“Instrumental or mechanical science is the noblest and, above all others, the most useful.”

-Leonardo da Vinci

Magnetic Resonance Imaging of Fast Turbulent Gas Flow

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What's so tricky about turbulence?

"When I meet God, I am going to ask him two questions: Why relativity? And why turbulence? I really believe he will have an answer for the first."

-Werner Heisenberg

(similar quote by Horace Lamb)

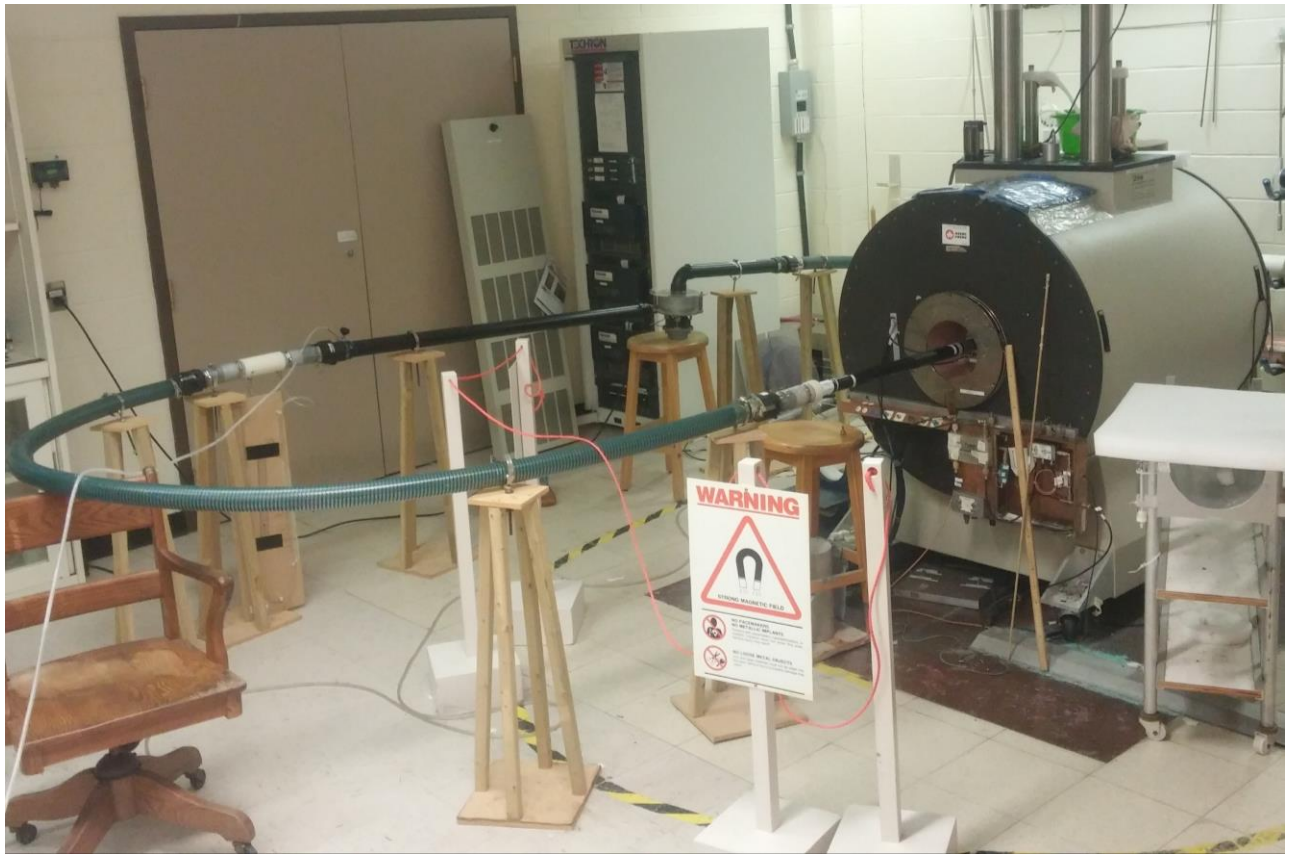
$$\vec{v}(t) = \bar{v}_t + \vec{v}'(t)$$

-Smoke plume from a candle, Wikimedia Commons

Why is MRI well-suited to turbulence?

