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Reevaluation of Control Performance for Turbulent Skin Friction Drag Reduction in terms of Energy Saving and Convenience

Money versus Time

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Center of
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Skin Friction Drag Reduction Technology

☐ Key Aspects of Practical Fluid Transport Systems

✓ **Convenience**

- flow rate in pipeline

- travel speed of vehicle

✓ **Energy Saving**

- energy consumption to achieve certain "*Convenience*"

☐ Evaluation of Control Performance in Fundamental Studies

✓ **Constant Flow Rate (CFR)**: wall friction is changed by control

Successful Control

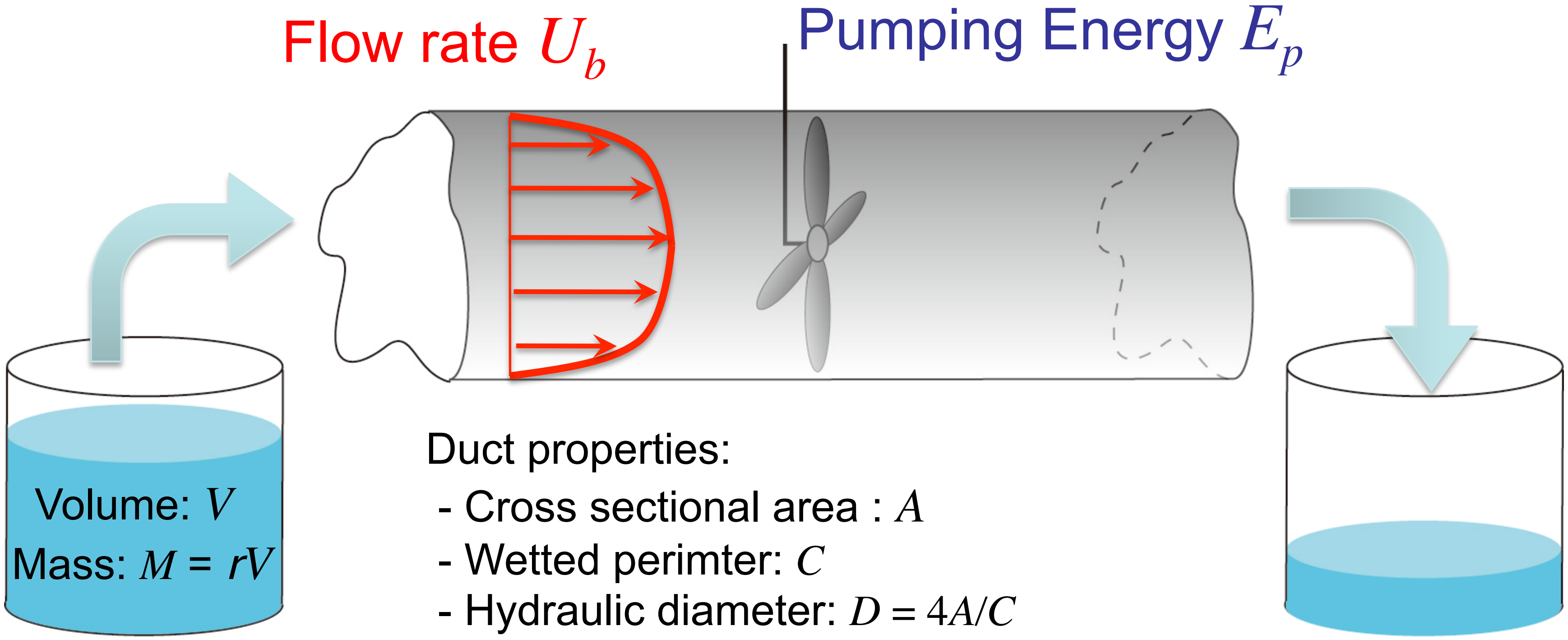
Reduction of wall friction (reduction of pumping power)

✓ **Constant Pressure Gradient (CPG)**: wall friction is kept constant by design

Successful Control

Increase of flow rate (increase of pumping power)

Internal Flow



Duct properties:

- Cross sectional area : A
- Wetted perimter: C
- Hydraulic diameter: $D = 4A/C$

✓ <u>Fluid travel time per unit length</u>: $1/U_b$

✓ <u>Pumping energy per unit wetted area</u>:

