Modeling the diverse geometry of insect wings

Jordan Hoffmann *
Seth Donoughe *
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Mary K. Salcedo
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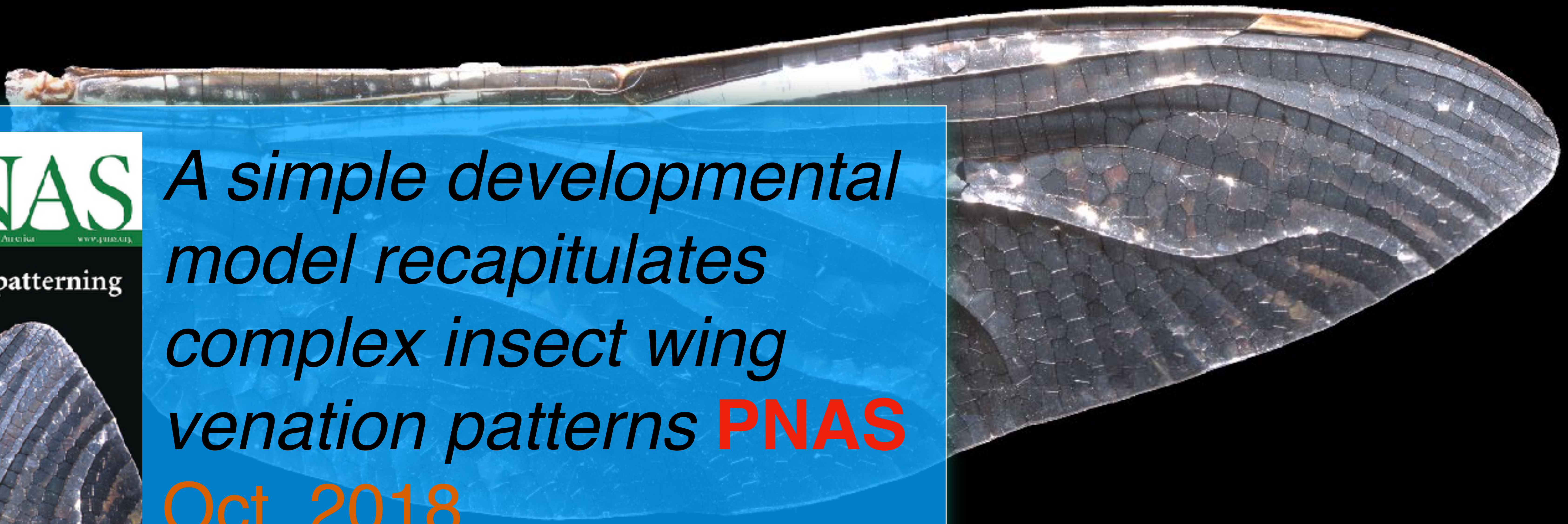

A simple developmental model recapitulates complex insect wing venation patterns **PNAS** Oct. 2018

Size, shape, and structure of insect wings **bioRxiv: 478768** Dec. 2018

Jordan Hoffmann *
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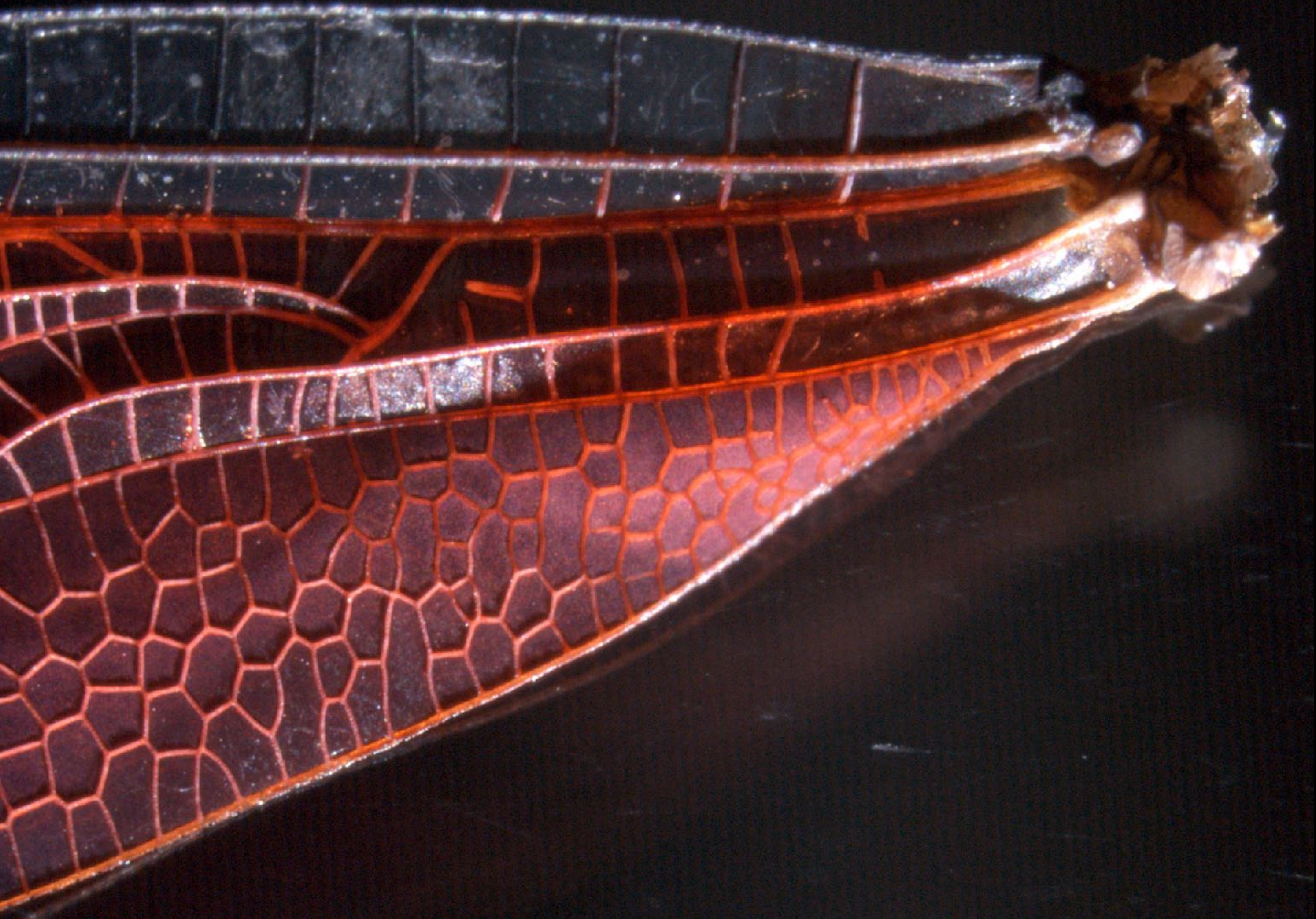
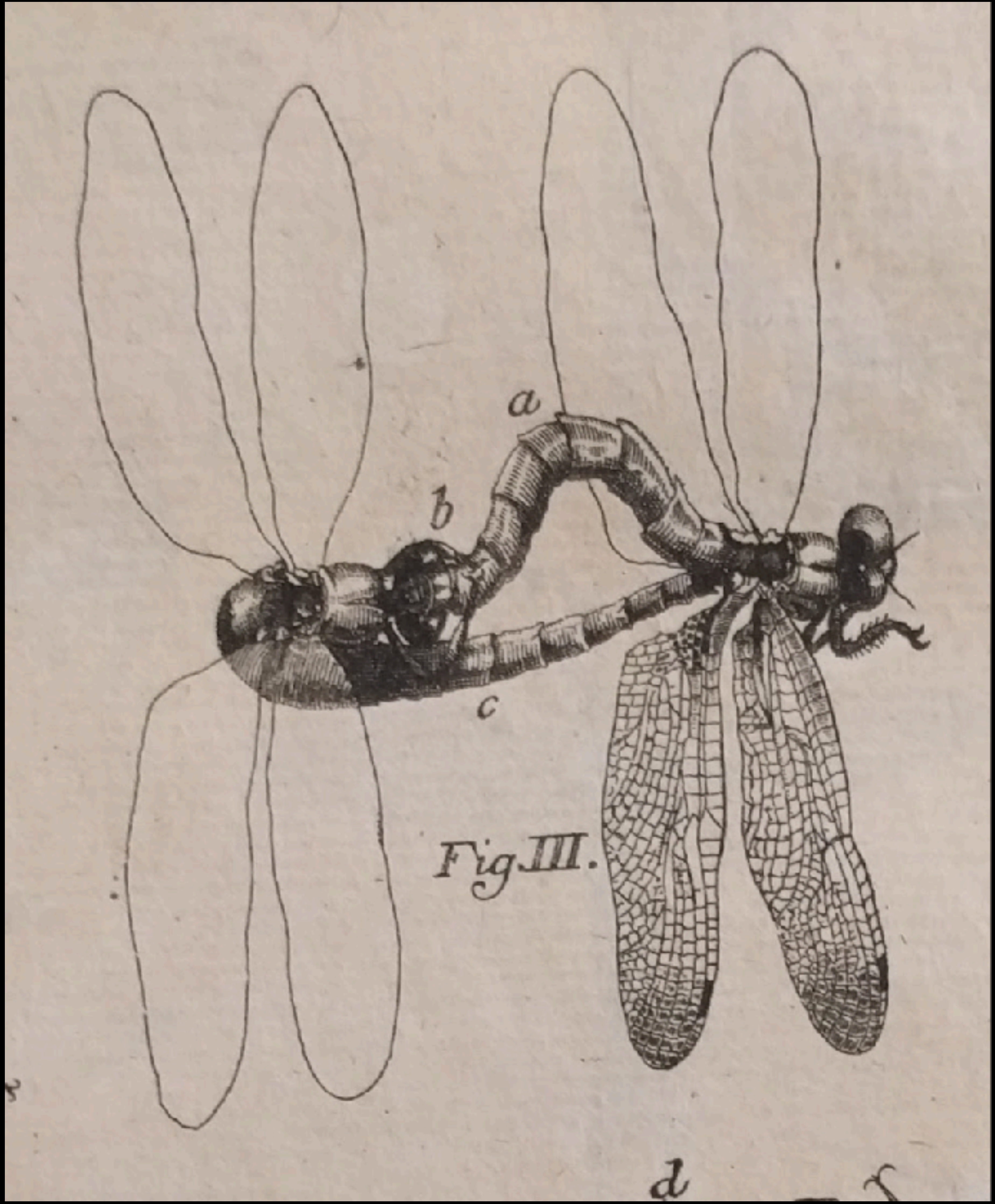
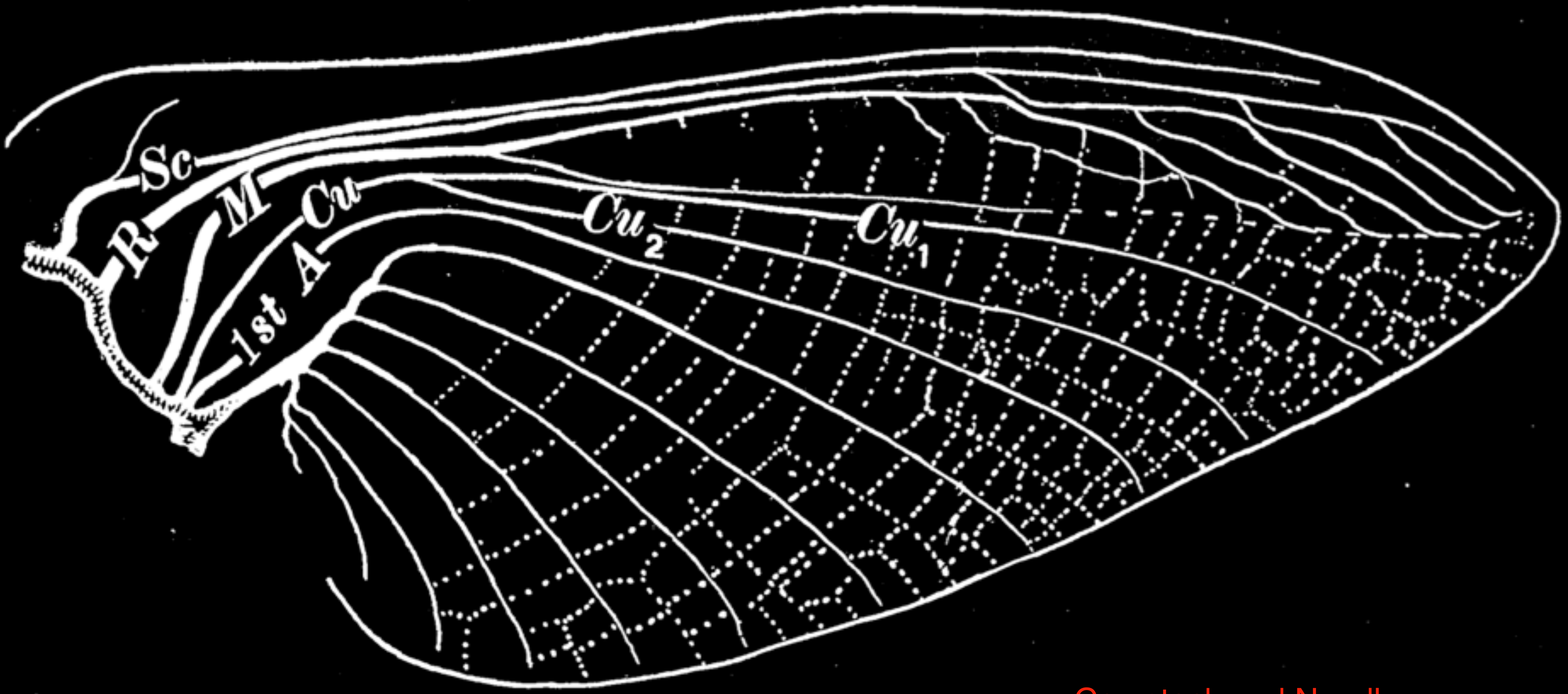
+ L. Mahadevan

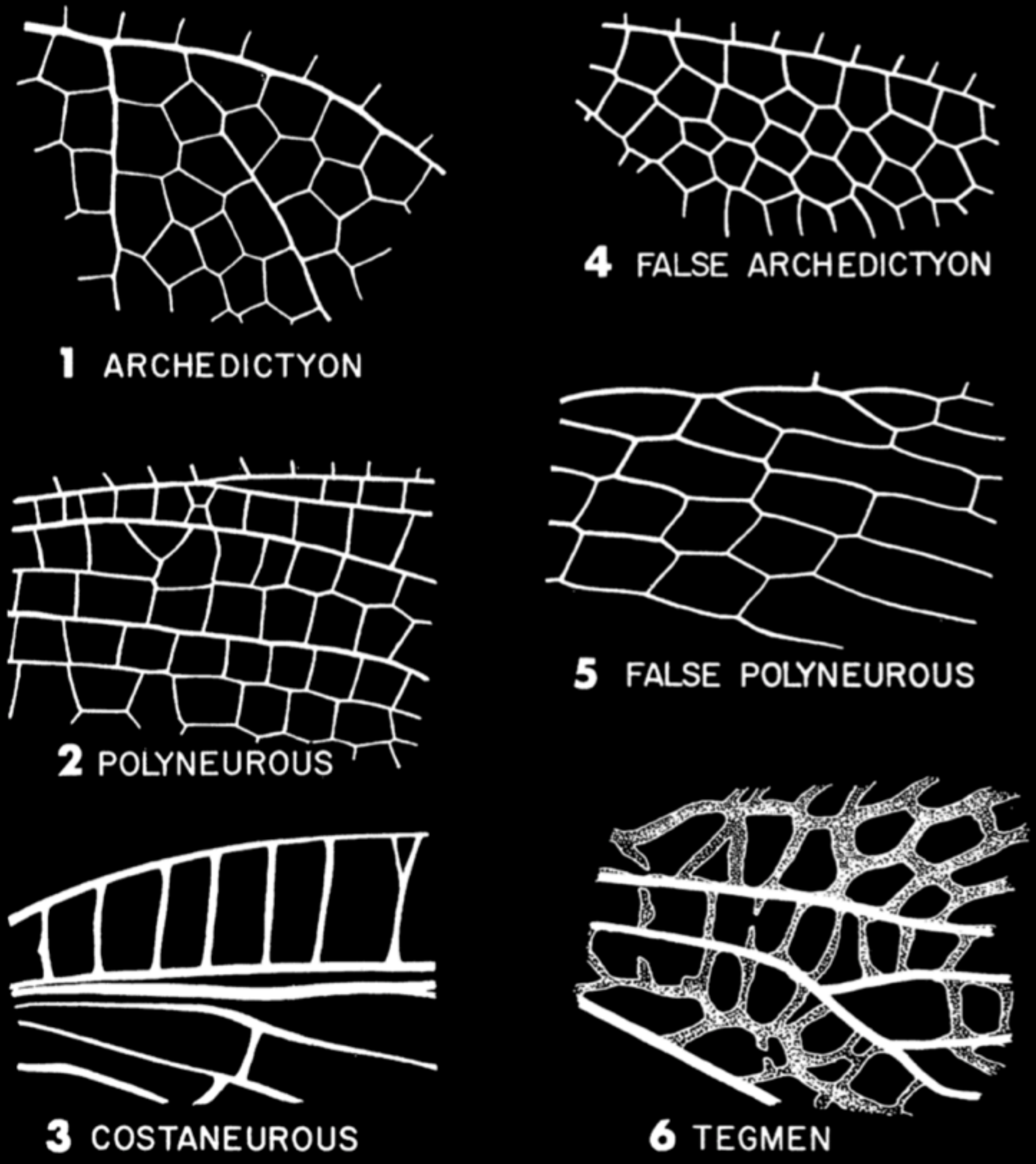




Swammerdam 1758



Comstock and Needham
1899



FIGS. 1–3. Primary venational types, as labeled. 1, Libellulidae; 2, Acrididae; 3, Corydalidae. Figs. 4–6. Secondary venational types, as labeled. 4, Ascalaphidae; 5, Perlidae; 6, Aetalionidae.

Hamilton 1972

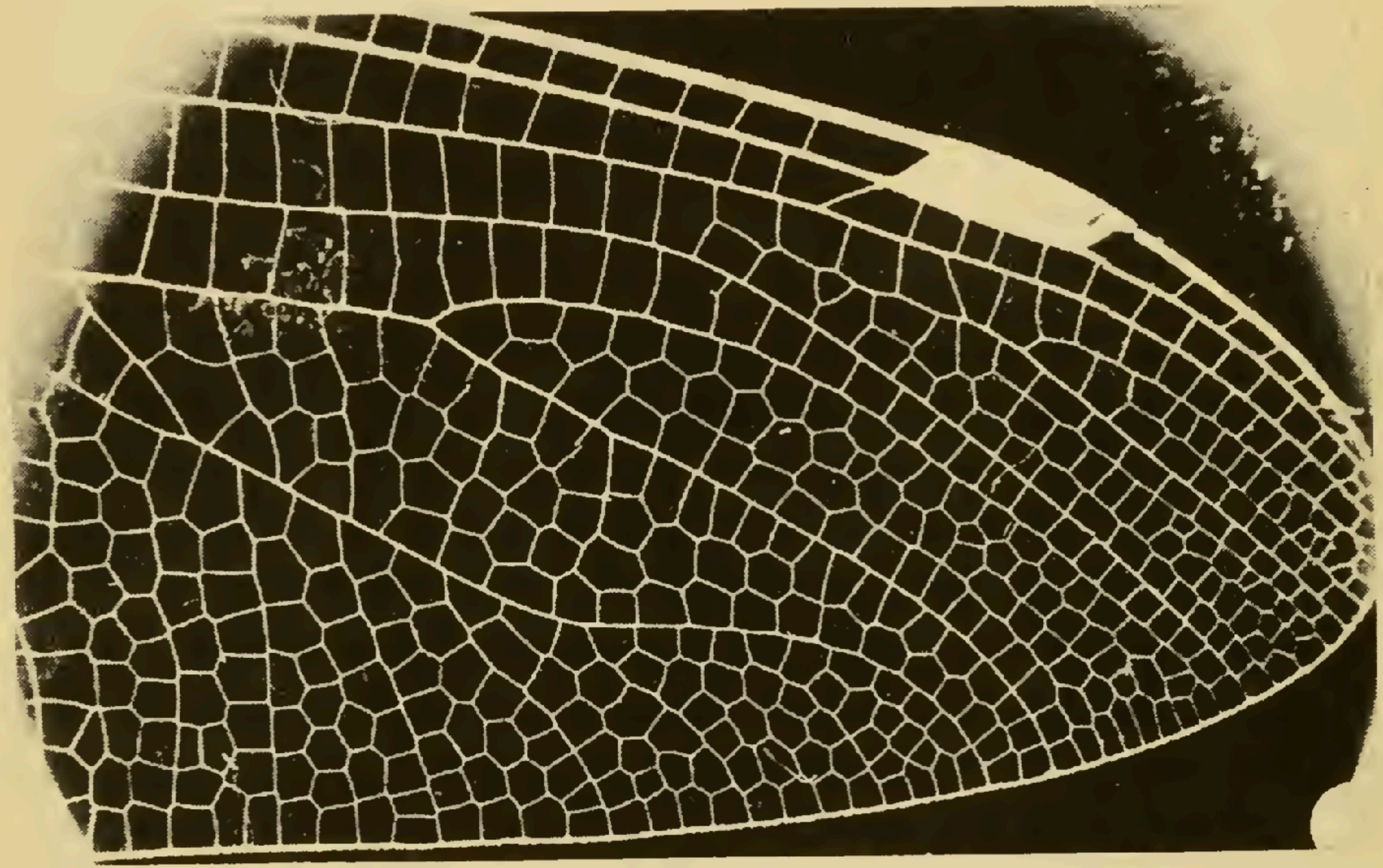


Fig. 162. Part of a dragonfly's wing.

Thompson 1942

GOALS:

1.) Can we **CHARACTERIZE** the diverse set of observed shapes?

2.) Can we propose a **DEVELOPMENTAL MODEL**?

