Induced Power Scaling Alone Cannot Explain Paleozoic Griffenfly Gigantism

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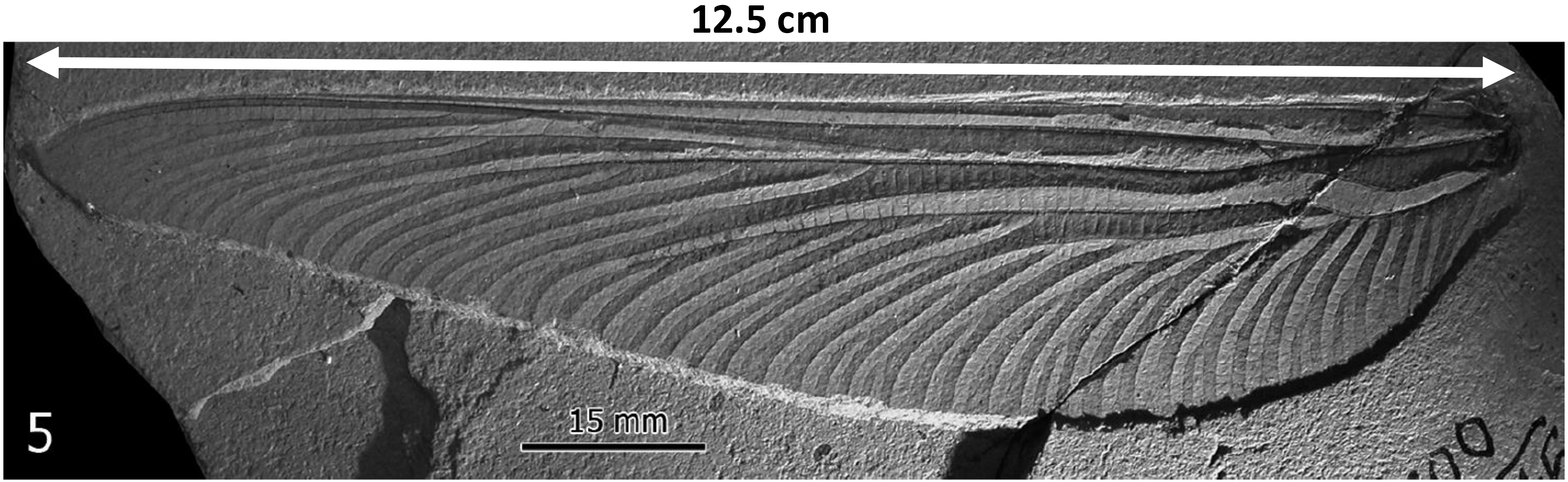
Photo of a model of the griffinfly *Meganeura monyi* at the California Academy of Sciences

