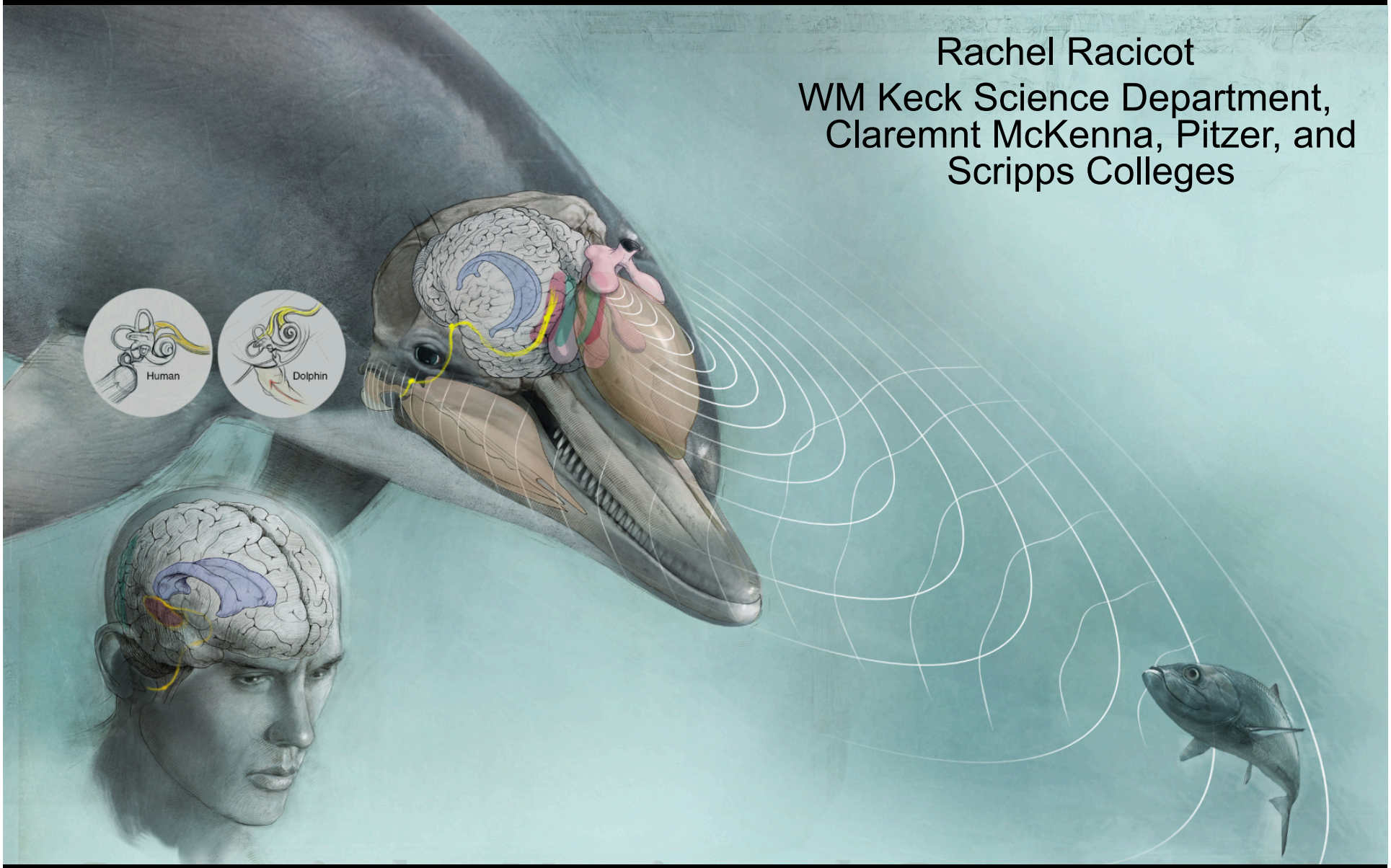
# Evolution of echolocation in toothed whales

Rachel Racicot
WM Keck Science Department, Claremnt McKenna, Pitzer, and Scripps Colleges




National Geographic

# Why is evolution of underwater echolocation important?

A) Conservation applications

–we need to know the anatomy of biosonar apparatus in marine animals to mitigate the impacts of human-produced sonar/sound

B) Engineering & robotics applications

–how & why one group of mammals evolved & uses underwater echolocation have direct human applications

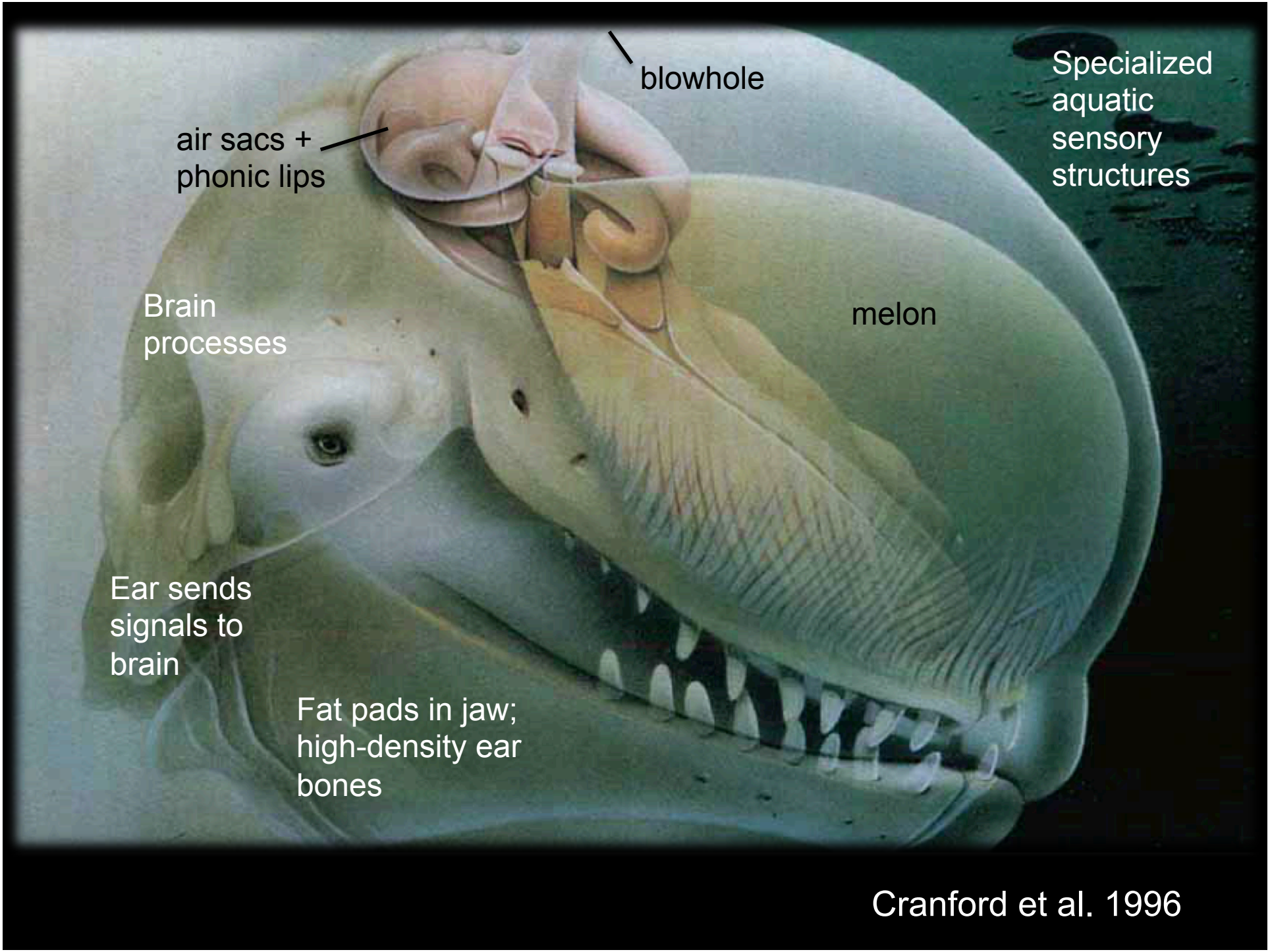
C) Understanding evolutionary trends

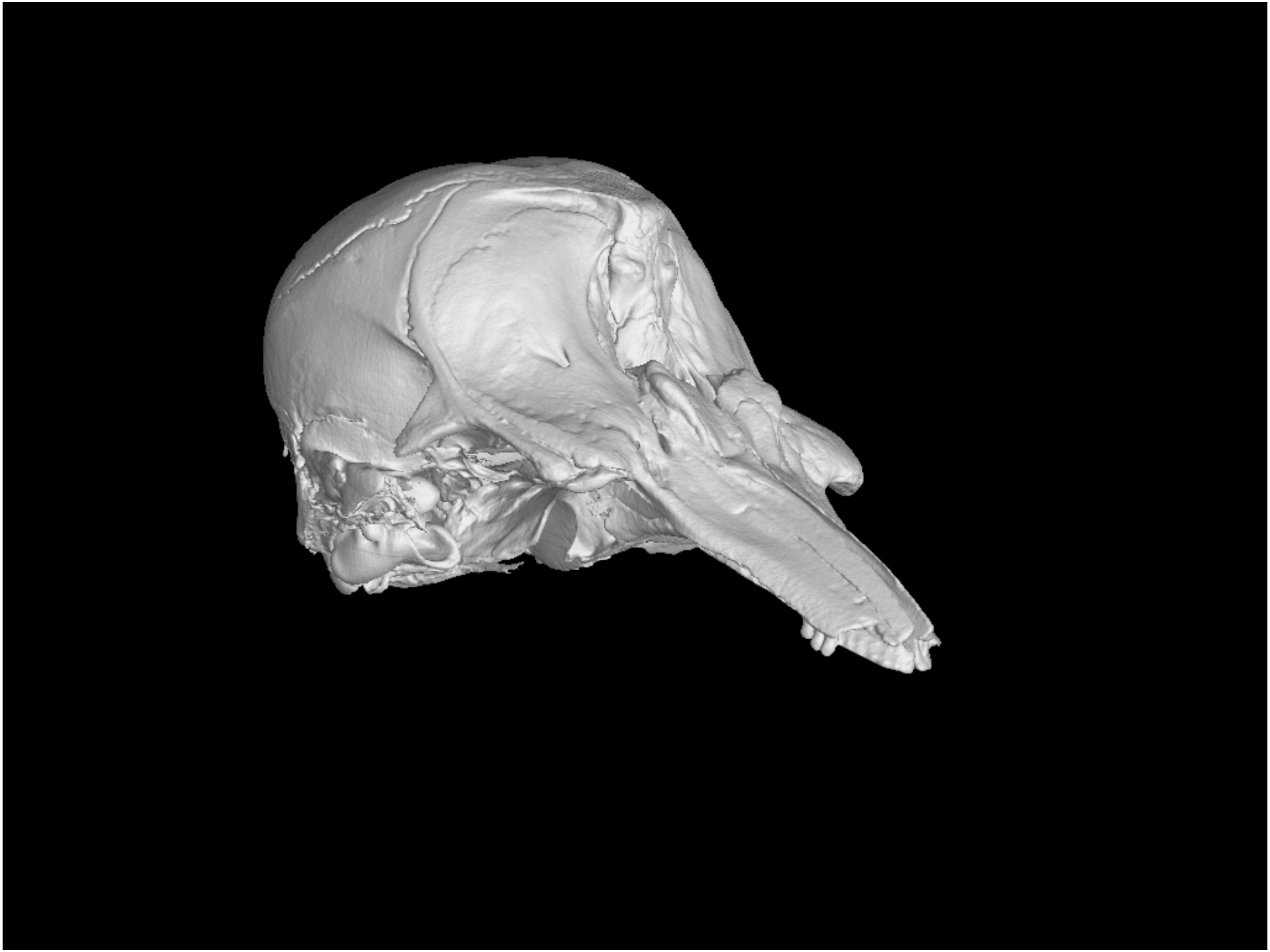
–are smaller, fully aquatic members of certain lineages destined to echolocate?

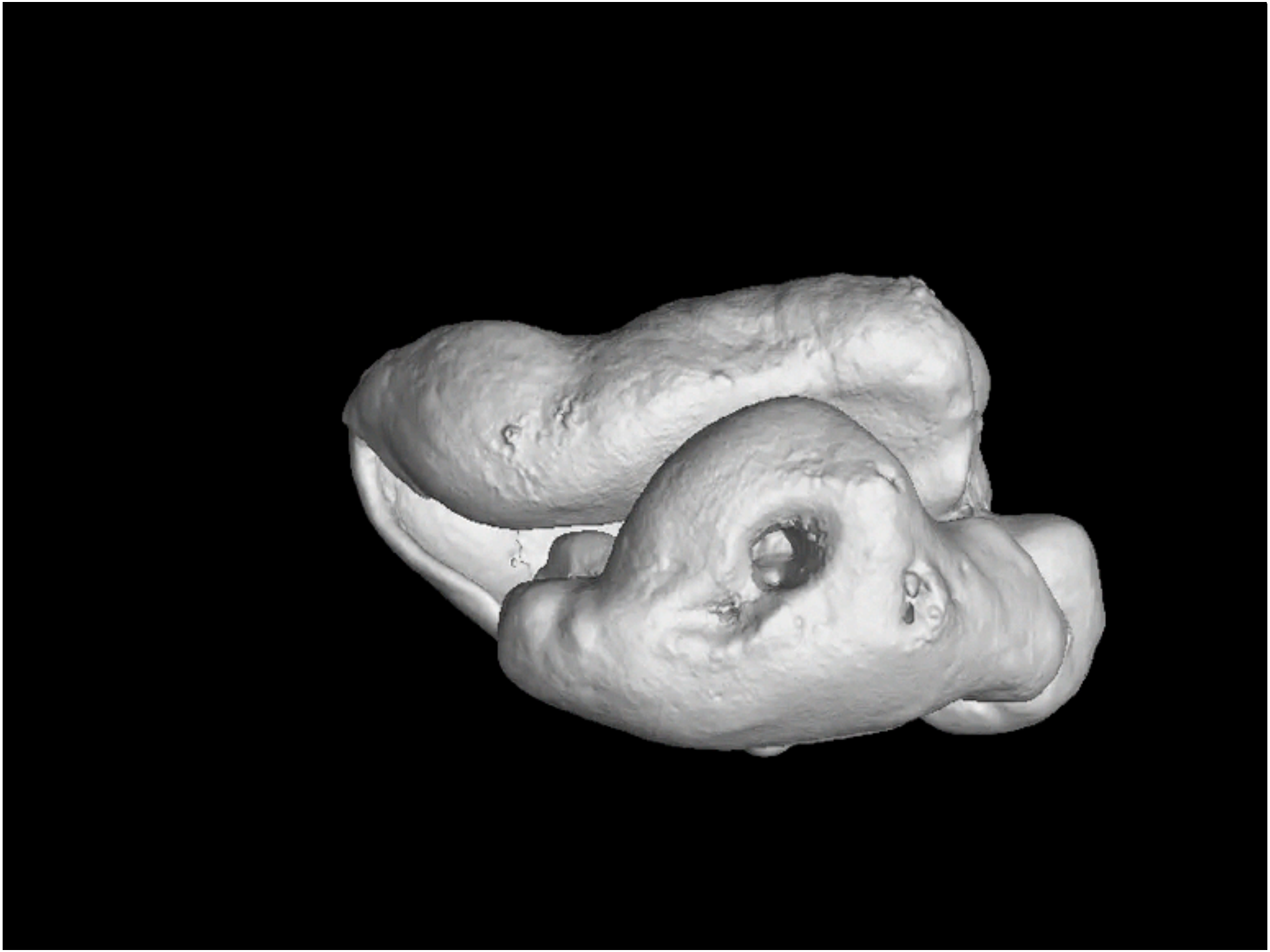
D) All of the above

–…and more!

What is the echolocation apparatus in toothed whales?

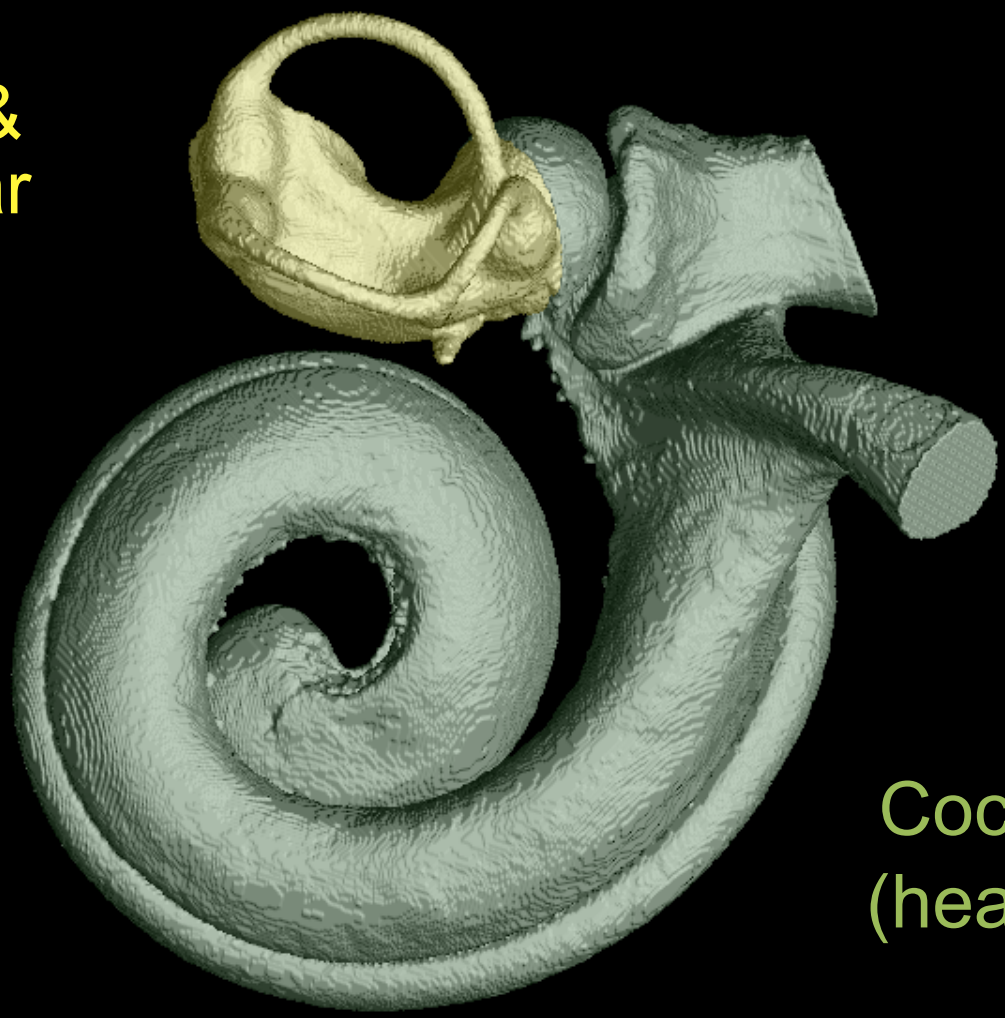

blowhole
Specialized aquatic sensory structures
air sacs + phonic lips
Brain processes
melon
Ear sends signals to brain
Fat pads in jaw; high-density ear bones
Cranford et al. 1996





