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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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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)

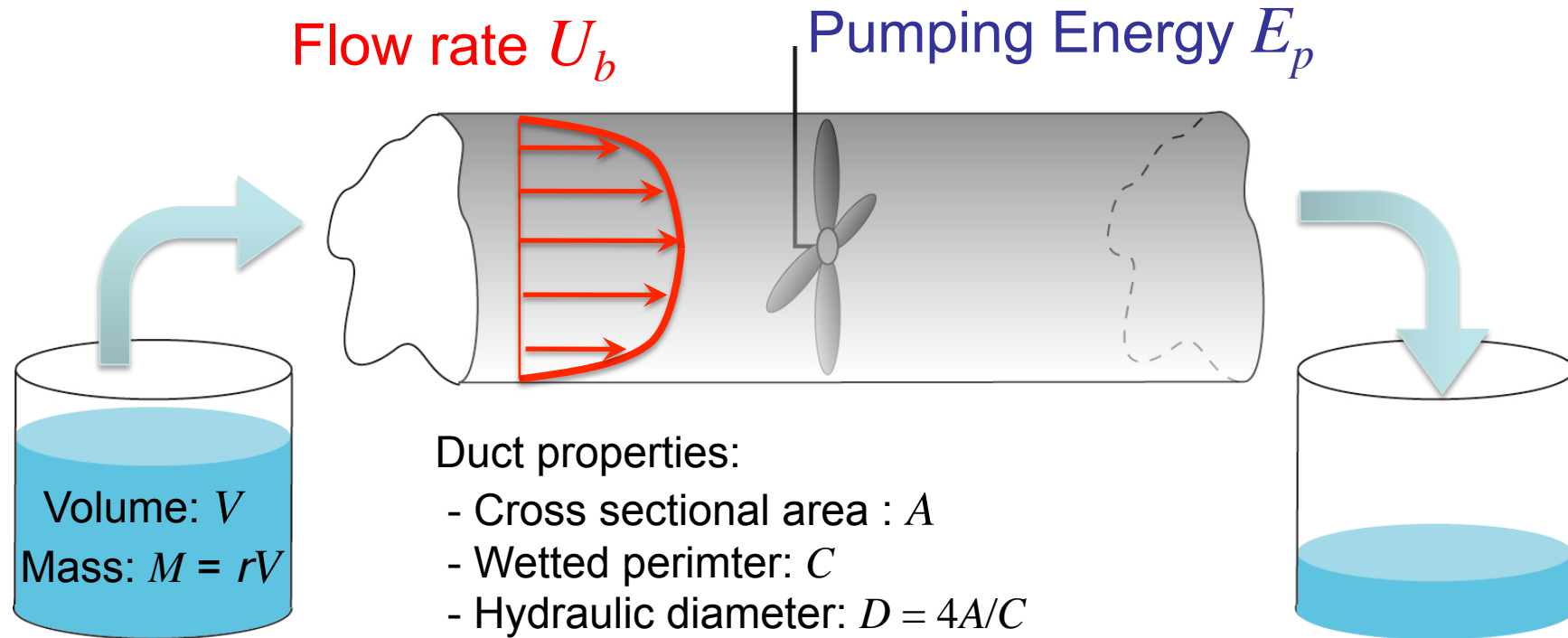
- ✓ **Constant Pressure Gradient (CPG):** wall friction is kept constant by design

Successful Control

Increase of flow rate (increase of pumping power)



