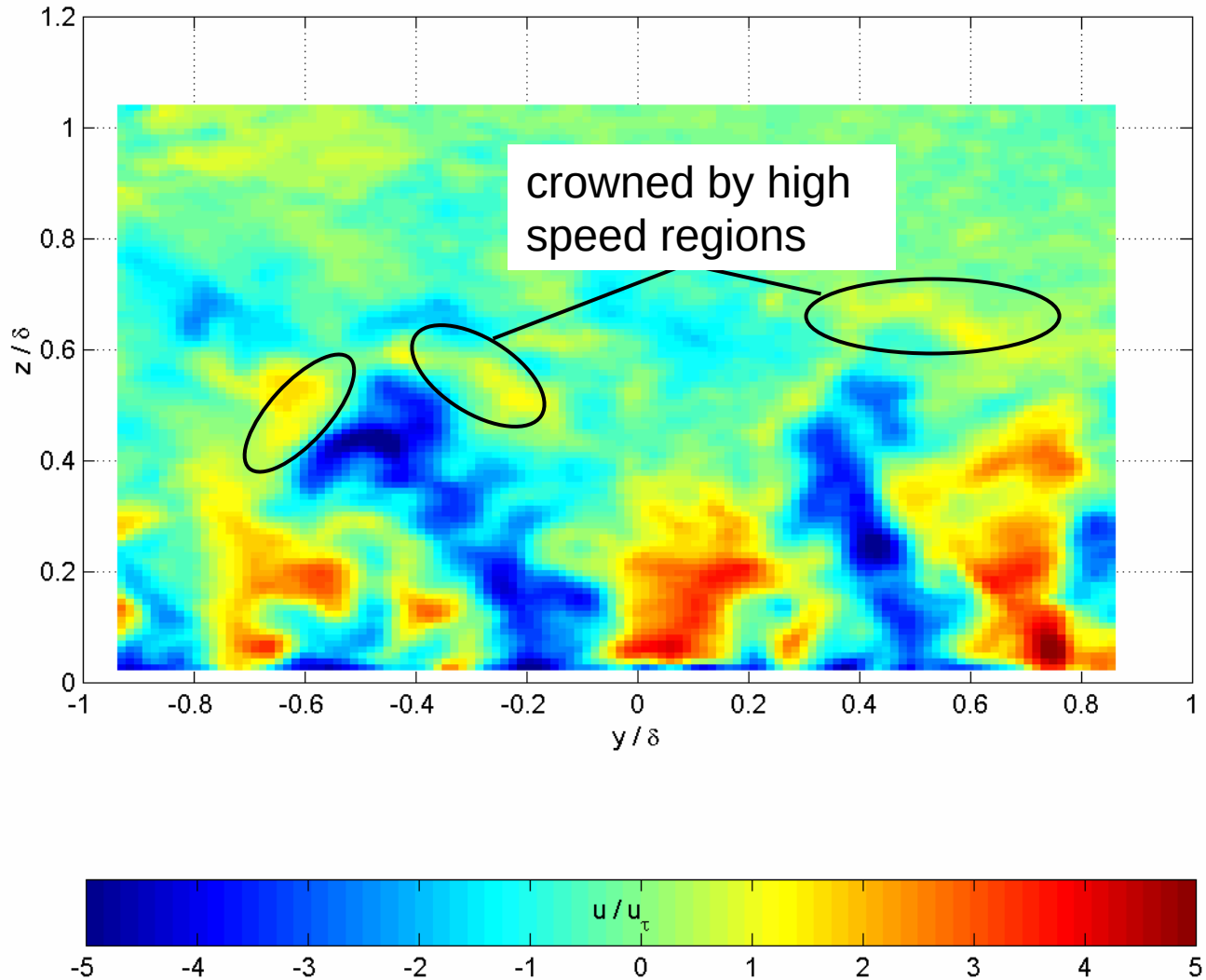
45° inclined plane – typical flow features



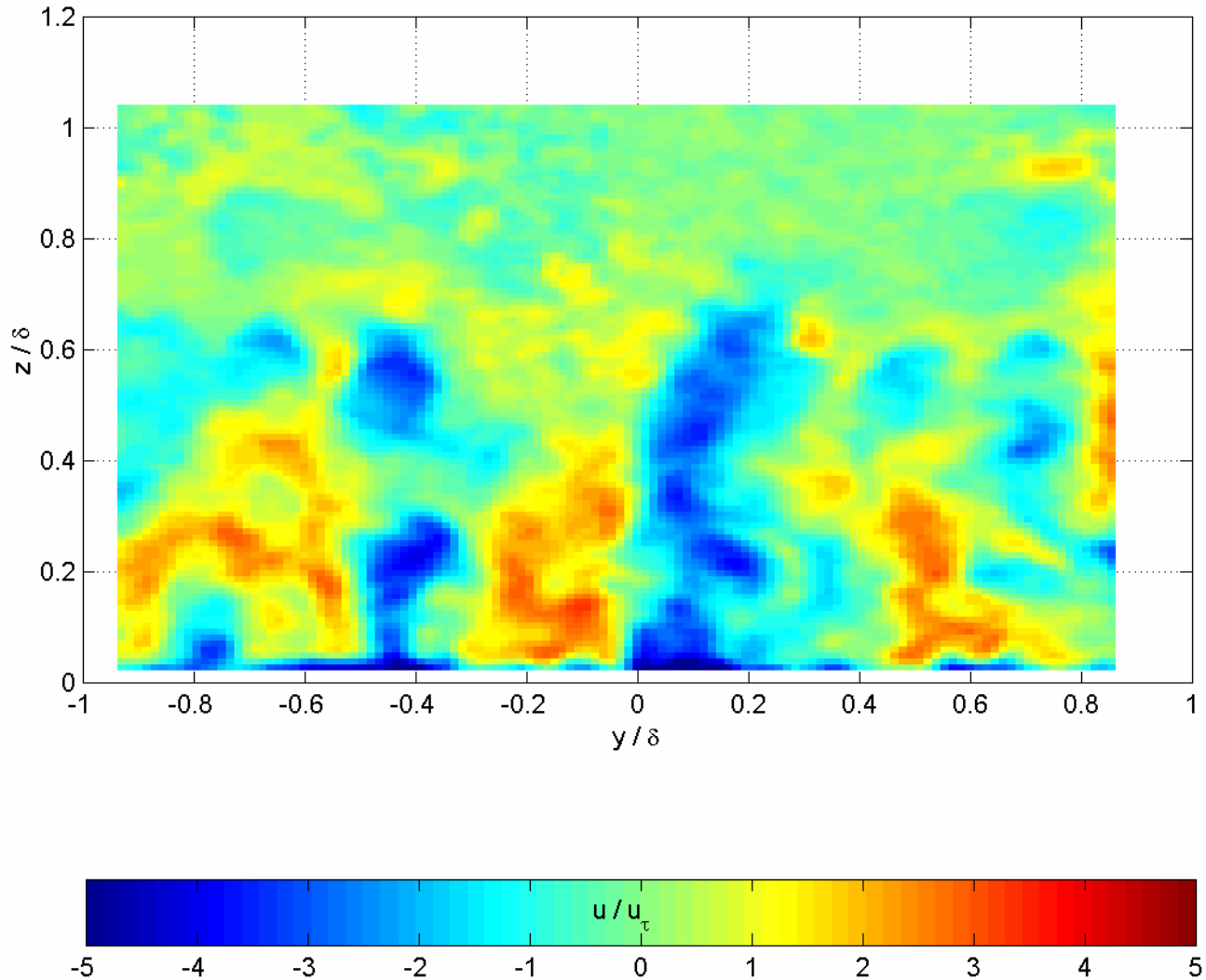
45° inclined plane – typical flow features



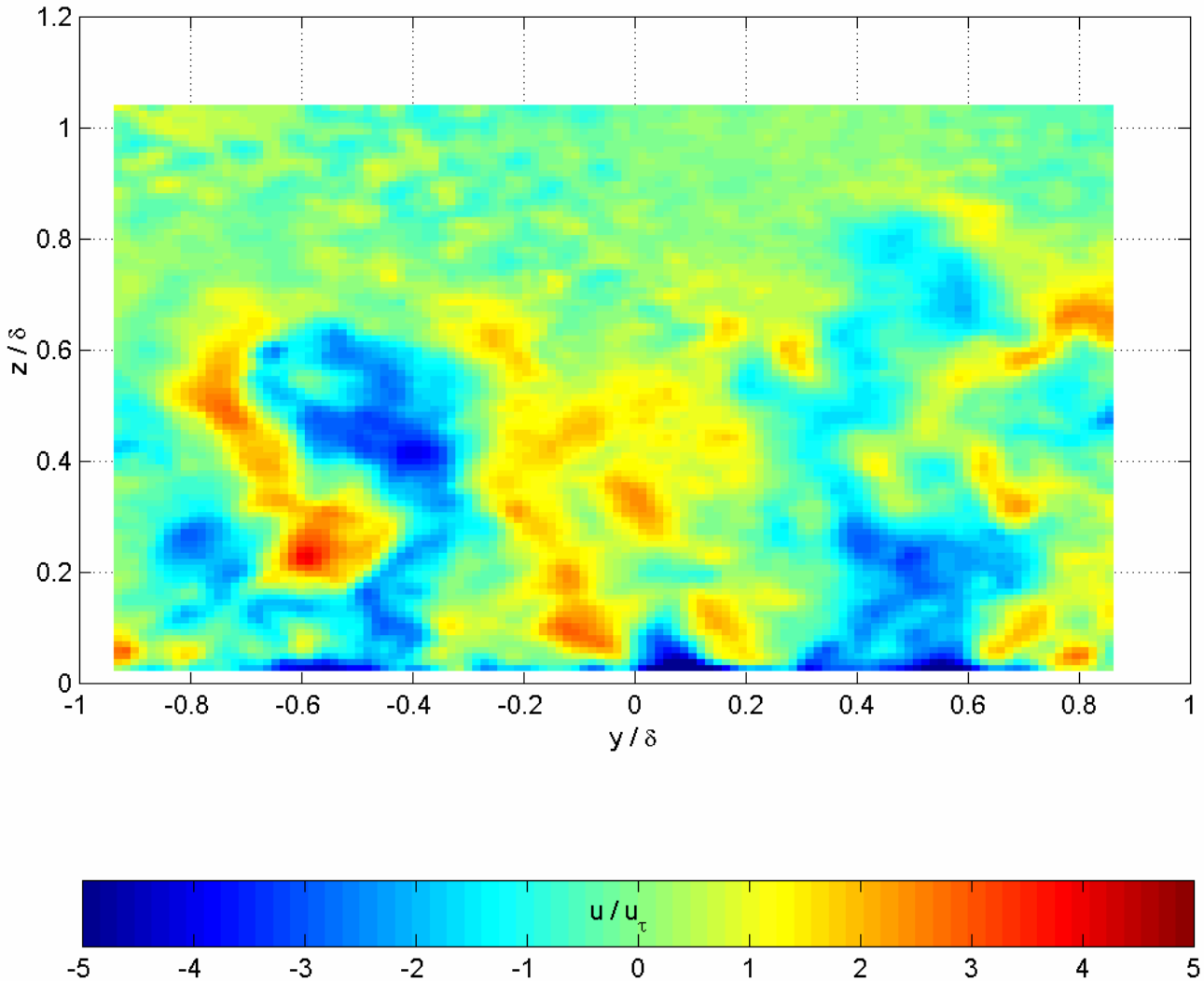
45° inclined plane – typical flow features



45° inclined plane – example frame



45° inclined plane – example frame



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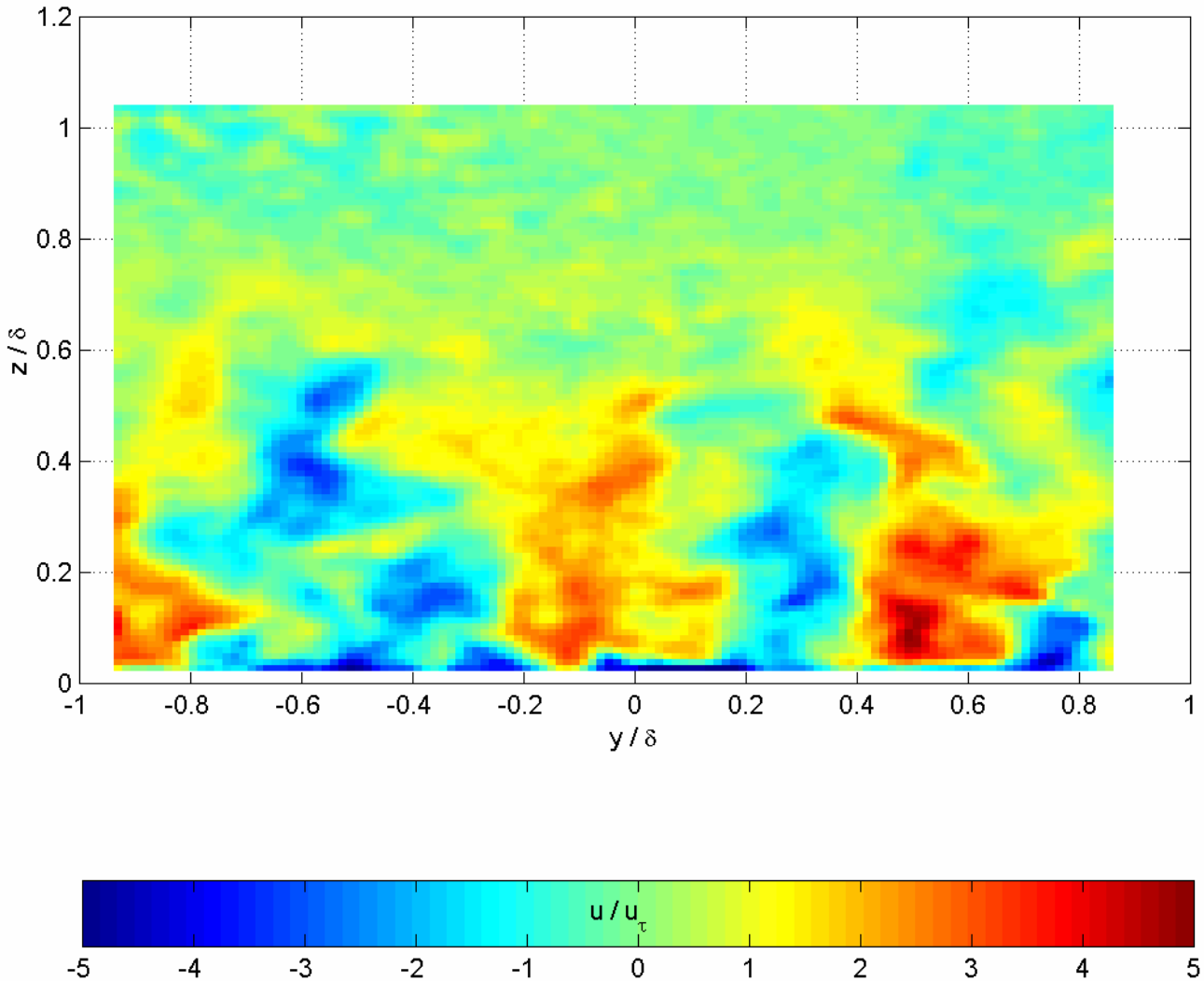

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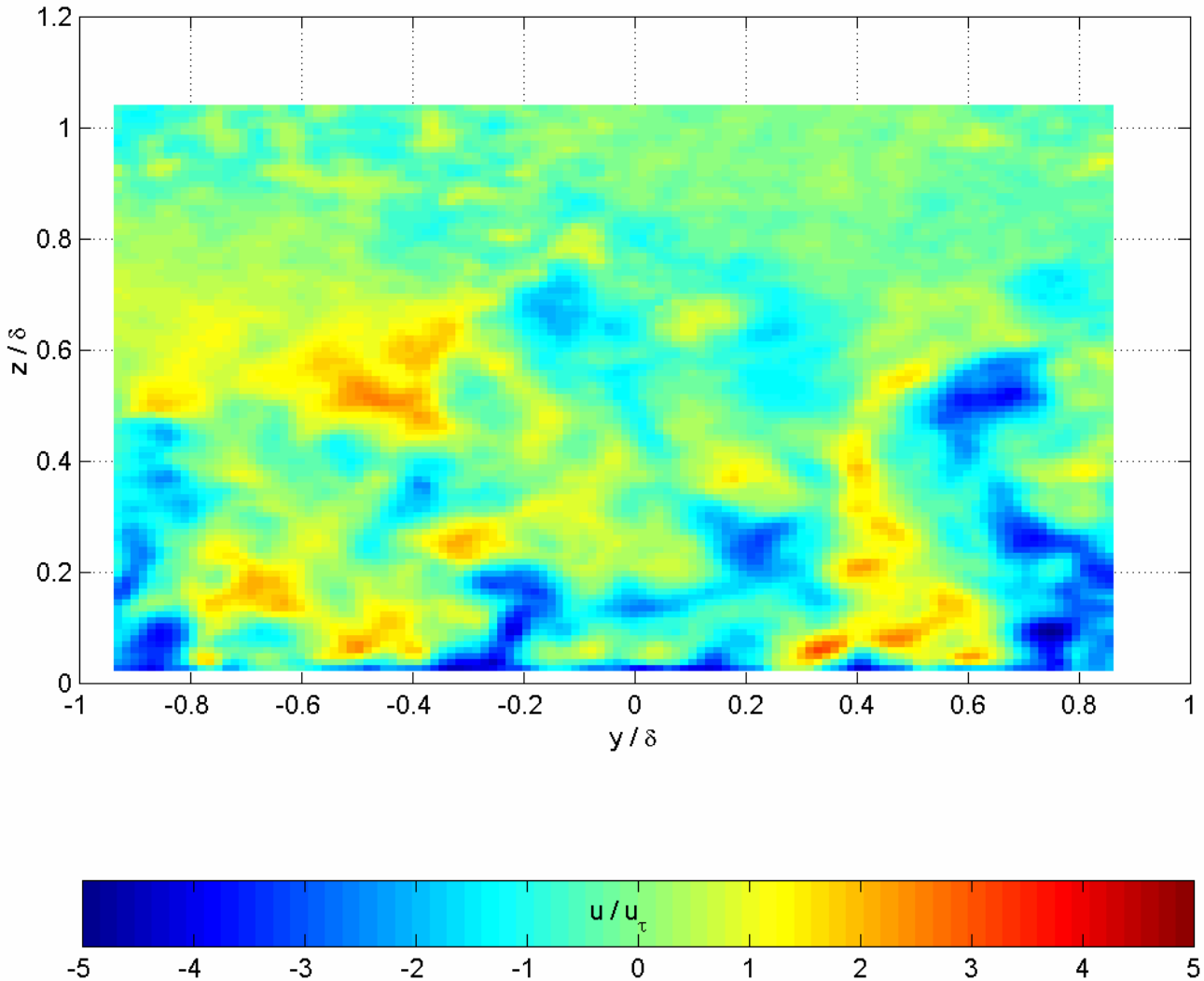
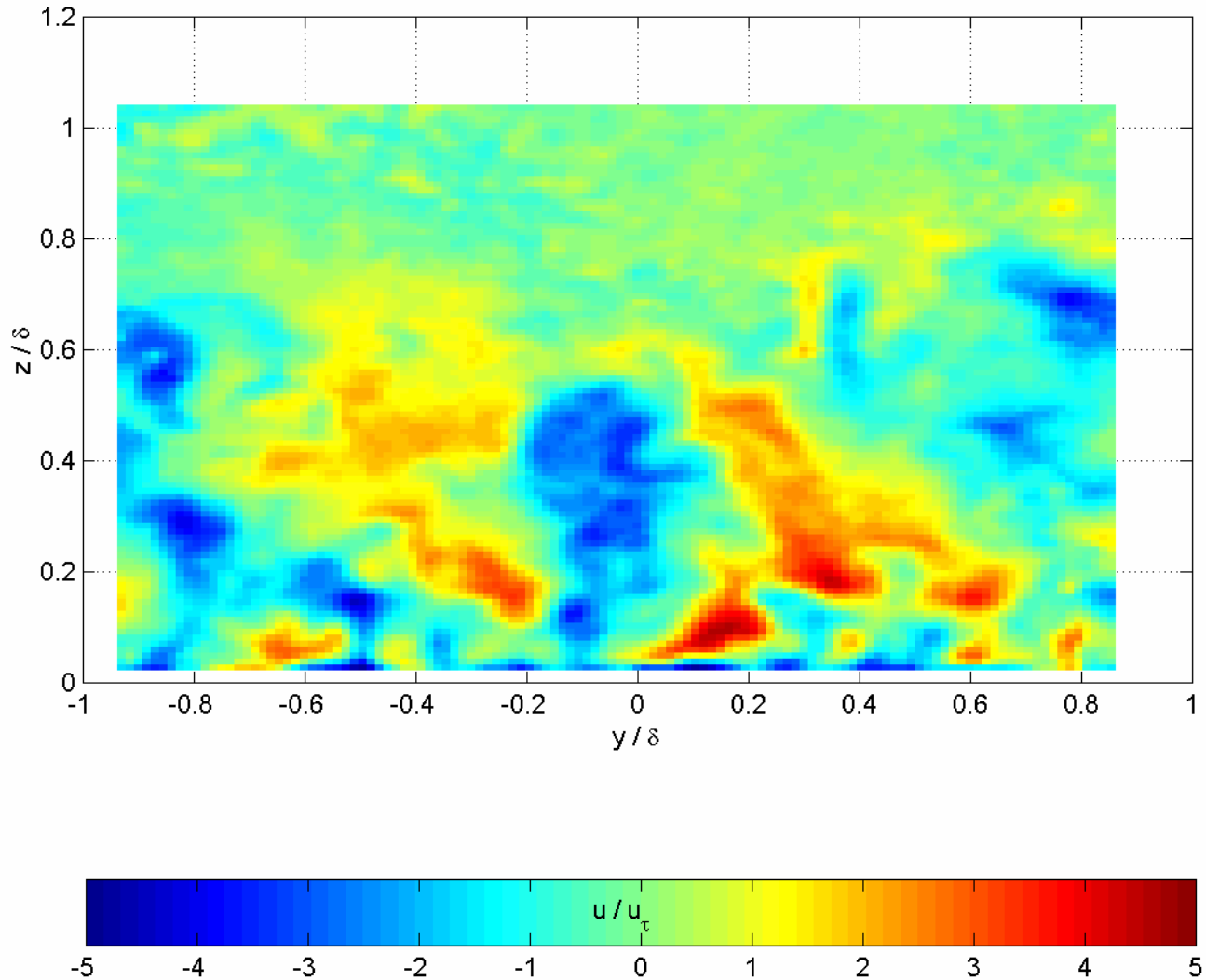


45° inclined plane – example frame



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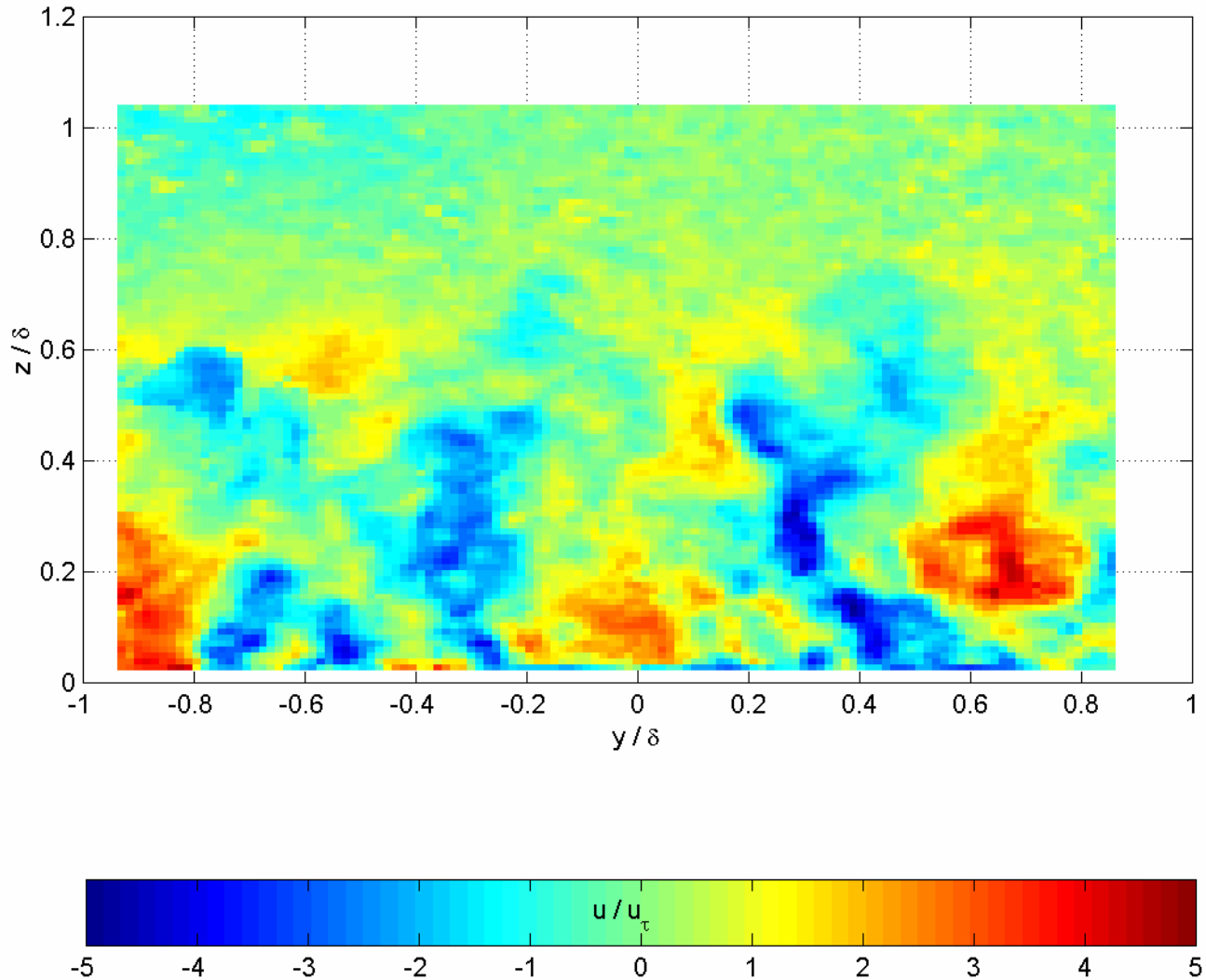
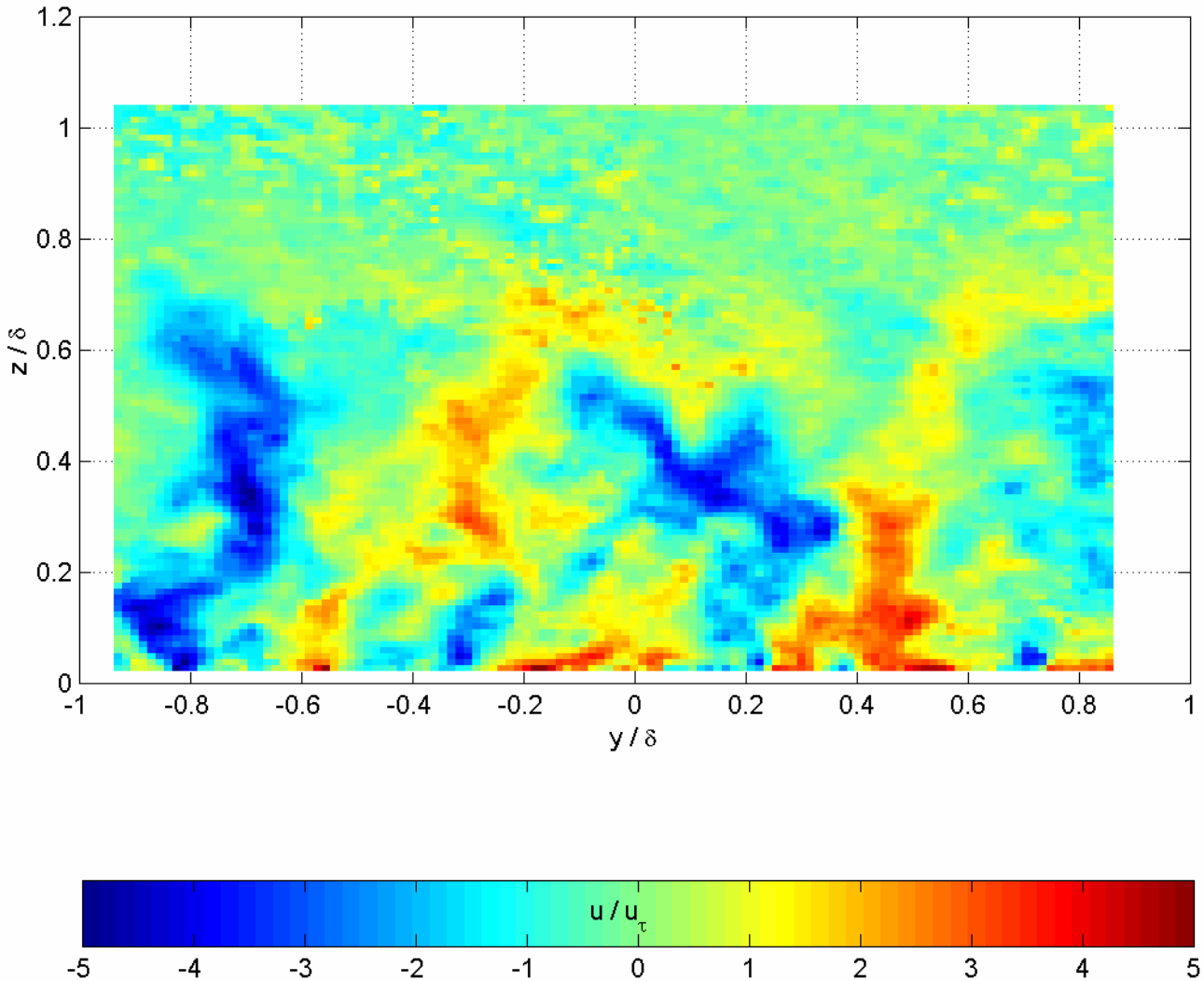


45° inclined plane – example frame



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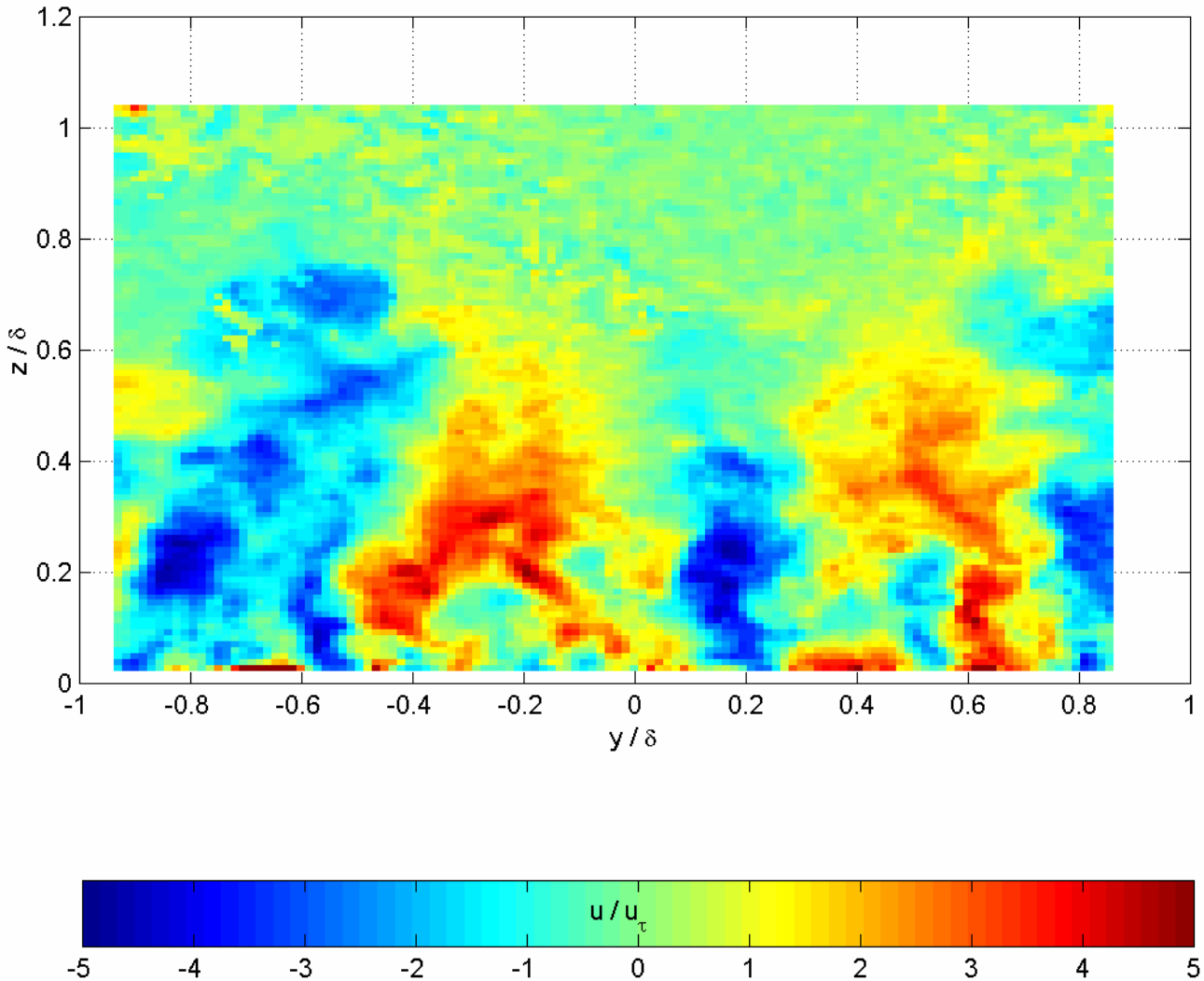
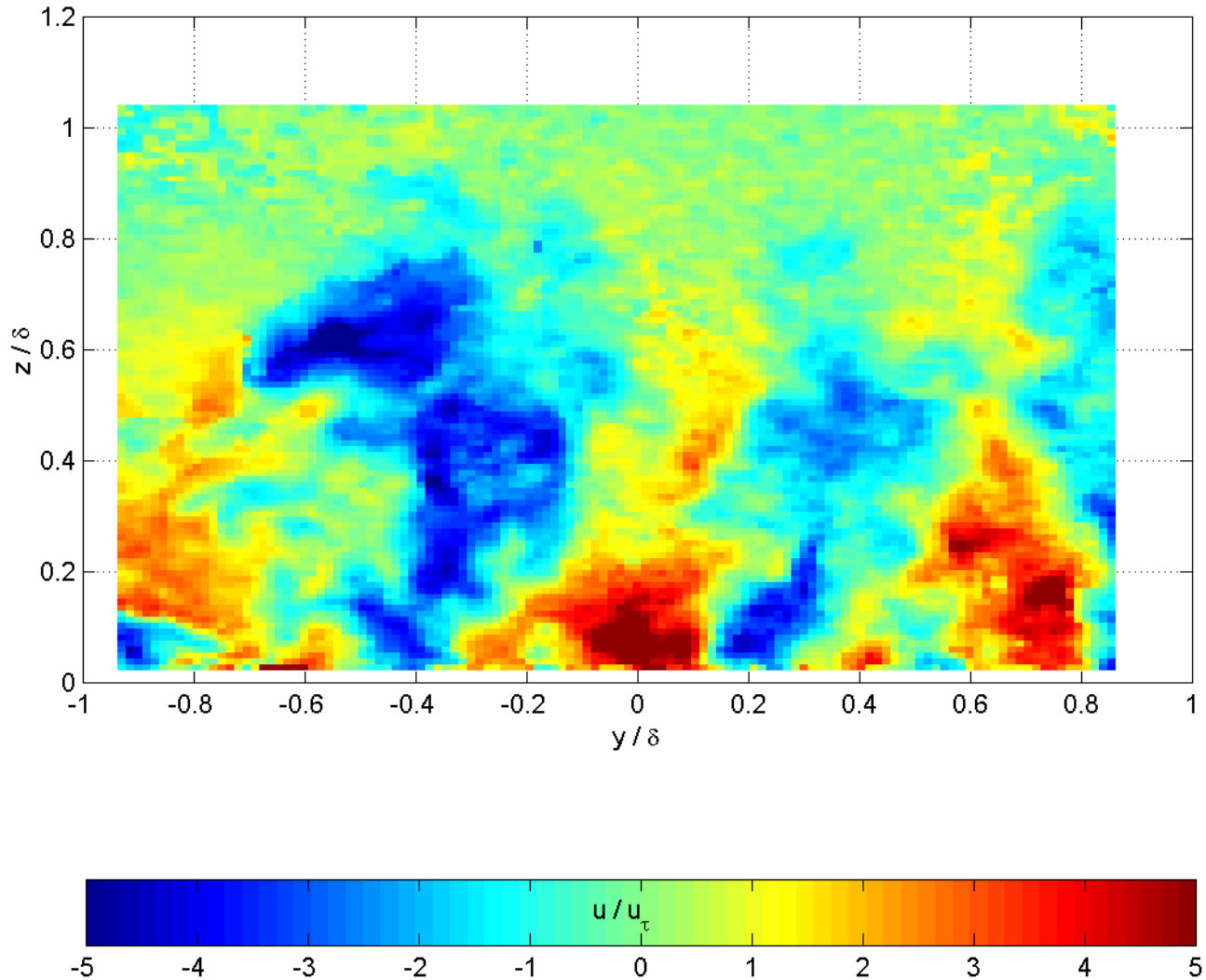
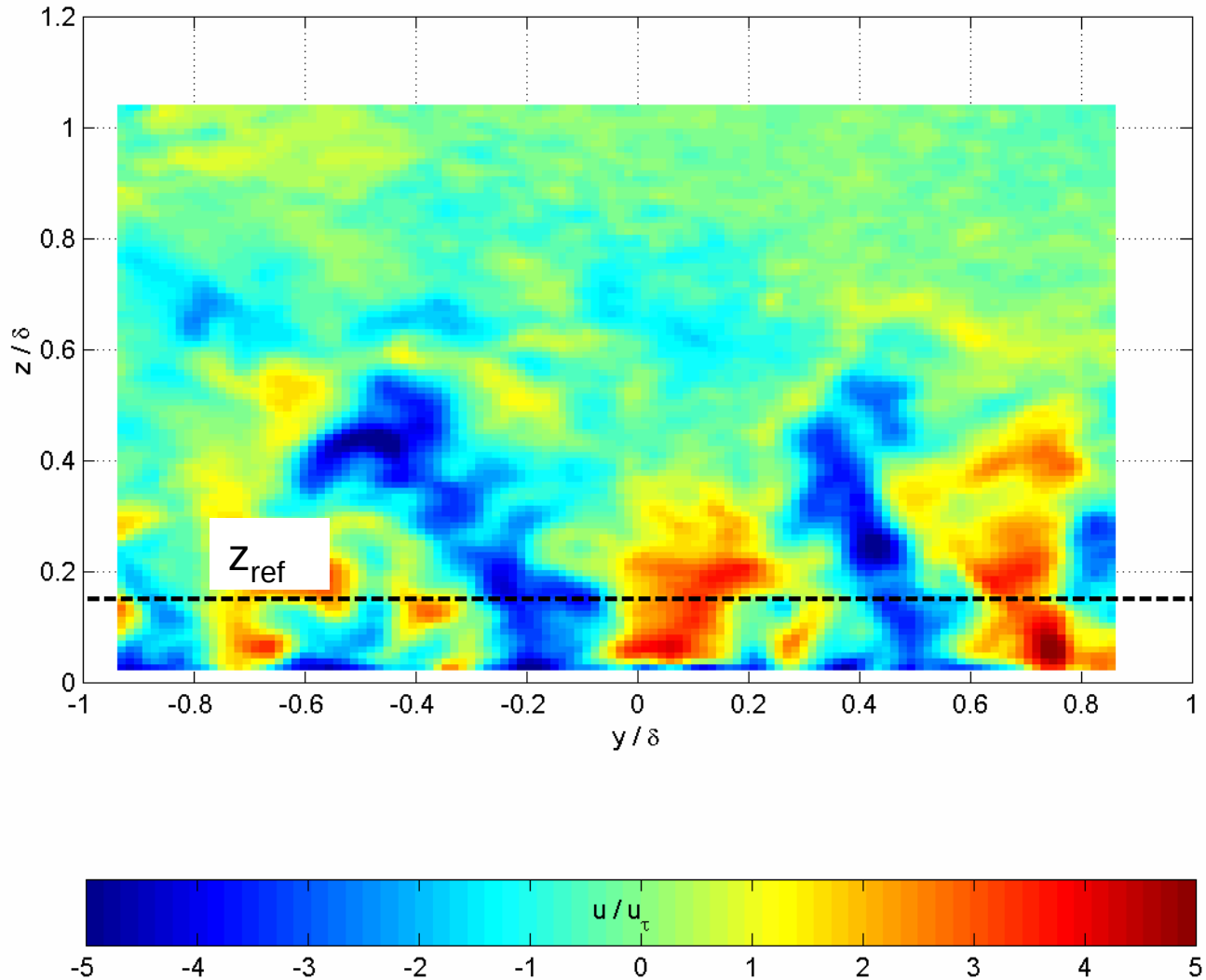


45° inclined plane – example frame

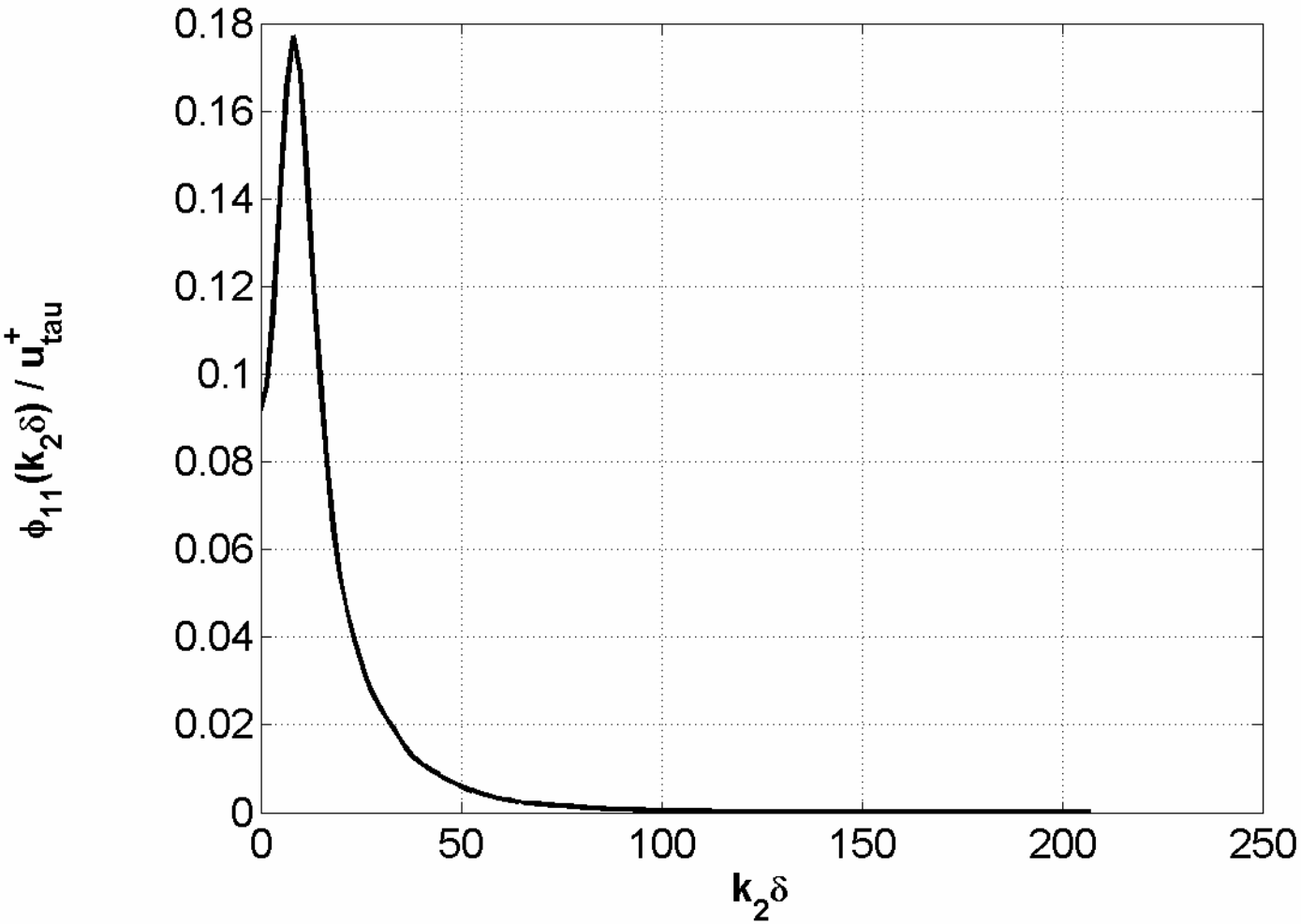


Select reference height.

