Stratified shear flow instability: Application to oceanic overflows

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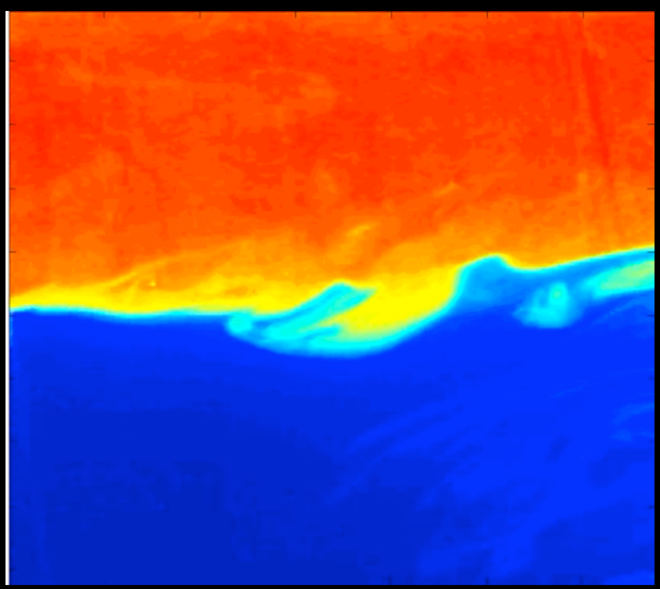
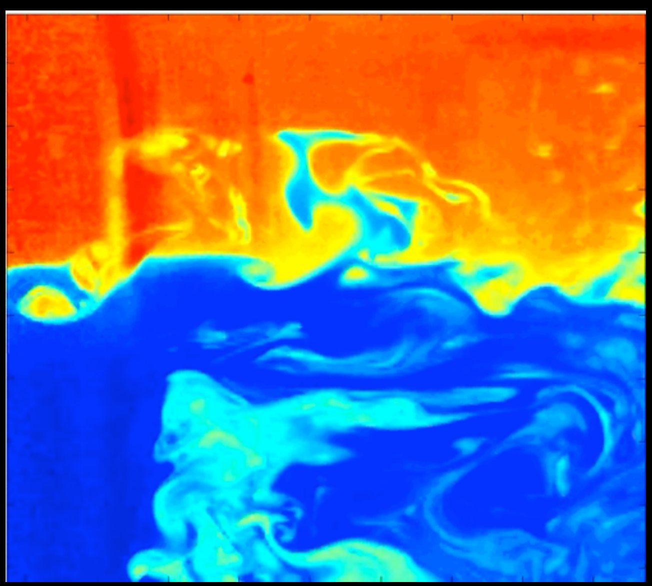
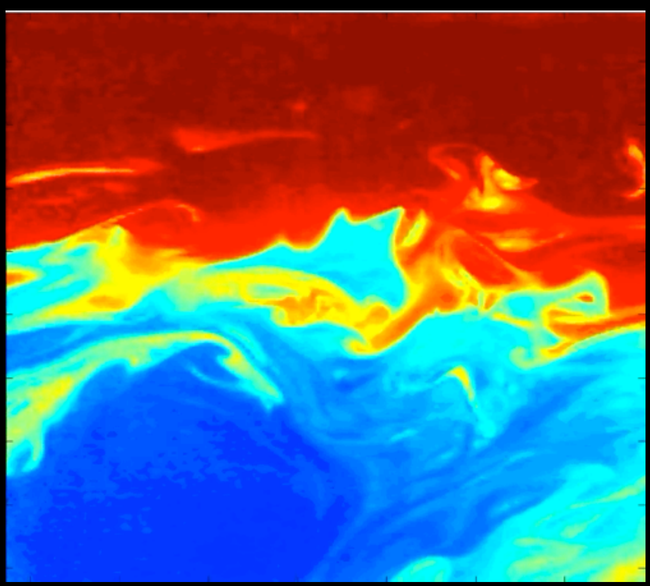
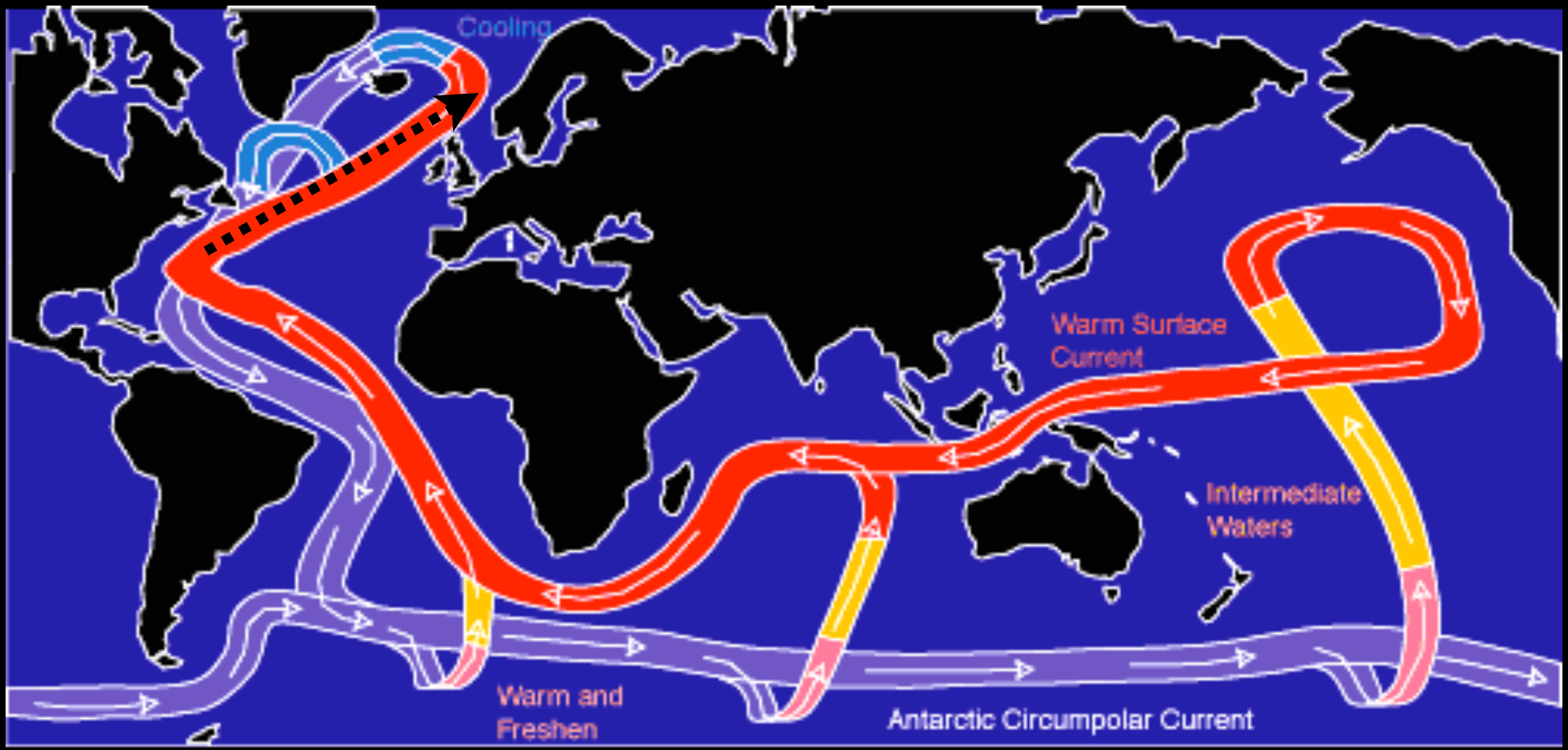




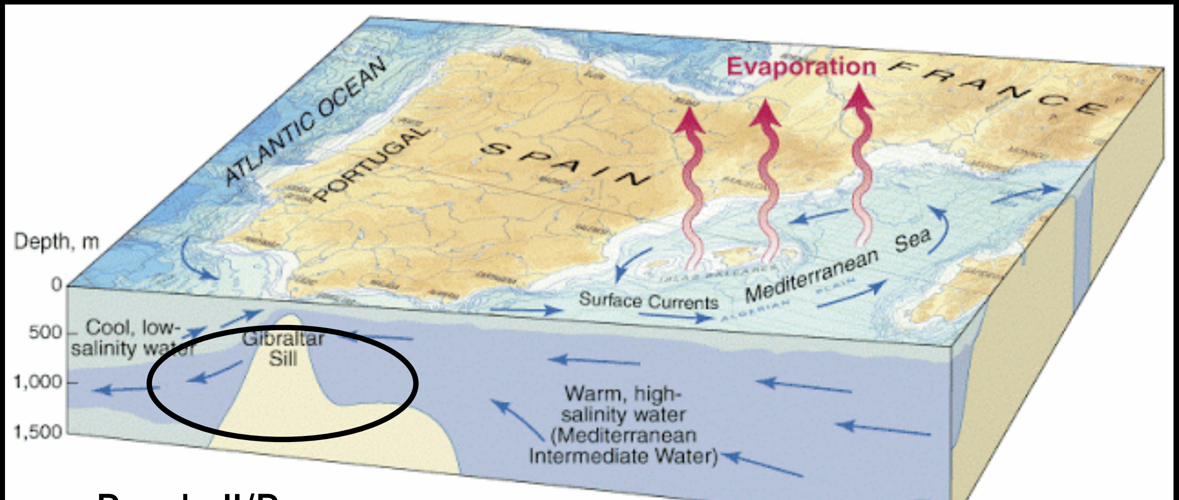


The oceanic circulation of heat and salinity are major determinants of long term climate and overflows are key component.

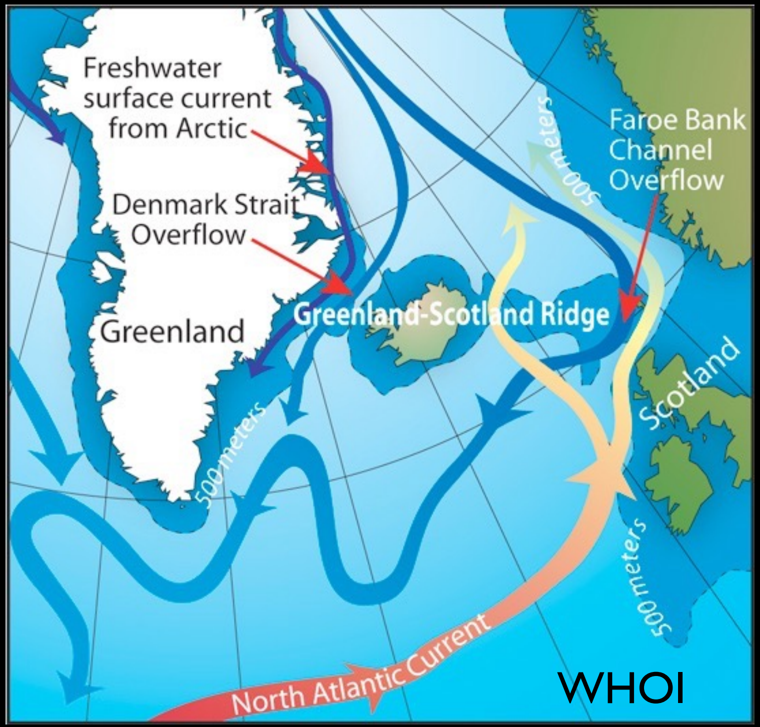


Oceanic Overflows

Mediterranean Outflow

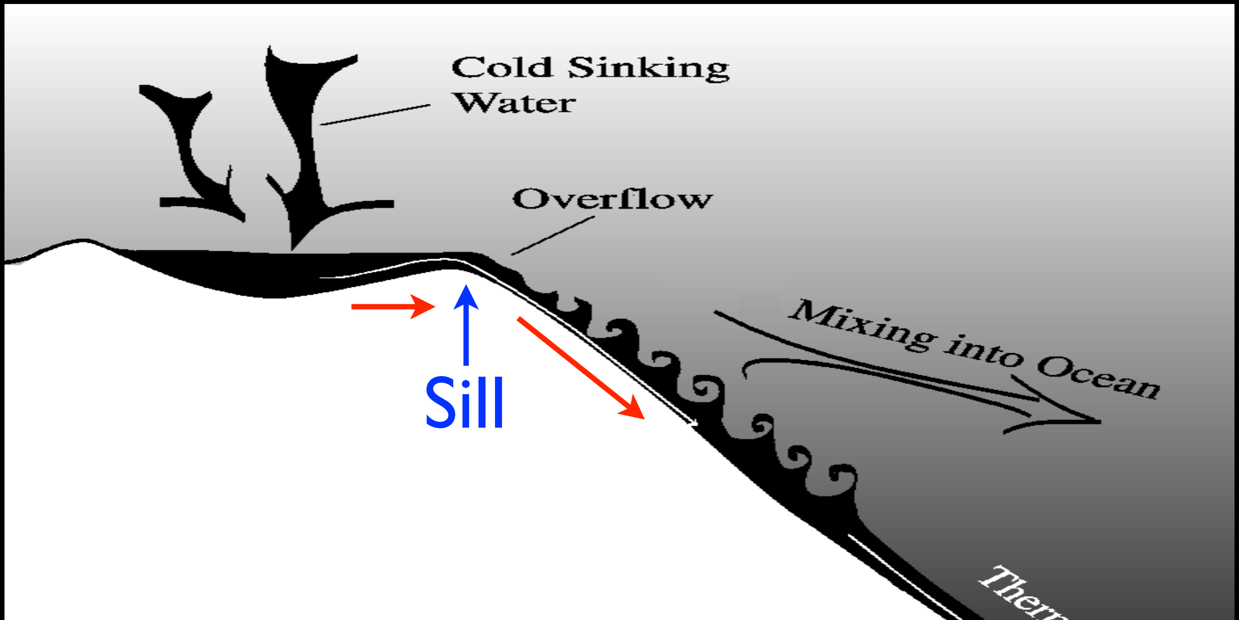


Prenhall/Pearson



WHOI

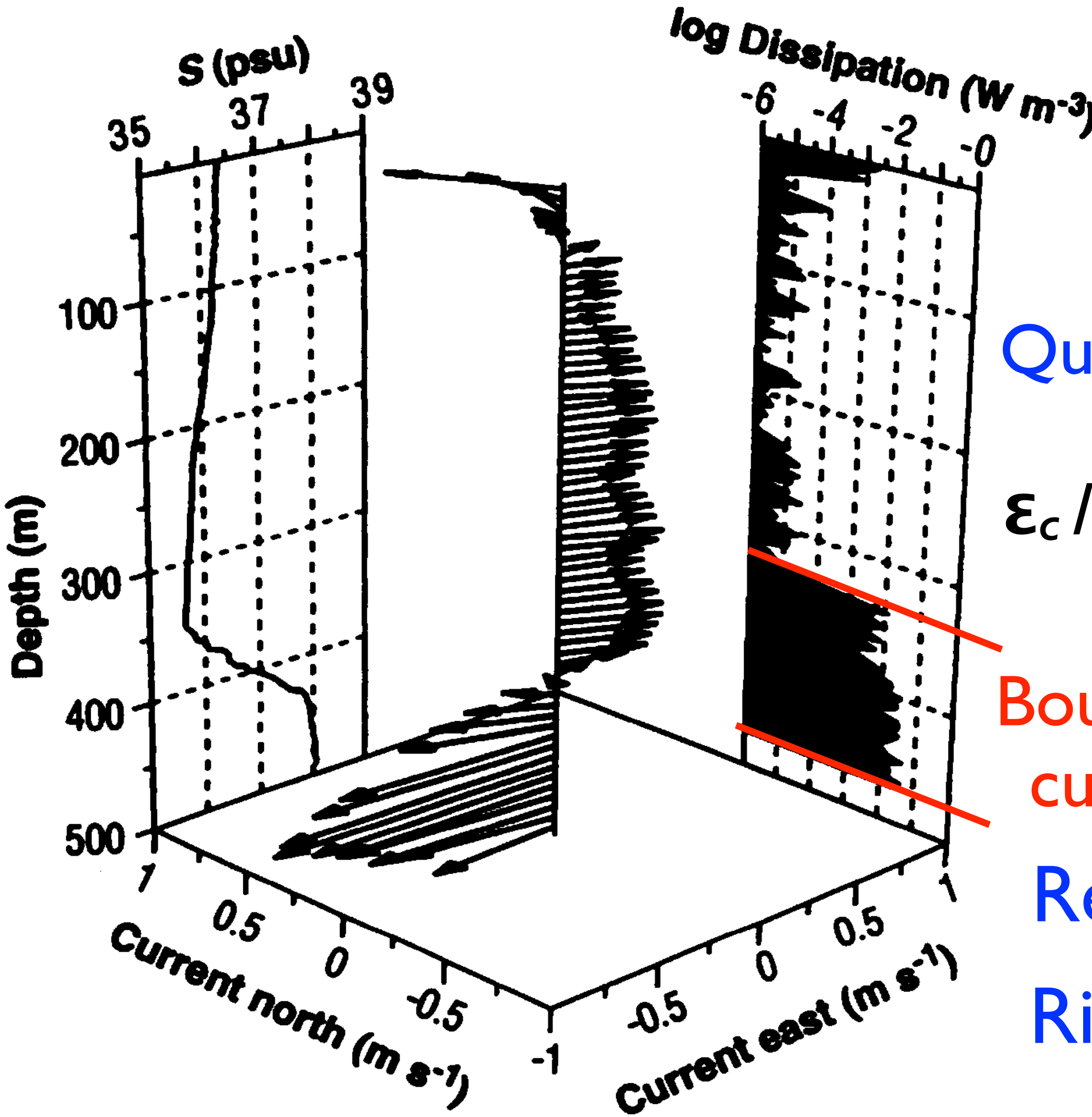
Thermohaline circulation



Schematic Representation

In-situ measurement is hard

Boundary Current Turbulent - top fluid much less turbulent (Mediterranean outflow - Price et al *Science* 1993)



