Features of vigorous turbulence in experiments

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with

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Max Planck Institute

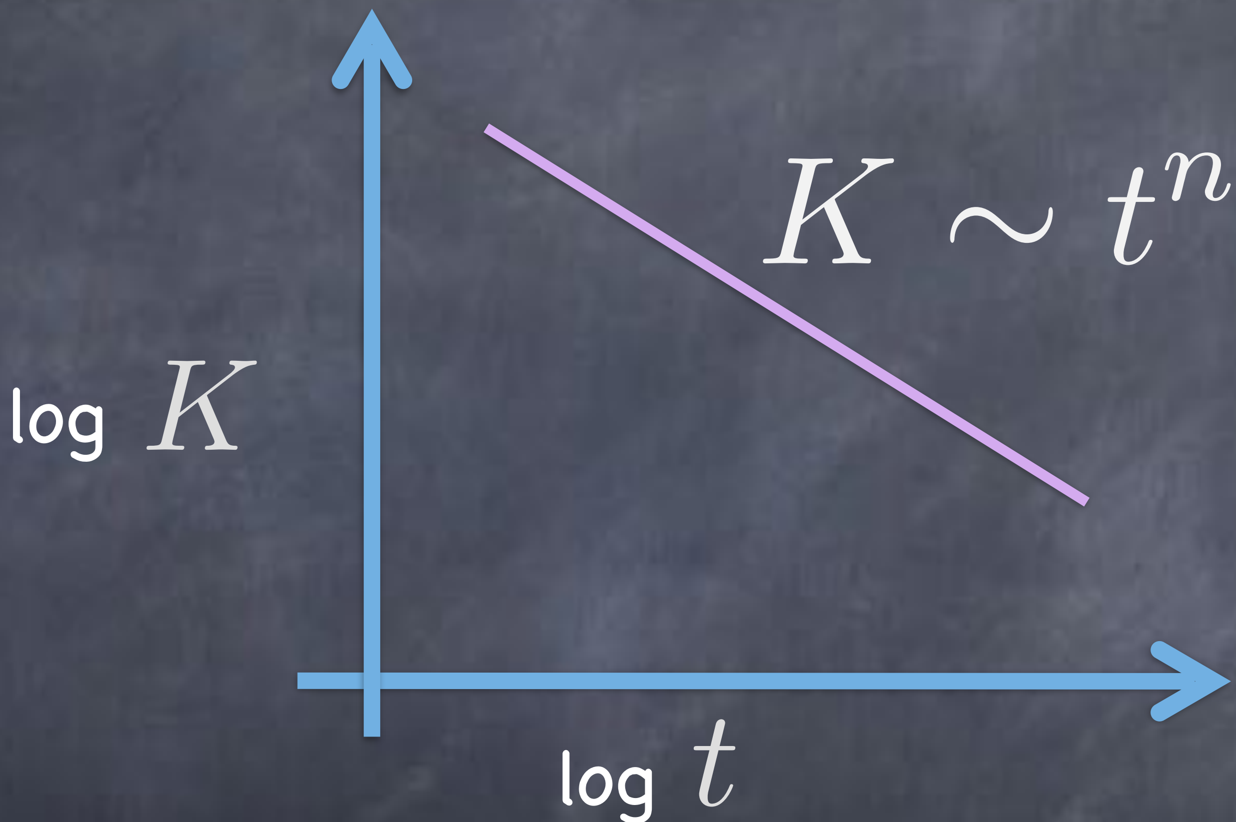
1. How quickly does turbulence decay?

Altman and Demler (2007) *Nature*

$$\frac{dK}{dt} = -\epsilon$$

$$T \sim \frac{L}{U}$$

1. How quickly does turbulence decay?



Theoretical predictions:

— Self-similar $K \sim t^{-1}$

for $Re \to \infty$

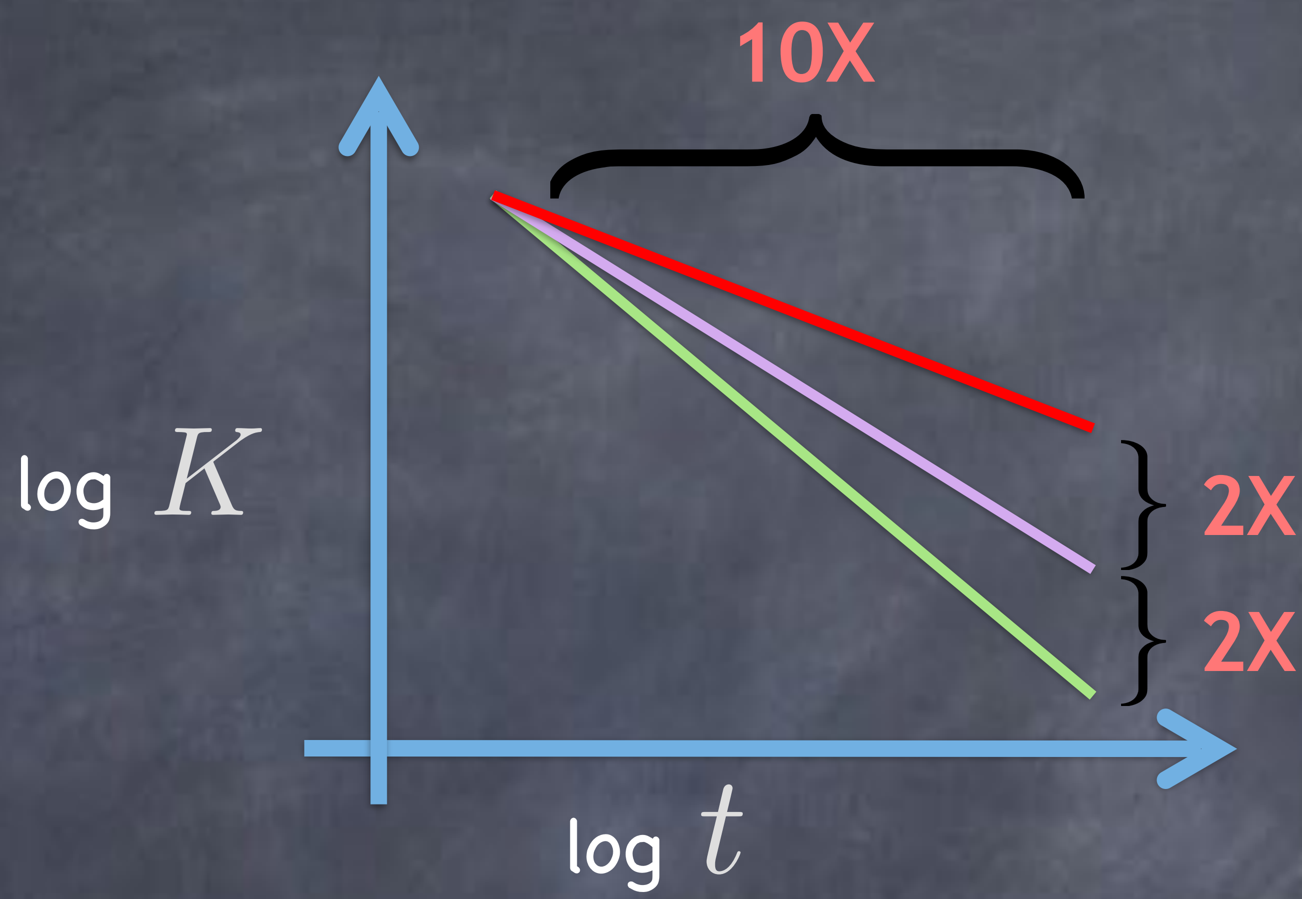
e.g. Dryden (1942) *Q. Appl. Math.*
Hinze (1975) *Turbulence*
George (1992) *Phys. Fluids*
Speziale and Bernard (1992) *JFM*

— Saffman $K \sim t^{-6/5}$

— Kolmogorov $K \sim t^{-10/7}$

depending on large-scale structure

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

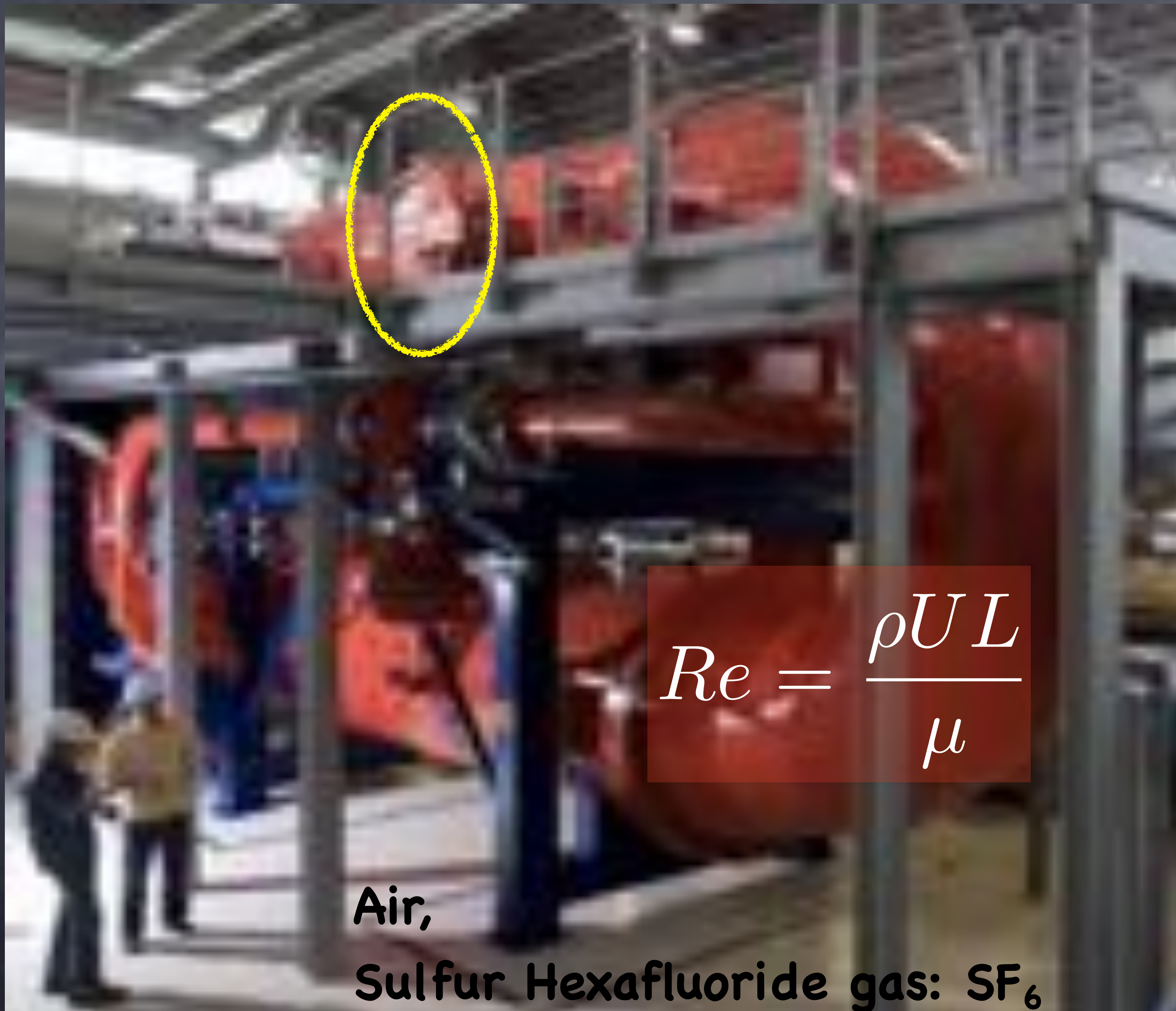


Self-similar $K \sim t^{-1}$

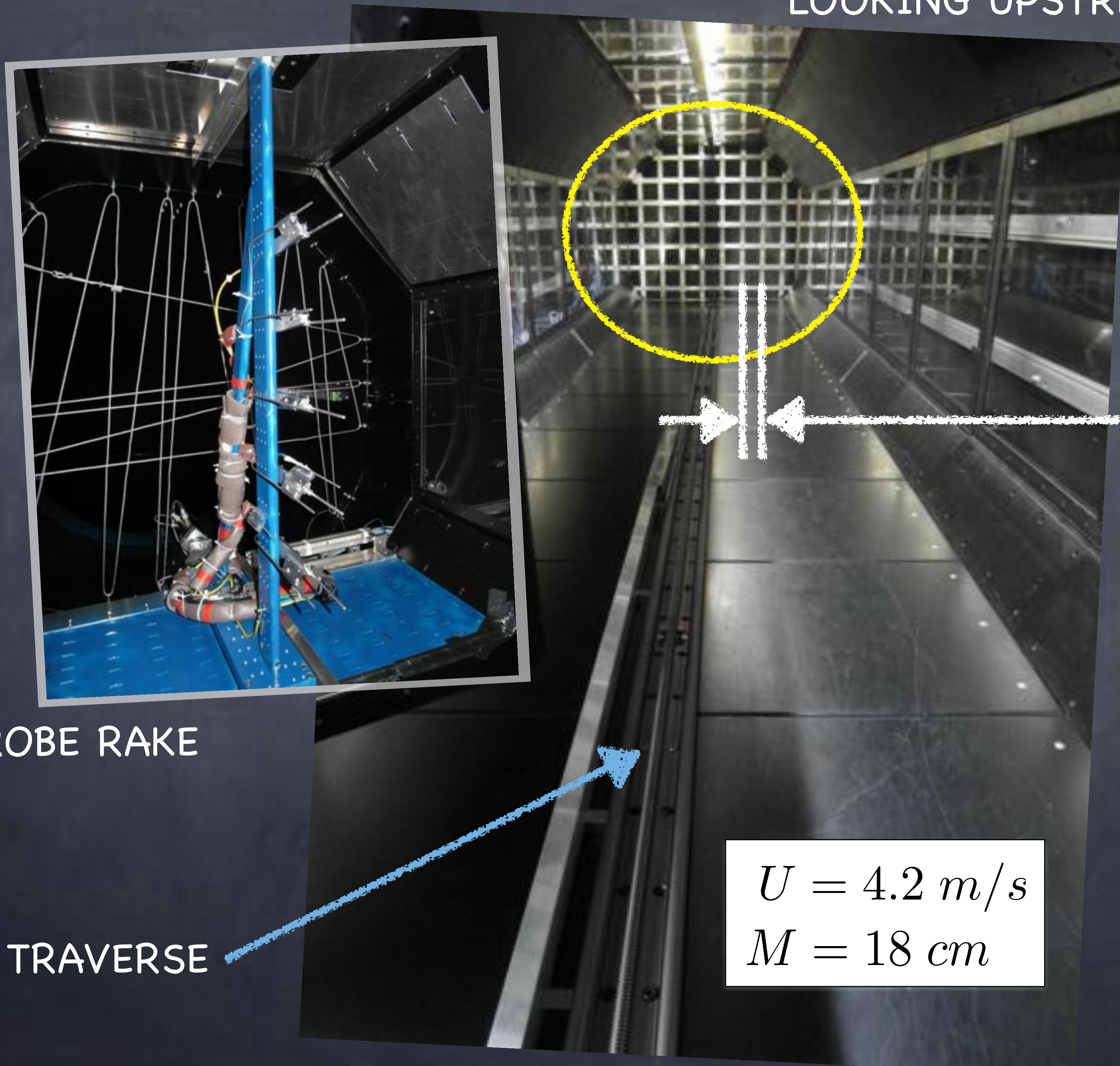
Saffman $K \sim t^{-6/5}$

Kolmogorov $K \sim t^{-10/7}$

THE VARIABLE DENSITY TURBULENCE TUNNEL (VDTT)