Internal Flow



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

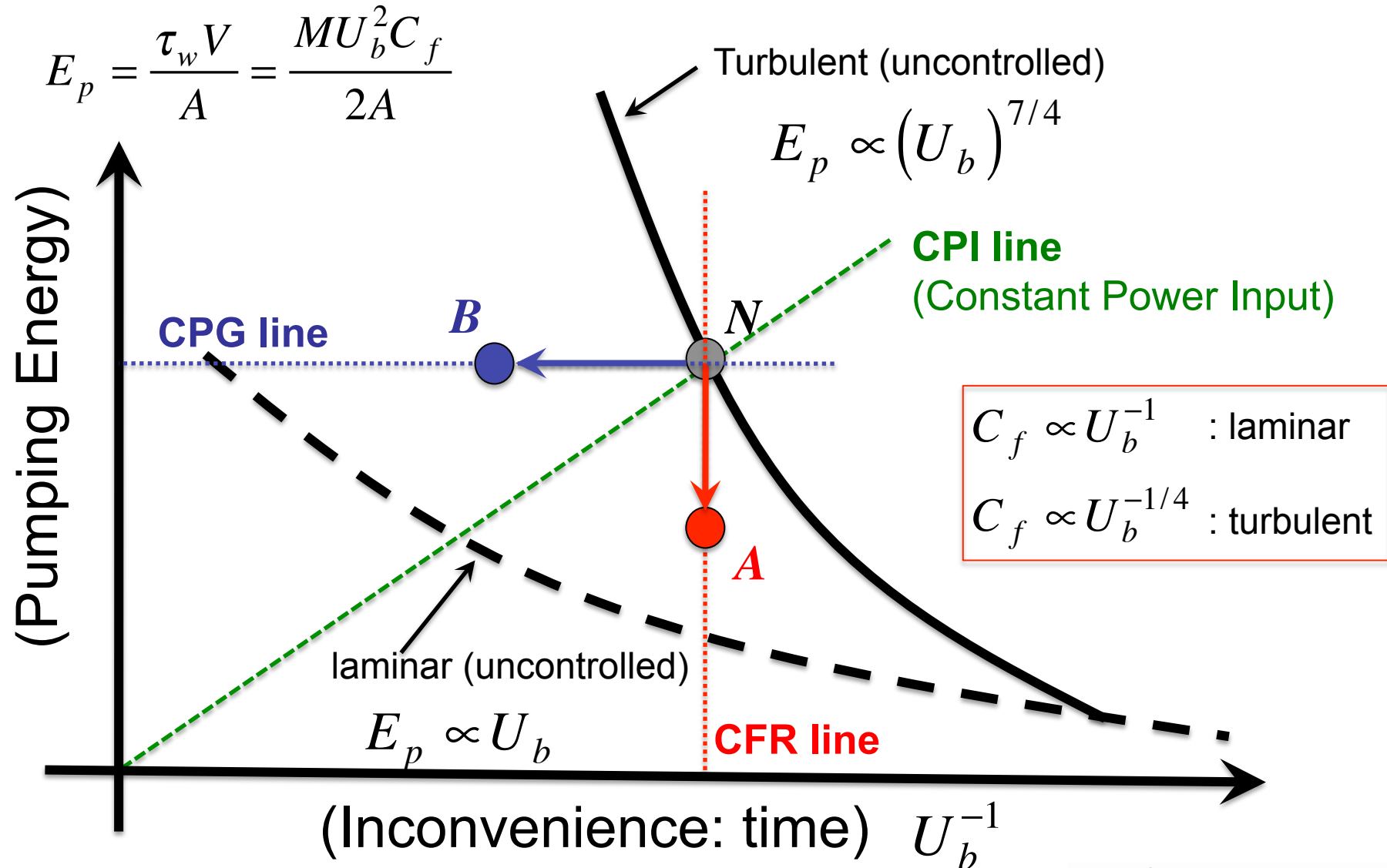
$$E_p = \frac{\tau_w V}{A} = \frac{MU_b^2 C_f}{2A}$$

