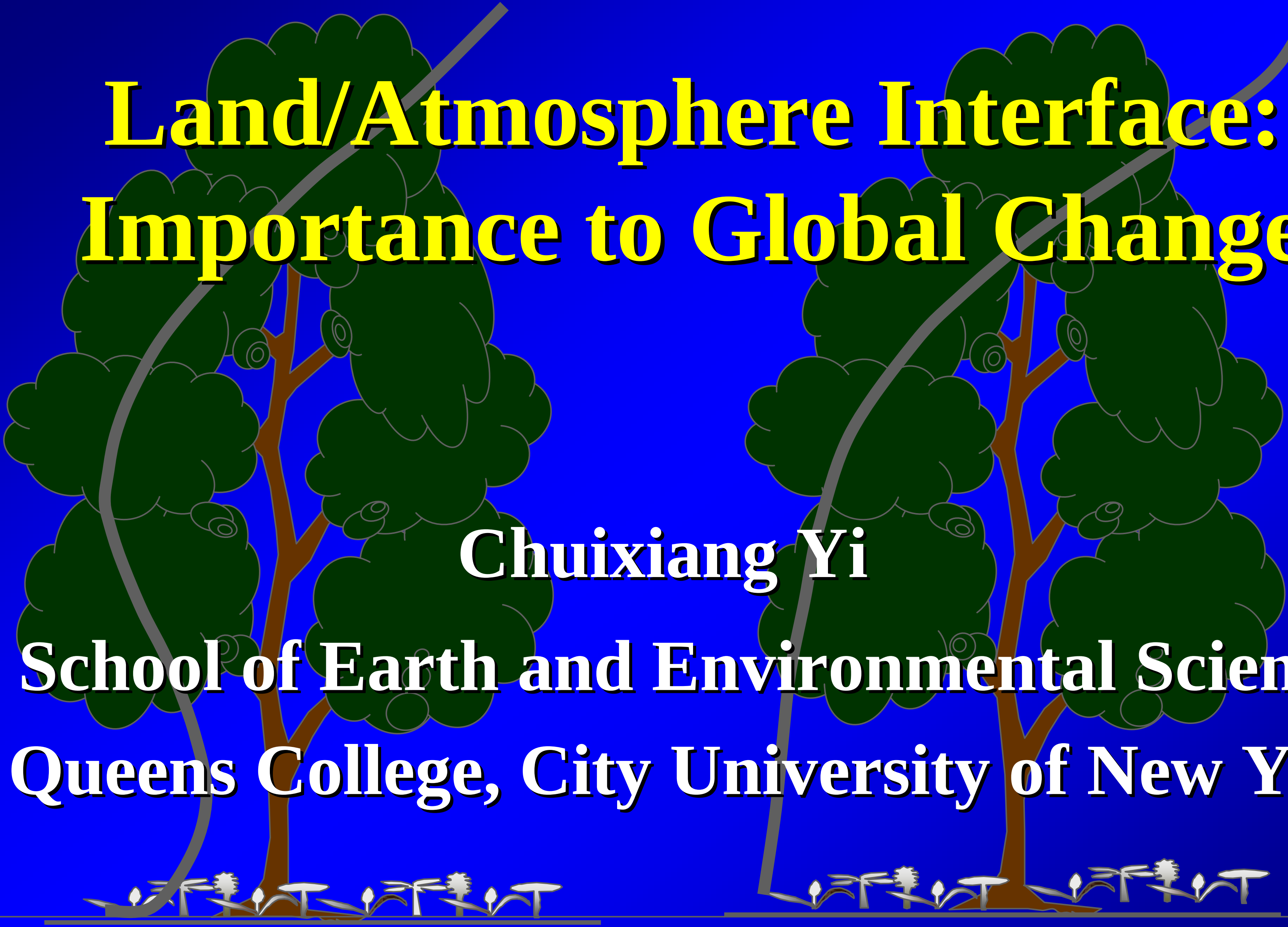
Land/Atmosphere Interface: Importance to Global Change



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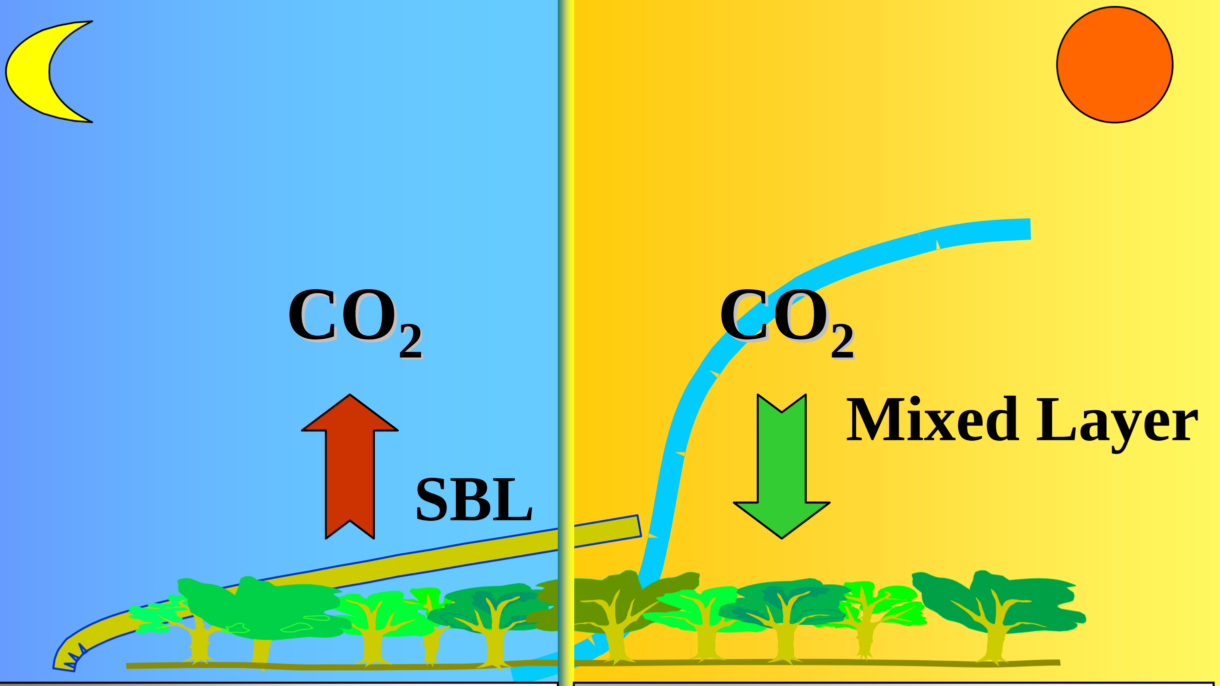
Outline

- Land / atmosphere interface
- Fundamental problems
- Progresses

Why land-atmosphere interactions are important to global change?

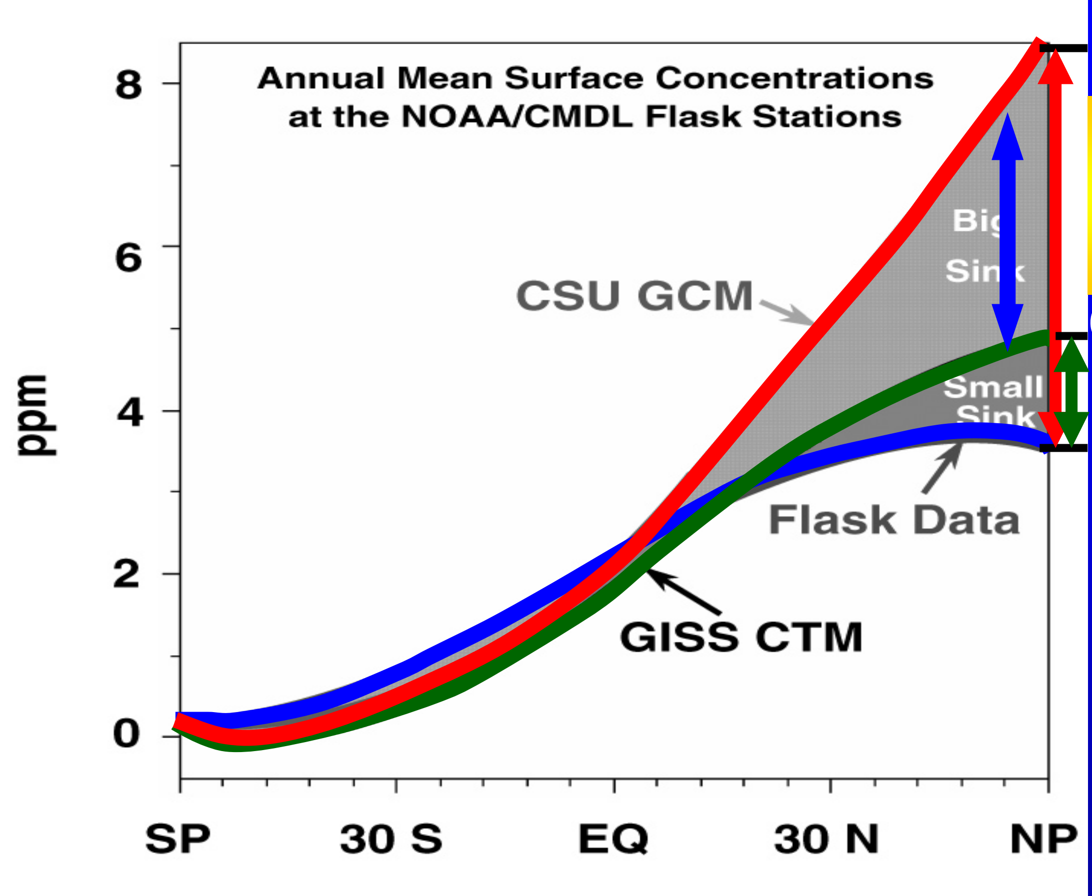
An example
Atmospheric CO_2 rectifier effect



Shallow layer
High CO_2
Respiration

Deep mixing
Low CO_2
Photosynthesis

Why land-atmosphere interactions are important?



Dynamic ABL

Missing sinks

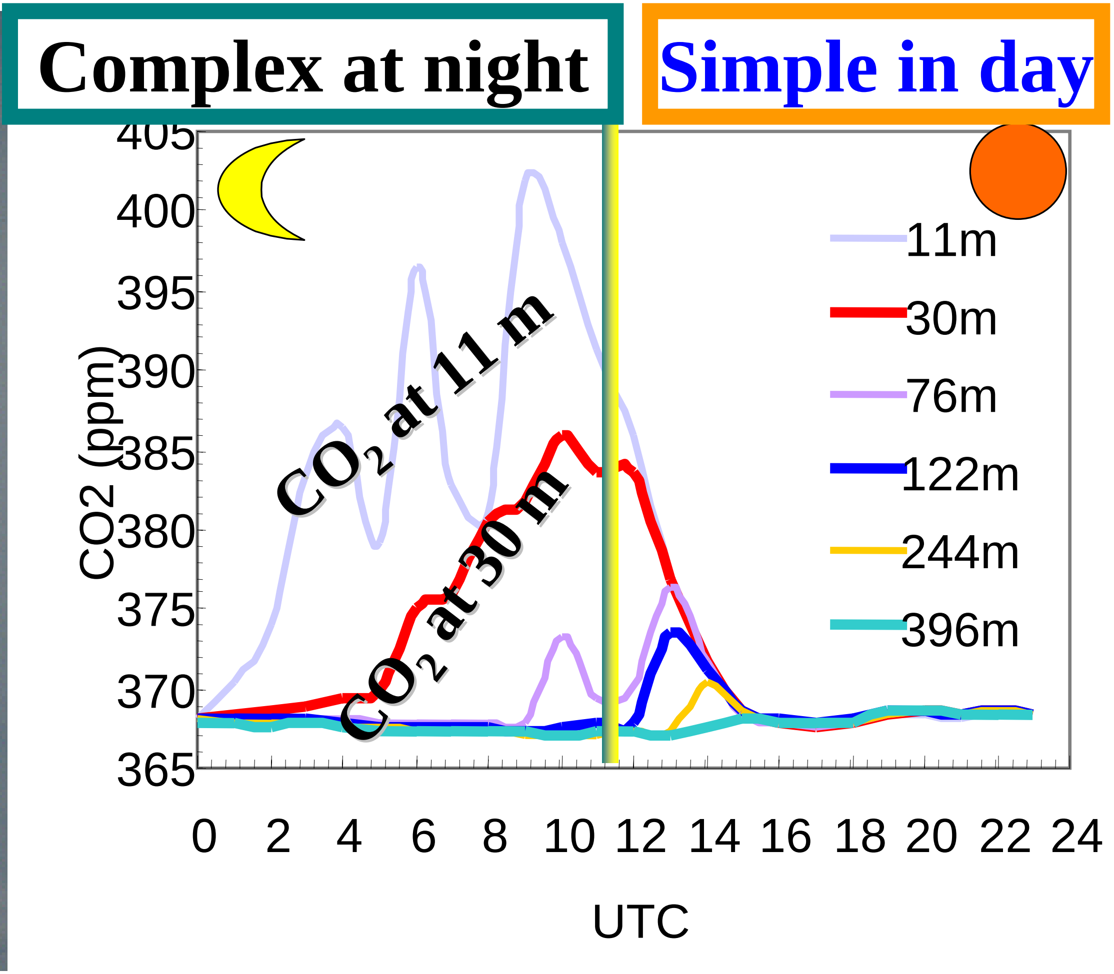
Constant ABL

ABL= Atmospheric boundary layer

(Denning et al., 1995)

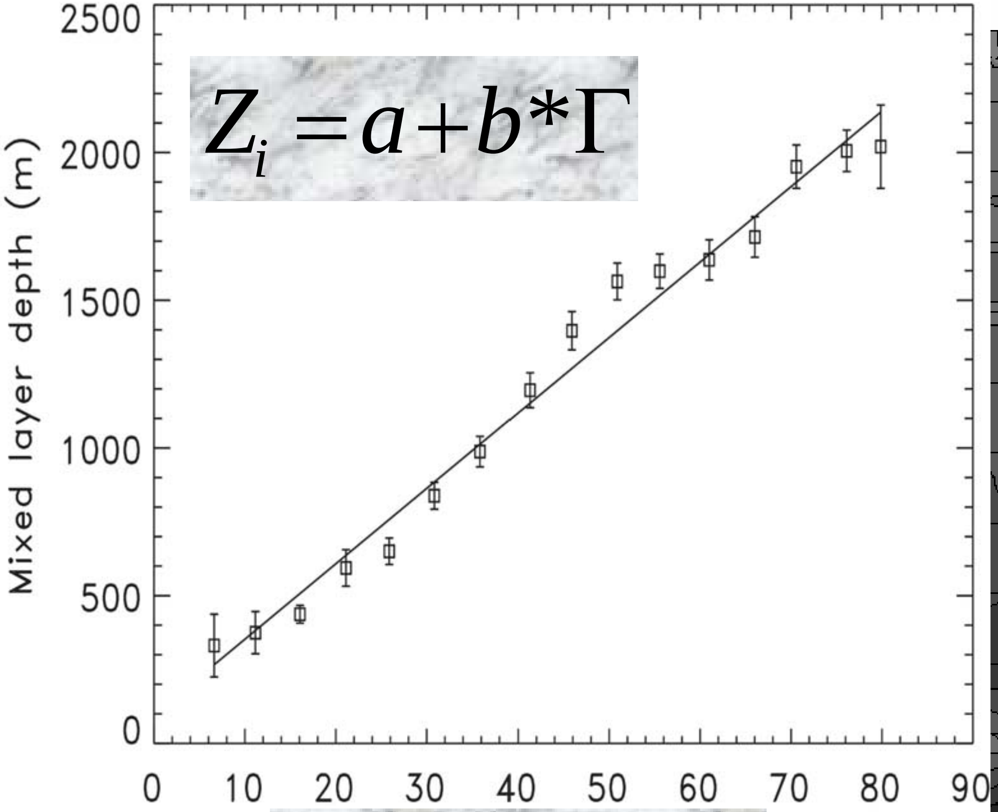
Measuring CO_2 by eddy flux tower

WLEF tall tower (447m)



(Yi et al., JGR 2000)