Quiescent fluid

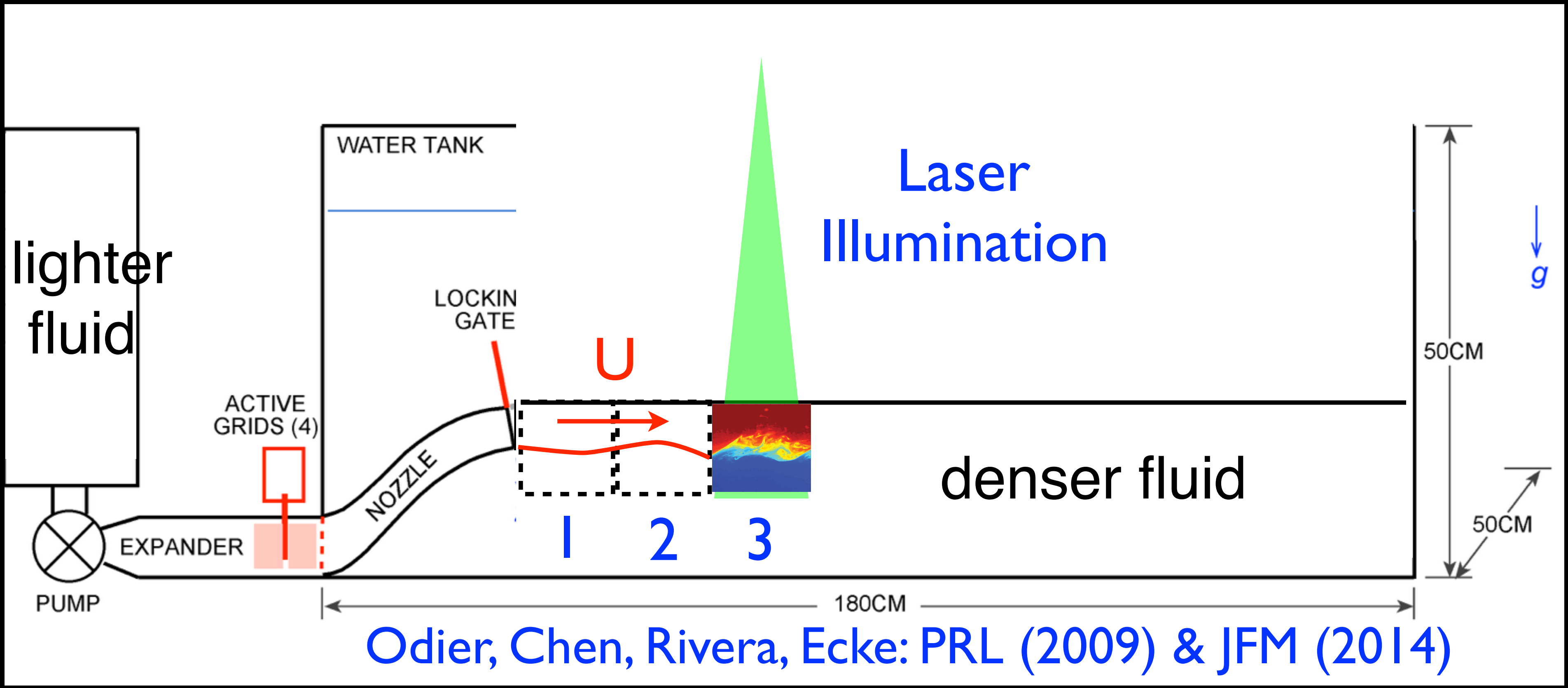
$\varepsilon_c / \varepsilon_T \approx 1000$

Boundary current

$Re \sim 10^6$

$Ri_b \sim 1\text{-}2$

Experimental Apparatus



Simultaneous PIV & PLIF ⇒

Velocity & Density

Experimental Properties

- High Reynolds number inside current
  $Re \sim 3000$; $R_\lambda \sim 100$; $Re_b = \varepsilon/(\nu N^2) \sim 100$

- Vary Ri through :
  current velocity U: $\{U_0$ and $U_0/2\}$
  density contrast $\Delta\rho$: $\{\Delta\rho_0$ and $2\Delta\rho_0\}$

  → $0.25 < Ri_b < 1$

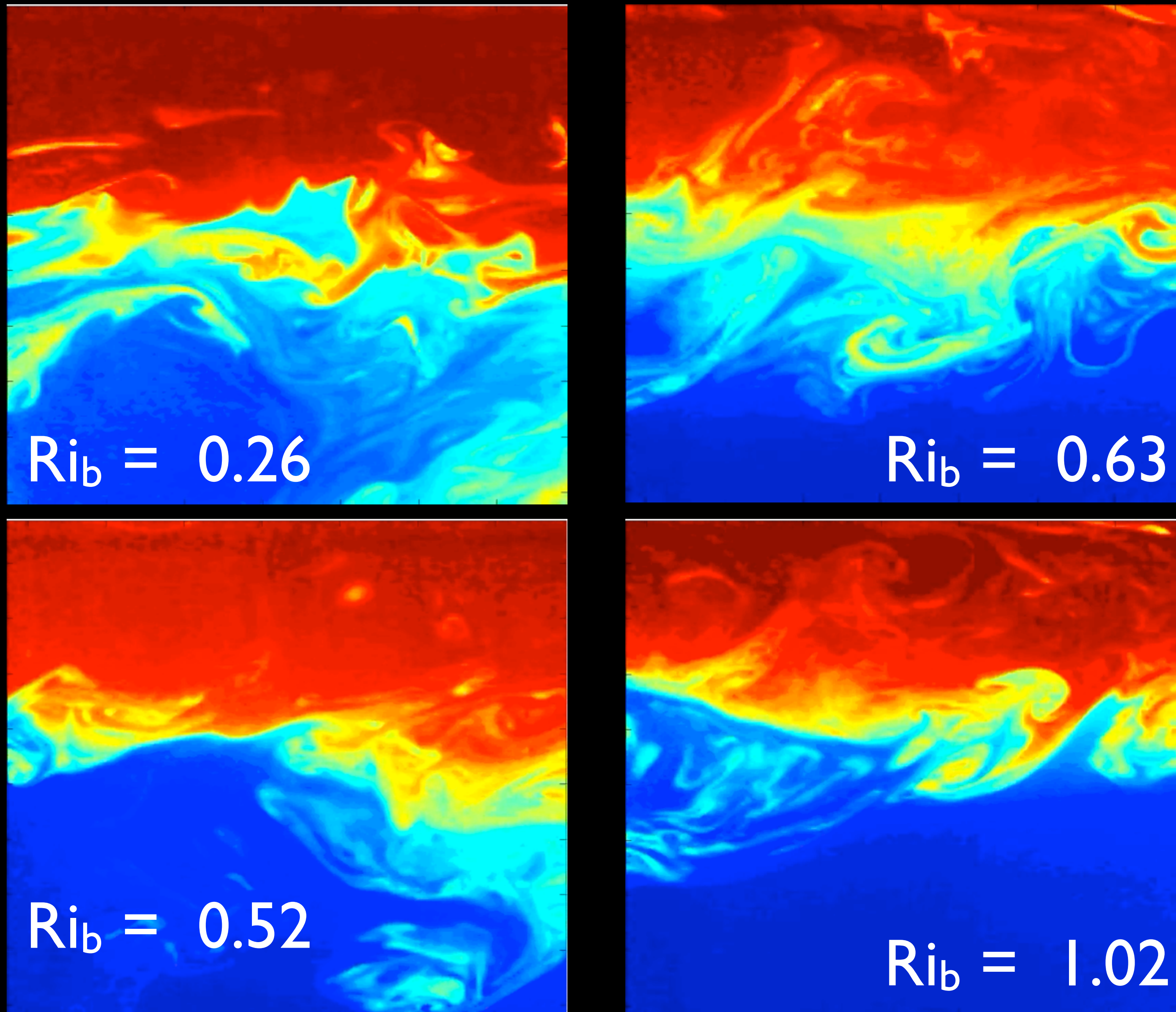
$$Ri_b = \frac{g\Delta\rho H}{\rho U_0^2}$$

- Simultaneous measurement of velocity and density fields $\{u,w\}(x,y)$ $\rho(x,z)$ - $\langle u'w'\rangle$, $\langle \rho' w'\rangle$, ε

- $Sc = \nu/D \sim 700$ ($Sc_T \sim 1$)

$\delta\rho/\rho \sim 0.0026$

$\delta\rho/\rho \sim 0.0052$



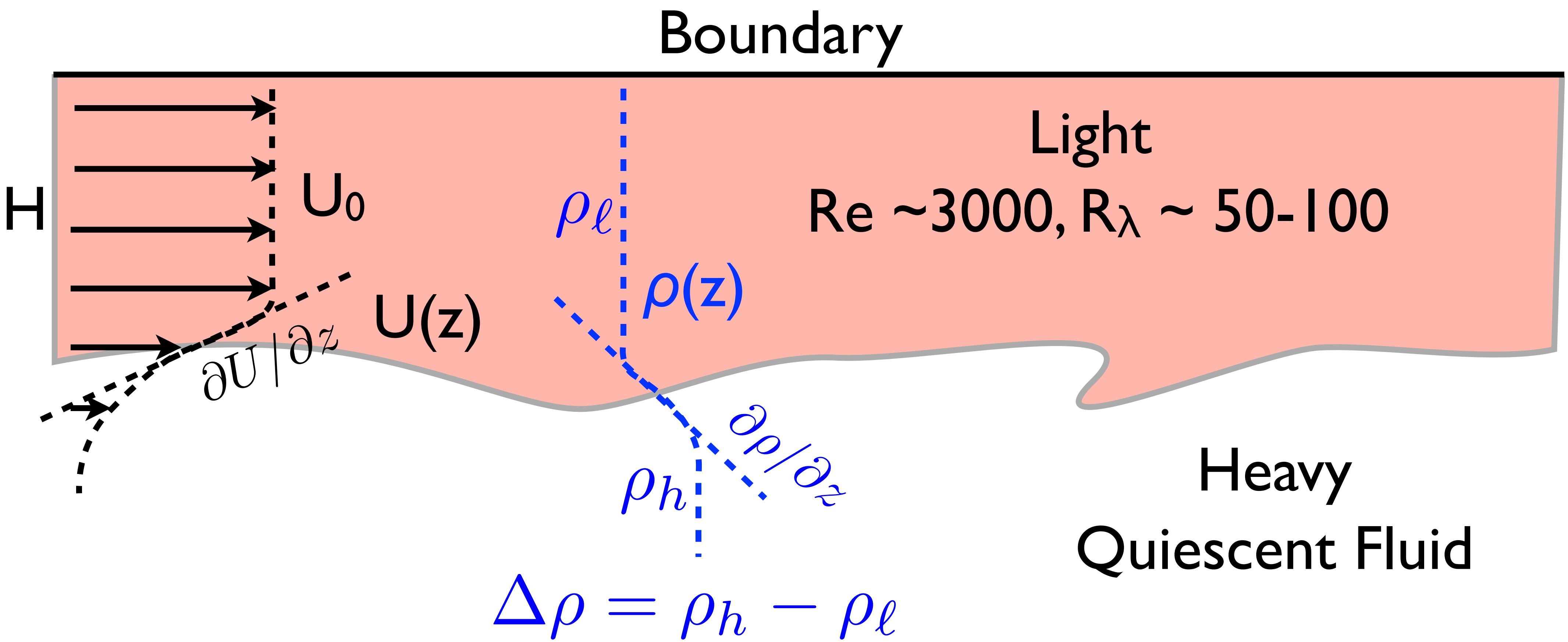
U ~ 8 cm/s

U ~ 5 cm/s

Outline

- How do we average quantities around a meandering interface ?
- Characterizing overturning → Thorpe displacements and Thorpe length L_T.
- Focus on intermittency and a measure of overturning as flow becomes more stable: Ri ~ 1
- Universal distribution of L_T gives insight into nature of overturning and instability.

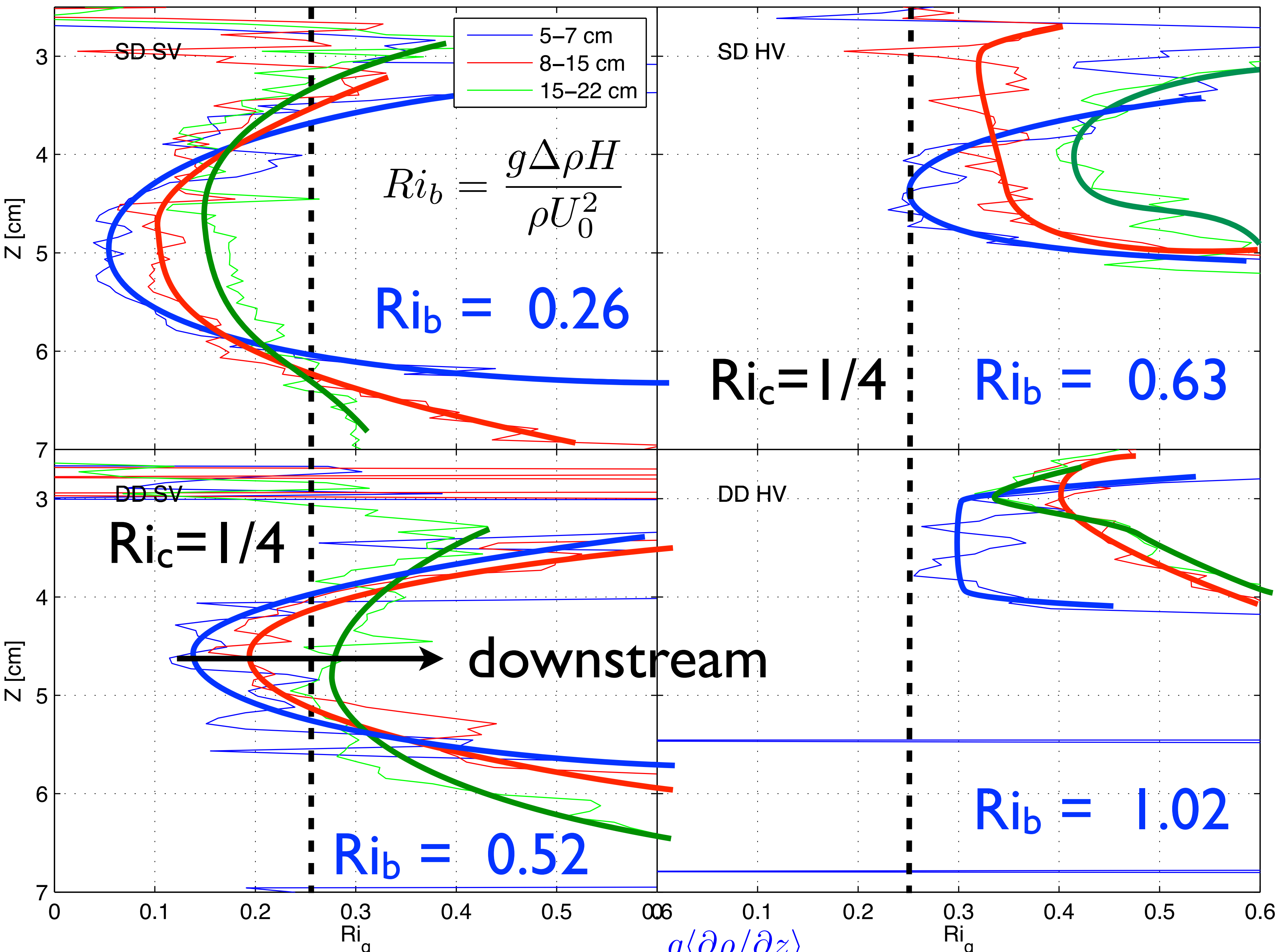
Stratified Shear Flow w/ Turbulent Current



Balance of Stratification and Shear: Richardson Number

$$Ri_b = \frac{g\Delta\rho H}{\rho U_0^2} \qquad Ri_g = \frac{g\langle\partial\rho/\partial z\rangle}{\rho\langle\partial U/\partial z\rangle^2}$$

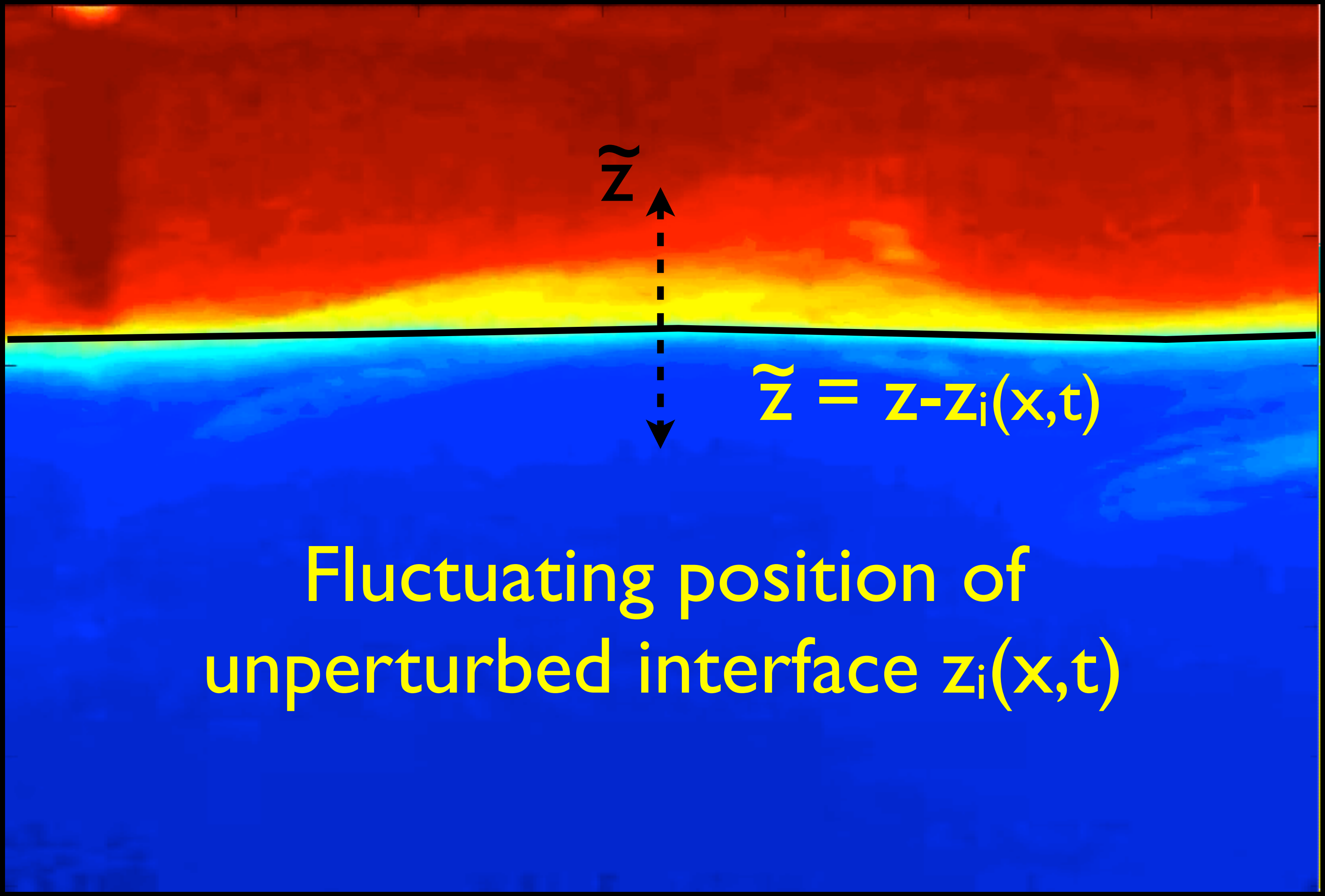
Which Ri? What average does one take?