# Porpoise fossil *Salumiphocaena stocktoni*

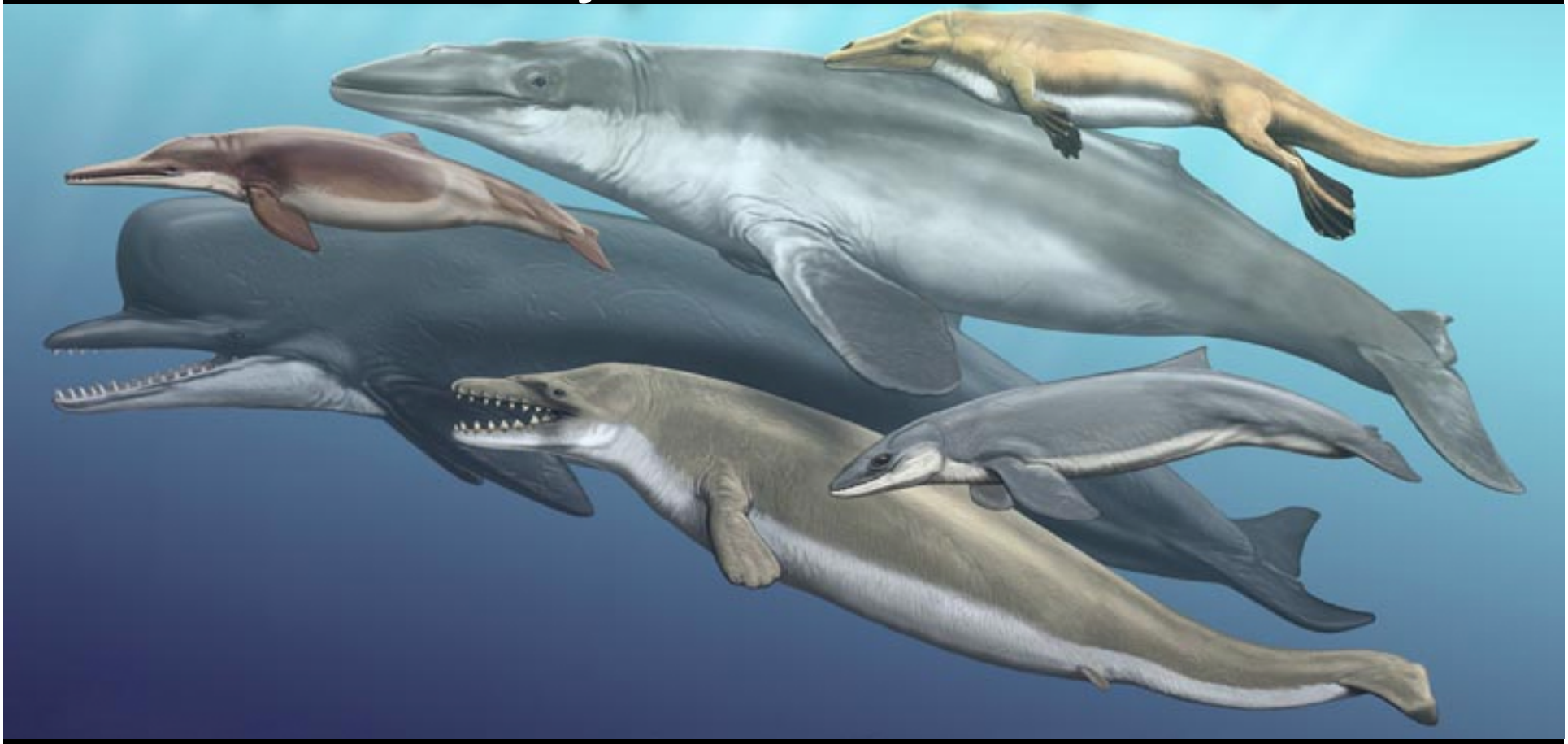
Vestibule & Semicircular canals (rotational movement detection)



Cochlea (hearing)

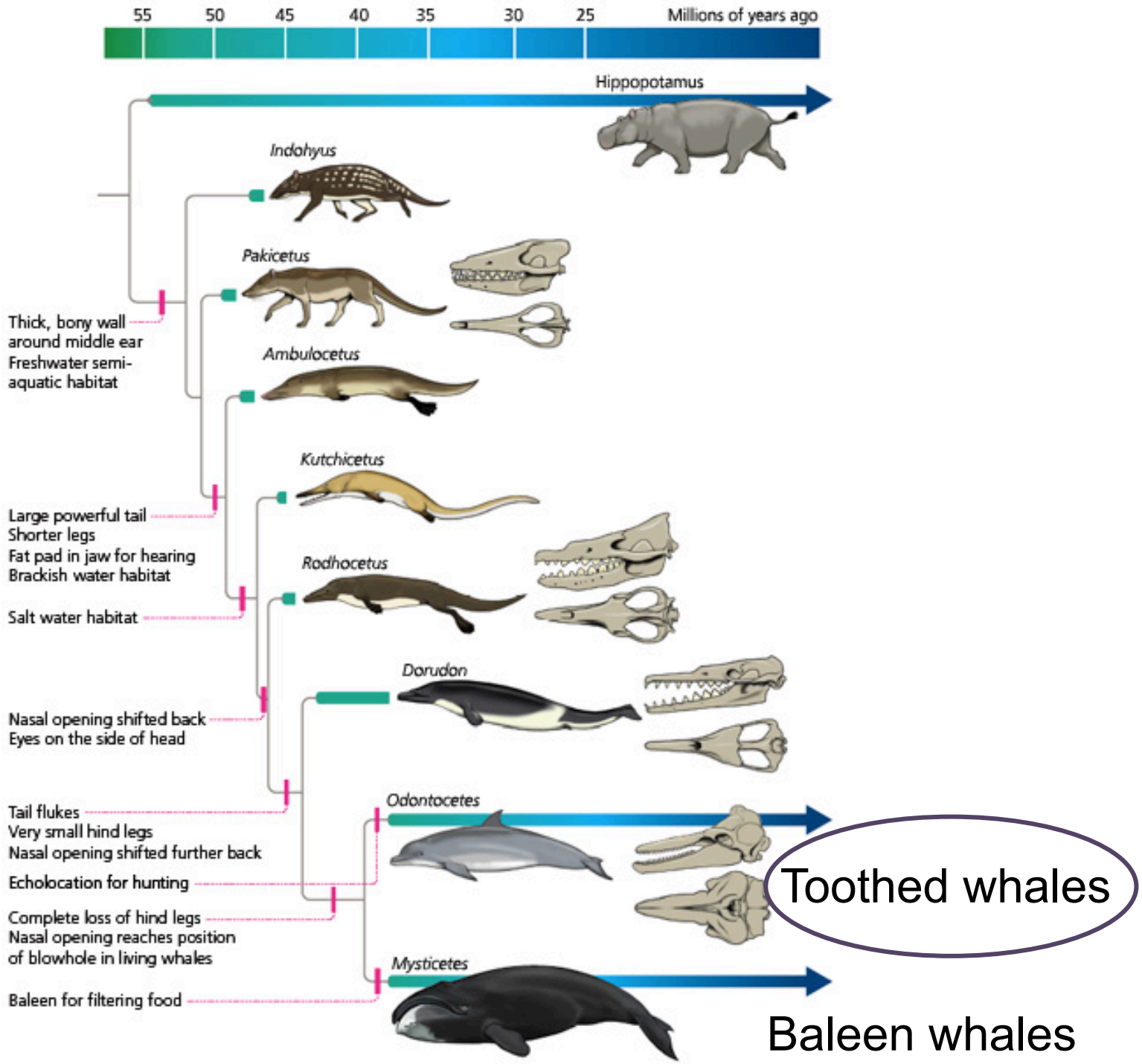
Racicot et al. 2016 *BJLS*

# Whales have undergone one of the most dramatic transitions in mammalian history



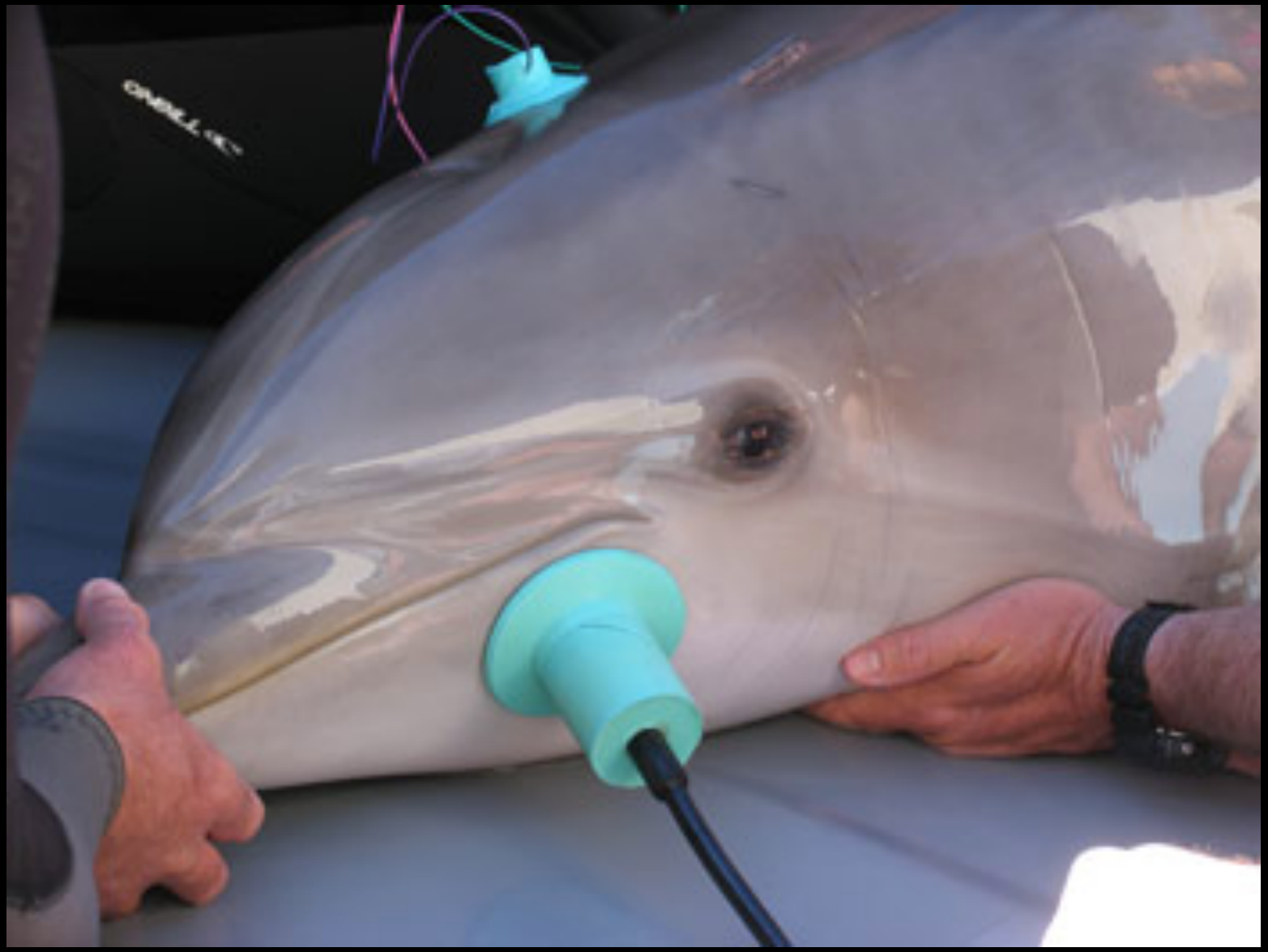
Carl Buell

Marine Mammal Encyclopedia



How do we measure hearing in whales?

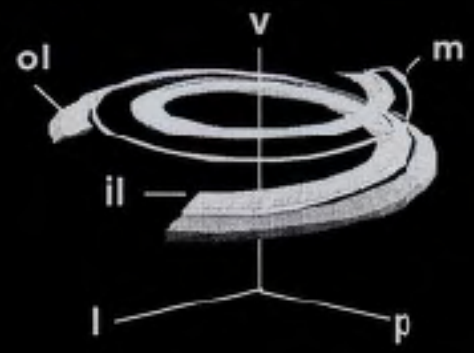
# How do we assess hearing in living whales?



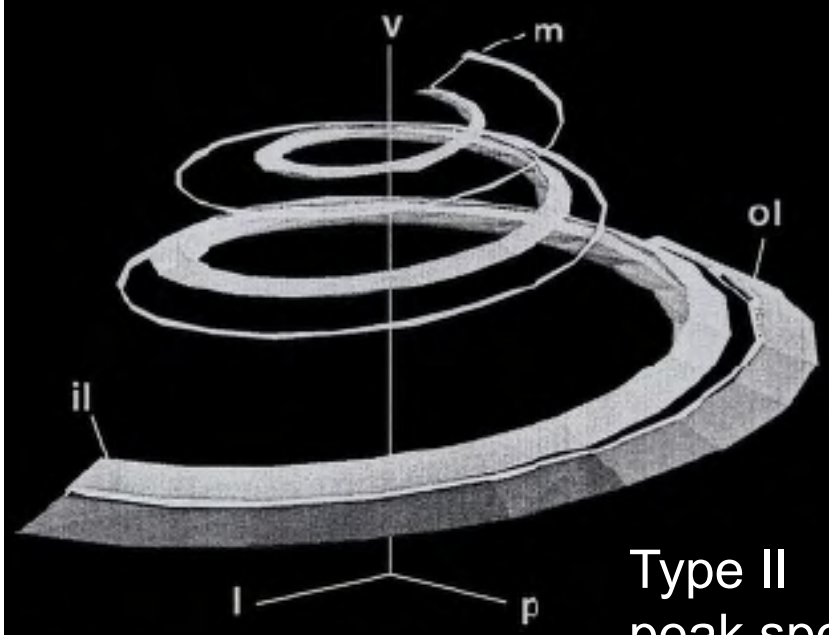
Houser 2014

# Spiral “types” associated with hearing

Odontoceti




Type I
peak spectra
above 100
kHz




Type II
peak spectra
below 80 kHz

My

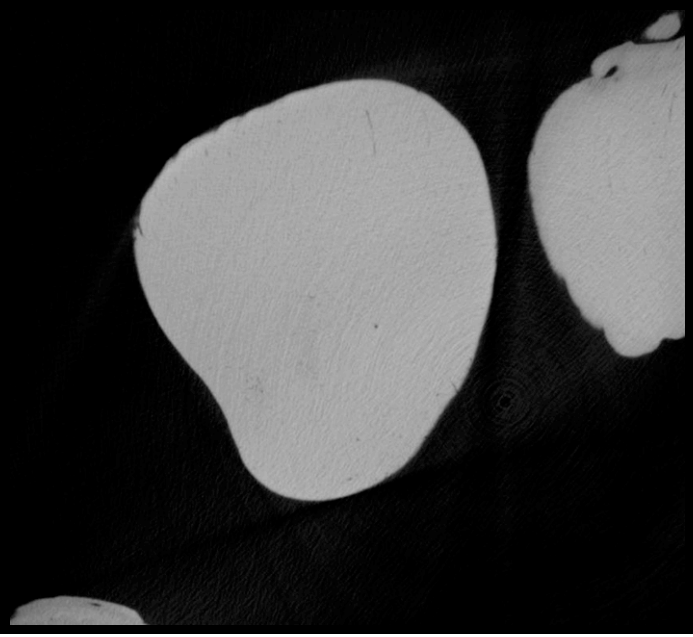
Ketten 1992

# If estimated for species with unknown hearing ranges, what about fossils?

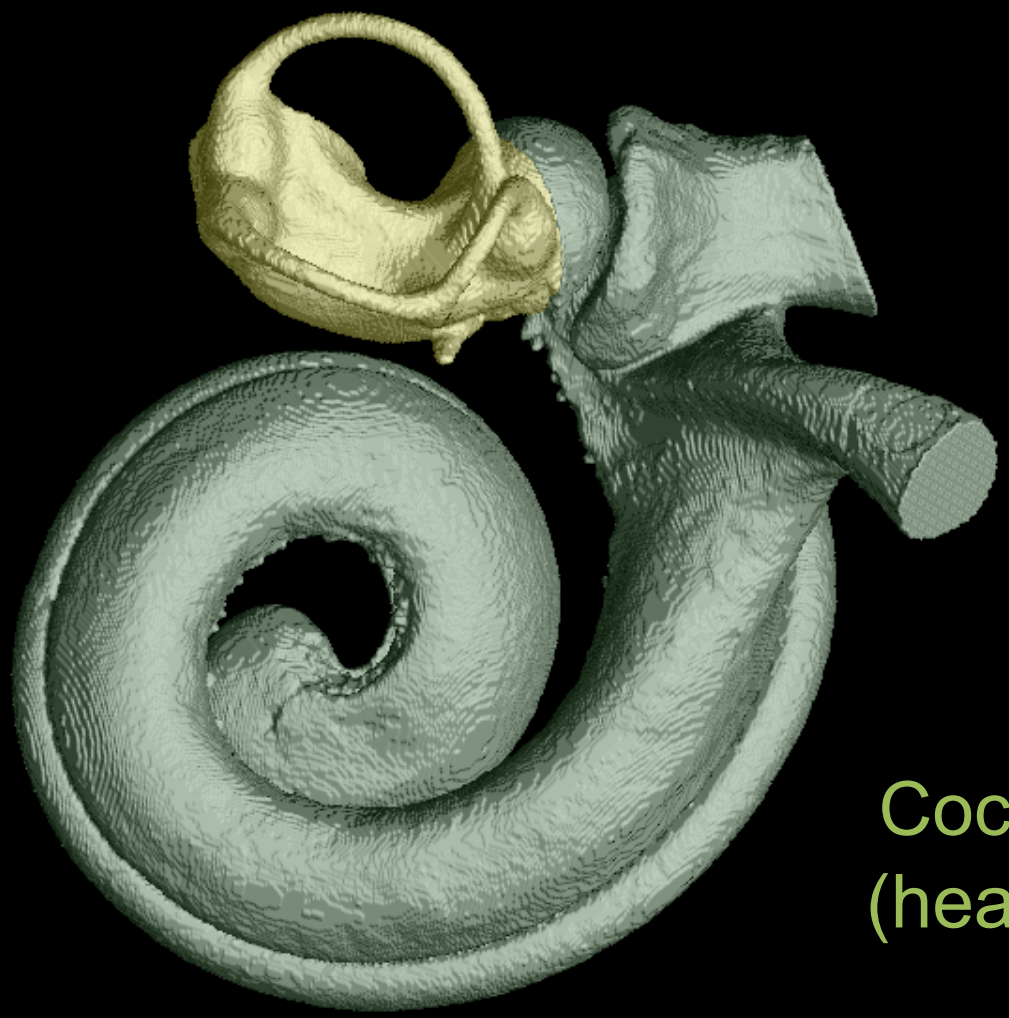
Fossils can then tell us when and possibly why specialized hearing evolved in certain lineages

# X-Ray microCT

Non-destructive, quick (< 1 hour), µm-scale resolution (maps X-ray attenuation)

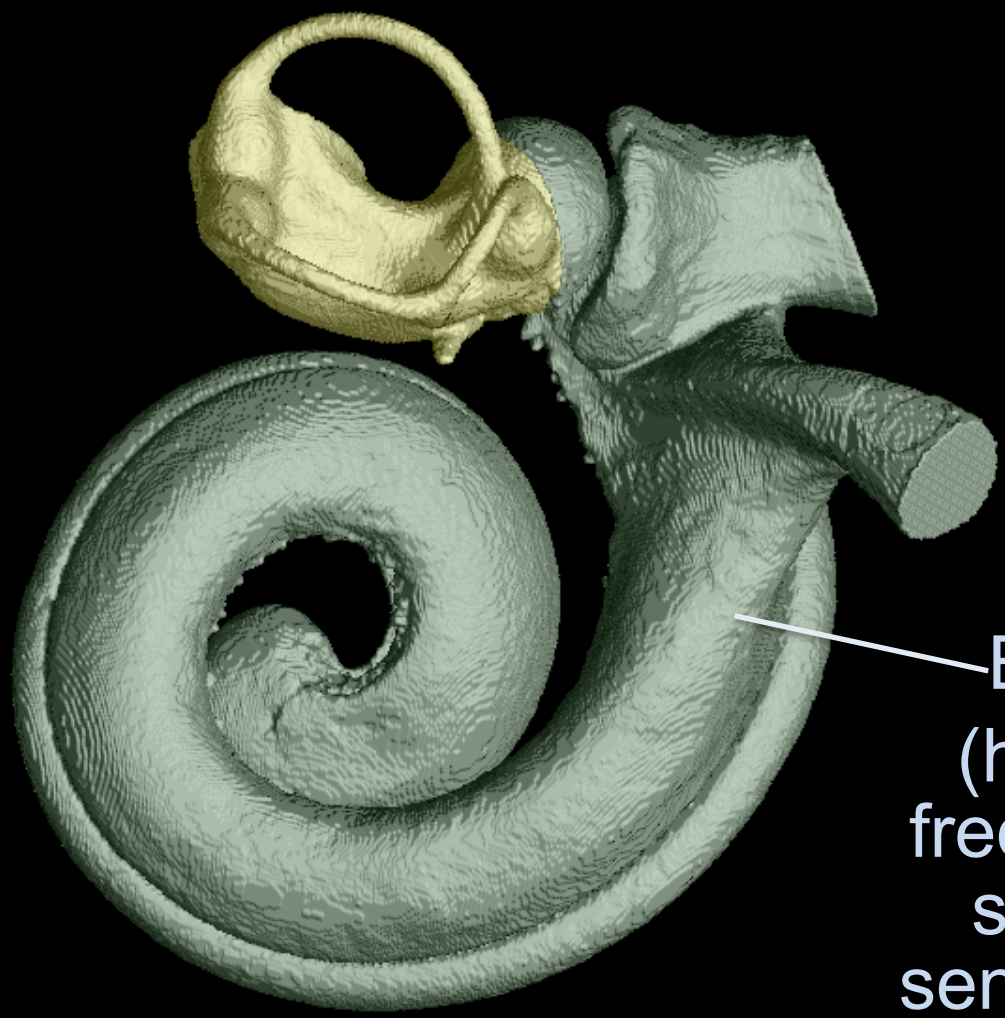
# Porpoise fossil *Salumiphocaena stocktoni*