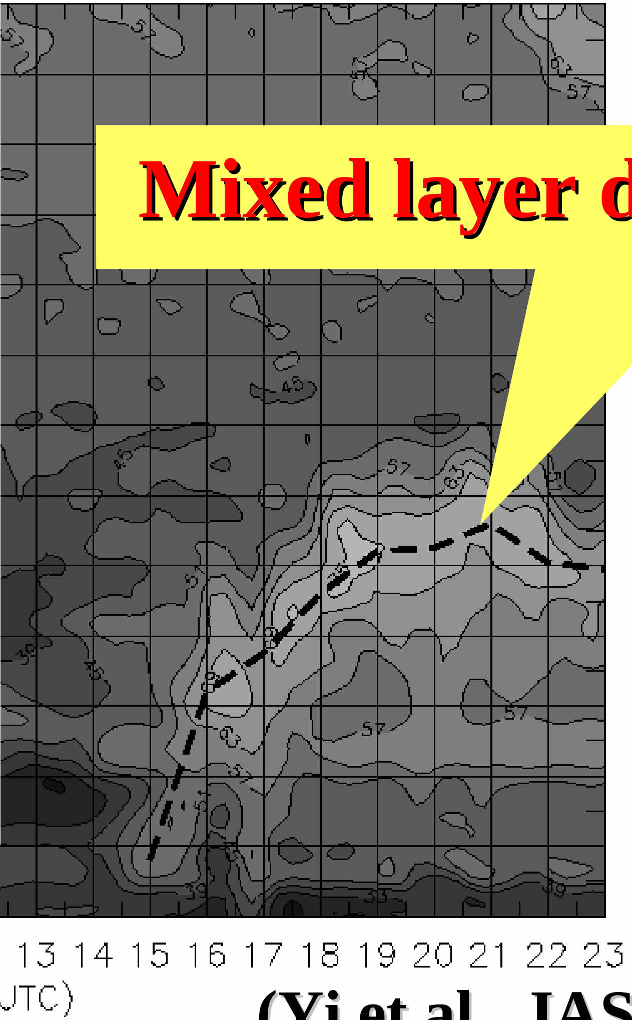
Measuring boundary layer evolution by 915-MHz ABL profiling radar



$$Z_i = a + b * \Gamma$$

$$\Gamma = \sqrt{\int_0^t \left(\overline{\theta w}\right)_s dt'}$$

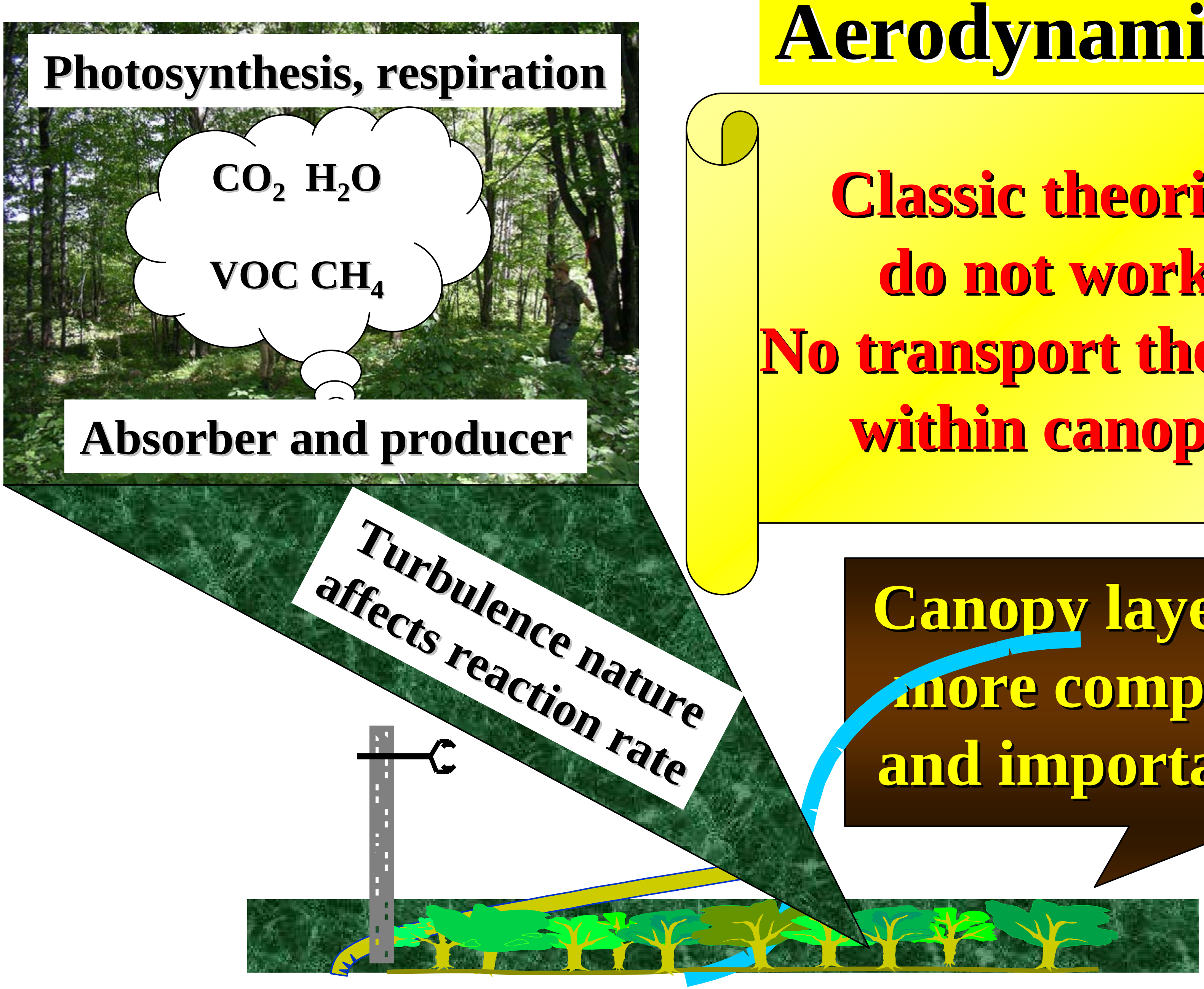
(Yi et al., JGR 2004)



Mixed layer depth

(Yi et al., JAS 2001)

Aerodynamics



Photosynthesis, respiration

CO_2 H_2O

VOC CH_4

Absorber and producer

Turbulence nature affects reaction rate

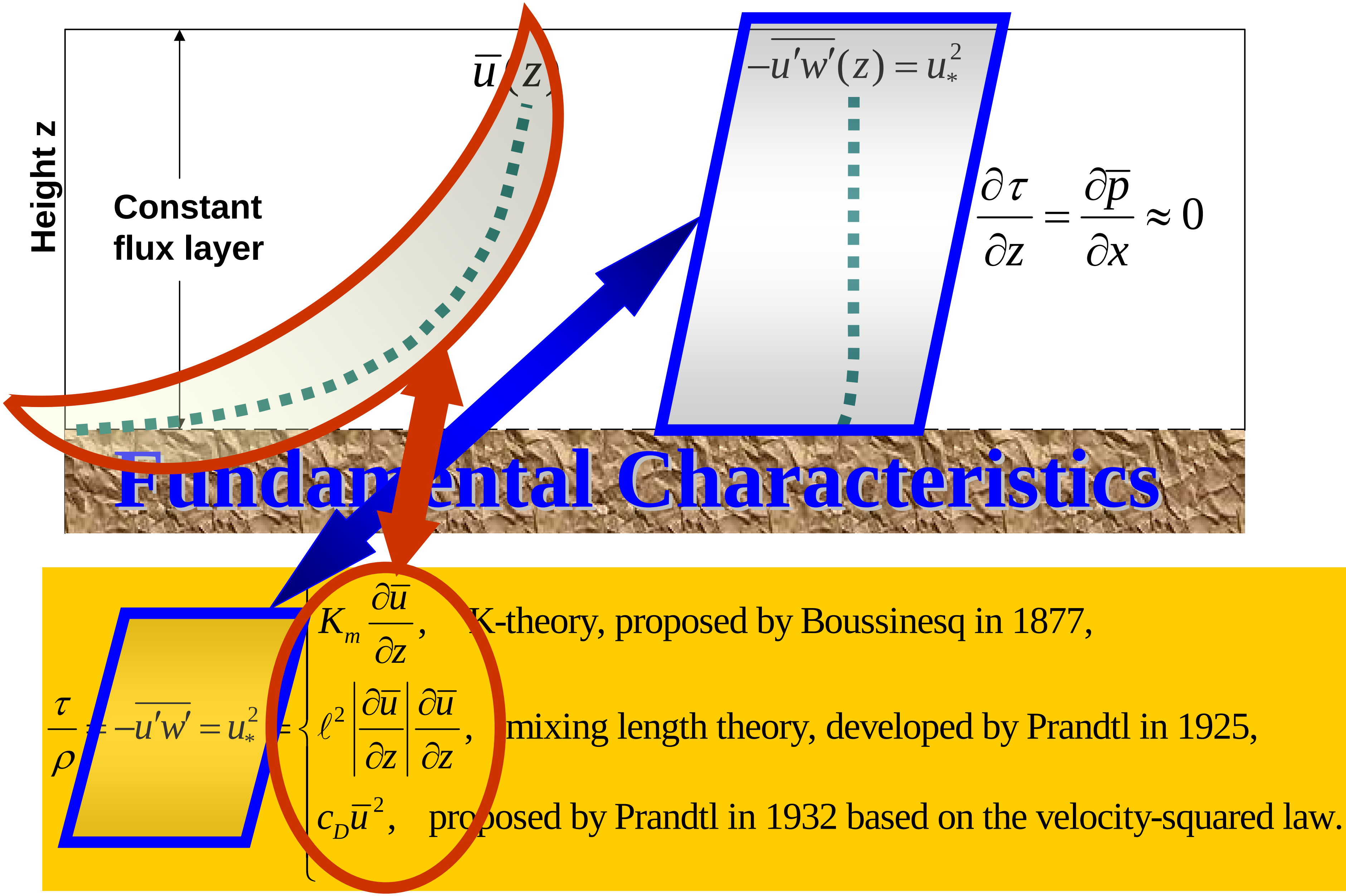
Classic theories do not work

No transport theory within canopy

Canopy layer is more complex and important!

Why classic turbulent theories do not work within canopies?

Fundamental Characteristics



$$-\overline{u'w'}(z) = u_*^2$$

$$\frac{\partial \tau}{\partial z} = \frac{\partial \bar{p}}{\partial x} \approx 0$$

$$\frac{\tau}{\rho} = -\overline{u'w'} = u_*^2 = \begin{cases} K_m \dfrac{\partial \bar{u}}{\partial z}, & \text{K-theory, proposed by Boussinesq in 1877,} \\ \ell^2 \left|\dfrac{\partial \bar{u}}{\partial z}\right| \dfrac{\partial \bar{u}}{\partial z}, & \text{mixing length theory, developed by Prandtl in 1925,} \\ c_D \bar{u}^2, & \text{proposed by Prandtl in 1932 based on the velocity-squared law.} \end{cases}$$

Yi, 2007

Von Karman's similarity hypothesis

$$\ell = \kappa \left| \frac{d\overline{u} / dz}{d^2\overline{u} / dz^2} \right|$$

Von Karman

Prandtl

$$\ell = \kappa \left| \frac{d\overline{u} / dz}{d^2\overline{u} / dz^2} \right|$$

$$\ell = \kappa z$$

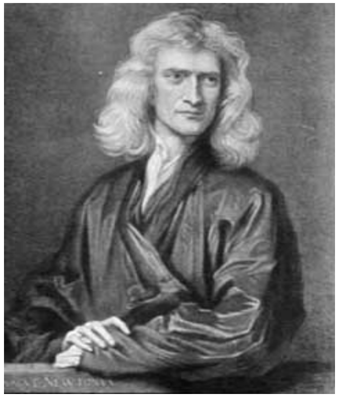
$$\overline{u}(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0} \right)$$

