Evolution of the bilaterian central nervous system: a developmental perspective

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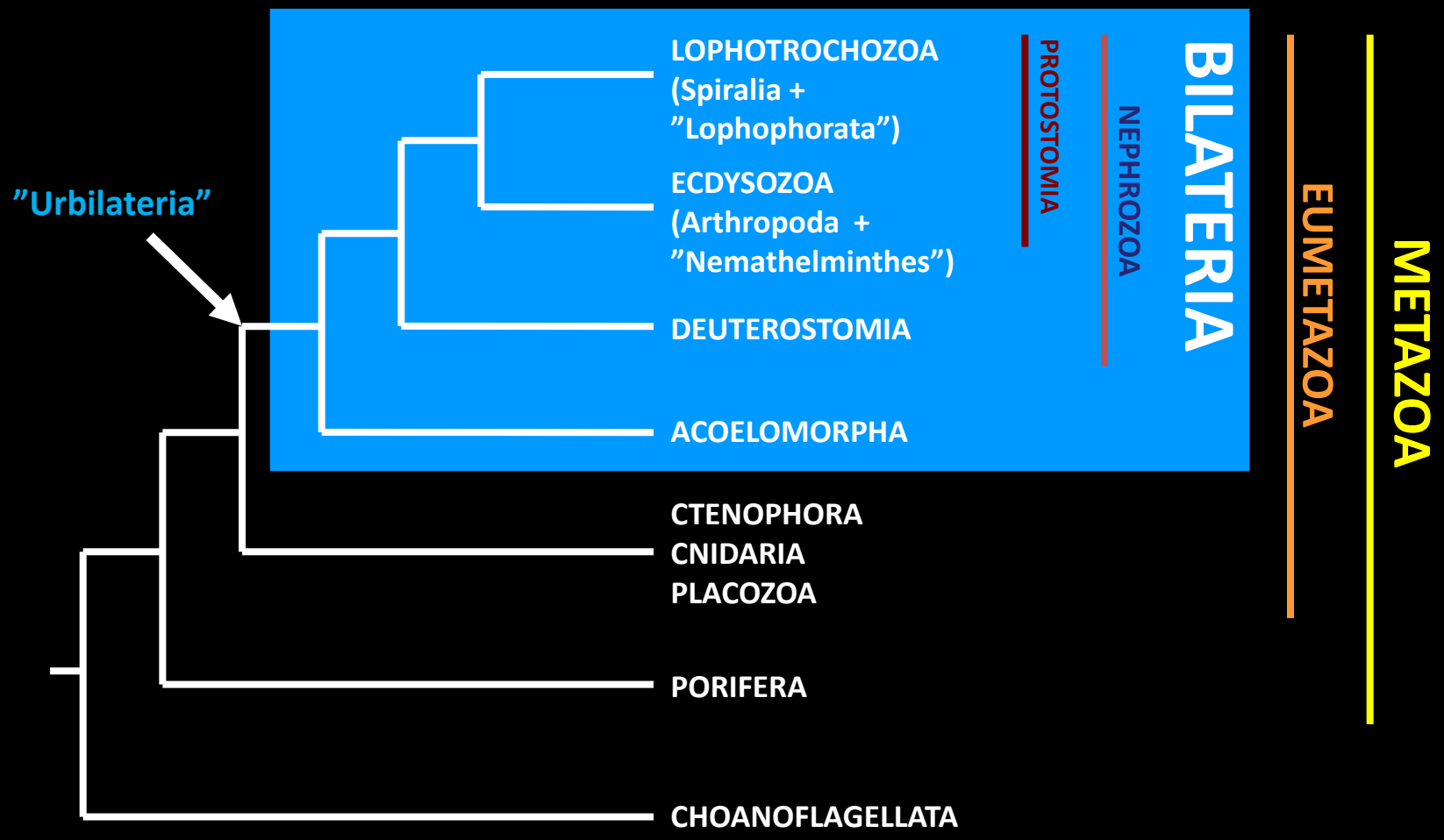
