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Slide of the Seminar

How quickly does turbulence die out ?

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ERC Advanced Grant (N. 339032) "NewTURB"
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How quickly does turbulence die out?

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Michael Sinhuber
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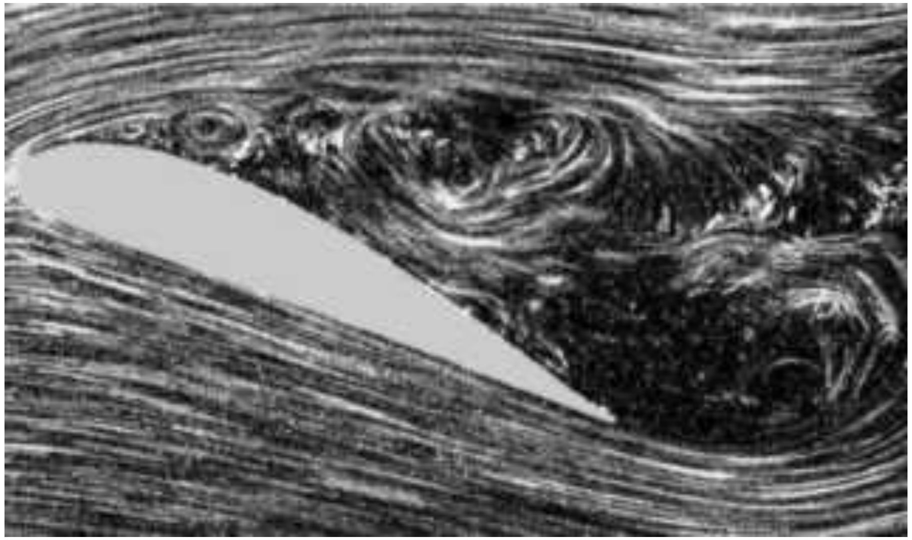
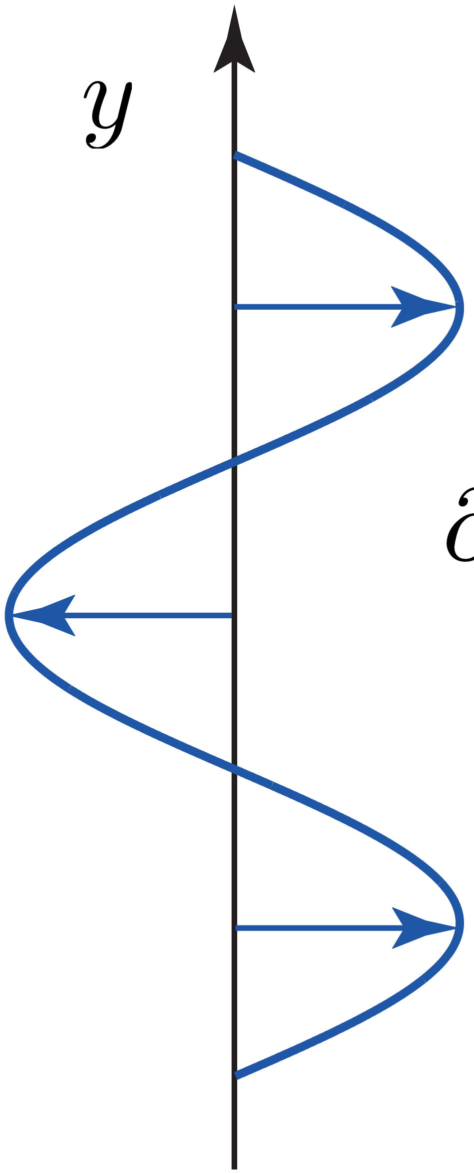


http://en.wikipedia.org/wiki/File:Flow_separation.jpg



$$u_x(\mathbf{x}, t_0) = U_0 \sin\left(\frac{y}{\lambda_y}\right)$$

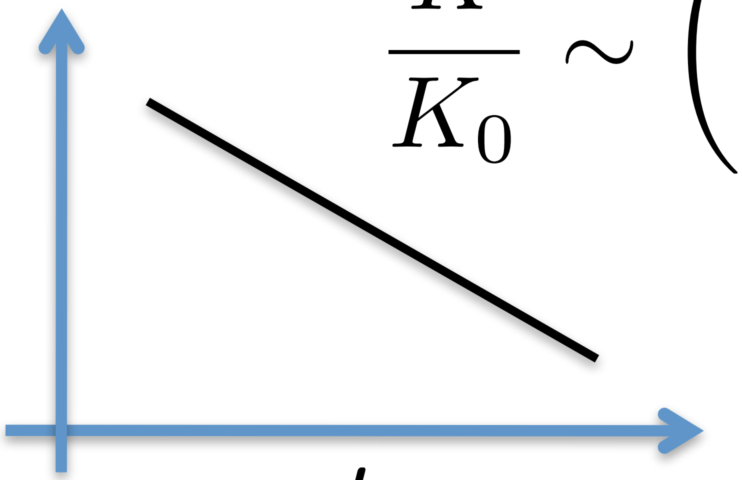
$$\partial_t \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla P + \nu \nabla^2 \mathbf{u}$$

$$\partial_t u_x = -\frac{\nu}{\lambda_y^2} u_x$$

$$u_x = U_0 \, e^{-\nu t/\lambda_y^2} \sin\left(\frac{y}{\lambda_y}\right)$$

Observation:

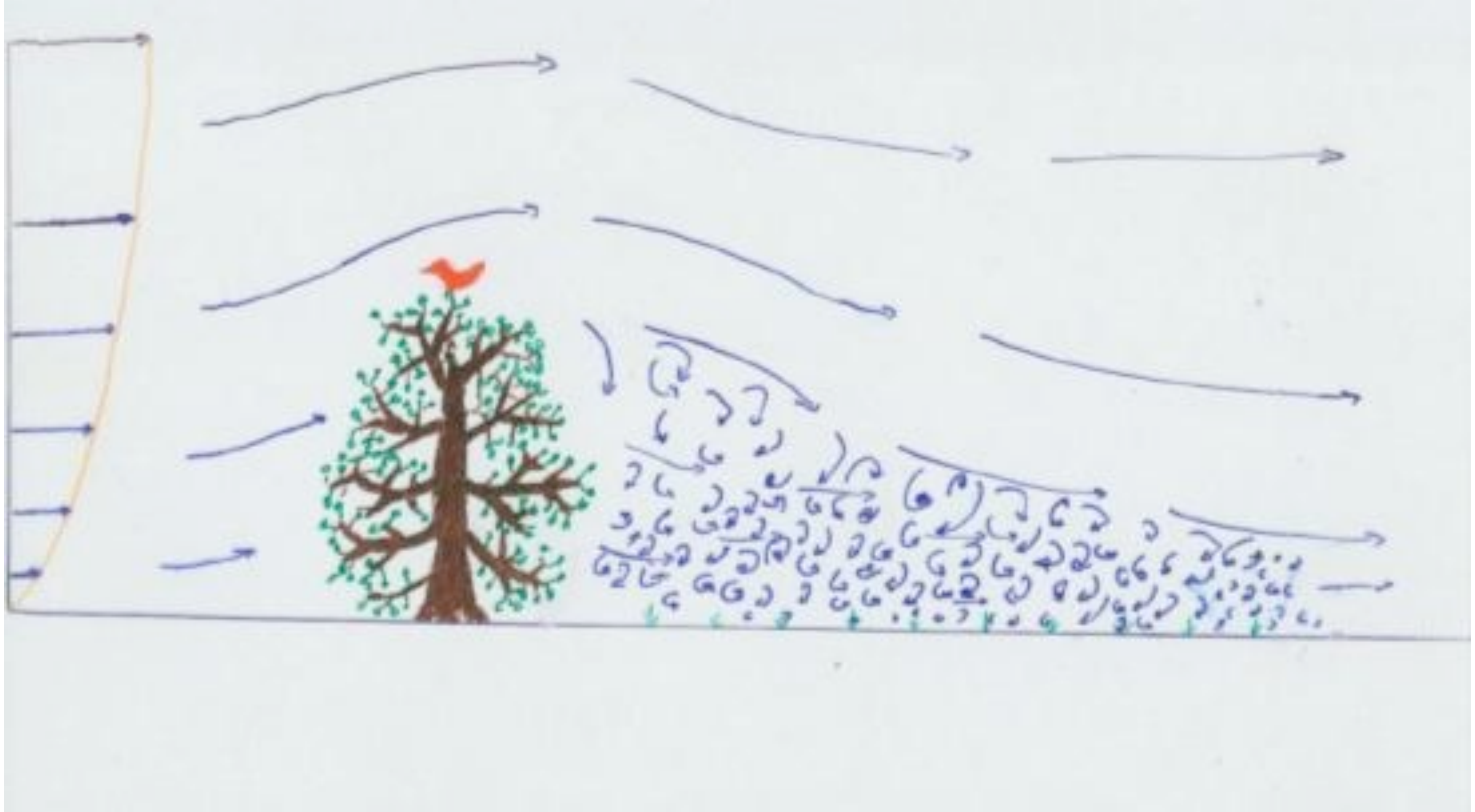
$$\frac{K}{K_0} \sim \left(\frac{tU_0}{\lambda_0} \right)^{-n}$$



$$K \equiv \frac{3}{2} u'^2$$

Von Kármán and Howarth, Kolmogorov, Dryden, Batchelor, Saffman, etc…

http://ict-aeolus.eu/images/horns_rev.jpg http://www.fao.org/docrep/010/ag127e/ag127e08.htm



effect of Reynolds number on:

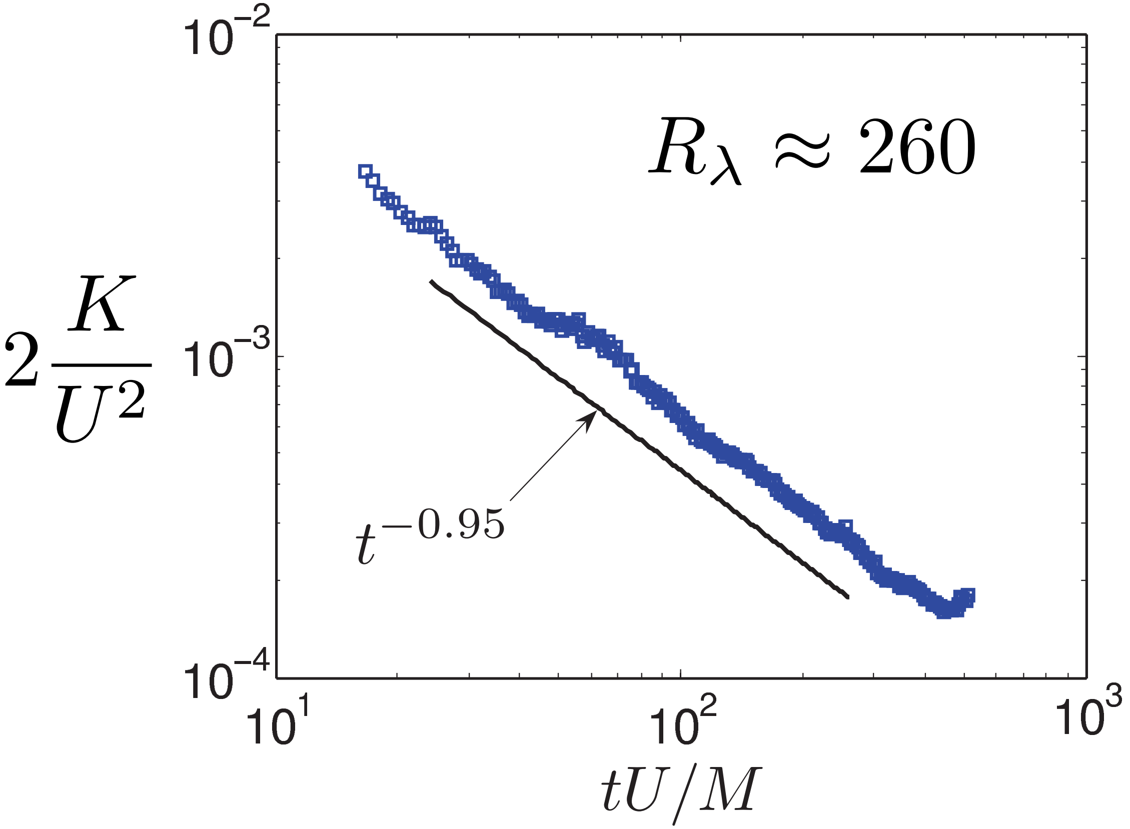
1. Decay of turbulence
2. Scaling in turbulence

RATE OF DECAY

1. $r, t \Rightarrow r/L(t)$
2. $Re = const$

$$\boxed{K \sim t^{-1}}$$

KINETIC ENERGY DECAY
AFTER MIXING LIQUID HELIUM WITH A GRID



Dryden (1941) *Q. Appl. Maths*
Speziale and Bernard (1992) *J. Fluid Mech.*

Bewley et al. (2007) *Phys. Fluids*

RATE OF DECAY

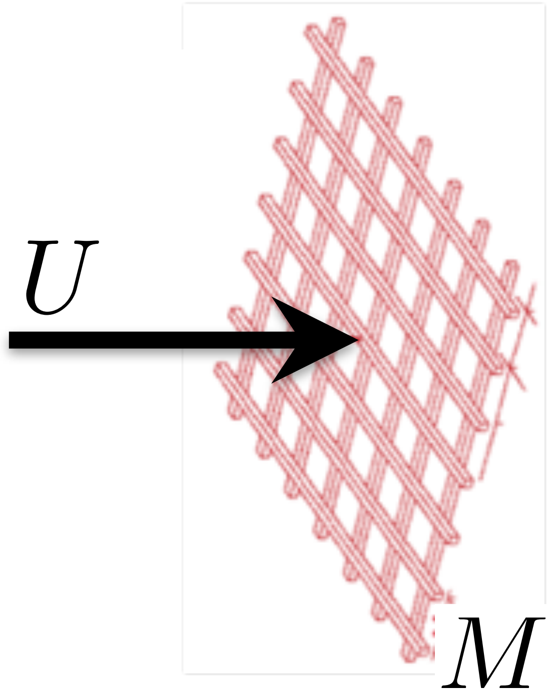
$$f(r,t) = \frac{\langle\, u(\vec{x},t)\, u(\vec{x}+\vec{r},t)\,\rangle}{u'^2}$$