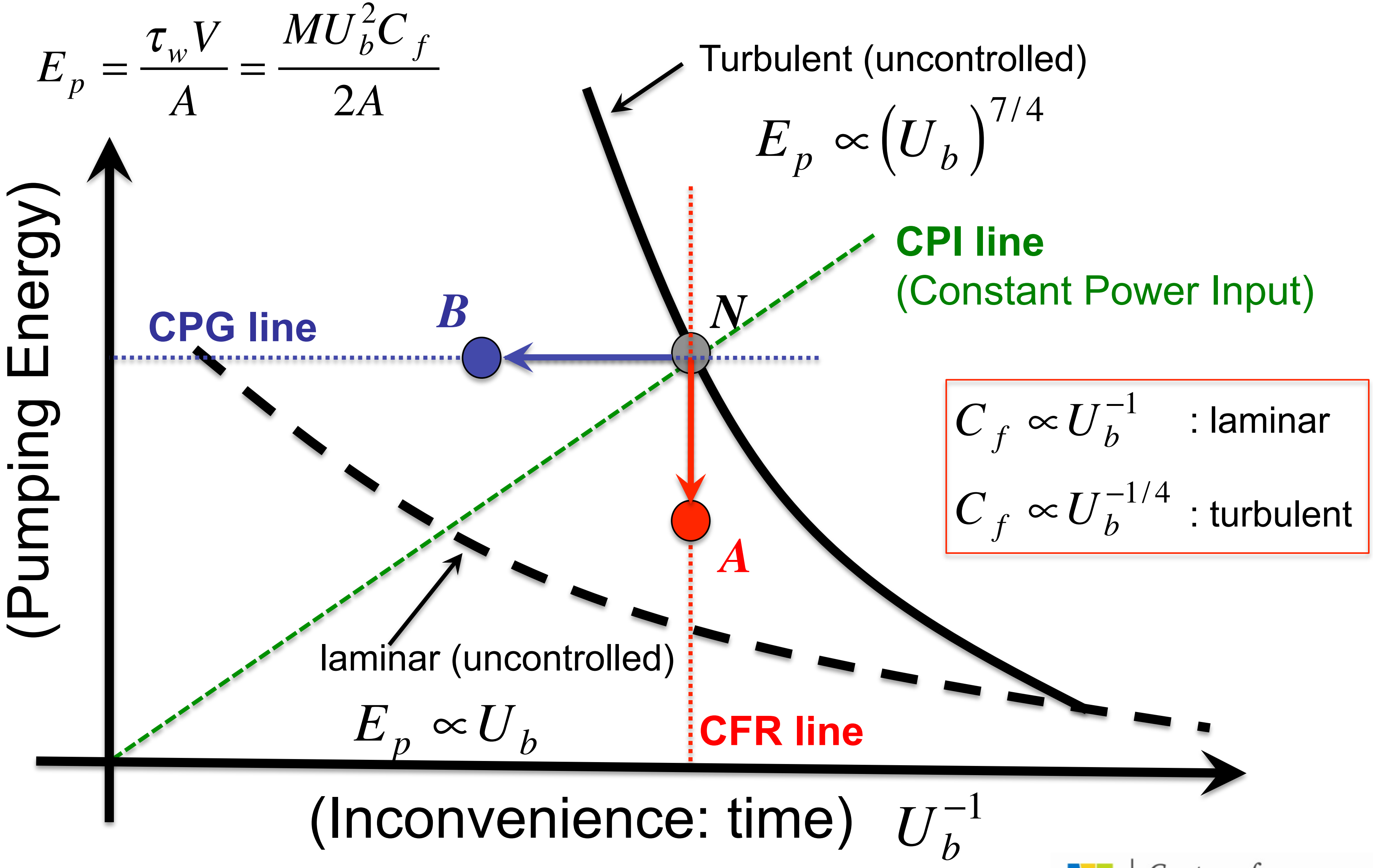
$$E_p = \frac{\tau_w V}{A} = \frac{M U_b^2 C_f}{2A}$$

Friction coefficient

$$C_f = \frac{\tau_w}{\frac{1}{2}\rho U_b^2}$$

Energy Saving vs Convenience

$$E_p = \frac{\tau_w V}{A} = \frac{M U_b^2 C_f}{2A}$$



Turbulent (uncontrolled)

$$E_p \propto \left(U_b\right)^{7/4}$$

CPI line
(Constant Power Input)

CPG line

B

N

A

laminar (uncontrolled)

