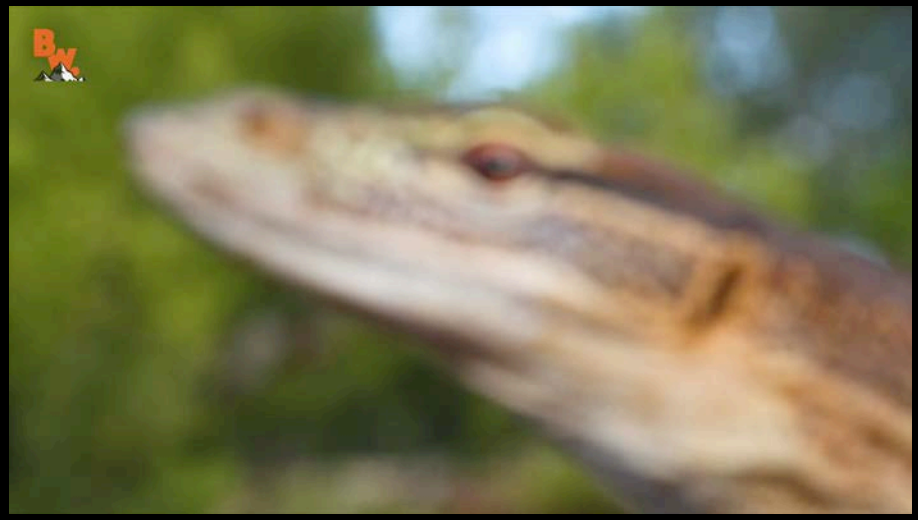
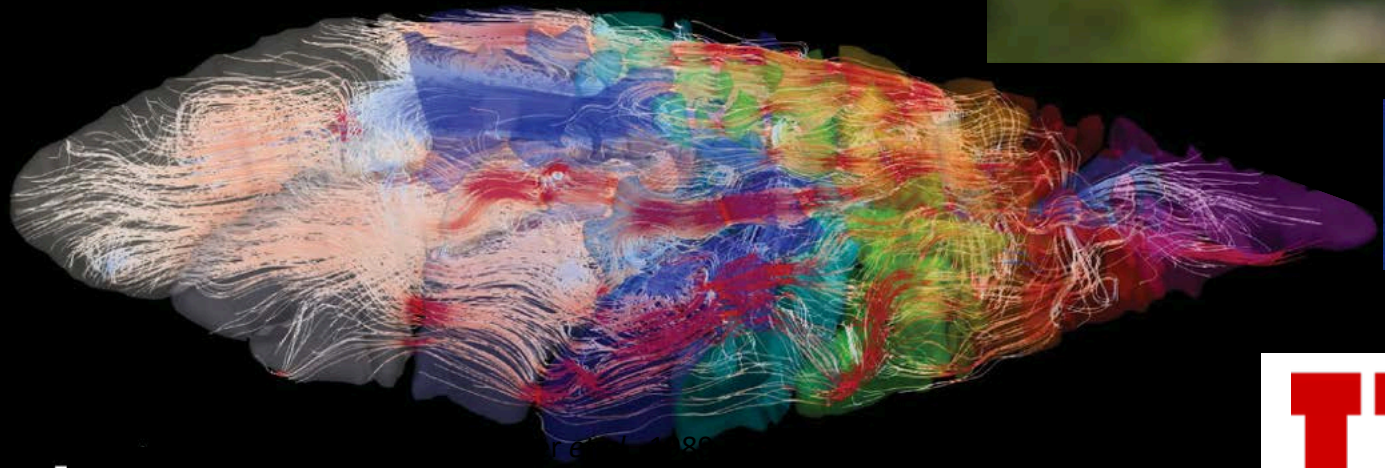
# Unidirectional Airflow in Monitor Lizard Lungs:

**High performance computational fluid dynamics (CFD) as a new tool for studying the evolution of structure and function of the vertebrate pulmonary system**





BLUE WATERS
SUSTAINED PETASCALE COMPUTING

**Symposium 2019**

THE UNIVERSITY OF UTAH®


**Robert L. Cieri**, CG Farmer

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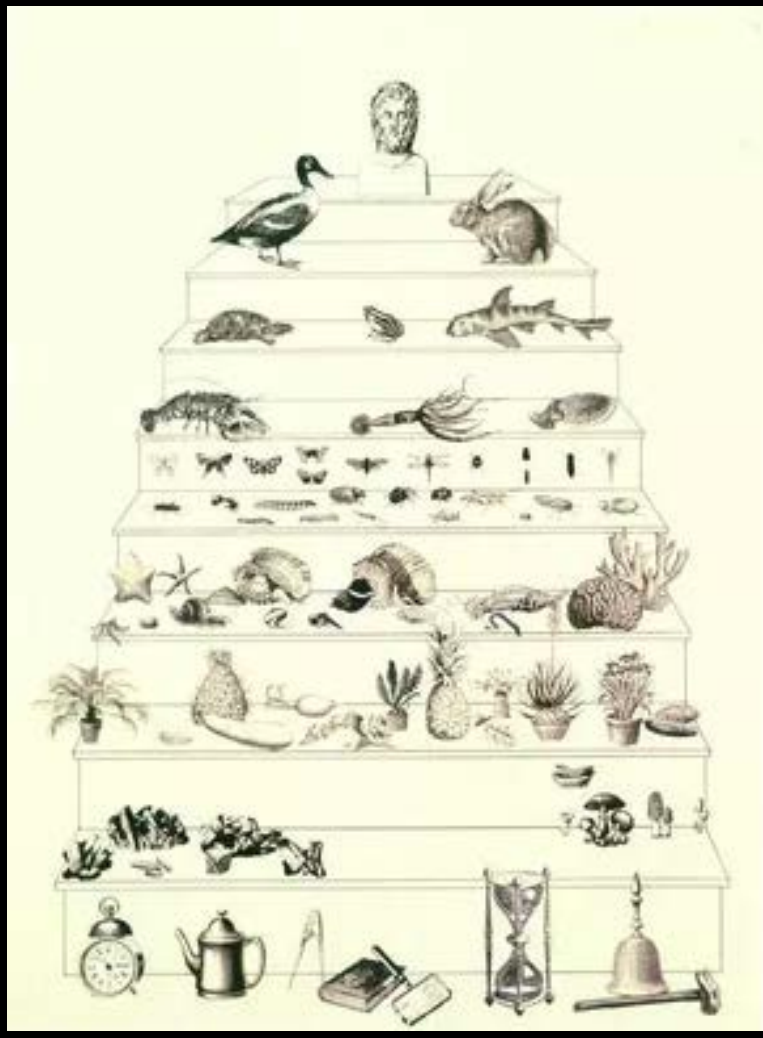
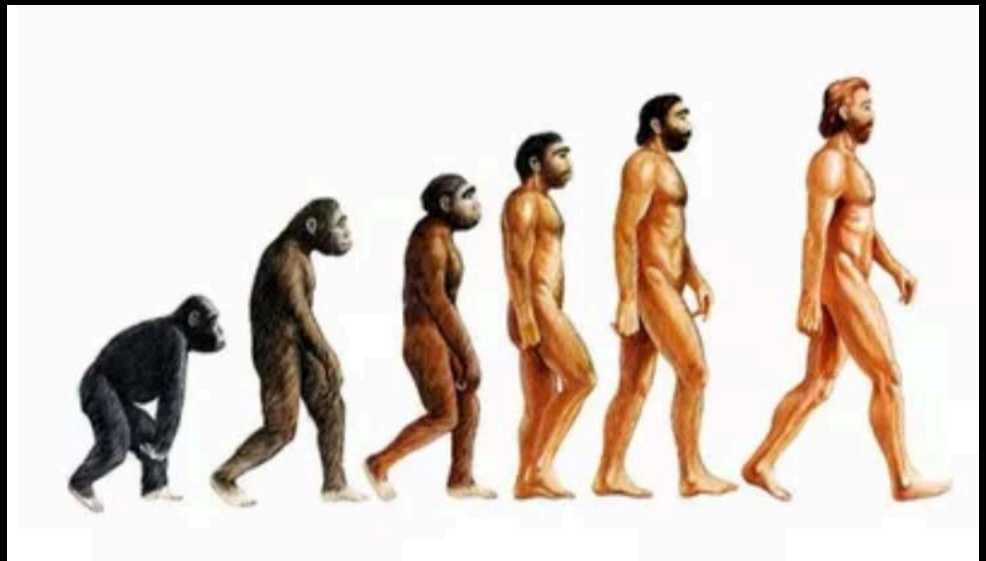
School of Biological Sciences
The University of Utah


FARMER LAB
ANATOMY, PHYSIOLOGY, EVODEVO & PALEONTOLOGY

# Evolutionary Organismal Biology:
# How do animals work and how do they evolve?

## Evolutionary Relationships





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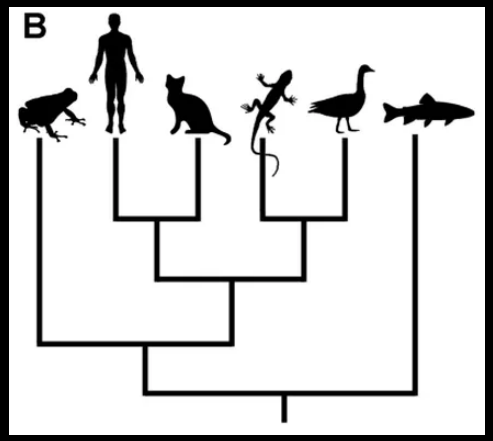
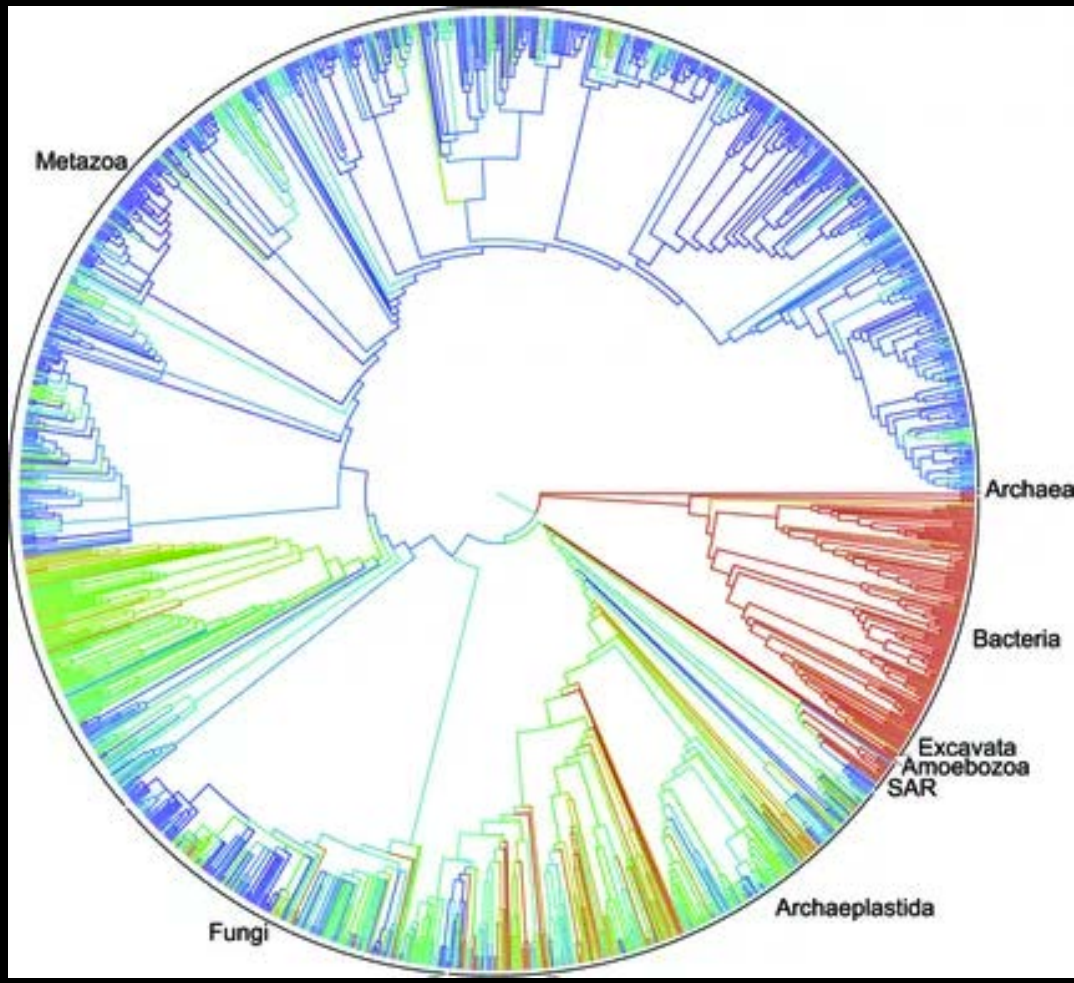
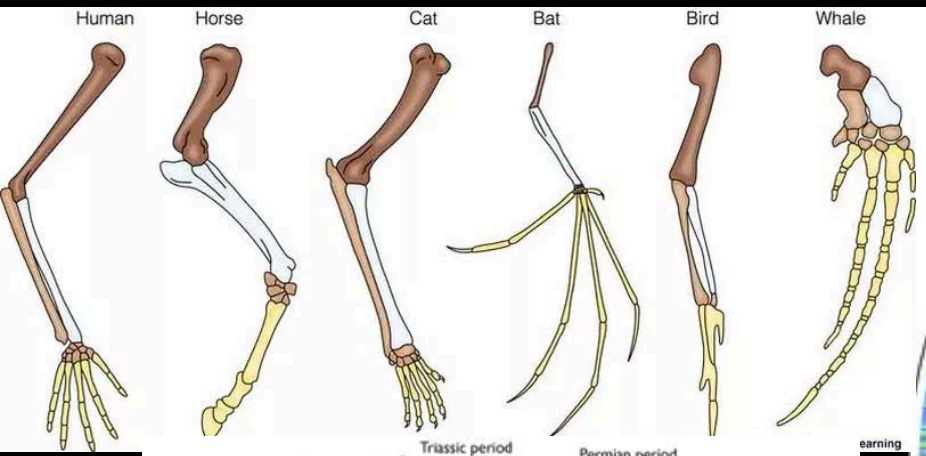