Friction coefficient

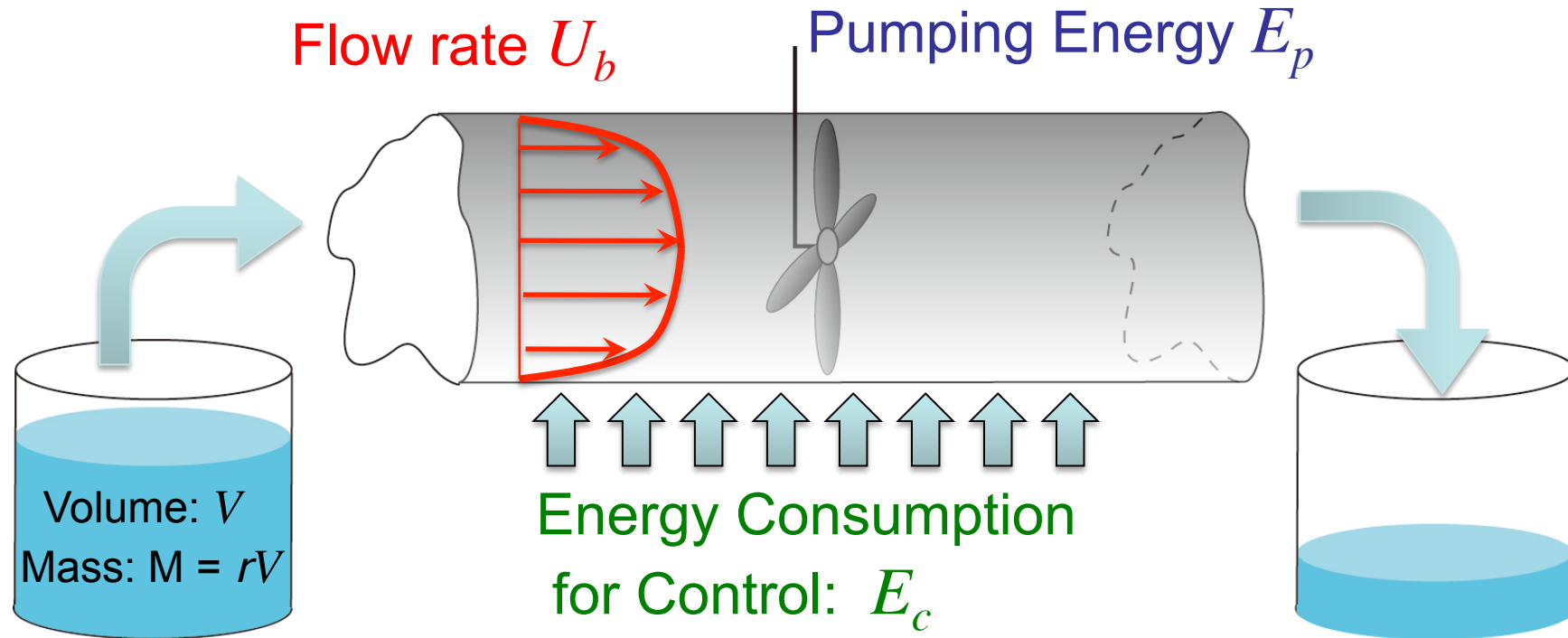
$$C_f = \frac{\tau_w}{\frac{1}{2} \rho U_b^2}$$