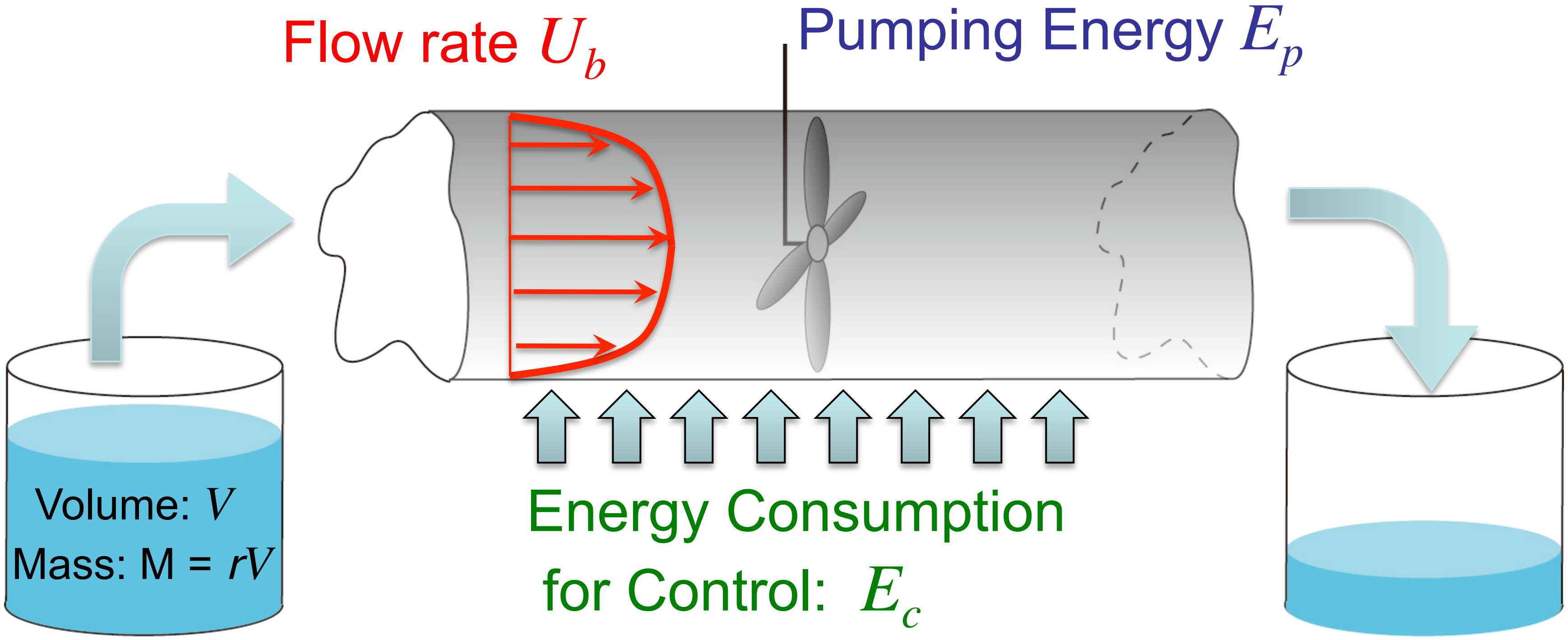
$$E_p \propto U_b$$

CFR line

$C_f \propto U_b^{-1}$: laminar

$C_f \propto U_b^{-1/4}$: turbulent

Active Control of Internal Flow



Flow rate U_b

Pumping Energy E_p

Volume: V

Mass: M = rV

Energy Consumption
for Control: E_c

- ✓ Fluid travel time per unit length: $1/U_b$
- ✓ **Total** energy consumption per unit wetted area:

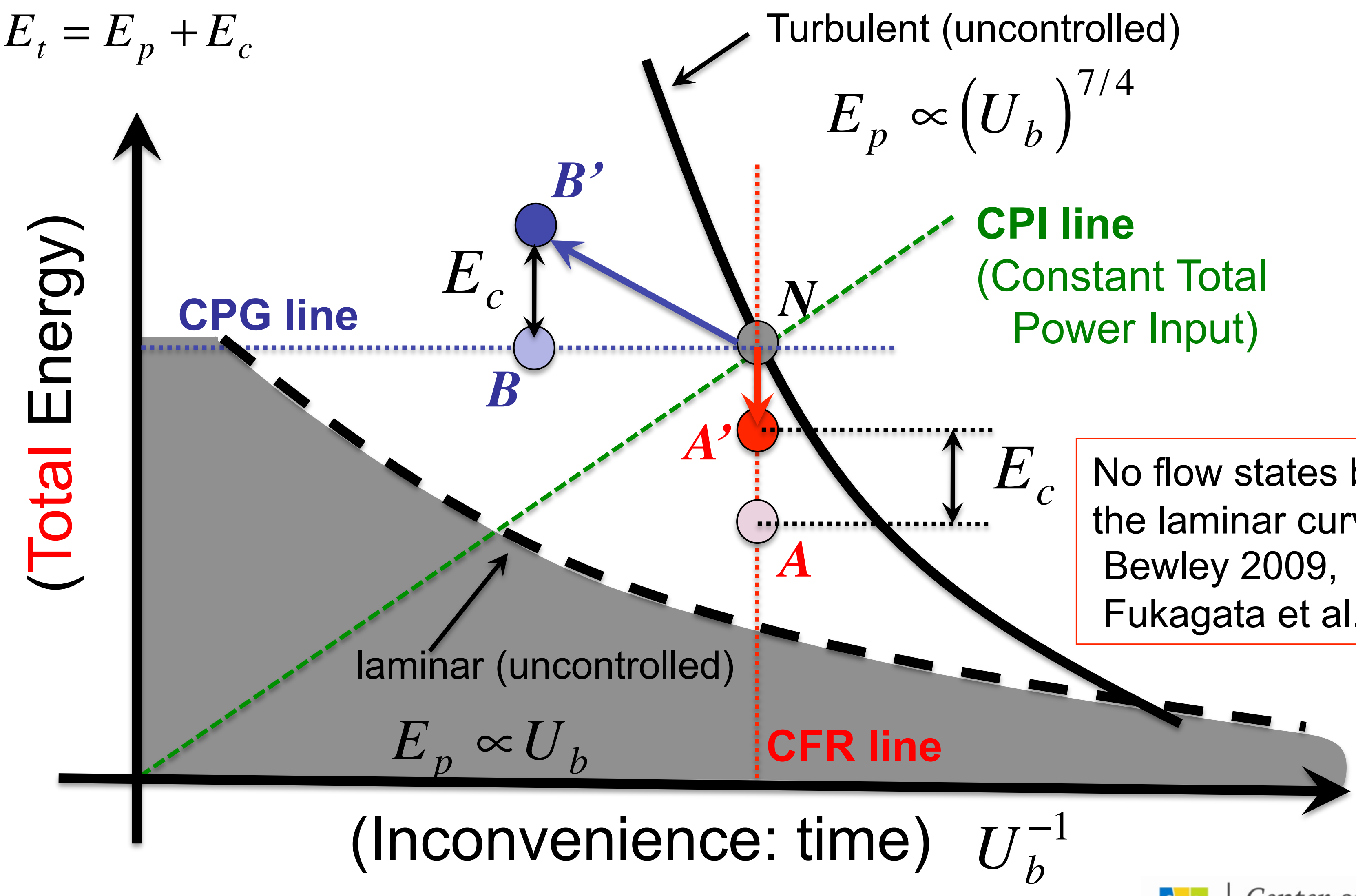
$$E_t = \boxed{E_p} + \boxed{E_c}$$

Control energy

Pumping energy

Energy Saving vs Convenience

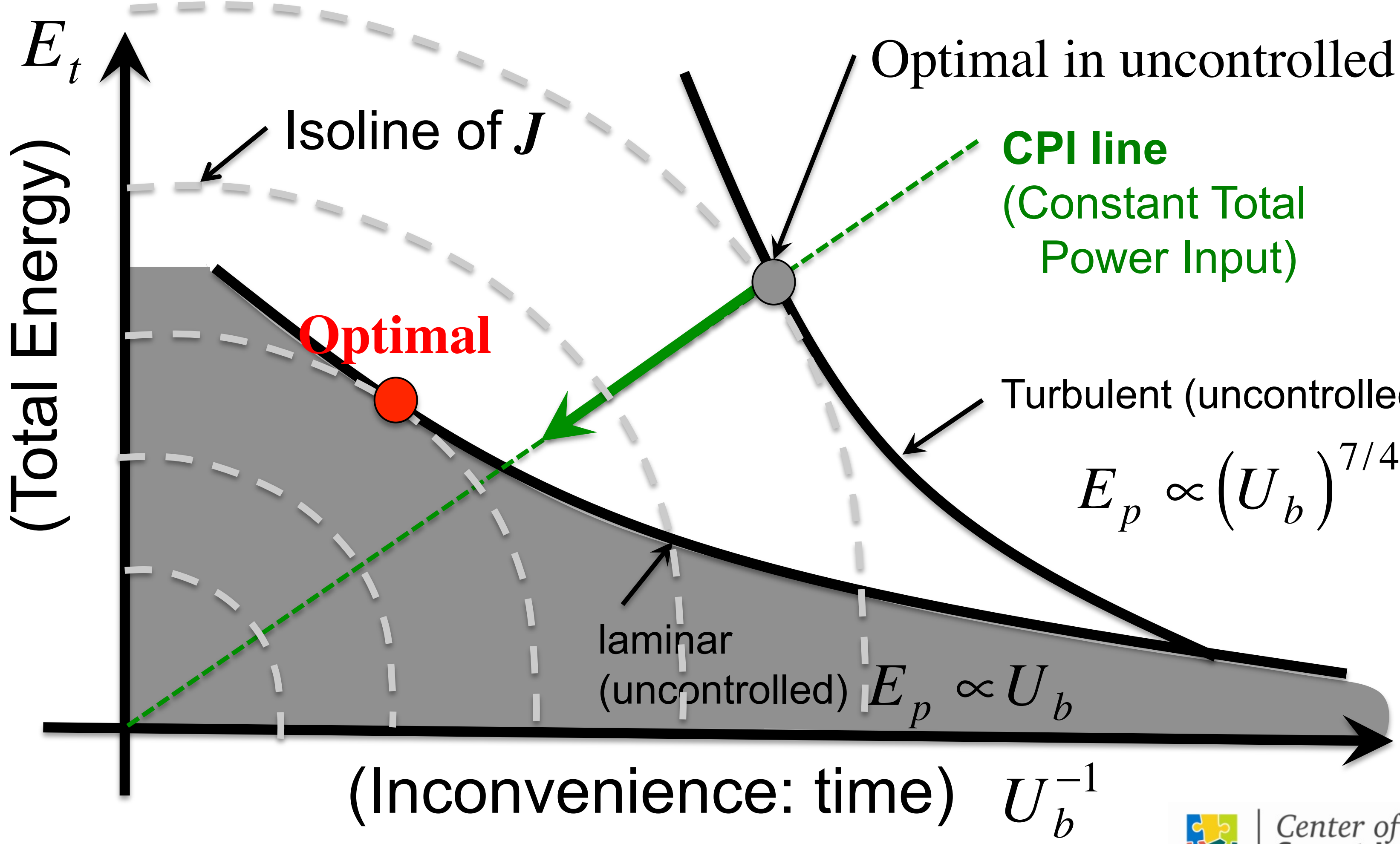
$$E_t = E_p + E_c$$



No flow states below the laminar curve
Bewley 2009,
Fukagata et al., 2009

Example

Cost function: $J = E_t^2 + \left(1/U_b\right)^2$



Non-dimensionalization

☐ Convenience (Fluid travel time per unit length)

$$T_c = 1/U_b \Rightarrow \left(\frac{1}{U_b}\right)\left(\frac{\nu}{D}\right) = \frac{\nu}{U_b D} = \mathrm{Re}_b^{-1}$$