$\kappa \approx 0.4$

Z_0 is roughness

Edme Mariotte 1673

Christiaan Huygens 1699



Sir Issac Newton 1687

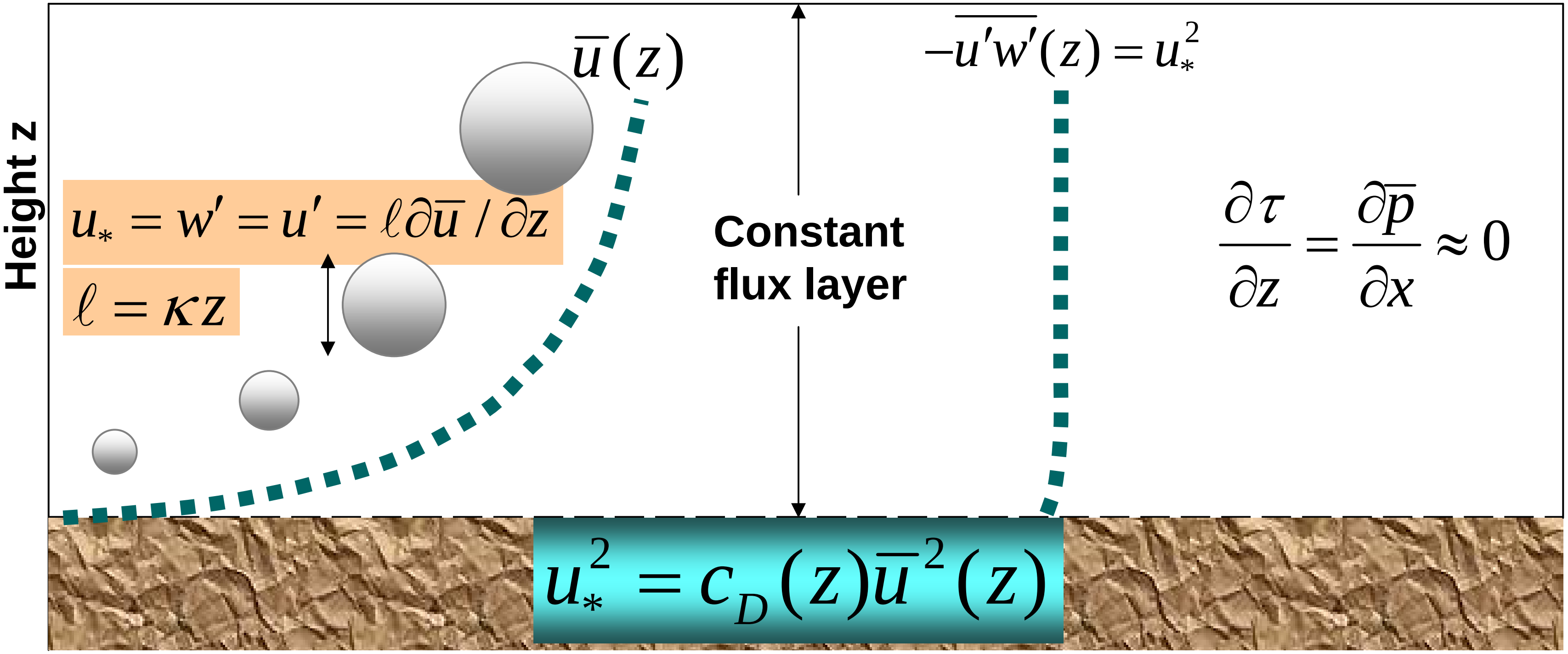
Velocity-Squared Law

$$Drag = C_D \rho S V^2$$

Navier in 1822

Stokes in 1845

Prandtl in 1905



Height z

$\overline{u}(z)$

$-\overline{u'w'}(z) = u_*^2$

$u_* = w' = u' = \ell \partial \overline{u} / \partial z$

$\ell = \kappa z$

Constant flux layer

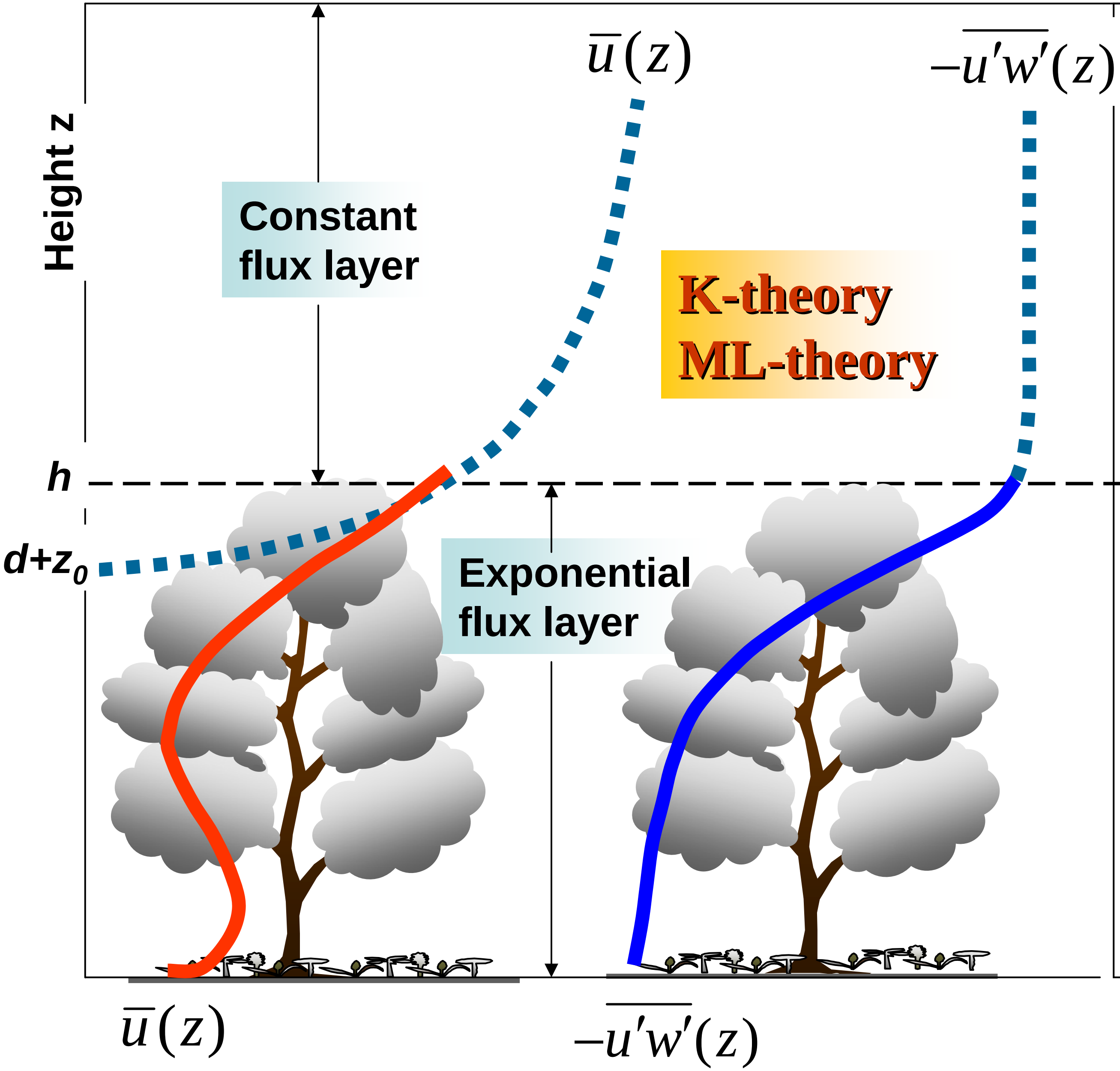
$$\frac{\partial \tau}{\partial z} = \frac{\partial \overline{p}}{\partial x} \approx 0$$

$$u_*^2 = c_D(z)\overline{u}^2(z)$$

“…the friction velocity is the artificial but related velocity for which the square law holds exactly”-Sutton **(1953, pp.76)**

Taylor (1916) was first to test the validity of the velocity-squared law on the earth’s surface and estimated its drag coefficient values.

The mixing length theory has achieved remarkable success. Thom (1971) rationalized the physical connection between length scale and velocity scale.



Constant flux layer

K-theory
ML-theory

Exponential flux layer

$$\frac{\partial \tau}{\partial z} = \frac{\partial \overline{p}}{\partial x} \approx 0$$

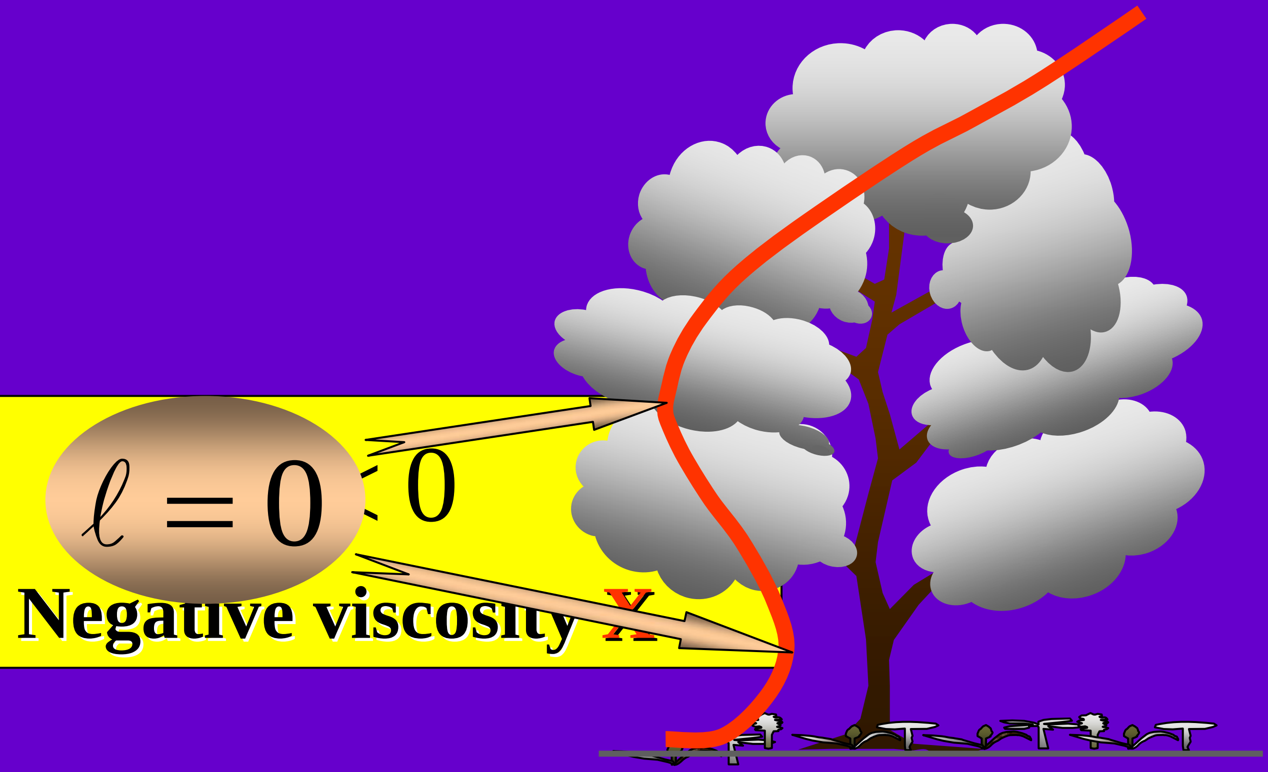
$$\frac{\partial \tau}{\partial z} \approx F_D,$$

$$F_D = \rho c_D a \overline{u}^2$$

Governing equation

Yi, 2007

Why classic theories do not work within canopy.



$\ell = 0$

< 0

Negative viscosity X

$\overline{u}(z)$

Von Karman similarity rule

$$\ell = \kappa \left| \frac{d\overline{u}/dz}{d^2\overline{u}/dz^2} \right|$$

$$-\overline{u'w'} = K_m \frac{\partial \overline{u}}{\partial z}$$

Yi, 2007

New developments in canopy flow theory

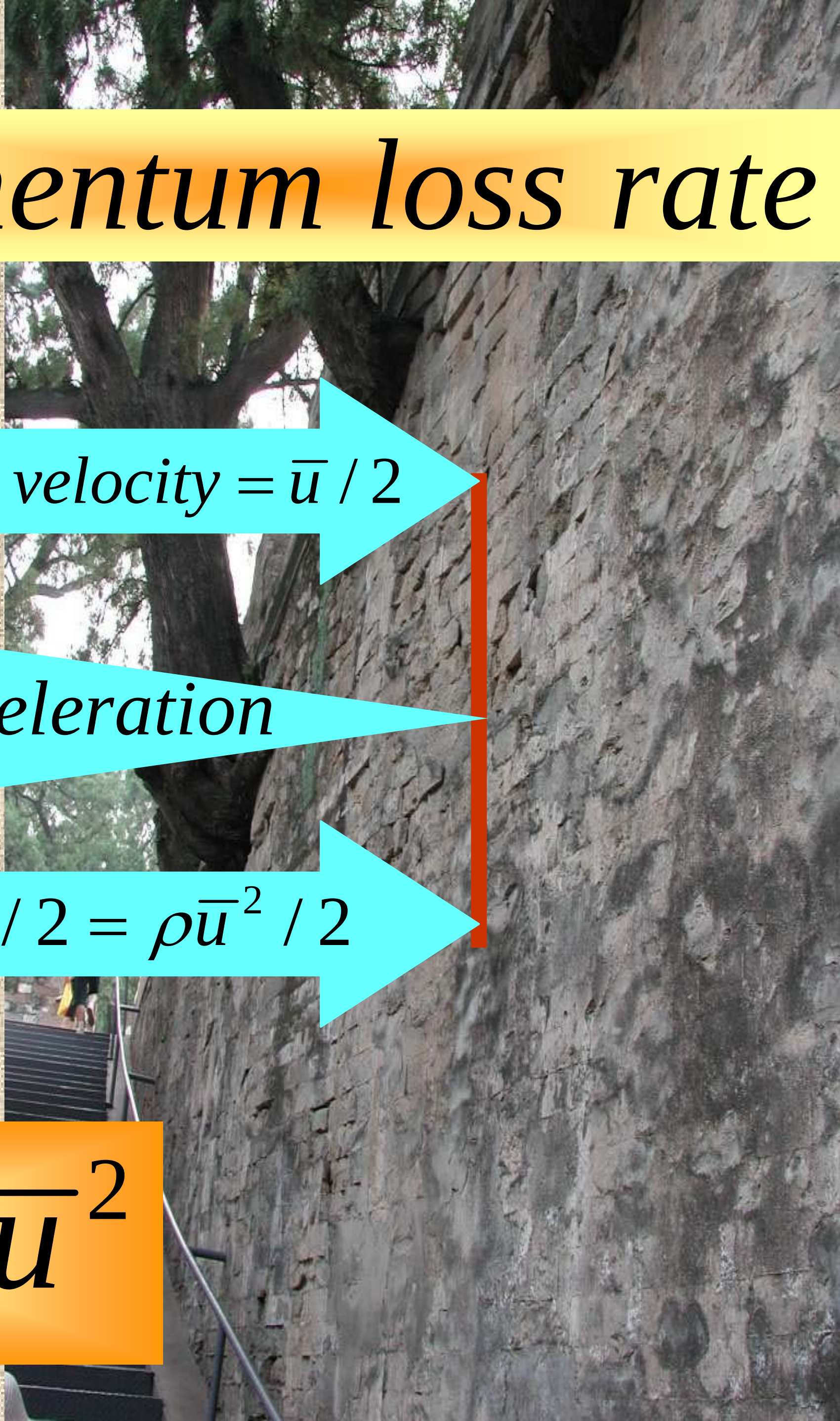
$$\tau = -\rho\overline{u'w'}$$

$$[\tau] = \frac{\mathrm{MLT^{-1}}}{\mathrm{L^2T}} = \frac{\text{mass}\cdot\text{velocity}}{\text{area}\cdot\text{time}} = \frac{\text{momentum}}{\text{area}\cdot\text{time}}$$