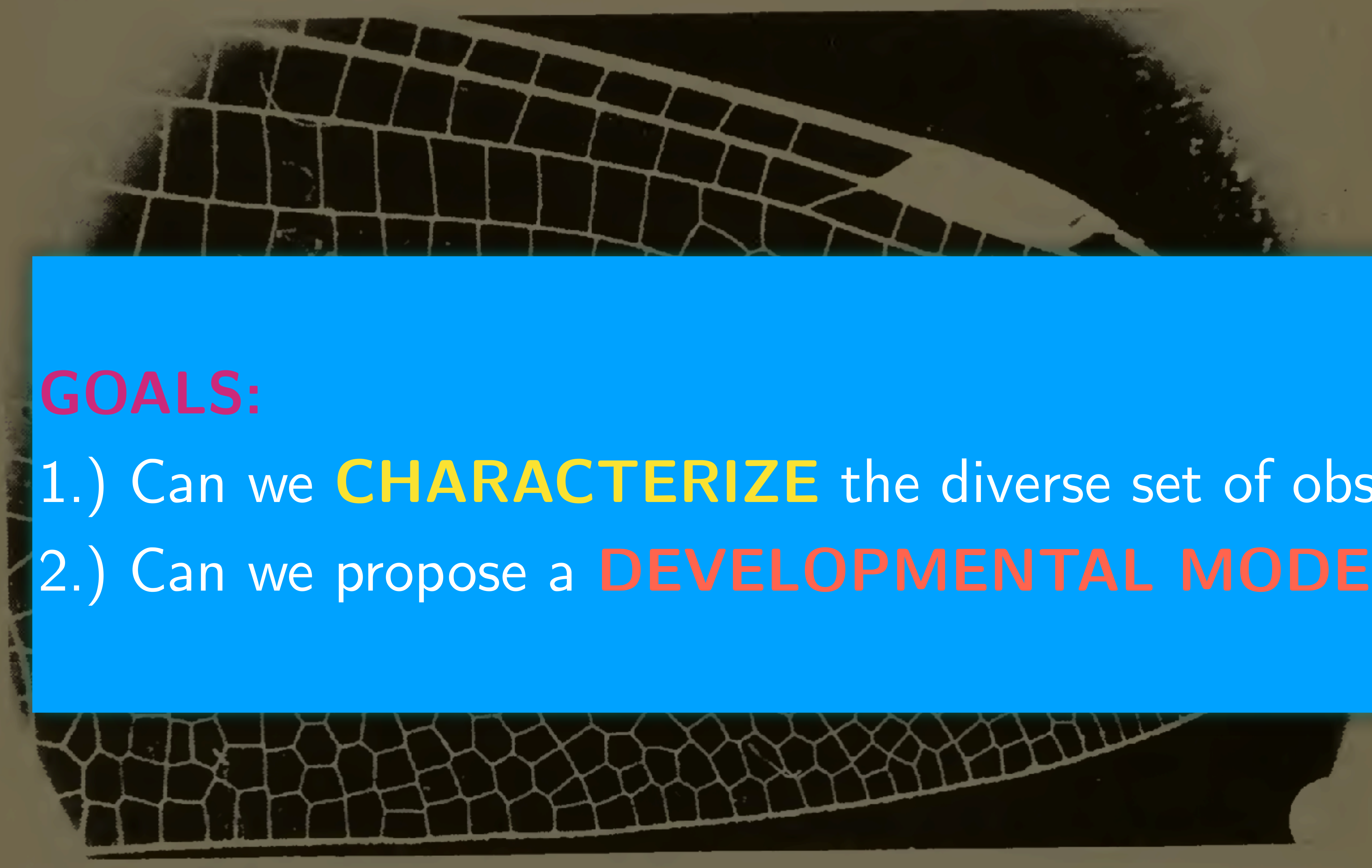
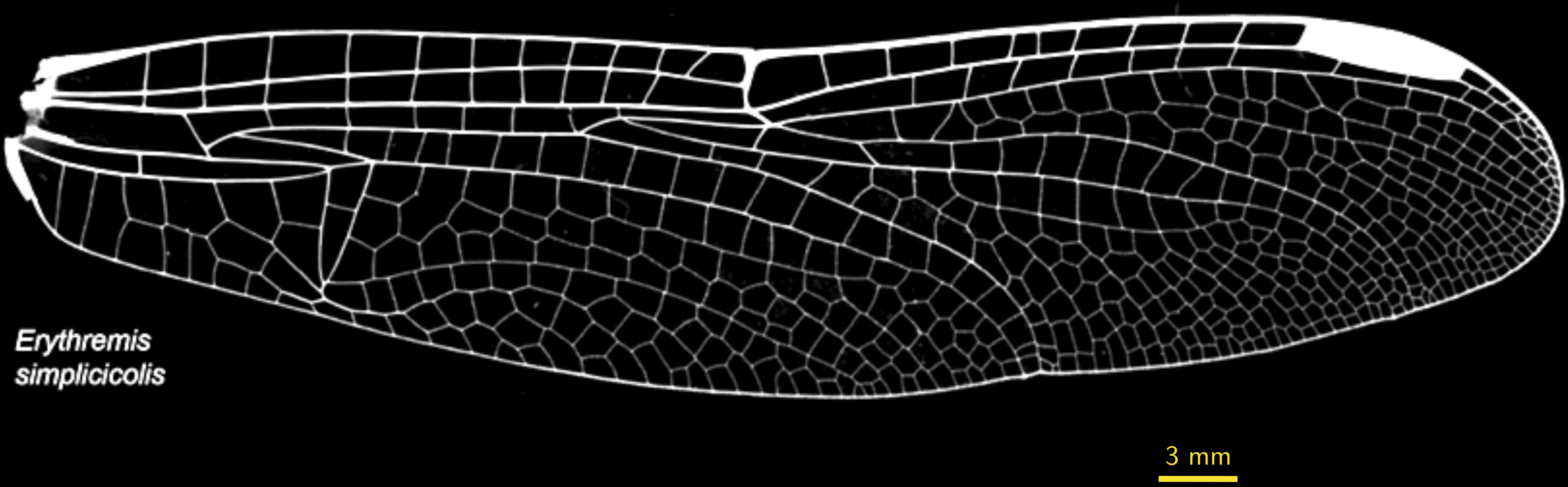
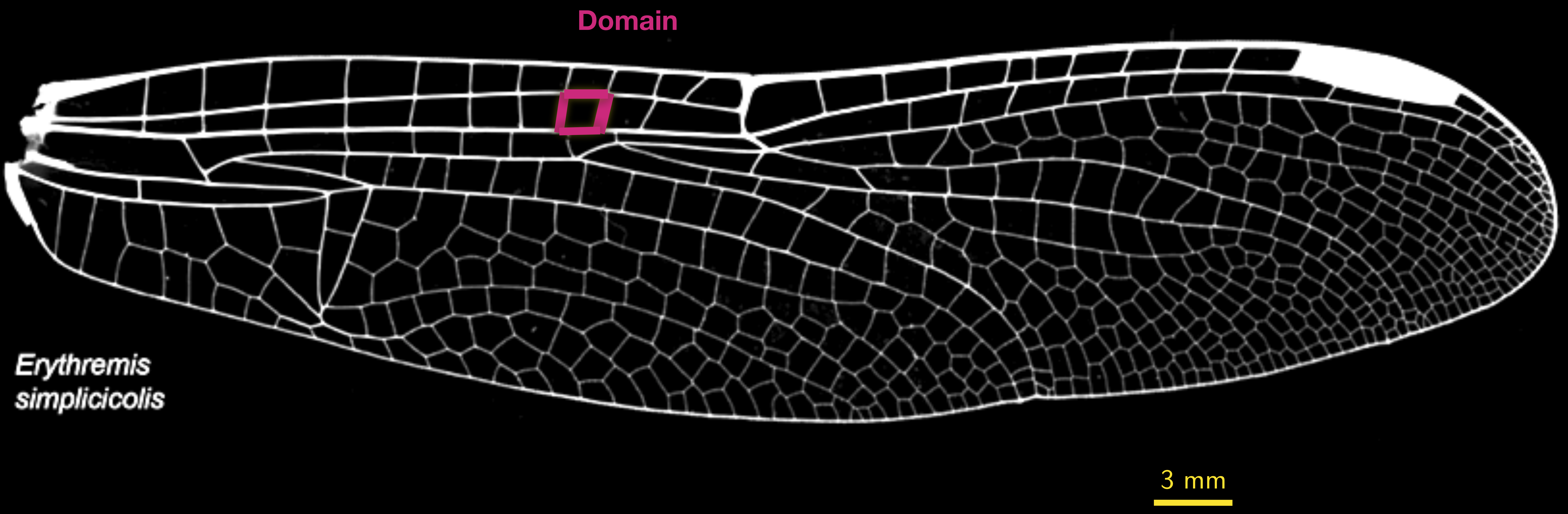
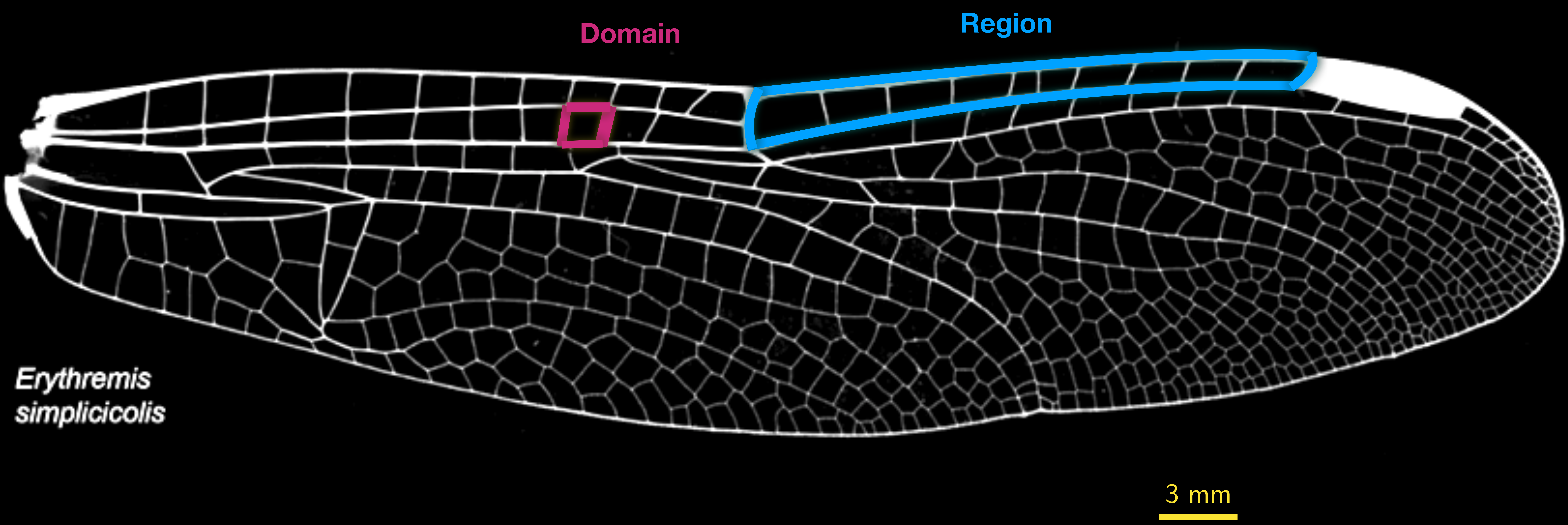


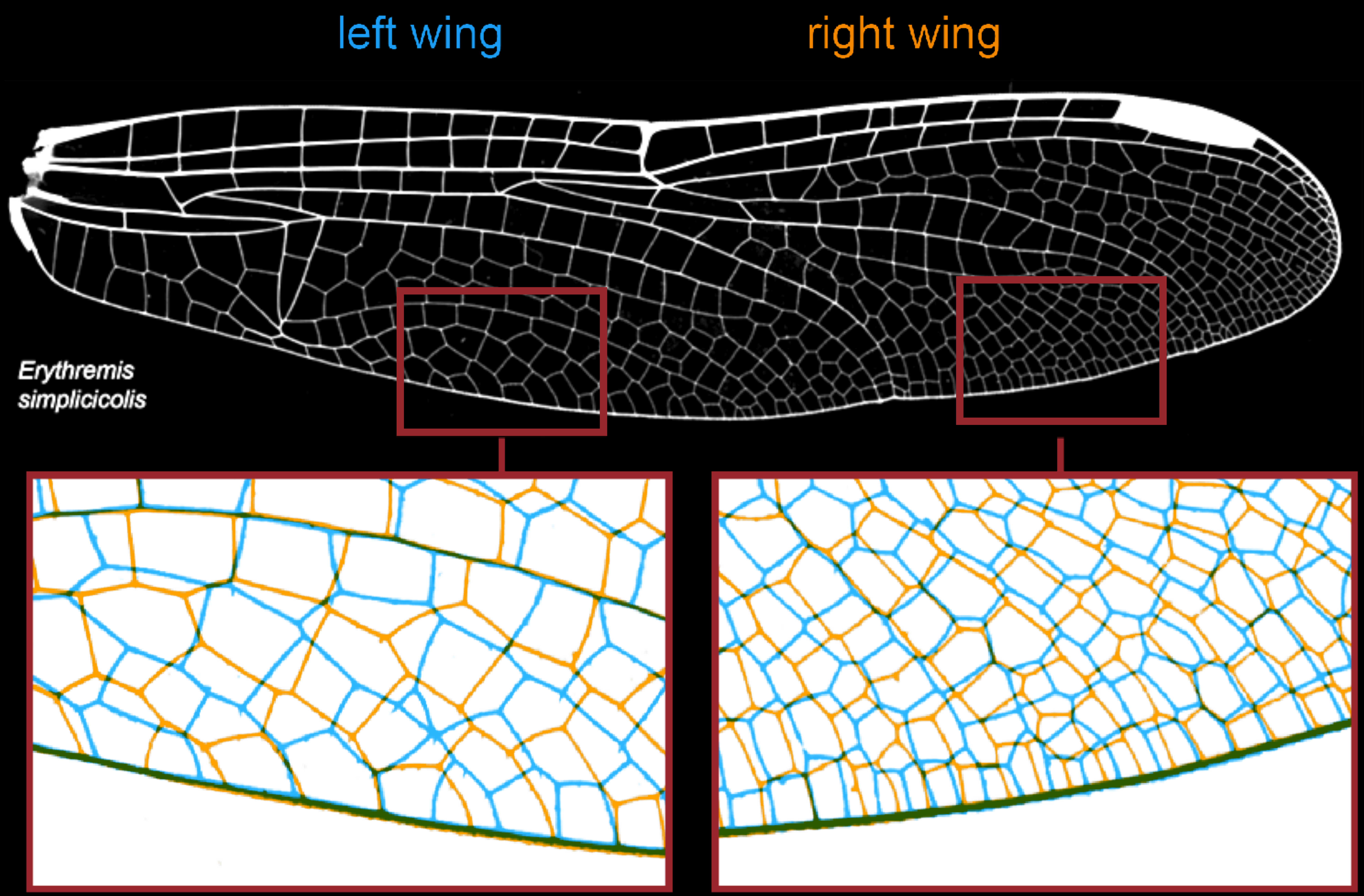
Fig. 162. Part of a dragonfly's wing.