☐ Energy Expenditure

✓ **Pumping Energy**

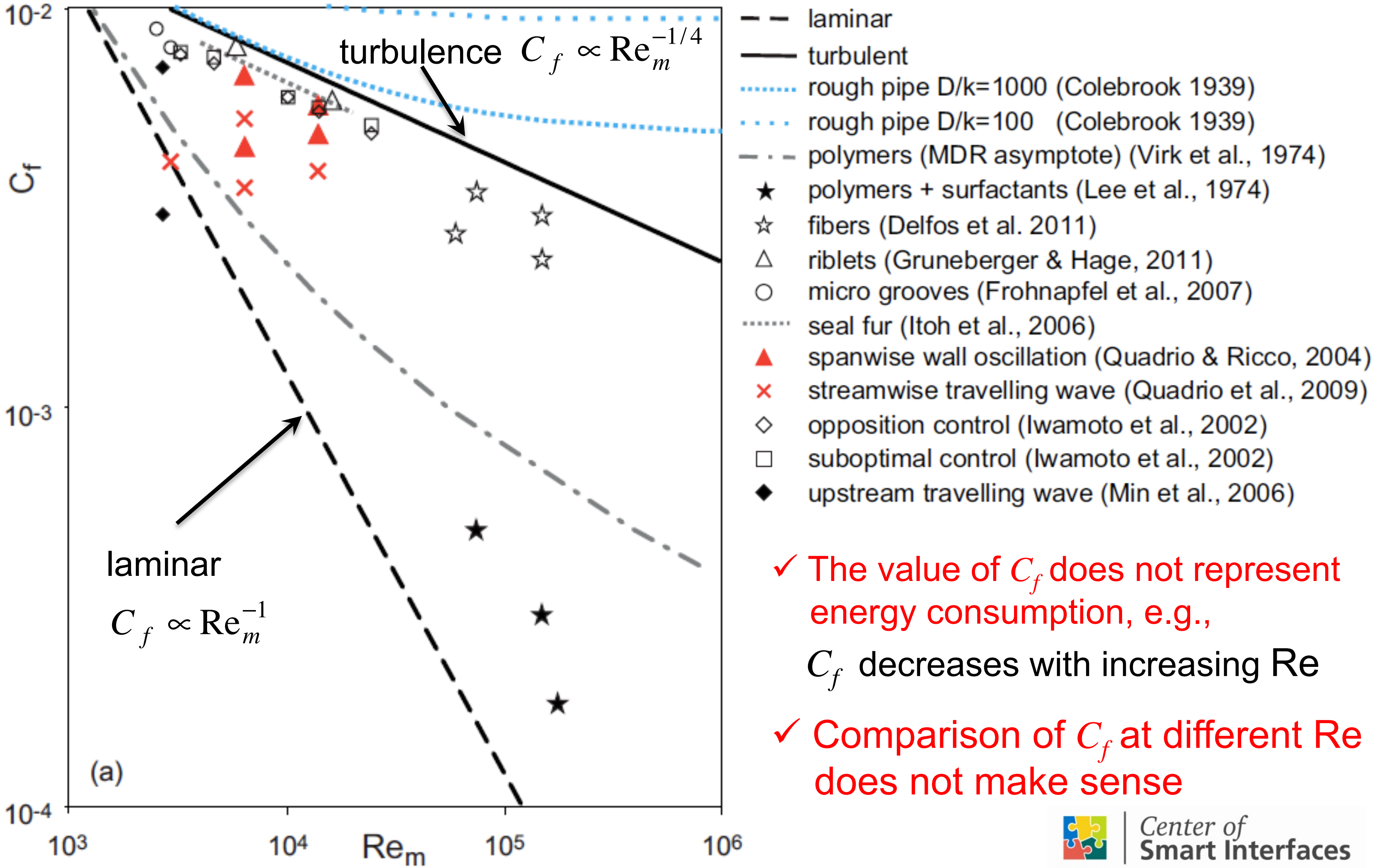
$$E_p = \frac{MU_b^2 C_f}{2A} \Rightarrow C_f = E_p\left(\frac{2A}{M\boxed{U_b^2}}\right) \Rightarrow C_f \mathrm{Re}_b^2 = E_p\left(\frac{2AD^2}{M\nu^2}\right)$$

✓ **Total Energy (Pumping + Control)**

***Effective* wall friction**

$$\tau_w^e = \frac{P_p + P_c}{U_b} = \tau_w + \frac{P_c}{U_b} \Rightarrow C_f^e \mathrm{Re}_b^2 = E_t\left(\frac{2AD^2}{M\nu^2}\right)$$