Momentum Transfer Rate

Yi, 2007

$\tau = -\rho\overline{u'w'} \propto \rho\overline{u}^2$ momentum loss rate



momentum = $\rho\overline{u}$

average velocity = $\overline{u}/2$

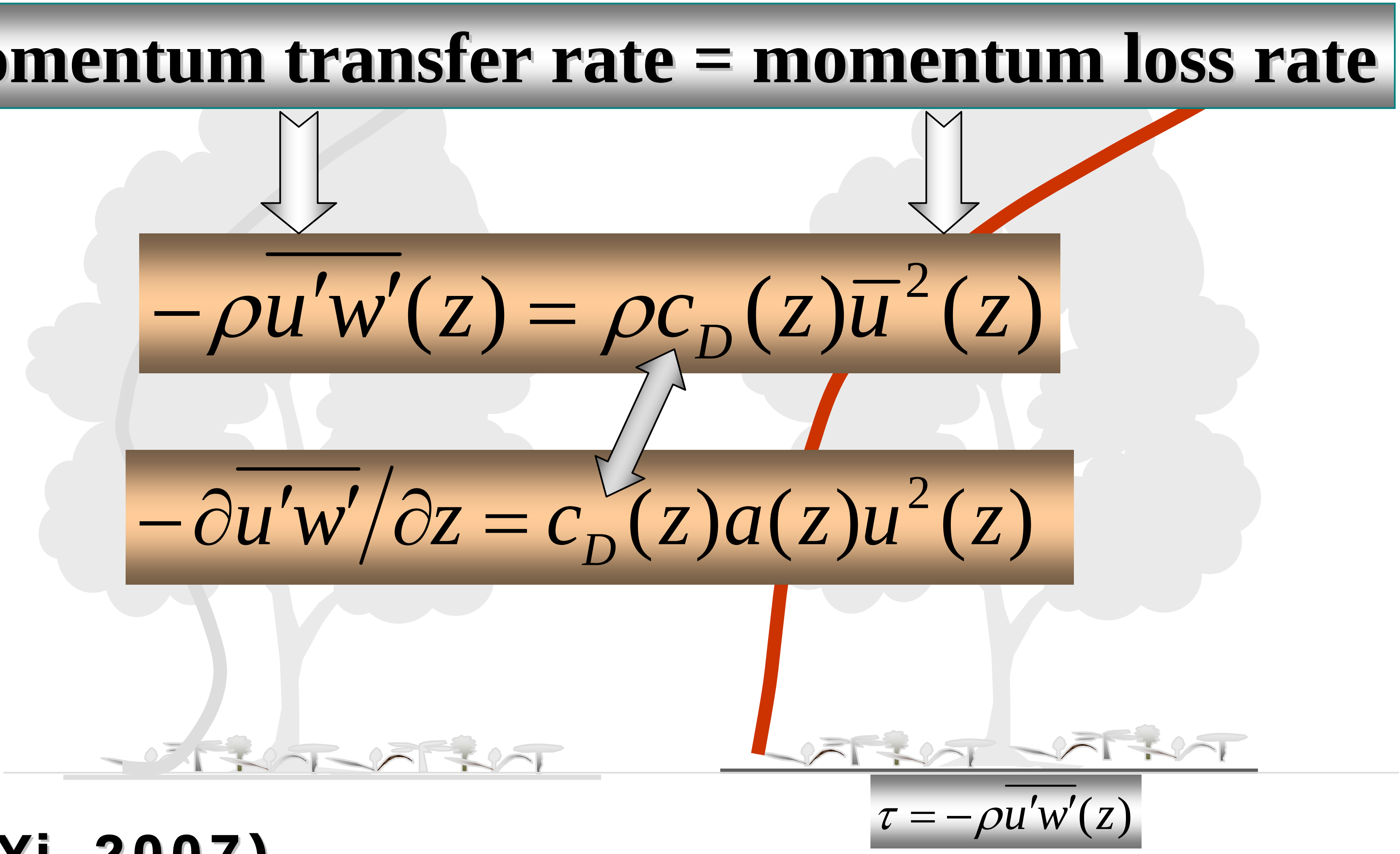
flow deceleration

$\rho\overline{u} \times \overline{u}/2 = \rho\overline{u}^2/2$

$$\tau = c_D\rho\overline{u}^2$$

Yi, 2007

Local Equilibrium Hypotheses



momentum transfer rate = momentum loss rate

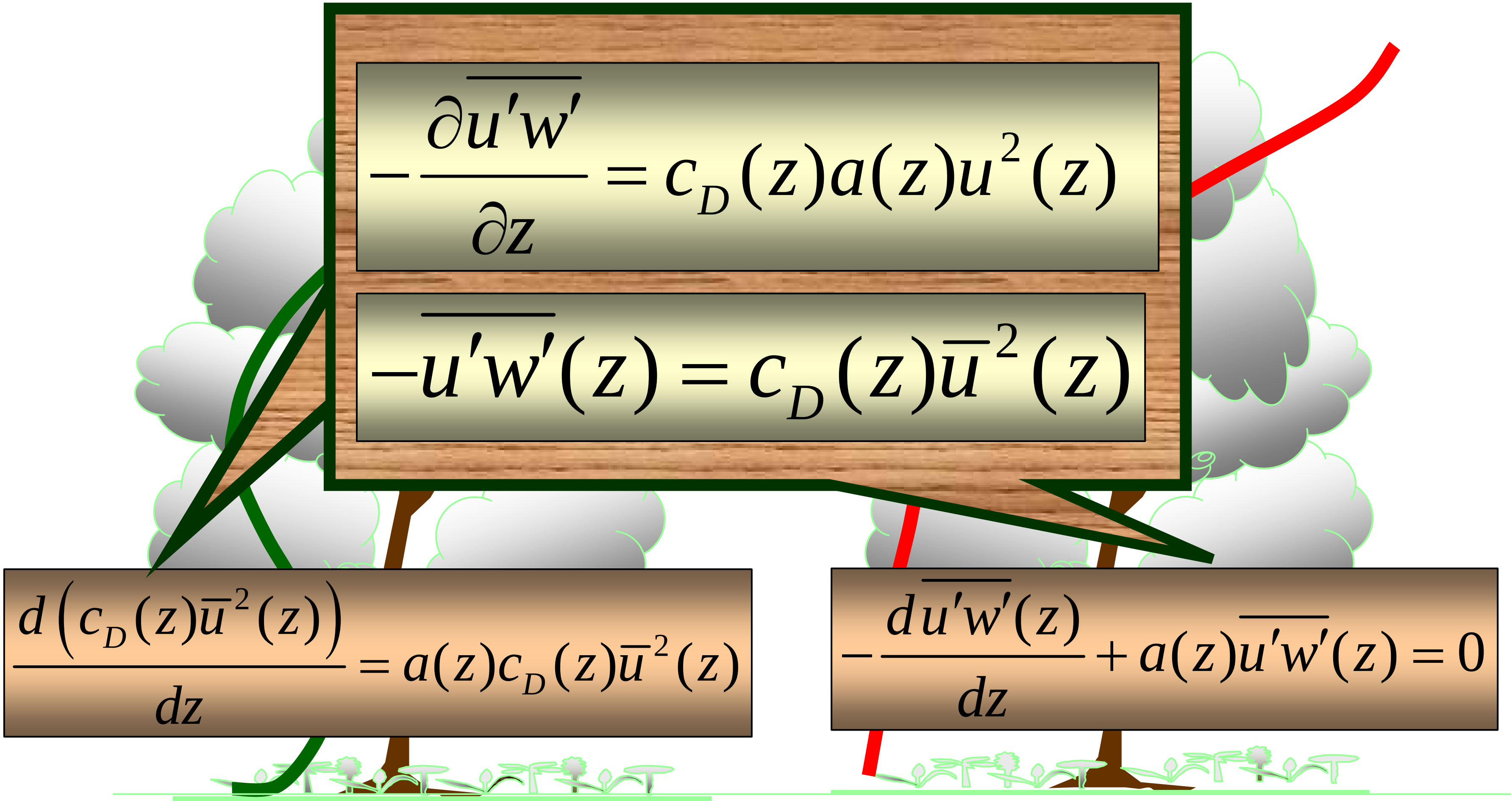
$$-\rho\overline{u'w'}(z) = \rho c_D(z)\overline{u}^2(z)$$

$$-\partial\overline{u'w'}/\partial z = c_D(z)a(z)u^2(z)$$

$$\tau = -\rho\overline{u'w'}(z)$$

(Yi, 2007)

Momentum Equations are closed



$$-\frac{\partial \overline{u'w'}}{\partial z} = c_D(z)a(z)u^2(z)$$

$$-\overline{u'w'}(z) = c_D(z)\bar{u}^2(z)$$

$$\frac{d\left(c_D(z)\bar{u}^2(z)\right)}{dz} = a(z)c_D(z)\bar{u}^2(z)$$

$$-\frac{d\overline{u'w'}(z)}{dz} + a(z)\overline{u'w'}(z) = 0$$

(Yi, 2007)

Uniform Vegetation

$$c_D(z) = c_D$$
$$a(z) = a$$

$$-\frac{\partial \overline{u'w'}}{\partial z} = a c_D u^2(z)$$

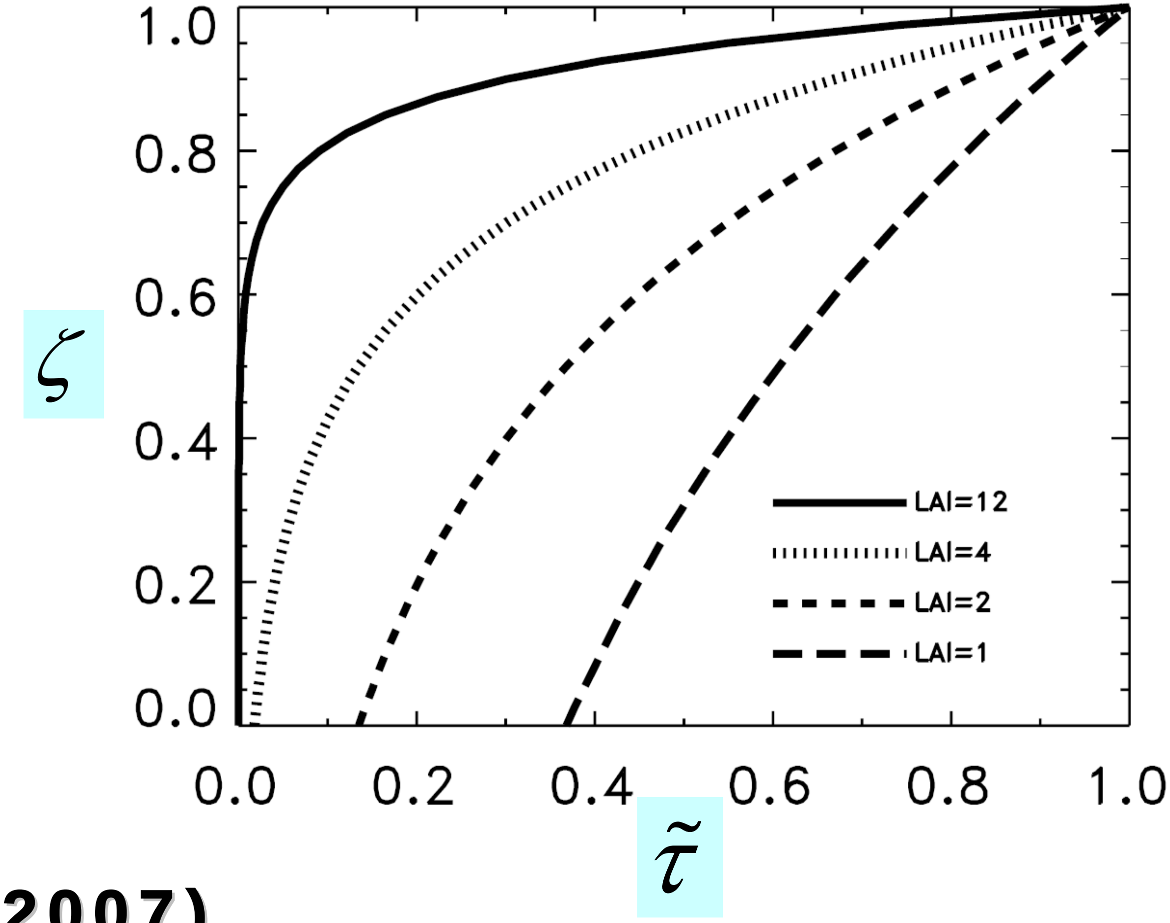
$$q(z) = c_D \overline{u}^2(z) = -\overline{u'w'}(z) \quad \Rightarrow \quad \frac{dq(z)}{dz} = aq(z)$$

$$\overline{u}(z) = \overline{u}_h e^{\alpha(\frac{z}{h}-1)} \quad \Leftrightarrow \quad \text{Inoue's model}$$

(Yi, 2007)

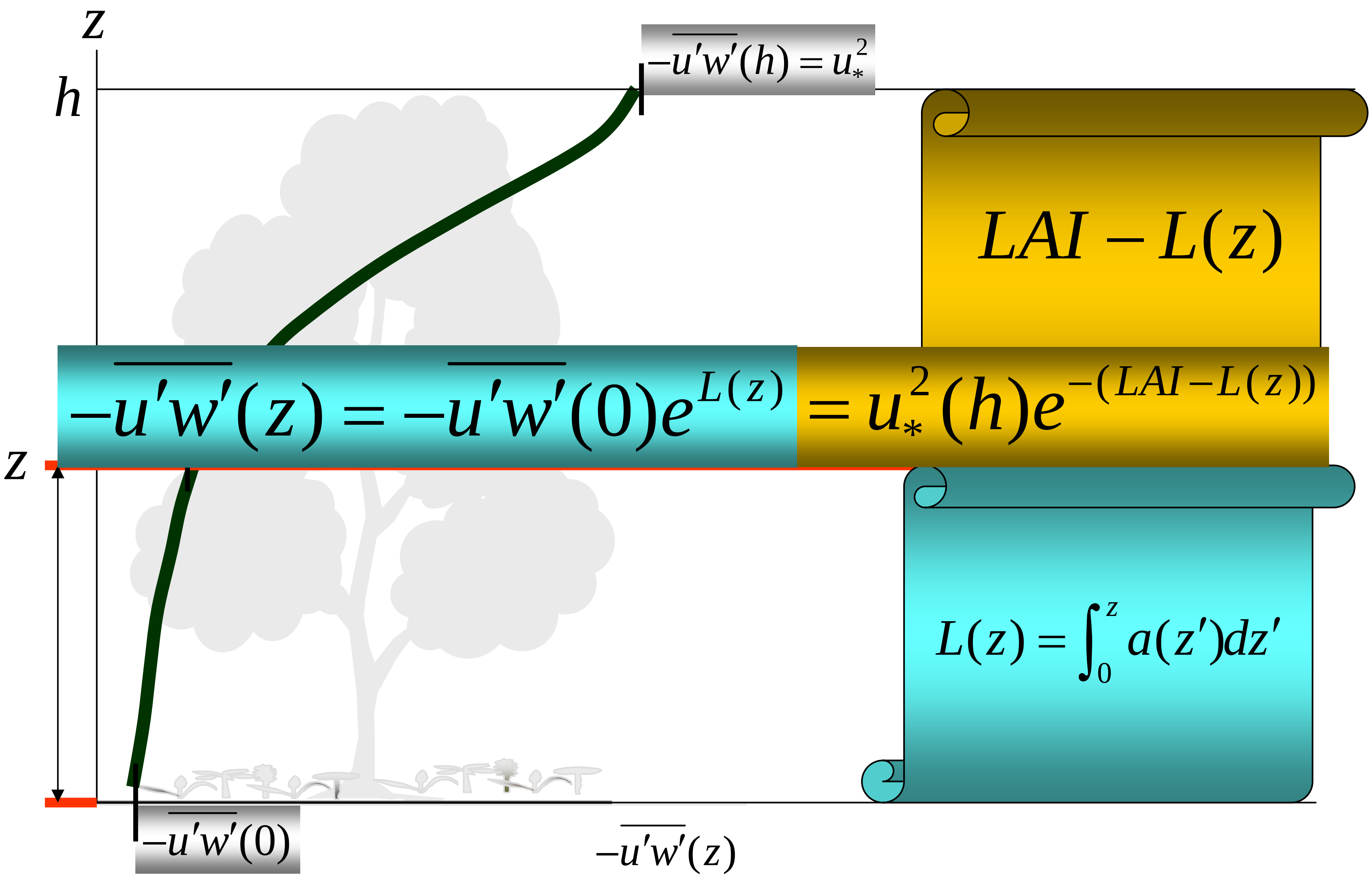
$$\tilde{\tau} = e^{LAI(\zeta - 1)}$$

$$\zeta = z/h, \quad \tilde{\tau} = \tau(z)/\tau_h$$



(Yi, 2007)

(Yi, 2007)



$$LAI - L(z)$$

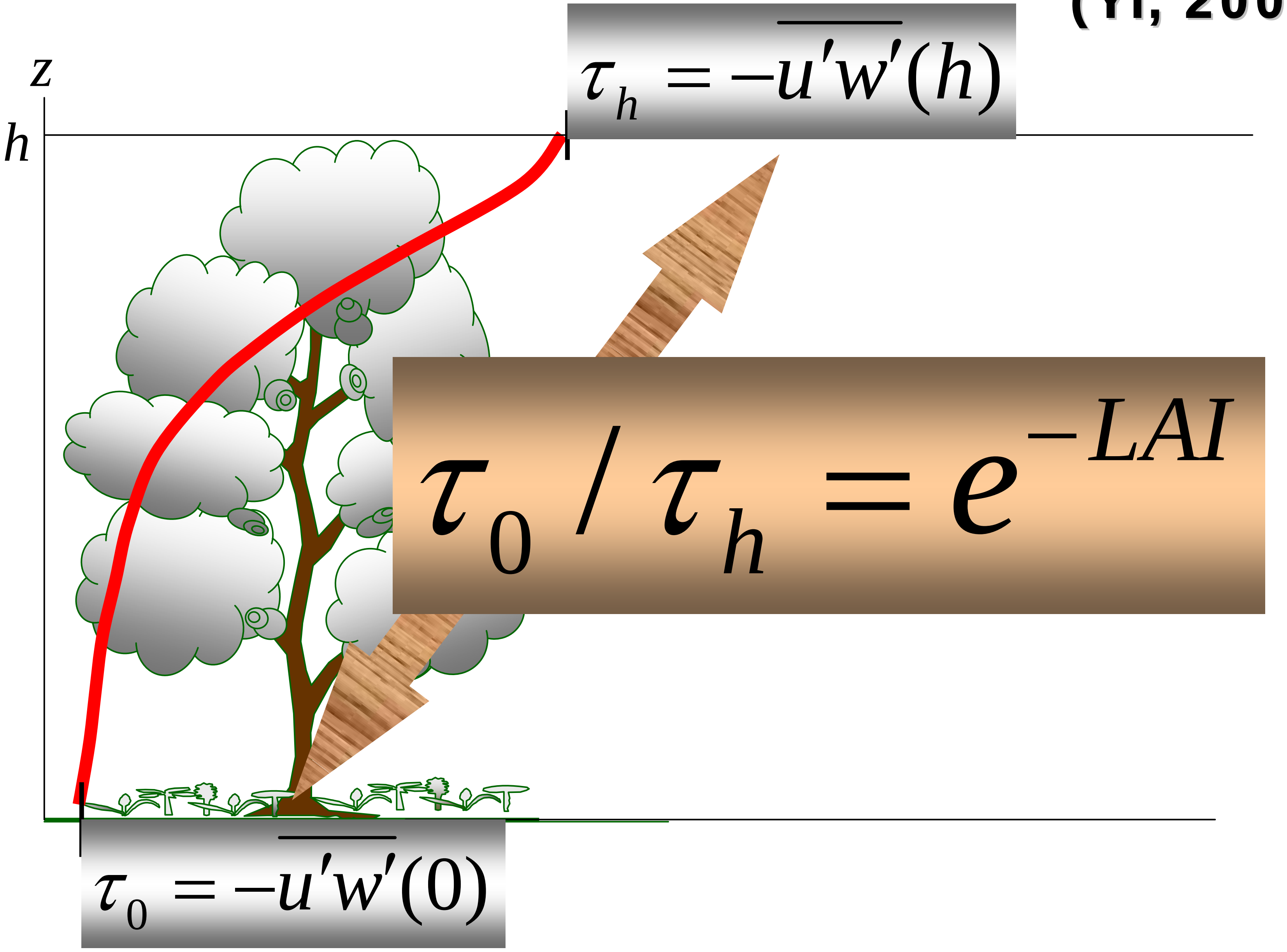
$$-\overline{u'w'}(z) = -\overline{u'w'}(0)e^{L(z)} = u_*^2(h)e^{-(LAI-L(z))}$$

$$L(z) = \int_0^z a(z')dz'$$

a (z) = leaf area density (m^2/m^3)

LAI = leaf area index = entire leaf area per m^2 ground

(Yi, 2007)