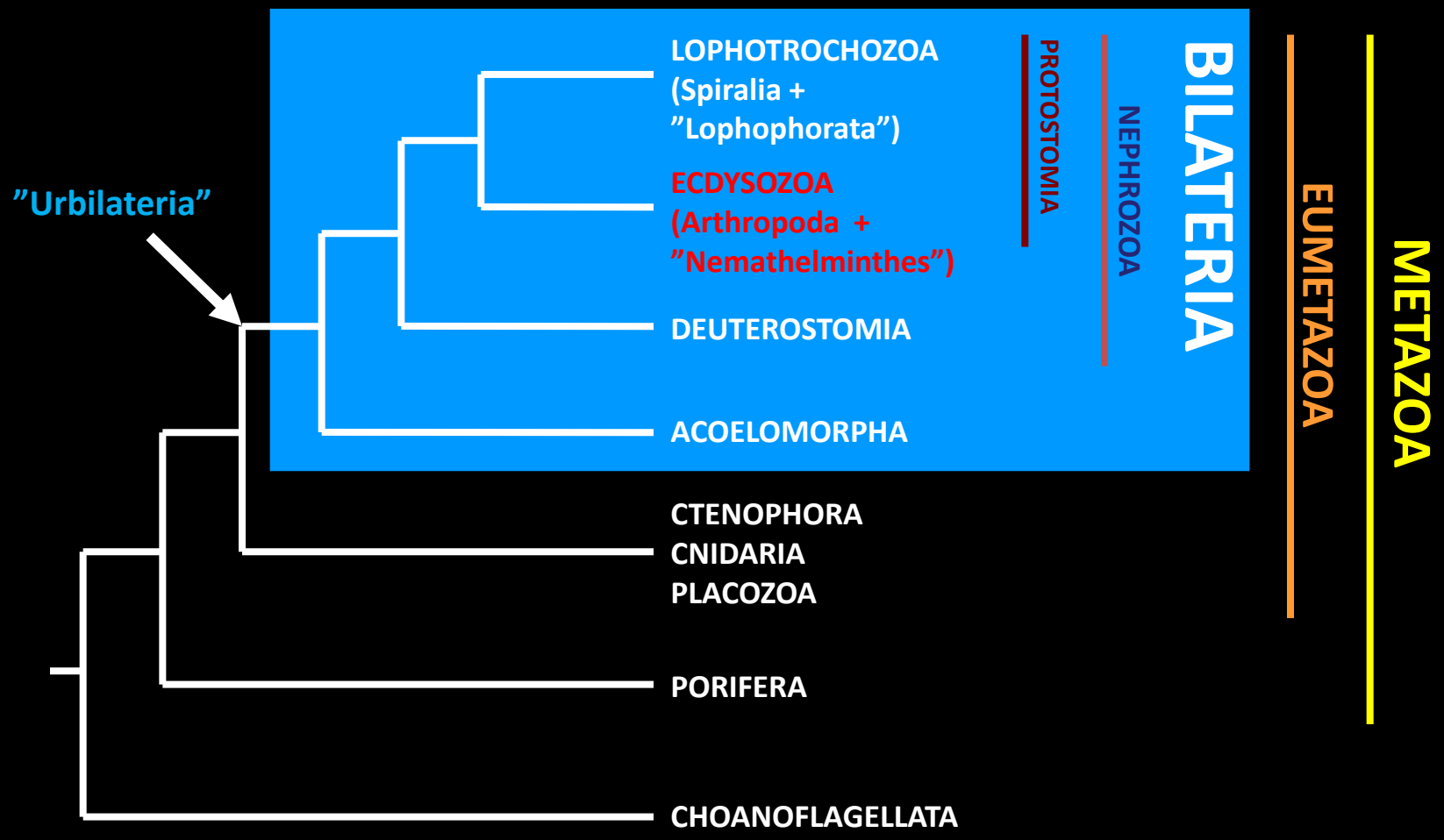
CENTER FOR ORGANISMAL SYSTEMS BIOLOGY

integrative zoology

Bilateria


”Urbilateria”
LOPHOTROCHOZOA
(Spiralia +
”Lophophorata”)