Cochlea
(hearing)

Racicot et al. 2016 *BJLS*

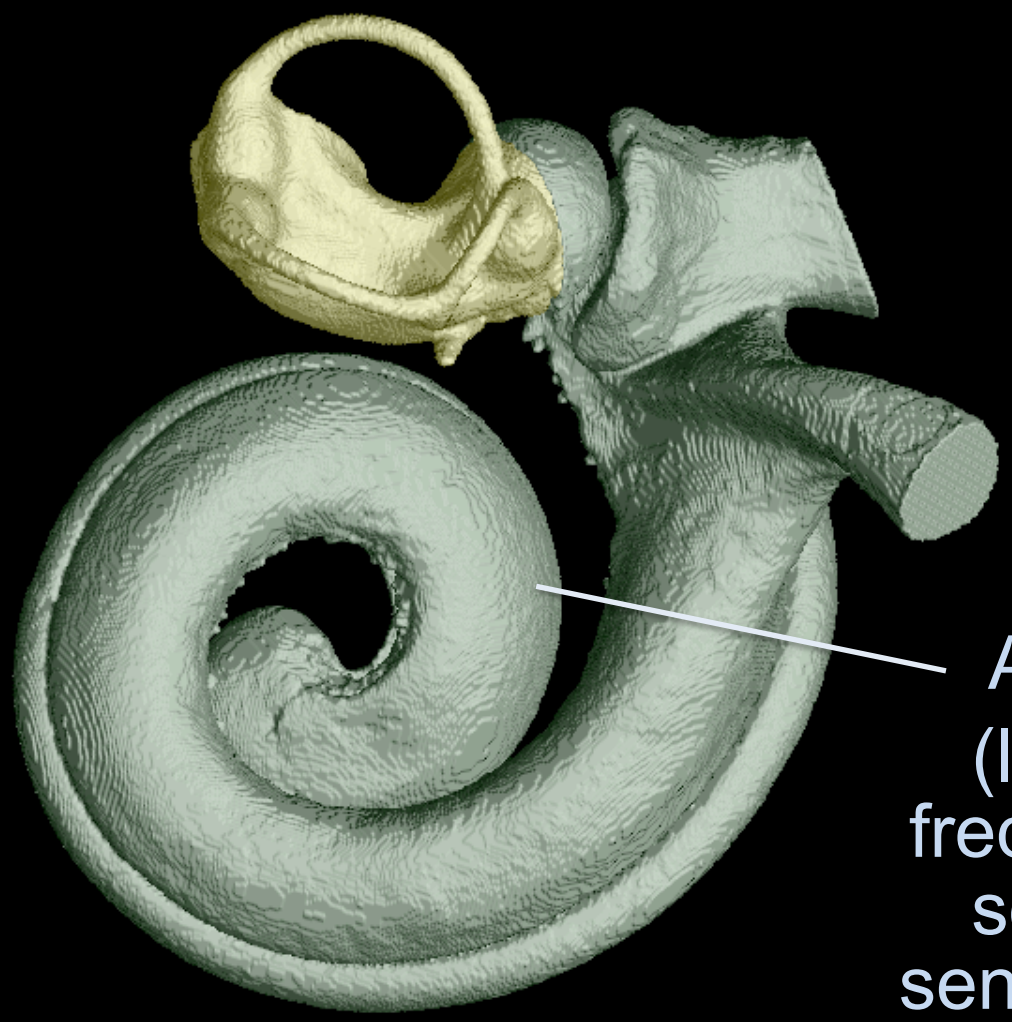
# *Salumiphocaena stocktoni*



Base
(higher frequency sound sensitivity)

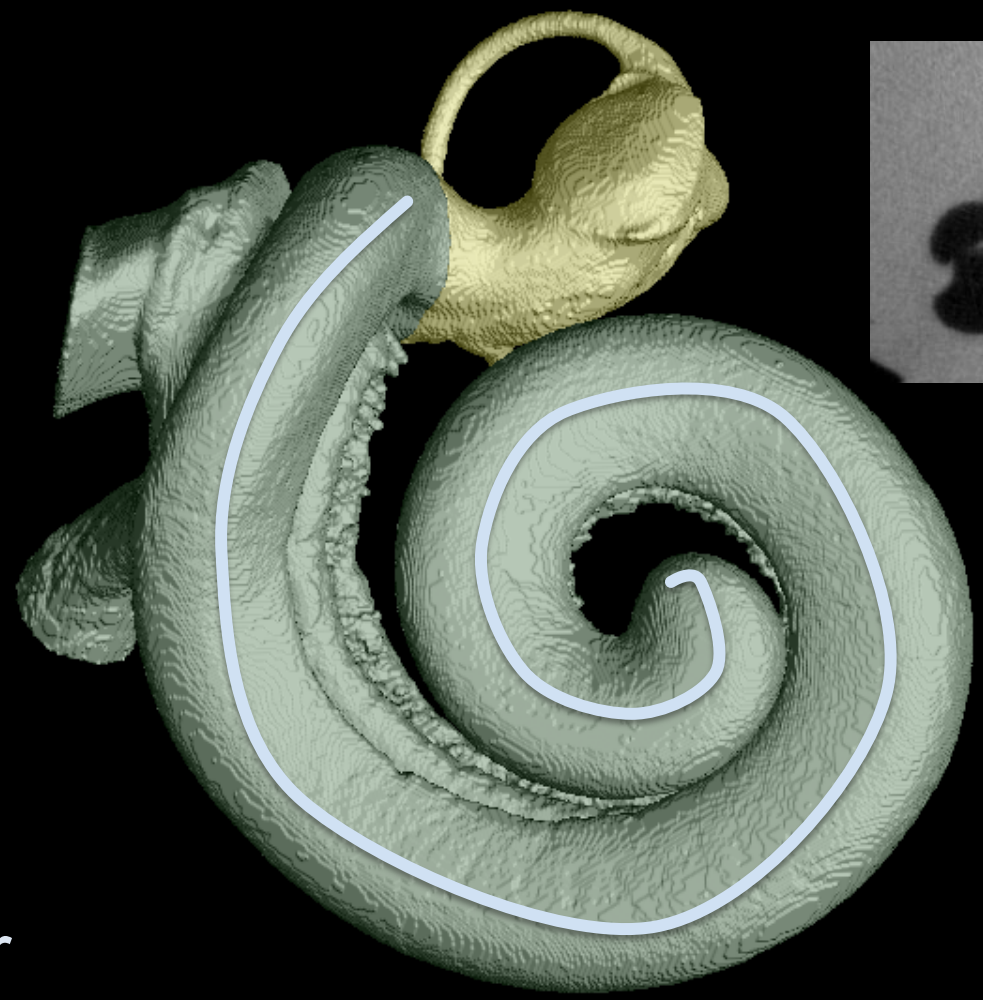
Racicot et al. 2016 *BJLS*

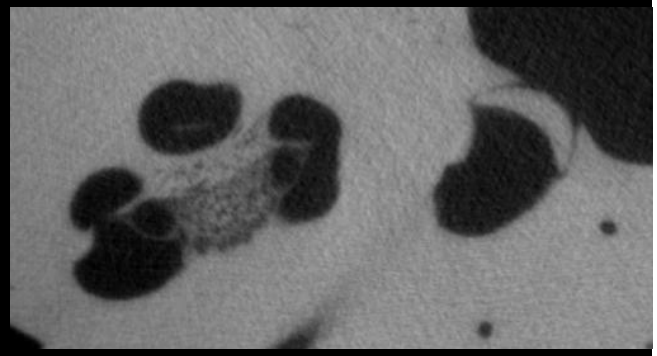
# *Salumiphocaena stocktoni*




Racicot et al. 2016 *BJLS*

# Measurements correlate with hearing sensitivity



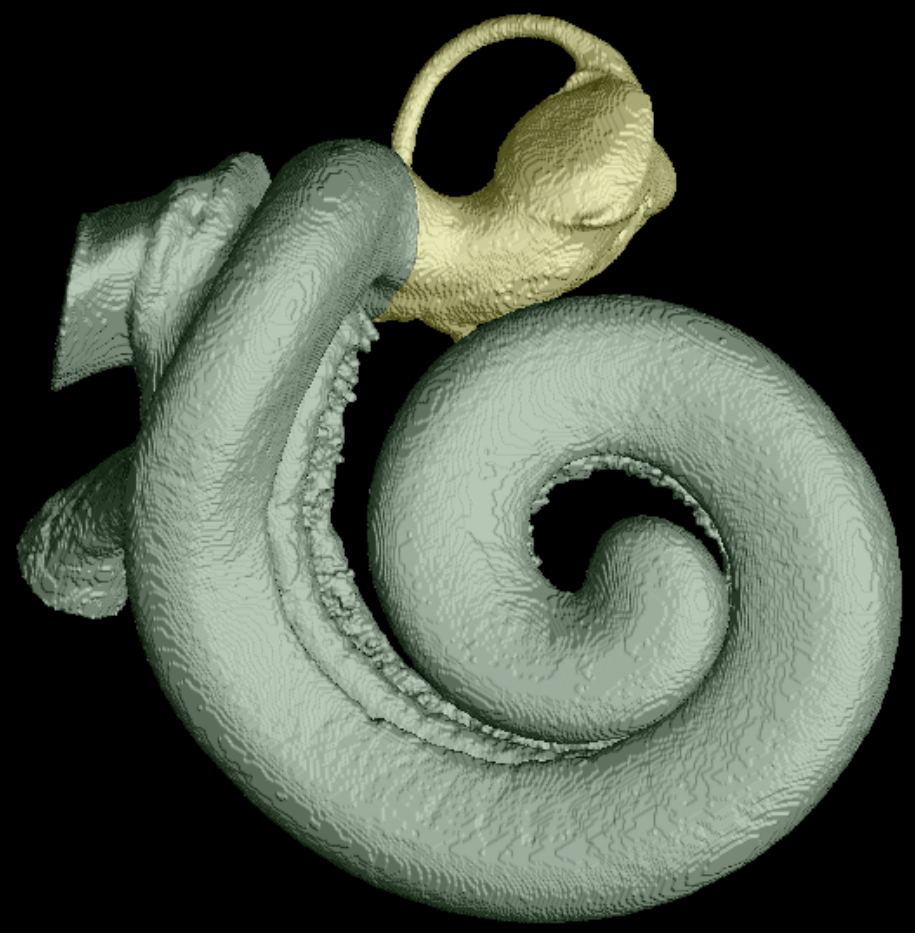


Cochlear
spiral length

Racicot et al. 2016 *BJLS*

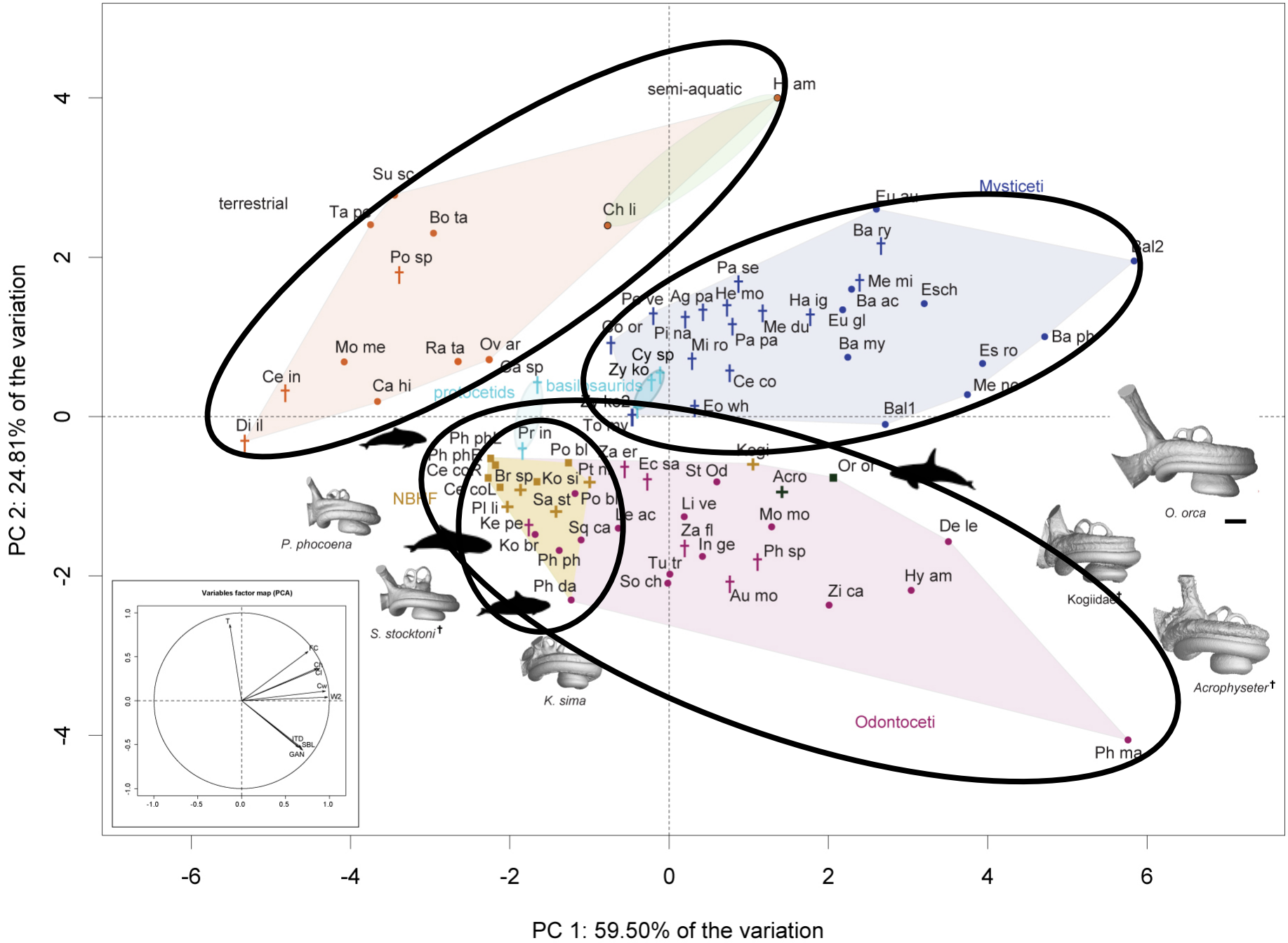
# Proxies for specialized hearing frequencies

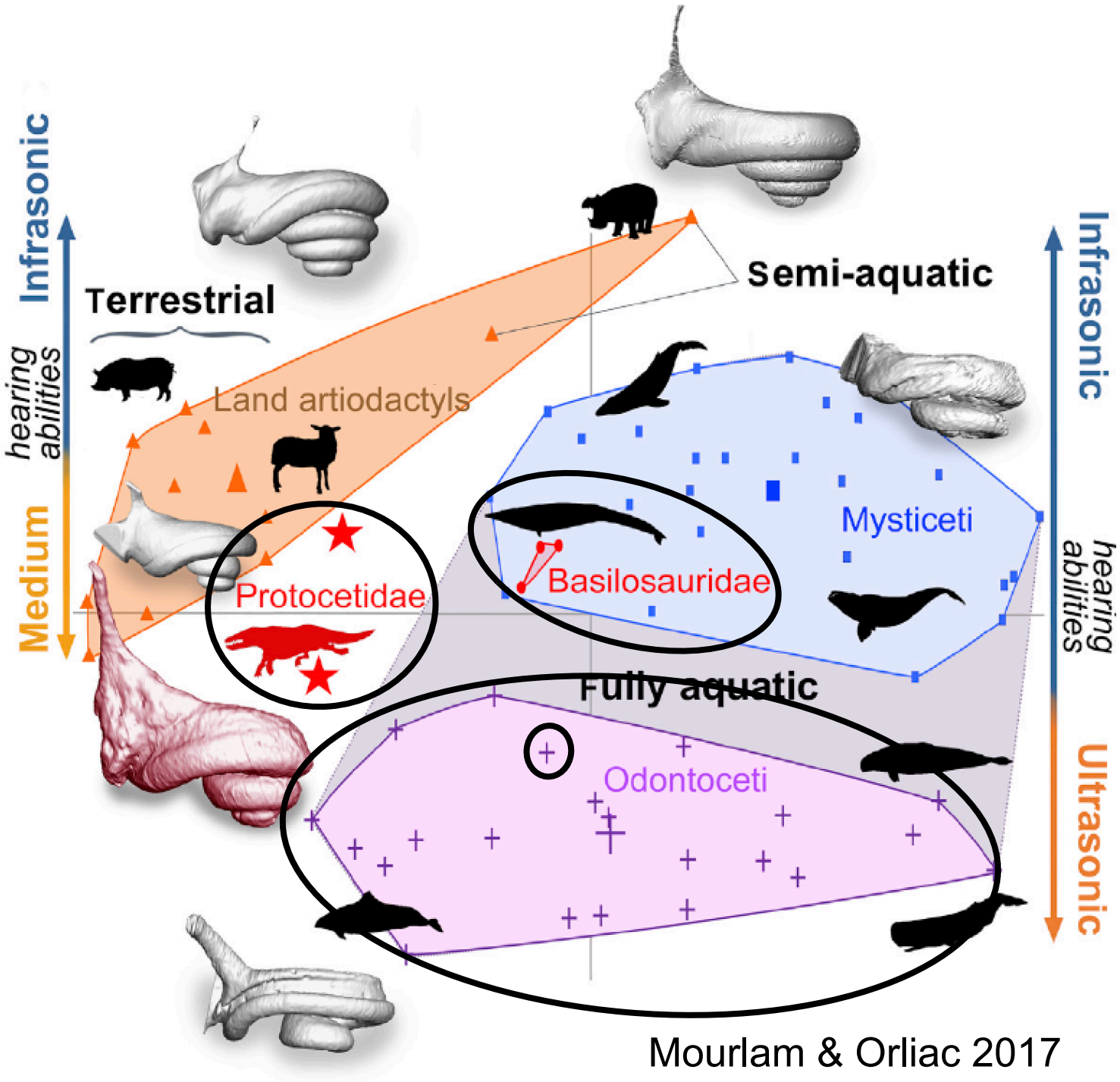
9 measurements for each taxon plugged into PCA