Energy Saving vs Convenience



Active Control of Internal Flow



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

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

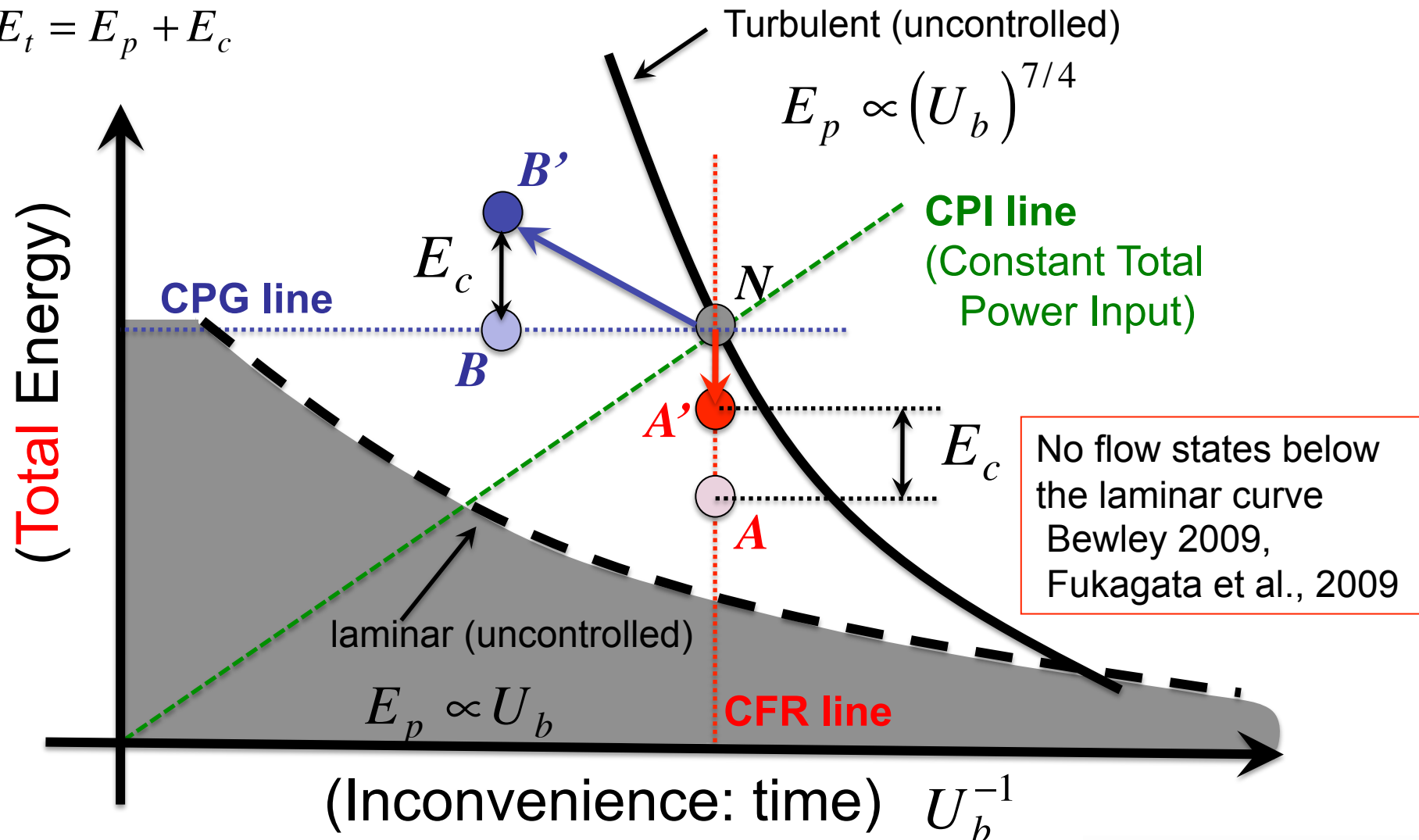
Pumping energy