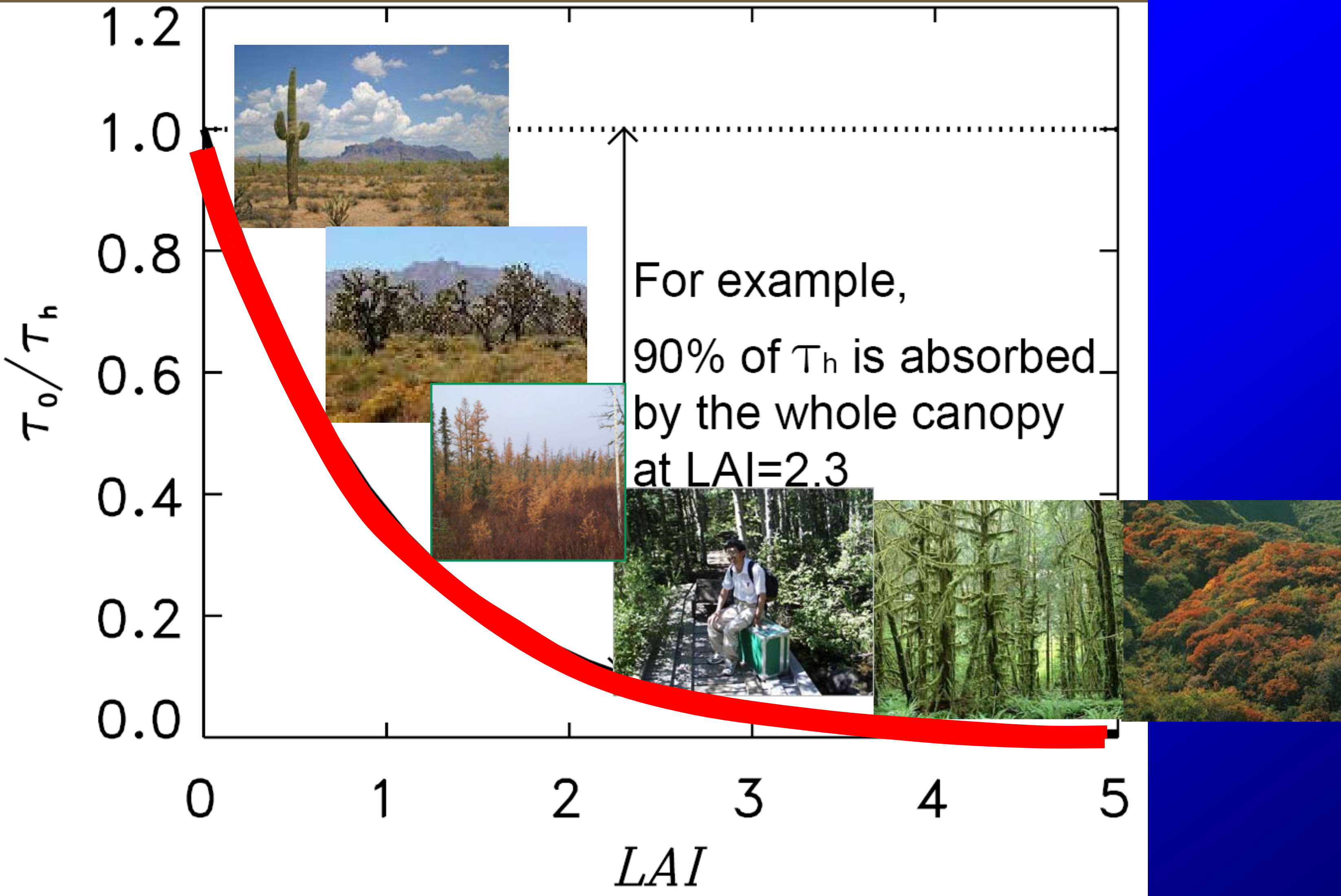
$$\tau_h = -\overline{u'w'}(h)$$

$$\tau_0 / \tau_h = e^{-LAI}$$

$$\tau_0 = -\overline{u'w'}(0)$$

LAI = leaf area index = entire leaf area per m^2 ground

A Universal Relationship

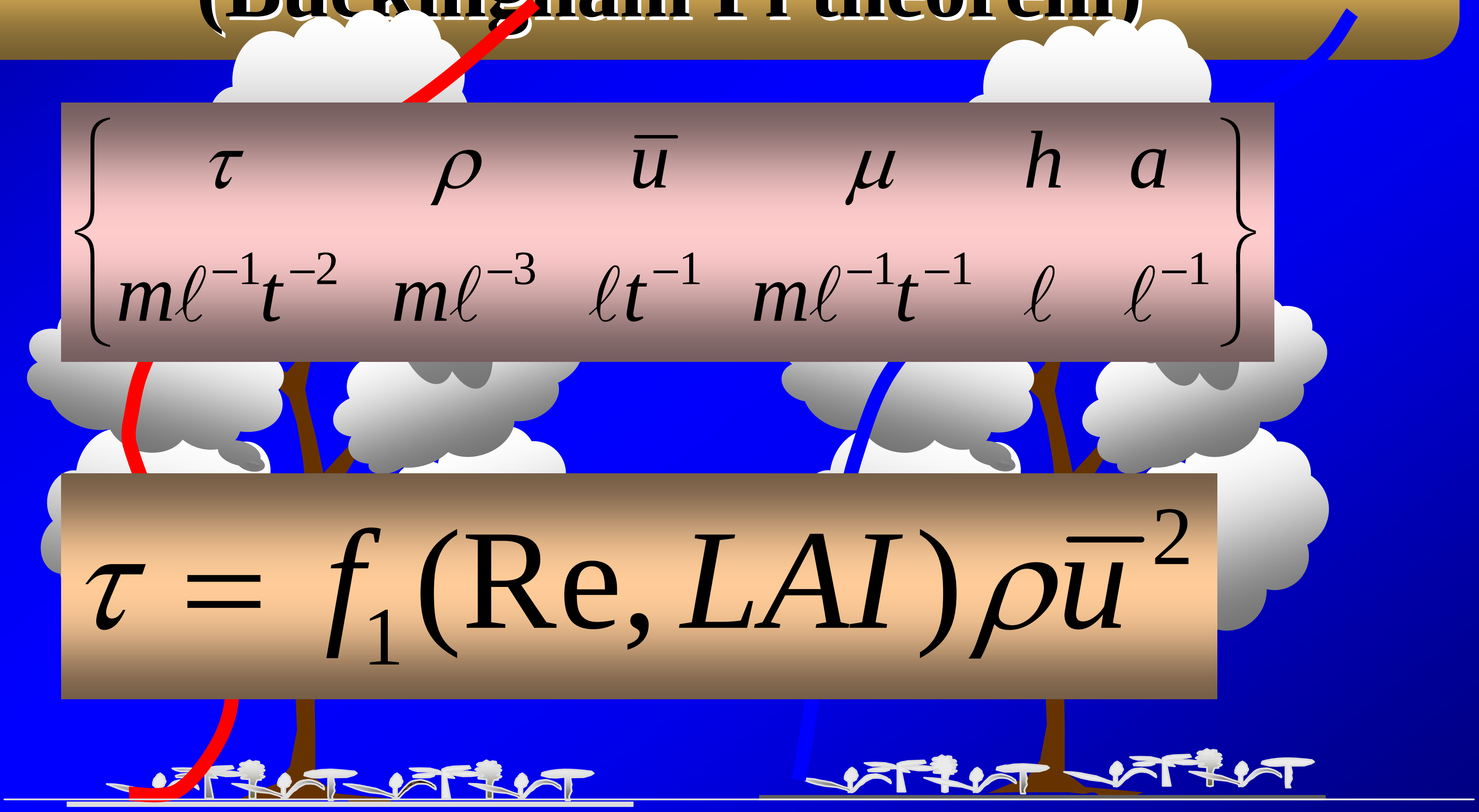


For example,

90% of τ_h is absorbed by the whole canopy at LAI=2.3

(Yi, 2007)

Dimensional Analysis
(Buckingham Pi theorem)

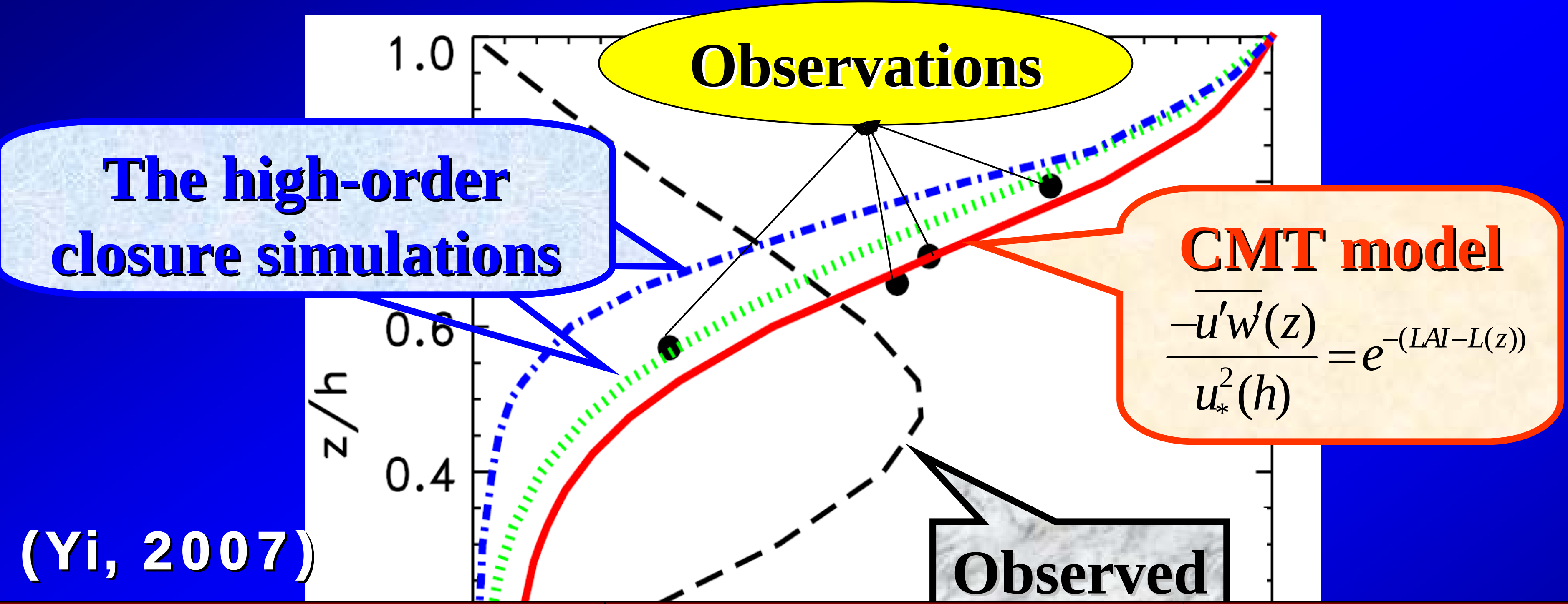


$$\begin{Bmatrix} \tau & \rho & \bar{u} & \mu & h & a \\ m\ell^{-1}t^{-2} & m\ell^{-3} & \ell t^{-1} & m\ell^{-1}t^{-1} & \ell & \ell^{-1} \end{Bmatrix}$$

$$\tau = f_1(\mathrm{Re}, LAI)\rho\bar{u}^2$$

(Yi, 2007)

Comparison with the High-Order Closure



Observations

The high-order closure simulations

CMT model

$$\frac{-\overline{u'w'}(z)}{u_*^2(h)} = e^{-(LAI-L(z))}$$

Observed

(Yi, 2007)

Requirement	*High-order model*	*CMT model*
Computing cost	A super-computer	A calculator
Adjustable constants	Produced from one dataset cannot be used for another	No constants universal

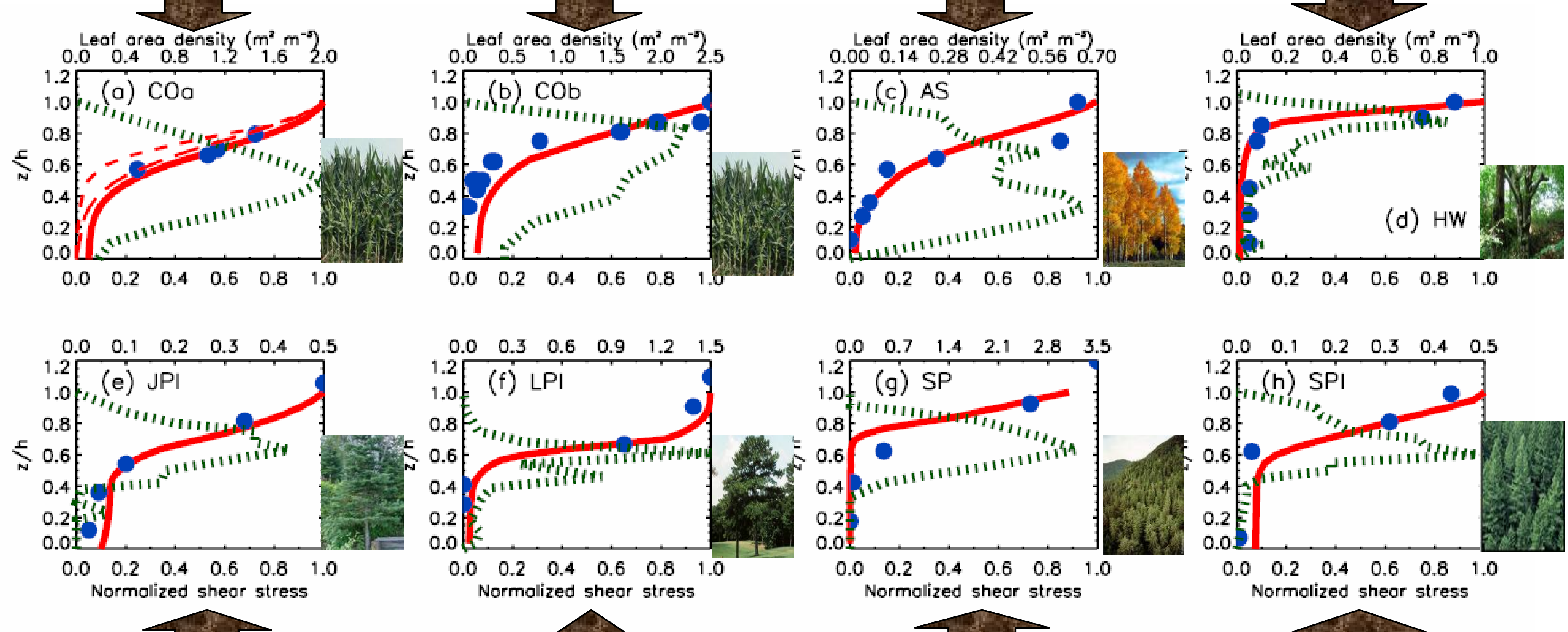
CMT predictions versus observations

Shaw 1977

Wilson 1988

Amiro 1990

Baldocchi & Meyers 1988



Amiro 1990

Katul & Albertson 1998

Amiro 1990

Kelliher et al. 1998

(Yi, 2007)

Conclusions

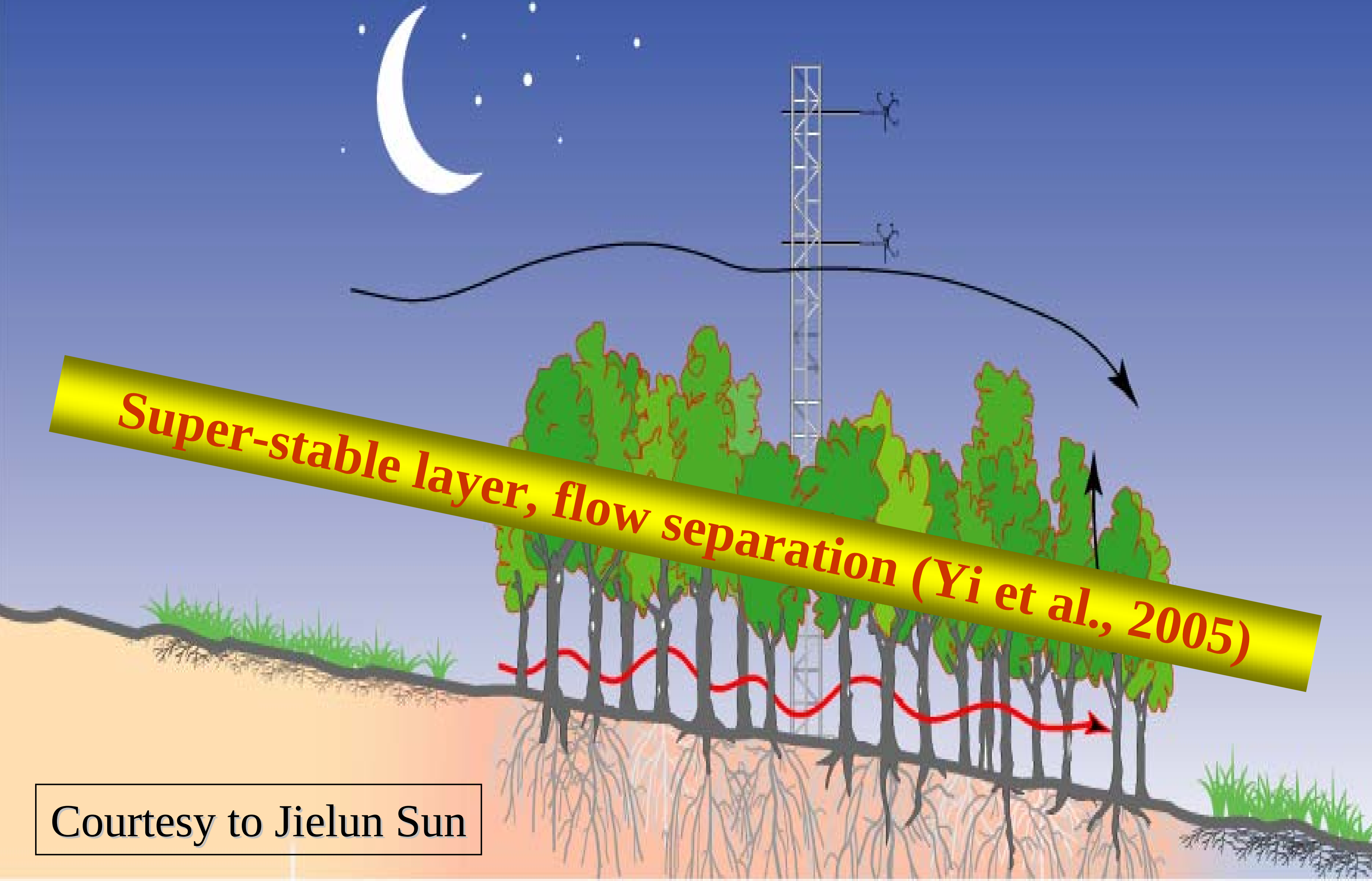
The robust agreements between the theoretical predictions and observations indicate that the nature of momentum transfer within canopies can be well understood by the CMT theory.