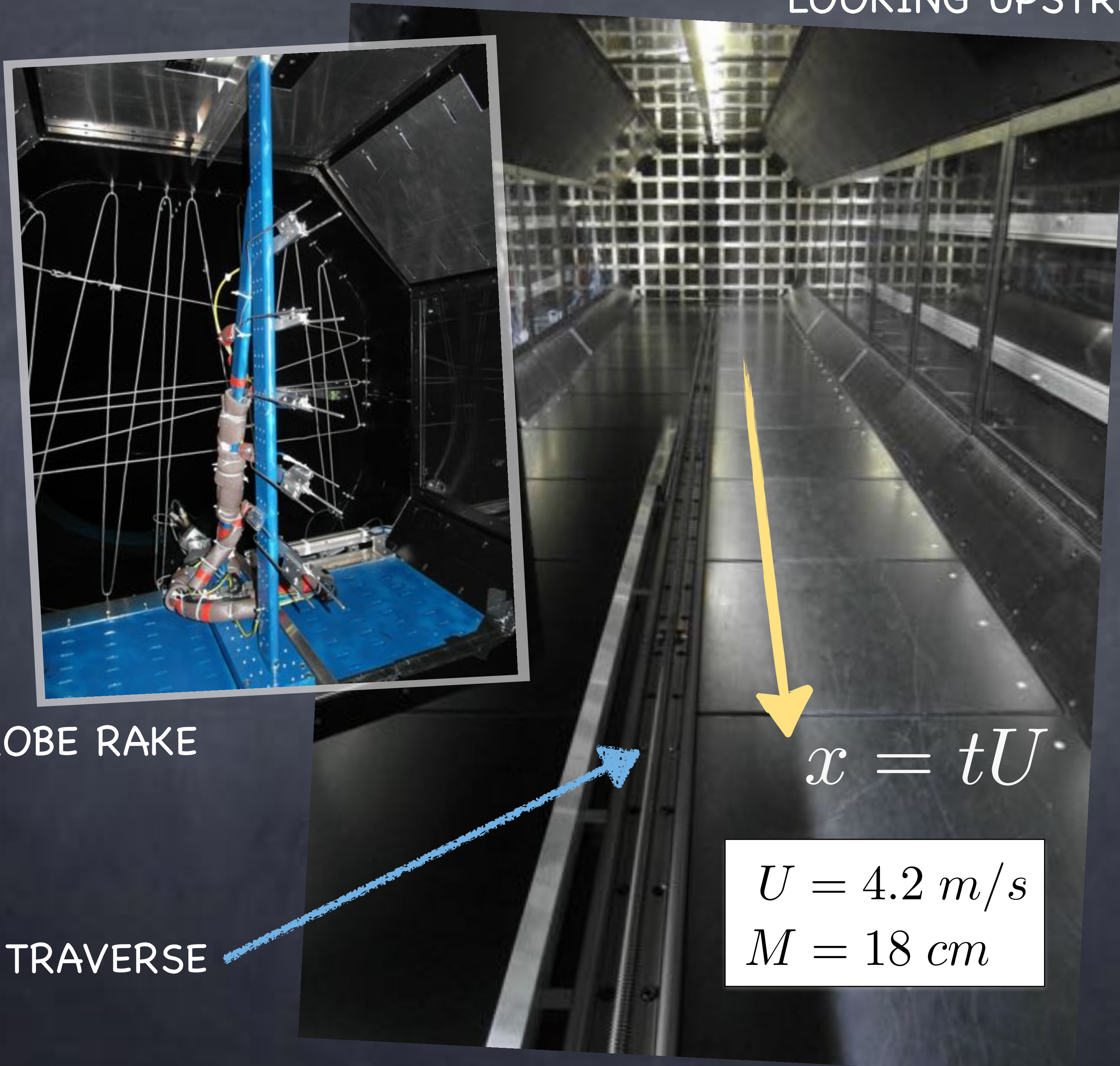


Bodenschatz, Bewley, Nobach, Sinhuber, Xu (2014) *Rev. Sci. Instr.*



$$U = 4.2\ m/s$$
$$M = 18\ cm$$

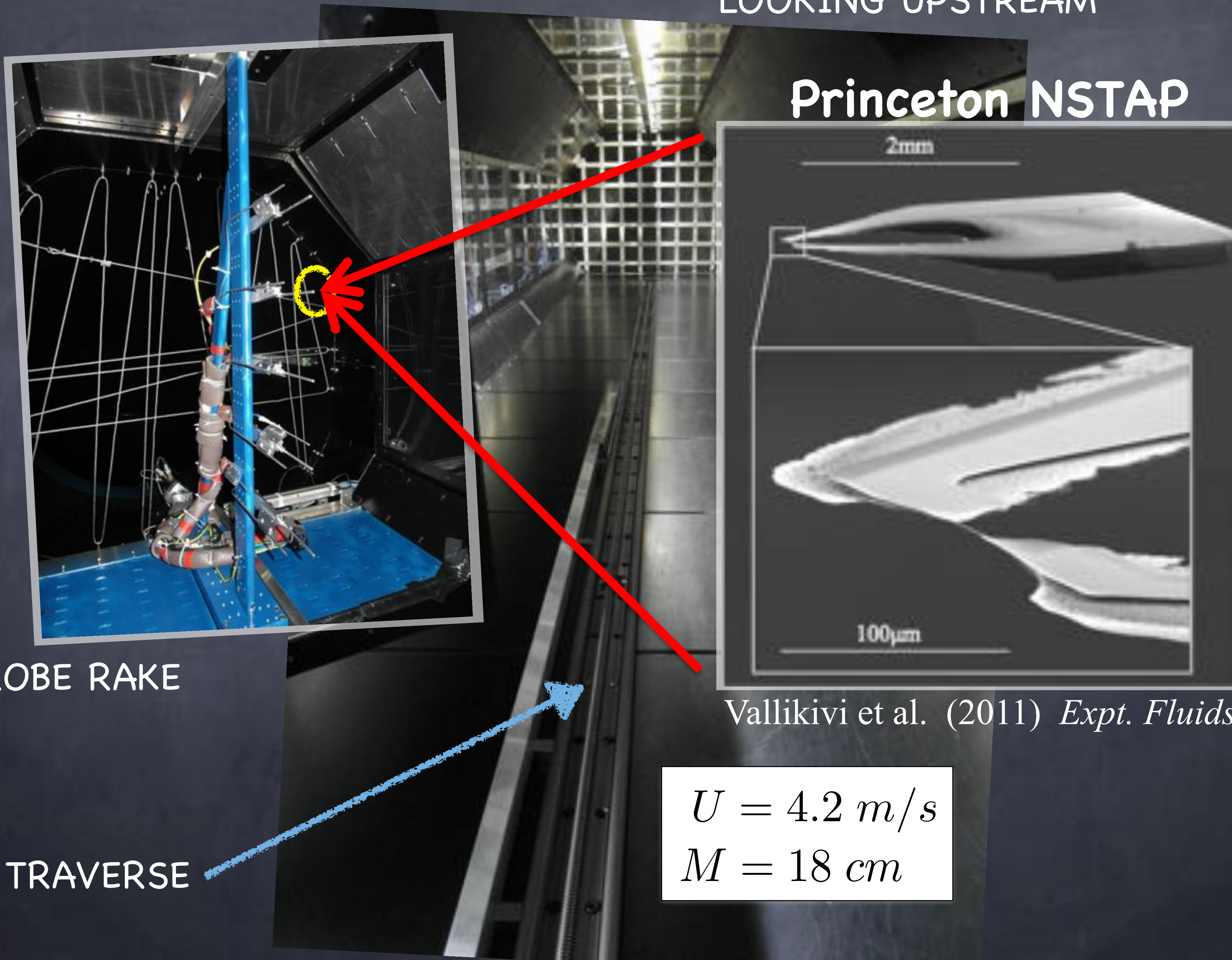
LOOKING UPSTREAM



PROBE RAKE

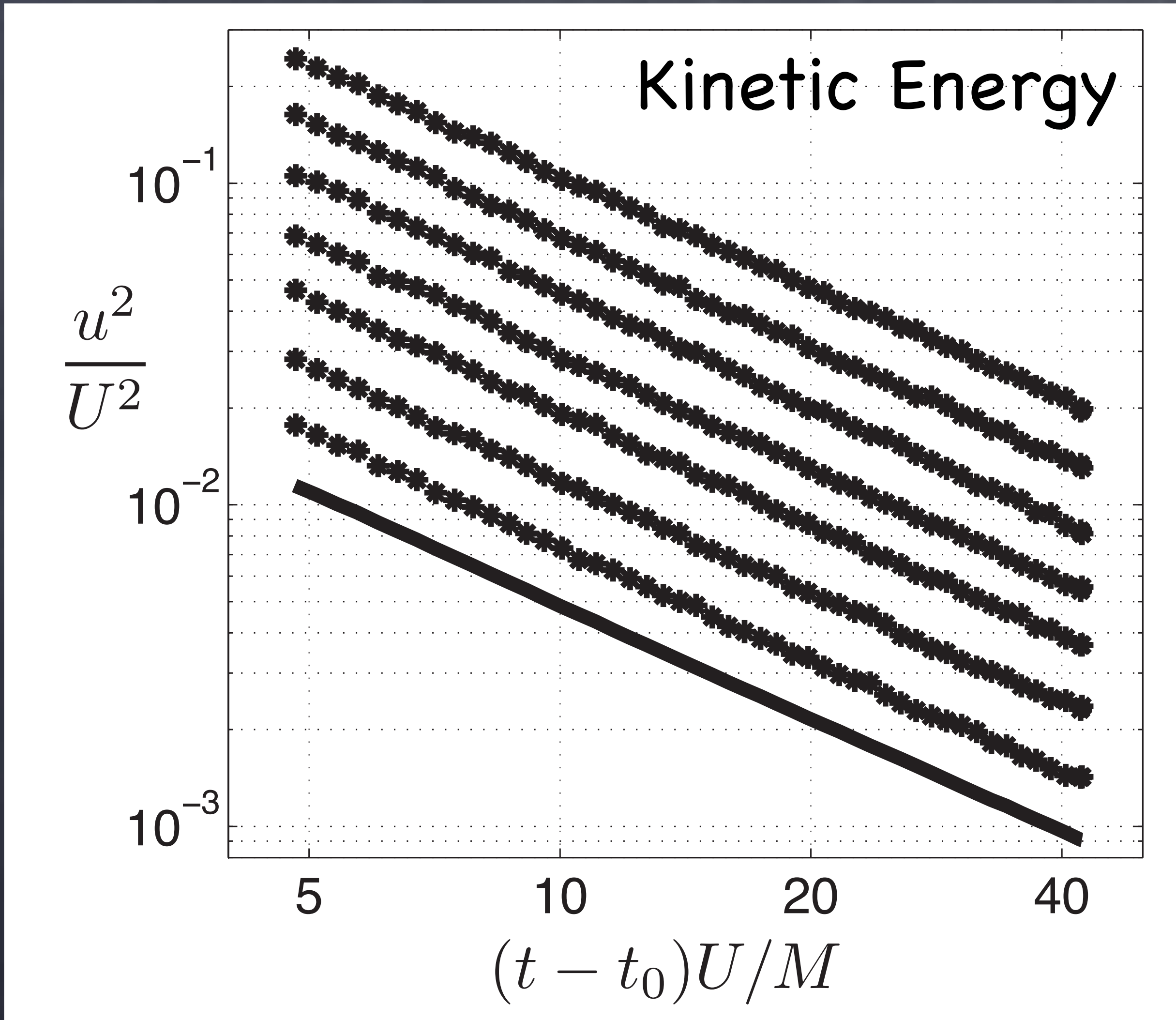
TRAVERSE

Princeton NSTAP



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

$$U = 4.2\ m/s$$
$$M = 18\ cm$$

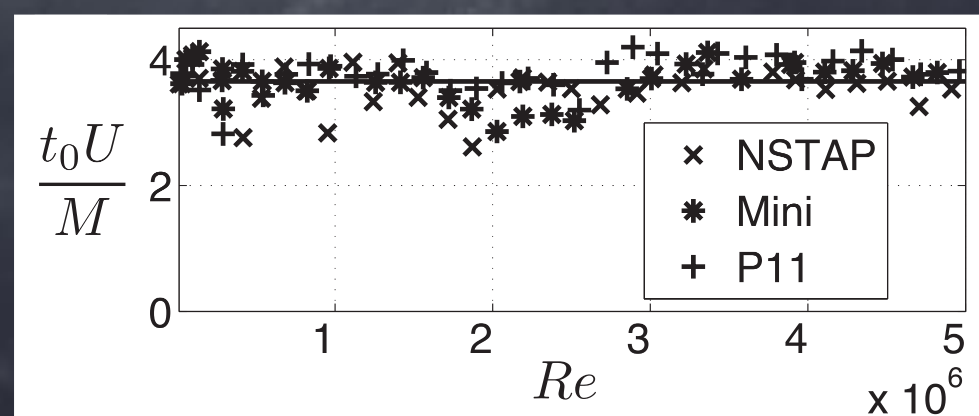


$$Re = \frac{UM}{\nu}$$

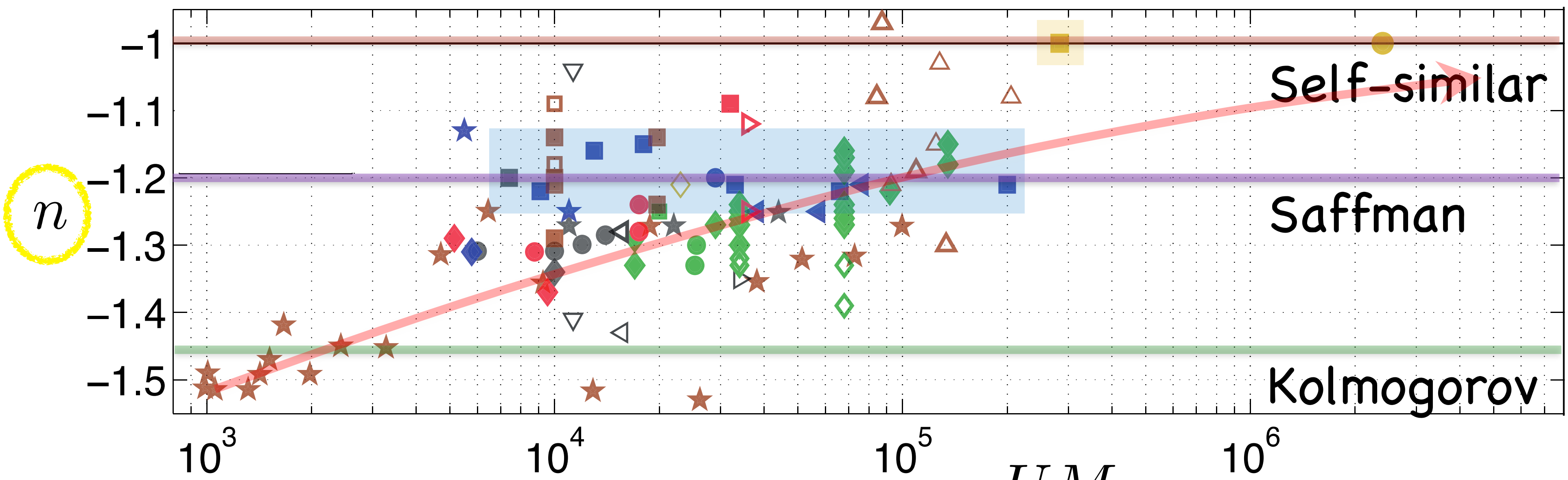
4.8×10^6
3.2×10^6
4.1×10^5
1.4×10^5
5.4×10^4
2.6×10^4

Sinhuber, Bodenschatz and Bewley (2015) *PRL*

$$\frac{u^2}{U^2} = C\left((t - t_0)\frac{U}{M}\right)^n$$



$$K \sim t^{n}$$

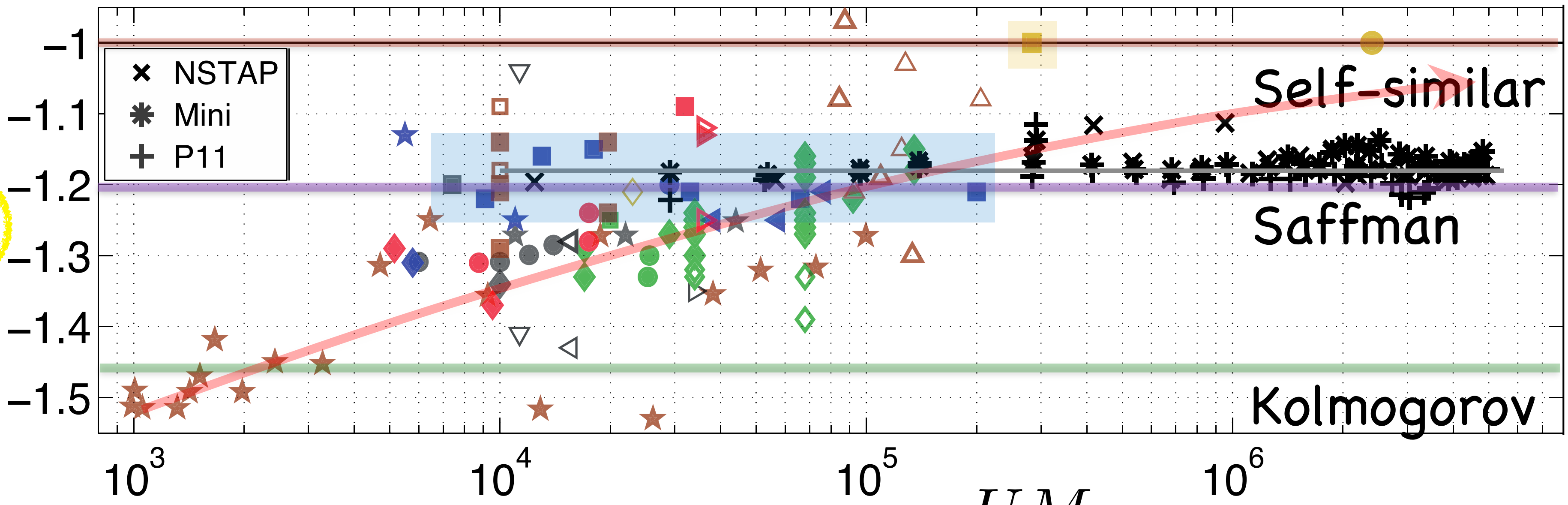


$$Re = \frac{UM}{\nu}$$

Sinhuber, Bodenschatz and Bewley (2015) *PRL*

★ Kurian and Fransson (2009), ★ Batchelor and Townsend (1948), ★ Wyatt (1955), ◆ Sirivat and Warhaft (1983), ◆ Yoon and Warhaft (1990), ◆ Warhaft and Lumley (1978), ◆ Comte-Bellot and Corrsin (1966), ◆ Mydlarski and Warhaft (1996), ■ Sreenivasan et al. (1980), ■ White et al. (2002), ■ Lavoie et al. (2007), ■ Antonia et al. (2003), ■ van Doorn et al. (1999), ■ Bewley et al. (2007), ● Mohamed and LaRue (1990), ● Uberoi and Wallis (1966), ● Van Atta and Chen (1968), ● Uberoi (1963), ● Kistler and Vrebalovich (1966), ▼ Poorte et al. (2002), ◀ Makita (1991), ▶ Krogstad and Davidson (2011), ◀ Valente and Vassilicos (2011), ▲ Thormann and Meneveau (2014),

$$K \sim t^{n}$$



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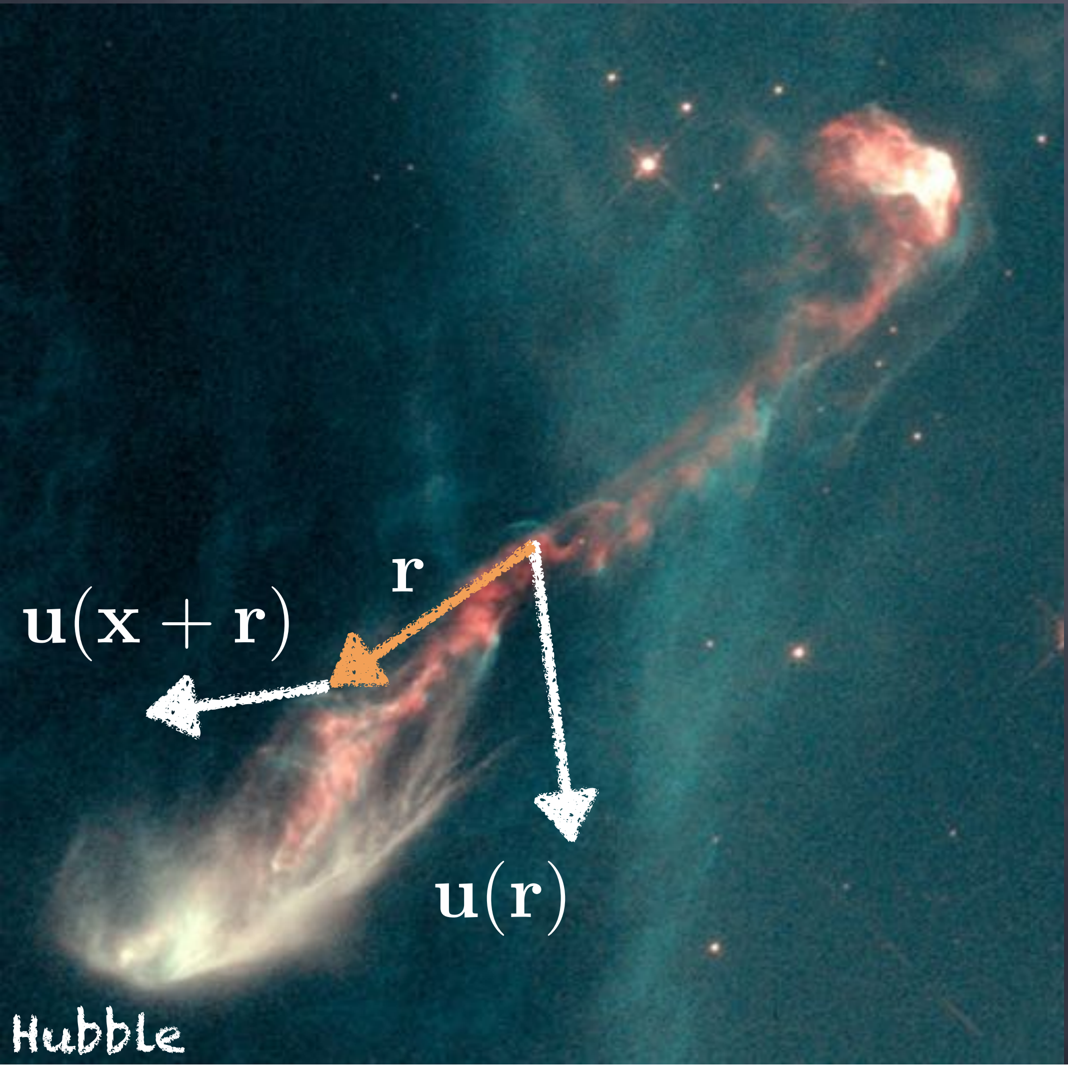
Sinhuber, Bodenschatz and Bewley (2015) *PRL*

★ Kurian and Fransson (2009), ★ Batchelor and Townsend (1948), ★ Wyatt (1955), ◆ Sirivat and Warhaft (1983), ◆ Yoon and Warhaft (1990), ◆ Warhaft and Lumley (1978), ◆ Comte-Bellot and Corrsin (1966), ◆ Mydlarski and Warhaft (1996), ■ Sreenivasan et al. (1980), ■ White et al. (2002), ■ Lavoie et al. (2007), ■ Antonia et al. (2003), ■ van Doorn et al. (1999), ■ Bewley et al. (2007), ● Mohamed and LaRue (1990), ● Uberoi and Wallis (1966), ● Van Atta and Chen (1968), ● Uberoi (1963), ● Kistler and Vrebalovich (1966), ▼ Poorte et al. (2002), ◀ Makita (1991), ▶ Krogstad and Davidson (2011), ◀ Valente and Vassilicos (2011), ▲ Thormann and Meneveau (2014),

2. What is the structure of turbulence?

Velocity differences

$$\delta u(r) \equiv (\mathbf{u}(\mathbf{x}+\mathbf{r}) - \mathbf{u}(\mathbf{x})) \cdot \hat{\mathbf{r}}$$