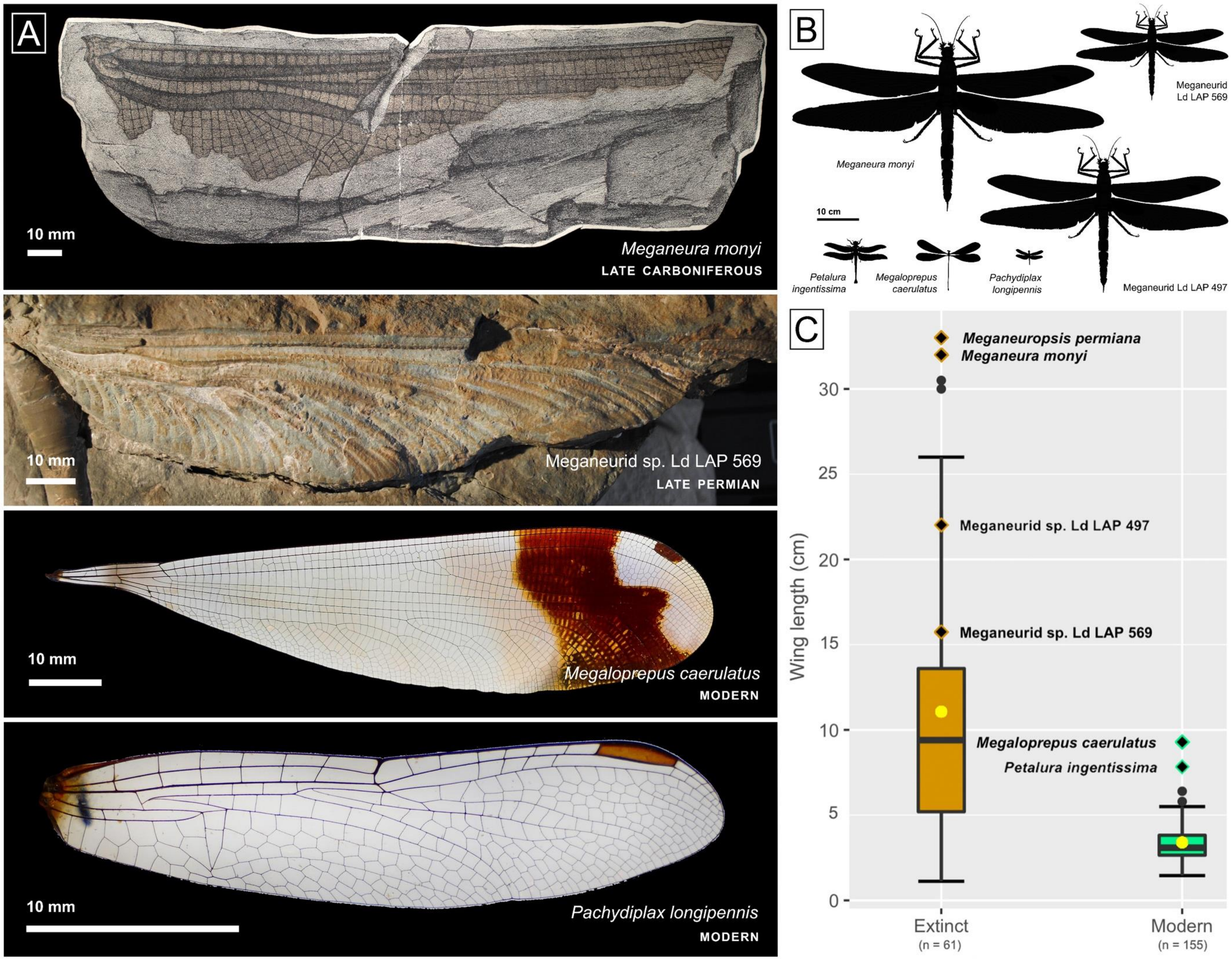
300 mya

May, 1982, 30 cm wing length
Atkinson, 2005, 66 cm wingspan



Sinomeganeura huangheensis

Ren et al. 2007



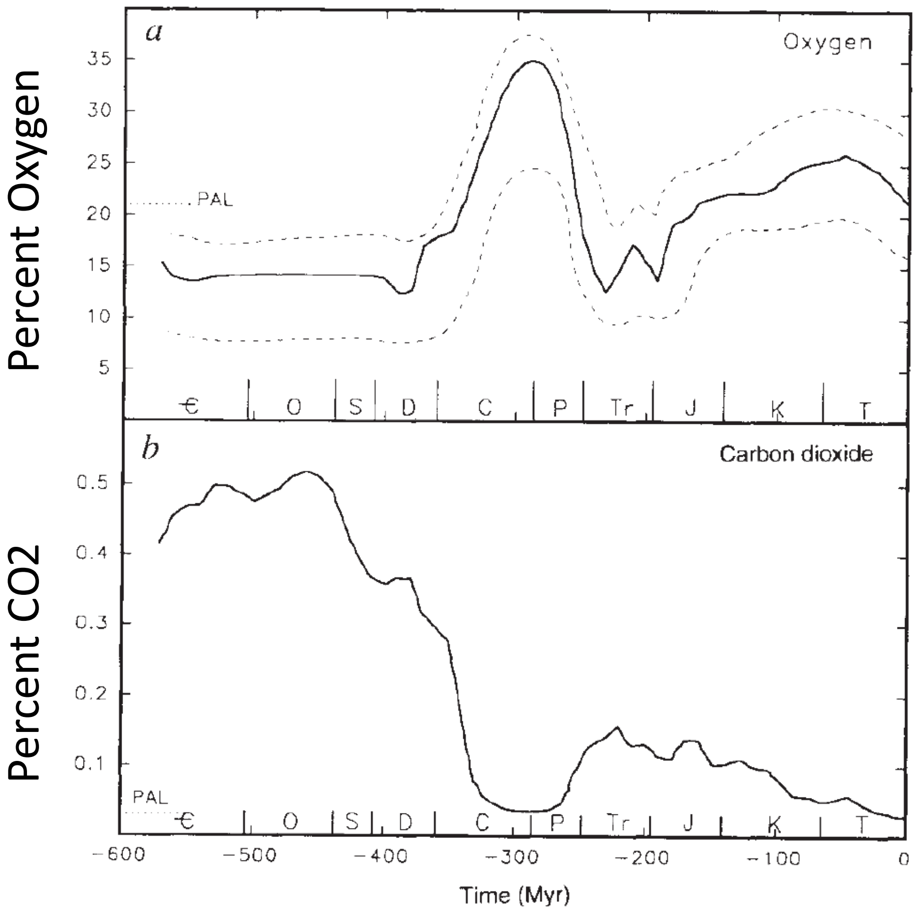
Ellers, et al. 2024

HYPOTHESIS

Implications of the late Palaeozoic oxygen pulse for physiology and evolution

Jeffrey B. Graham, Robert Dudley, Nancy M. Aguilar & Carl Gans

NATURE · VOL 375 · 11 MAY 1995



↑ O_2 ⇒ growth to <u>larger size</u>

↑ O_2 ⇒ <u>more fuel</u> for metabolism and flight

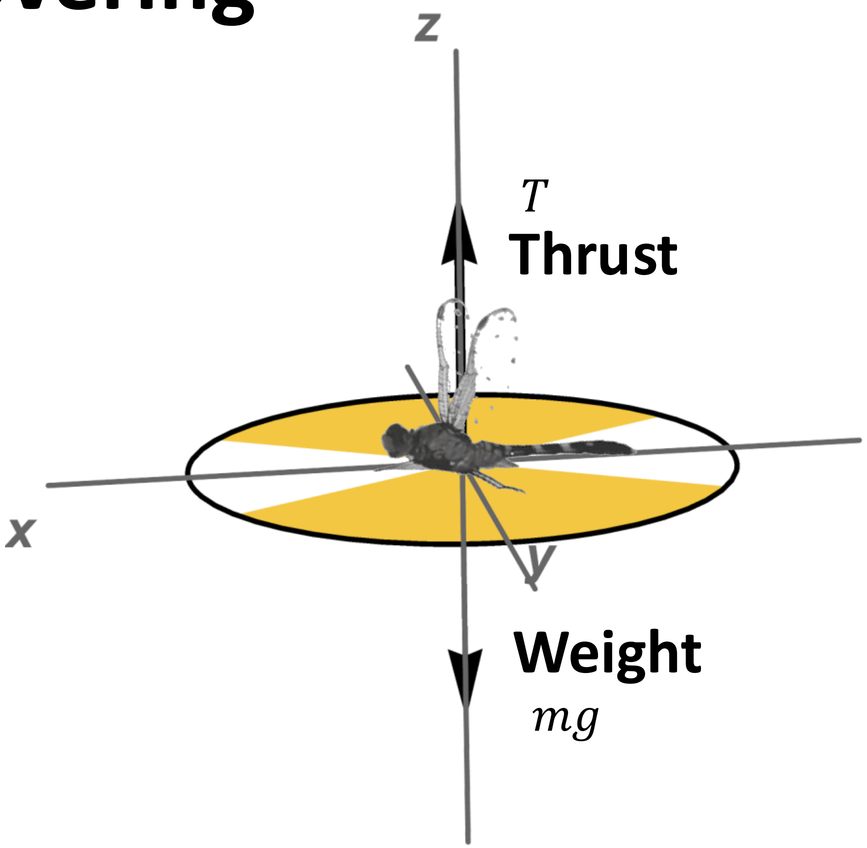
↑ O_2 ⇒ ↑ atmospheric density ⇒ <u>greater lift</u>

	% O_2	Atmospheric Density (kg/m^3)
Present	21	1.29
Late Carboniferous, 285 MYA	35	1.56

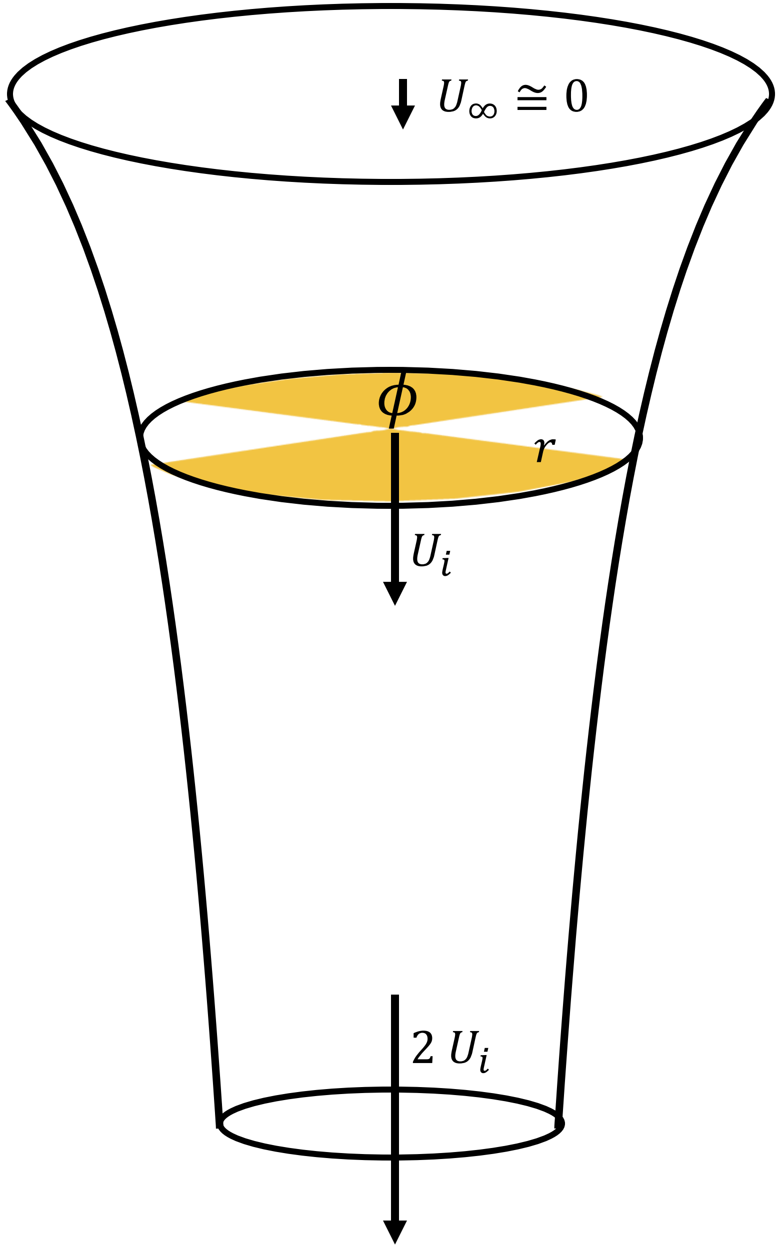
<u>Question:</u>

In a denser, more oxygen-rich atmosphere, <u>*how much larger*</u> could a dragonfly-like flyer theoretically be?

Hovering



$$T = mg$$



Actuator disk generates thrust

$$U_i = \sqrt{\frac{m\,g}{2\,\rho\phi\,r^2}}$$

$$P_i = T U_i$$

$$P_i = \sqrt{\frac{(m\,g)^3}{2\rho\phi\,r^2}}$$

Induced Power

Dragonfly image from: https://www.science.org/content/article/video-reveals-secret-dragonfly-s-backward-flight

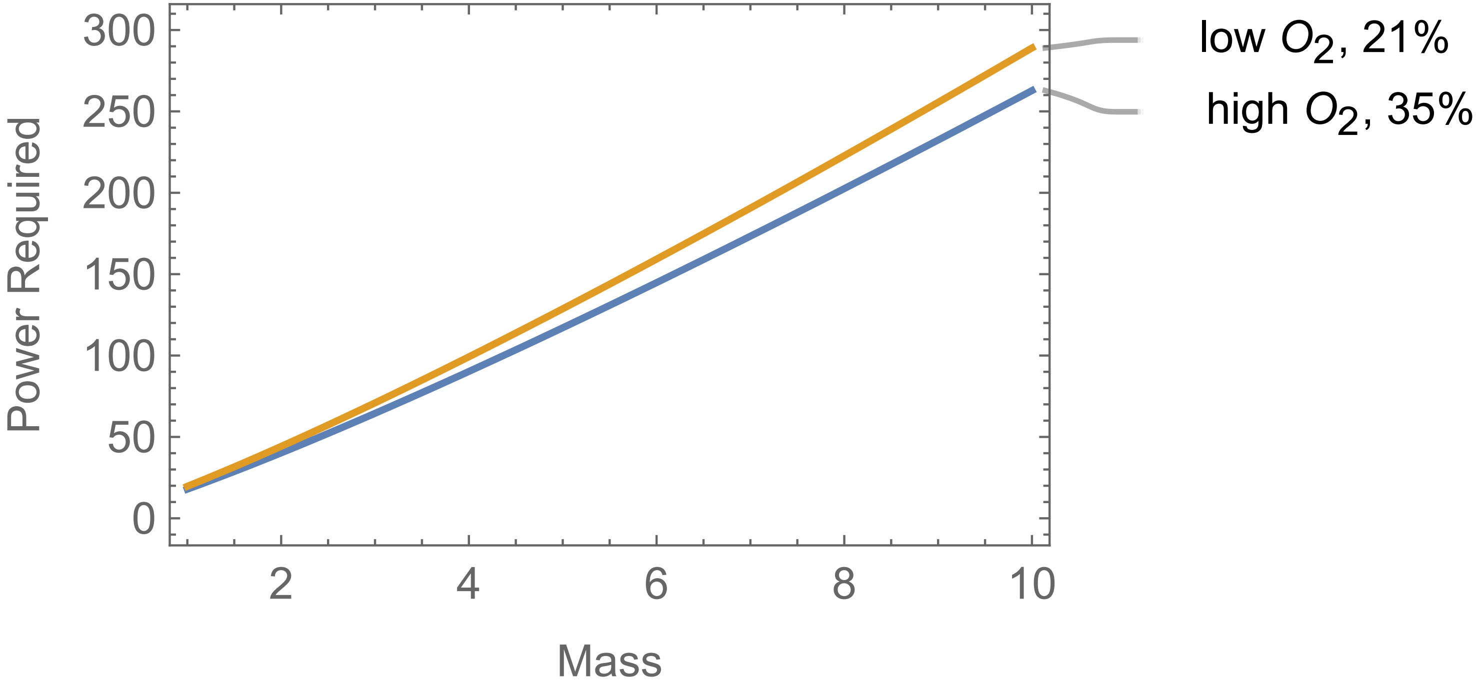
$$P_i = \sqrt{\frac{(mg)^3}{2\,\rho\,\phi\,r^2}}$$