Questions

What are canopy MASS and ENERGY transfer theories?

Super-Stable Layer Theory

Advection issues on eddy flux measurements



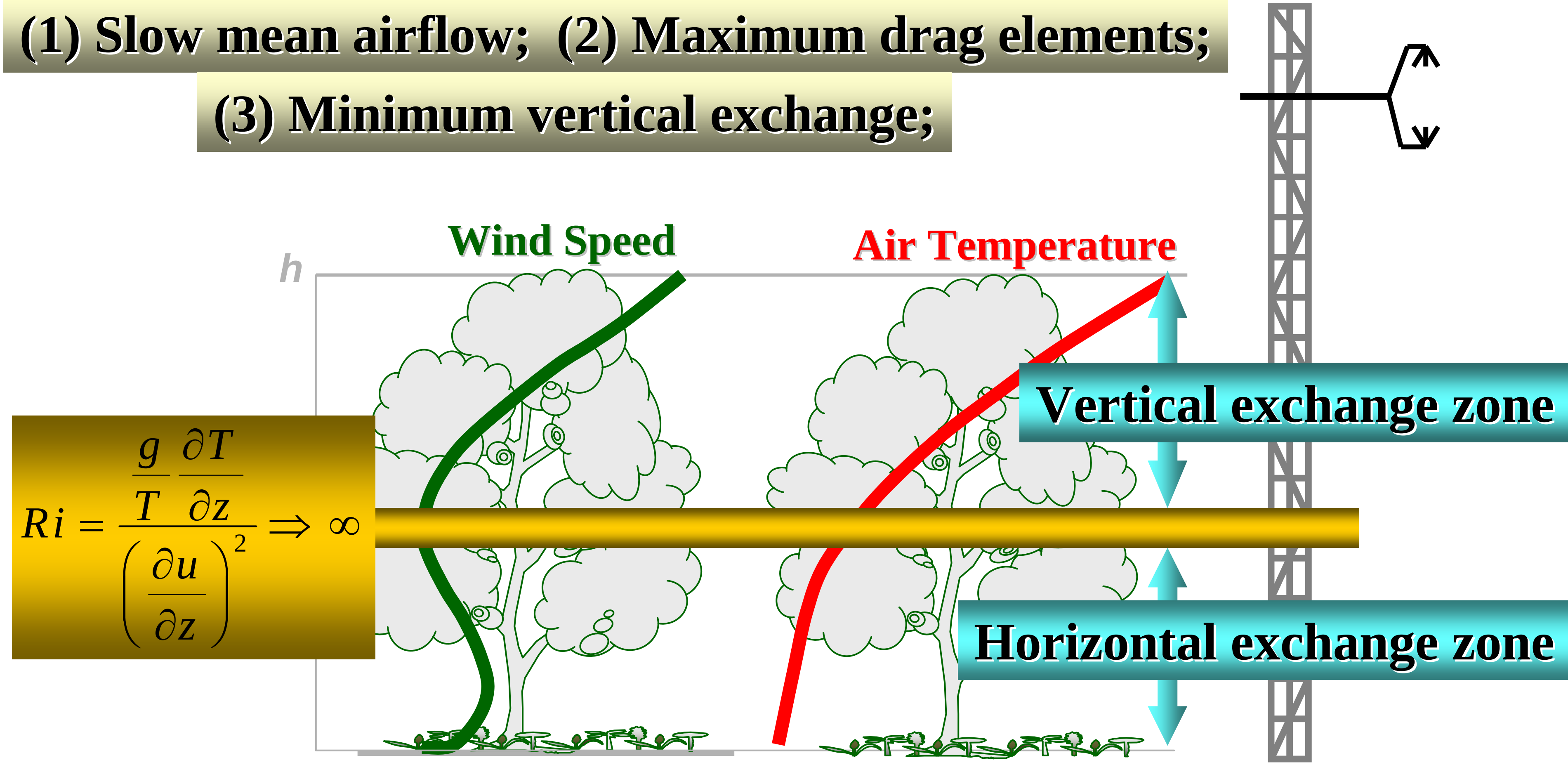
Super-stable layer, flow separation (Yi et al., 2005)

Courtesy to Jielun Sun

A super stable layer

(1) Slow mean airflow; (2) Maximum drag elements;

(3) Minimum vertical exchange;



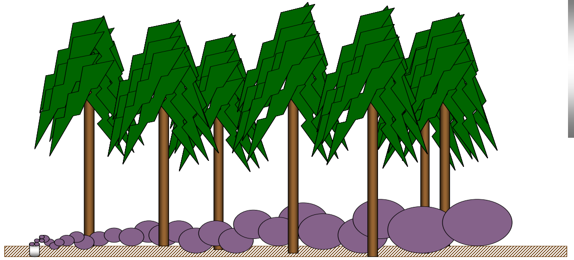
$$Ri = \frac{\frac{g}{T}\frac{\partial T}{\partial z}}{\left(\frac{\partial u}{\partial z}\right)^2} \Rightarrow \infty$$

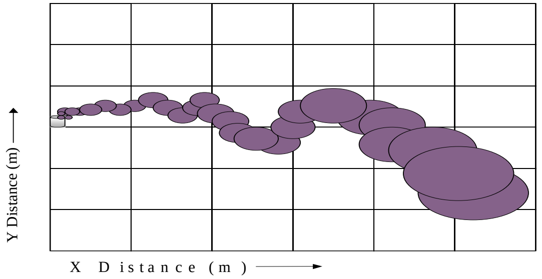
(4) Maximum horizontal CO2 (or other scalar) gradient;

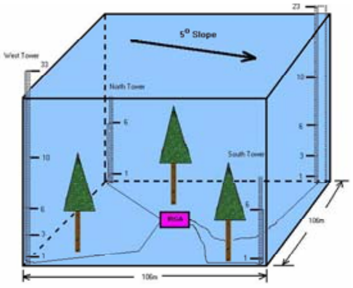
(5) Maximum ratio of wake and shear production rate.

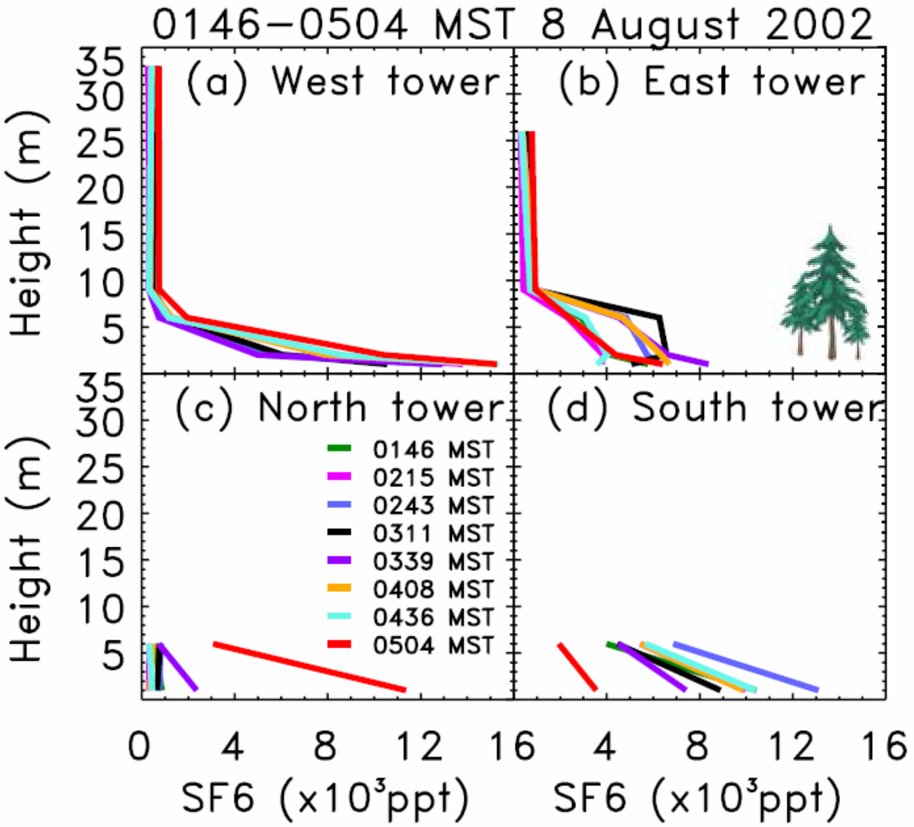
(Yi, 2007; Yi et al., 2005)