ECDYSOZOA
(Arthropoda +
”Nemathelminthes”)
DEUTEROSTOMIA
ACOELOMORPHA
CTENOPHORA
CNIDARIA
PLACOZOA
PORIFERA
CHOANOFLAGELLATA
PROTOSTOMIA
NEPHROZOA
BILATERIA
EUMETAZOA
METAZOA

Bilateria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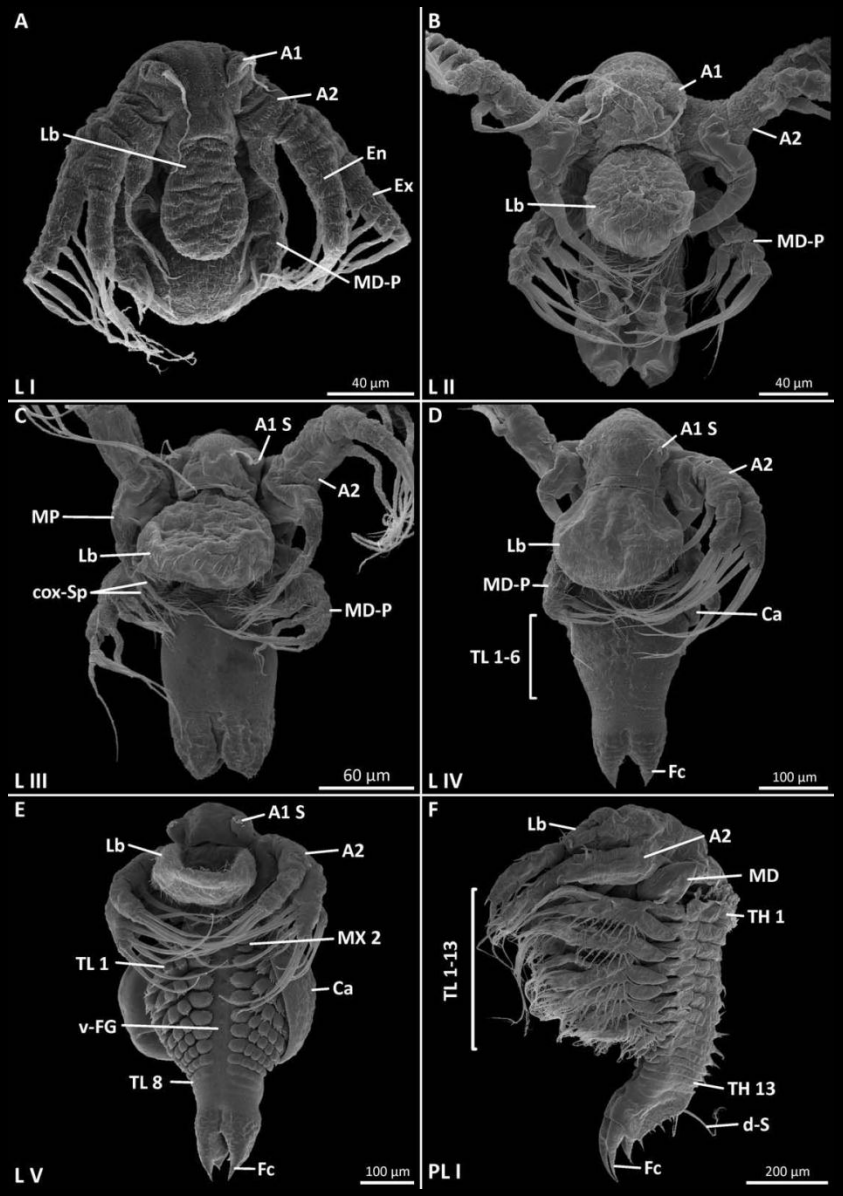
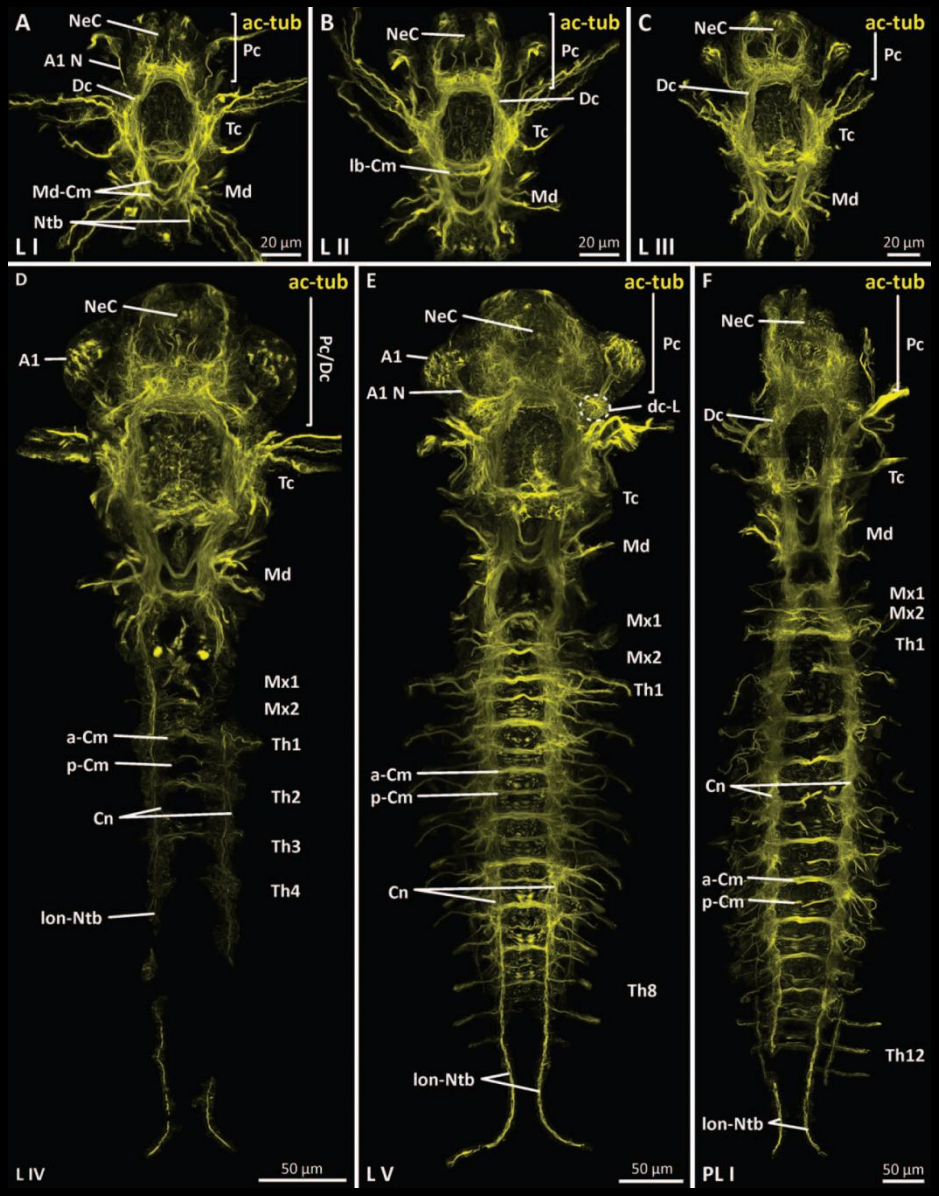
Neuroanatomy in Ecdysozoa