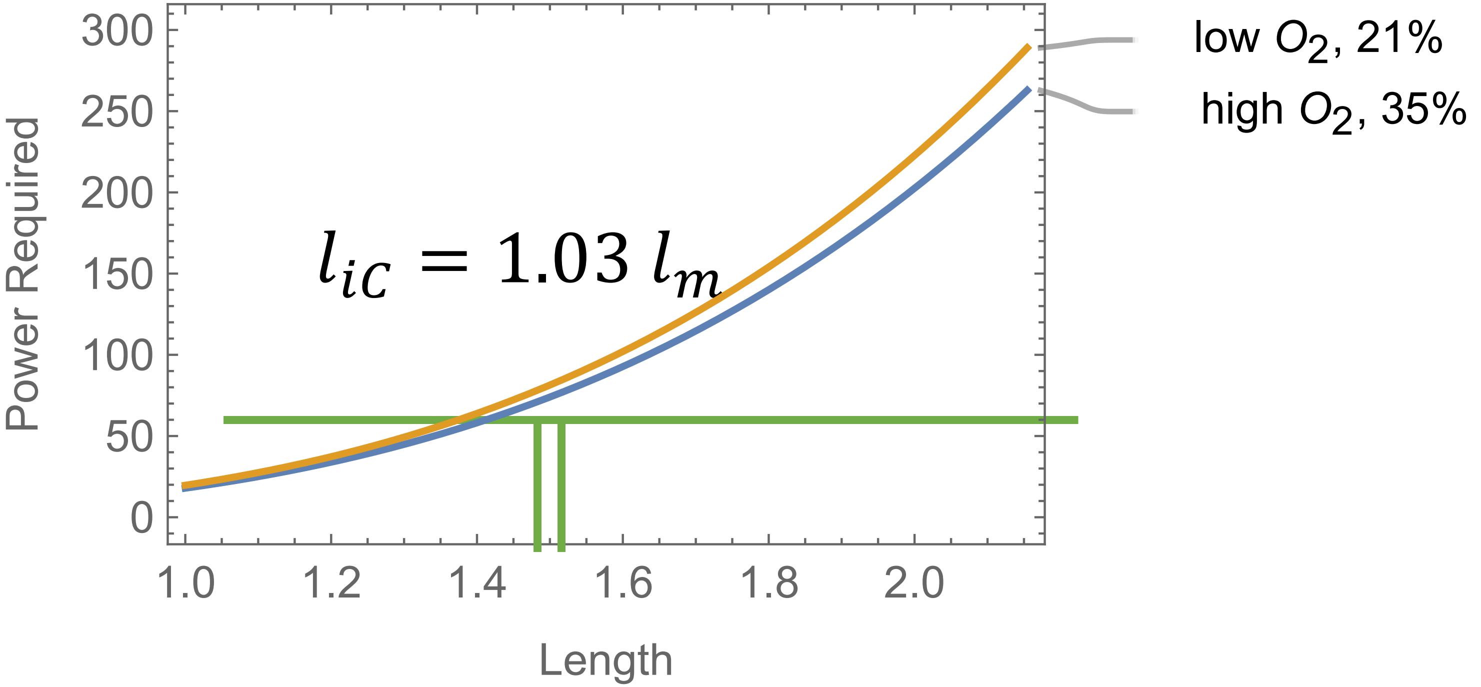
Induced Power required to support weight

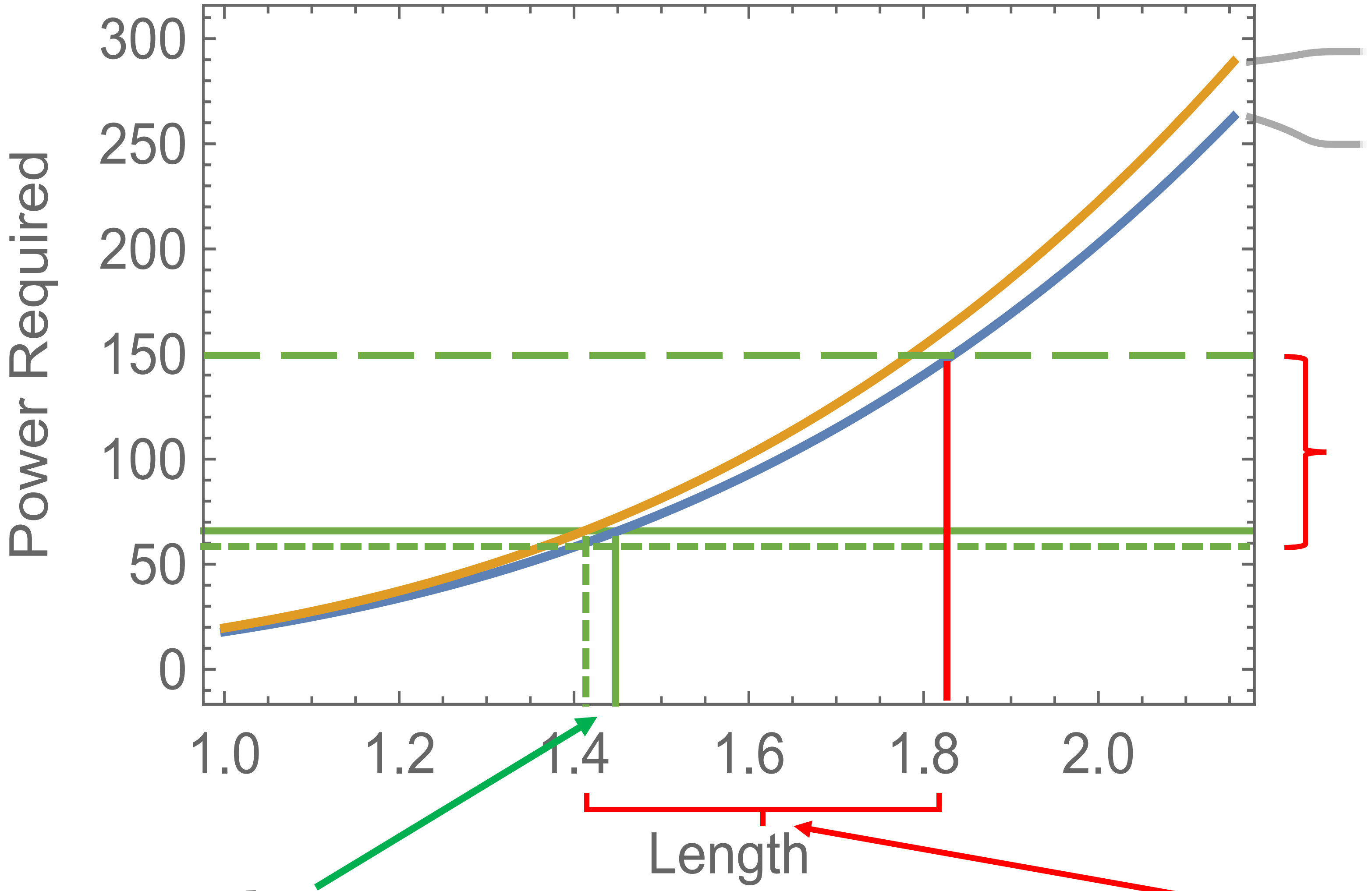
$$\frac{P_{i_C}}{P_{i_m}} = \frac{\sqrt{\frac{(mg)^3}{2\rho_C\phi\,r^2}}}{\sqrt{\frac{(mg)^3}{2\rho_m\phi\,r^2}}} = \sqrt{\frac{\rho_m}{\rho_C}} = \sqrt{\frac{1.29}{1.56}} = 0.9$$

$$P_i = \sqrt{\frac{(k_1 l^3)^3}{2\,\rho\,k_2 l^2}} \propto l^{\frac{7}{2}}$$

$$\frac{P_{iC}}{P_{im}} \propto \frac{l_{ic}^{\frac{7}{2}}}{l_m^{\frac{7}{2}}} \propto 0.9$$







low O_2, 21%

high O_2, 35%

Extra power from extra oxygen

$$\frac{35\%/21\%}{0.91} = 1.9$$

$$\frac{P_{iC}}{P_{im}} \propto \frac{l_{ic}^{\frac{7}{2}}}{l_m^{\frac{7}{2}}} \propto 1.9$$

