Using PIV to measure decaying turbulence with and without rotation

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- adventures in particle selection
- some observations of rotating turbulence


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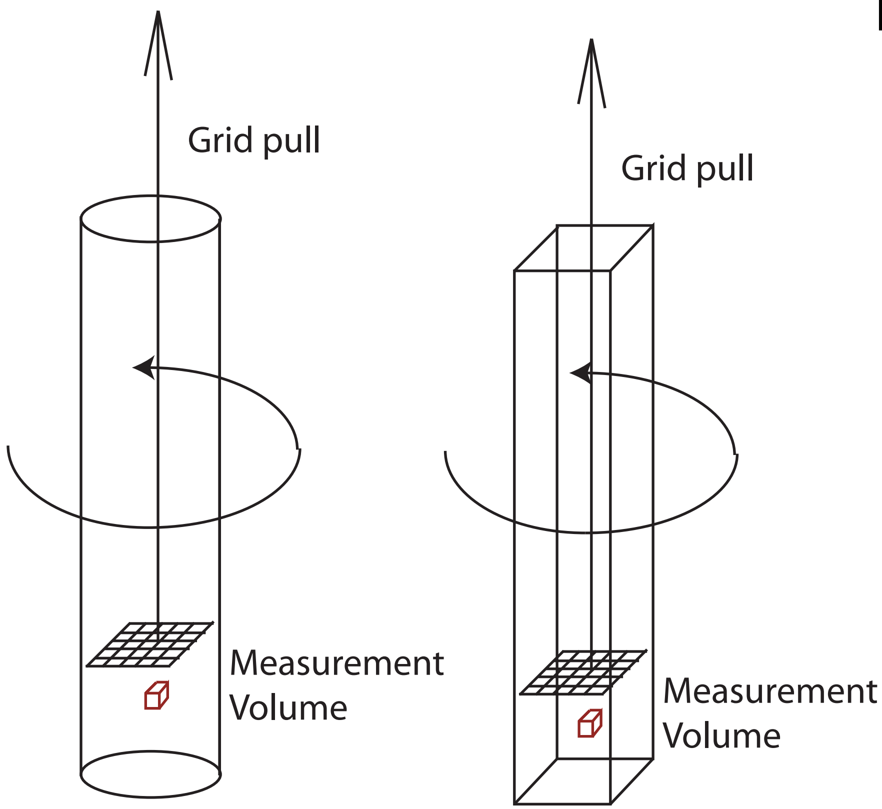
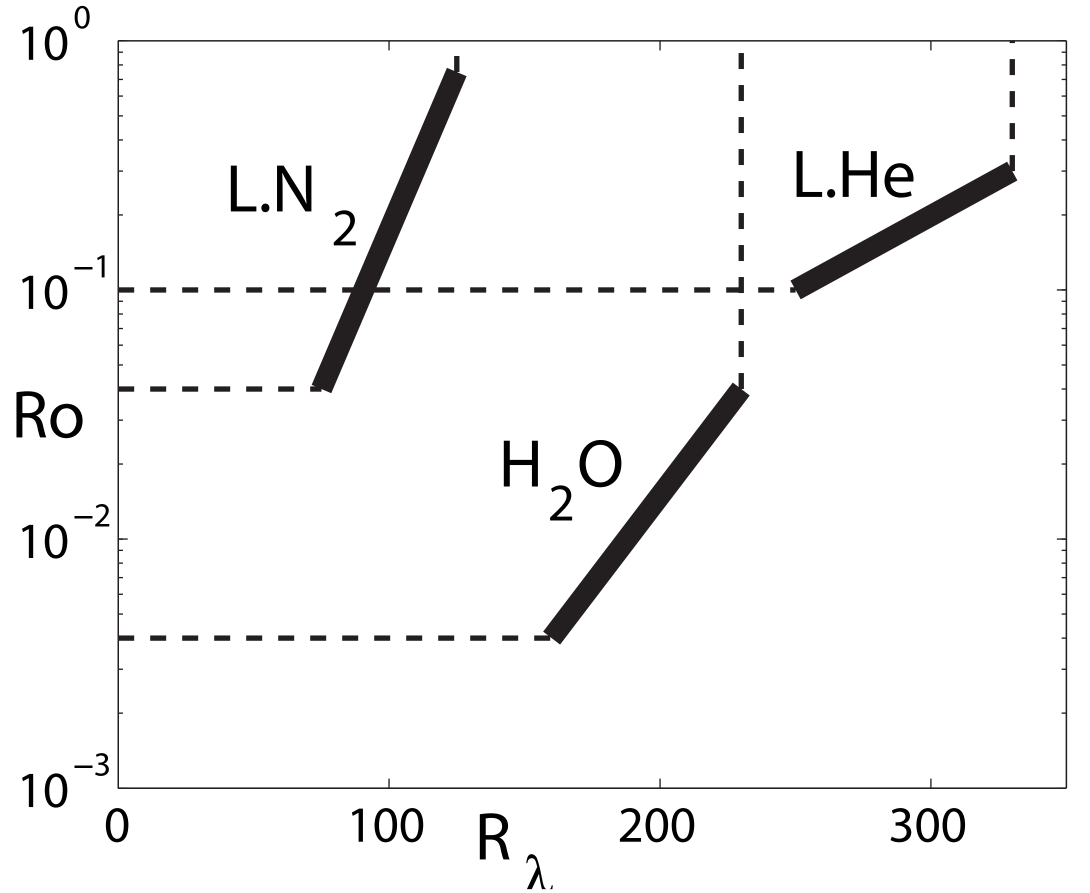
Grid generated turbulence





$Ro = v_{rms} / \Omega b$ Rossby No.

$R_\lambda = v_{rms}\, \lambda / \nu$ Reynolds No.

Rapidly Rotating -- Coriolis Large

$$\partial_t \vec{v} + \left(\vec{v} \bullet \vec{\nabla}\right) \vec{v} + 2\vec{\Omega} \times \vec{v} = -\frac{1}{\rho}\vec{\nabla} P + \nu \nabla^2 \vec{v}$$

$$\vec{\nabla} \bullet \vec{v} = 0$$

$$\partial_t \vec{v} + 2\vec{\Omega} \times \vec{v} = -\frac{1}{\rho}\vec{\nabla} P$$

$$2\vec{\Omega} \times \vec{v} = -\frac{1}{\rho}\vec{\nabla} P$$

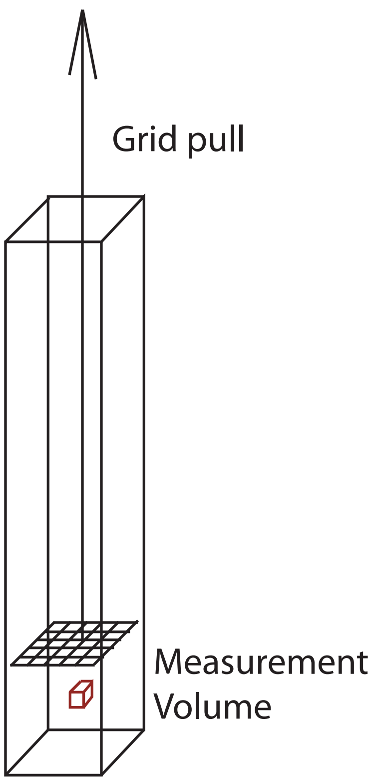
$$(\vec{\Omega} \bullet \vec{\nabla})\vec{v} = 0$$