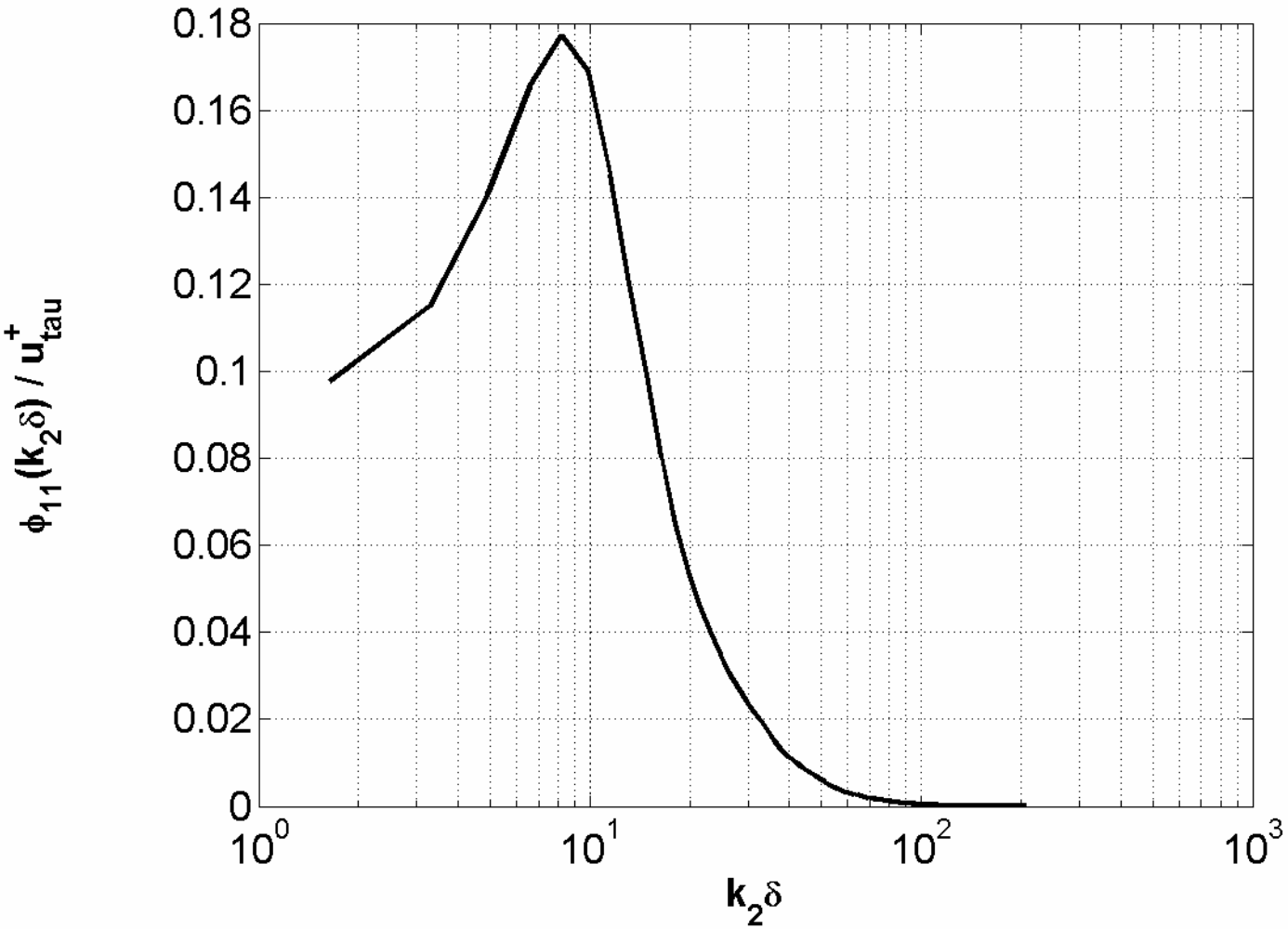
$z_{ref} / \delta = 0.15$ $(z^+_{ref} = 140)$



Energetic spanwise modes in the streamwise velocity signal at $z_{ref} / \delta = 0.15$ ($z^+_{ref} = 140$)



Energetic spanwise modes in the streamwise velocity signal at $z_{ref} / \delta = 0.15$ $(z^+_{ref} = 140)$



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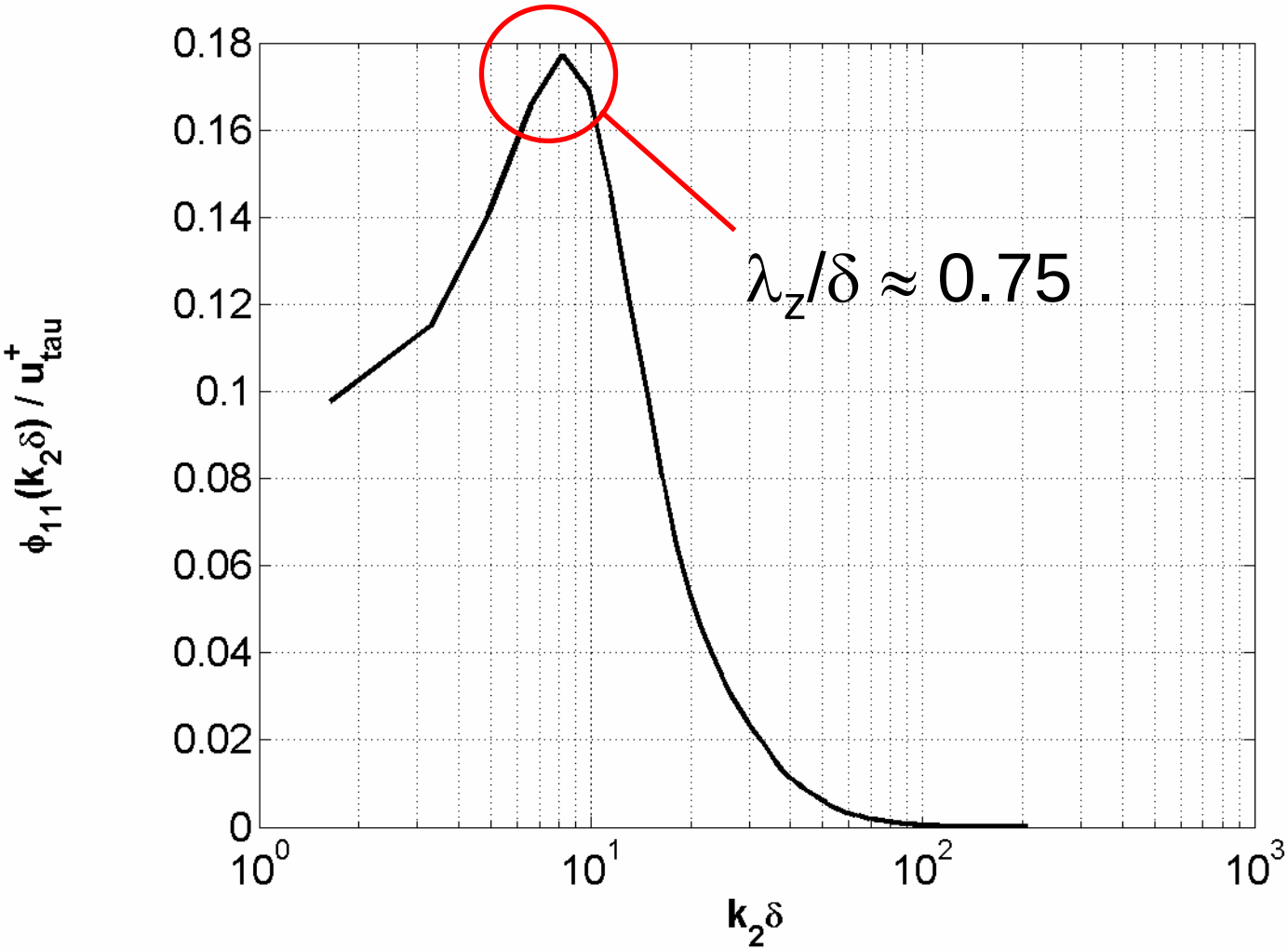
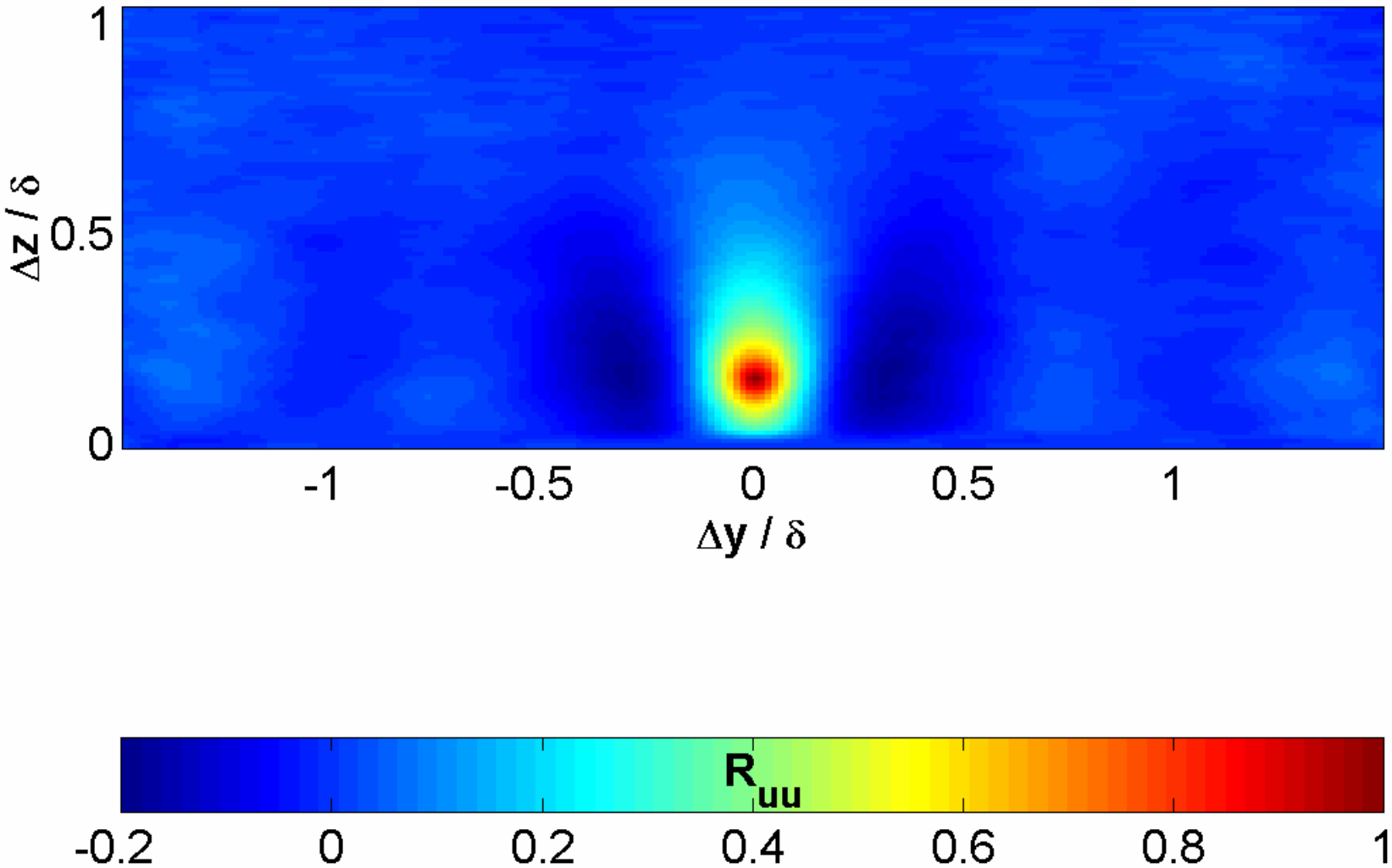
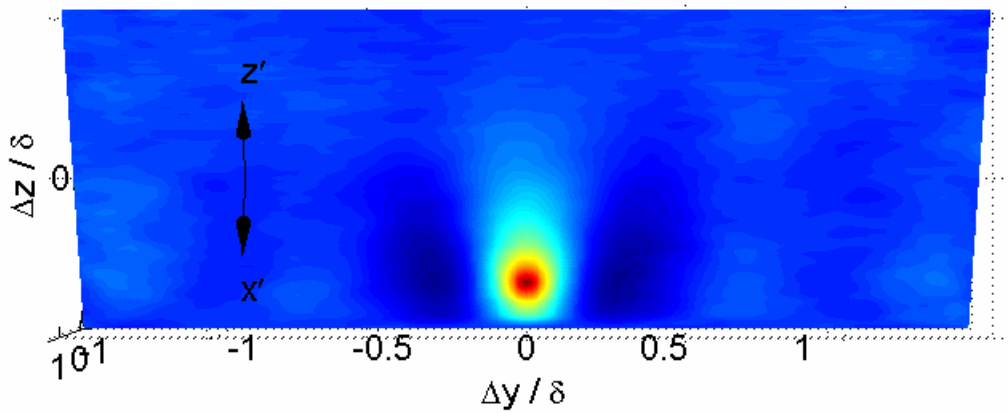
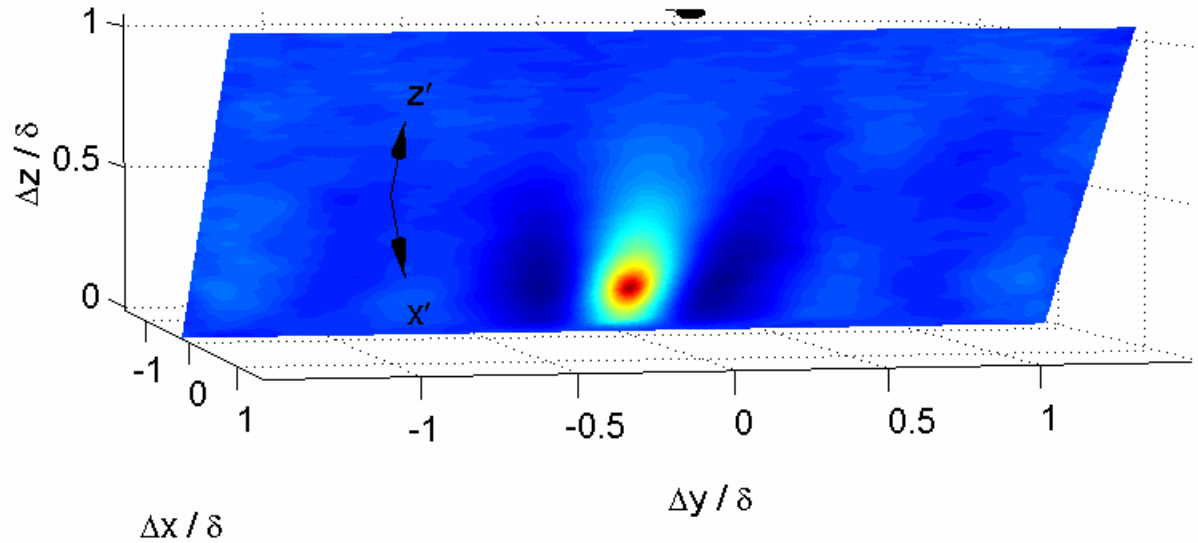


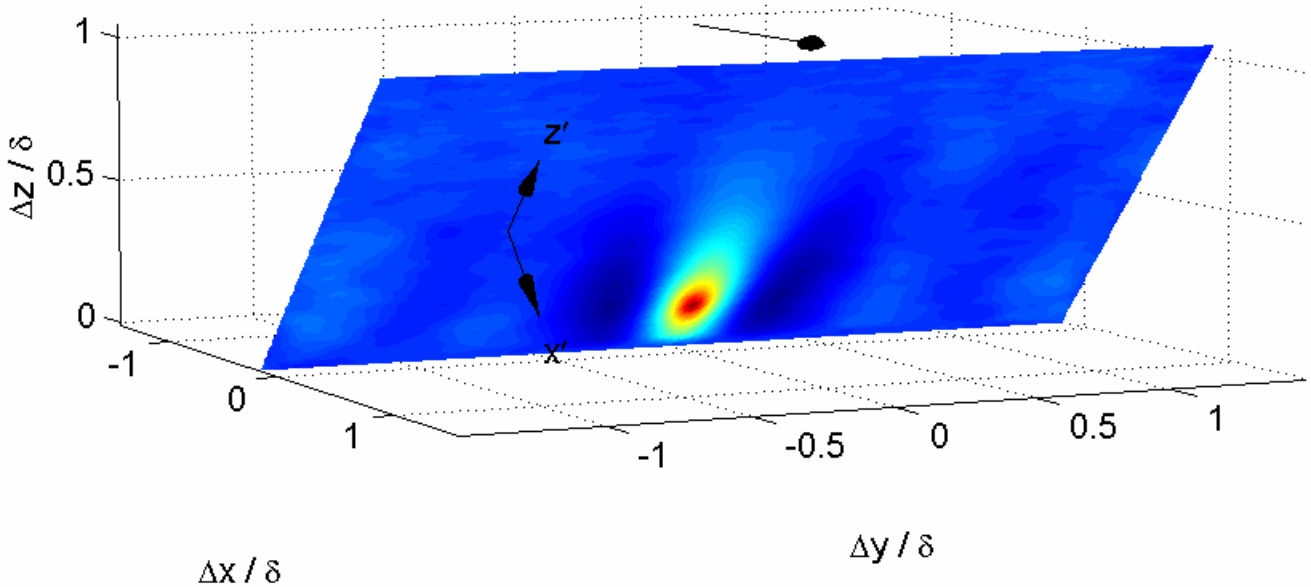
Two-point correlation R_{uu}

$z_{ref} / \delta = 0.15$ $(z^{+}_{ref} = 140)$




z′
x′
Δz / δ
0
-1
-0.5
0
0.5
1
Δy / δ


1
0.5
0
Δz / δ
z′
x′
-1
0
1
Δx / δ
-1
-0.5
0
0.5
1
Δy / δ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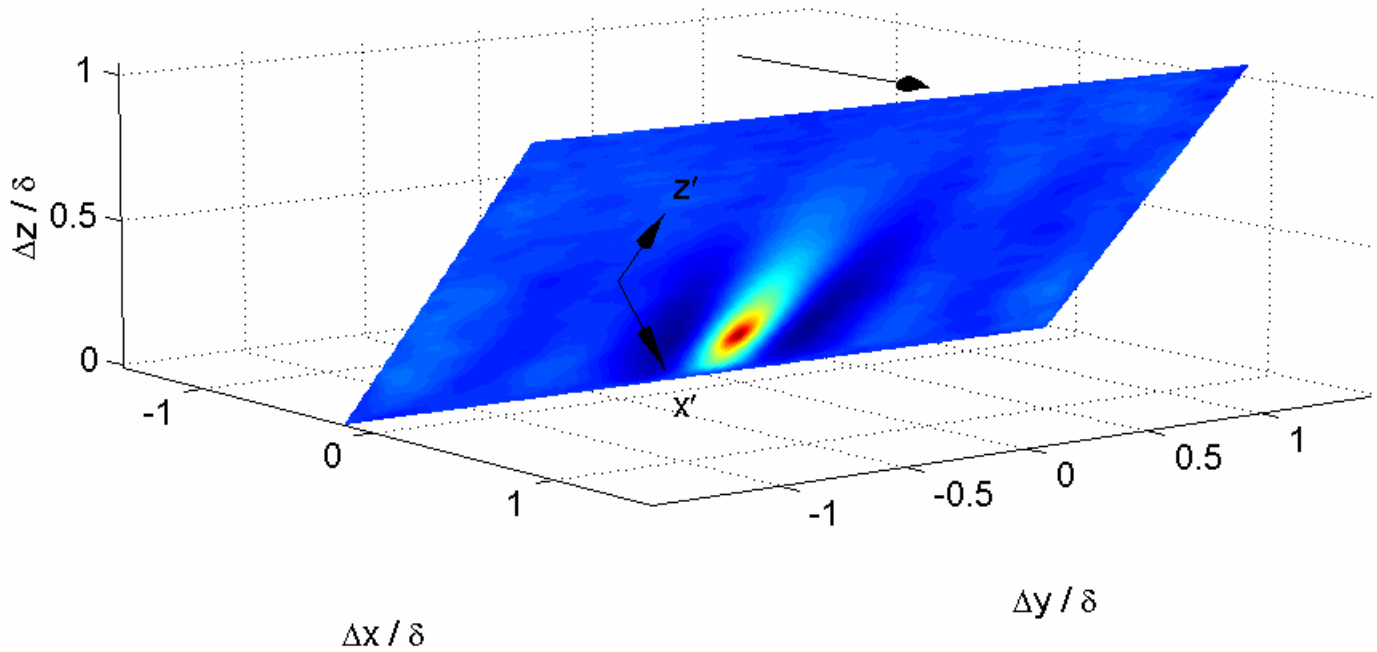
0.5
0
Δz / δ
z'
x'
-1
0
1
Δx / δ
-1
-0.5
0
0.5
1
Δy / δ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Δz / δ
z′
x′
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0
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Δx / δ
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0
0.5
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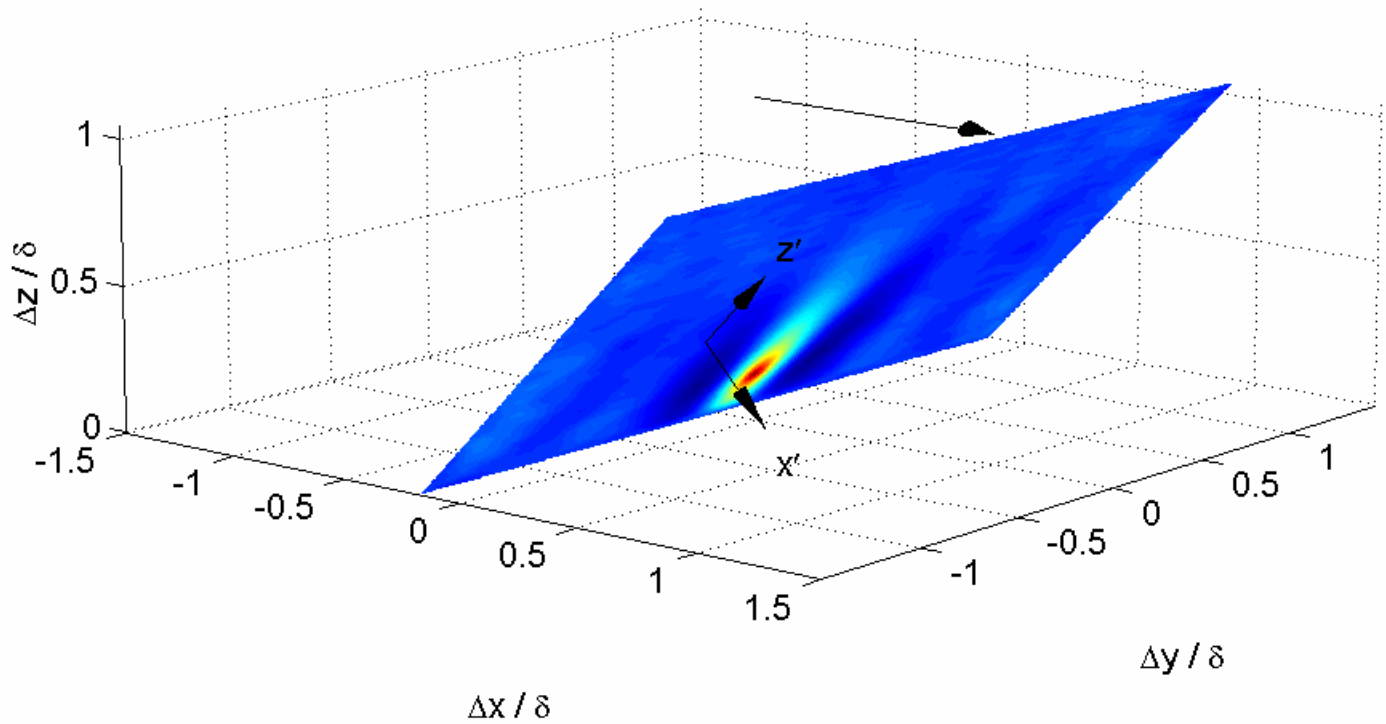
Δy / δ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Δz / δ
z′
x′
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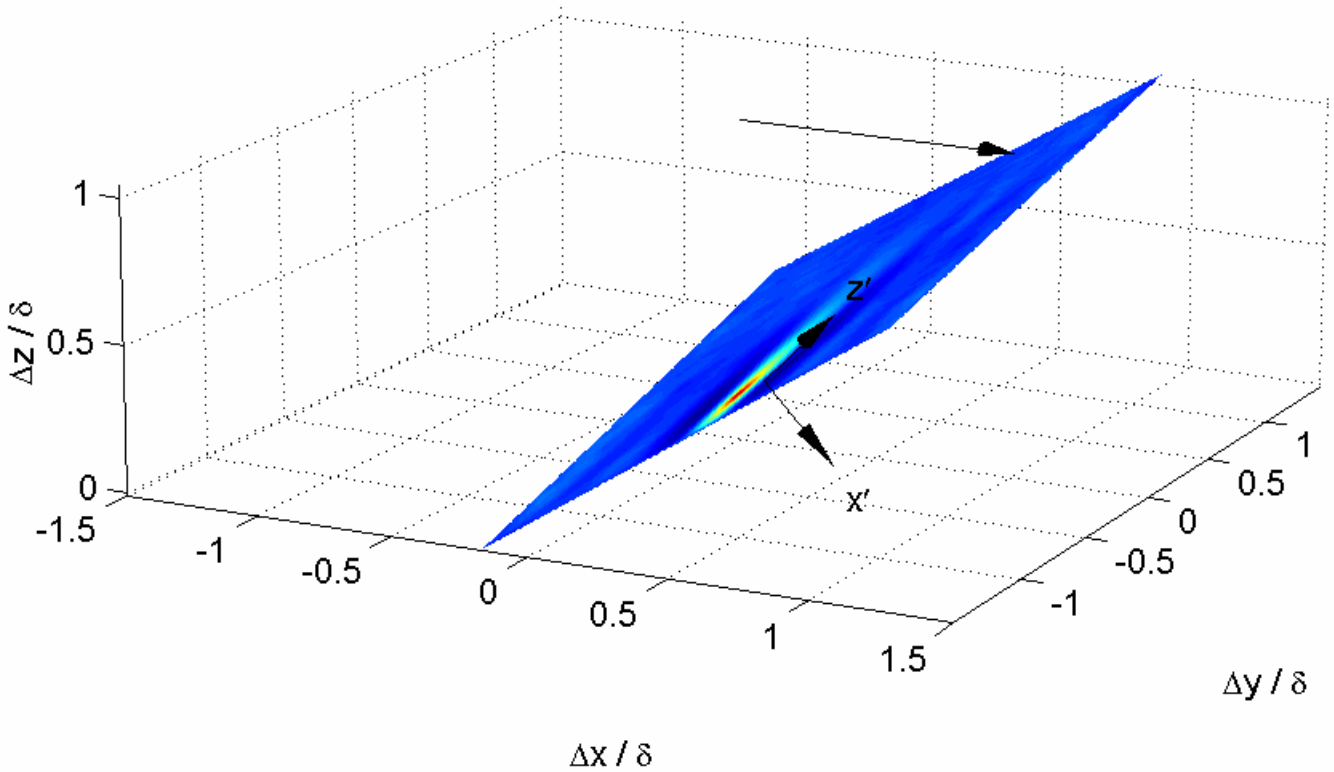
0
0.5
1
1.5
Δx / δ
-1
-0.5
0
0.5
1
Δy / δ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1.5
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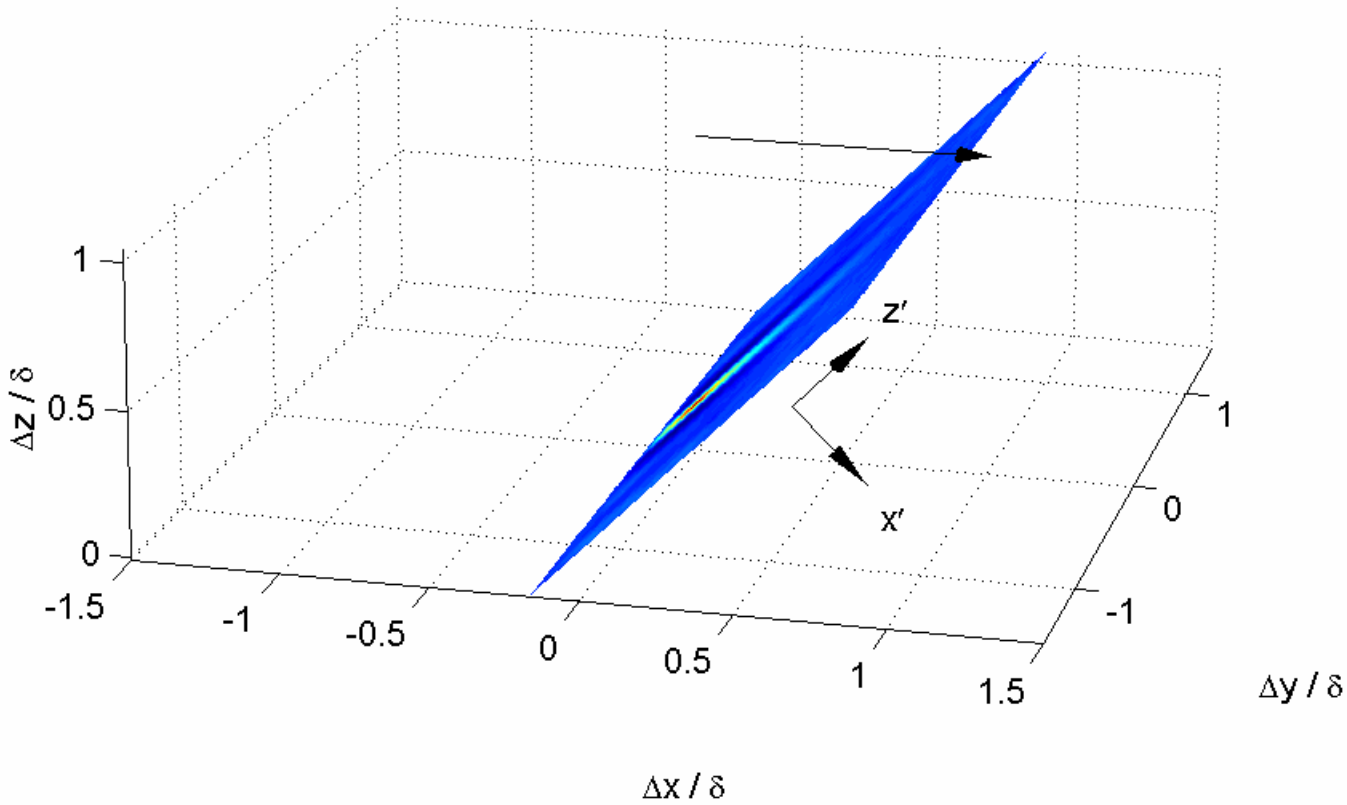
x′
1
0.5
0
-0.5
-1
Δy / δ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Δz / δ
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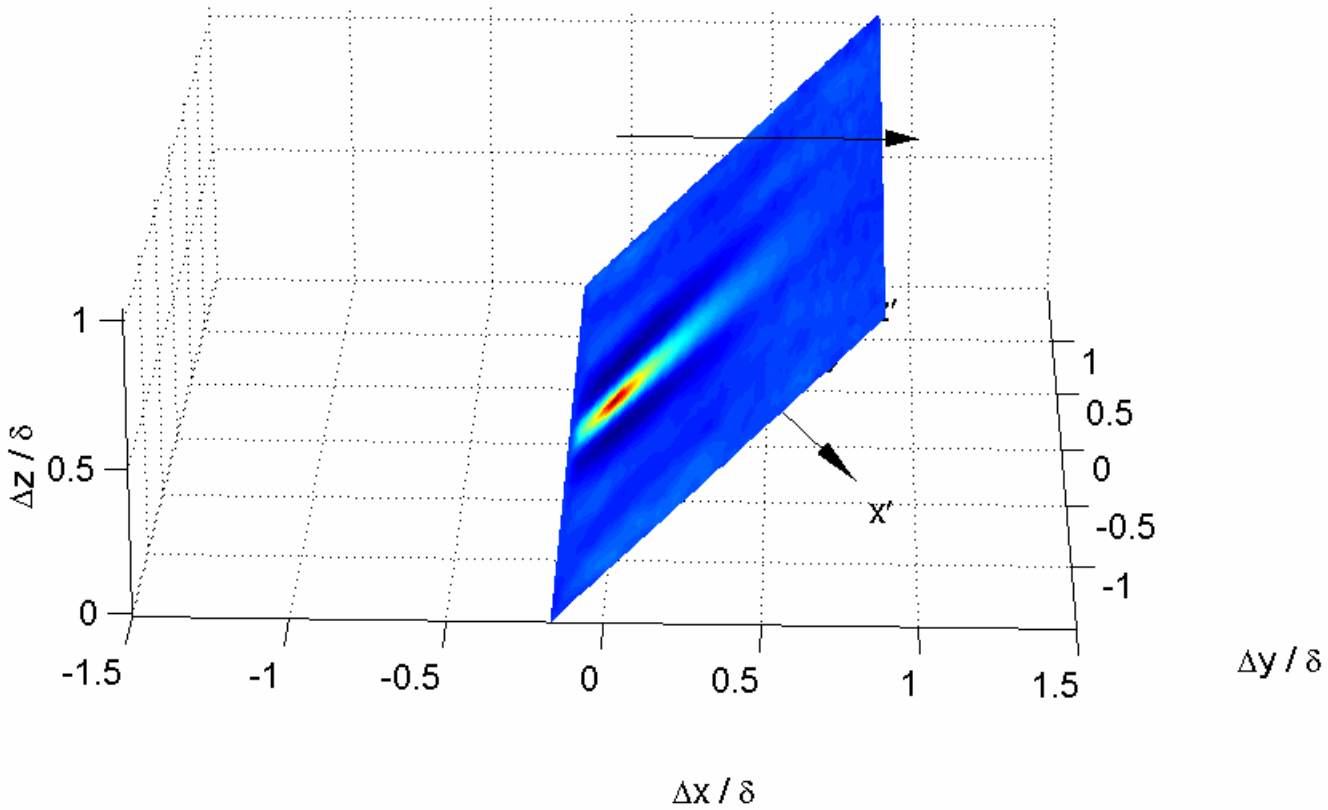
0.5
1
1.5
Δx / δ
z′
x′
1
0
-1
Δy / δ


Δz / δ
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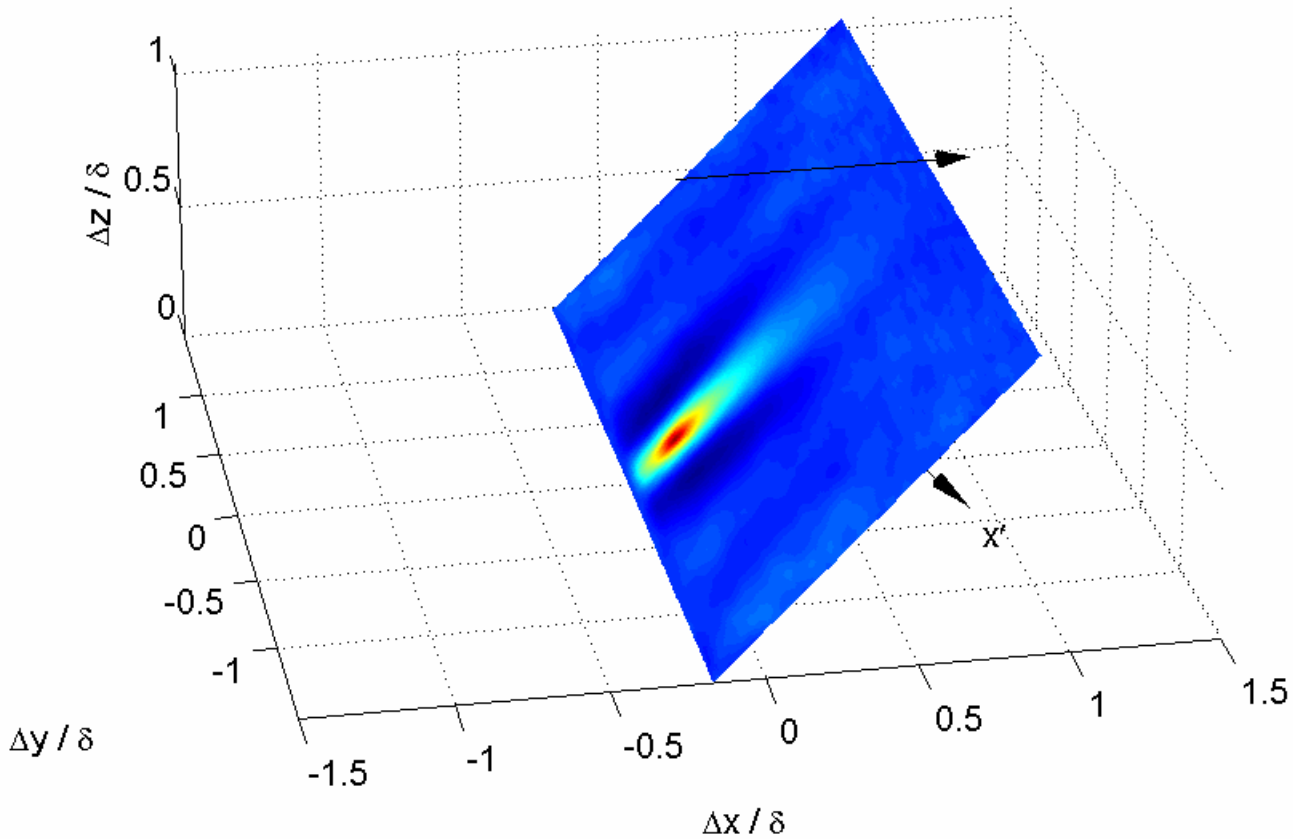
-1.5
-1
-0.5
0
0.5
1
1.5
Δx / δ
1
0.5
0
-0.5
-1
Δy / δ
x'


Δz / δ
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0
Δy / δ
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-1
Δx / δ
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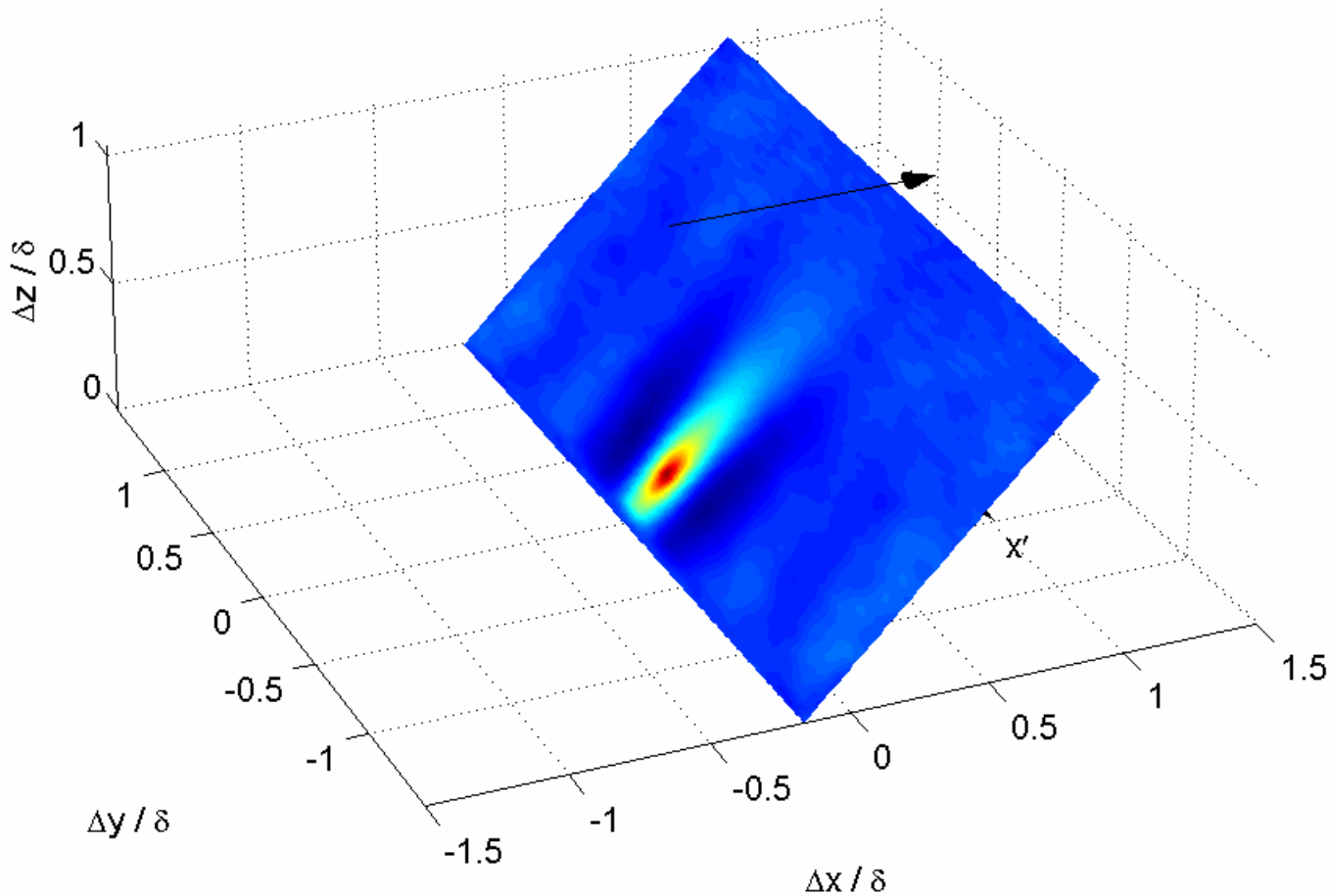
-1
-0.5
0
0.5
1
1.5
x'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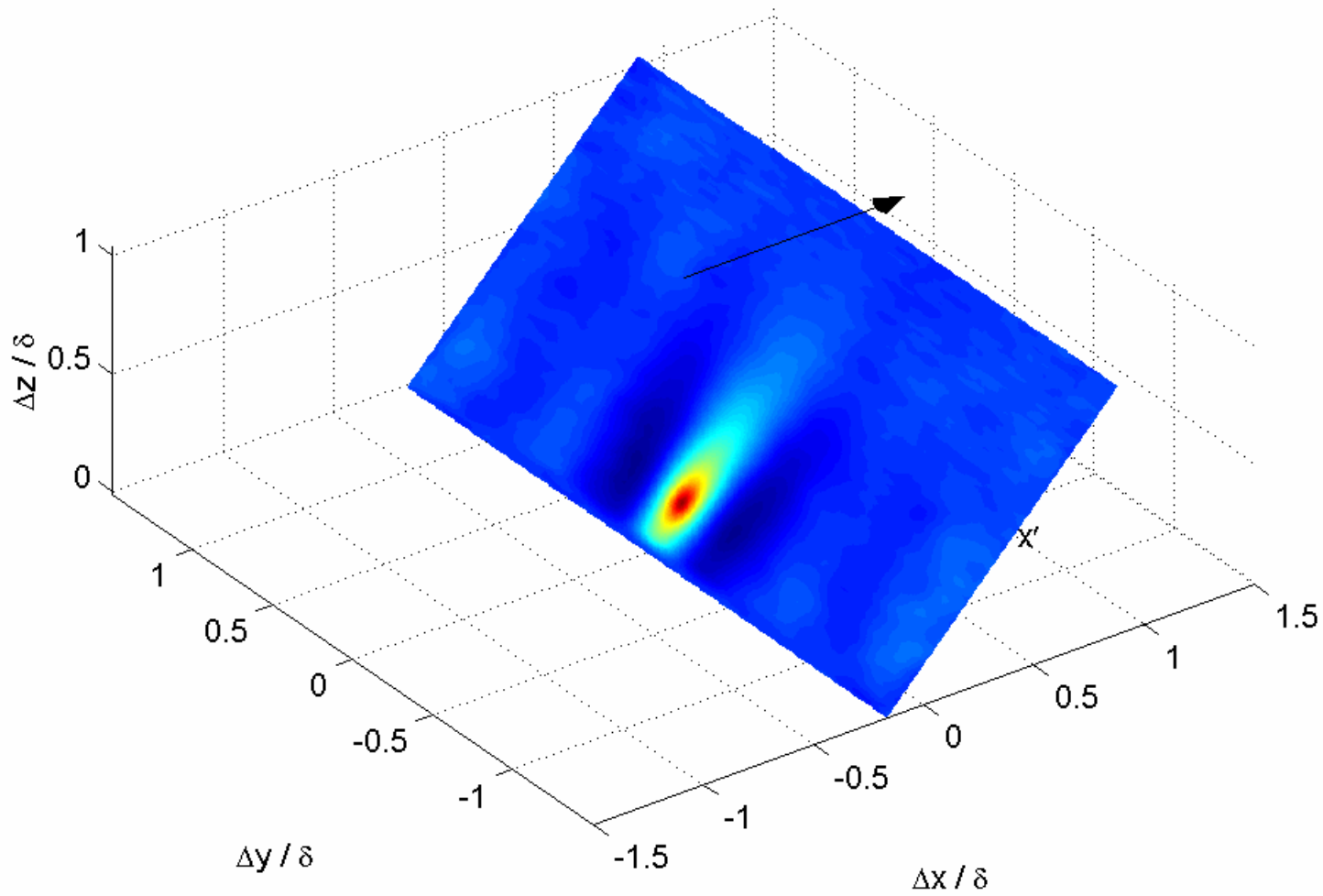
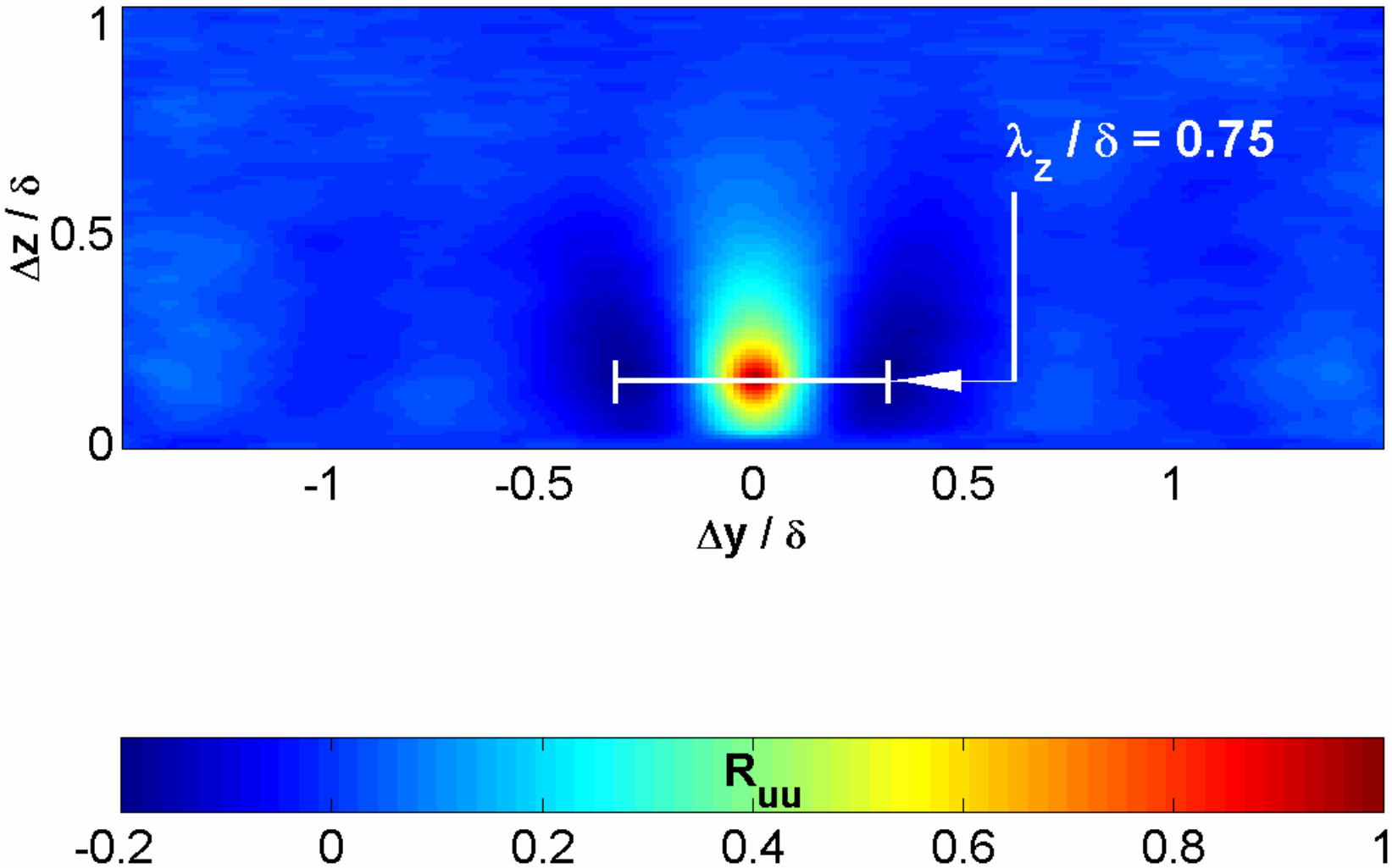
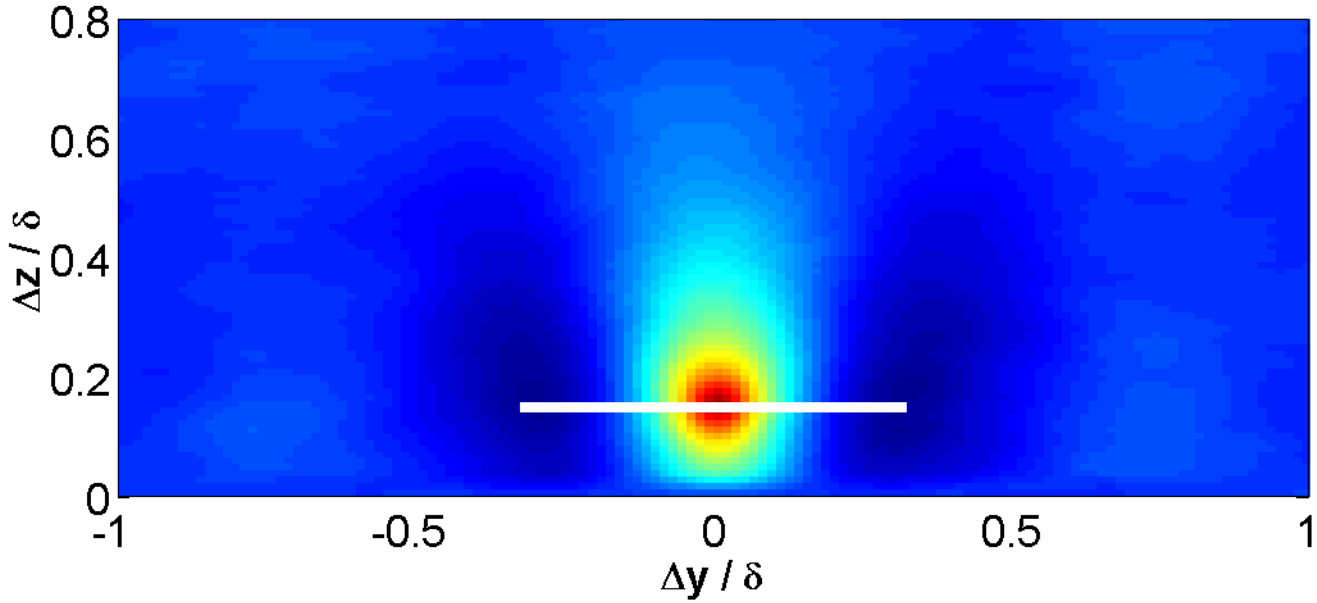
0
Δz / δ
1
0.5
0
-0.5
-1
Δy / δ
-1.5
-1
-0.5
0
0.5
1
1.5
Δx / δ
x'


1
0.5
0
Δz / δ
1
0.5
0
-0.5
-1
Δy / δ
-1.5
-1
-0.5
0
0.5
1
1.5
Δx / δ
x′

Two-point correlation R_{uu}

$z_{ref} / \delta = 0.15$ $(z^{+}_{ref} = 140)$

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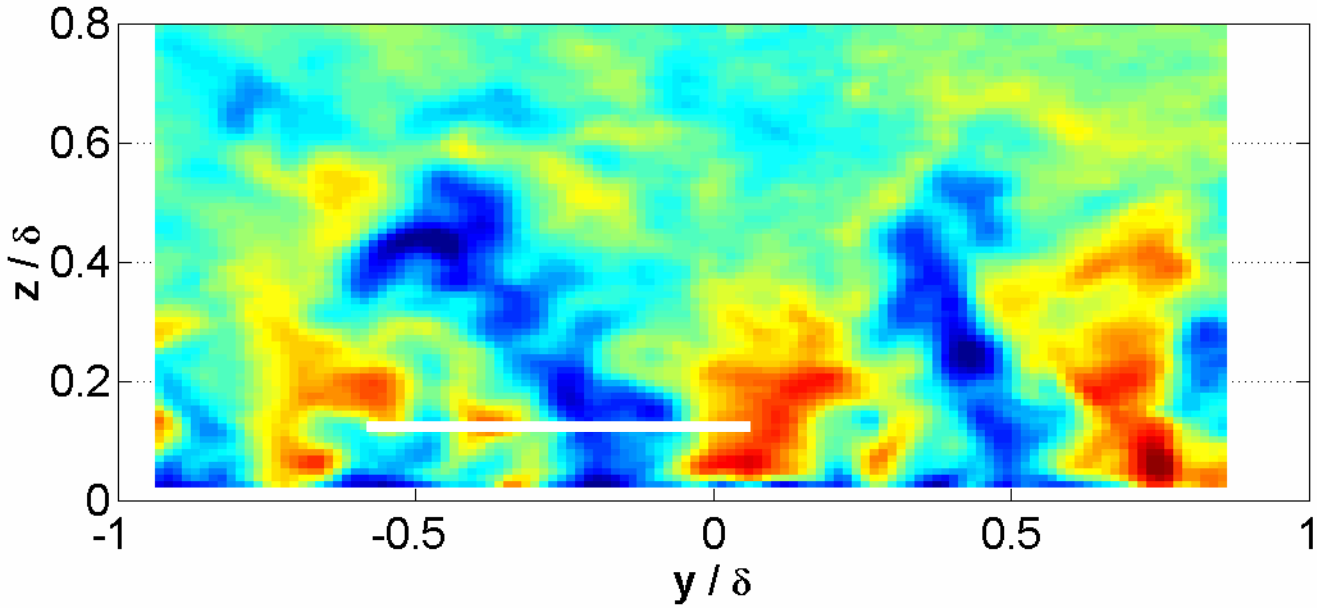
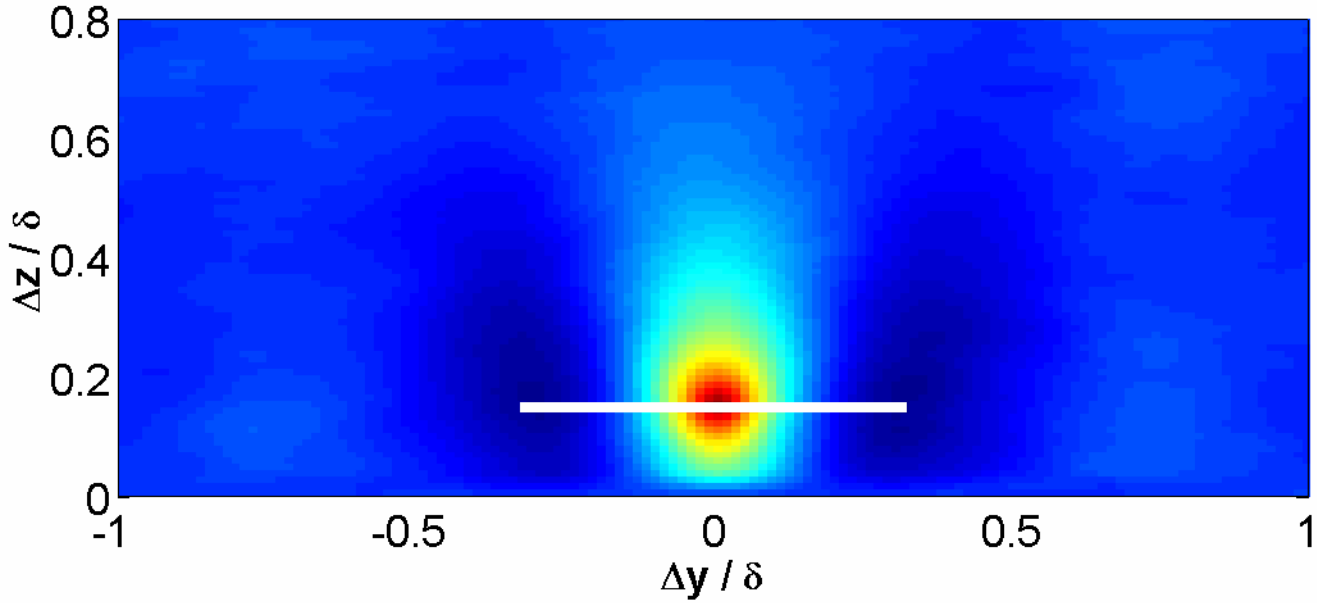
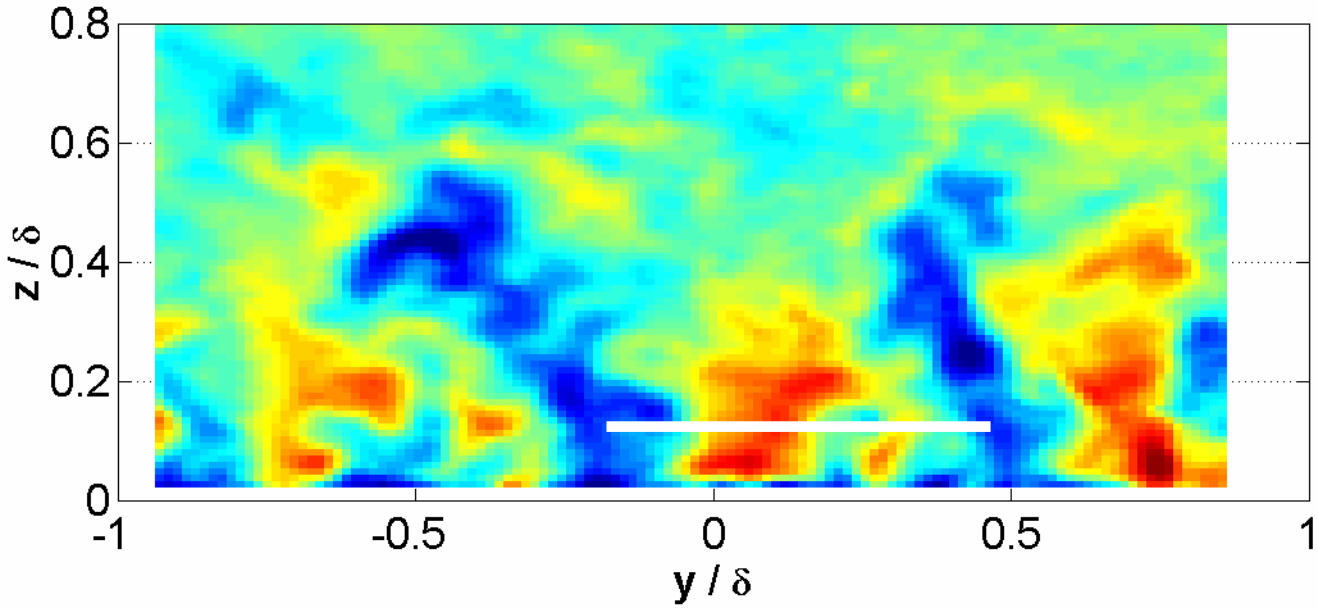
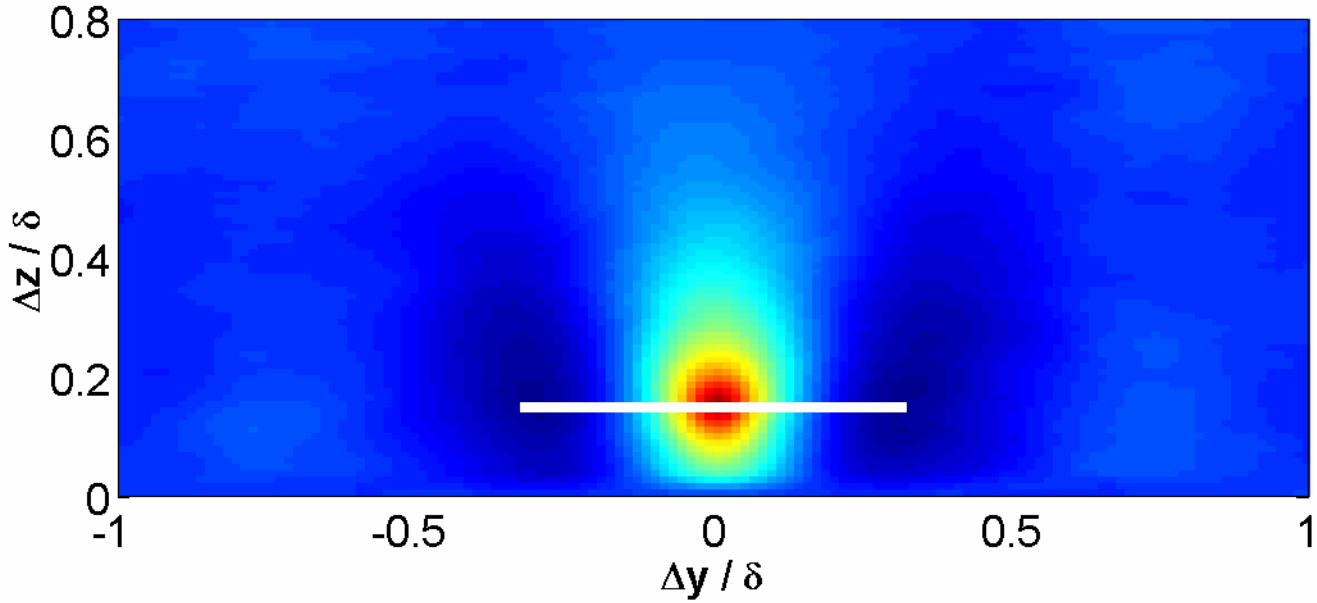
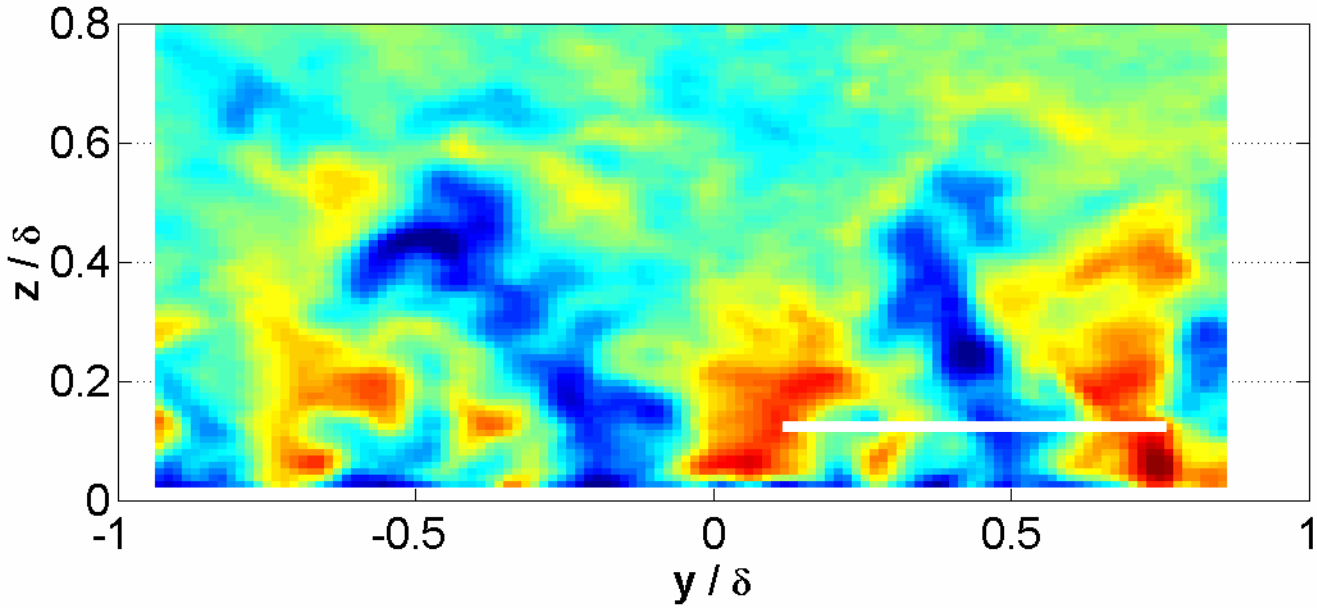
0.6
0.4
0.2
0
Δz / δ
-1
-0.5
0
0.5
1
Δy / δ