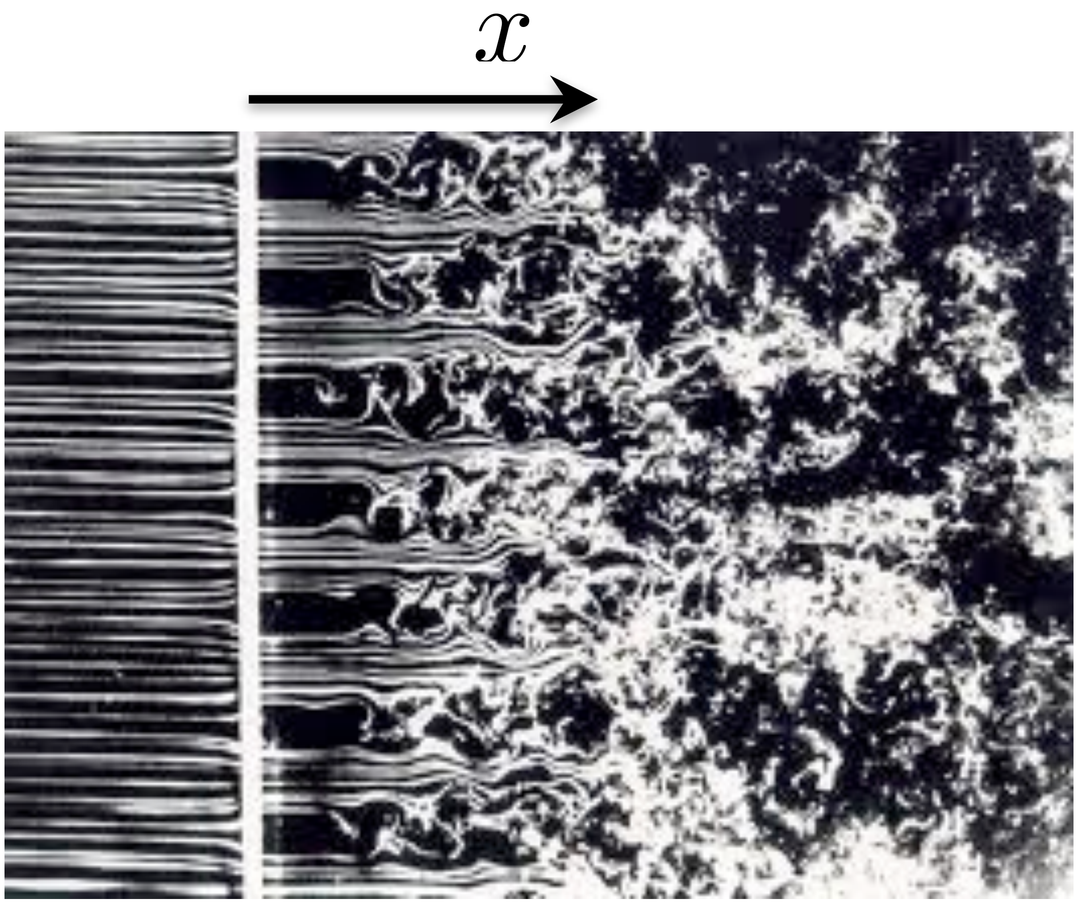
$f(r,t) \sim r^{-2}$ ⇔ $K \sim t^{-6/5}$ (Saffman)

$f(r,t) \sim r^{-6}$ ⇔ $K \sim t^{-10/7}$ (Kolmogorov)

e.g. Davidson (2011) *Phys. Fluids*

GRID TURBULENCE





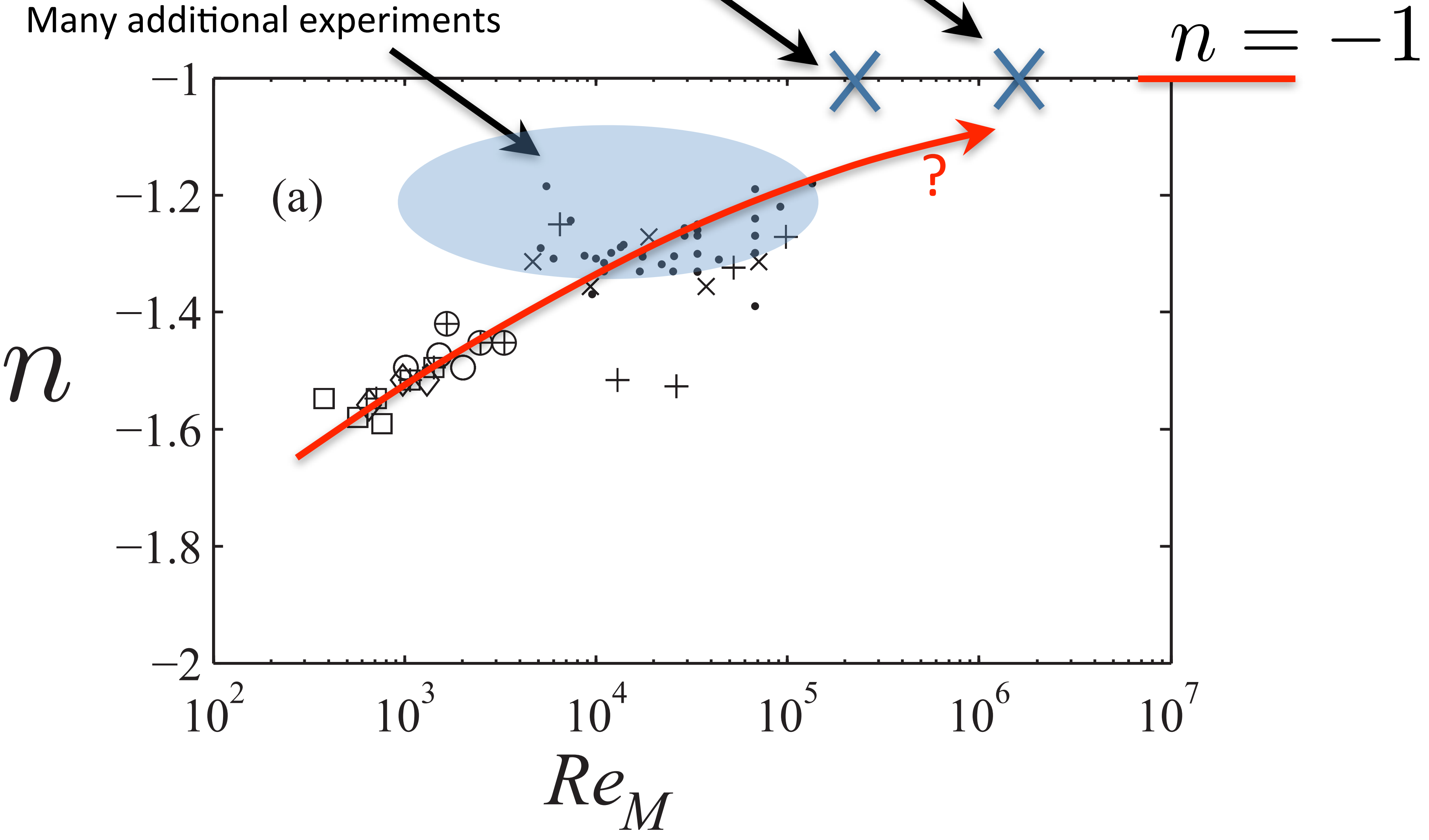
$$Re_M = \frac{UM}{\nu}$$

http://fdrc.iit.edu/research/images/GridTurbulenceRe2.jpg

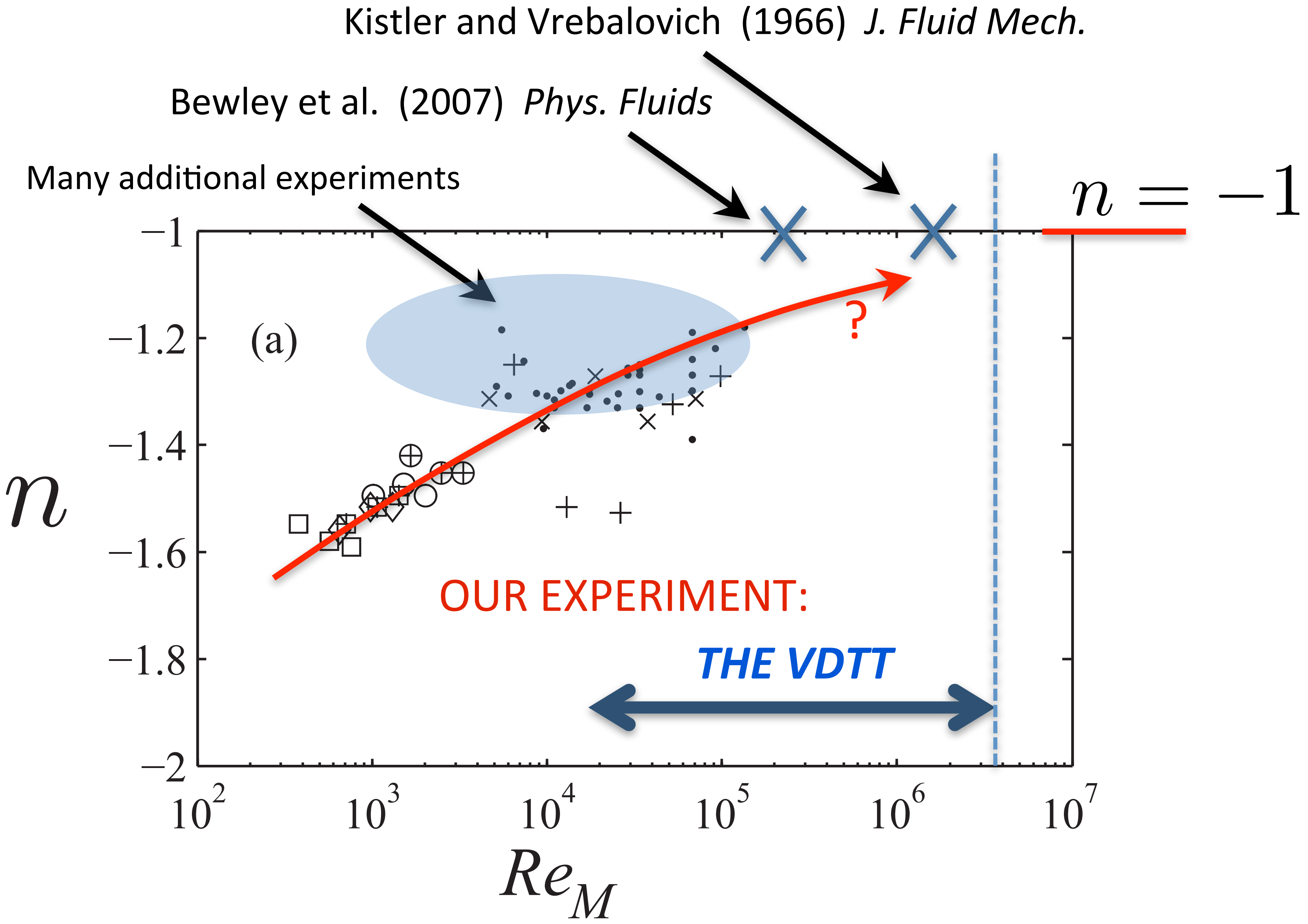
Kistler and Vrebalovich (1966) *J. Fluid Mech.*

Bewley et al. (2007) *Phys. Fluids*

Many additional experiments



Kurian and Fransson (2009) *Fluid Dyn. Res.*



Kistler and Vrebalovich (1966) *J. Fluid Mech.*

Bewley et al. (2007) *Phys. Fluids*

Many additional experiments

OUR EXPERIMENT:

THE VDTT

Kurian and Fransson (2009) *Fluid Dyn. Res.*

THE VARIABLE DENSITY TURBULENCE TUNNEL (VDTT)

Bewley, Nobach, Sinhuber, Xu, Bodenschatz (2014) *under review.*

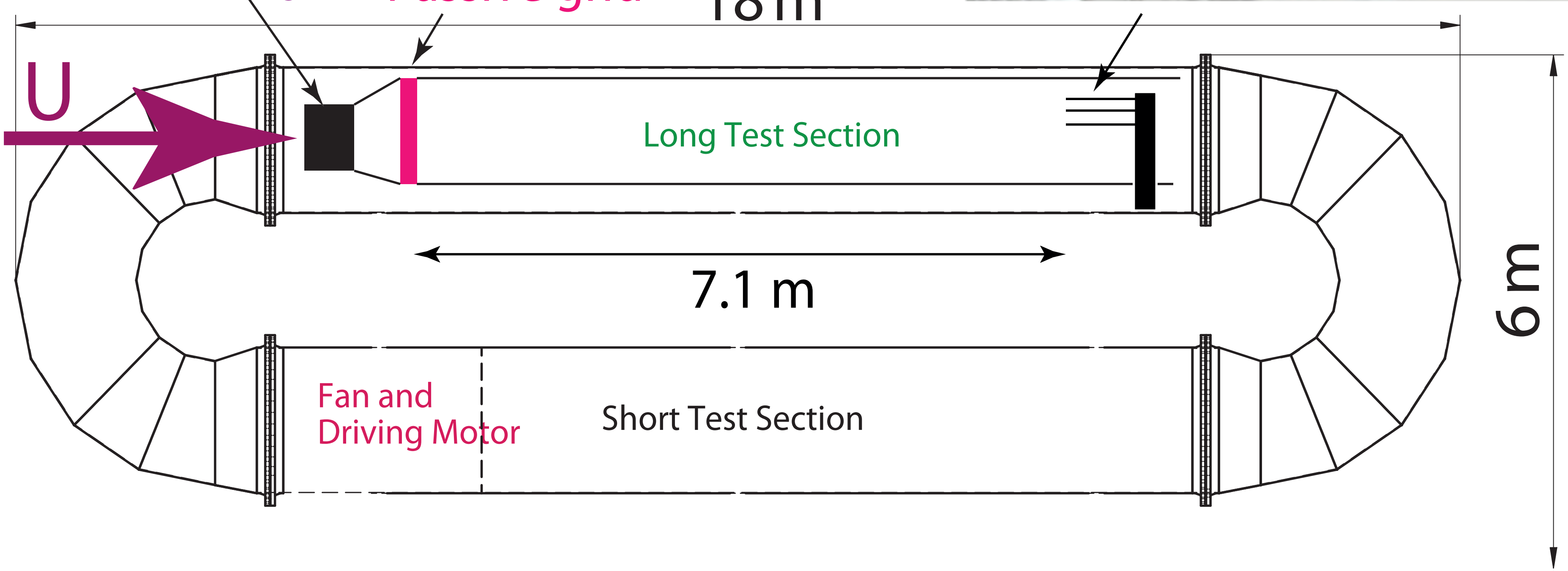
$$Re = \frac{\rho U L}{\mu}$$

Air and **Sulfur Hexafluoride** gas (SF_6)