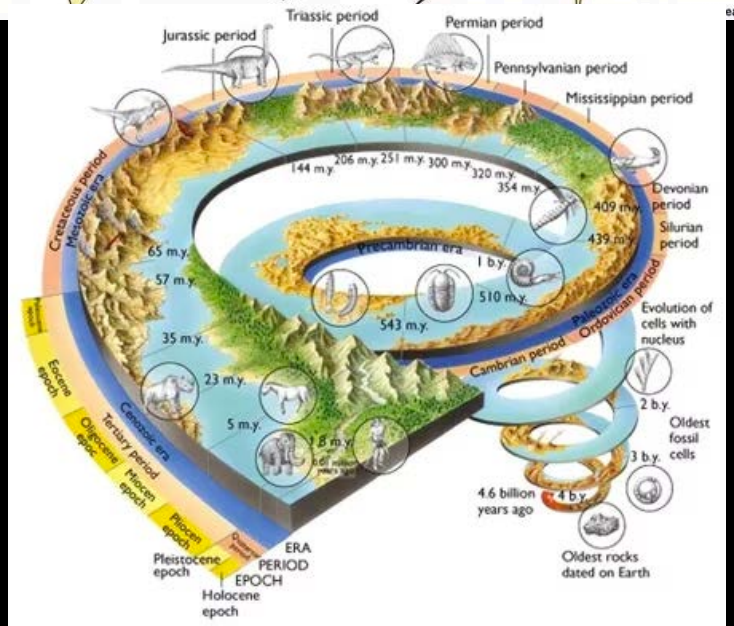



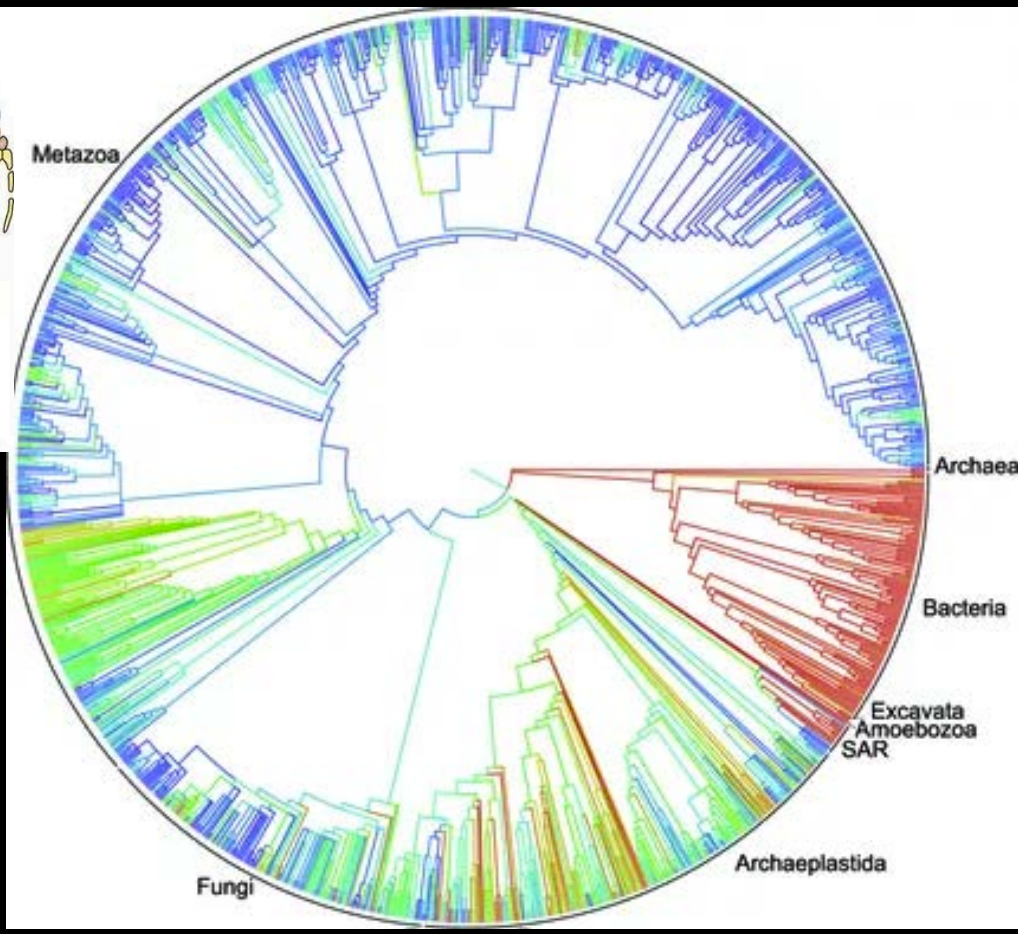

**What evolutionary stories lead to functional diversity?**

# Evolutionary Organismal Biology:
# How do animals work and how do they evolve?

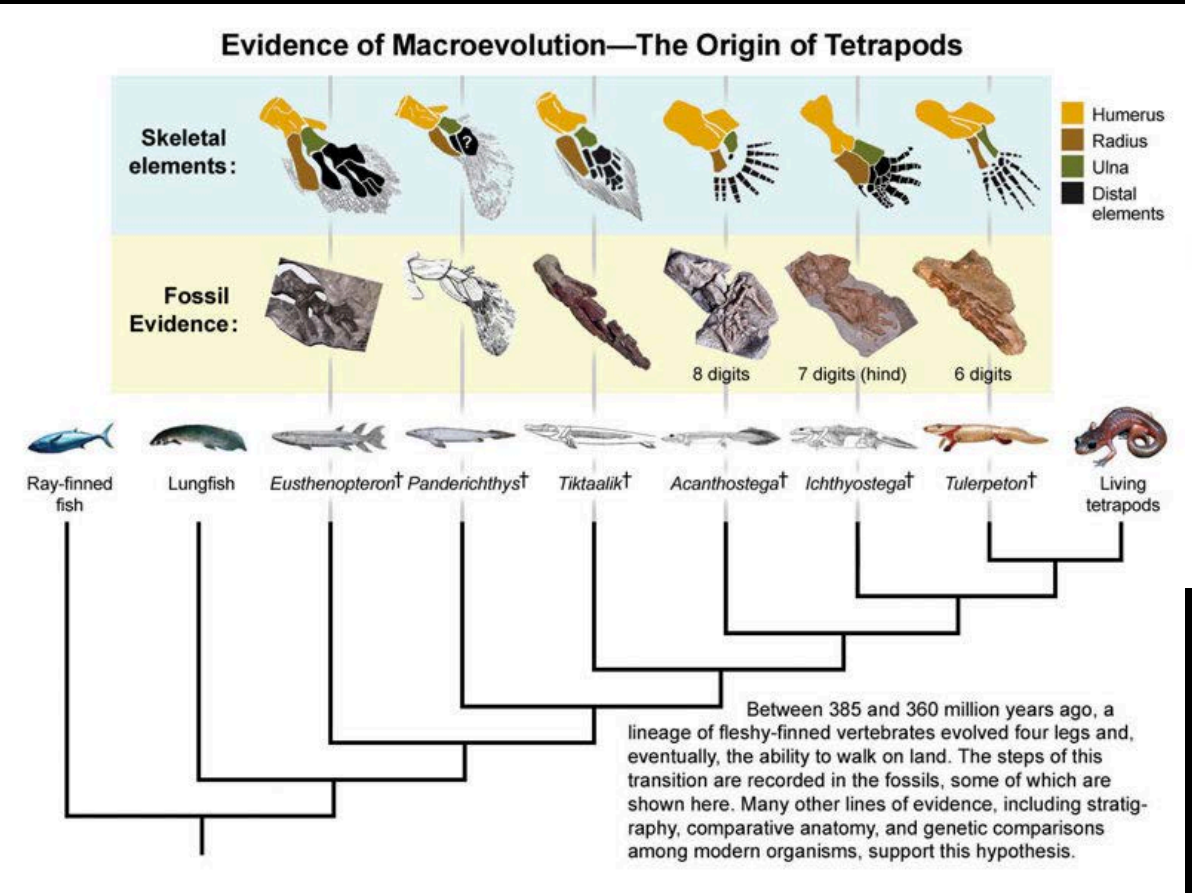
## Evolutionary Relationships

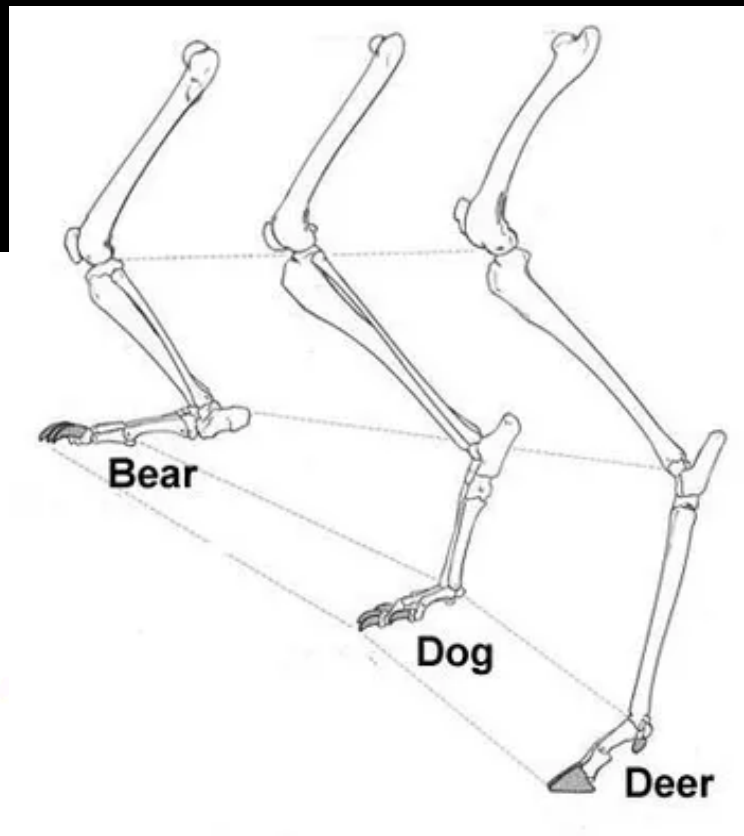


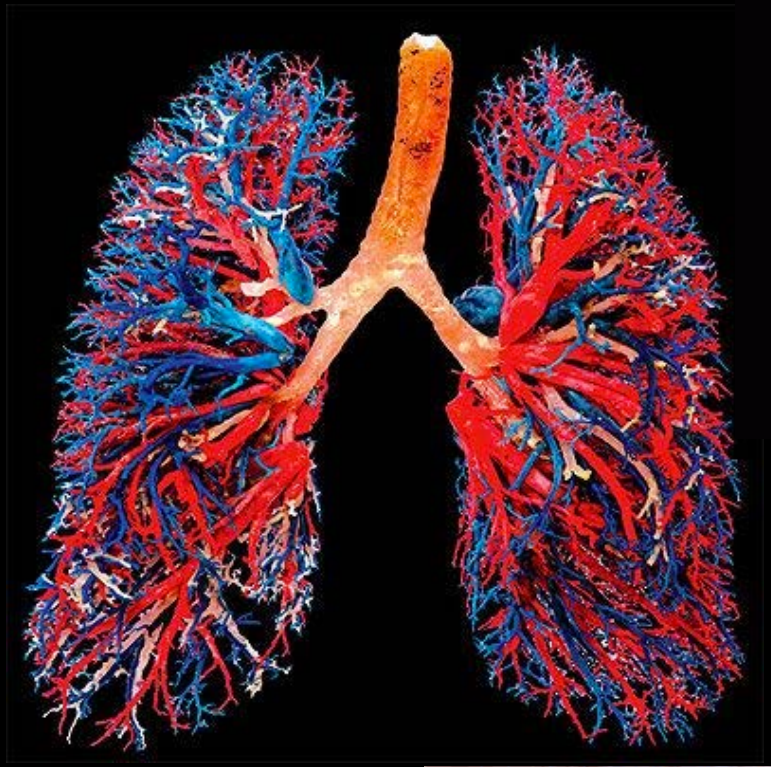



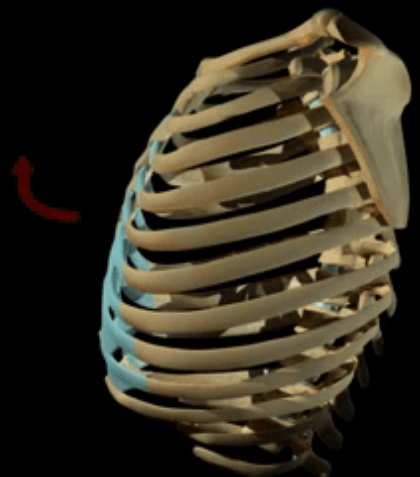
# Evolutionary physiology seeks to understand the function and evolutionary origin of natural structures

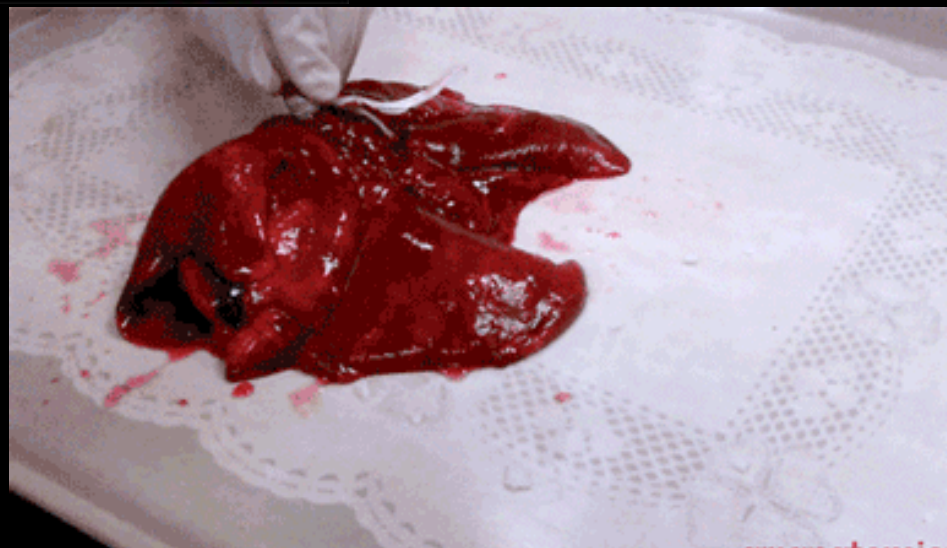


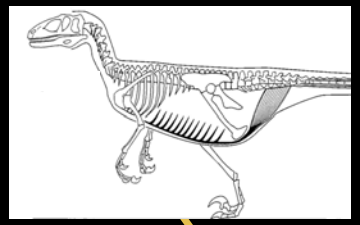



# We're using Blue Waters to apply the same approach to breathing

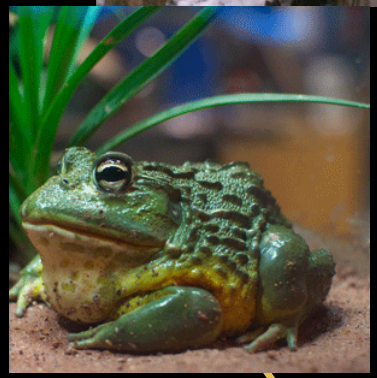




Birds



Crocodiles

Reptiles

Dinosaurs

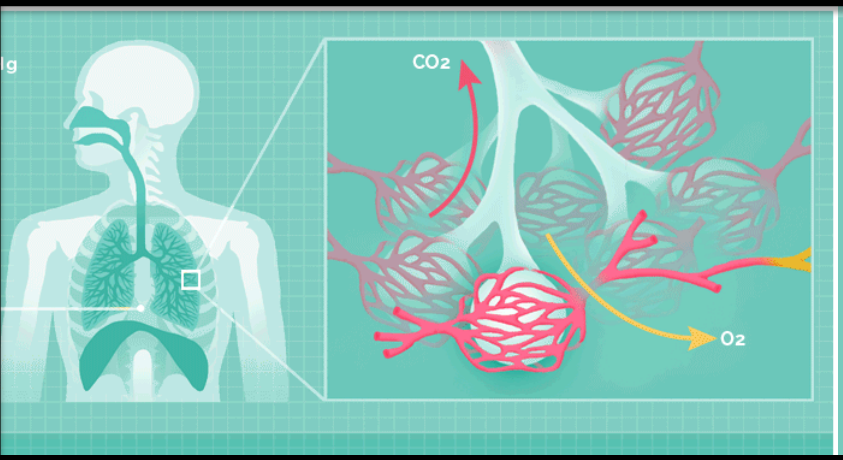
Mammals

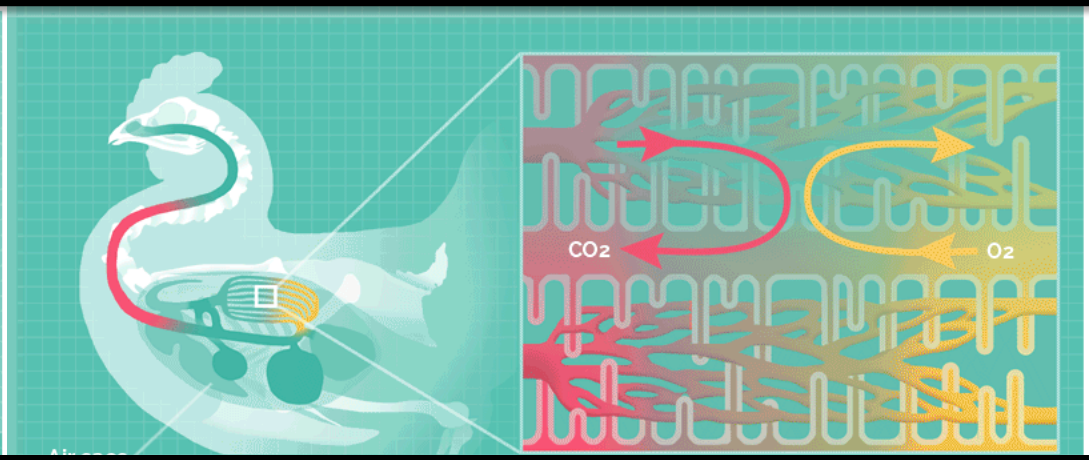

Amphibians

Fish

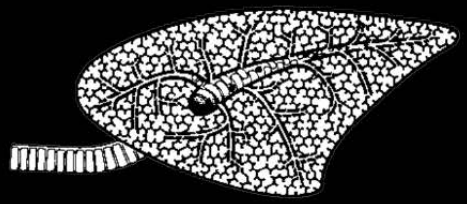
# Breathing isn’t so simple

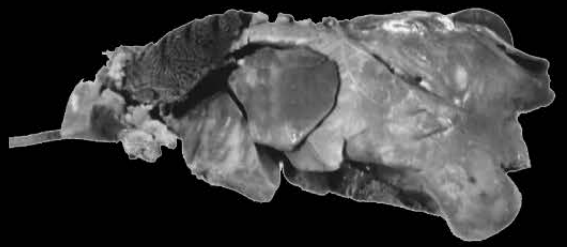
**Key Question:** Birds and mammals have quite different pulmonary systems. How do these different lungs work and how did they evolve?




Eleanor Lutz – Tabletop Whale





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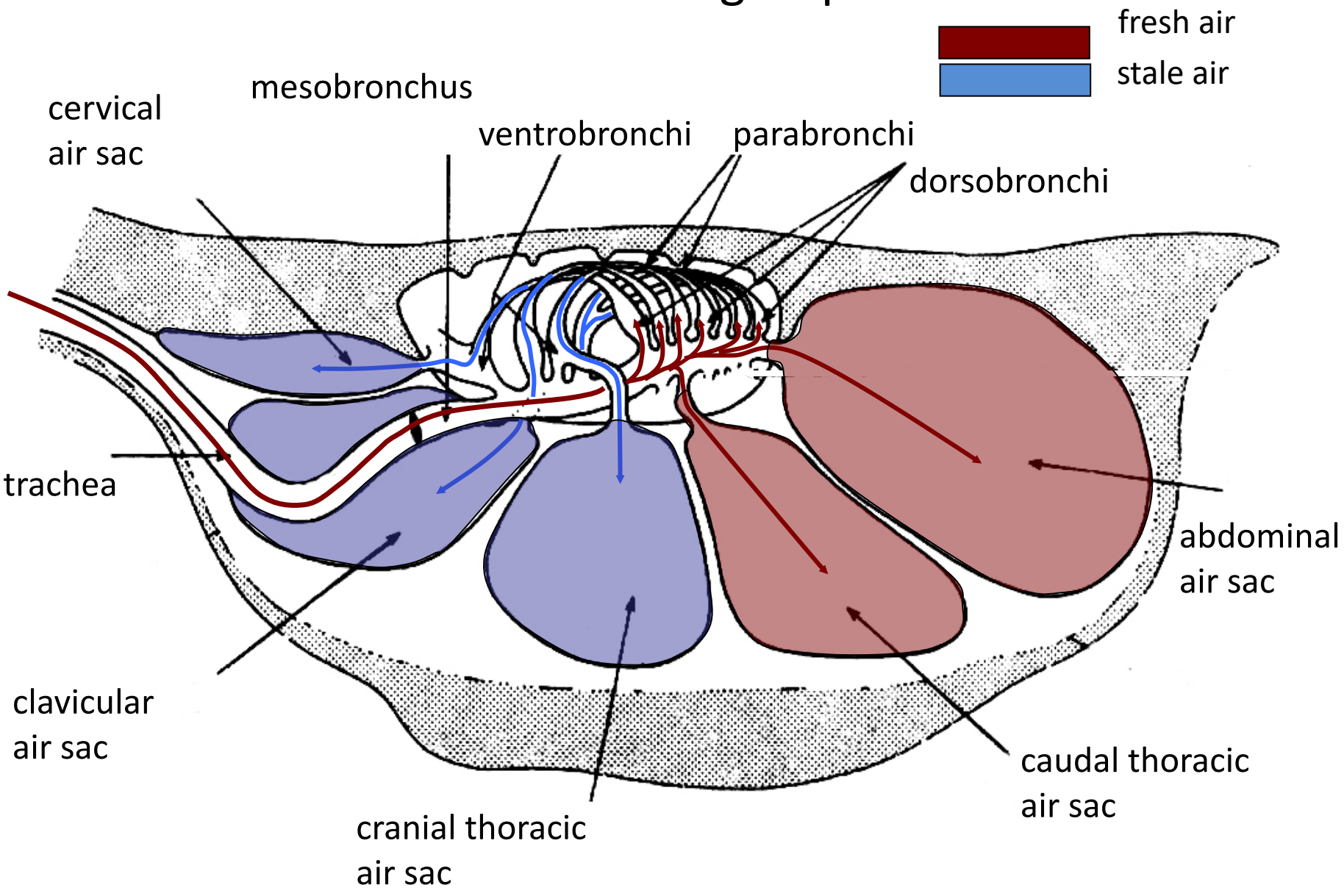
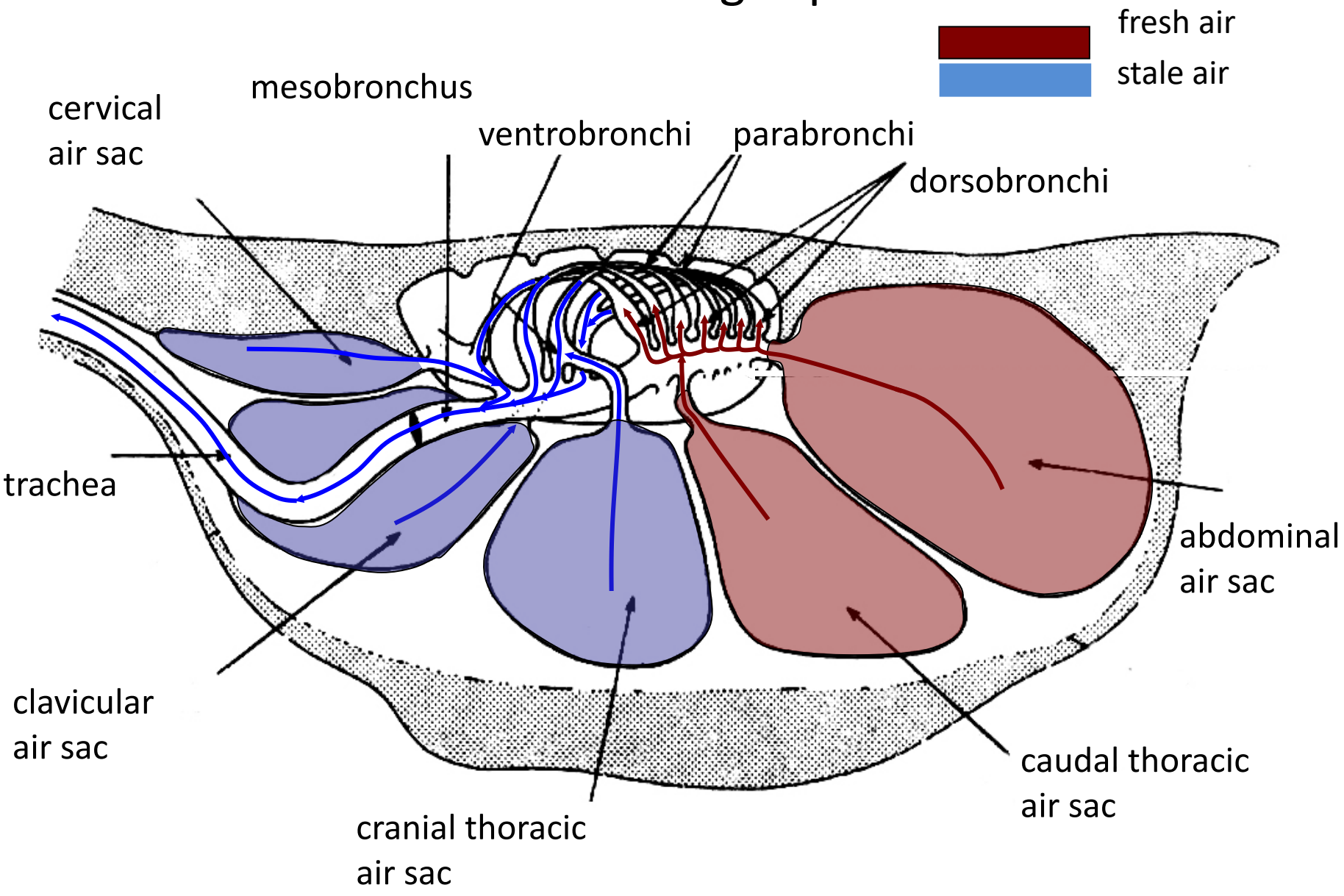
AVES

# Avian airflow during inspiration




Modified from Brackenbury 1987

# Avian airflow during expiration

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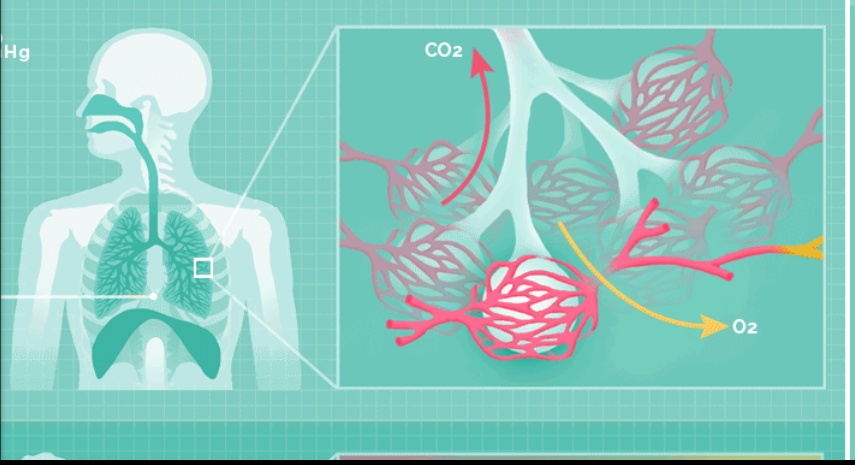


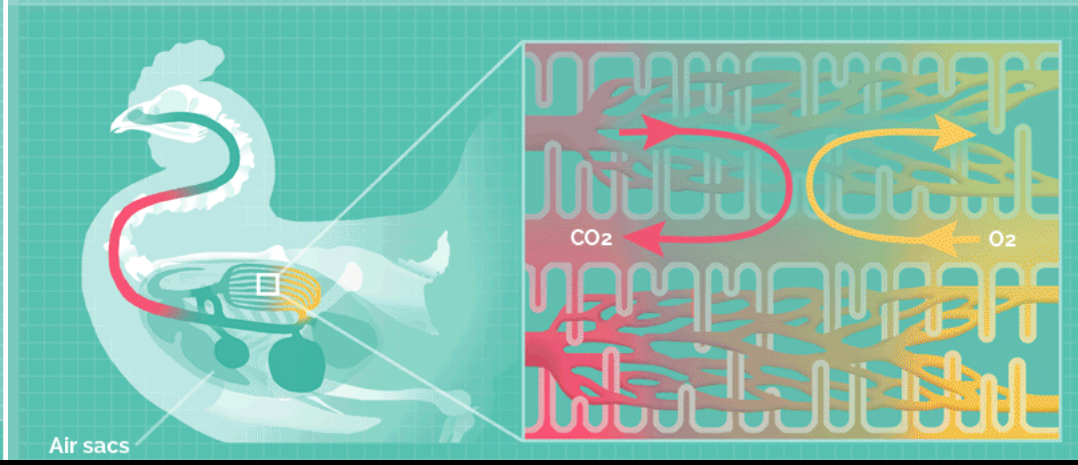


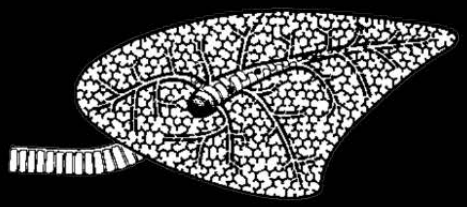

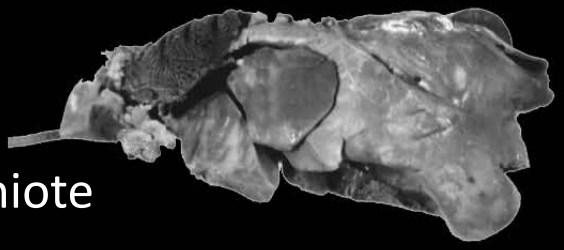

Some Extinct Permian Amniote
~360 mya

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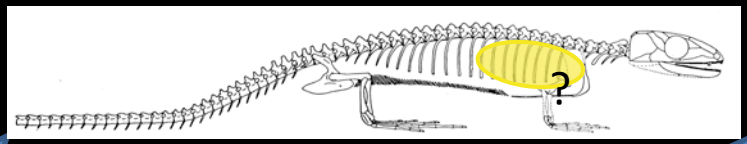