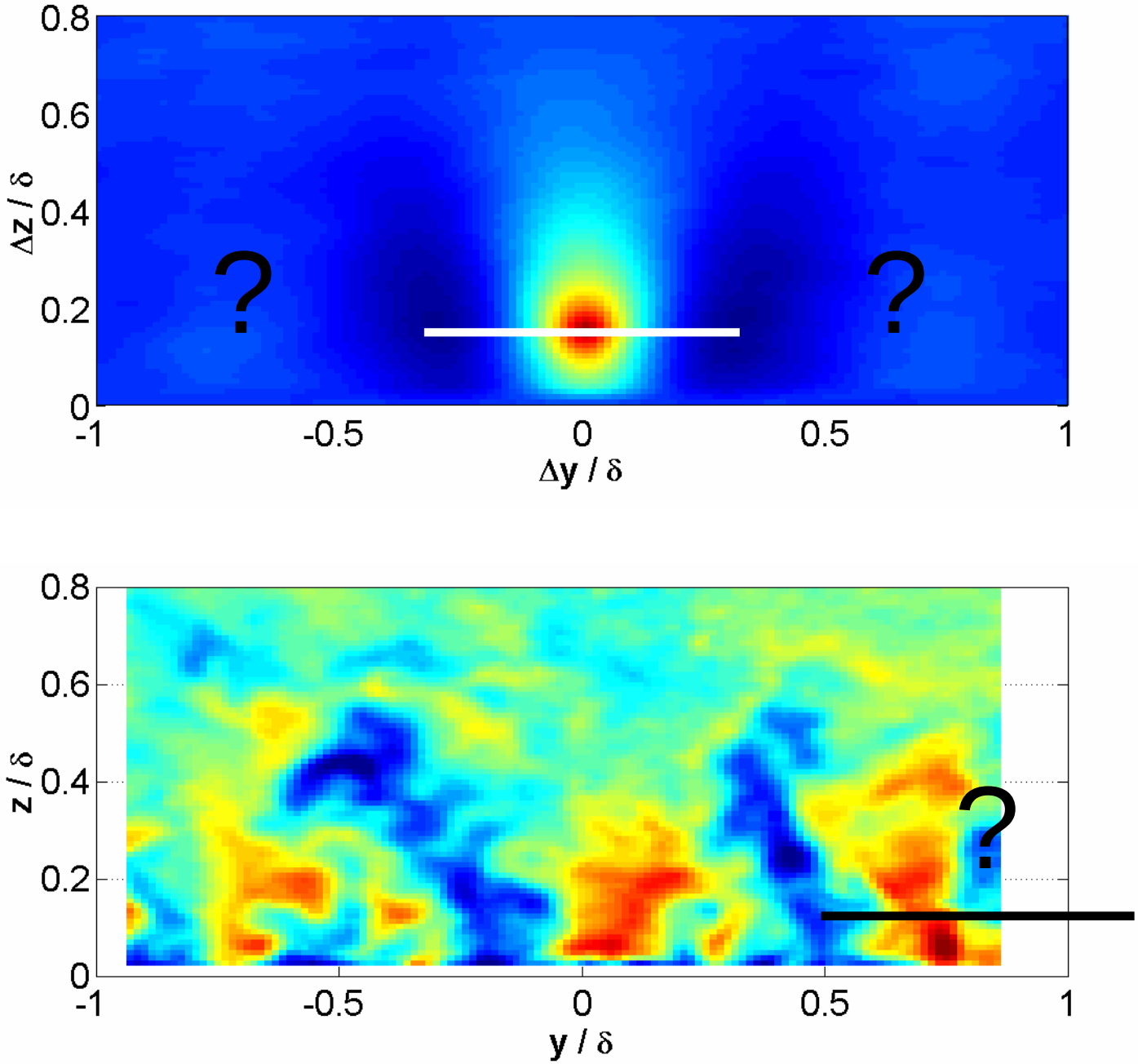

0.8
0.6
0.4
0.2
0
z / δ
-1
-0.5
0
0.5
1
y / δ


0.8
0.6
0.4
0.2
0
Δz / δ
-1
-0.5
0
0.5
1
Δy / δ


0.8
0.6
0.4
0.2
0
z / δ
-1
-0.5
0
0.5
1
y / δ


0.8
0.6
0.4
0.2
0
Δz / δ
-1
-0.5
0
0.5
1
Δy / δ


0.8
0.6
0.4
0.2
0
z / δ
-1
-0.5
0
0.5
1
y / δ

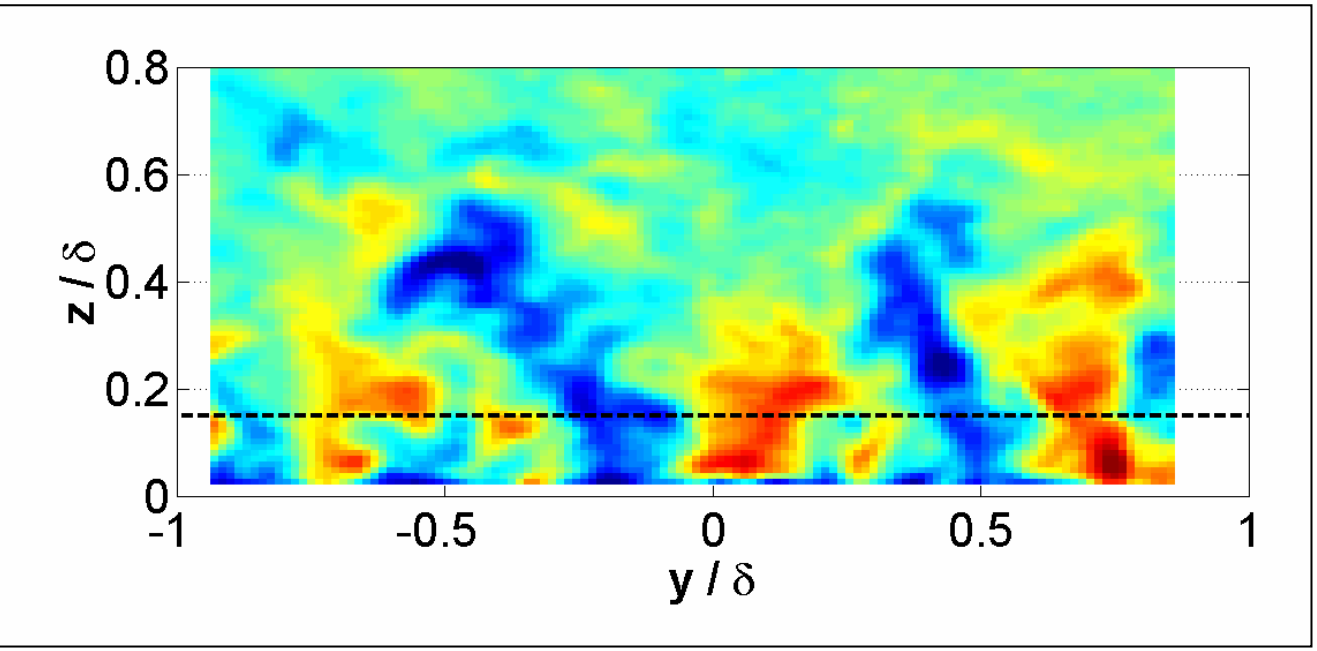

0.8
0.6
0.4
0.2
0
Δz / δ
?
?
-1
-0.5
0
0.5
1
Δy / δ
0.8
0.6
0.4
0.2
0
z / δ
?
-1
-0.5
0
0.5
1
y / δ

But turbulence is a multi-scale problem……..

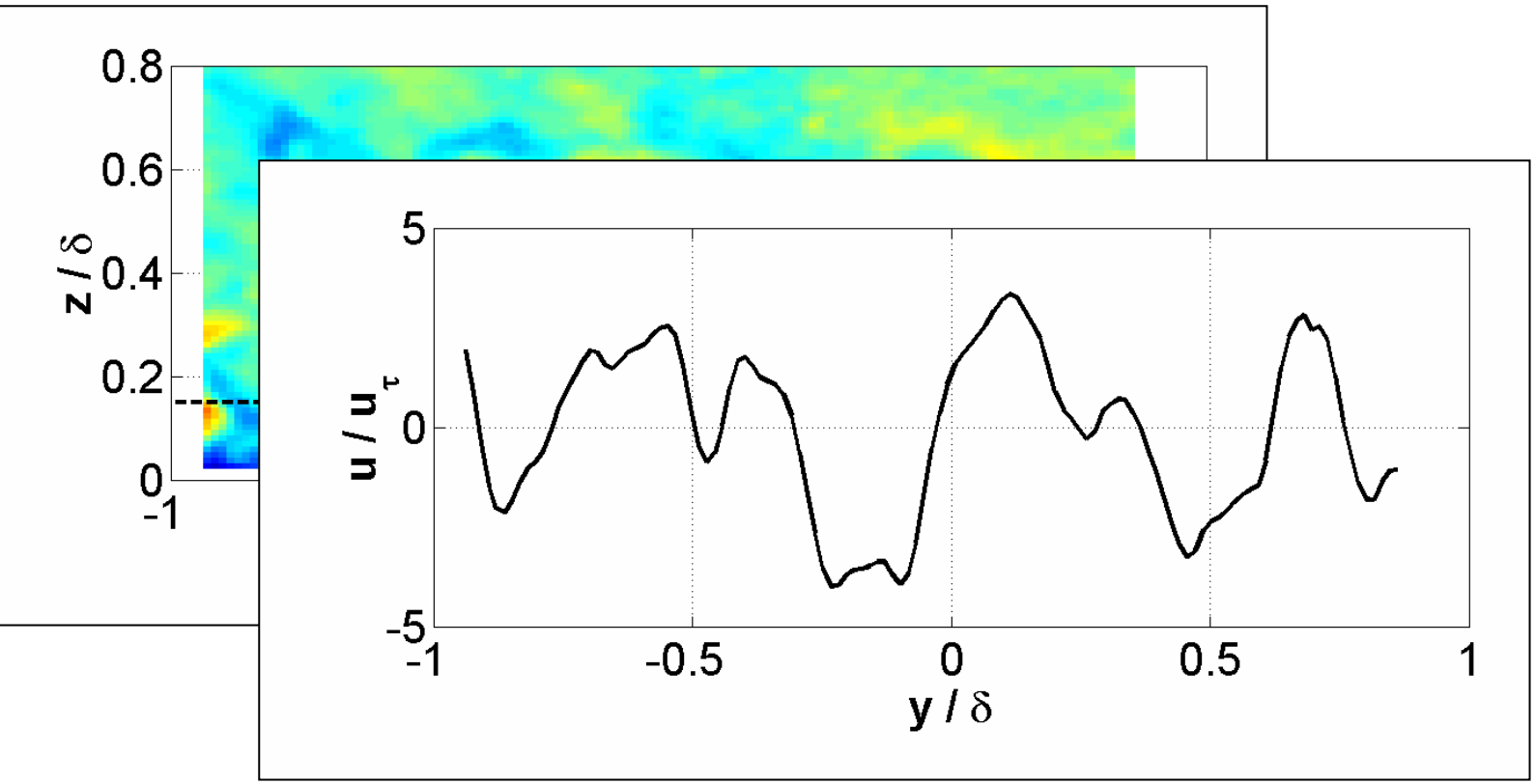
We need to De-jittered the data

i. Select a PIV frame.
ii. Extract the spanwise *u* signal at the reference height.
iii. Look at the spanwise energetic modes for *that particular frame.*
iv. ‘Bin’ or sort the frame according to dominant spanwise wavenumber.

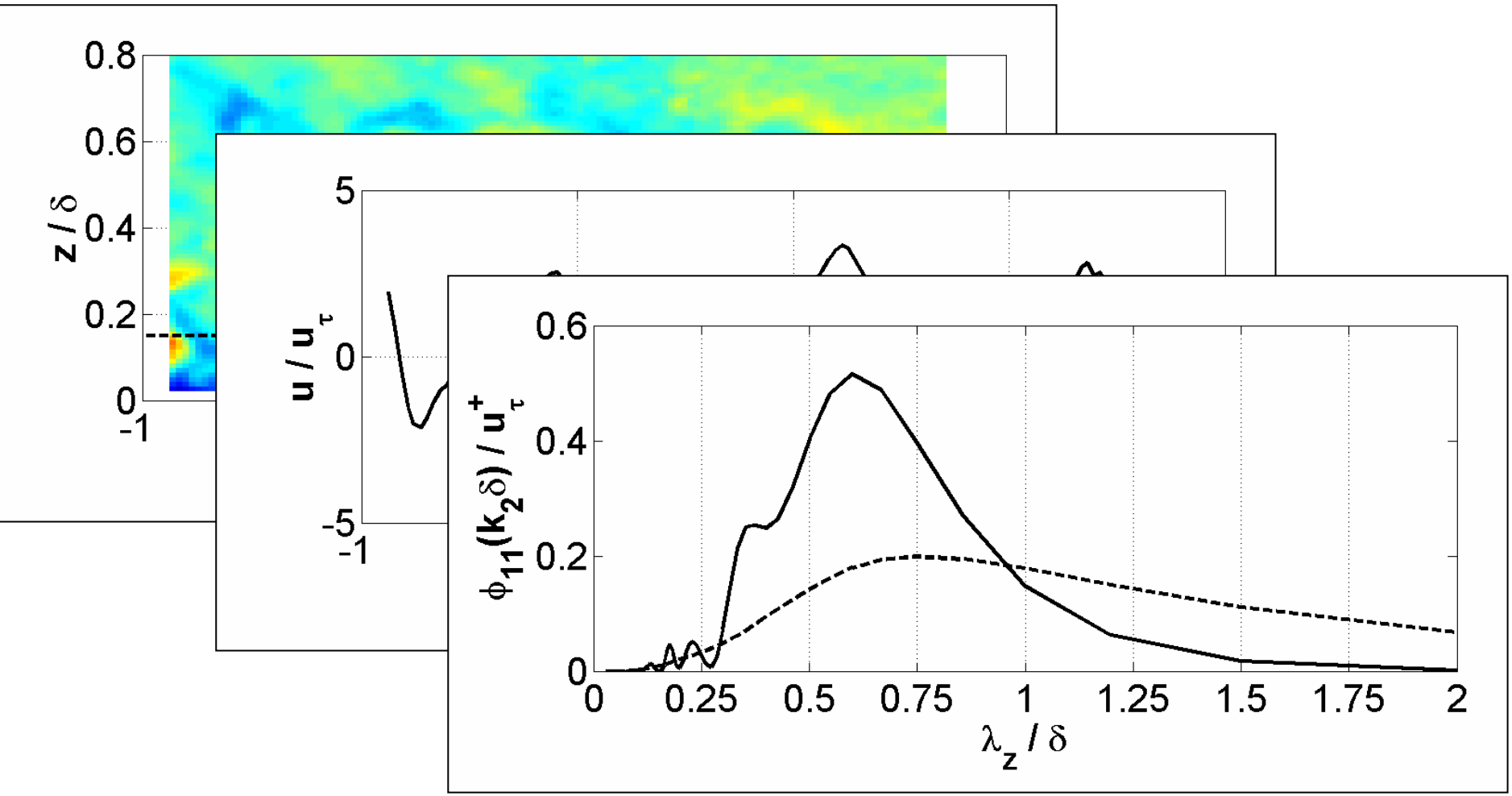
i. Select a PIV frame (frame 1)



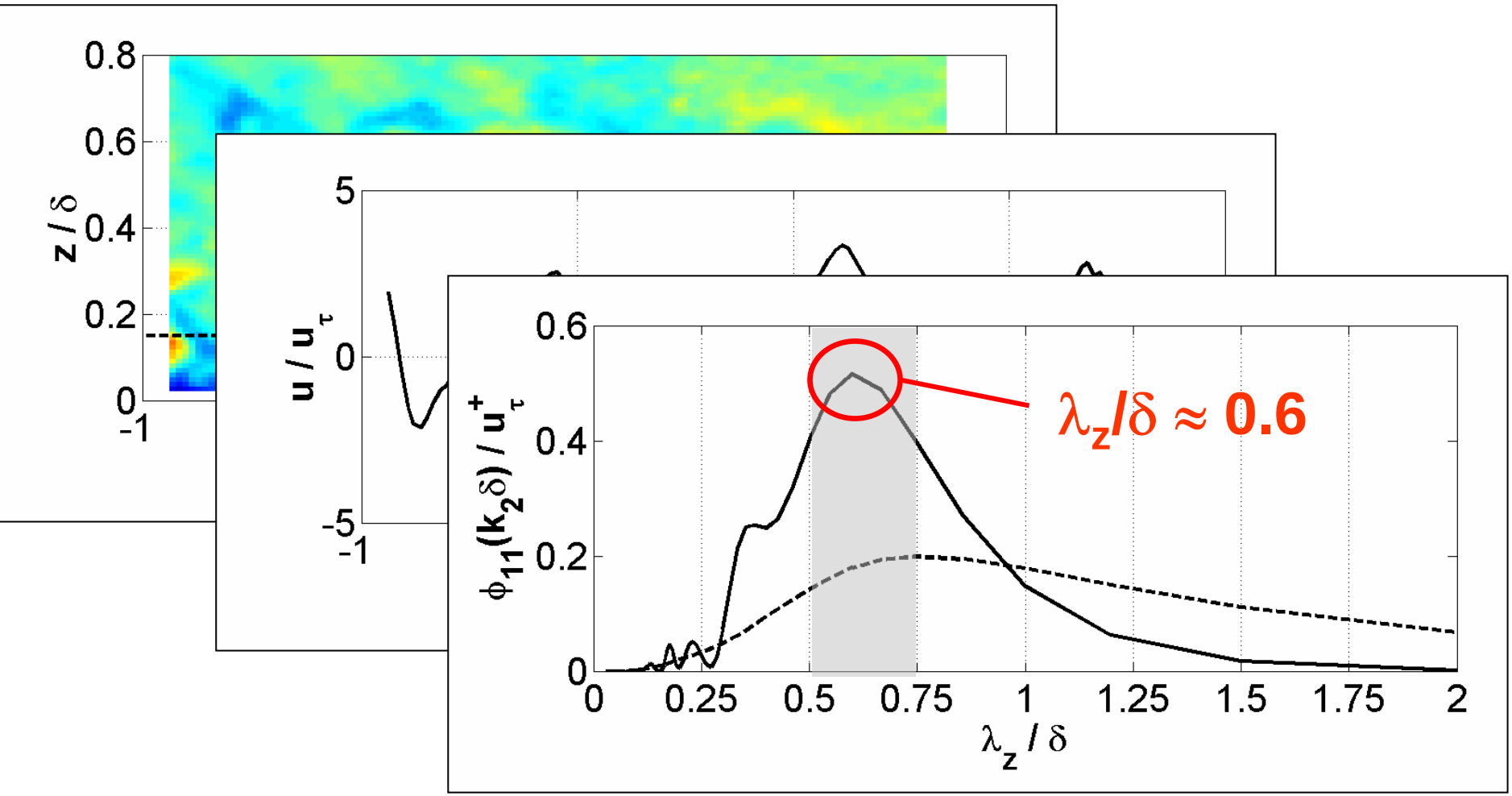
ii. Extract the spanwise *u* signal at the reference height.



iii. Look at the spanwise energetic modes.

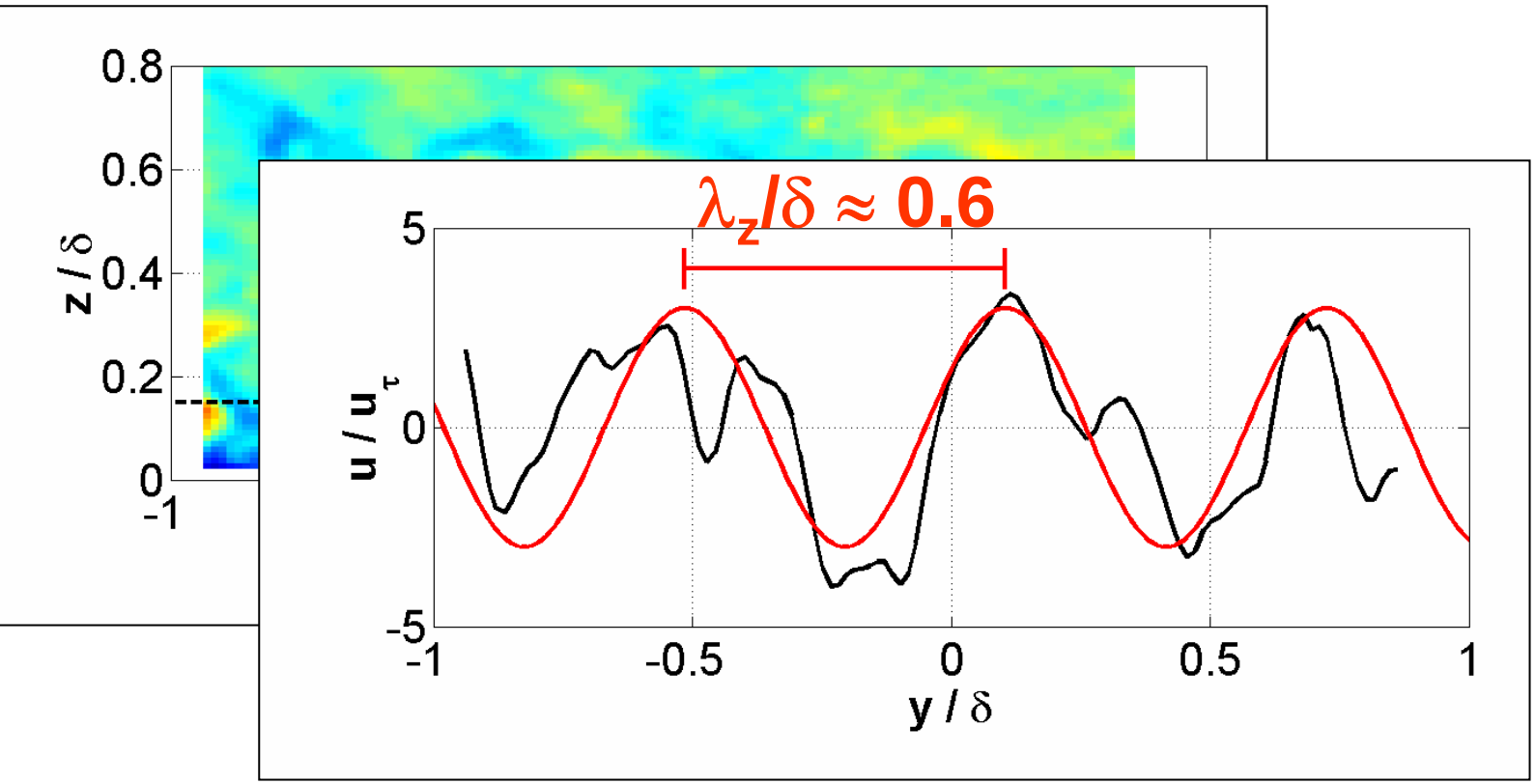


iii. Look at the spanwise energetic modes.



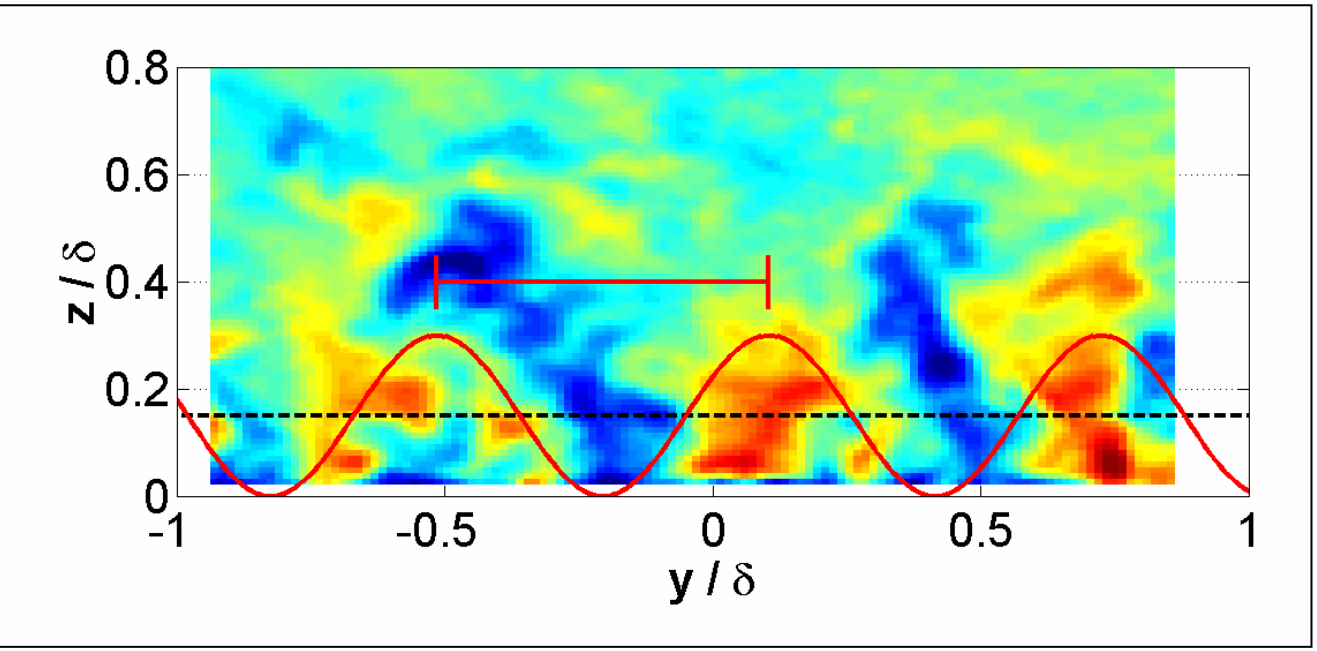
iv. ‘Bin’ accordingly ($0.5 < \lambda_z/\delta < 0.75$)

iii. Look at the spanwise energetic modes.



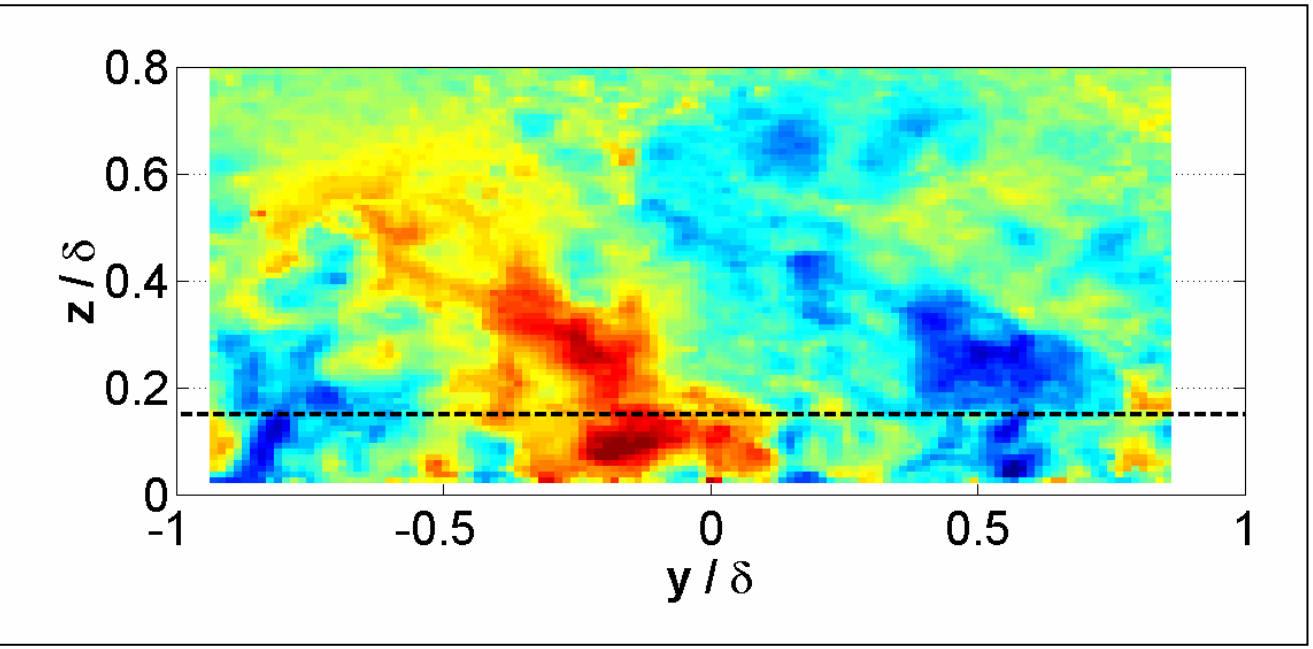
iv. ‘Bin’ accordingly ($0.5 < \lambda_z/\delta < 0.75$)

iii. Look at the spanwise energetic modes.

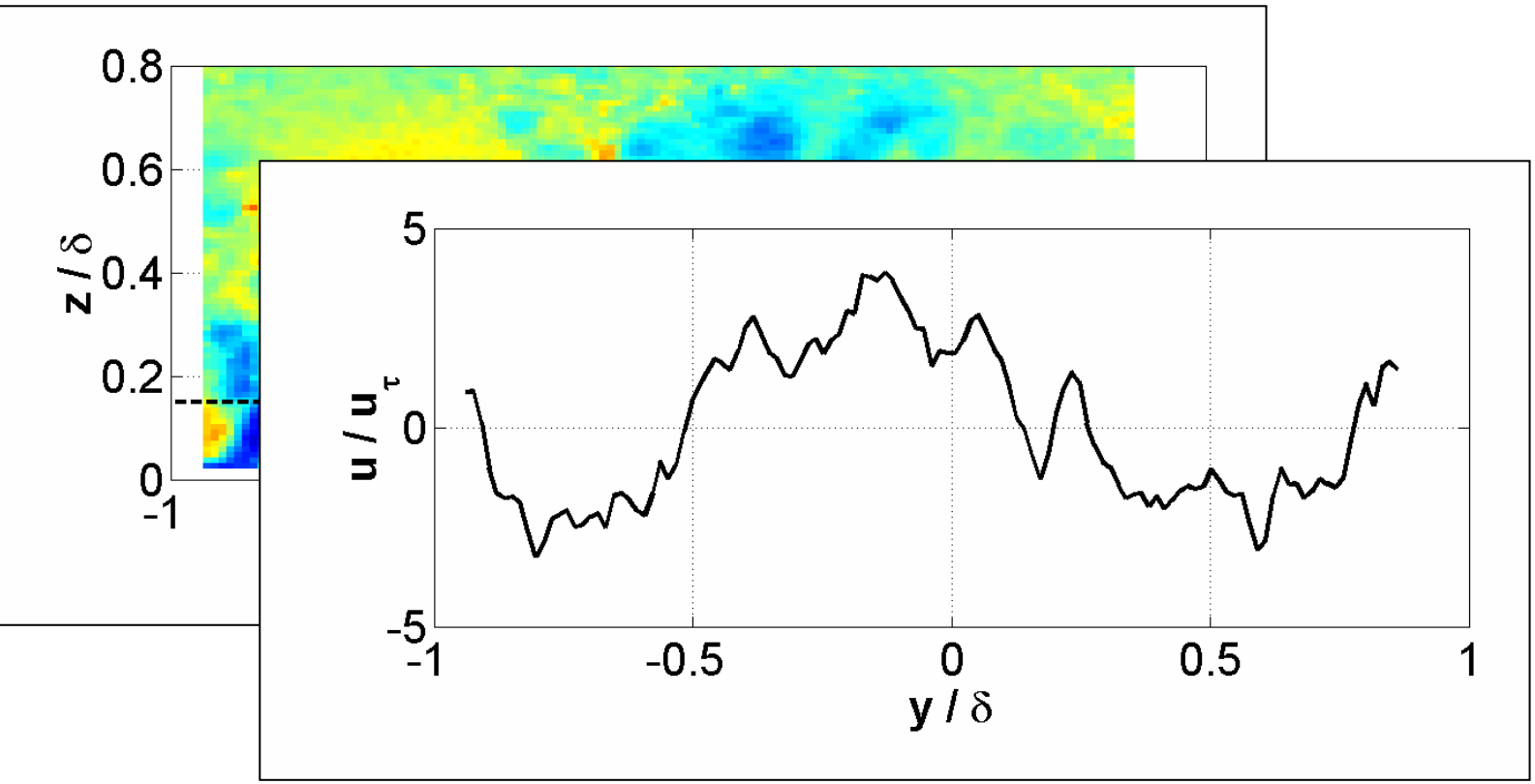


iv. ‘Bin’ accordingly $(0.5 < \lambda_z/\delta < 0.75)$

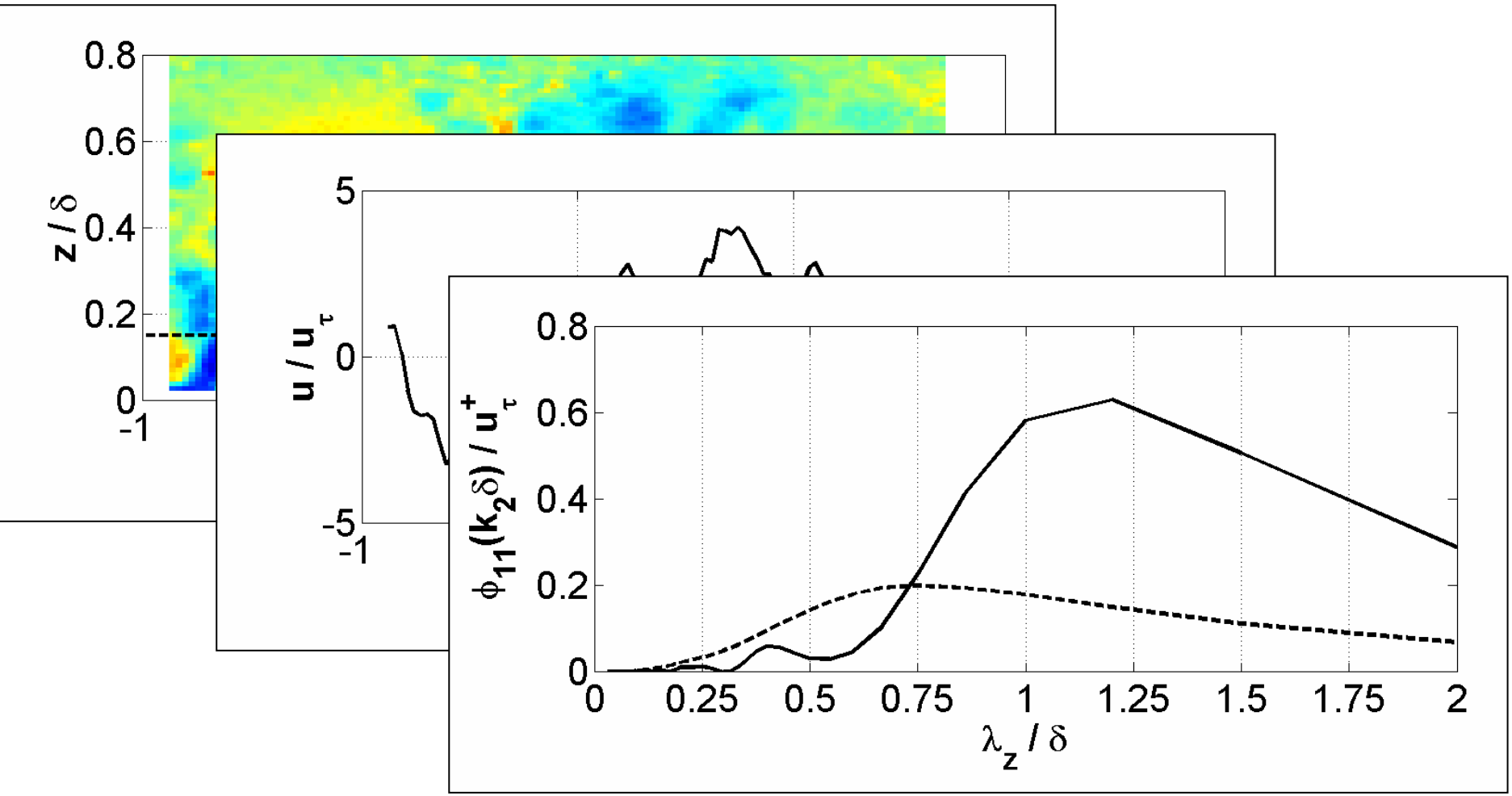
i. Select a PIV frame (frame 209)



ii. Extract the spanwise *u* signal at the reference height.

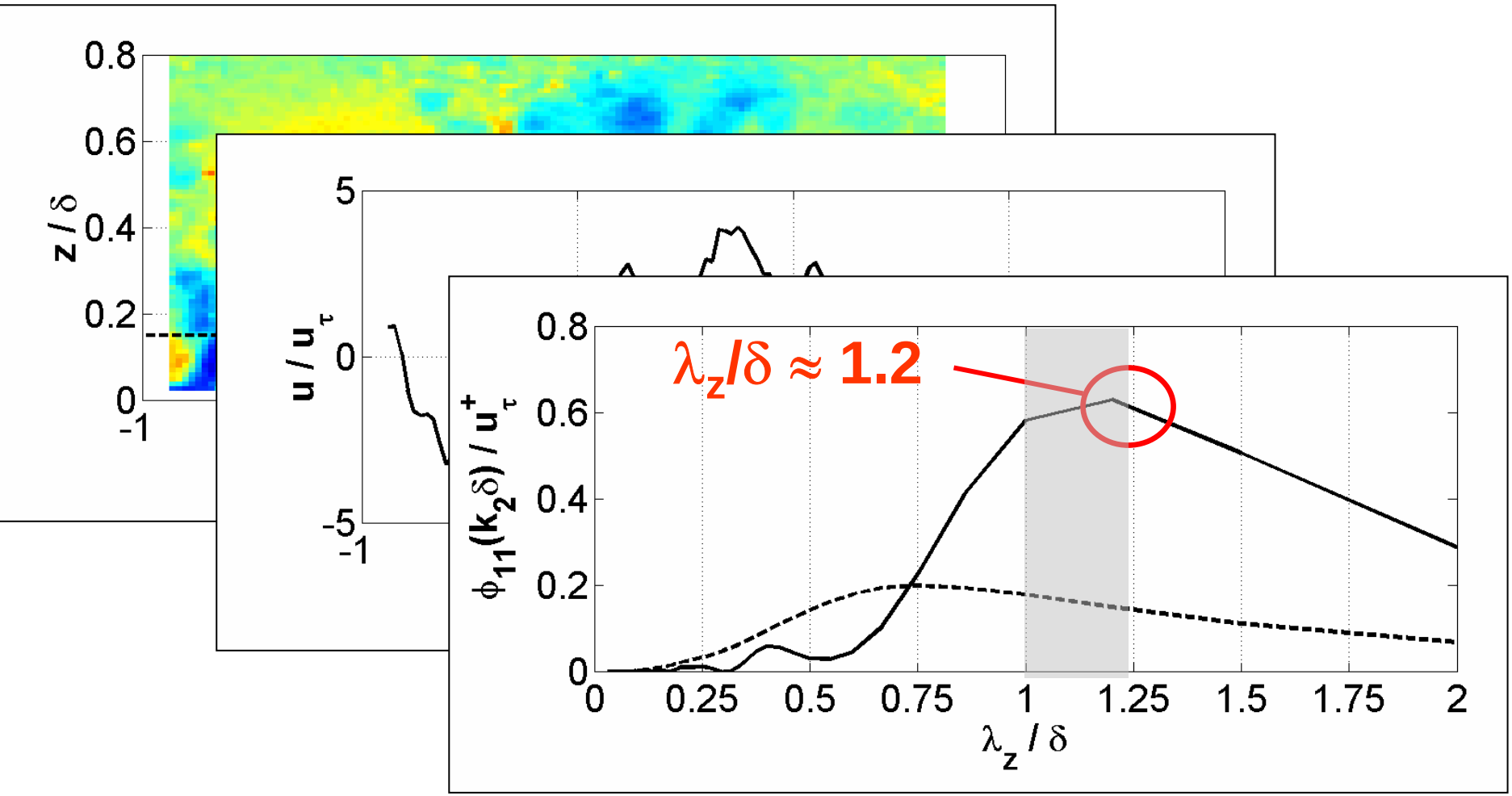


iii. Look at the spanwise energetic modes.



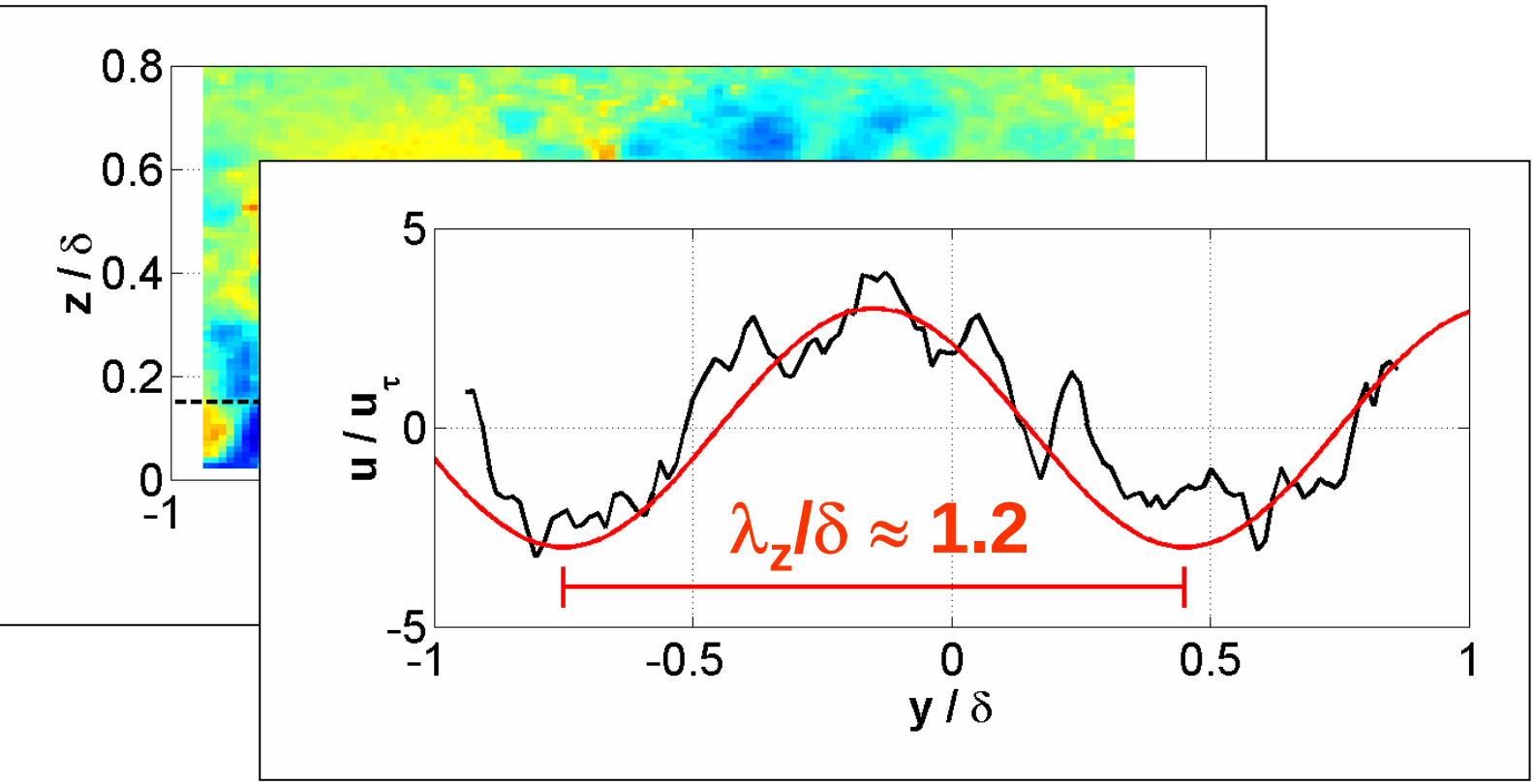
iv. ‘Bin’ accordingly ($1 < \lambda_z/\delta < 1.25$)

iii. Look at the spanwise energetic modes.



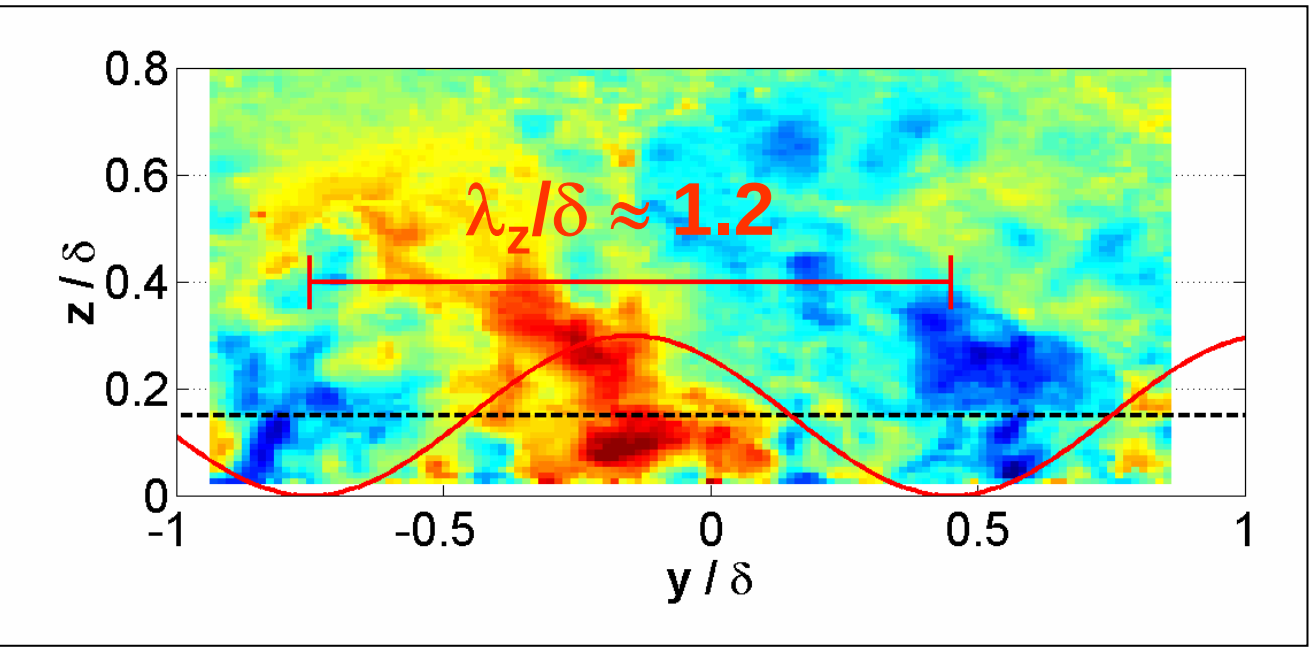
iv. ‘Bin’ accordingly ($1 < \lambda_z/\delta < 1.25$)

iii. Look at the spanwise energetic modes.