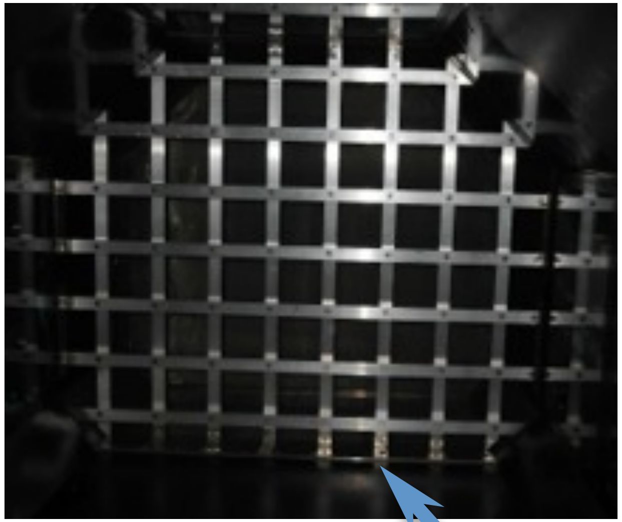
$$U \leq 5\, m/s$$

$$\eta \geq 20\, \mu m$$

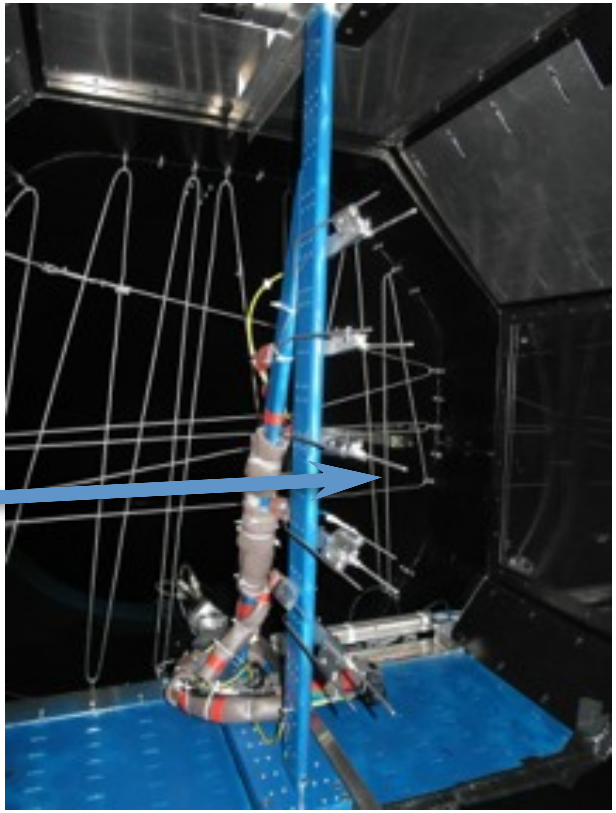
$$\tau_\eta \geq 2\, ms$$

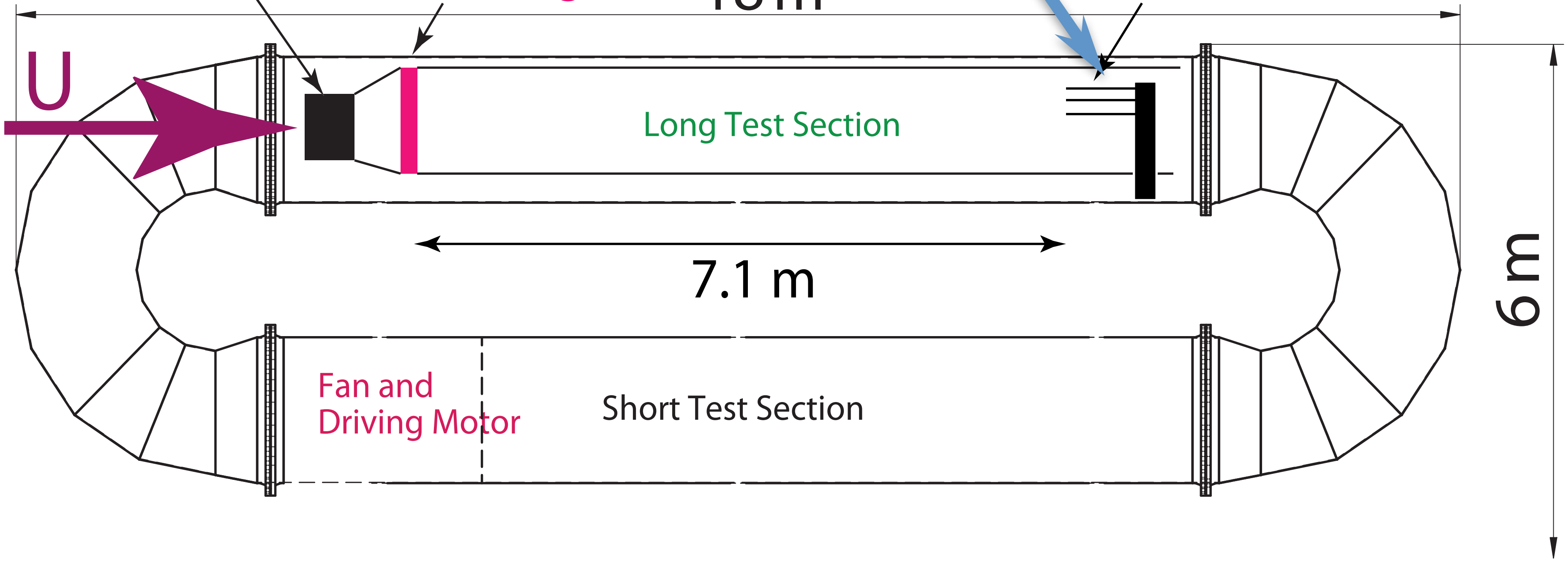


M = 180 mm

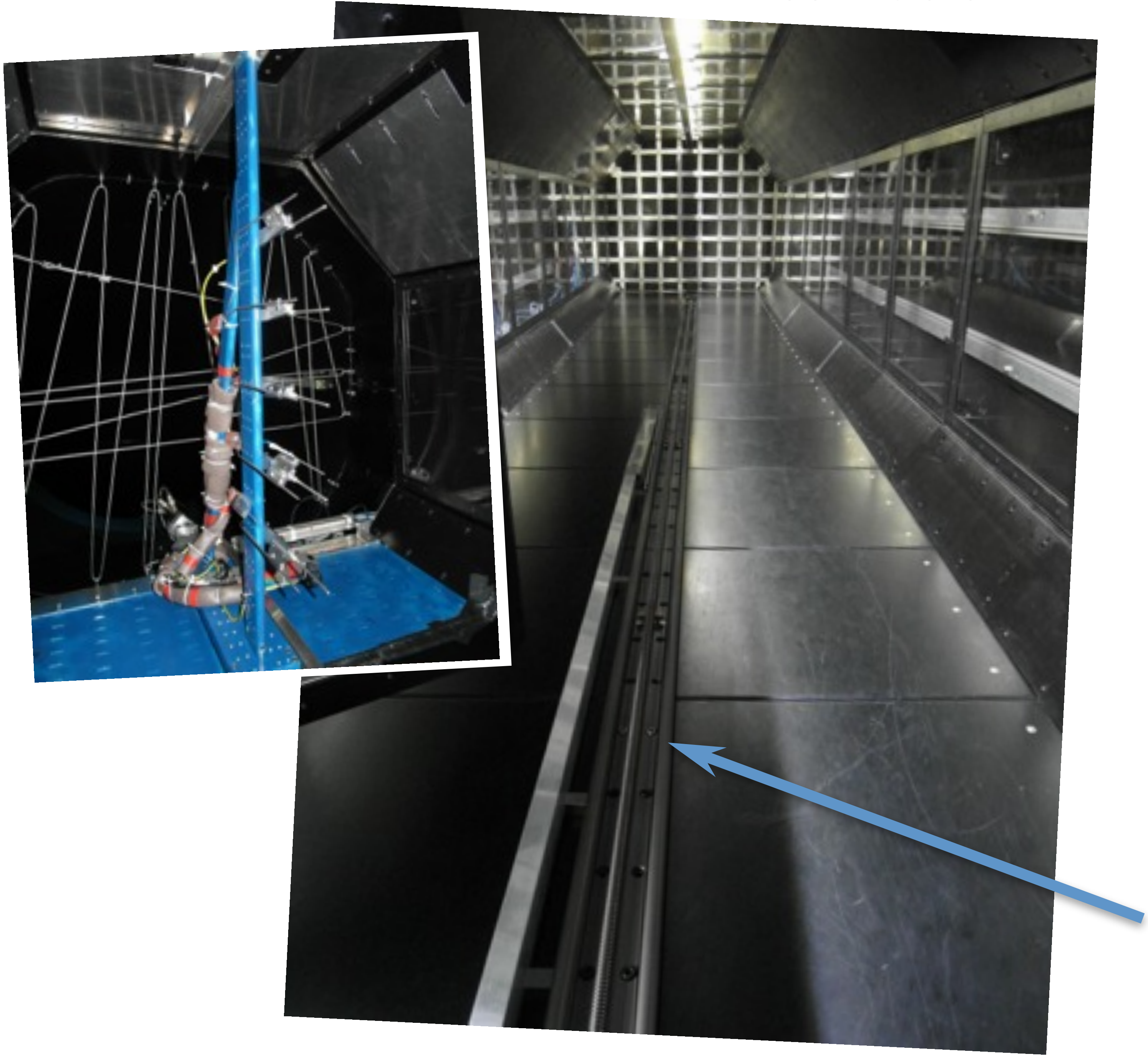


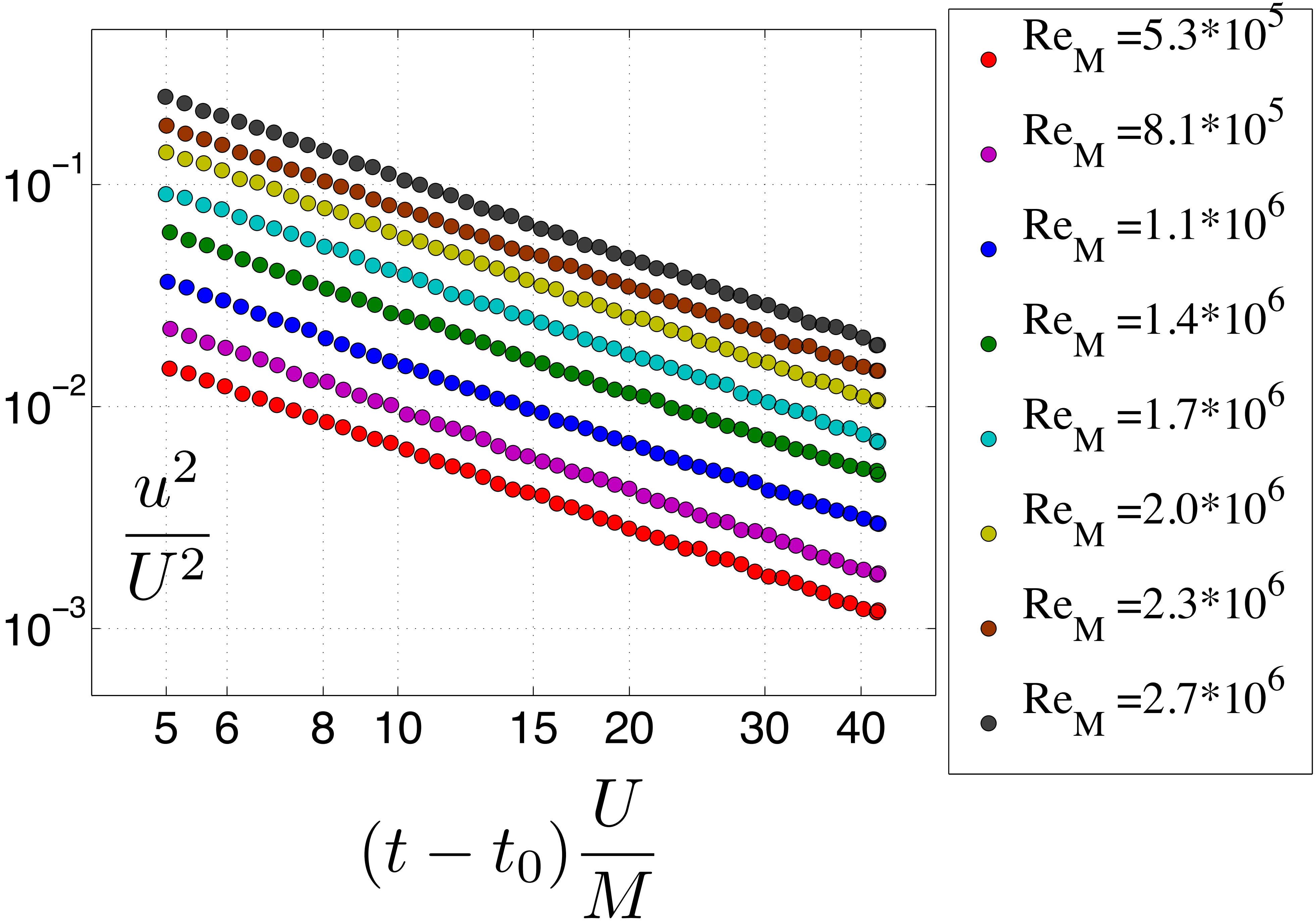
HOT WIRE
PROBES
ON TRAVERSE



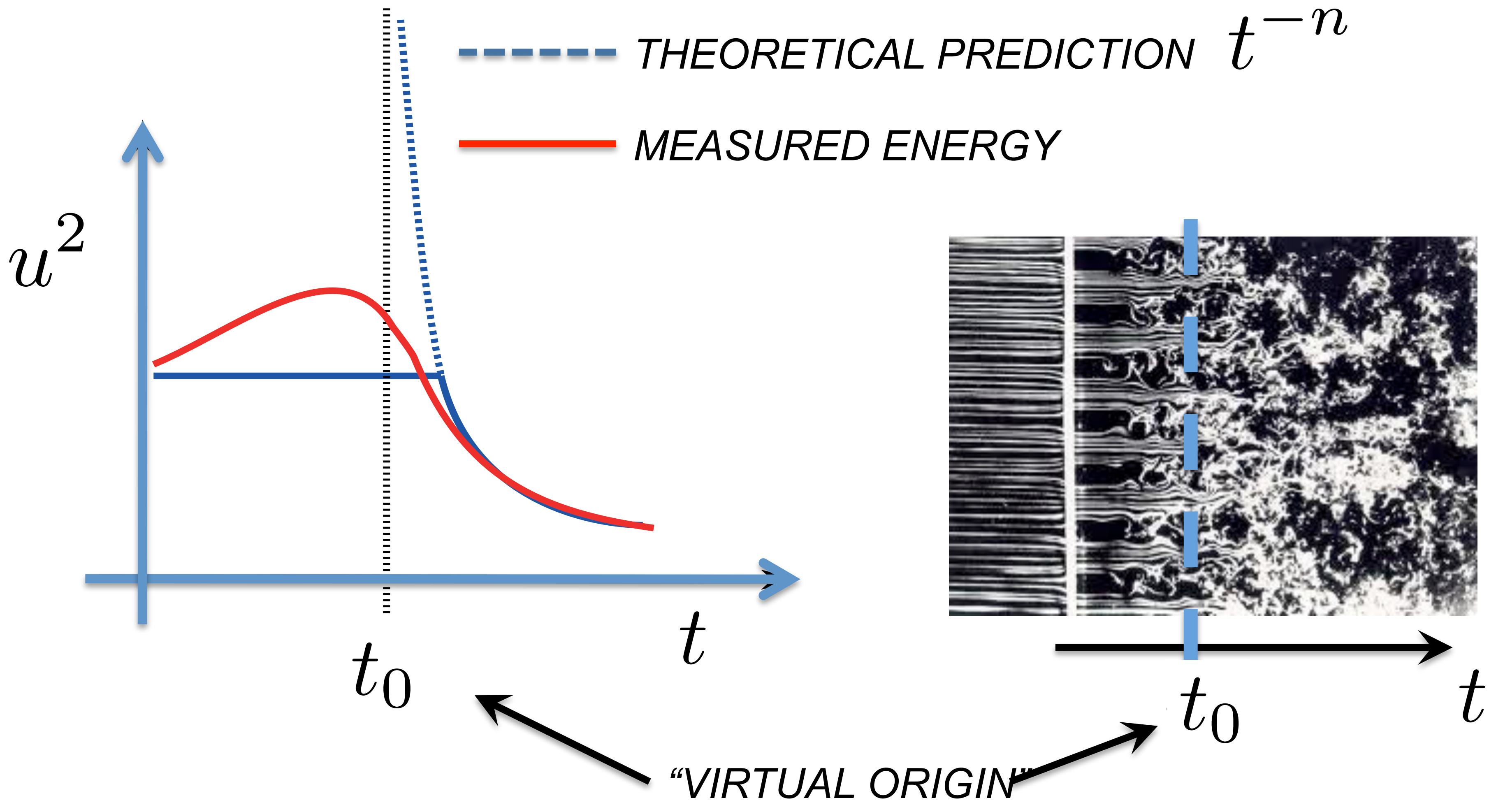


LOOKING UPSTREAM




$\mathrm{Re}_M = 5.3*10^5$
$\mathrm{Re}_M = 8.1*10^5$
$\mathrm{Re}_M = 1.1*10^6$
$\mathrm{Re}_M = 1.4*10^6$
$\mathrm{Re}_M = 1.7*10^6$
$\mathrm{Re}_M = 2.0*10^6$
$\mathrm{Re}_M = 2.3*10^6$
$\mathrm{Re}_M = 2.7*10^6$
10^{-1}
10^{-2}
10^{-3}
$\frac{u^2}{U^2}$
5
6
8
10
15
20
30
40
$(t - t_0)\frac{U}{M}$