$$l_{iC} = 1.03\ l_m$$

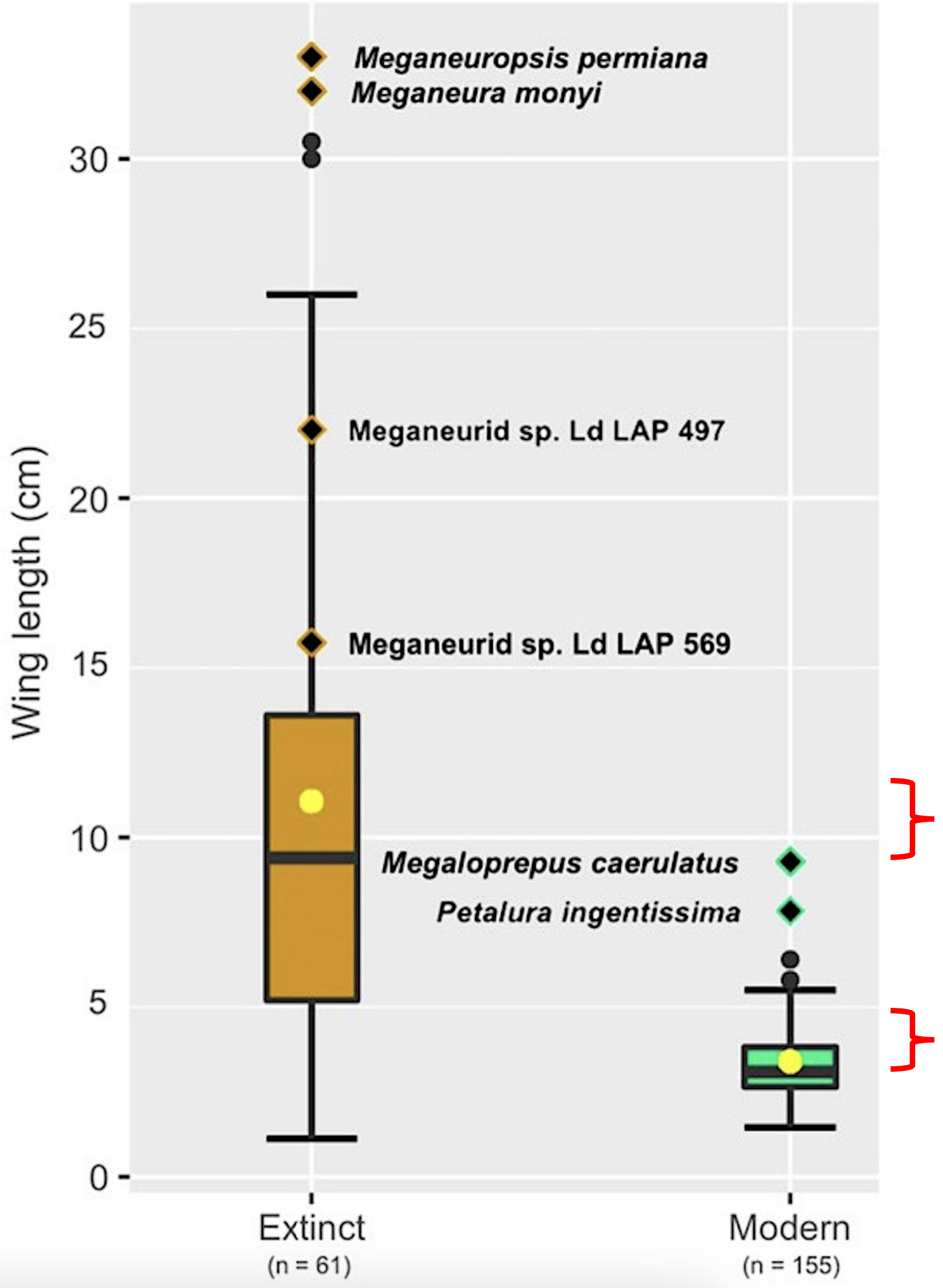
$$l_{iC} = 1.2\ l_m$$

Increase in length due to air density

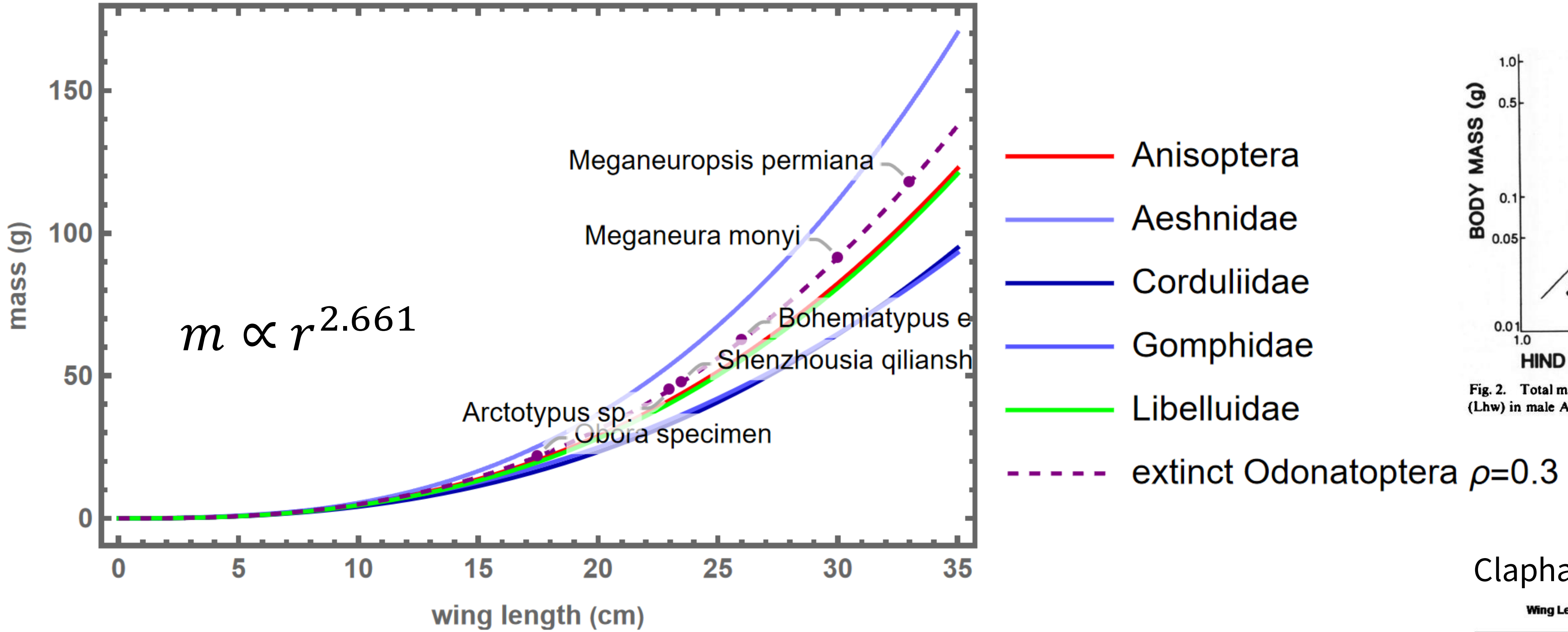
Aerodynamics

Increase in length due to fuel, 35% O_2

Energy Density



Meganeuropsis permiana
Meganeura monyi
Meganeurid sp. Ld LAP 497
Meganeurid sp. Ld LAP 569
Megaloprepus caerulatus
Petalura ingentissima
Wing length (cm)
30
25
20
15
10
5
0
Extinct
(n = 61)
Modern
(n = 155)



May, 1981

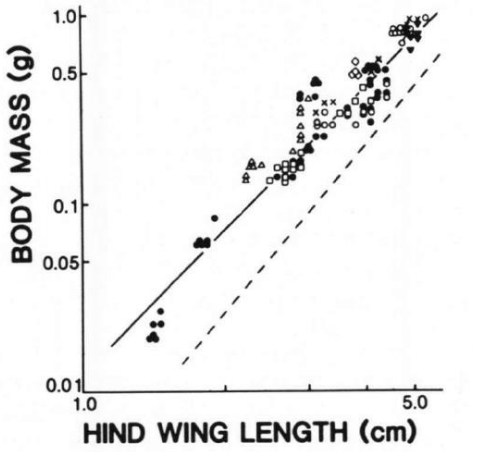
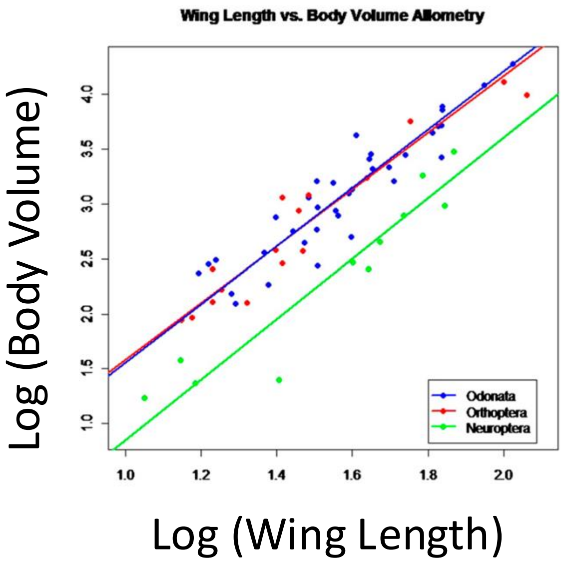


Fig. 2. Total mass (M) as a function of hindwing length (Lhw) in male Anisoptera. Symbols as in Fig. 1.