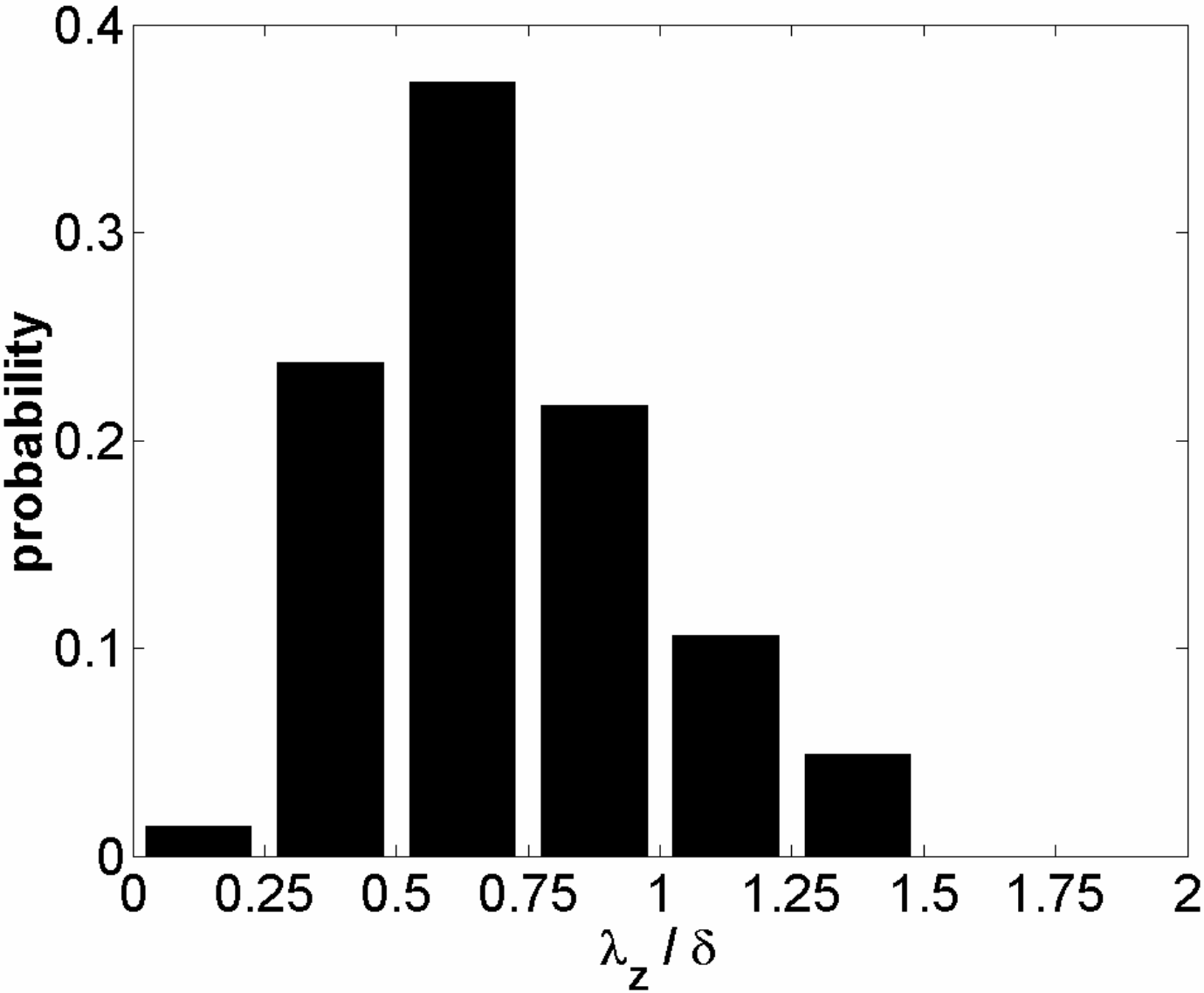
iv. ‘Bin’ accordingly ($1 < \lambda_z/\delta < 1.25$)

iii. Look at the spanwise energetic modes.

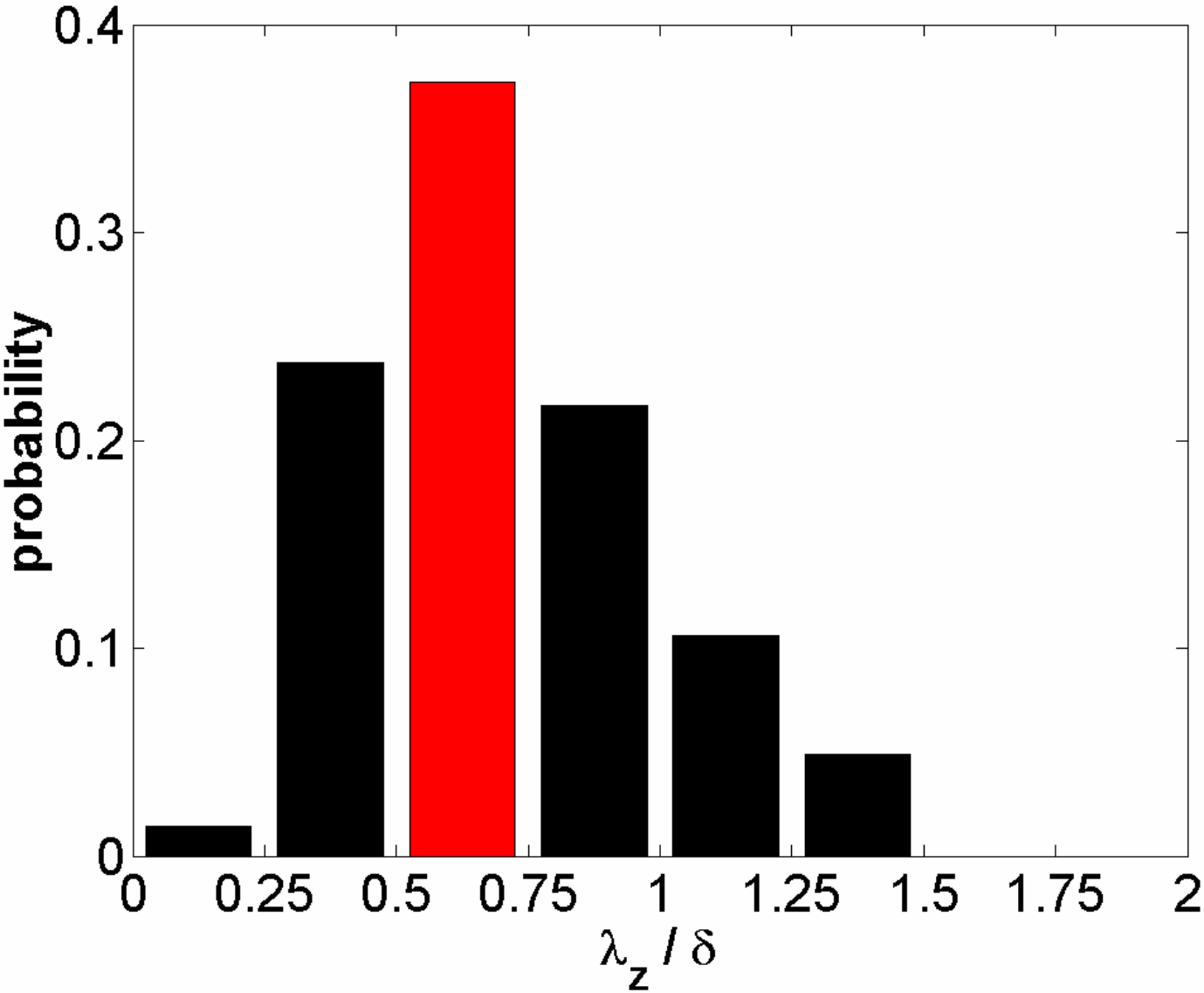


iv. ‘Bin’ accordingly ($1 < \lambda_z/\delta < 1.25$)

Binned frames according to dominant spanwise mode



Binned frames according to dominant spanwise mode



Calculate R_{uu} on only those frames that fall in the $0.5 < \lambda_z/\delta < 0.75$ bin

↓

Because of the ‘sorting condition’ we would expect some ringing in the correlation at $z_{ref} = 0.2\delta$, with an approximate lengthscale $0.5 < \lambda_z/\delta < 0.75$

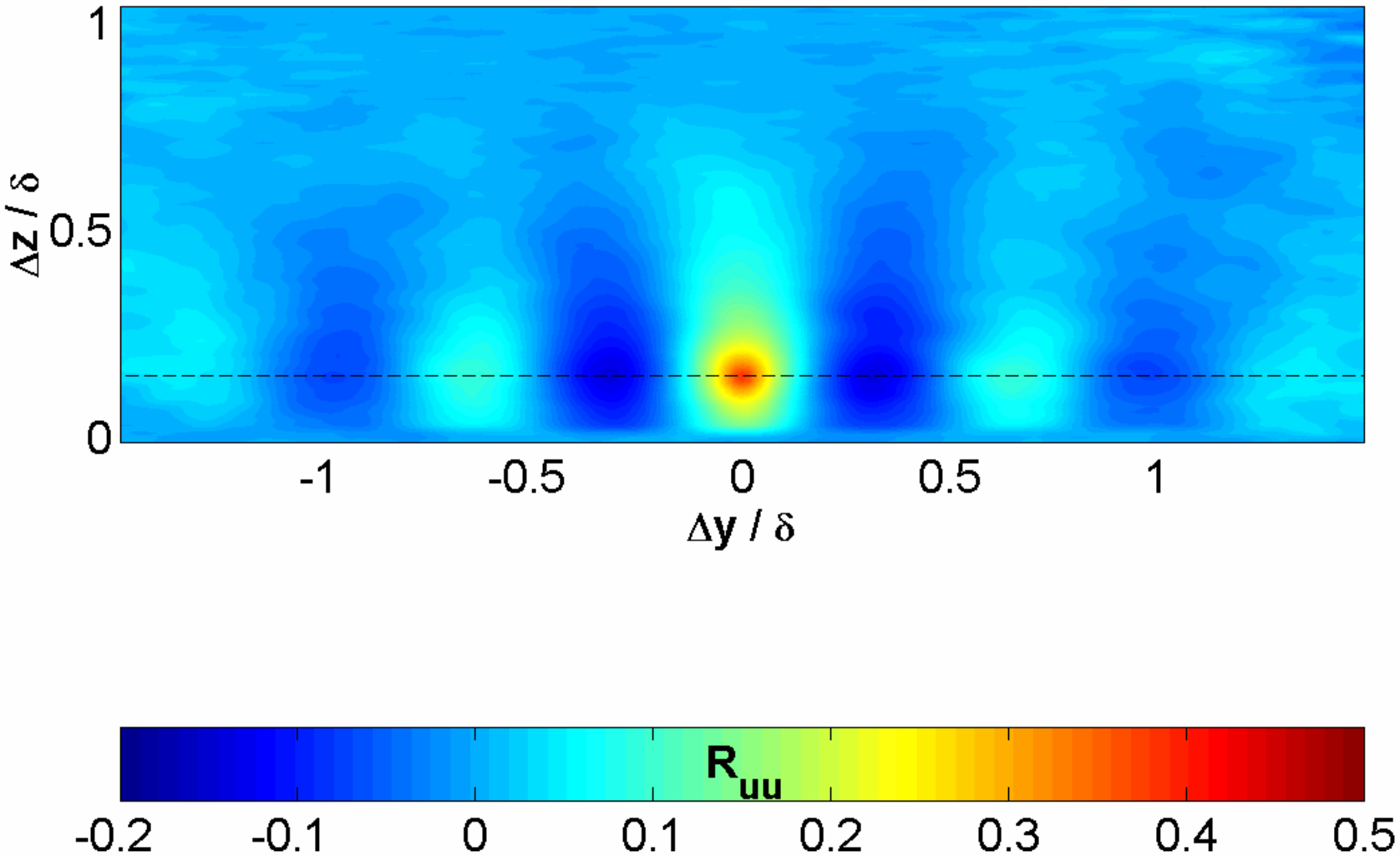
↓

However such behaviour is only prescribed by the method at z_{ref}

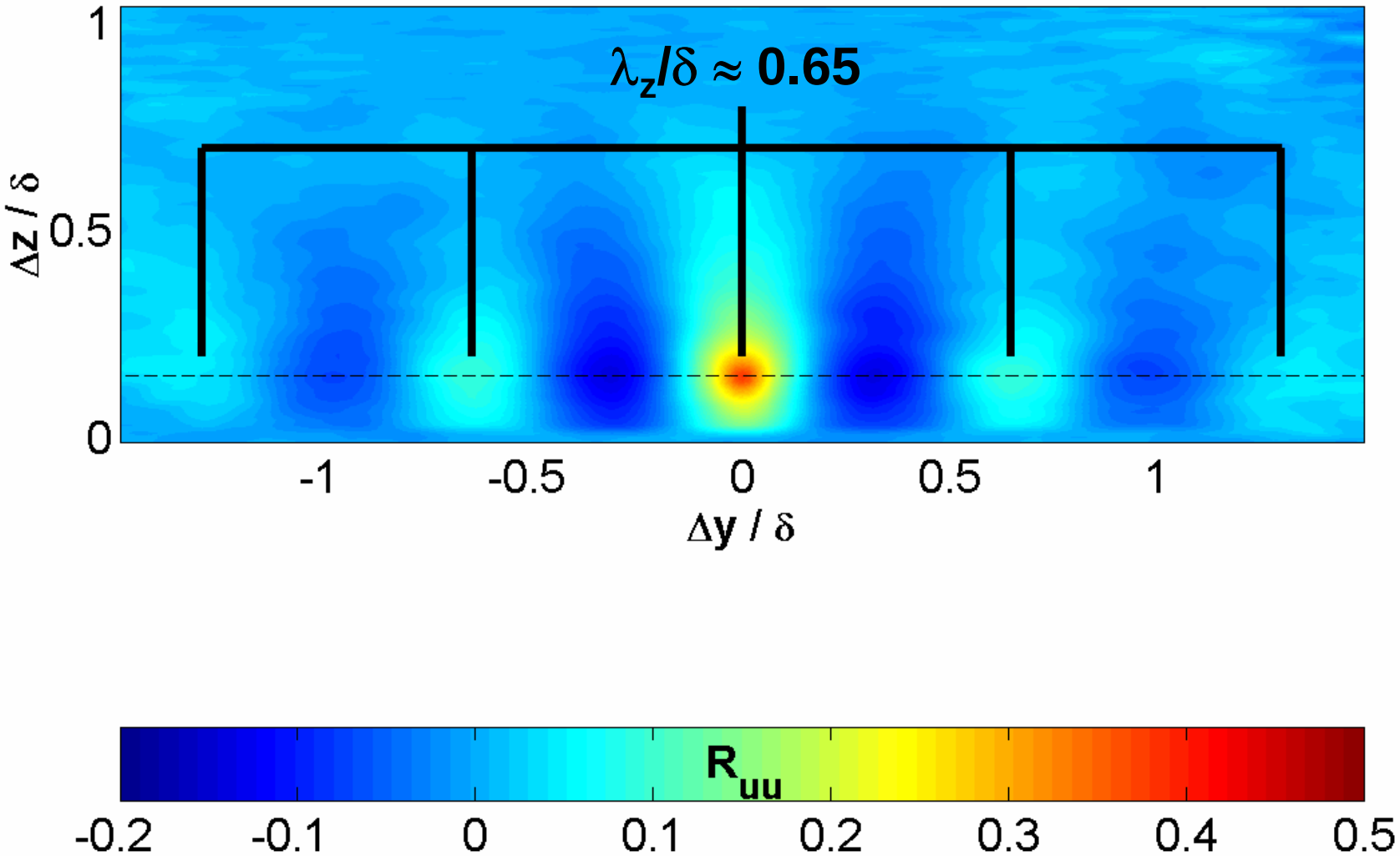
↓

Beyond which any wall-normal coherence is indicative of a wider structural behaviour

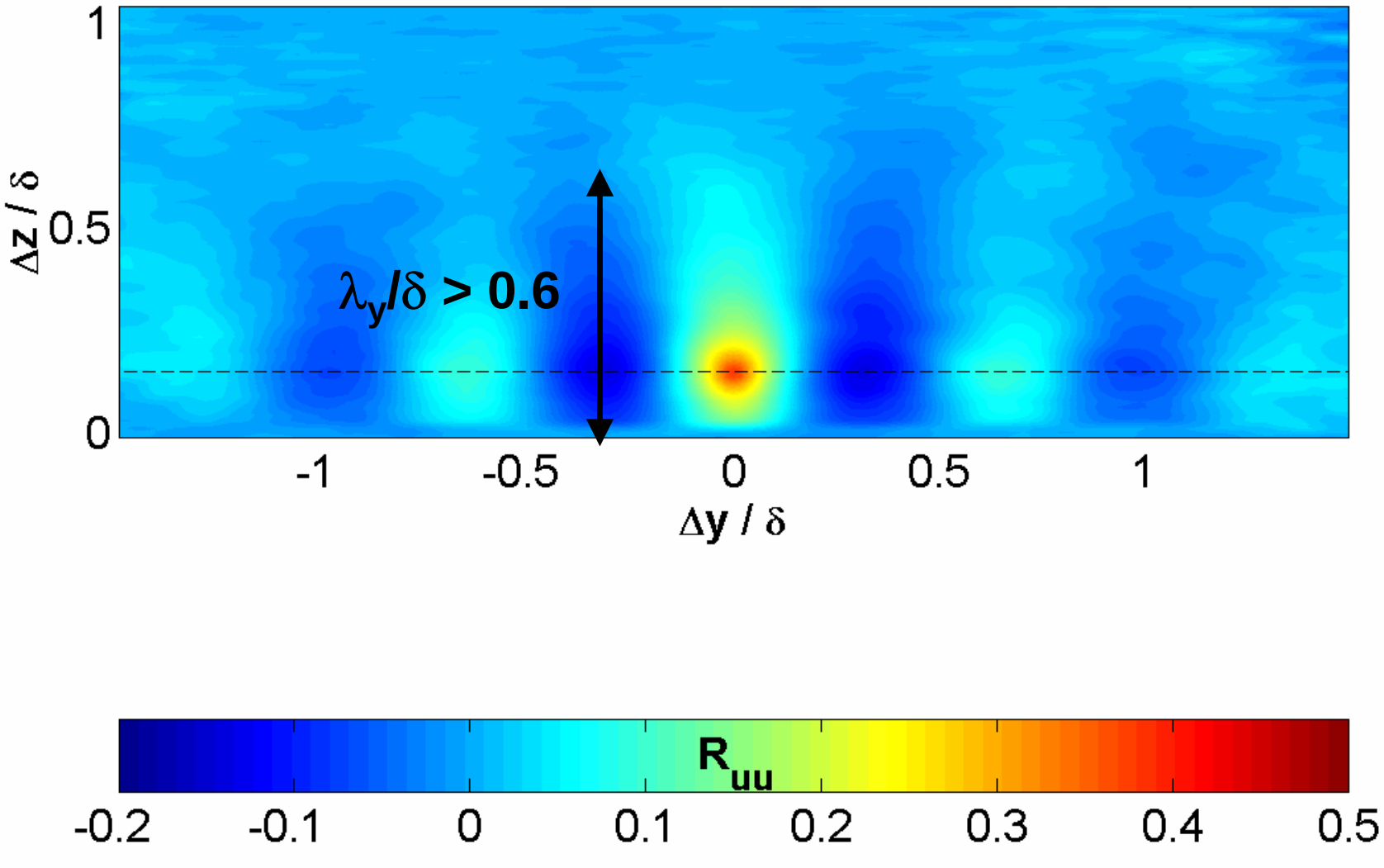
Calculate R_{uu} on only those frames that fall in the $0.5 < \lambda_z\delta < 0.75$ bin



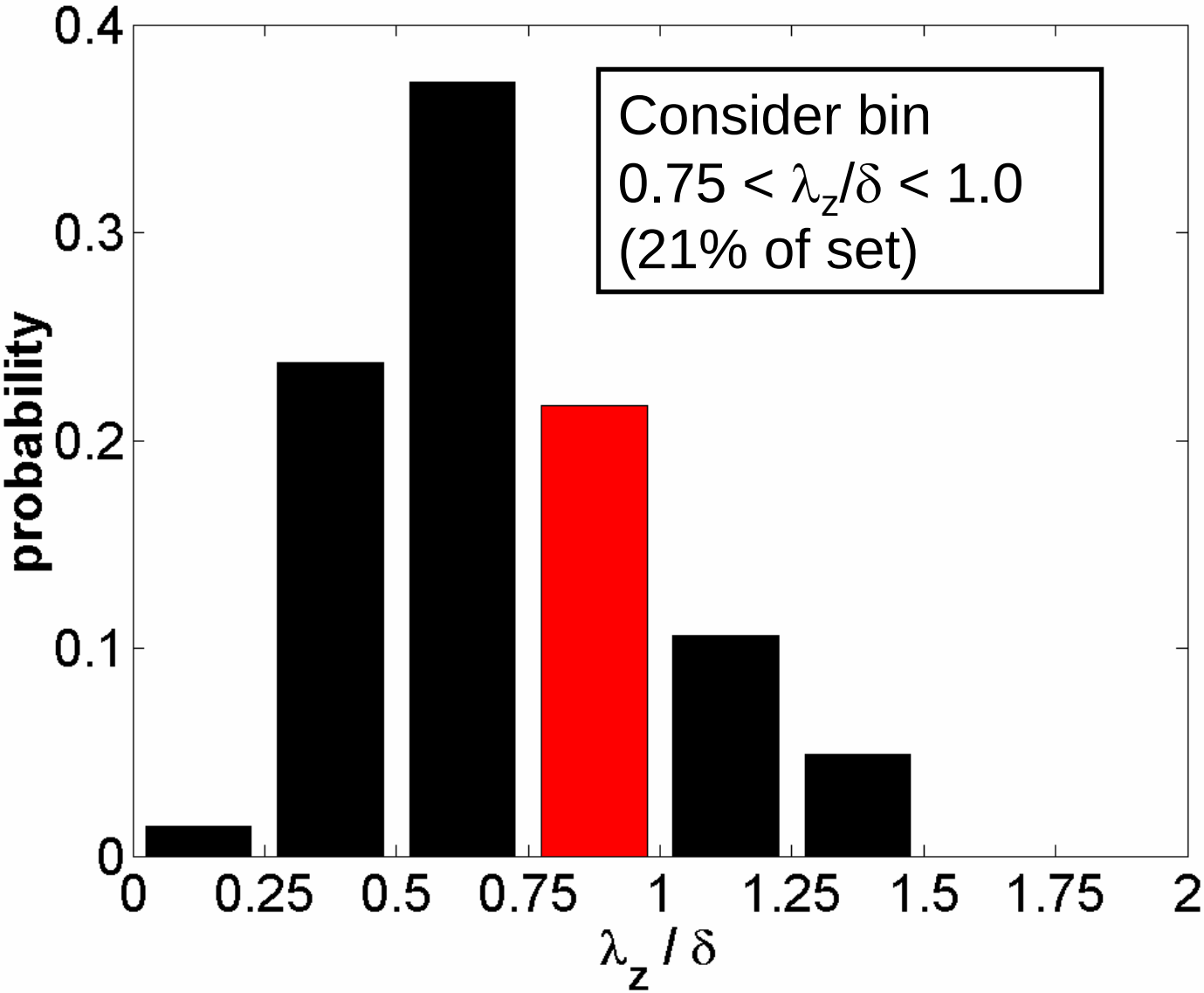
Calculate R_{uu} on only those frames that fall in the $0.5 < \lambda_z\delta < 0.75$ bin



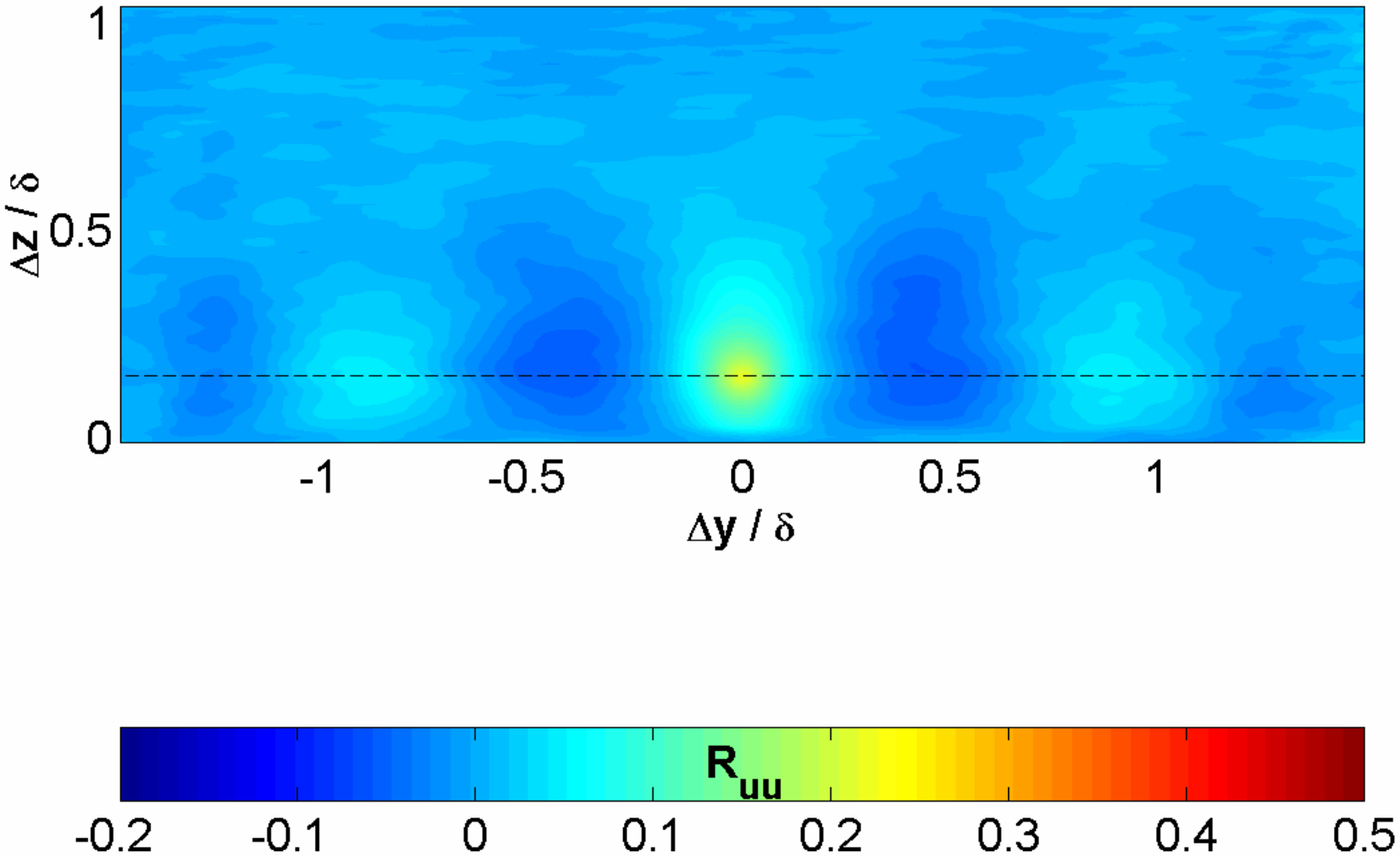
Calculate R_{uu} on only those frames that fall in the $0.5 < \lambda_z\delta < 0.75$ bin



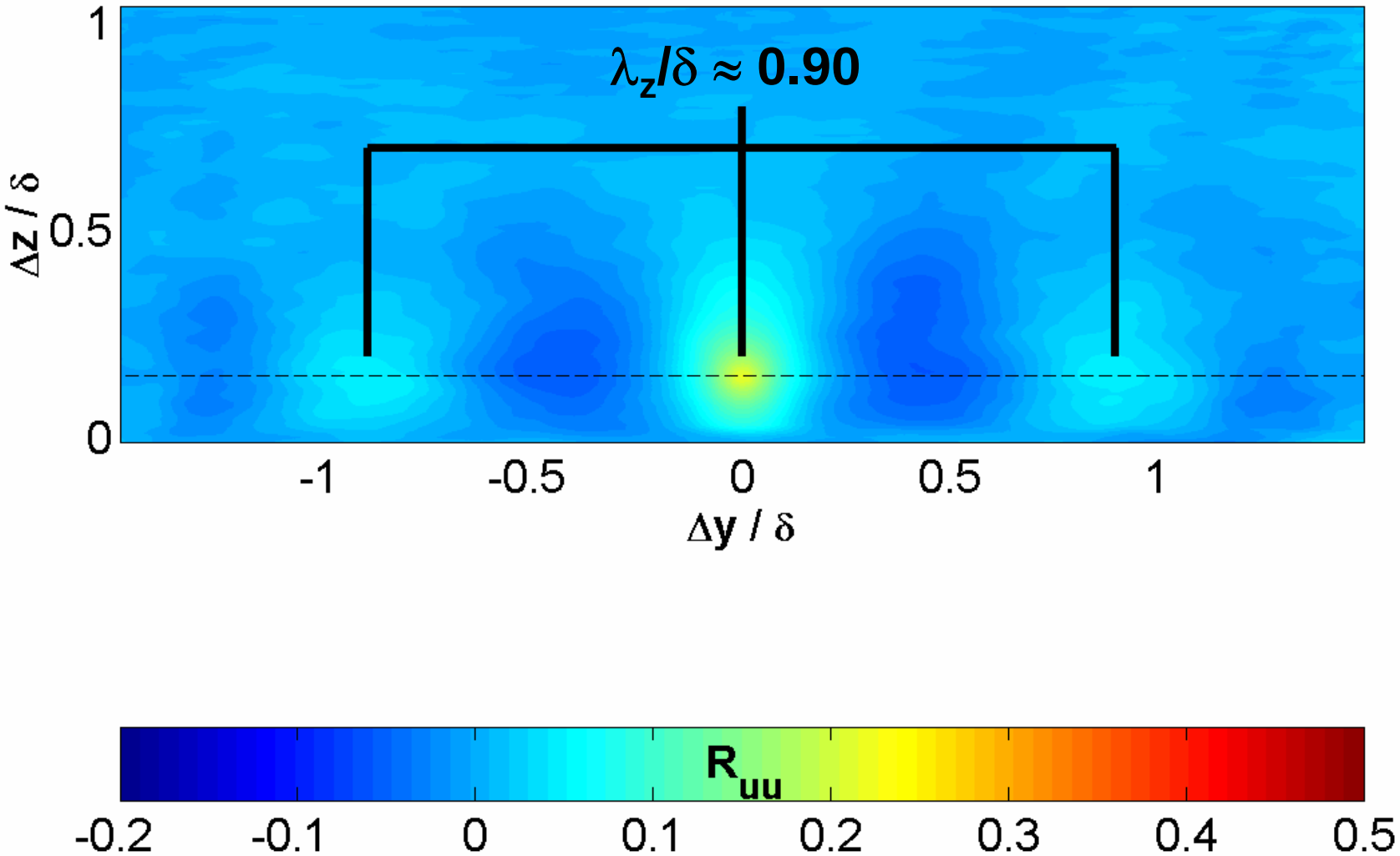
Off-peak modes



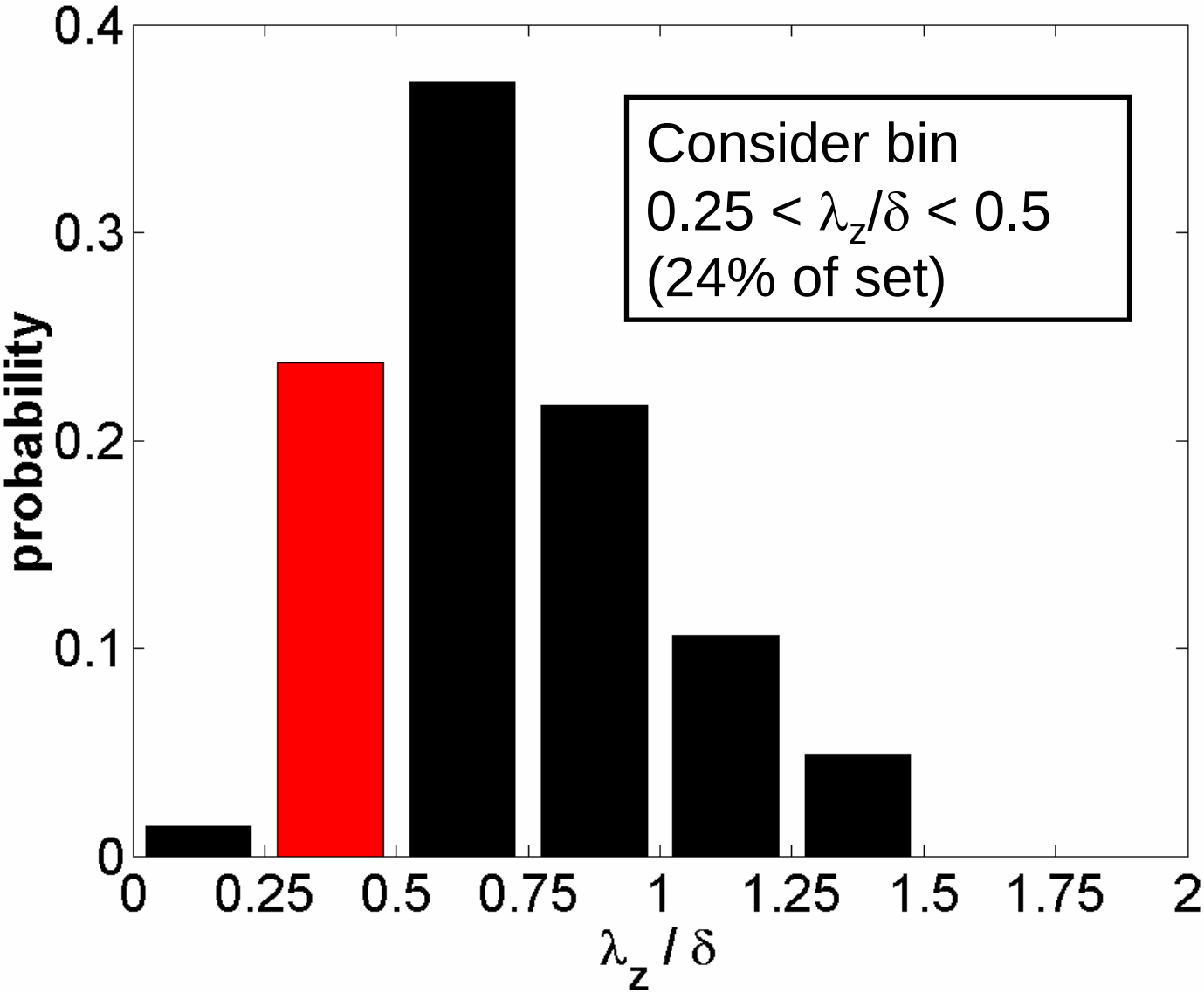
Calculate R_{uu} on only those frames that fall in the $0.75 < \lambda_z\delta < 1.0$ bin



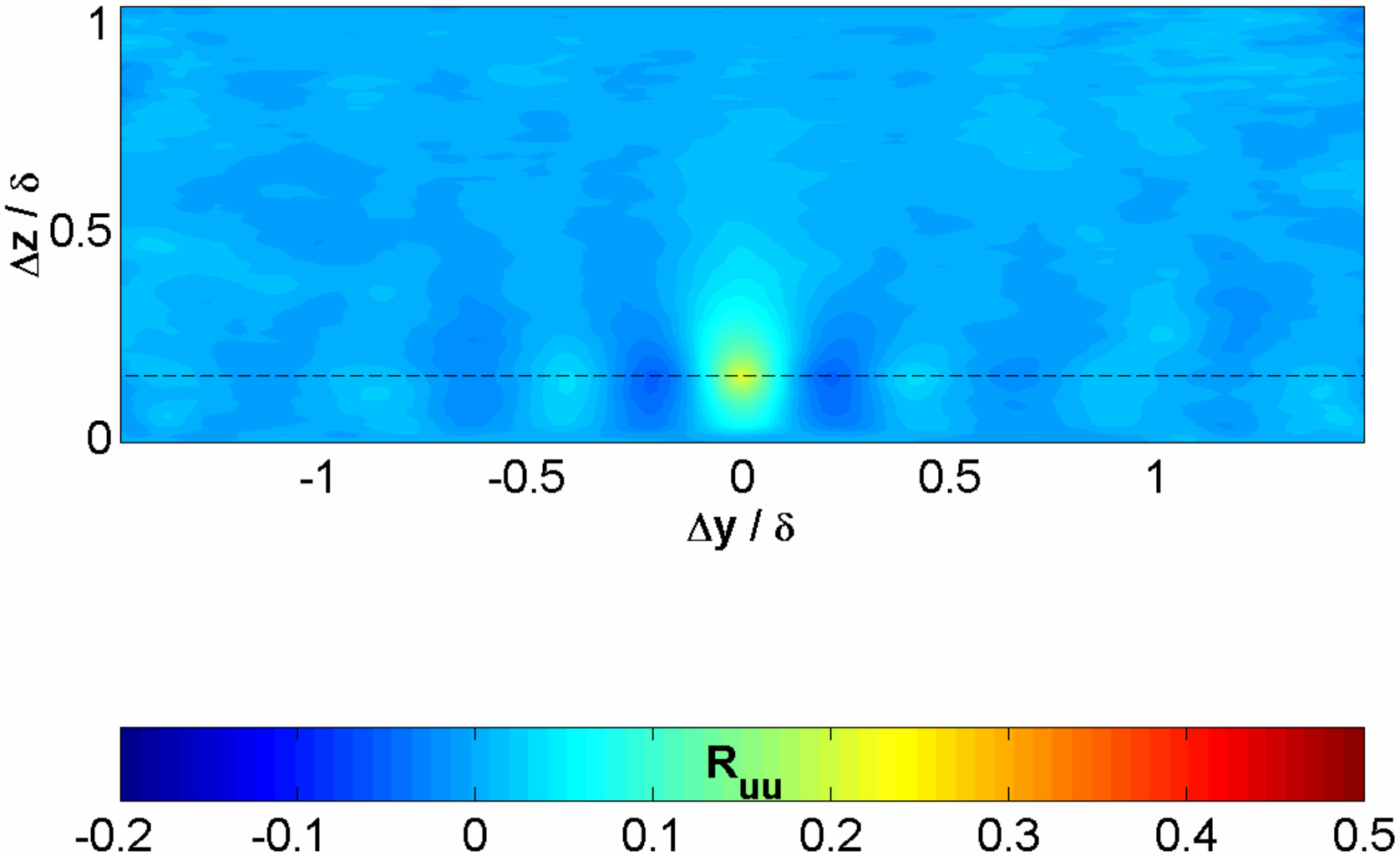
Calculate R_{uu} on only those frames that fall in the $0.75 < \lambda_z\delta < 1.0$ bin



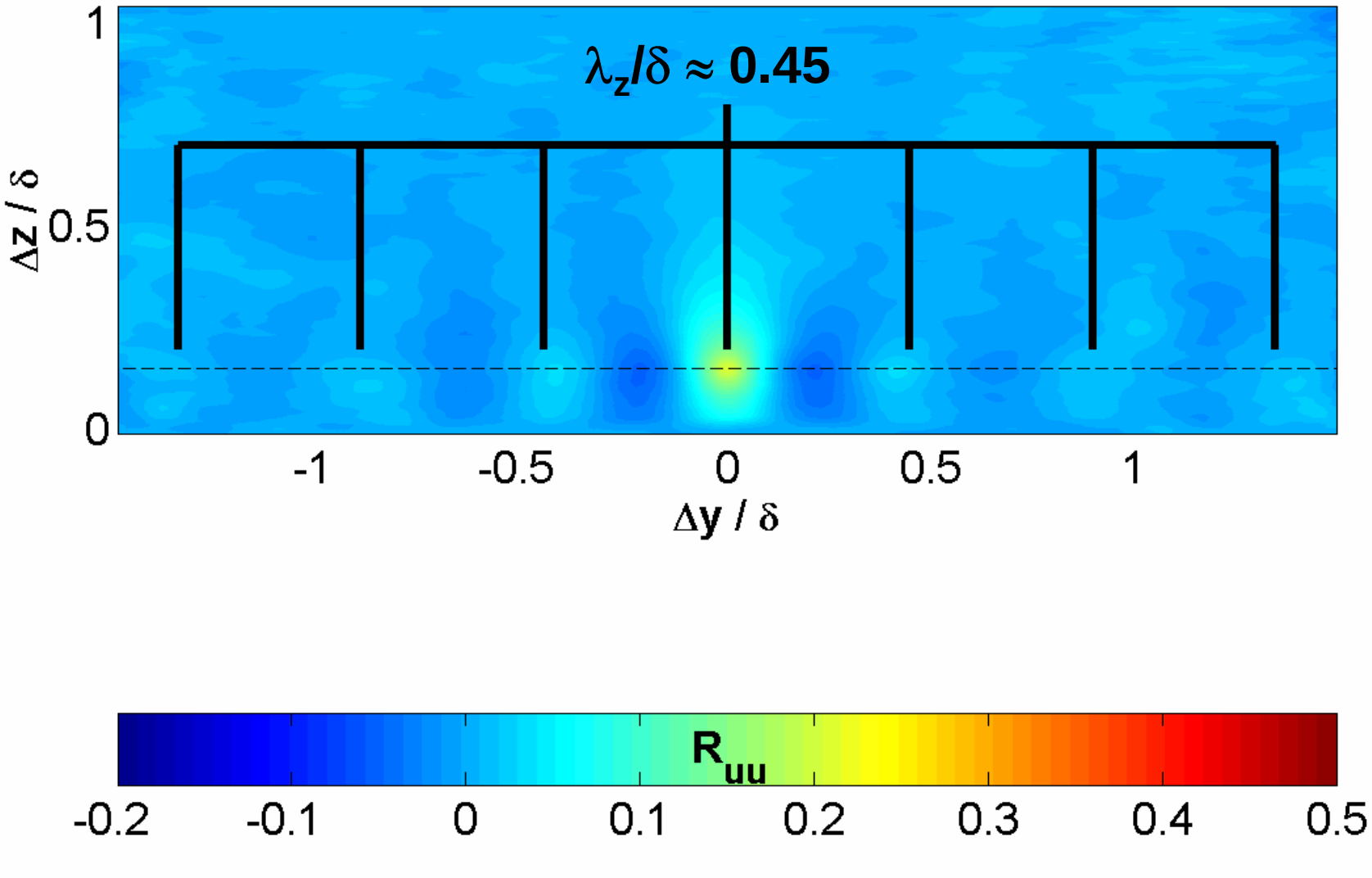
Off-peak modes



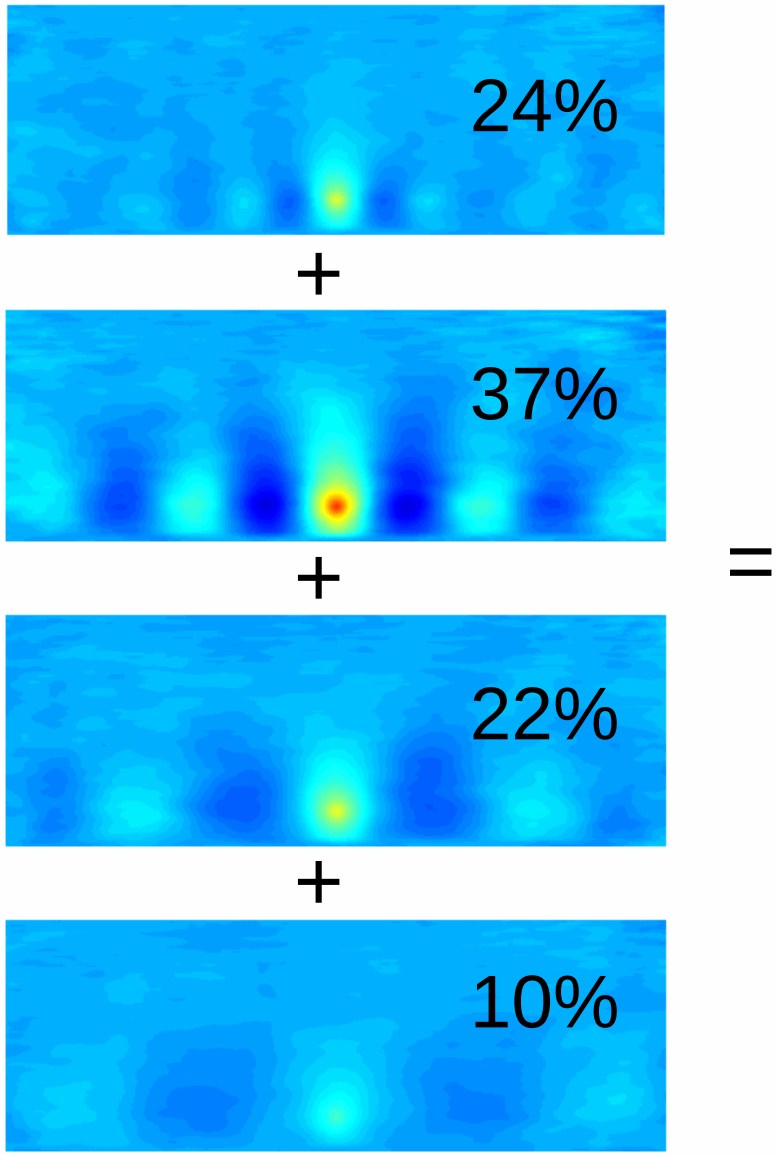
Calculate R_{uu} on only those frames that fall in the $0.25 < \lambda_z\delta < 0.5$ bin



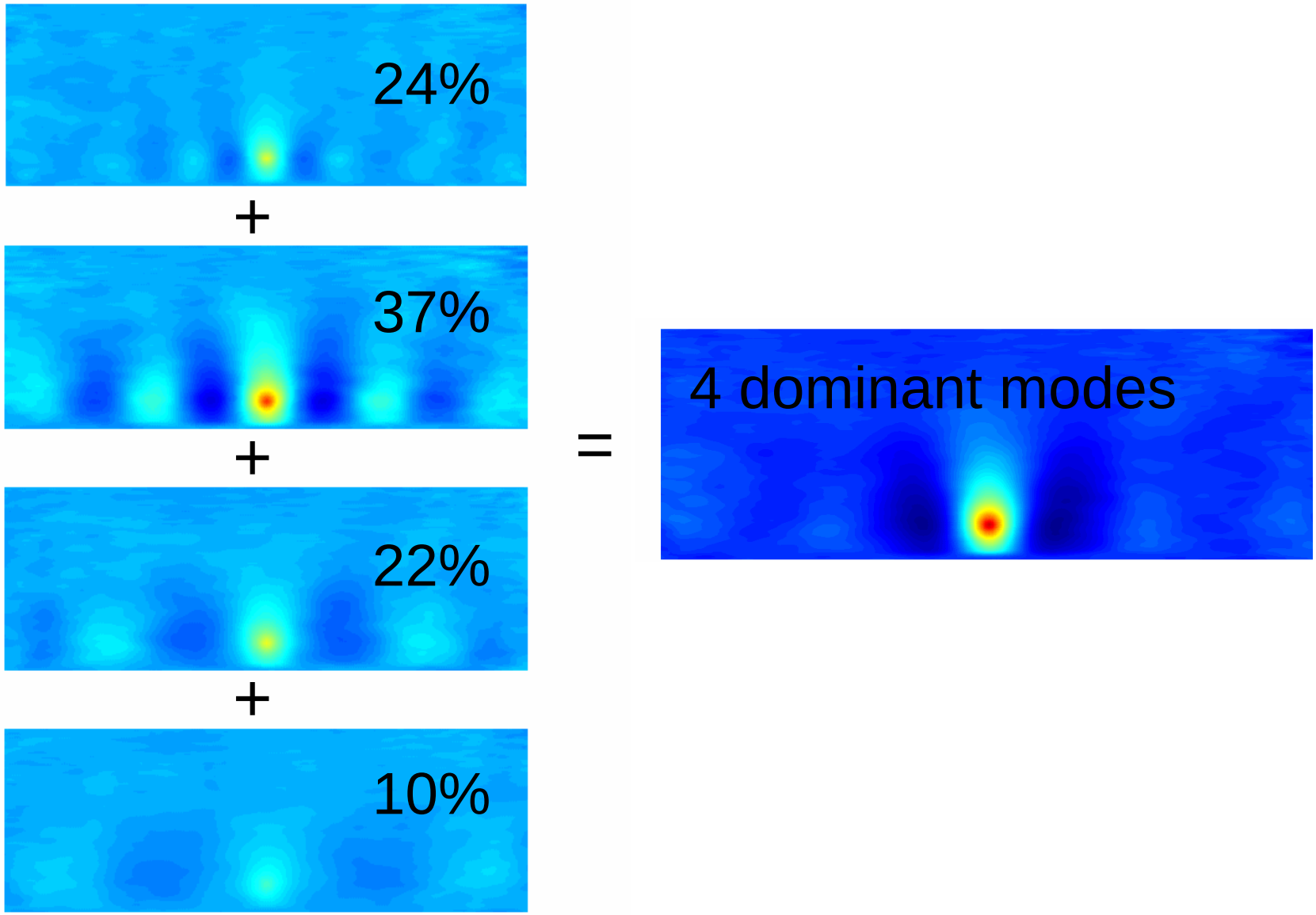
Calculate R_{uu} on only those frames that fall in the $0.25 < \lambda_z\delta < 0.5$ bin



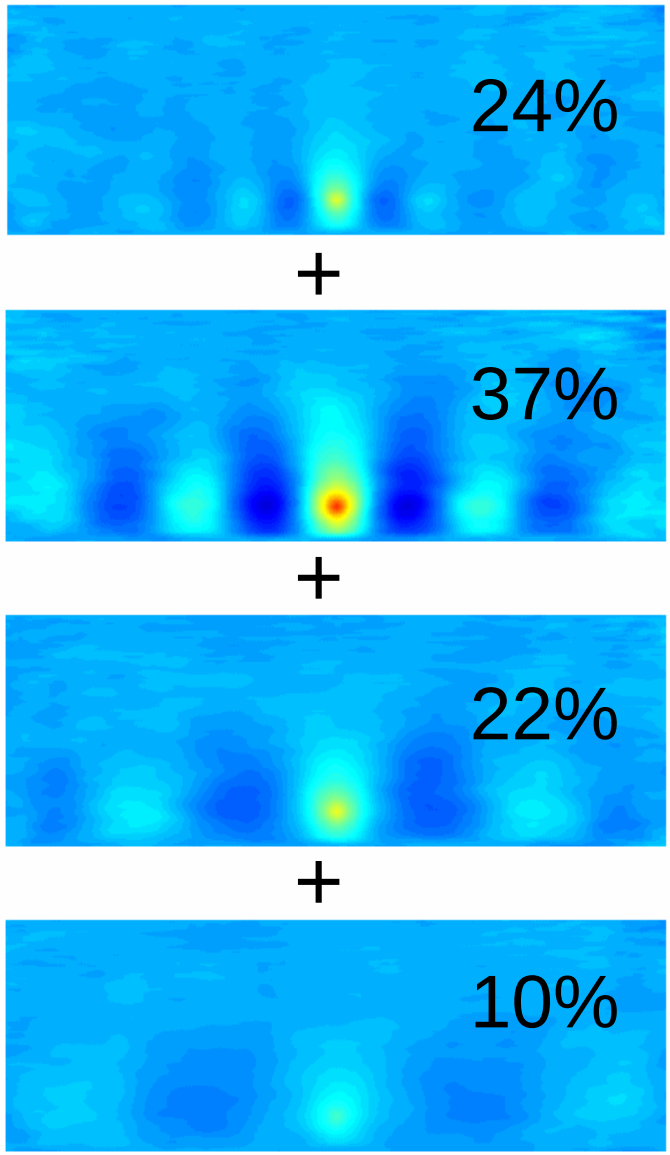
So, is the mean two-point correlation R_{uu} a red-herring?



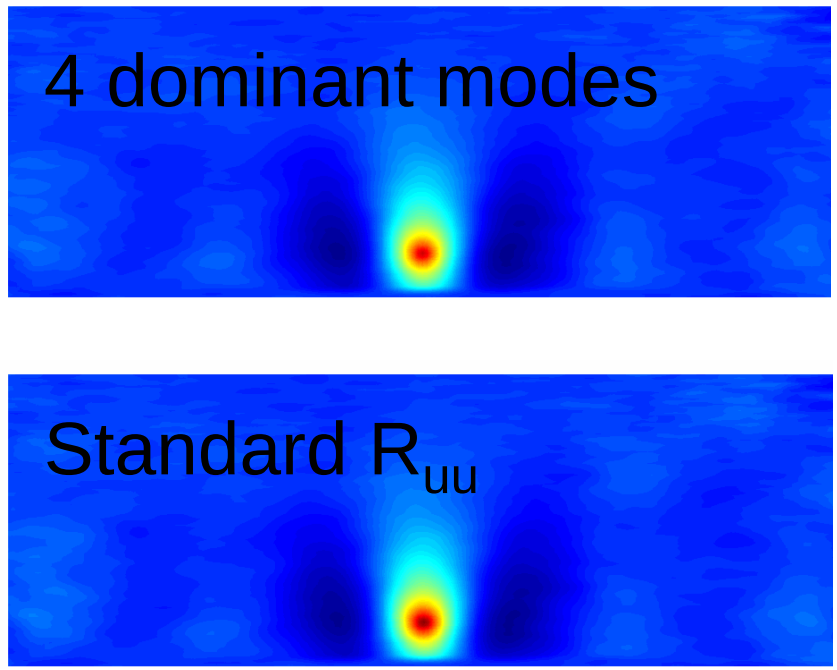
So, is the mean two-point correlation R_{uu} a red-herring?