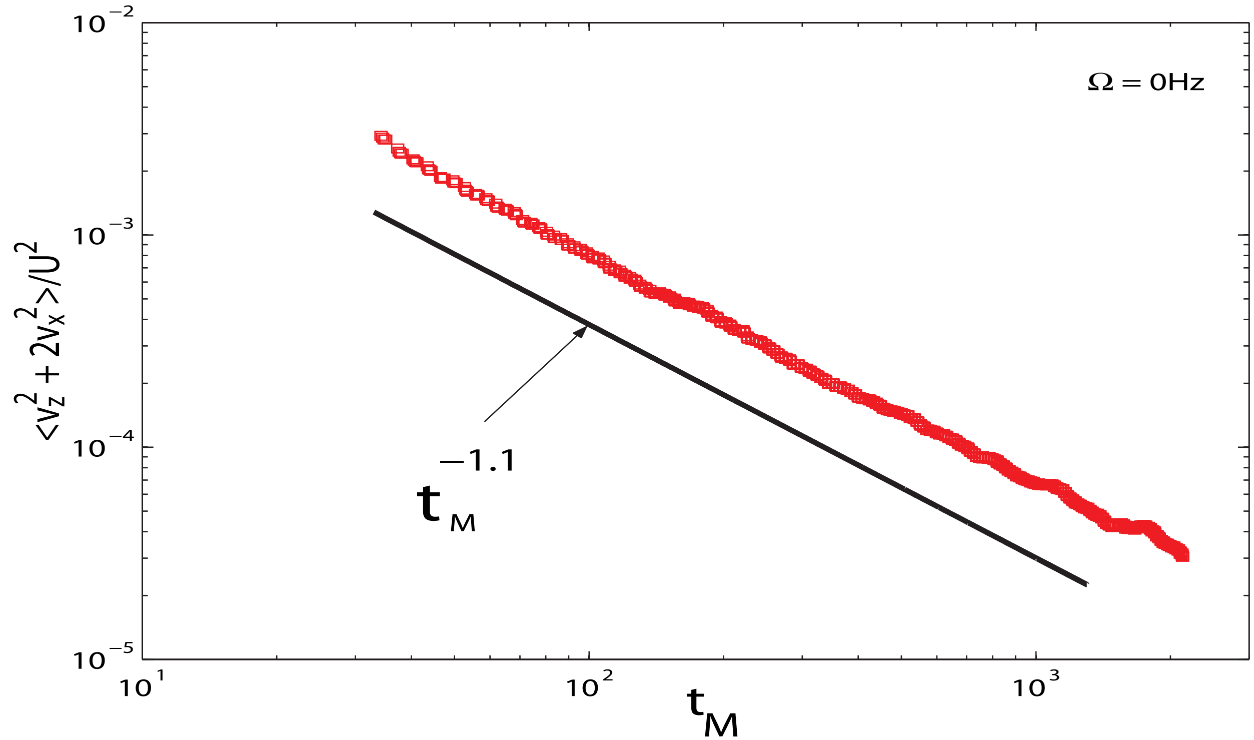
Taylor-Proudman theorem

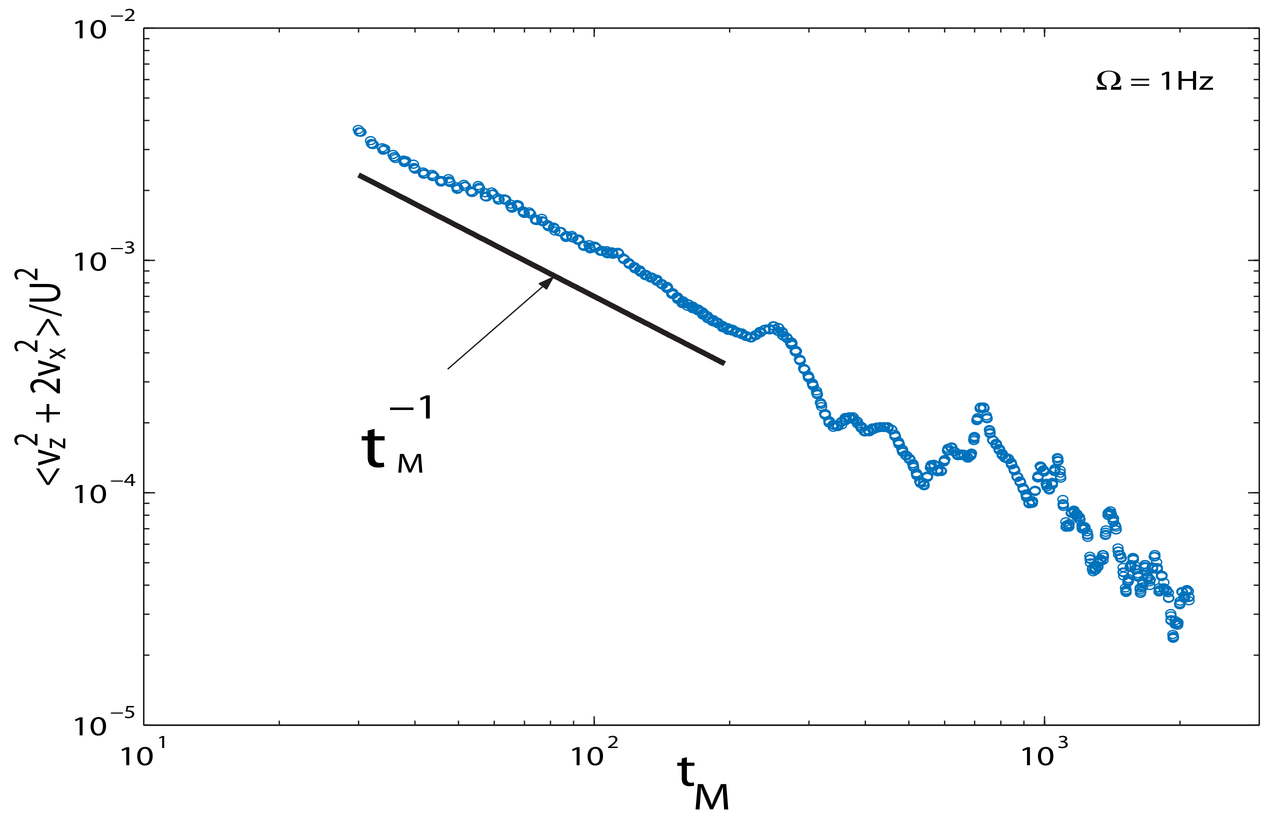
Decay of kinetic energy

Liquid Nitrogen

Grid generated turbulence







$$\partial_t \vec{v} + 2\vec{\Omega} \times \vec{v} = -\frac{1}{\rho}\vec{\nabla} P$$

$$\partial_t \vec{\omega} = 2(\vec{\Omega} \cdot \vec{\nabla})\vec{v} = 2\Omega_o \partial_z \vec{v}$$

Plane wave solutions

$$\vec{v} = \vec{v}_o e^{i(\vec{k} \cdot \vec{r} - \omega t)}$$

$$\omega = \pm 2\Omega_o \frac{k_z}{k}$$

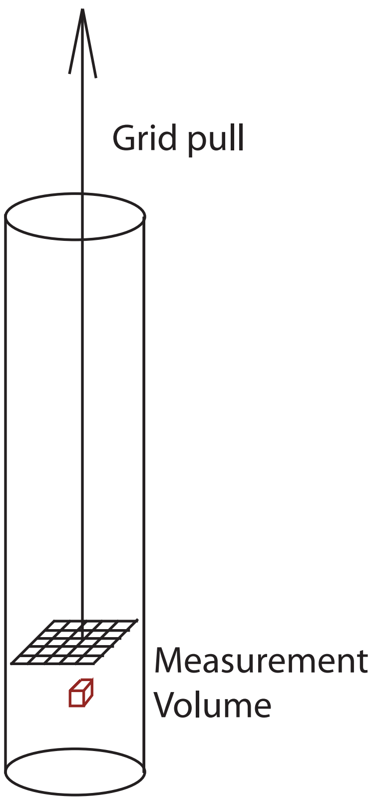
$$0 < |\omega| < 2\Omega_o$$

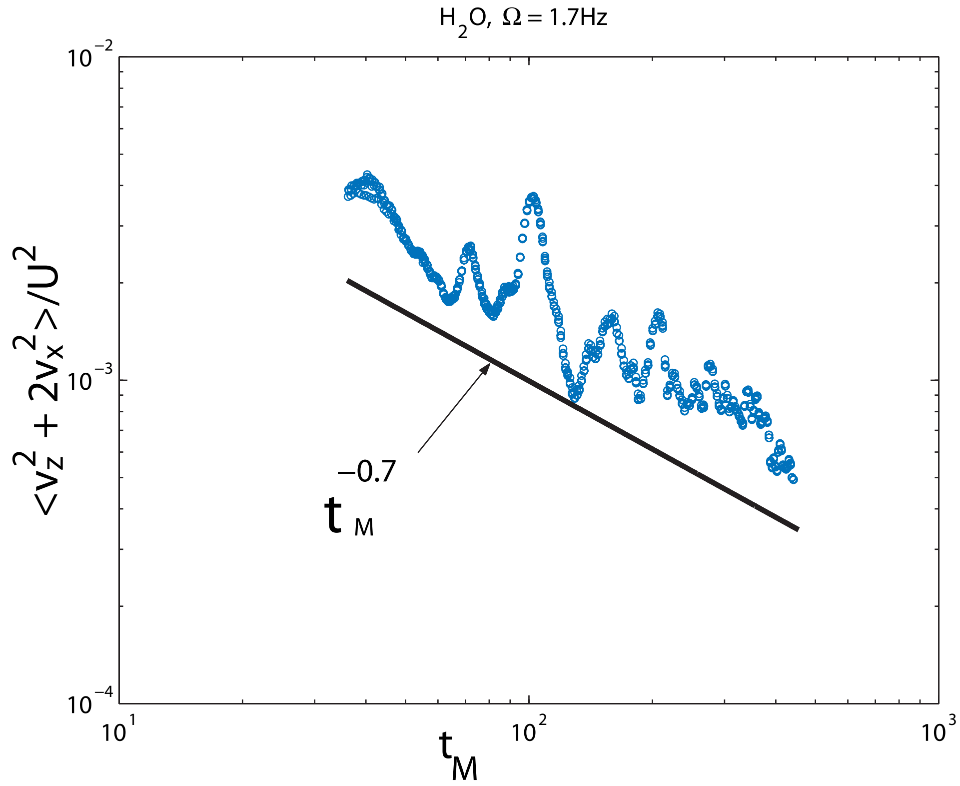
Modes of Containers

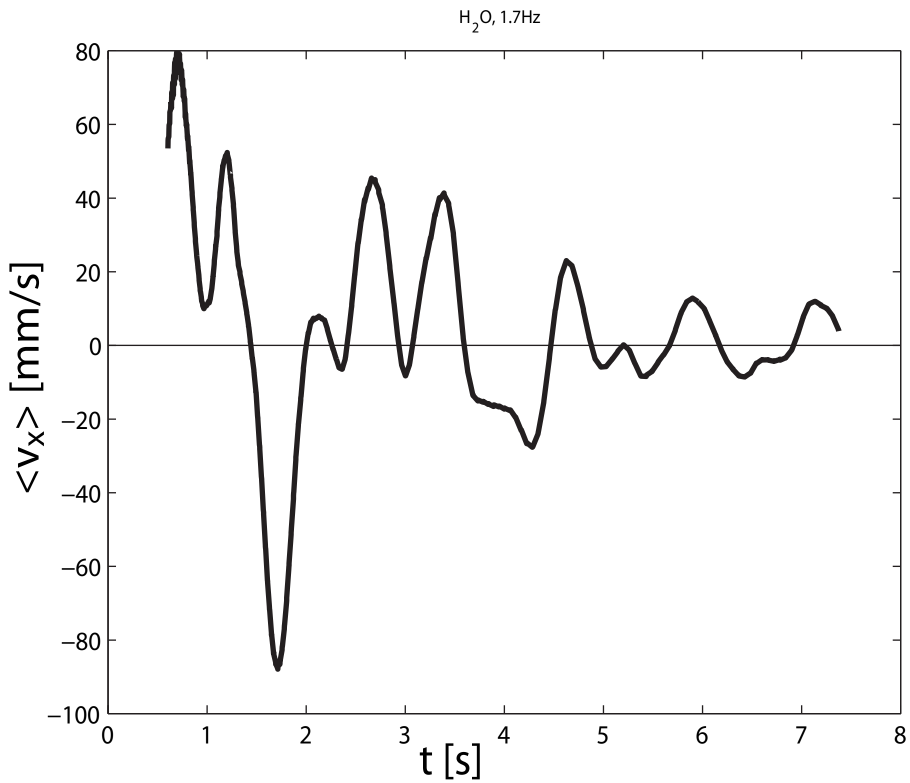
Decay of kinetic energy -- oscillations!