$$Ri_b = \frac{g\Delta\rho H}{\rho U_0^2}$$

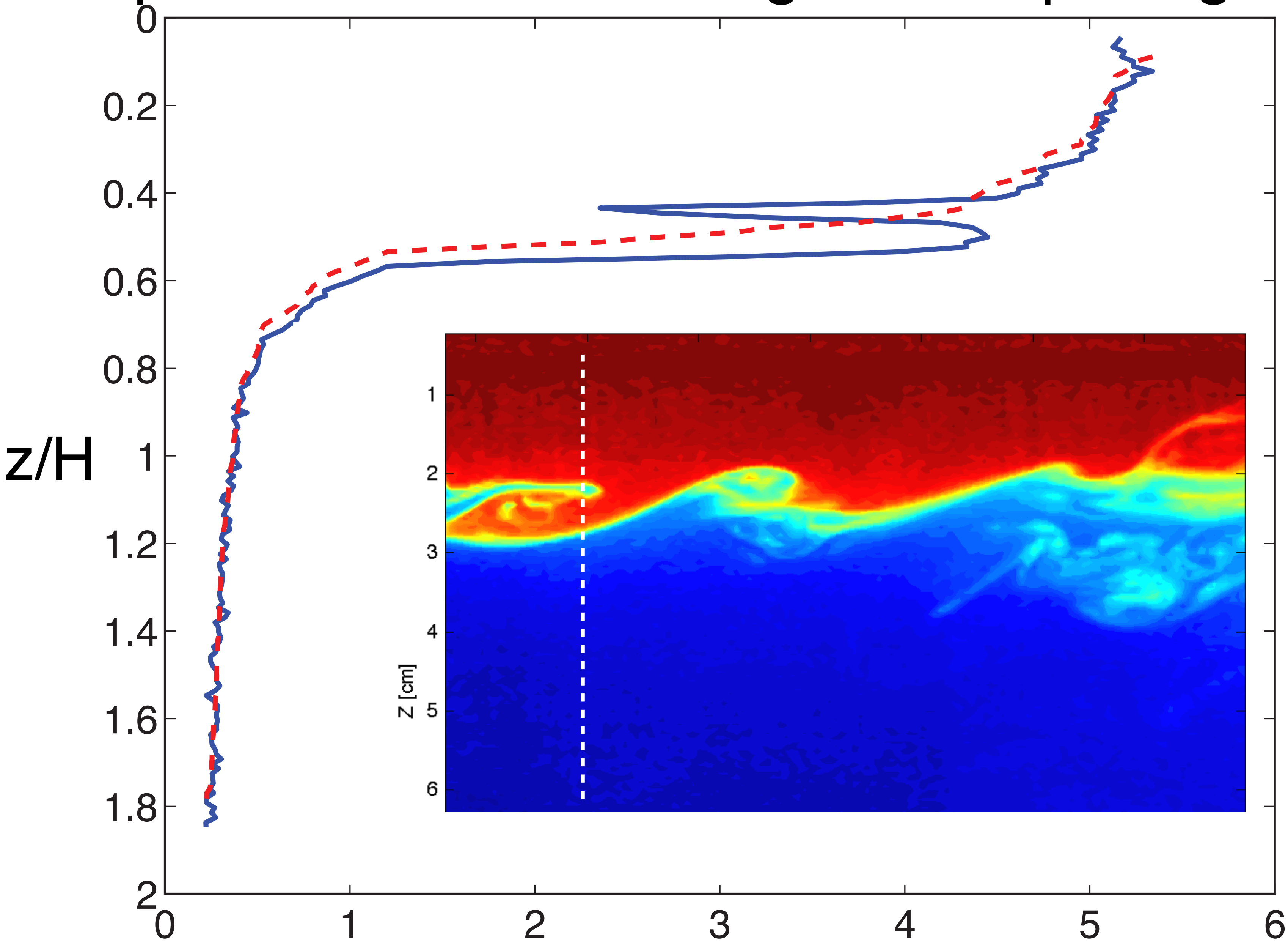
$$Ri_g = \frac{g\langle\partial\rho/\partial z\rangle}{\rho\langle\partial U/\partial z\rangle^2}$$

Most Stable $Ri_b \sim 1$



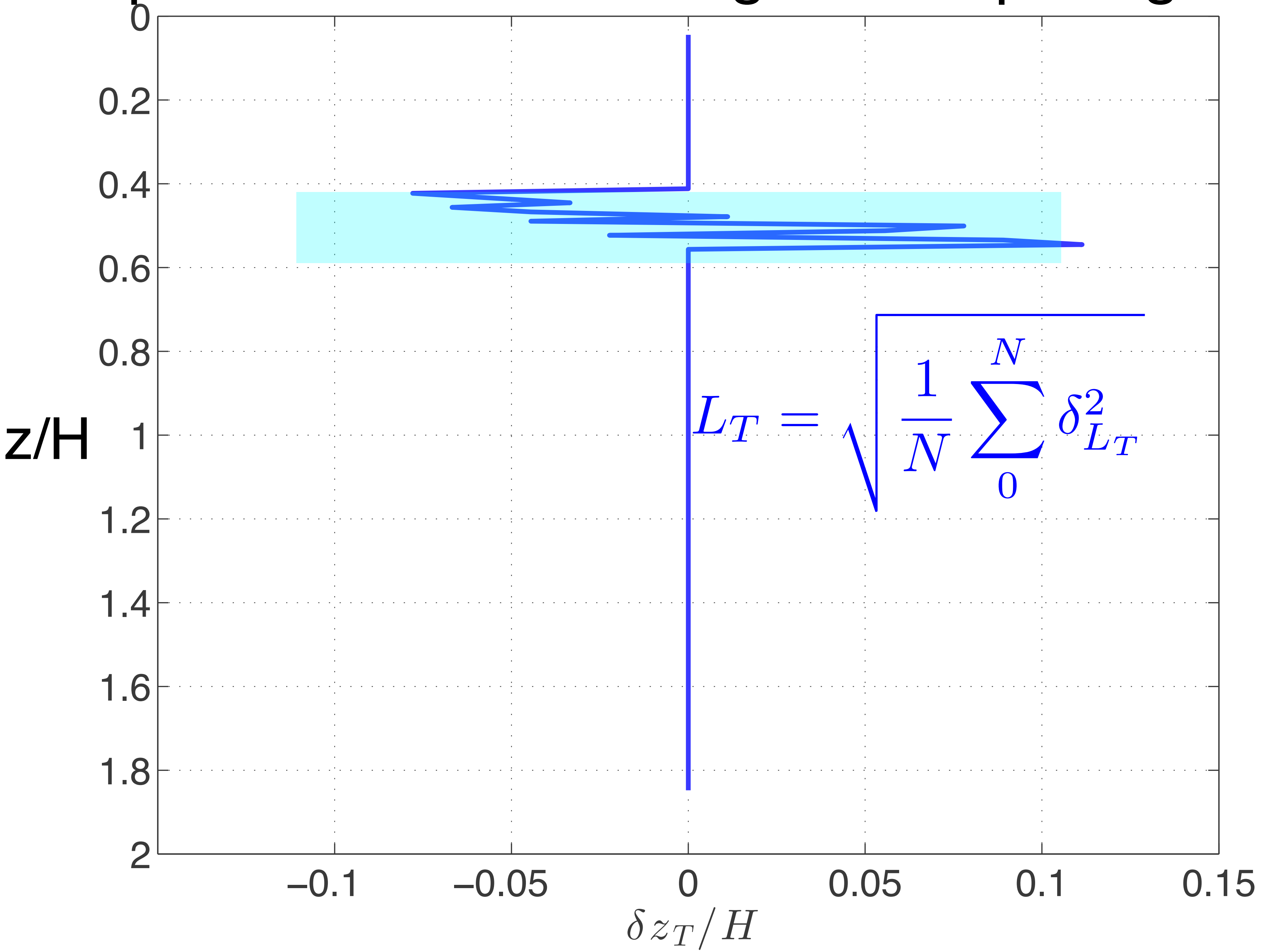
Intermittent fraction of unperturbed interface high; averaging questionable?

Divide into perturbed (overturning) and unperturbed interface using the Thorpe length L_T



Thorpe, S.A., JFM 1977 & *The Turbulent Ocean* (2005)

Divide into perturbed (overturning) and unperturbed interface using the Thorpe length L_T



Thorpe, S.A., JFM 1977 & *The Turbulent Ocean* (2005)

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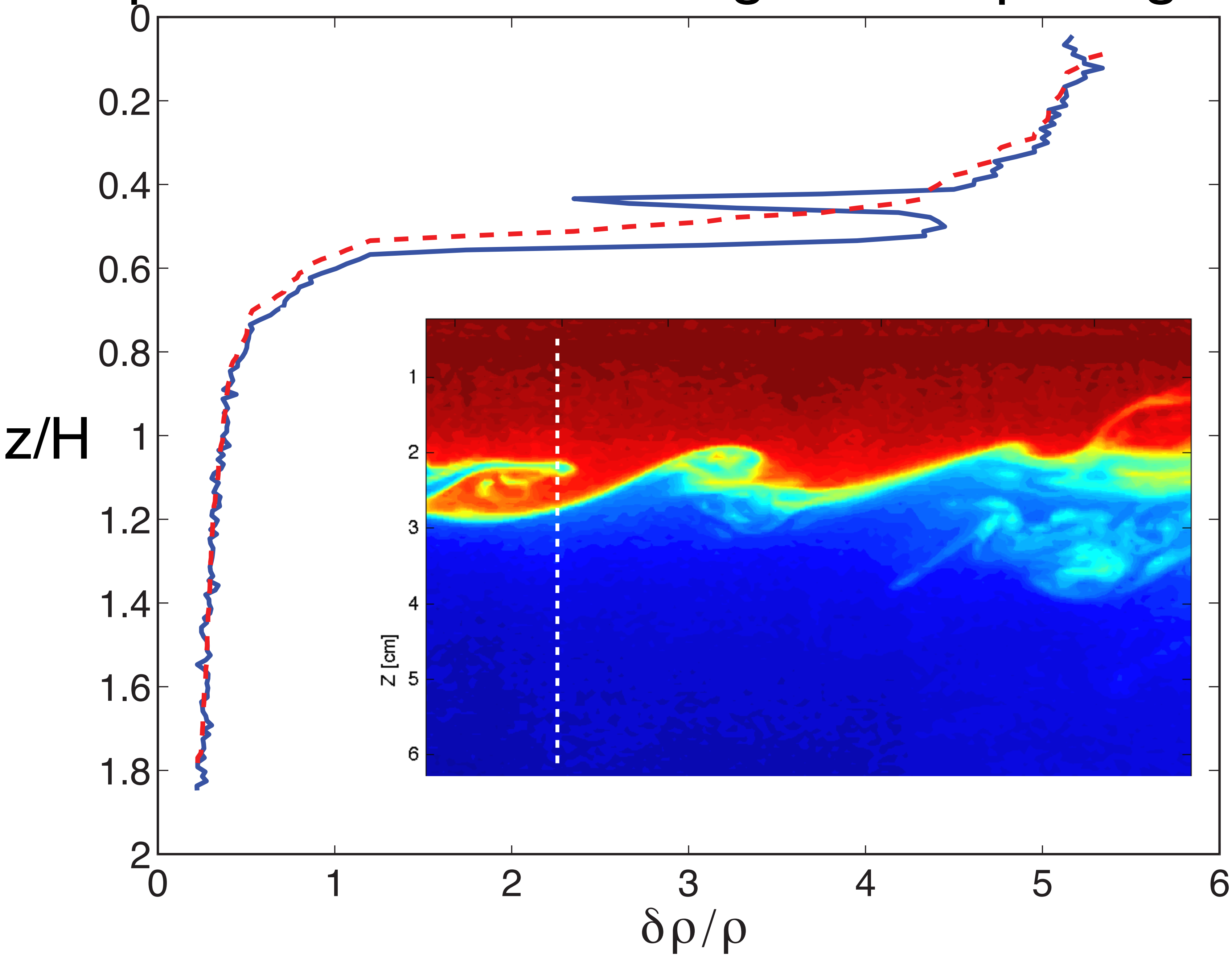

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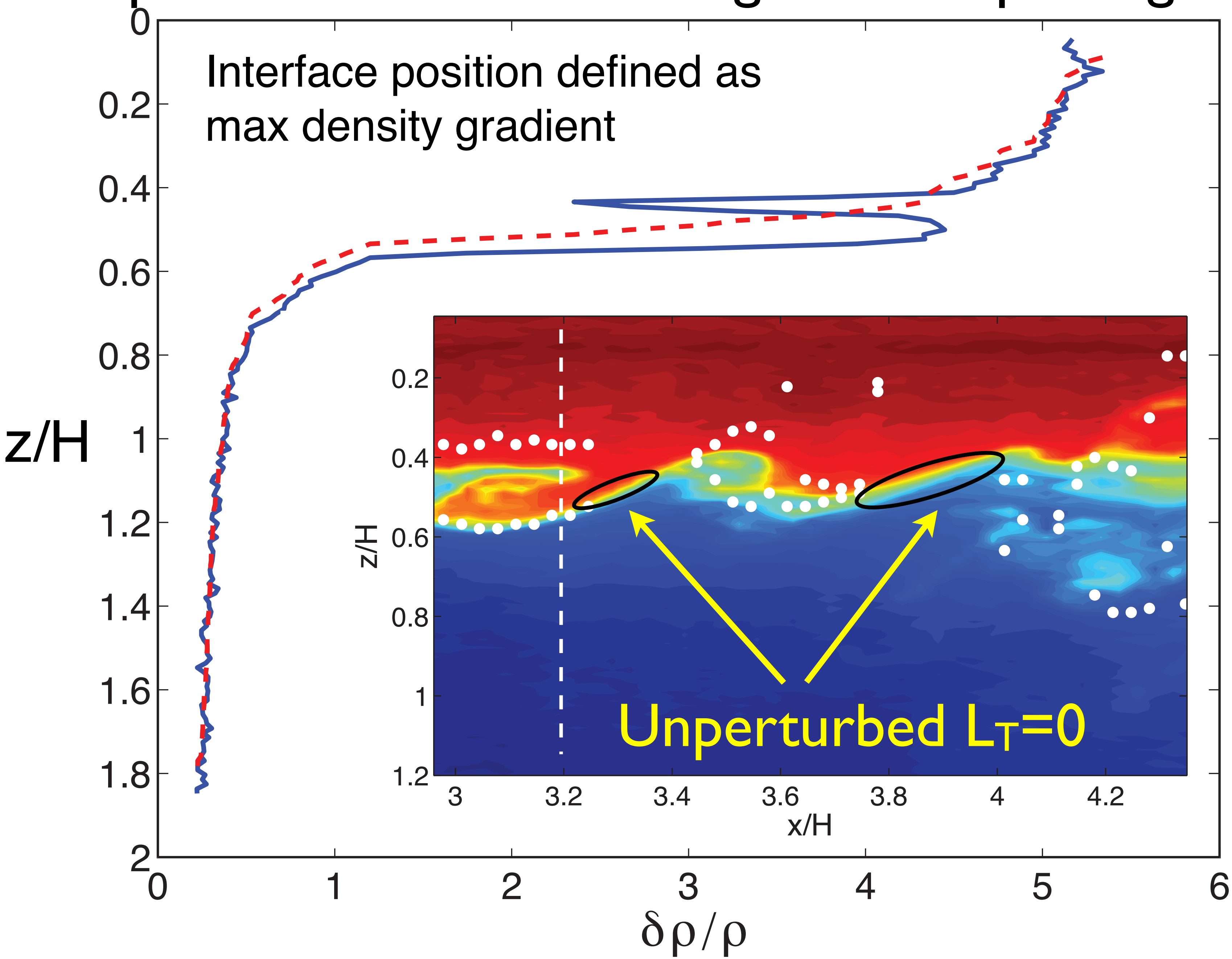
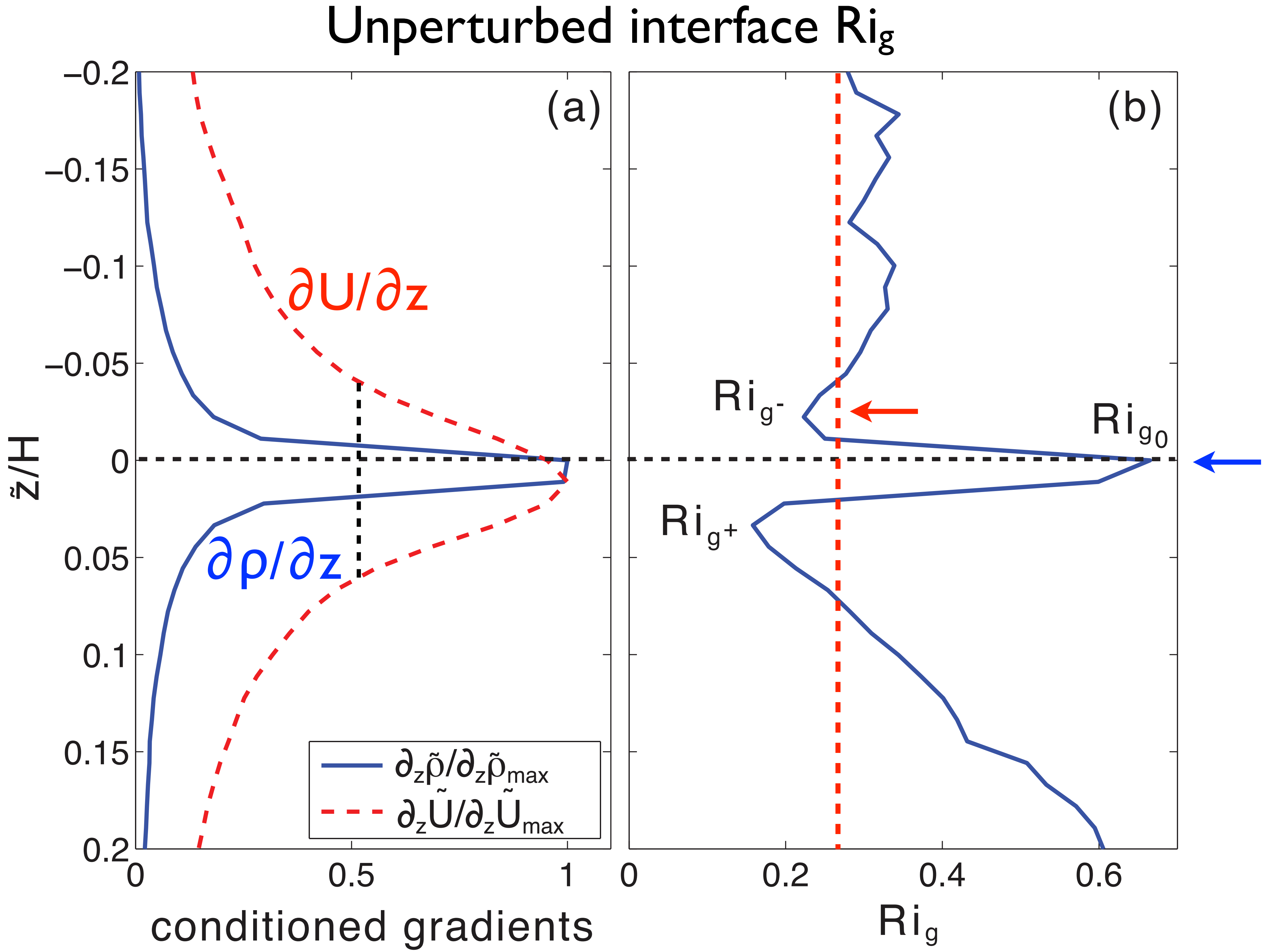
Divide into perturbed (overturning) and unperturbed interface using the Thorpe length L_T