Racicot et al. 2016 *BJLS*

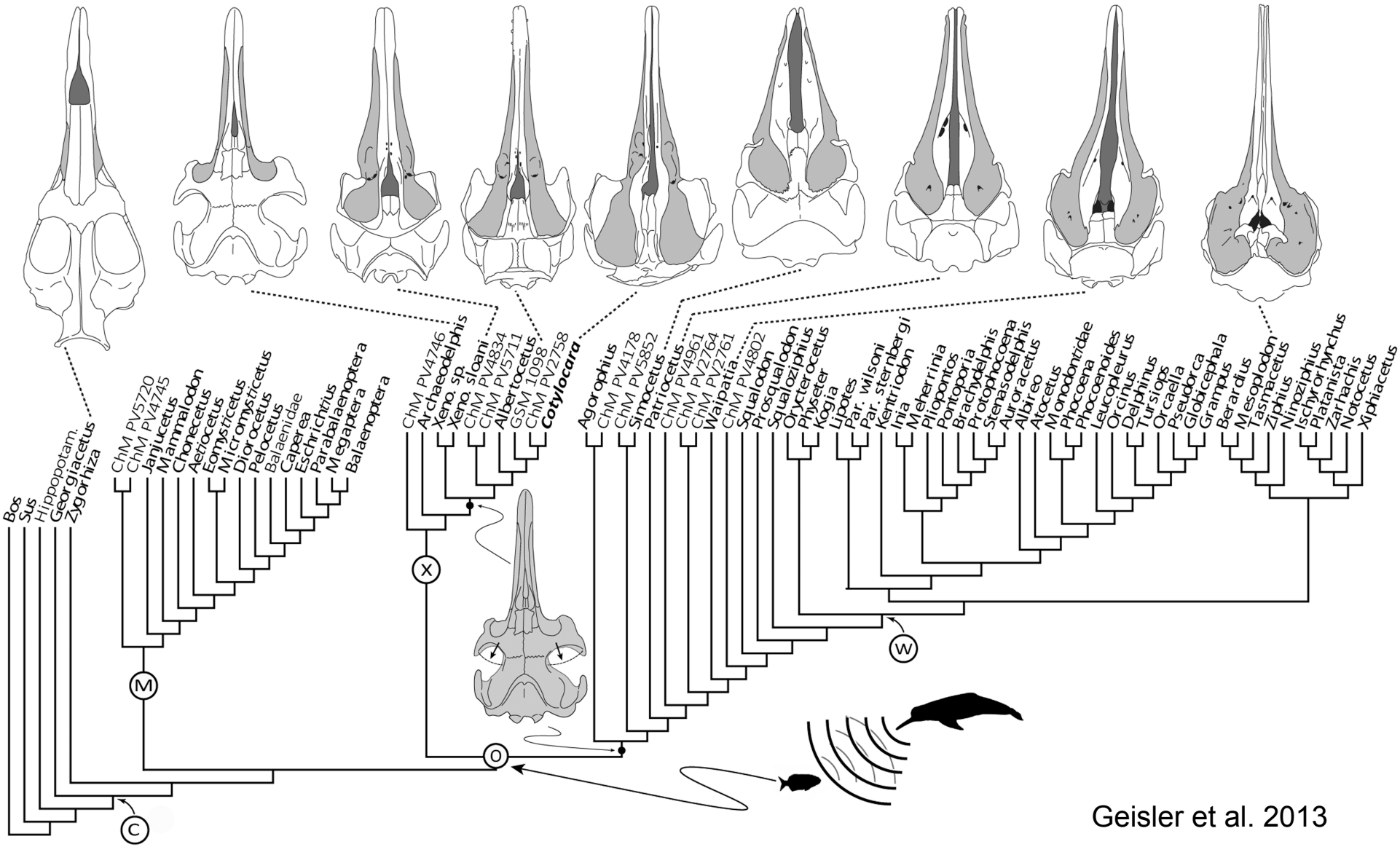
Galatius, Racicot et al. 2018 *BJLS*






Mourlam & Orliac 2017

# Oligocene: Key time for evolution of echolocation




Geisler et al. 2013

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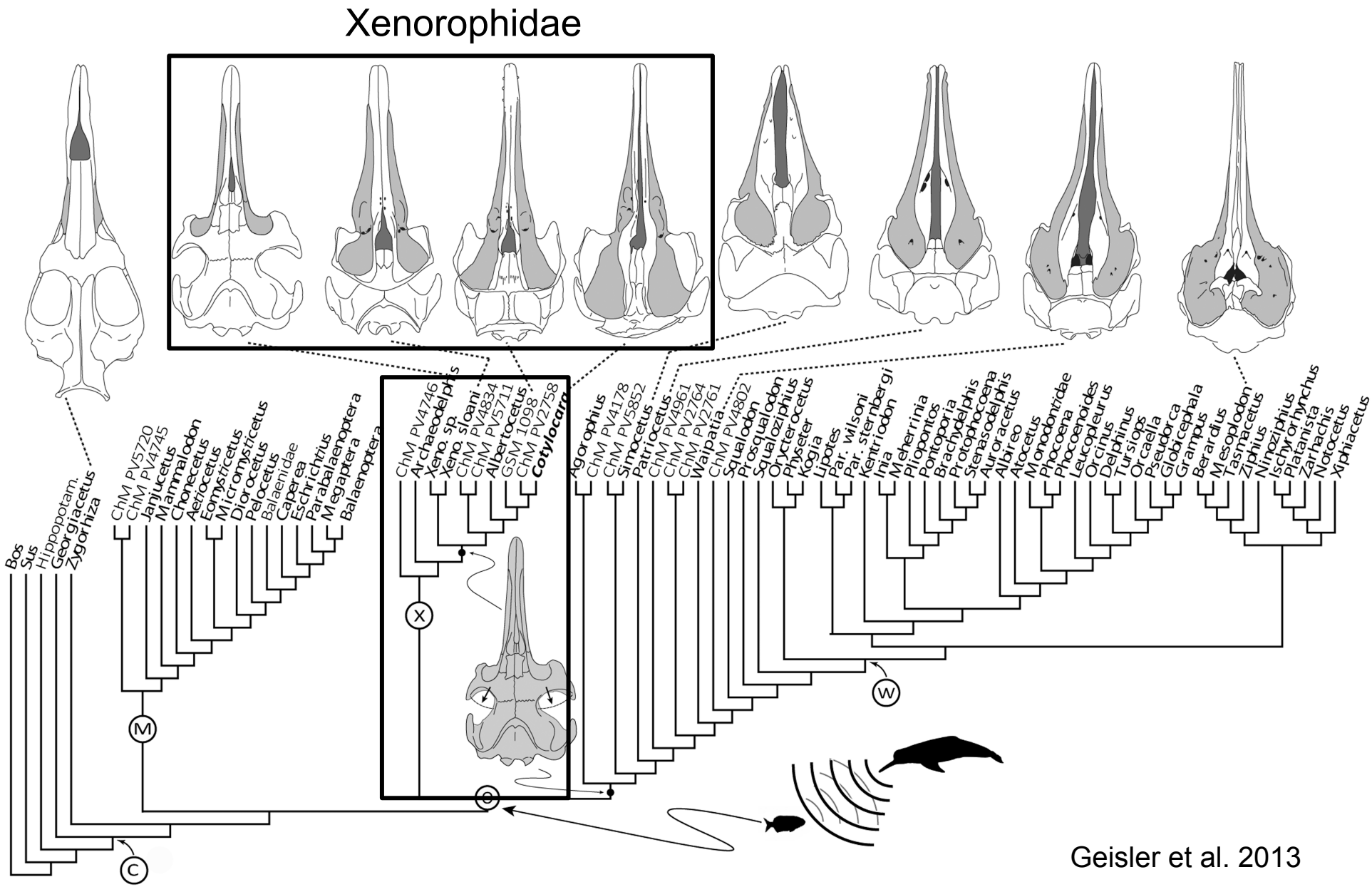

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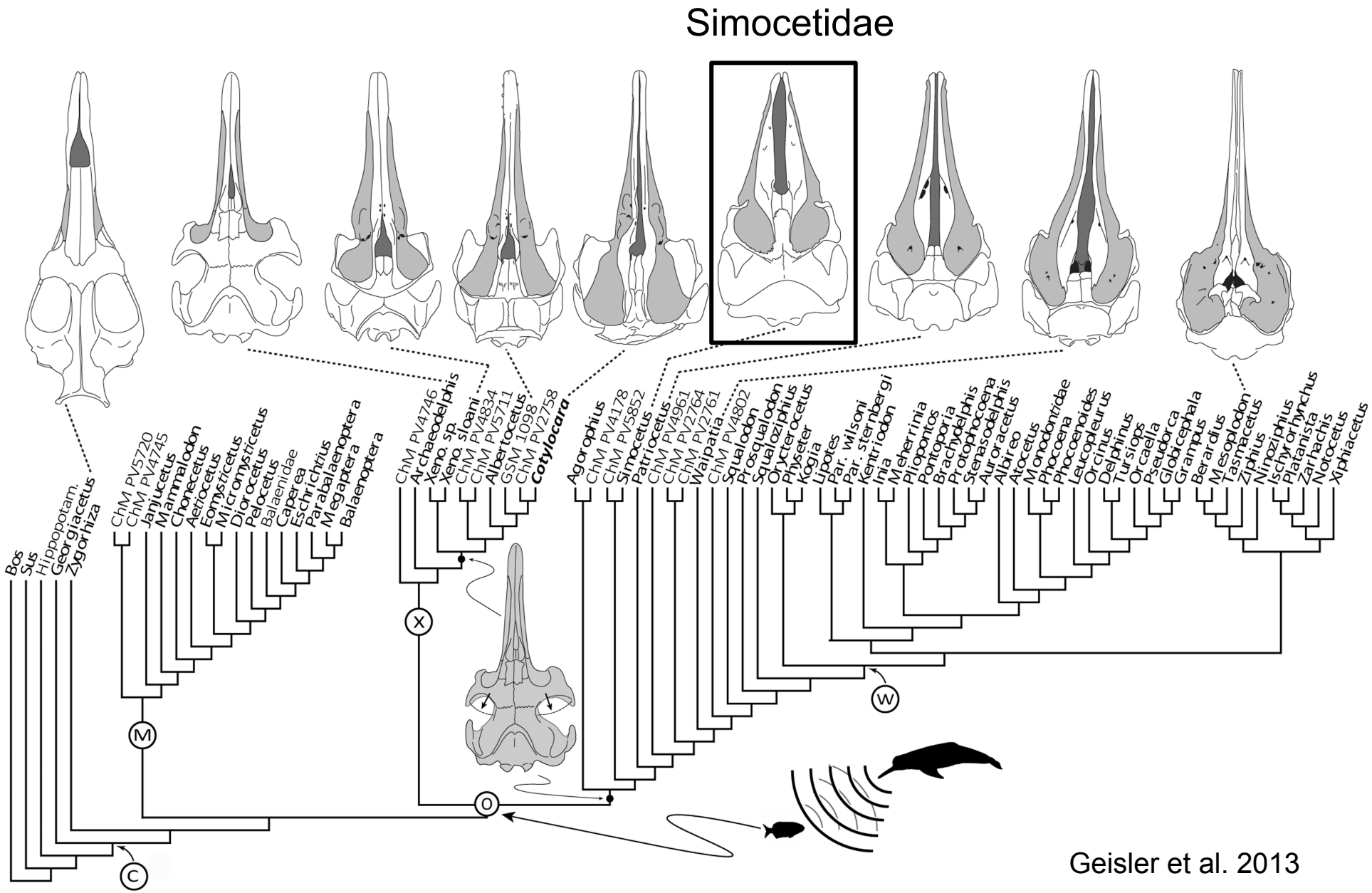
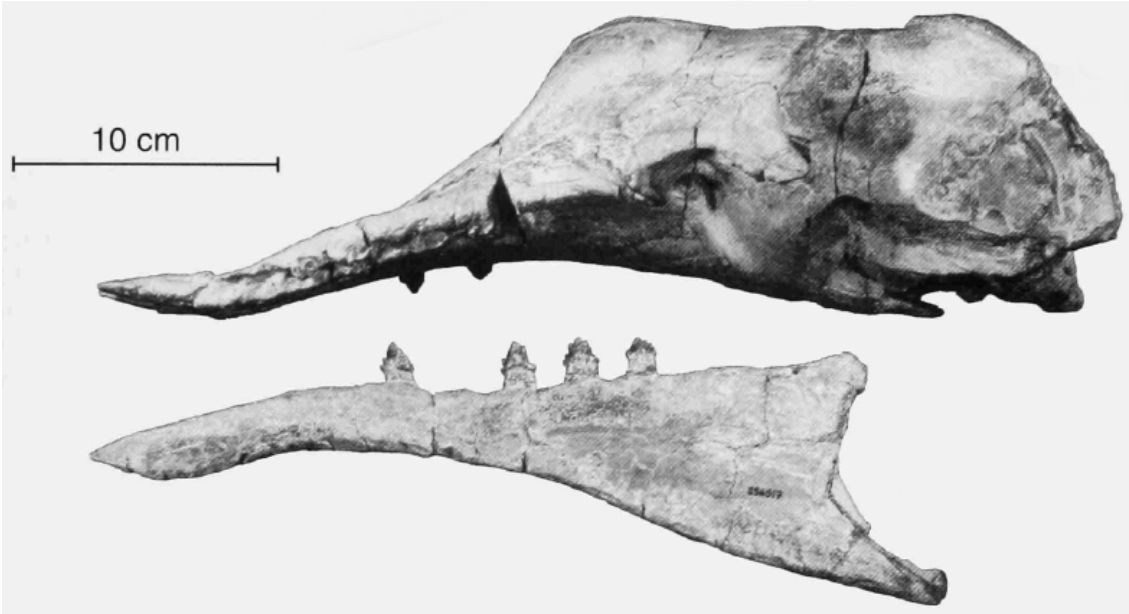



Geisler et al. 2013

# *Simocetus rayi*

Illustration by Carl Buell

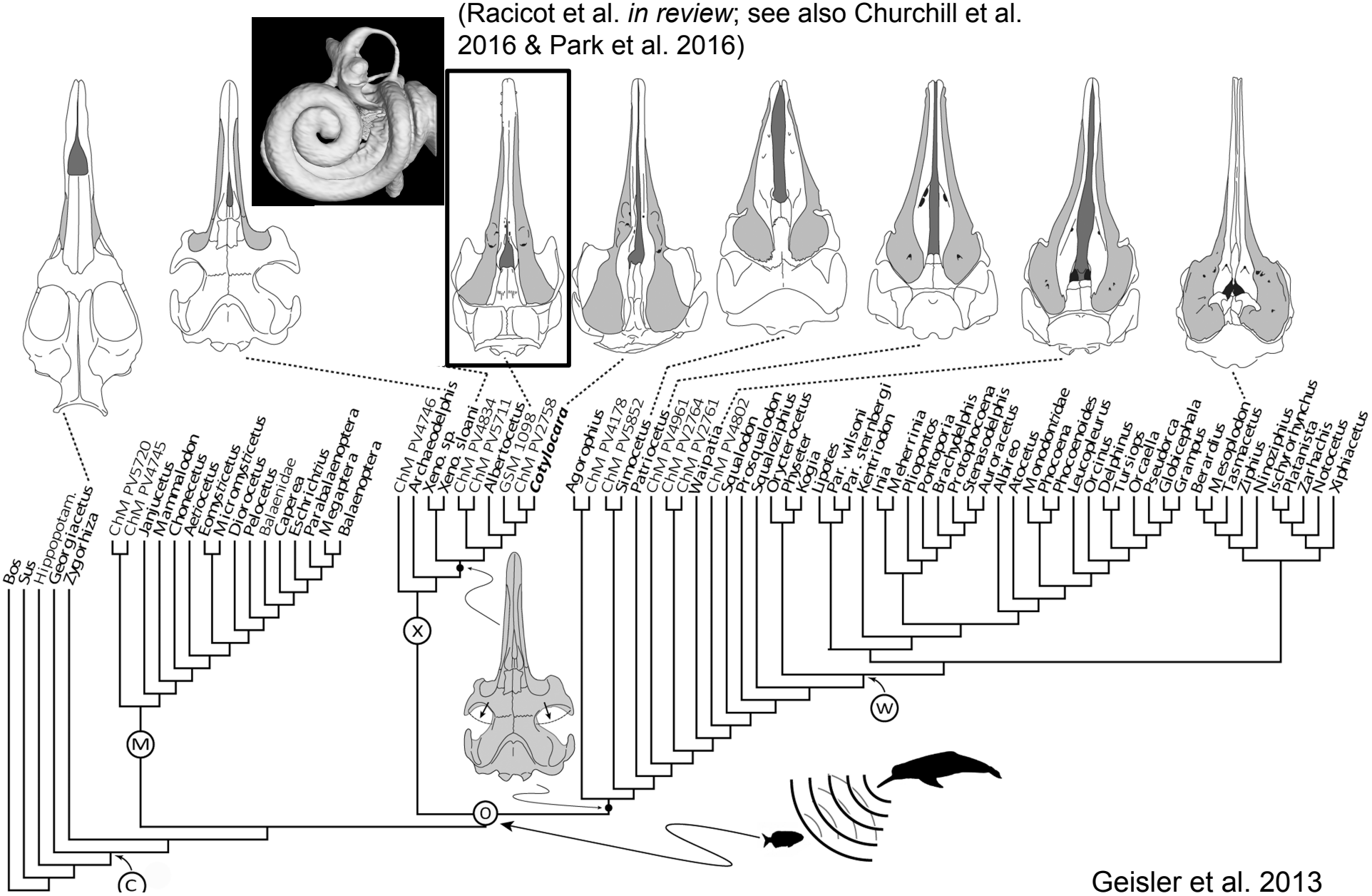



Unusual skull shape may represent specialized feeding mode

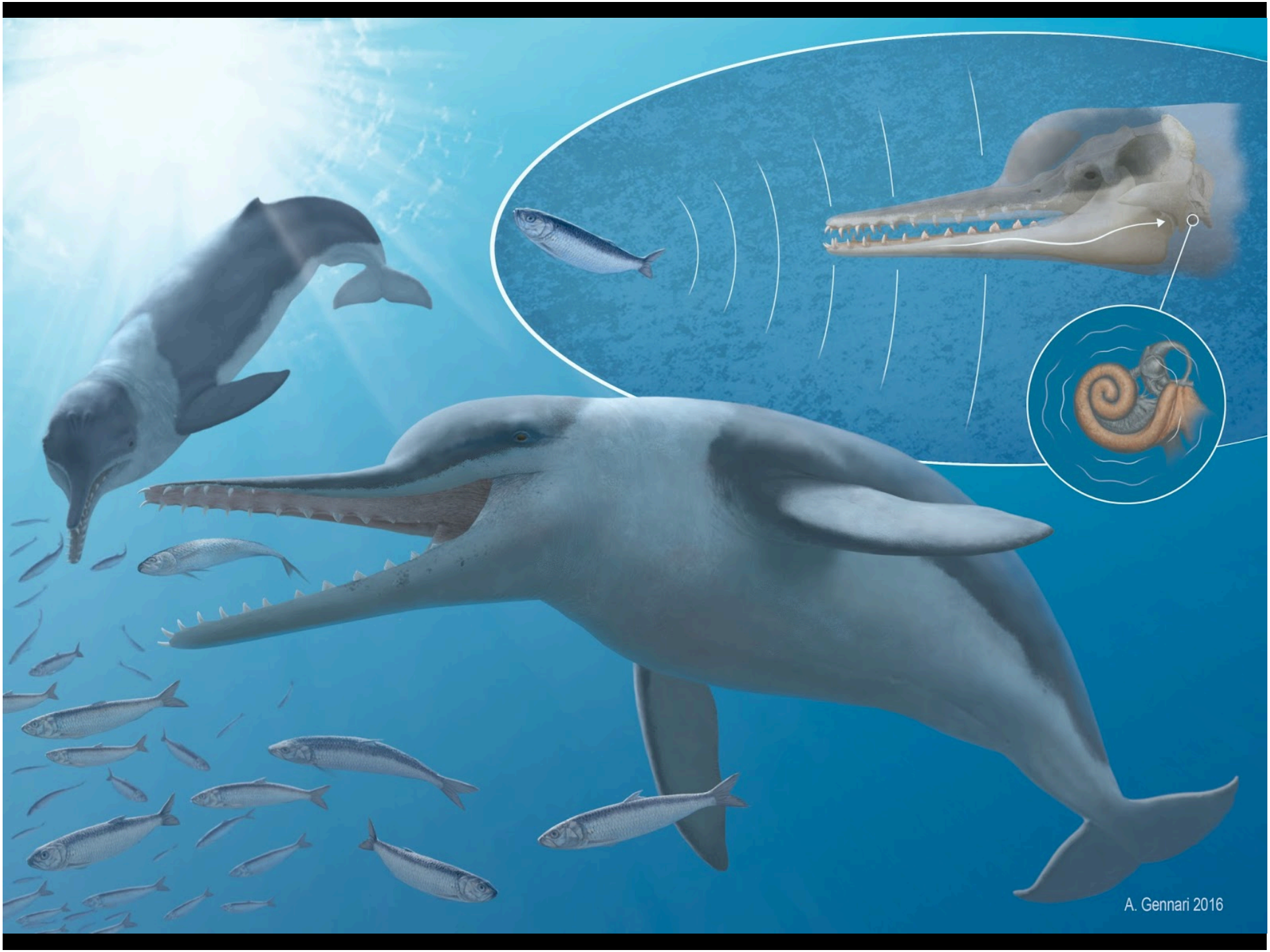
Evidence for echolocation on skull surface (Fordyce 2002)