Conventional C_f-Re_b Plot

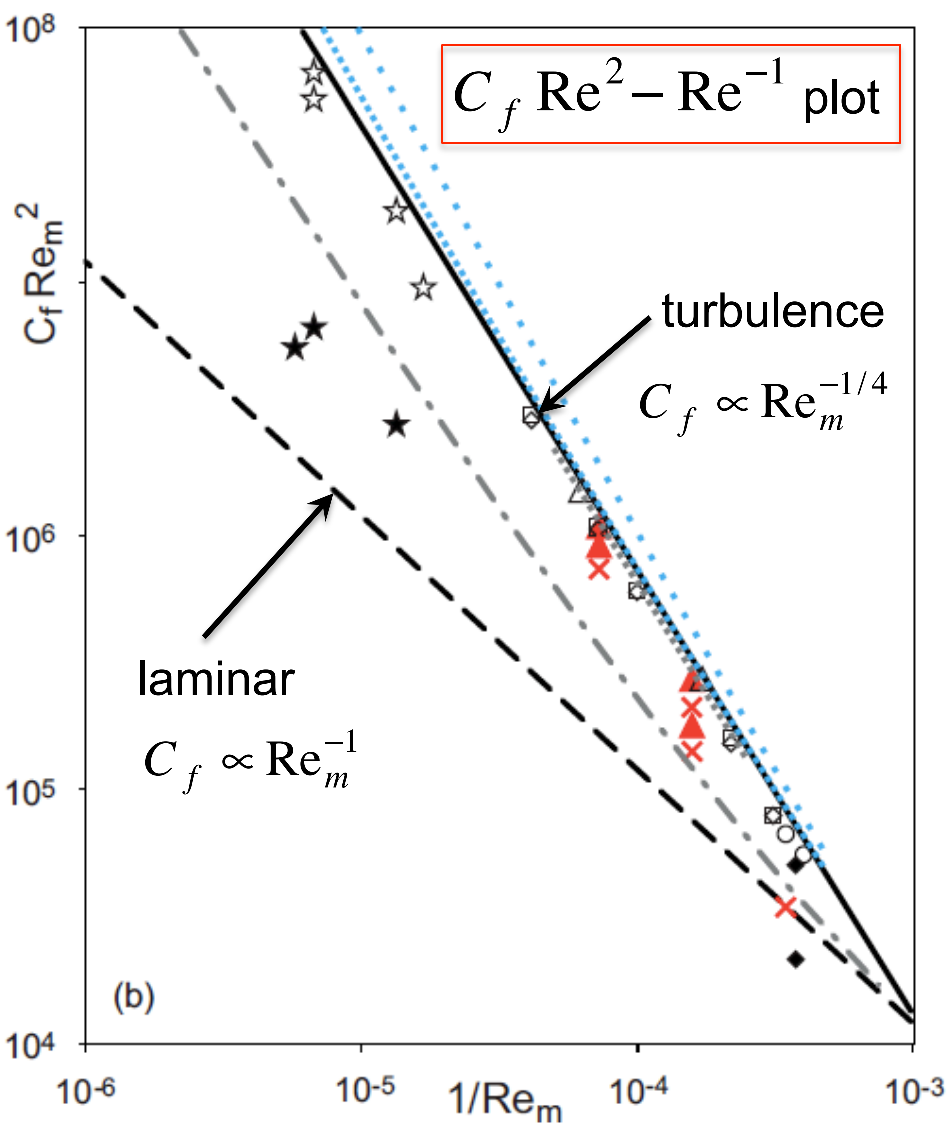


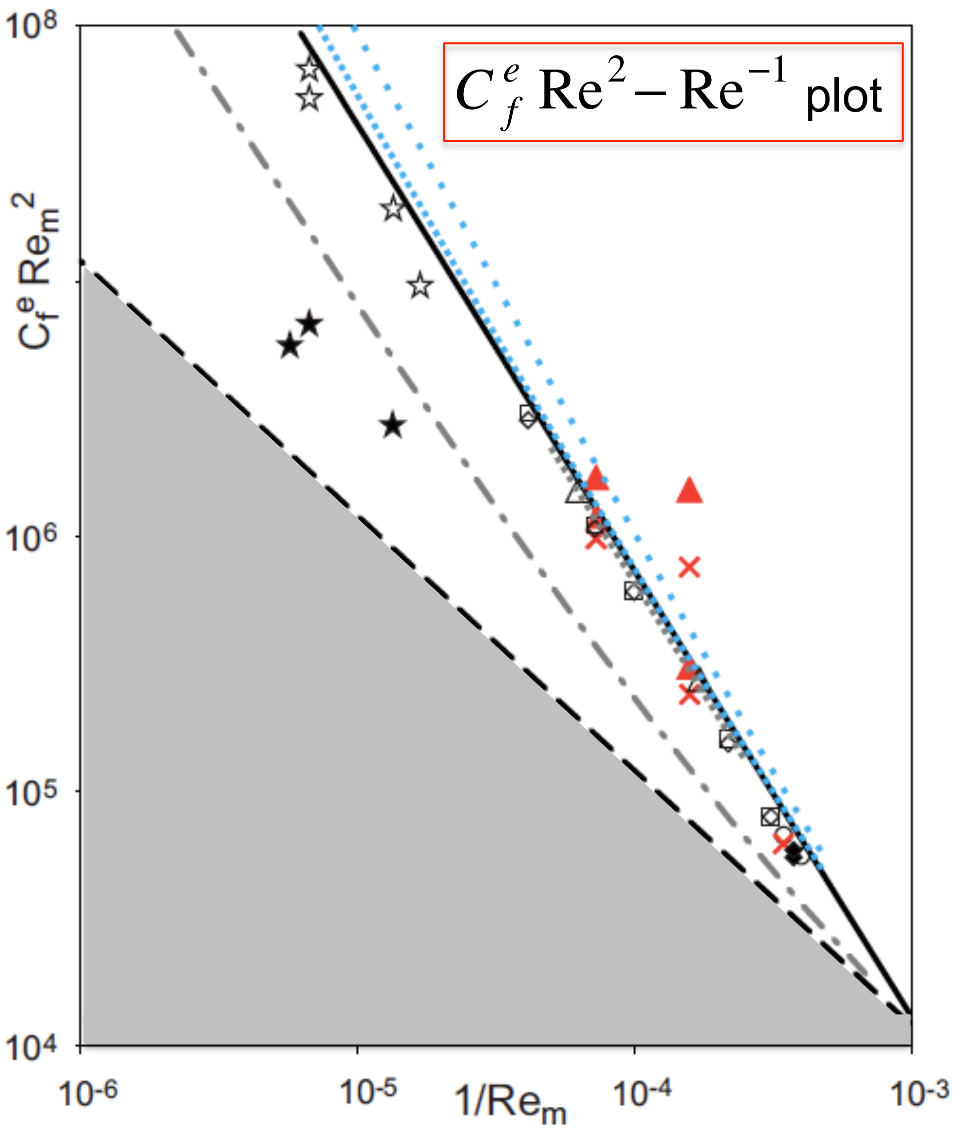
- ✓ The value of C_f does not represent energy consumption, e.g.,