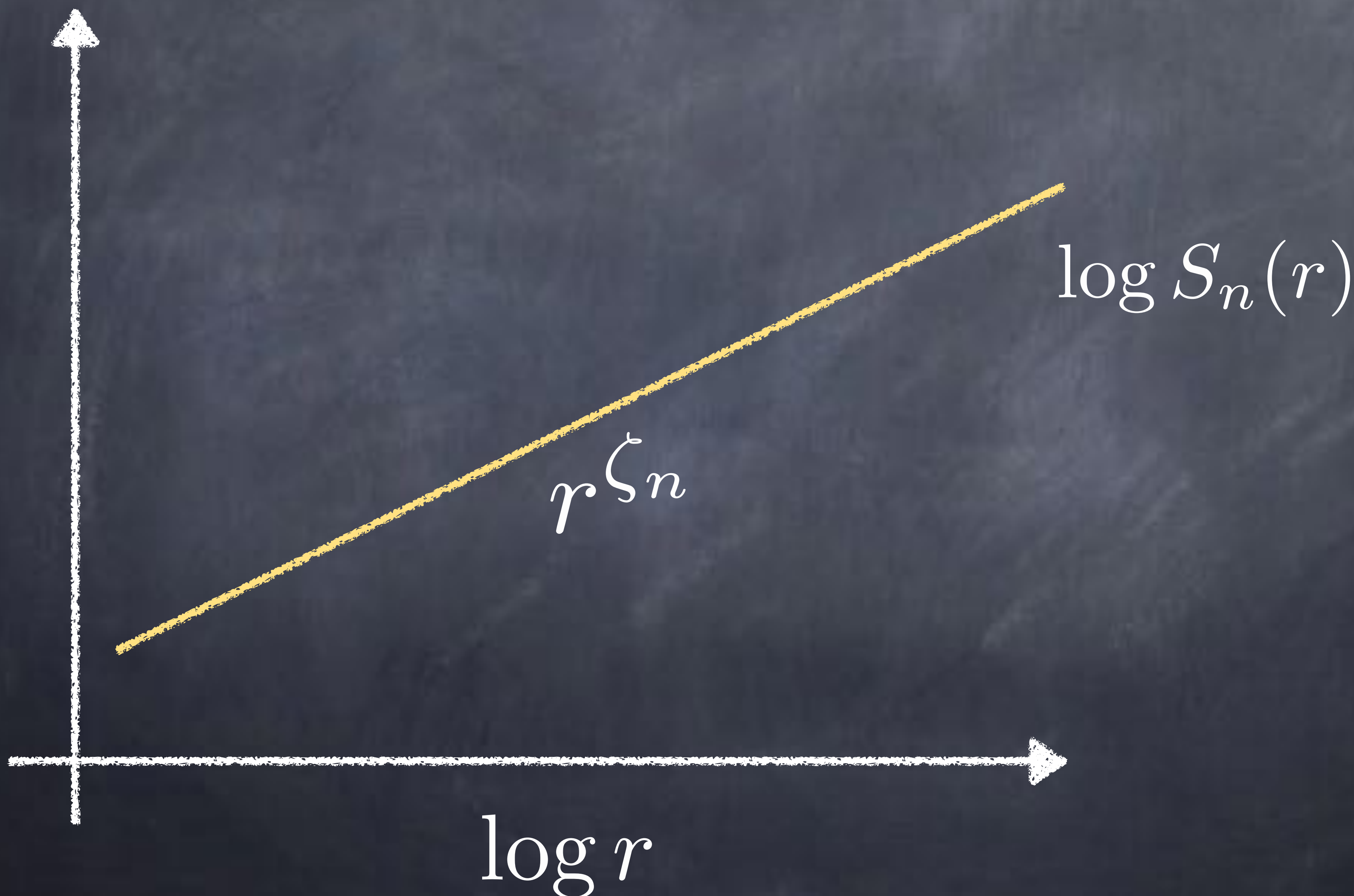


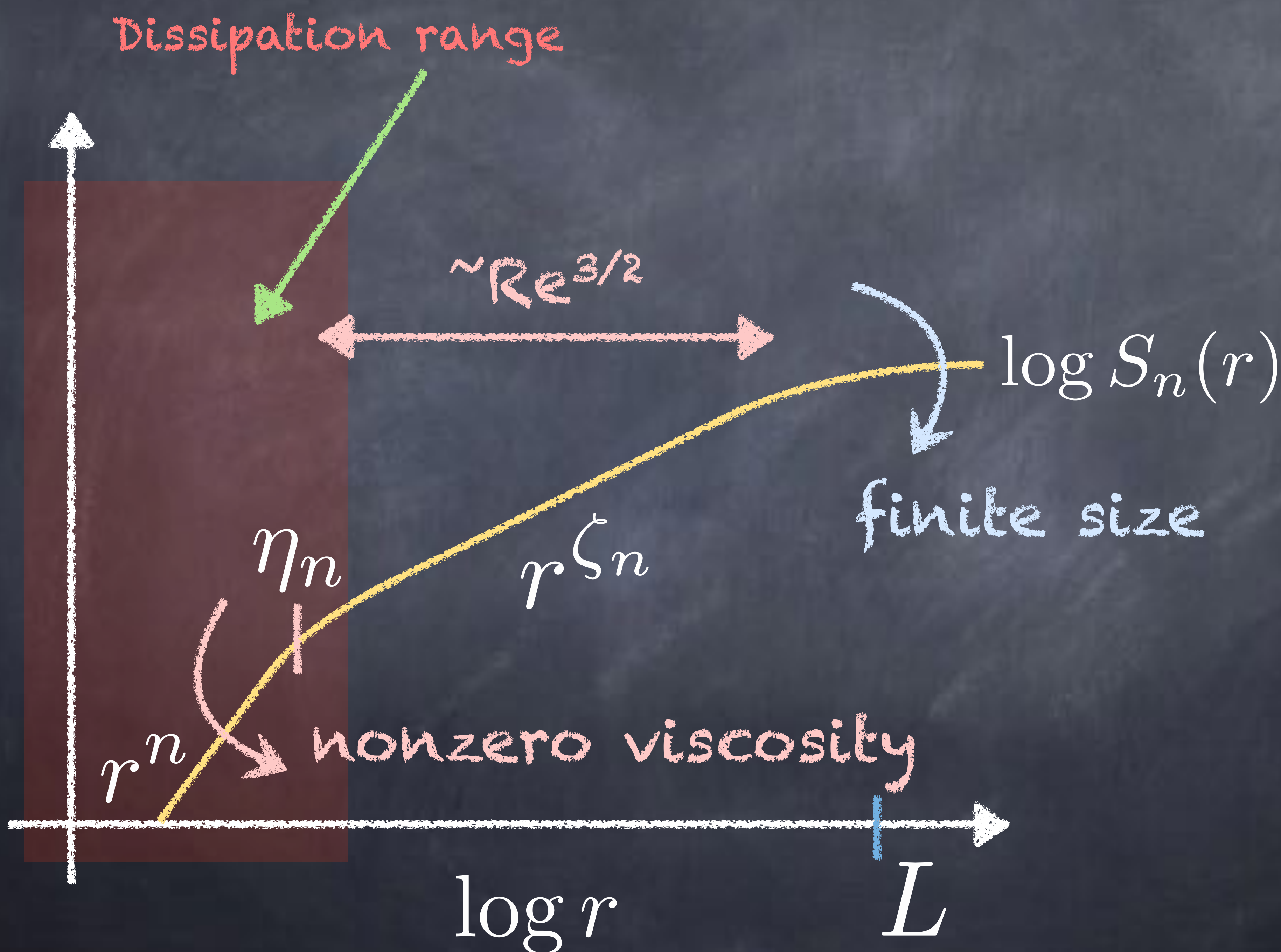
$$S_n(r) \equiv \langle \delta u^n(r) \rangle$$

Structure functions

$$S_n \sim r^{\zeta_n}$$

Kolmogorov (1941), *etc.*


$\log S_n(r)$
r^{ζ_n}
$\log r$

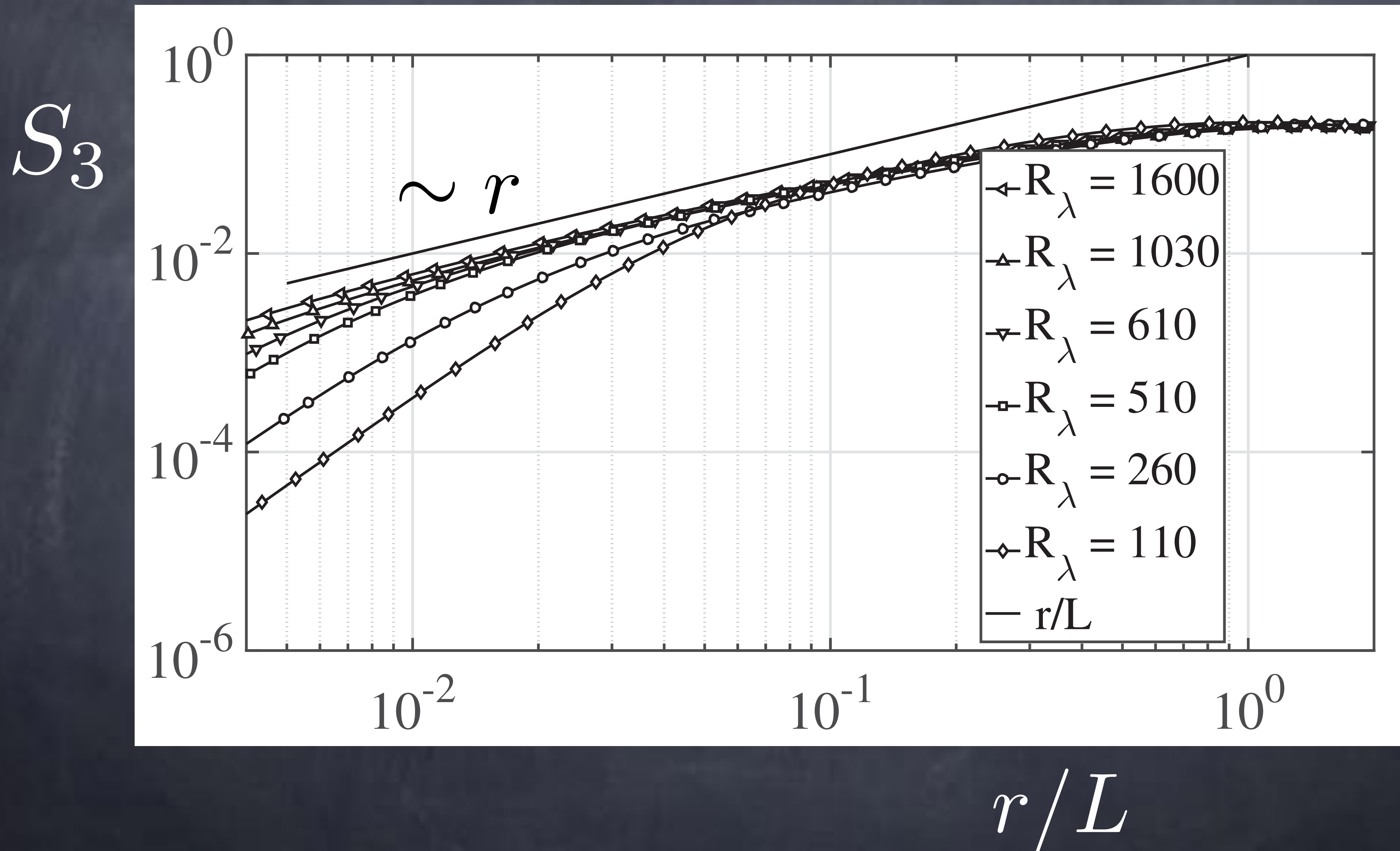


Dissipation range
~Re$^{3/2}$
$\log S_n(r)$
finite size
η_n
r^{ζ_n}
r^n
nonzero viscosity
$\log r$
L

The 4/5ths law

Kolmogorov (1941)

Our data



Sinhuber Bewley, and Bodenschatz (2017) *PRL*

Our data

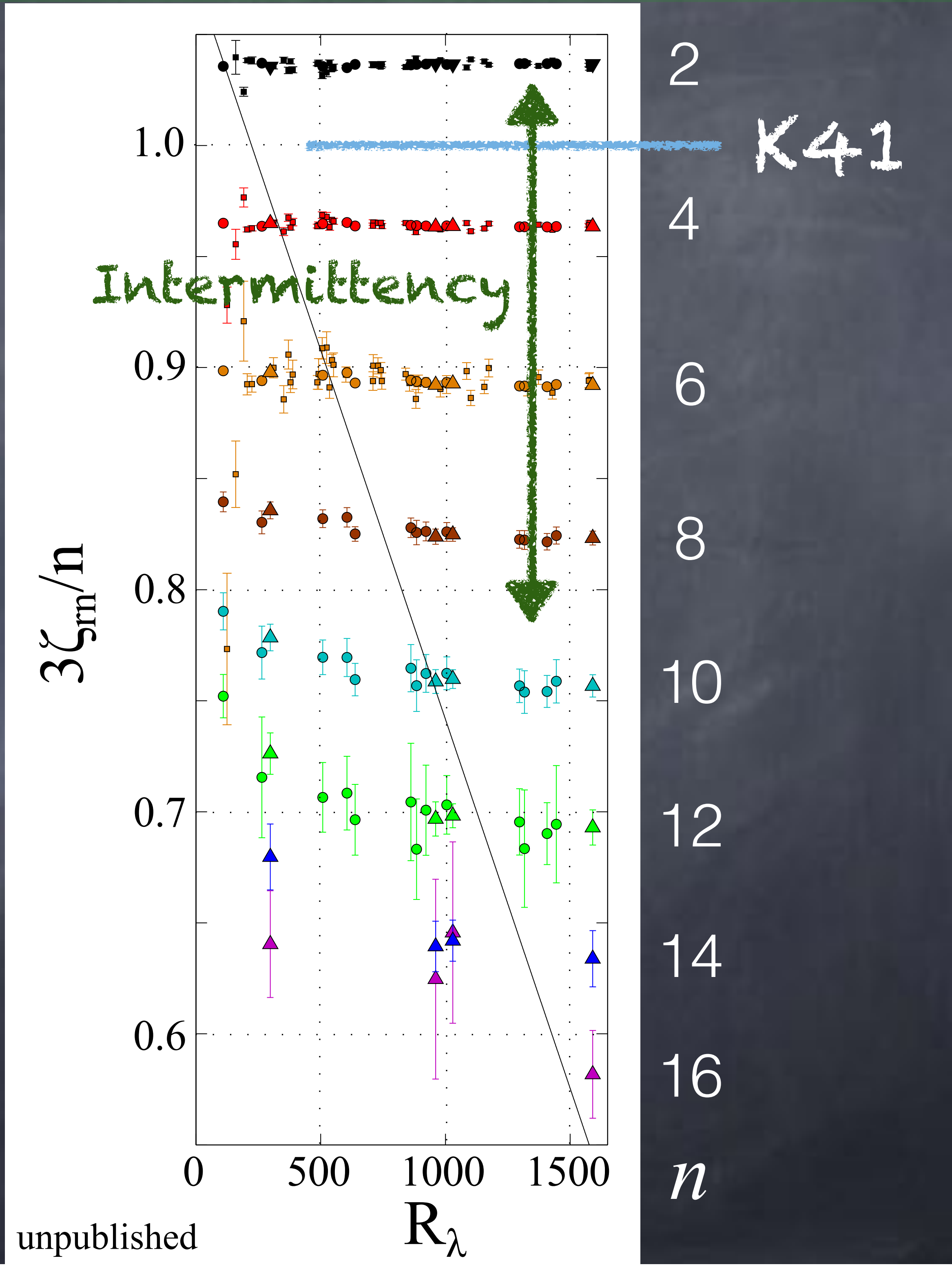
$$S_n \sim r^{\zeta_n}$$

ESS assuming

$$\zeta_3 = 1$$

for

$$\langle |\delta u^3(r)| \rangle$$



order of moment	DNS exponents	present exponents
−0.80	−0.317	−0.313
−0.20	−0.077	−0.078
0.10	0.036	0.039
0.20	0.073	0.076
0.30	0.112	0.113
0.40	0.150	0.150
0.50	0.187	0.190
0.60	0.223	0.221
0.70	0.260	0.265
0.80	0.296	0.292
0.90	0.332	0.333
1	0.366	0.372
1.25	0.452	0.458
1.50	0.536	0.542
1.75	0.619	0.628
2	0.699	0.708
3	1	1
4	1.279	1.26
5	1.536	1.56
6	1.772	1.71
7	1.989	1.97
8	2.188	2.05
9	2.320	2.20
10	2.451	2.38