The two-point correlation R_{uu} is a composite of four dominant modes

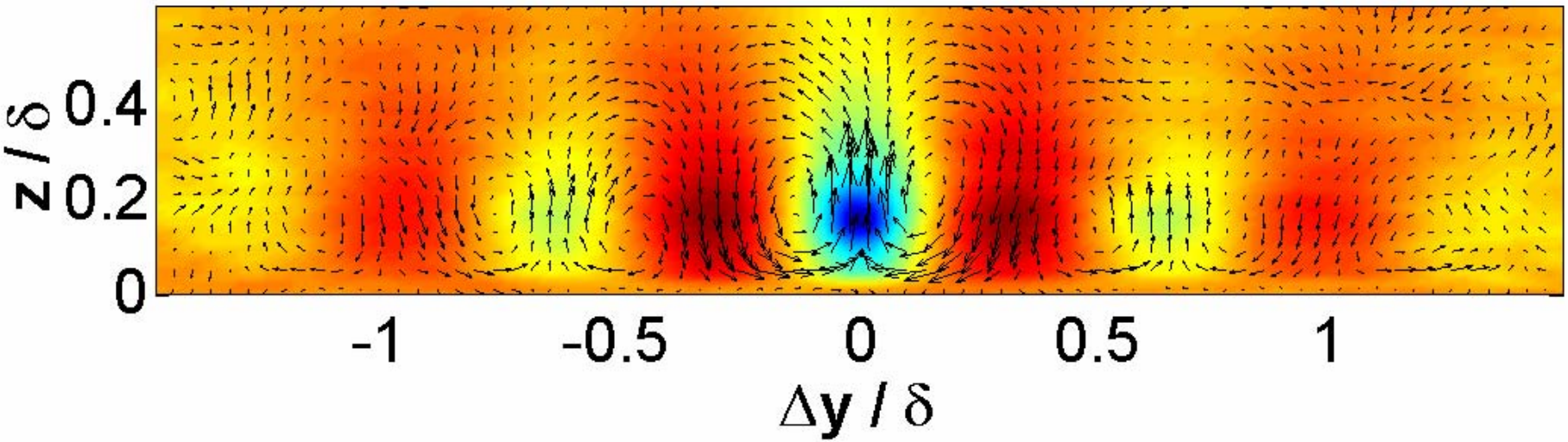


=



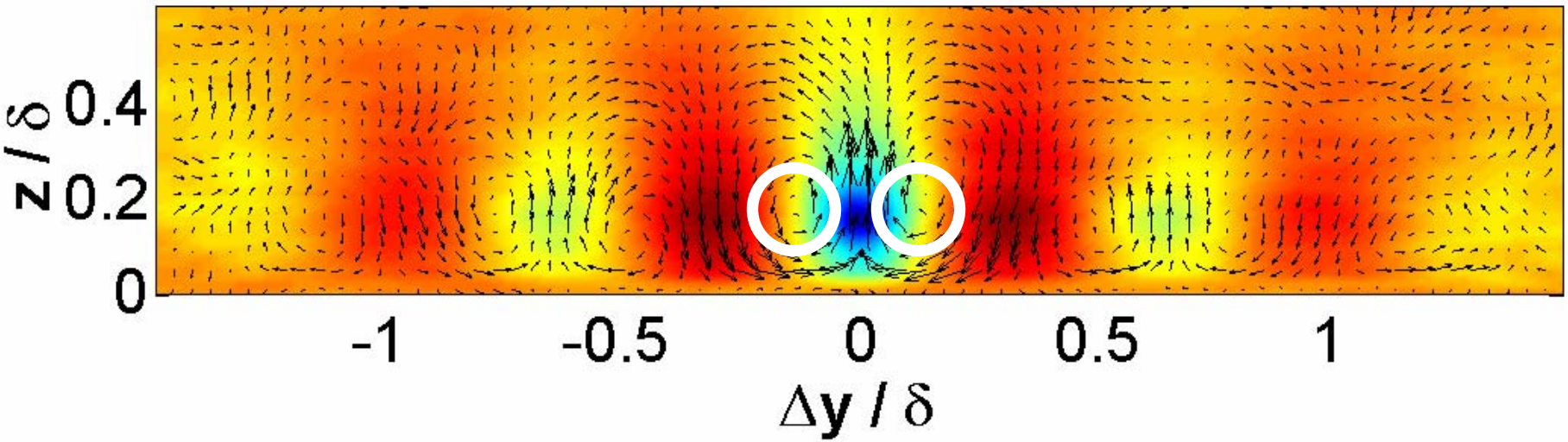
LSE result

Conditioned on low-speed event at $(0,z_{ref})$, for the frames binned with $0.5 < \lambda_z(u)/\delta < 0.75$



LSE result

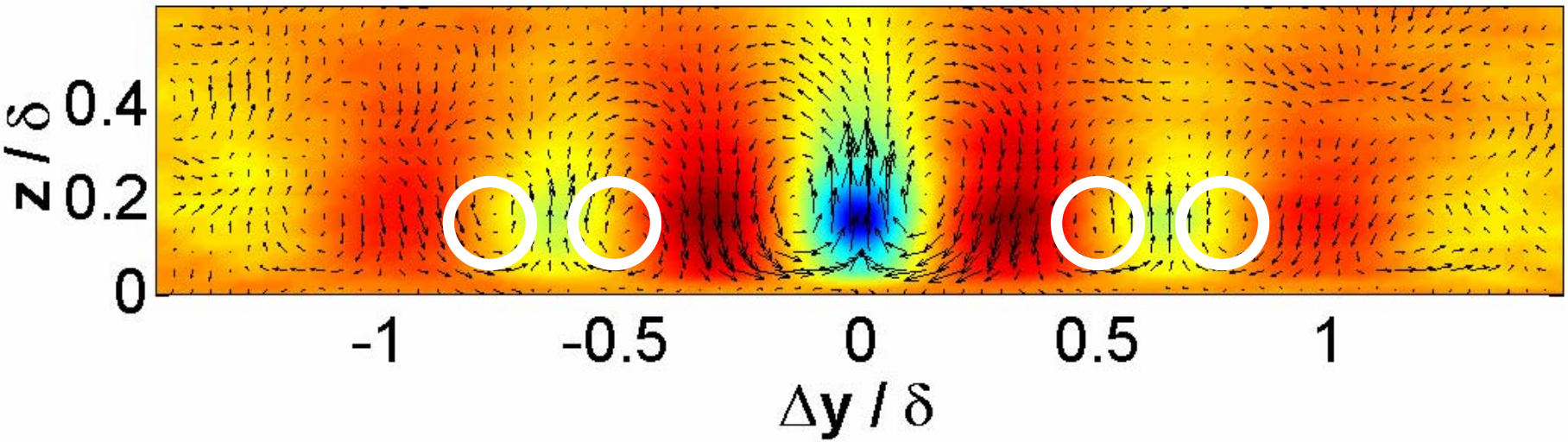
Conditioned on low-speed event at $(0,z_{ref})$, for the frames binned with $0.5 < \lambda_z(u)/\delta < 0.75$



Note: the low-speed events are actually ejections (Q2), flanked by counter-rotating swirling motions

LSE result

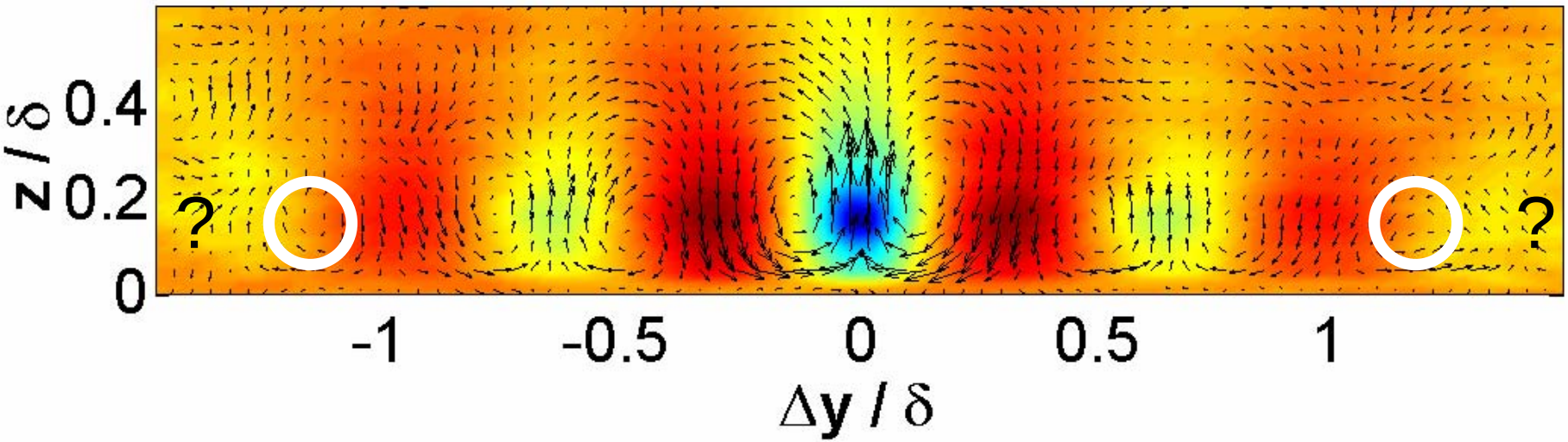
Conditioned on low-speed event at $(0,z_{ref})$, for the frames binned with $0.5 < \lambda_z(u)/\delta < 0.75$



Note: the low-speed events are actually ejections (Q2), flanked by counter-rotating swirling motions

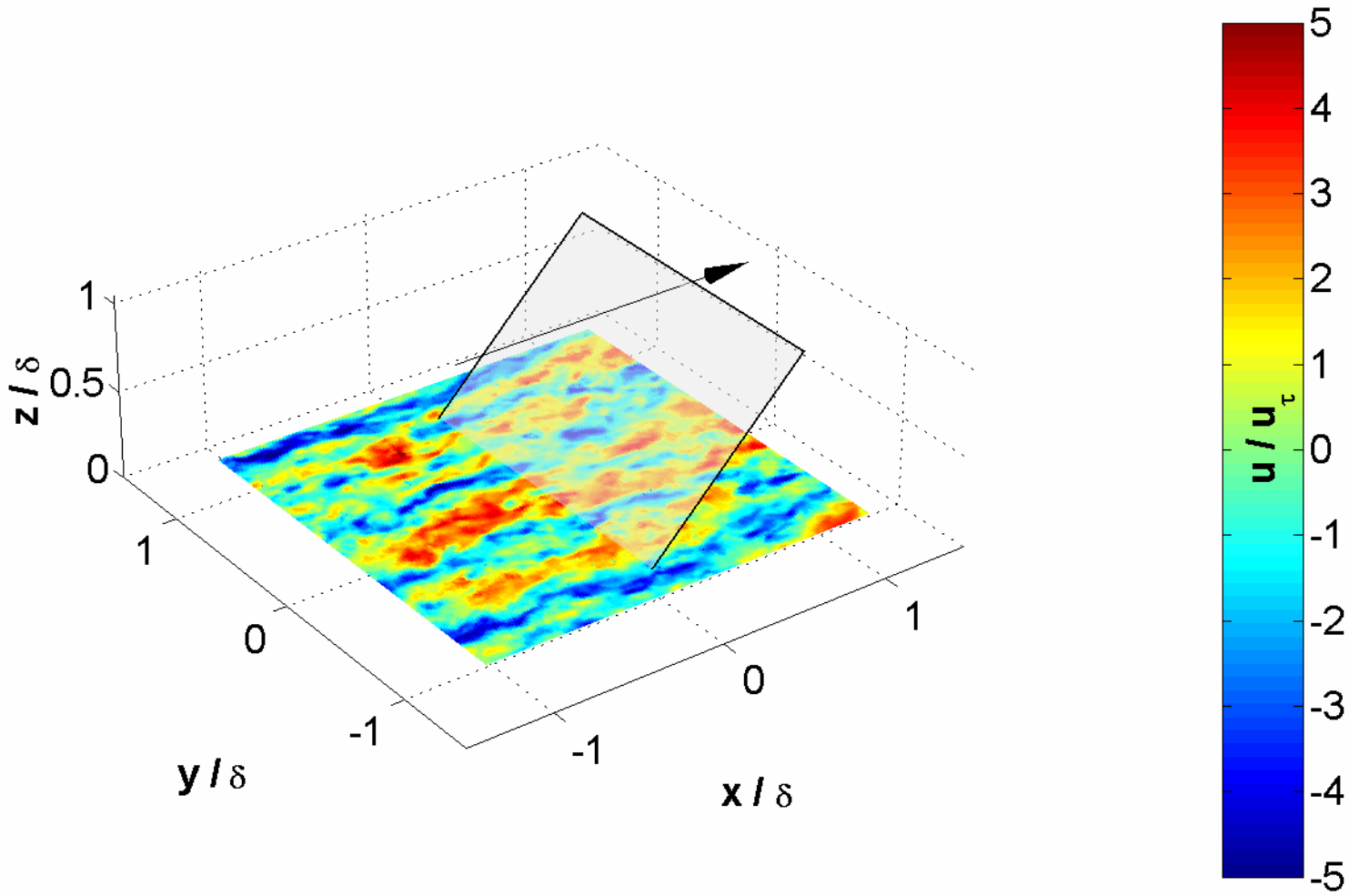
LSE result

Conditioned on low-speed event at $(0,z_{ref})$, for the frames binned with $0.5 < \lambda_z(u)/\delta < 0.75$

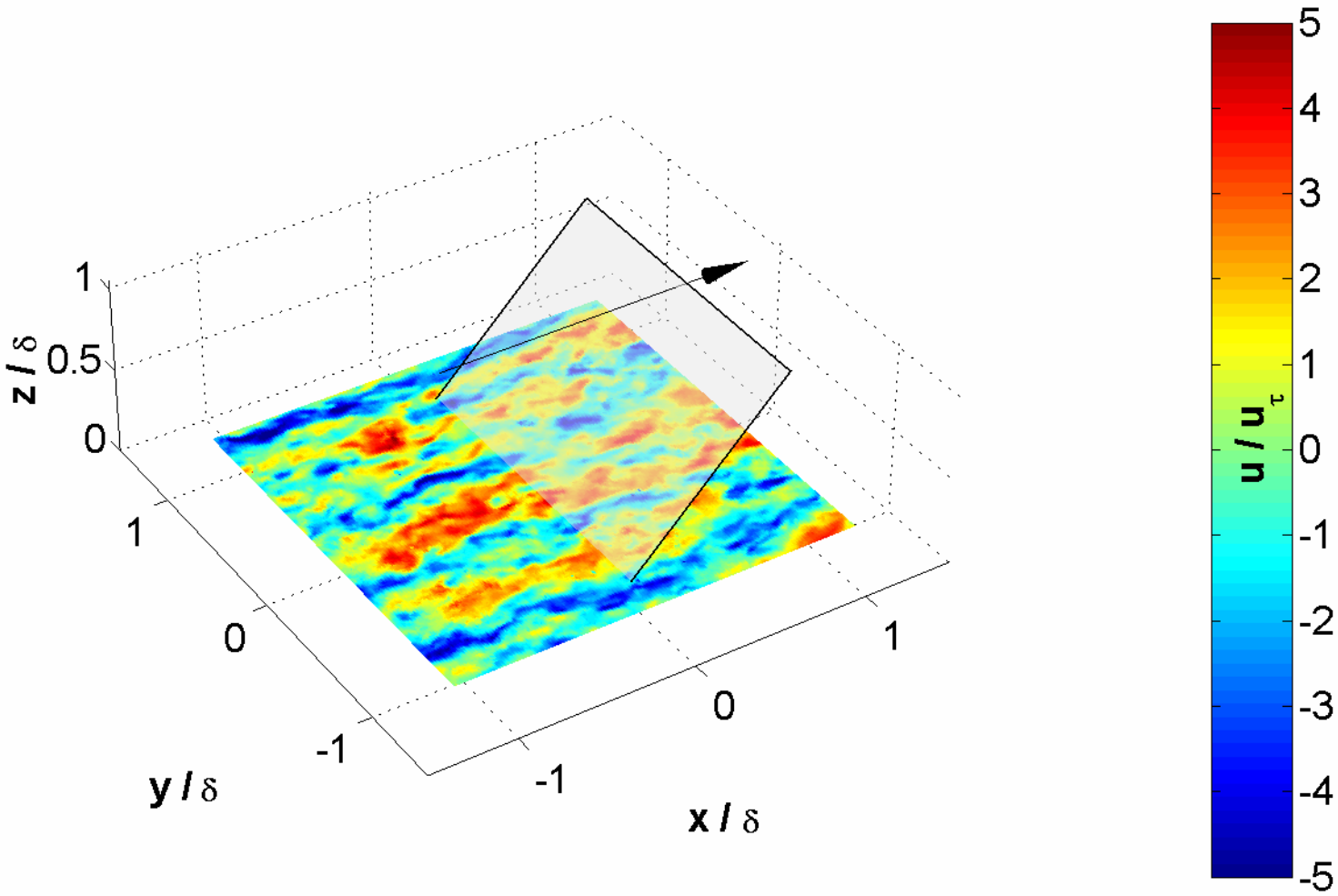


Note: the low-speed events are actually ejections (Q2), flanked by counter-rotating swirling motions

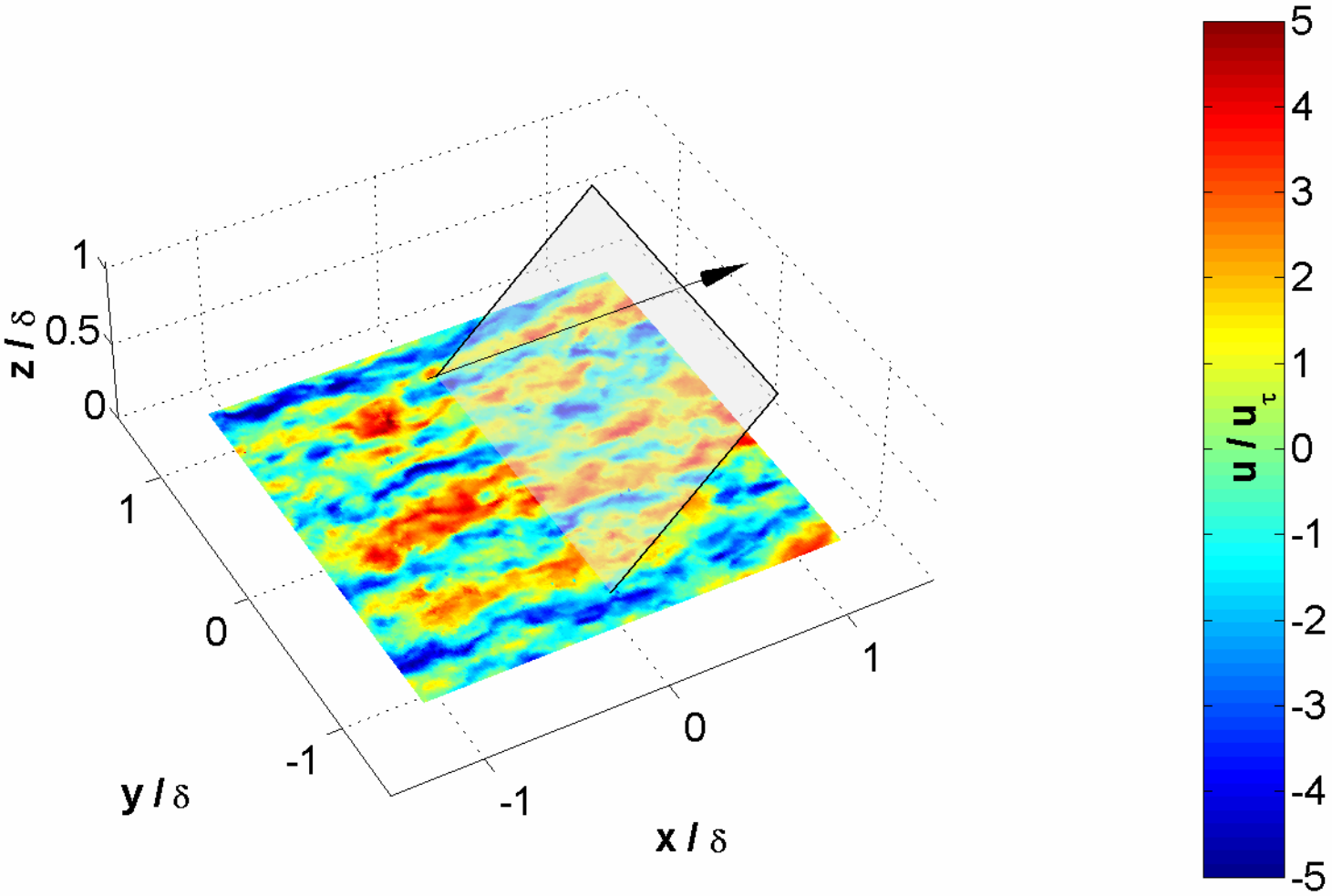
Streamwise / spanwise plane results offer a further slice through these spanwise modes.



Streamwise / spanwise plane results offer a further slice through these spanwise modes.



Streamwise / spanwise plane results offer a further slice through these spanwise modes.



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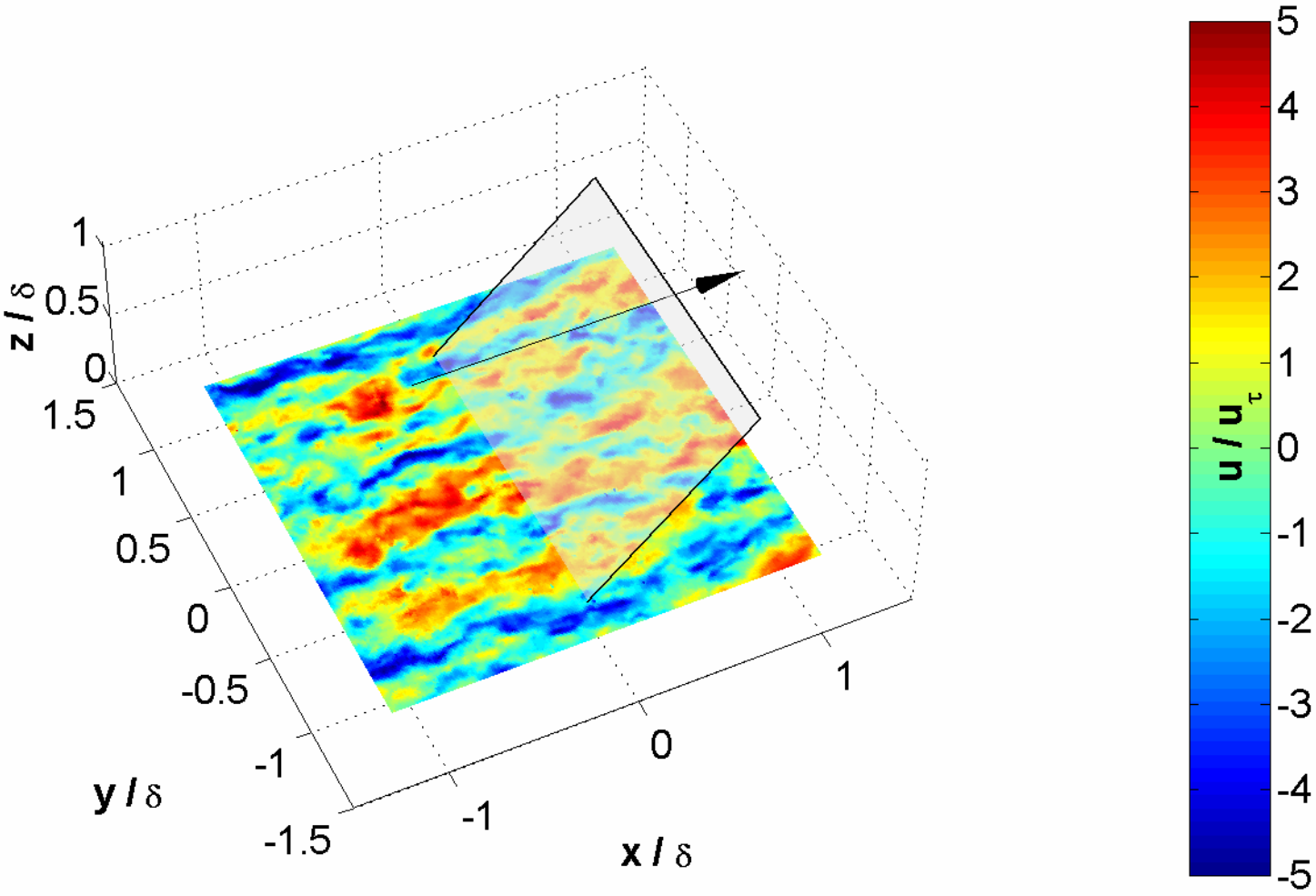
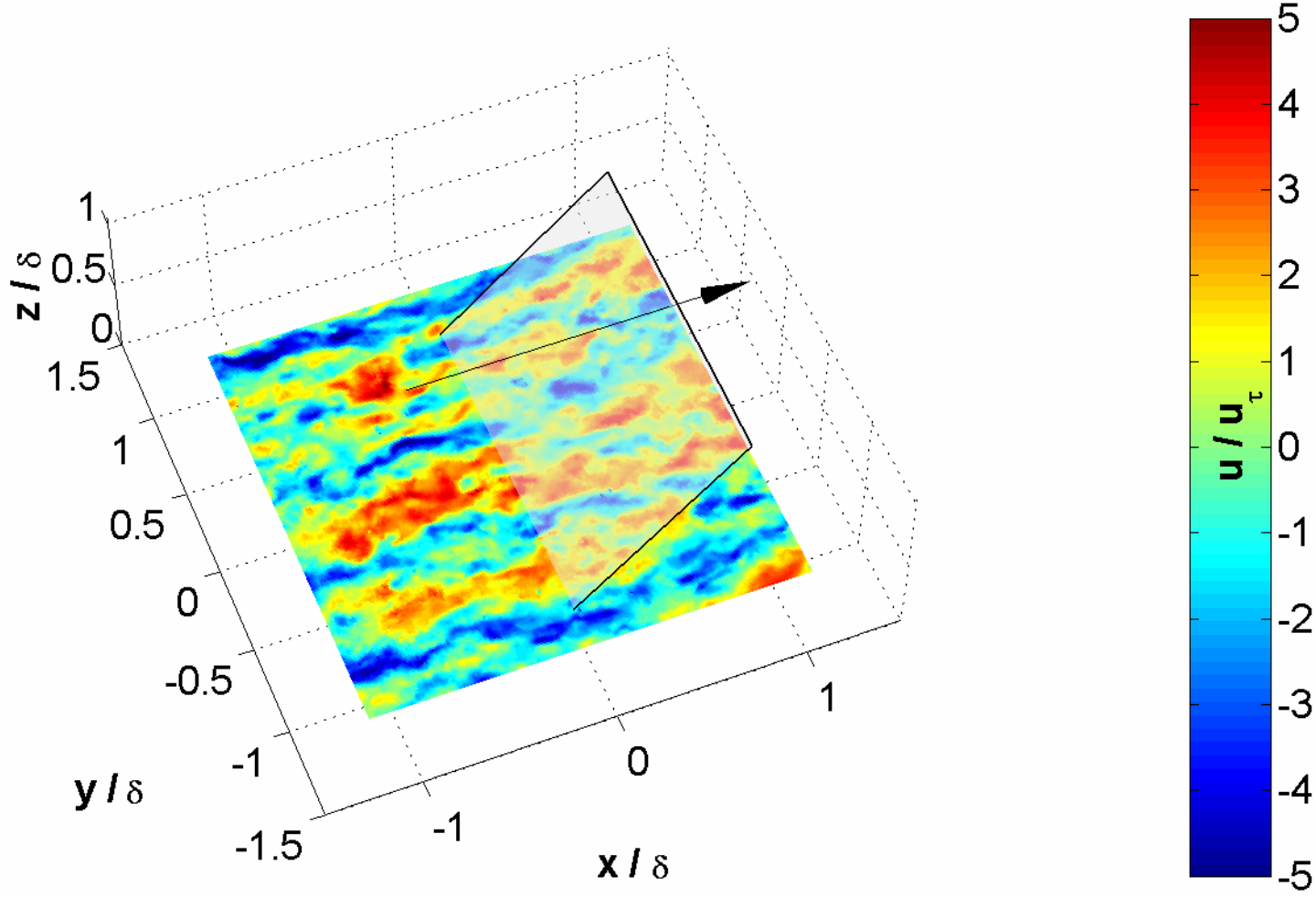
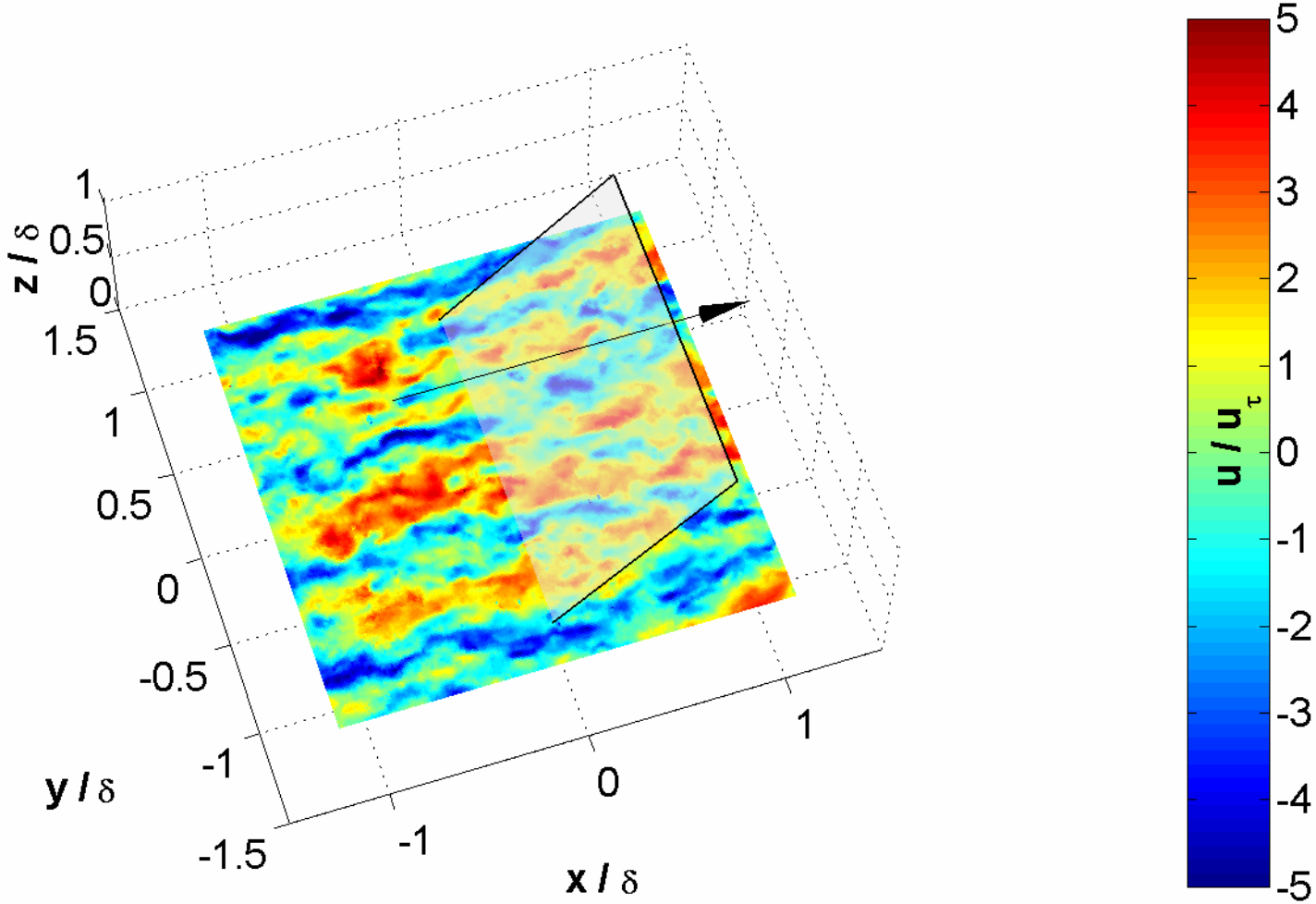


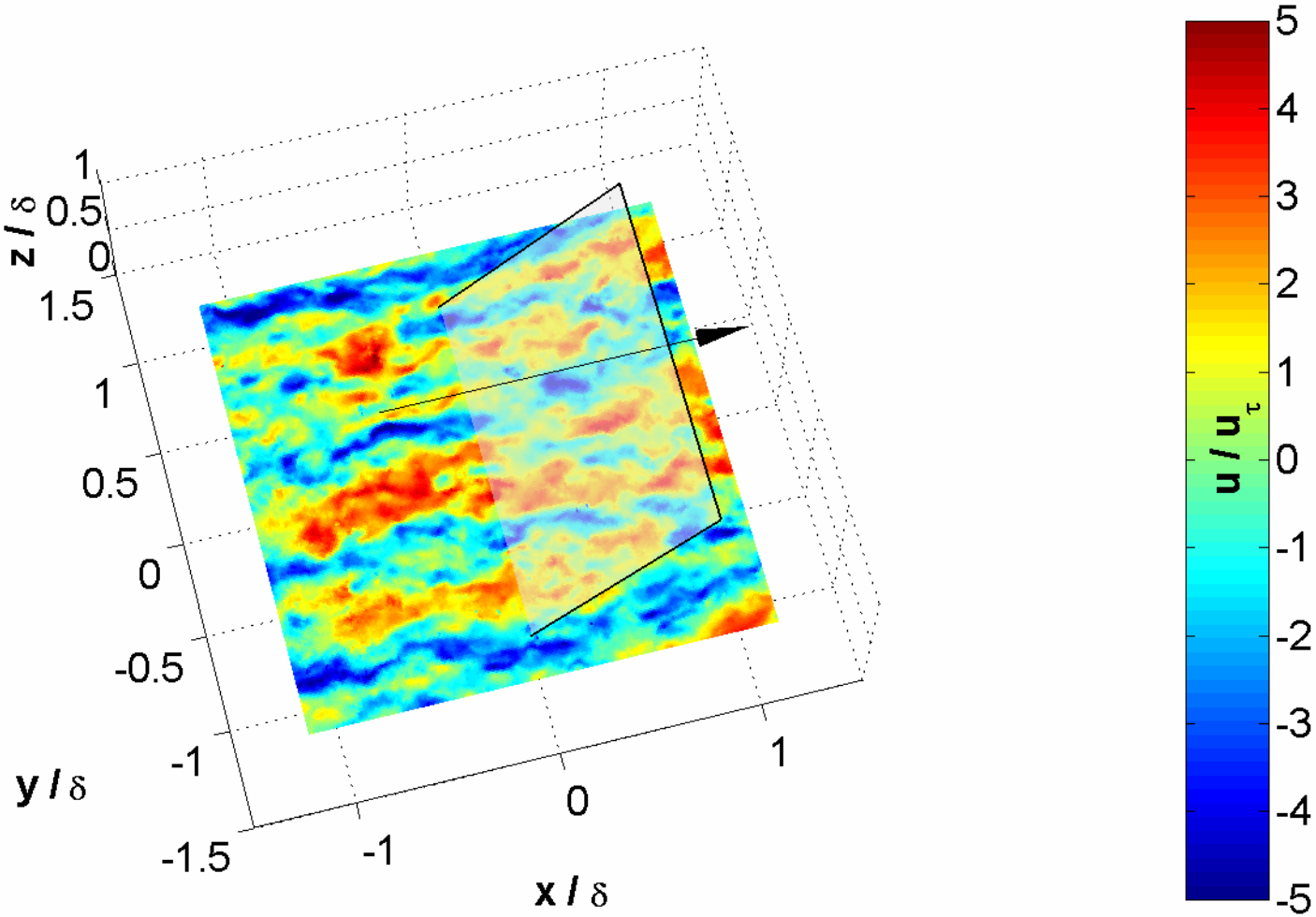
Streamwise / spanwise plane results offer a further slice through these spanwise modes.



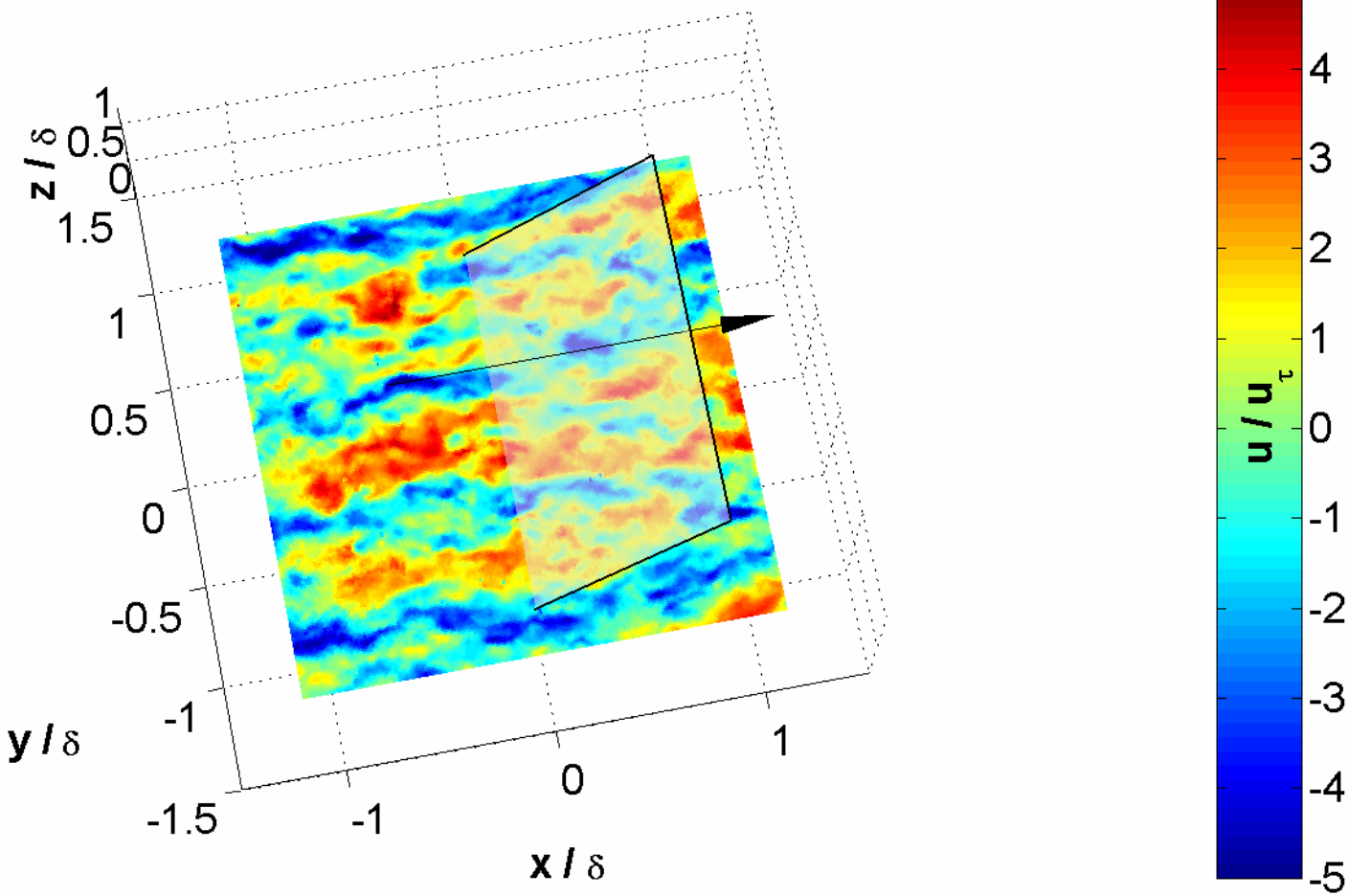
Streamwise / spanwise plane results offer a further slice through these spanwise modes.



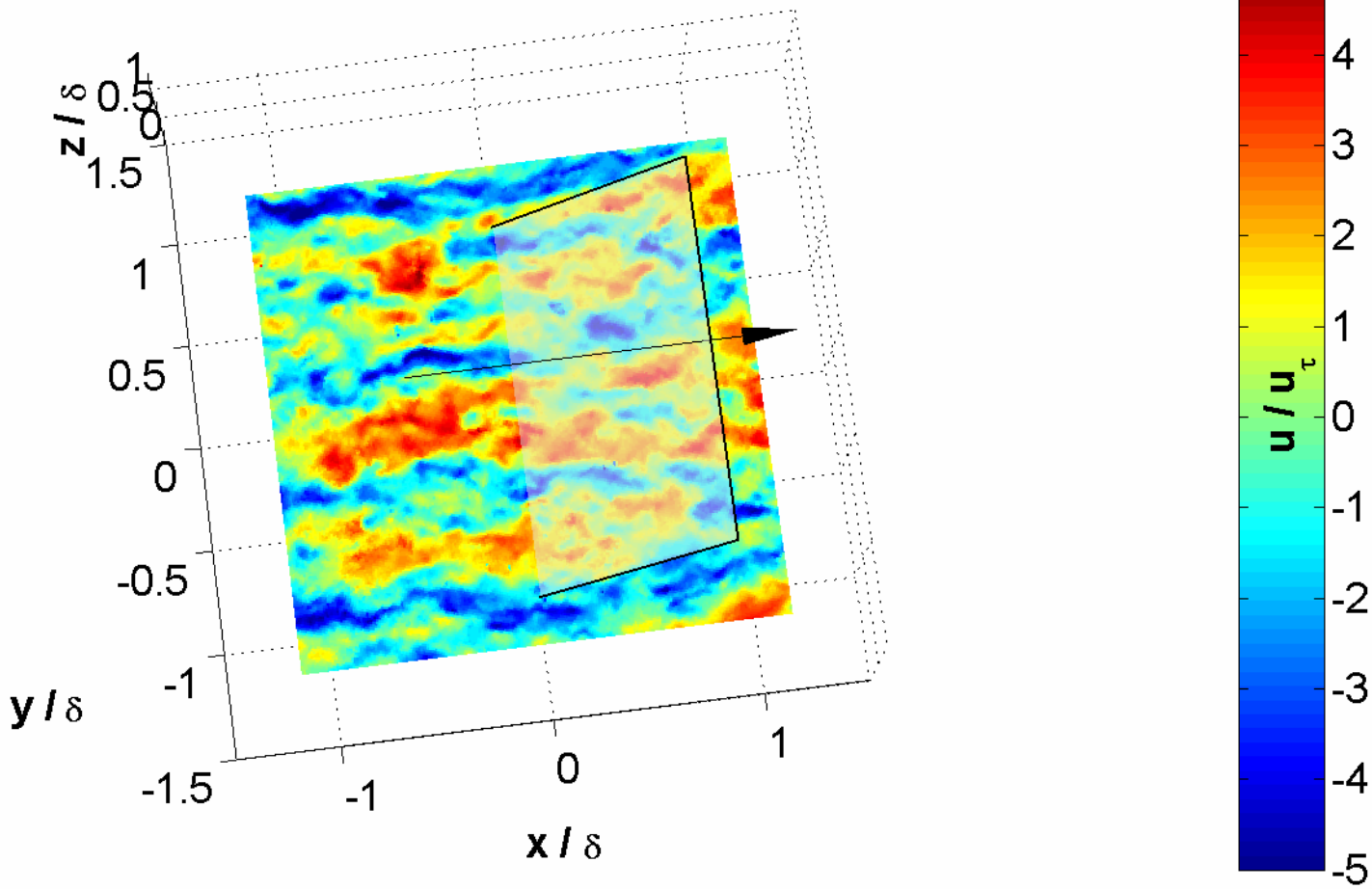
Streamwise / spanwise plane results offer a further slice through these spanwise modes.



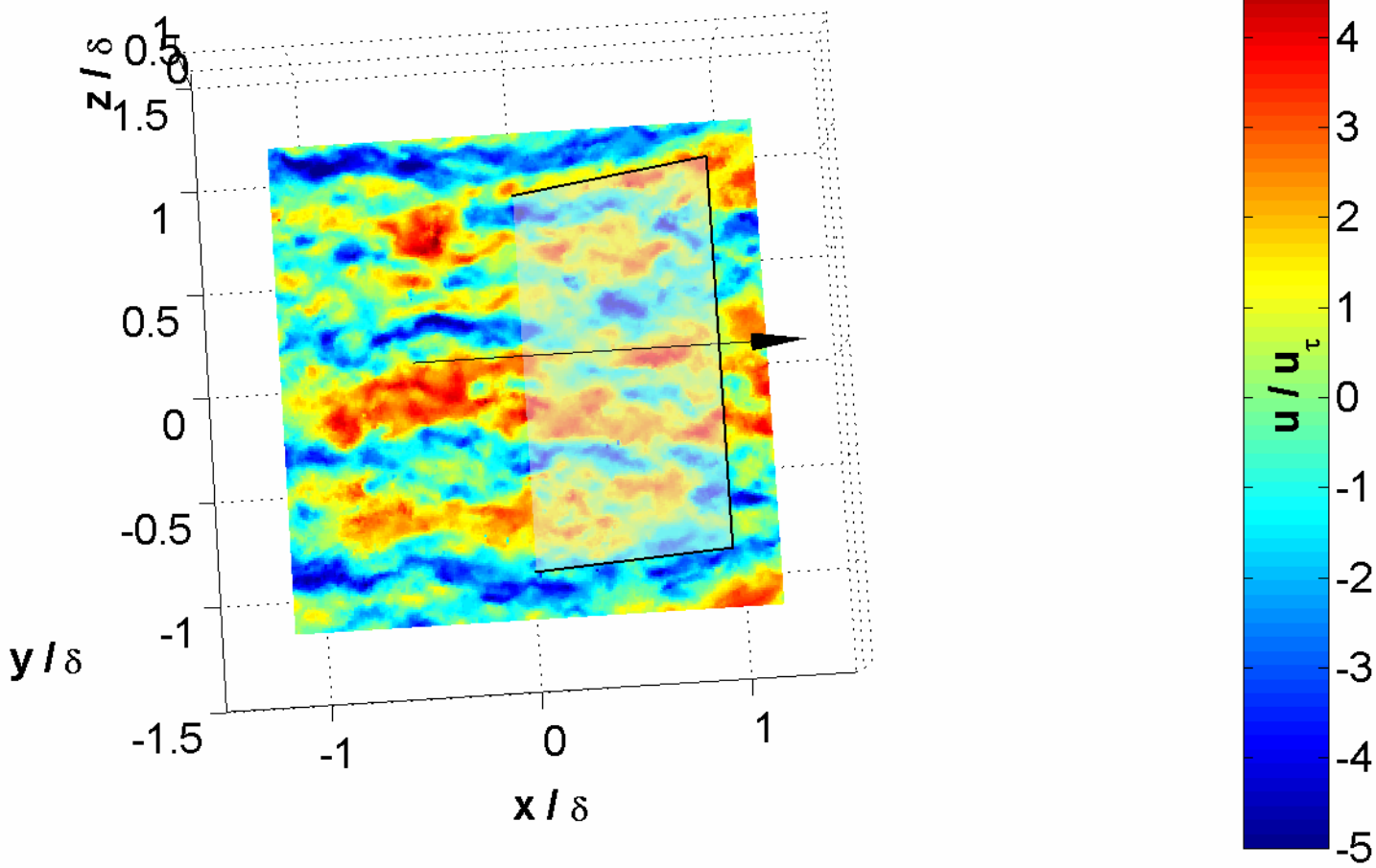
Streamwise / spanwise plane results offer a further slice through these spanwise modes.



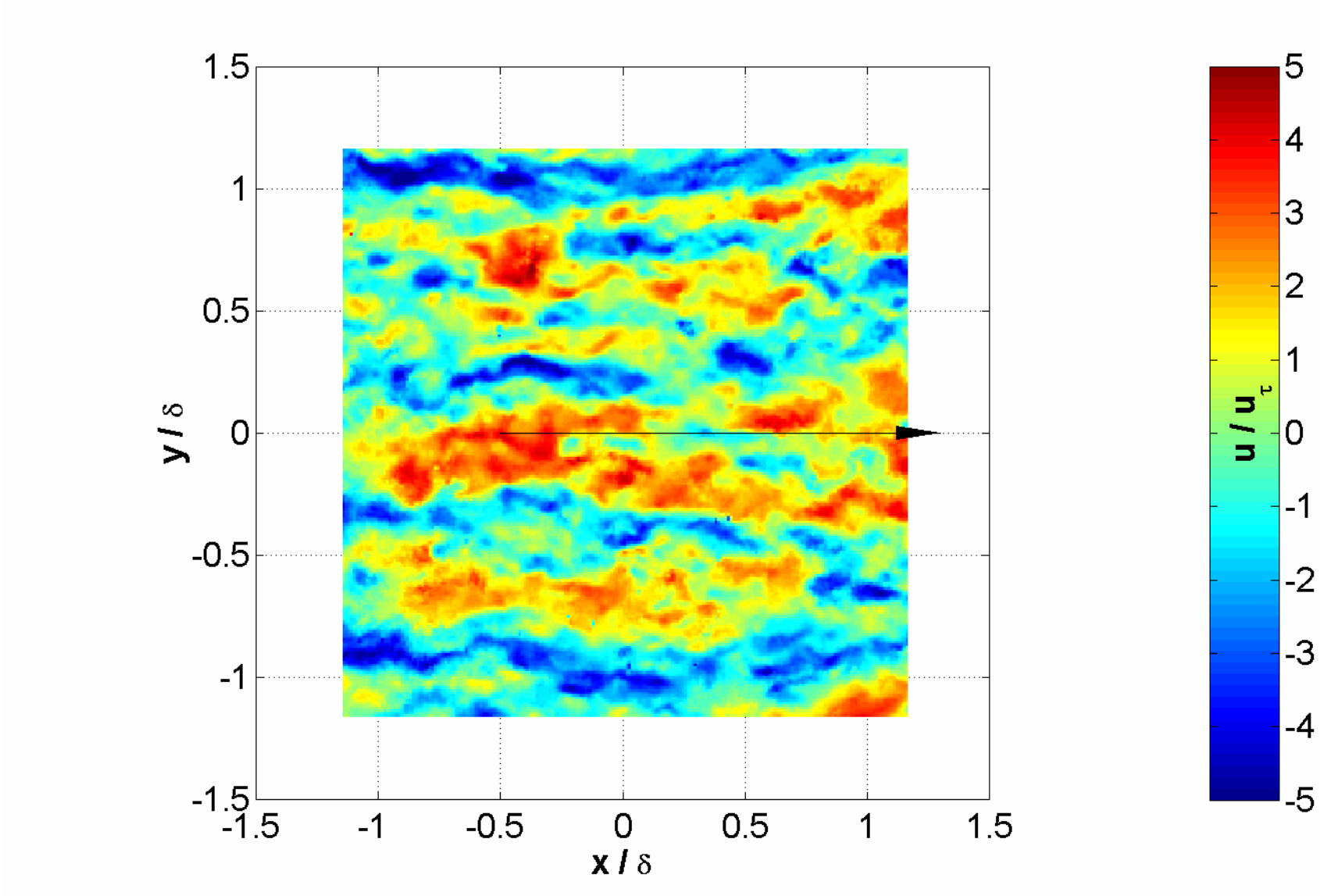
Streamwise / spanwise plane results offer a further slice through these spanwise modes.



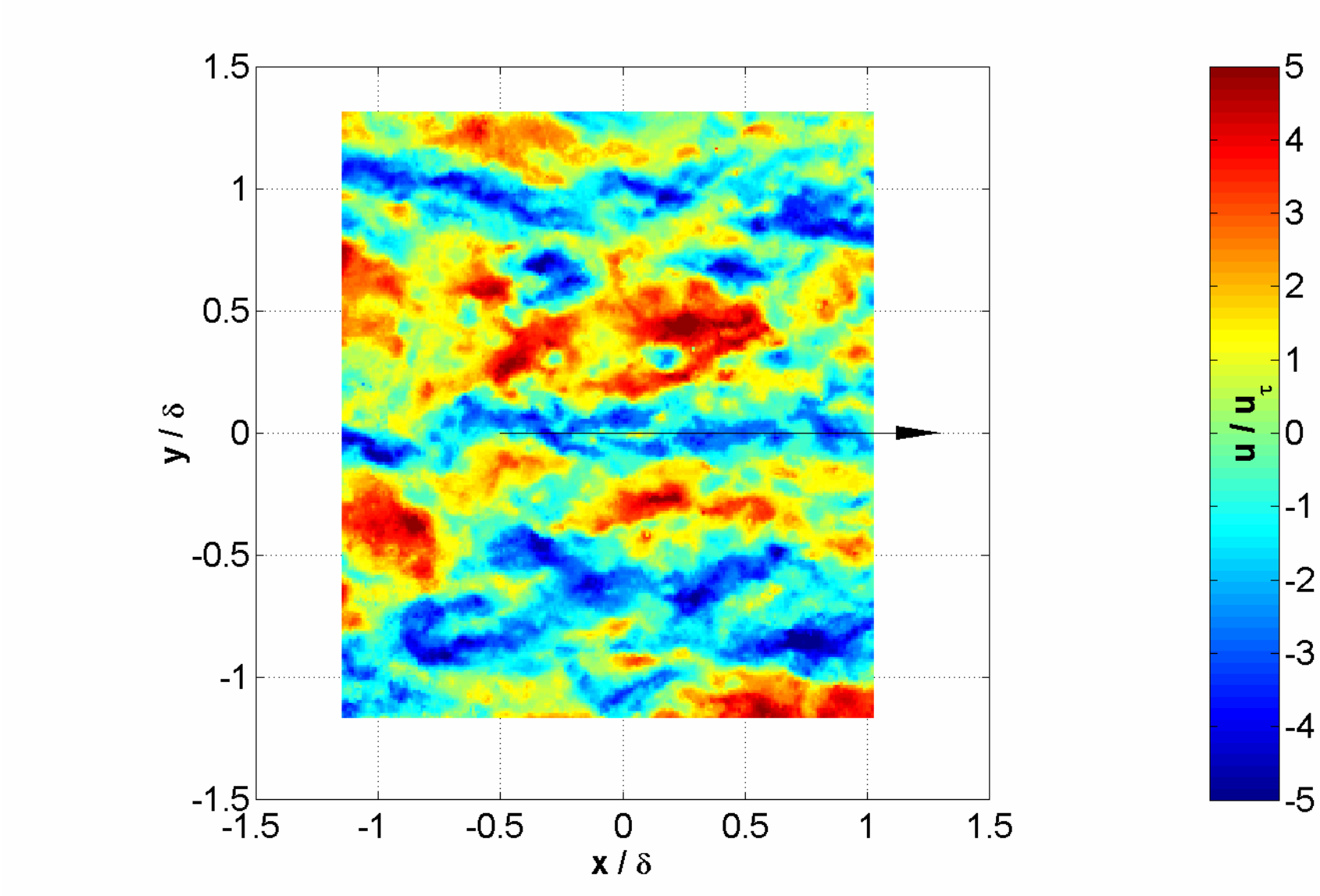
Streamwise / spanwise plane results offer a further slice through these spanwise modes.