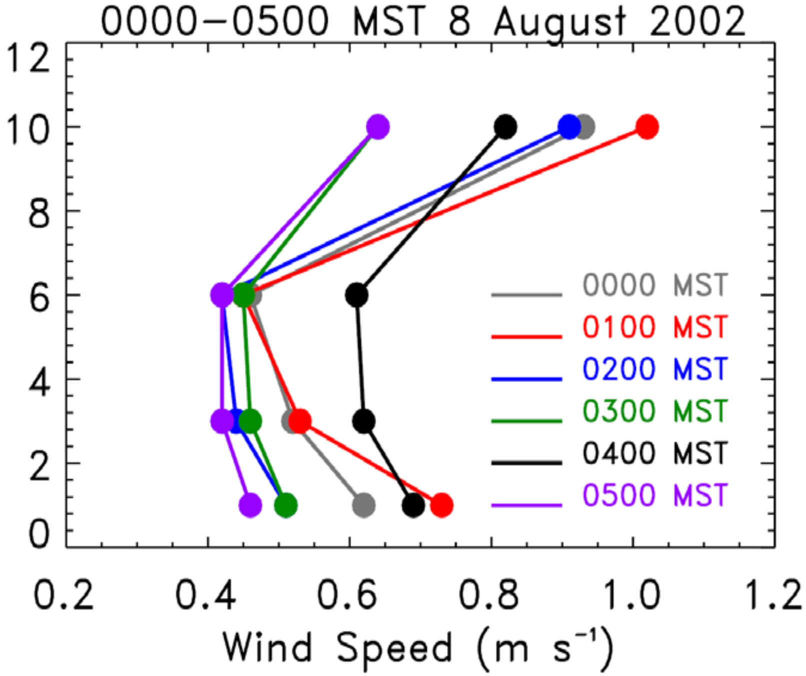
SF_6 experiments





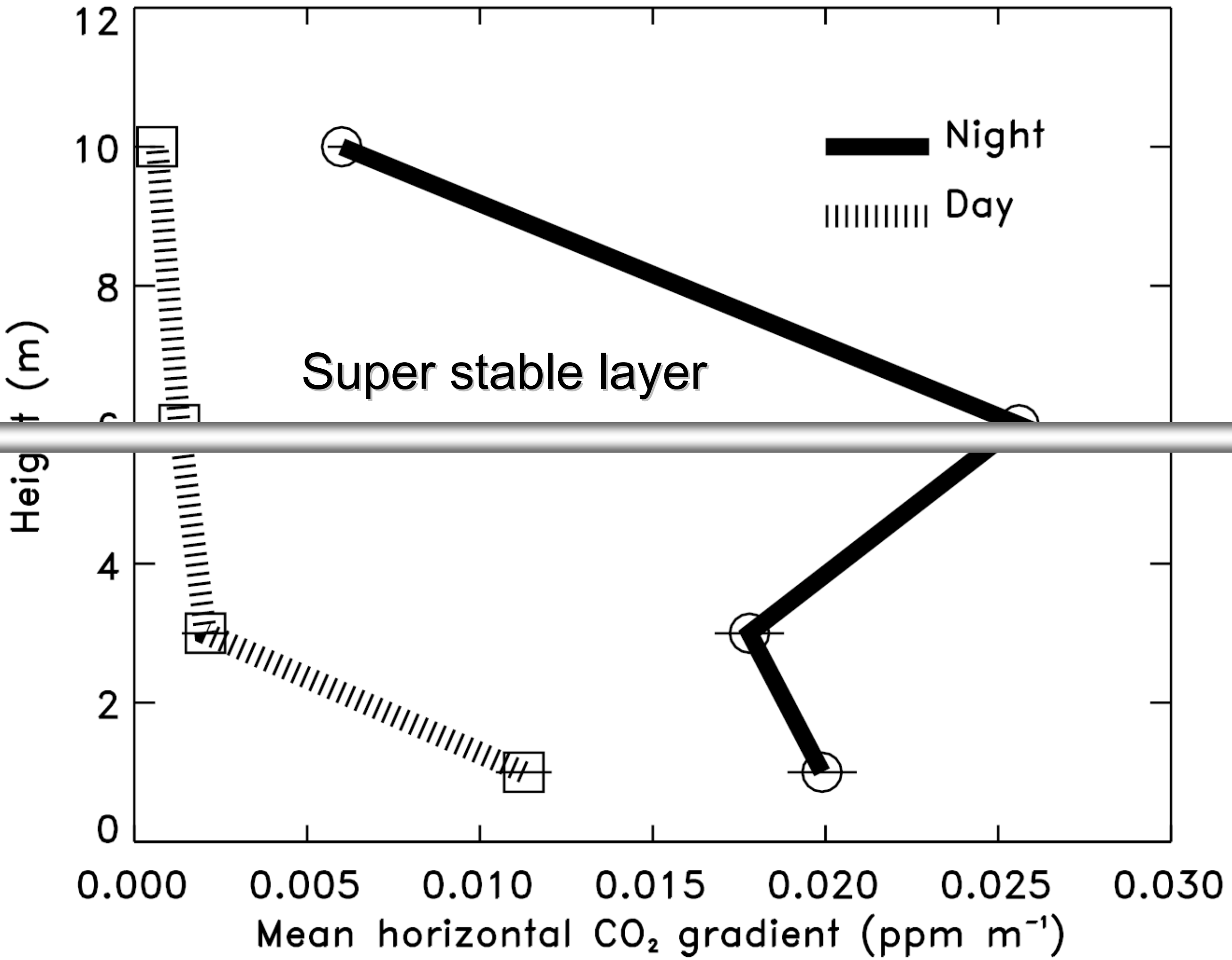






Yi et al. 2005

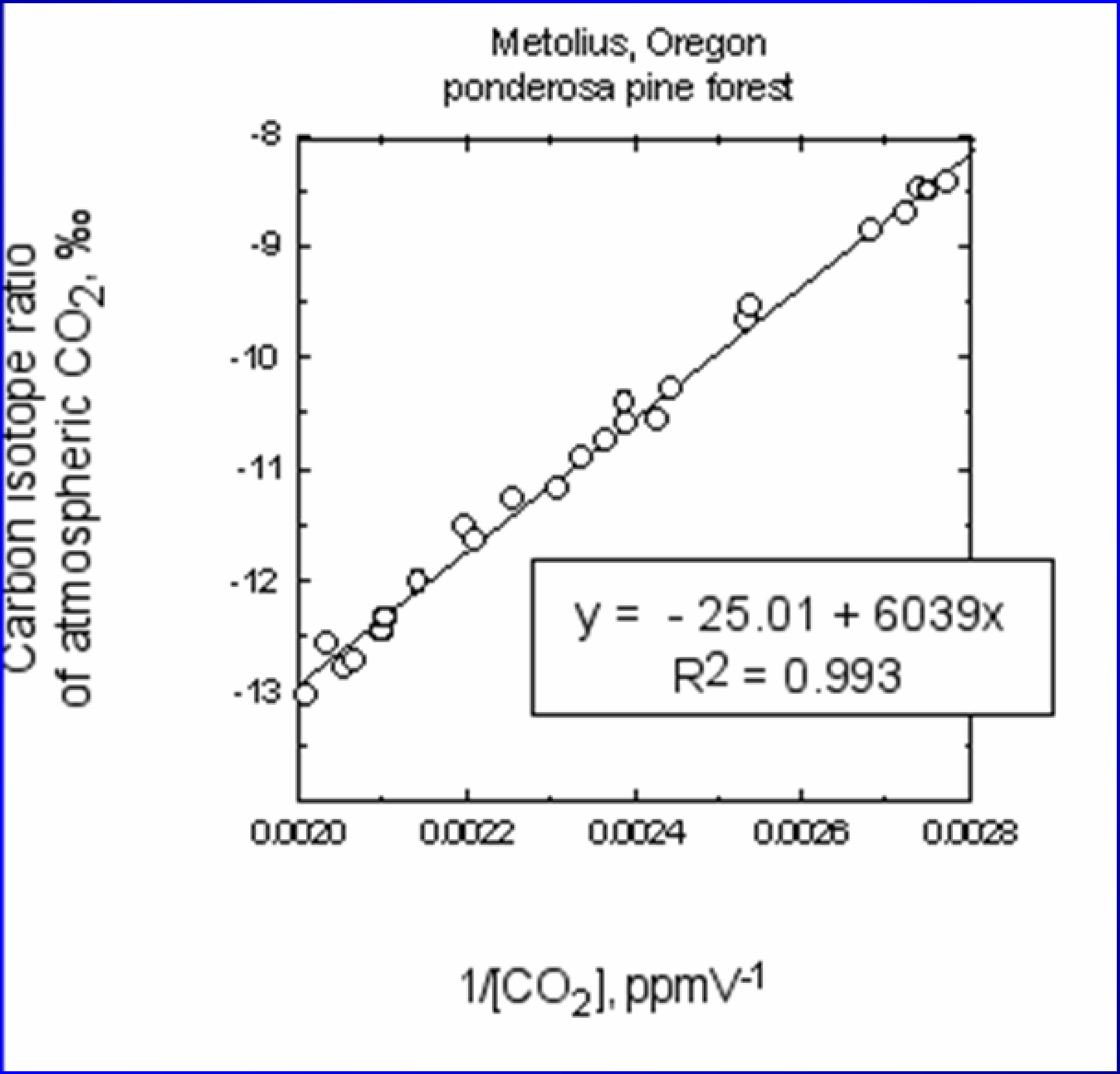
Horizontal CO$_2$ gradient in summer



Super stable layer

Yi et al. 2007

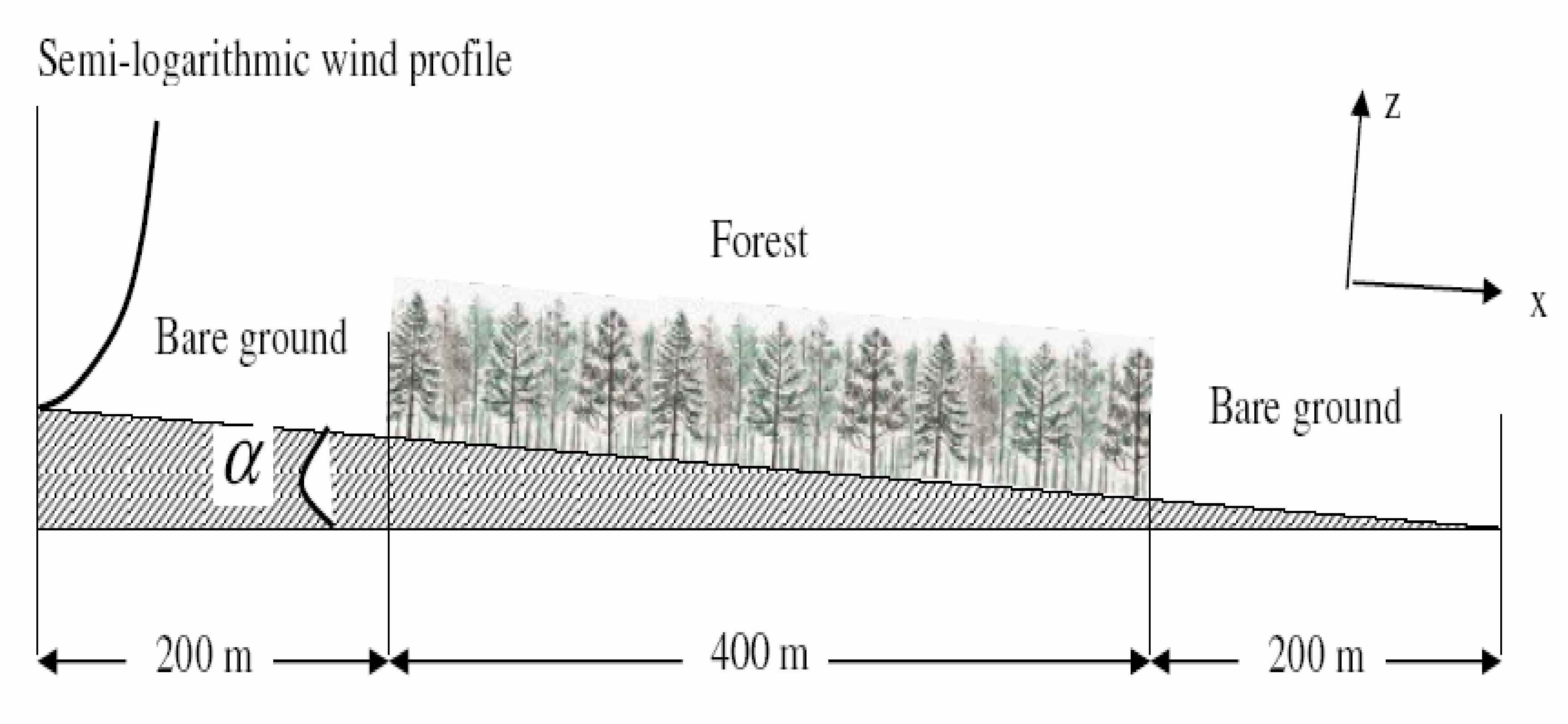
Keeling Plot



Apply the computational fluid dynamics (CFD) approach to simulate canopy flow

Renormalization-group k-ε turbulence model

Leaf area density and drag coefficient profile derived from the analytical model were used