# Xenorophid inner ear labyrinths indicate echolocation

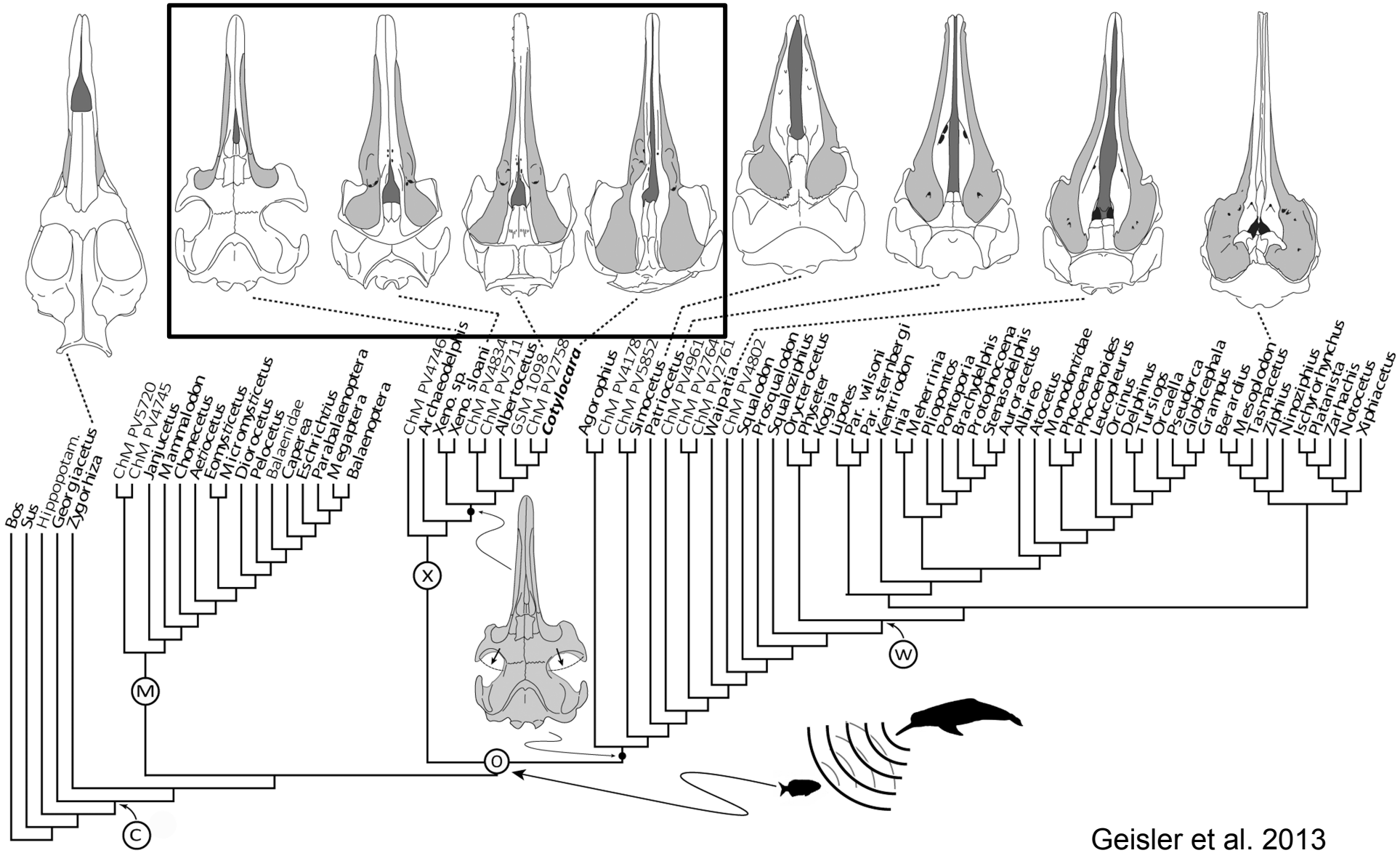
*Echovenator sandersi*
(Racicot et al. *in review*; see also Churchill et al. 2016 & Park et al. 2016)




Geisler et al. 2013


A. Gennari 2016

# Echolocation evolved in one early odontocete lineage, but what about those more closely related to Crown Odontoceti?




Geisler et al. 2013

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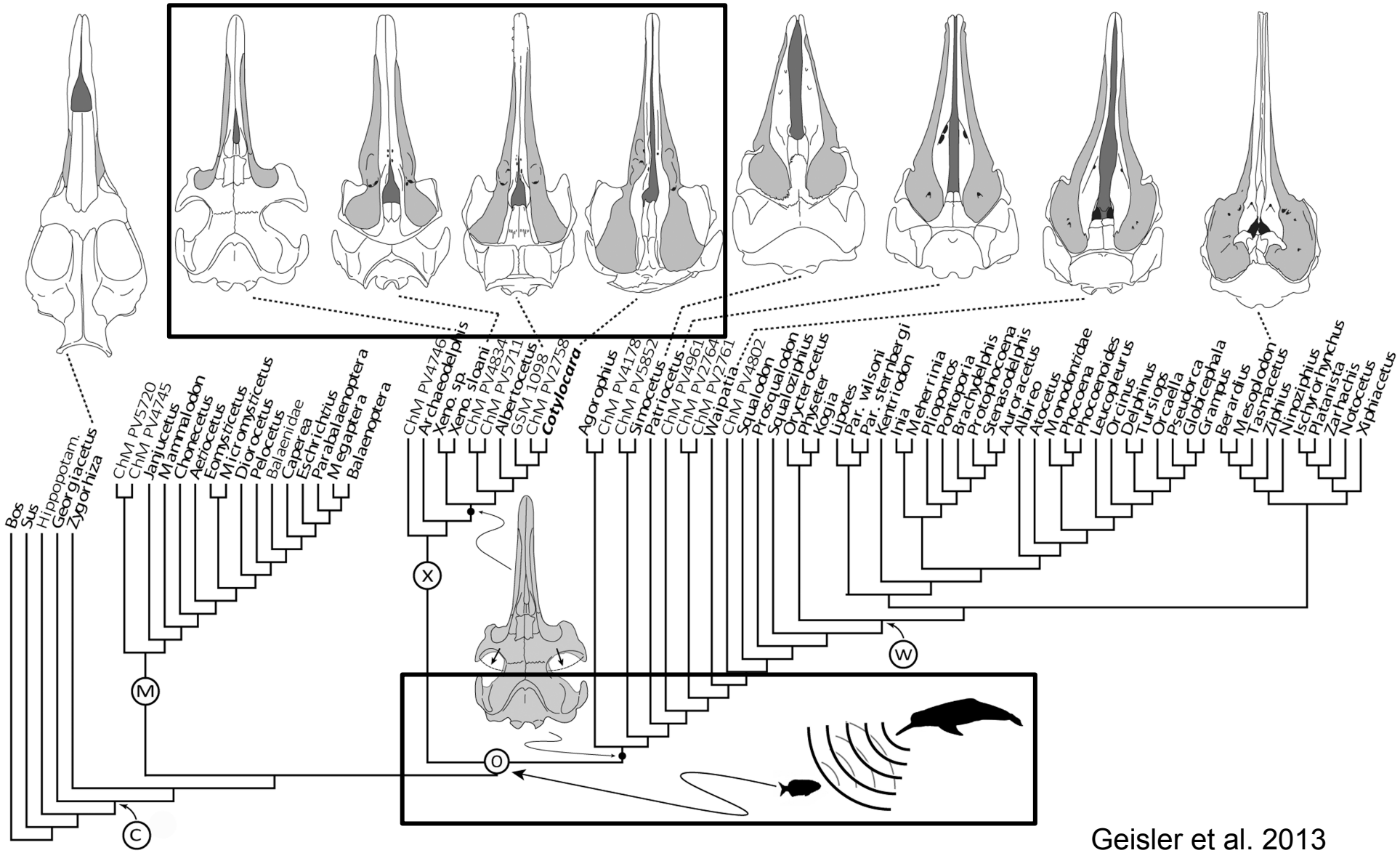


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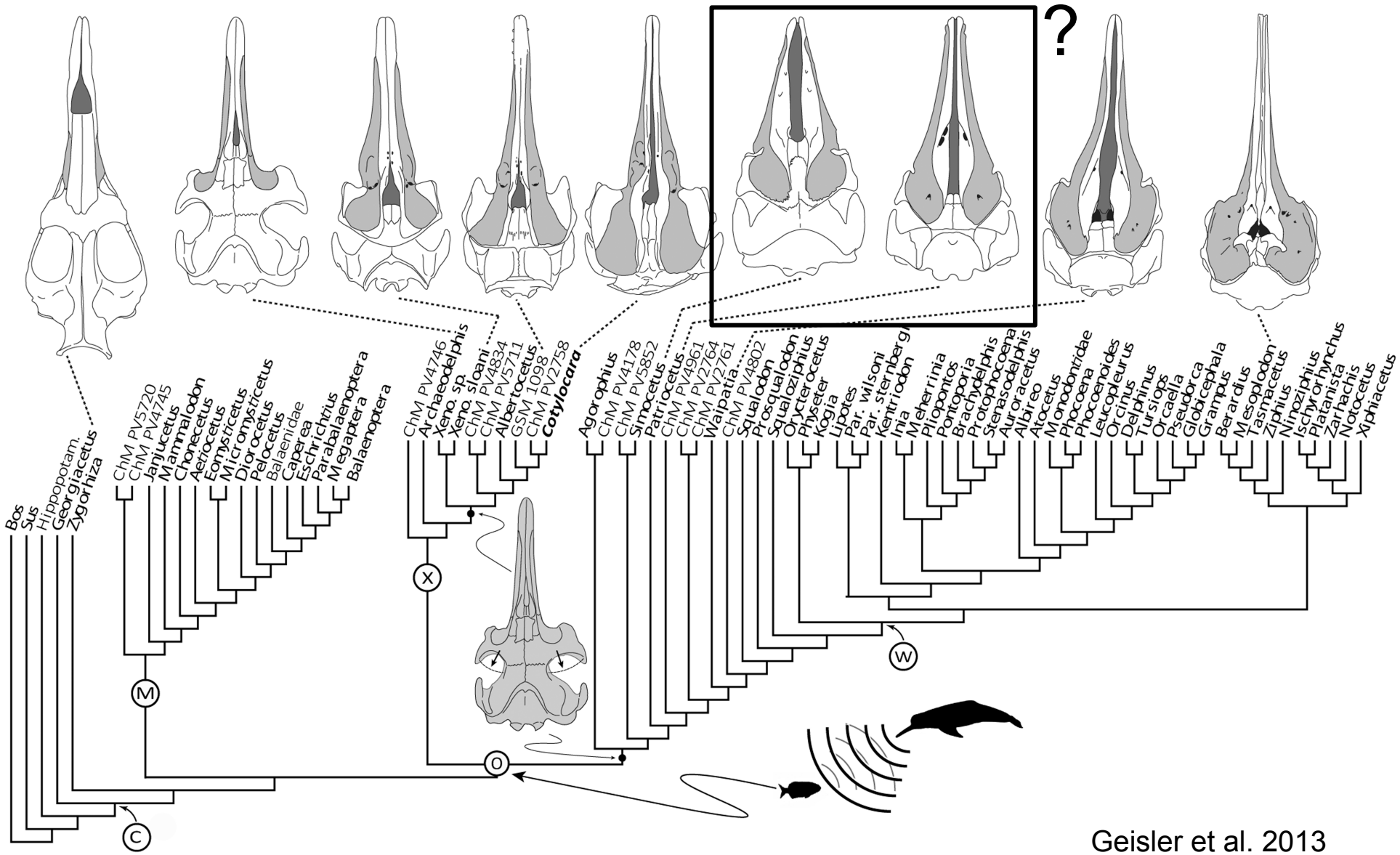
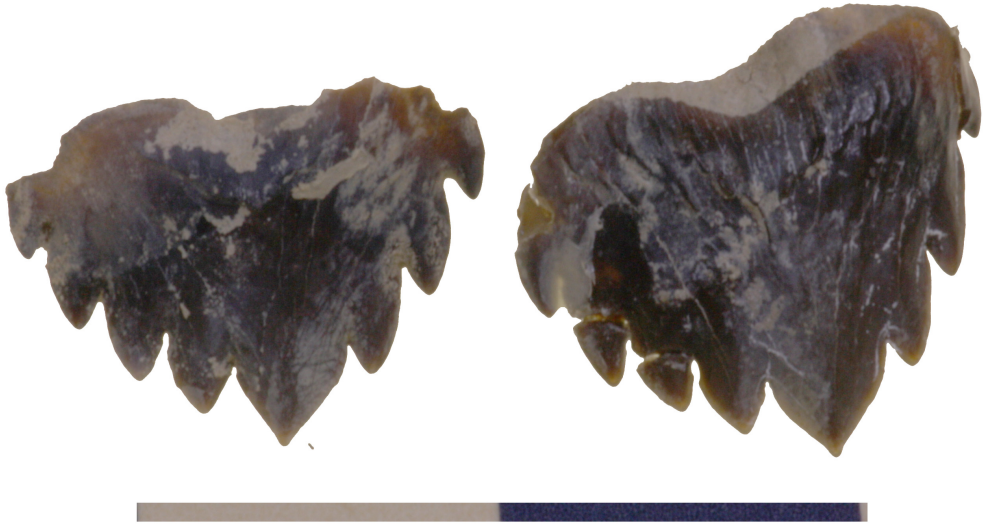
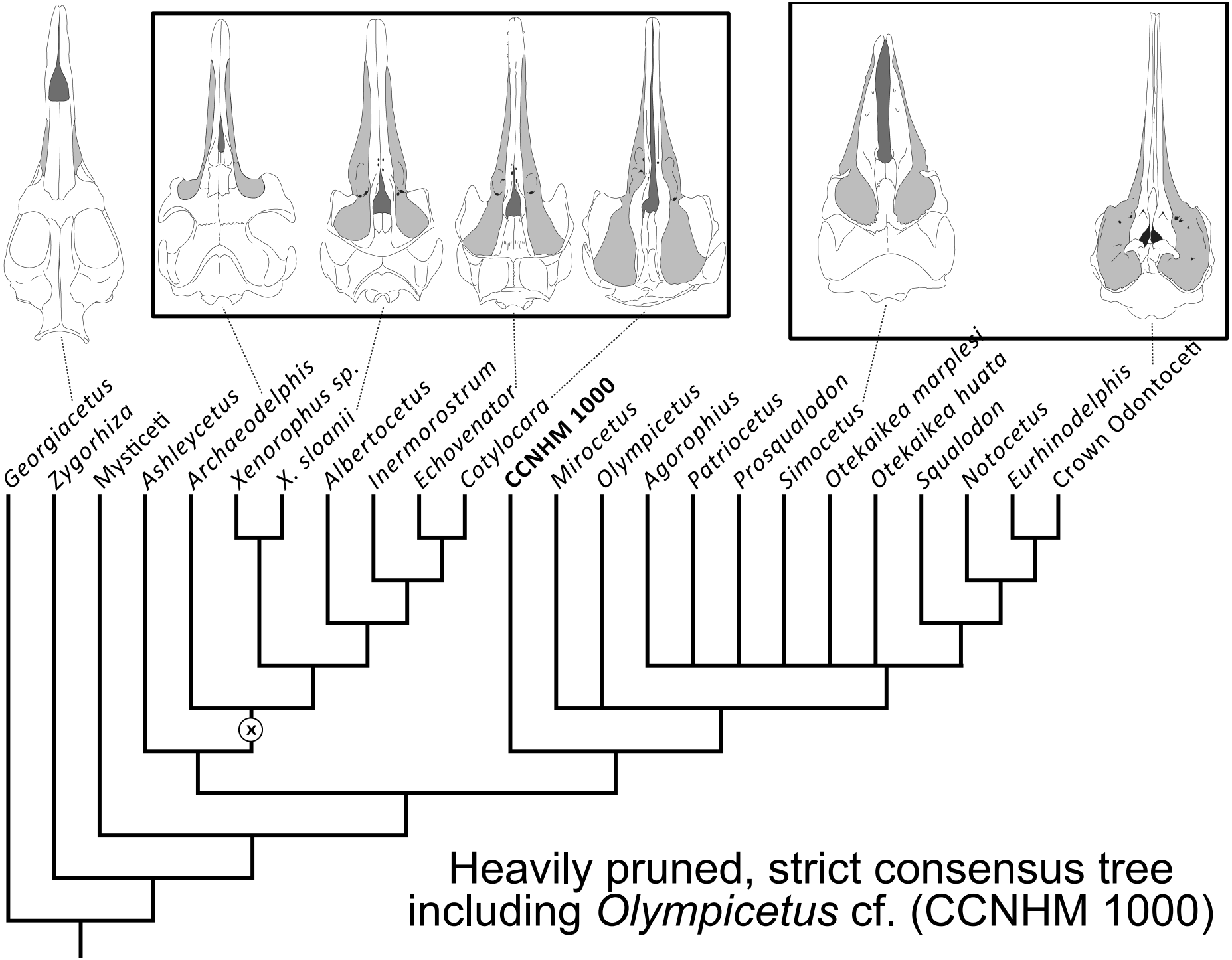


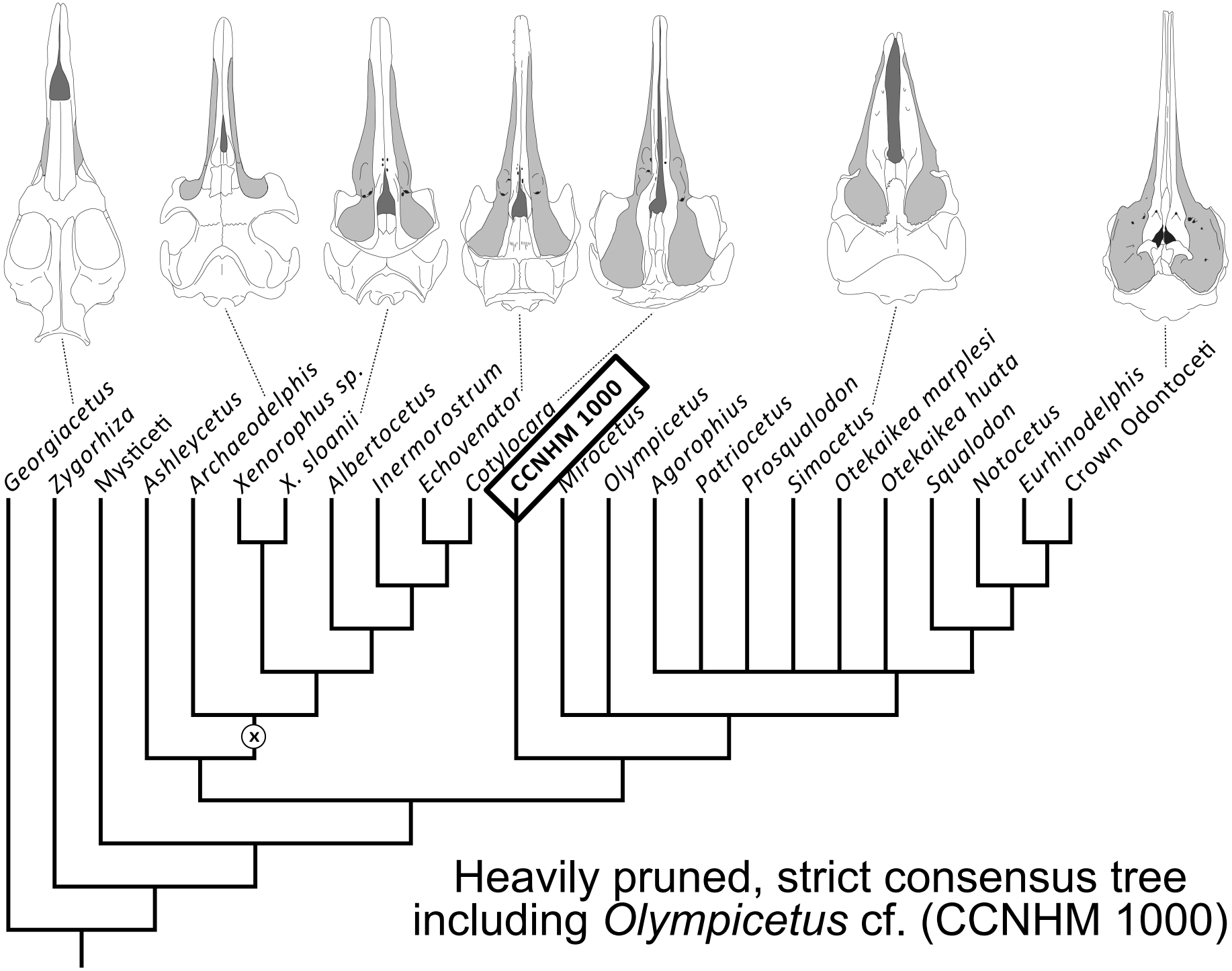

Geisler et al. 2013

*Olympicetus* cf. closely resembles *Olympicetus avitus* (Vélez-Juarbe 2017)