n ζ_n ζ_n

Previous results

$$S_n \sim r^{\zeta_n}$$

Sreenivasan and Dhruva (1998)
Prog. Theor. Phys. Suppl.

mass of an electron:

$$m_e = 0.000\ 548\ 579\ 909\ 067(14)(9)(2)$$

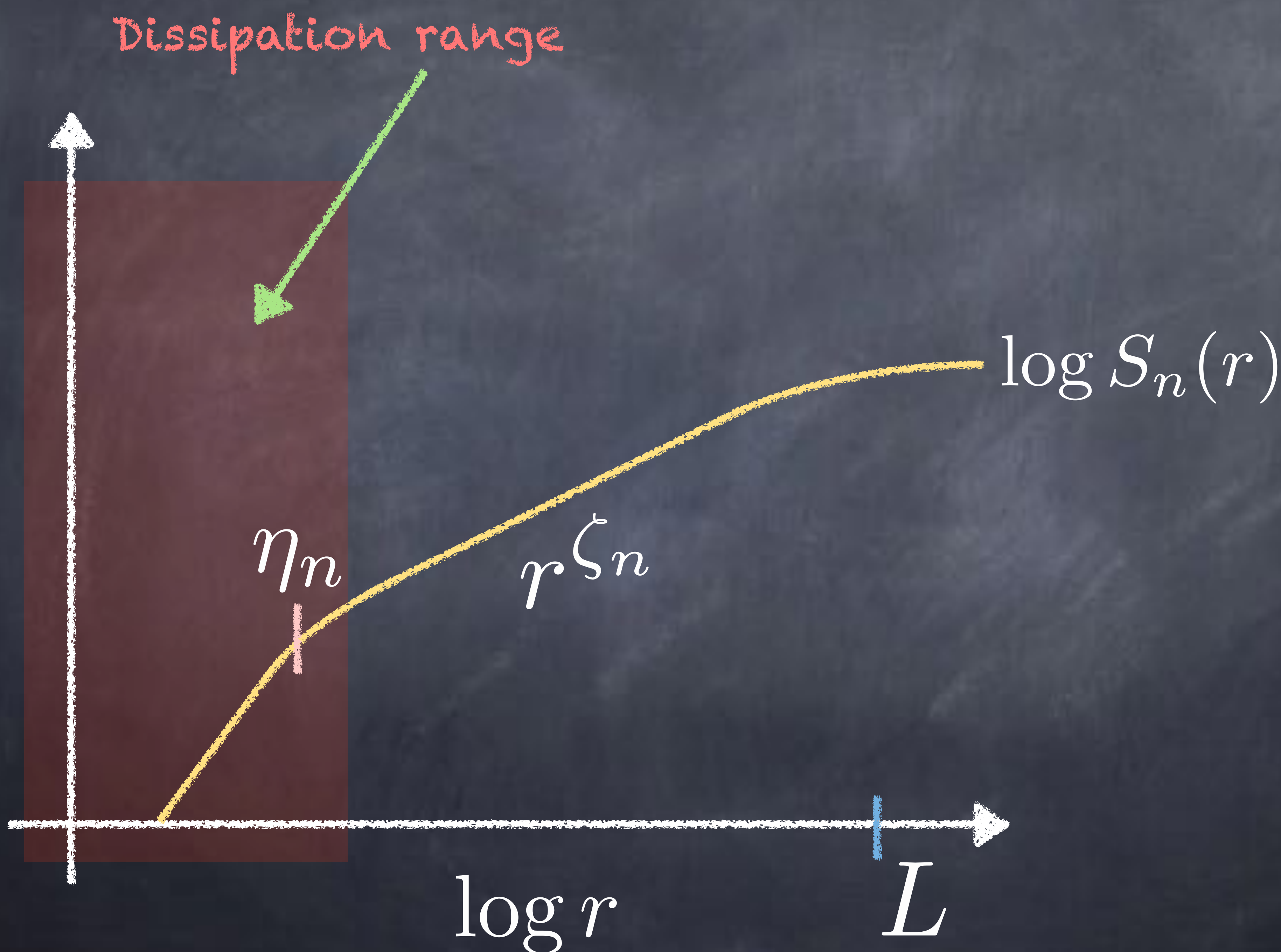
Sturm, Köhler *et al.* (2014) *Nature*

critical exponent for superfluid phase transition in helium:

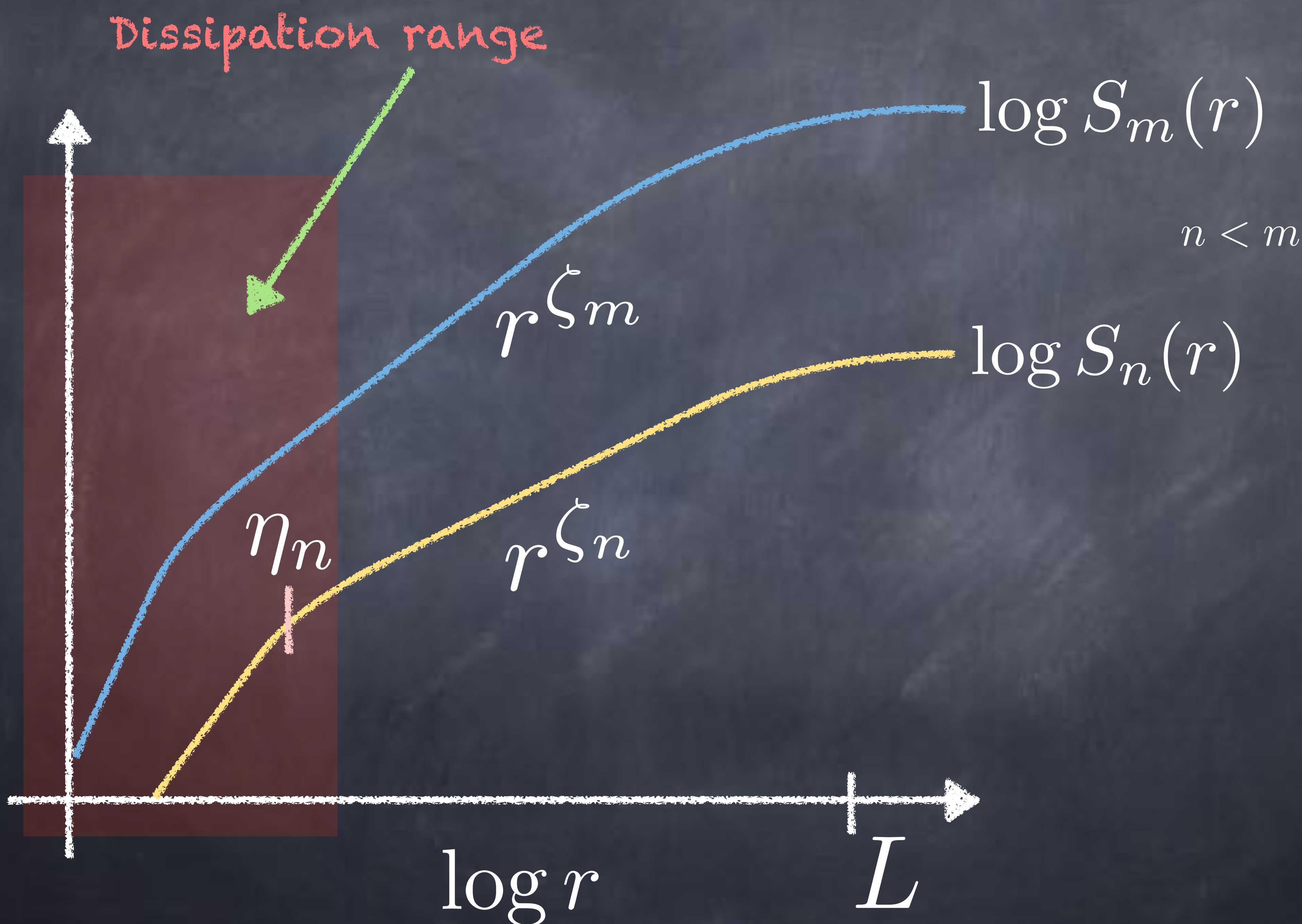
$$\alpha = -0.0127(3)$$

Lipa *et al.* (2003) *PRB*

How accurately can we determine the exponents of turbulence?



Dissipation range
$\log S_n(r)$
η_n
r^{ζ_n}
$\log r$
L


Dissipation range
$\log S_m(r)$
$n < m$
r^{ζ_m}
$\log S_n(r)$
η_n
r^{ζ_n}
$\log r$
L

ESS:

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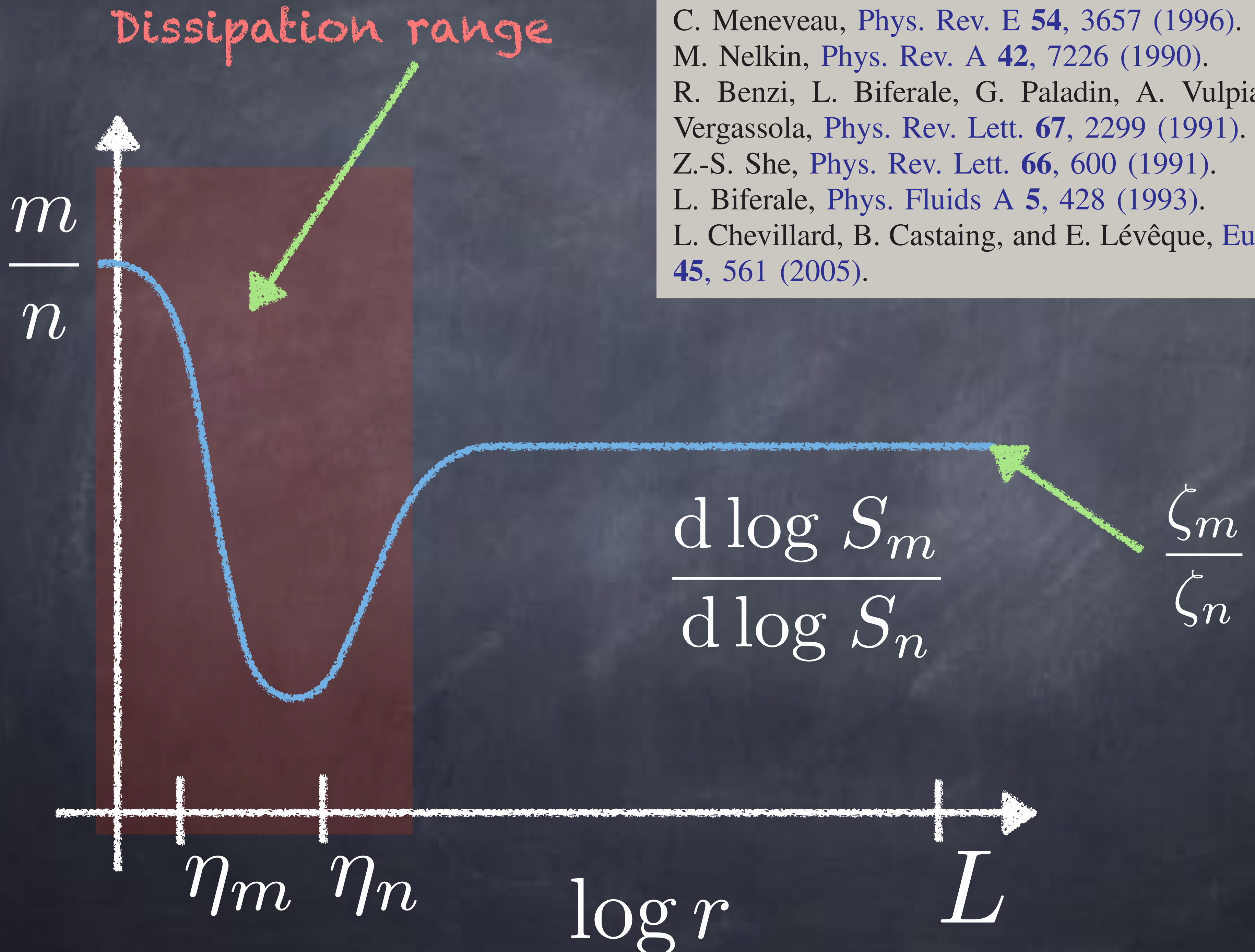