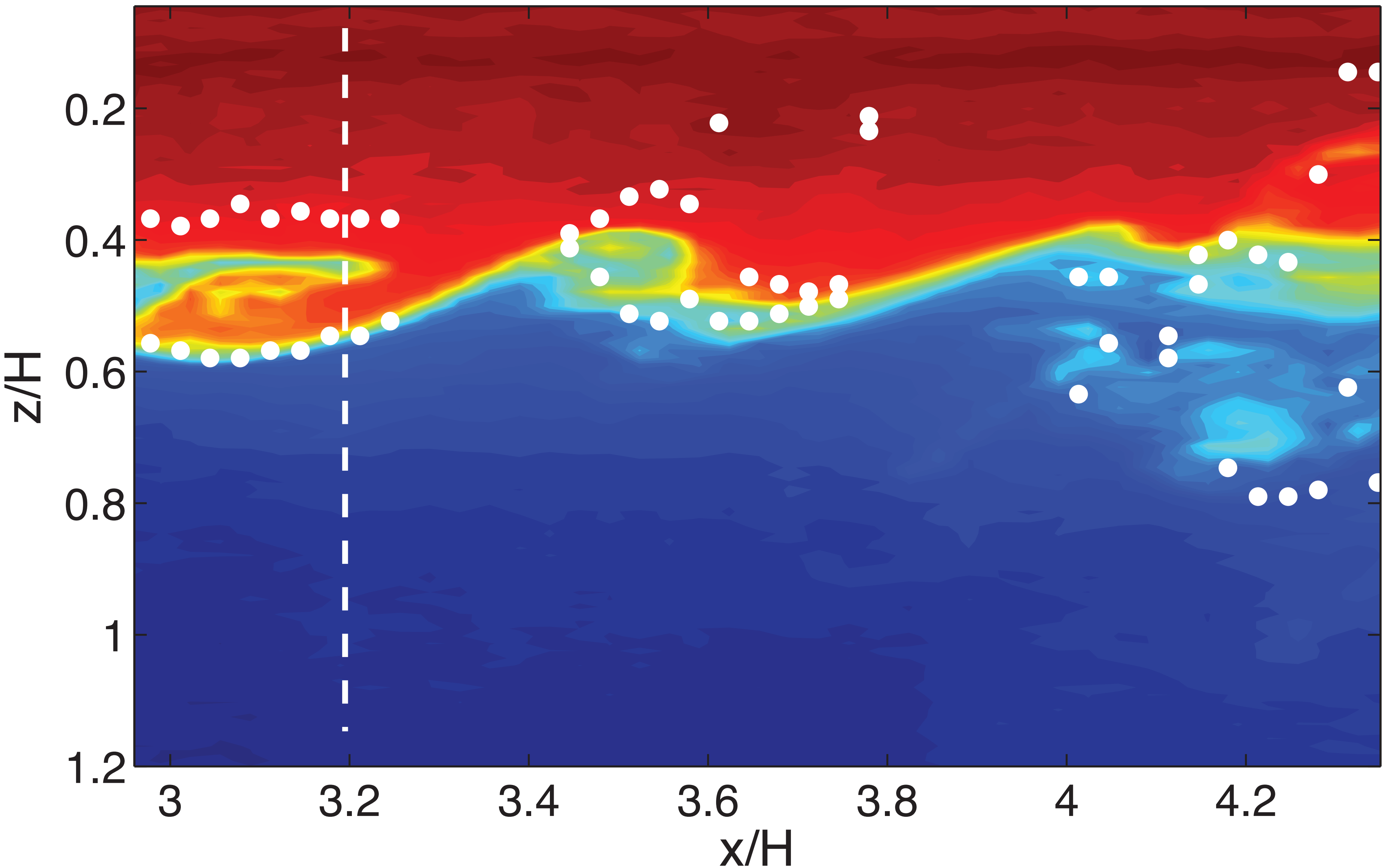


Thorpe, S.A., JFM 1977 & *The Turbulent Ocean* (2005)



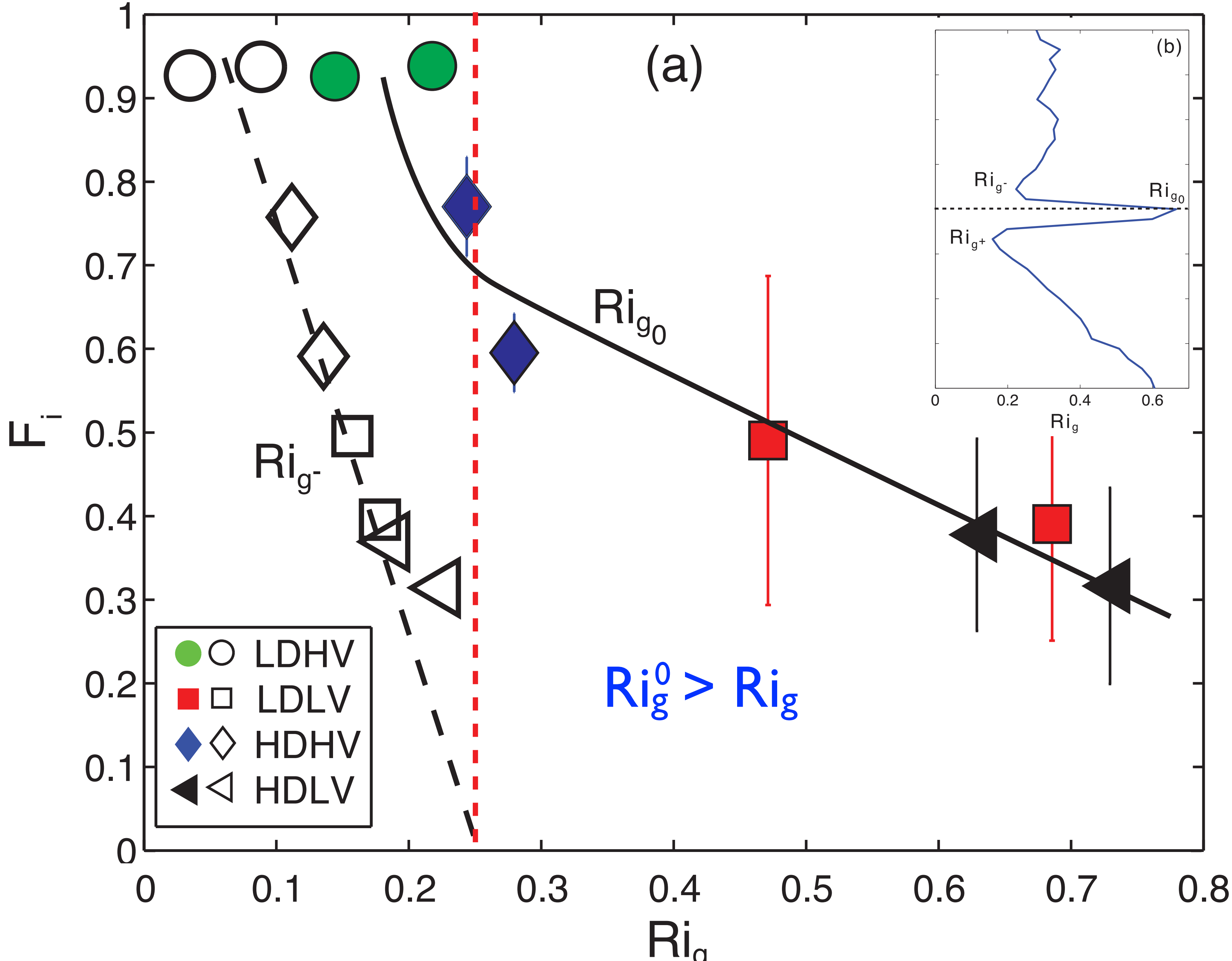
Unperturbed interface Ri_g
(a)
(b)
$\partial U/\partial z$
$\partial \rho/\partial z$
$\partial_z\tilde{\rho}/\partial_z\tilde{\rho}_{max}$
$\partial_z\tilde{U}/\partial_z\tilde{U}_{max}$
Ri_{g^-}
Ri_{g_0}
Ri_{g^+}
$\tilde{z}/H$
conditioned gradients
Ri_g
−0.2
−0.15
−0.1
−0.05
0
0.05
0.1
0.15
0.2
0
0.5
1
0
0.2
0.4
0.6

Quantifying the overturning intermittency

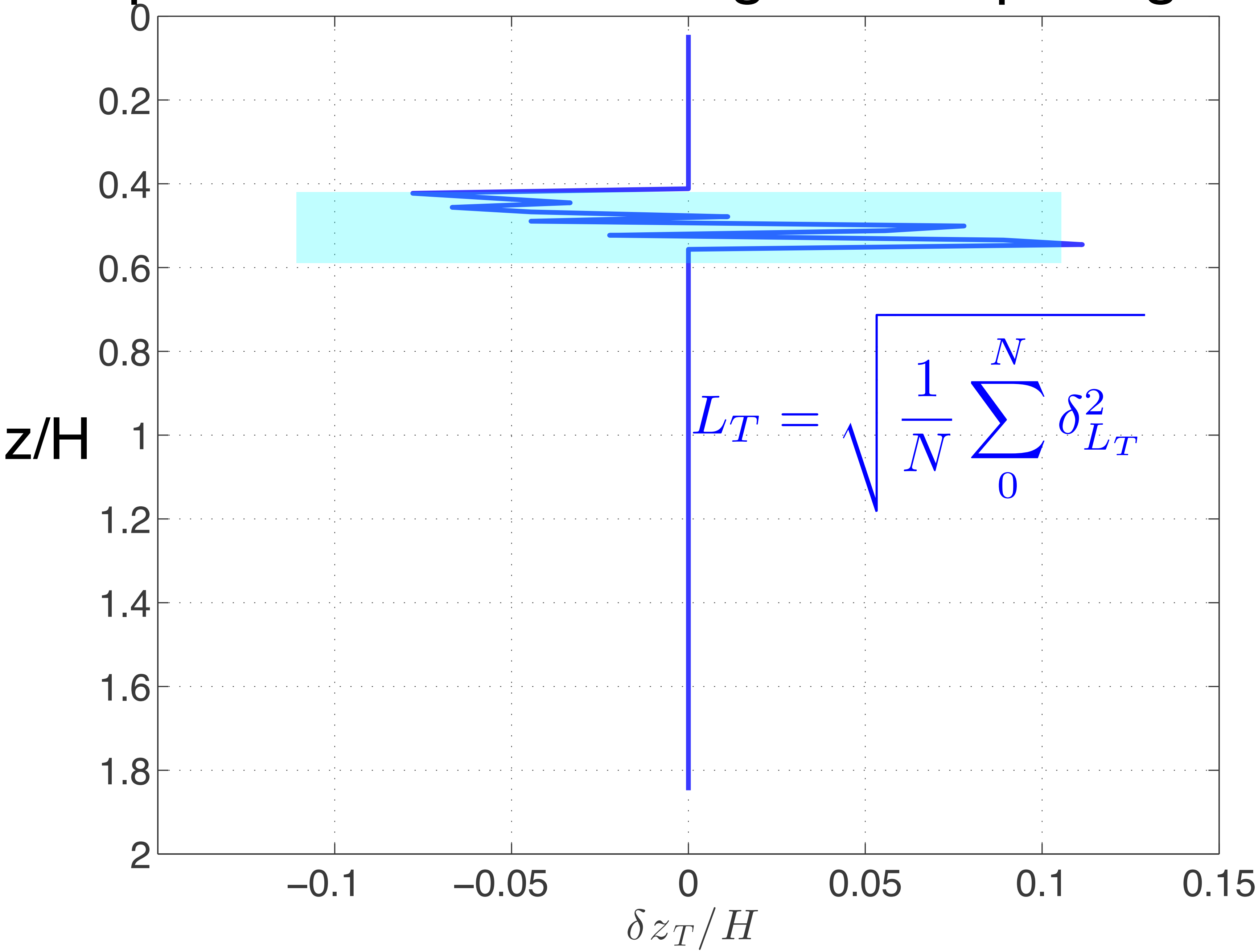


F_i=fraction of overturning local events

Quantifying the overturning intermittency

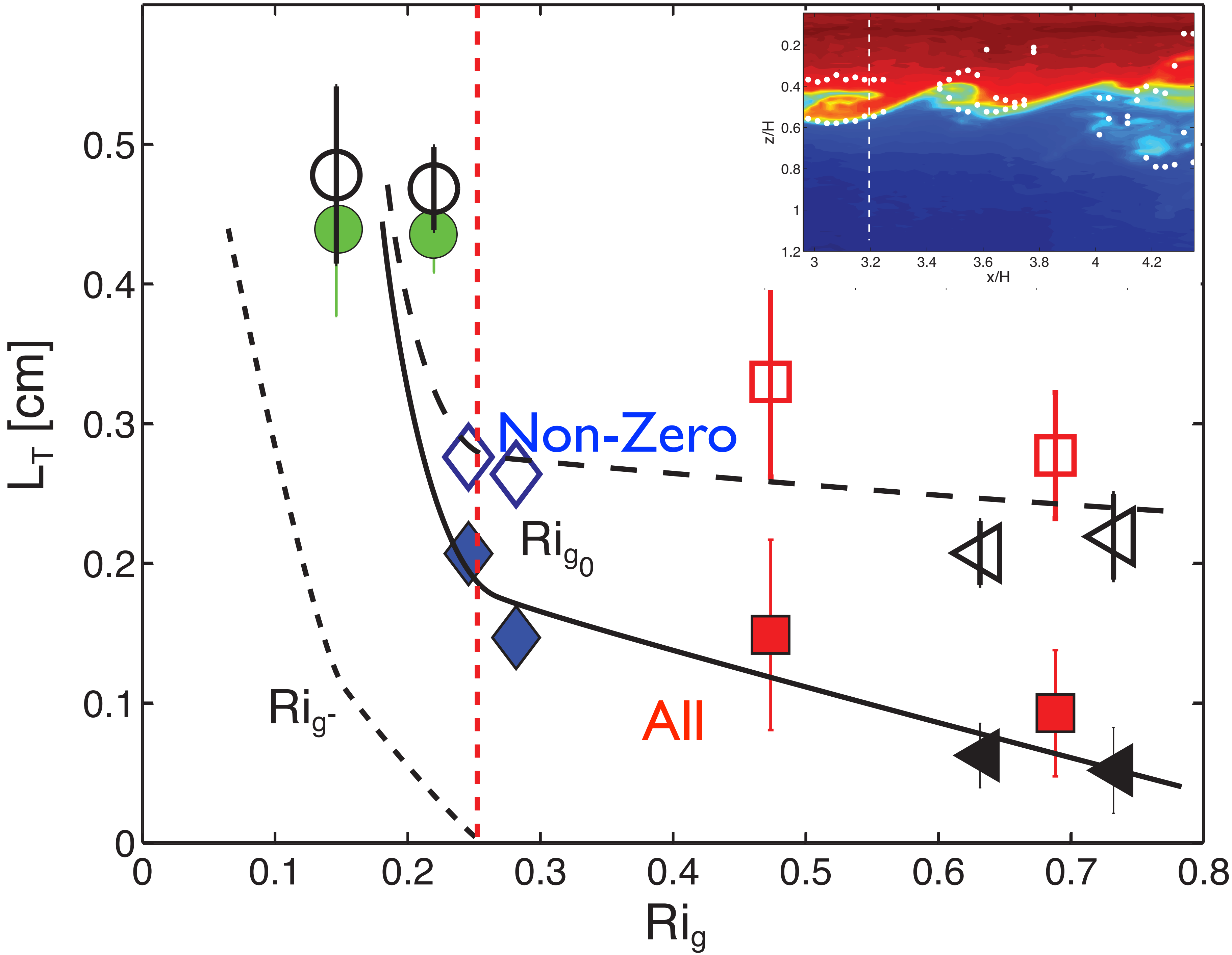


Divide into perturbed (overturning) and unperturbed interface using the Thorpe length L_T

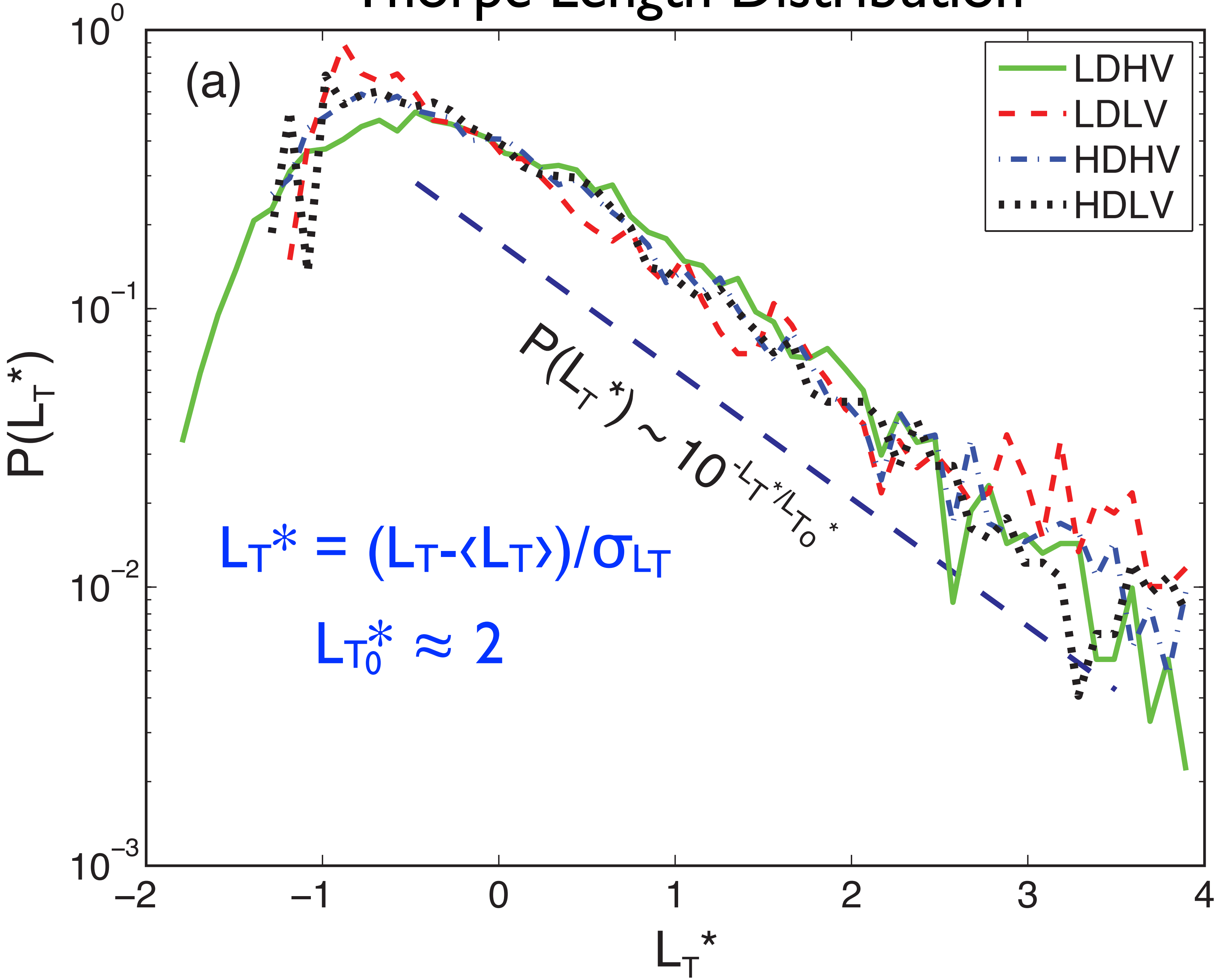


Thorpe, S.A., JFM 1977 & *The Turbulent Ocean* (2005)