TO DETERMINE THE DECAY RATE IN AN EXPERIMENT:



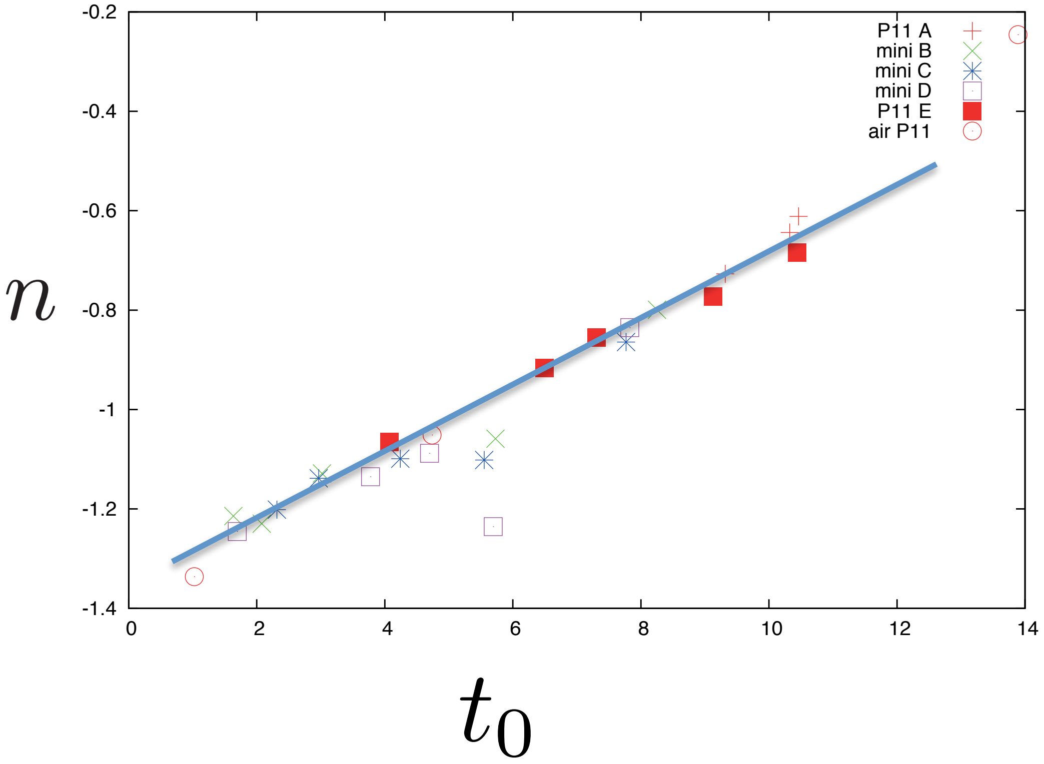
THEORETICAL PREDICTION t^{-n}

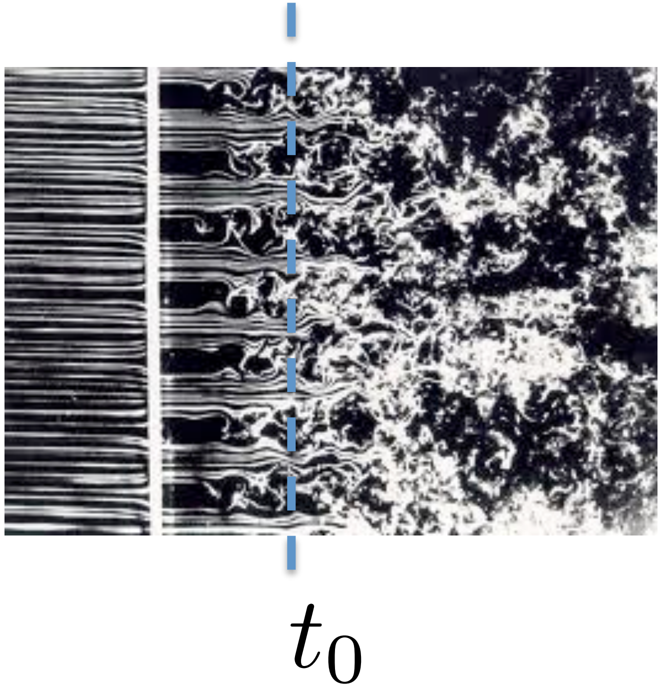
MEASURED ENERGY

“VIRTUAL ORIGIN”

least squares fit to: $u^2 = A(t - t_0)^{-n}$

$$u^2 = A(t - t_0)^{-n}$$





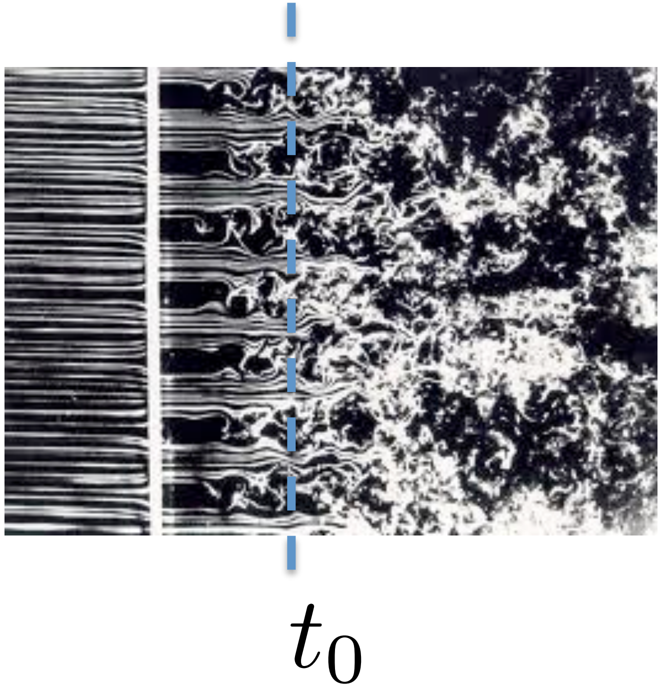
e.g. Mohammed and LaRue (1990) *J. Fluid Mech.*

$$u^2 = A(t - t_0)^{-n}$$

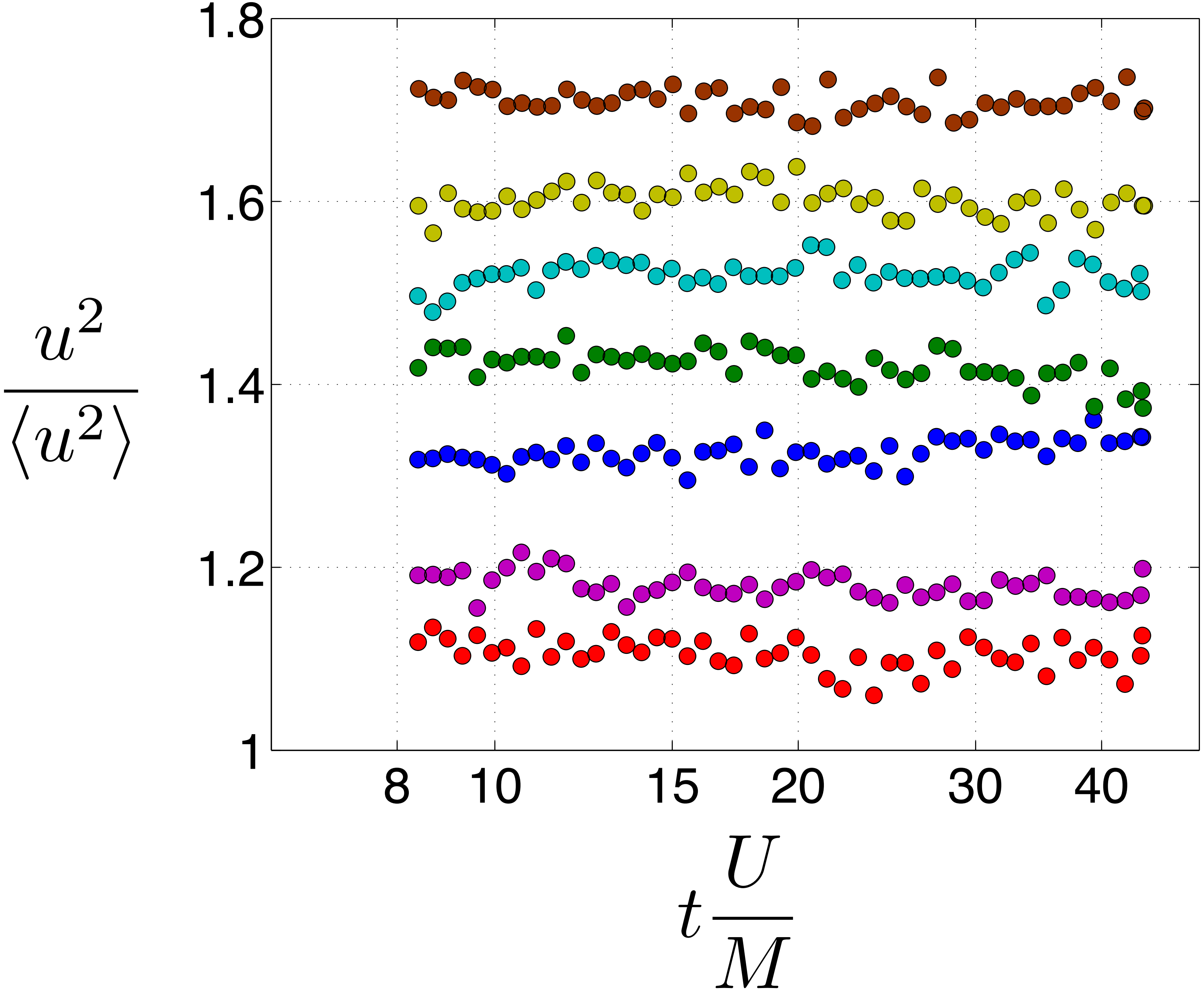
IDEA:

$$u_i^2 \sim (u_0^2)^{n_i/n_0}$$

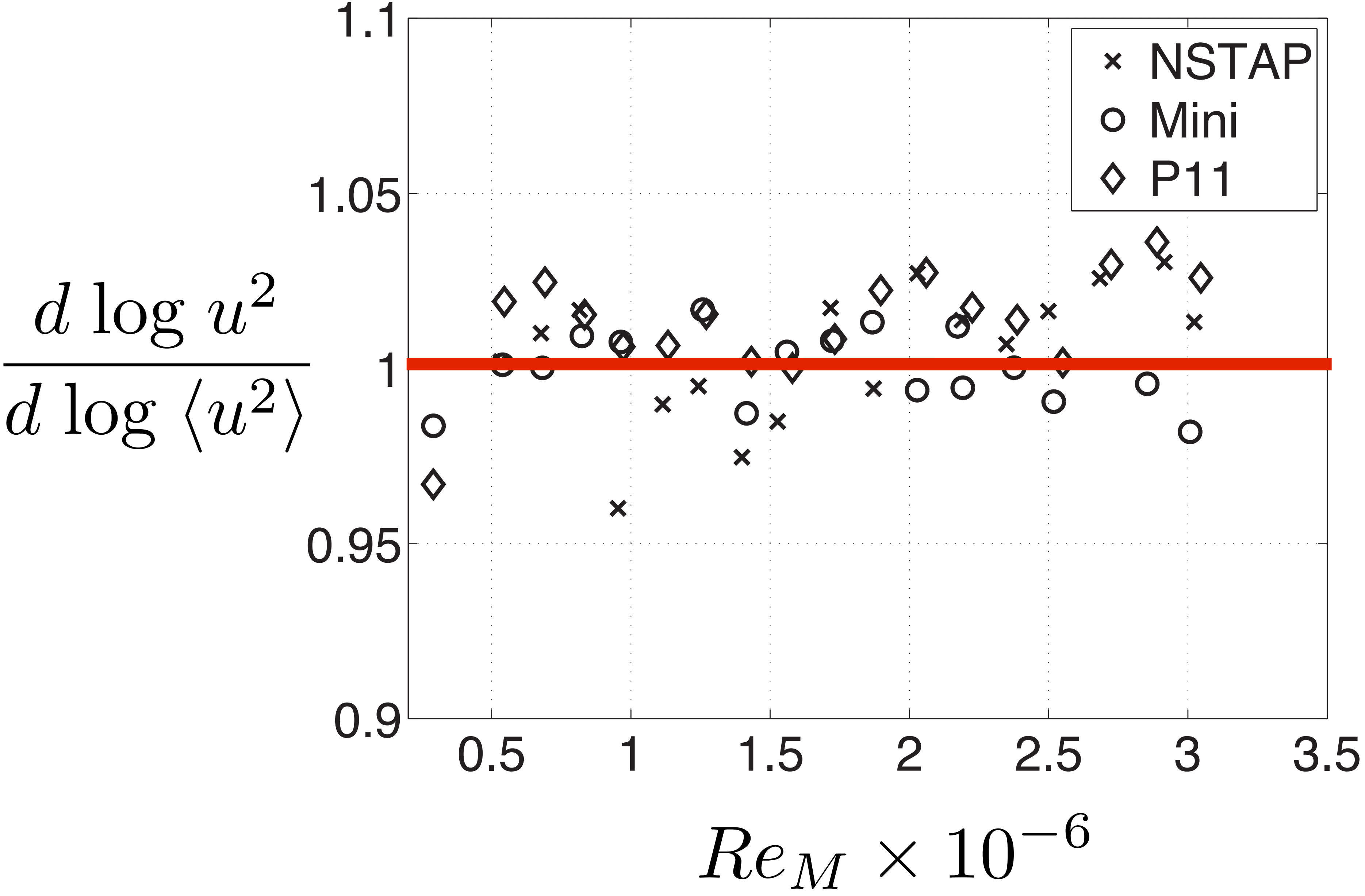
Eliminates dependence on t_0



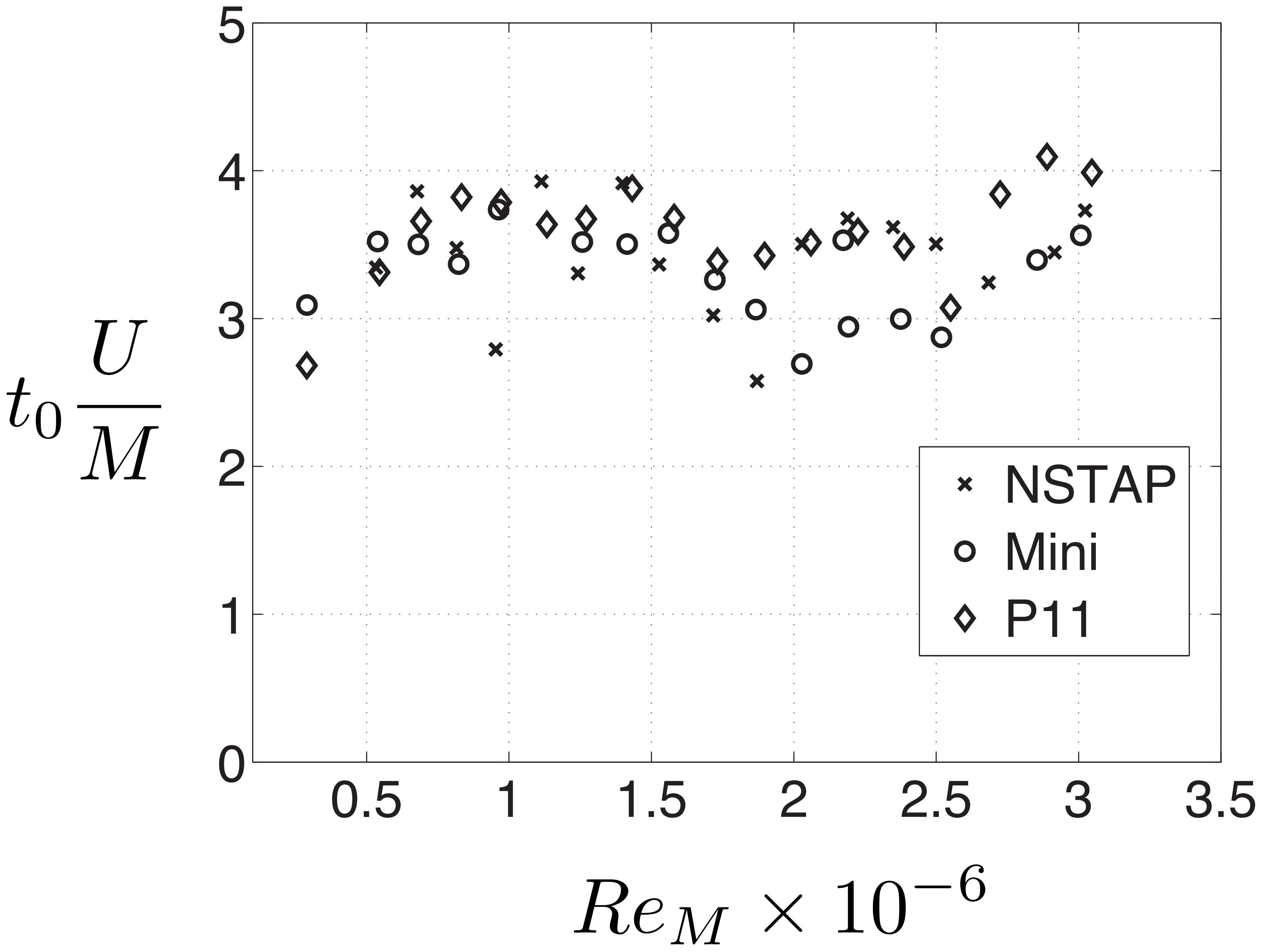
Valid if variation in virtual origin with Reynolds number is small.


$\frac{u^2}{\langle u^2 \rangle}$
1.8
1.6
1.4
1.2
1
8
10
15
20
30
40
$t\,\frac{U}{M}$

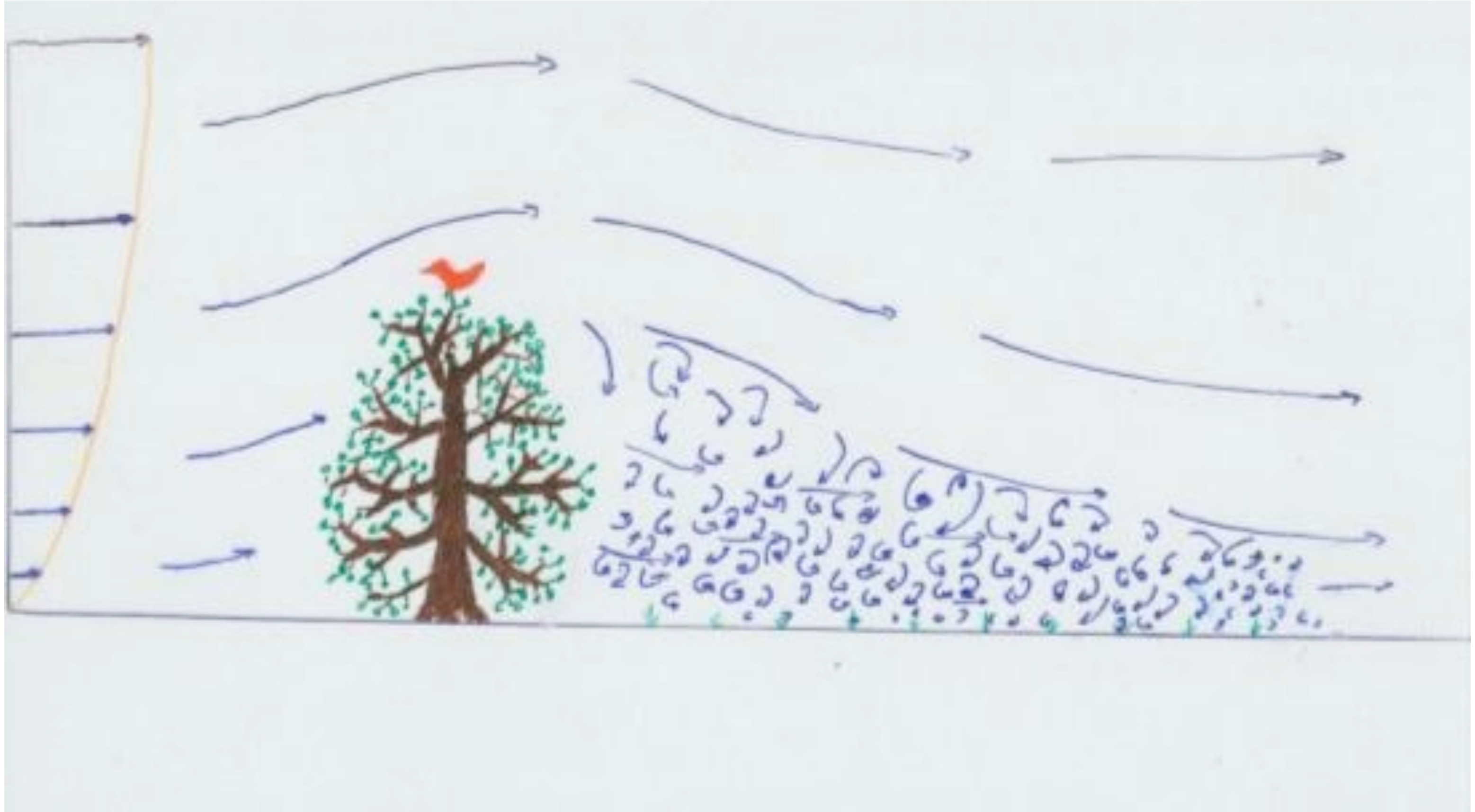
RELATIVE DECAY EXPONENT n_{rel}



VIRTUAL ORIGIN



SCALING



http://www.fao.org/docrep/010/ag127e/ag127e08.htm

$$\boxed{\begin{array}{l} \delta v = v(x+r,t) - v(x,t) \\[2em] S_n(r) = \langle \delta v^n \rangle \end{array}}$$

SCALING

$$\frac{3}{r^3}\int_0^r \frac{\partial}{\partial t} S_2(s,t)\, ds + S_3 = -\frac{4}{5}\epsilon r + 6\nu \frac{\partial S_2}{\partial r}$$

$$\epsilon = \nu \left\langle \frac{\delta u_i}{\delta x_j} \frac{\delta u_i}{\delta x_j} \right\rangle$$

for *locally* isotropic turbulence
and sufficiently
high Reynolds number:

$$\frac{3}{r^3}\int_0^r \frac{\partial}{\partial t} S_2(s,t)\,ds + \boxed{S_3 = -\frac{4}{5}\epsilon r} + 6\nu \frac{\partial S_2}{\partial r}$$

Kolmogorov (1941) Dokl. Akad. Nauk. SSSR...