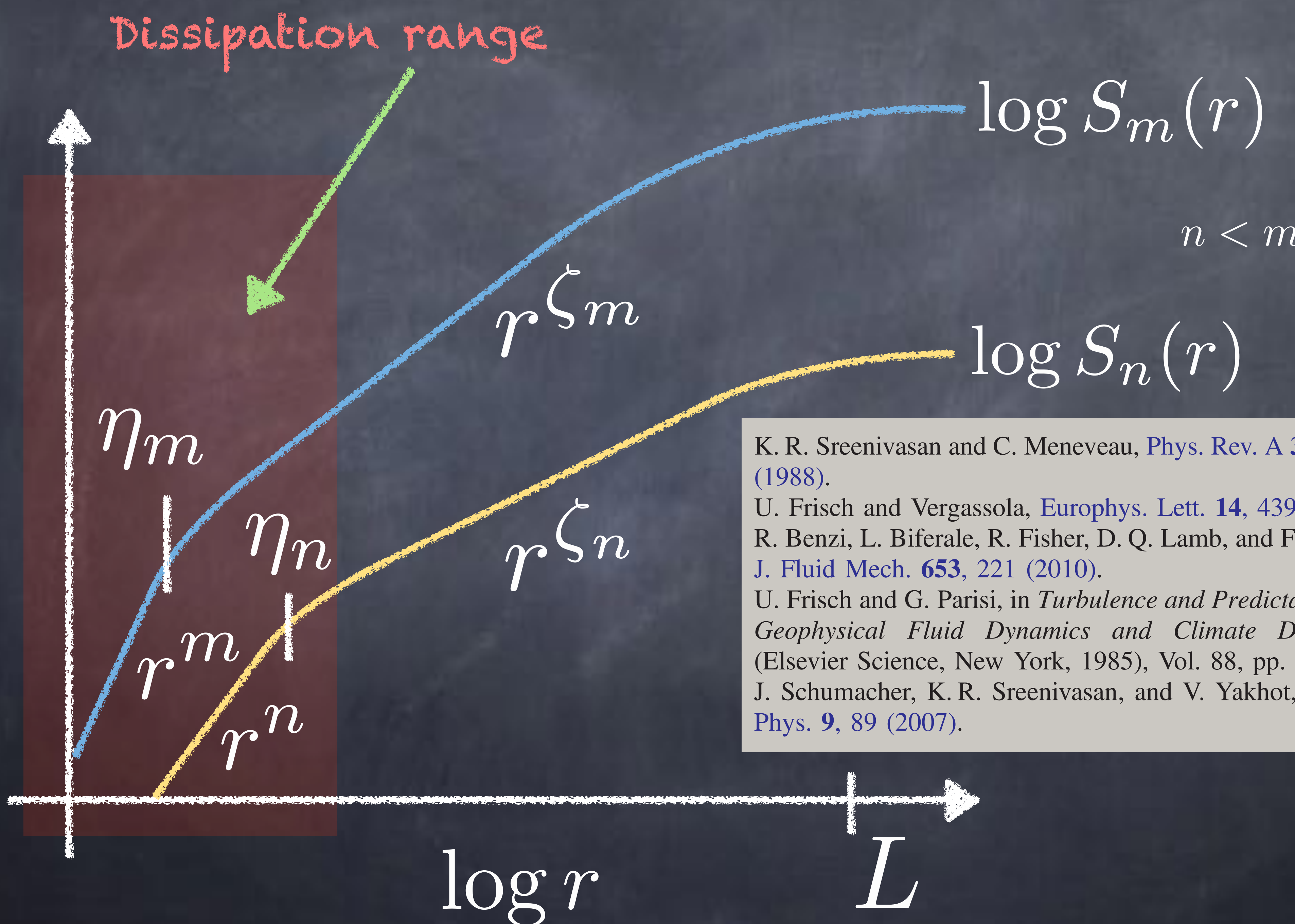

K. R. Sreenivasan and C. Meneveau, Phys. Rev. A **38**, 6287 (1988).

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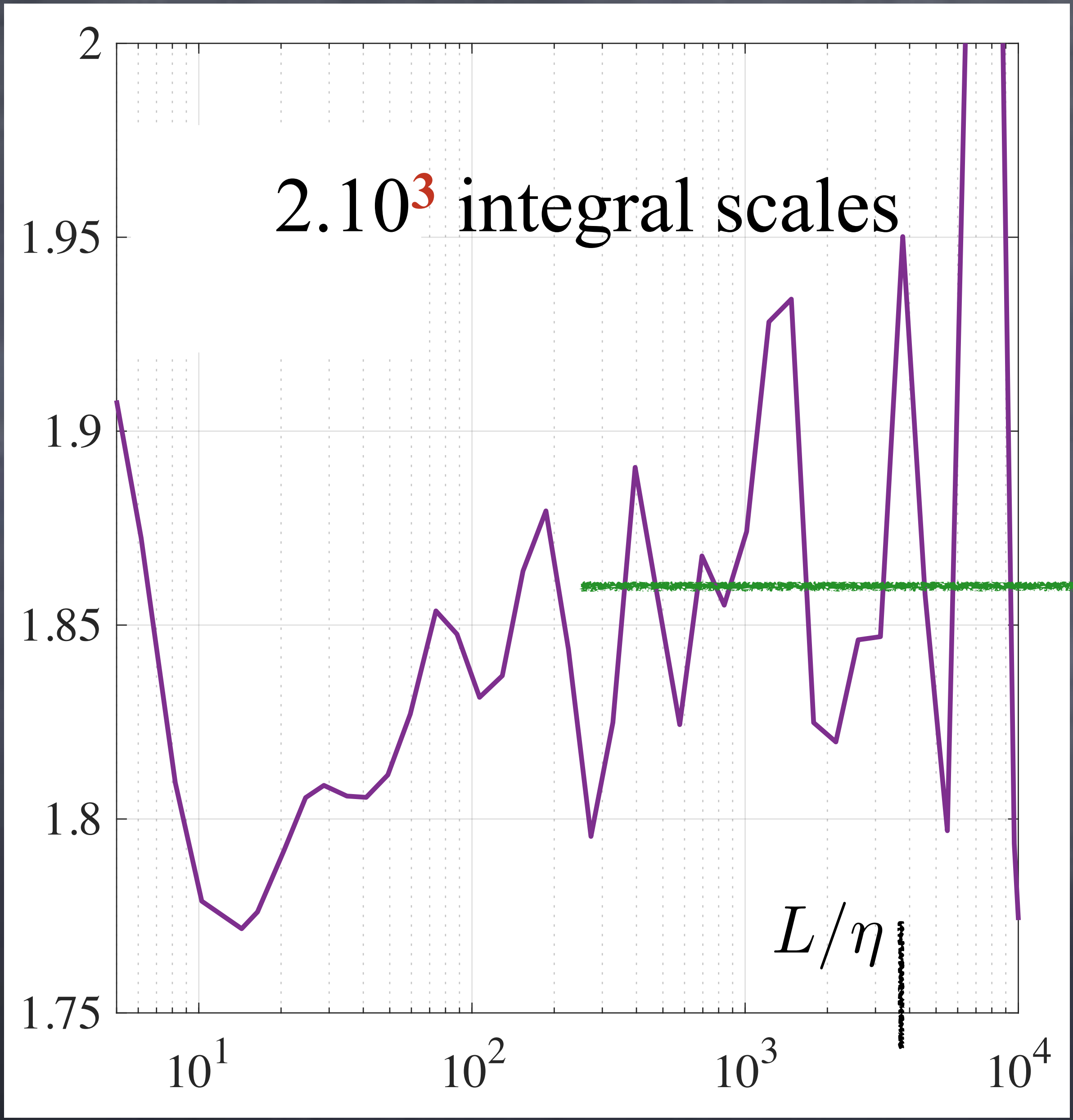
R. Benzi, L. Biferale, R. Fisher, D. Q. Lamb, and F. Toschi, J. Fluid Mech. **653**, 221 (2010).

U. Frisch and G. Parisi, in *Turbulence and Predictability in Geophysical Fluid Dynamics and Climate Dynamics* (Elsevier Science, New York, 1985), Vol. 88, pp. 71–88.

J. Schumacher, K. R. Sreenivasan, and V. Yakhot, New J. Phys. **9**, 89 (2007).

How much data?

$R_\lambda = 1030$



$$\frac{d\log S_4}{d\log S_2}$$

r/η

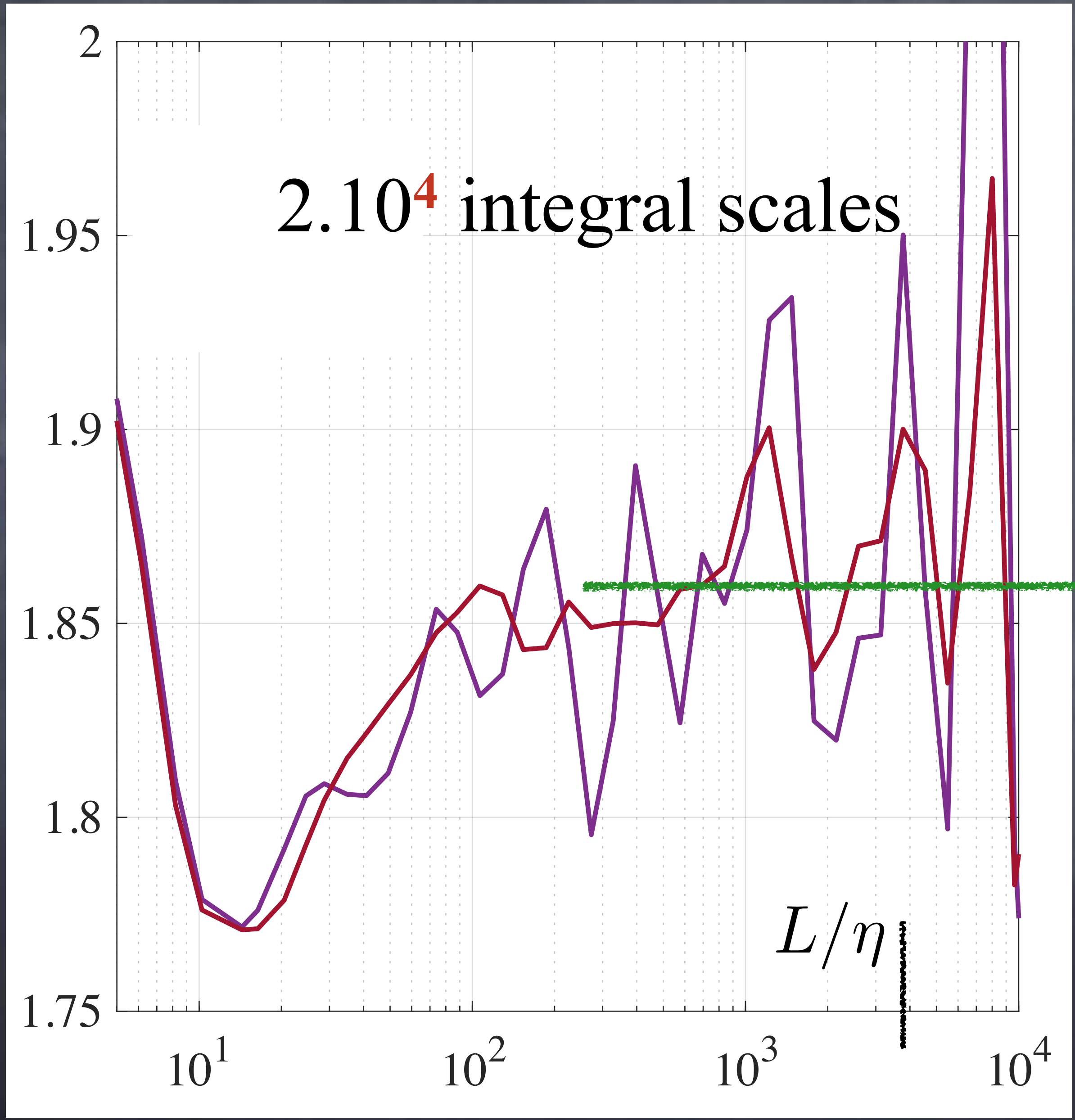
0.2 km of data

$$\frac{\zeta_4}{\zeta_2}$$

How much data?