Mean Thorpe Length



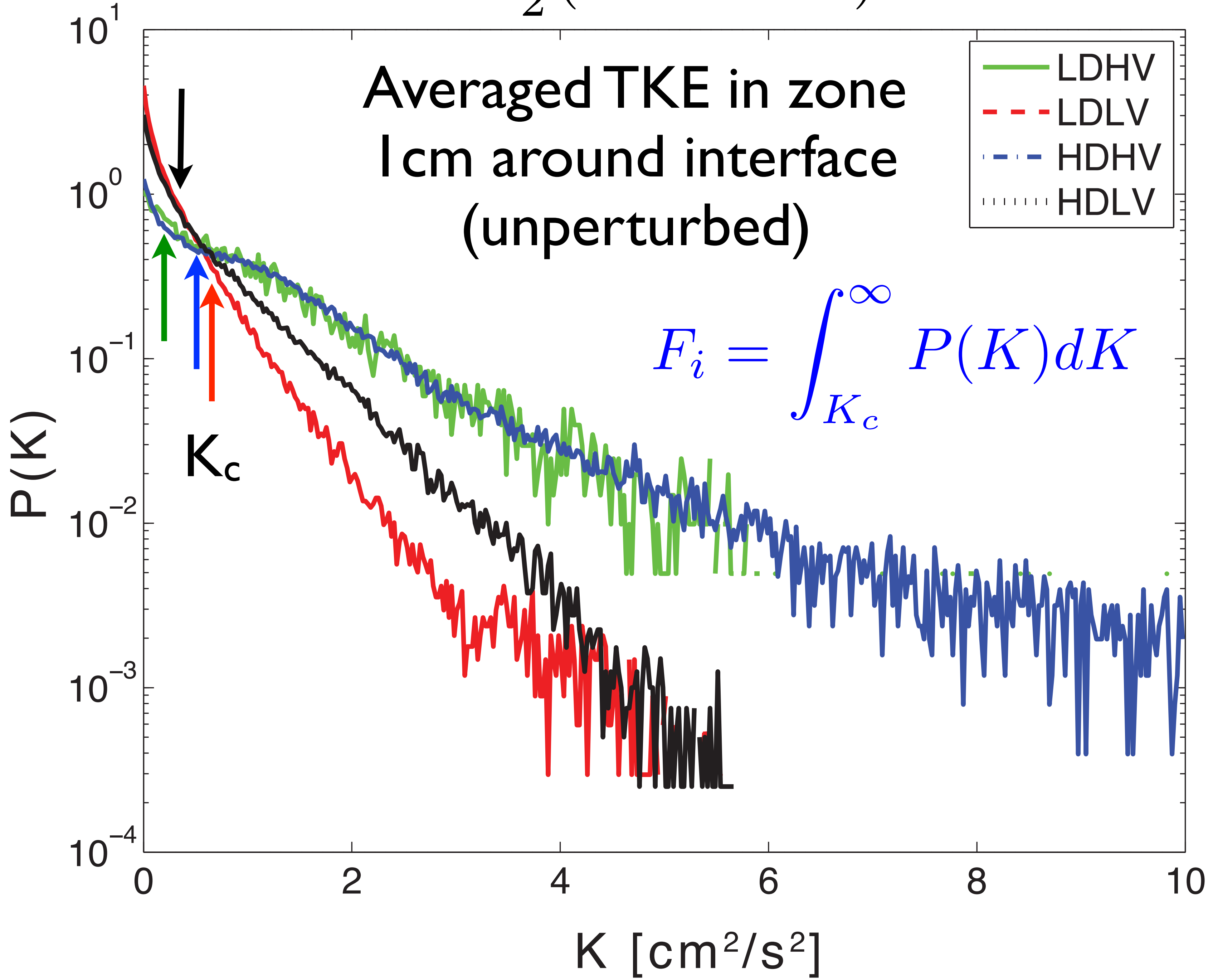
Thorpe Length Distribution



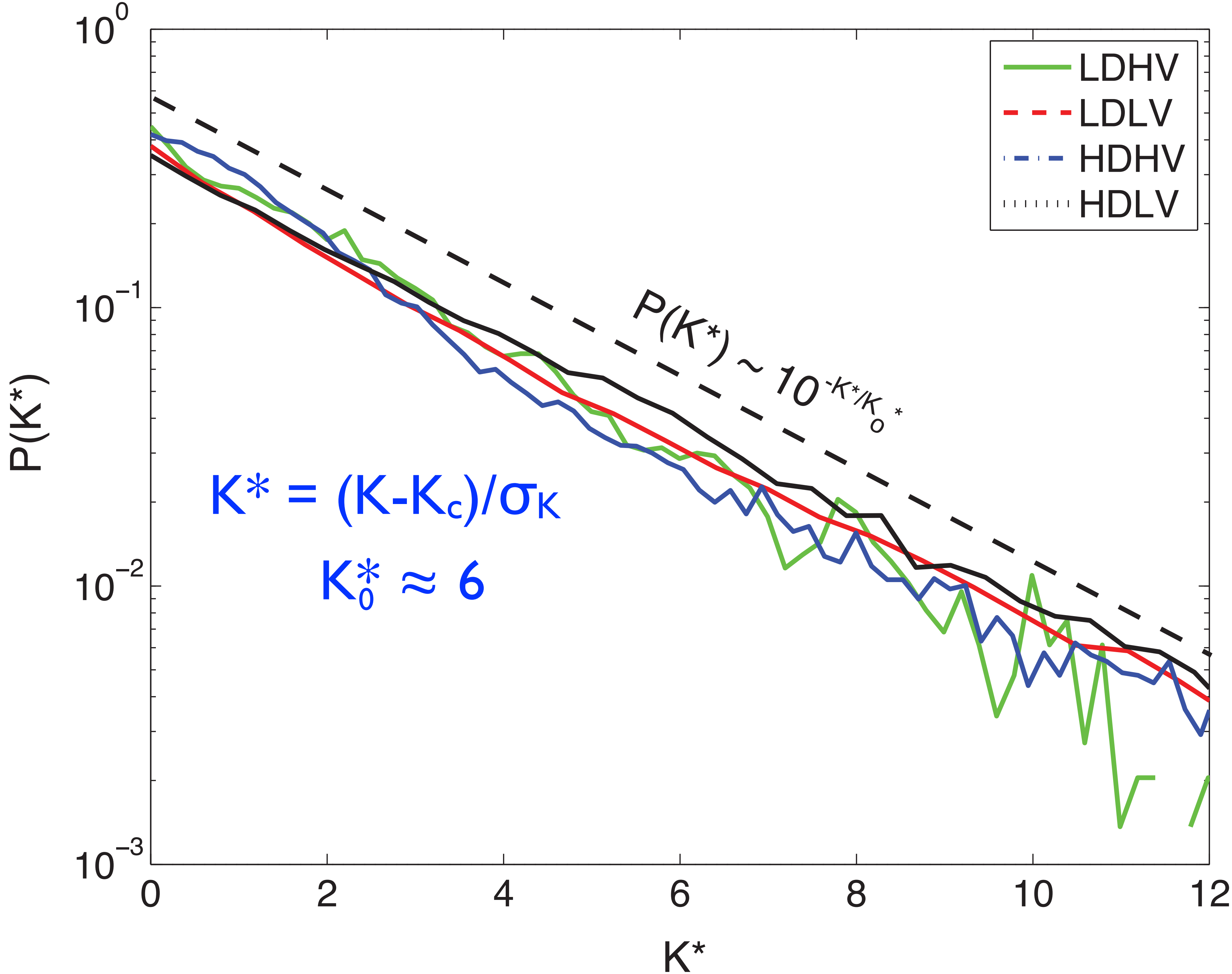
Origin of Exponential Scaling of Tails?

It takes kinetic energy to overcome potential energy barrier

$$K = \frac{1}{2}(u'^2 + 2v'^2)$$



Turbulent Kinetic Energy Distribution



Take home message

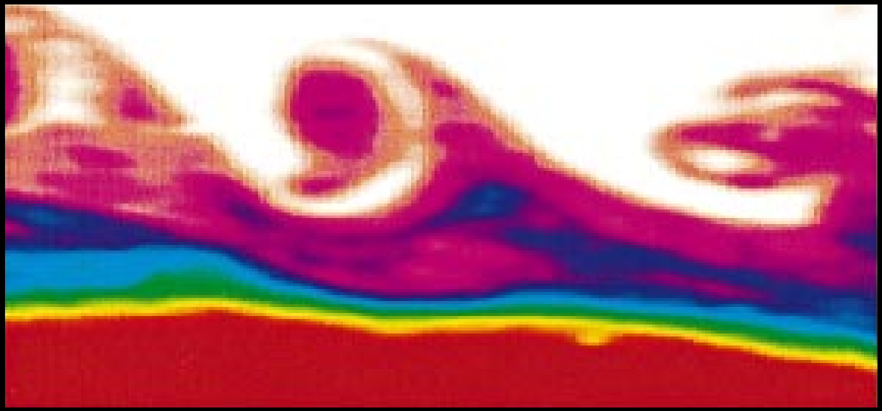
- Laboratory experiments give detailed insight into the instability mechanisms of stratified shear flows.

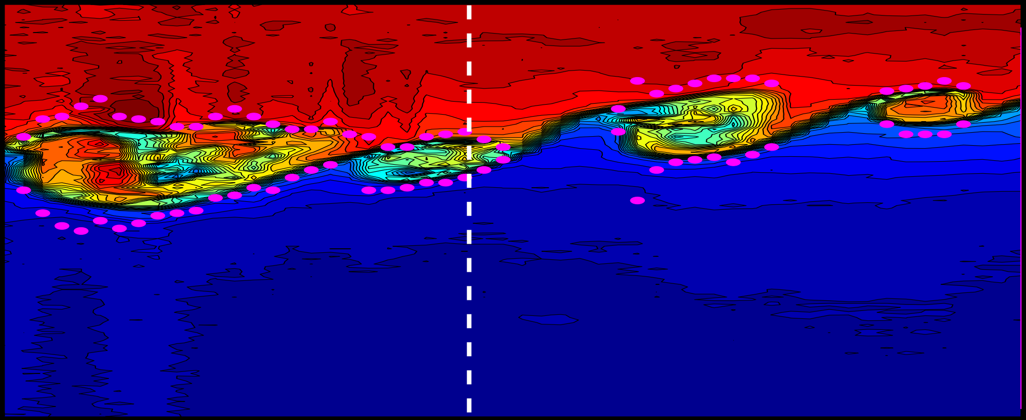
- An analysis of density overturning using the Thorpe length reveals universal features of turbulent mixing in stratified shear flows.

- These insights may help characterize real overflows and understand their mechanisms for mixing.

- Use Thorpe length to define overturning disturbance: Local length scales - L_E, L_O, L_S Also examine relationship with available Potential Energy ....