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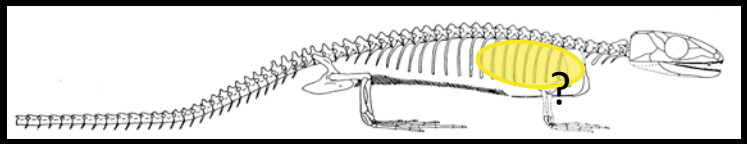
**Tidal airflow**
**Entire lung expands and contracts**
**Branching Tree Design**

**Unidirectional airflow**
**Air sacs expand and contract**
**Parallel Tube Design**

# Well, what about the reptiles?



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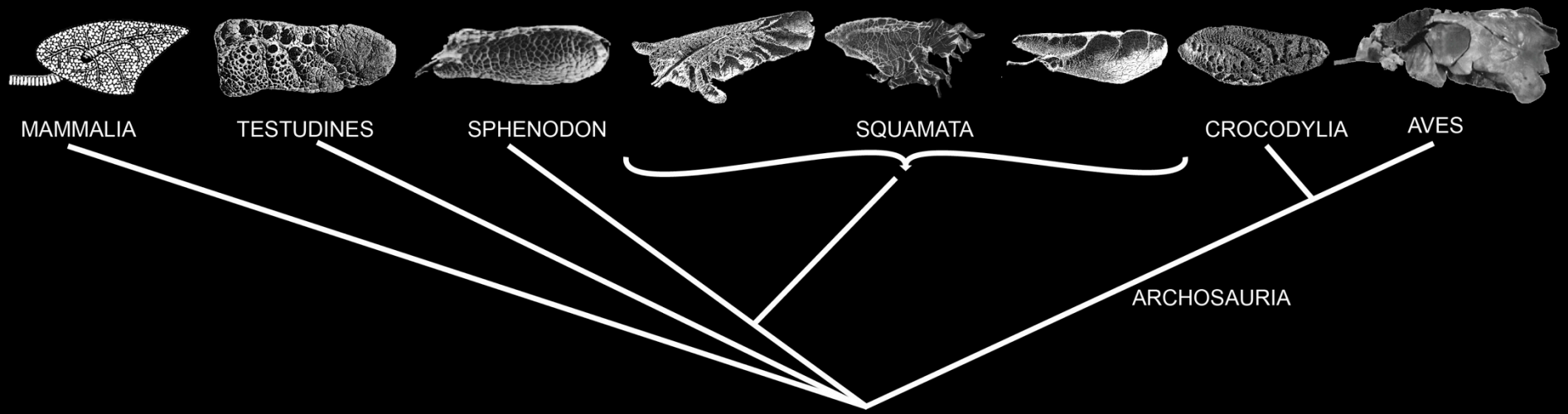
**Although reptile lungs come in many designs, they were assumed to have tidal airflow, like mammals.**



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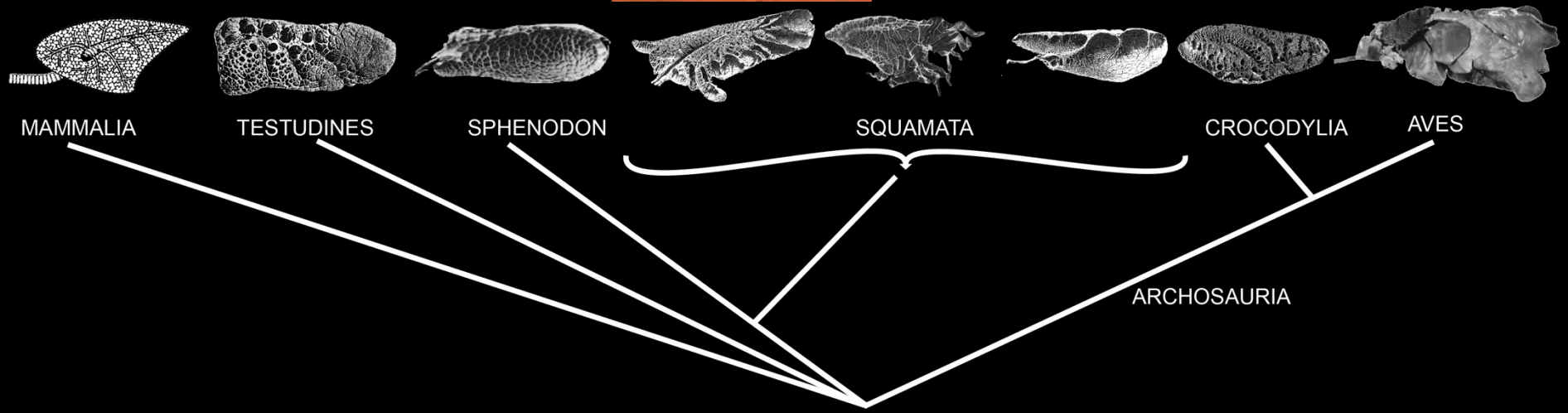


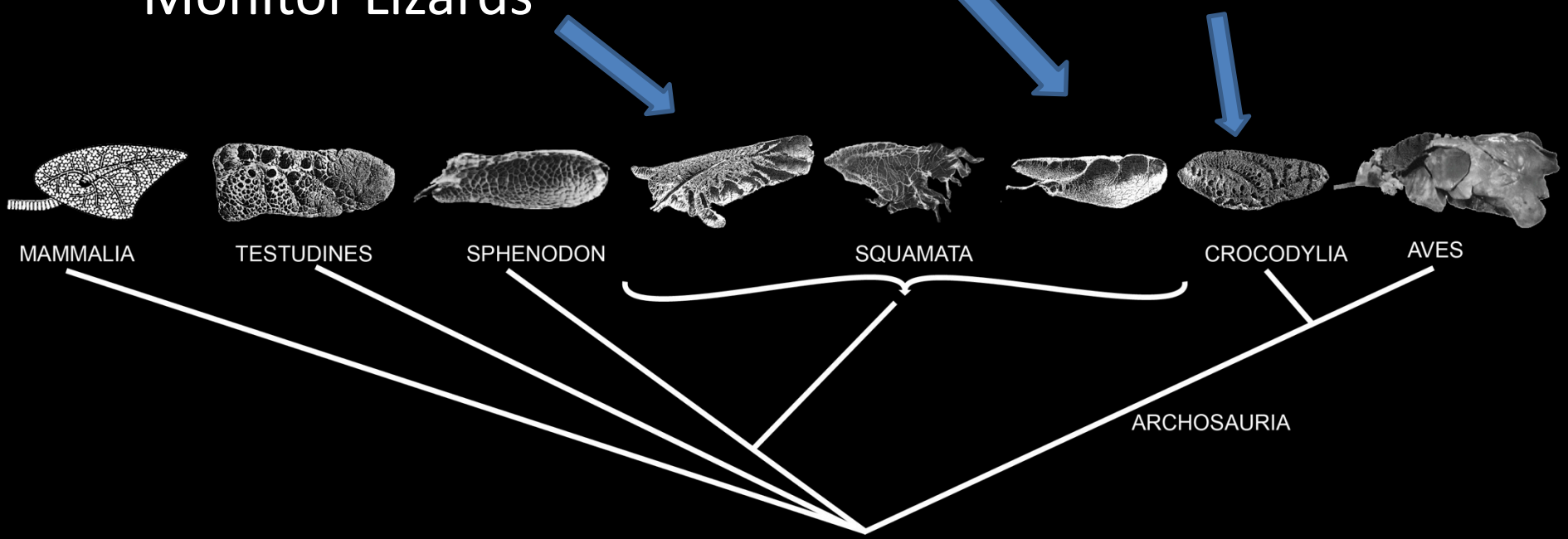
# Many of these lungs actually have unidirectional flow

## Reptile lungs deserve a much closer look

Monitor Lizards

Iguanas

Crocodilians



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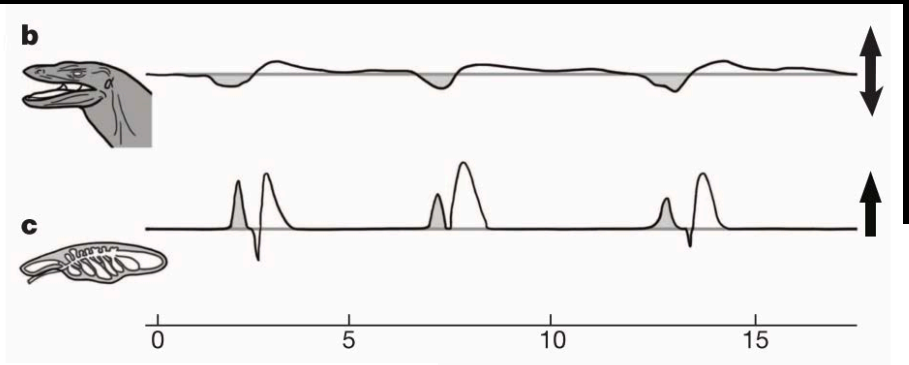


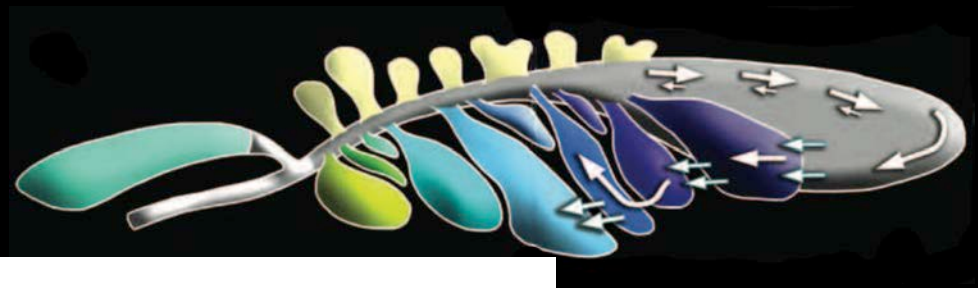

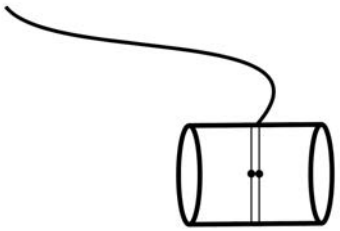

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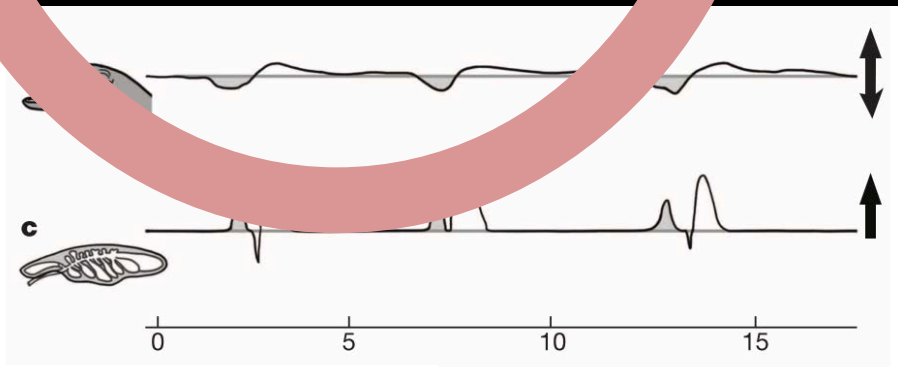
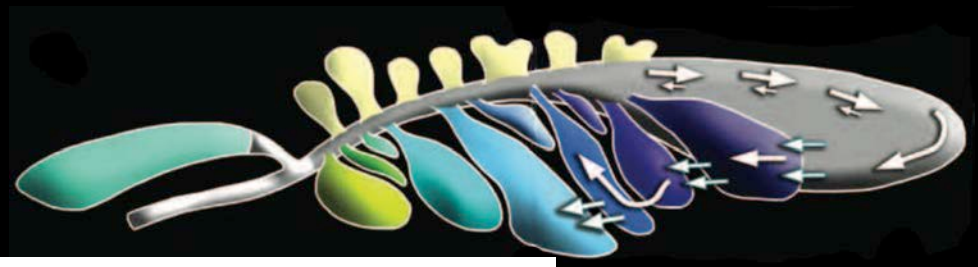
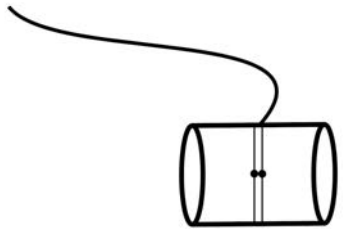
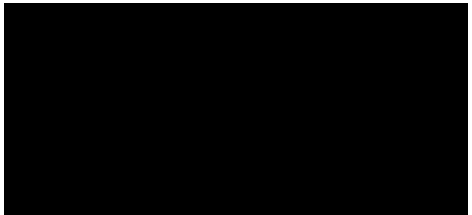
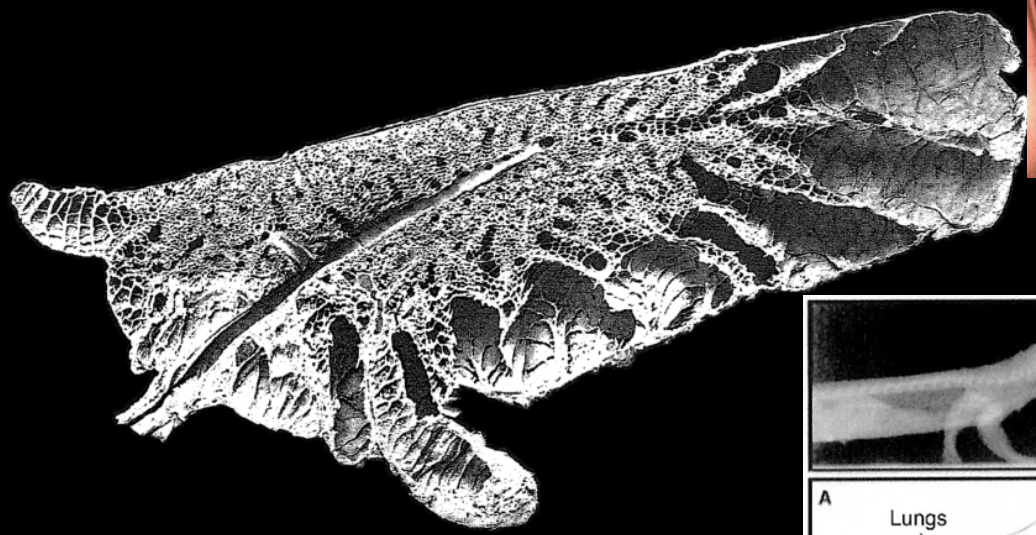


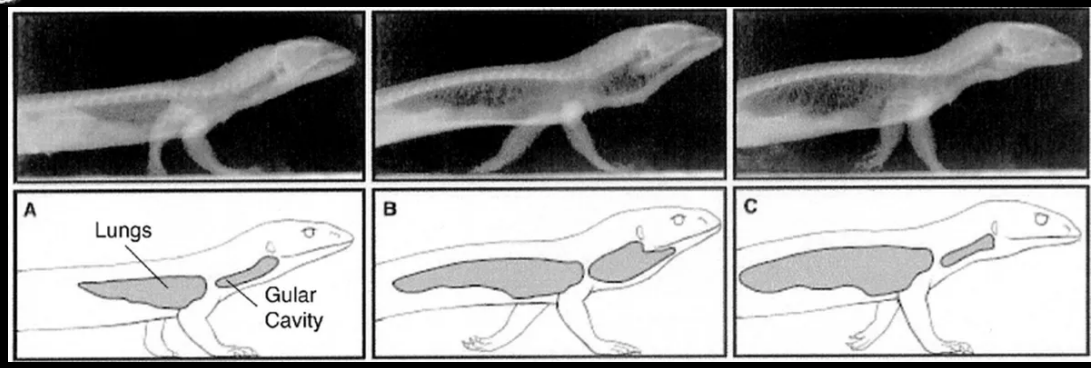





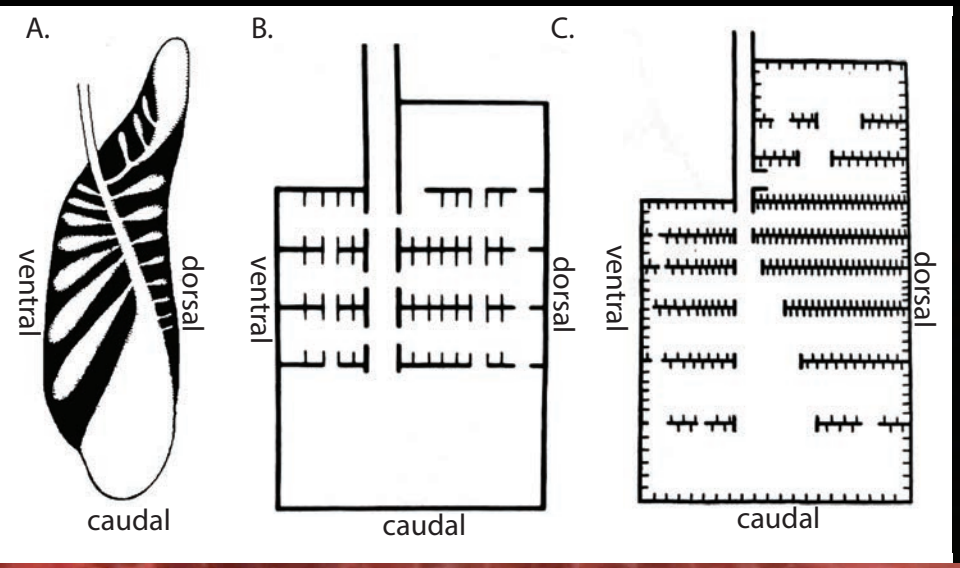


# Monitor lizards are athletes with complex lungs

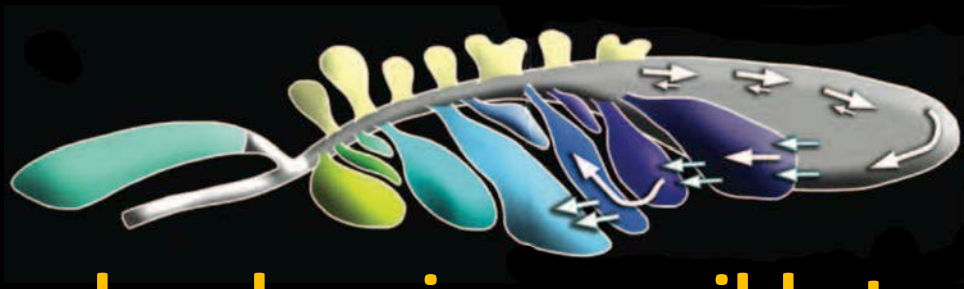





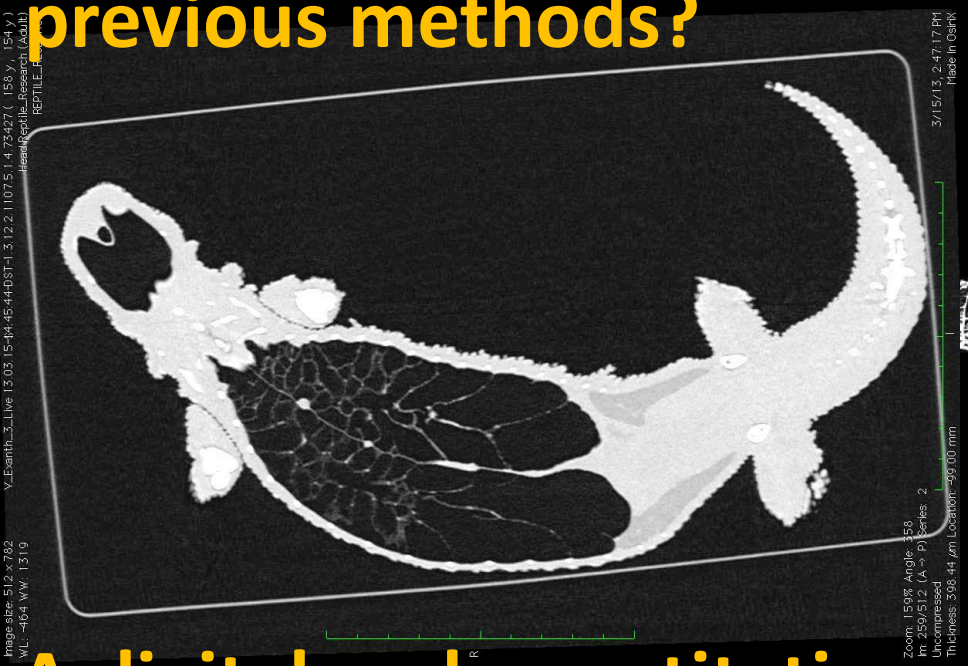
# Monitor lizard lungs have intercameral perforations

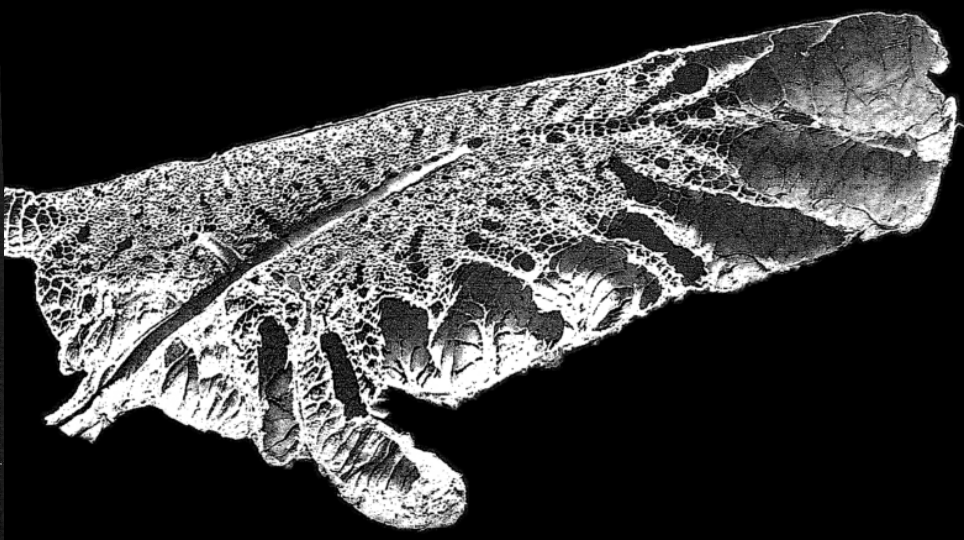


We have gained a superficial understanding that some unidirectional flow occurs...