- Non-invasive
- Inherently 3D
- Use SF_6 instead of air
- Spin angular momentum vectors align with B-fields
- Bulk magnetization vector precesses at Larmor frequency:

$$\omega = \gamma B$$



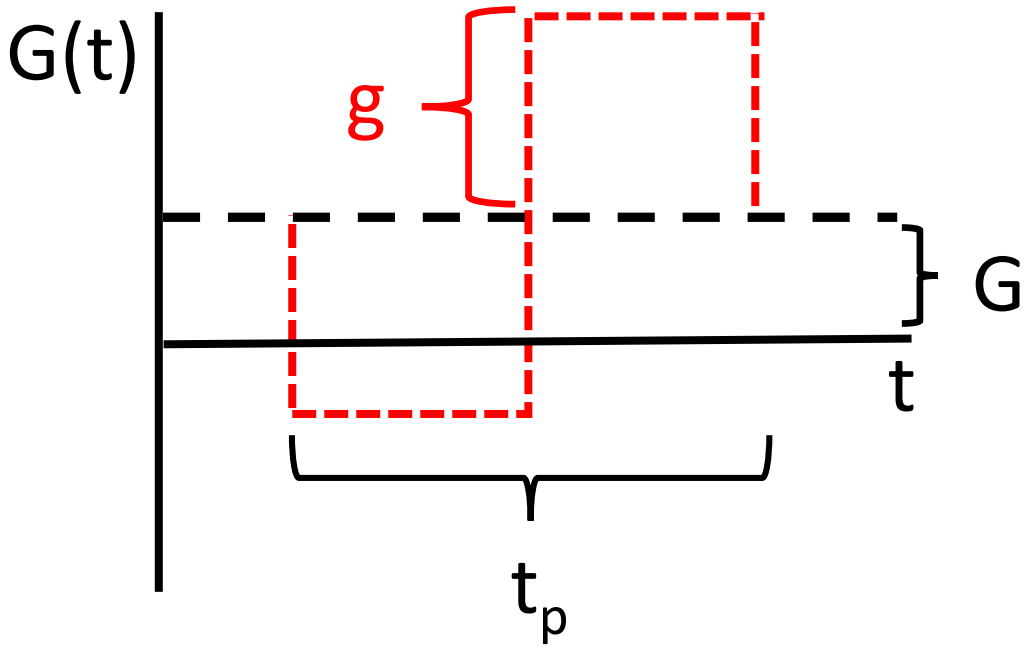
Motion-Encoded SPRITE MRI

- Phase is related to time-averaged velocity field, $\bar{v}_t$

$$\phi = r\left(\gamma t_p G\right) + \bar{v}_t \left(\frac{\gamma t_p^2}{4} g\right) + \ldots$$

- Signal amplitude is related to the turbulence

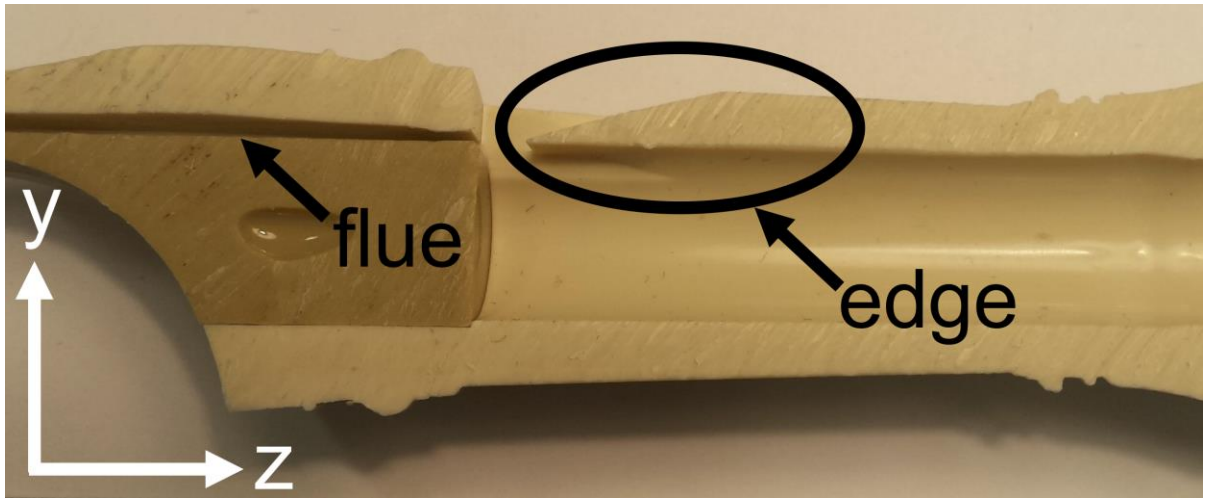
$$\boldsymbol{D}\colon \boldsymbol{b}(\boldsymbol{g}) = -\left(\ln \frac{S}{S_o}\right)$$