Heavily pruned, strict consensus tree including *Olympicetus* cf. (CCNHM 1000)



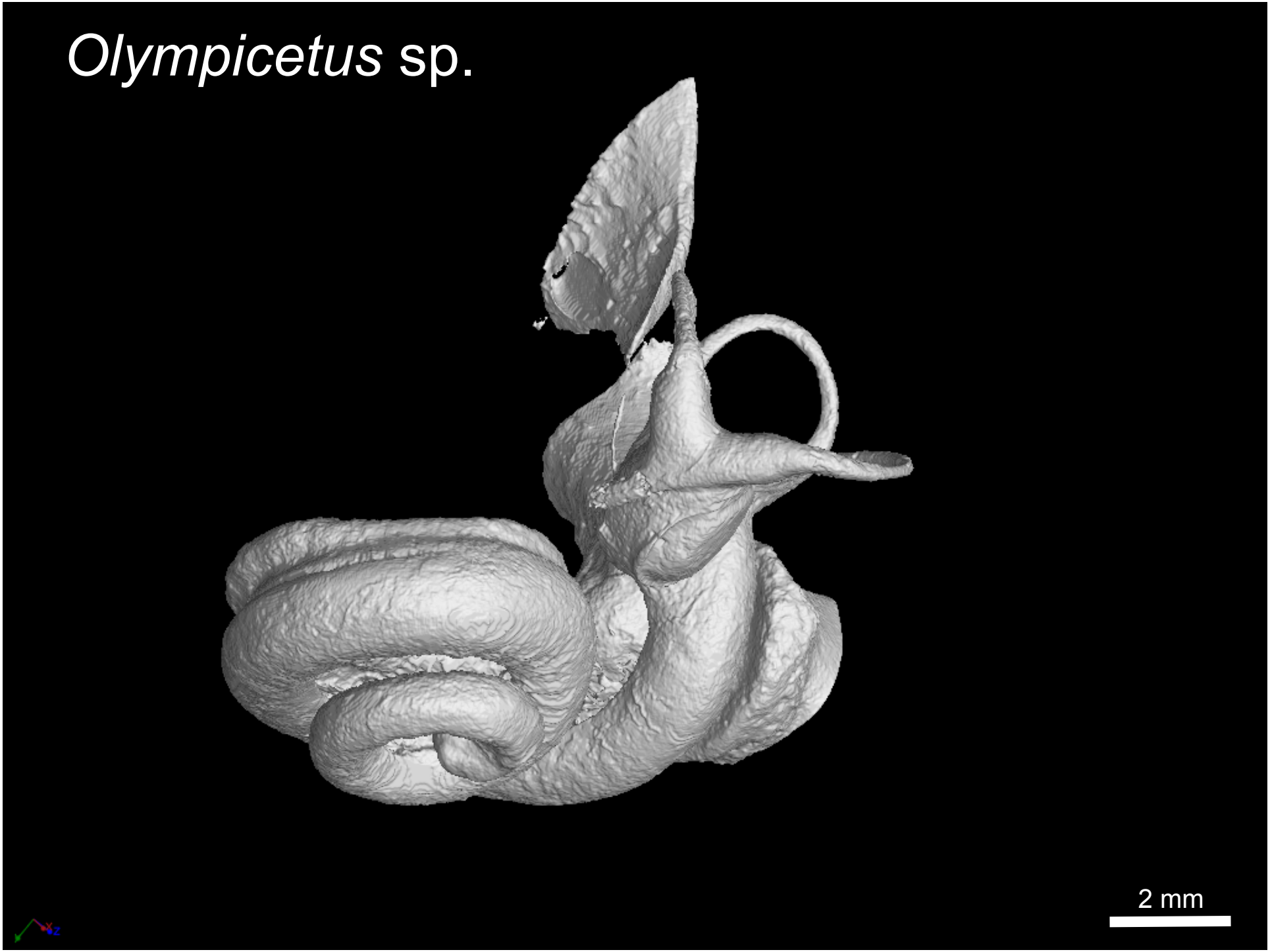

Heavily pruned, strict consensus tree including *Olympicetus* cf. (CCNHM 1000)

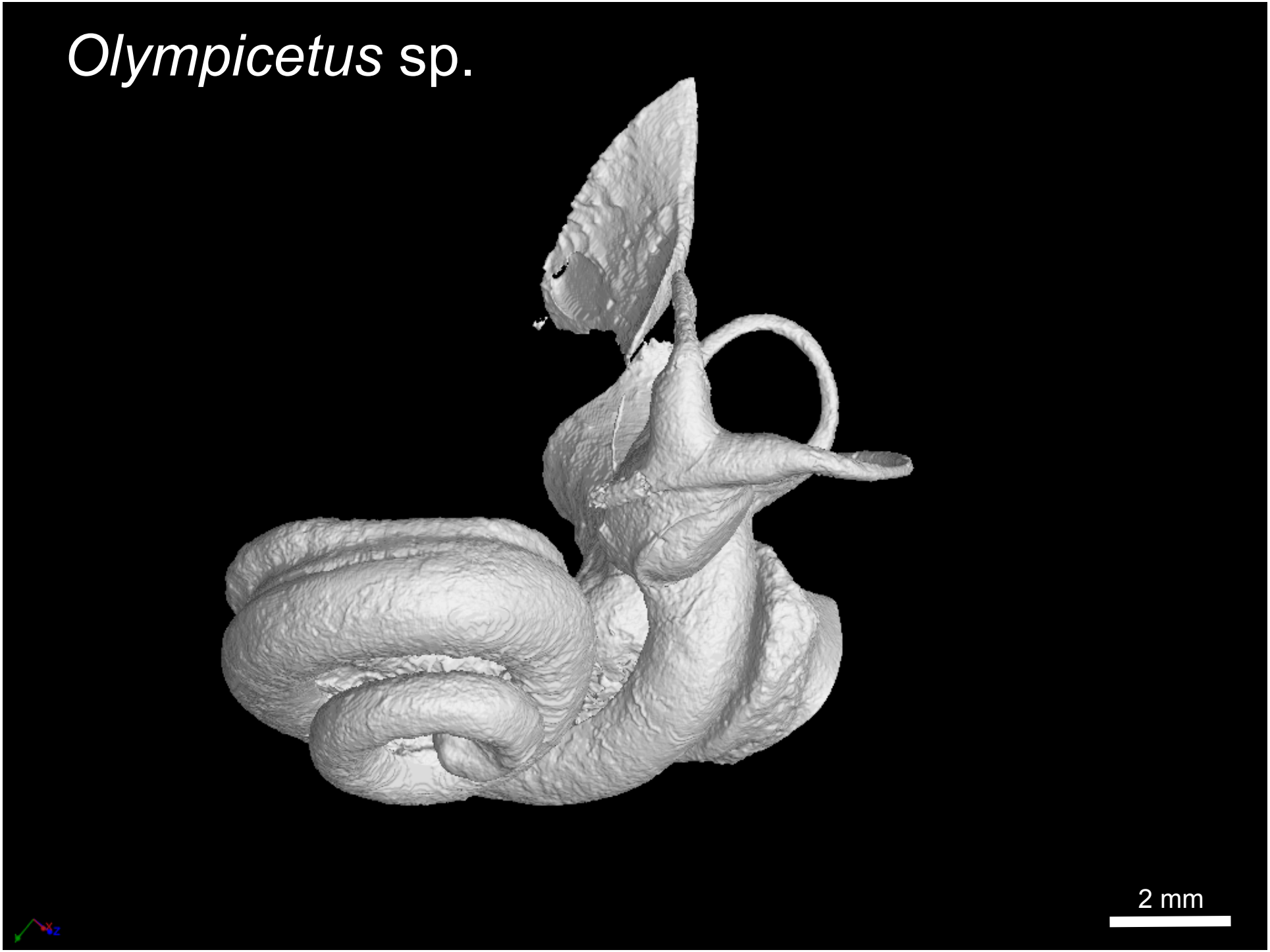
# *Olympicetus* sp. ear bone

Whole petrosal & close-up of bony labyrinth µCT scanned at Department of Earth and Environmental Sciences, Vanderbilt University

Resolution: 17.2 µm

Digital endocast constructed using VGStudioMax 2.2; measurements taken using Avizo and VGStudioMax


*Olympicetus* sp.
2 mm


*Olympicetus* sp.
2 mm

# *Olympicetus* sp. anatomy, measurements

9 cochlear measurements *sensu* Mourlam & Orliac 2017

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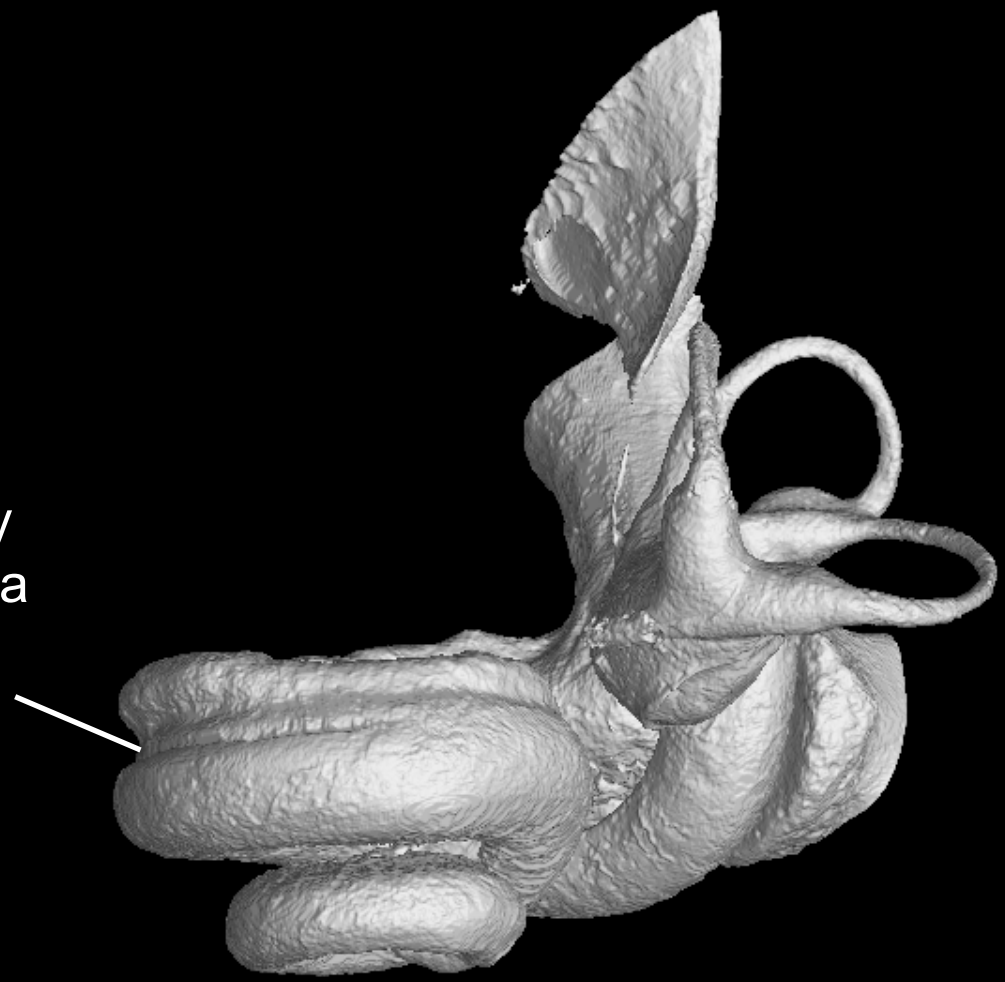


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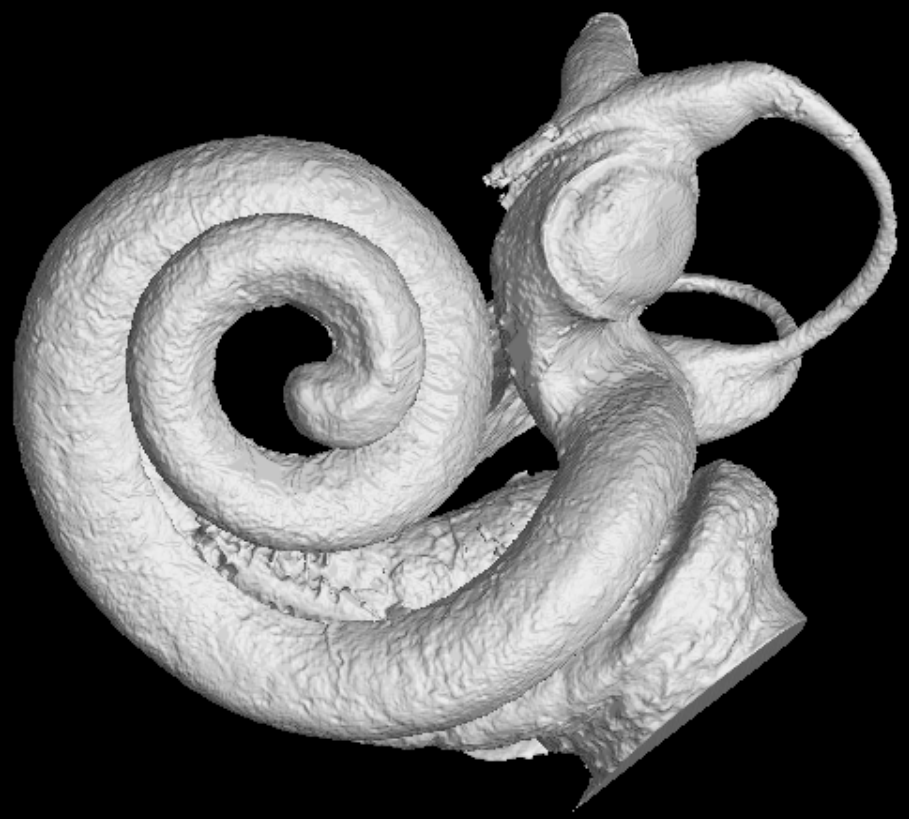


9 cochlear measurements *sensu* Mourlam & Orliac 2017

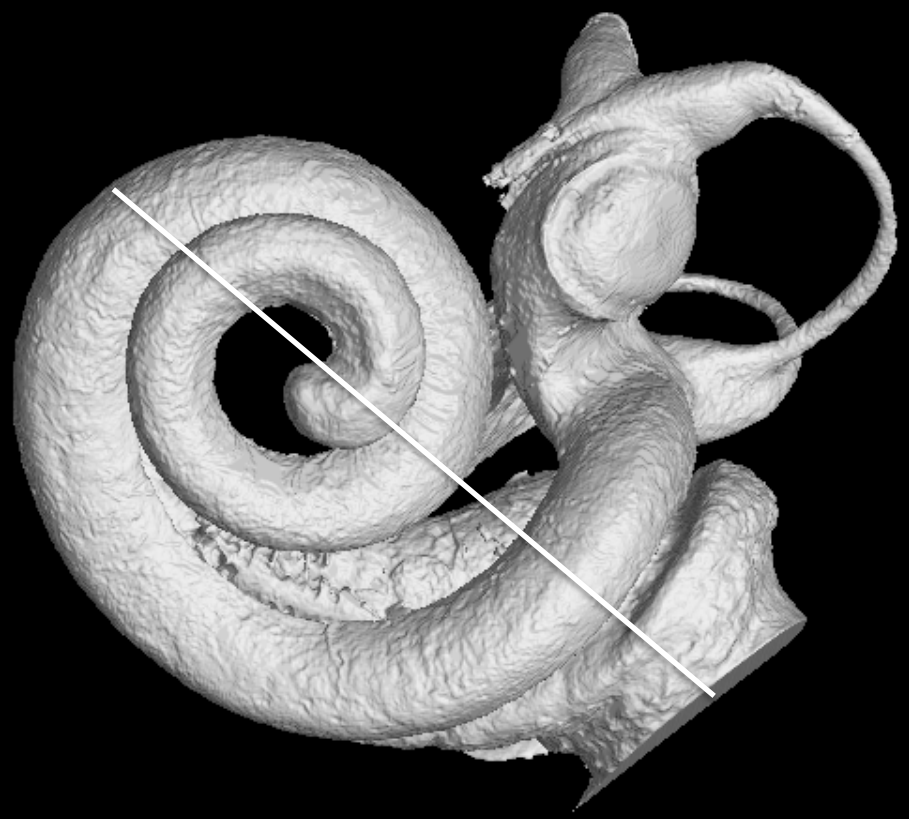
# *Olympicetus* sp. anatomy, measurements

Cochlear length (full length along laminar gap)

9 cochlear measurements *sensu* Mourlam & Orliac 2017

# *Olympicetus* sp. anatomy, measurements

Cochlear width



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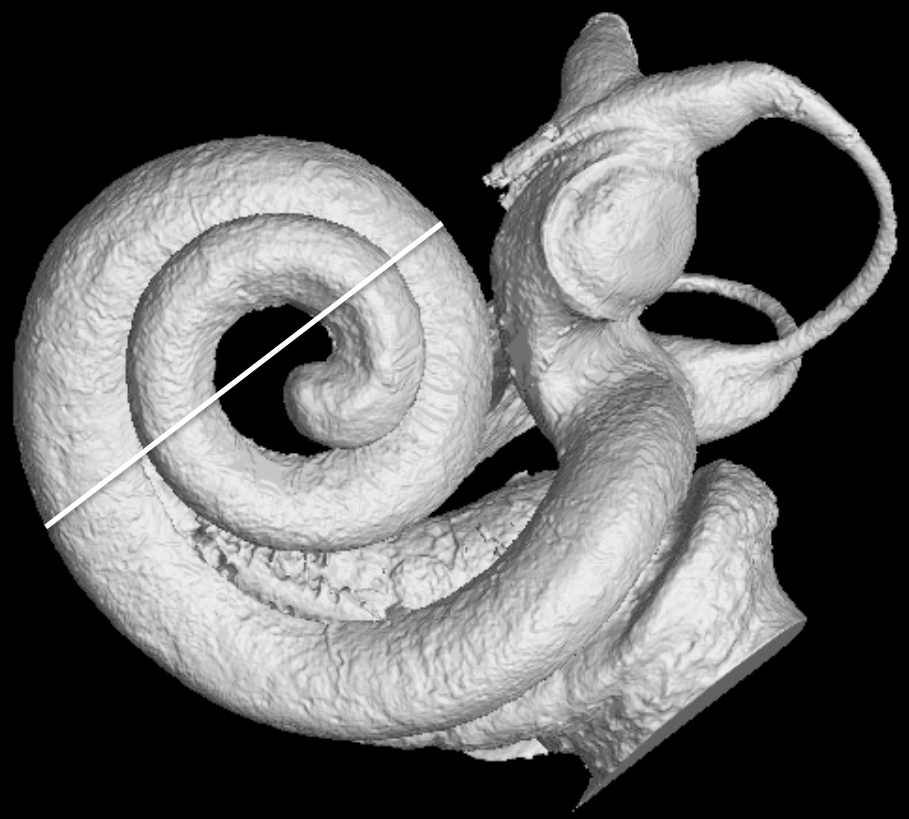
# *Olympicetus* sp. anatomy, measurements