Control energy



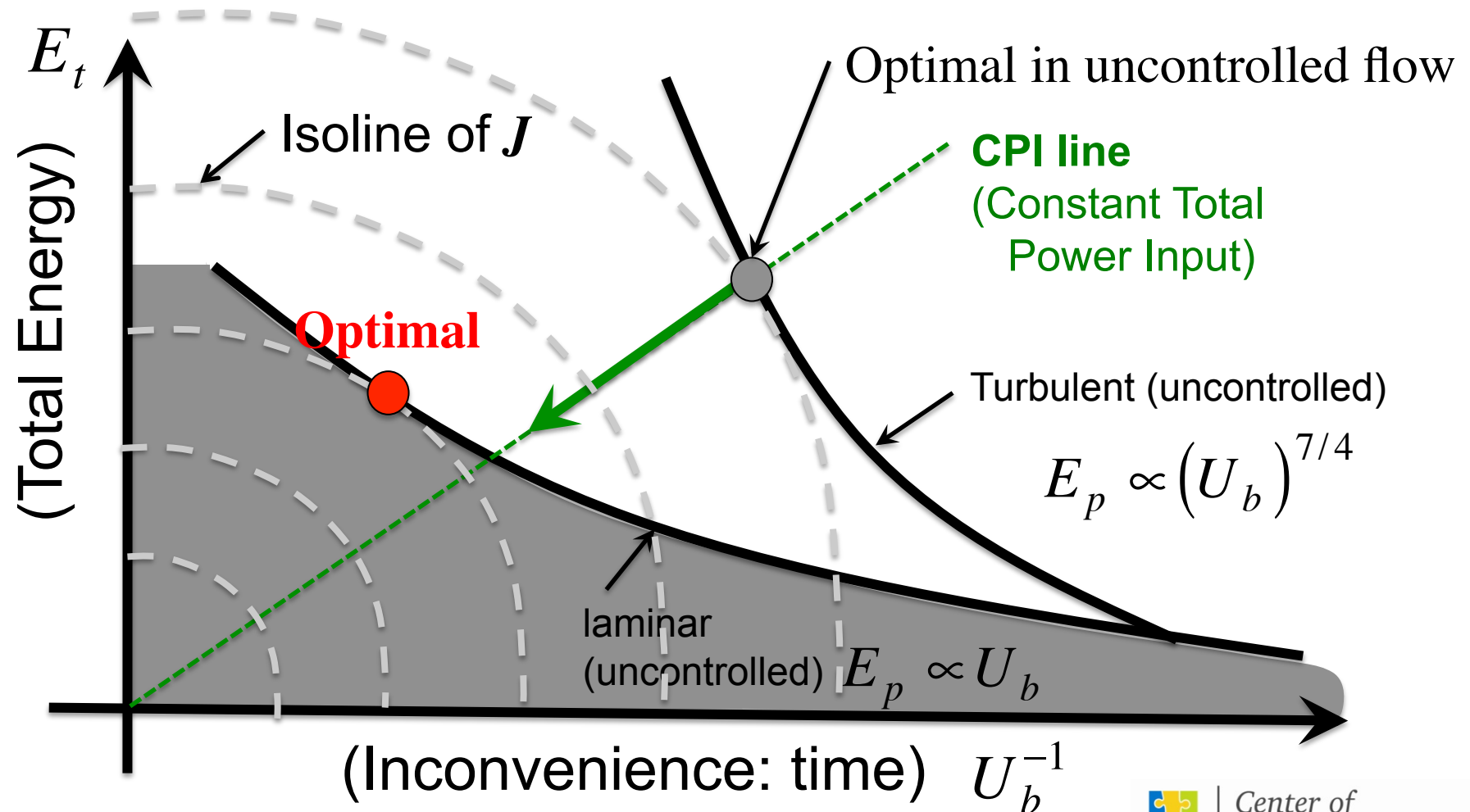
Energy Saving vs Convenience

$$E_t = E_p + E_c$$



Example

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



□ Convenience (Fluid travel time per unit length)