Turbulent System #1: The Recorder

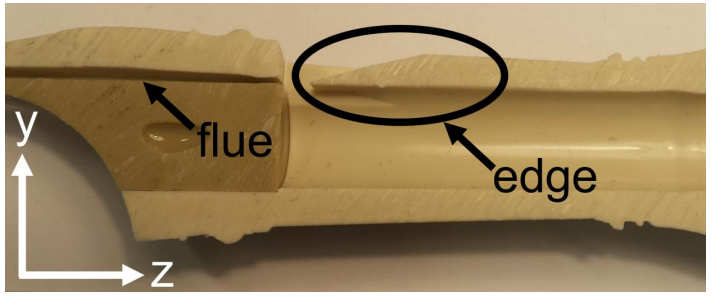
- Demonstration of time-averaged velocity field mapping
- Expect to see gas moving through the flue, then oscillating above and below the edge

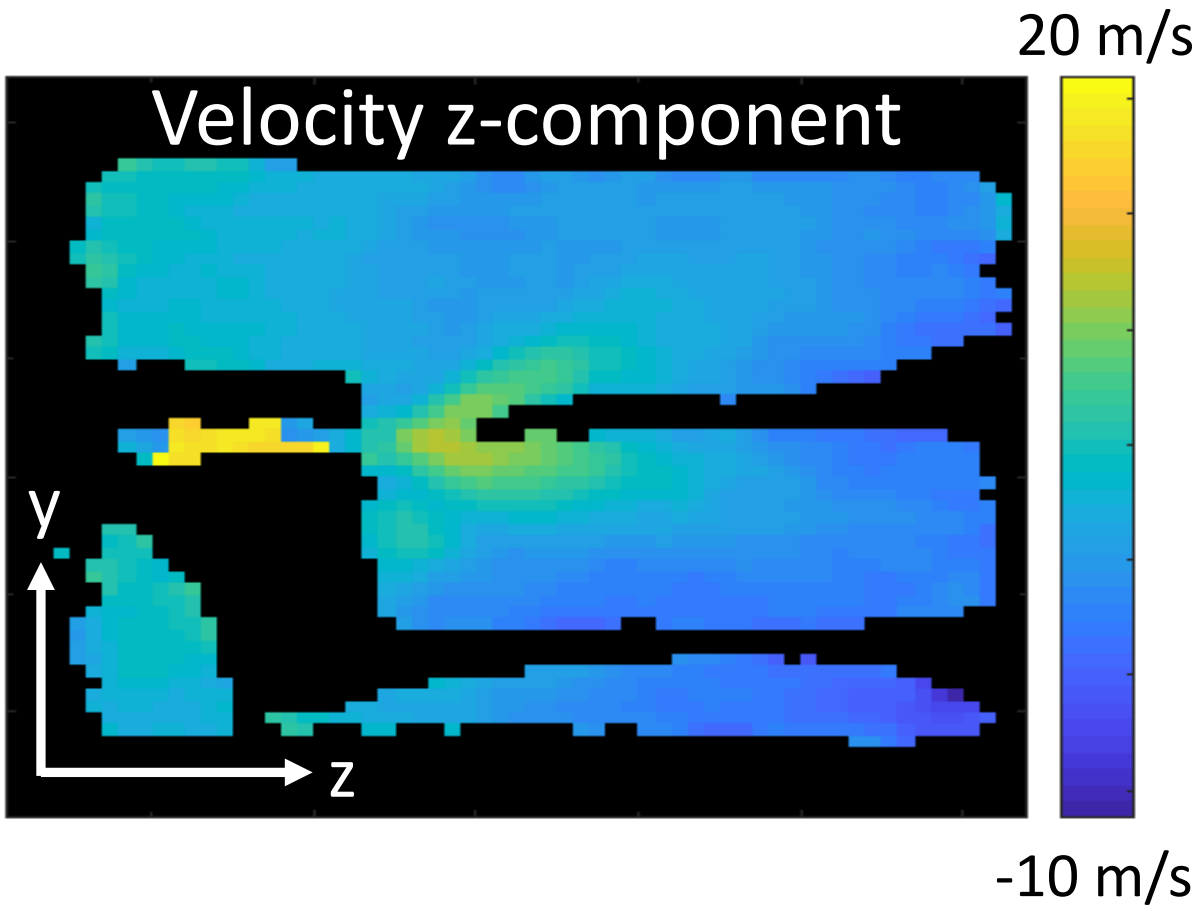
$$\vec{v}(t) = \bar{v}_t + \vec{v}'(t)$$