Perpendicular width of cochlea



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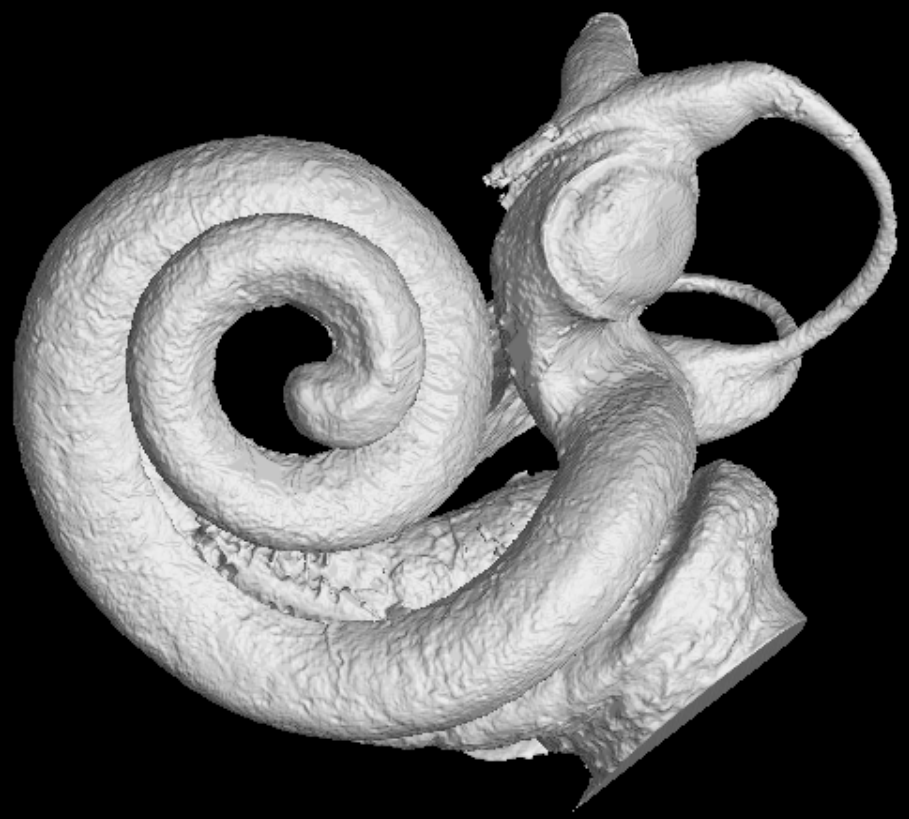

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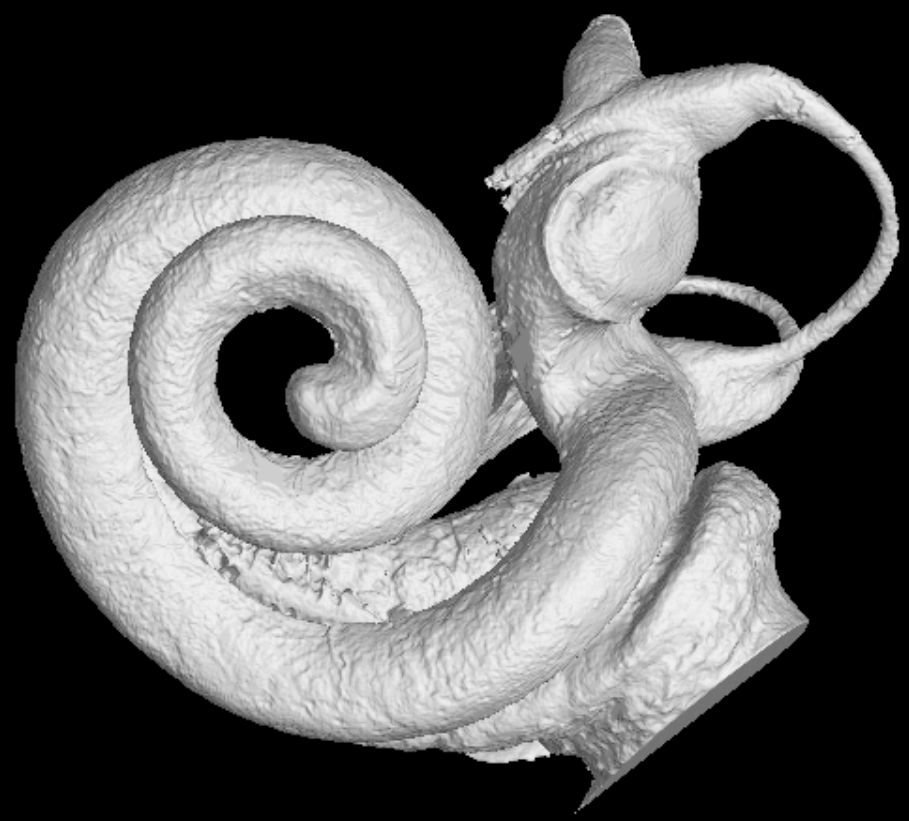

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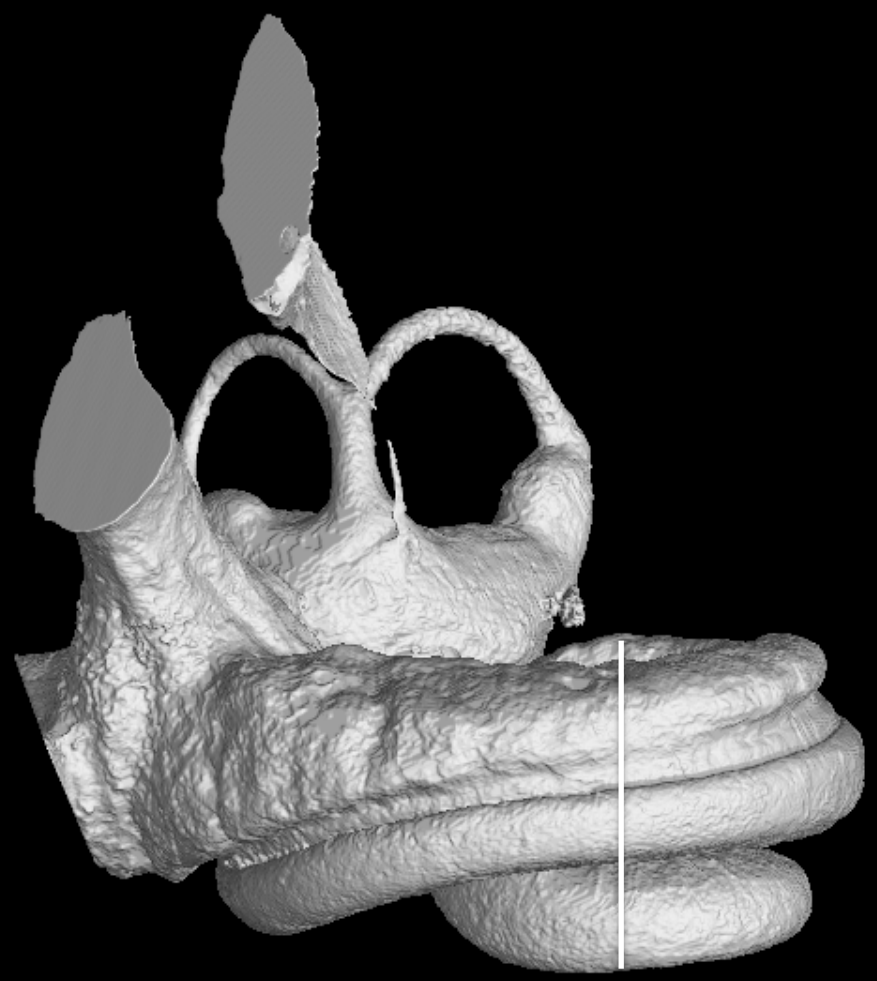
# *Olympicetus* sp. anatomy, measurements

Cochlear height



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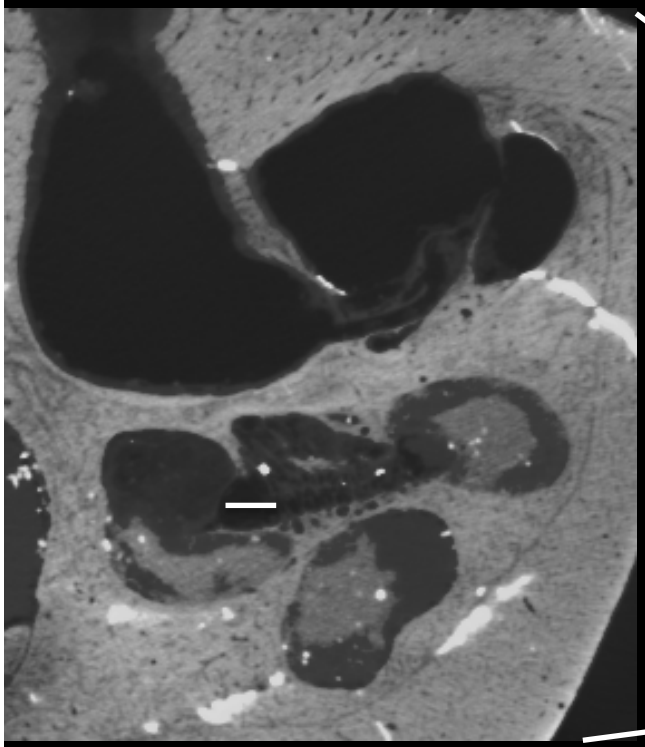
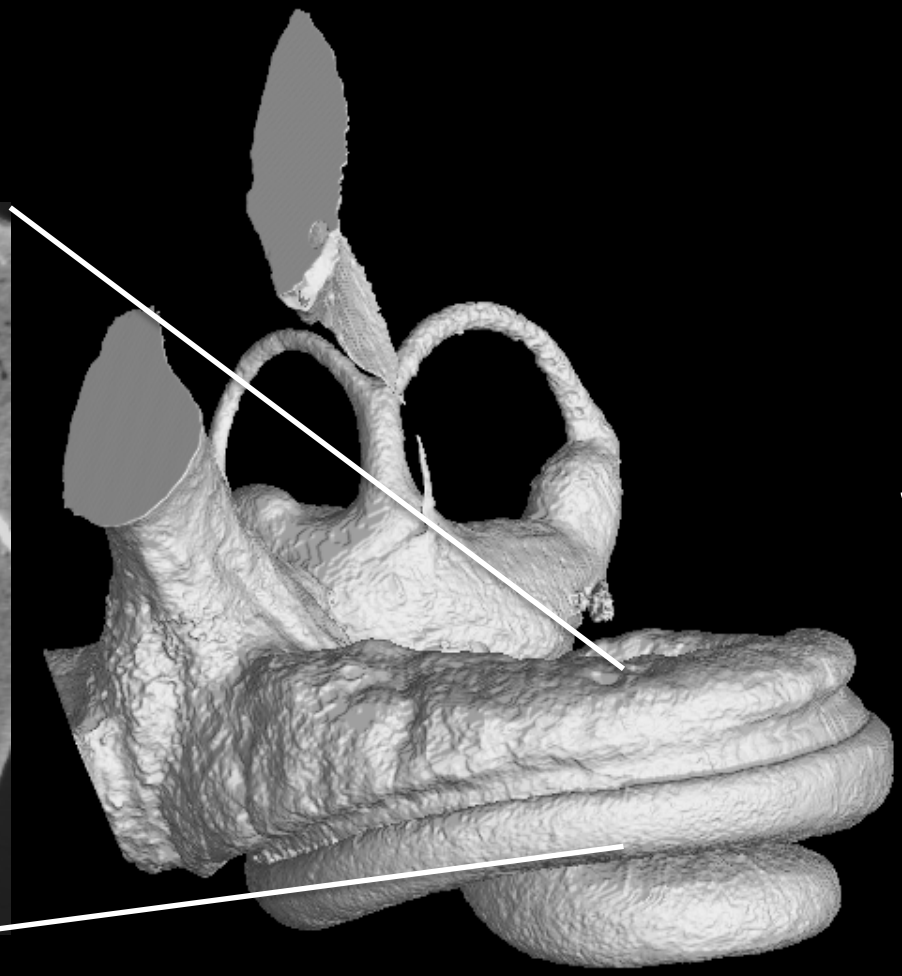




At first quarter turn:

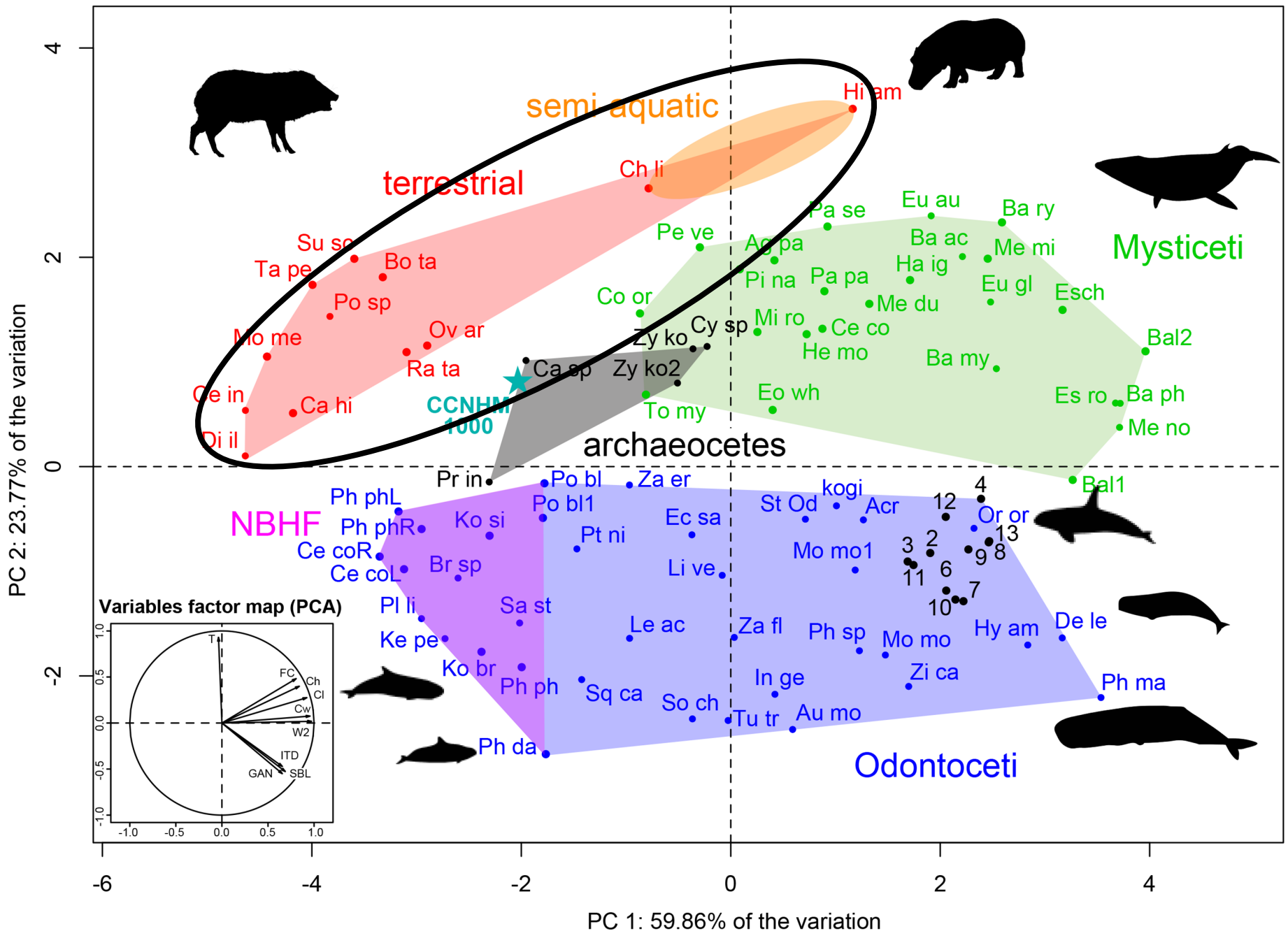
Spiral ganglion canal width

9 cochlear measurements *sensu* Mourlam & Orliac 2017

# What do you think I found?

A) *Olympicetus* sp. had specialized high frequency hearing, & consequently echolocated

B) *Olympicetus* sp. did not have high frequency hearing, & consequently may not have echolocated