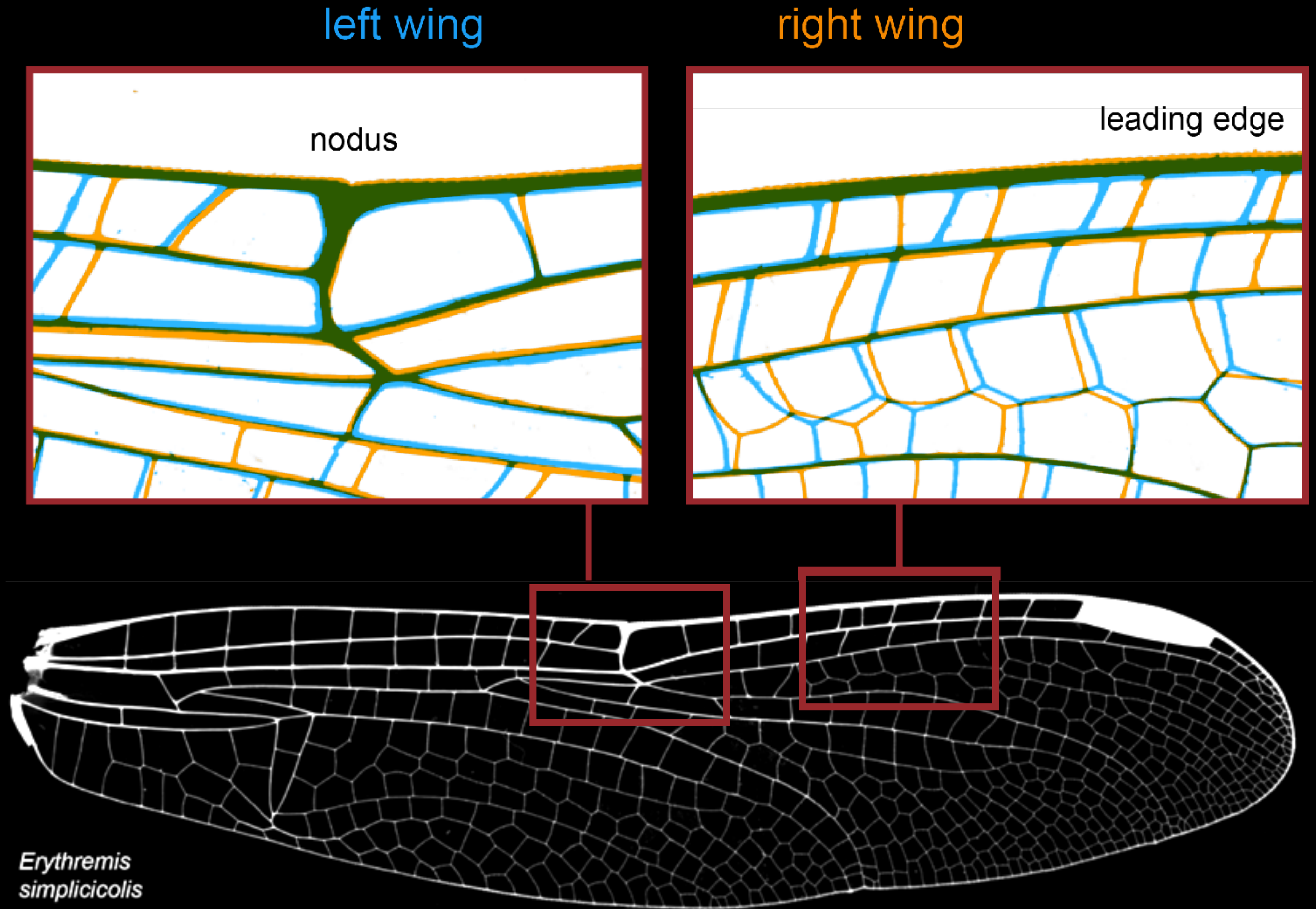
Thompson 1942


Erythremis simplicicolis
3 mm

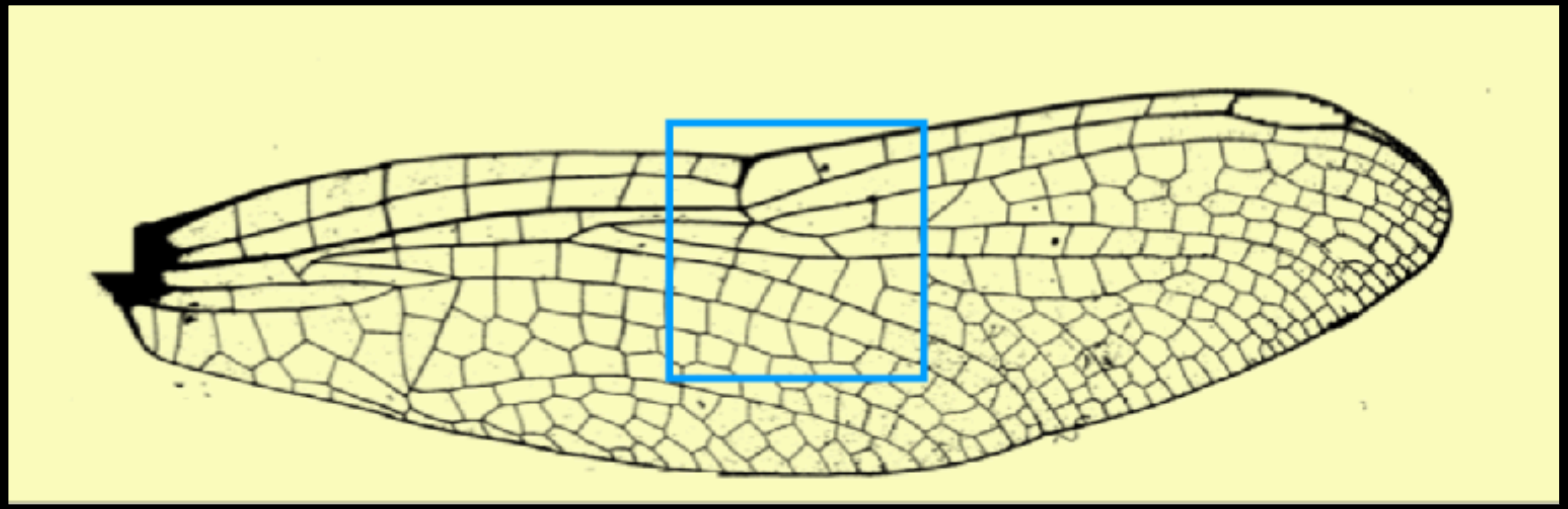

Domain
Erythremis simplicicolis
3 mm

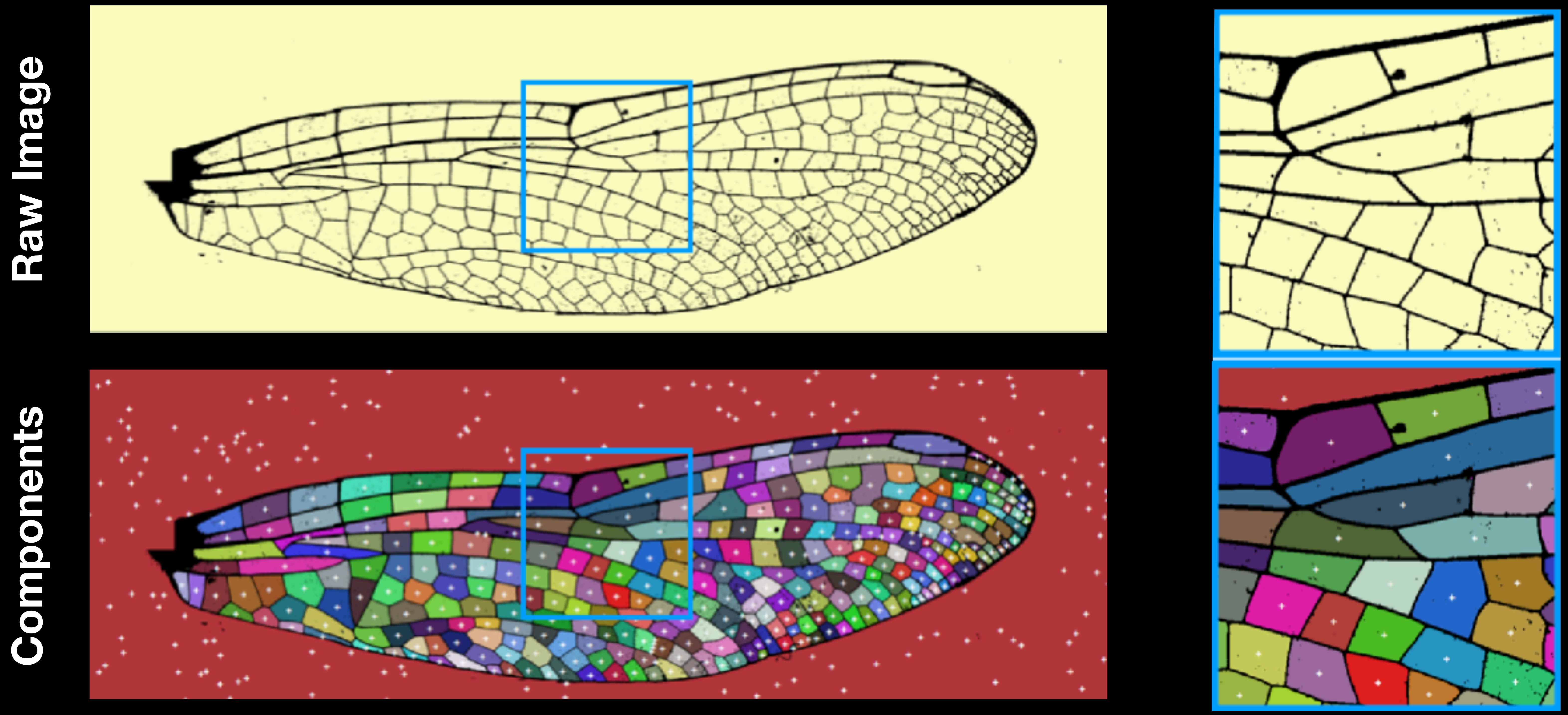

Domain
Region
Erythremis
simplicicolis
3 mm


left wing
right wing
Erythremis
simplicicolis

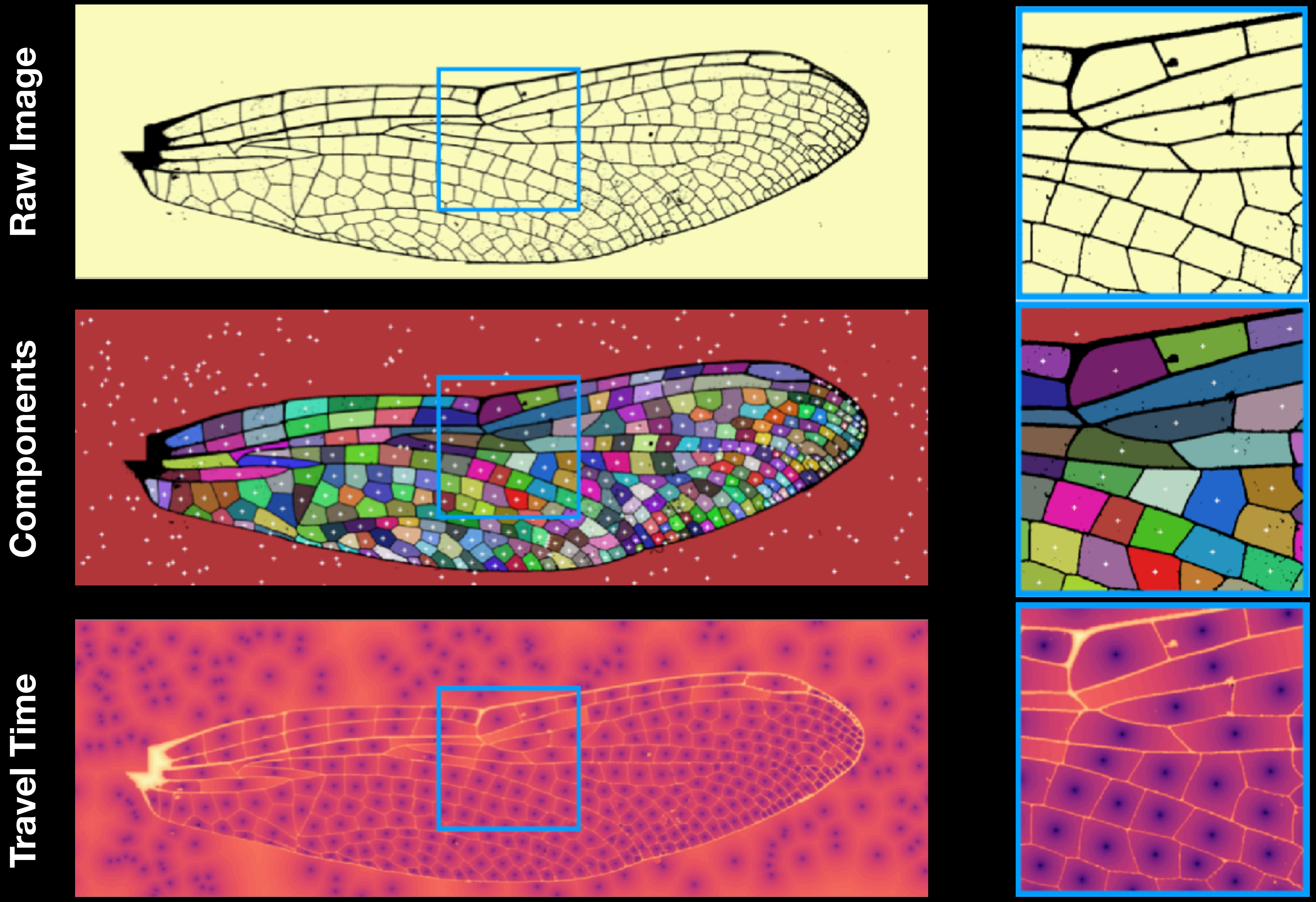

left wing
right wing
nodus
leading edge
Erythremis
simplicicolis

Raw Image



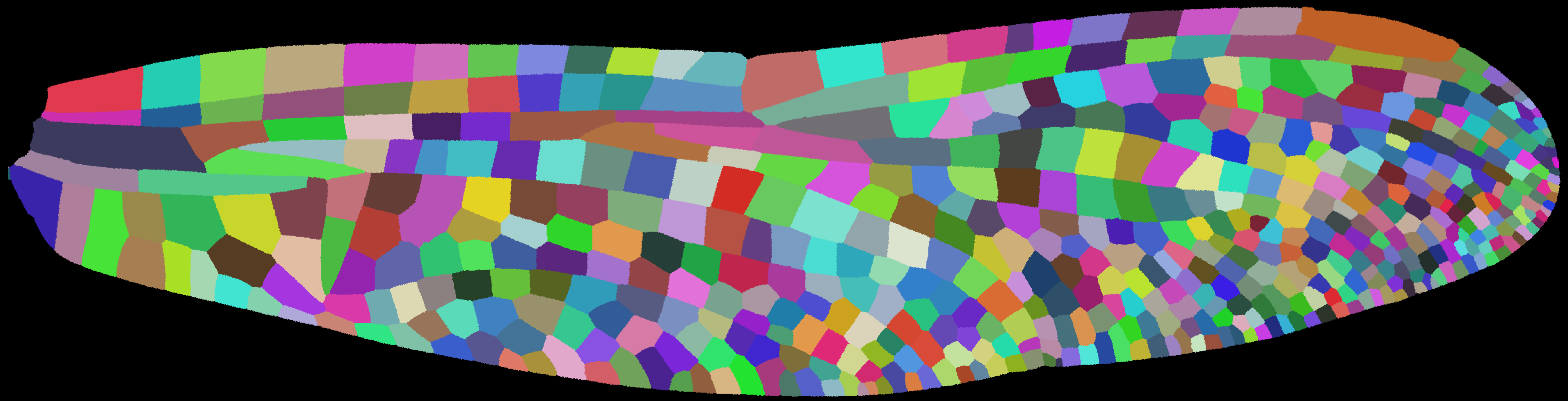


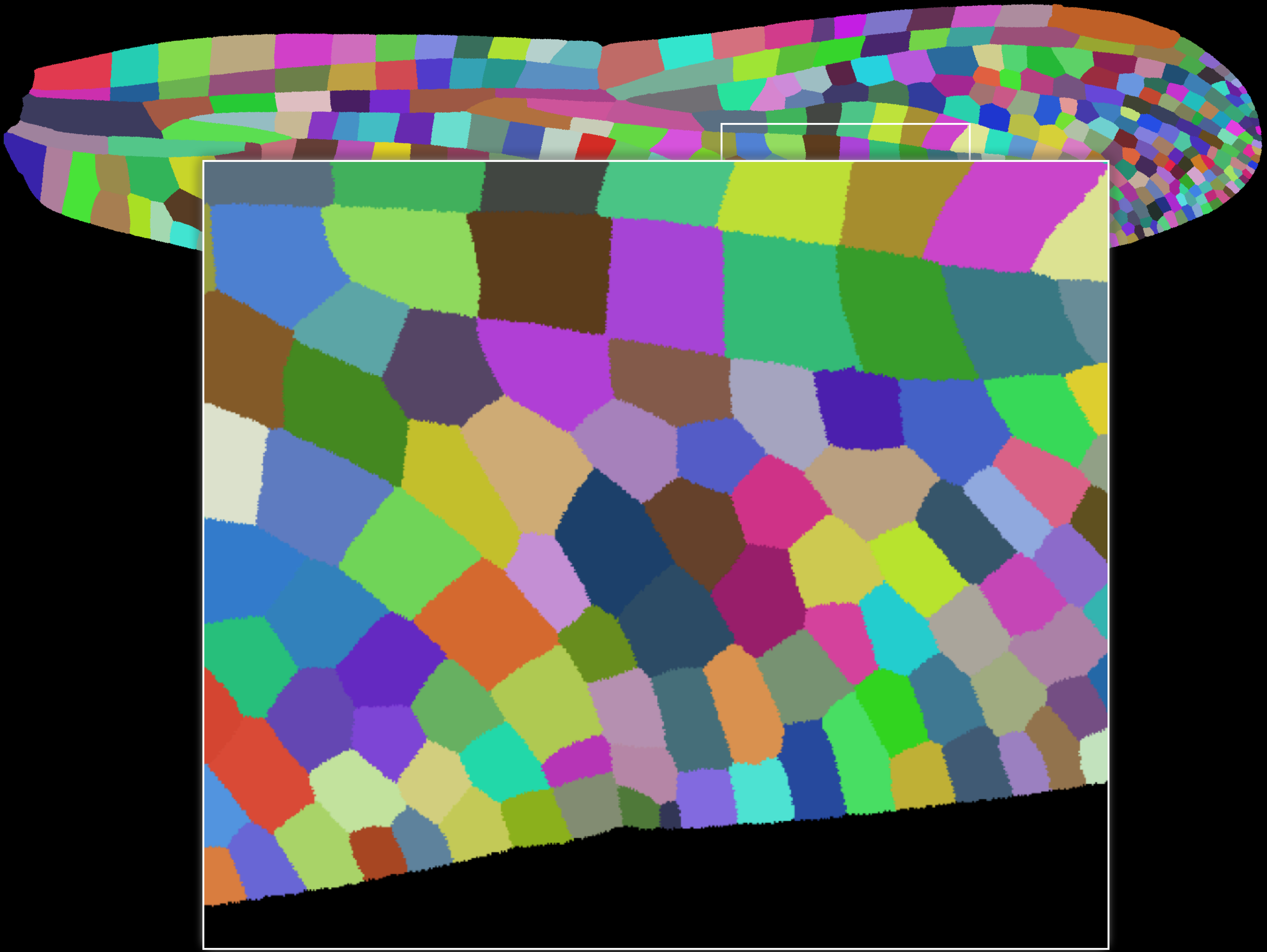
Raw Image
Components

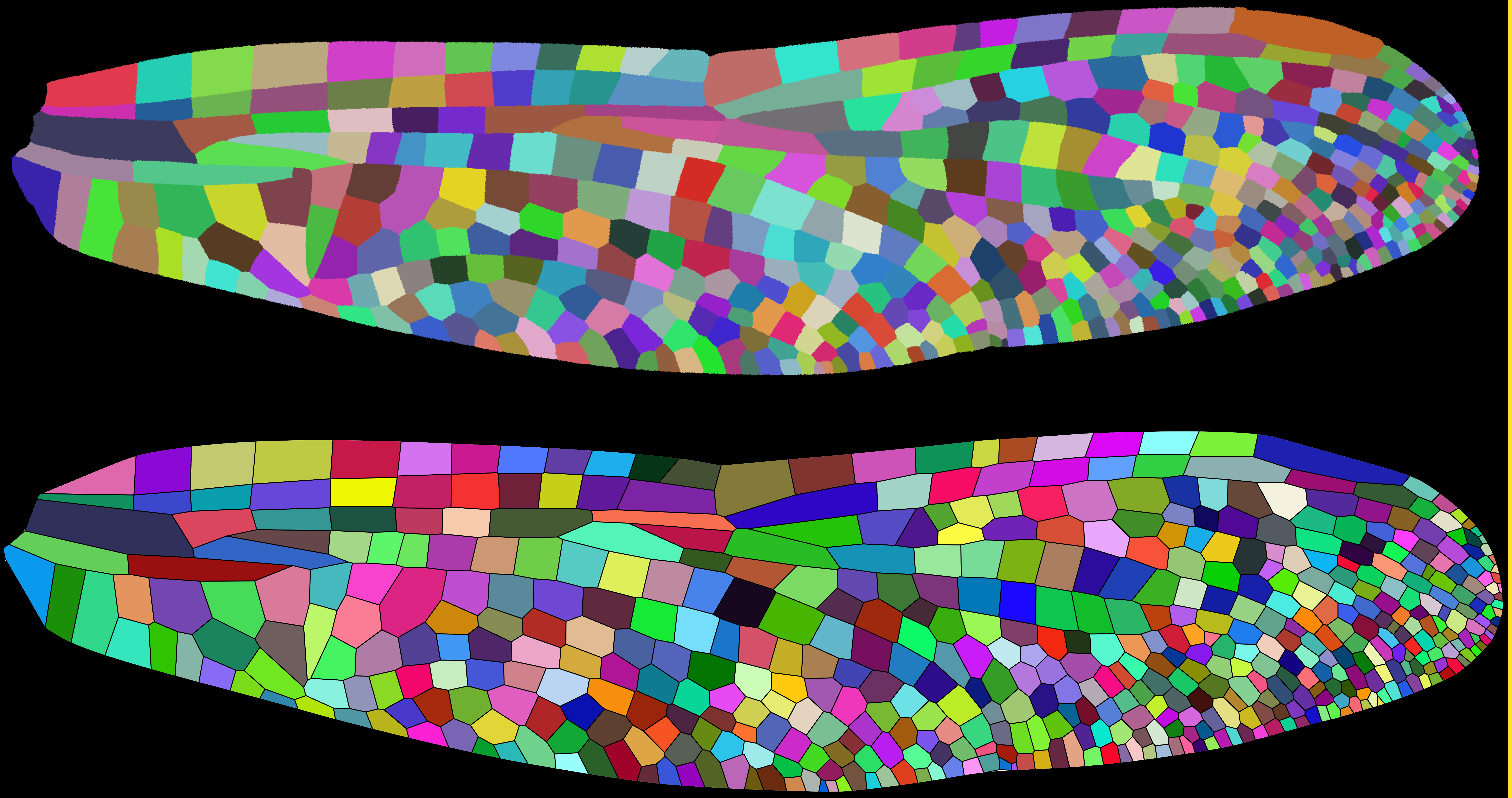


$$F(x)|\nabla T(x)| = 1$$

F: Speed Matrix ***T:*** Travel Time Matrix



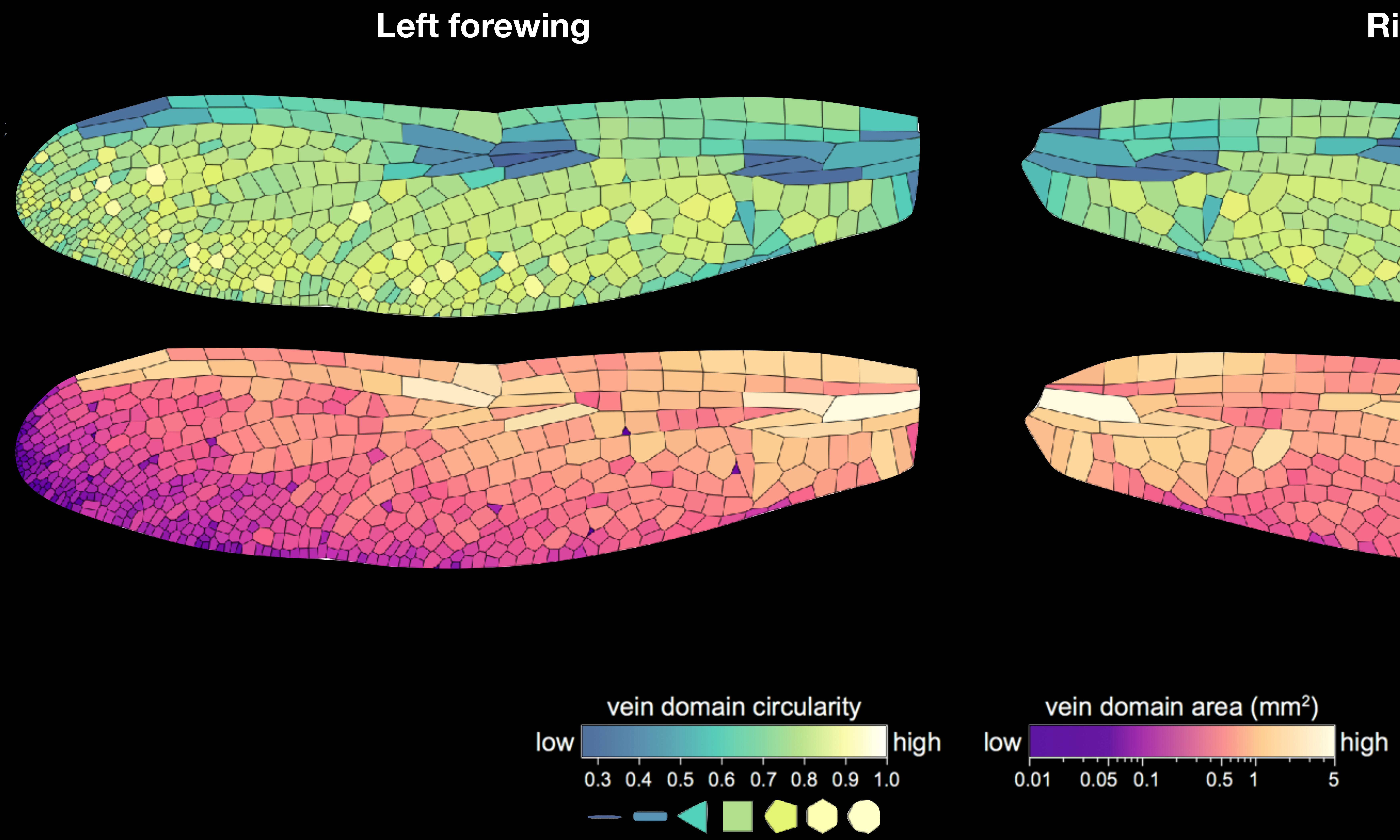




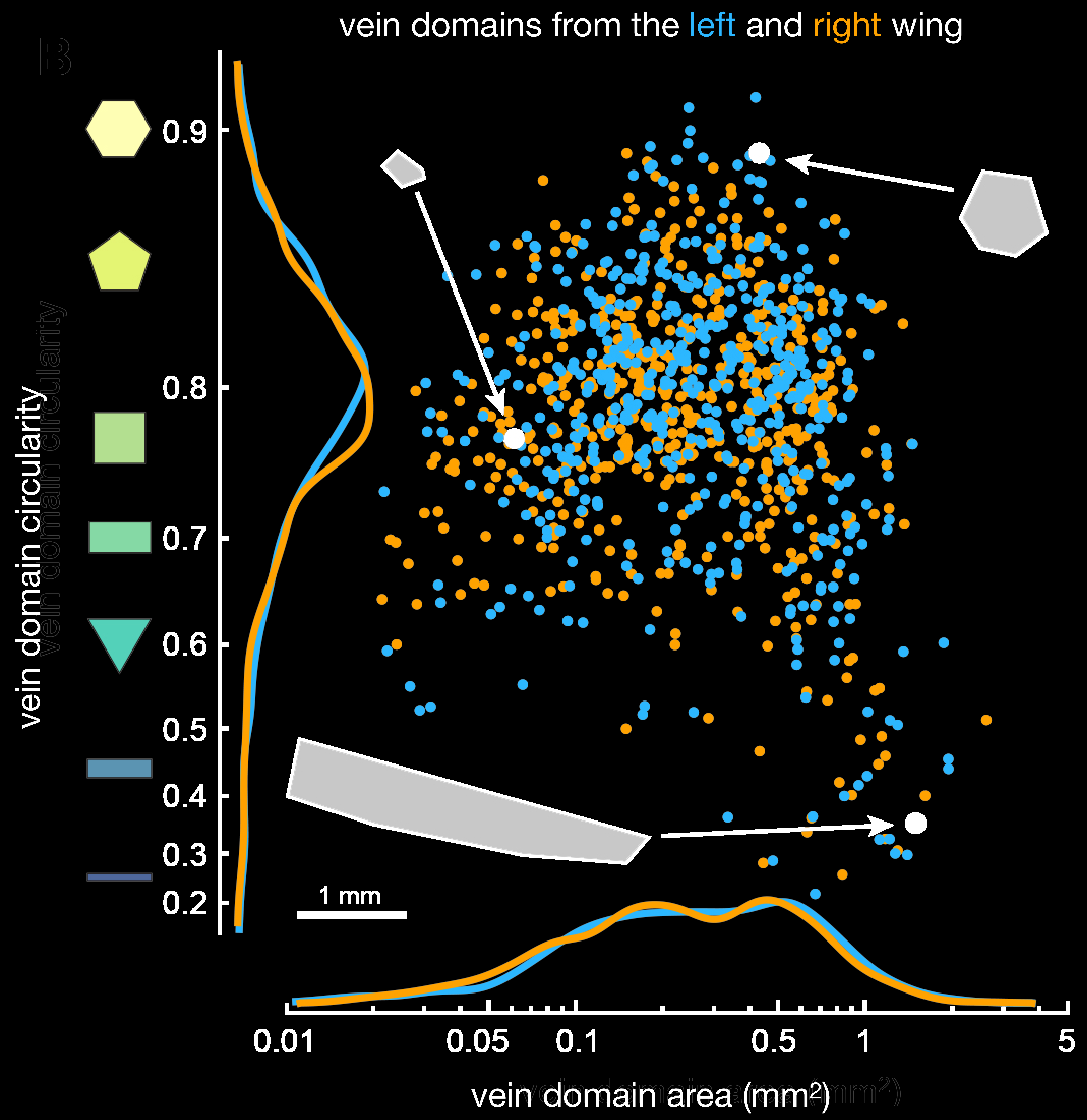
Note: a dataset of over 800 segmented wings and segmentation code is included with the manuscript.

Available at:

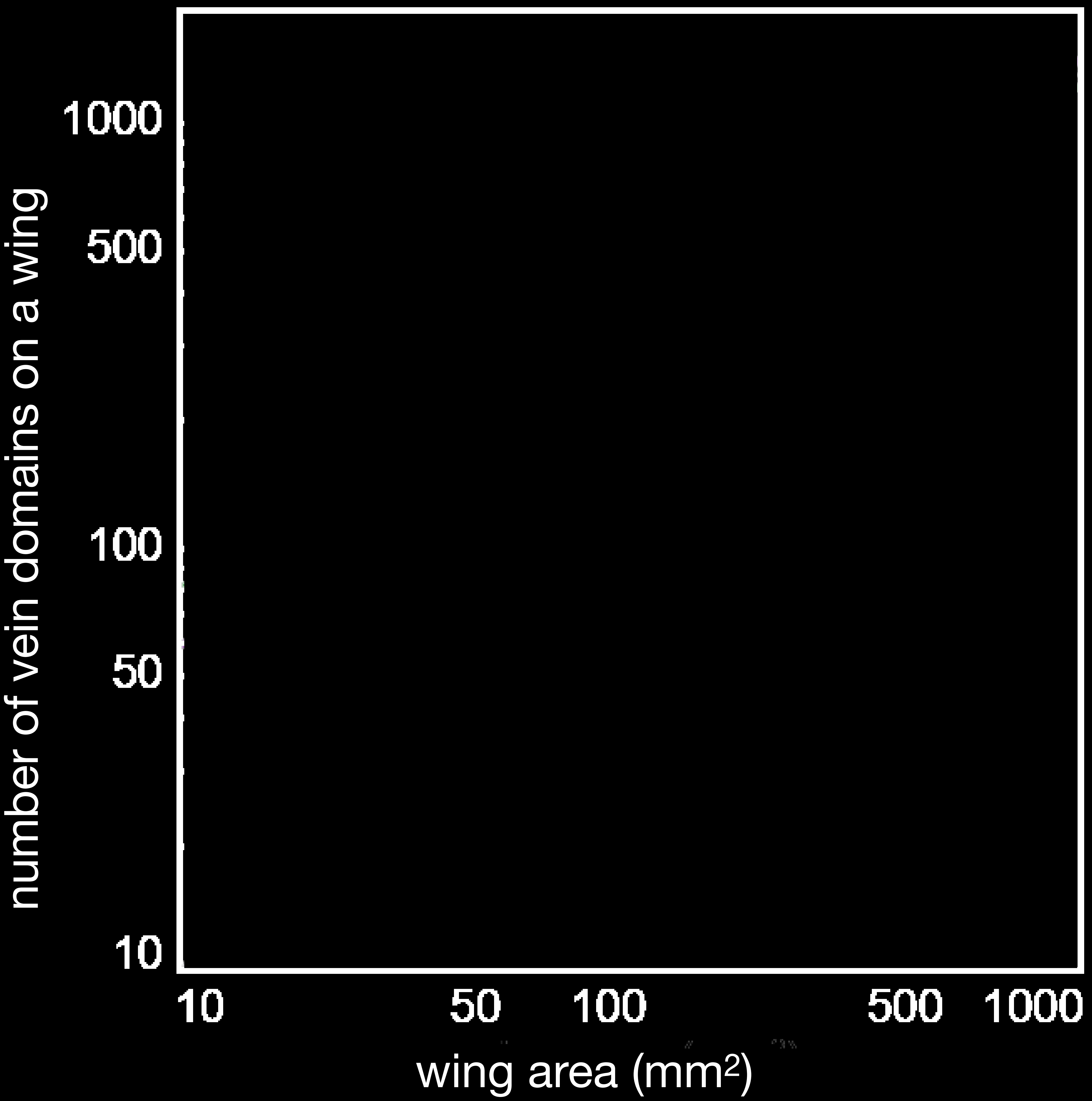
/hoffmannjordan

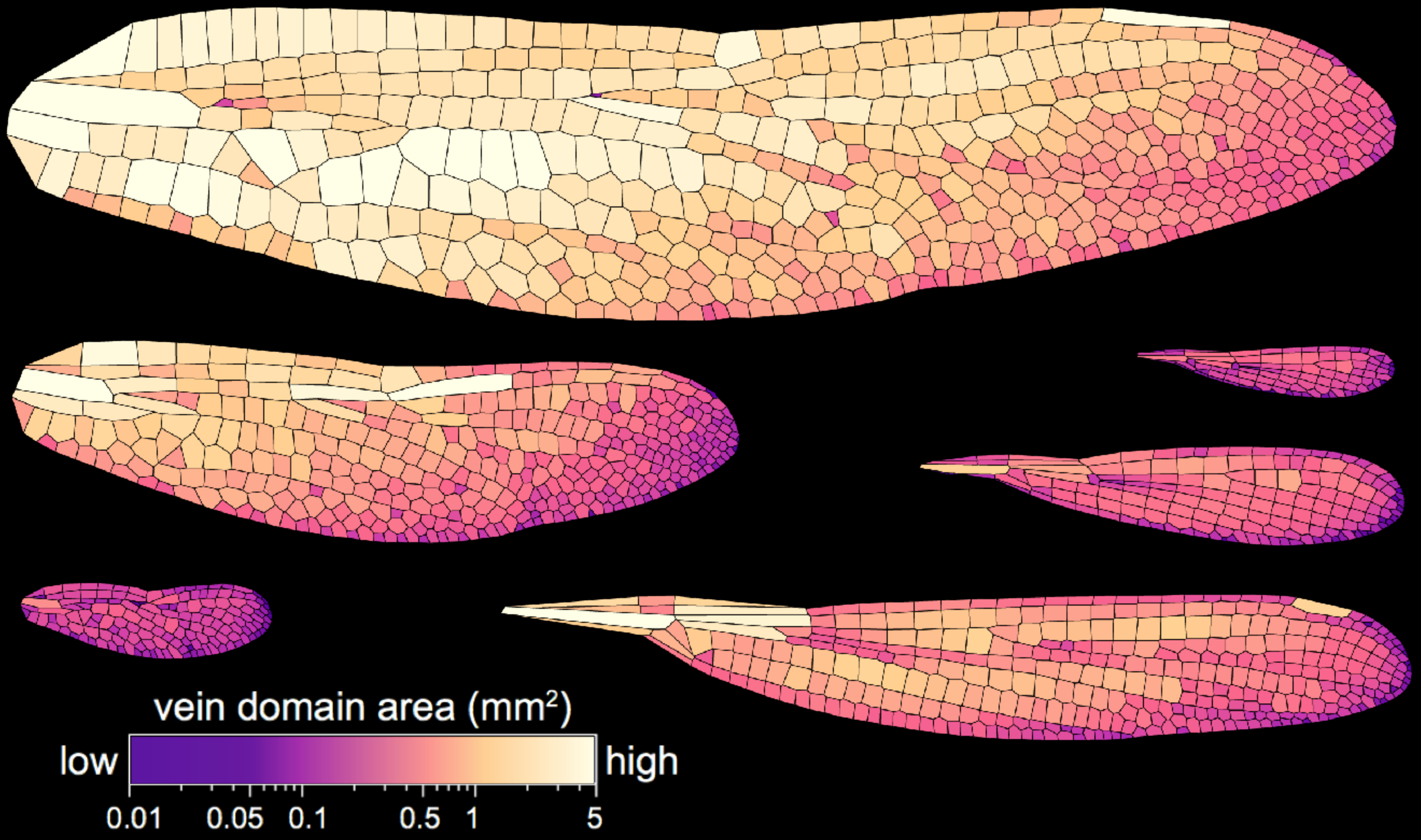


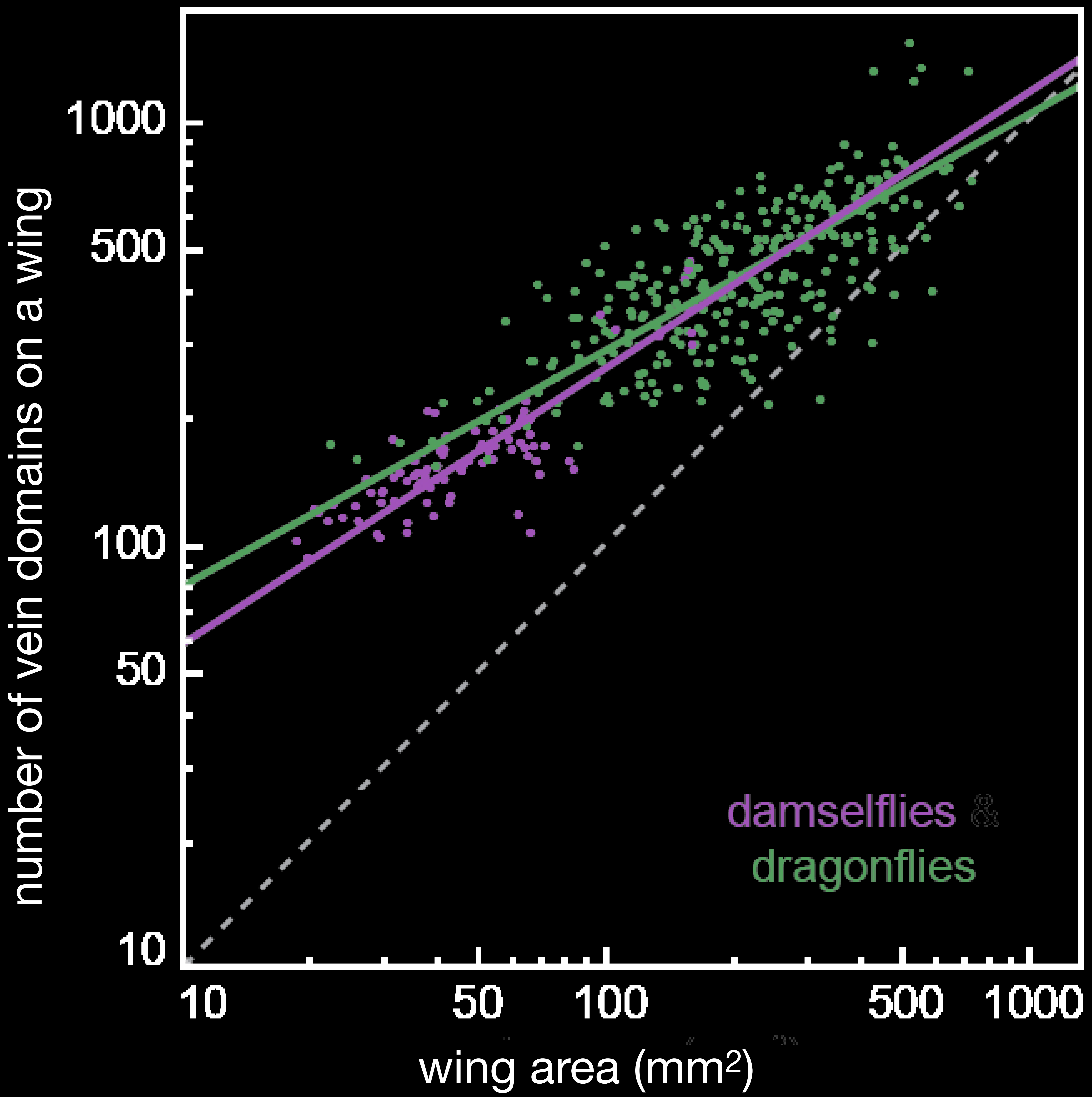
Left forewing
Right forewing
vein domain circularity
low
high
0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
vein domain area (mm²)
low
high
0.01 0.05 0.1 0.5 1 5

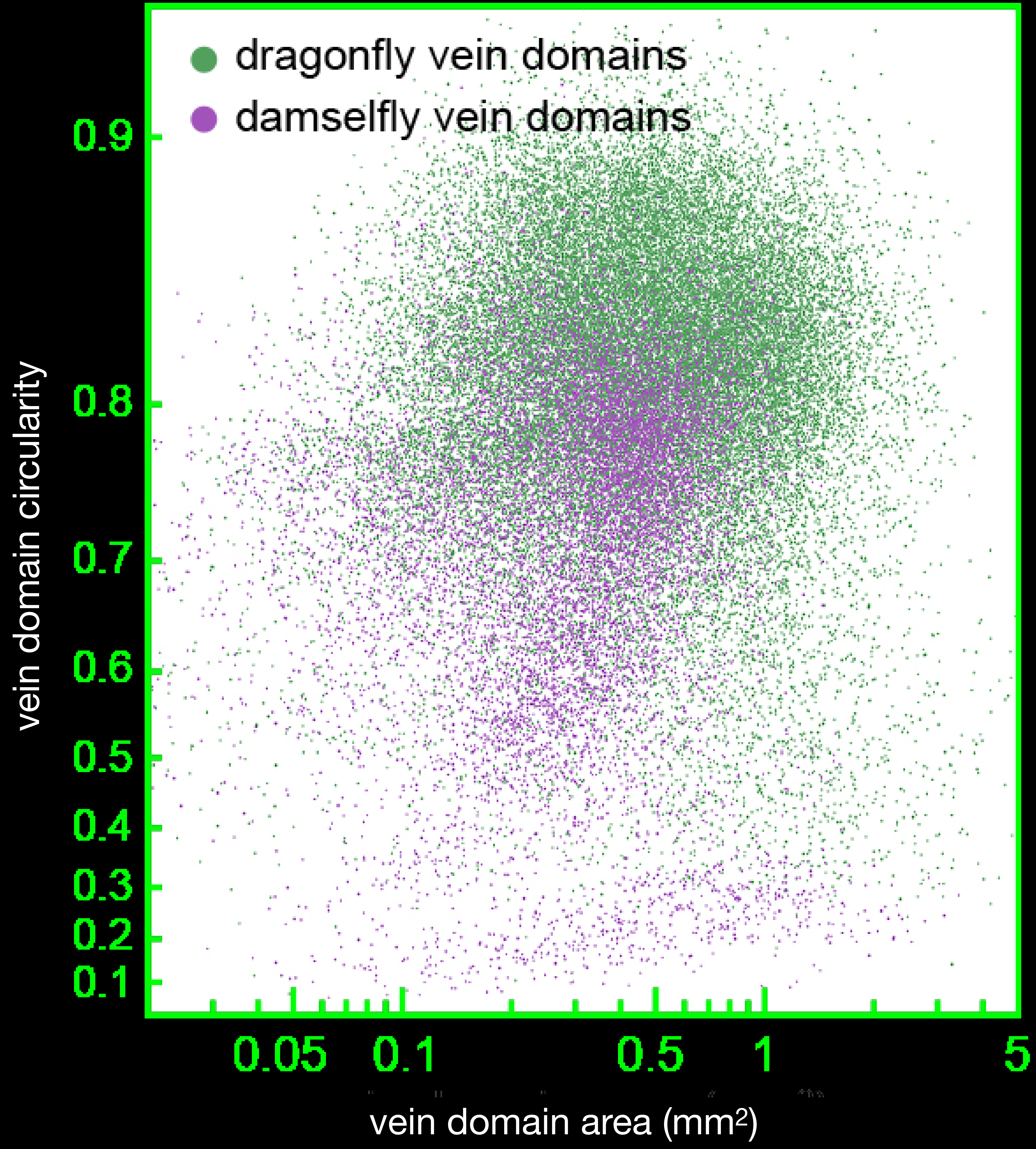


vein domains from the left and right wing
B
vein domain circularity
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1 mm
0.01
0.05
0.1
0.5
1
5
vein domain area (mm²)


number of vein domains on a wing
1000
500
100
50
10
10
50
100
500
1000
wing area (mm2)

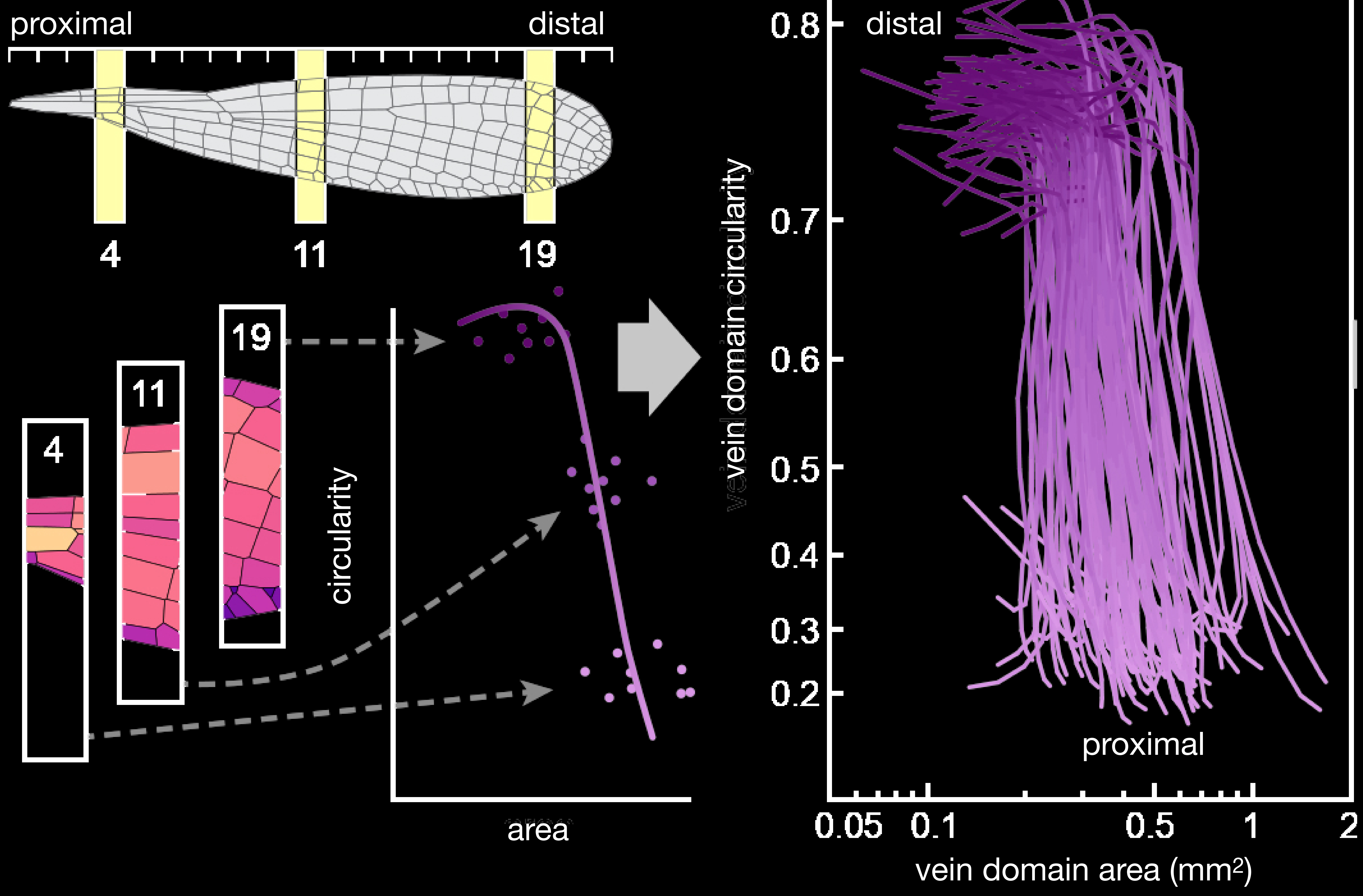

vein domain area (mm^2)
low
high
0.01
0.05
0.1
0.5
1
5

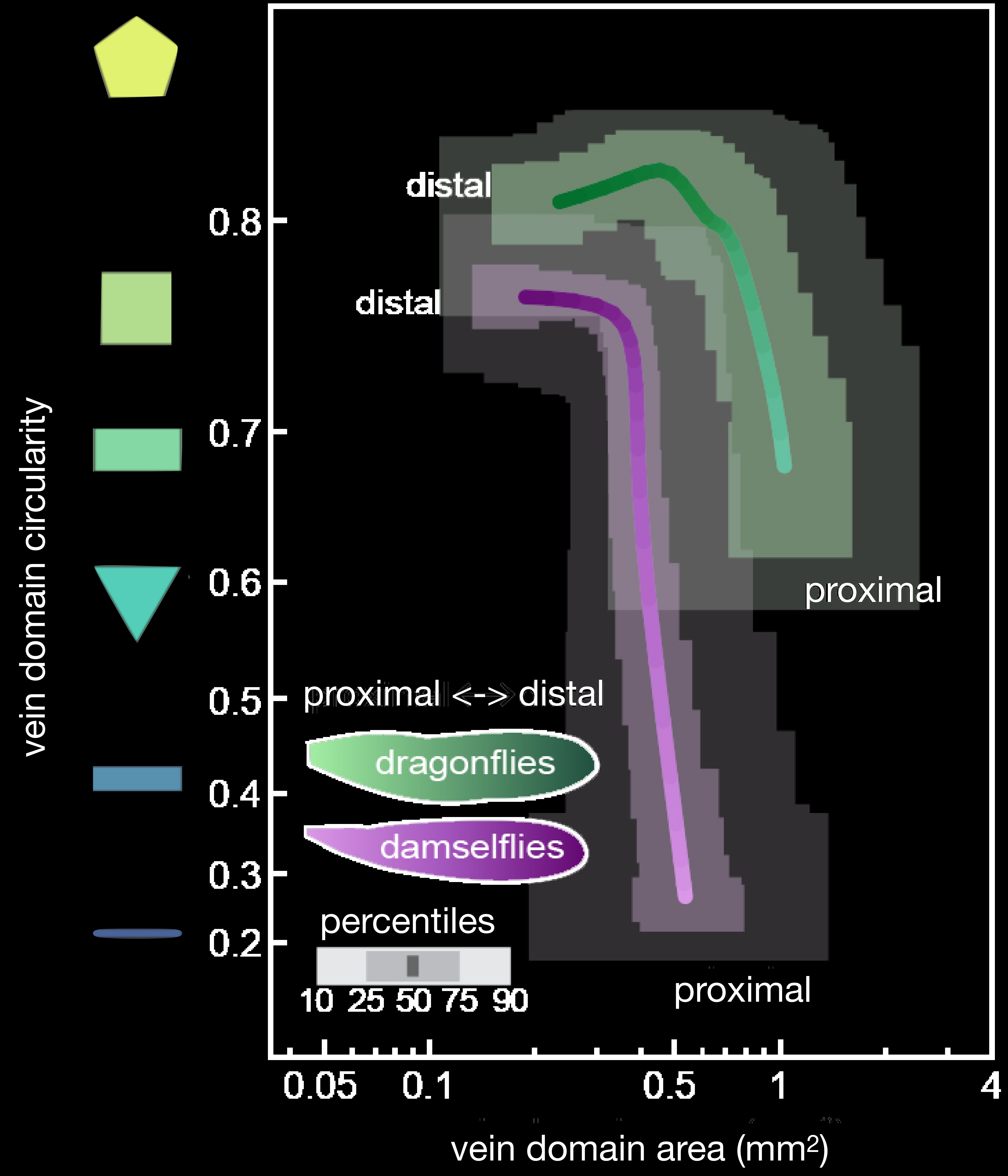

number of vein domains on a wing
1000
500
100
50
10
10
50
100
500
1000
wing area (mm²)
damselflies &
dragonflies



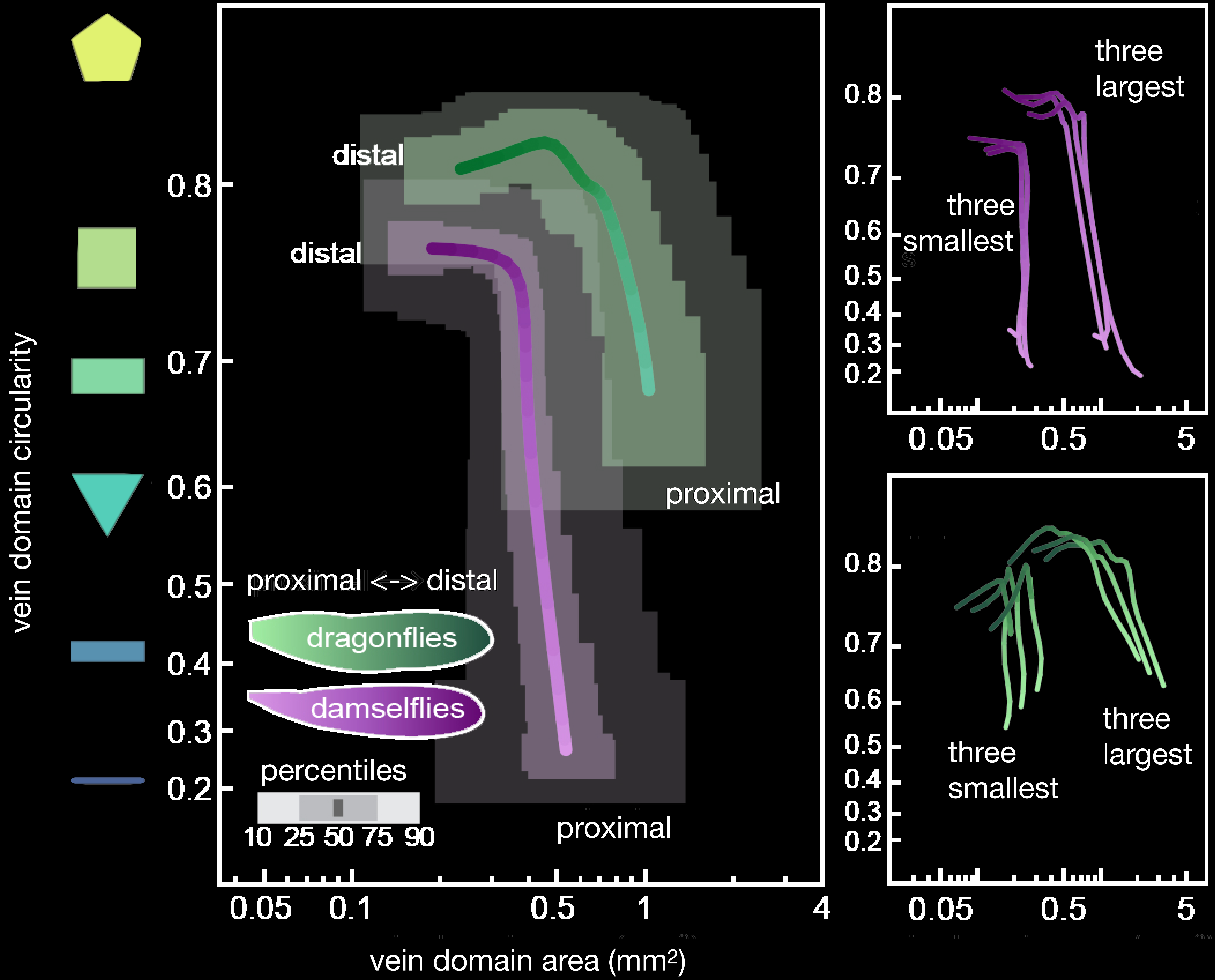
dragonfly vein domains
damselfly vein domains
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
vein domain circularity
0.05
0.1
0.5
1
5
vein domain area (mm2)

proximal to distal morphology traces



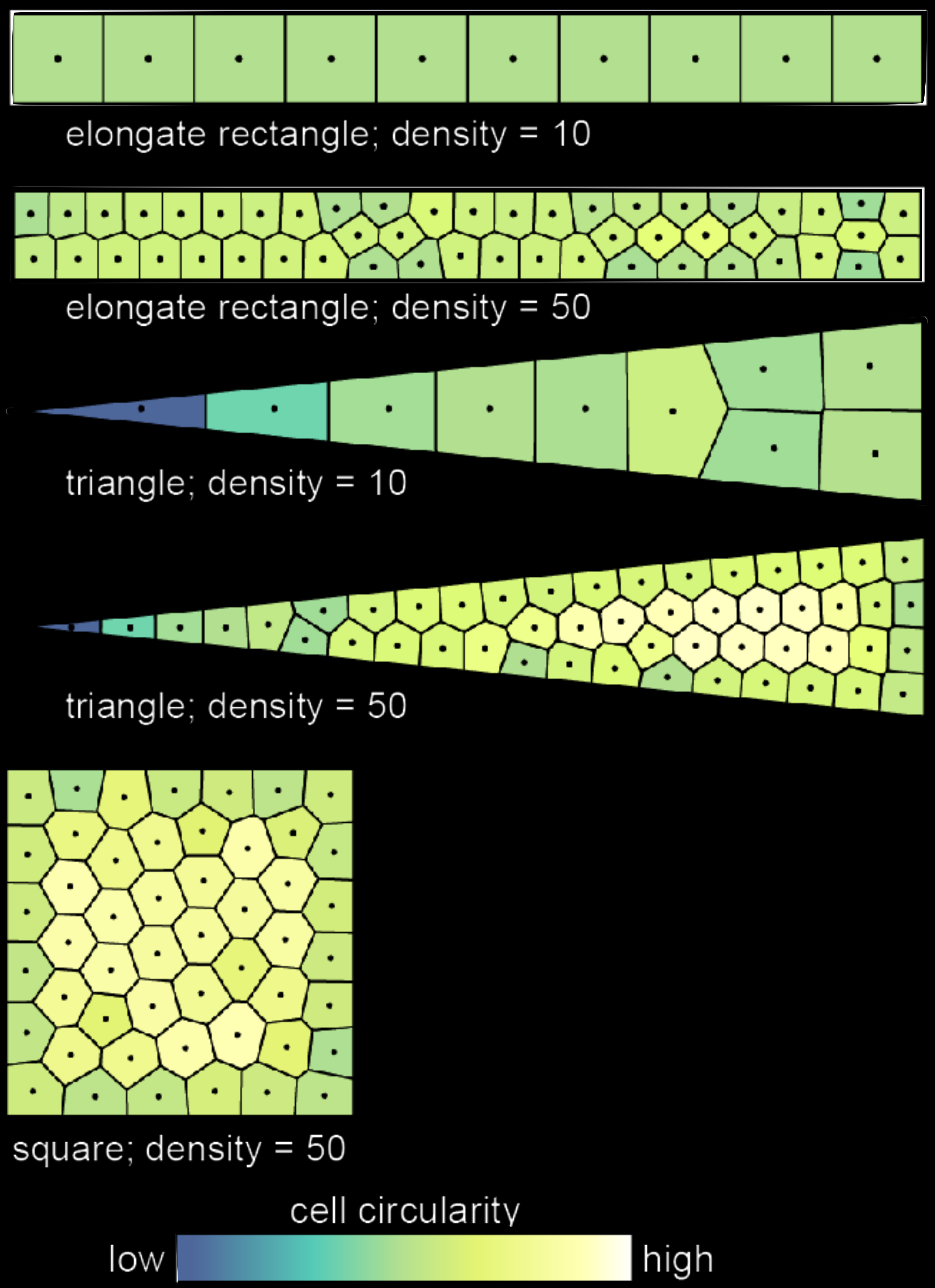


vein domain circularity
0.8
0.7
0.6
0.5
0.4
0.3
0.2
distal
distal
proximal
proximal <-> distal
dragonflies
damselflies
percentiles
10 25 50 75 90
proximal
0.05
0.1
0.5
1
4
vein domain area (mm^2)