Water

Grid generated turbulence



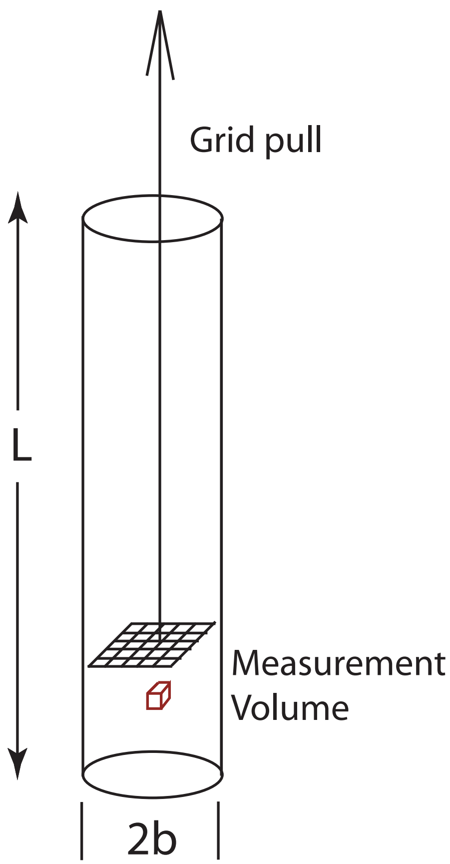


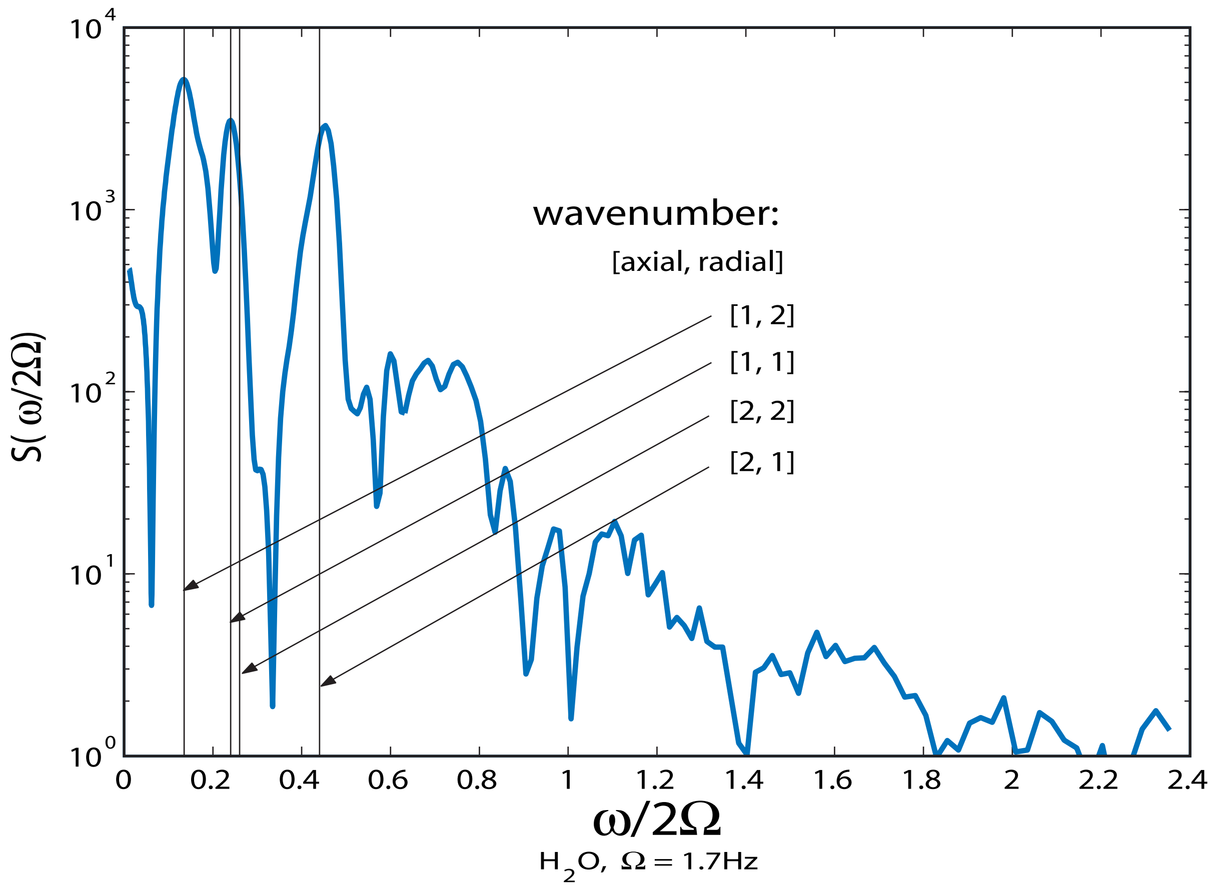


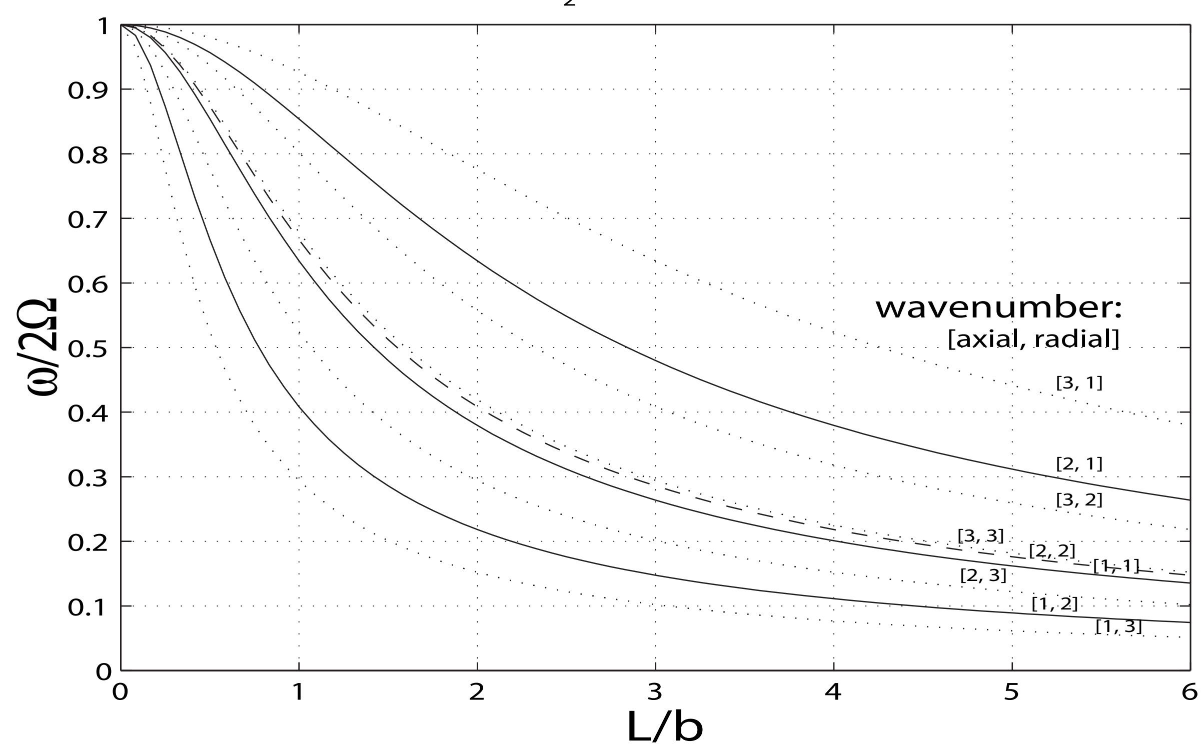
Frequency spectra of <v>

Water

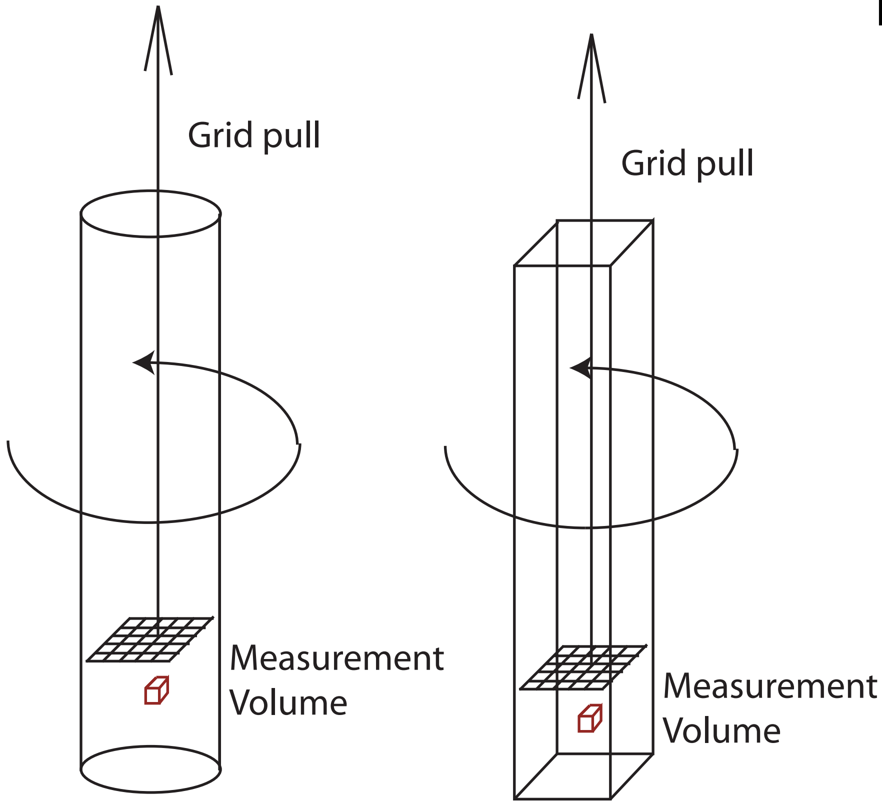
Grid generated turbulence

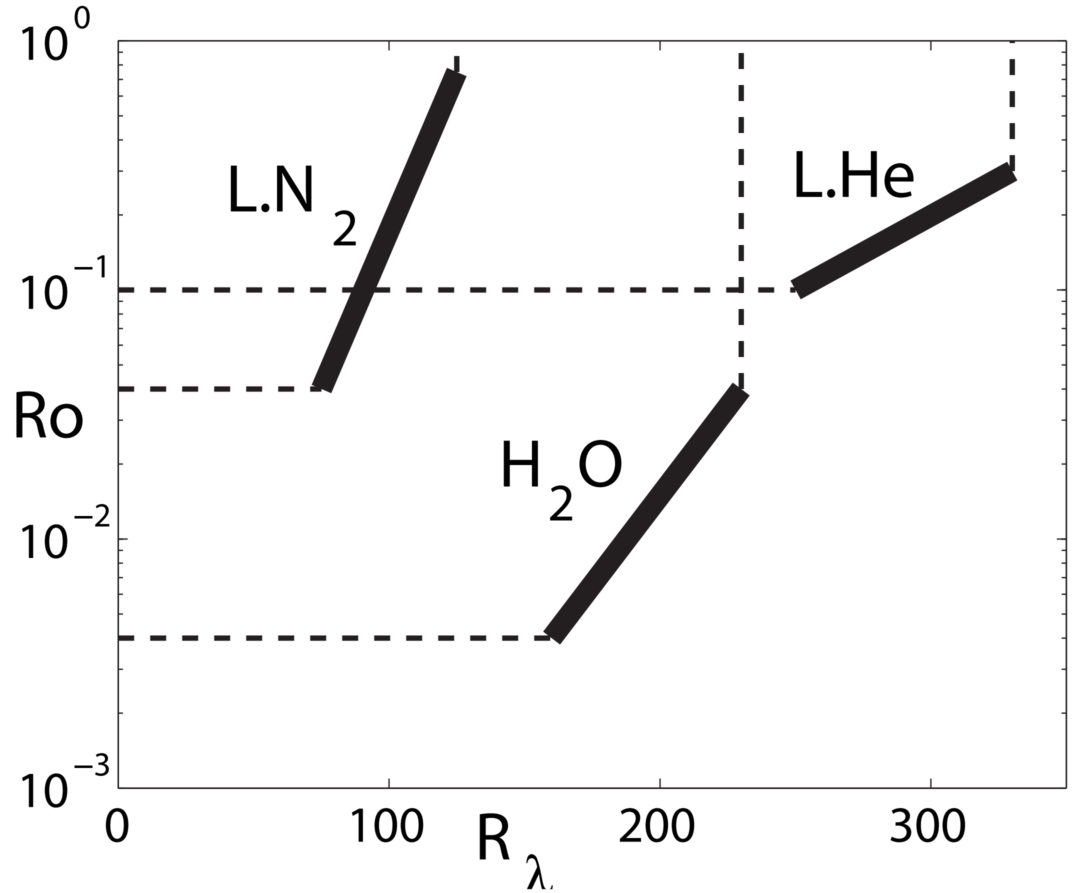






Grid generated turbulence





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Tracer Particle Evaluation

$$\frac{4}{3}\pi a^3 \rho_p \frac{dV}{dt} = \frac{4}{3}\pi a^3 (\rho_p - \rho_f) g - 6\pi \mu a (V - U) + \text{history terms} + \ldots$$

Maxey and Riley (1983)

V - particle velocity
U - fluid velocity

for $Re = 0$:

$$\frac{\tau_p}{\tau_f}\frac{dV^*}{dt^*} = \frac{u_p}{u_f} - (U^* - V^*)$$