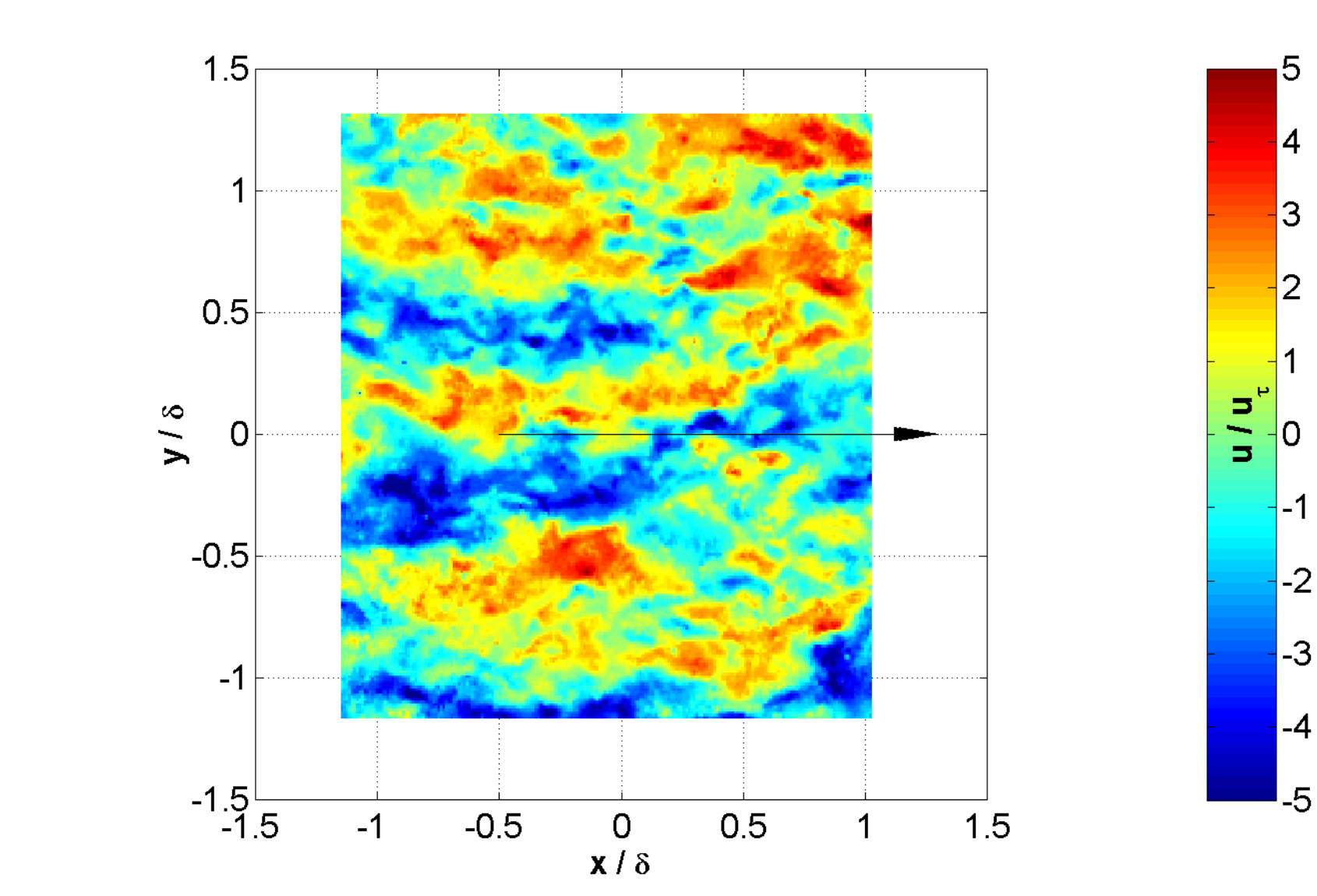
Note: general spanwise stripiness of u fluctuations.



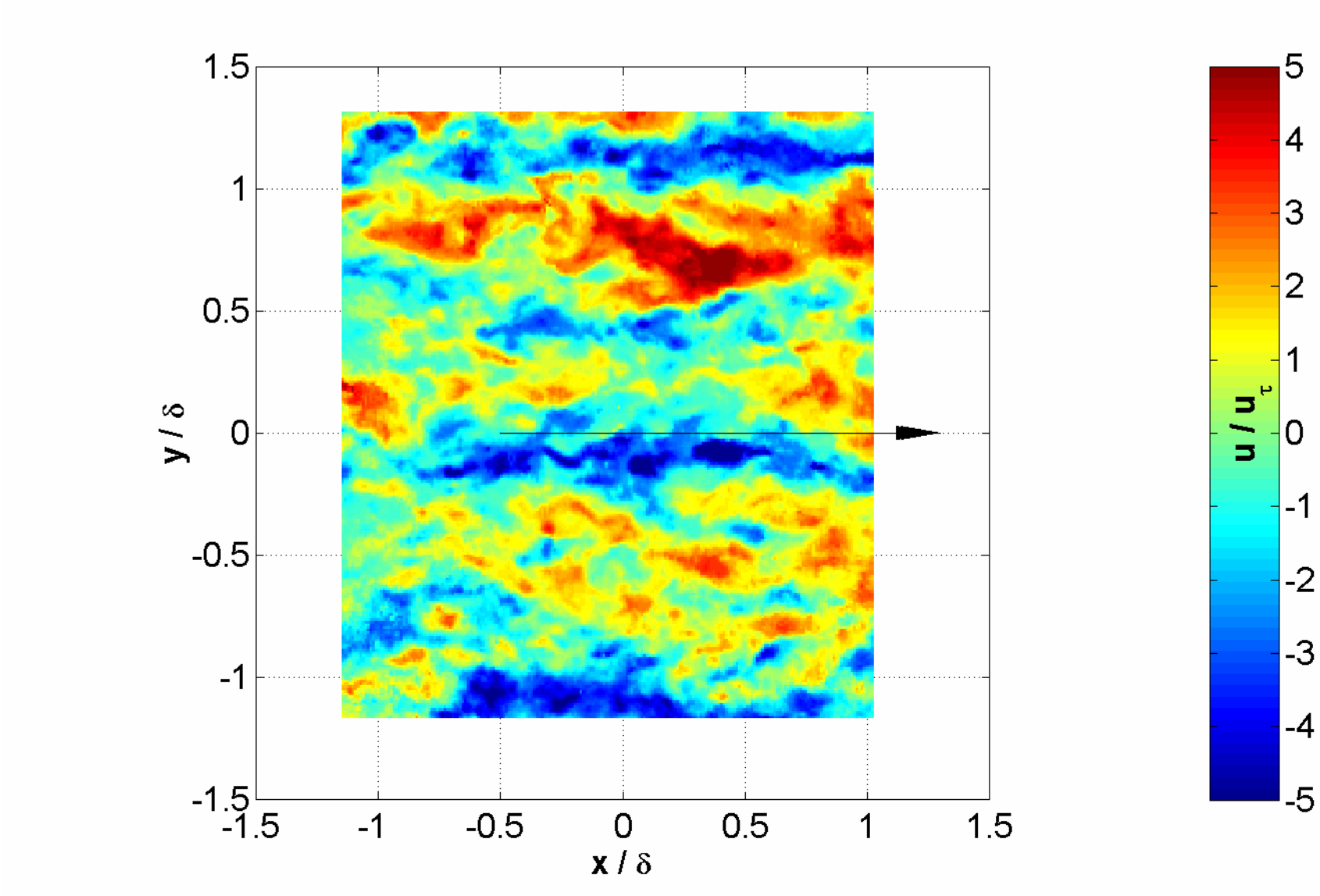
Note: general spanwise stripiness of u fluctuations.



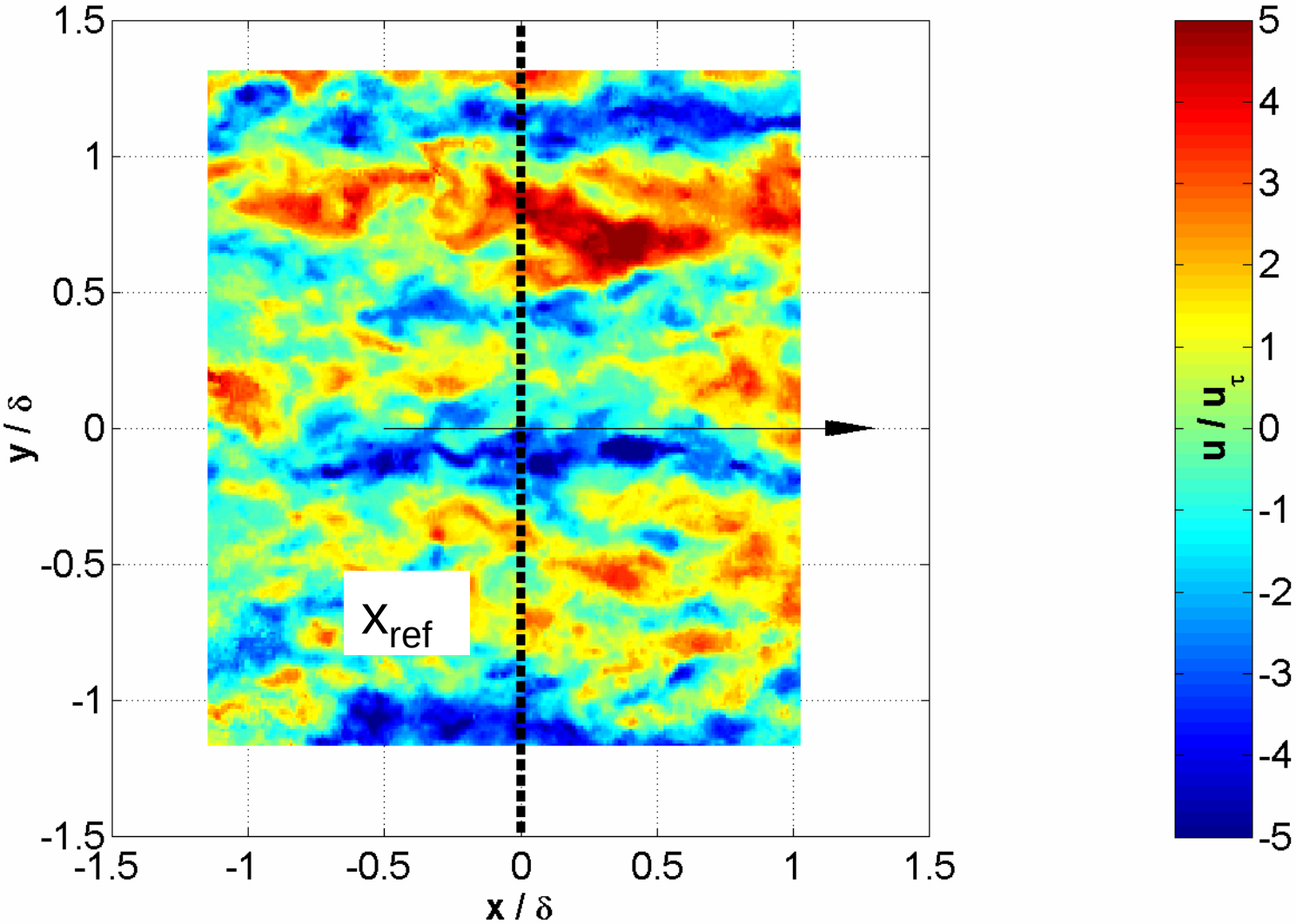
Note: general spanwise stripiness of u fluctuations.



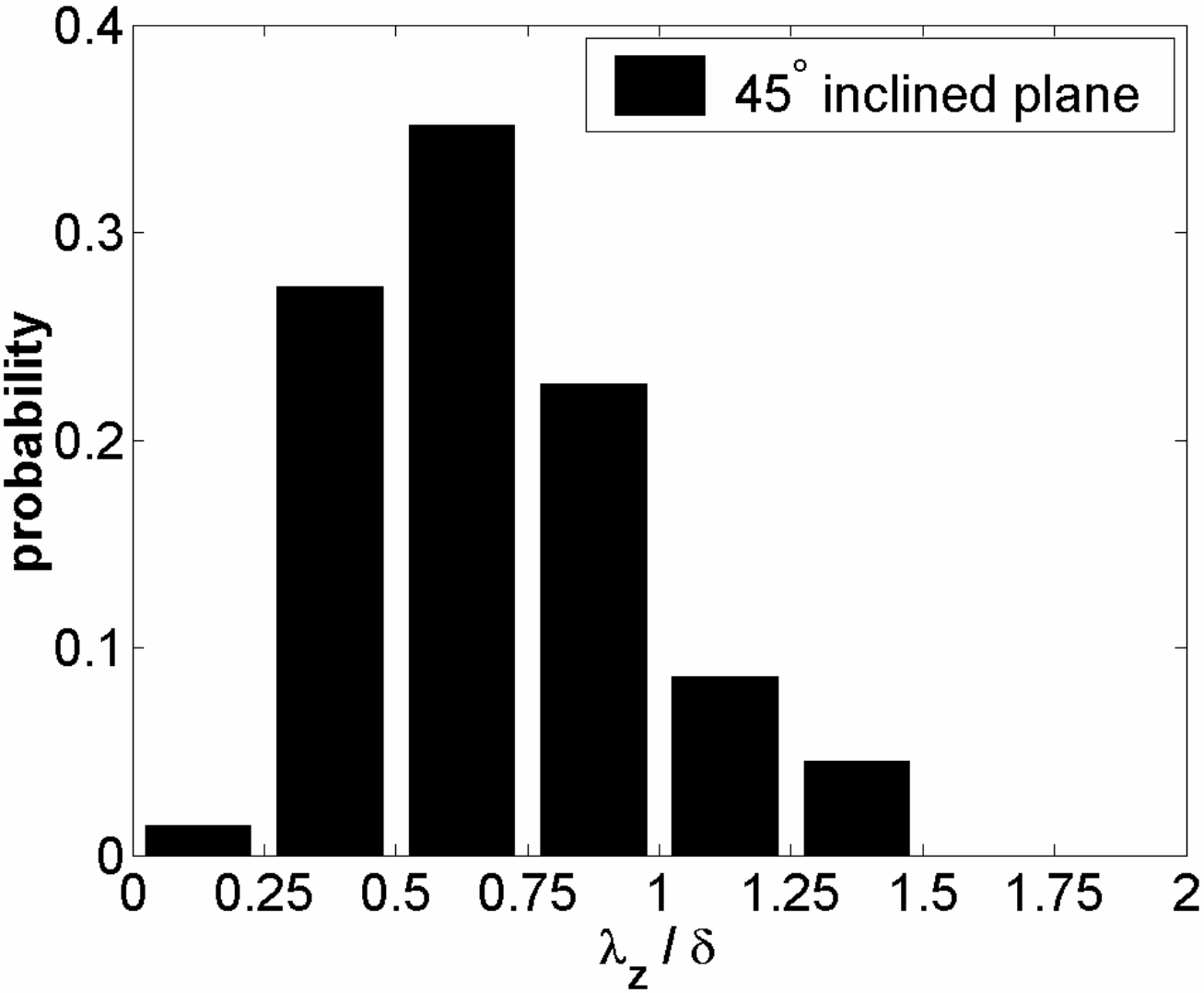
Note: general spanwise stripiness of u fluctuations.



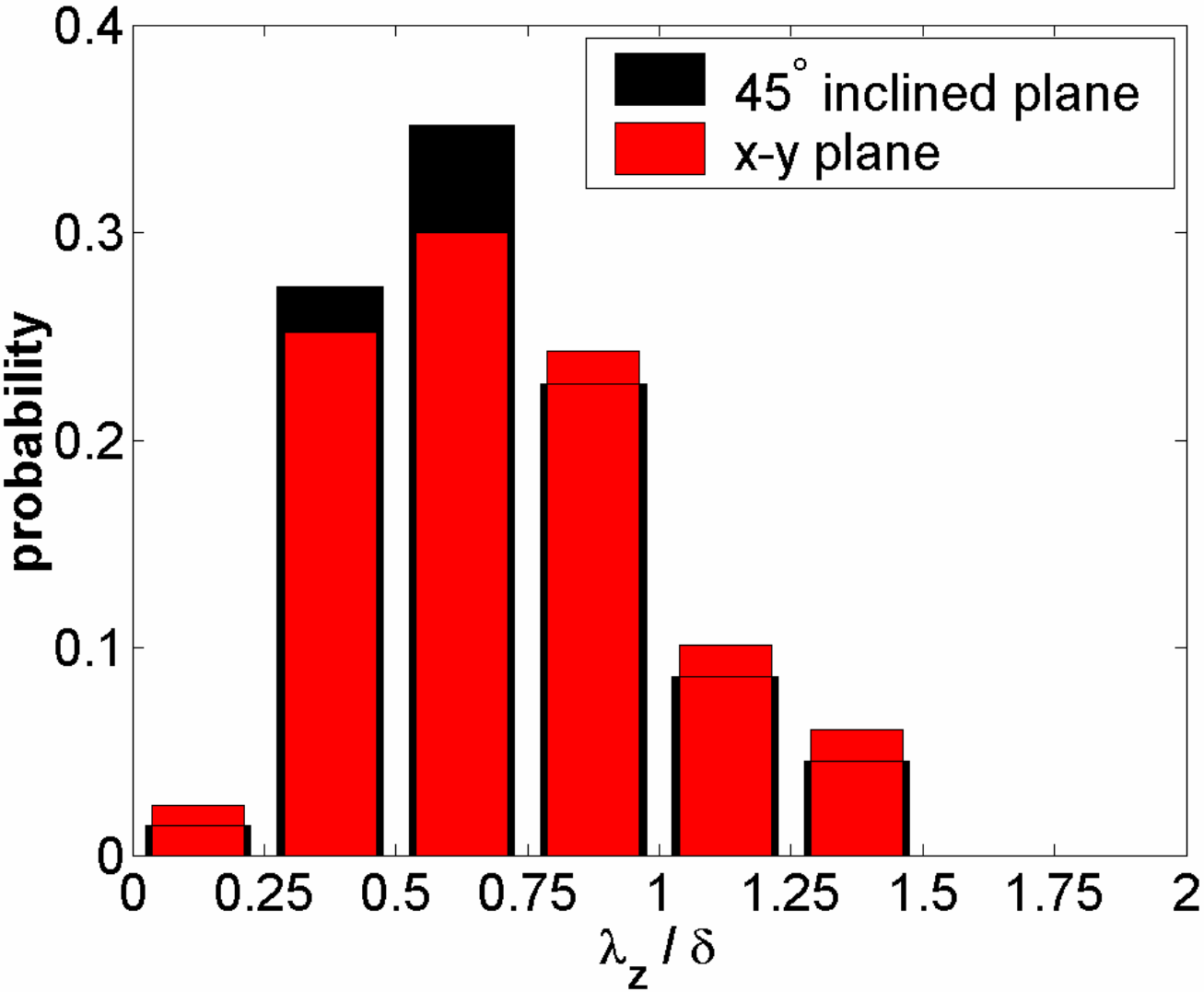
Establish a reference line, and bin frames according to dominant spanwise modes.



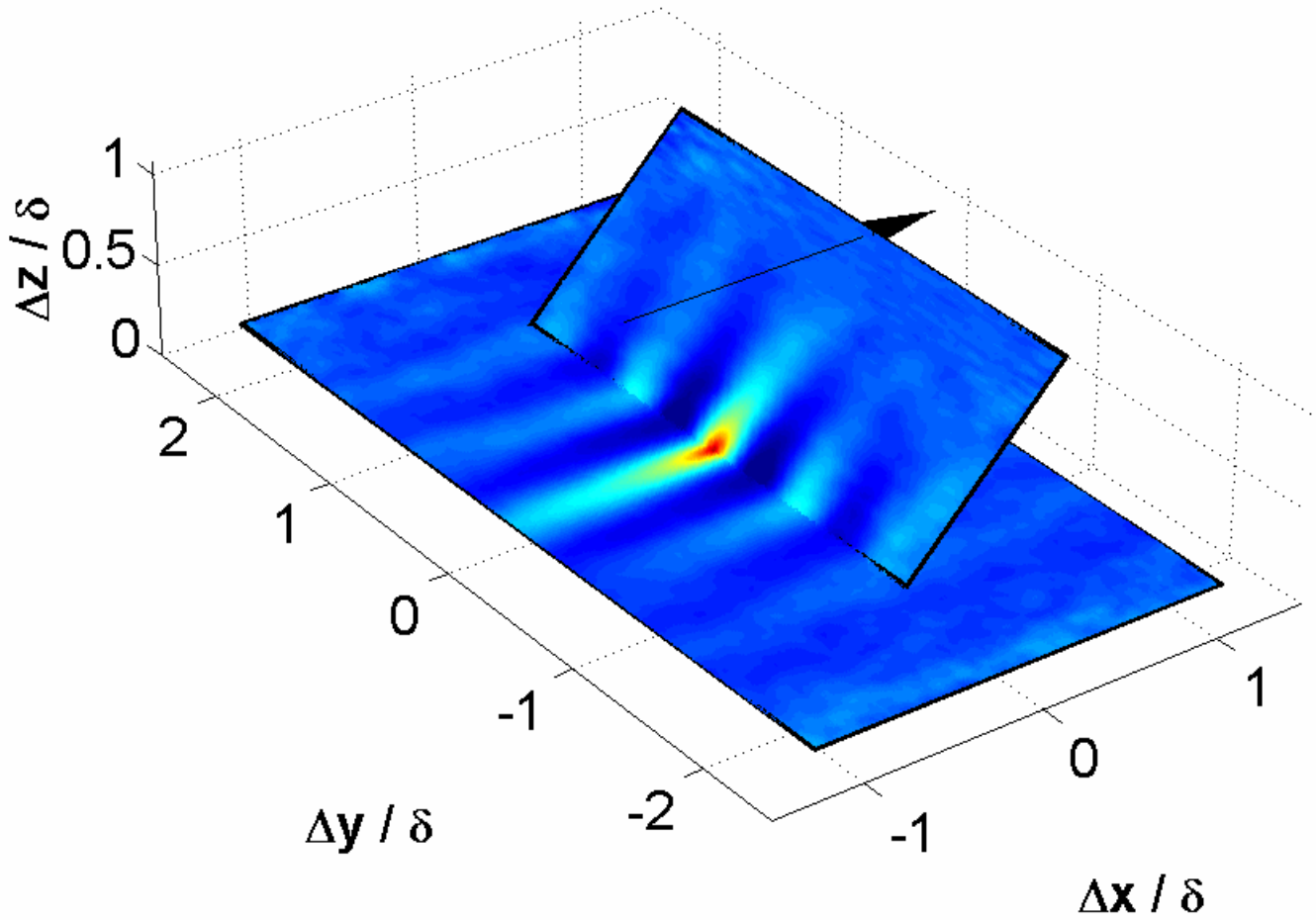
Binned frames according to dominant spanwise mode



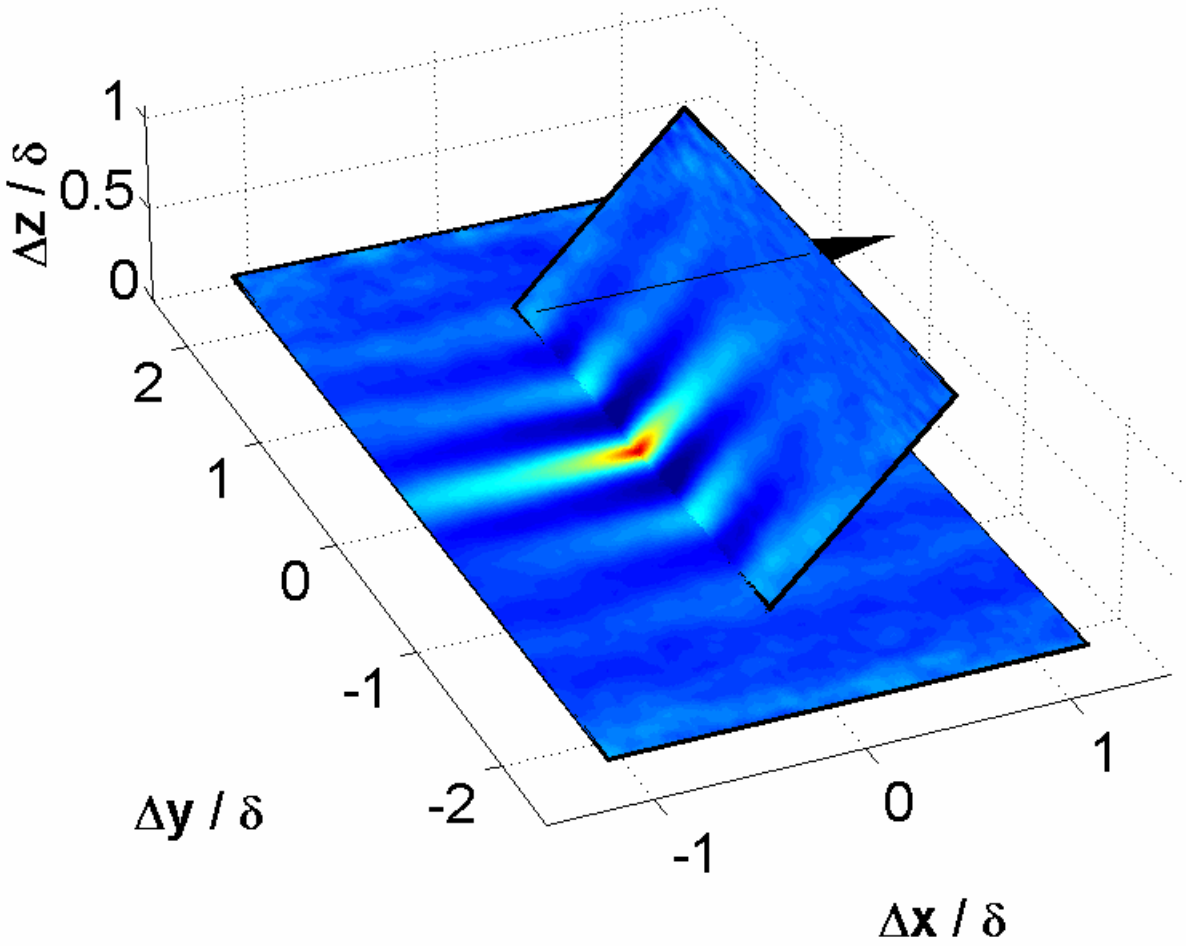
Binned frames according to dominant spanwise mode



Calculate R_{uu} on frames that fall in the $0.5 < \lambda_z\delta < 0.75$ bin



Calculate R_{uu} on frames that fall in the $0.5 < \lambda_z \delta < 0.75$ bin



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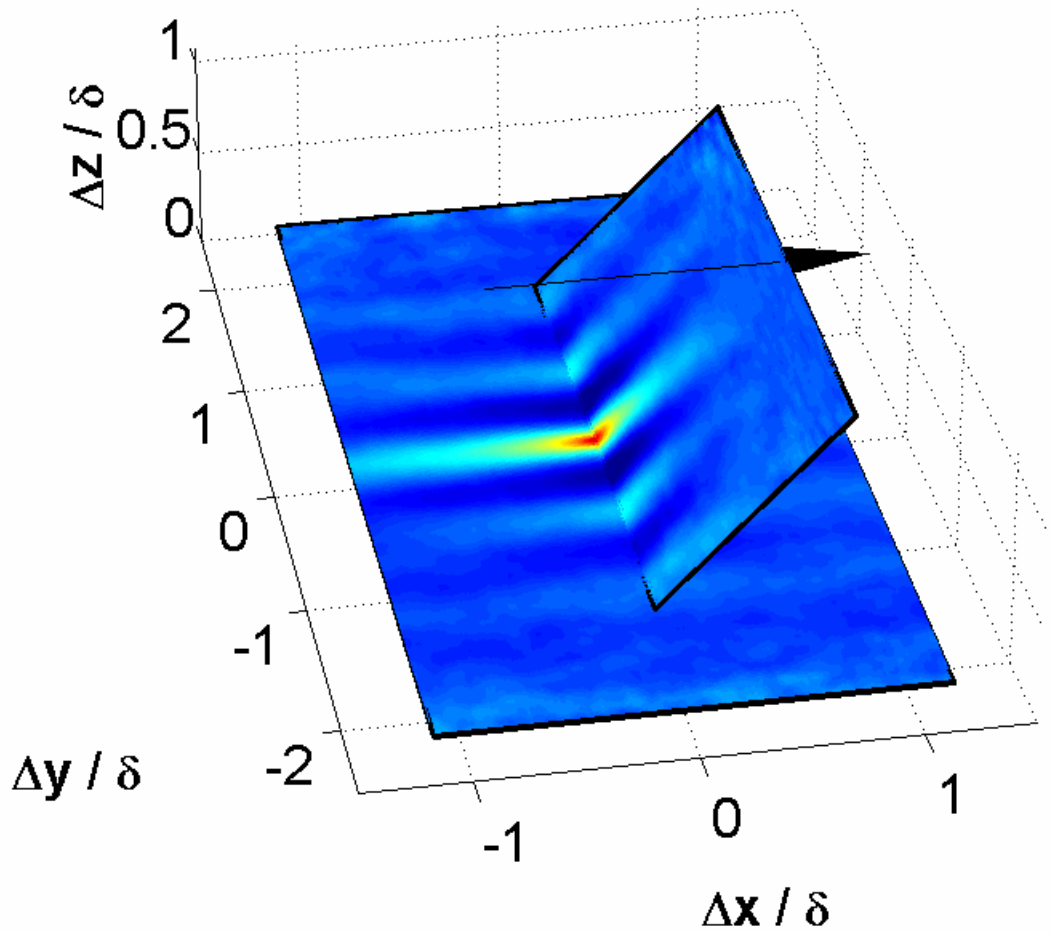

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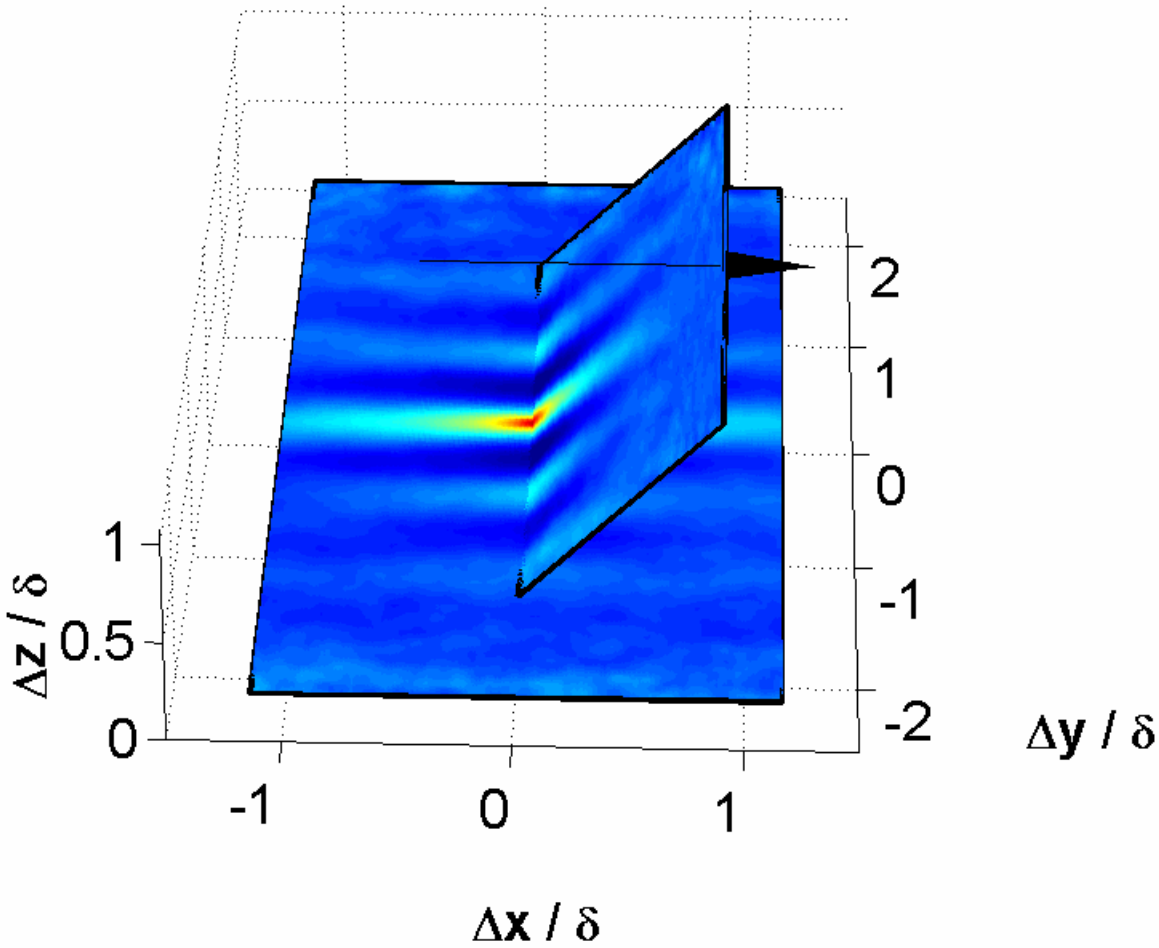

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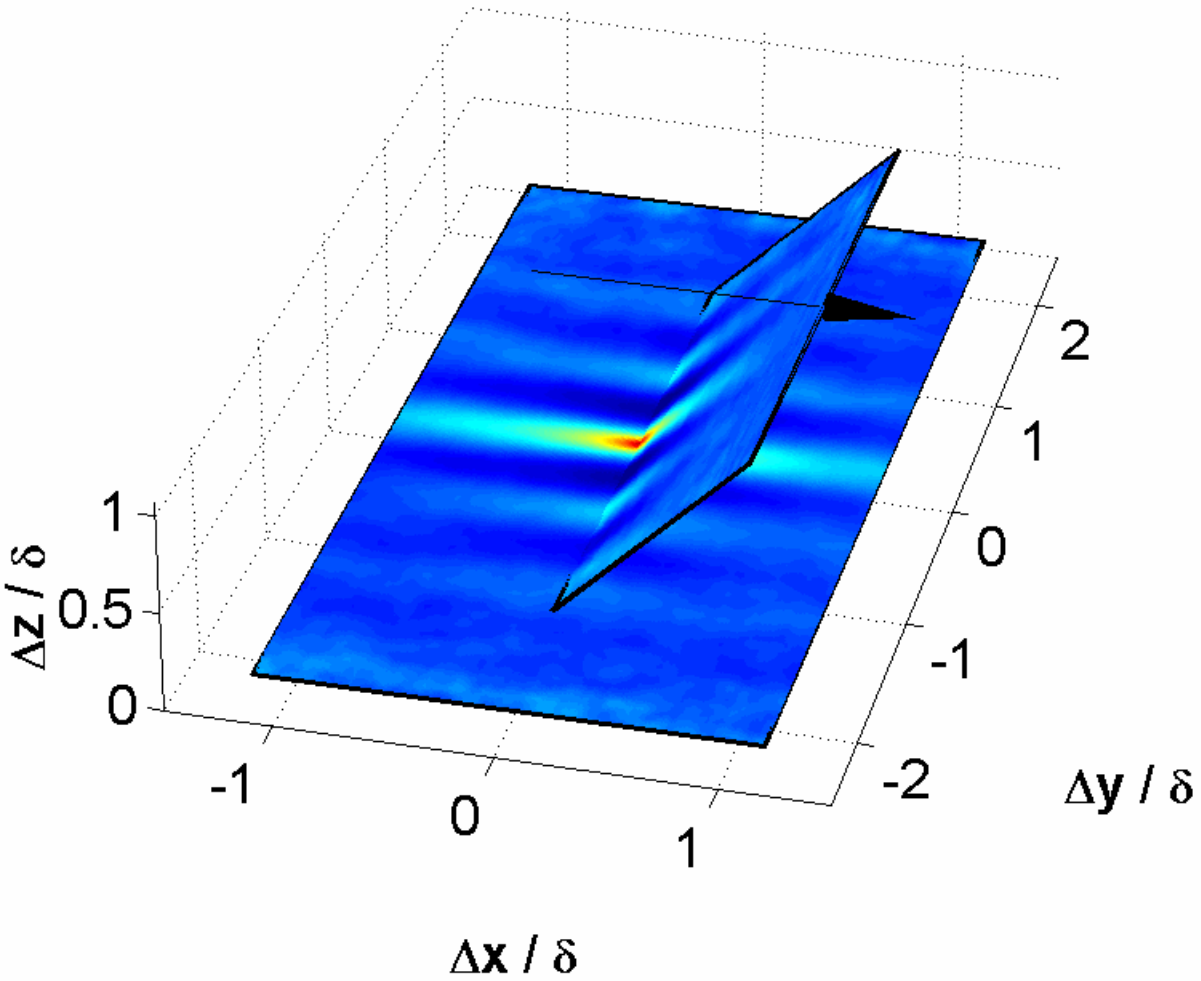

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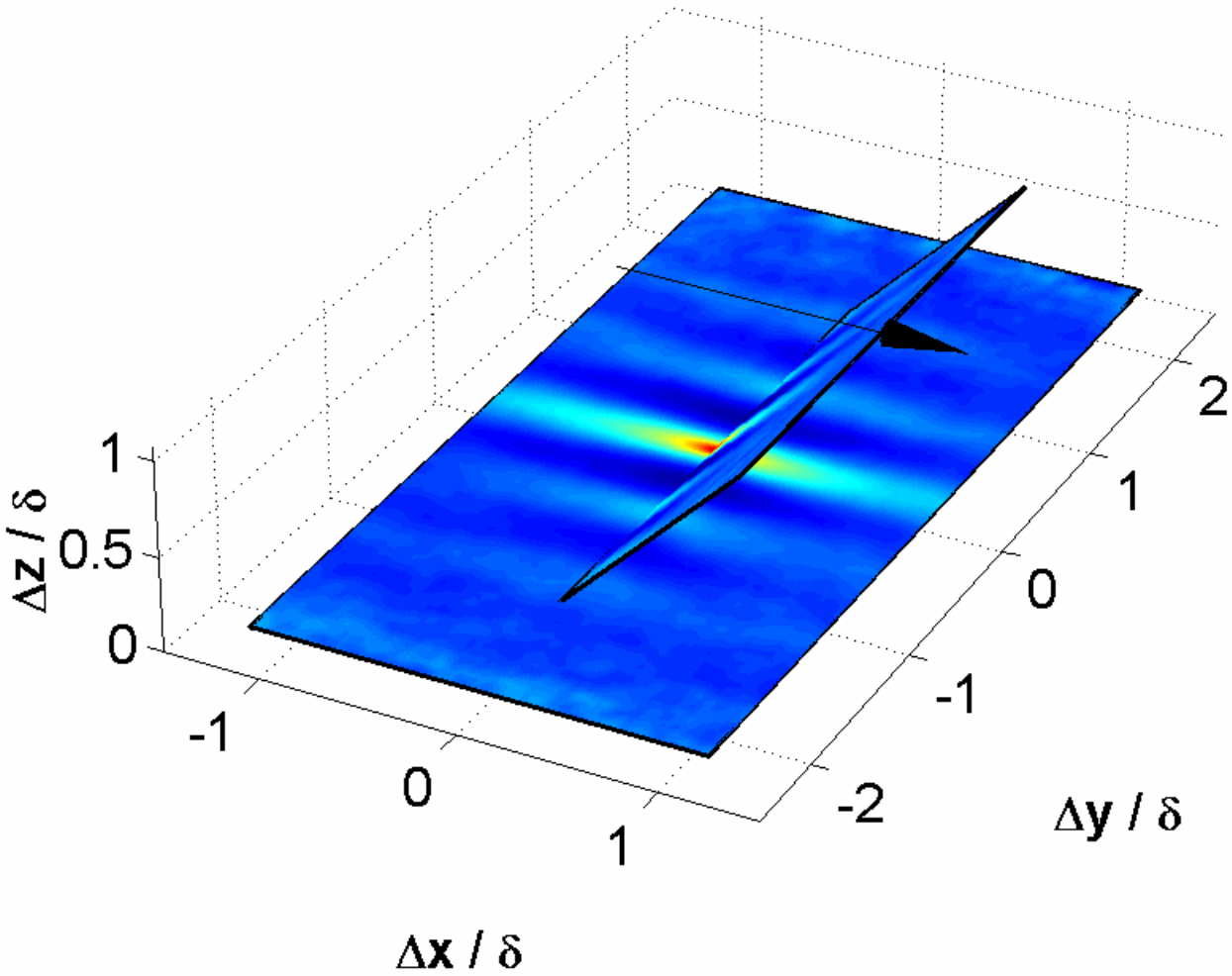

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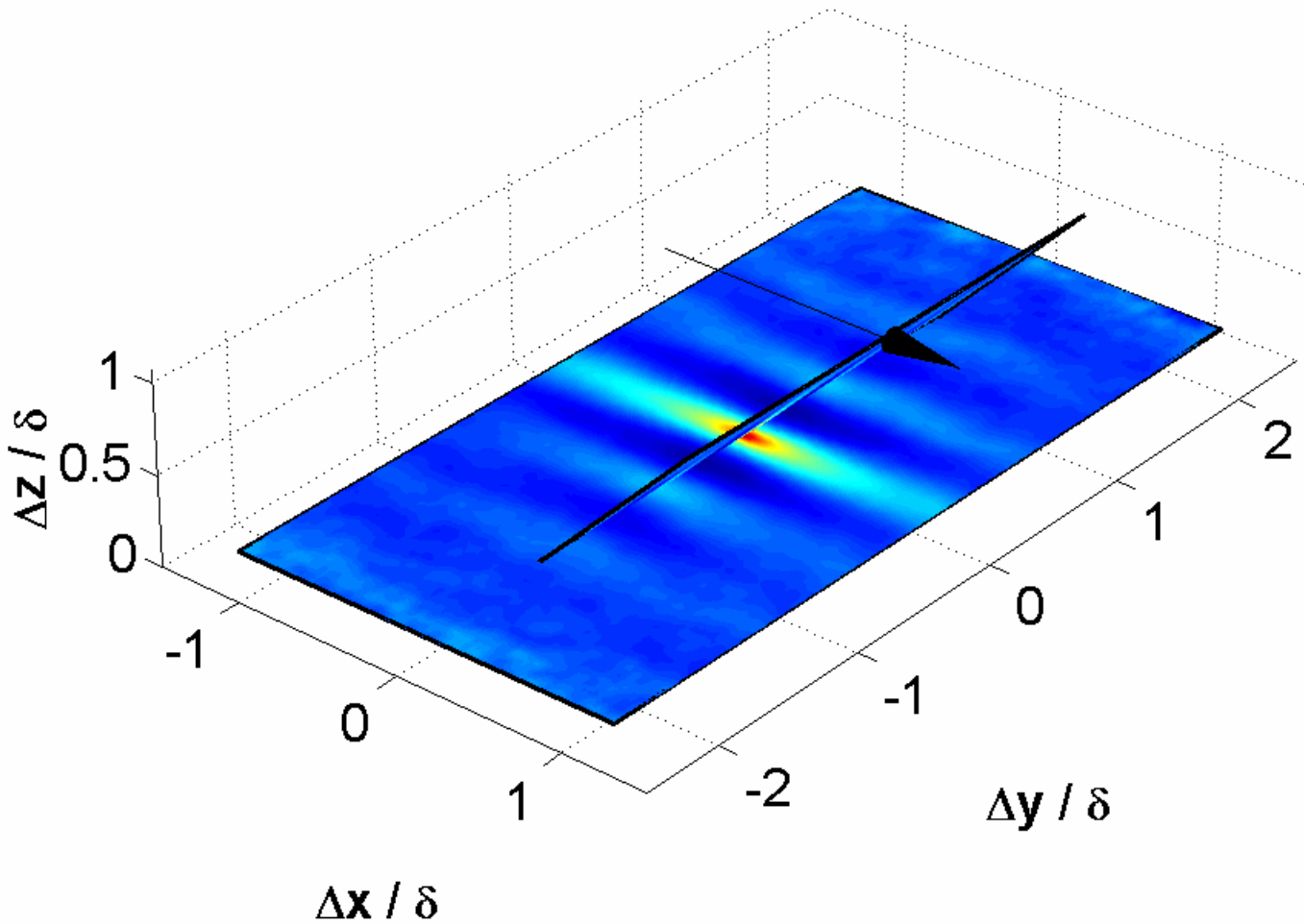

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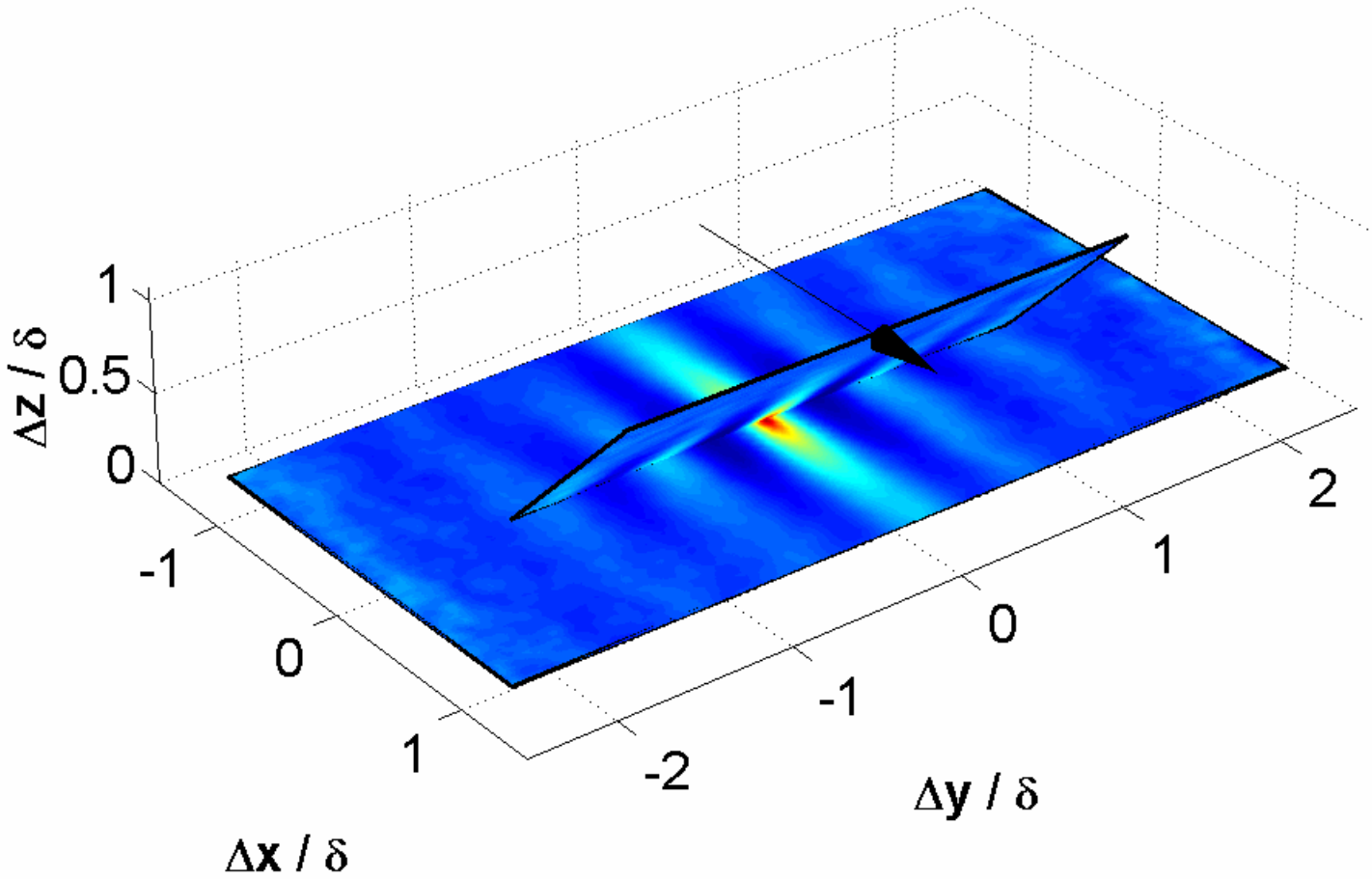

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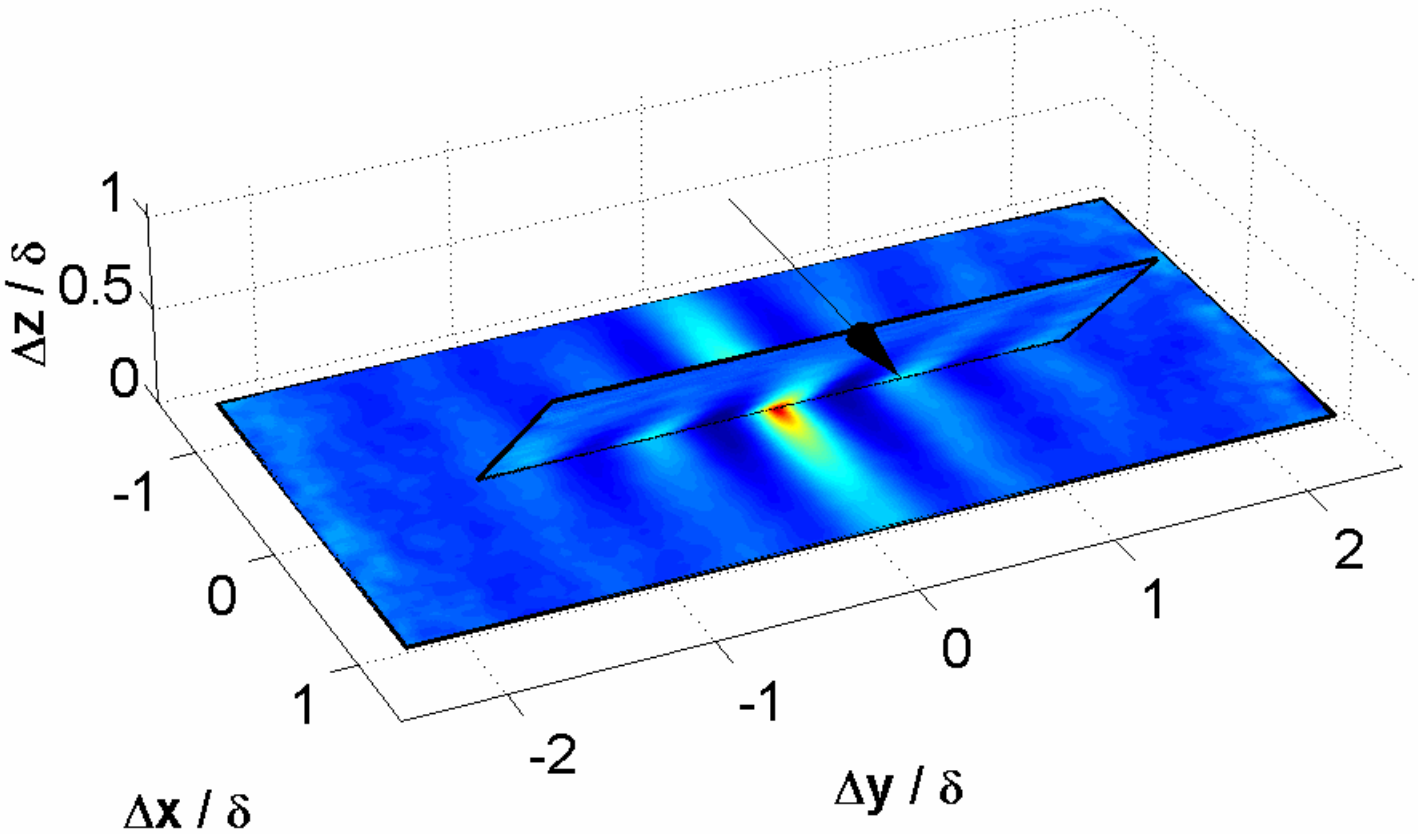