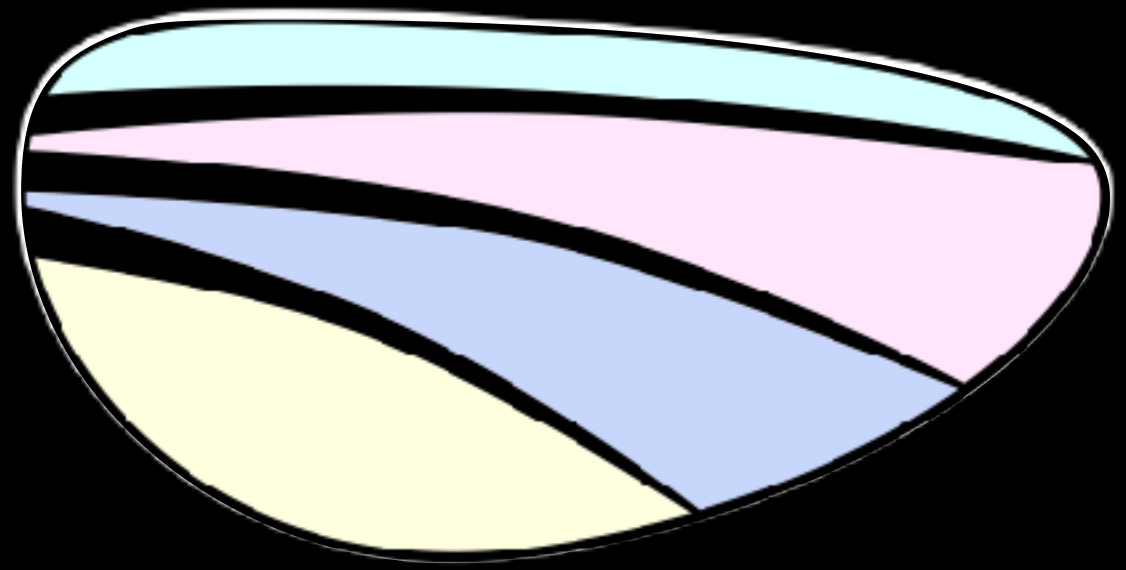


vein domain circularity
0.8
0.7
0.6
0.5
0.4
0.3
0.2
distal
distal
proximal
proximal<-> distal
dragonflies
damselflies
percentiles
10 25 50 75 90
proximal
0.05
0.1
0.5
1
4
vein domain area (mm2)
three
largest
three
smallest
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.05
0.5
5
0.8
0.7
0.6
0.5
0.4
0.3
0.2
three
largest
three
smallest
0.05
0.5
5

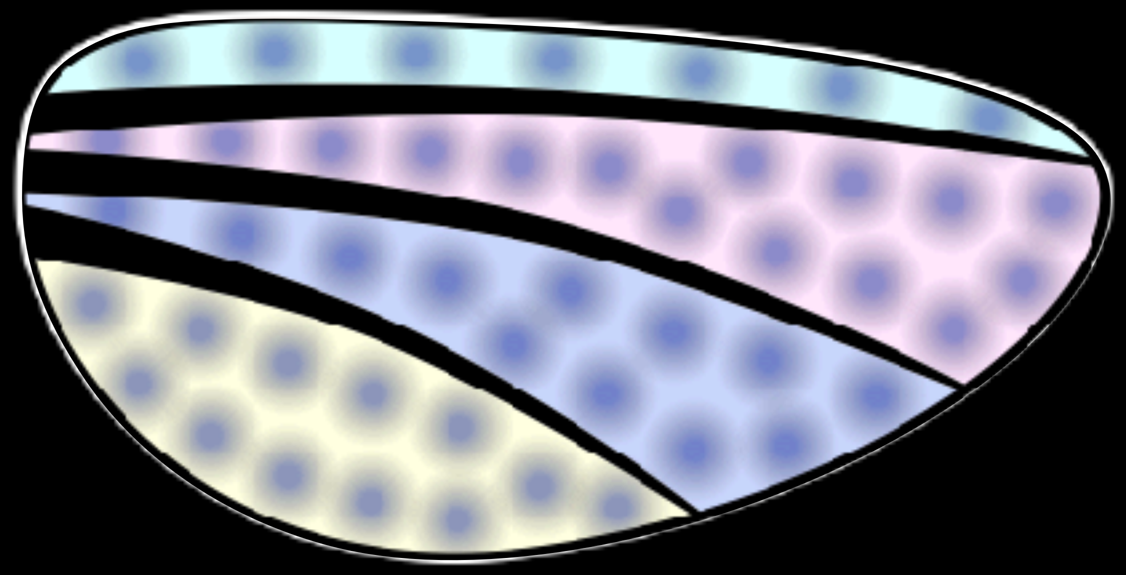
Voronoi tessellation of evenly spaced seeds



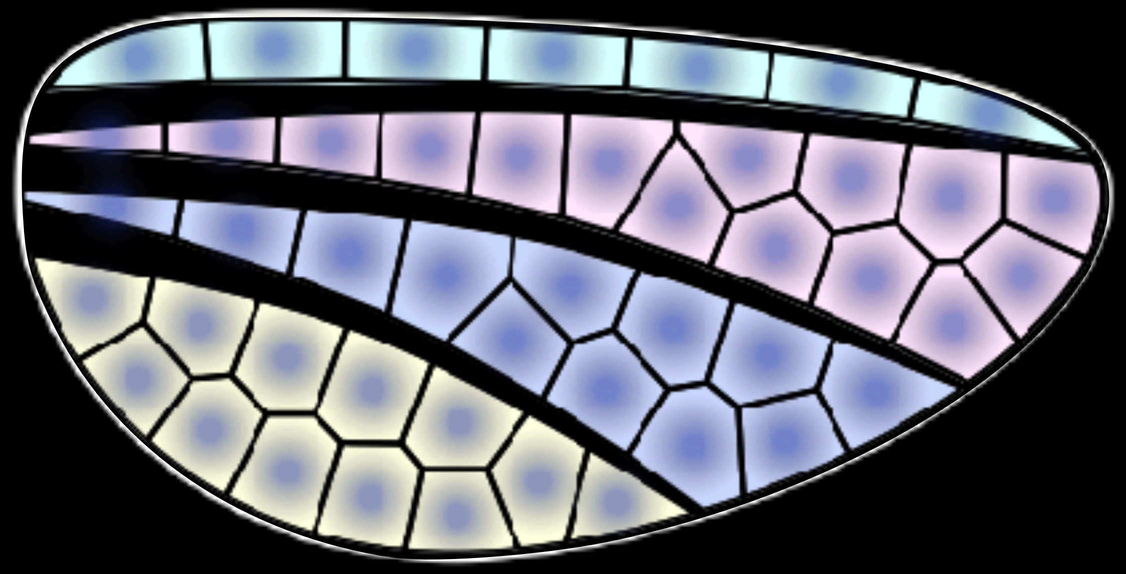
Simplified developmental sequence



Positions of primary veins are established.

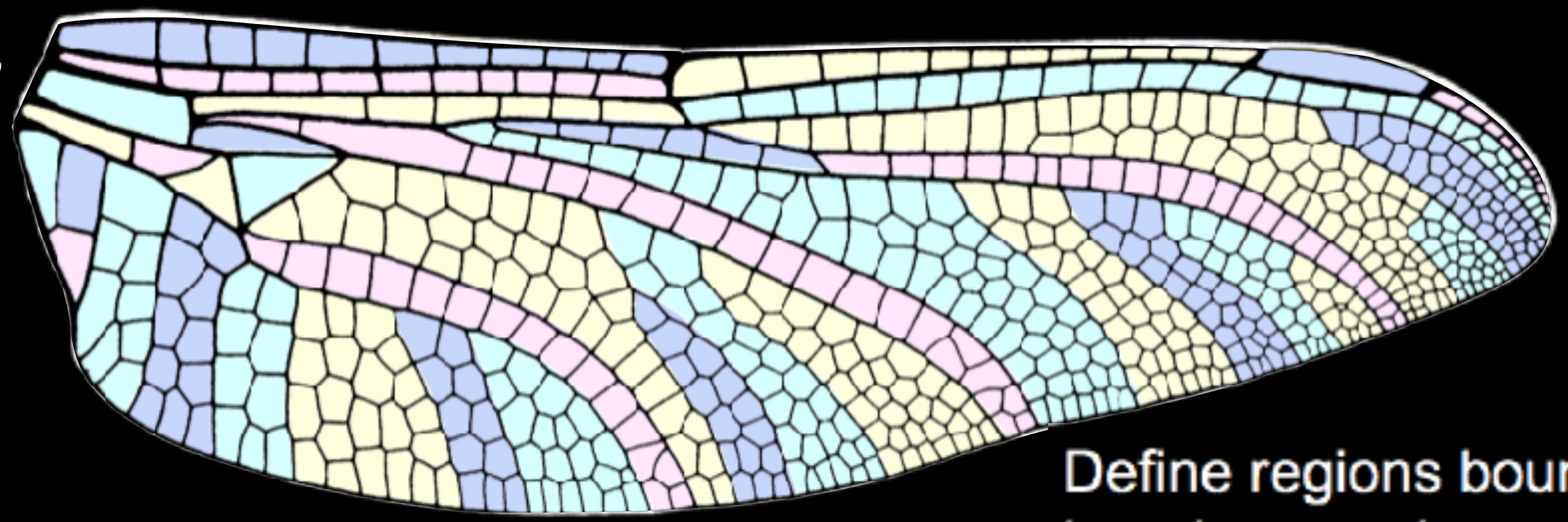


Evenly spaced inhibitory zones emerge in each wing region.

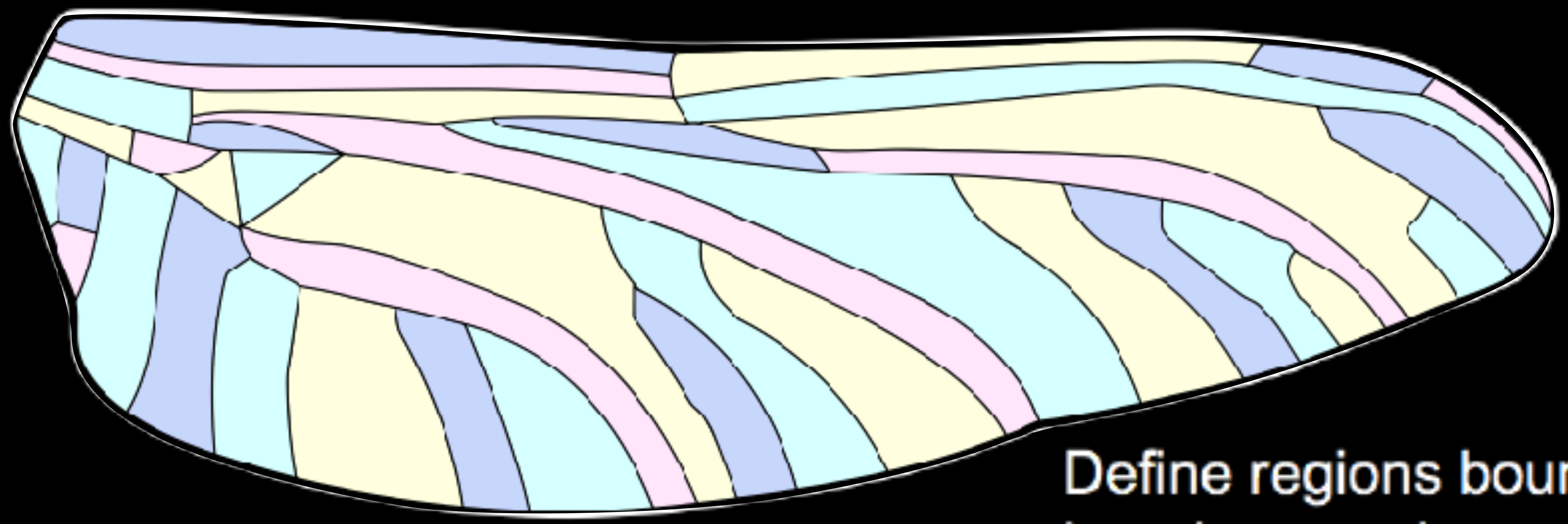


Secondary veins form at local signaling minima.