or

$$U^* - V^* = Fr - St\frac{dV^*}{dt^*}$$

where

$$St = \frac{\tau_p}{\tau_f}$$

- particle inertial time
- fluid time scale

$$Fr = \frac{u_p}{u_f}$$

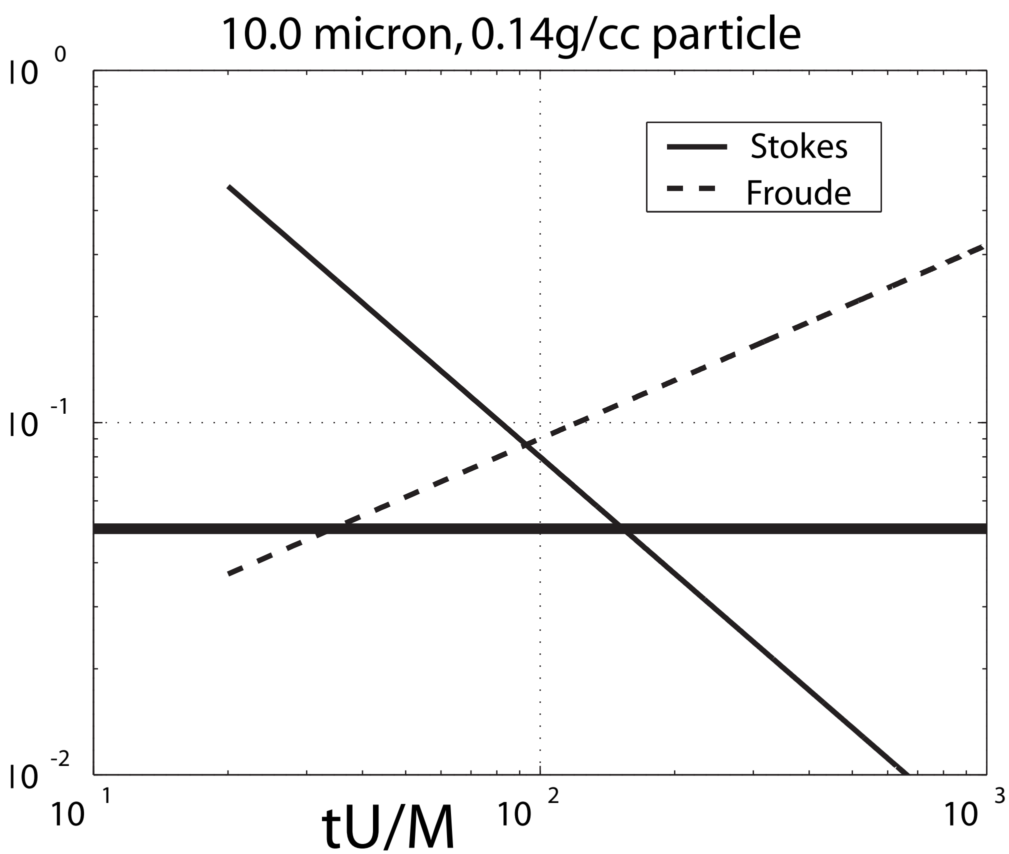
- particle settling velocity
- fluid velocity scale

and

$$\tau_p = \frac{\rho_p (2a)^2}{18\mu}$$

$$u_p = \frac{(\rho_f - \rho_p)(2a)^2 g}{18\mu}$$

Tracer Particle Example



Hollow Glass (eg. Q-cel)

U = 2 m/s
M = 7.2 mm

$$St = \frac{\tau_p}{\tau_f}$$

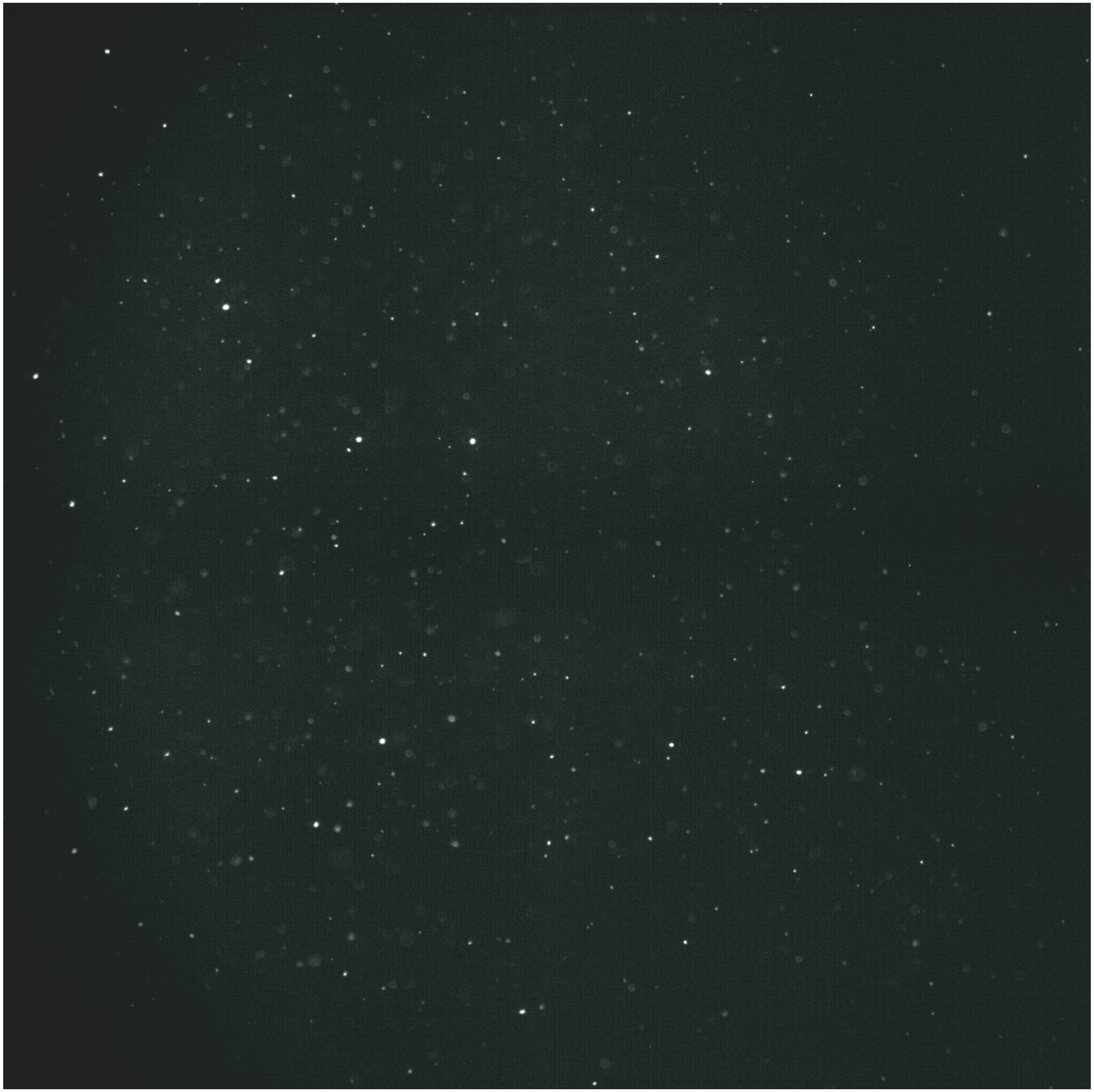
$$Fr = \frac{u_p}{u_f}$$

with

$$\tau_f = (\frac{\nu}{\epsilon})^{1/2}$$

$$u_f = (\nu\epsilon)^{1/4}$$

10-30 micron hollow glass spheres



Tracer Particle Clumping

- thermal energy:

$$k_B T \approx 10^{-21} J$$

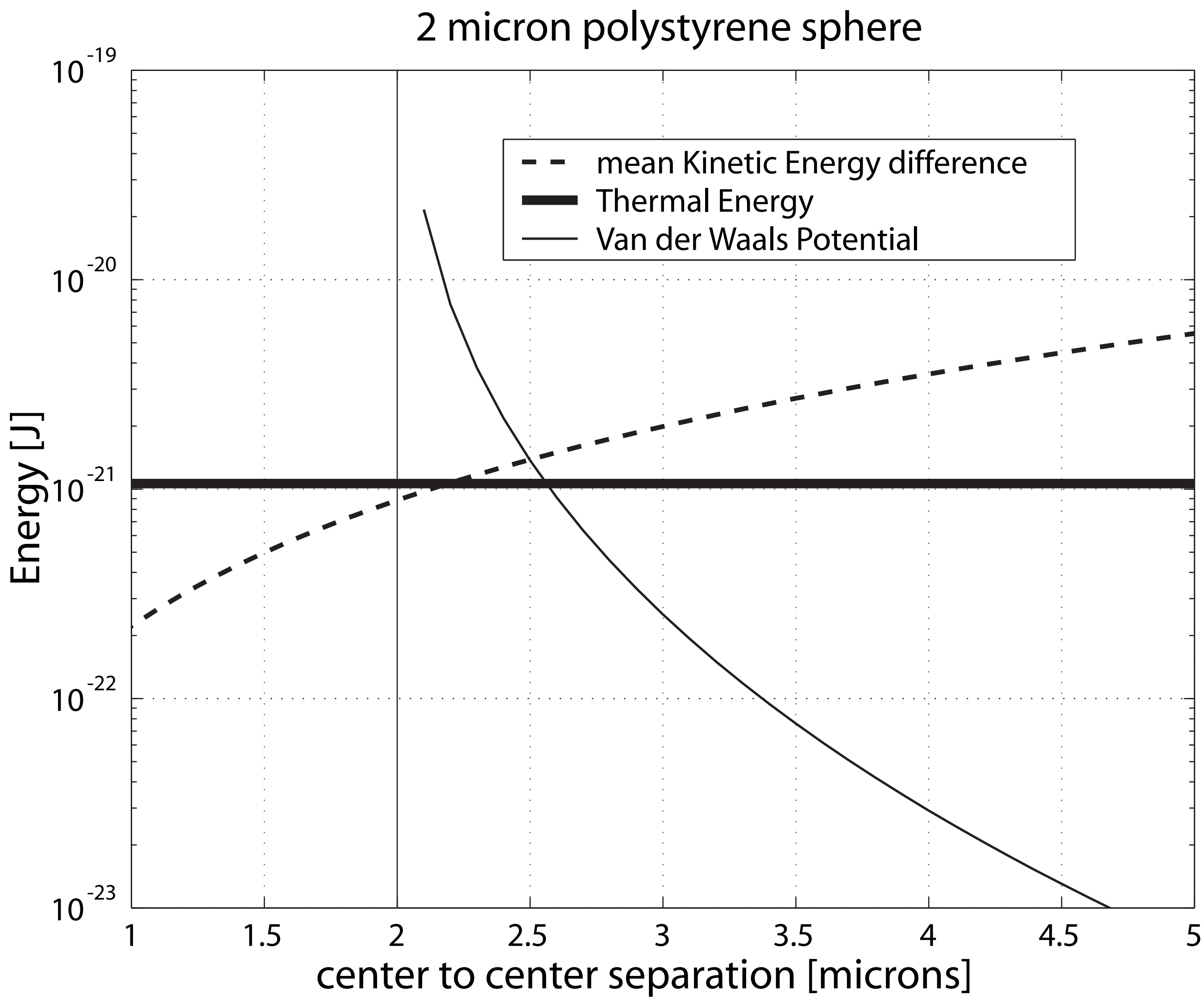
- kinetic energy difference between particles due to turbulence:

$$m_p \Delta u^2 \approx m_p (\frac{l}{\eta} u_f)^2 = m_p l^2 \frac{\epsilon}{\nu}$$

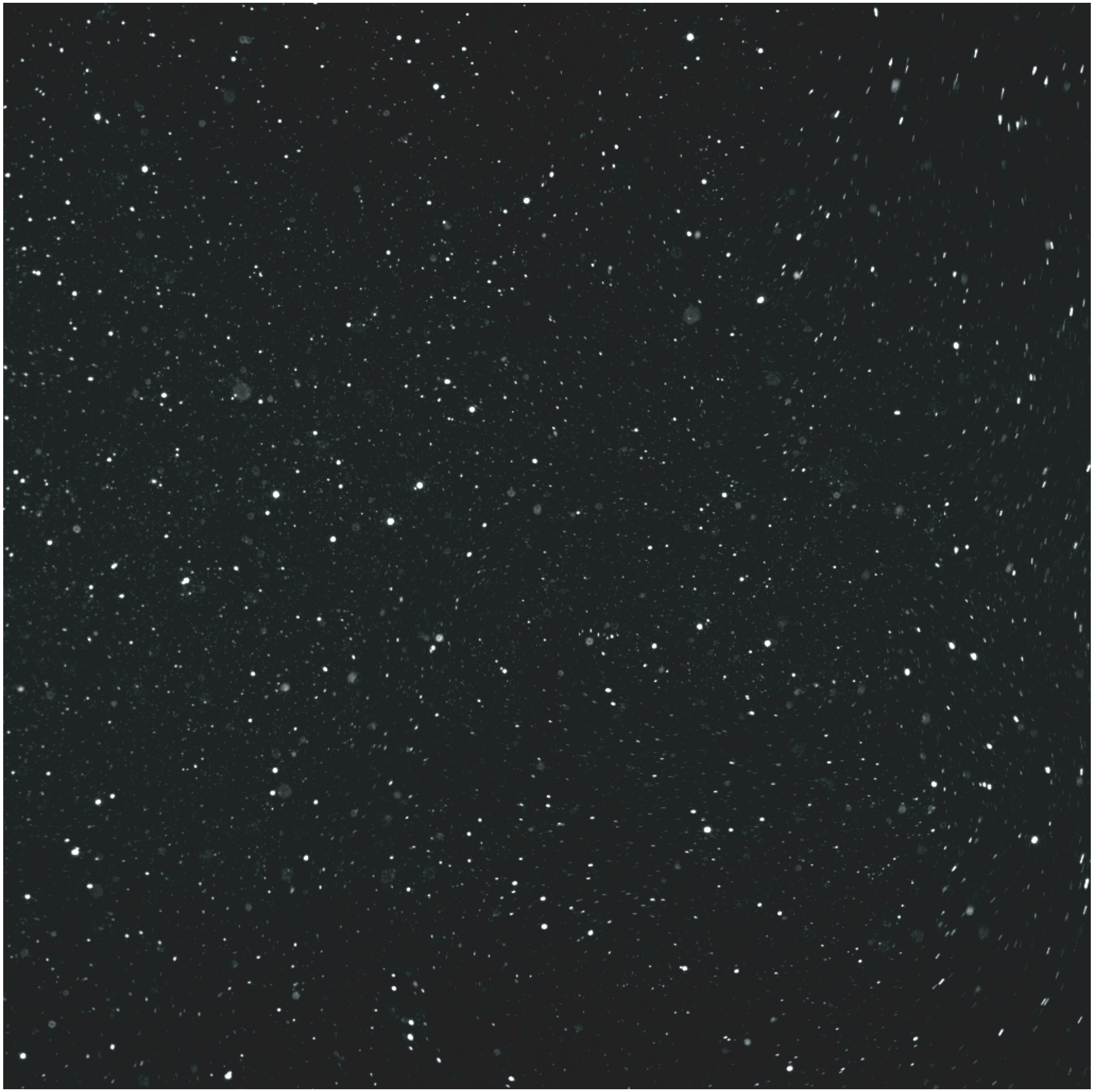
- Van der Waals potential:

$$-\frac{A}{6}(\frac{2R_s^2}{d^2 + 4R_s d} + \frac{2R_s^2}{d^2 + 4R_s d + 4R_s^2} + ln(\frac{d^2 + 4R_s d}{d^2 + 4R_s d + 4R_s^2}))$$