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

□ Energy Expenditure

✓ Pumping Energy

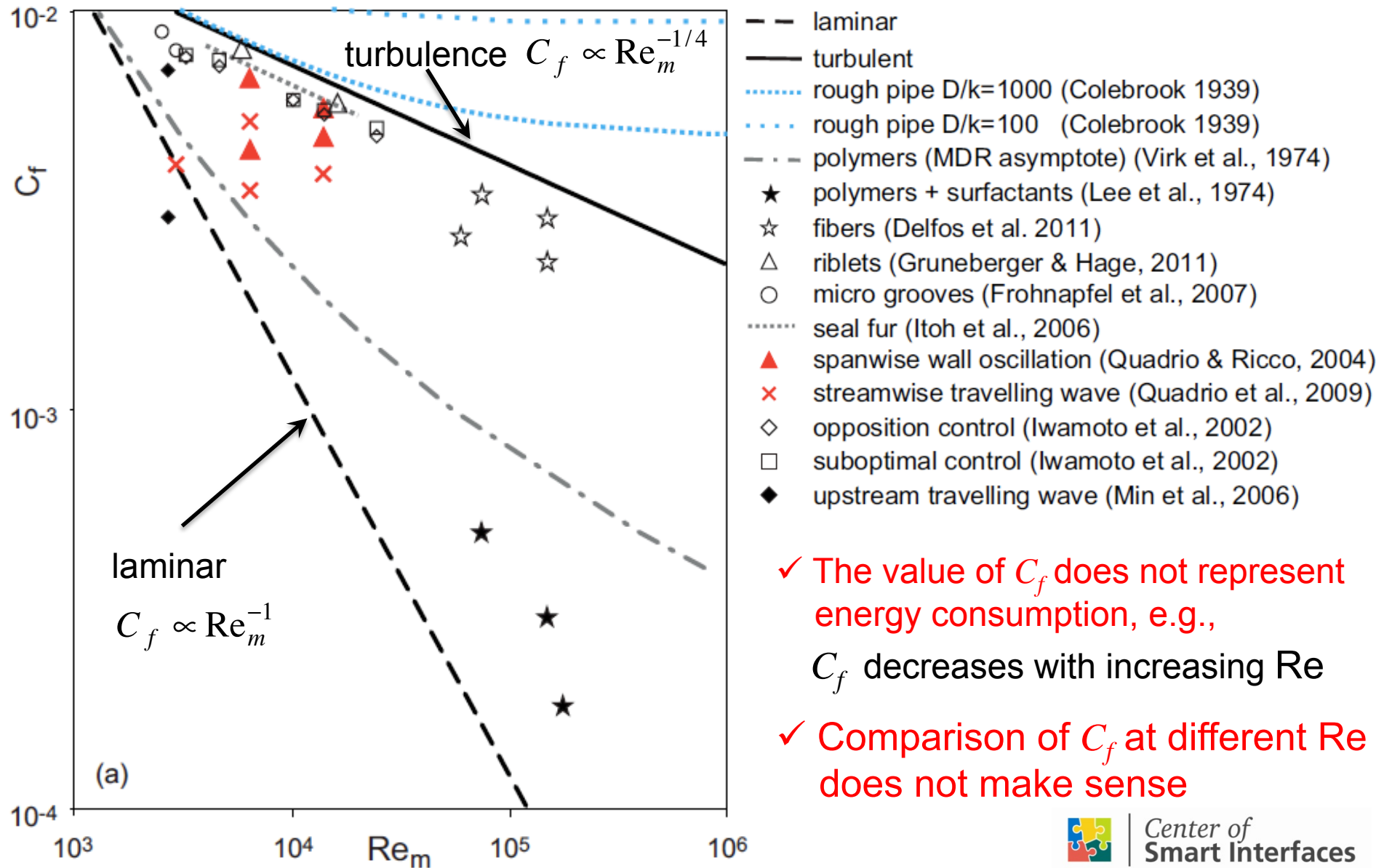
$$E_p = \frac{MU_b^2 C_f}{2A} \quad \Rightarrow \quad C_f = E_p \left(\frac{2A}{MU_b^2} \right) \quad \Rightarrow \quad C_f \text{Re}_b^2 = E_p \left(\frac{2AD^2}{Mv^2} \right)$$

✓ Total Energy (Pumping + Control)