by extension $S_n = C_n (\epsilon r)^{n/3}$

when $\epsilon(\vec{x}, t) = \langle \epsilon \rangle$

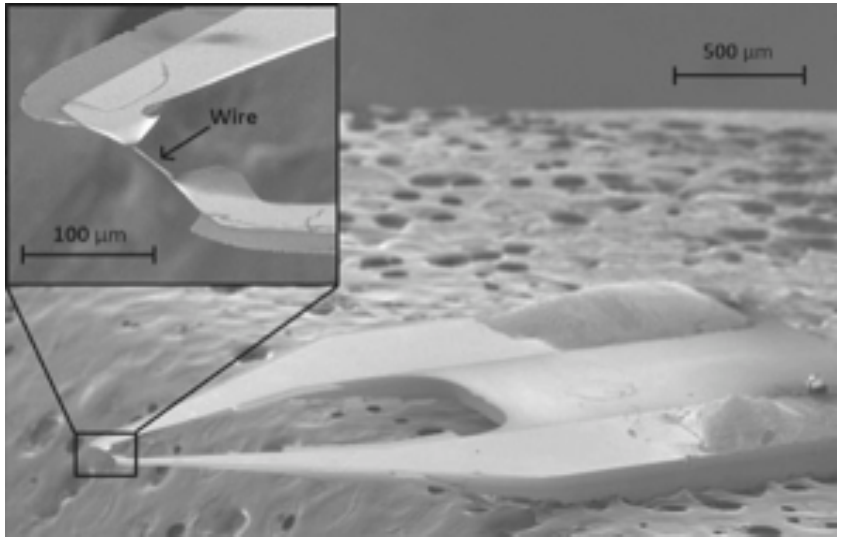
THE VDTT

~18 meters

Margit Vallikivi
Marcus Hultmark
Lex Smits

Princeton University

THE NSTAP



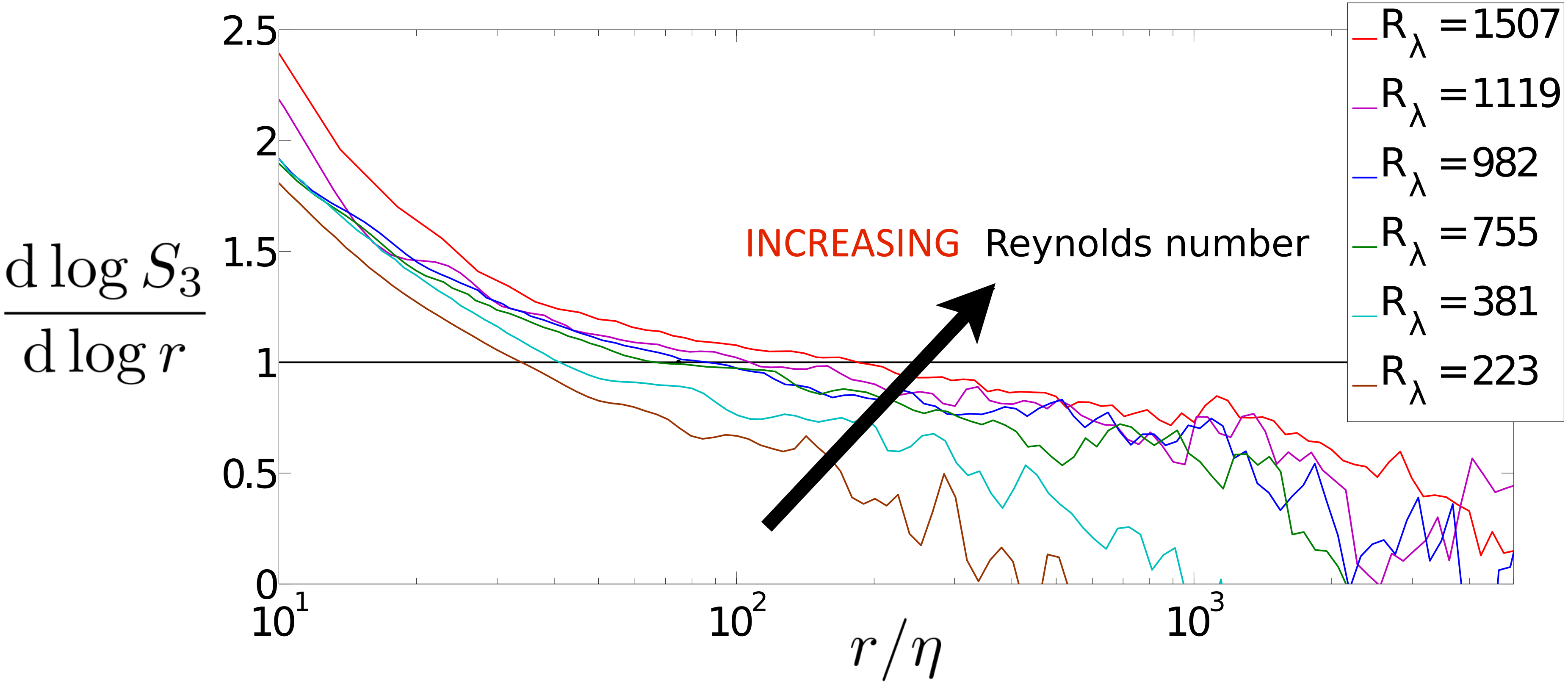
30 – 60 micron

HOT WIRE PROBES

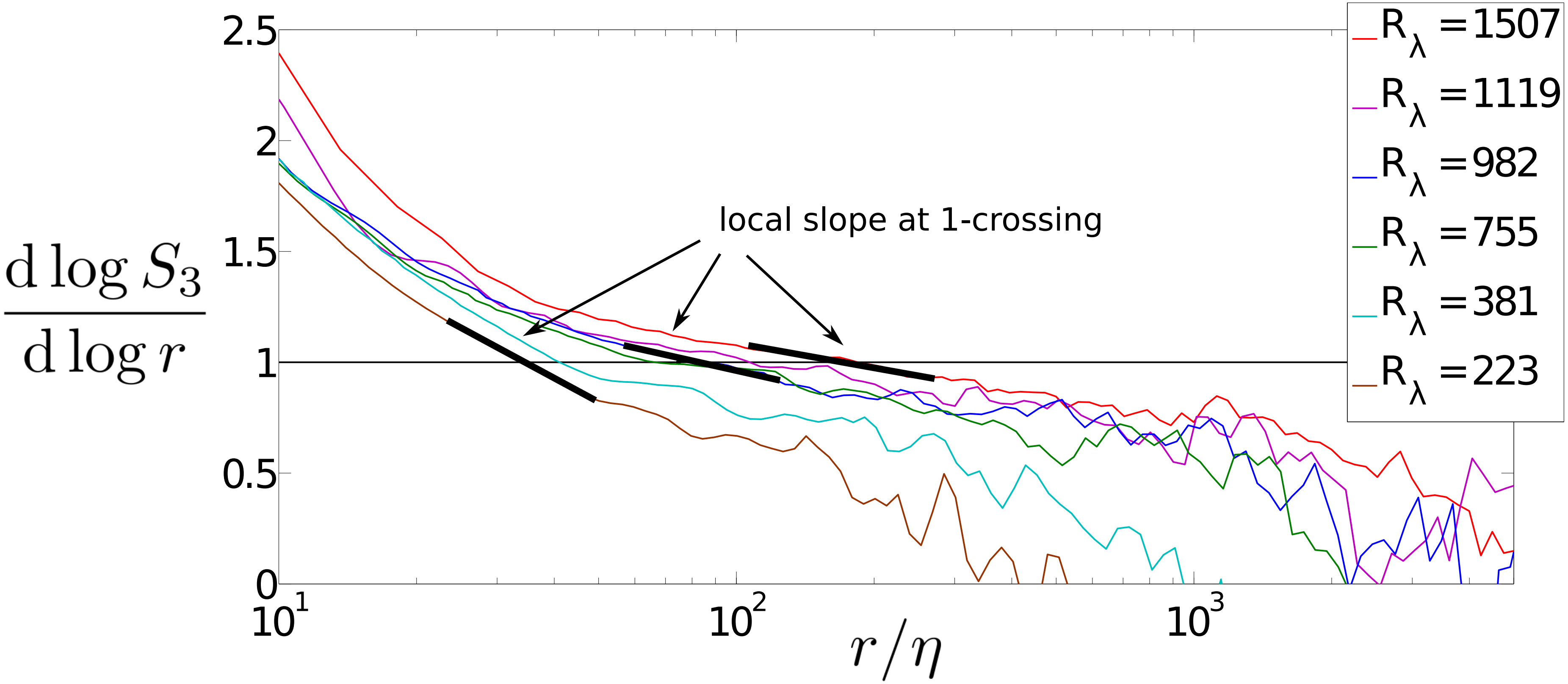
Vallikivi et al. (2011) *Expt. Fluids*

let $S_3 = Cr^{\zeta_3}$ => $\dfrac{d\log S_3}{d\log r} = \zeta_3$

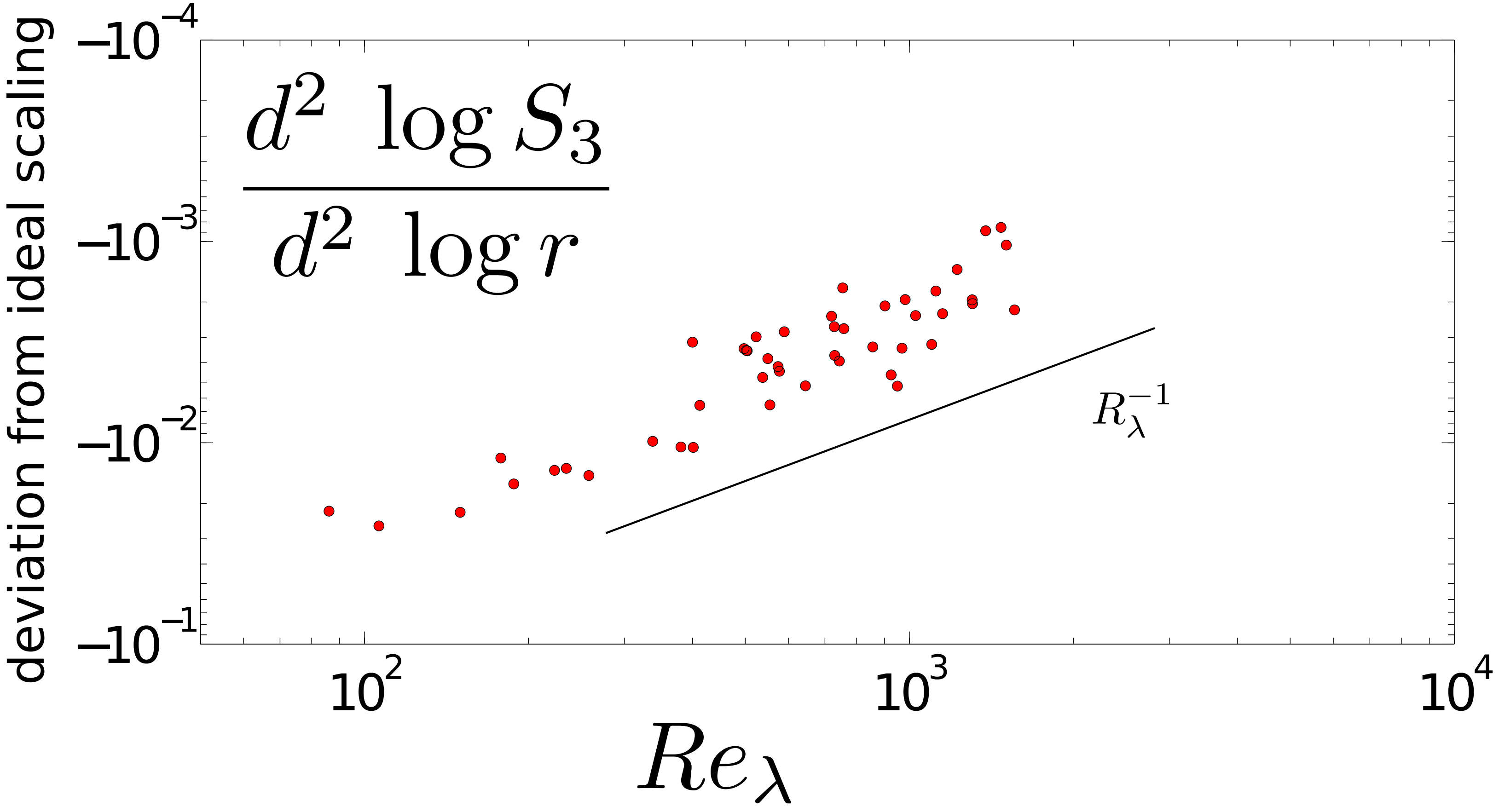
scaling would appear as a range of constant logarithmic slope



let $S_3 = Cr^{\zeta_3}$ => $\dfrac{d\log S_3}{d\log r} = \zeta_3$



When do we first get a range of constant slope?