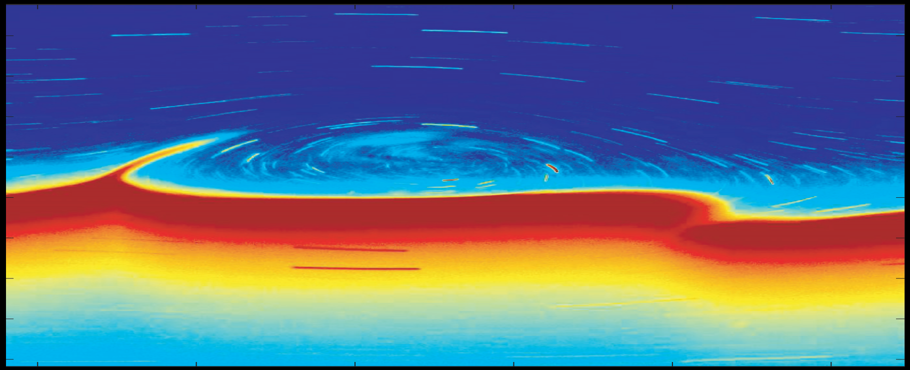
Kelvin-Helmholtz Instability - Small Ri

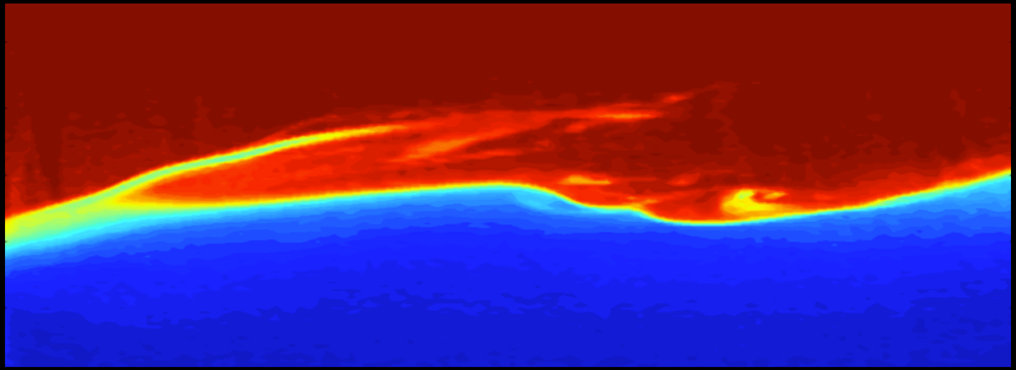




Strang & Fernando JFM 2001

Holmboe Instability - Large Ri



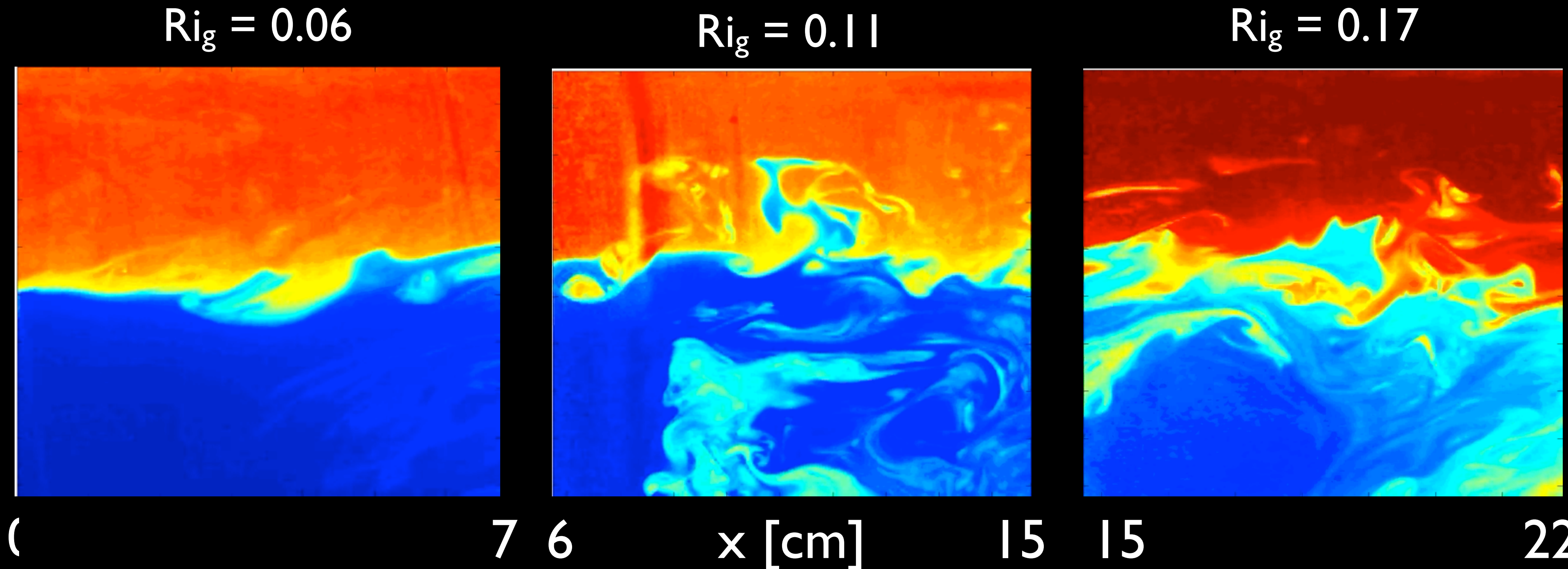


Tedford, Pieters & Lawrence JFM 2009

"Scouring": Woods, Caulfield, Landel & Kuesters JFM 2010

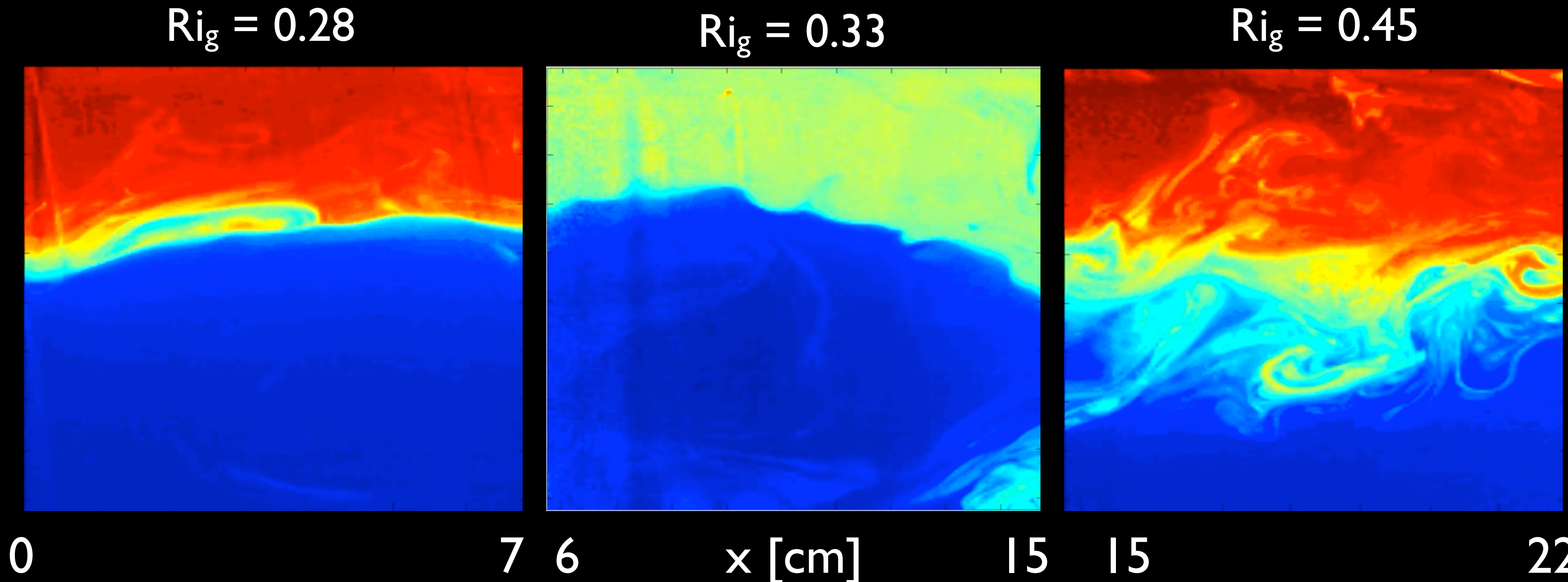
$\delta\rho/\rho = 0.0026$ $U = 7$ cm/s

SDSV



SDHV

$\delta\rho/\rho = 0.0026$ $U = 4.5$ cm/s



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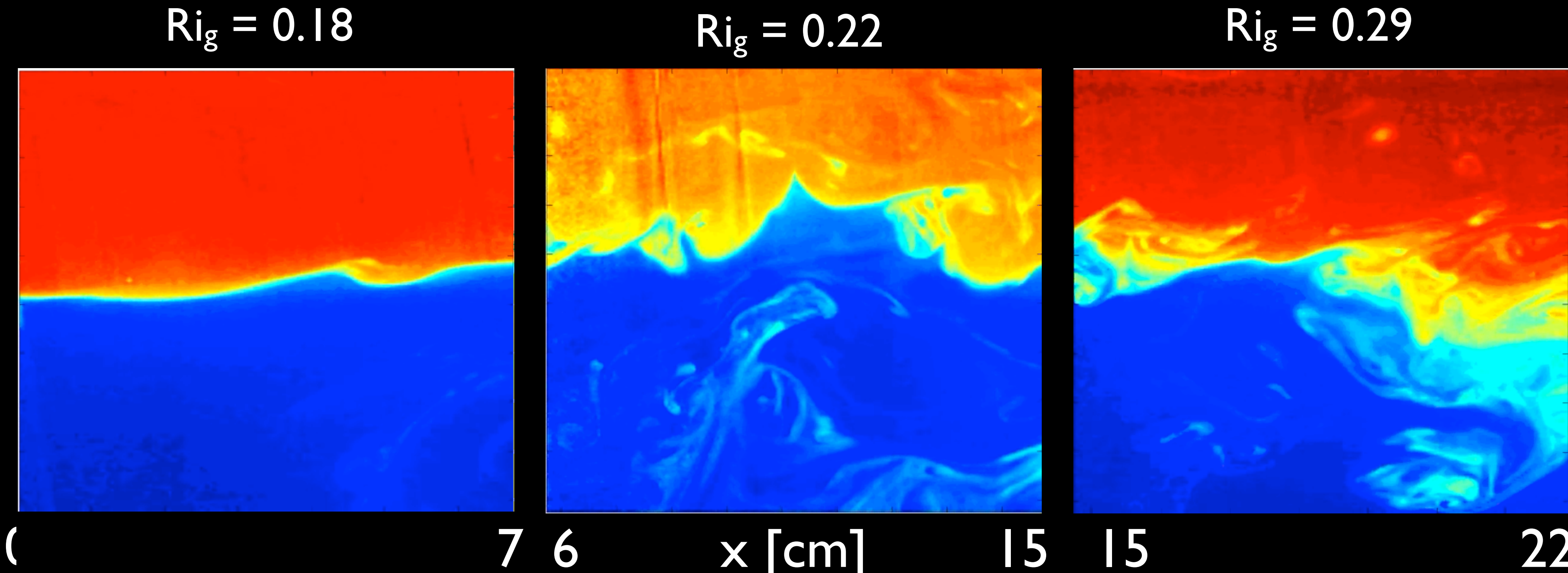
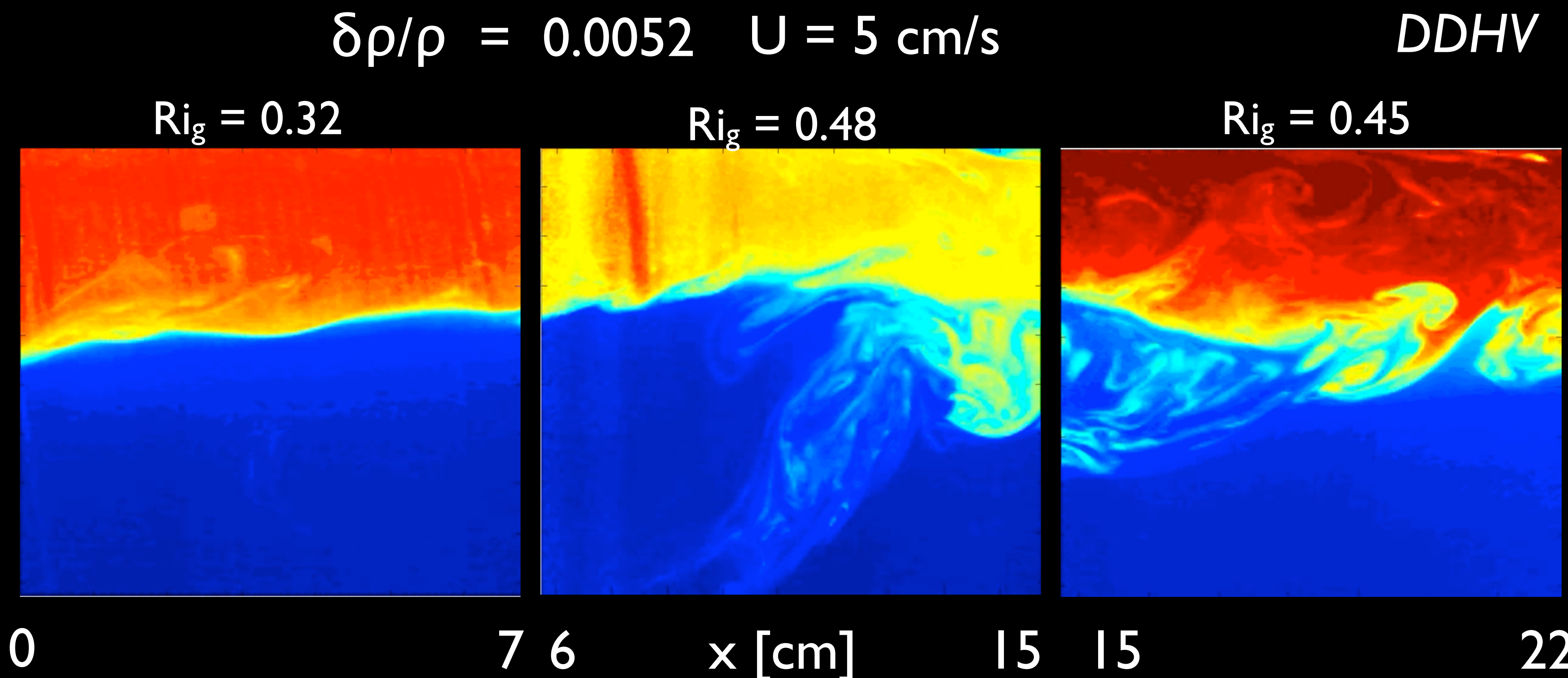
Center for Nonlinear Studies

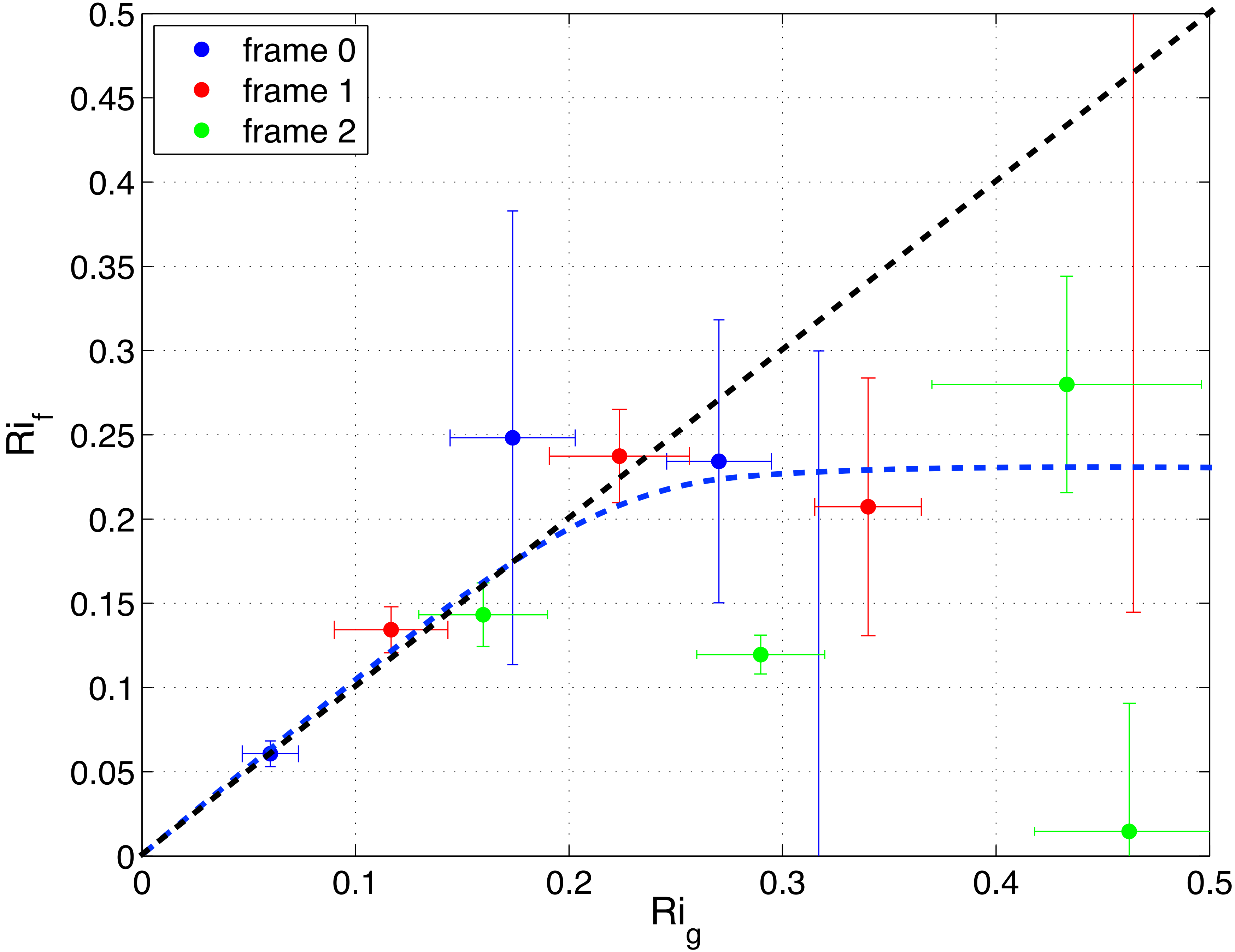
Los Alamos

$\delta\rho/\rho$ = 0.0052   U = 7 cm/s   *DDSV*

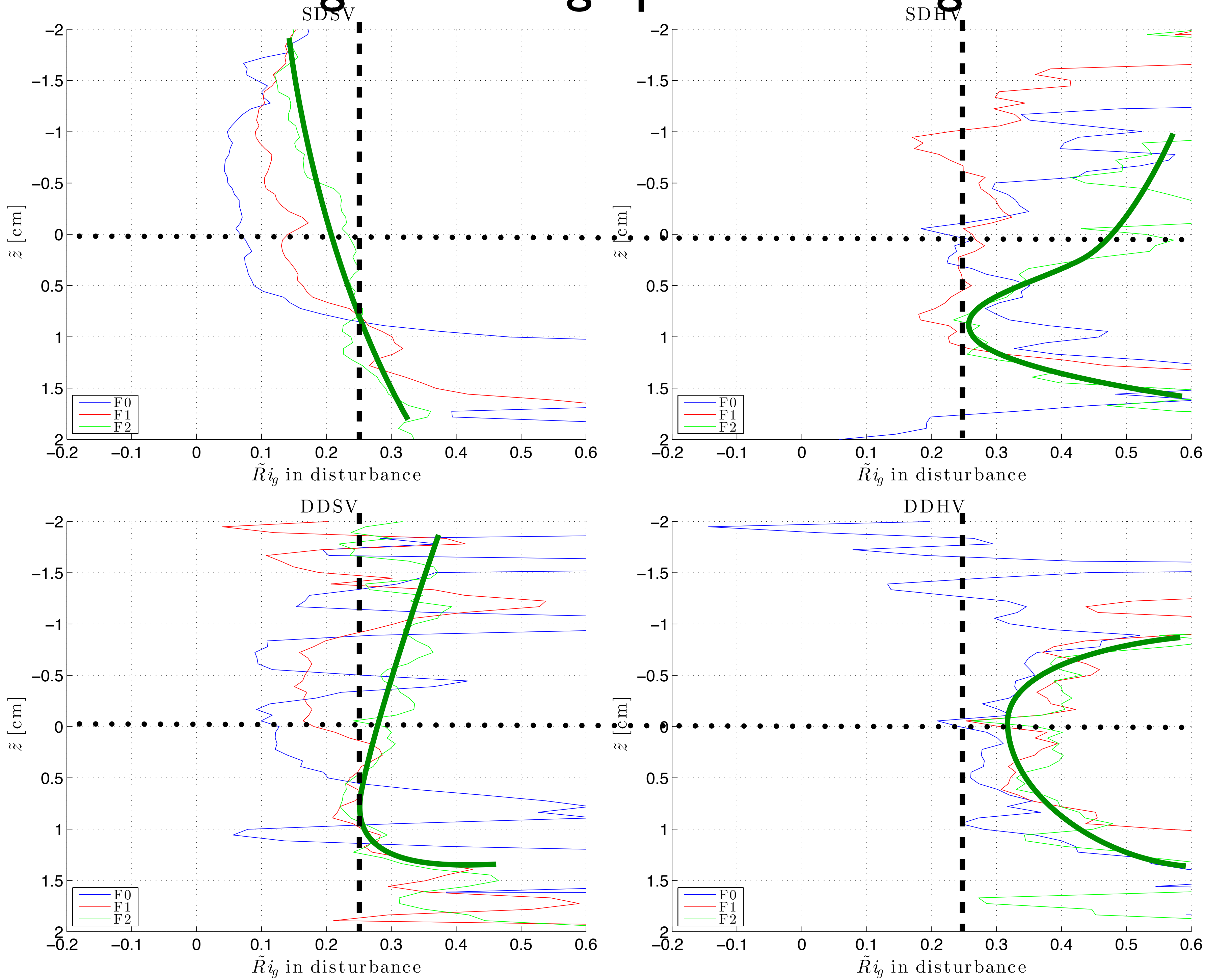



δρ/ρ = 0.0052 U = 5 cm/s
DDHV
Ri_g = 0.32
Ri_g = 0.48
Ri_g = 0.45
0
7
6
x [cm]
15
15
22

Flux Richardson Number



Rig for average perturbed regions



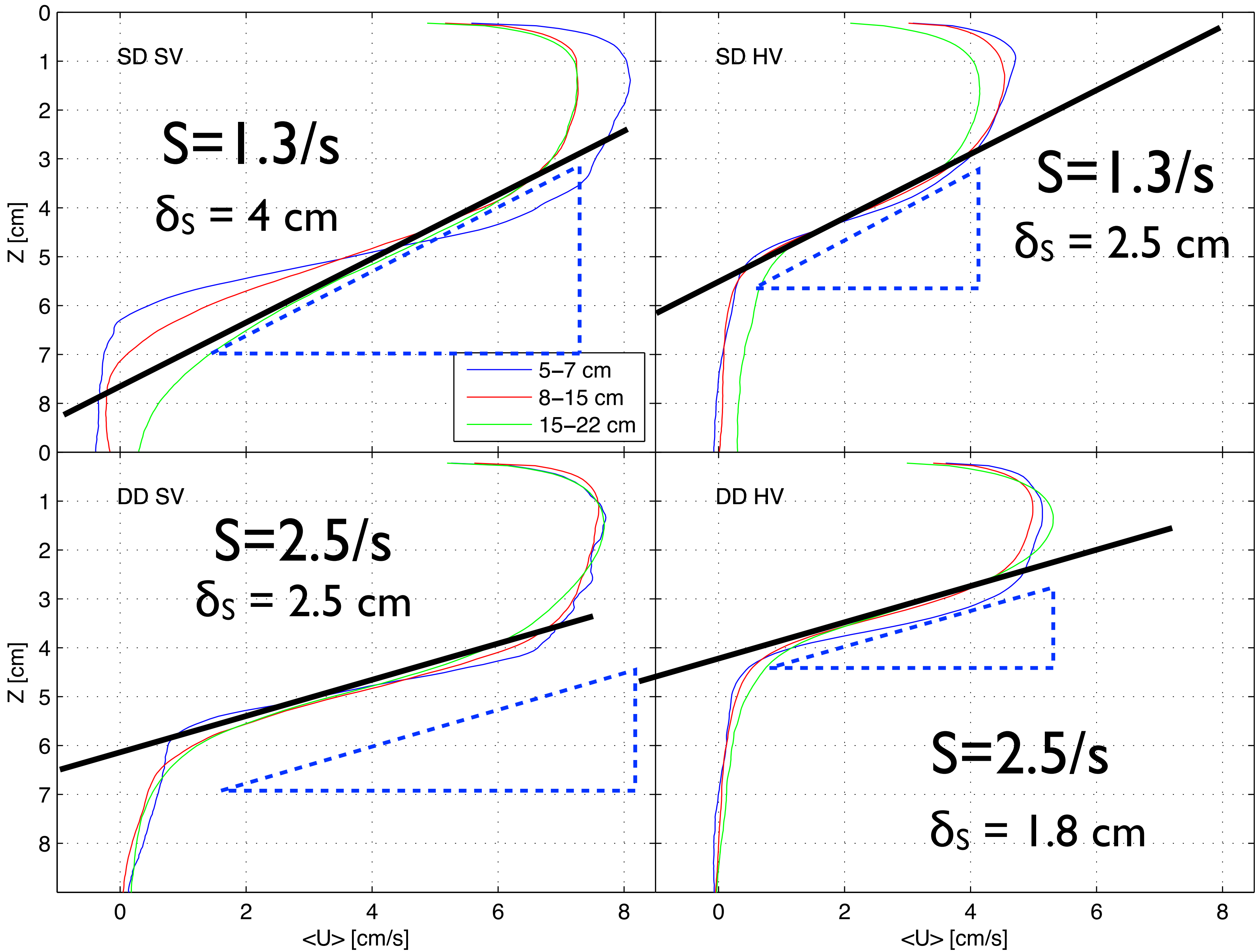


Figure 1: Mean velocity $\langle \overline{u} \rangle$ component vertical profiles for different x.