semi aquatic
terrestrial
Mysticeti
archaeocetes
NBHF
Odontoceti
CCNHM 1000
Variables factor map (PCA)
PC 1: 59.86% of the variation
PC 2: 23.77% of the variation
Hi am
Ch li
Su sc
Ta pe
Bo ta
Po sp
Mo me
Ov ar
Ra ta
Ce in
Ca hi
Di il
Pe ve
Pa se
Eu au
Ba ry
Ag pa
Ba ac
Me mi
Ha ig
Pi na
Pa pa
Eu gl
Esch
Co or
Me du
Mi ro
Ce co
He mo
Ba my
Bal2
Cy sp
Zy ko
Ca sp
Zy ko2
To my
Eo wh
Es ro
Ba ph
Me no
Bal1
Pr in
Po bl
Za er
Po bl1
Ph phL
Ph phR
Ko si
Ce coR
Ce coL
Br sp
Pt ni
Ec sa
Li ve
Pl li
Sa st
Ke pe
Ko br
Ph ph
Sq ca
So ch
Ph da
Le ac
Za fl
Tu tr
In ge
Au mo
Ph sp
Mo mo
Zi ca
Hy am
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GAN
SBL
-6
-4
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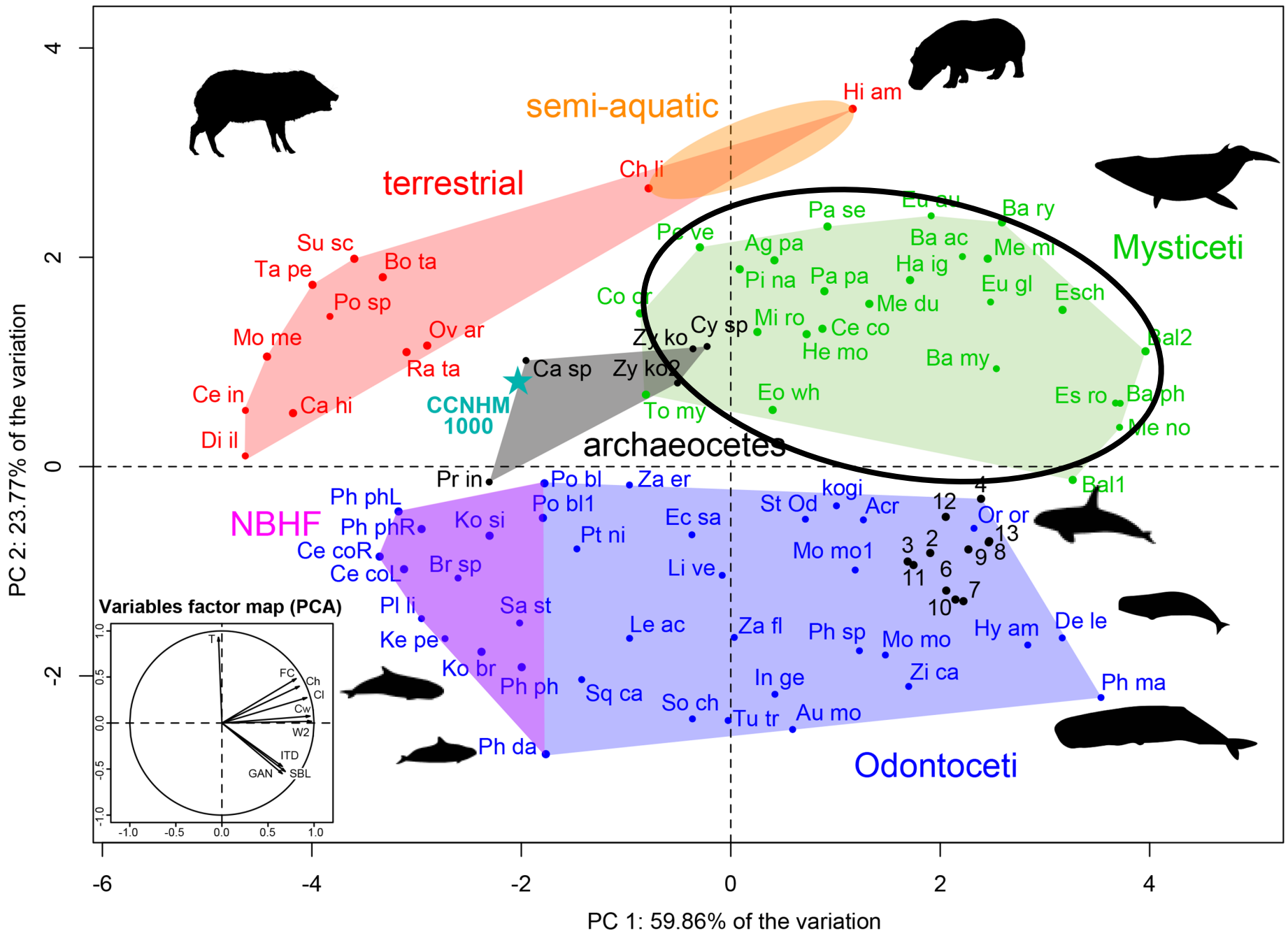
semi-aquatic
terrestrial
Mysticeti
archaeocetes
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Odontoceti
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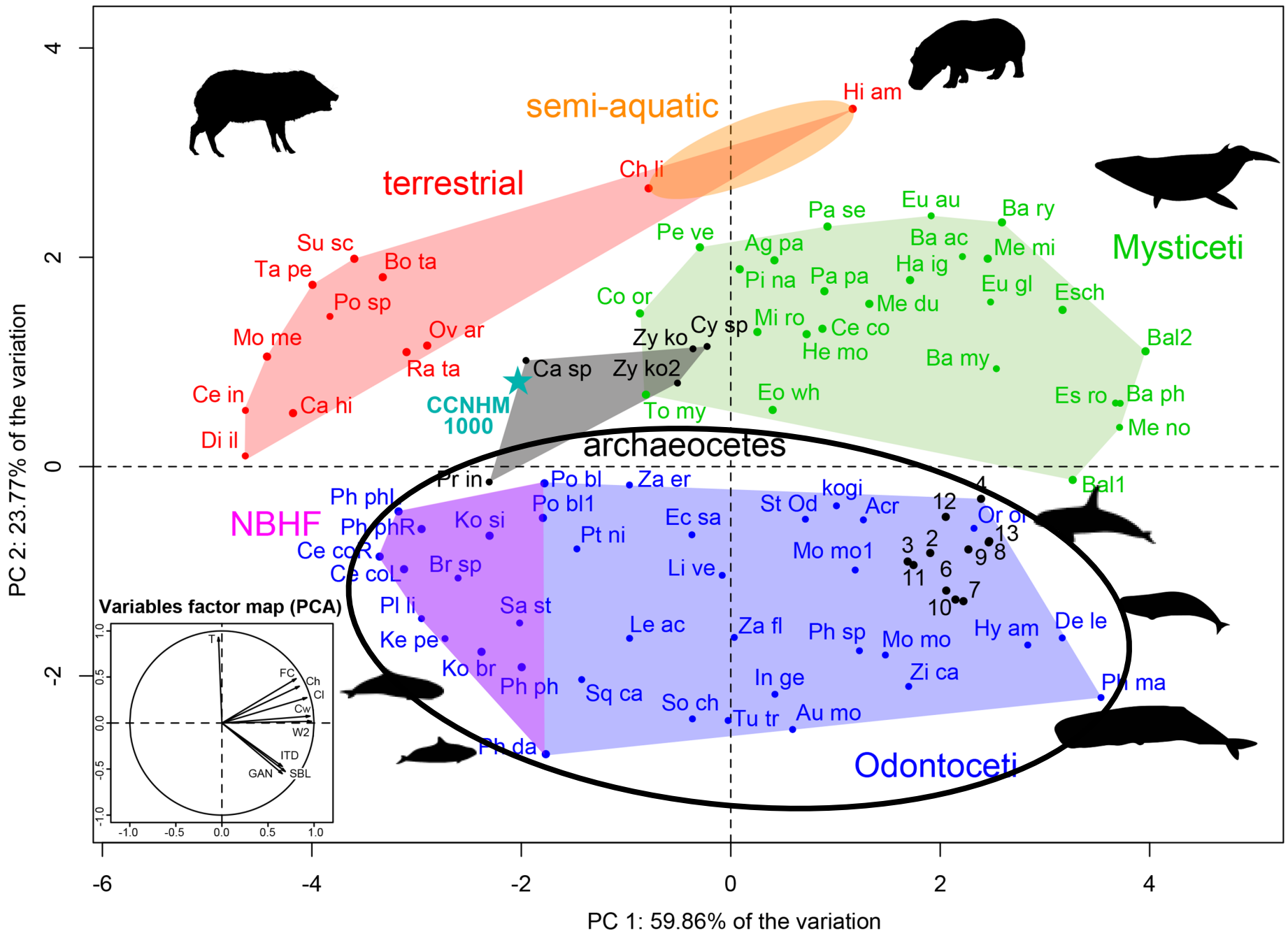
Hi am
Ch li
Su sc
Ta pe
Bo ta
Po sp
Mo me
Ov ar
Ra ta
Ce in
Ca hi
Di il
Ca sp
Zy ko
Zy ko2
Cy sp
Co cr
Po ve
Pa se
Ag pa
Pi na
Pa pa
Ba ry
Ba ac
Me mi
Ha ig
Eu gl
Esch
Me du
Mi ro
Ce co
He mo
Ba my
Bal2
Eo wh
Es ro
Ba ph
Me no
To my
Bal1
Pr in
Po bl
Za er
Po bl1
Ph phL
Ph phR
Ko si
Ce coR
Ce coL
Br sp
Pt ni
Ec sa
Li ve
Pl li
Sa st
Ke pe
Ko br
Ph ph
Sq ca
So ch
Le ac
Ph da
kogi
St Od
Acr
Or or
Mo mo1
Za fl
Ph sp
Mo mo
Hy am
De le
In ge
Zi ca
Tu tr
Au mo
Ph ma
1
2
3
4
6
7
8
9
10
11
12
13
Variables factor map (PCA)
T
FC
Ch
Cl
Cw
W2
ITD
GAN
SBL
PC 2: 23.77% of the variation
PC 1: 59.86% of the variation
-6
-4
-2
0
2
4


semi-aquatic
terrestrial
Mysticeti
archaeocetes
NBHF
Odontoceti
CCNHM 1000
Hi am
Ch li
Su sc
Ta pe
Bo ta
Po sp
Mo me
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To my
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Cy sp
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Ca sp
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8
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7
10
Variables factor map (PCA)
T
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Cw
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GAN
SBL
PC 2: 23.77% of the variation
PC 1: 59.86% of the variation
-6
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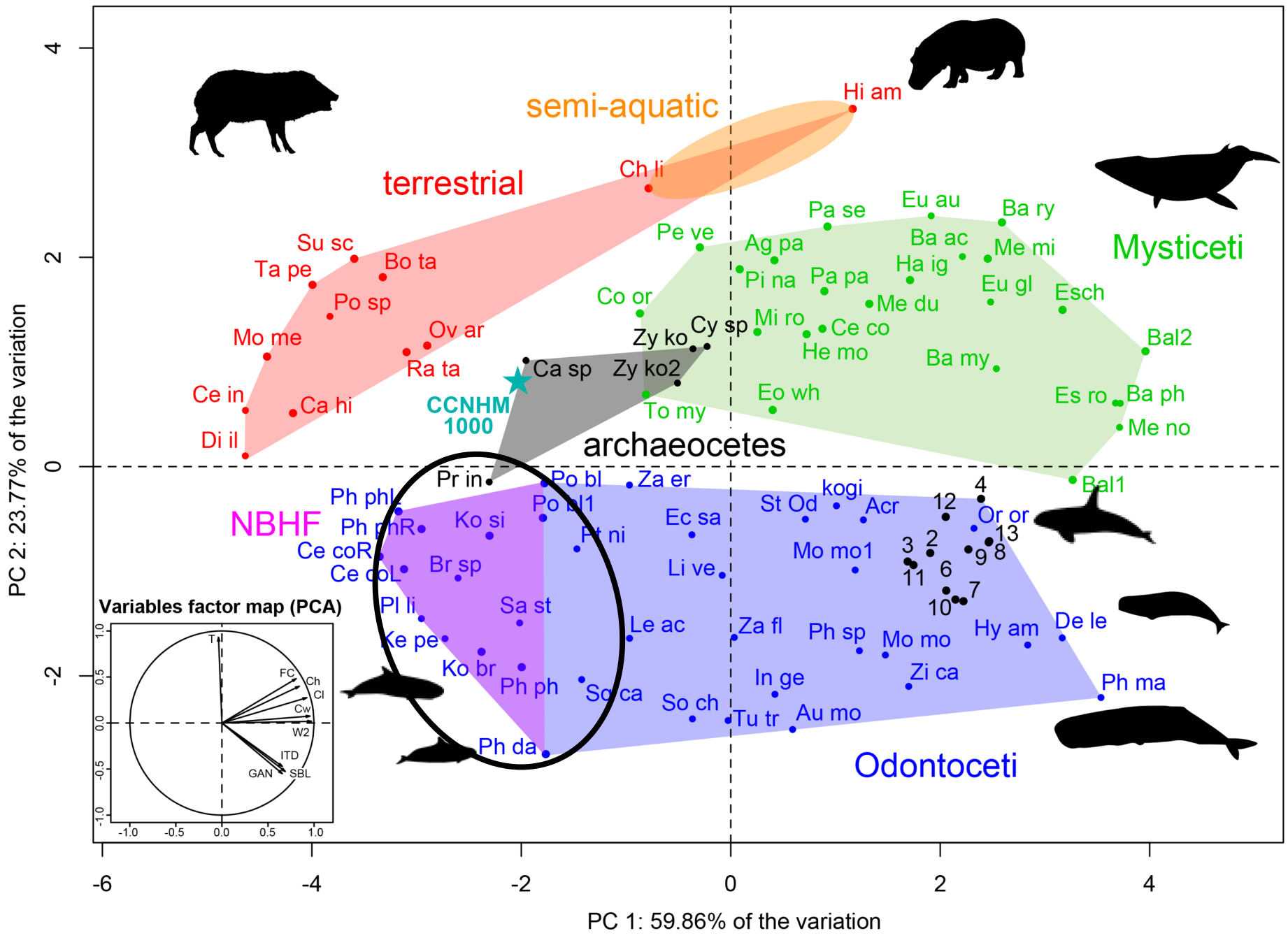
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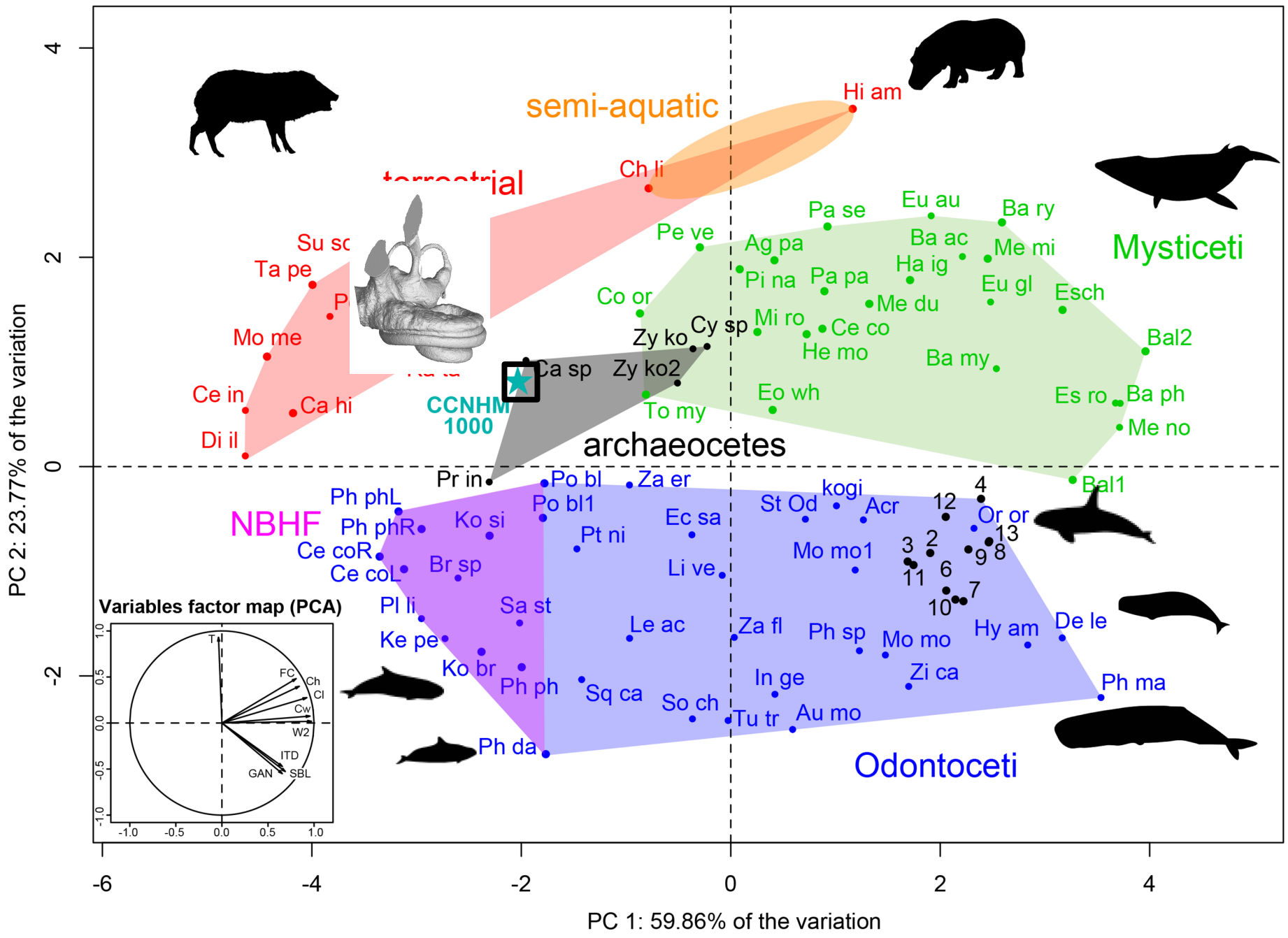
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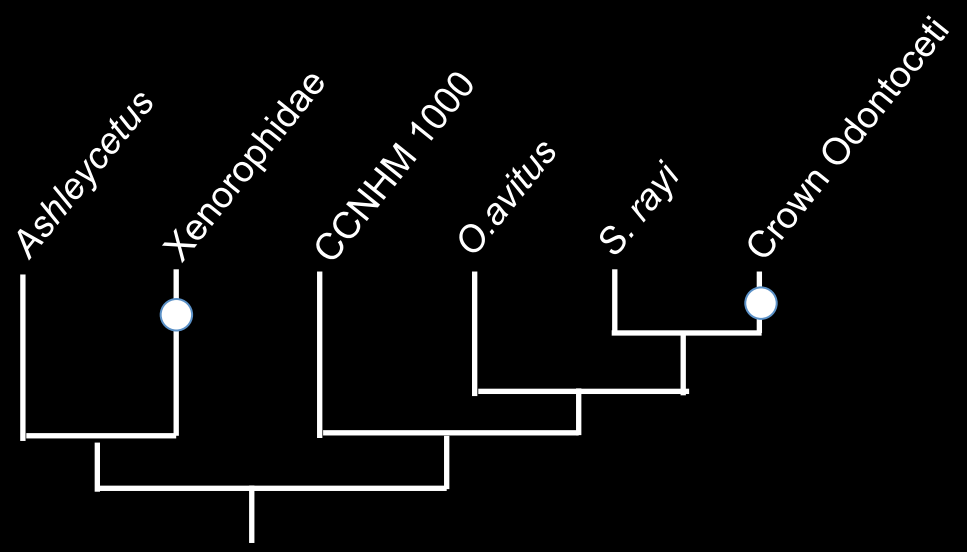
# Discussion/Conclusions

Transitional (between archaeocete and modern) type of hearing in *Olympicetus* sp., other early dolphins? – which have a parallel style of “telescoping” of the skull and different skull structure to xenorophids

# Discussion/Conclusions

Transitional (between archaeocete and modern) type of hearing in *Olympicetus* sp., other early dolphins? – which have a parallel style of “telescoping” of the skull and different skull structure to xenorophids

Possible multiple origins of echolocation in toothed whales!




Where do we go from here?

# Multiple origins of echolocation in dolphins?

Fine examination of lineages more closely related to extant species should illuminate origins in the lineage we see today

More work to be done!

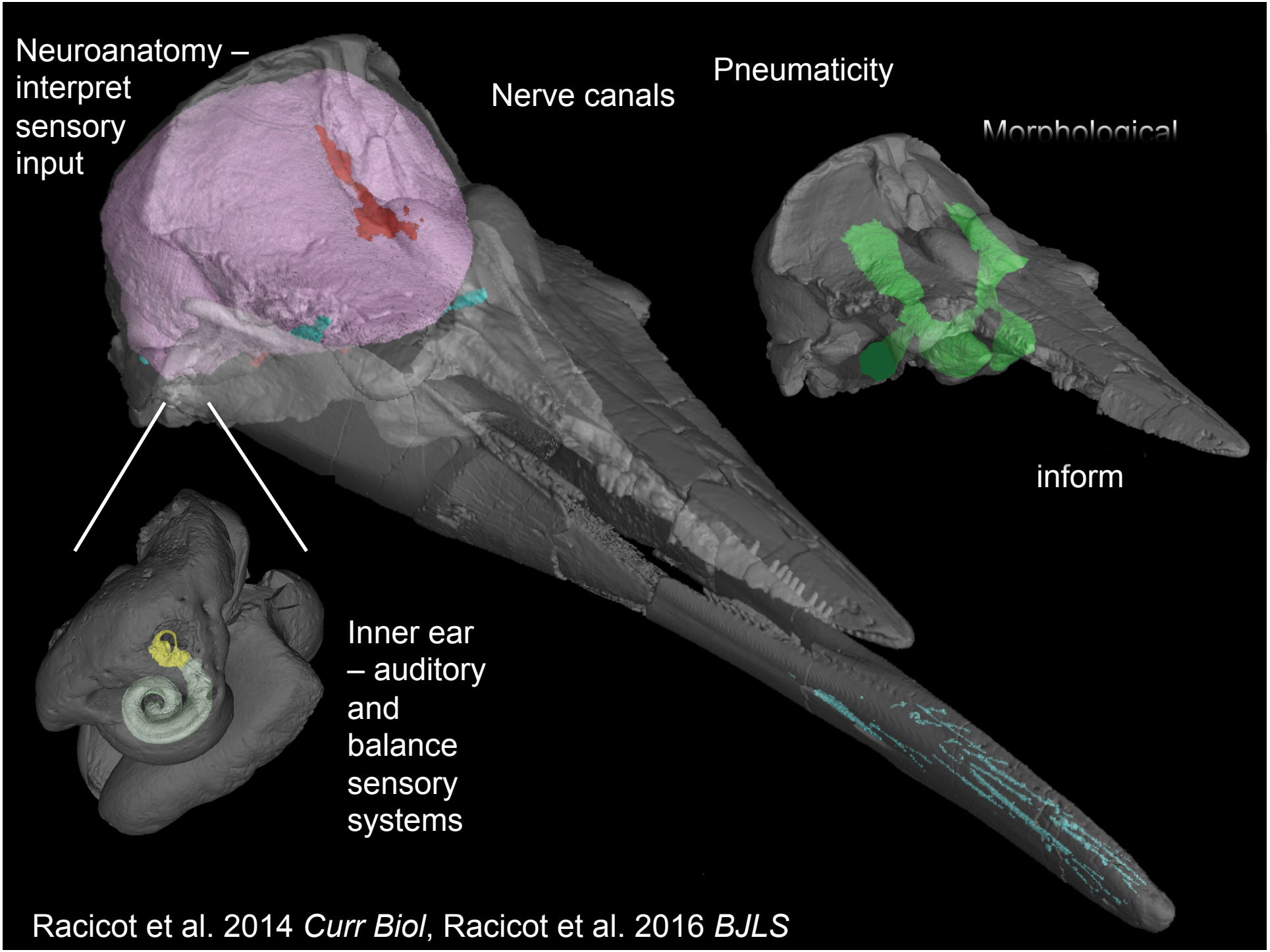
## What does it mean?

Different ways to converge on biosonar

– conservation

– robotics/engineering applications

– large-scale evolutionary patterns in dolphins & early relatives


Neuroanatomy – interpret sensory input
Nerve canals
Pneumaticity
Morphological
inform
Inner ear – auditory and balance sensory systems
Racicot et al. 2014 *Curr Biol*, Racicot et al. 2016 *BJLS*

# Thank you

Collections: AMNH, NMNH, NMNS, SDNHM, LACM, MCZ, UCMP

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