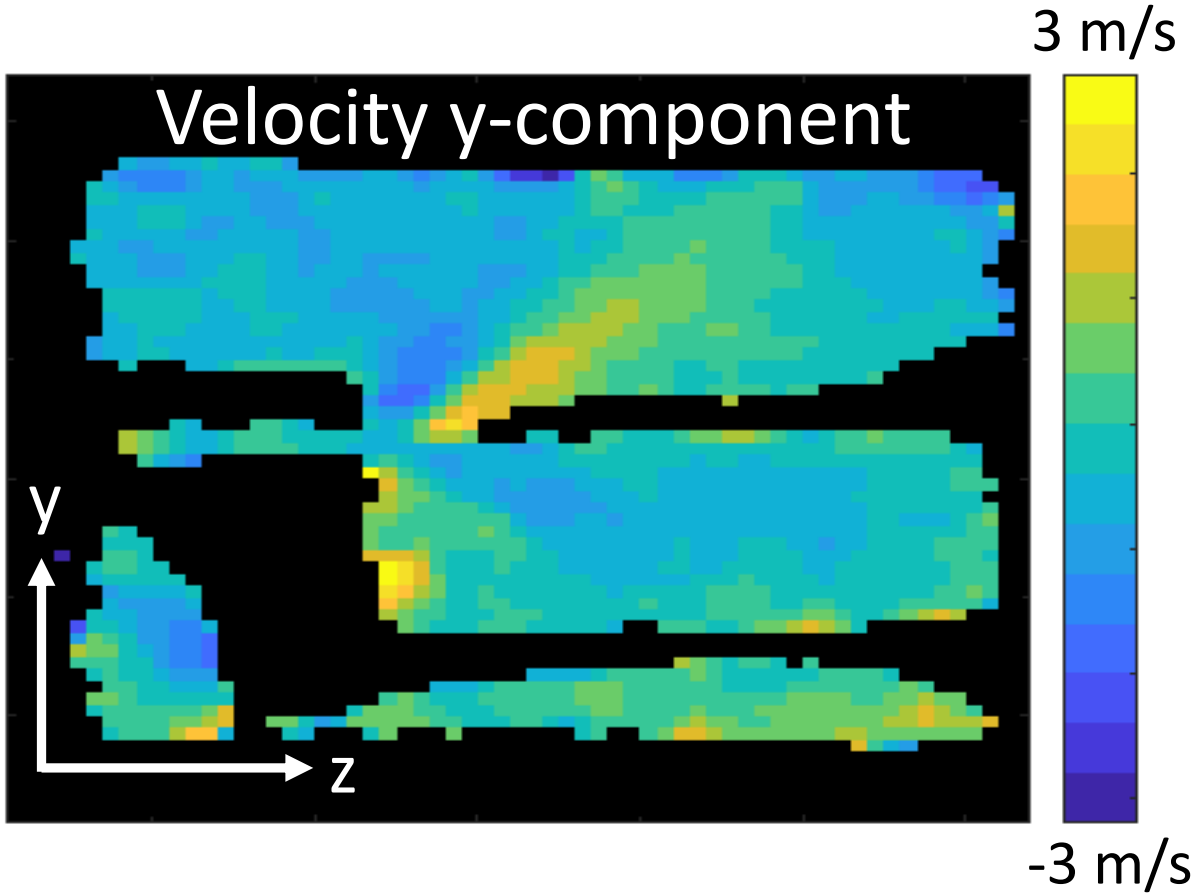


Direction of Flow

Turbulent System #1: The Recorder



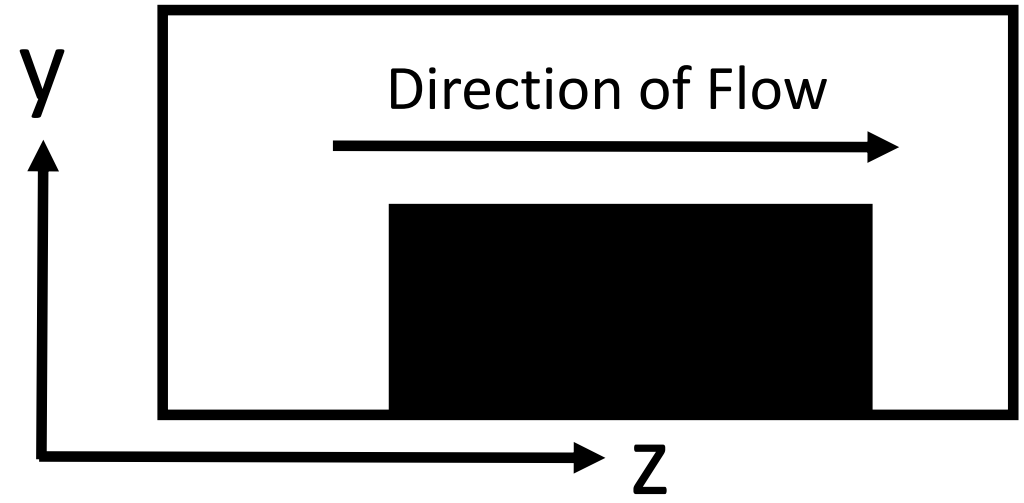