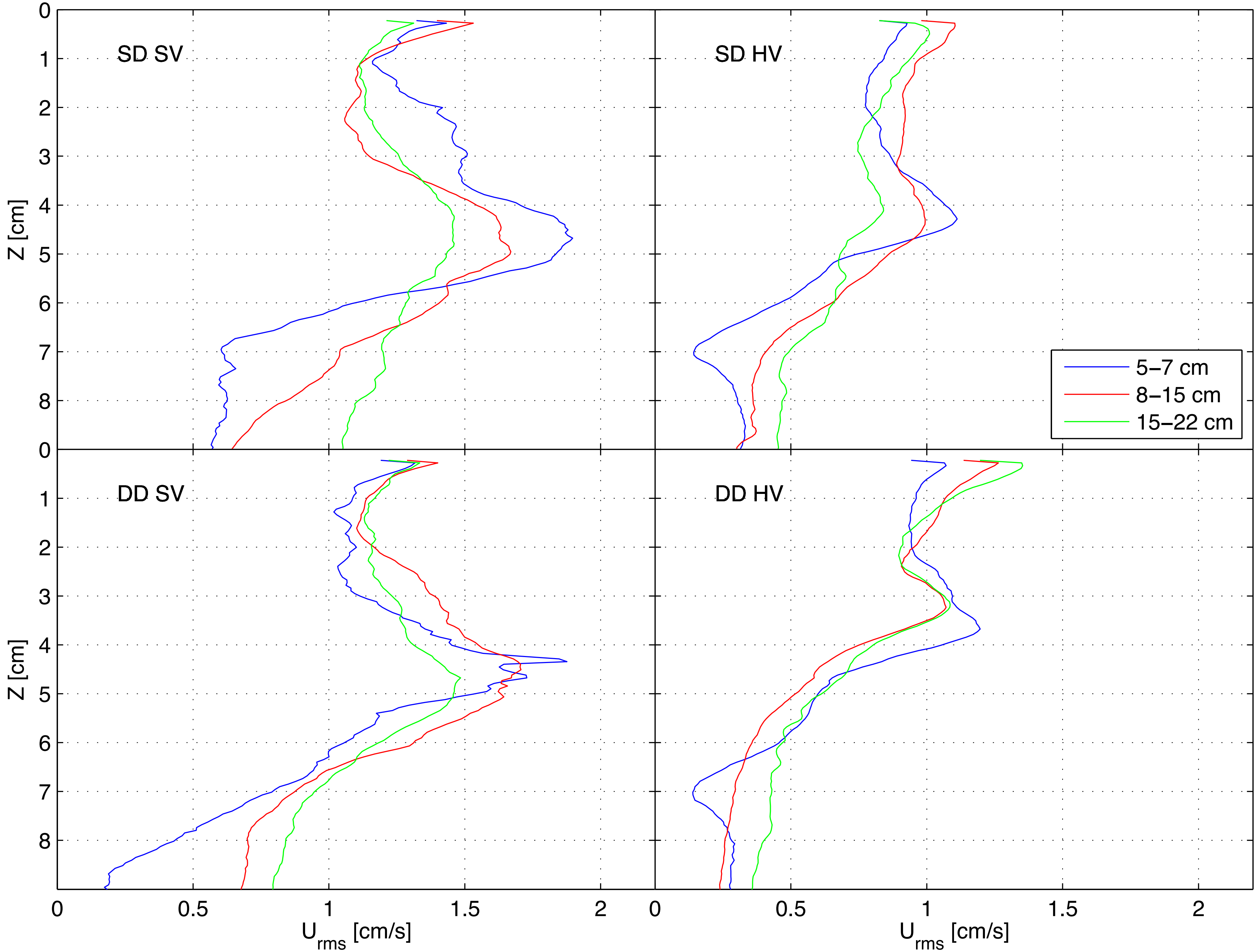
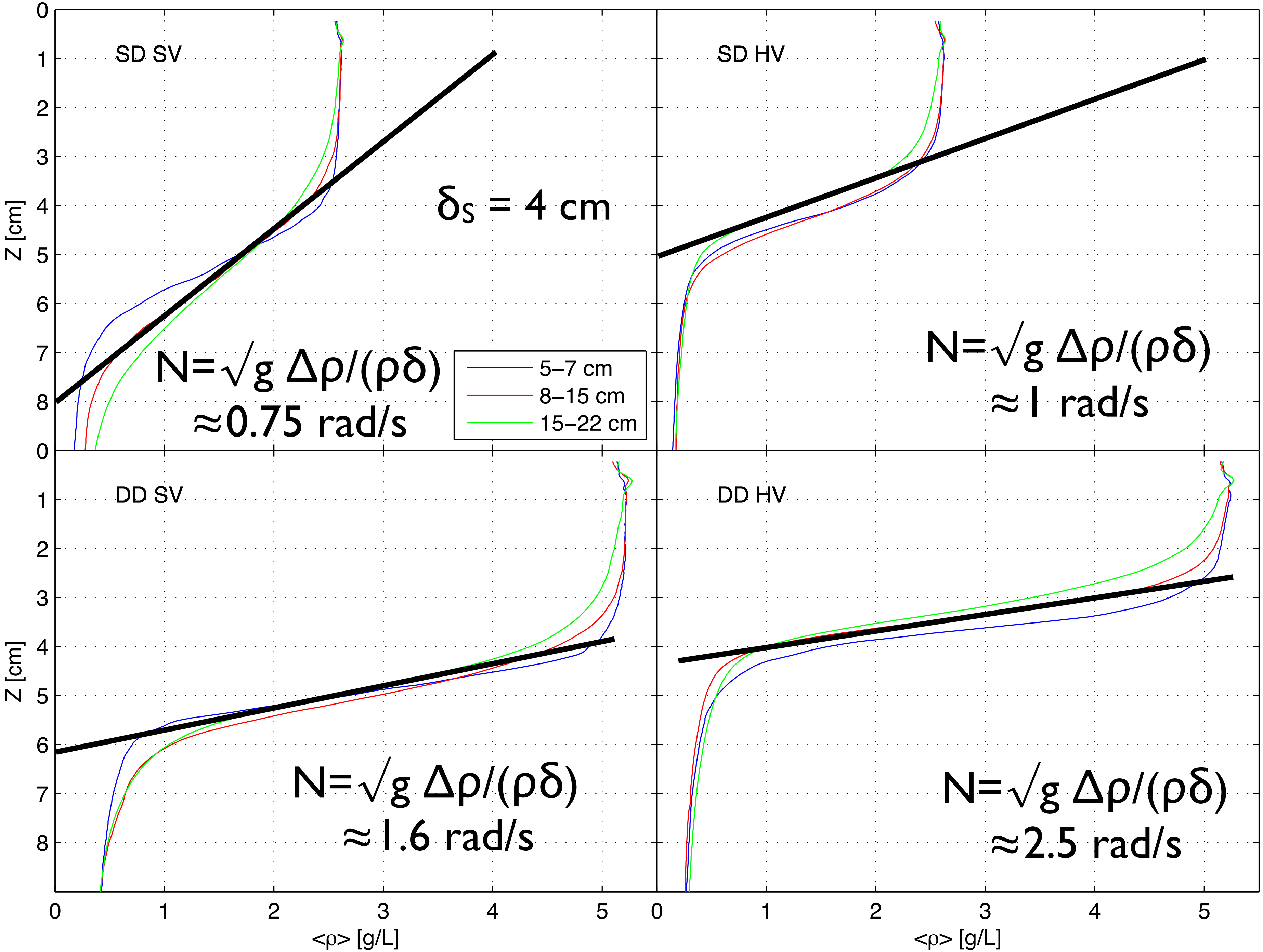


Figure 8: u_{rms} vertical profiles for different x.

Density Profile



Density Fluctuations

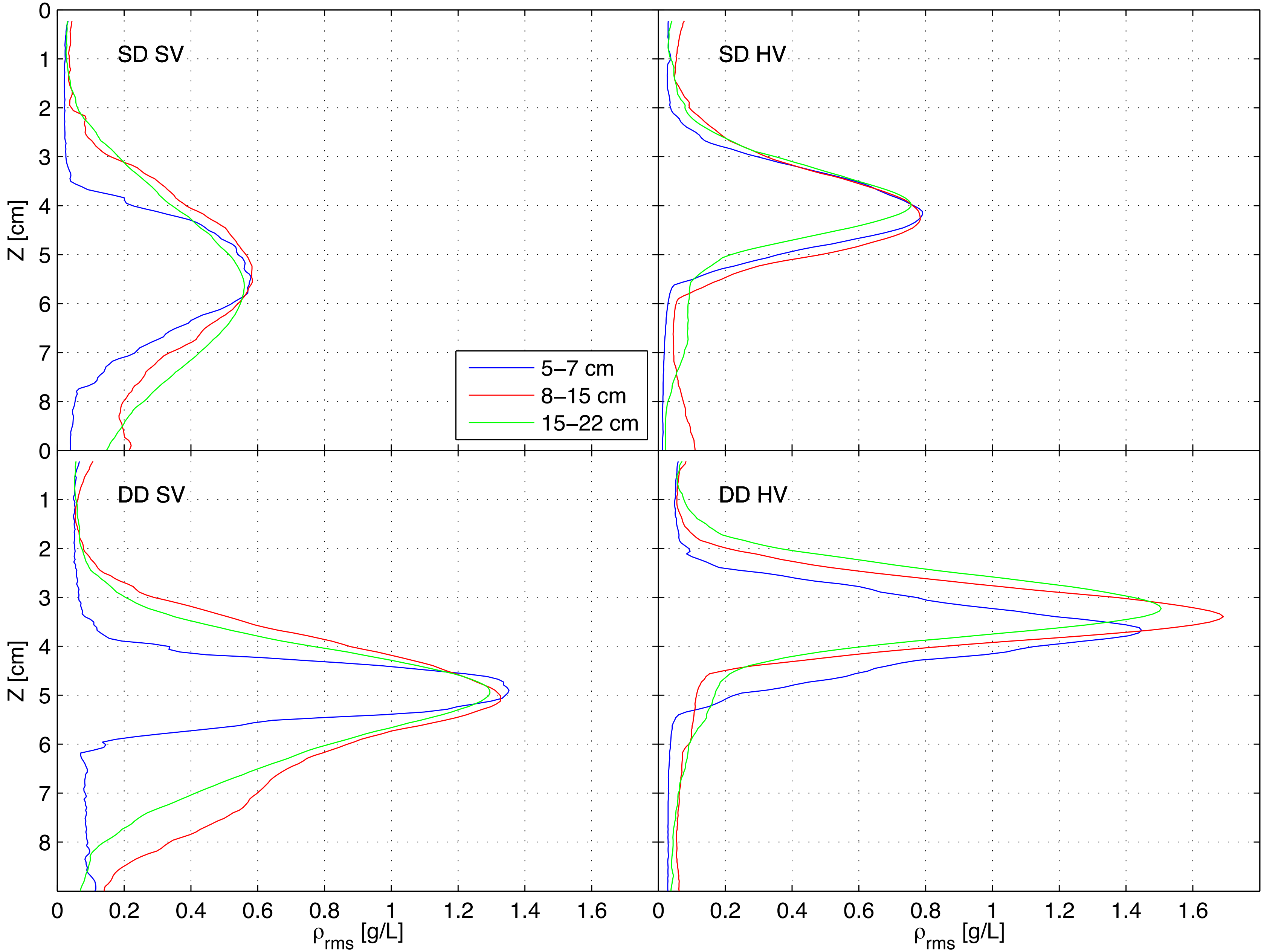
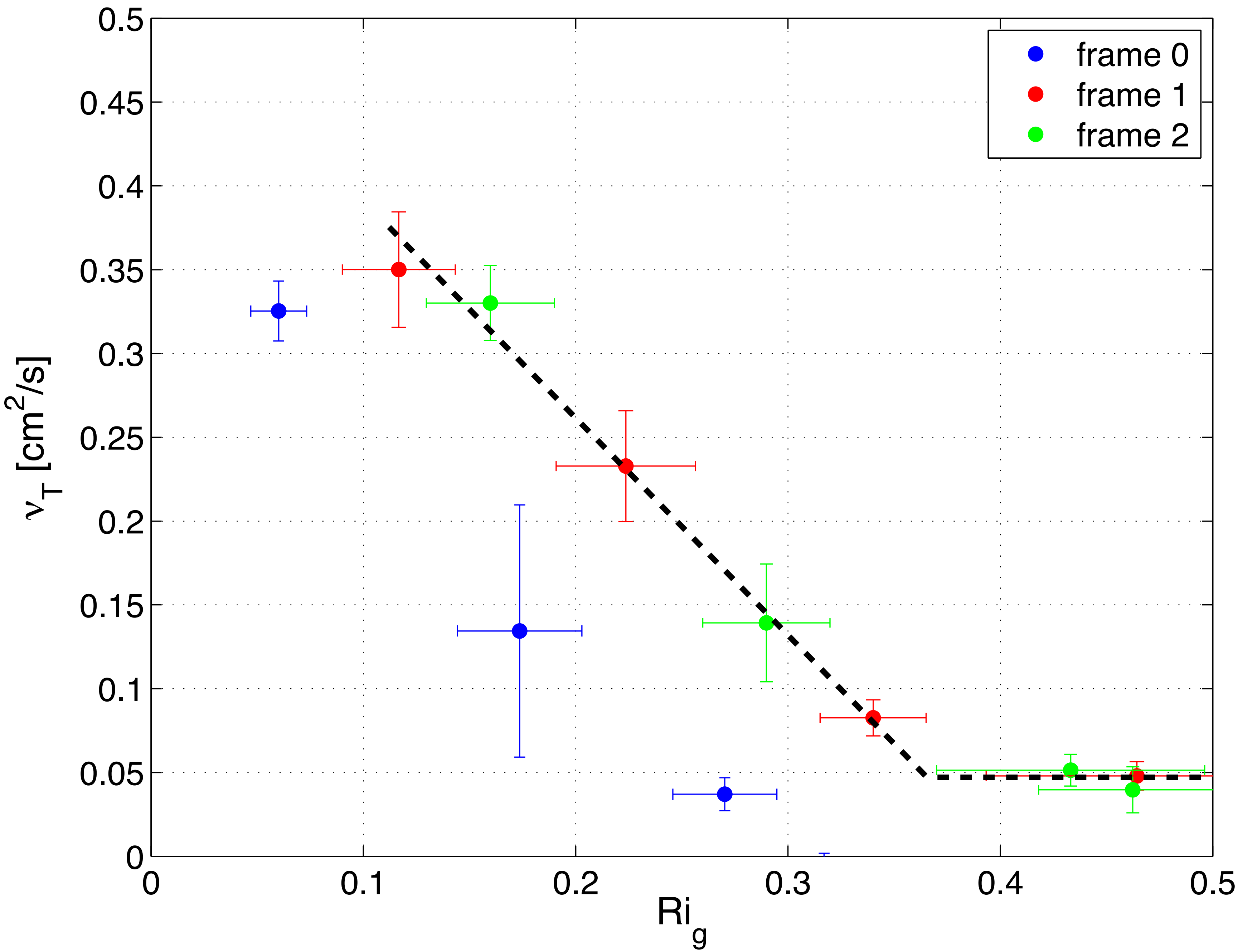
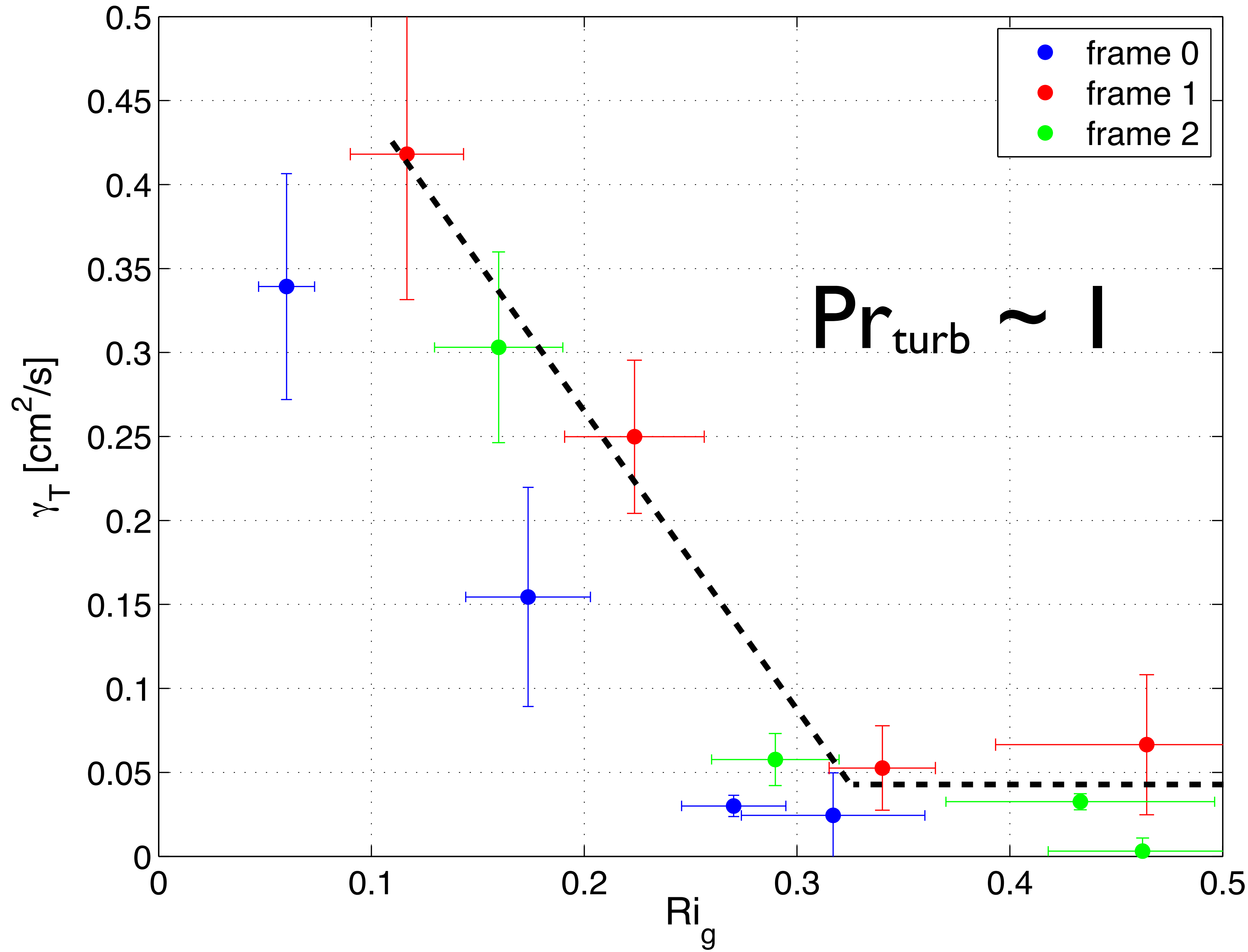