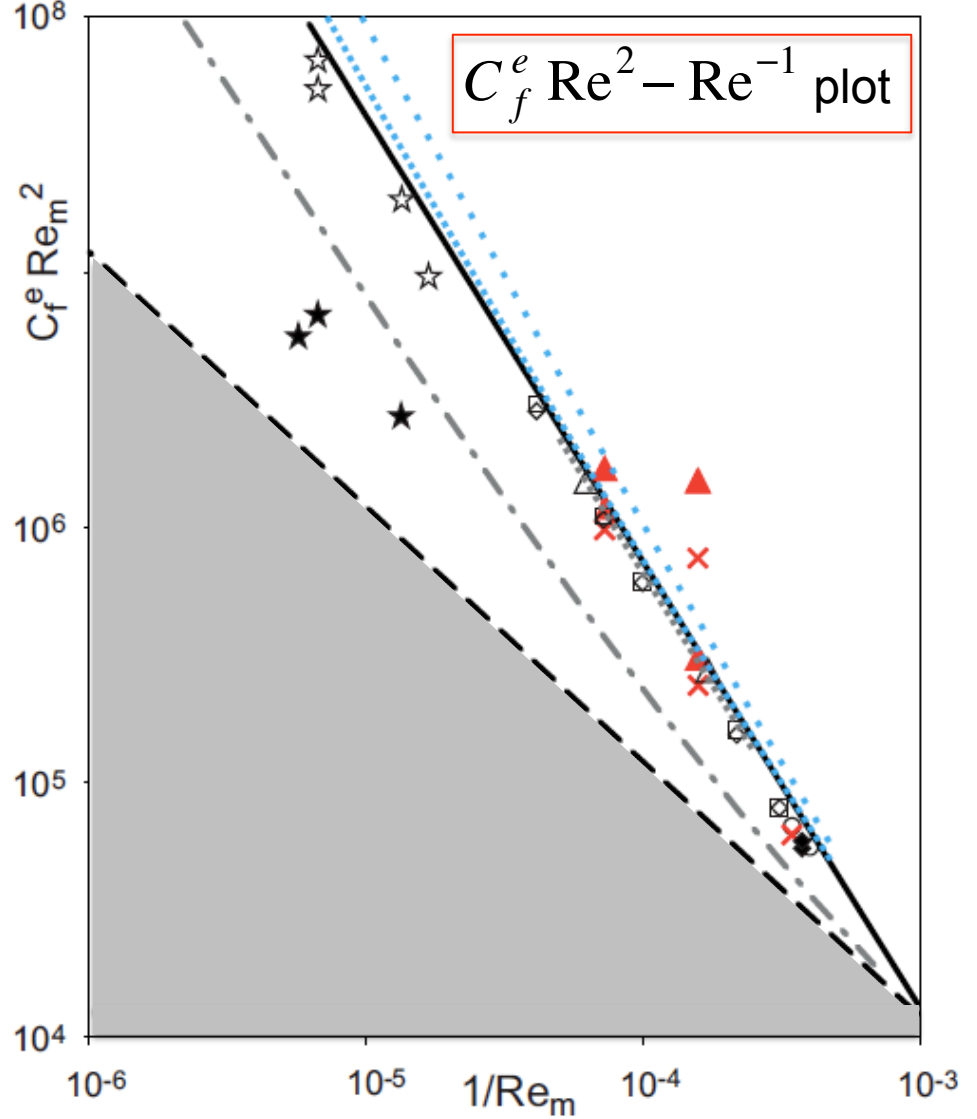
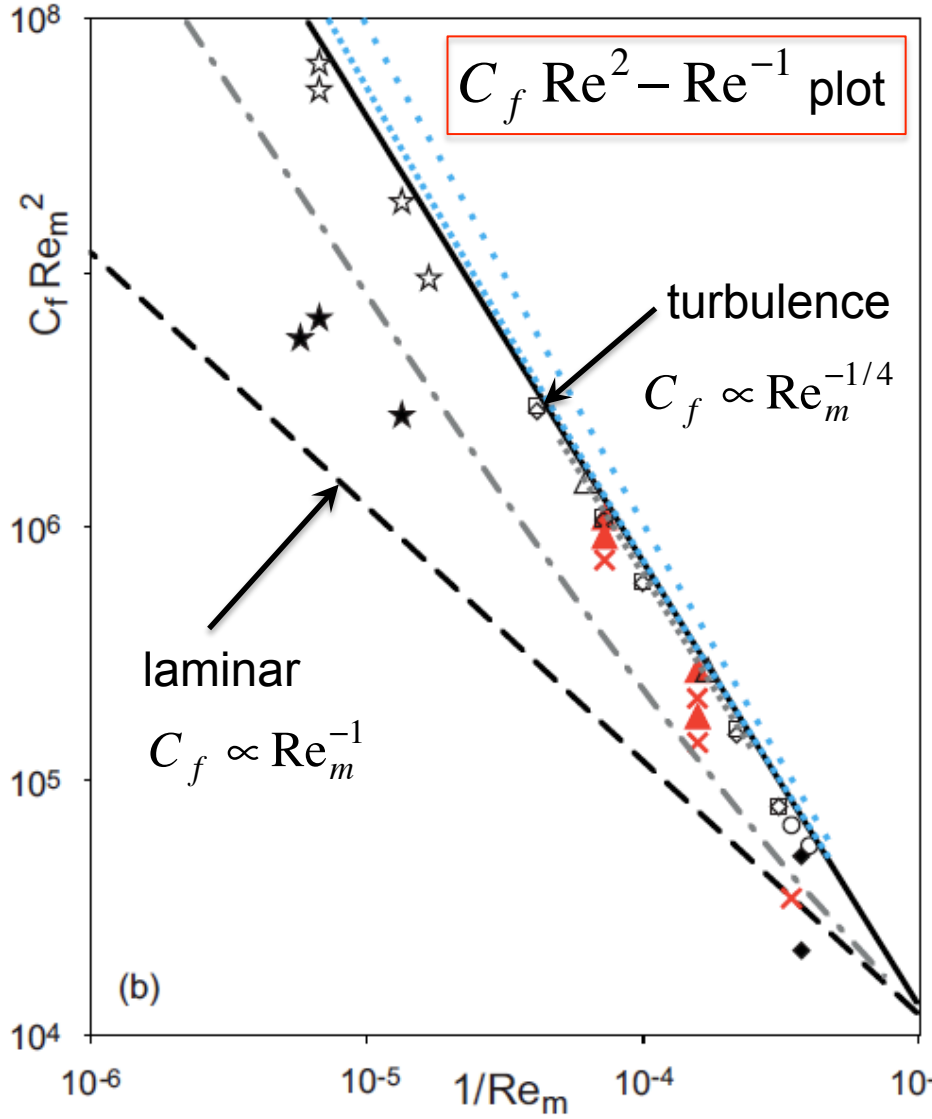
Effective wall friction