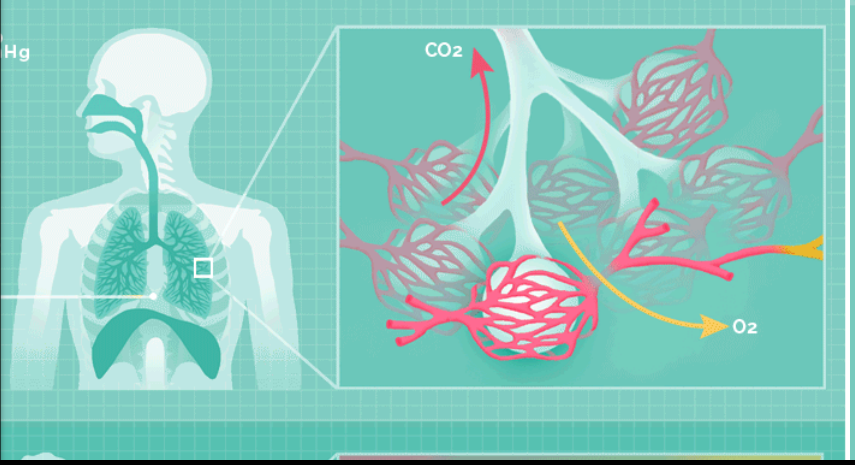


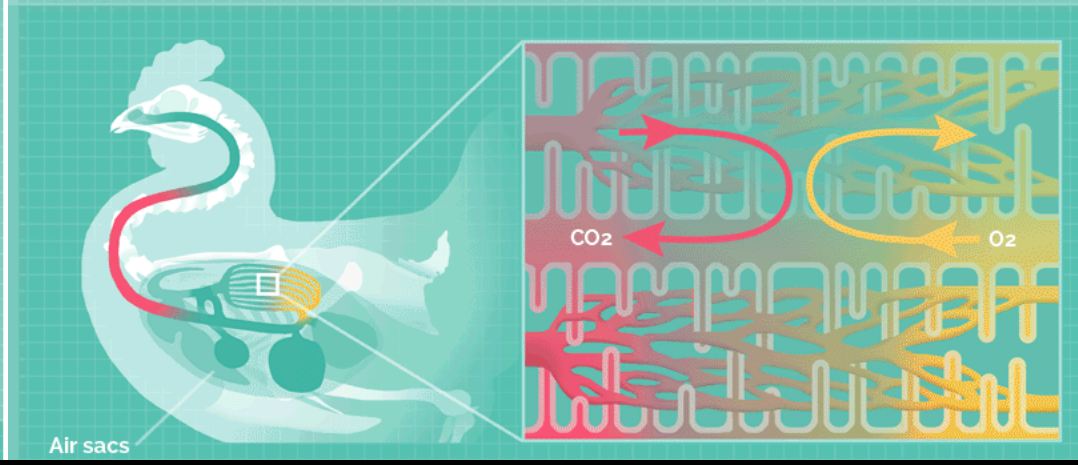
But what about the smaller chambers inaccessible to previous methods?

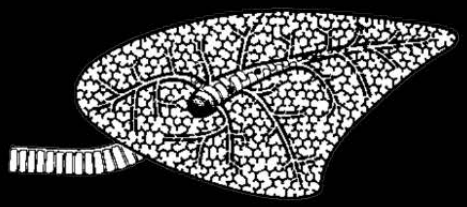


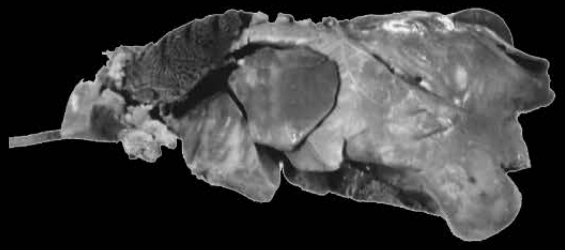


A digital and quantitative approach using computed tomography and CFD modelling is required



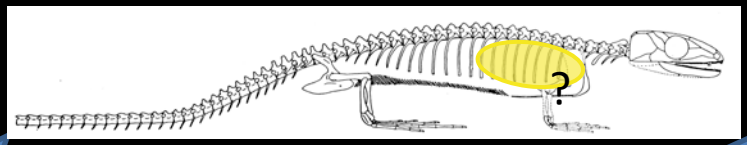





*ARCHAEOTHYRIS* 306 MYA

MAMMALIA

AVES

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**Tidal airflow**
**Entire lung expands and contracts**
**Branching Tree Design**

**Unidirectional airflow**
**Air sacs expand and contract**
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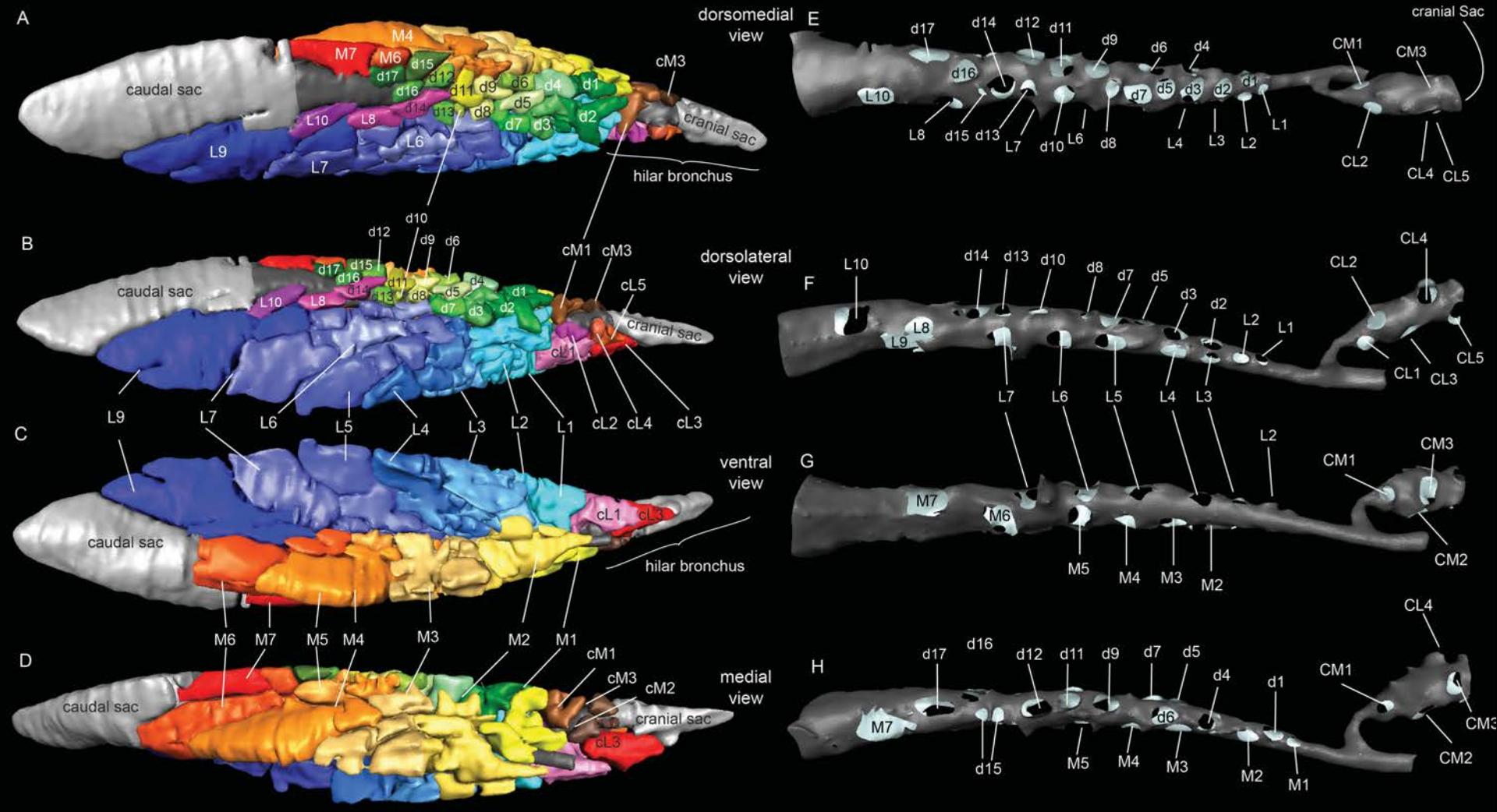
# Studying the anatomy digitally through CT Scans

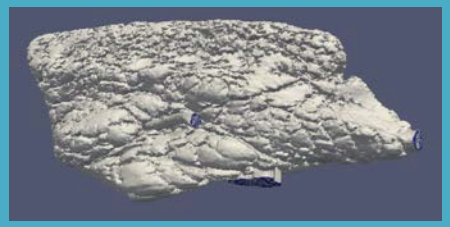



Intrapulmonary bronchus surrounded by secondary bronchi

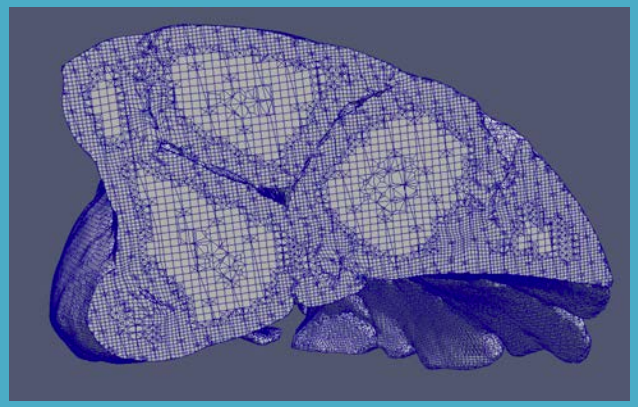
# Computational Fluid Dynamics (CFD) Modeling Pipeline

**Segmentation**

**3D surface model**



**High-fidelity computational hexahedral mesh**




**CT scan**

**Compute iterative solution to discretized NS Equations**

**Visualization and Analysis of pulmonary air flow pattern**

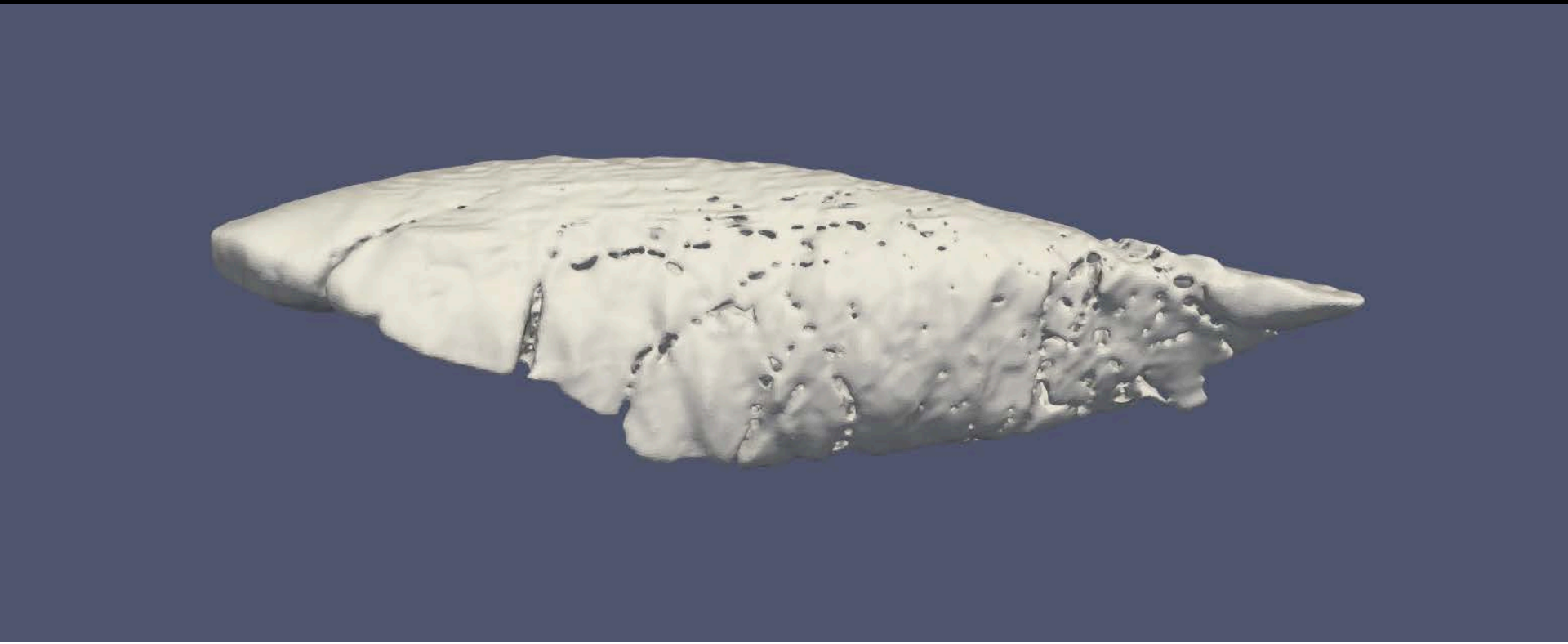
# Blue Waters Makes it Possible!! Model specifics

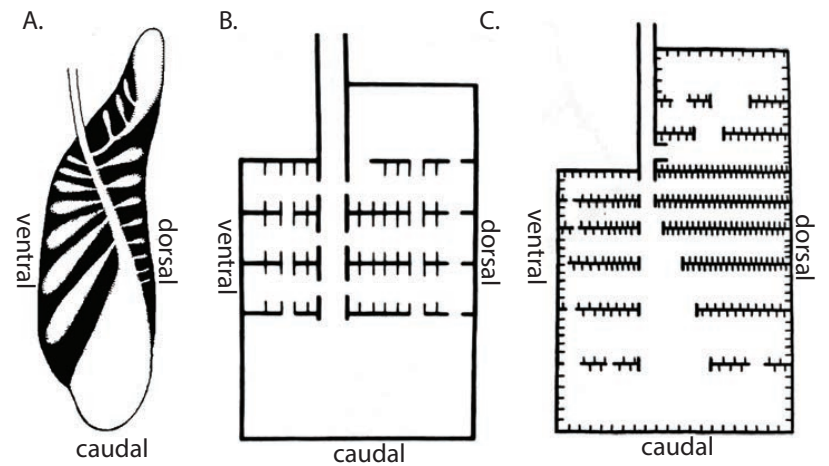
**Software –** OpenFOAM Library
**Meshing – snappyHexMesh**
**Solver –** dynamic PIMPLE algorithm
transientSimpleDyMFoam
No slip wall conditions

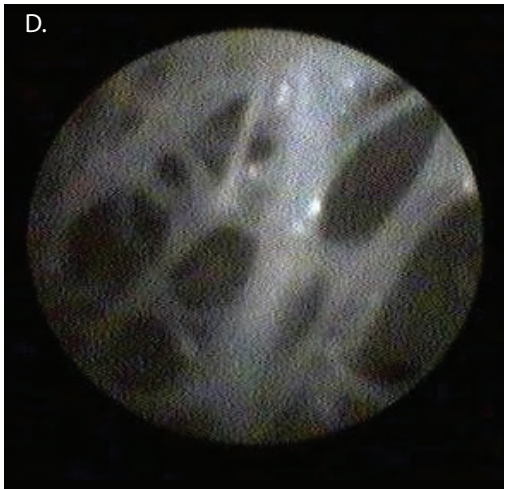
**Blue Waters System**
1.2 million mesh elements
256 processors
~ 240 hours per simulation
35,000 node hours remaining
deltaT 0.0001 seconds
Allows me to make changes and mistakes!
15 different configurations so far

Visualization assistance from
Mark Van Moer

# Pulsating “skin” and inner skeletal architecture



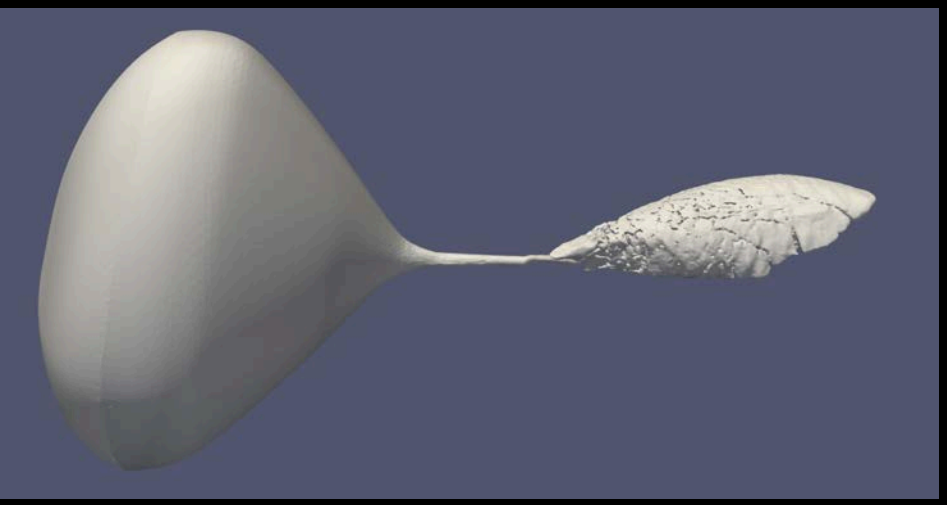


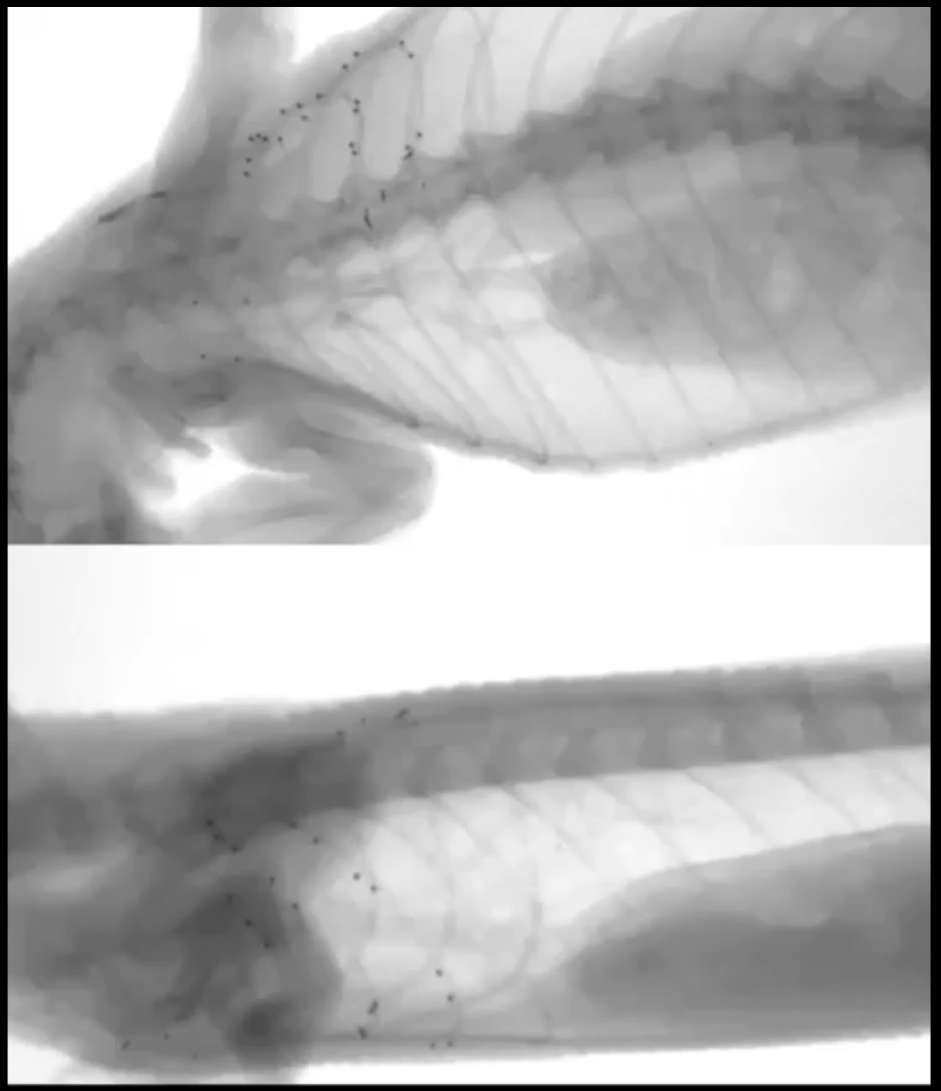




**Segmentation**

- Remove noise
- Thresholding to separate walls from air
- Surface reconstruction
- Simplification and smoothing