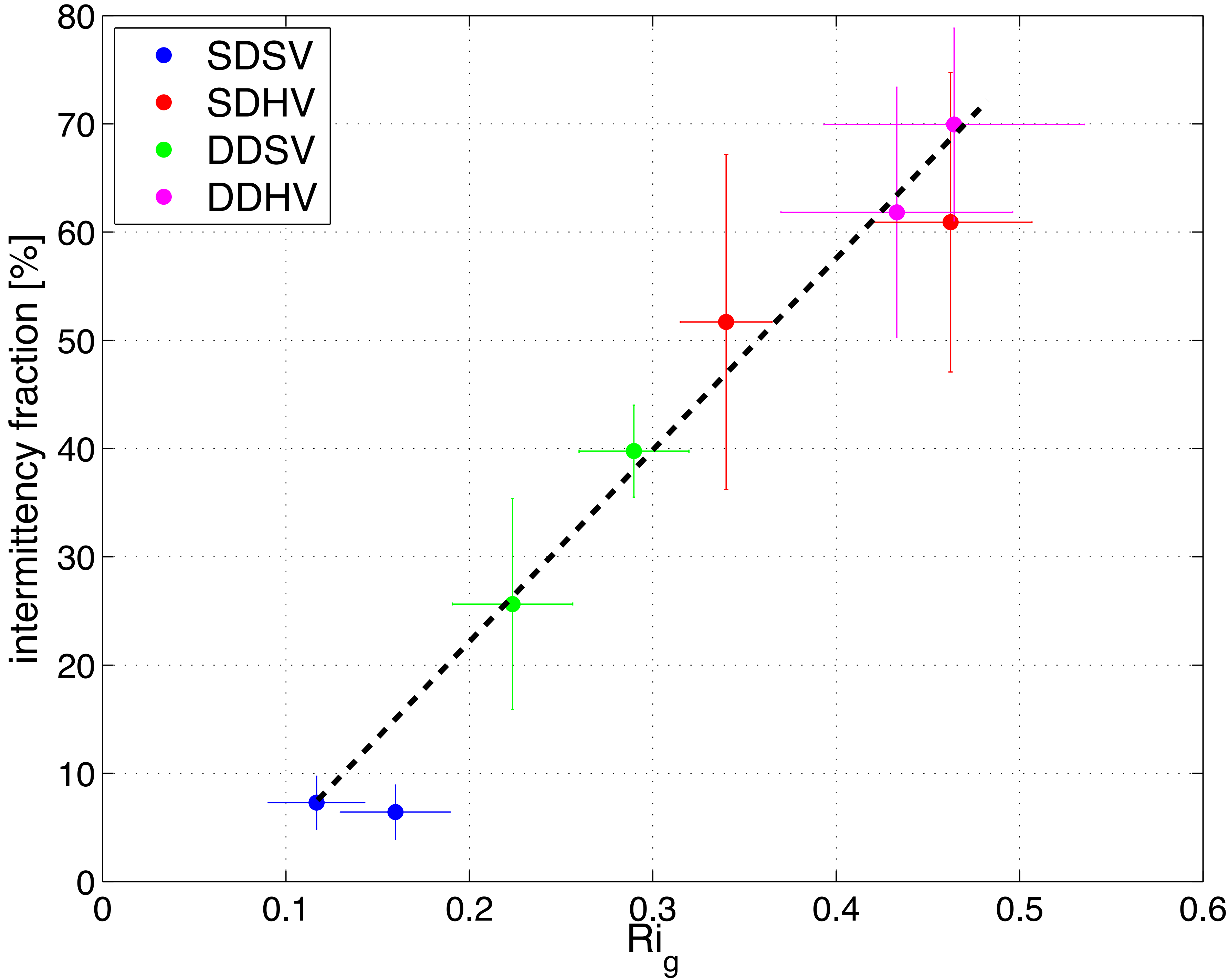
Figure 10: ρ_{rms} vertical profiles for different x.



0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
ν_T [cm^2/s]
0
0.1
0.2
0.3
0.4
0.5
Ri_g
frame 0
frame 1
frame 2

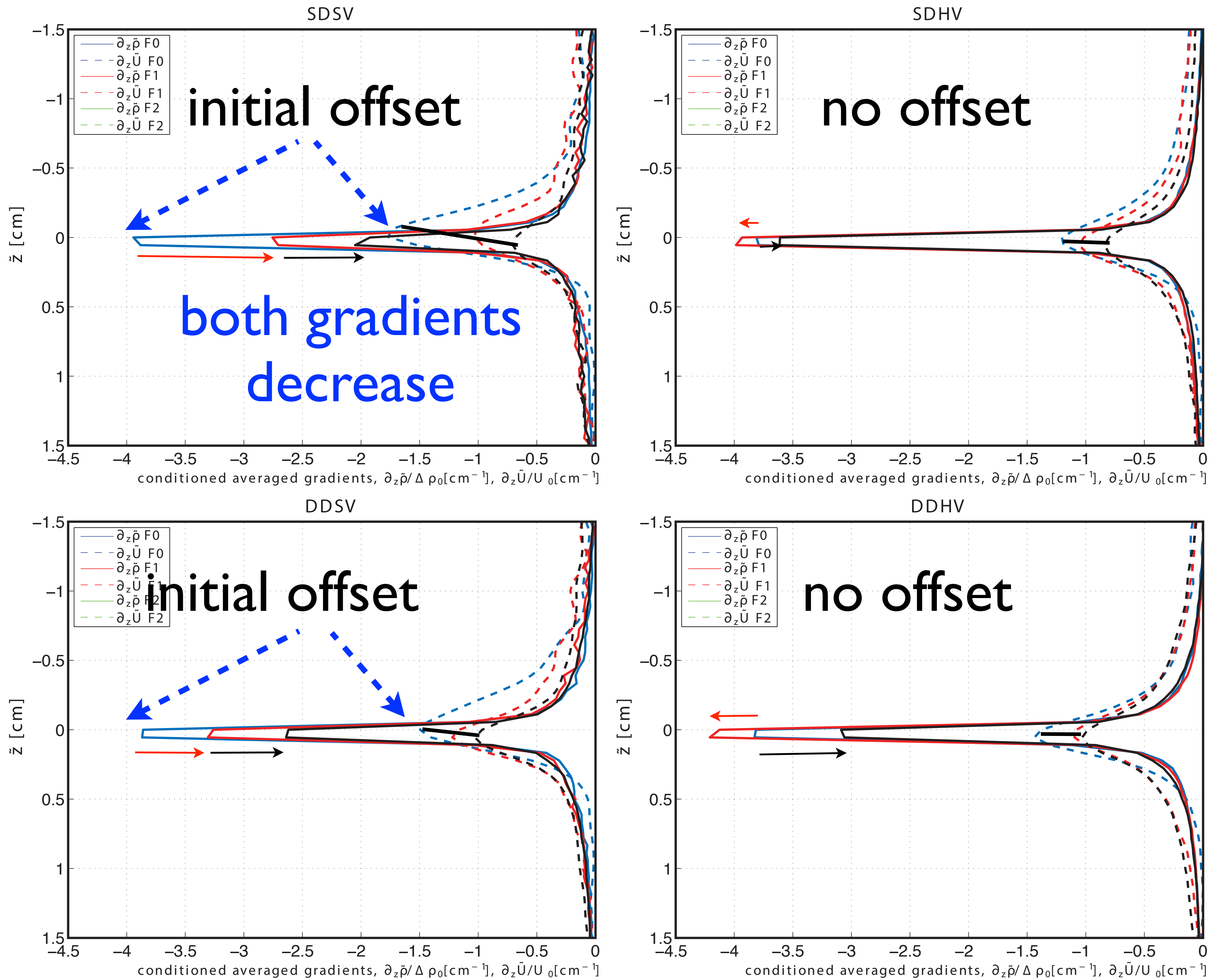


0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.1
0.2
0.3
0.4
0.5
γ_T [cm^2/s]
Ri_g
frame 0
frame 1
frame 2
$Pr_{turb} \sim 1$

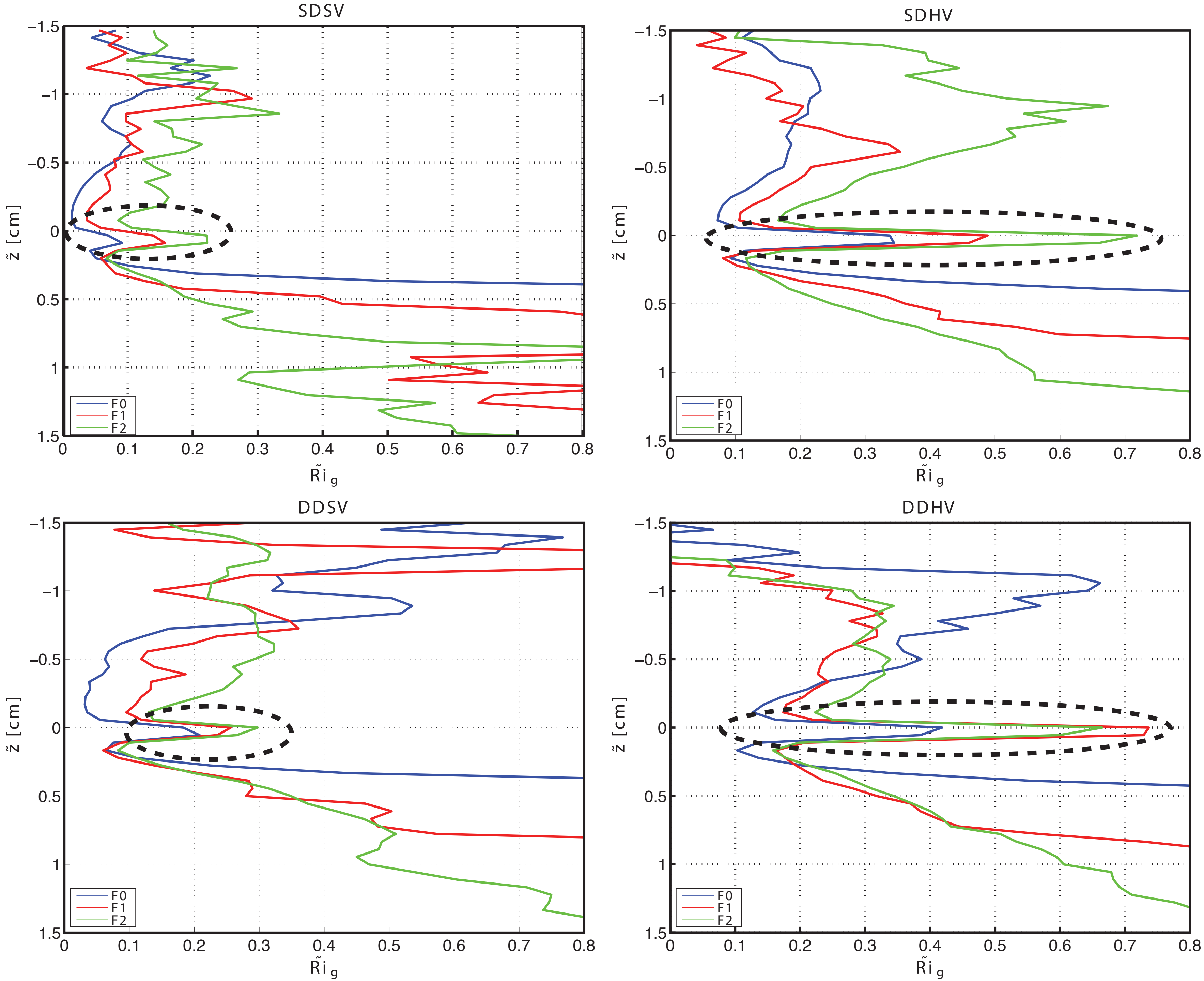


SDSV
SDHV
DDSV
DDHV
intermittency fraction [%]
Ri_g
0
10
20
30
40
50
60
70
80
0
0.1
0.2
0.3
0.4
0.5
0.6

Unperturbed Interface density and velocity gradients



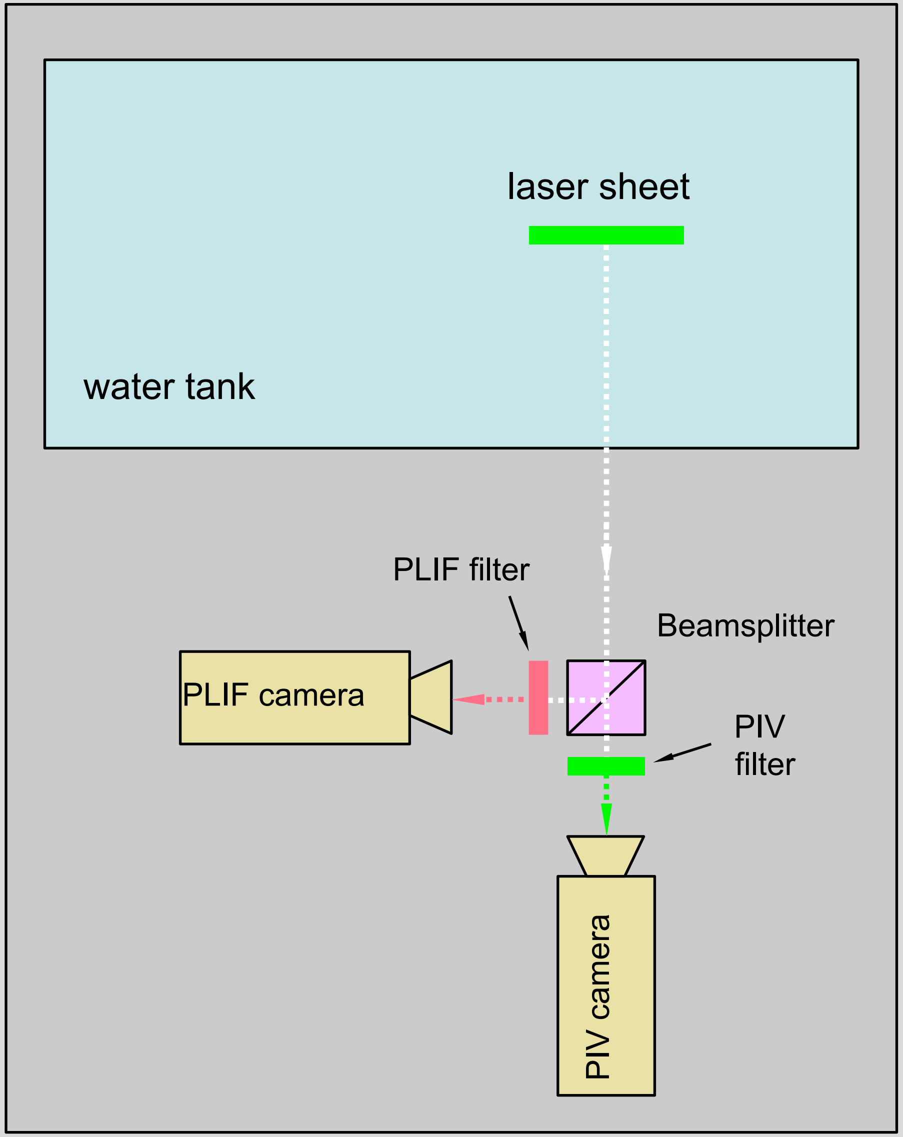
Gradient Richardson for unperturbed interface



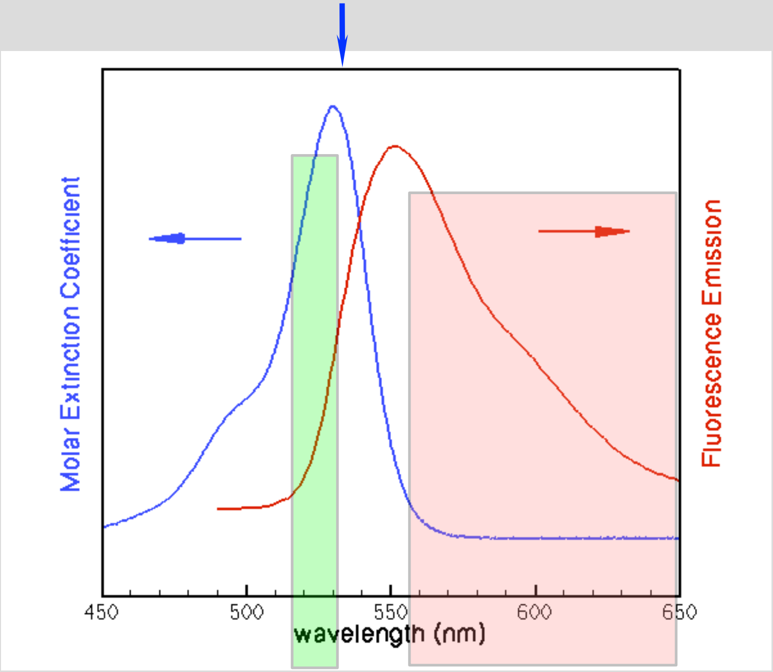
Conference Notes

- Frenkel Prize talk on Thorpe length and comparison with Ozmidov Length: POF (2013) + follow on paper. Decaying turbulence. Colm pointed to this paper as an important entre into the issues associated with different length scales.
- Morning discussion with Colm. Important point is that our scenario is exactly what theory expects and we have all the data to make big contribution to debate about “fossilized turbulence”. There should be an age dependence to the behavior of the unstable parts of the flow. Early time instability should have one ratio of LT/Lo whereas late time unstable parts should have the opposite ratio. Highly testable.
- Action items - we very much need to get the dissipation field. Then evaluate the turbulent dissipation over the unstable region defined by the Thorpe length analysis.
- Note - Thorpe length is a conduit for indirect inference about turbulent dissipation without measuring velocity.

Measuring U(x,z) and ϱ(x,z) simultaneously



Scattered Light
of PIV Particle



Absorption & Emission of Rhodamine 6G

Correct PLIF
for absorption