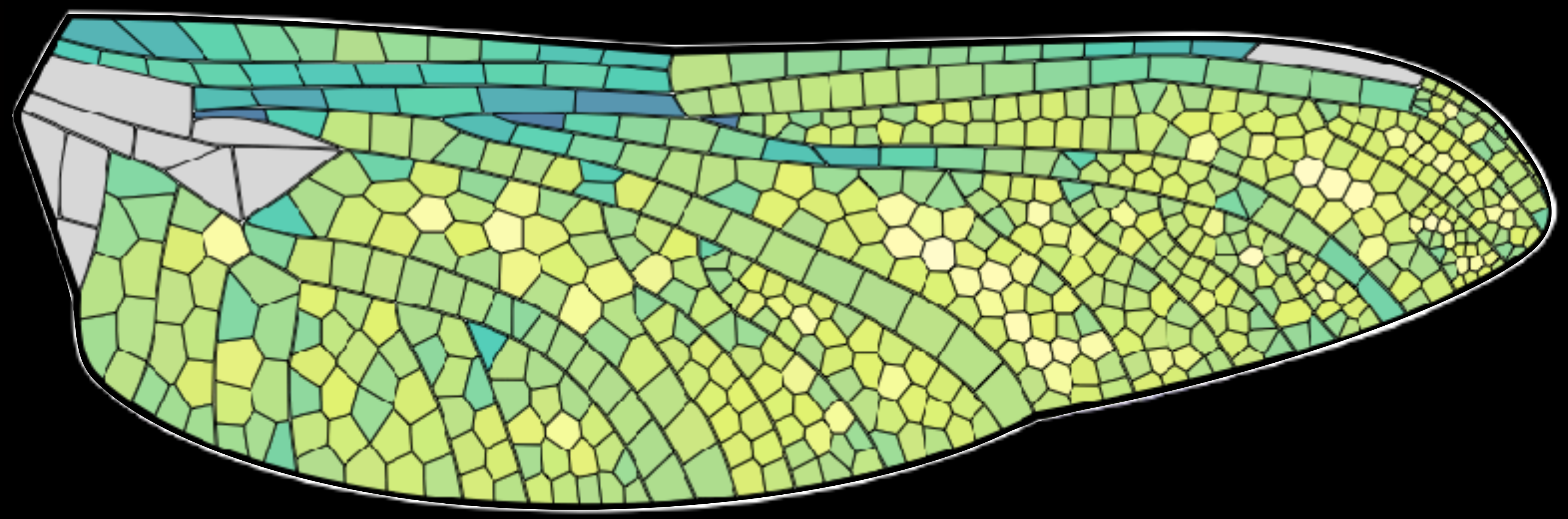
Simulating secondary veins on a wing



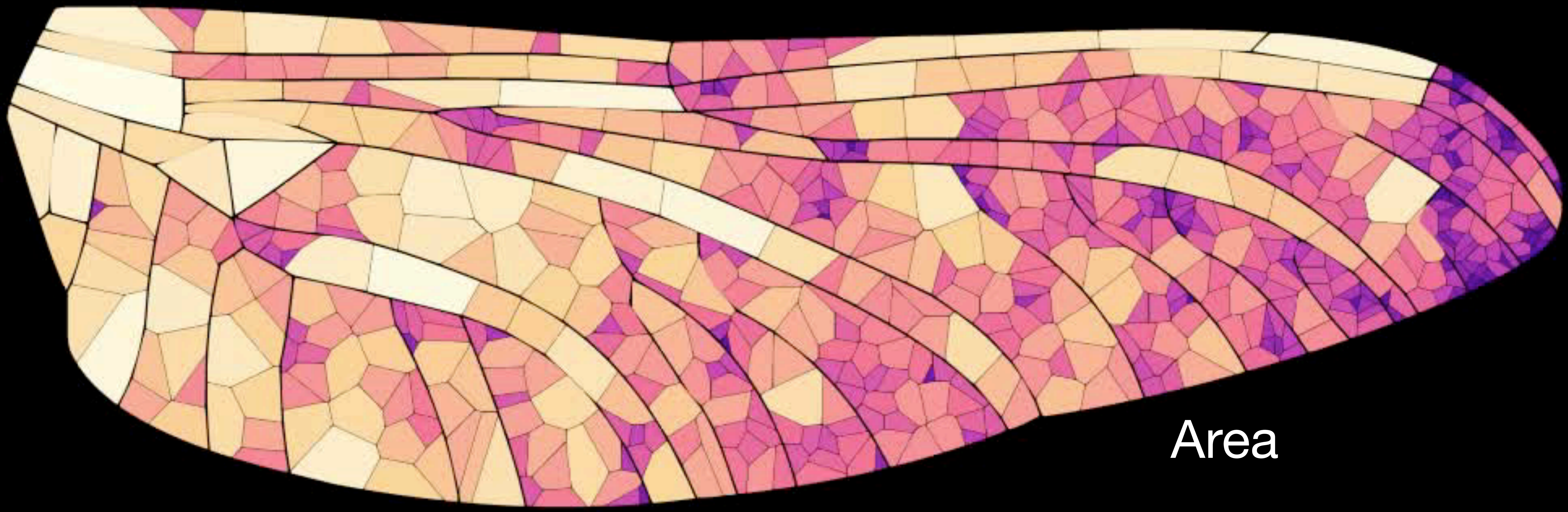
Define regions bounded by primary veins

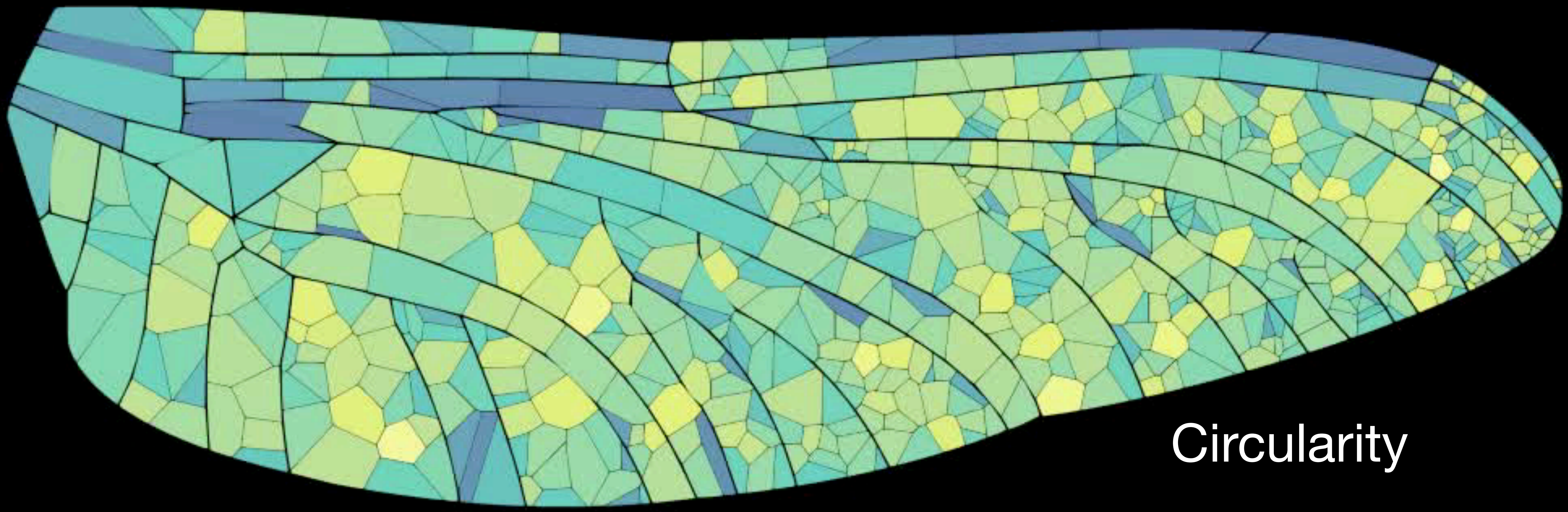


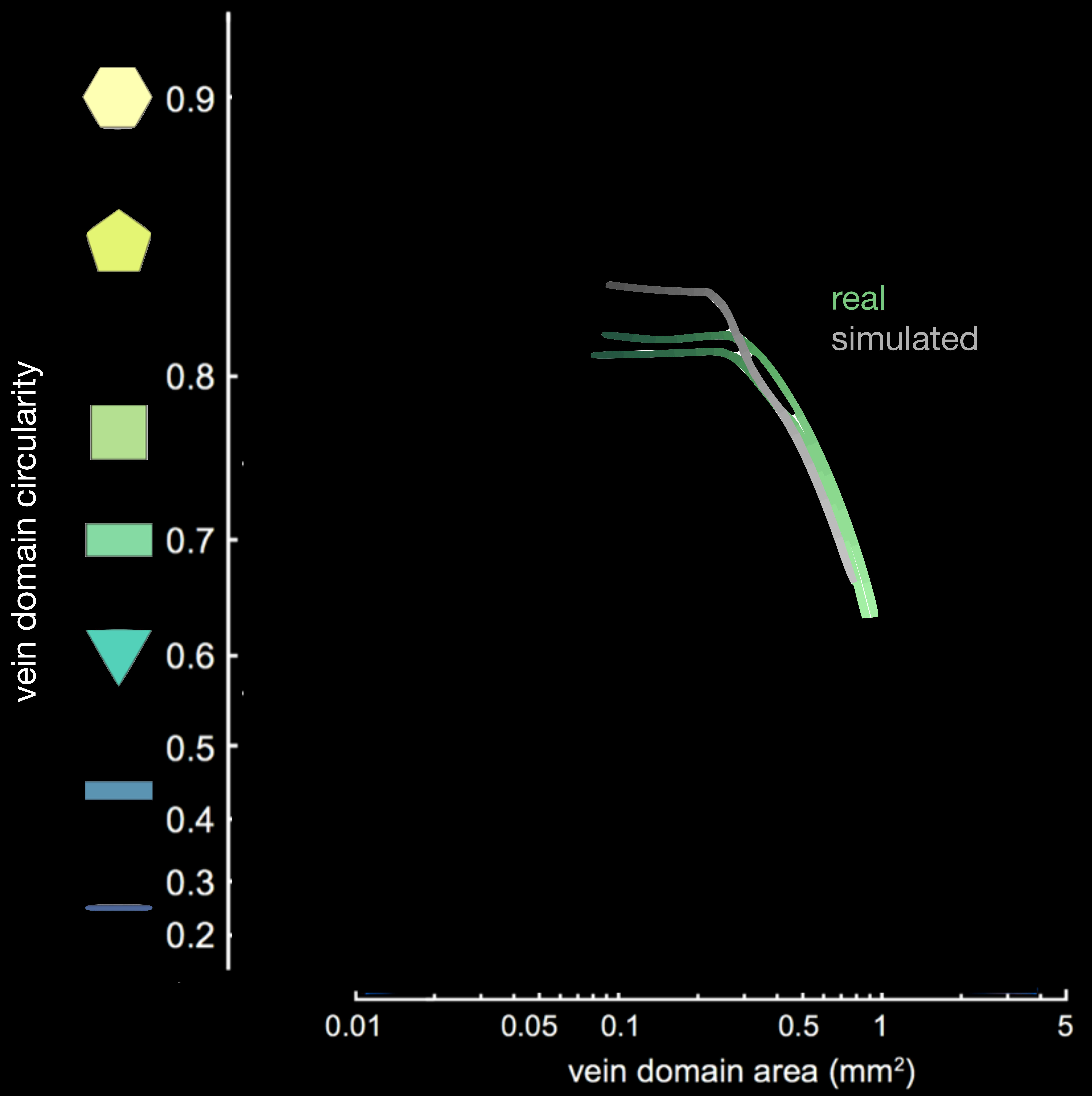
Define regions bounded by primary veins

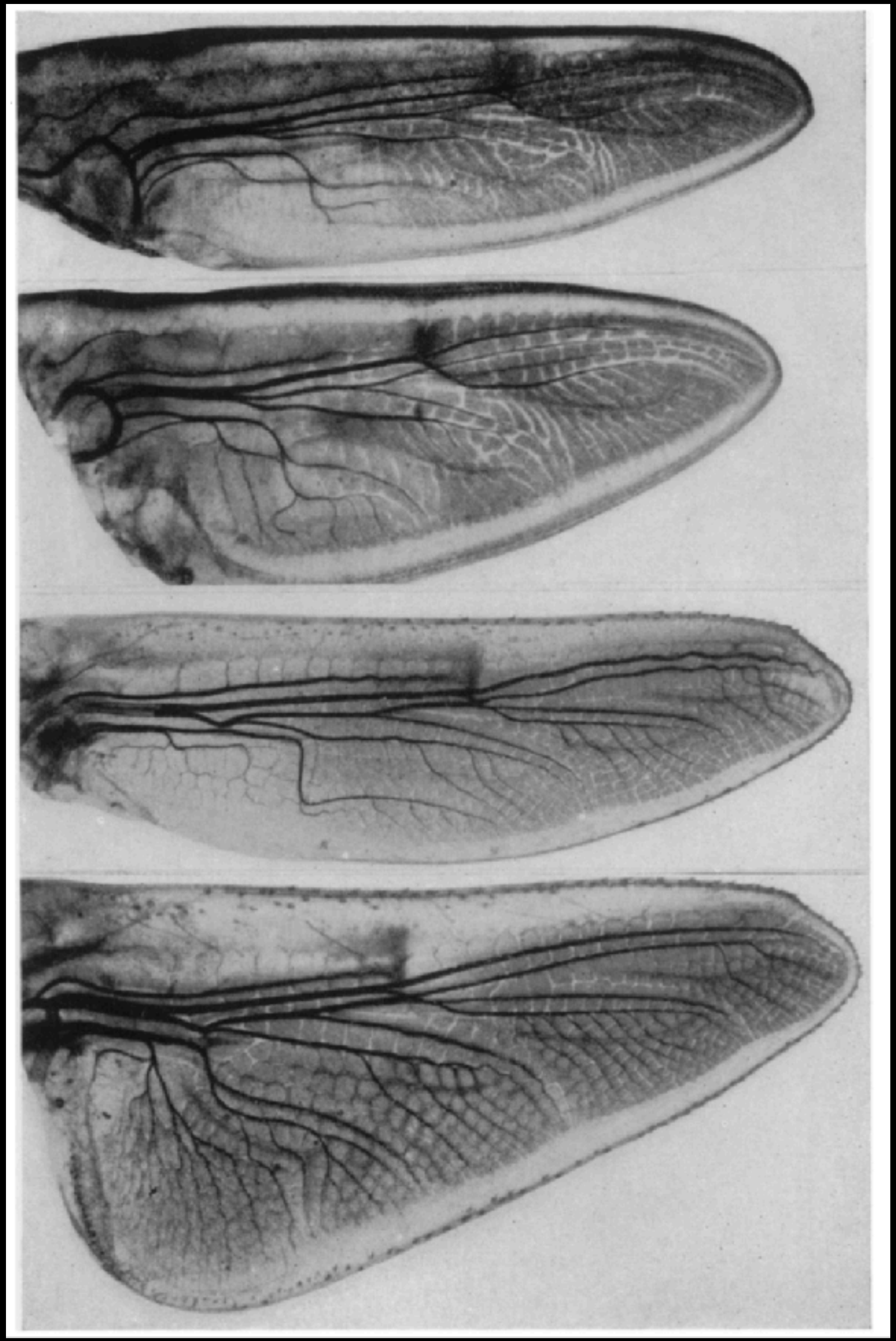


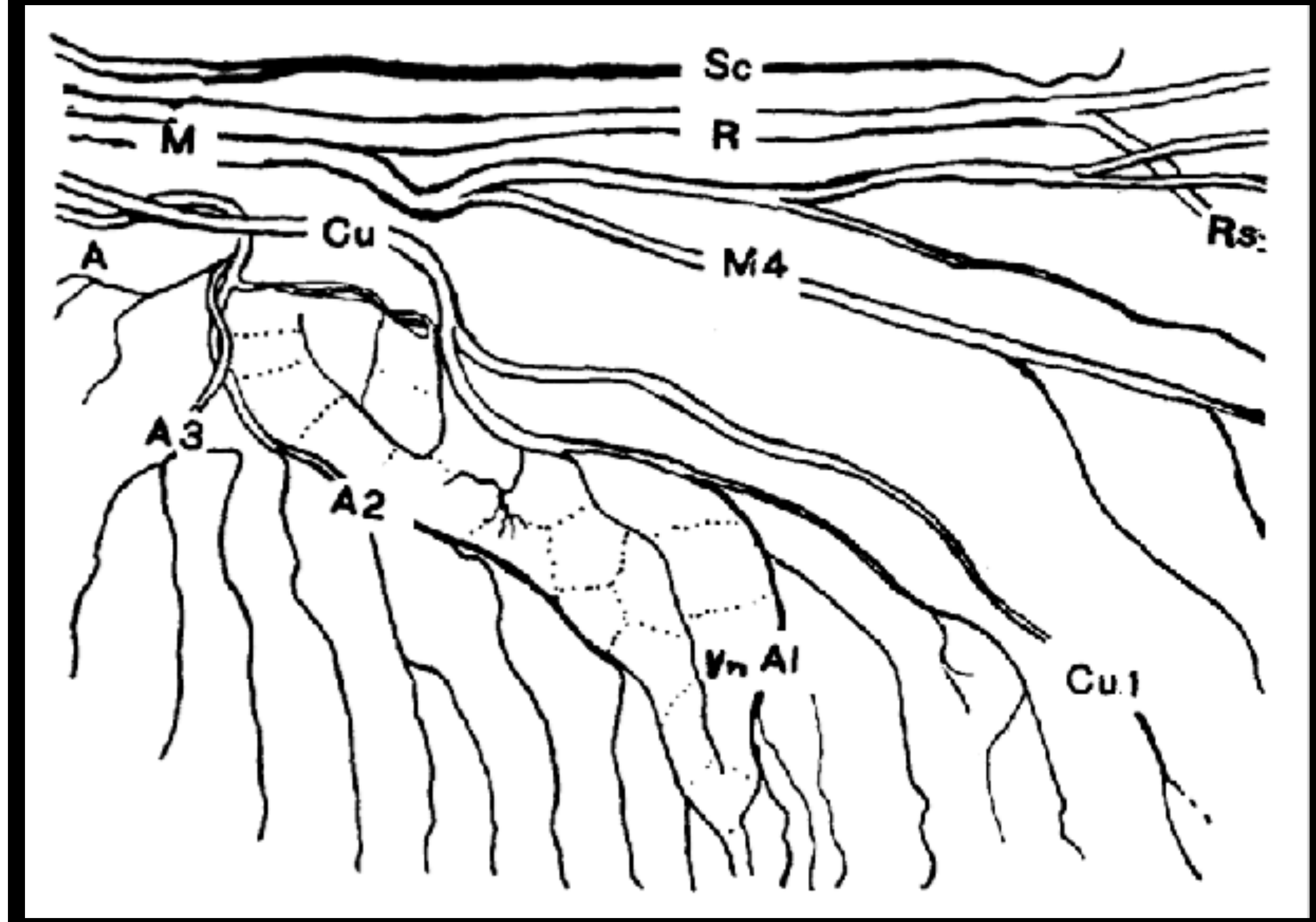
Evenly space inhibitory centers, then place secondary veins at local minima


Area

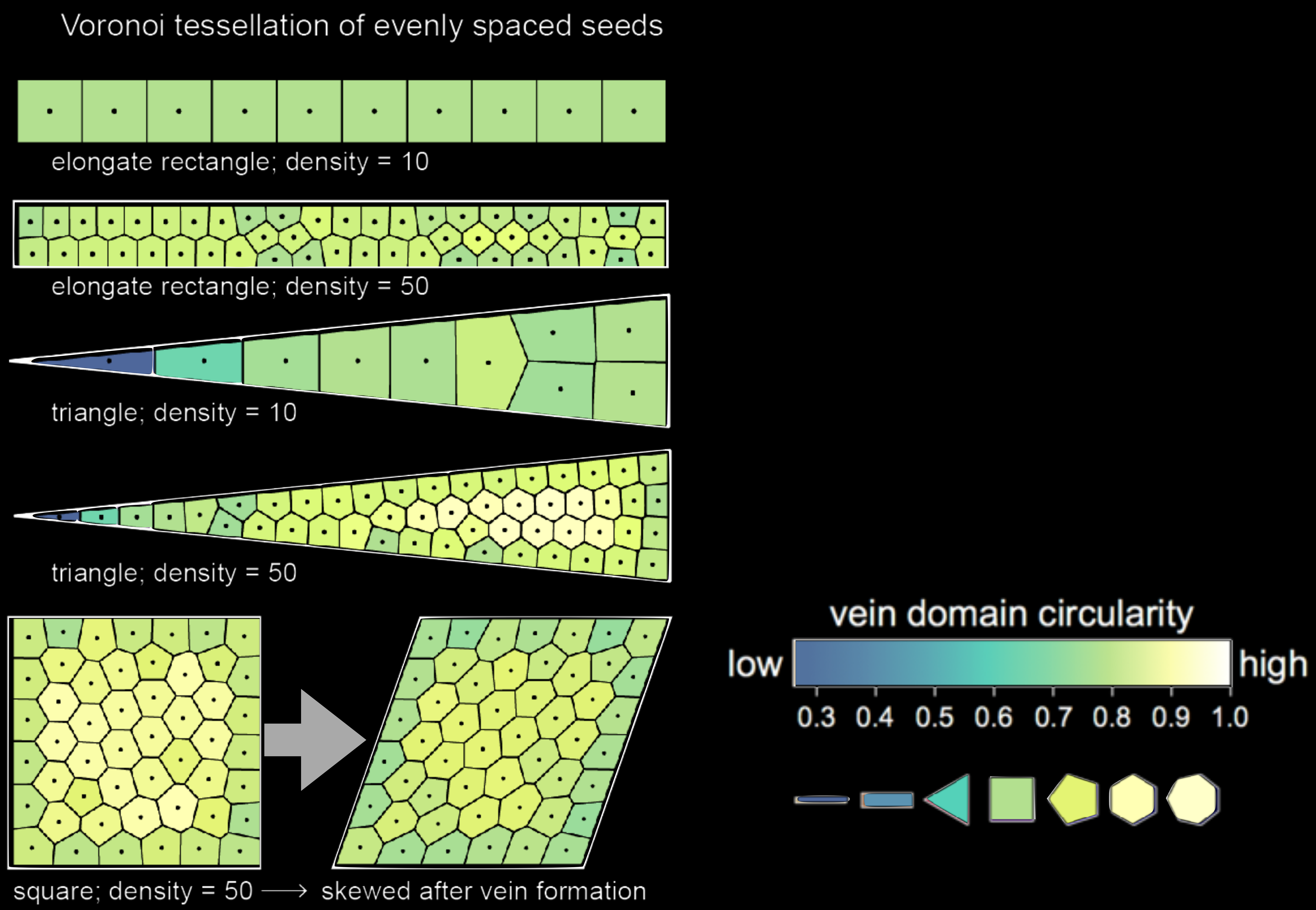

Circularity


vein domain circularity
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
real
simulated
0.01
0.05
0.1
0.5
1
5
vein domain area (mm²)

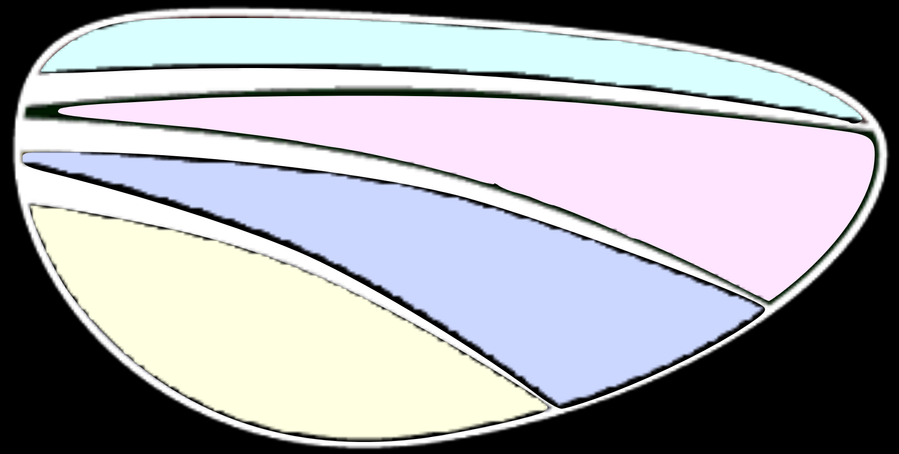




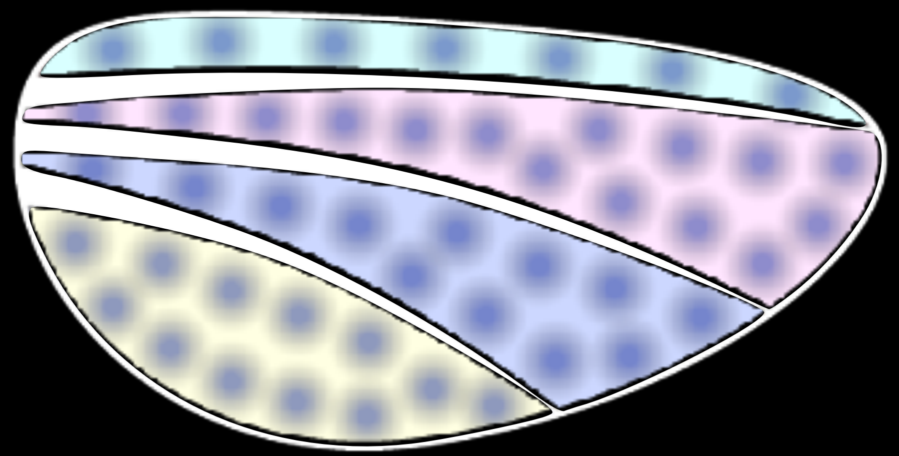
Needham 1951


Voronoi tessellation of evenly spaced seeds
elongate rectangle; density = 10
elongate rectangle; density = 50
triangle; density = 10
triangle; density = 50
square; density = 50 ⟶ skewed after vein formation
vein domain circularity
low
high
0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

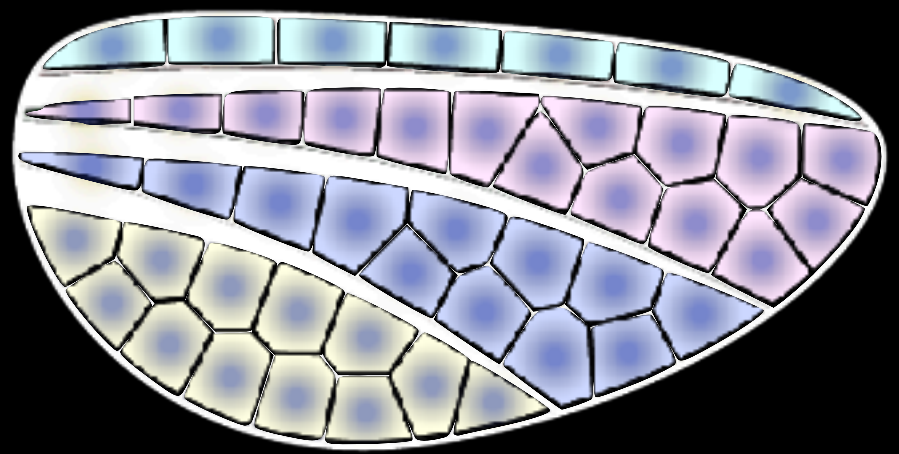
Simplified developmental sequence



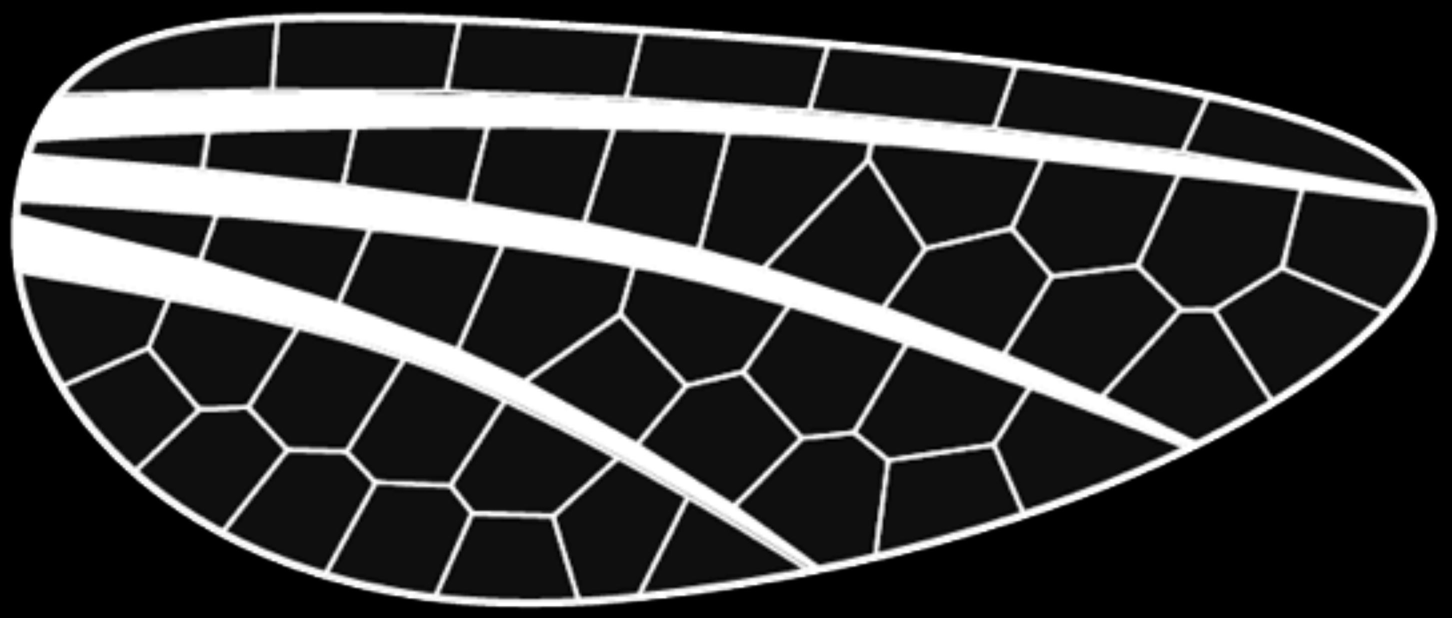
Positions of primary veins are established.



Evenly spaced inhibitory zones emerge in each wing region.

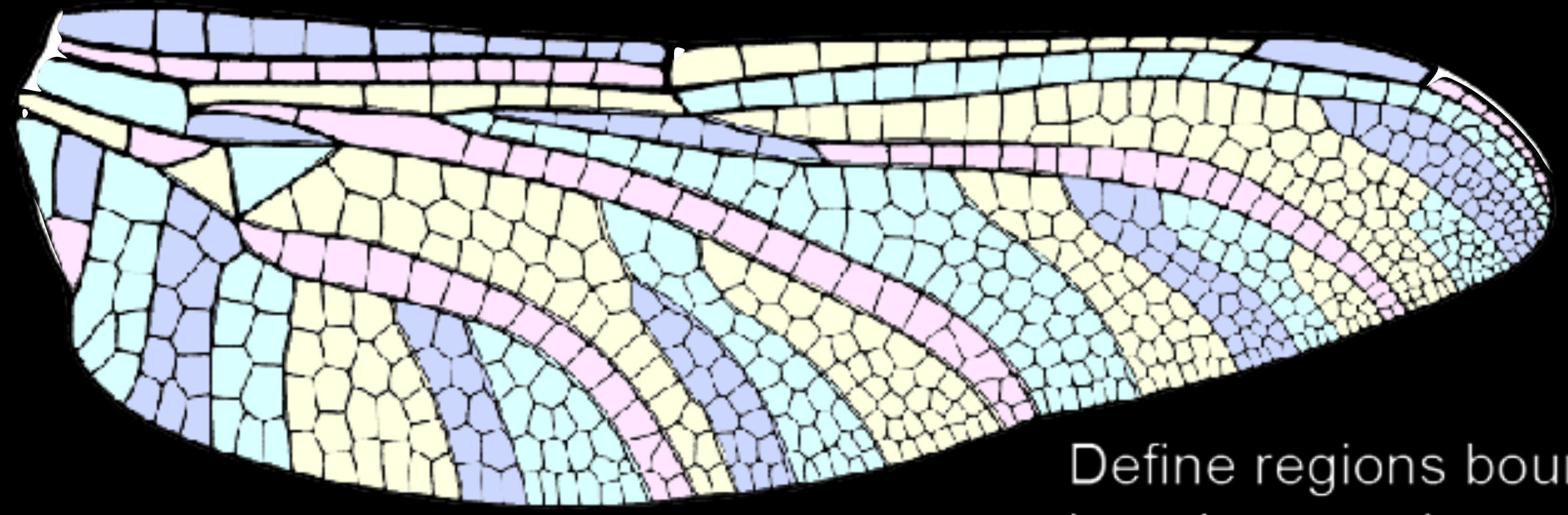


Secondary veins form at local signaling minima.