# Boundary conditions from realistic lung motion





Modeled Resting $V_T$ = 17.6 mL

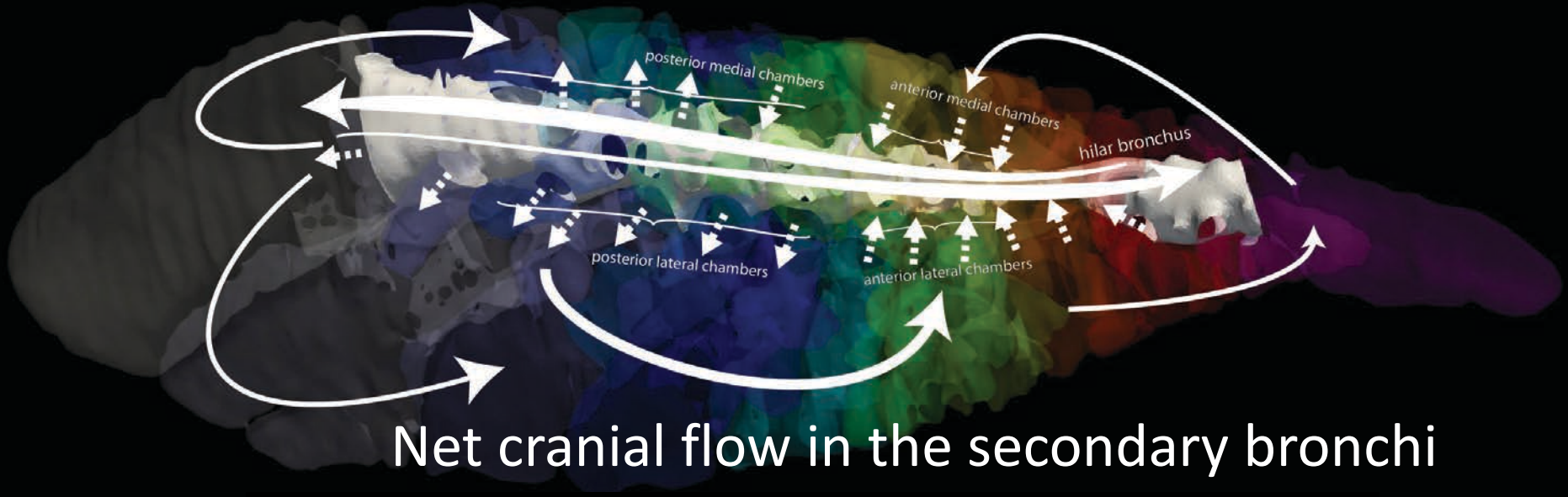
Target $V_T$ =17.15

based resting $V_T$ 35 mL/kg (Wang et al., 1997)

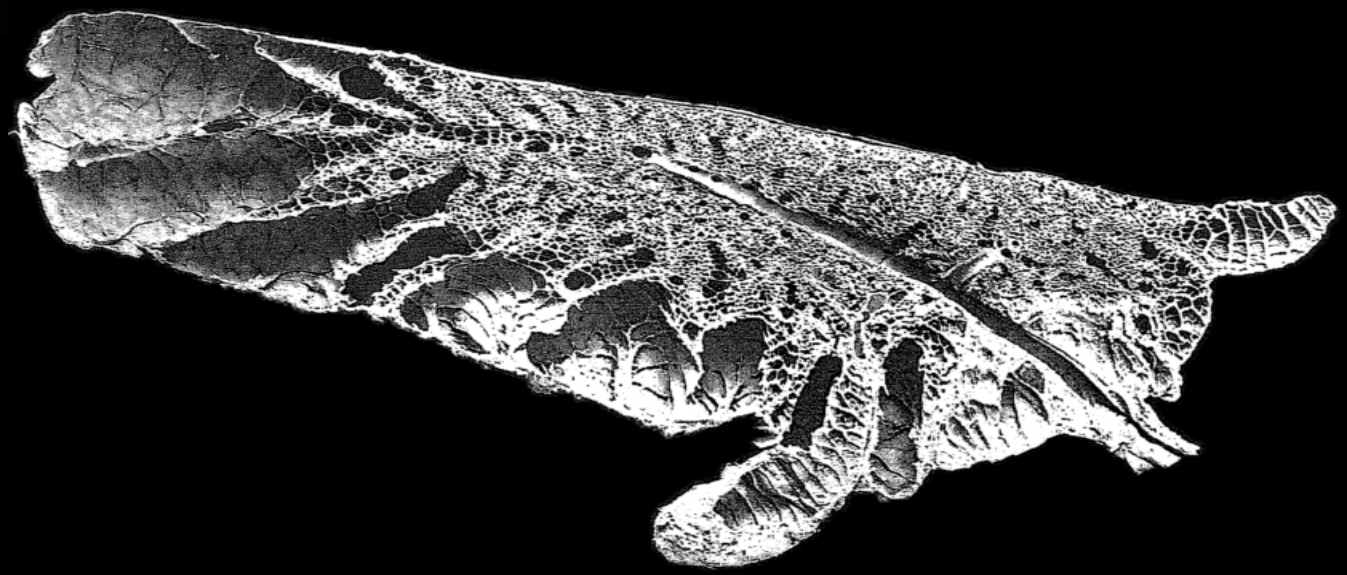
$V_T$ During recovery ranges to 50 mL/kg/lung

# Results: **Net** unidirectional airflow

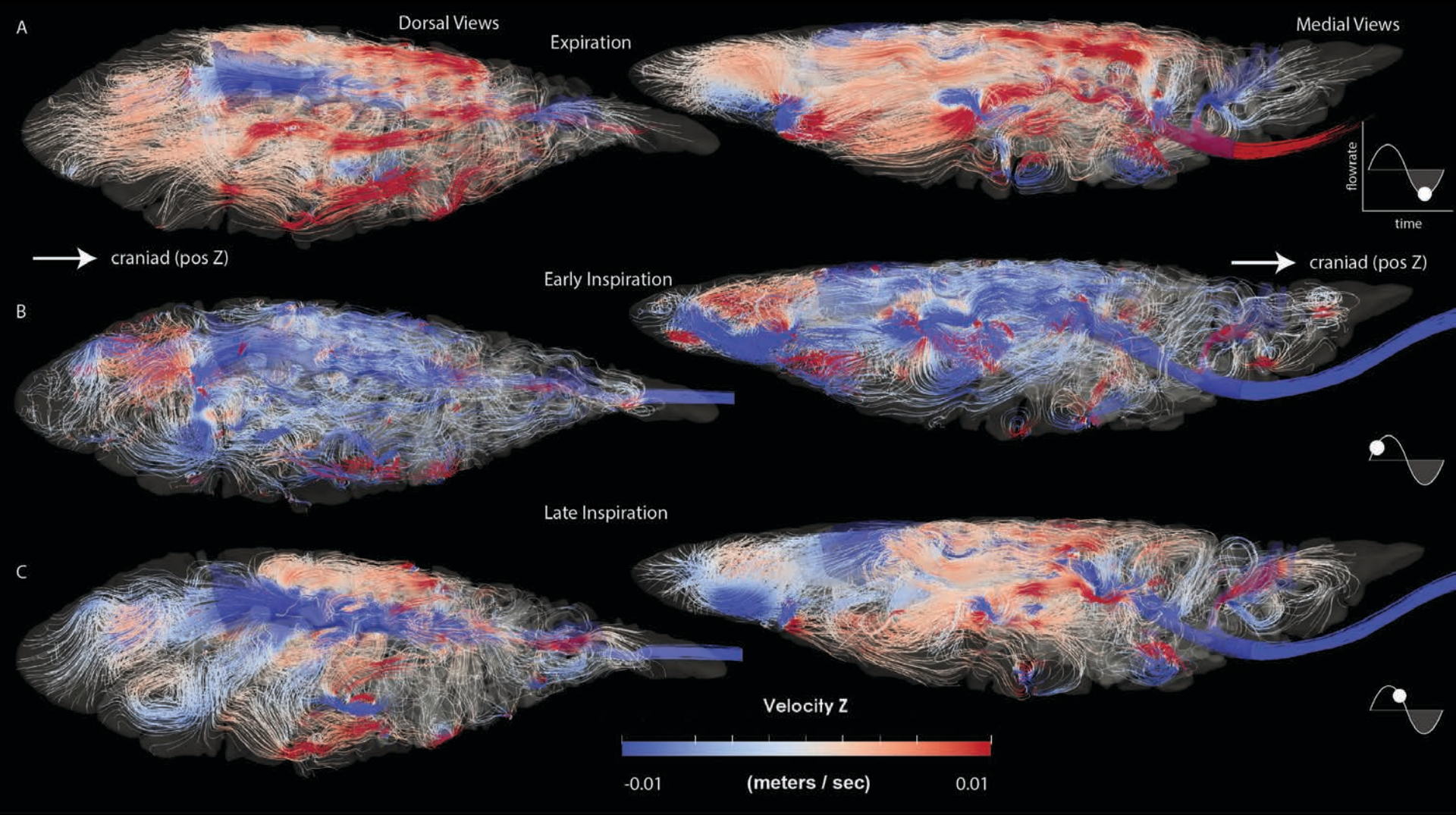
Net caudal flow in the intrapulmonary bronchus




Net cranial flow in the secondary bronchi

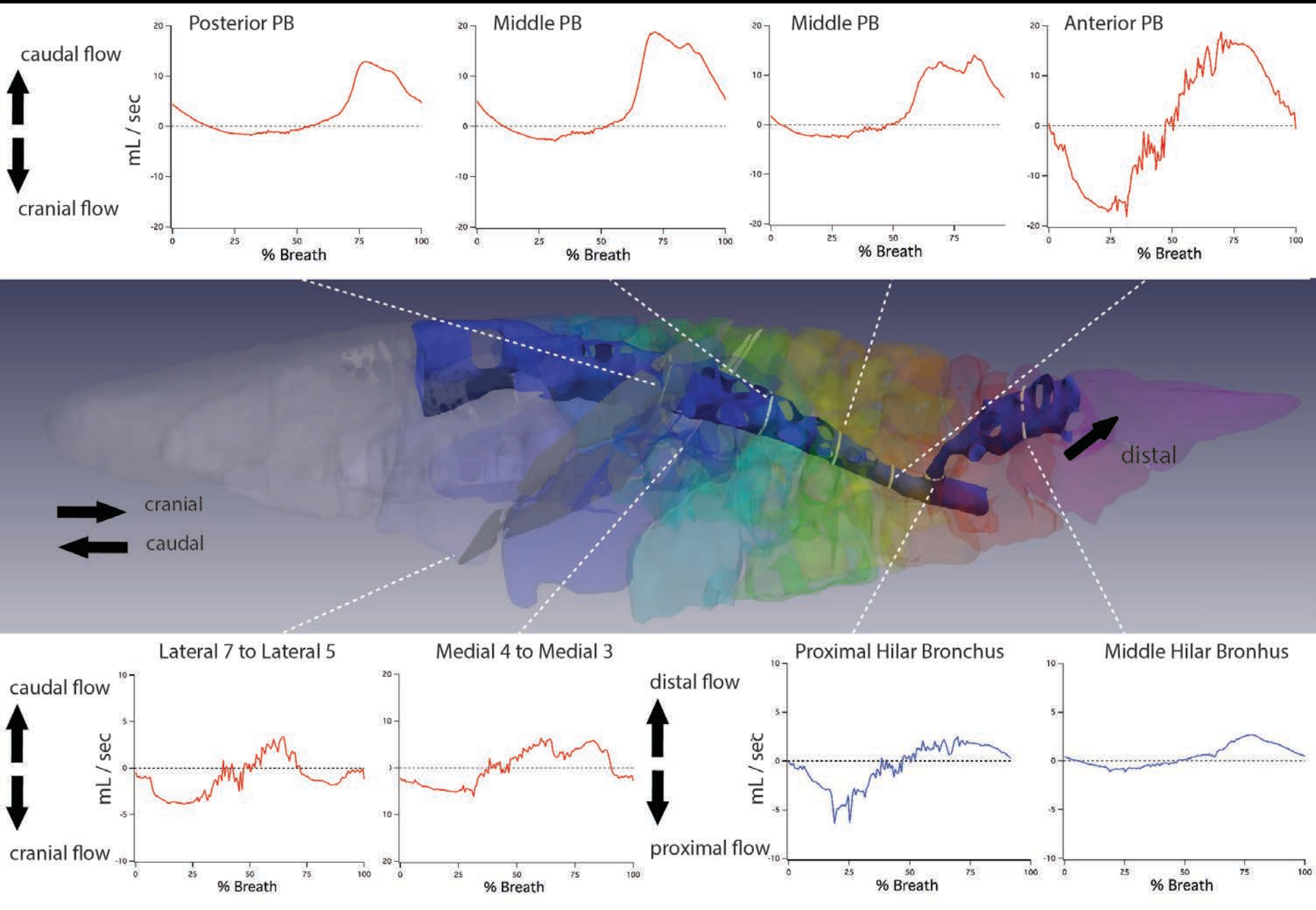


# Results: Lung is a mix of tidal and unidirectional flow

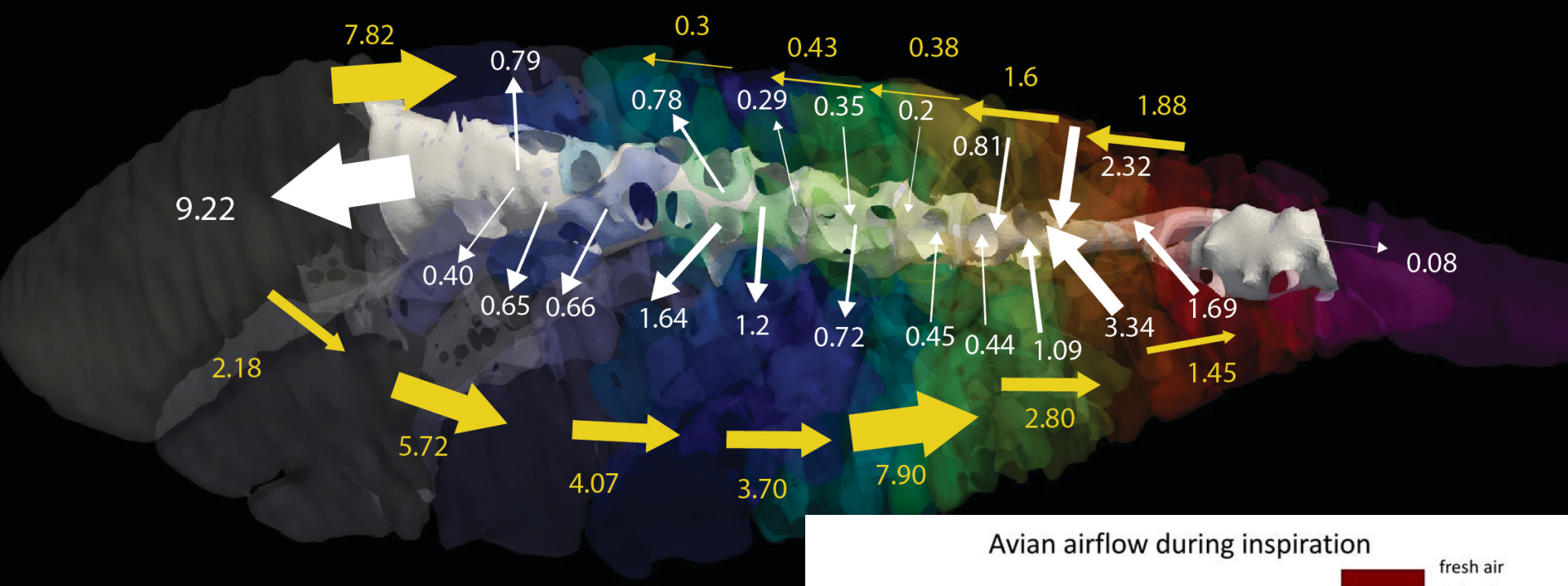


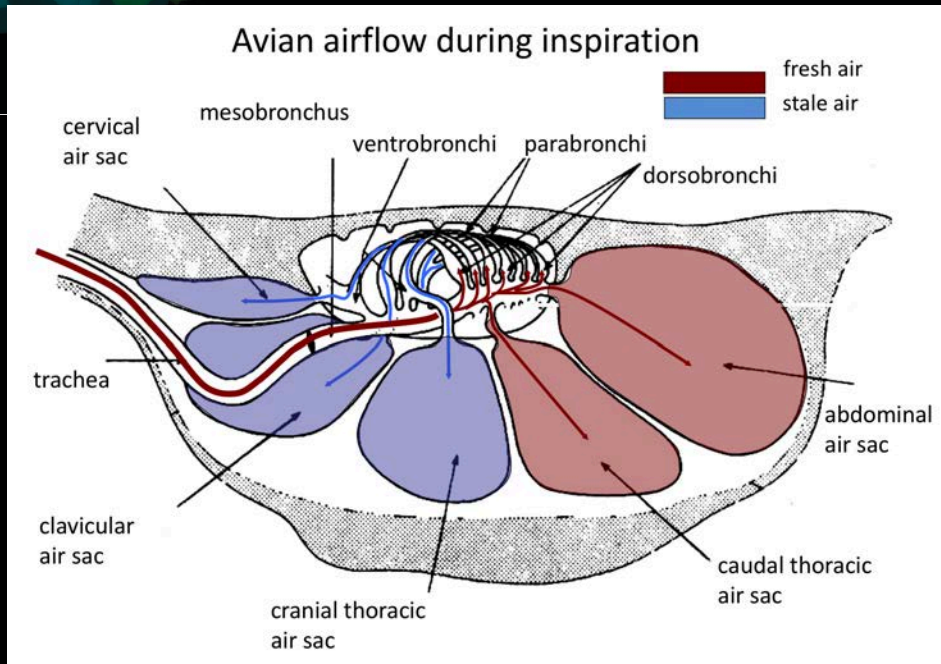

Air flows the same direction in expiration and late inspiration

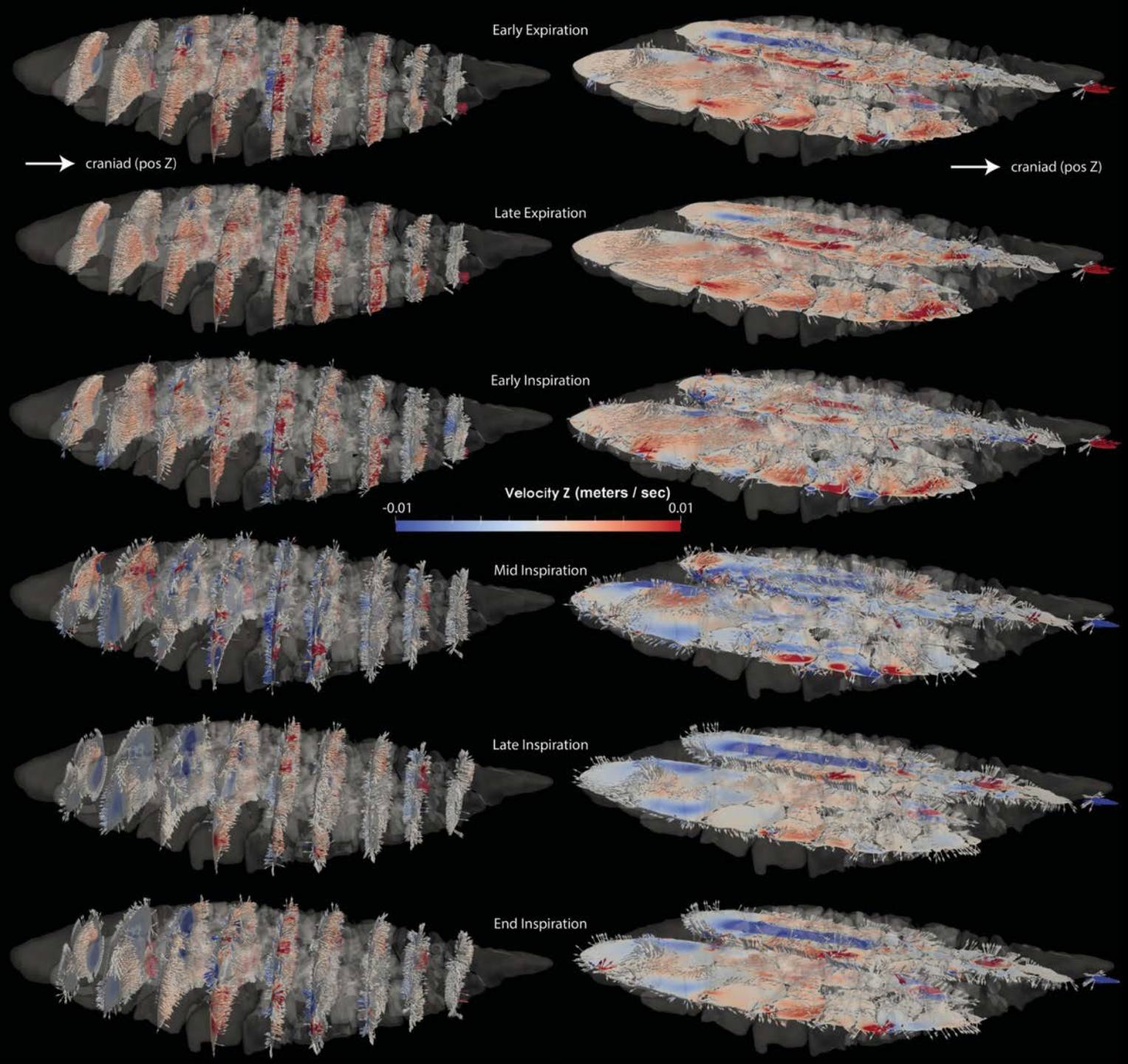
# Results: Net unidirectional airflow



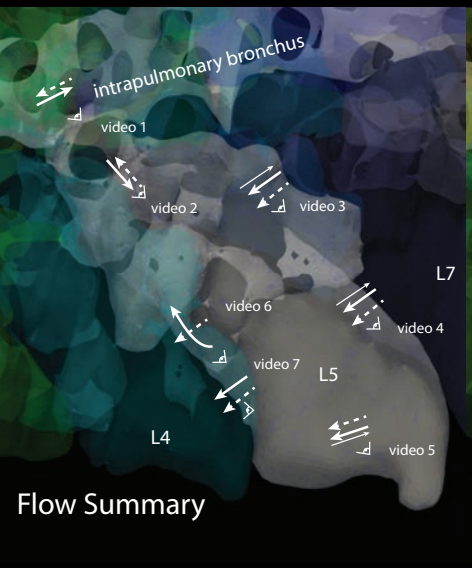
# Results: Net unidirectional airflow

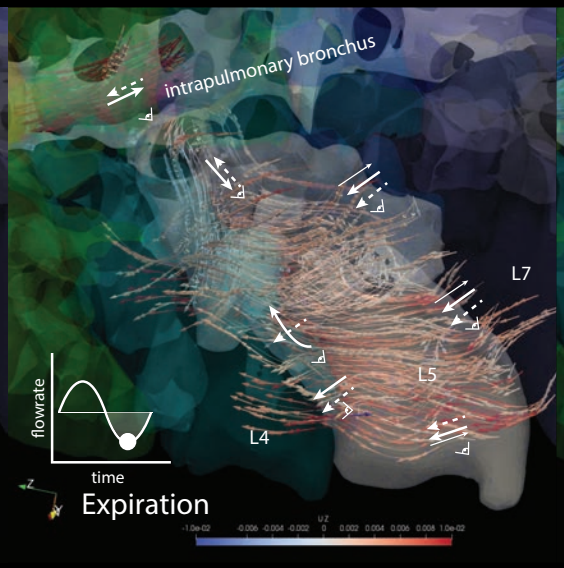


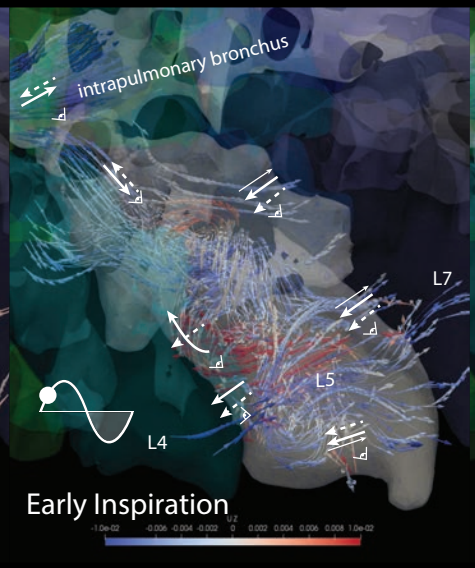



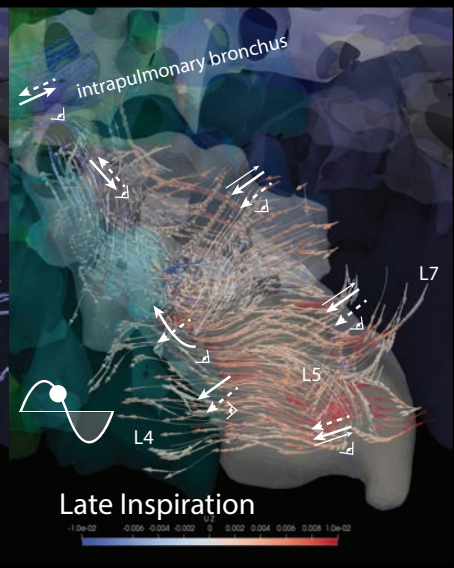

Early Expiration
craniad (pos Z)
craniad (pos Z)
Late Expiration
Early Inspiration
Velocity Z (meters / sec)
-0.01
0.01
Mid Inspiration
Late Inspiration
End Inspiration