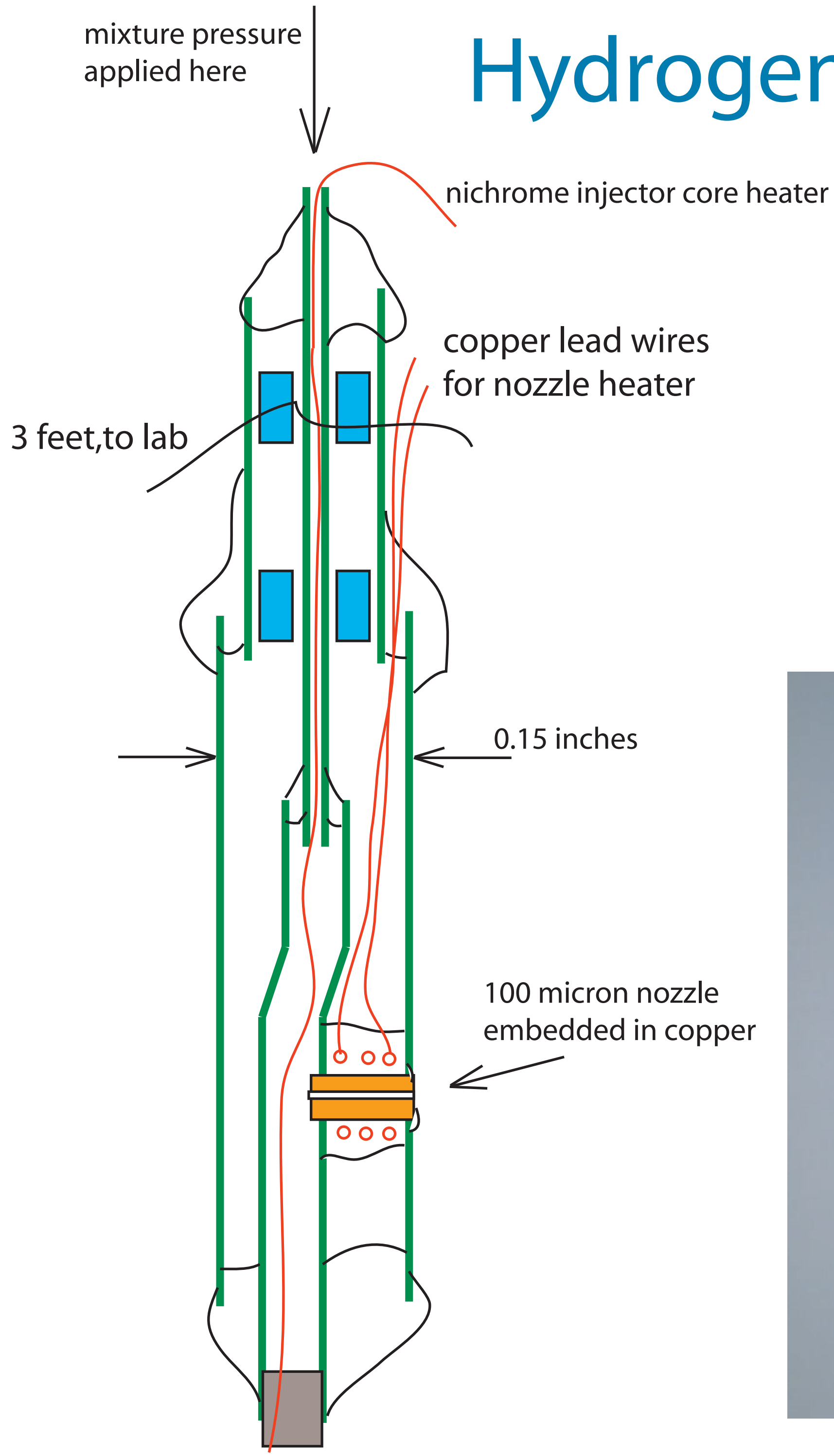
Particle Clumping Example



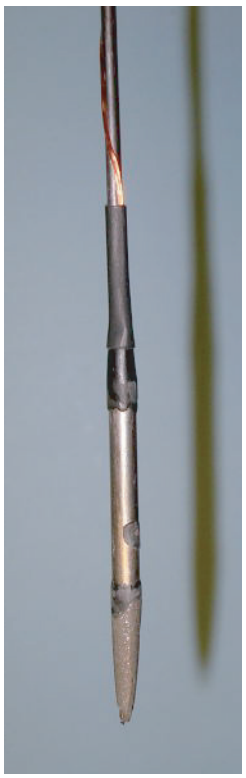
Clumps of 2 micron polystyrene spheres



Hydrogen particle generation

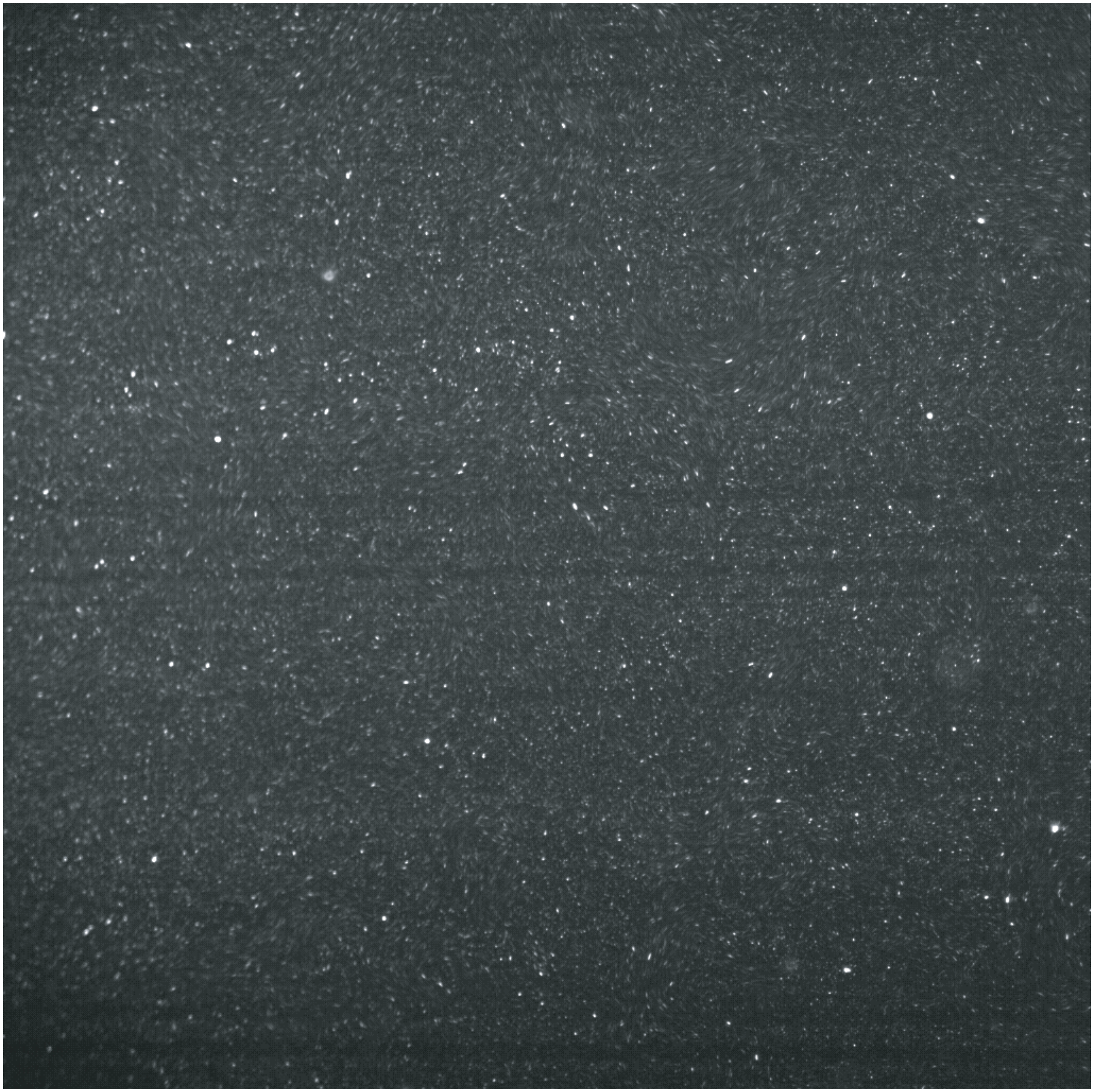


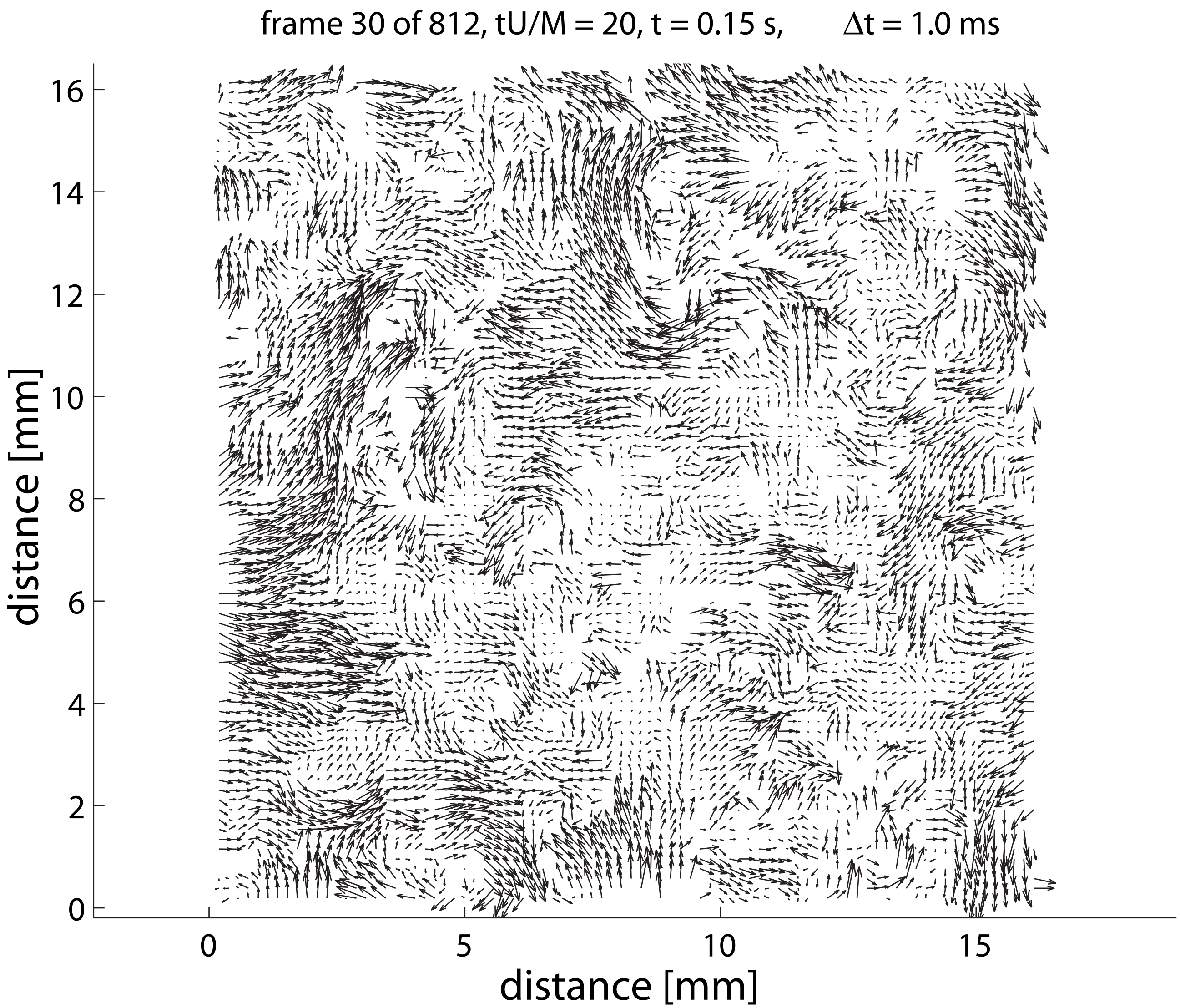
hydrogen diluted with helium:
1:6 hydrogen:helium mixture ratio