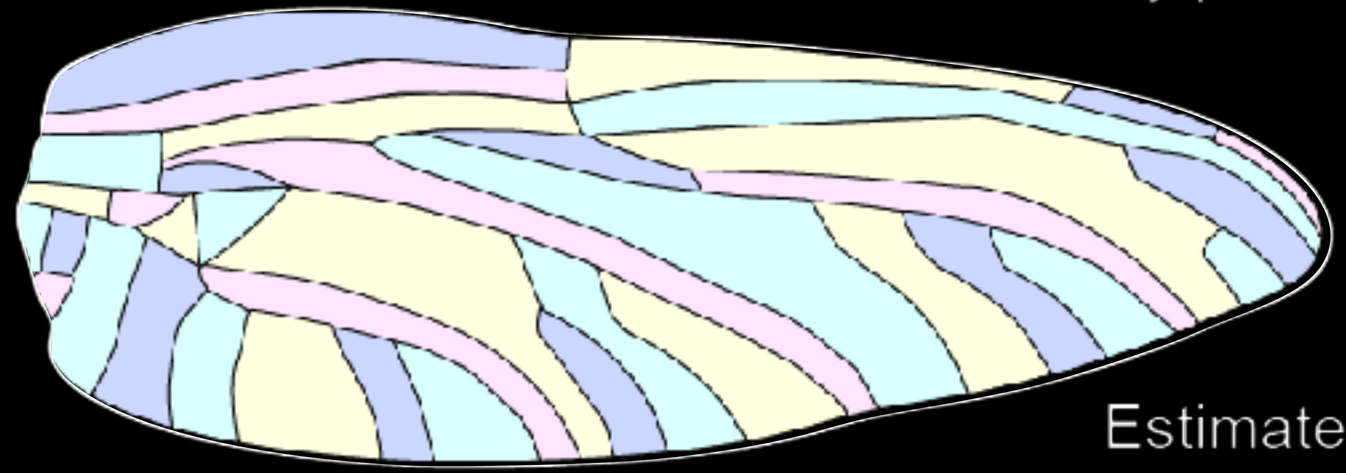


Wing grows anisotropically

Simulating secondary veins on a wing

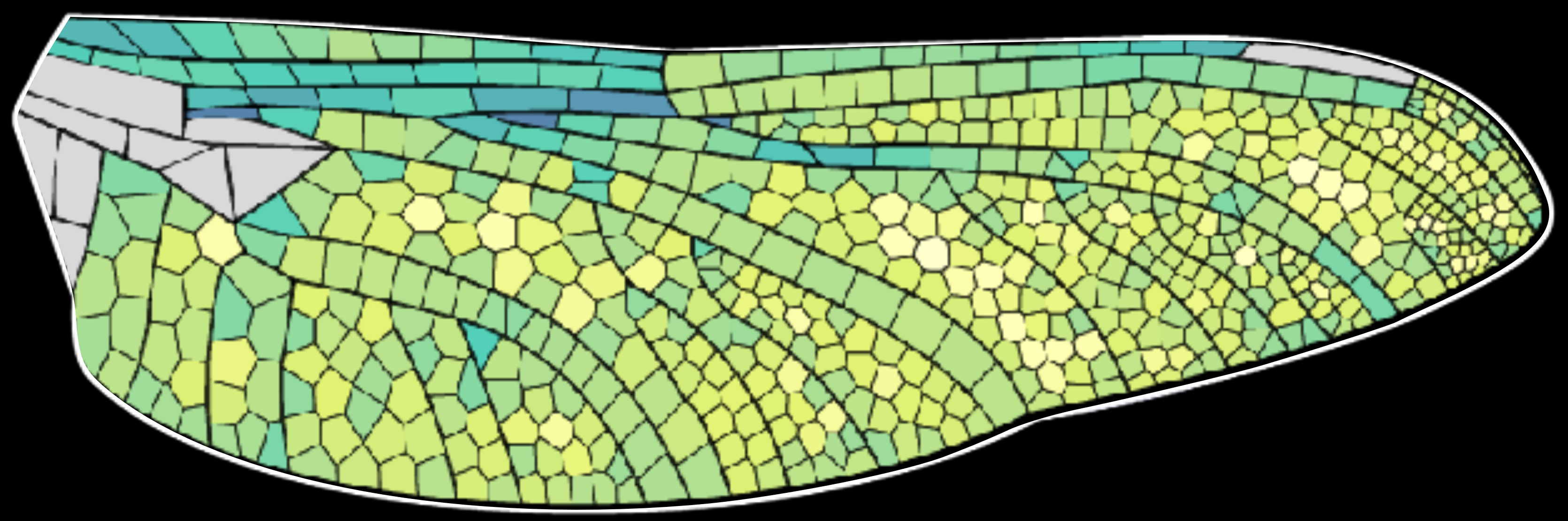


Define regions bounded by primary veins

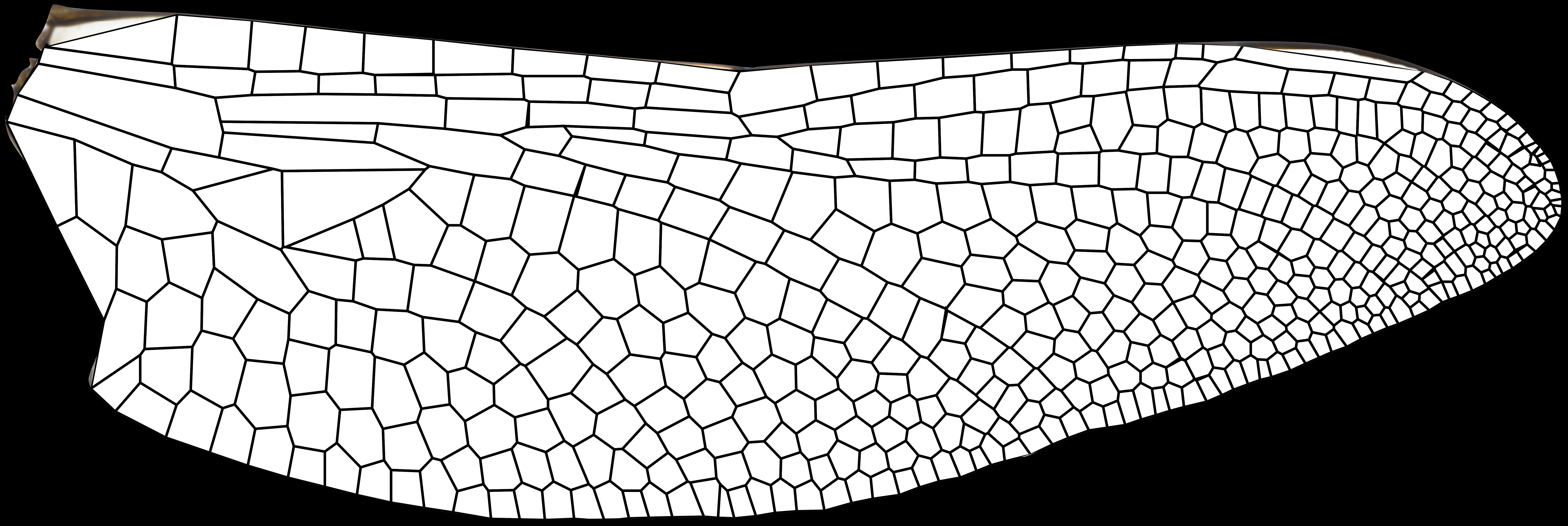


Estimate former wing pad morphology

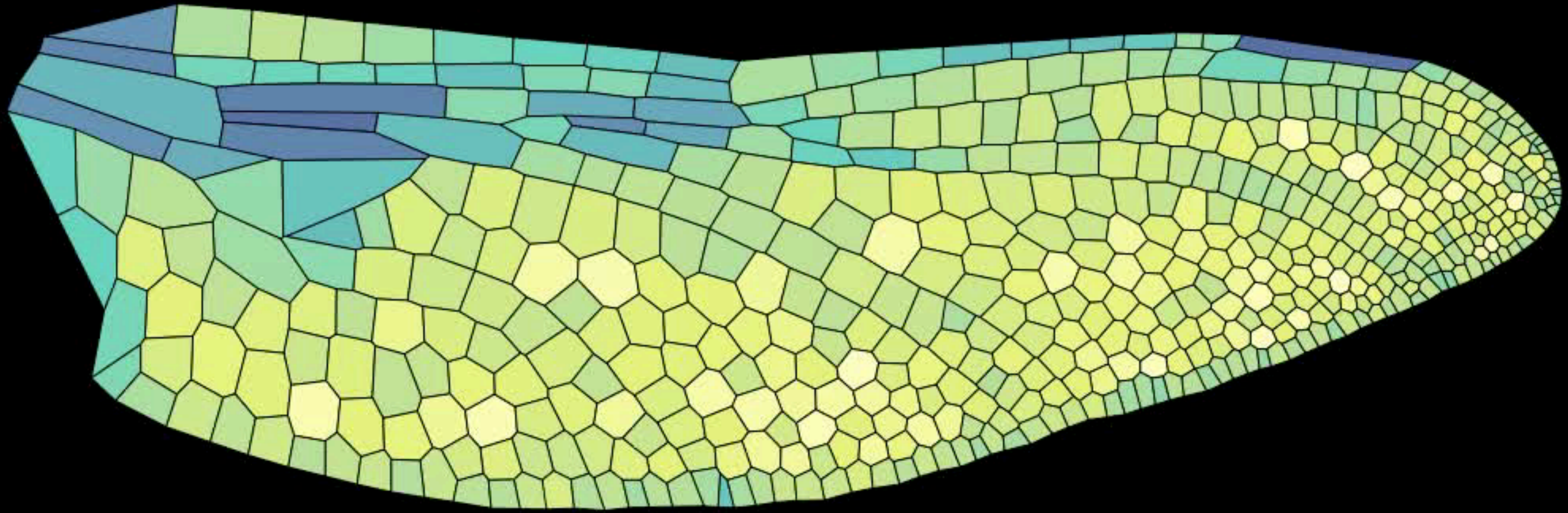
Evenly space inhibitory centers, then place secondary veins at local minima

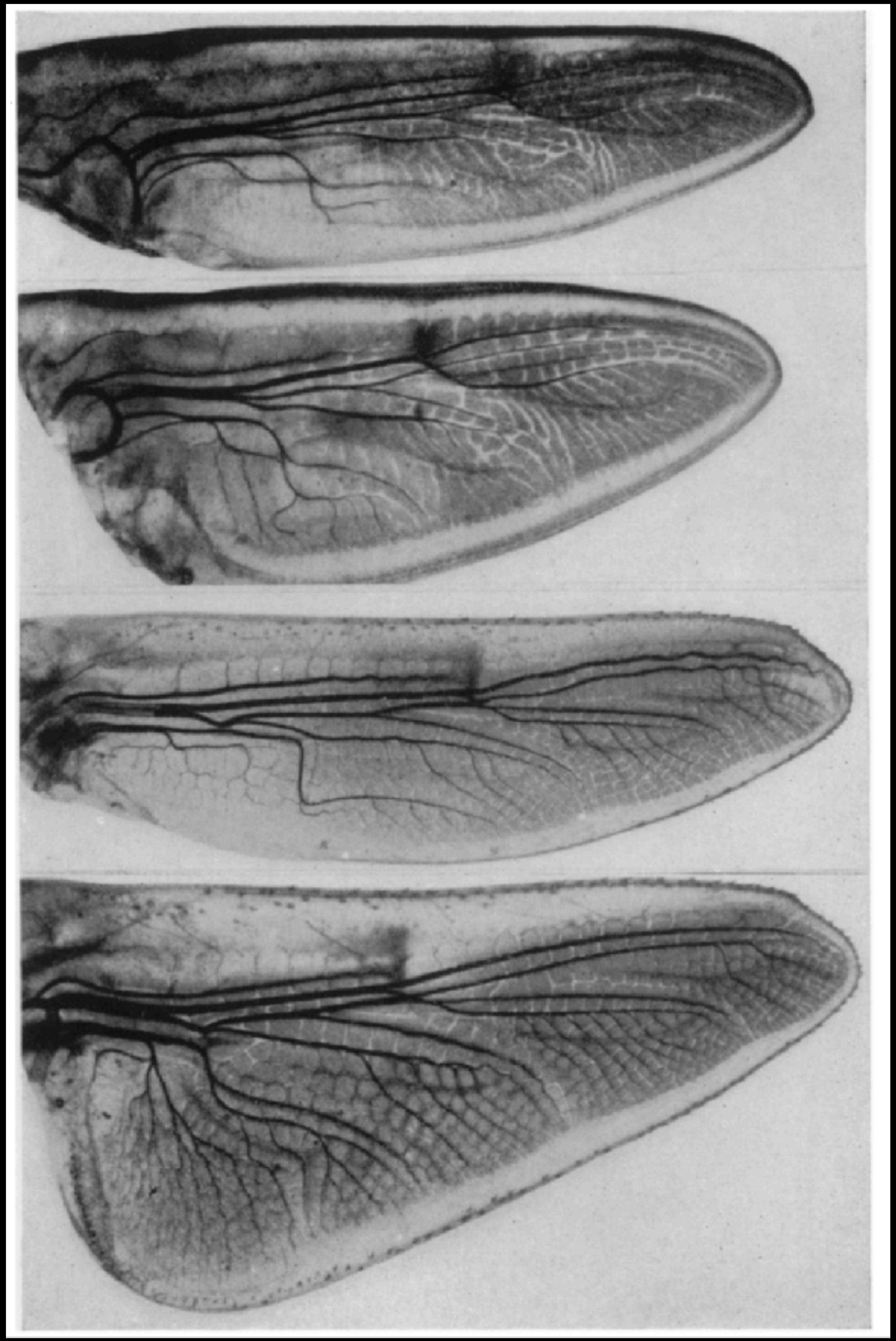


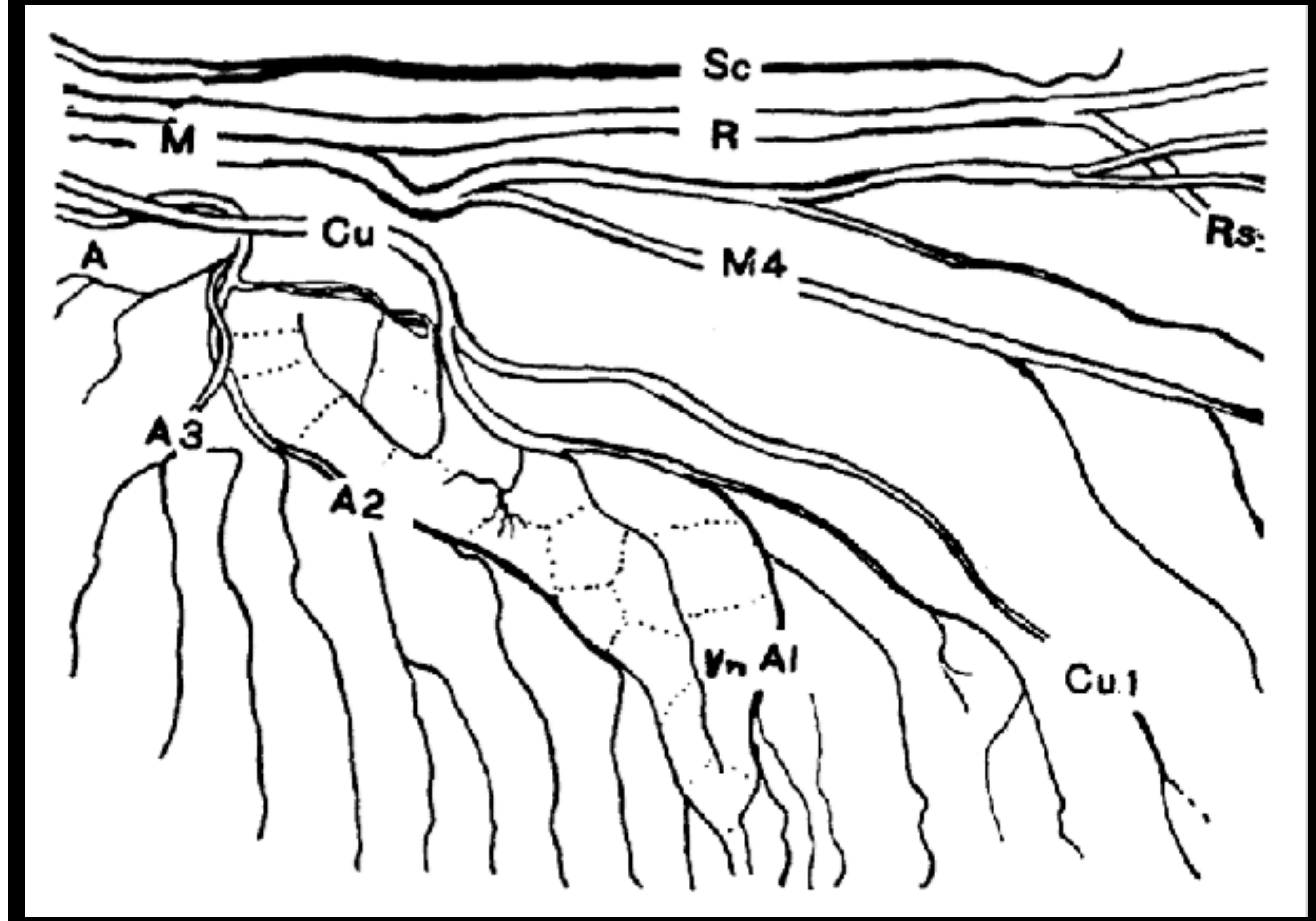
Reverse wing pad deformation



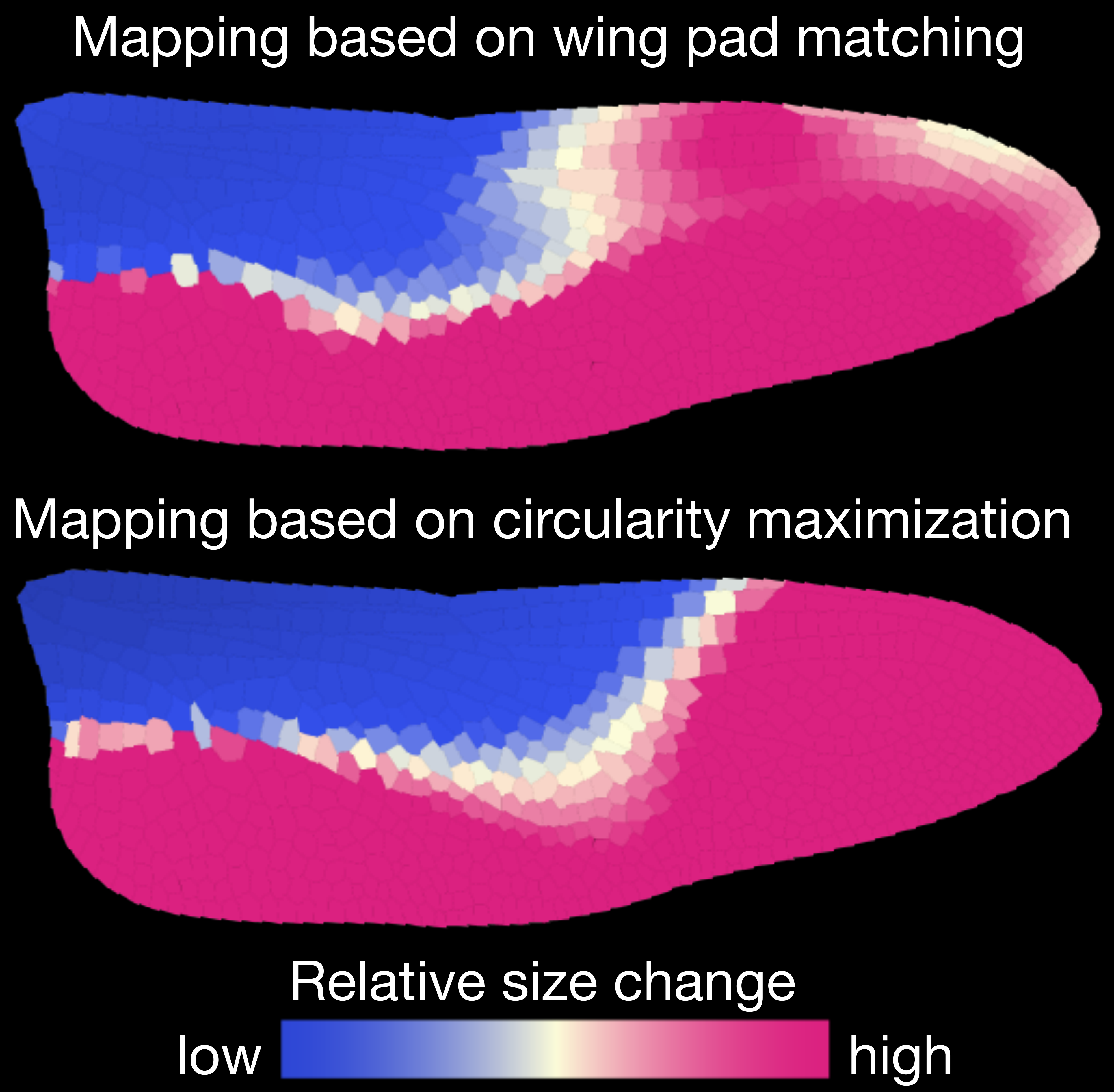
Cost: 0.729606



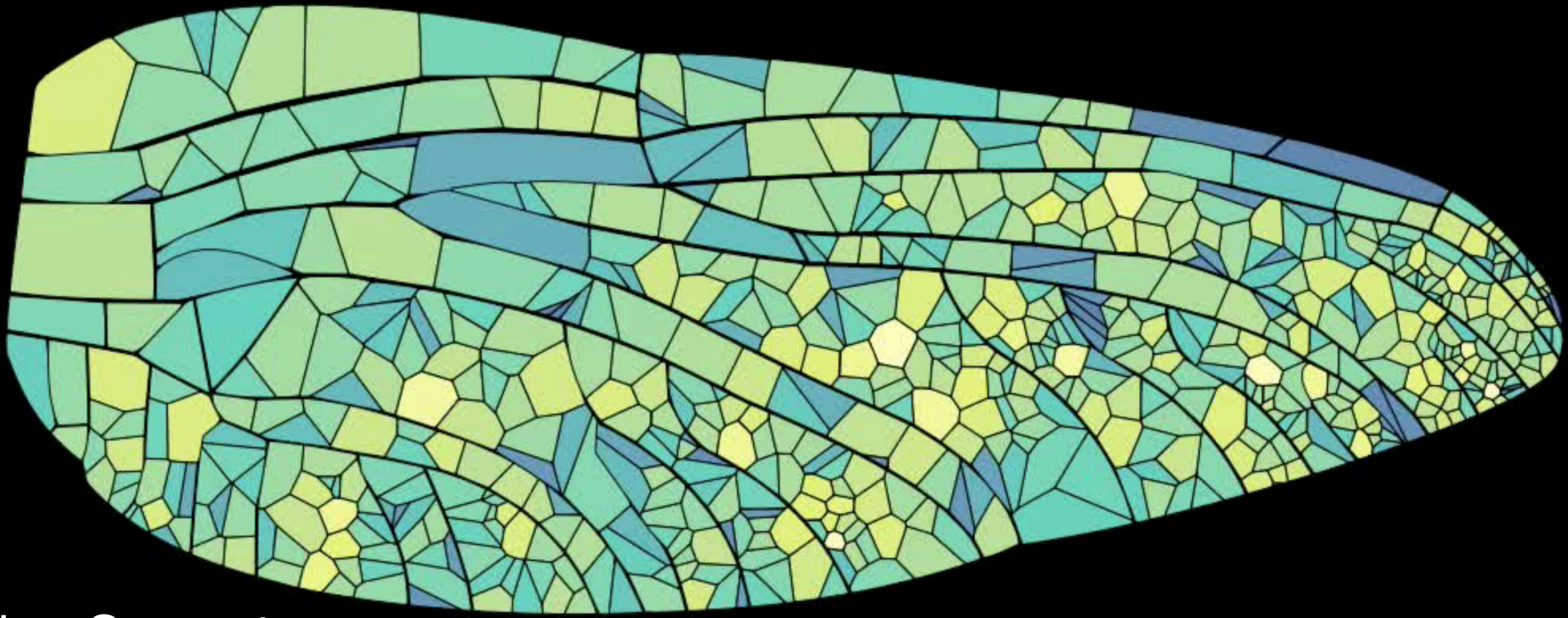




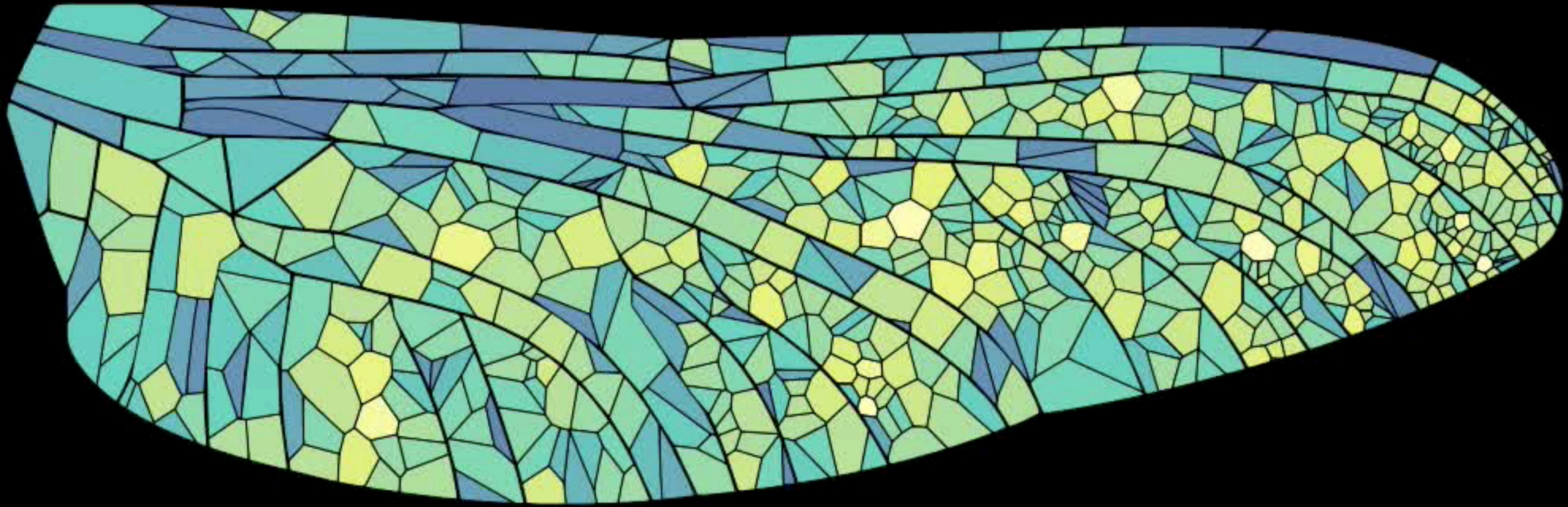
Needham 1951


Mapping based on wing pad matching
Mapping based on circularity maximization
Relative size change
low
high