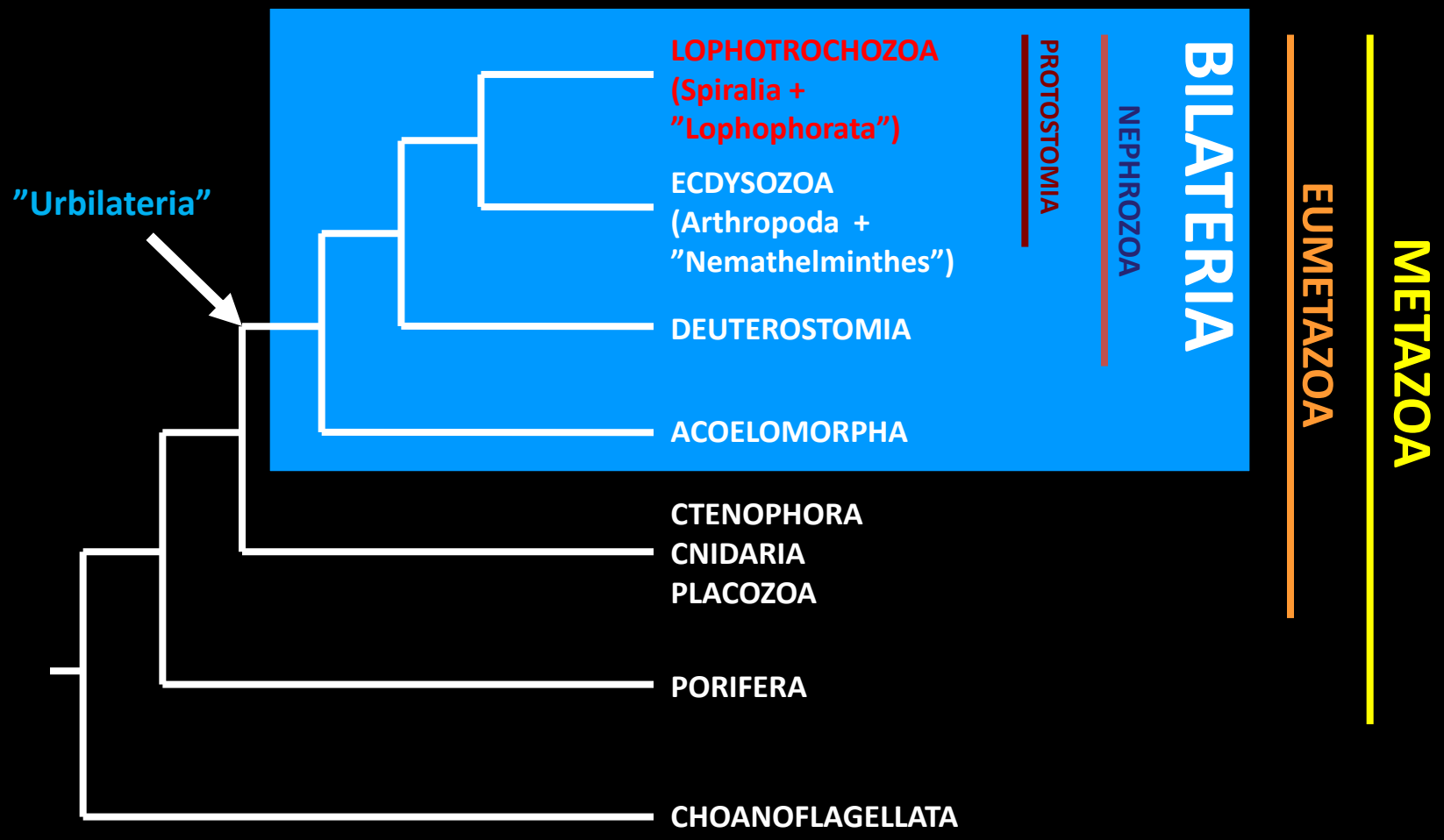
Arthropoda, Crustacea, Branchiopoda (*Leptestheria*): paired ventral nerve cord with commissures