Clapham & Karr, 2012.

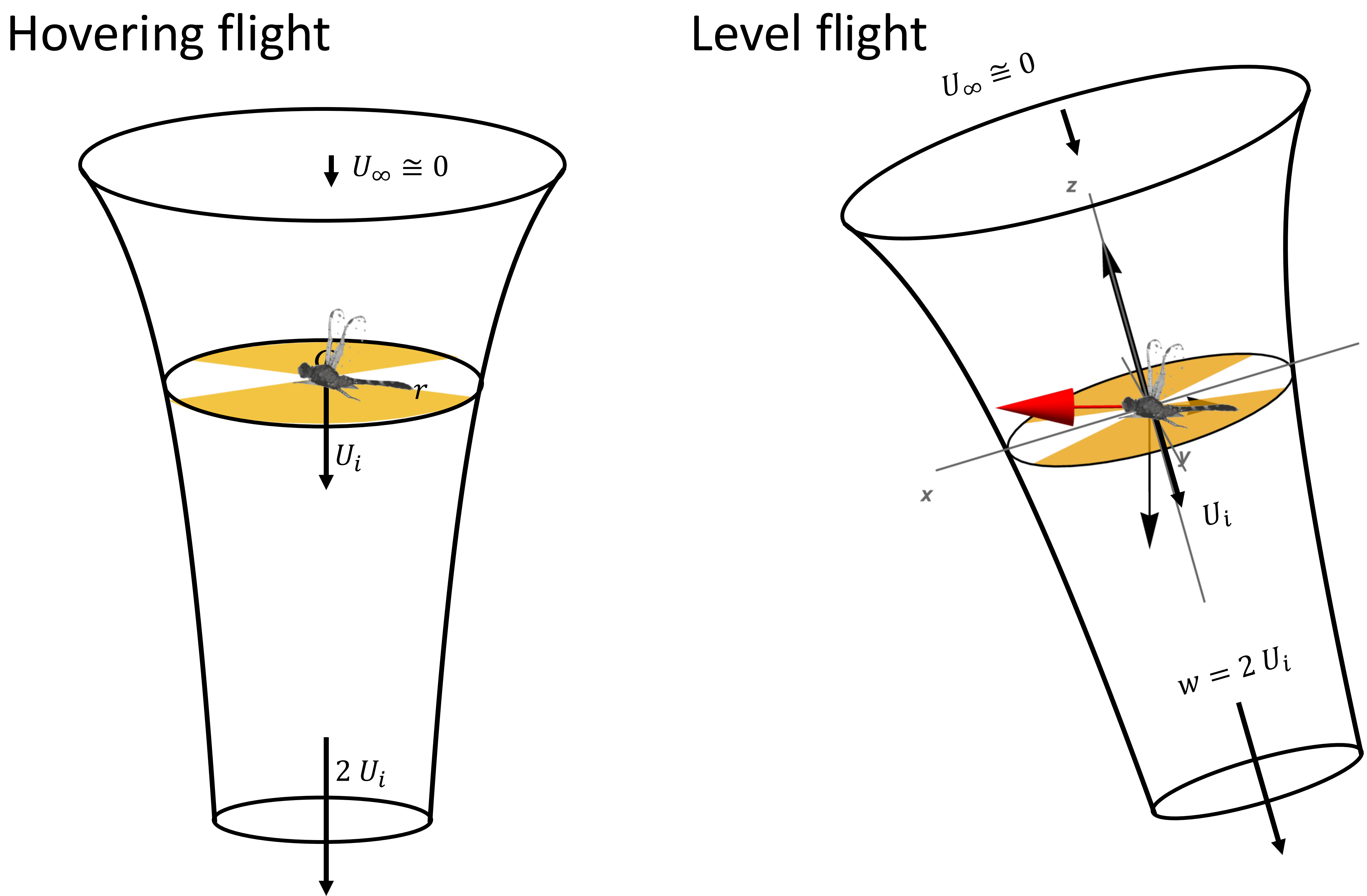


Scaling is anisometric

$$l_c = l_m \left(\frac{P_{i,C}}{P_{i,m}}\right)^{\frac{2}{3*2.661-2}} \left(\frac{\rho_C}{\rho_m}\right)^{\frac{1}{3*2.661-2}}$$

$$= l_m \left(\frac{35}{21}\right)^{\frac{2}{5.983}} \left(\frac{1.56}{1.29}\right)^{\frac{1}{5.983}}$$

$$\boxed{l_c = 1.22\, l_m}$$



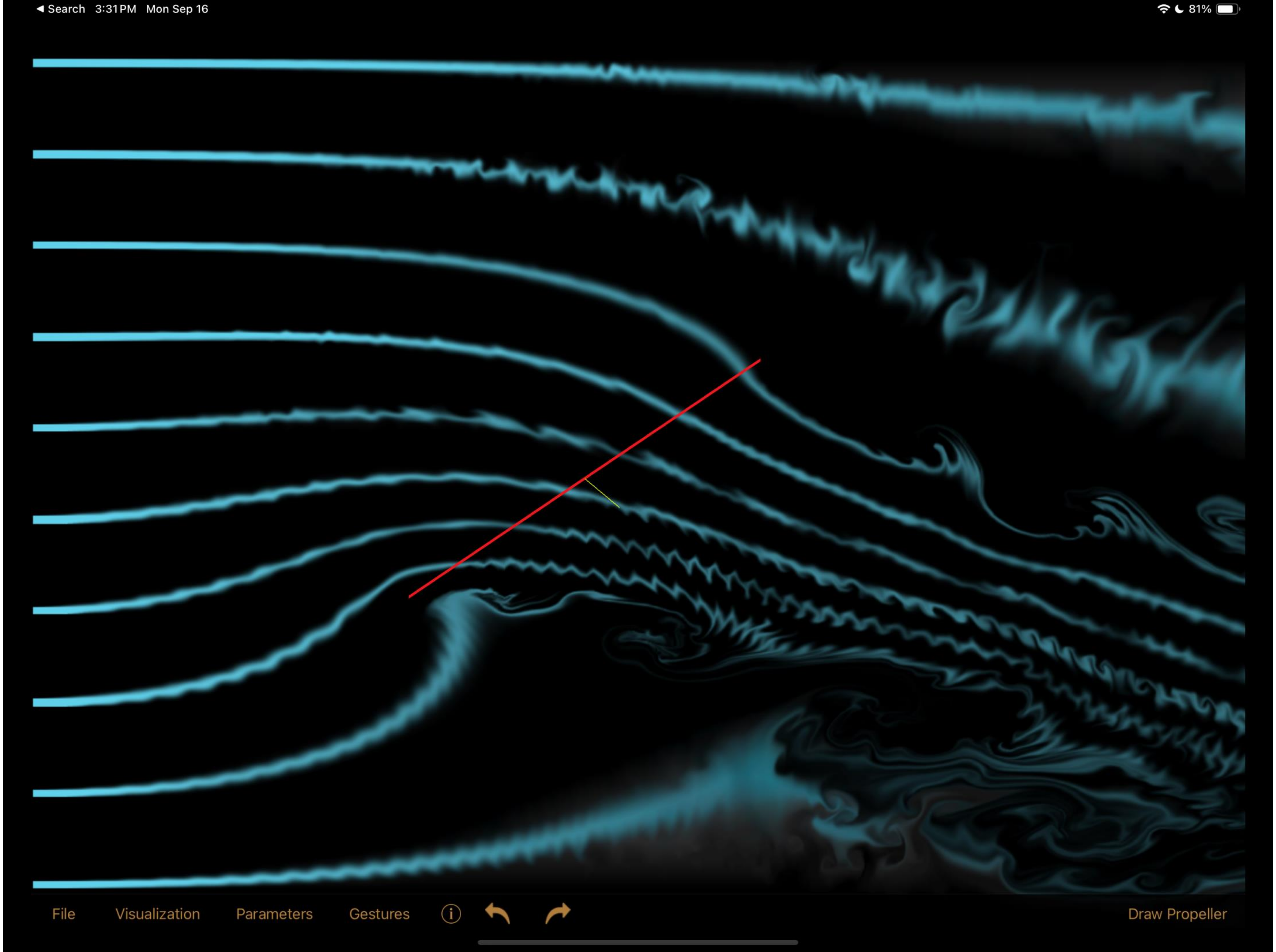
Hovering flight
Level flight
$U_\infty \cong 0$
r
U_i
$2\ U_i$
$U_\infty \cong 0$
z
x
y
$\mathrm{U_i}$
$\mathrm{w} = 2\ \mathrm{U_i}$