# CFD results were validated on real lungs



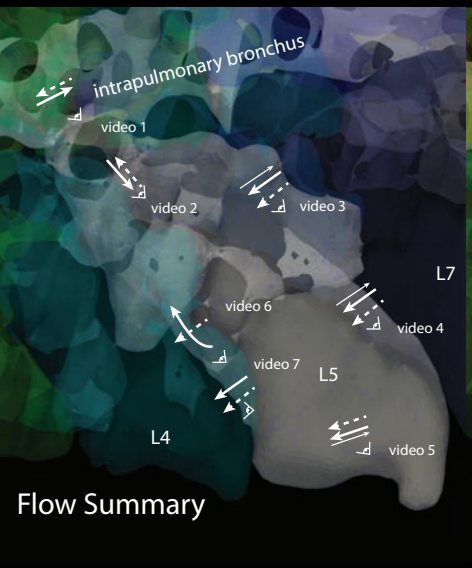



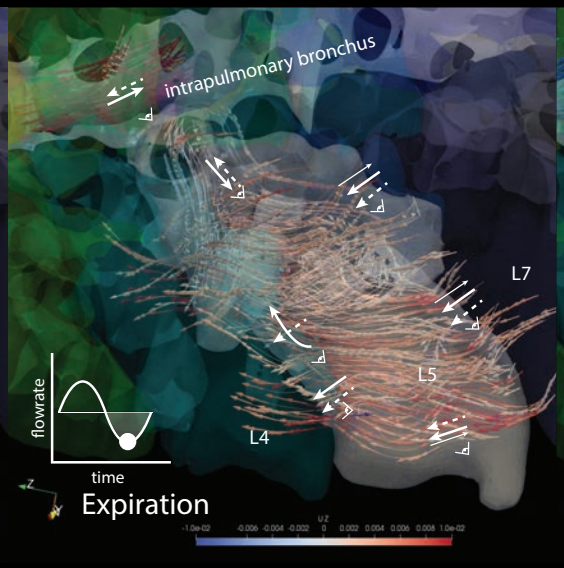





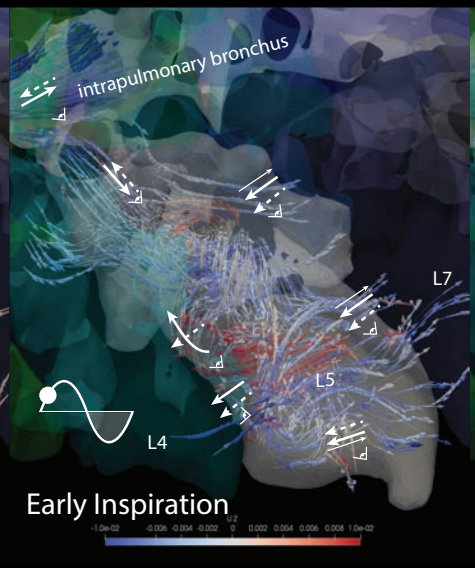
# CFD results were validated on real lungs