  C_f decreases with increasing Re

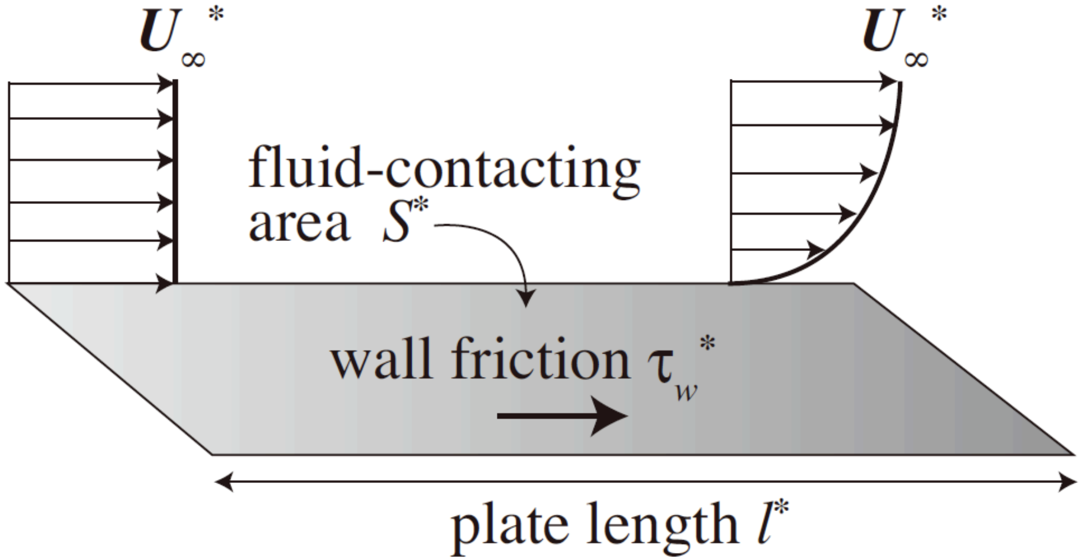
- ✓ Comparison of C_f at different Re does not make sense

New Plot (*Energy vs Convenience Plot*)





Application to External Flow



- ☐ **Convenience (traveling time per unit distance)**

$$\left(U_\infty\right)^{-1} \Rightarrow \nu/\left(U_\infty l\right) = \boxed{\mathrm{Re}_l^{-1}}$$

- ☐ **Propulsion energy per unit fluid-contacting area and unit distance**

$$E_p = \frac{1}{2}\rho U_\infty^2 \overline{C_f} \Rightarrow \boxed{\overline{C_f}\,\mathrm{Re}_l^2} = E_p / \left(\frac{\rho \nu^2}{2l^2}\right)$$

$C_f Re^2$-Re^{-1} plot can also be used for external flows

Conclusions

- **In real applications, a compromise between *Convenience* (Time) and *Energy expenditure* (Money) has to be reached so as to accomplish a goal which in general depends on a specific application.**

- **Based on this idea, we propose a new evaluation plane (money-time plane), which can be viewed as an improved version of the conventional Cf-Re plot.**

- **The new plane consists of two dimensionless parameters Re^{-1} and $C_f Re^2$ which represent the flow rate (convenience) and the energy expenditure required to achieve that flow rate, respectively.**

- **The new evaluation plane is useful to seek the optimal control strategy for minimizing the application-dependent cost function.**

- **The above considerations can be easily extended to external flows.**

Reference:

Frohnapfel, Hasegawa & Quadrio, "Money versus Time", JFM Vol. 700, pp.406-418, 2012