Nakano and Murakami (1992)
Boltnev, Frossati, Gordon, Krushinskaya,
Popov, and Usenko (2002)
Zhang, Celik, andVan Sciver (2004)

Hydrogen particles

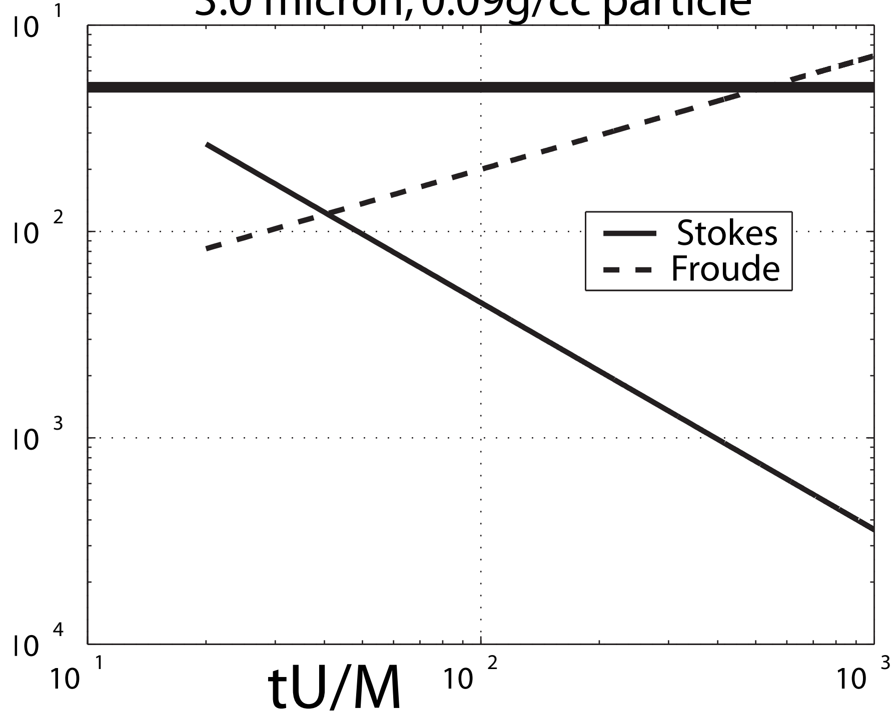




frame 30 of 812, tU/M = 20, t = 0.15 s,   Δt = 1.0 ms
distance [mm]
distance [mm]
0
2
4
6
8
10
12
14
16
0
5
10
15

Hydrogen particle technique

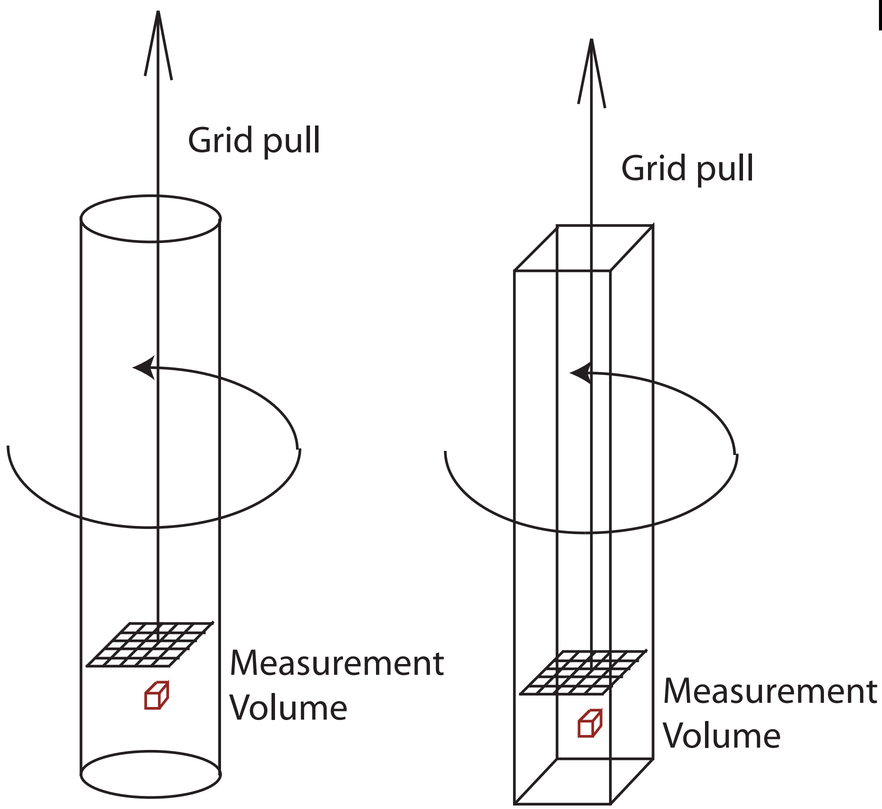
3.0 micron, 0.09g/cc particle

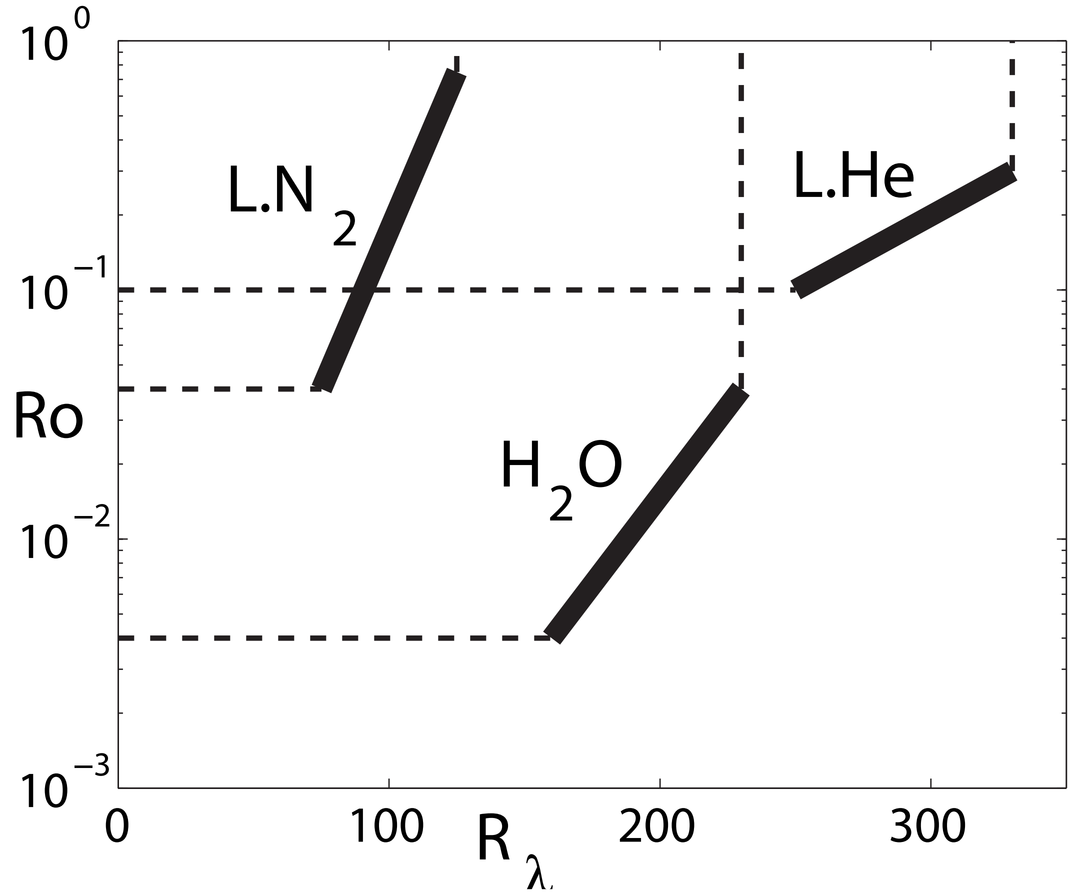


-inject hydrogen particles:
- apply nozzle tube core heat
- apply mixture pressure to nozzle
- mix channel gently with grid
- open nozzle with nozzle heater

-clear clumps from channel with periodic grid mixing
-run experiment
-clear old particles and clumps with periodic mixing