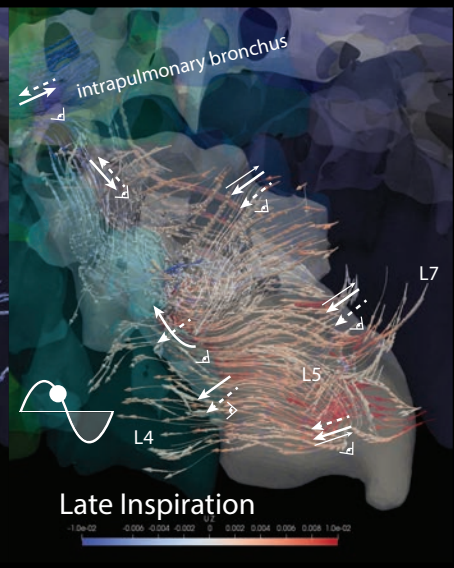
Flow Summary



Expiration

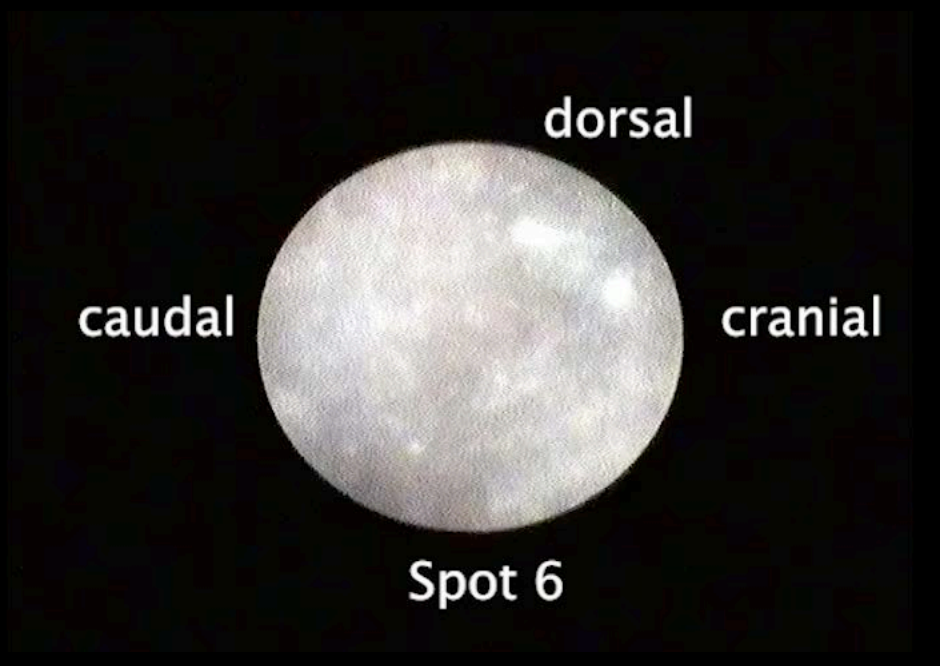


Early Inspiration



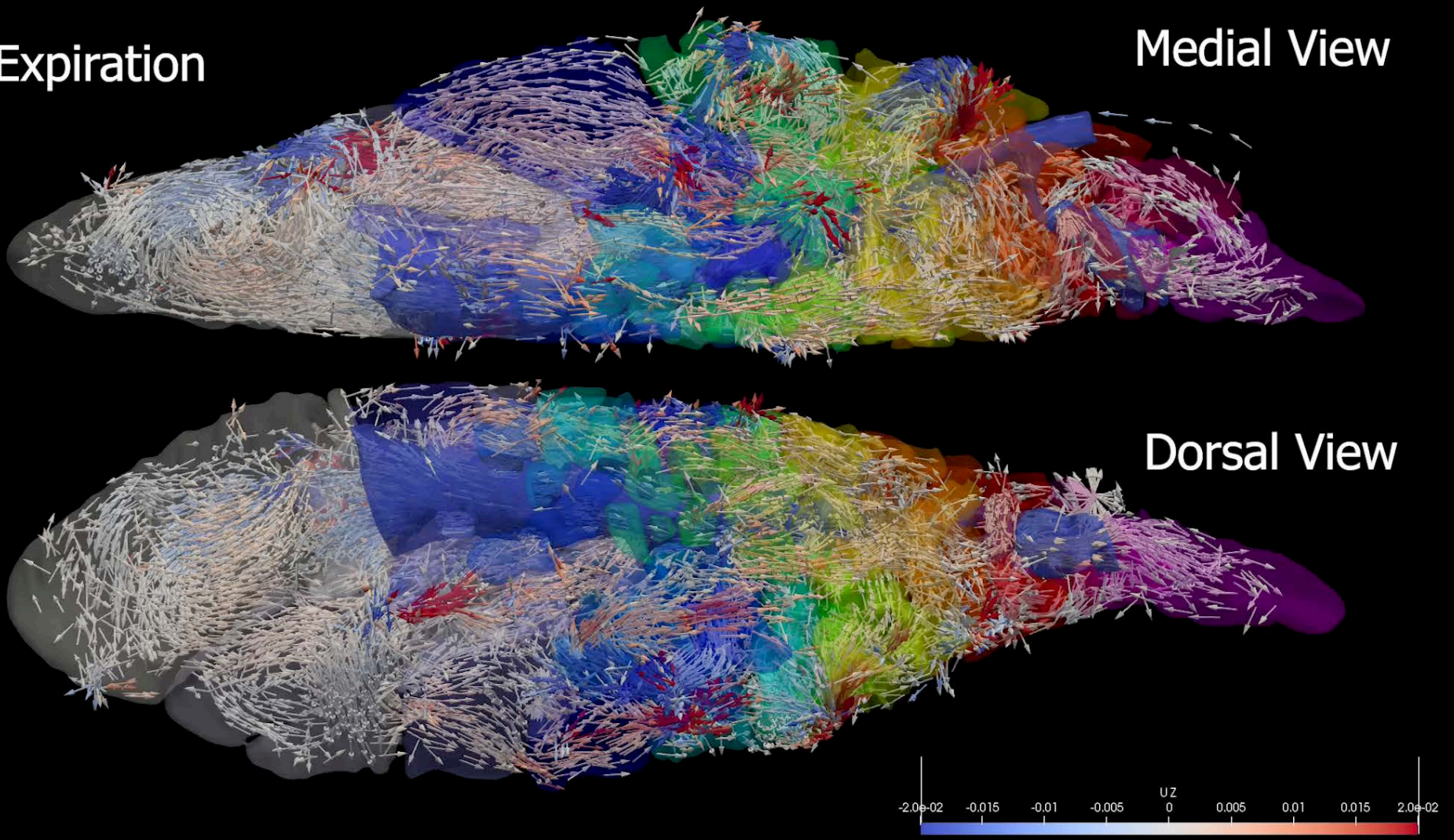
Late Inspiration

Spot 3

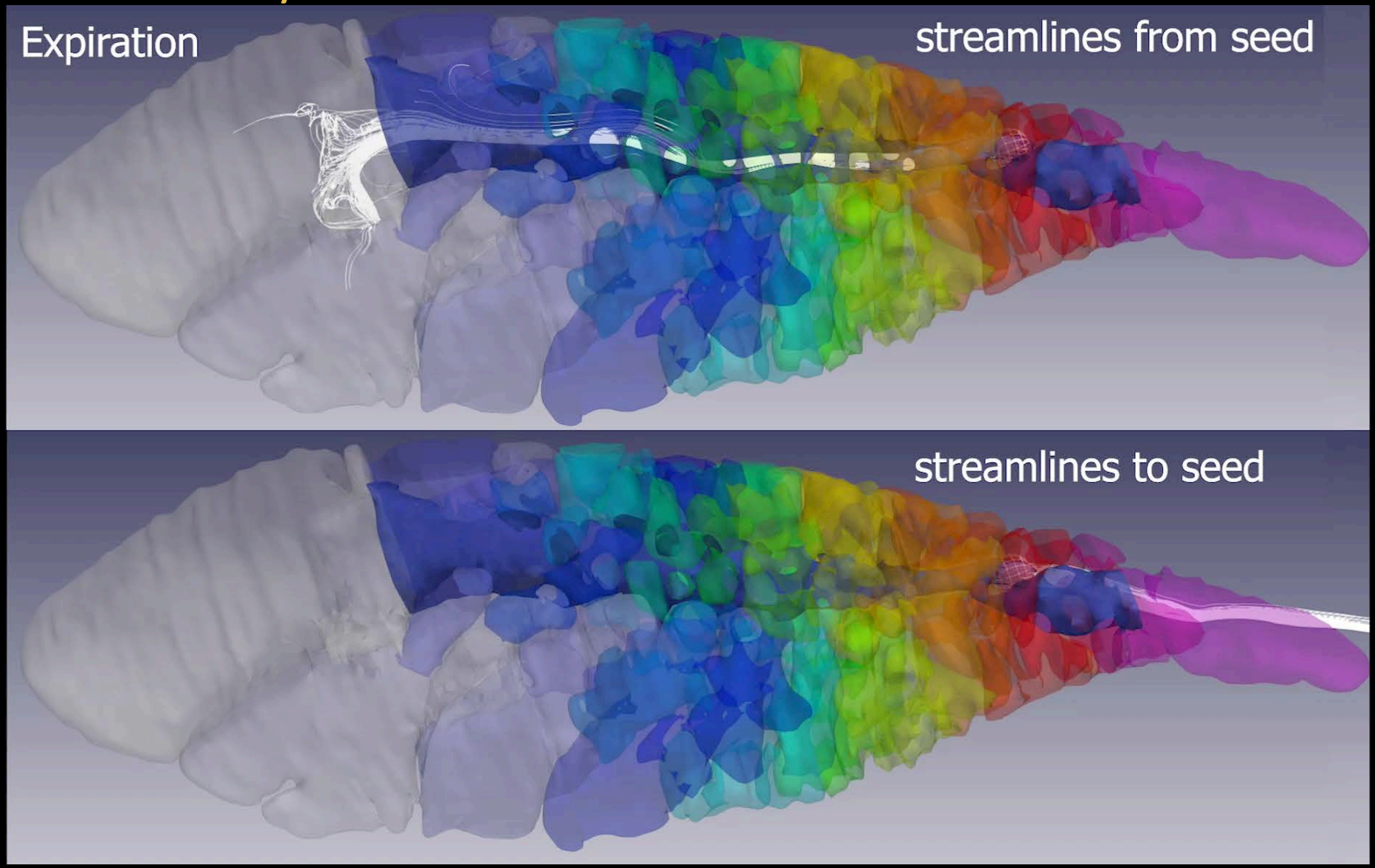


Spot 6

# Video of streamlines shows net flow and reversal

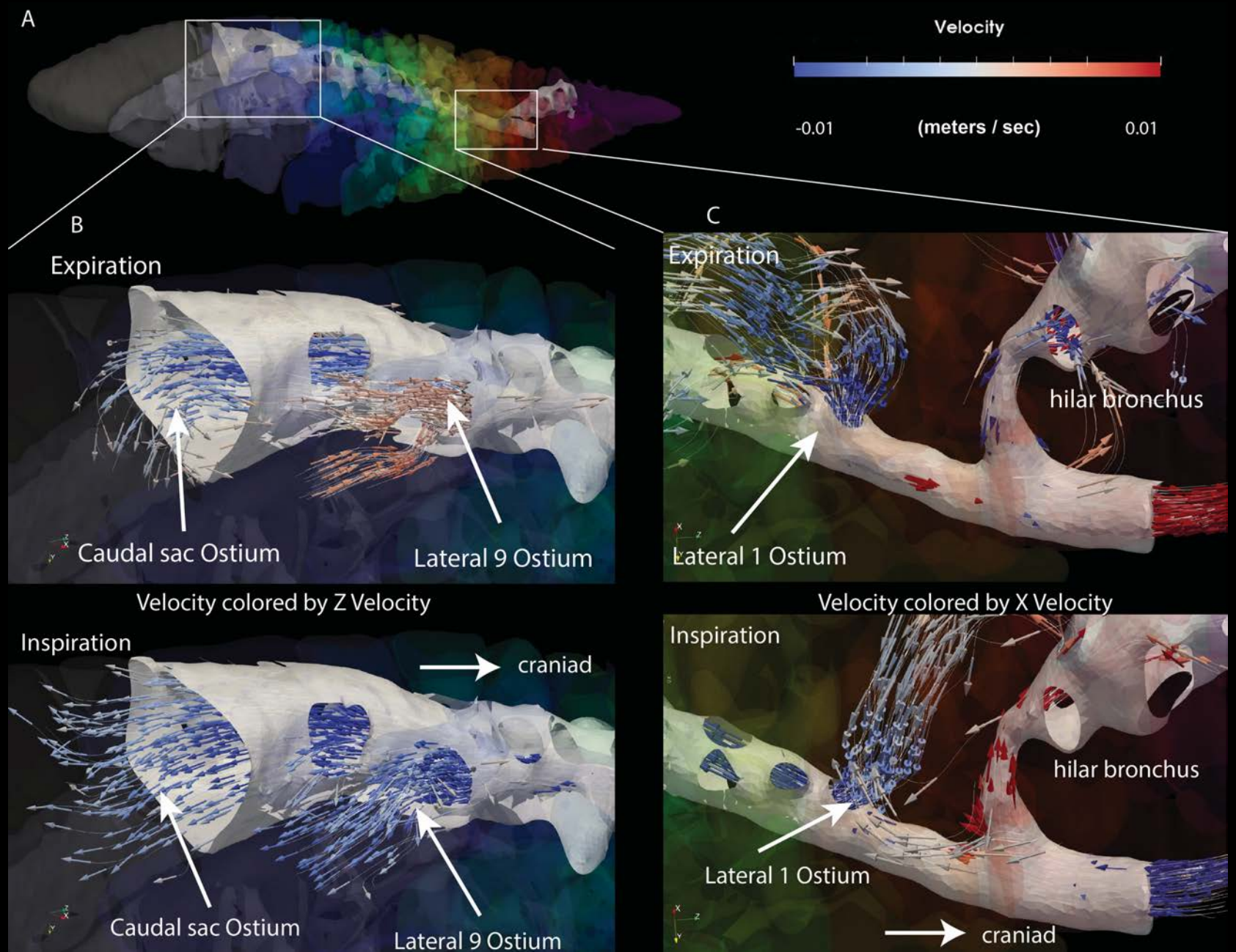


# Distribution of inspired flow to secondary bronchi varies over the breath cycle

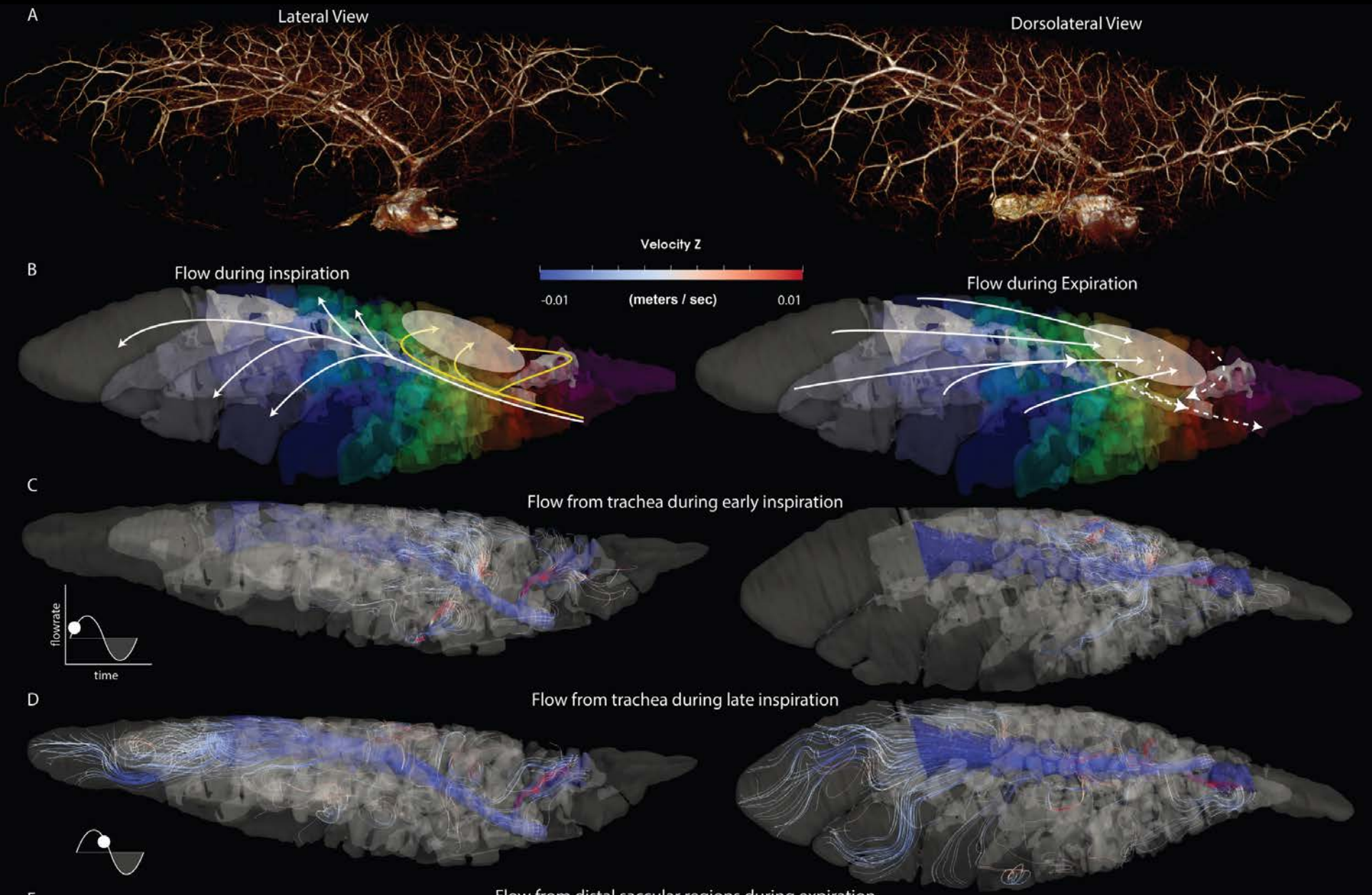



Most air flows from secondary bronchi during expiration

# First secondary bronchus is strongly tidal



# Tidal flow in first bronchus may optimize capillary airflow



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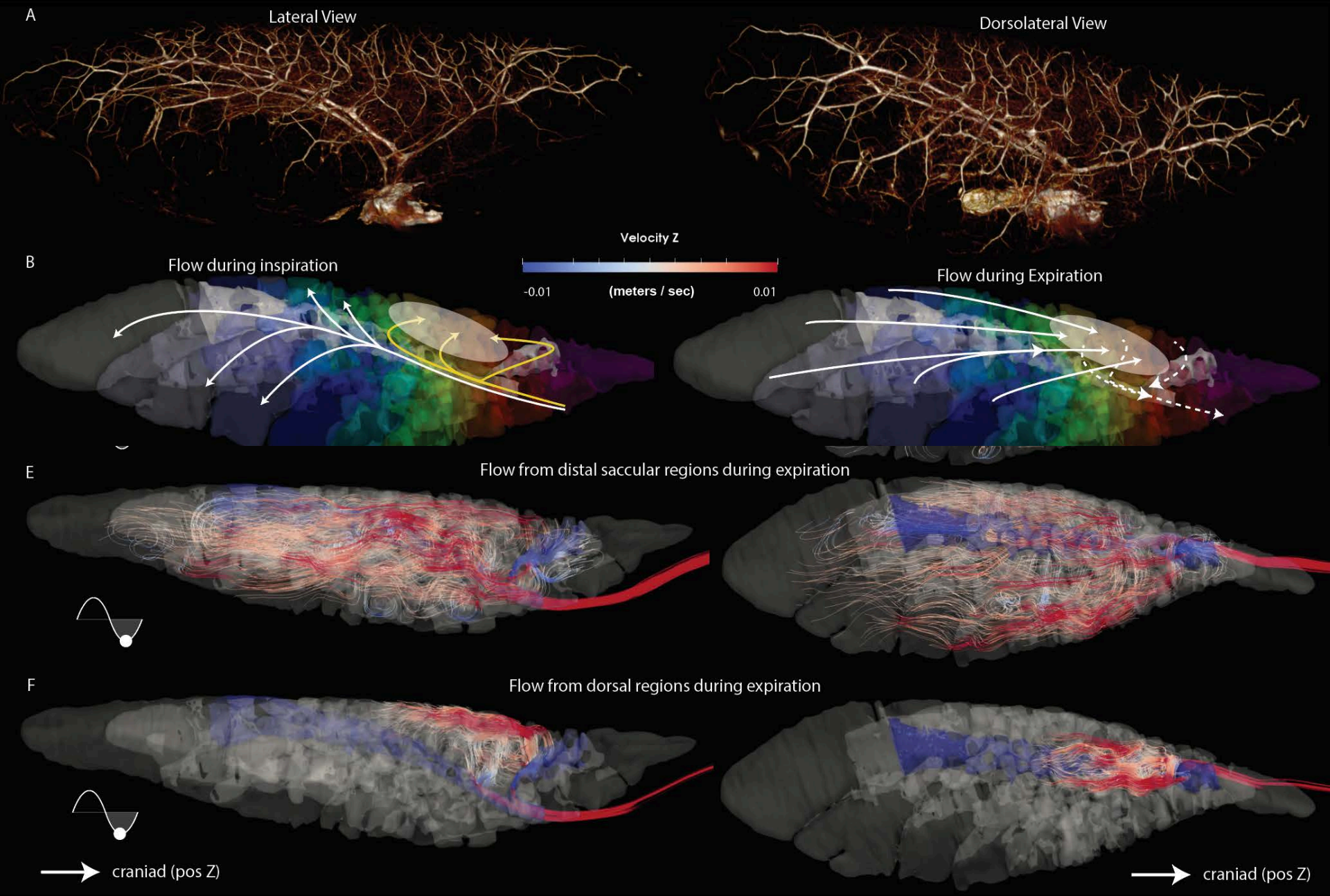
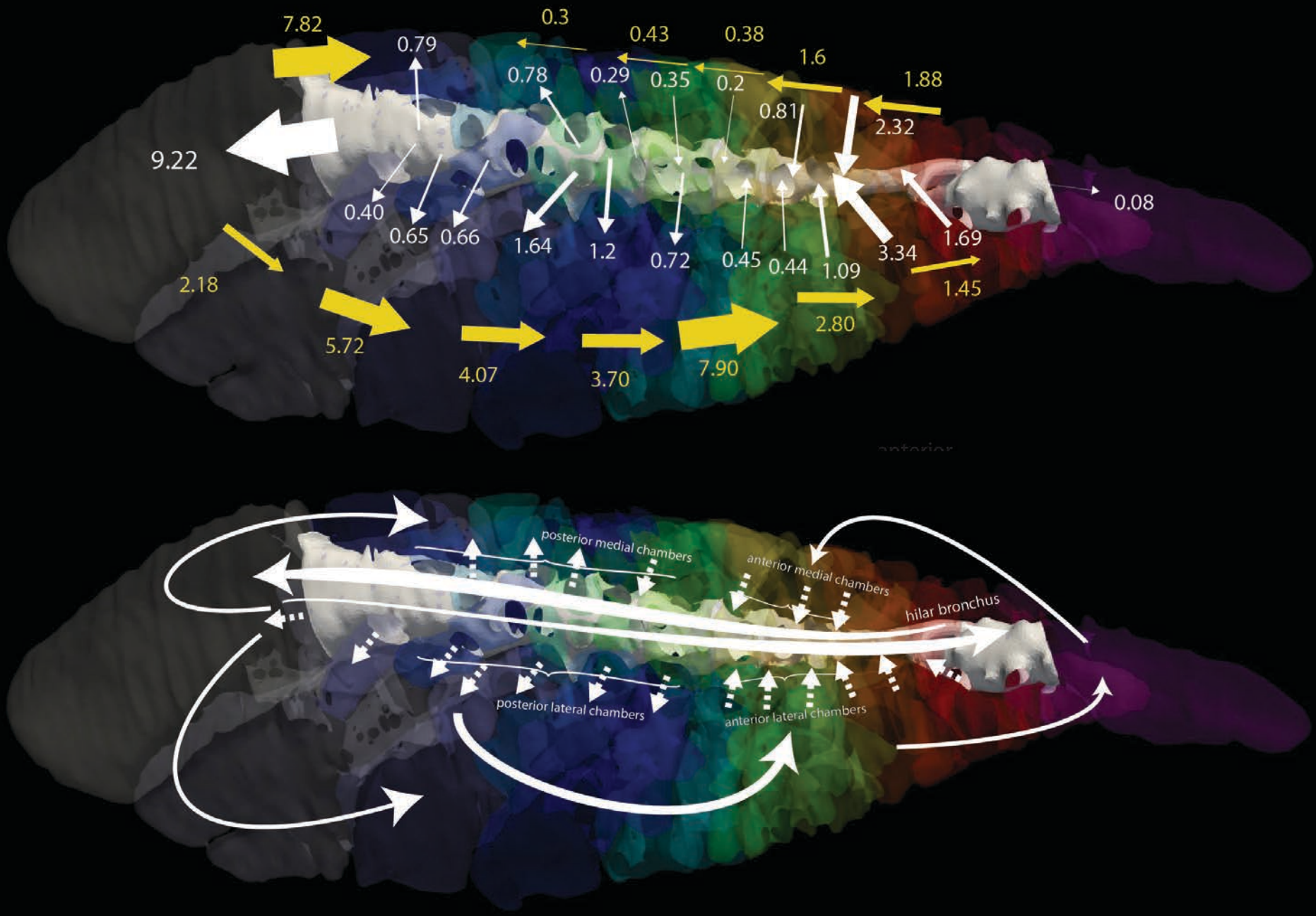
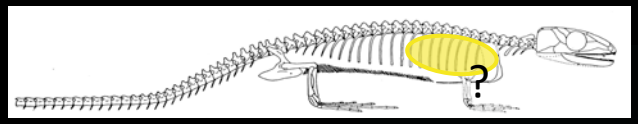
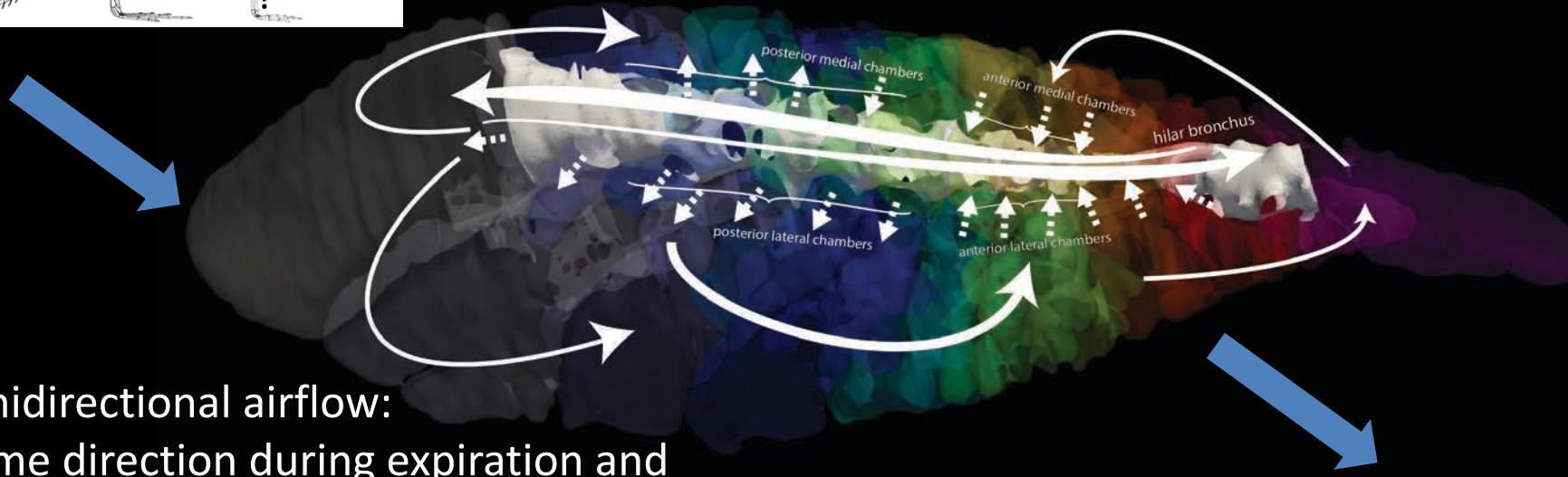


# Overall Lung Airflow Pattern



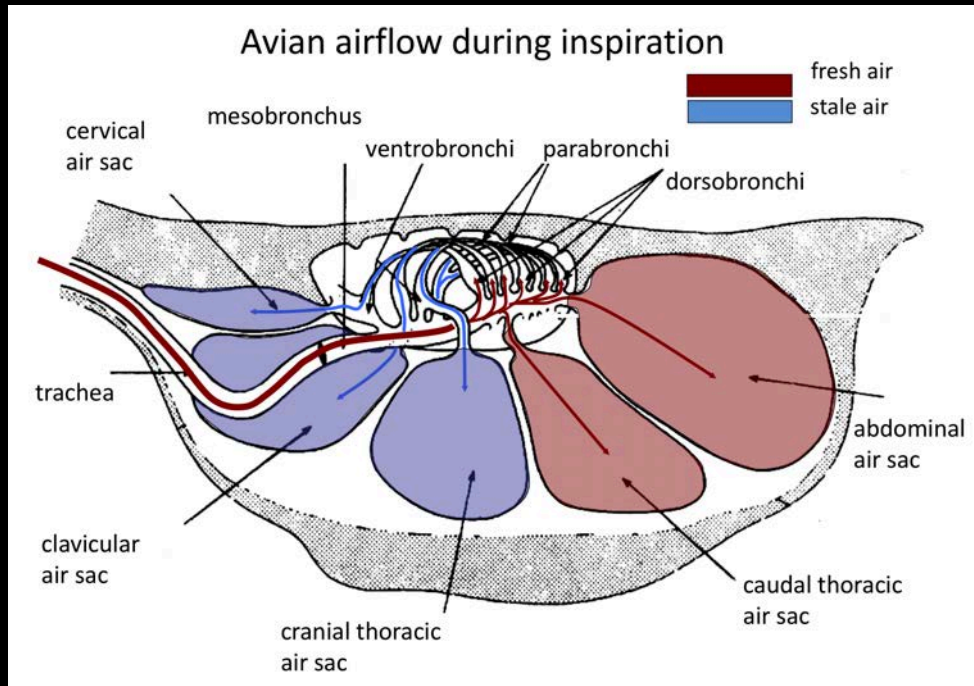
# Monitors have hybrid tidal / unidirectional lungs




Net unidirectional airflow:

- Same direction during expiration and late inspiration
- Intrapulmonary bronchus transports air mostly caudally
- Secondary bronchi transport air mostly cranially
- The hilar bronchus (first secondary bronchus) is fully tidal.
- Analogous to an avian air sac?
- Possible evolutionary pathway between simple lungs and bird lungs



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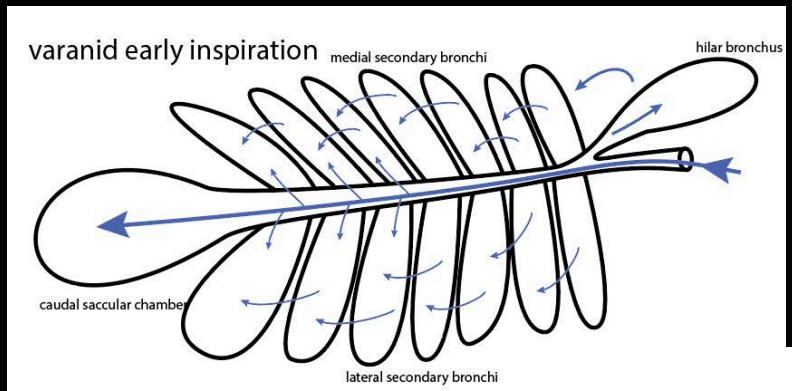
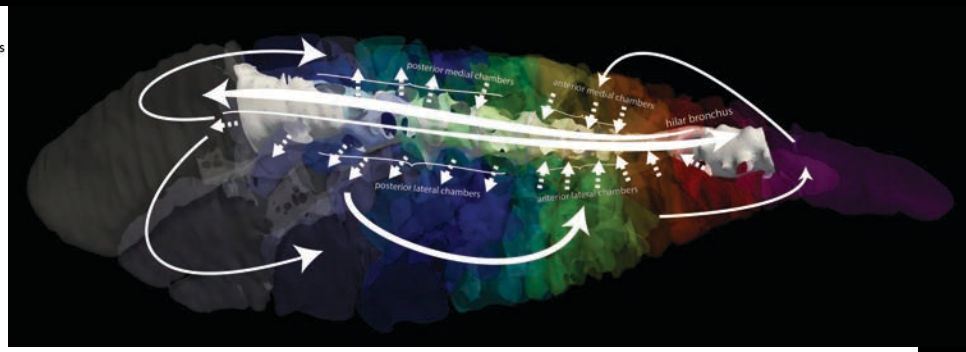
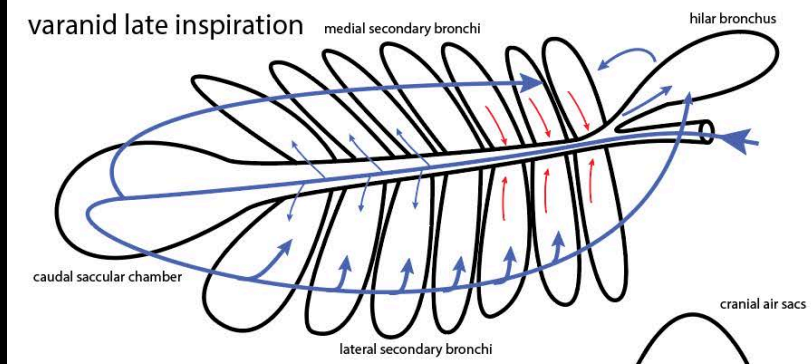
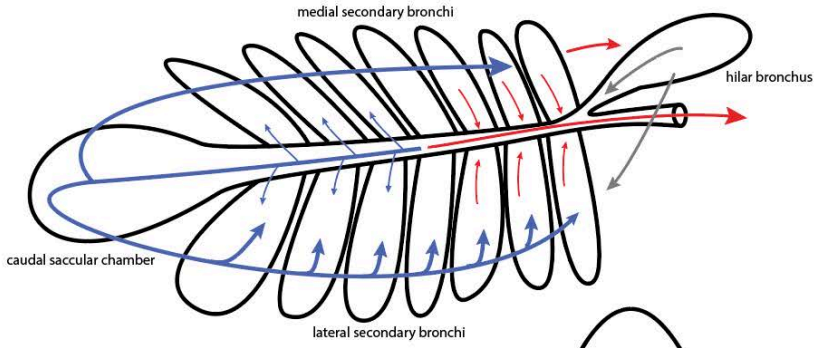
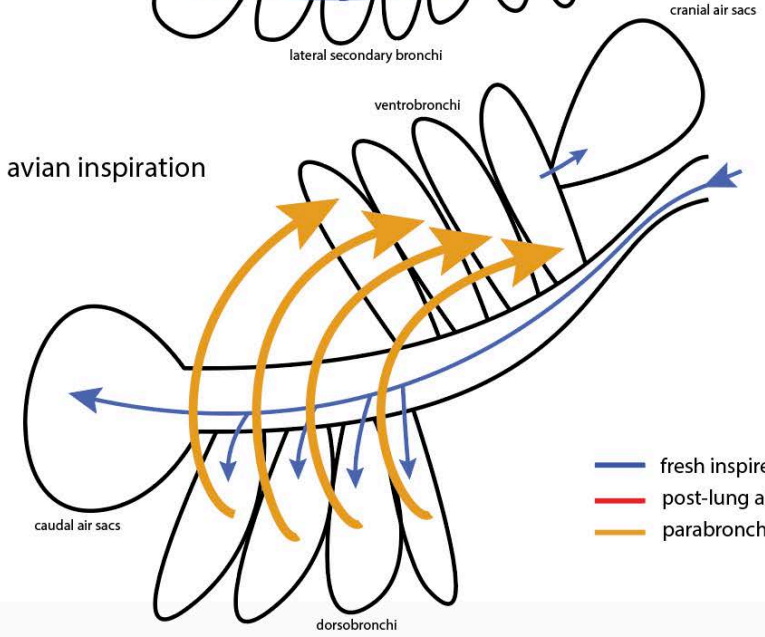
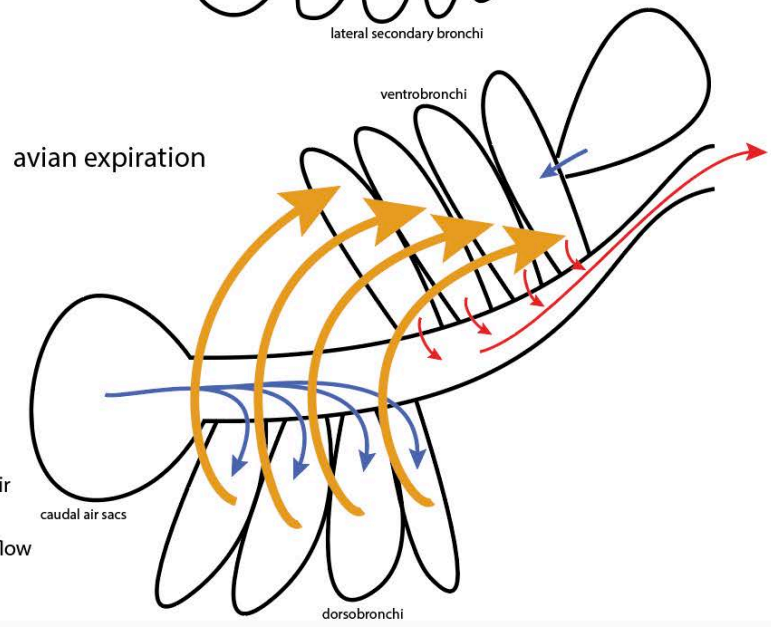


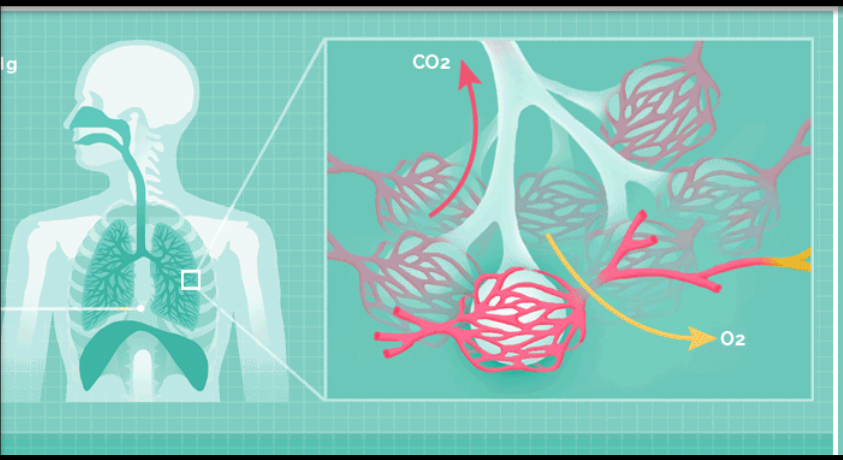



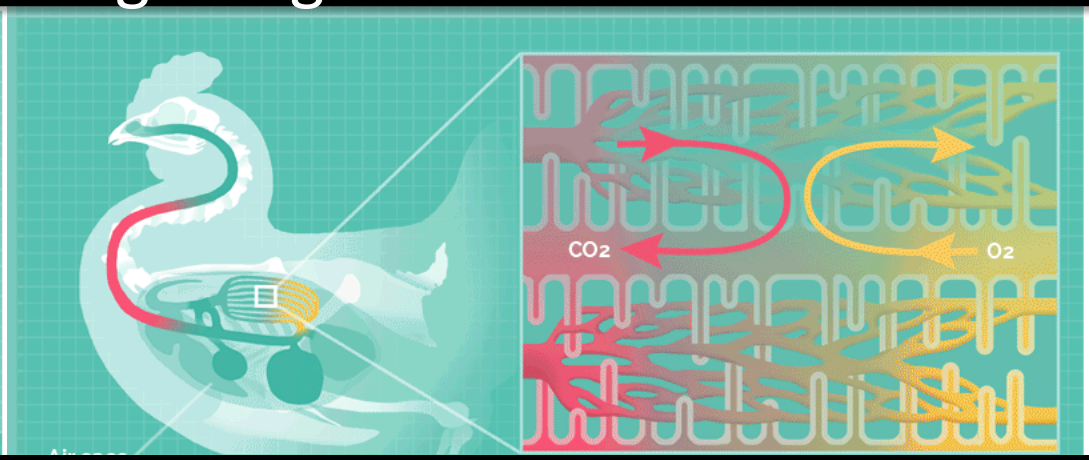



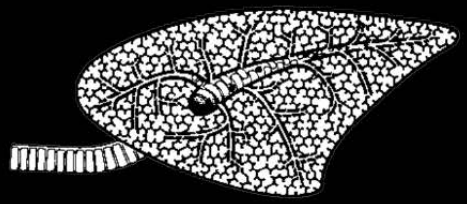

fresh inspired air
post-lung air
parabronchial flow

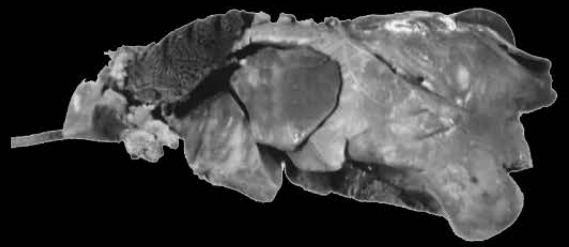
**Key Question:** Birds and mammals have quite different pulmonary systems. Why did each lineage develop a different pulmonary system? What biological traits are associated with each lung design?