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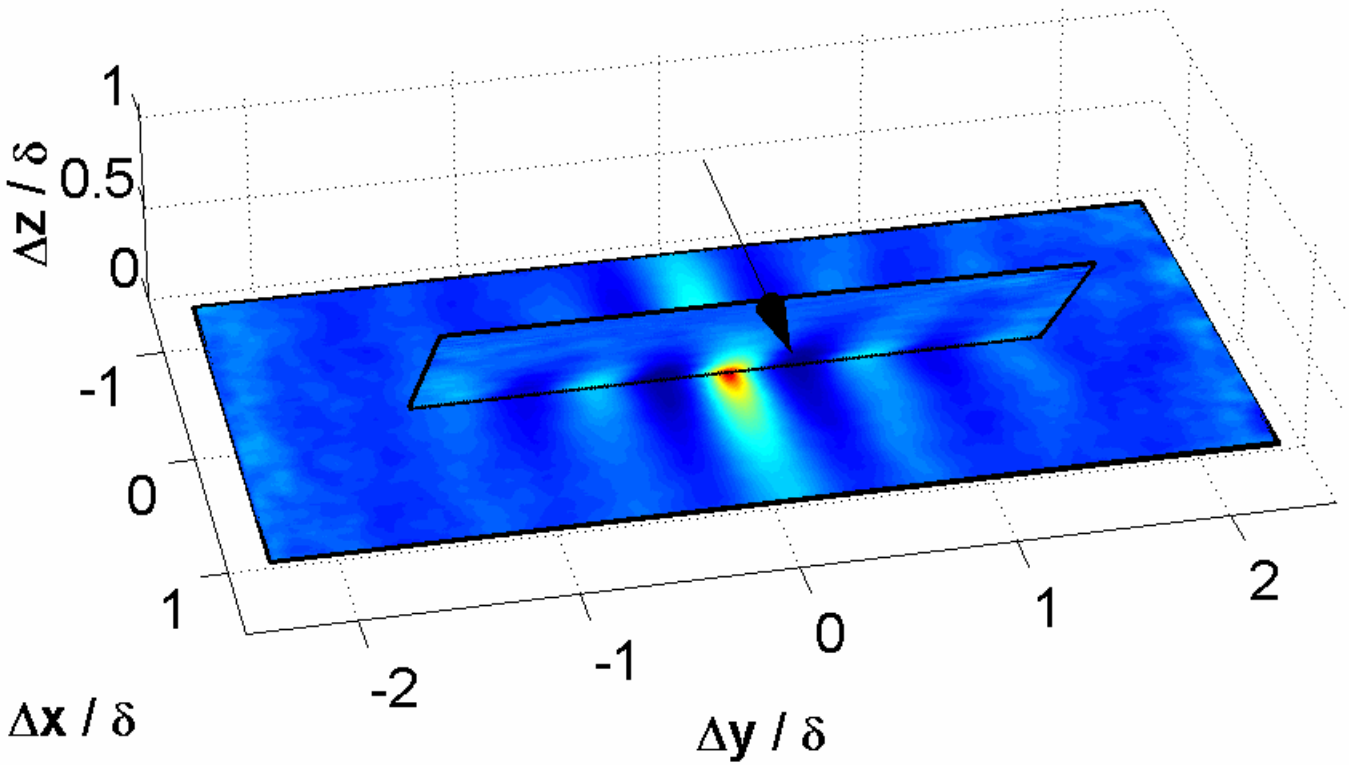
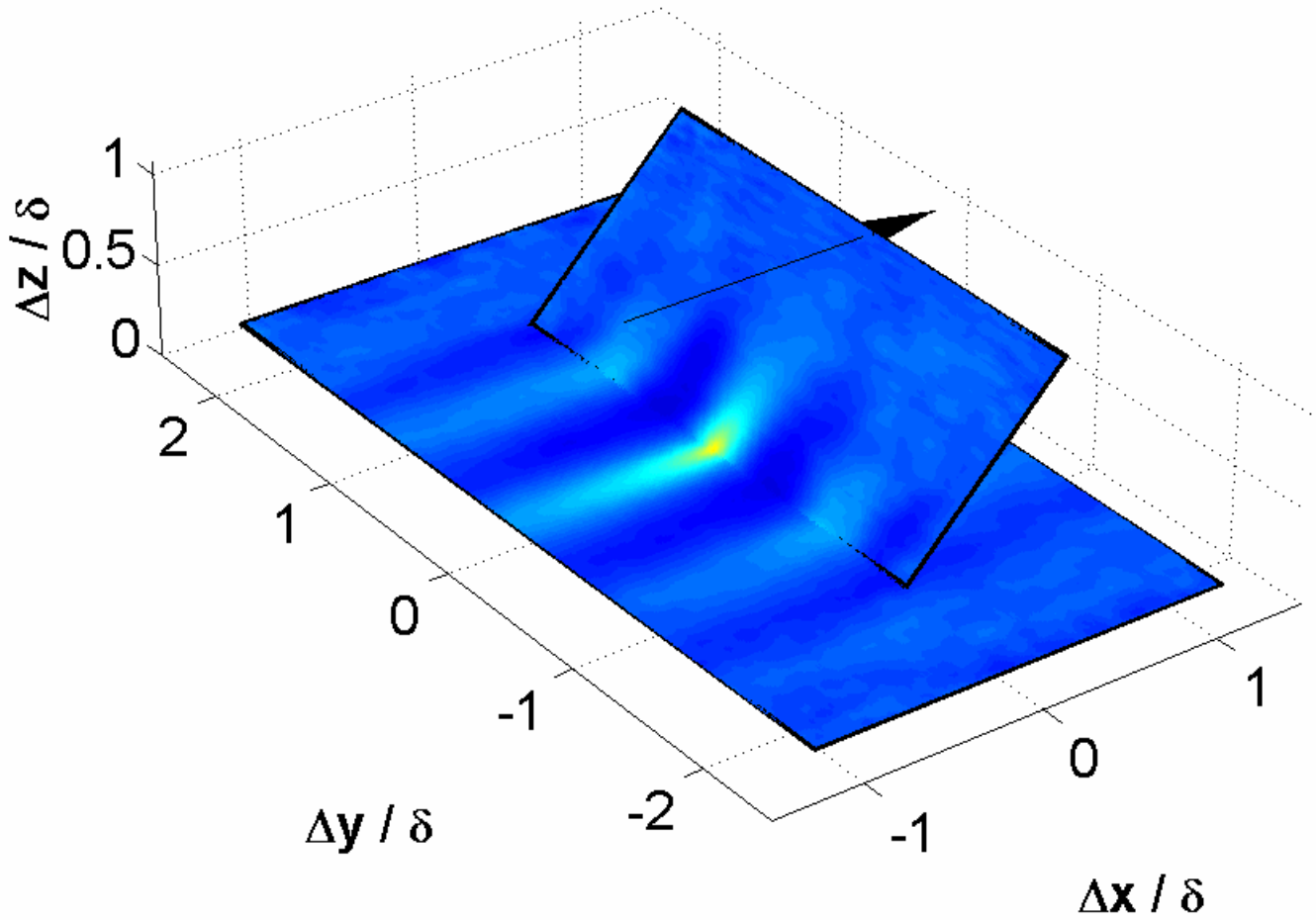


Calculate R_{uu} on frames that fall in the $0.75 < \lambda_z \delta < 1$ bin



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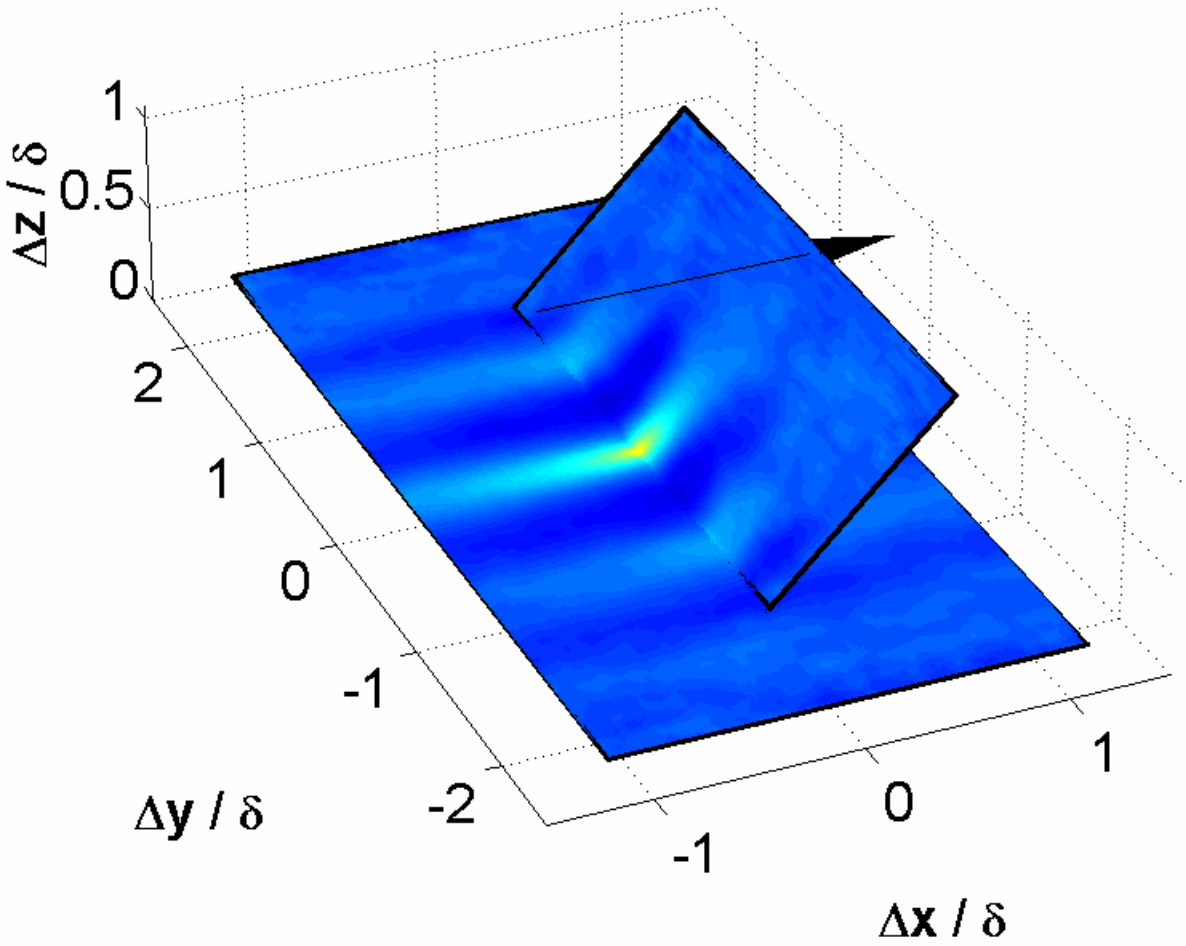

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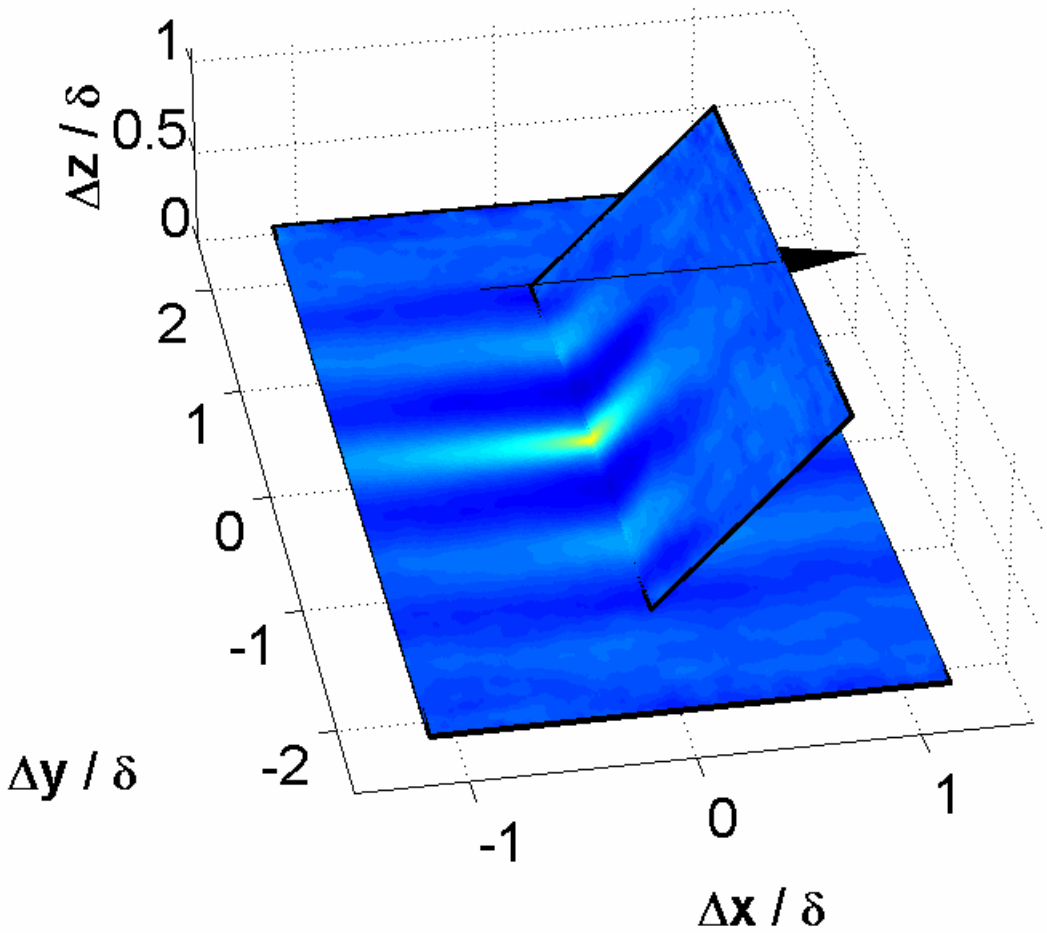

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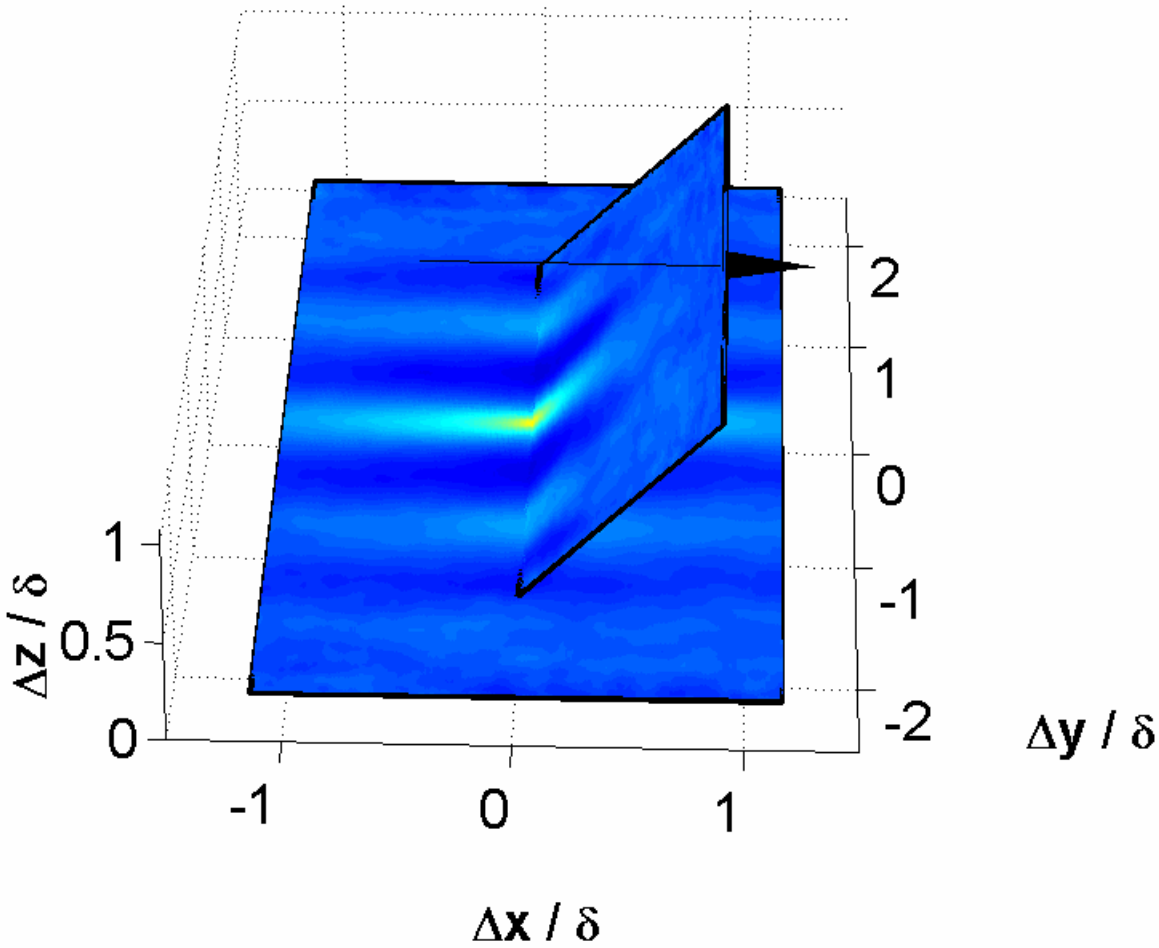

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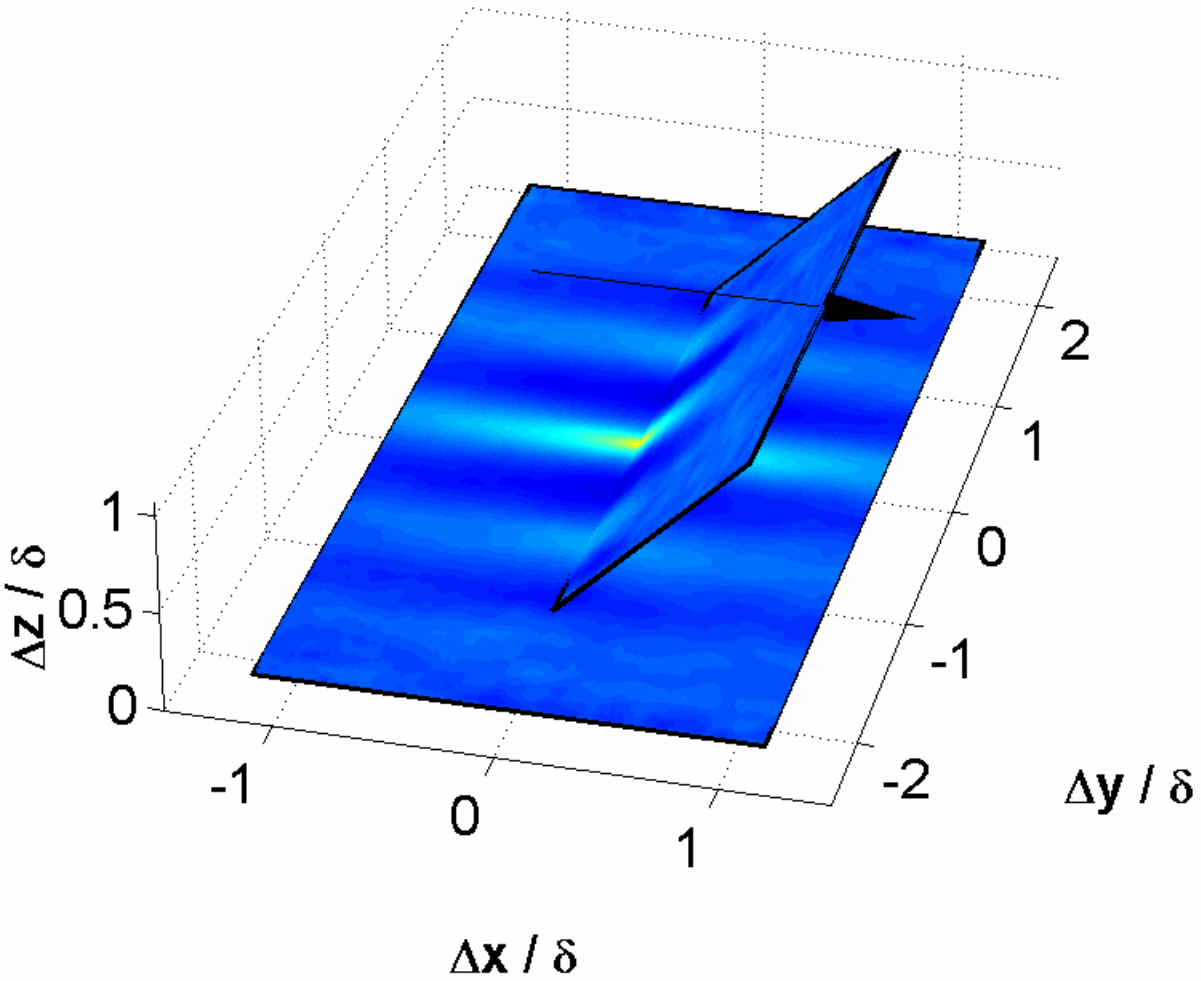

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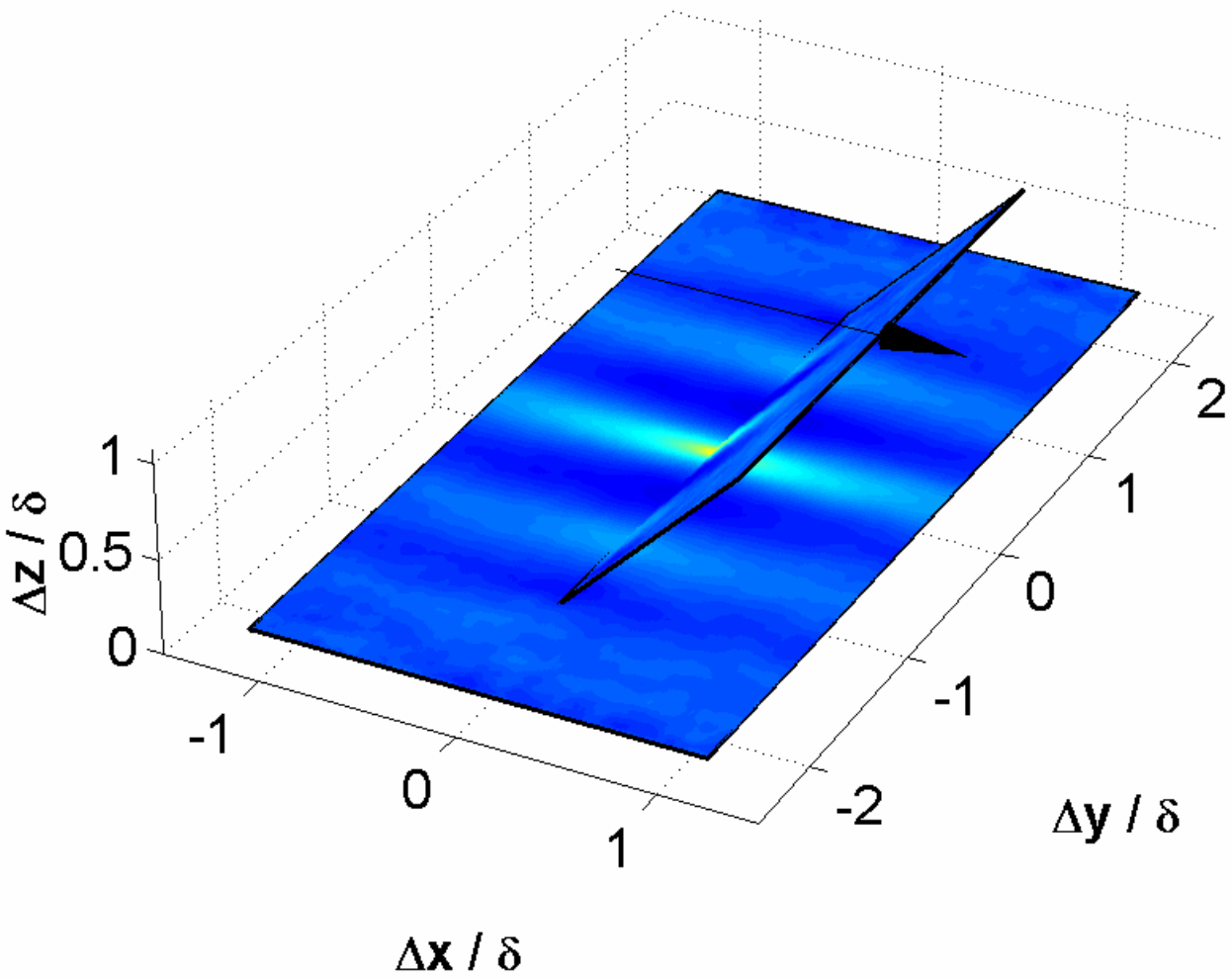

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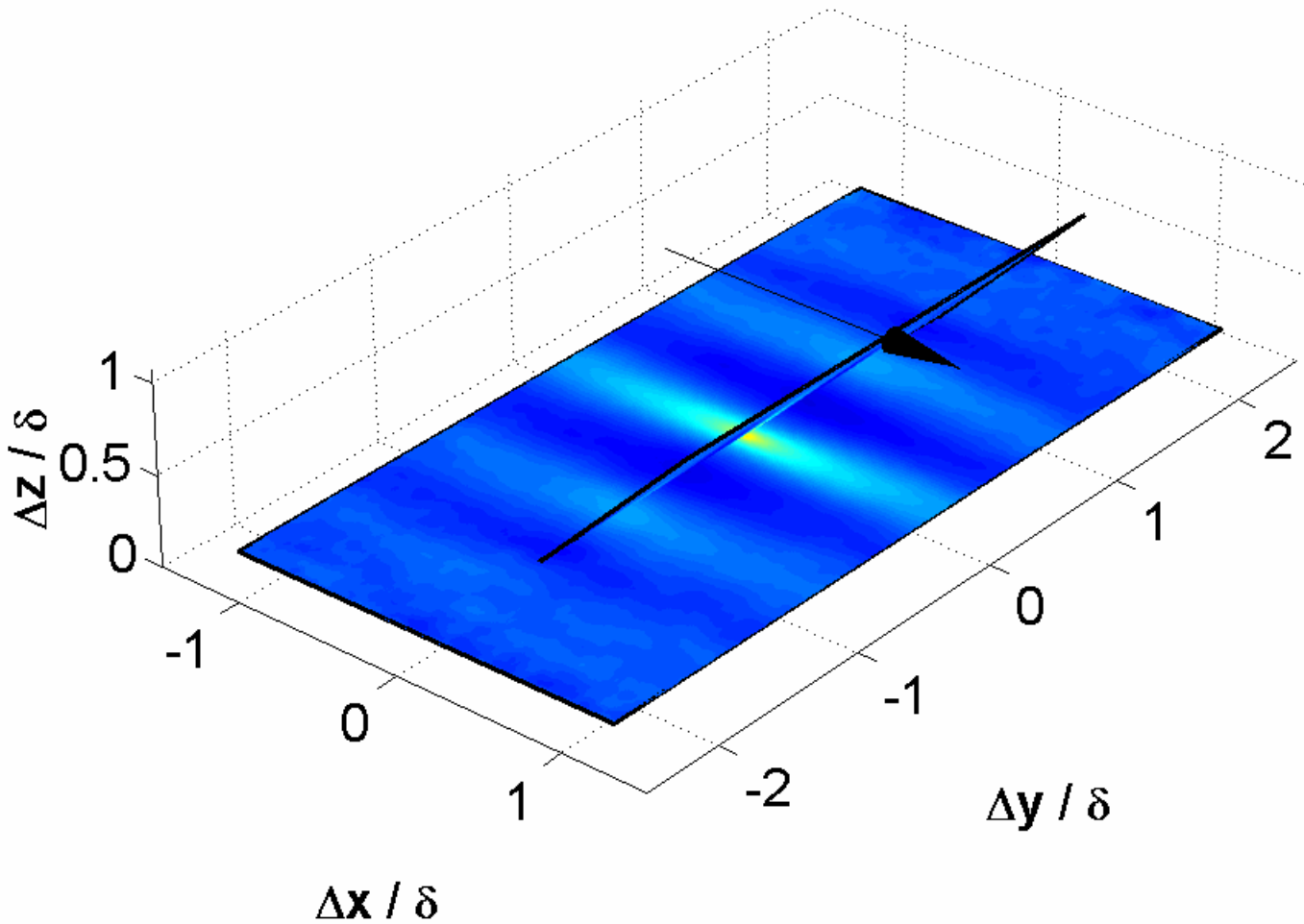

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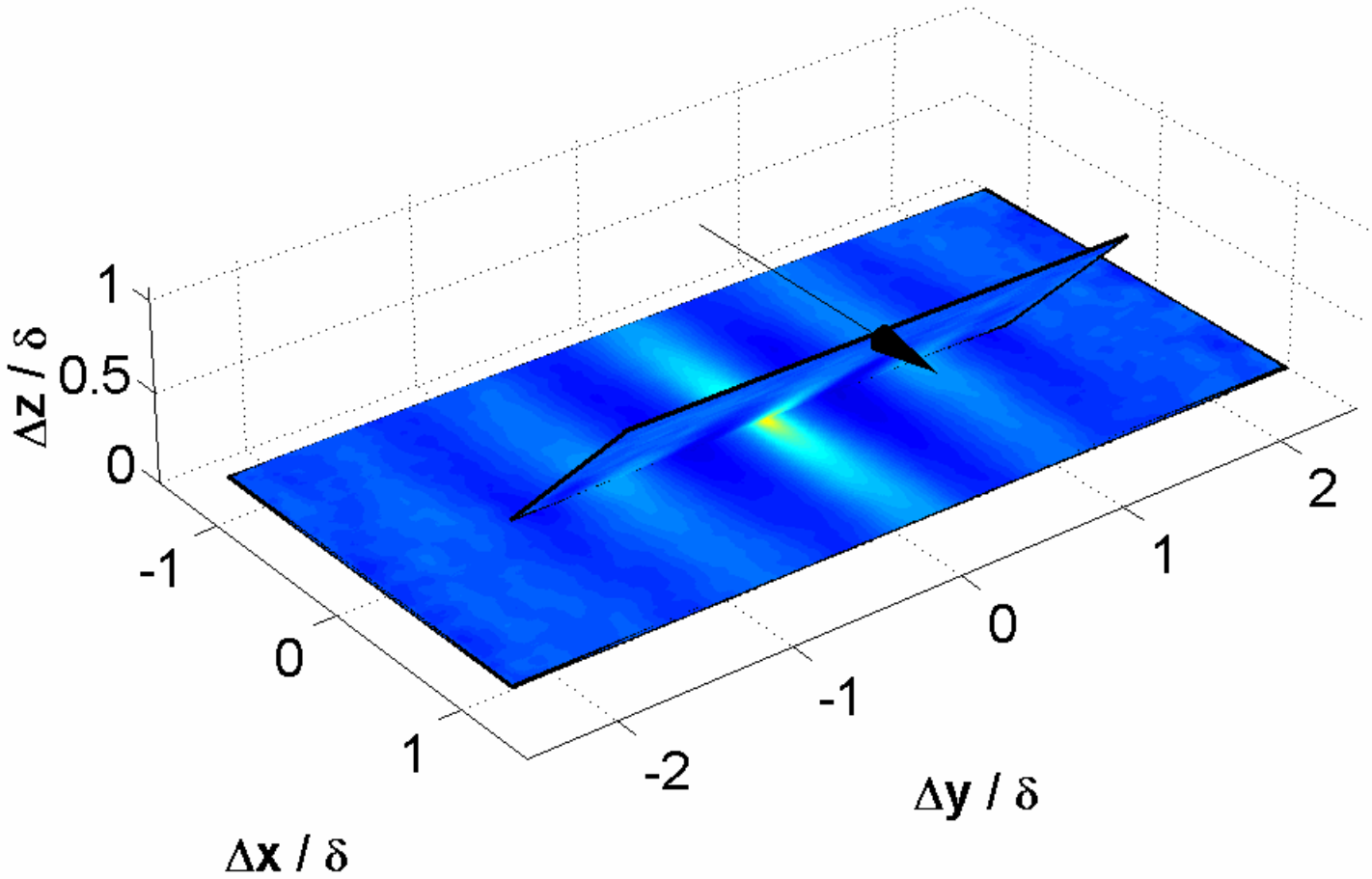

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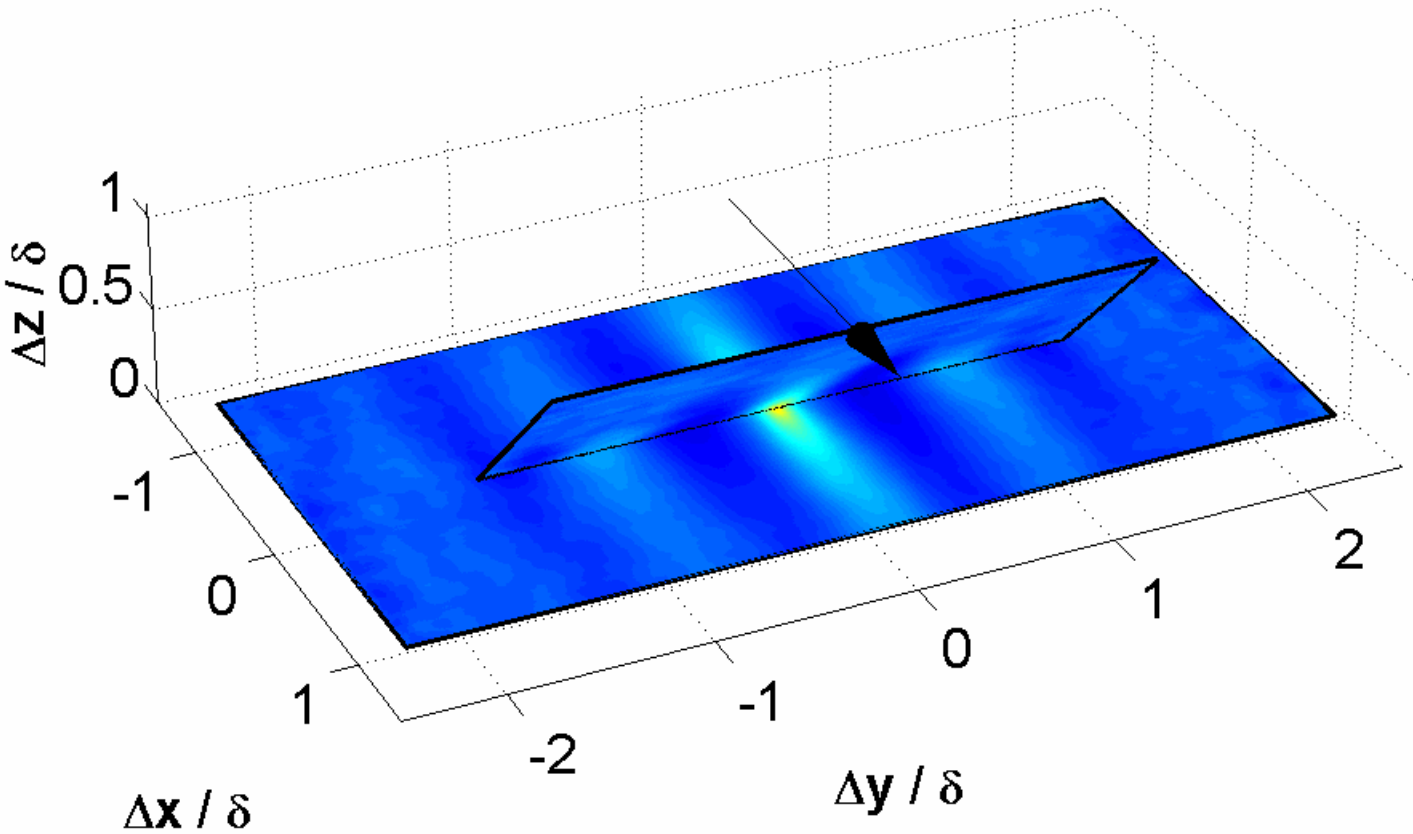

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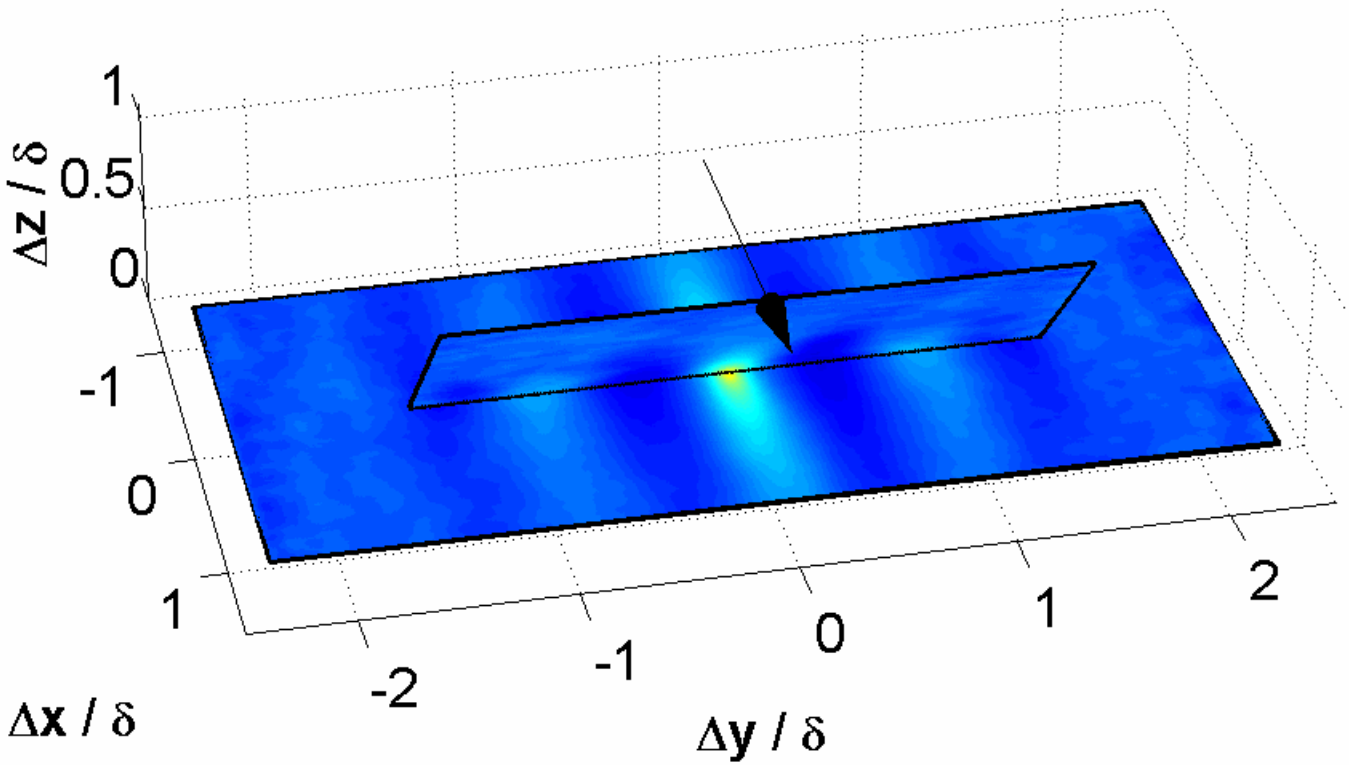
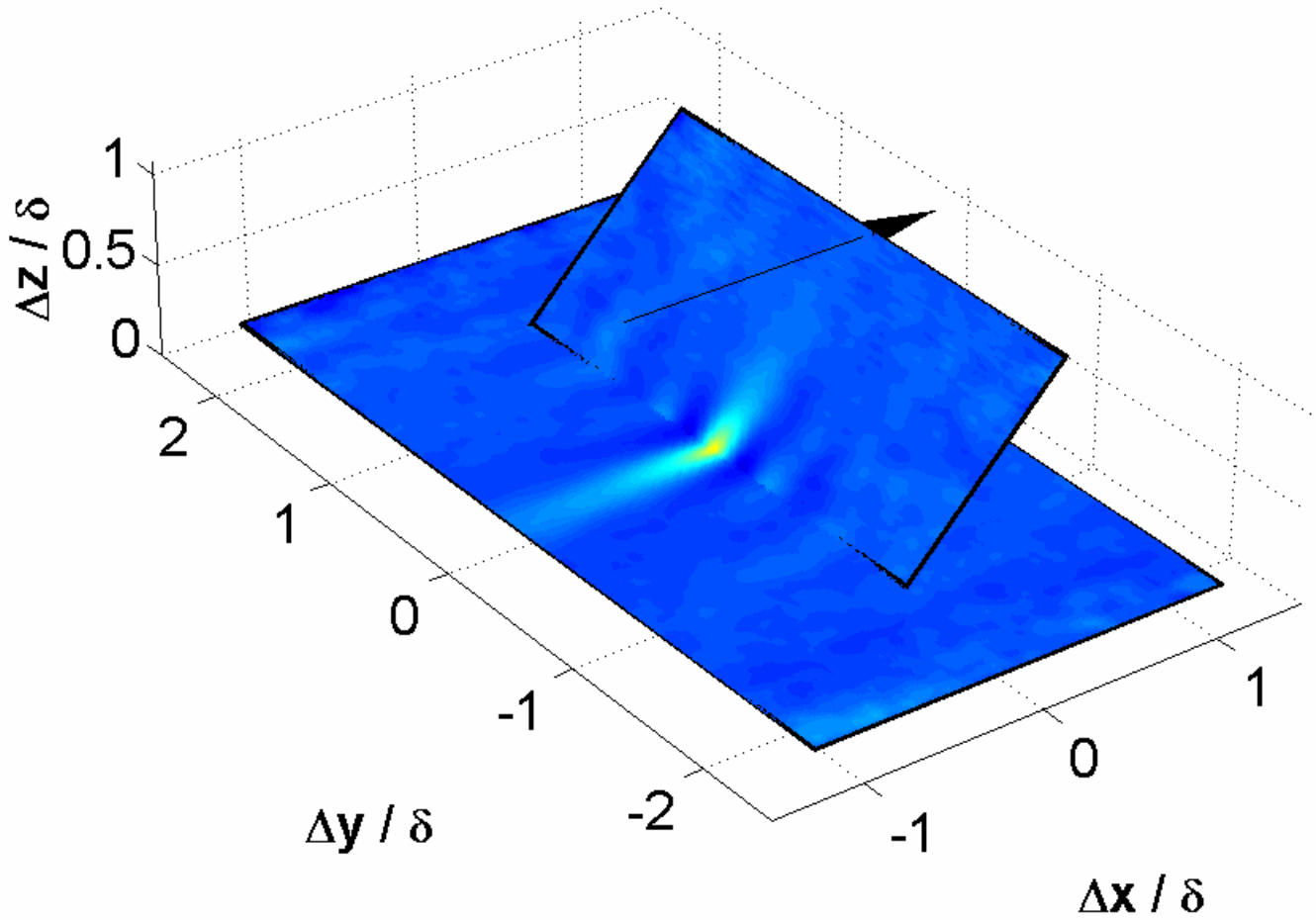


Calculate R_{uu} on frames that fall in the $0.25 < \lambda_z \delta < 0.5$ bin



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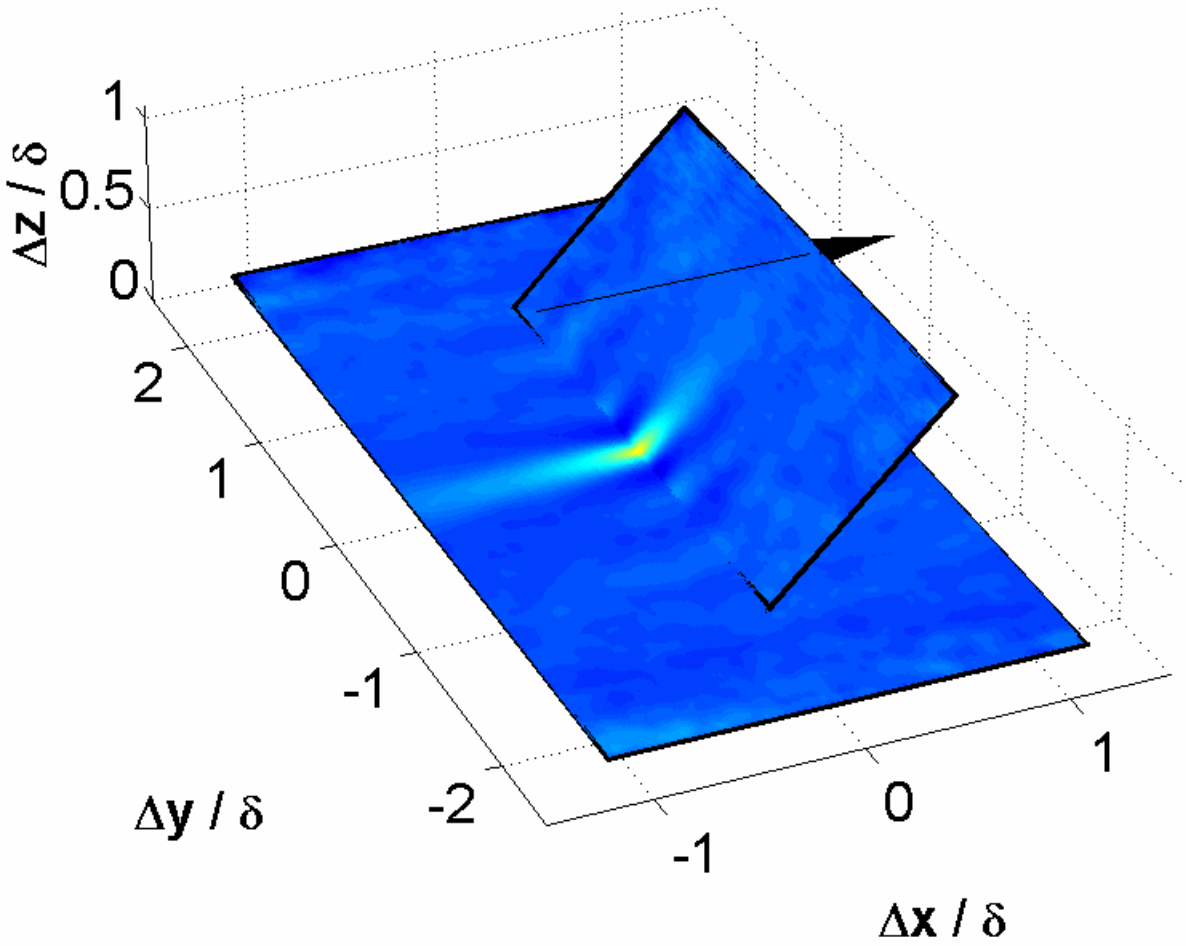

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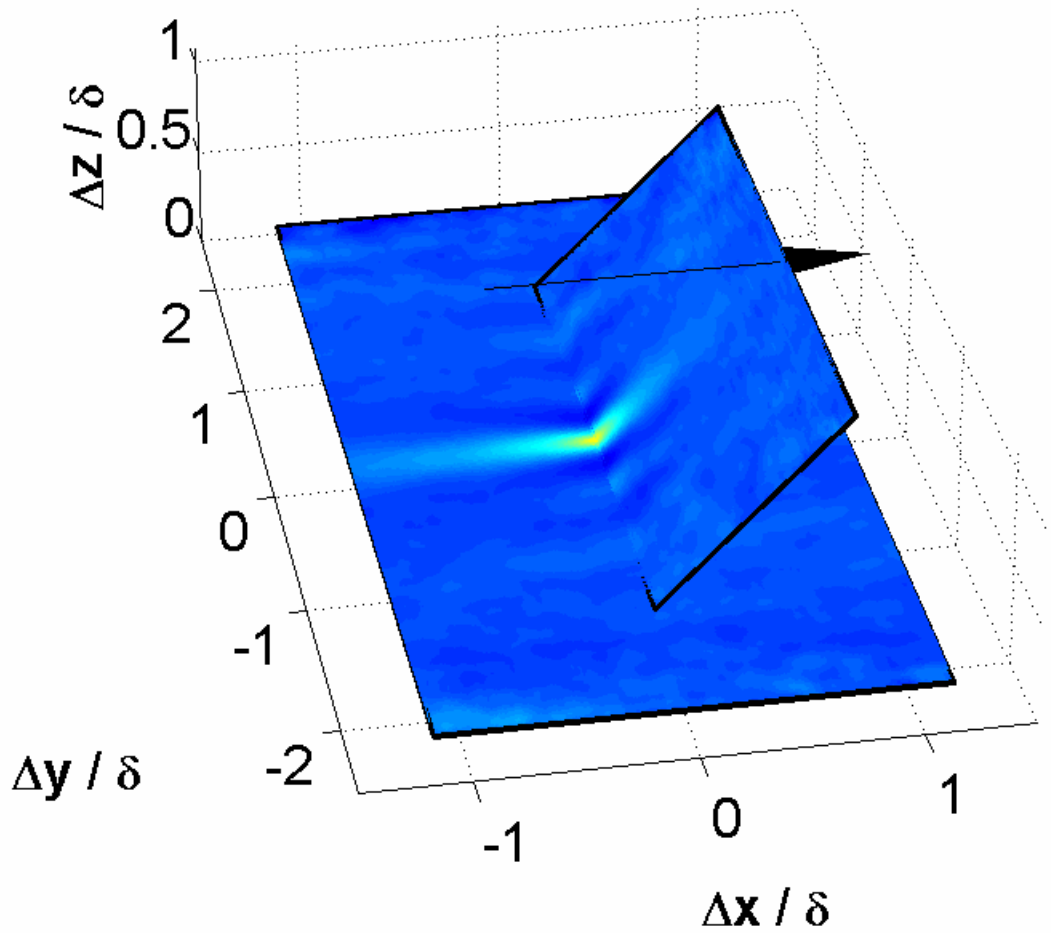

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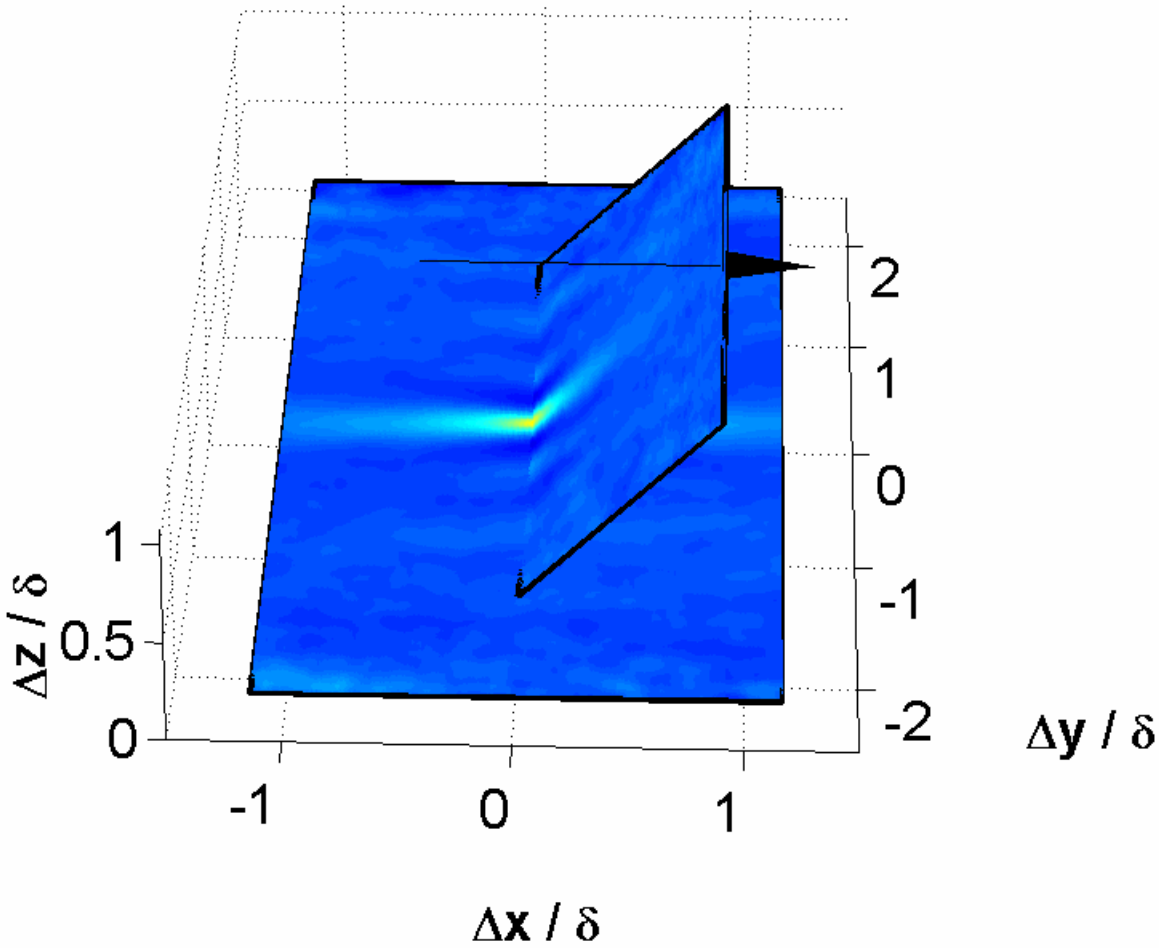