Grid generated turbulence





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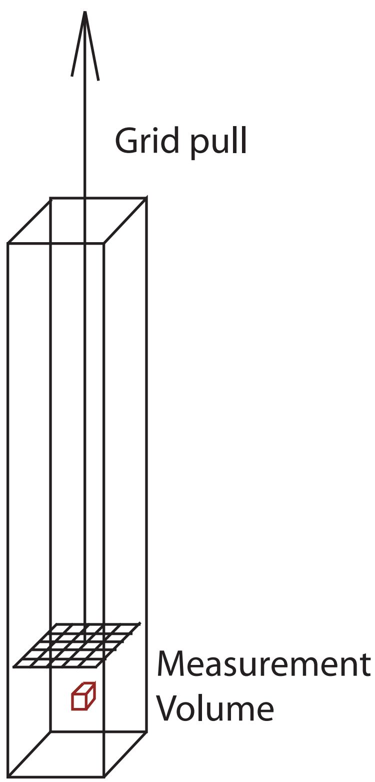
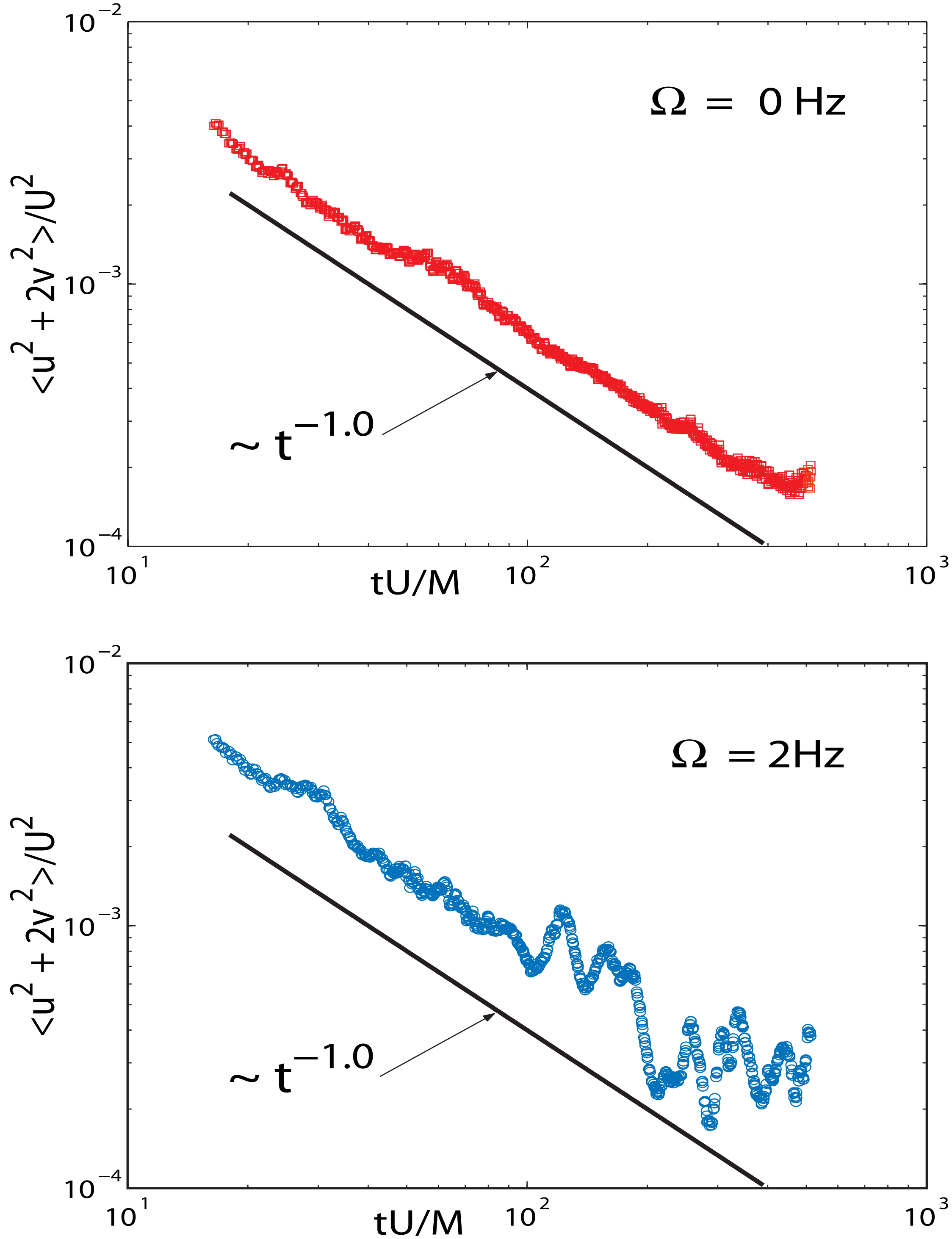
Decay of kinetic energy

Liquid Helium

Grid generated turbulence





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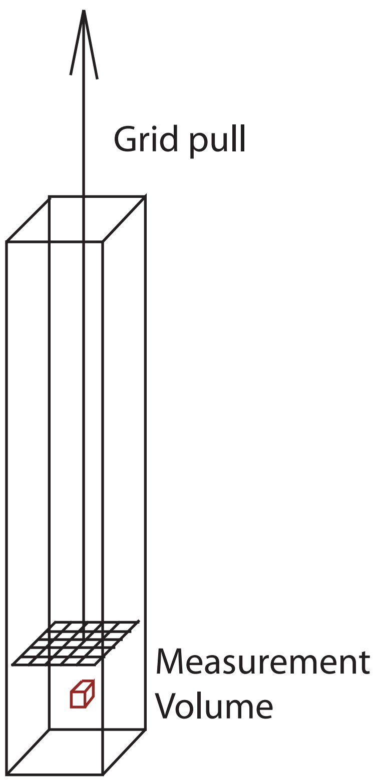

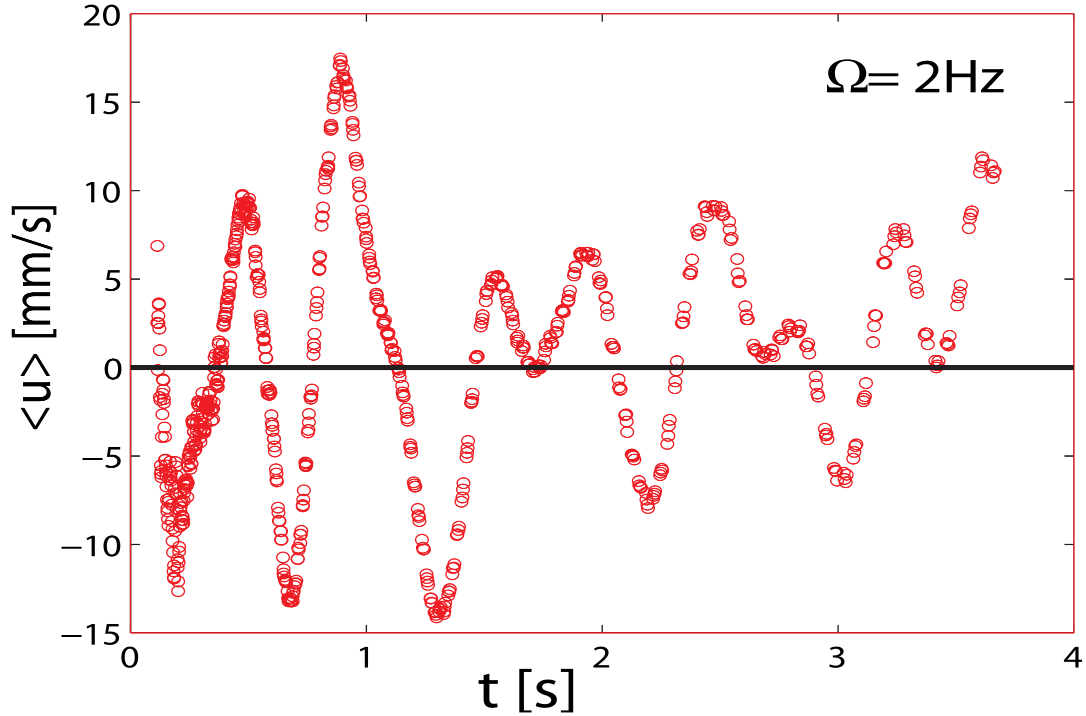

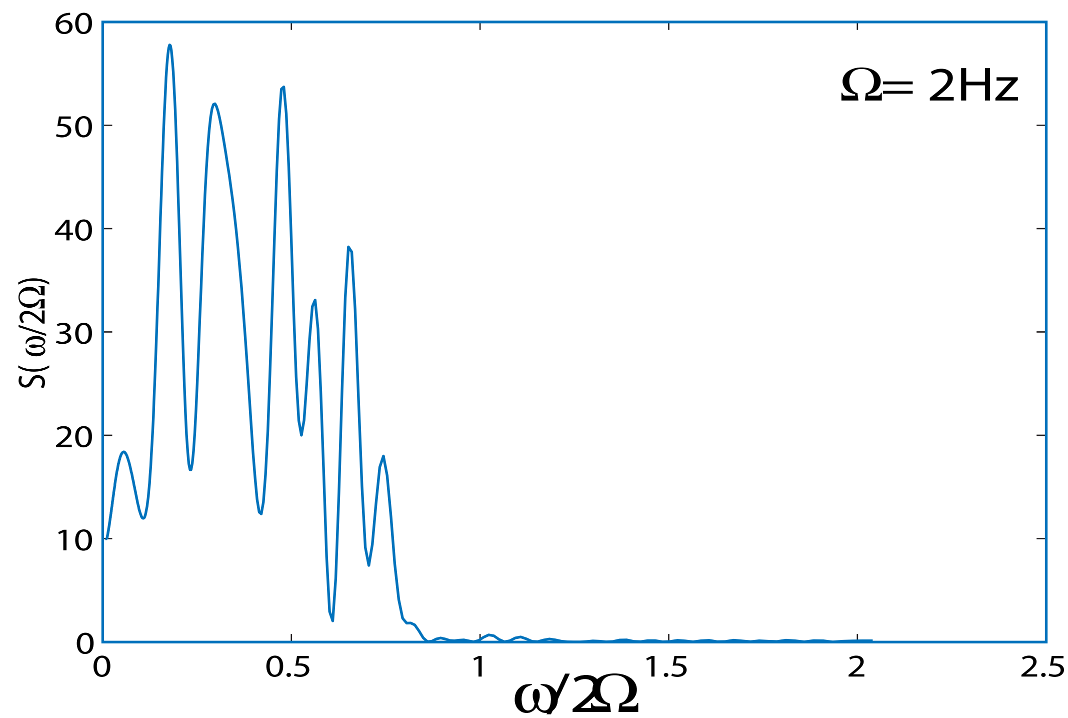

- inertial waves dominate rotating turbulence.
- observation of rotating homogeous turbulence may be impossible.
- have refined a way to observe liquid helium flows using hydrogen particles.