$R_\lambda = 1030$

$$\frac{d \log S_4}{d \log S_2}$$



r/η

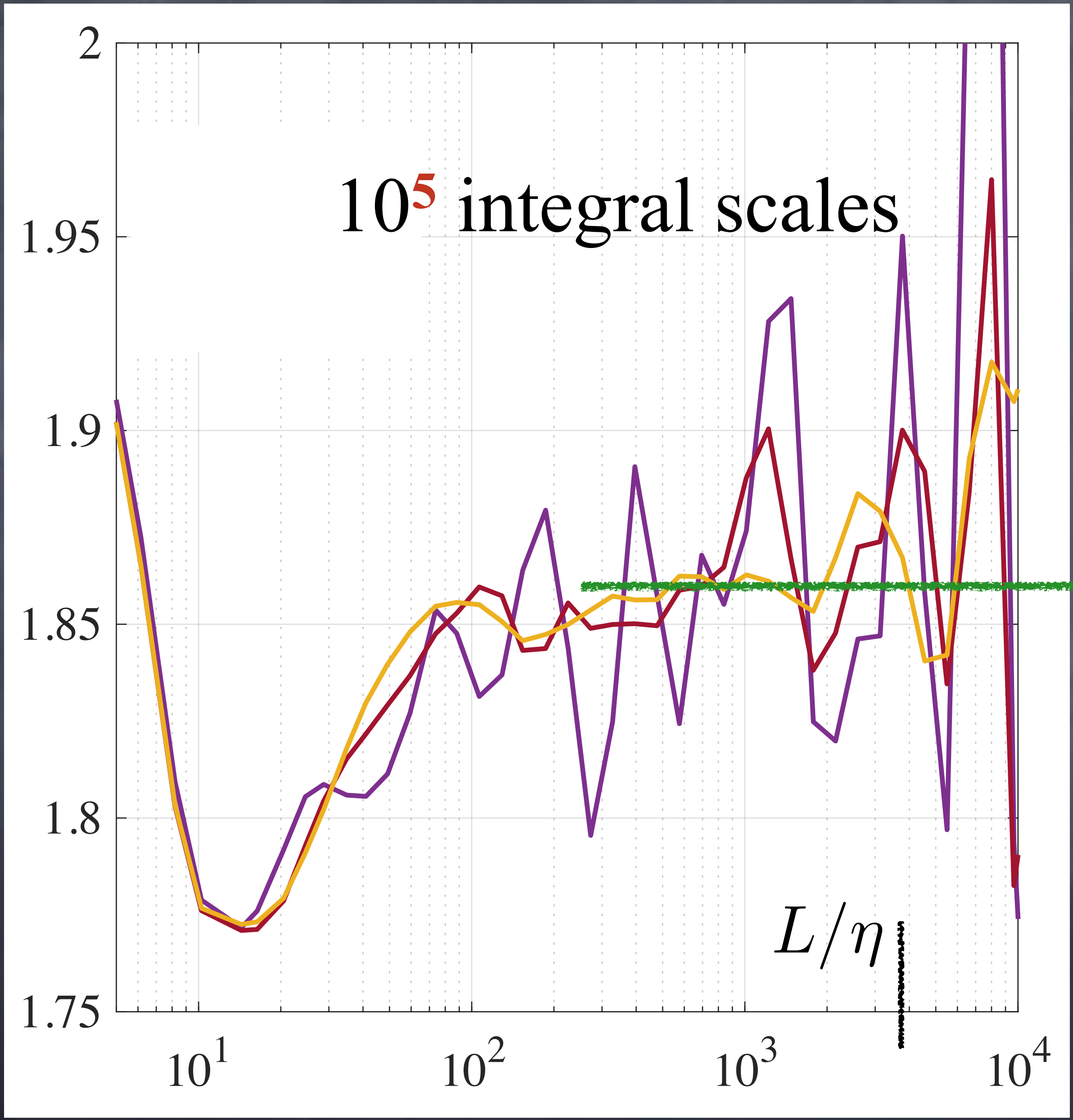
2 km of data

$$\frac{\zeta_4}{\zeta_2}$$

How much data?

$R_\lambda = 1030$

$$\frac{d \log S_4}{d \log S_2}$$



r/η

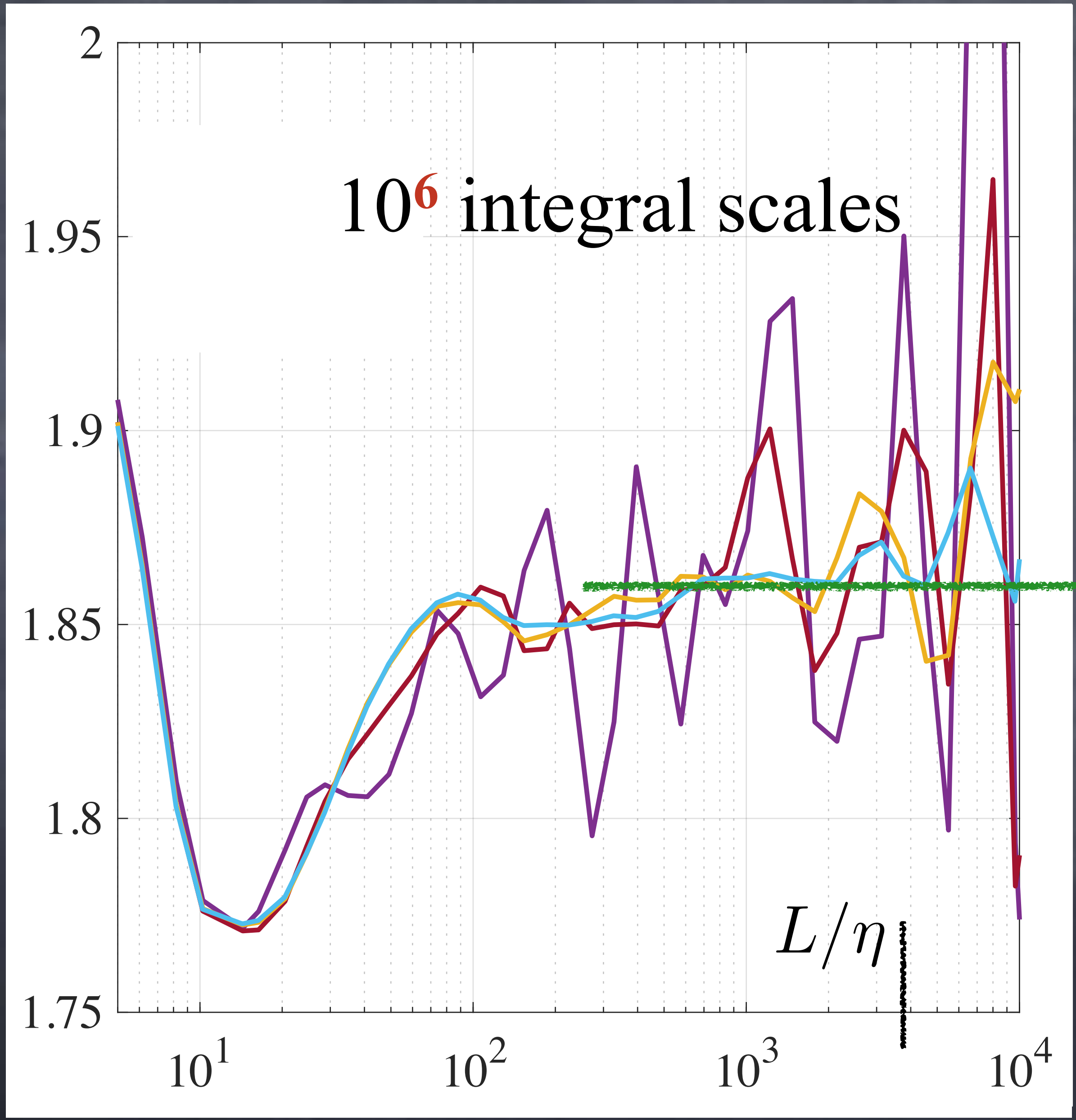
10 km of data

$$\frac{\zeta_4}{\zeta_2}$$

How much data?

$R_\lambda = 1030$

$$\frac{\mathrm{d}\log S_4}{\mathrm{d}\log S_2}$$



r/η

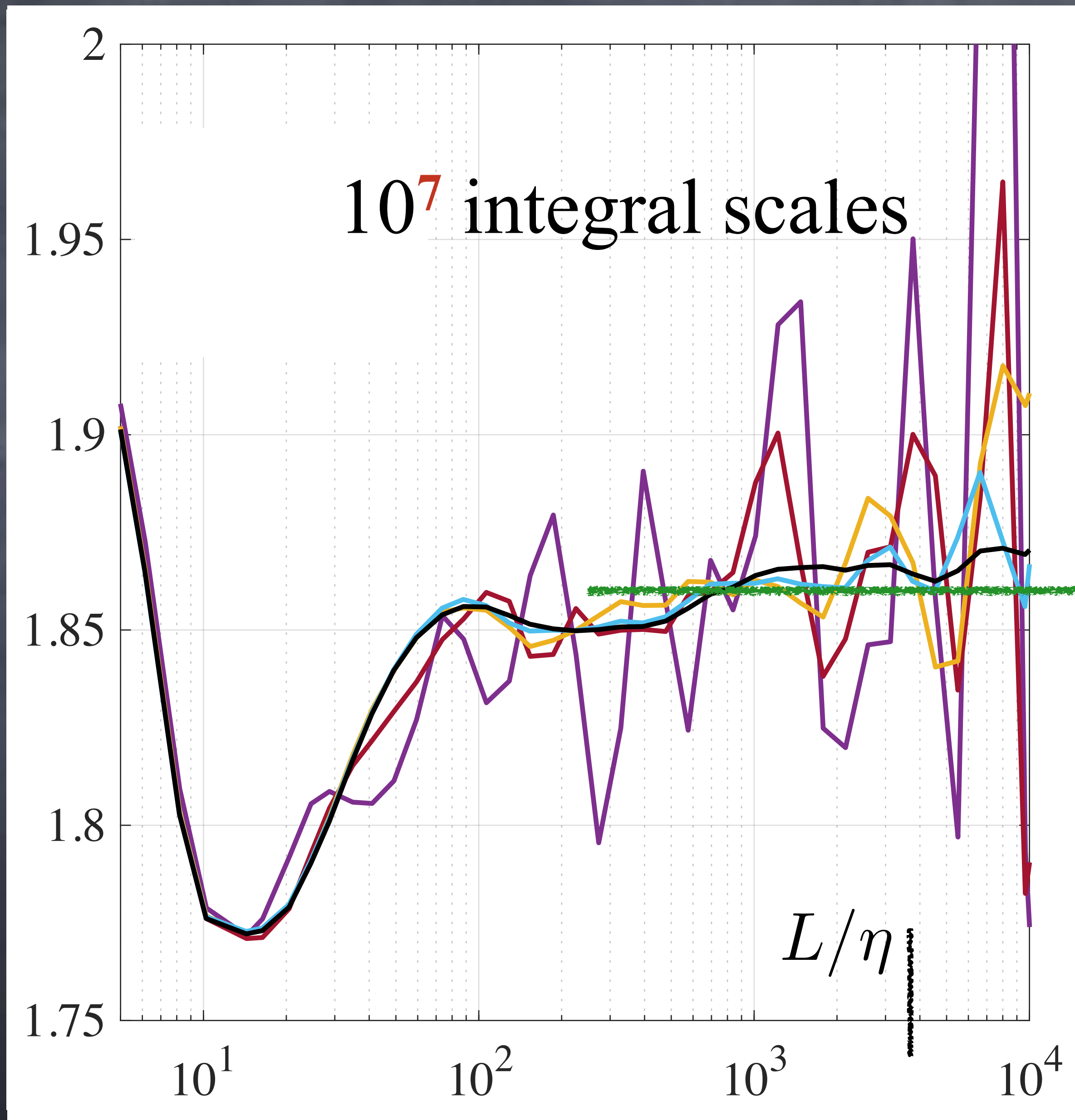
100 km of data

$$\frac{\zeta_4}{\zeta_2}$$

How much data?

$R_\lambda = 1030$

$$\frac{d \log S_4}{d \log S_2}$$



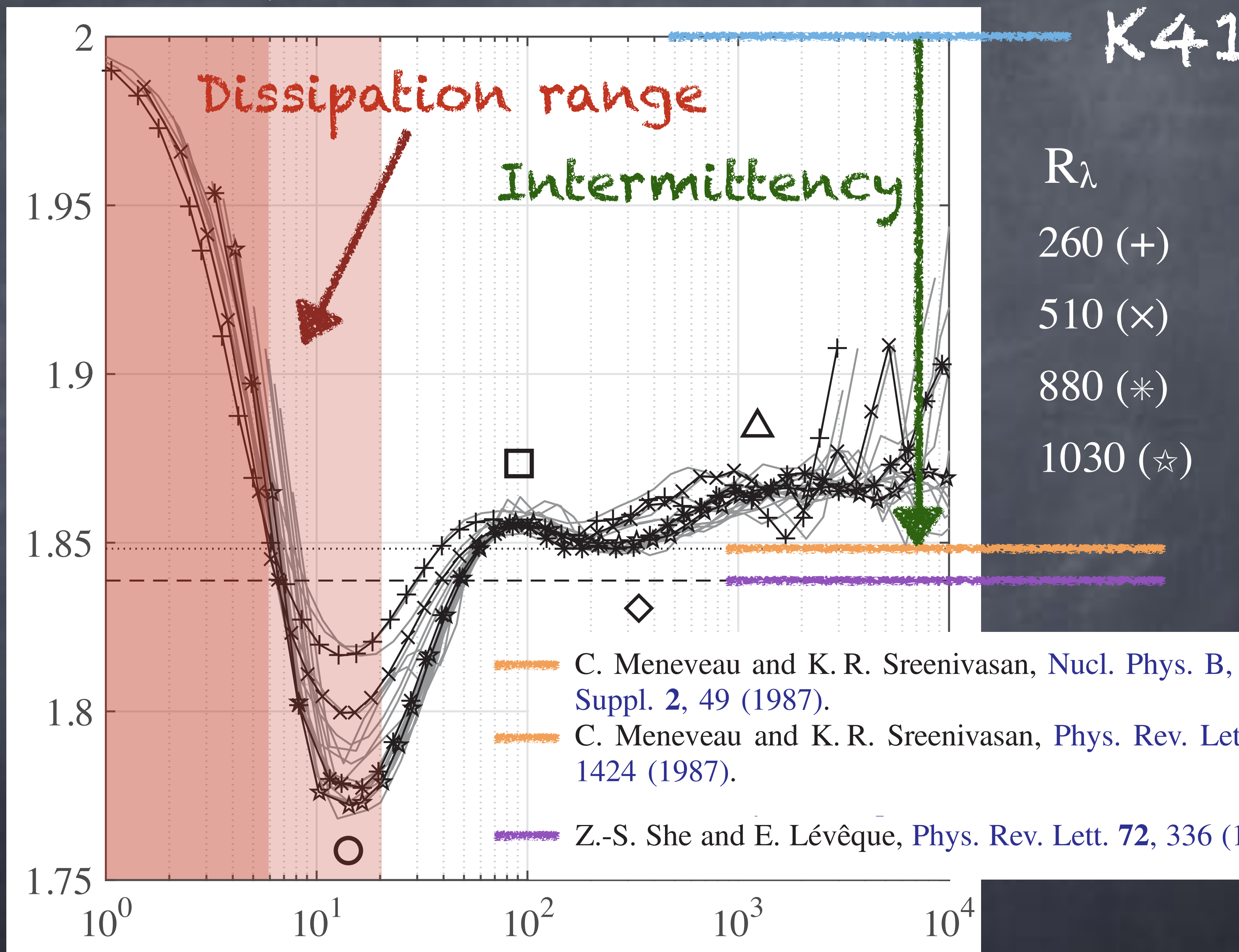
1000 km of data

$$\frac{\zeta_4}{\zeta_2}$$

r/η

For various Reynolds numbers:

$$\frac{d \log S_4}{d \log S_2}$$



C. Meneveau and K. R. Sreenivasan, Nucl. Phys. B, Proc. Suppl. **2**, 49 (1987).

C. Meneveau and K. R. Sreenivasan, Phys. Rev. Lett. **59**, 1424 (1987).

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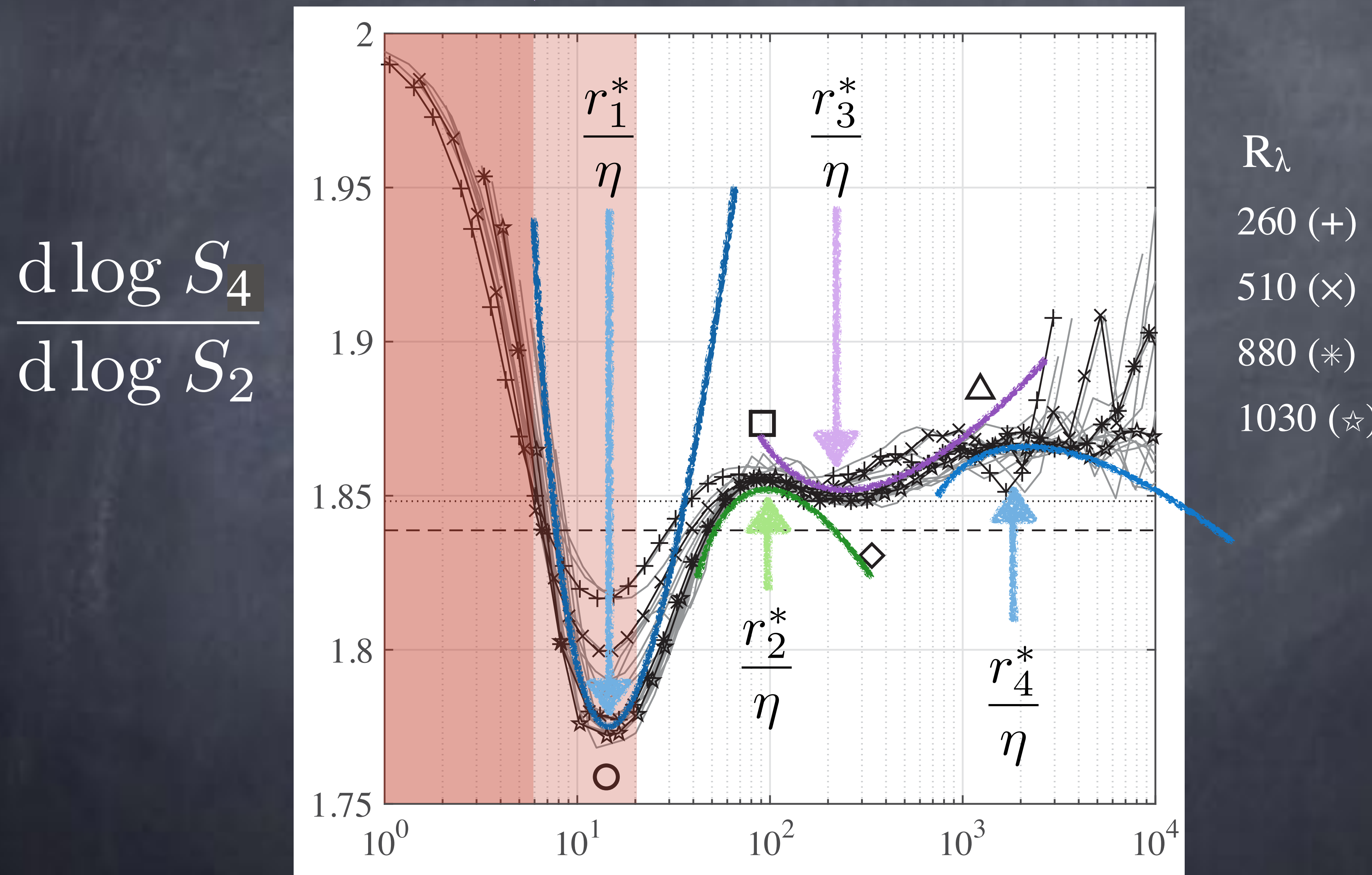
r/η

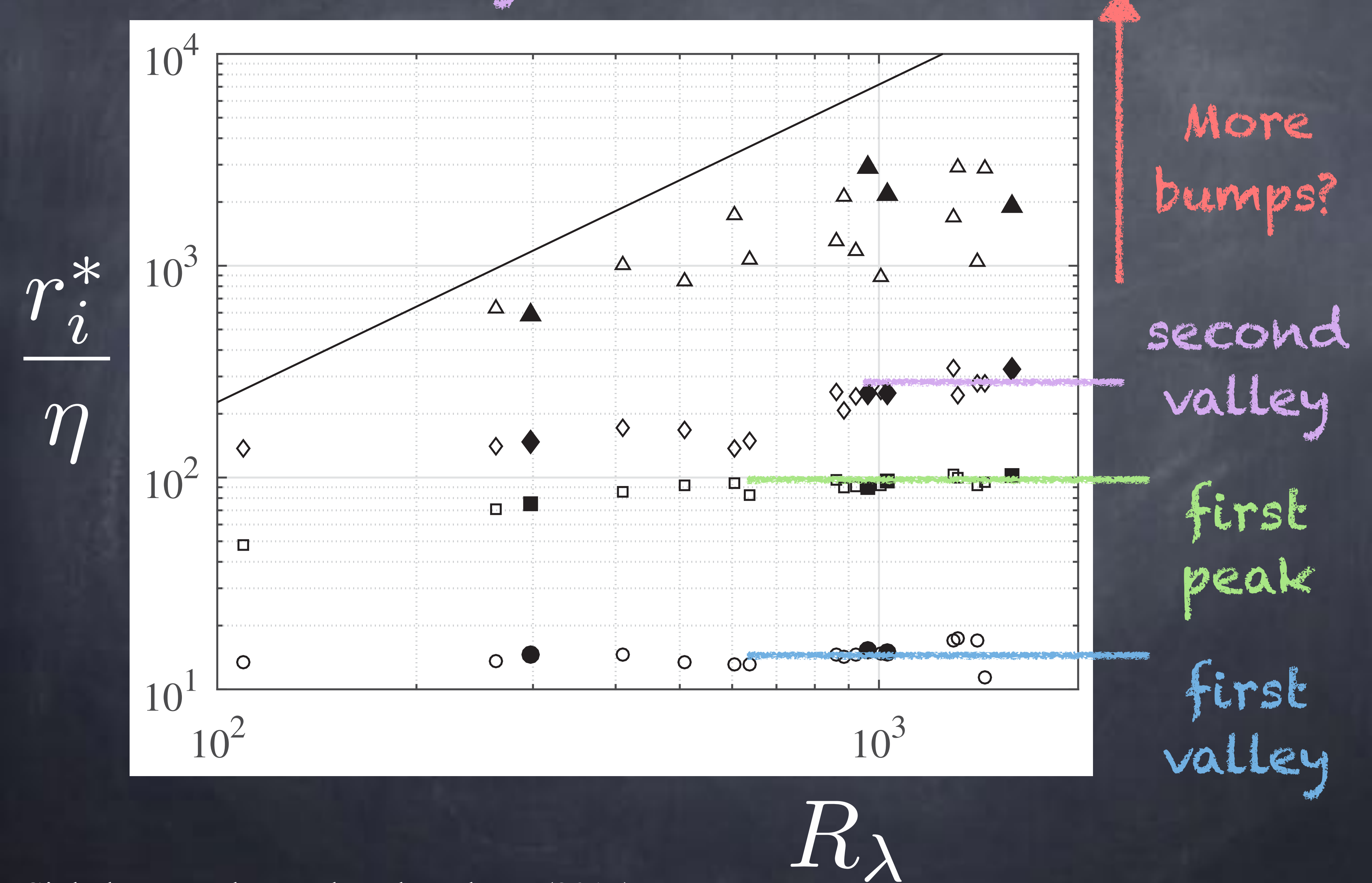
Sinhuber, Bewley, and Bodenschatz (2017) *PRL*

For various Reynolds numbers:



Sinhuber, Bewley, and Bodenschatz (2017) *PRL*

For various Reynolds numbers:



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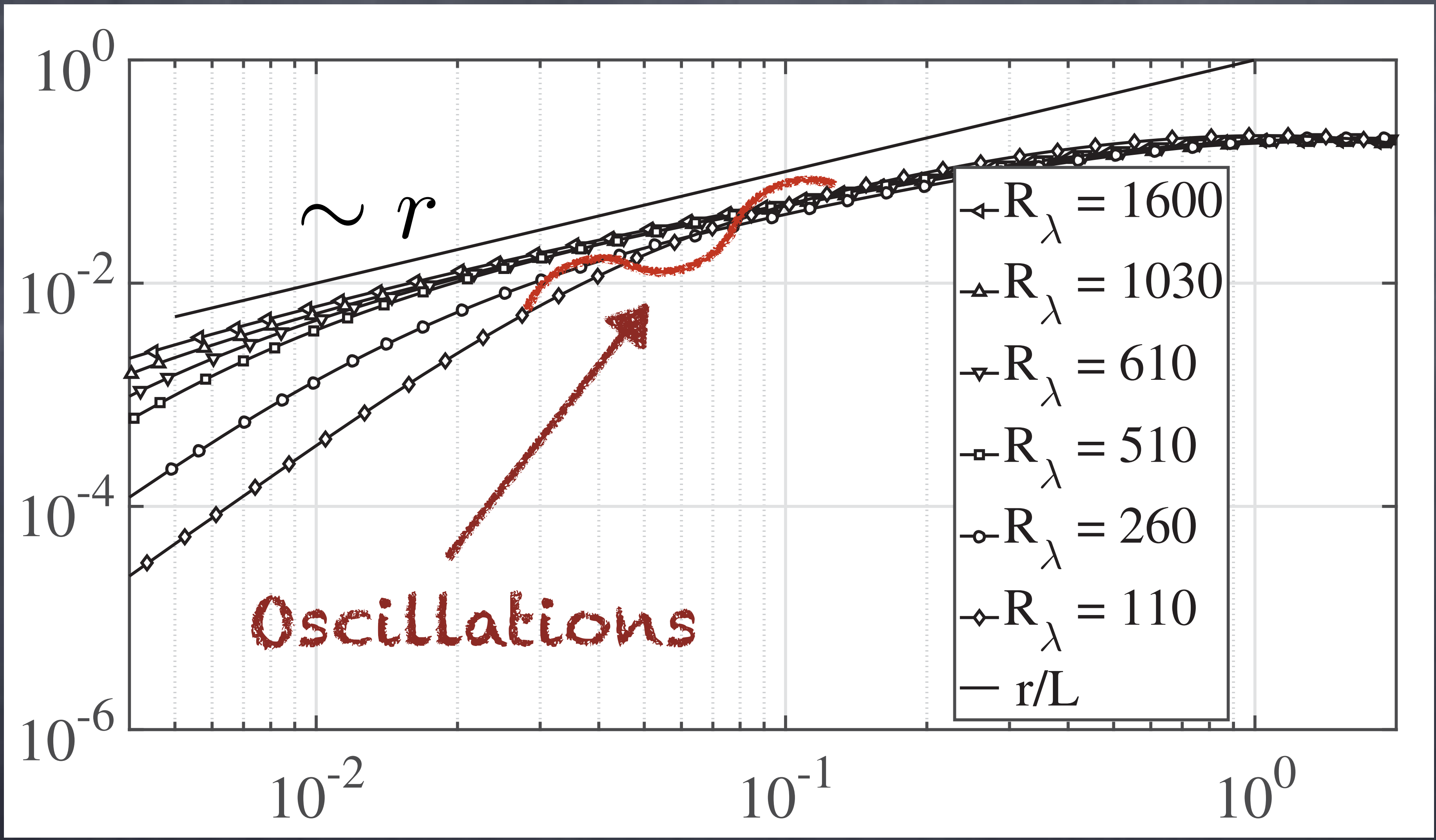
S_3



r/L

Sinhuber, Bewley, and Bodenschatz (2017) *PRL*

Implications

- Structure functions oscillate.
- To measure scaling exponents accurately, these oscillations need to be understood theoretically.

The Bewley applied turbulence lab

Thanks!

Cornell University

Come to Cornell!

THANK YOU!

Wind tunnel

A. Costanzo
C. Küchler
H. Nobach
H. Eckelmann
G. Schewe

NSTAP

M. Vallikivi
M. Hultmark
A. Smits

Active grid

E. Cekli
F. Köhler
J. Kassel
F. Lachaussée
H. Grajewski
H. Zhang
J. Liu
K. Griffin
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W. v.d.Water
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