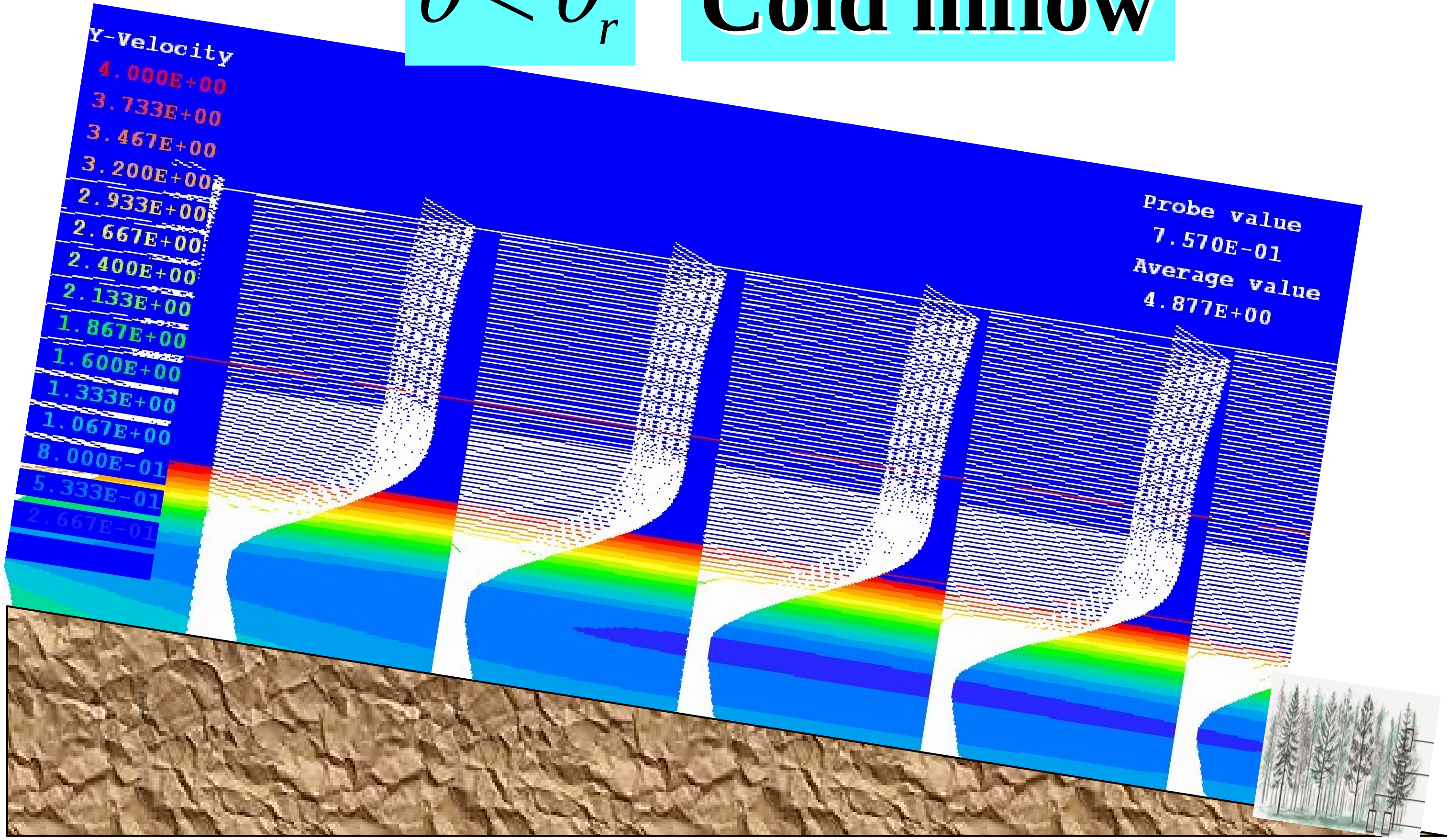


Yi et al. 2005

‘S’-shaped wind profile

$\theta < \theta_r$

Cold inflow

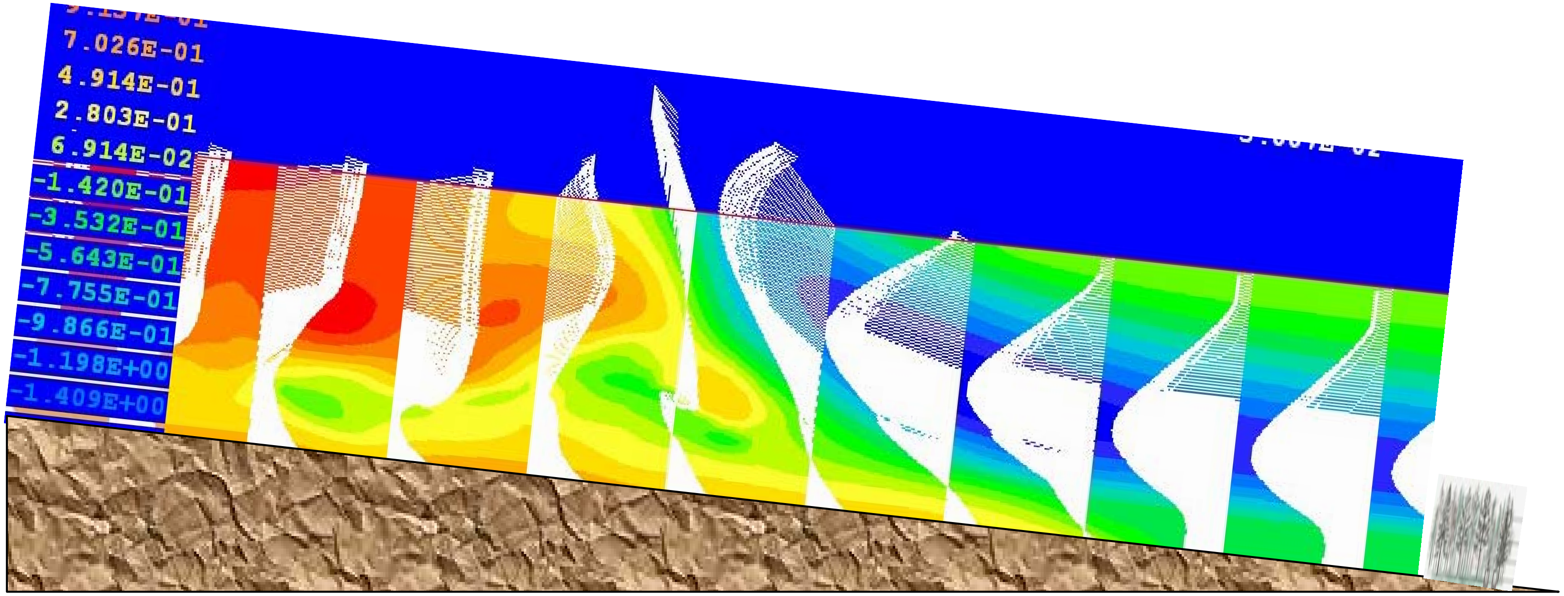


Yi et al. 2005

Chimney phenomenon

$\theta \geq \theta_r$

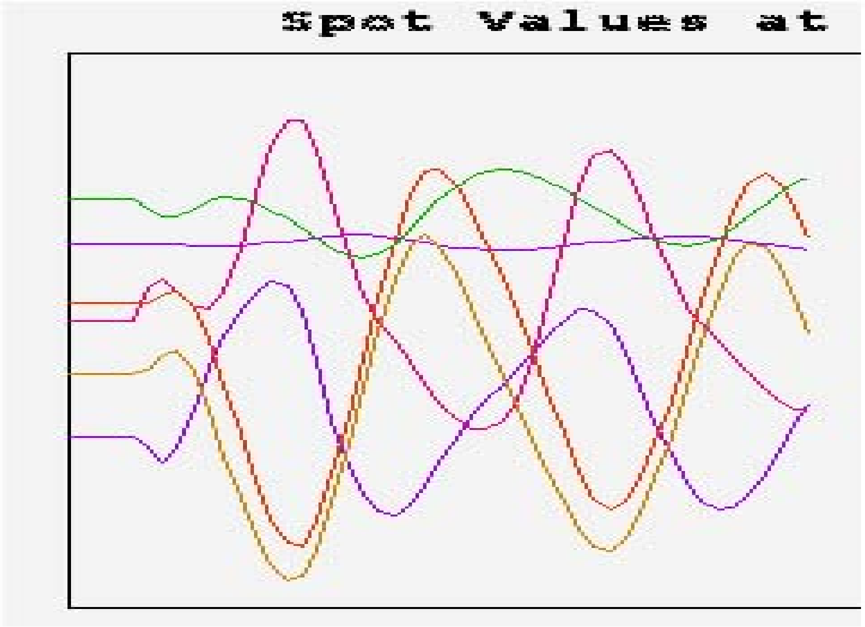
Warm inflow

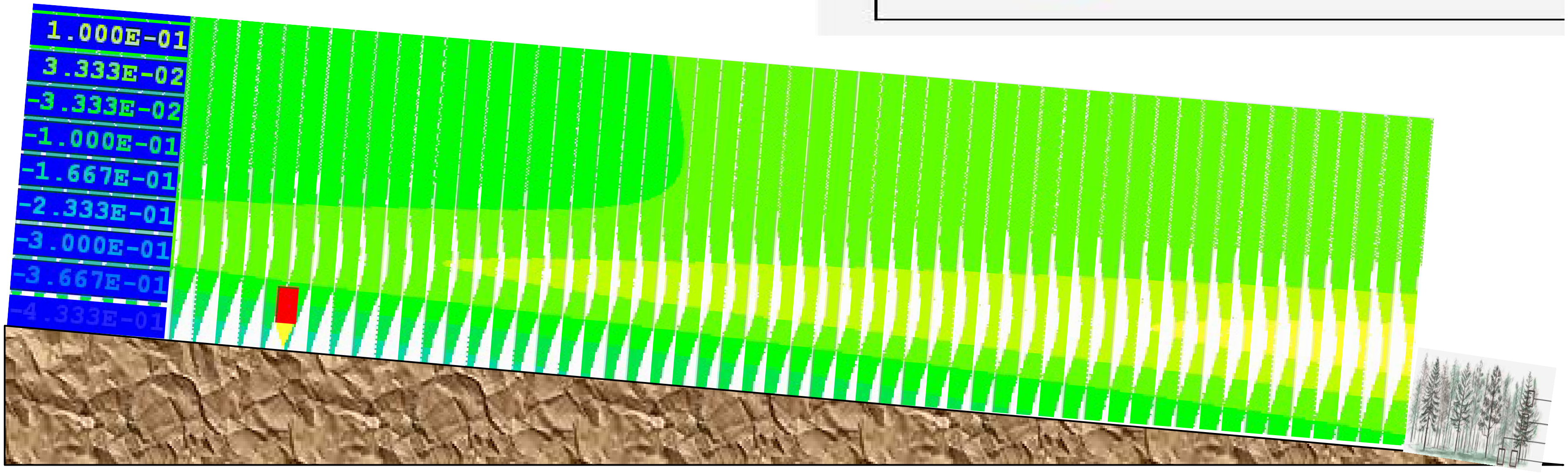


Yi et al. 2007b

Oscillation

$$\theta \approx \theta_r$$



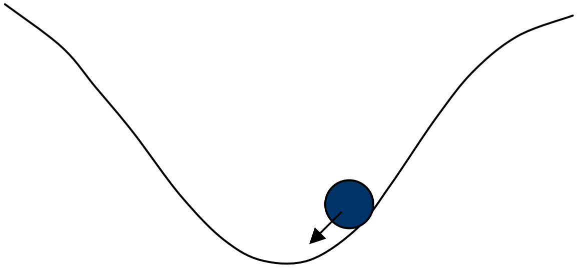


Yi et al. 2007b

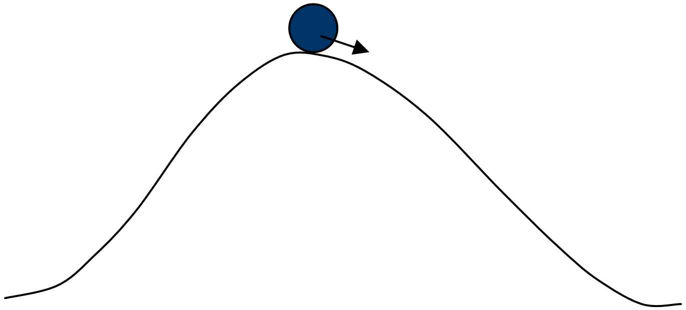
Steady States

$$\begin{cases} \dfrac{du_0}{dt} = 0 = f_u(u_0, \theta_0), \\ \dfrac{d\theta_0}{dt} = 0 = f_\theta(u_0, \theta_0). \end{cases}$$

$$\begin{cases} u_0^{\pm} = \pm\sqrt{\dfrac{g}{c_D \ell}\left(\dfrac{\theta_r - \theta_0}{\theta_r}\right)}, \\ \theta_0 = \theta_r\left(1 - \dfrac{c_D \ell L_{c0}^2}{g\gamma^2 \sin^2\alpha}\right), \end{cases}$$



Stable



Unstable

Yi et al. 2007b

Synopsis

$$\theta_r - \theta_0 \geq \theta_c = \frac{\gamma \sin \alpha}{c_D \ell} \approx 0.194 \text{ K}$$

$\left(u_0^+, \theta_0\right)$ **stable.**

$\left(u_0^-, \theta_0\right)$ **unstable.**

$$0 \leq \theta_r - \theta_0 \leq \theta_c \approx 0.194$$

Oscillation.

Yi et al. 2007b

Acknowledgements to

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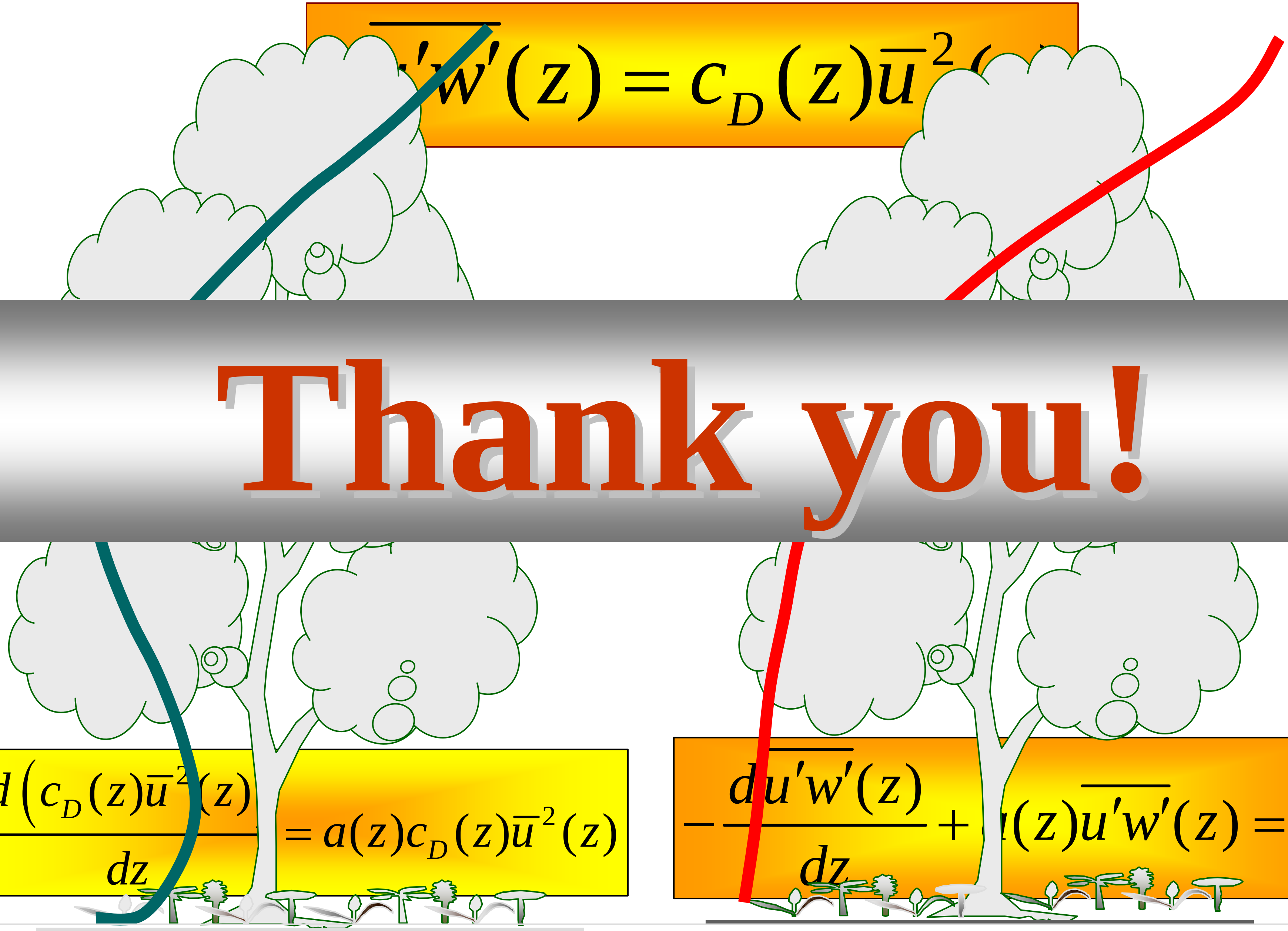
Lamb lab, Washington State University
Denning lab, Colorado State University



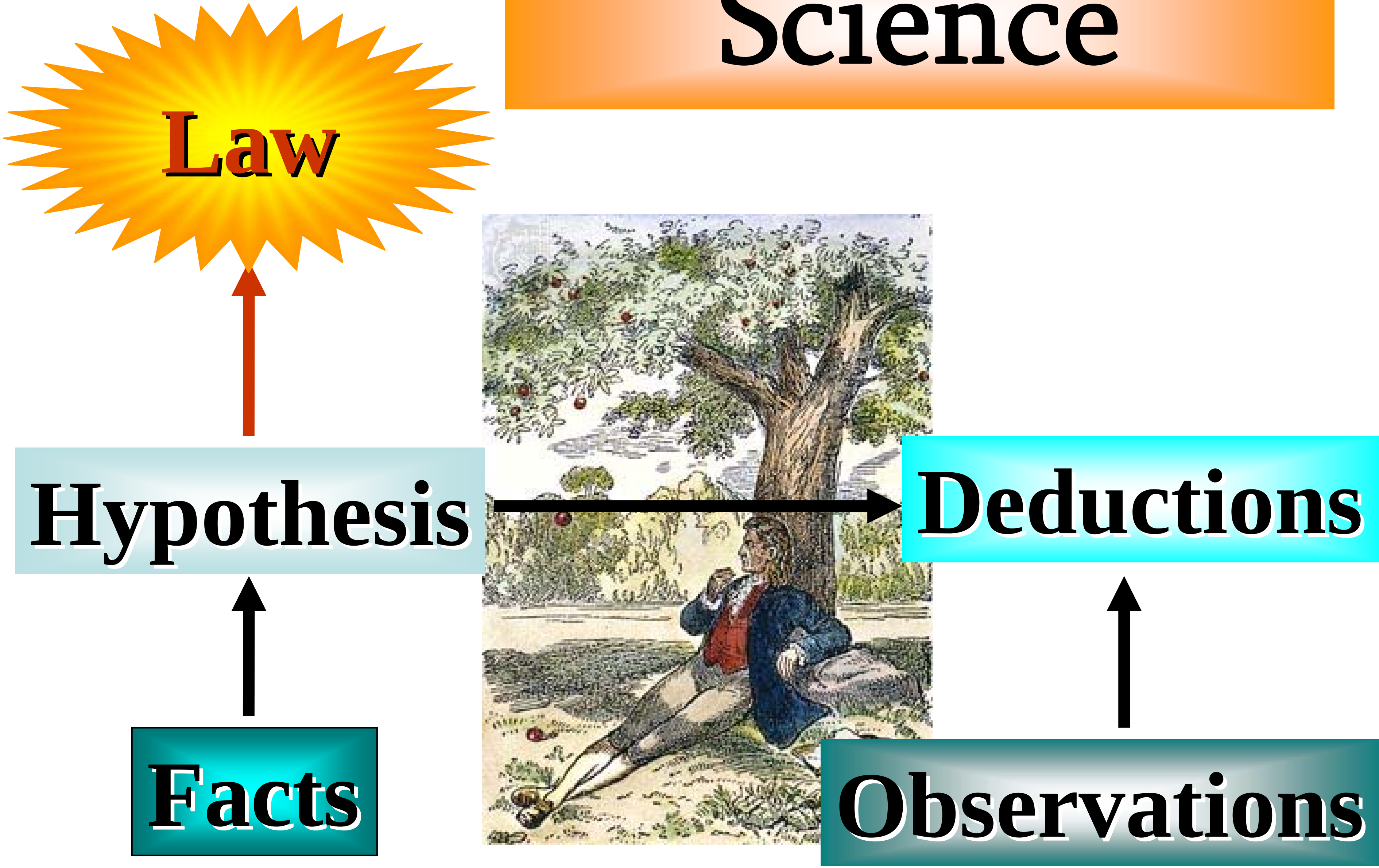
$$\overline{u'w'}(z) = c_D(z)\overline{u}^2(z)$$

Thank you!

$$\frac{d\left(c_D(z)\overline{u}^2(z)\right)}{dz} = a(z)c_D(z)\overline{u}^2(z)$$

$$-\frac{d\overline{u'w'}(z)}{dz} + a(z)\overline{u'w'}(z) = 0$$

Science



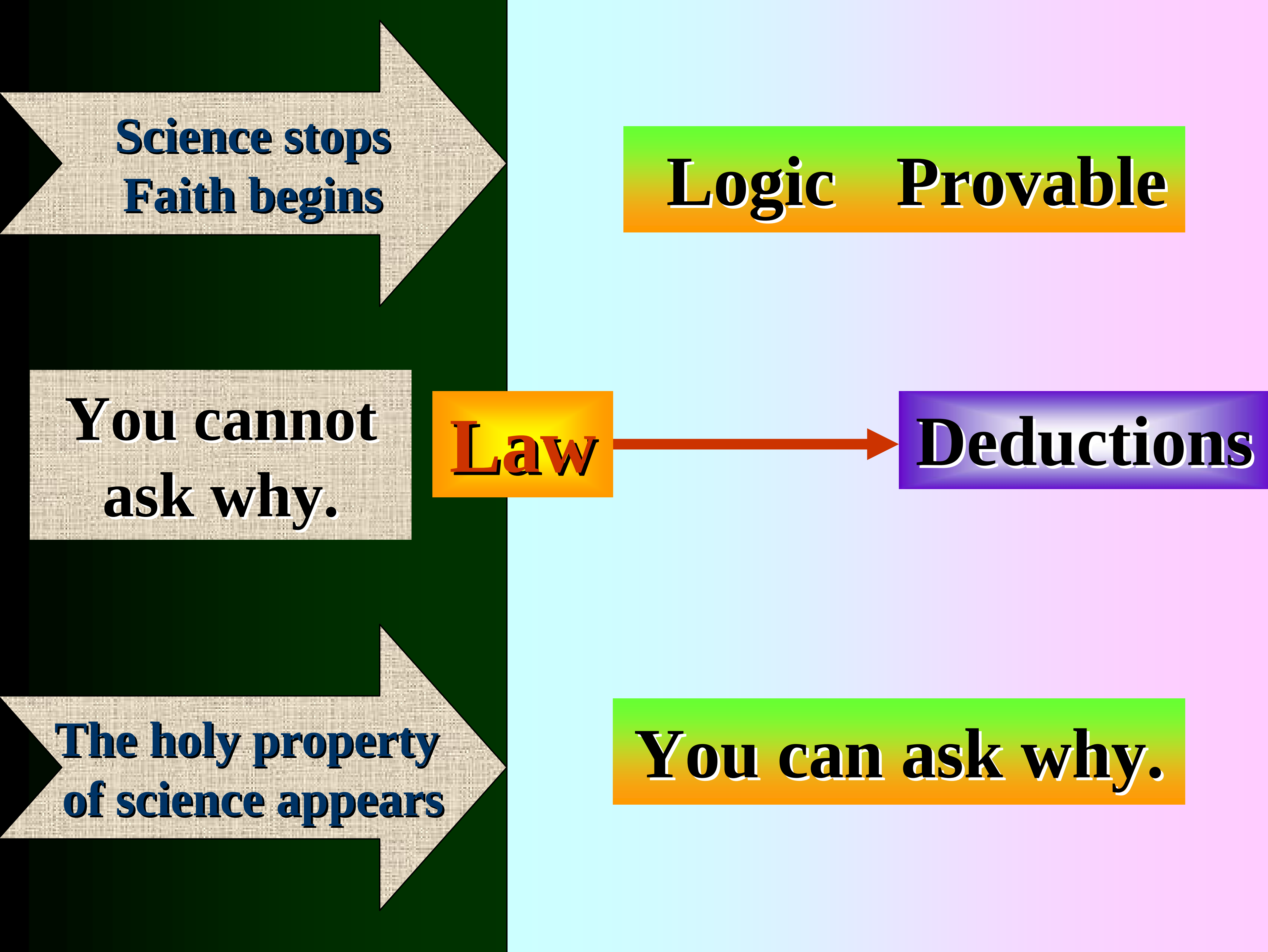
Law

Hypothesis

Deductions

Facts

Observations



Science stops
Faith begins

You cannot ask why.

The holy property of science appears

Law → Deductions

Logic Provable

You can ask why.

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