Thomas et al. 2004 JEB

CFD
Simulation

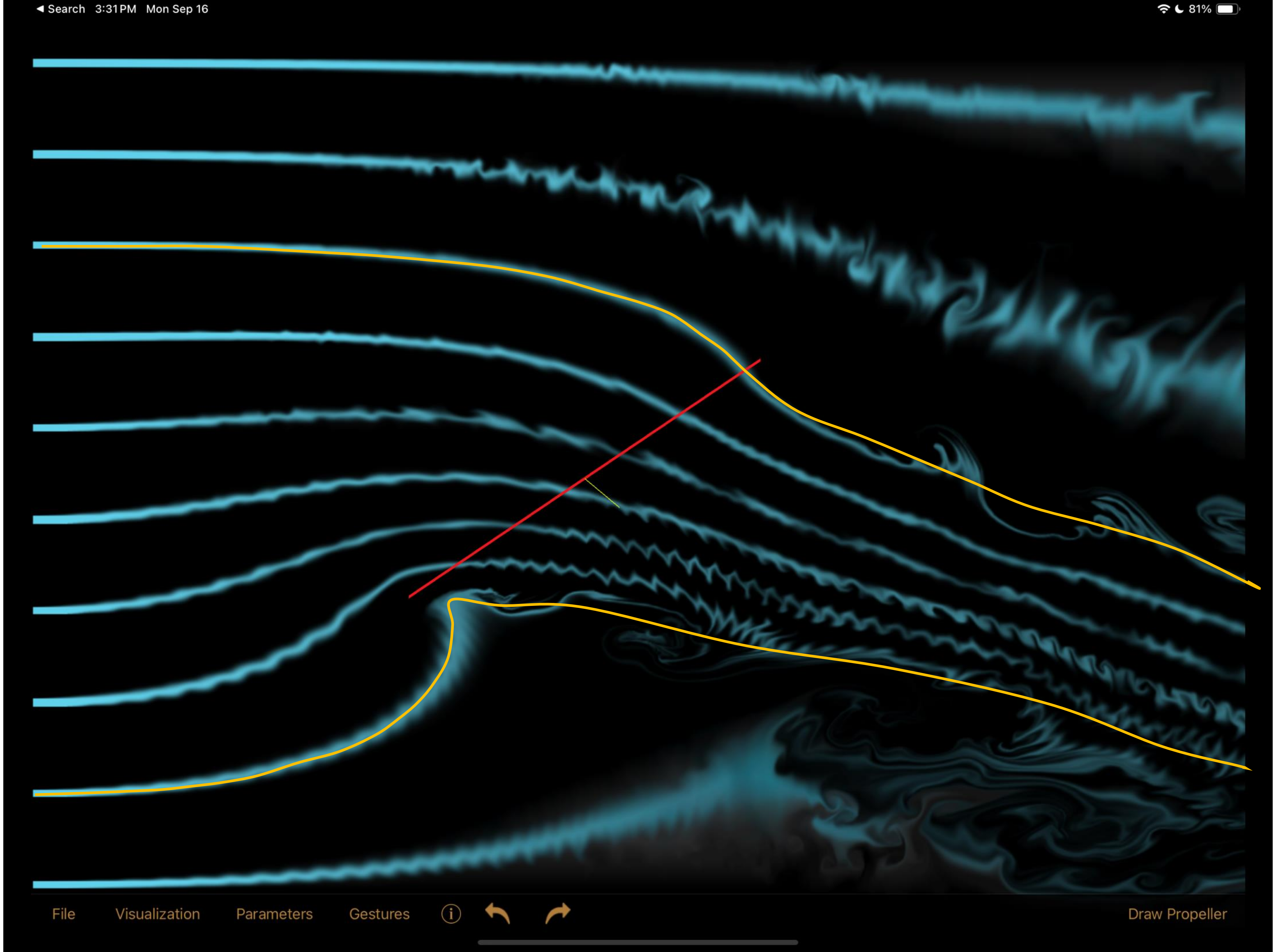
Streaklines
Blue

Propeller
red

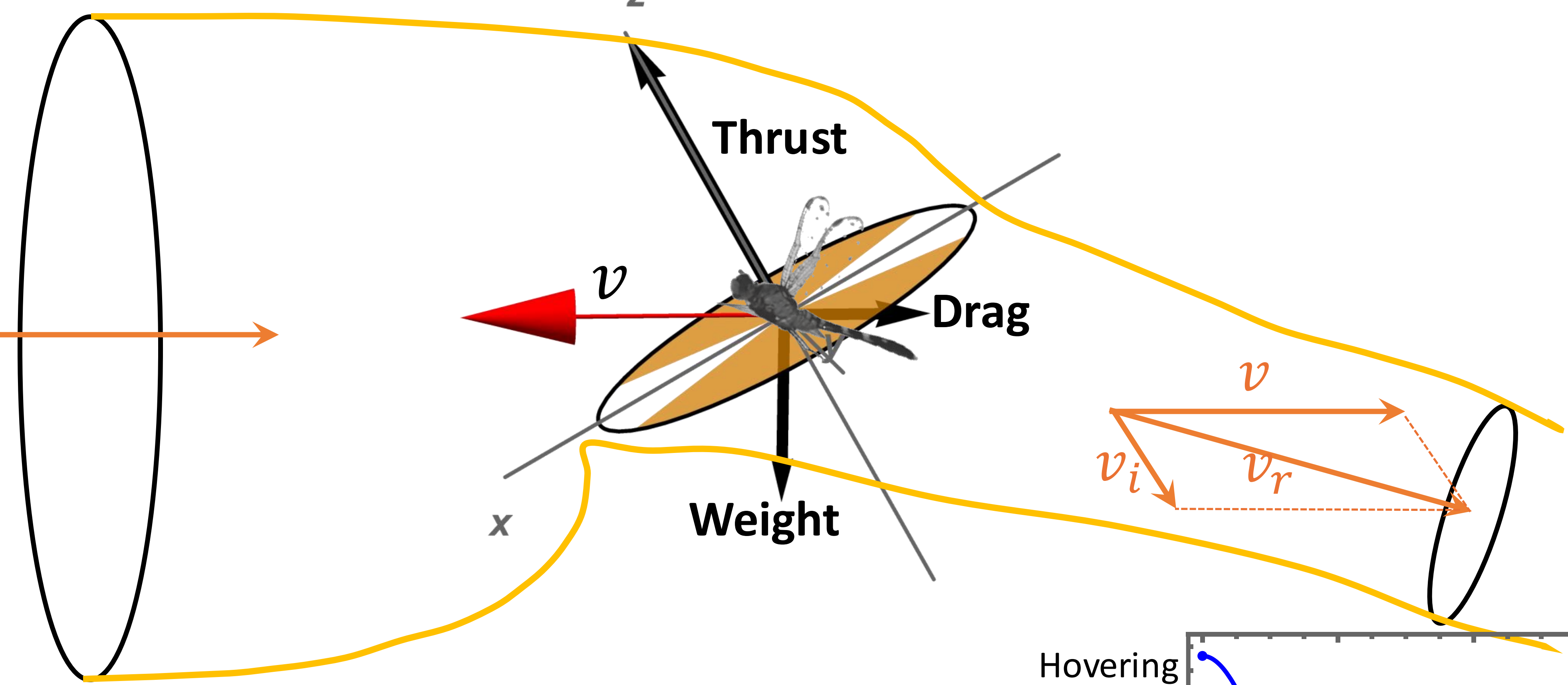


Wind tunnel ap

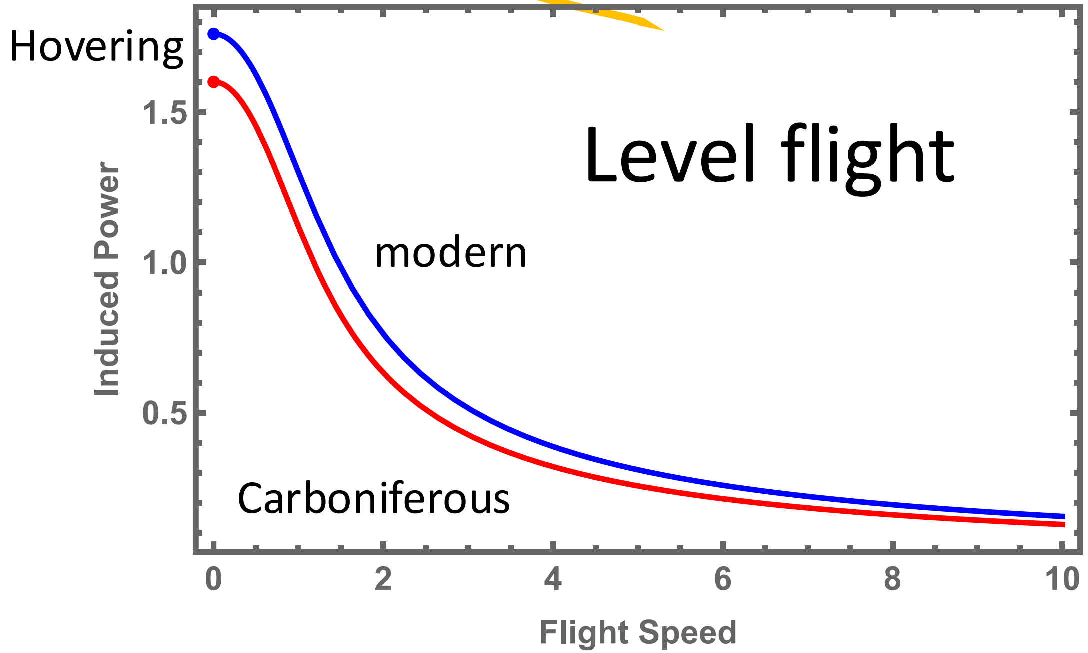
“Tube” of flow yellow lines



Wind tunnel ap



$$v_r \cong \sqrt{v^2 + v_i^2}$$



Conventional rotor in forward flight:

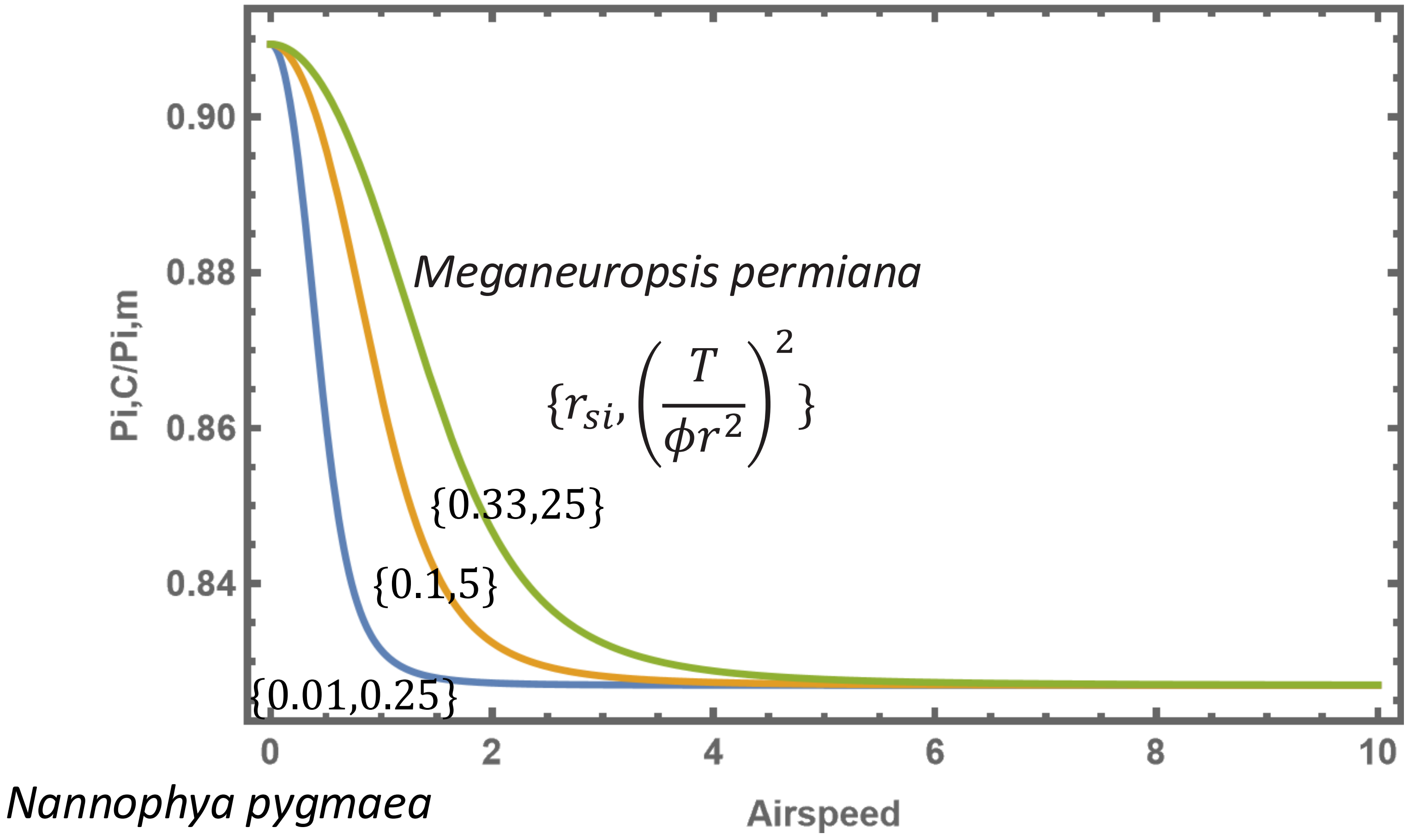
$$v_i = \frac{T}{2\rho\phi r^2 v_r} = \frac{T}{2\rho\phi r^2\sqrt{v^2+v_i^2}}$$

$$P_i = T v_i = \frac{T}{\sqrt{2}}\sqrt{-v^2 + \sqrt{\left(\frac{T}{\rho\phi r^2}\right)^2 + v^4}}$$

$$\frac{P_{i,c}}{P_{i,m}} = \frac{l_c^3 g\sqrt{-v^2+\sqrt{\left(\frac{l_c^3 g}{\rho_c l_c^2}\right)^2+v^4}}}{l_m^3 g\sqrt{-v^2+\sqrt{\left(\frac{l_m^3 g}{\rho_m l_m^2}\right)^2+v^4}}}.$$

$$\lim_{v\to 0}\frac{P_{i,c}}{P_{i,m}} = \frac{l_c^{7/2}\rho_m^{1/2}}{l_m^{7/2}\rho_c^{1/2}} = 0.91\frac{l_c^{7/2}}{l_m^{7/2}},$$

$$\lim_{v\to\infty}\frac{P_{i,c}}{P_{i,m}} = \frac{l_c^4\rho_m}{l_m^4\rho_c} = 0.83\frac{l_c^4}{l_m^4},$$



Therefore: How much bigger?

$$l_c = l_m\left(\frac{P_{i,c}}{P_{i,m}}\right)^{1/4}\left(\frac{\rho_c}{\rho_m}\right)^{1/4}$$

$$= l_m(1)^{1/4}\left(\frac{1.56}{1.29}\right)^{1/4} = 1.05 l_m$$

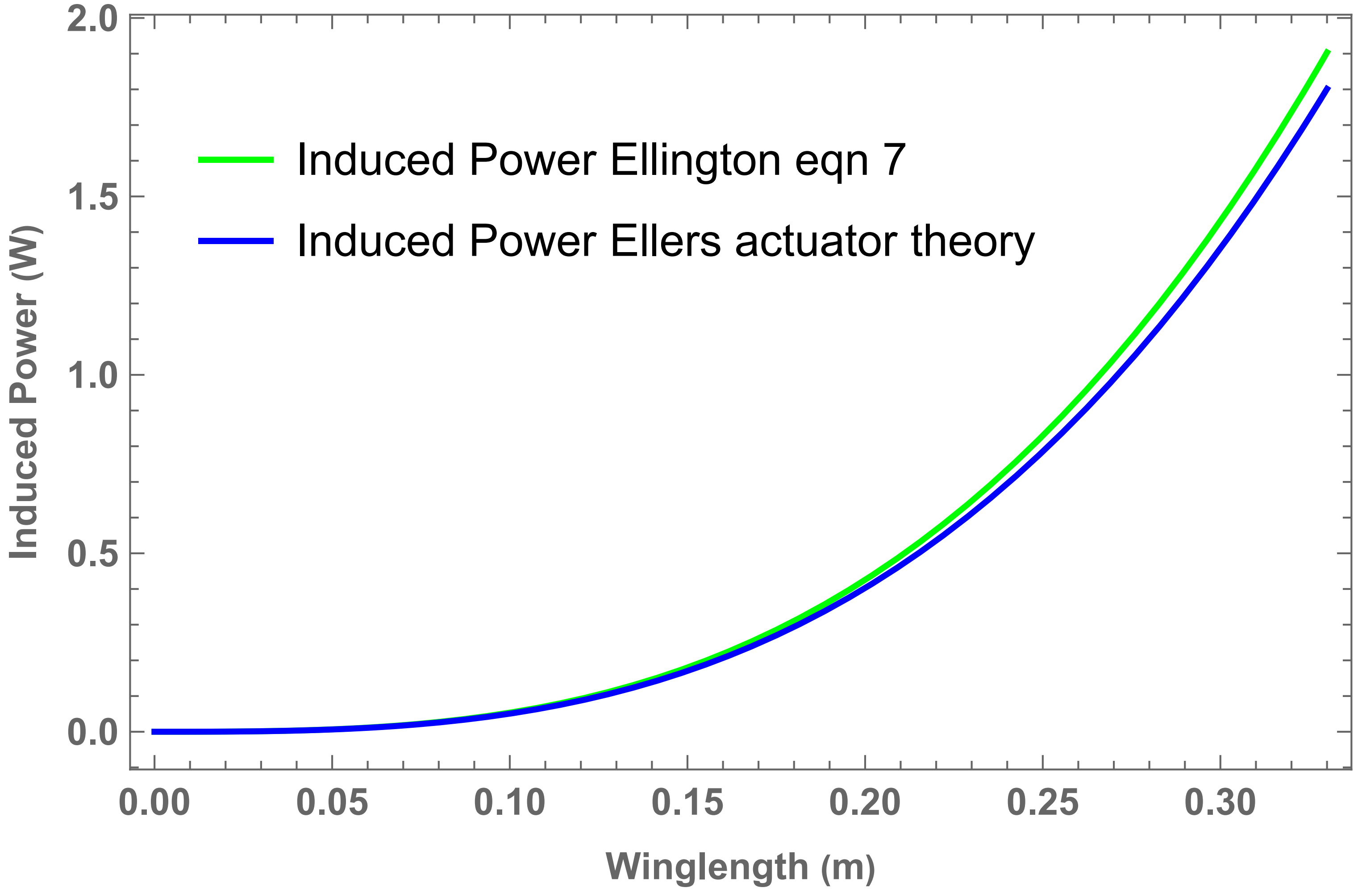
Take Home Haiku:

When in level flight,
high density atmosphere
Five percent longer

Conclusions

Griffenflies could be:

- 1.03 times longer while hovering due to higher density air
- 1.05 times longer during level flight
- 1.20 times longer due to higher density plus higher oxygen for fuel
- 1.23–1.25 times longer due to the above plus anisometry



$$\mathrm{pi} = \sqrt{\frac{(mg)^3}{2\rho a}}$$

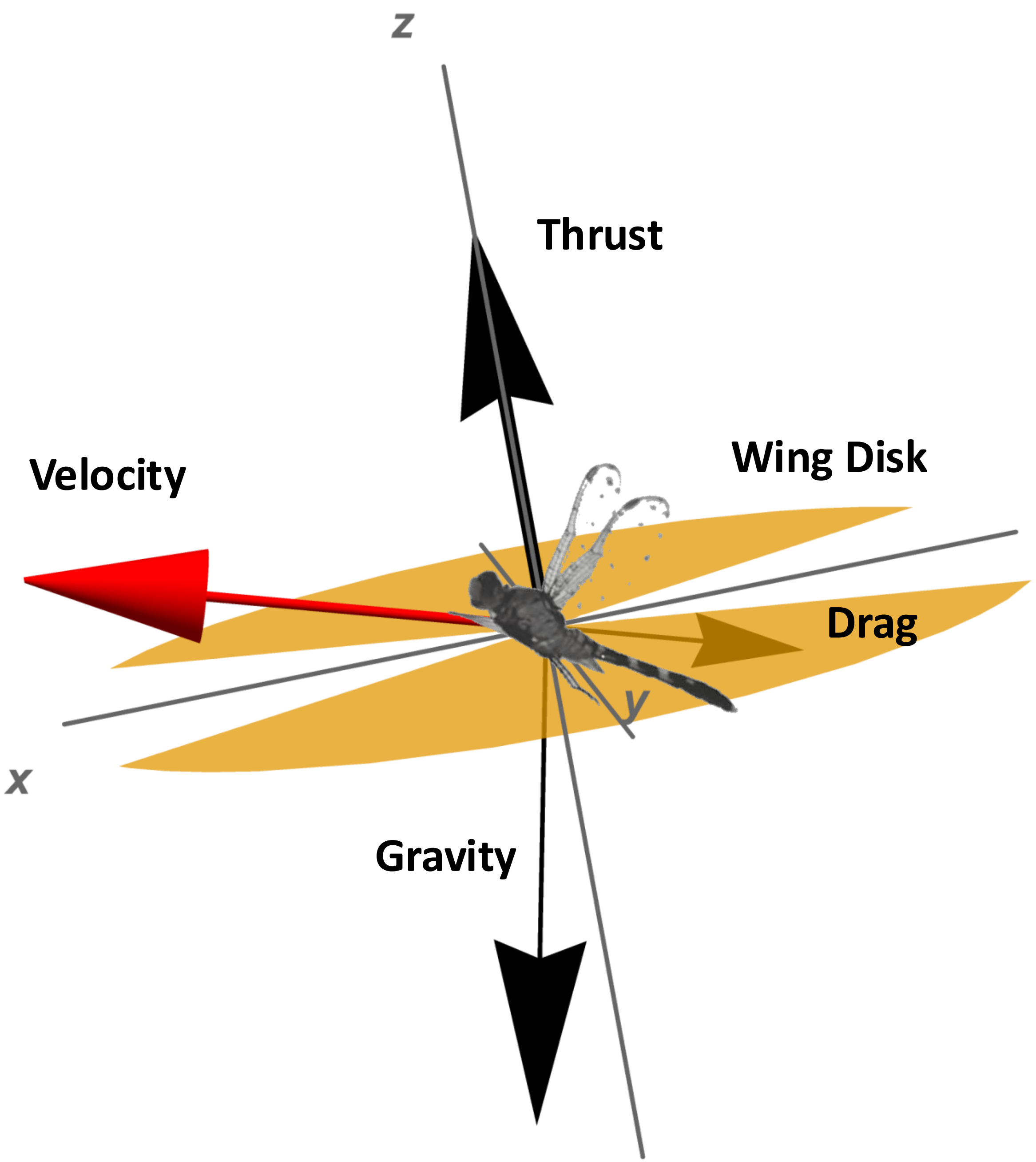
$$a = \Phi\, r^2$$

$$m_{hov} = 0.387\,\frac{\Phi^2\, n^2\, r^4 cl}{ar}$$

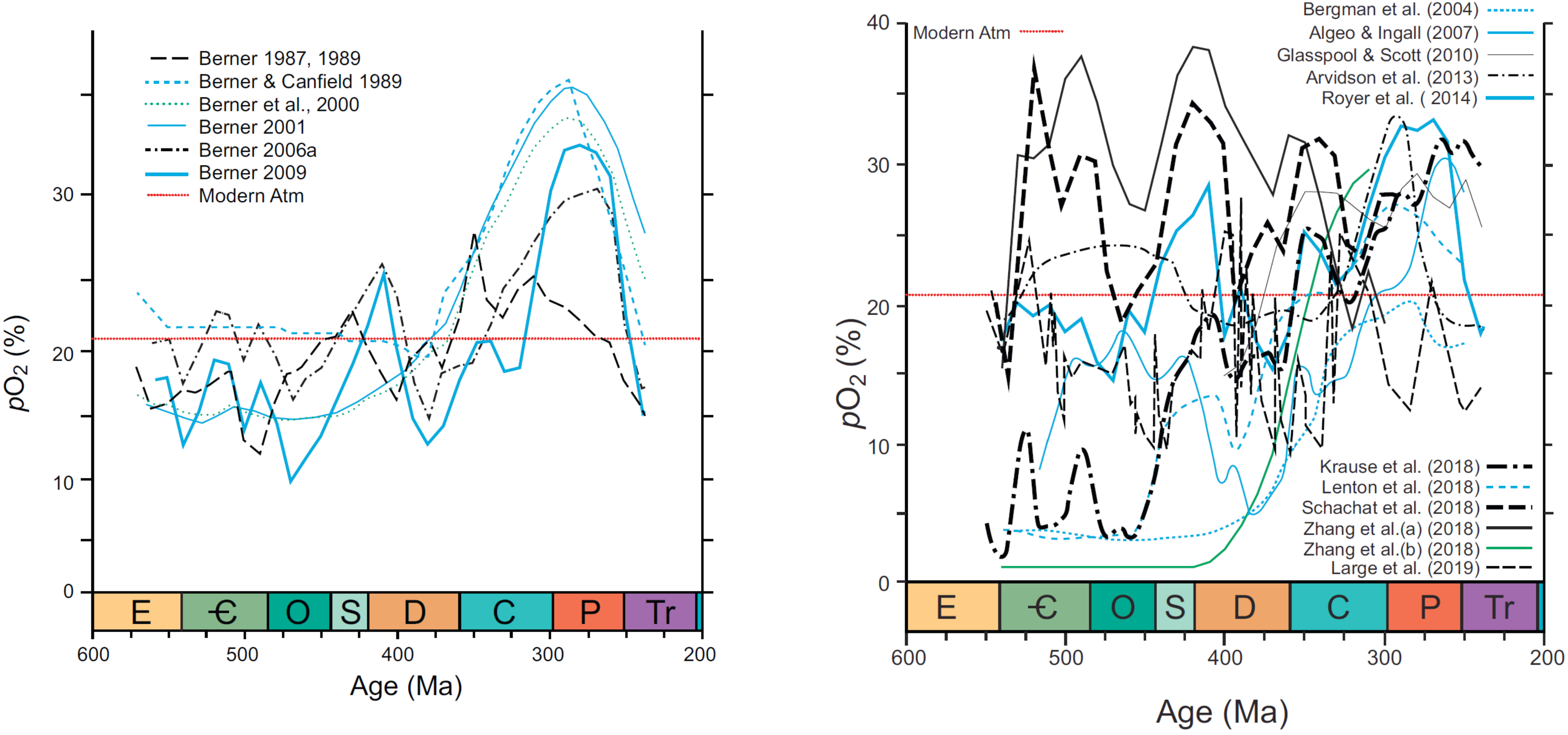
$$P^*_{ind} = 14\, n\, r\sqrt{\frac{\Phi\, cl}{ar}}$$

m_{hov} Hovering mass supported
m_{hov} Power induced per muscle mass
ar Aspect ratio of wing
cl Coefficient of lift
r Wing length
n Wing beat frequency

Ellington, C . P . 1999. "The Novel Aerodynamics of Insect Flight : Applications to Micro - Air Vehicles ." Journal of Experimental Biology 202 (23) : 3439\[Dash]48. https : // doi . org/10.1242/jeb .202 .23 .3439 .


z
Thrust
Wing Disk
Velocity
Drag
y
x
Gravity

U. Brand et al. 2021 Earth-Science Reviews



Considerable disagreement in estimates of past %O_2 and even less information about atmospheric density.