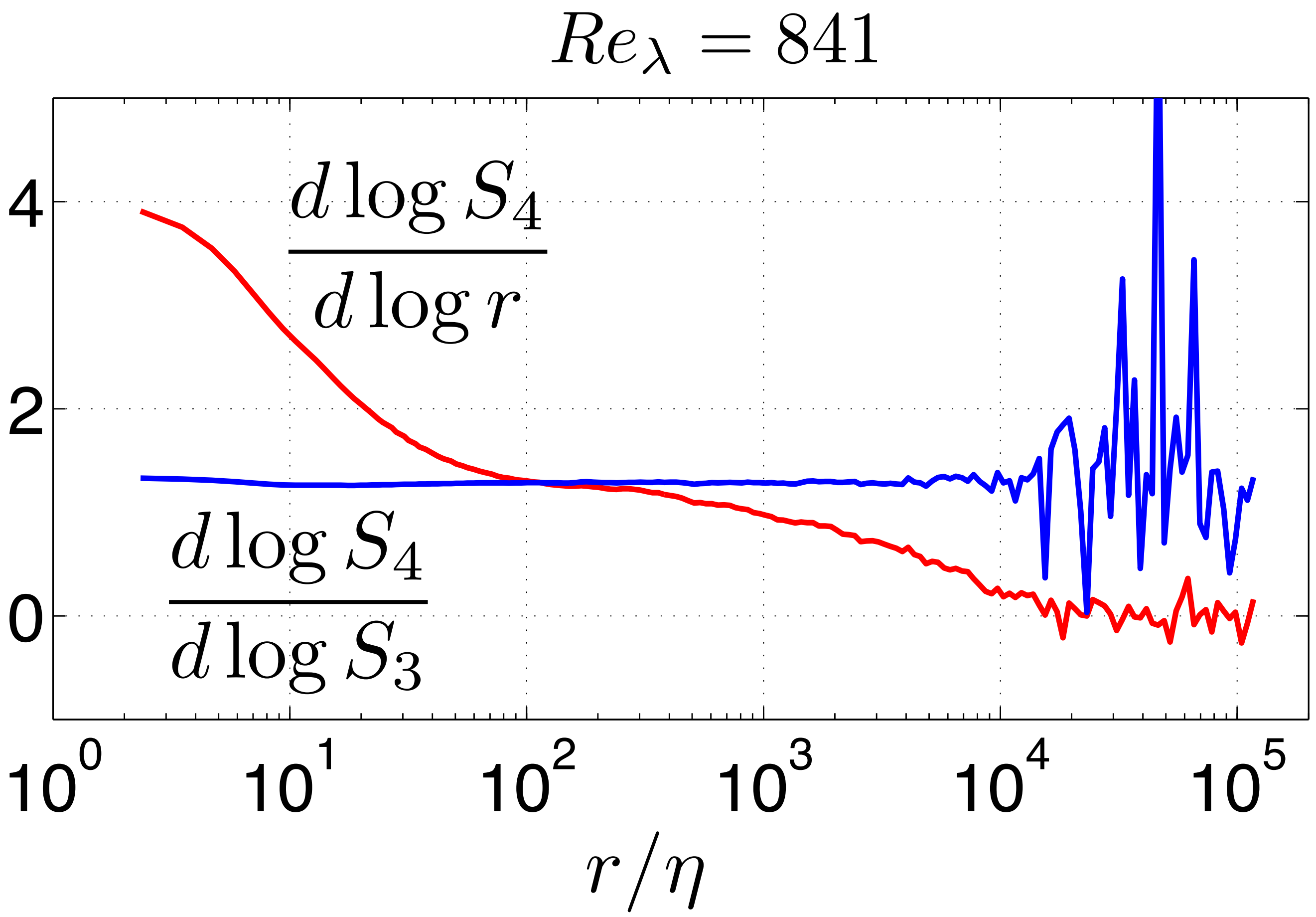
Qian (1999) *Phys. Rev. E*

Lundgren (2002) *Phys. Fluids*

EXTENDED SELF-SIMILARITY

Benzi et al. (1993) *PRE*

$$S_n \sim S_3^{\zeta_n} \qquad \zeta_n = \frac{d\,log\,S_n}{d\,log\,S_3}$$

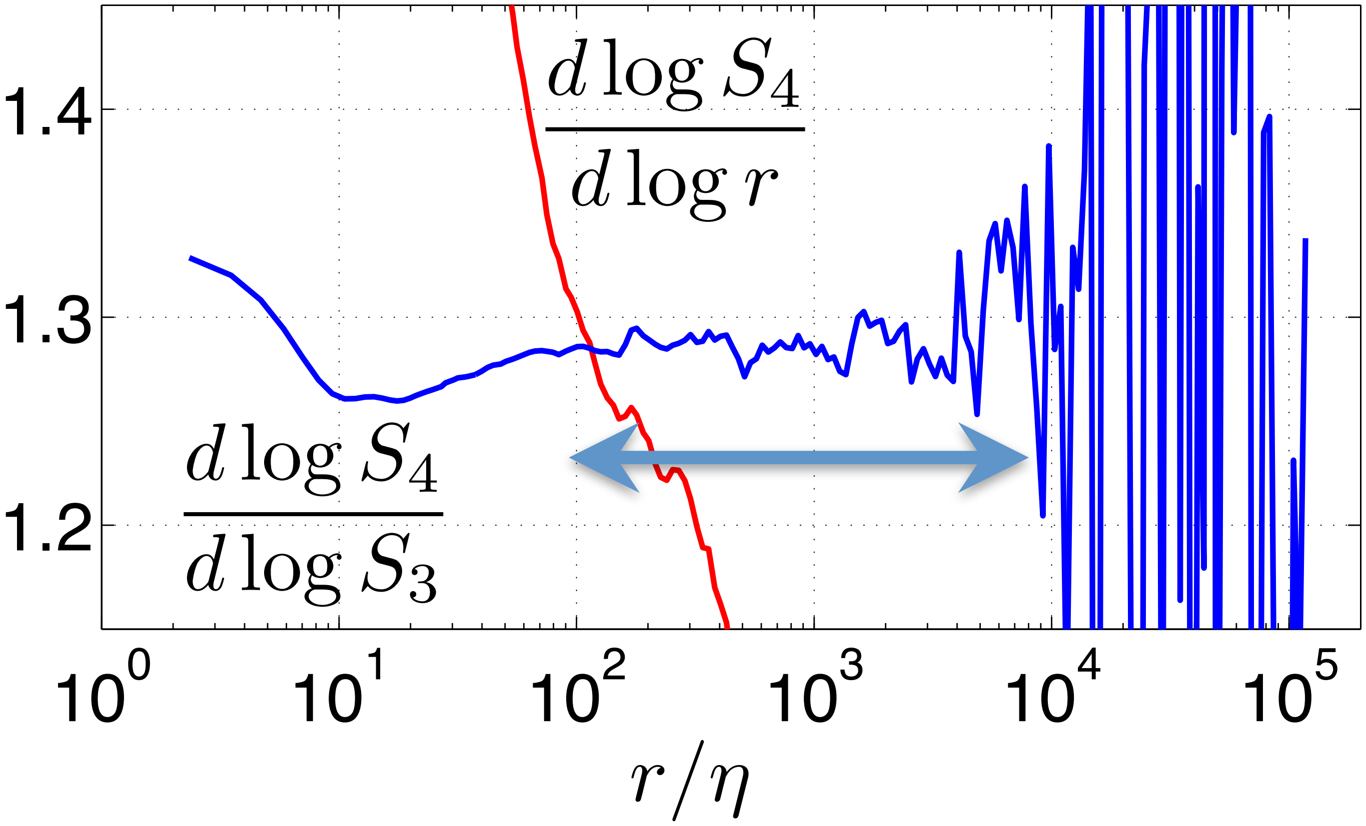


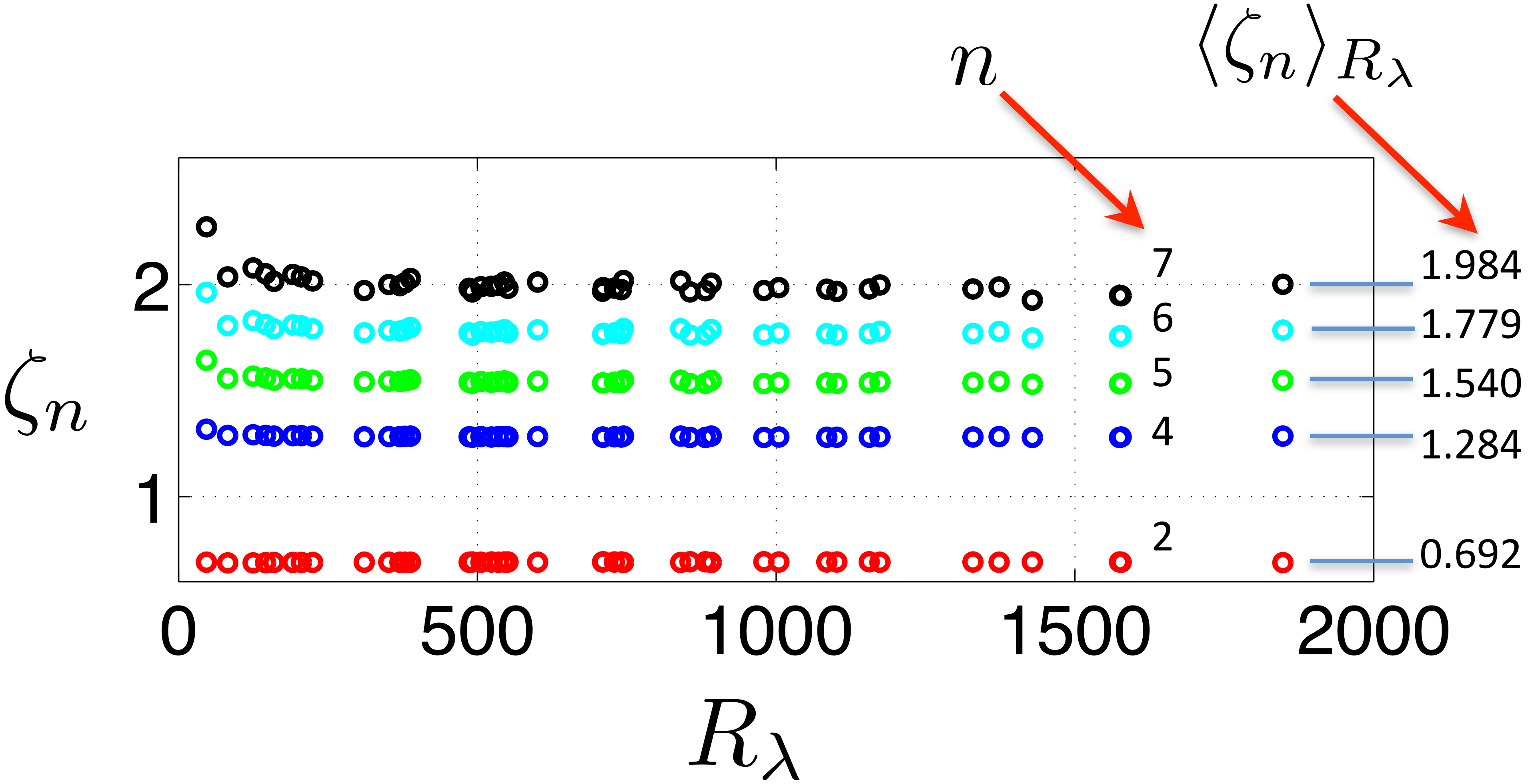
EXTENDED SELF-SIMILARITY

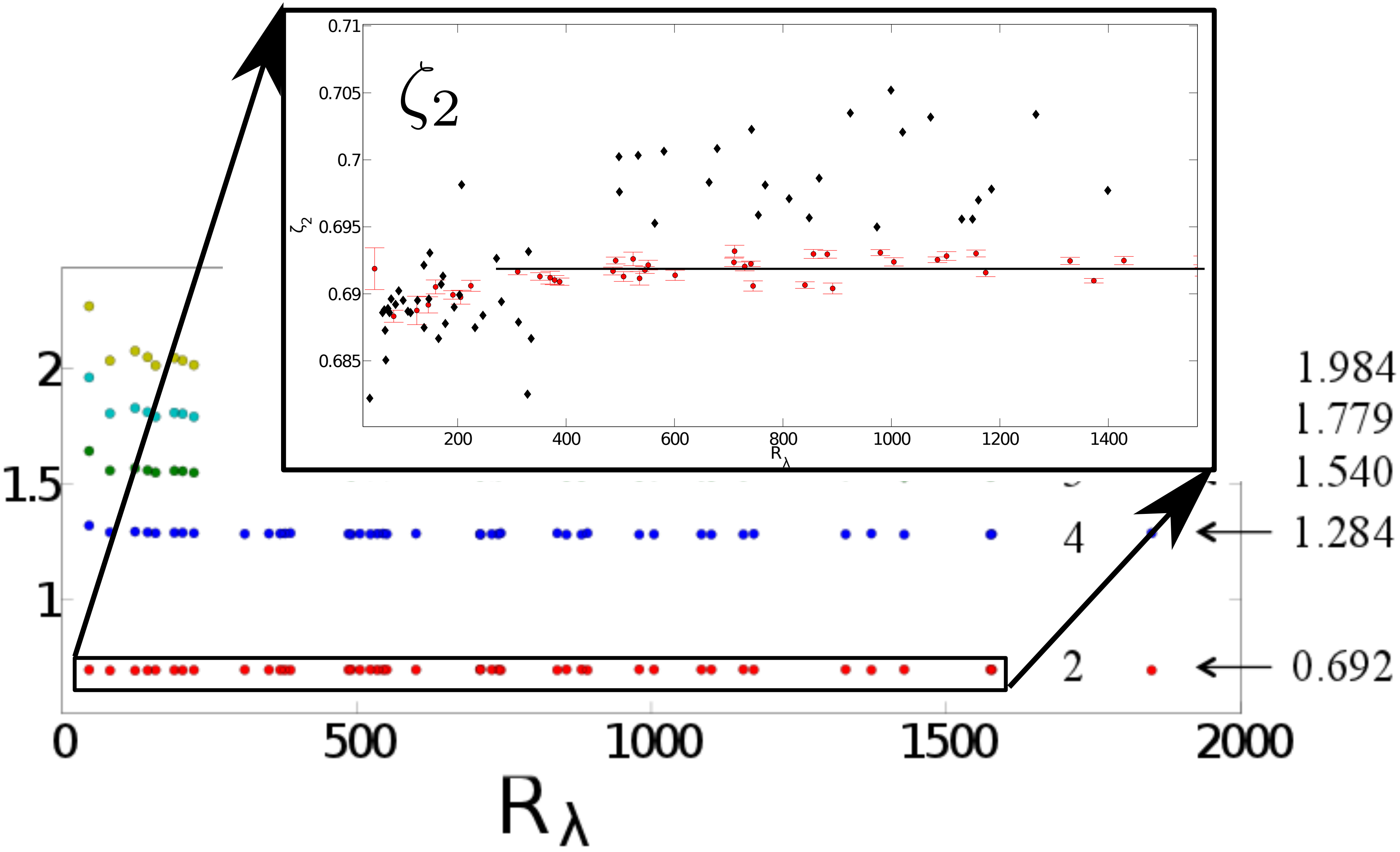
Benzi et al. (1993) *PRE*

$$S_n \sim S_3^{\zeta_n} \qquad \zeta_n = \frac{d\,log\,S_n}{d\,log\,S_3}$$

$Re_\lambda = 841$




n
$\langle \zeta_n \rangle_{R_\lambda}$
7
6
5
4
2
1.984
1.779
1.540
1.284
0.692
ζ_n
2
1
0
500
1000
1500
2000
R_λ



Pearson and Antonia (2001) *JFM*

	VDTT	BL	DNS	S-L	K41
ζ_2	0.6915 ± 0.0006	0.708	0.699	0.695	0.666…
ζ_4	1.284 ± 0.001	1.26	1.279	1.280	1.333…
ζ_6	1.779 ± 0.009	1.71	1.772	1.778	2.000…

BL: Sreenivasan and Dhruva (1996) *Prog. Theo. Supp.*
DNS: Cao, Chen and She (1996) *PRL*
S-L: She and Lévêque (1994) *PRL*
K41: Kolmogorov (1941) Dokl. Akad. Nauk. SSSR…

$$f(r,t) = \frac{\langle\, u(\vec{x},t)\, u(\vec{x}+\vec{r},t)\,\rangle}{u'^2}$$

$f(r,t) \sim r^{-2}$ ⇔ $K \sim t^{-6/5}$ (Saffman)

$f(r,t) \sim r^{-6}$ ⇔ $K \sim t^{-10/7}$ (Kolmogorov)

e.g. Davidson (2011) *Phys. Fluids*

Is it possible to imprint desired long-range correlations?

CONTROL OF LARGE-SCALE STRUCTURE

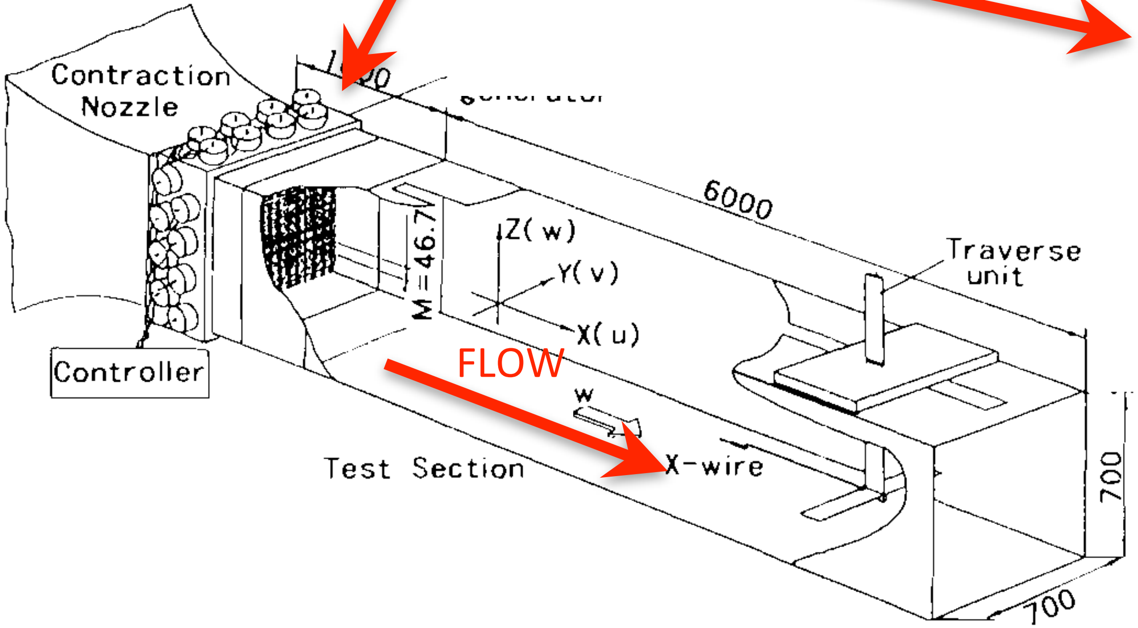
-for high Reynolds numbers

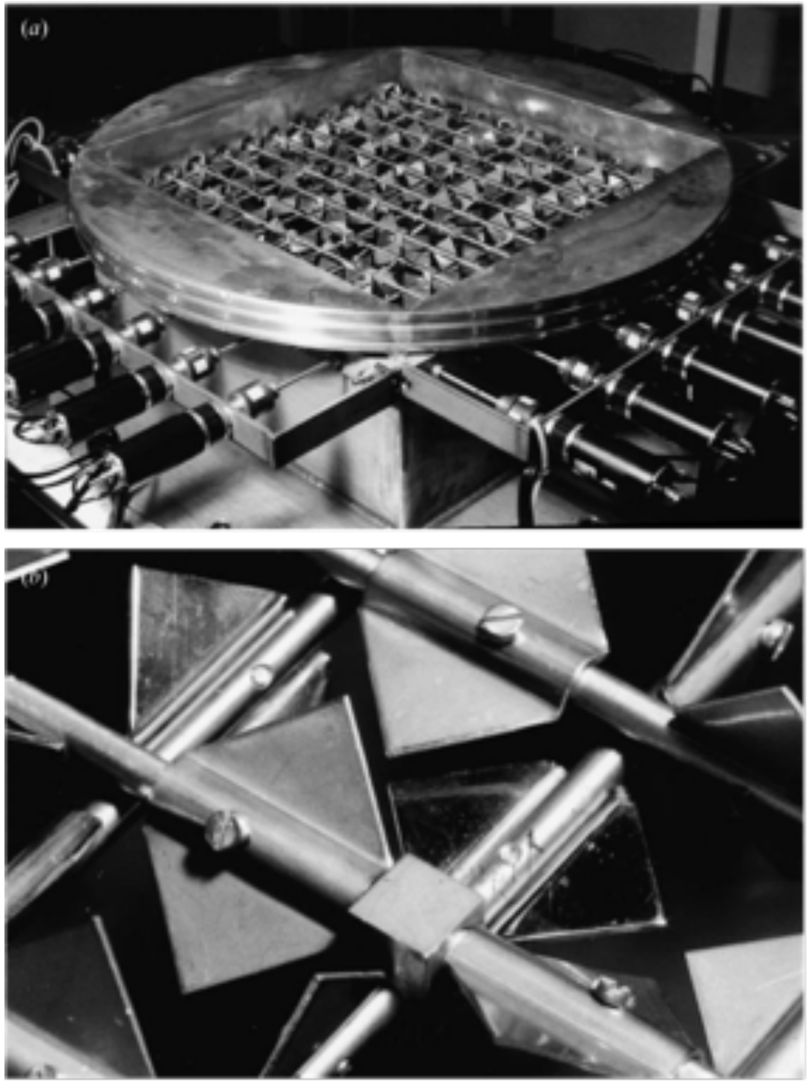
e.g. Makita (1991*) Fluid. Dyn. Res.*

-for control

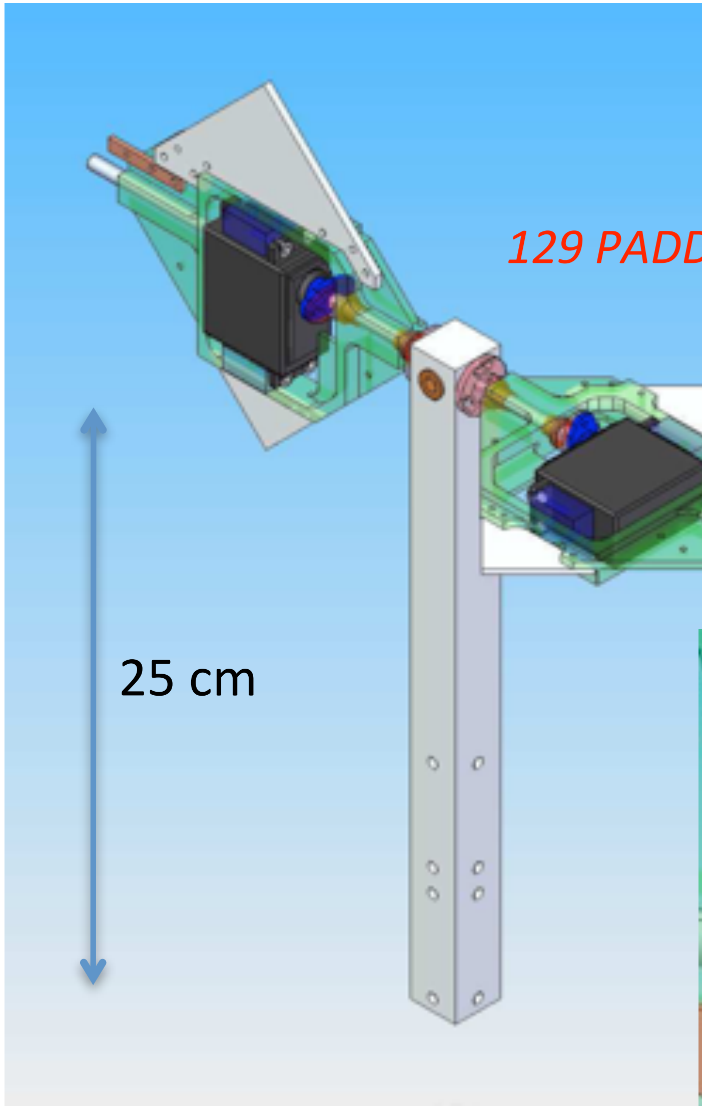
e.g. Poorte and Biesheuvel (2002) *JFM*
Cekli, Tipton and van de Water (2010) *PRL*