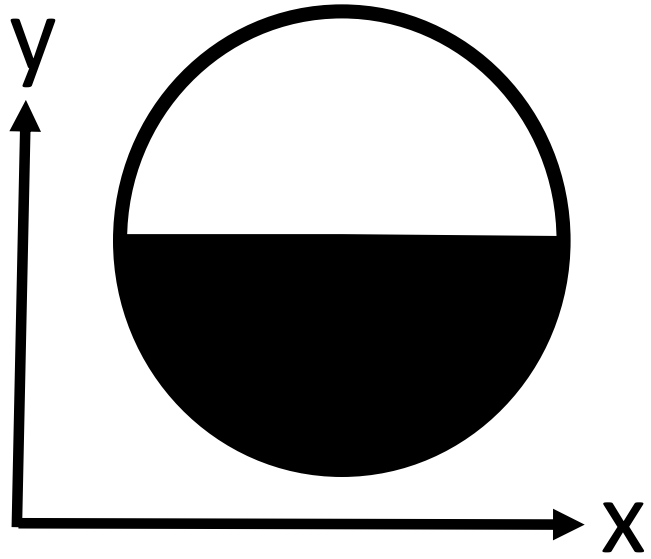


Turbulent System #2: Obstructed Pipe

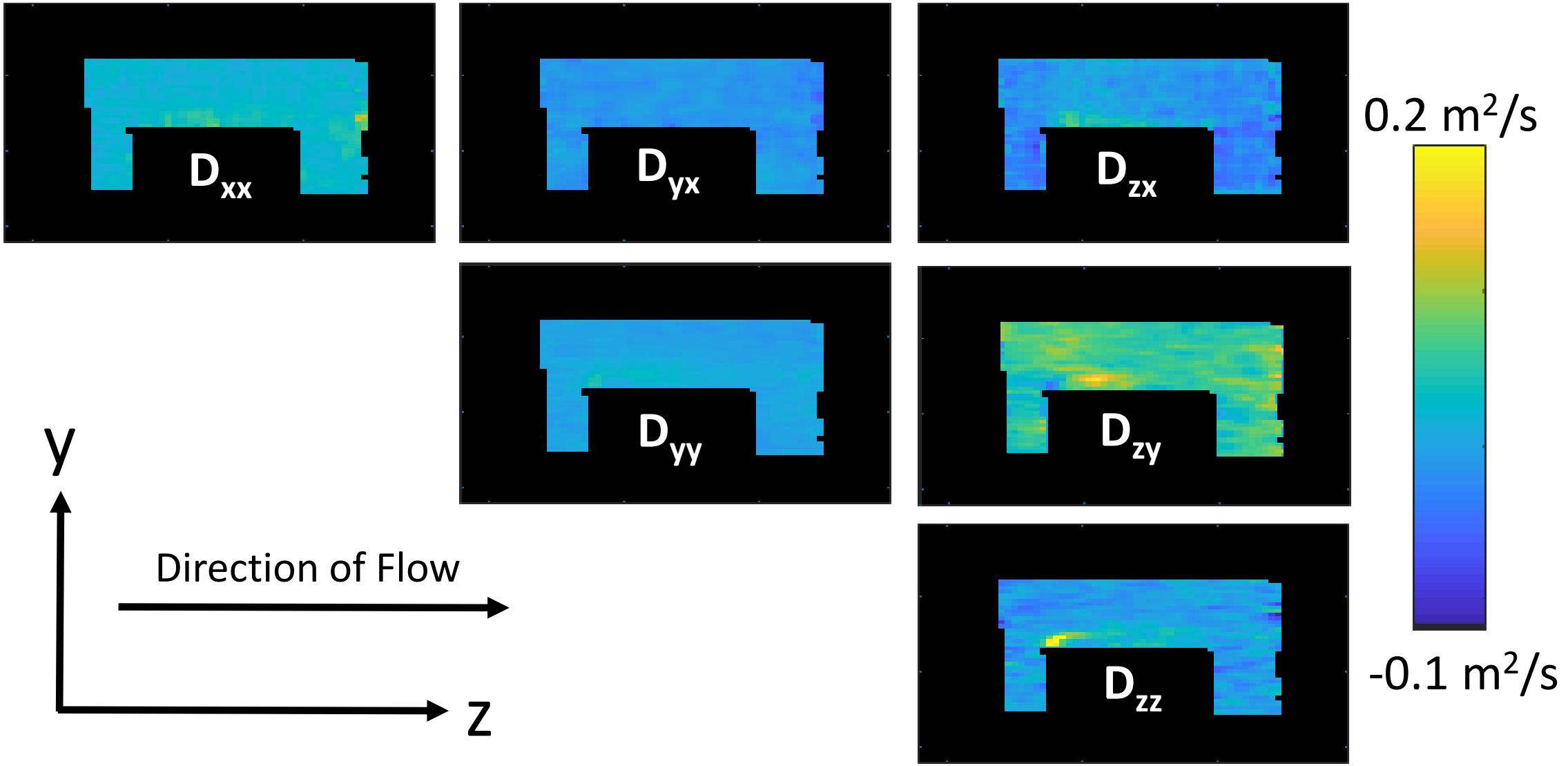
- Demonstration of Eddy-Self Diffusivity measurement
- Tells us where the turbulent fluctuations have the greatest effect
- Expect the greatest turbulence when the gas hits the edge