Eleanor Lutz – Tabletop Whale





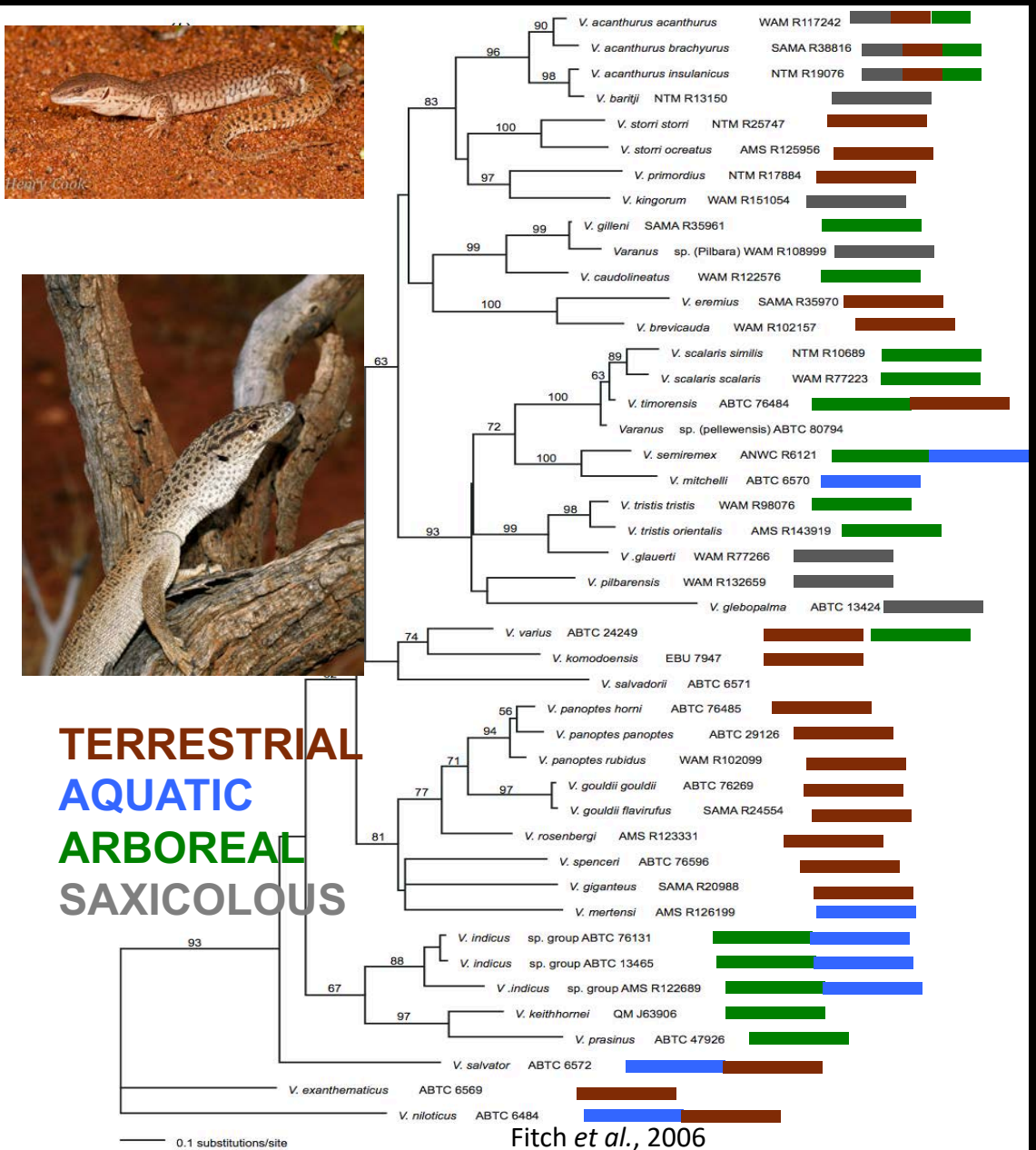
MAMMALIA

AVES

# Future Directions: compare lung airflow traits across different monitor species as a test case for vertebrates







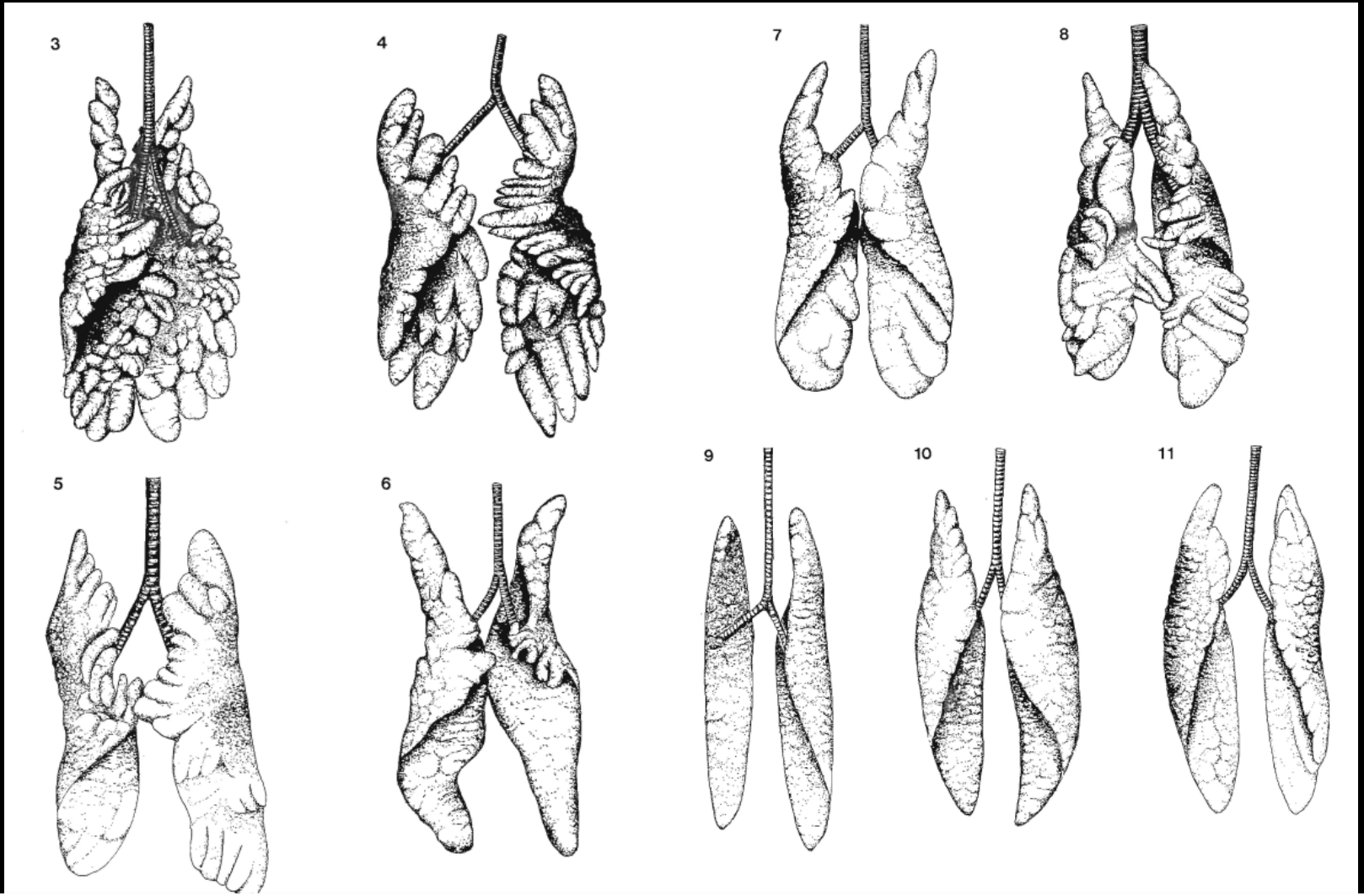

**TERRESTRIAL**
**AQUATIC**
**ARBOREAL**
**SAXICOLOUS**

Fitch *et al.*, 2006

Monitor lizards range widely in:

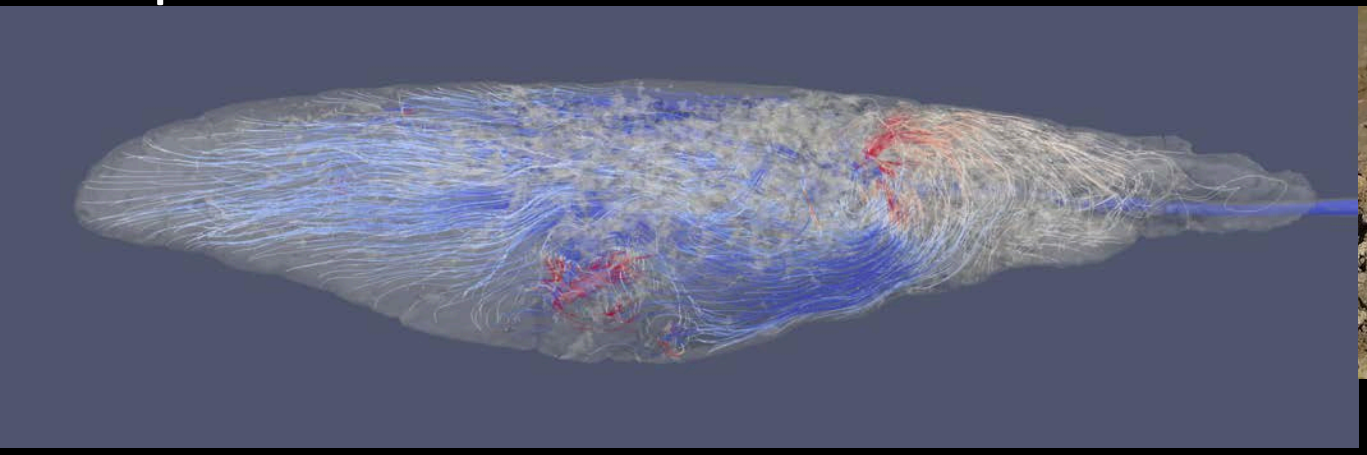
- body size (8g ← → 5 kg)
- metabolic rate
  - Thompson and Withers, 1997
- endurance / activity (40-700 sec)
  - Clemente *et al.*,. 2009
- Habitat (see phylogeny at left)

# Can the co-variation in biological traits and lung designs in monitor lizards tell us anything about how lungs evolve?

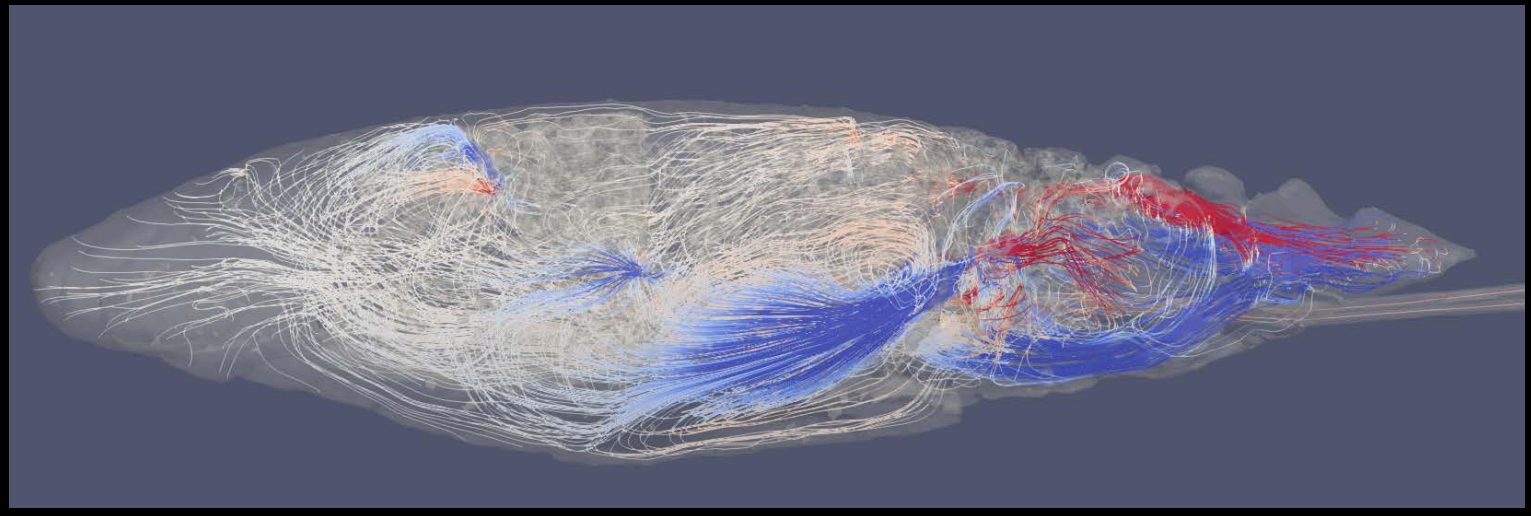


# Can the co-variation in biological traits and lung designs in monitor lizards tell us anything about how lungs evolve?

…results in progress! 12 species scanned, 3 CFD models complete




Spencer's monitor



Lace Monitor

# Final Outcomes / Broader Impacts

This work is currently in review at The Anatomical Record -- Allows publication of movies and 3D Interactive PDFs in the actual manuscript file

Virtual-reality ready images available on SketchFab

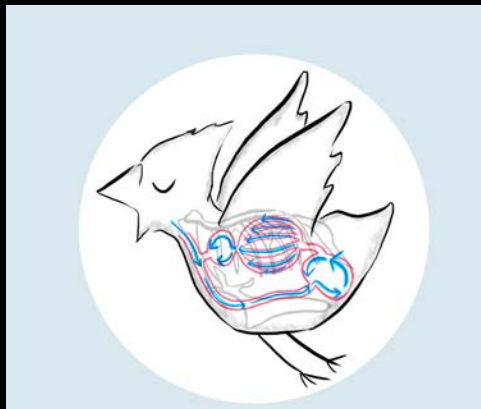
The CFD model and CT scans associated with the project will be made available on Data Dryad after publication – a huge boon to other scientists!

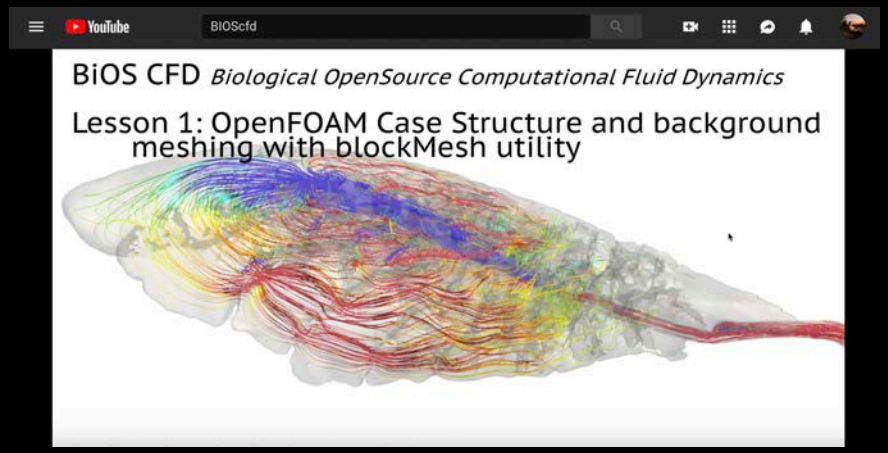
Methods are being shared via YouTube tutorials called BiOS CFD (CFD is still new to biologists)

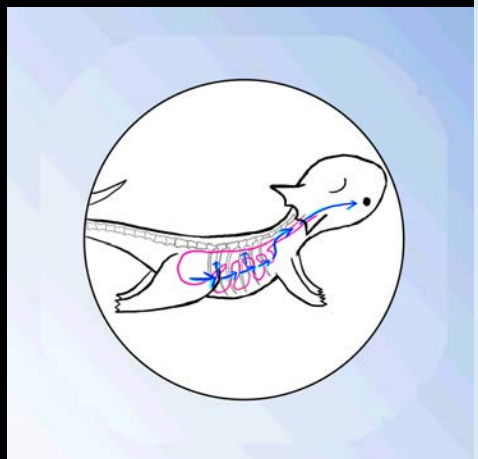
Outreach Animations

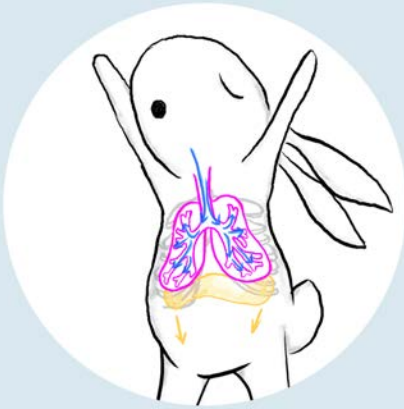
- How animals breathe
- Outreach to yoga studios
- Local schools
- INSPIRE Program for the Incarcerated

Animations by Brian Russo (www.yogabunny.com)







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Blue Waters Graduate Fellowship

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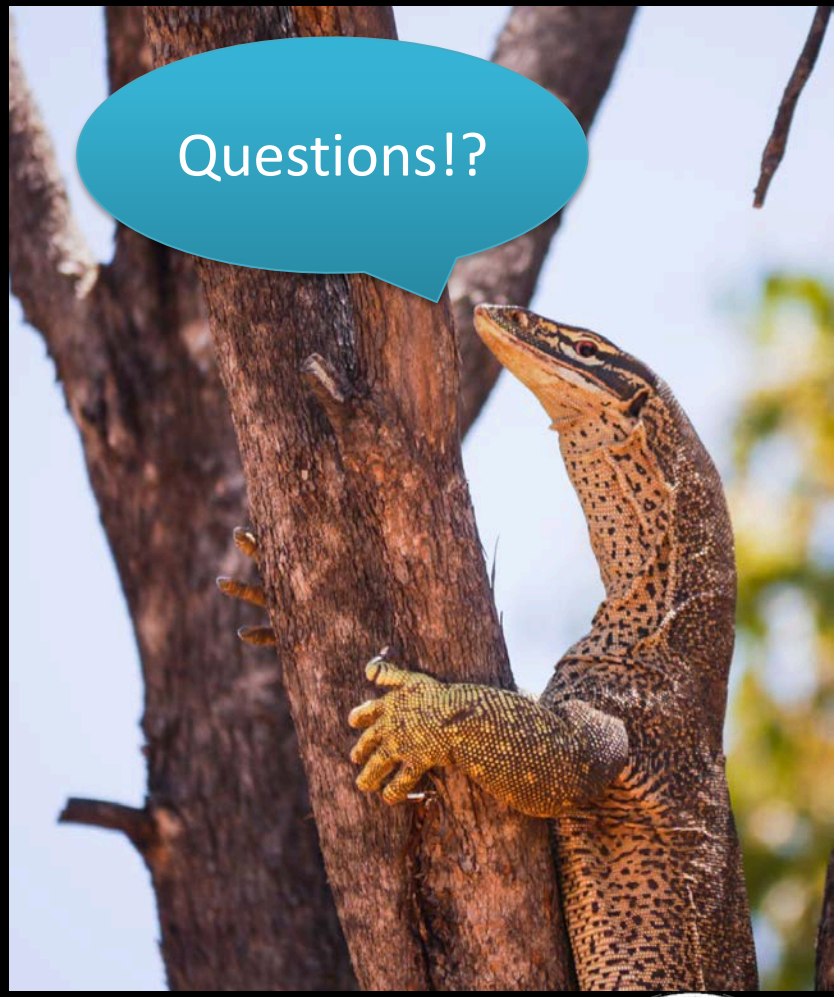
Center for High Performance
Computing (University of Utah)




BLUE WATERS
SUSTAINED PETASCALE COMPUTING