AN **ACTIVE GRID**



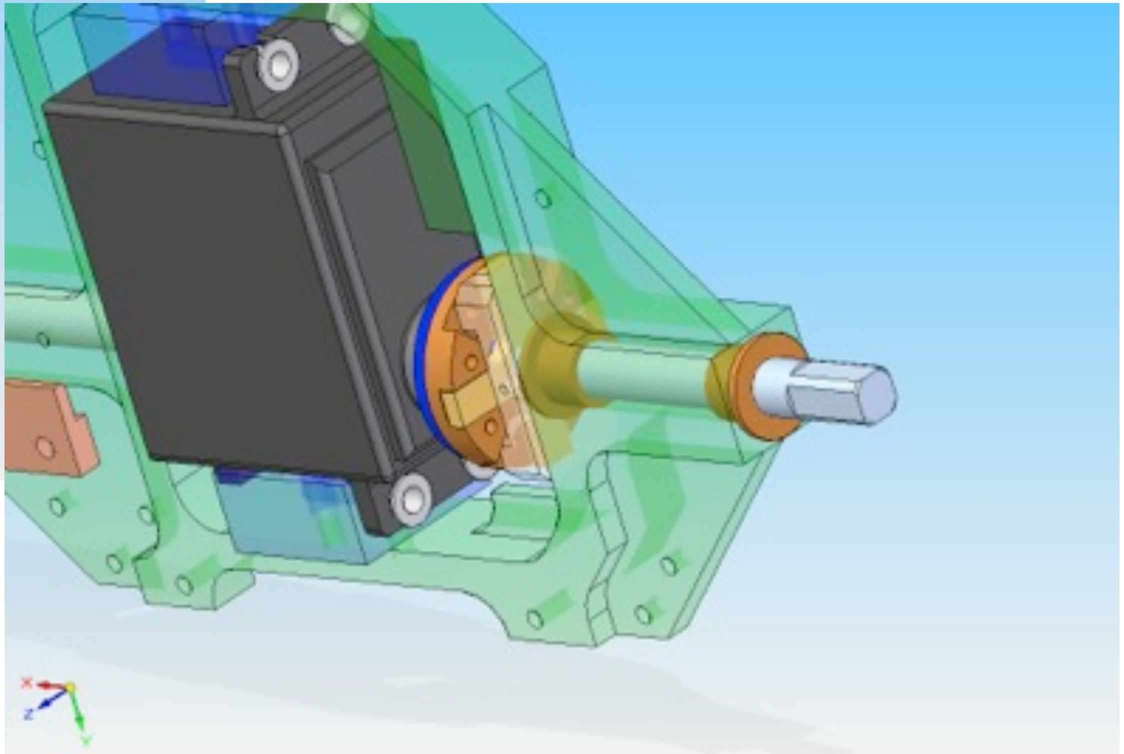


OUR GRID

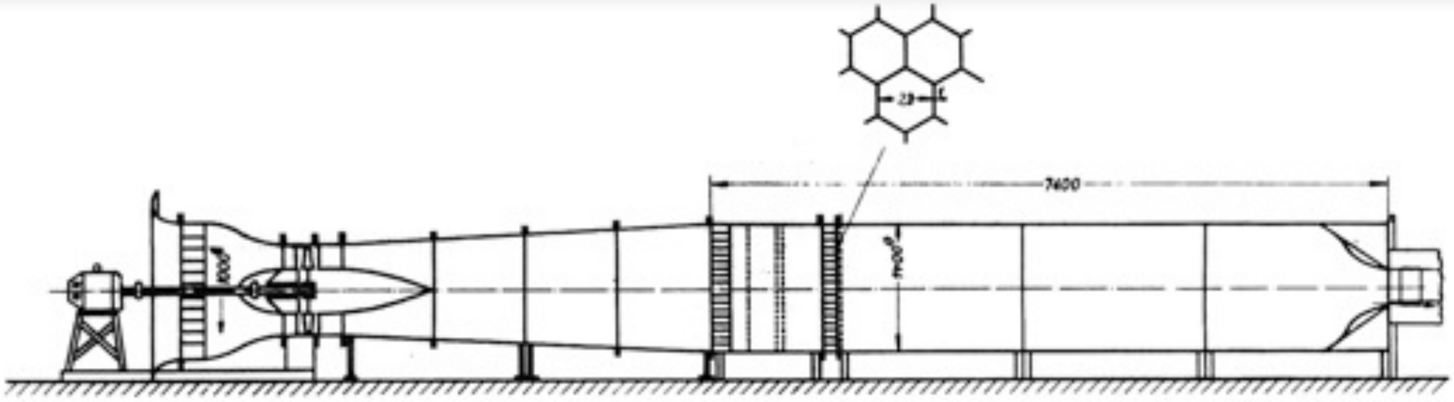


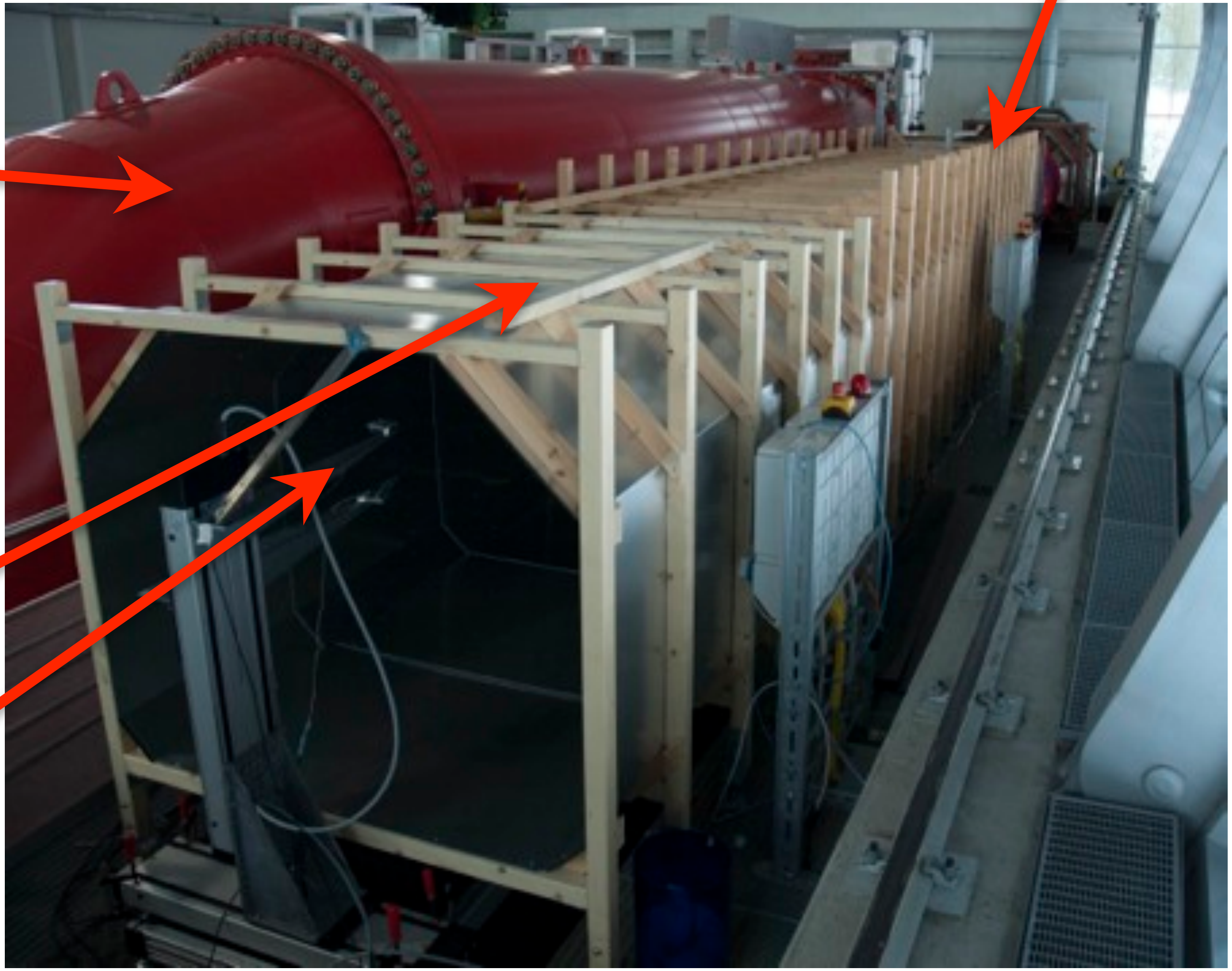
We (*uniquely*) have:

- -independent paddles
- -feedback-control of angle



M = 163 mm



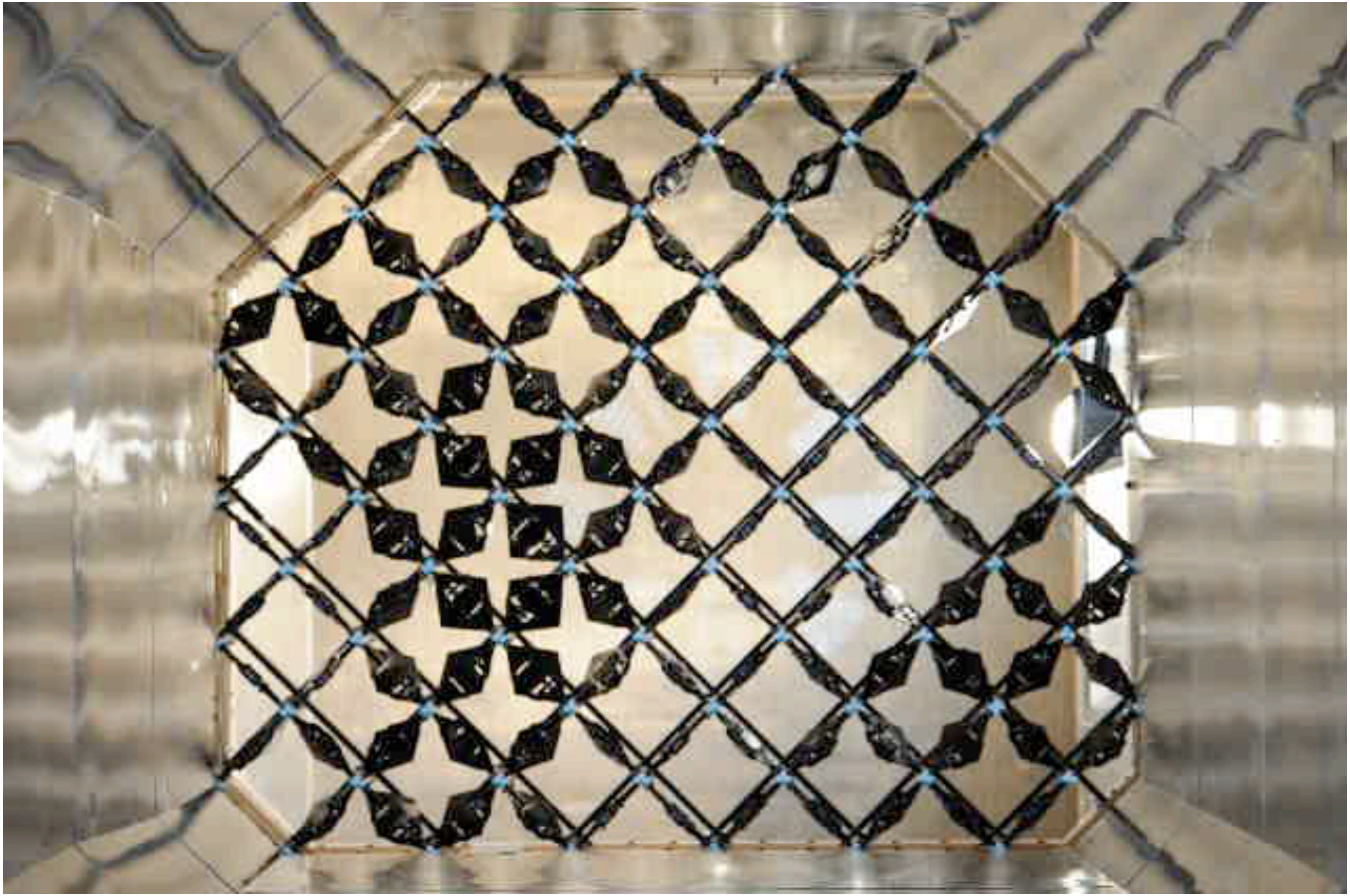


THE ACTIVE GRID

THE VDTT

THE PRANDTL TUNNEL
(1938)

HOT WIRE PROBES
50M DOWNSTREAM



Thank you:

E. Bodenschatz

Active grid

E. Cekli
F. Köhler
J. Kassel
F. Lachaussée
H. Grajewski

Wind tunnel

M. Sinhuber
H. Eckelmann

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G. Good
D. Ivanov

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J. Vollmer
H. Xu

A. Kopp
A. Kubitzek
O. Kurre
A. Renner
U. Schminke *et al.*