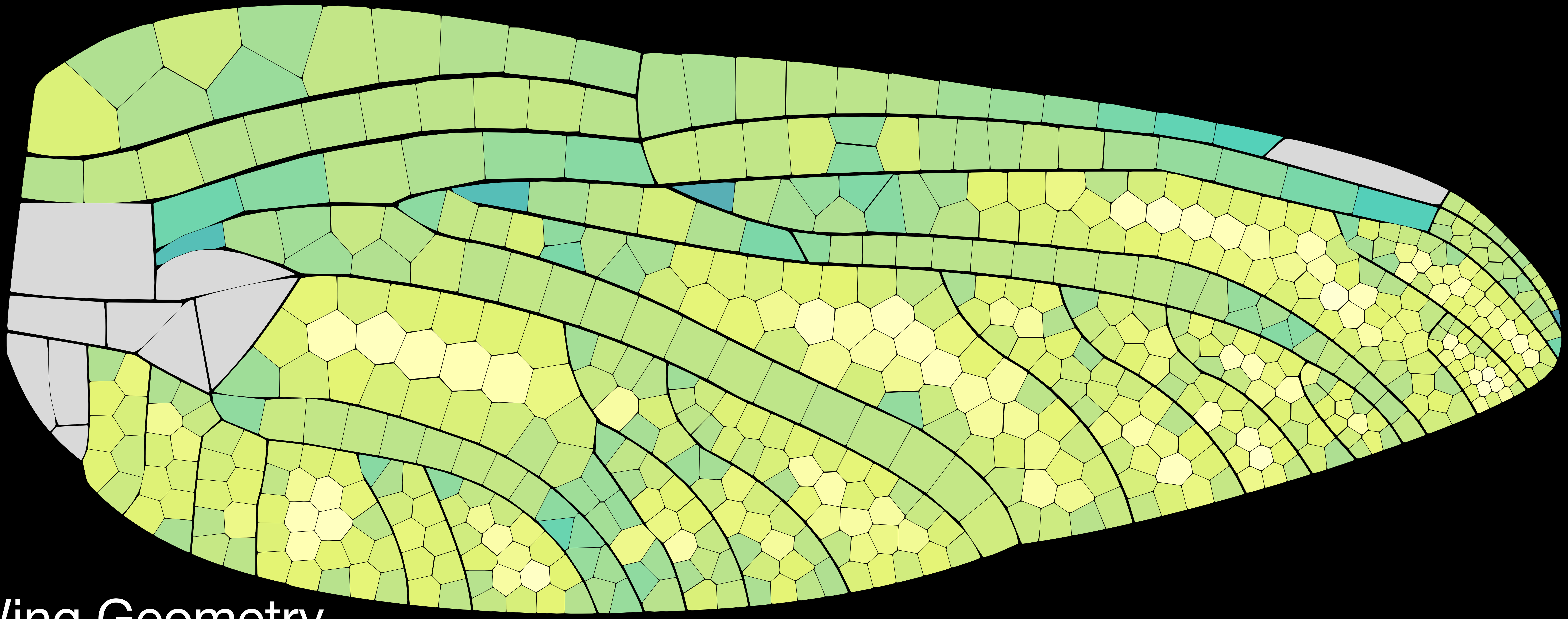
Wing Pad



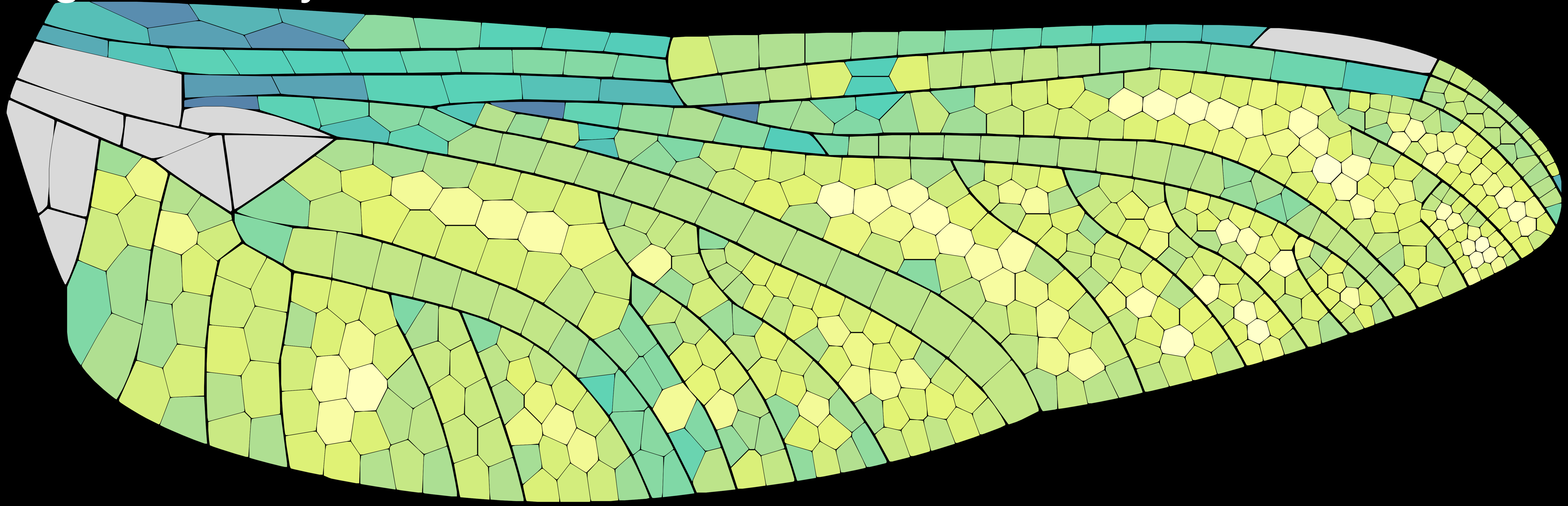
Observed Wing Geometry



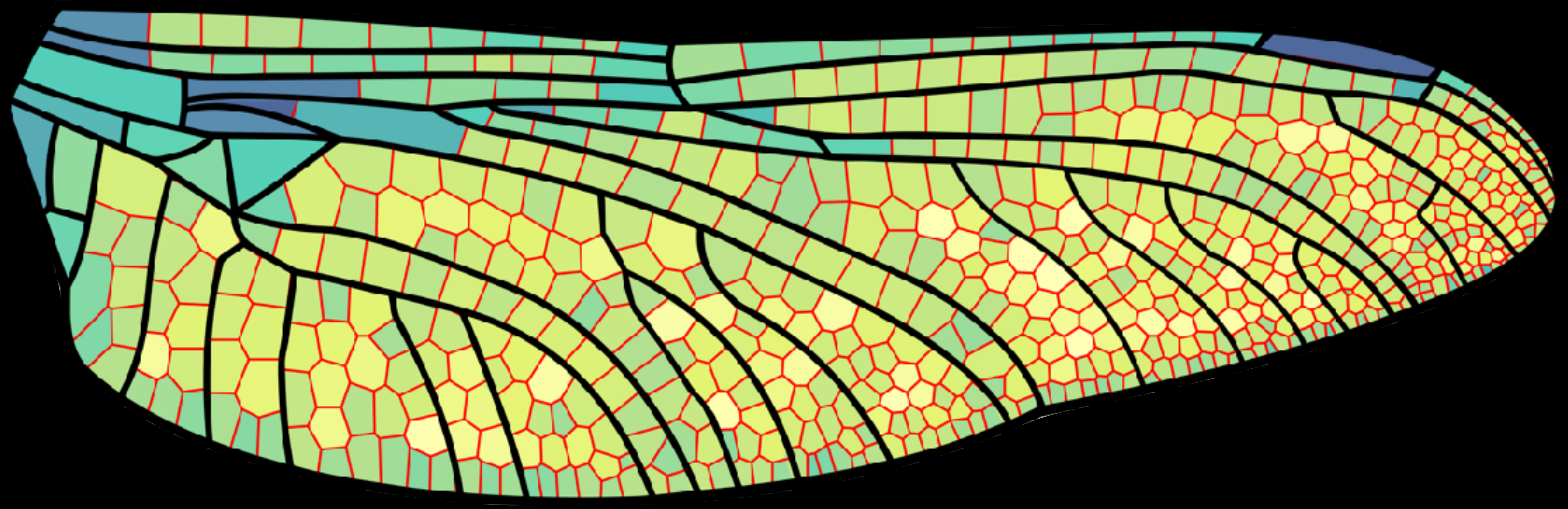
Wing Pad



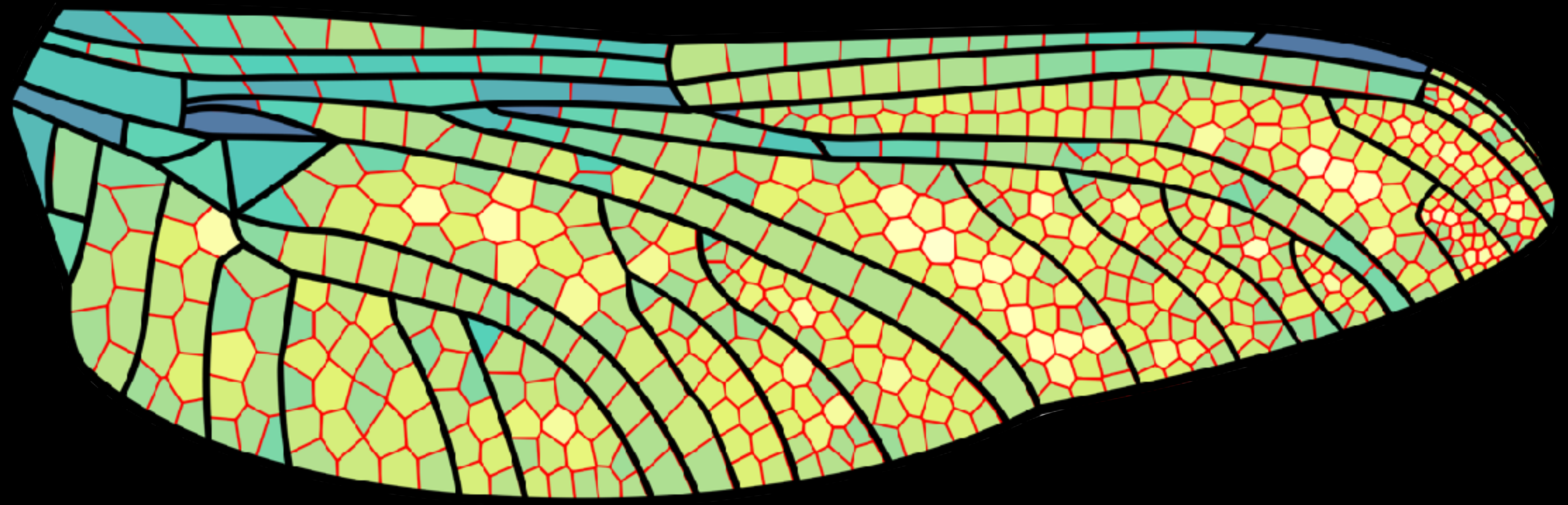
Observed Wing Geometry



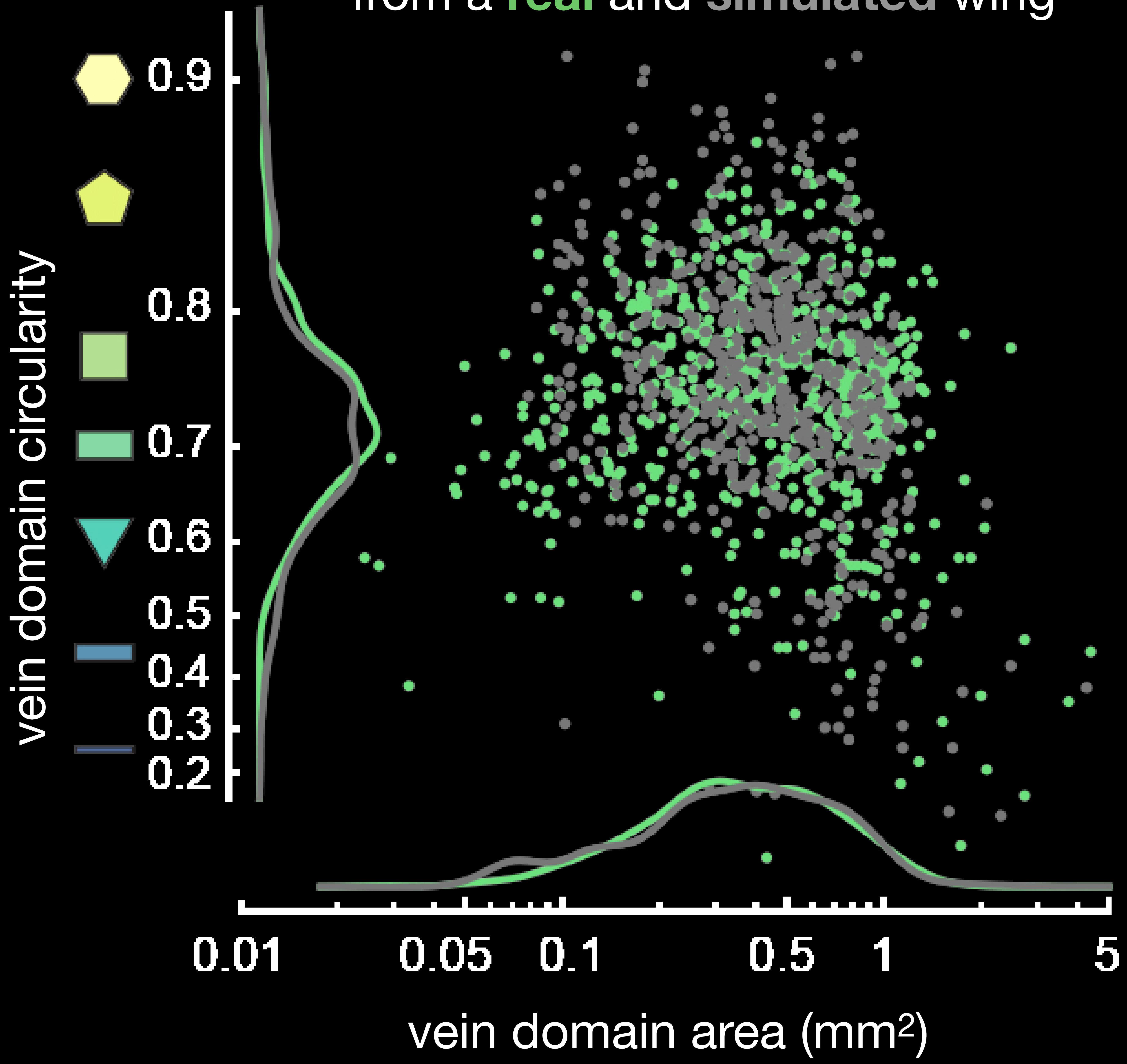
Real vein pattern



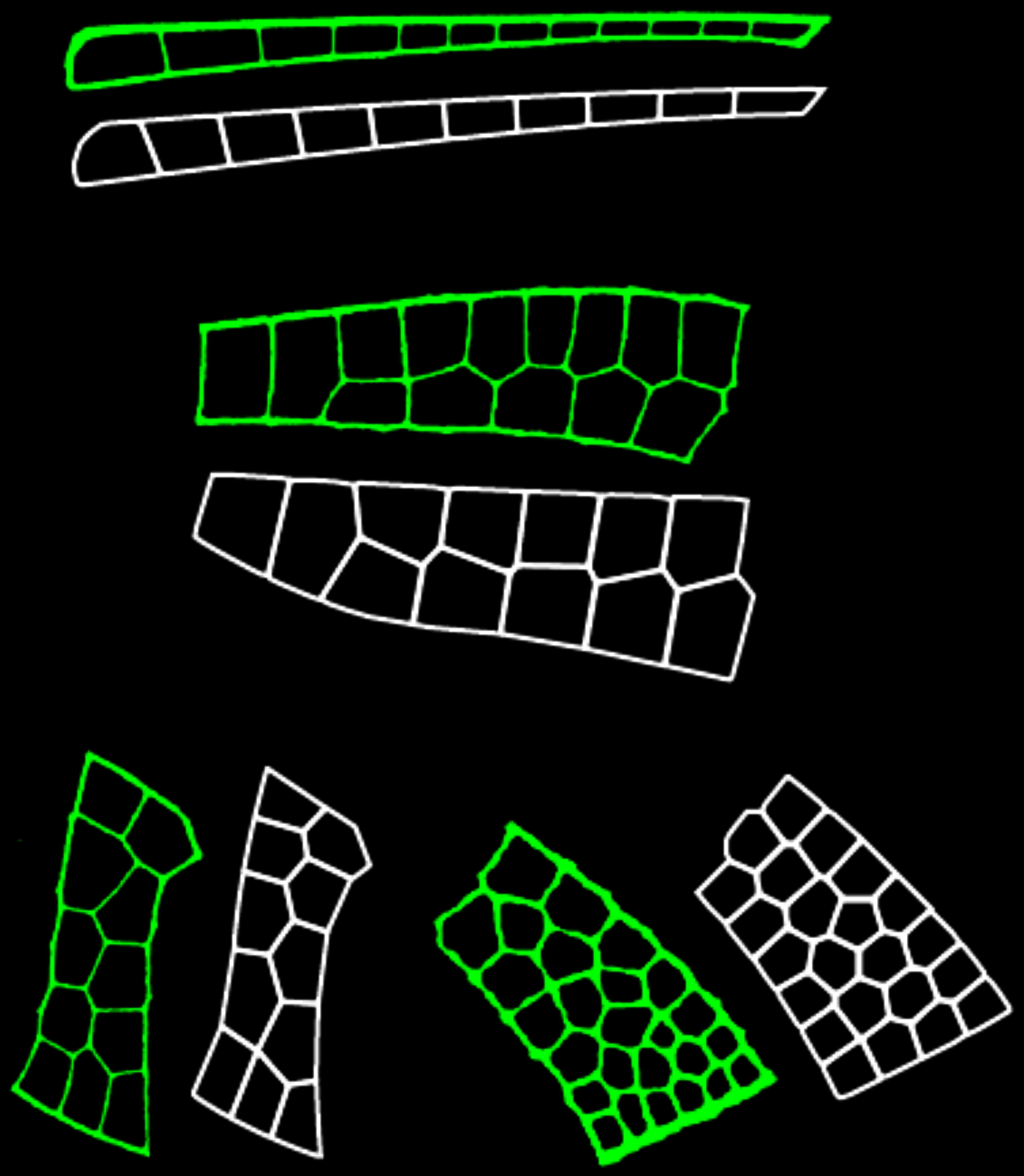
Simulated vein pattern



vein domain shape distributions from a **real** and **simulated** wing



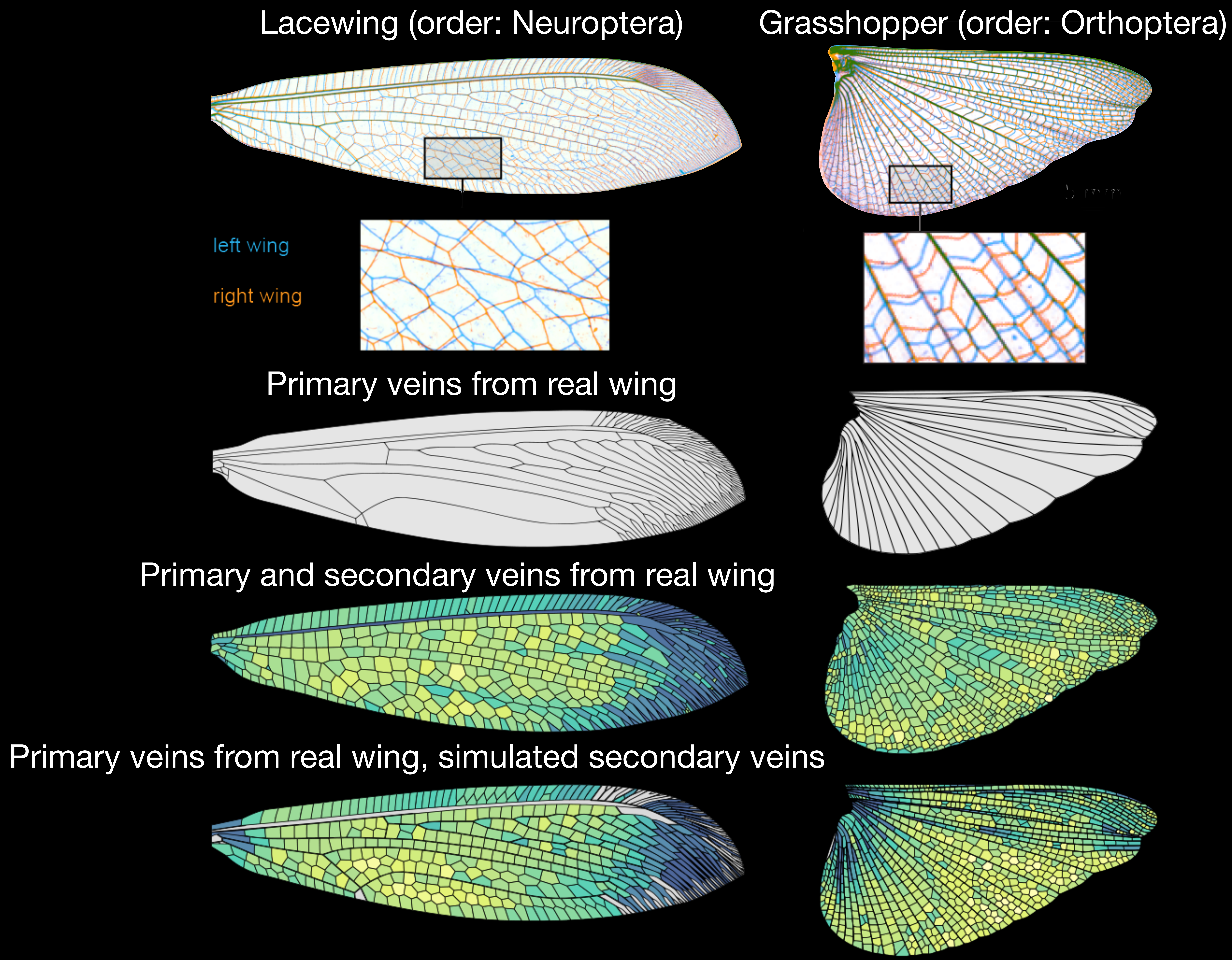

vein domain shape distributions
from a real and simulated wing
vein domain circularity
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.01
0.05
0.1
0.5
1
5
vein domain area (mm²)
P-D morphology traces
from a simulated and a
left right pair of real wings
vein domain circularity
0.85
0.80
0.75
0.70
0.65
0.60
distal
proximal
real
simulated
0.05
0.1
0.5
1
2
vein domain area (mm²)



Matched pairs

Real

Simulated


Lacewing (order: Neuroptera)
Grasshopper (order: Orthoptera)
left wing
right wing
Primary veins from real wing
Primary and secondary veins from real wing
Primary veins from real wing, simulated secondary veins

A simple developmental model recapitulates complex insect wing venation patterns **PNAS** Oct. 2018

Size, shape, and structure of insect wings **bioRxiv: 478768** Dec. 2018

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Thanks!