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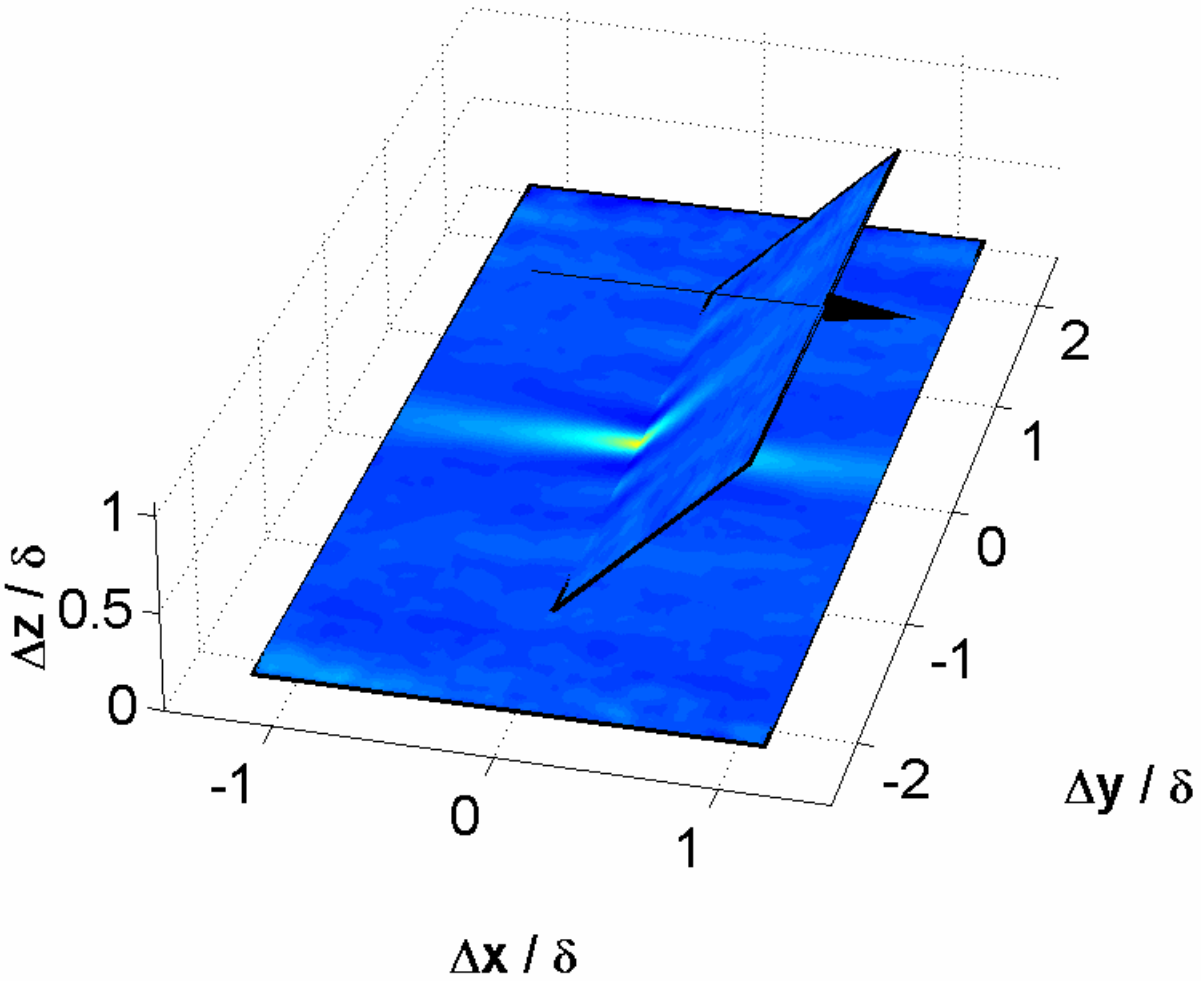

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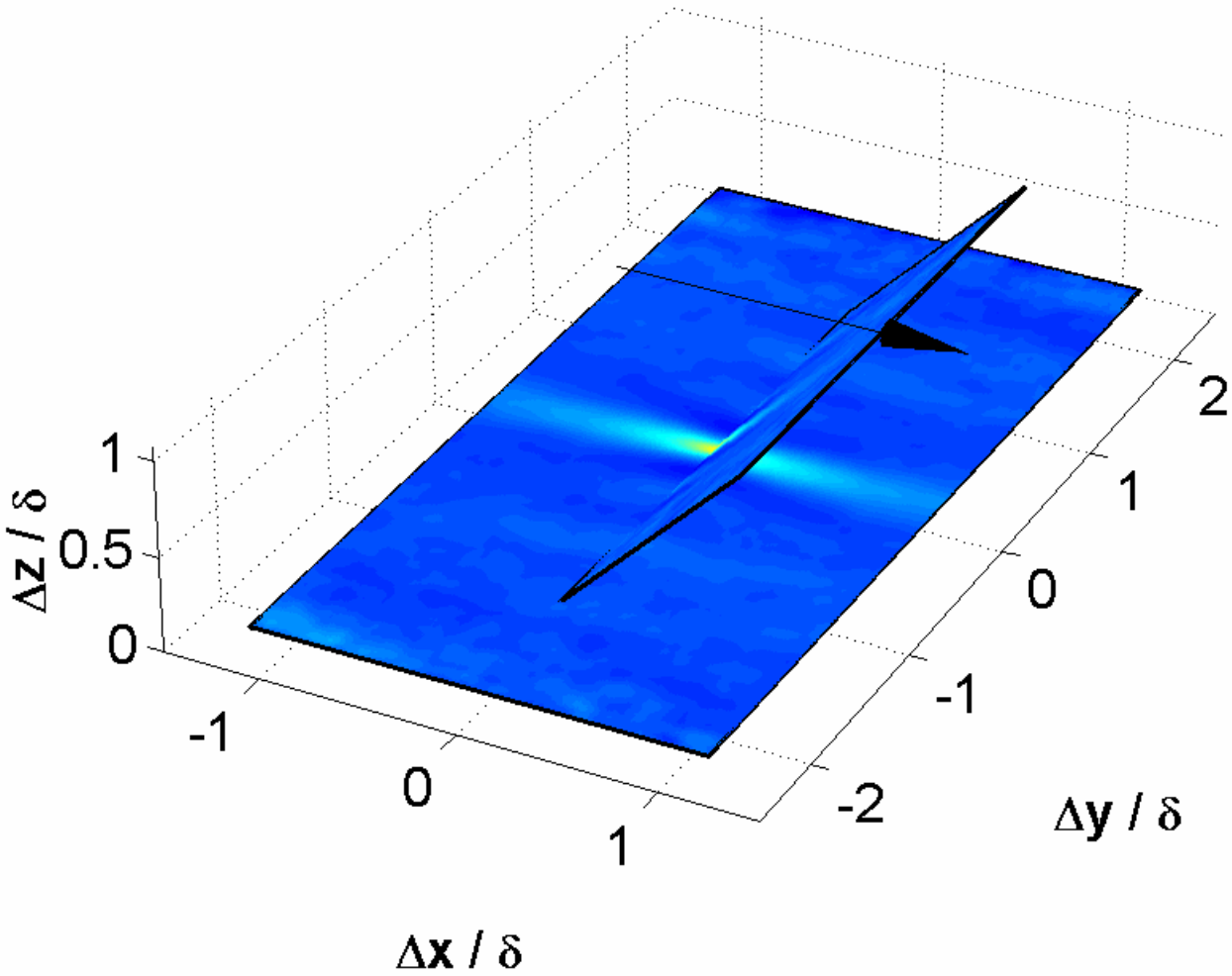

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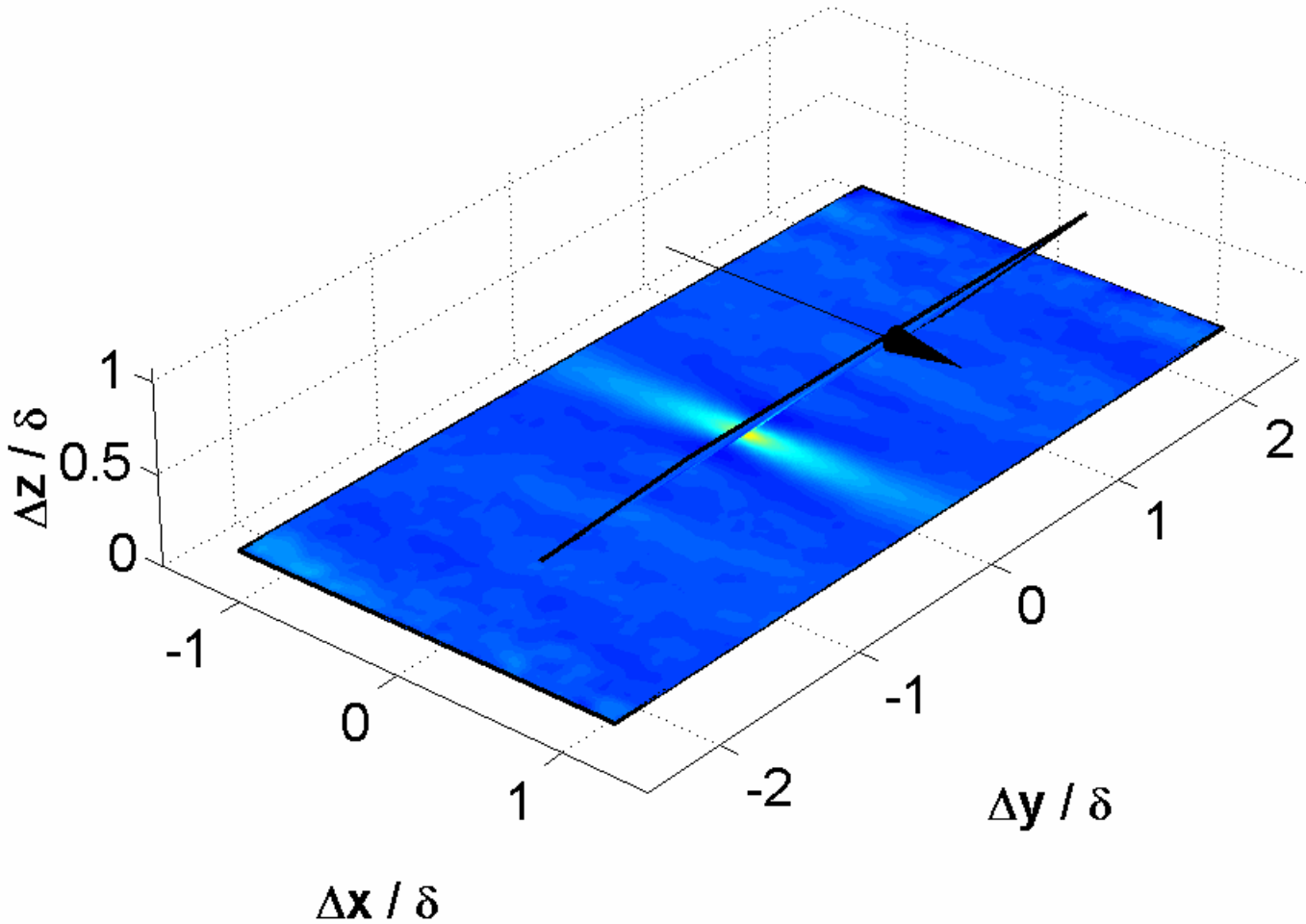

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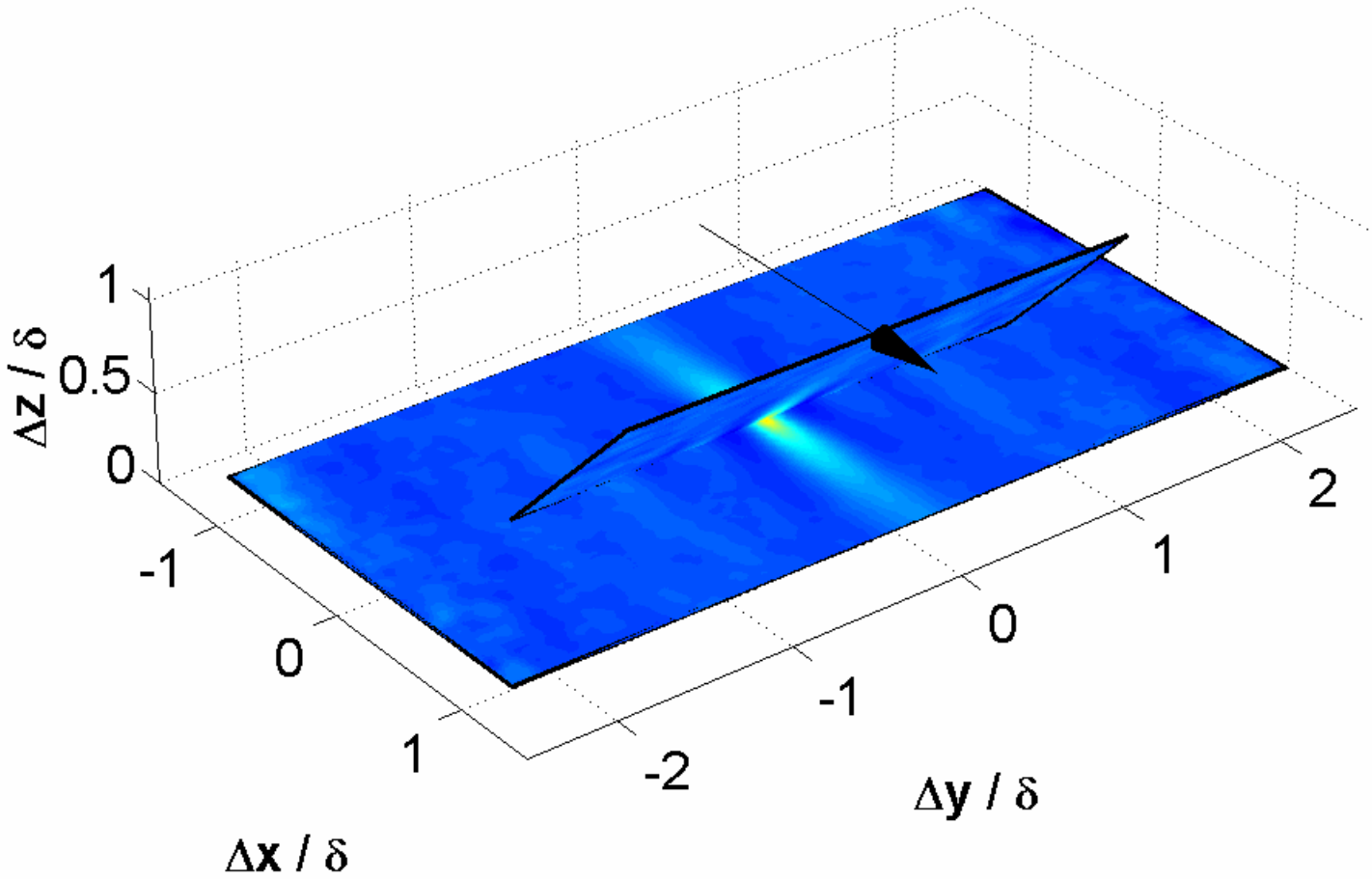

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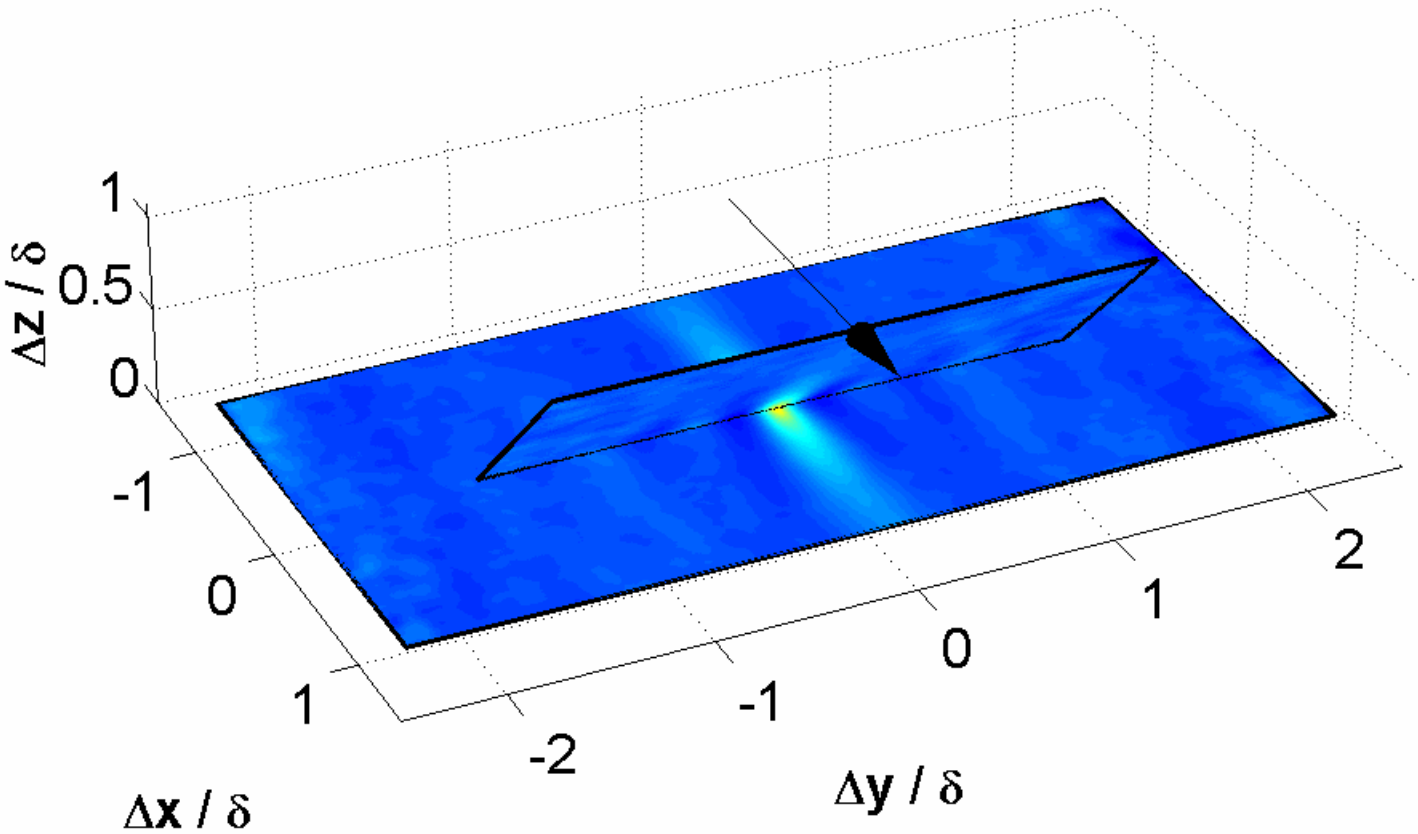

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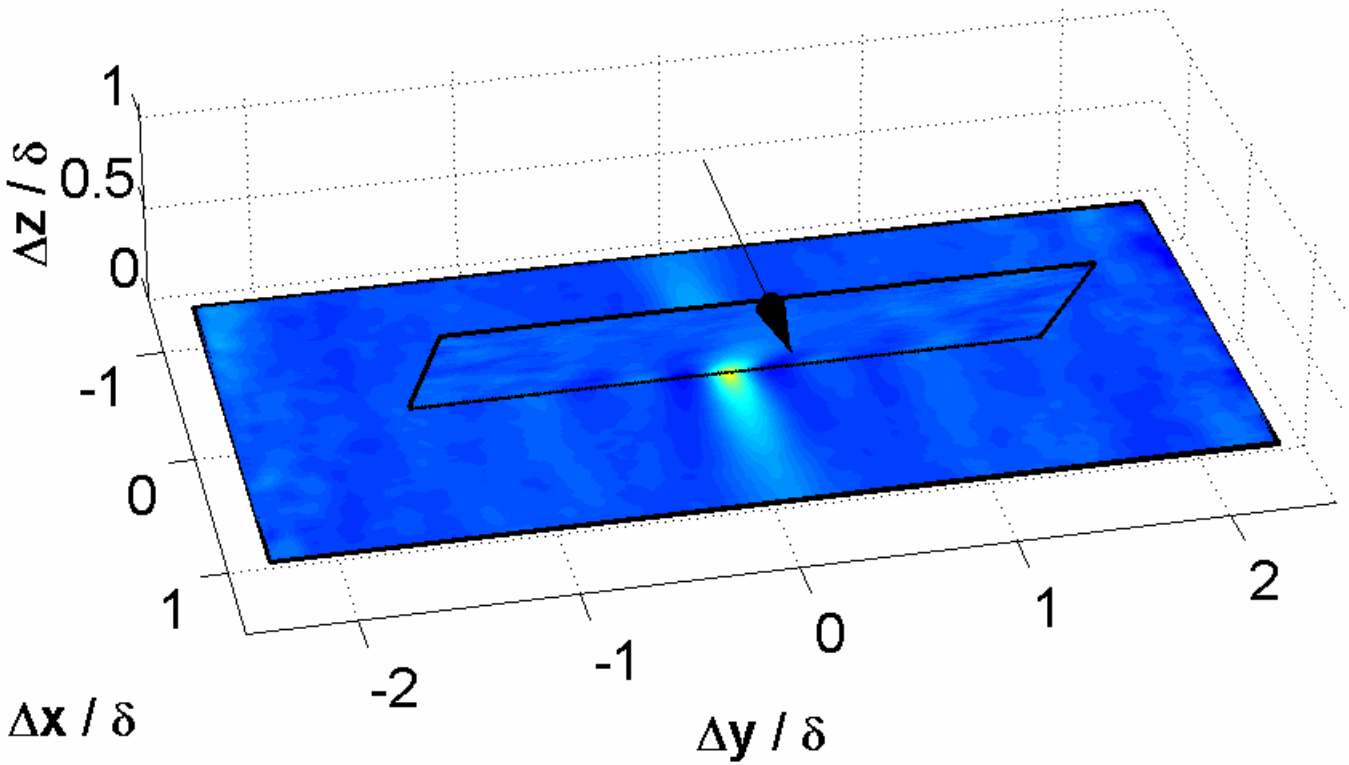
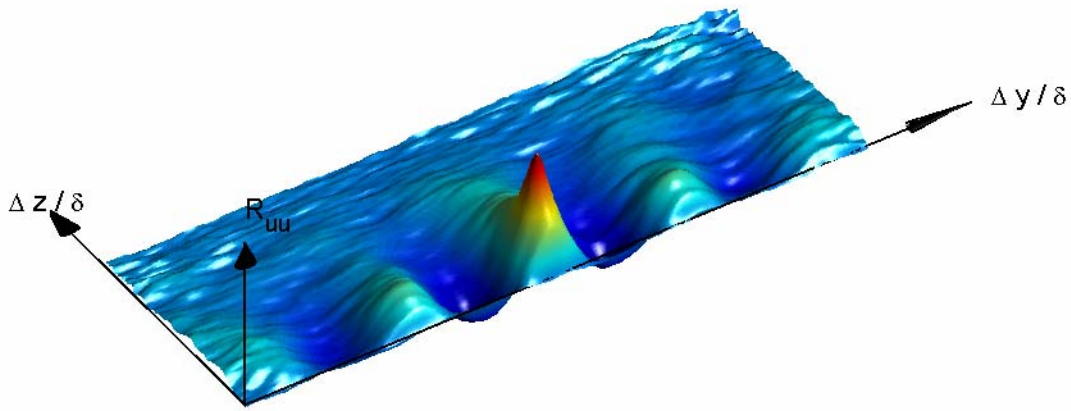


What does this mean?

•Instantaneously the spanwise *u* behaviour seems to be well described by single spanwise sinusoidal modes extending a considerable distance in the wall-normal and streamwise directions.



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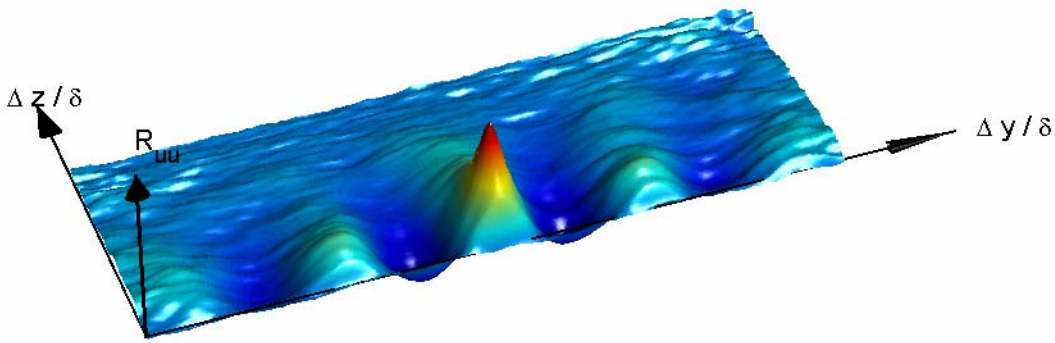

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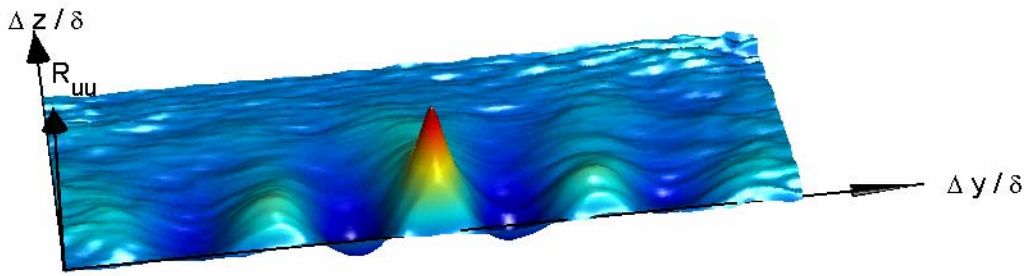

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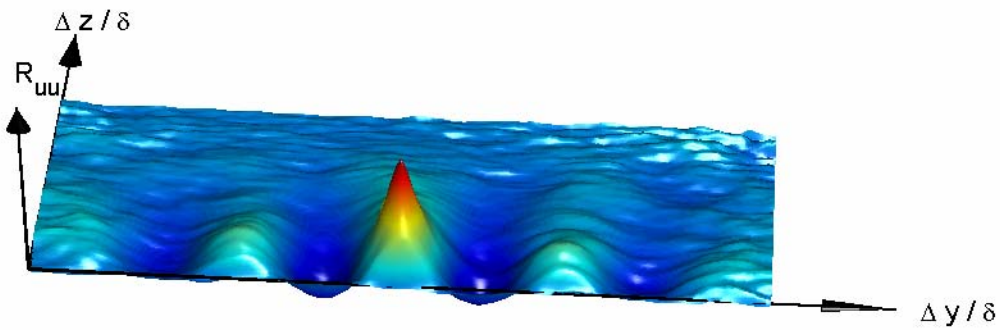

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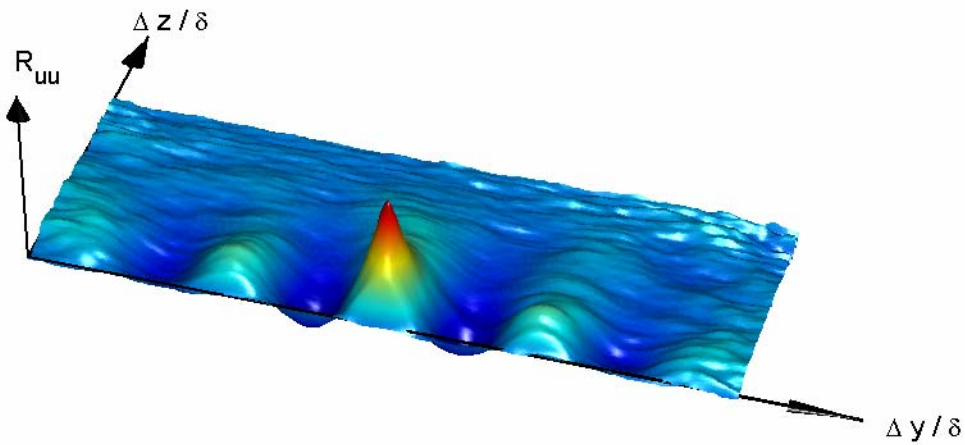

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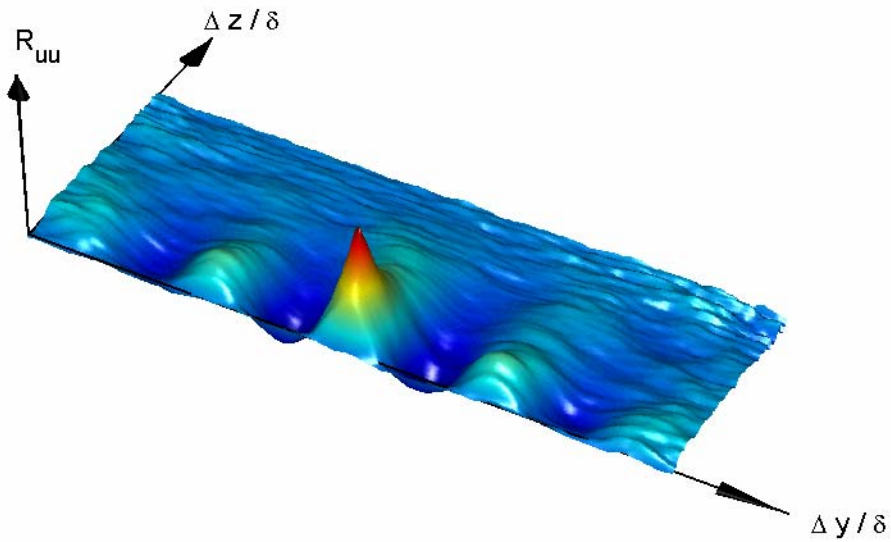

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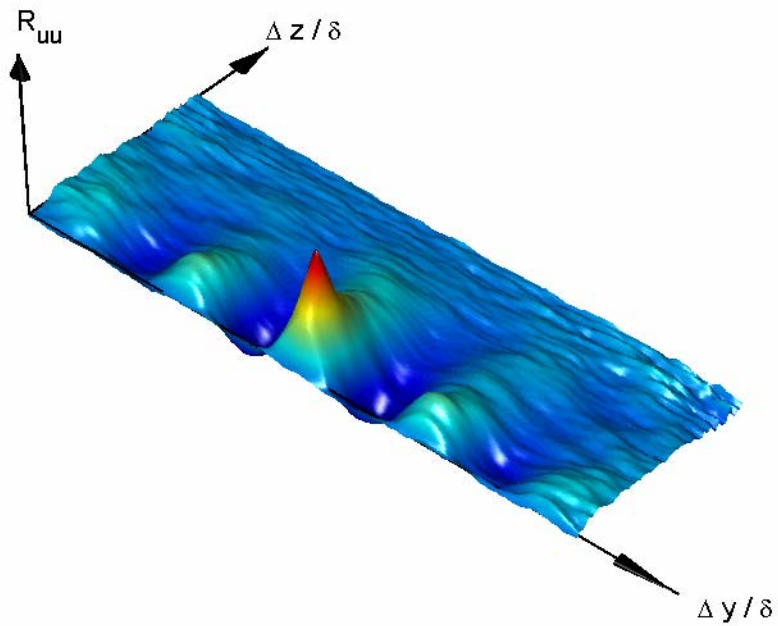

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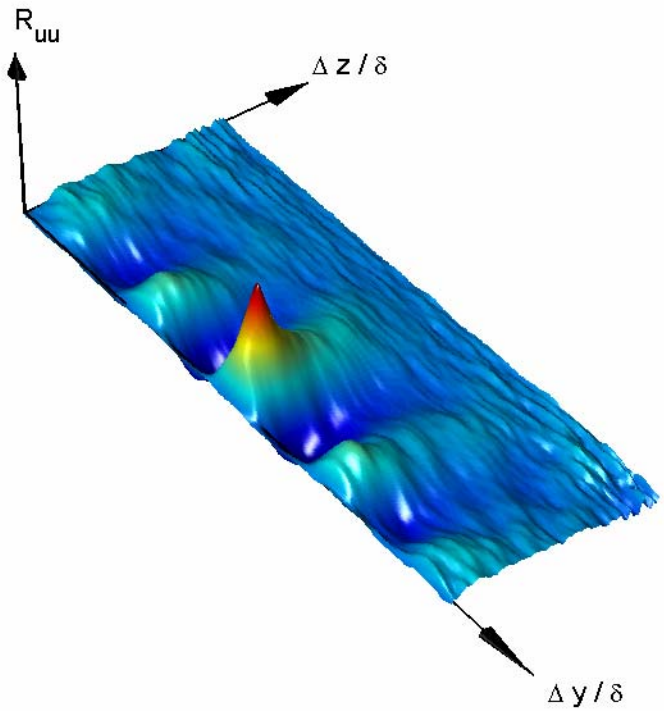

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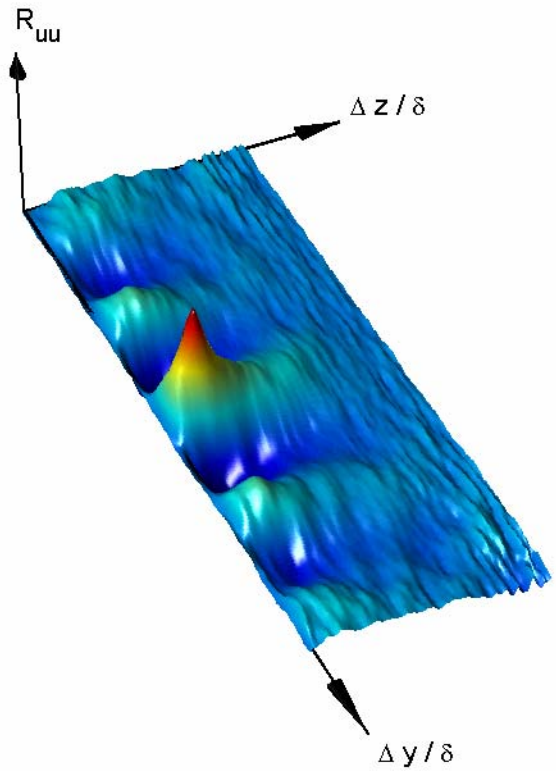

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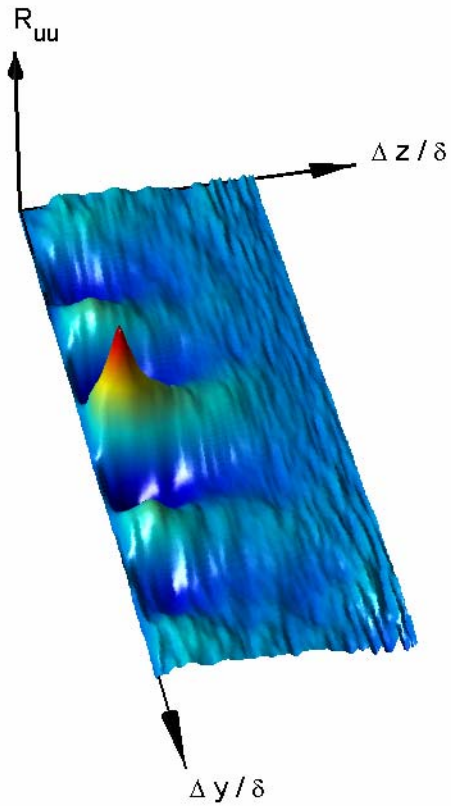

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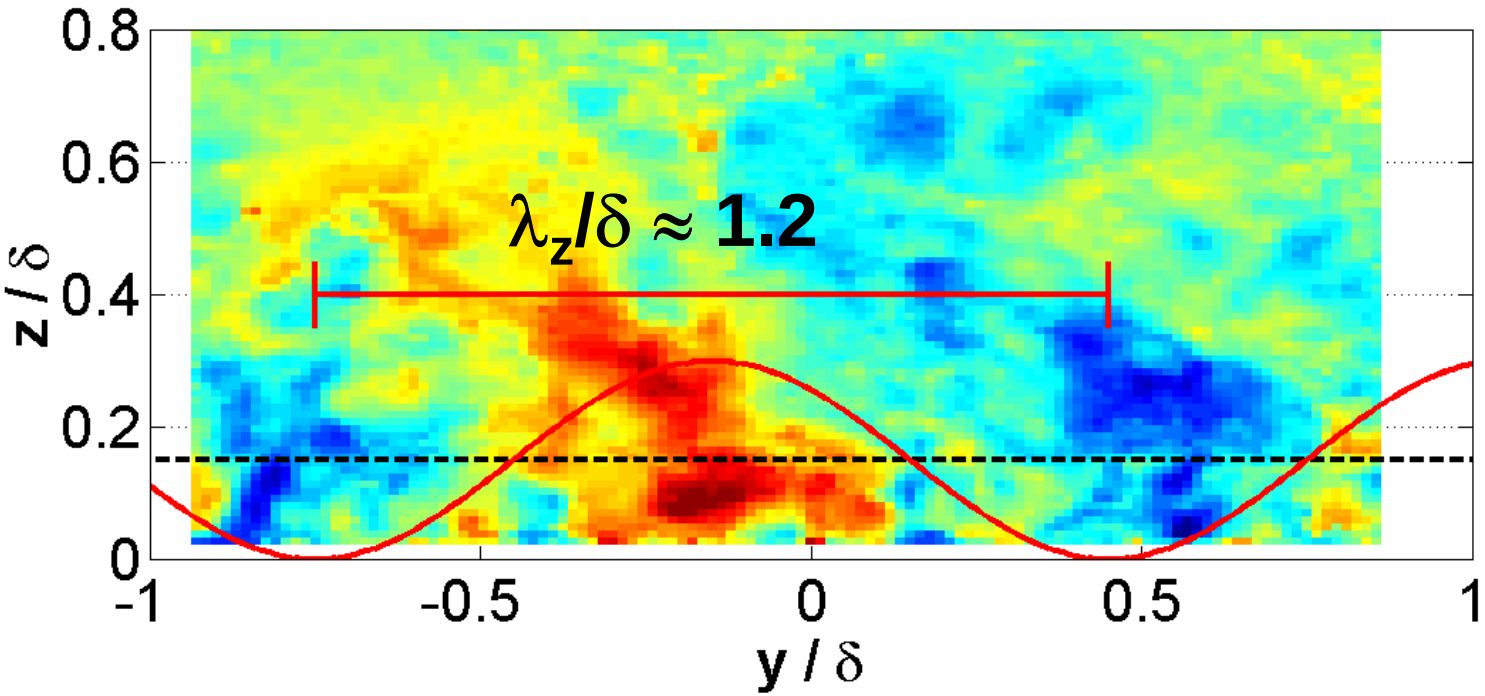

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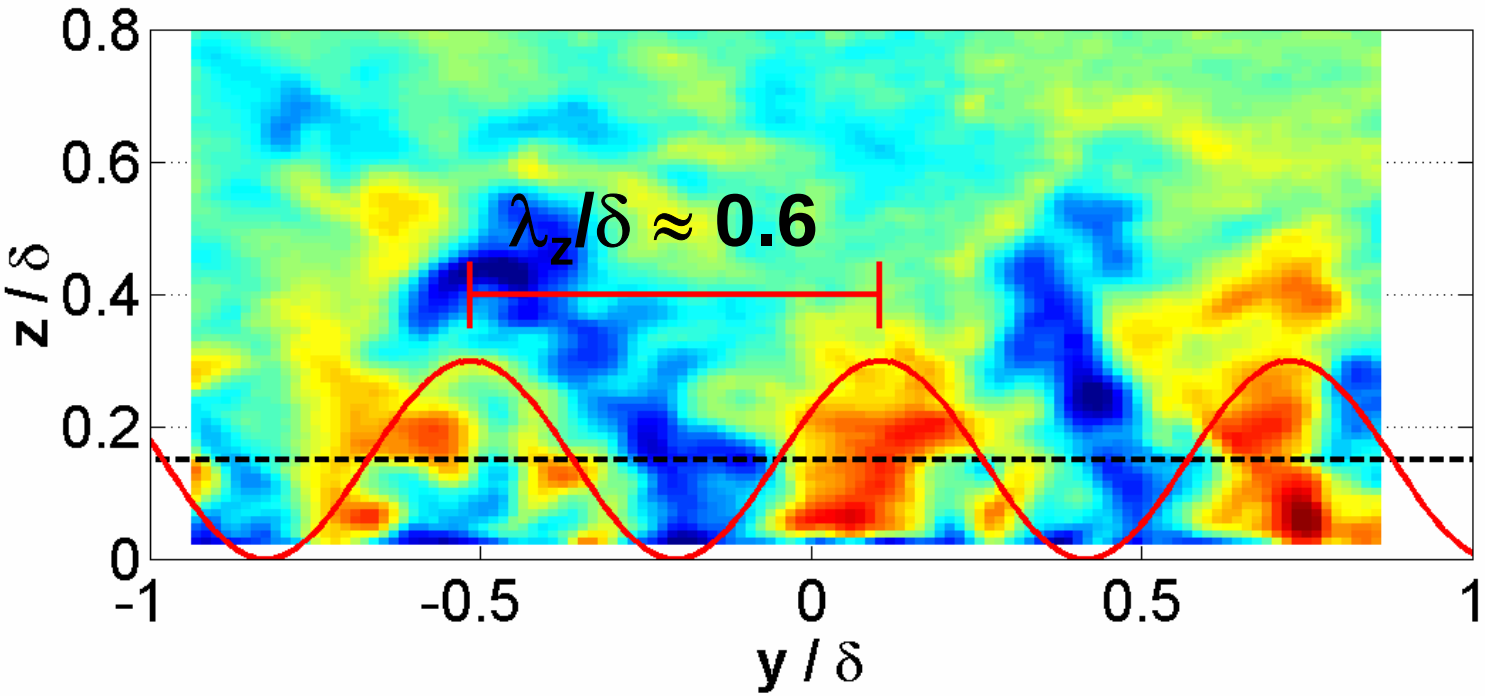

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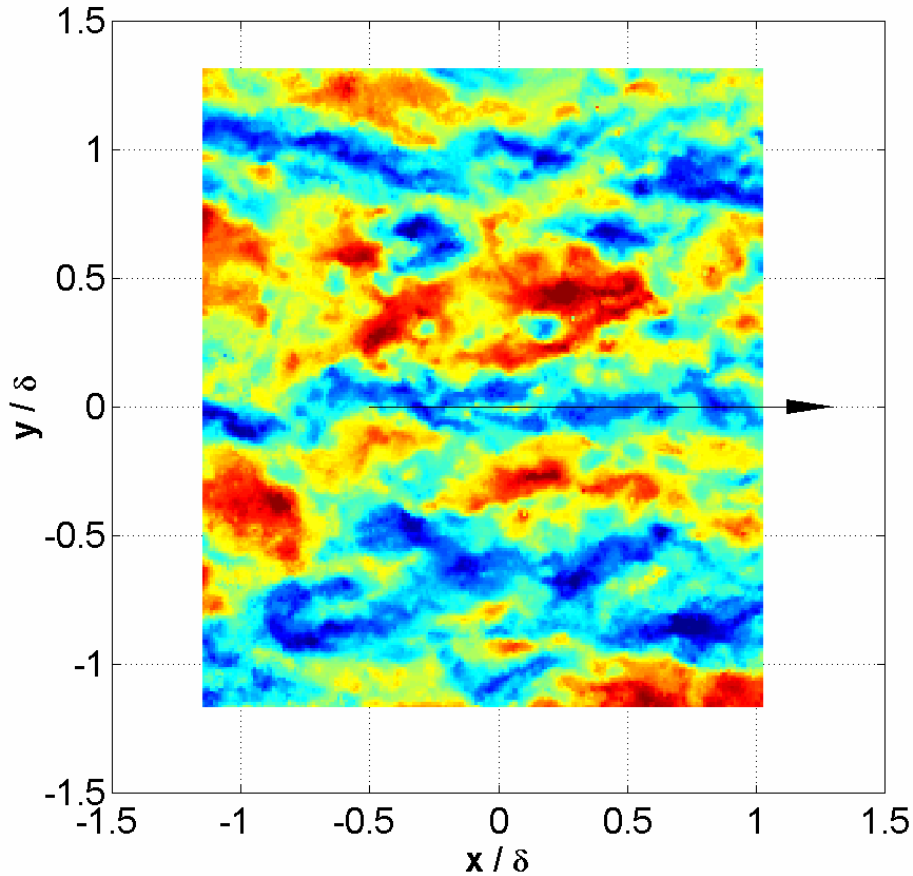

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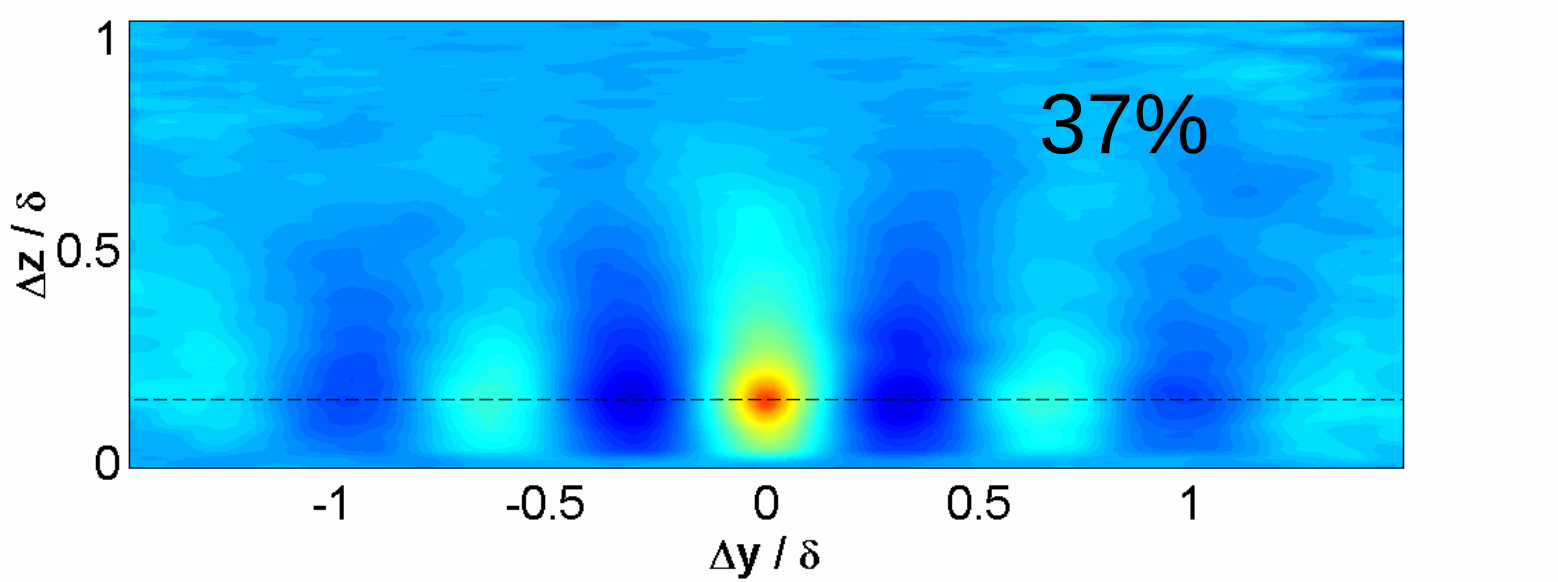
•Instantaneously the spanwise *u* behaviour seems to be well described by single spanwise sinusoidal modes extending a considerable distance in the wall-normal and streamwise directions.

•Large low-speed events at the origin are going to be accompanied by similar flanking events at $y/\delta = \pm$ 0.5-0.75 with a 37% probability.



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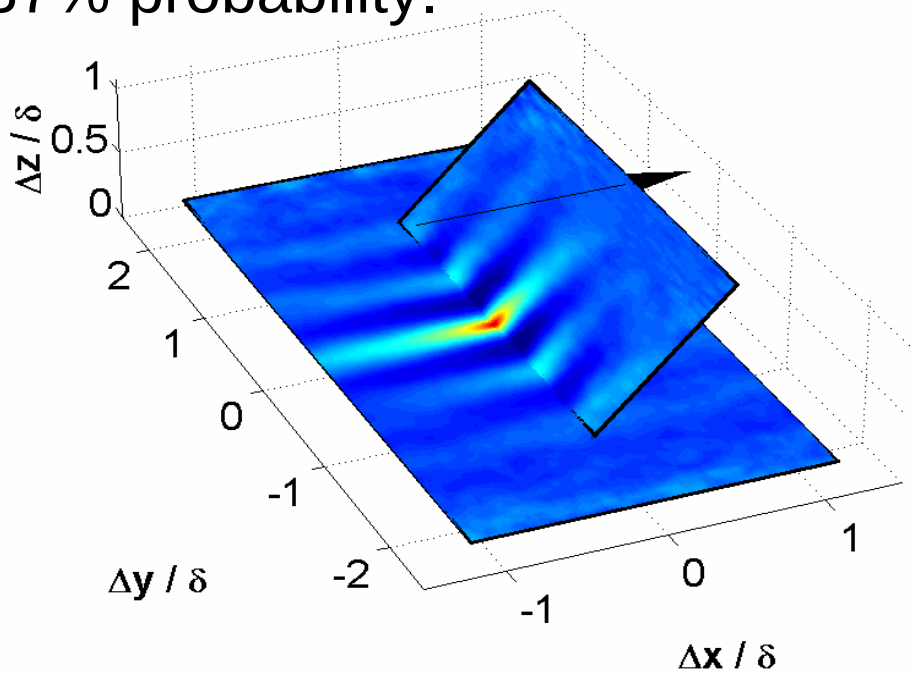

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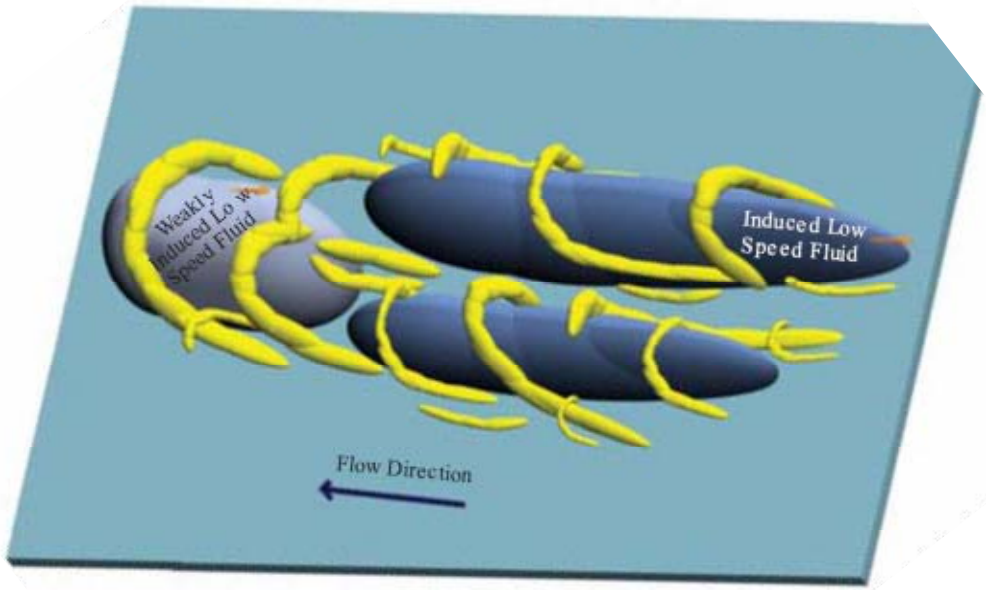
- There is a strong <u>spanwise periodicity</u> associated with the largest streamwise velocity fluctuations.

- These velocity fluctuations are actually a slice through some wider structural coherence.

Further thoughts

- Scale growth through packet merging (Tomkins and Adrian 2003)



- Reynolds number scaling issues?
  - SLTEST – 40m spanwise coherence ??