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

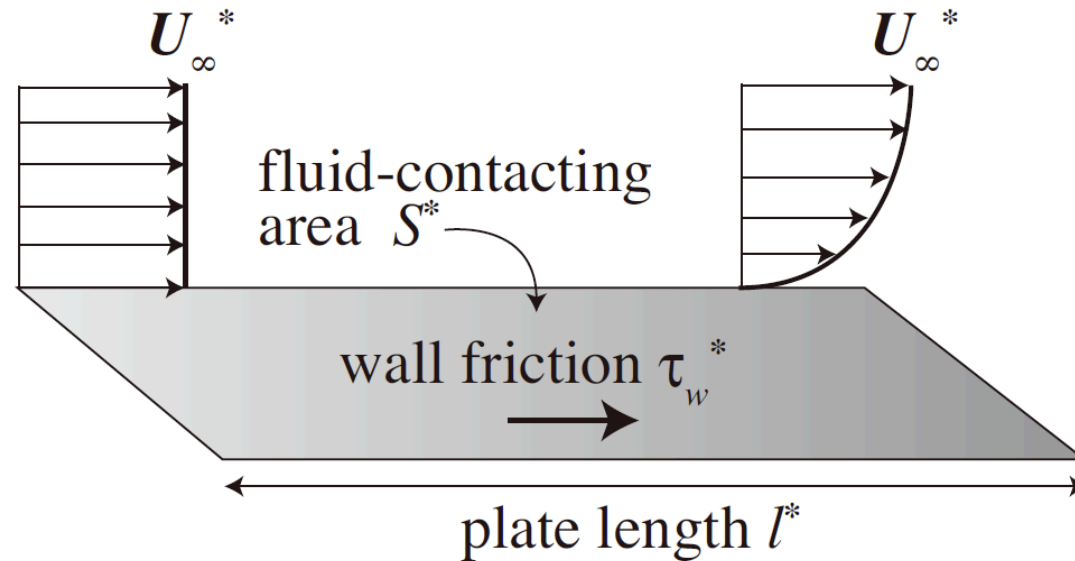
Conventional C_f - Re_b Plot



New Plot (*Energy vs Convenience Plot*)



Application to External Flow



- Convenience (traveling time per unit distance)

$$(U_\infty)^{-1} \Rightarrow v / (U_\infty l) = \boxed{\text{Re}_l^{-1}}$$

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

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

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

- ❑ 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:

Frohnäpfel, Hasegawa & Quadrio, “Money versus Time”, JFM Vol. 700, pp.406-418, 2012