$$\vec{v}(t) = \bar{v}_t + \vec{v}'(t)$$





Turbulent System #2: Obstructed Pipe



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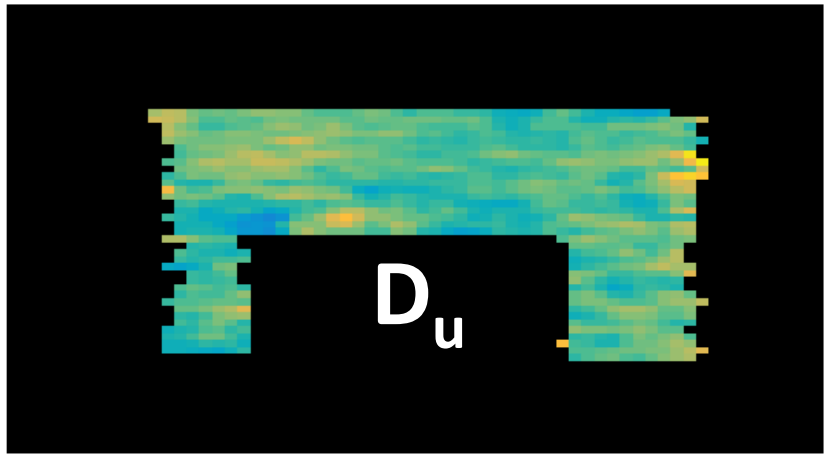

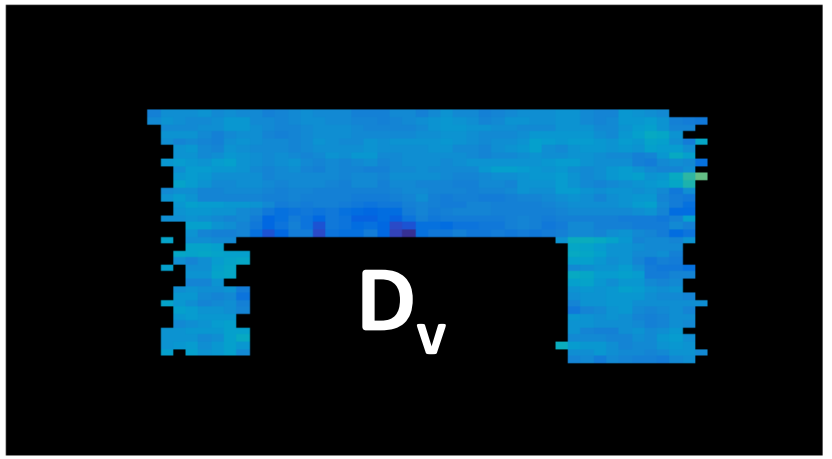

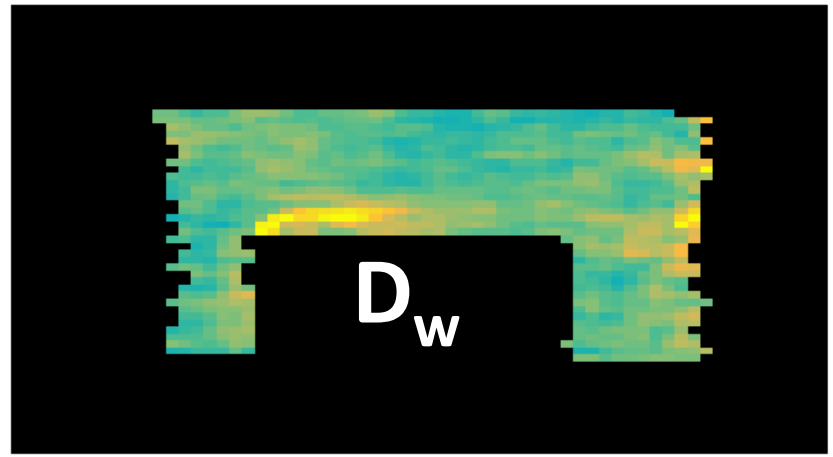

-0.1 m^2/s  0.2 m^2/s

Turbulence is anisotropic!

Summary

- MRI is a non-invasive and naturally 3D measurement tool
- Motion-encoded SPRITE is a robust tool useful for measurements of fast turbulent gas flow
- The phase accumulation gives us information about the time-averaged velocity field
- The signal attenuation gives us information about the turbulent anisotropy

MERCI/THANK YOU

Further reading:

Newling, B. et al, “Velocity Imaging of Highly Turbulent Gas Flow”, Phys Rev Lett, 93 (15), 2004

Kuethe, D. O., “Measuring Distributions of Diffusivity in Turbulent Fluids with Magnetic Resonance Imaging”, Phys Rev A, 40 (8), 1989

Basser, P. et al, “MR Diffusion Tensor Spectroscopy and Imaging”, Biophysical Journal, 66 (1) , 1994