Fritsch & Richter: *J. Morphol.* (2012)

Bilateria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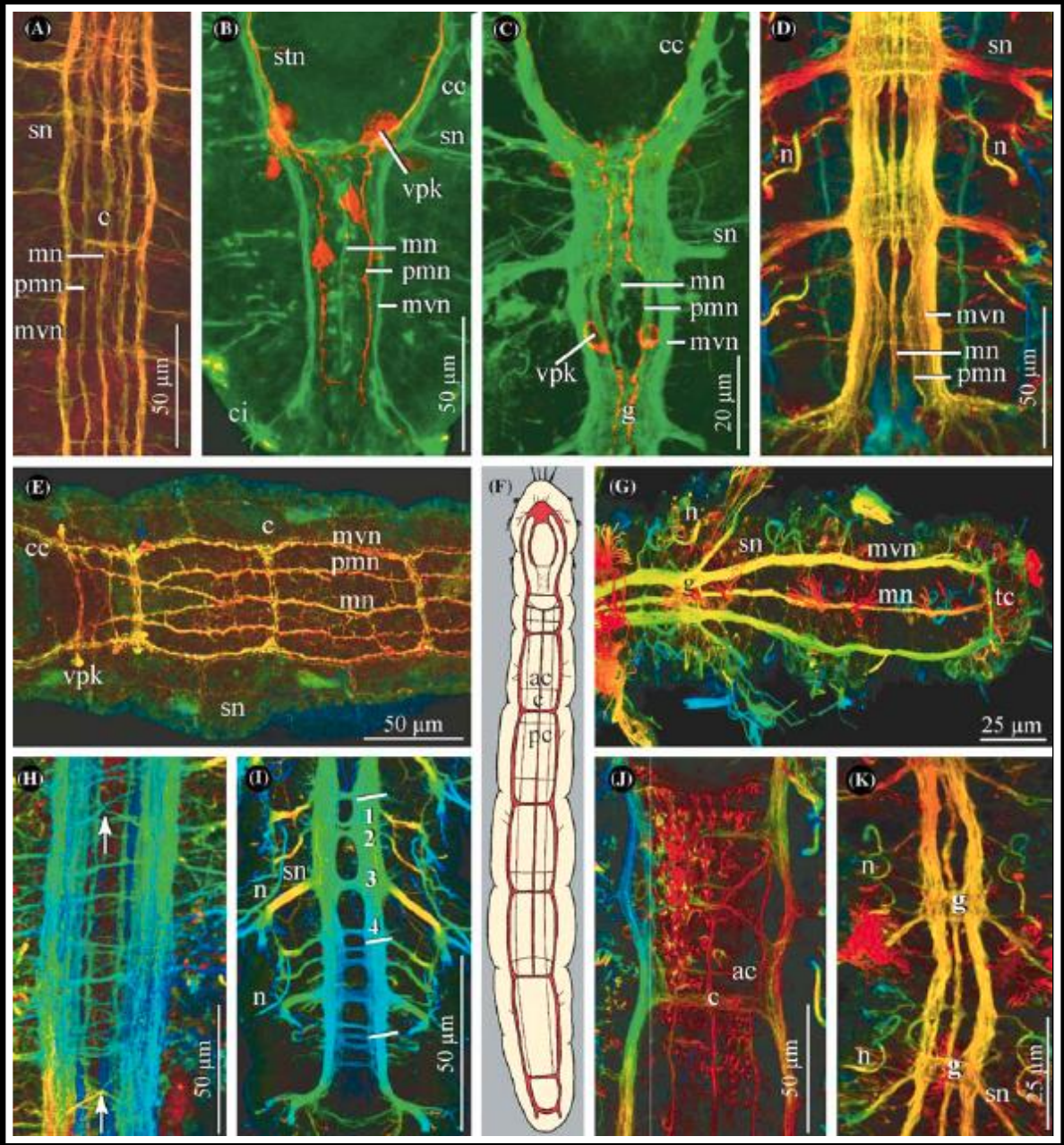
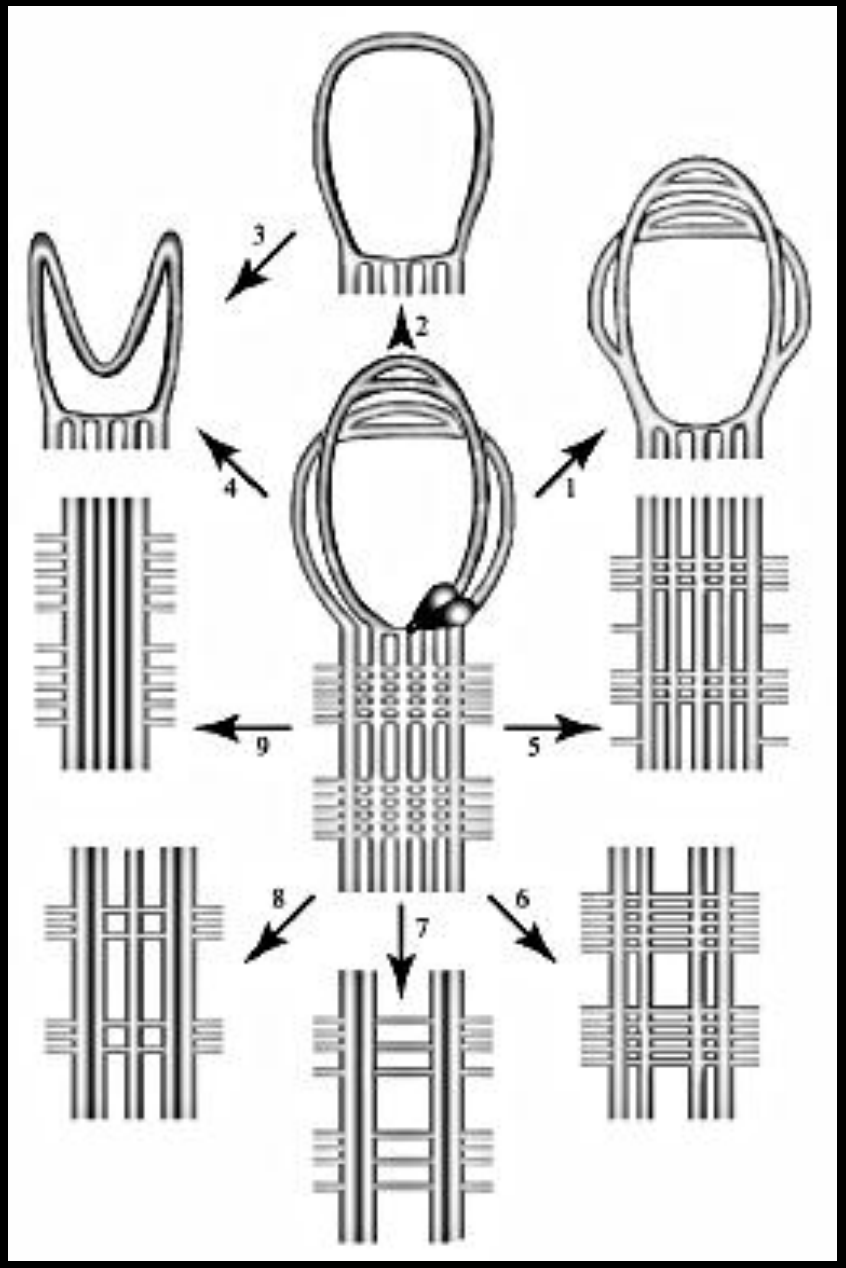
METAZOA

Neuroanatomy in Annelida (polychaetes)



Orrhage & Müller: *Hydrobiologia (2005)*

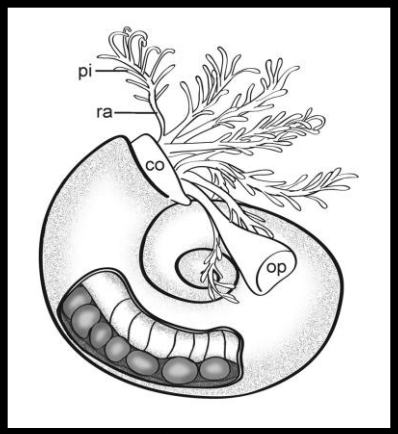
Evolution of the annelid nervous system

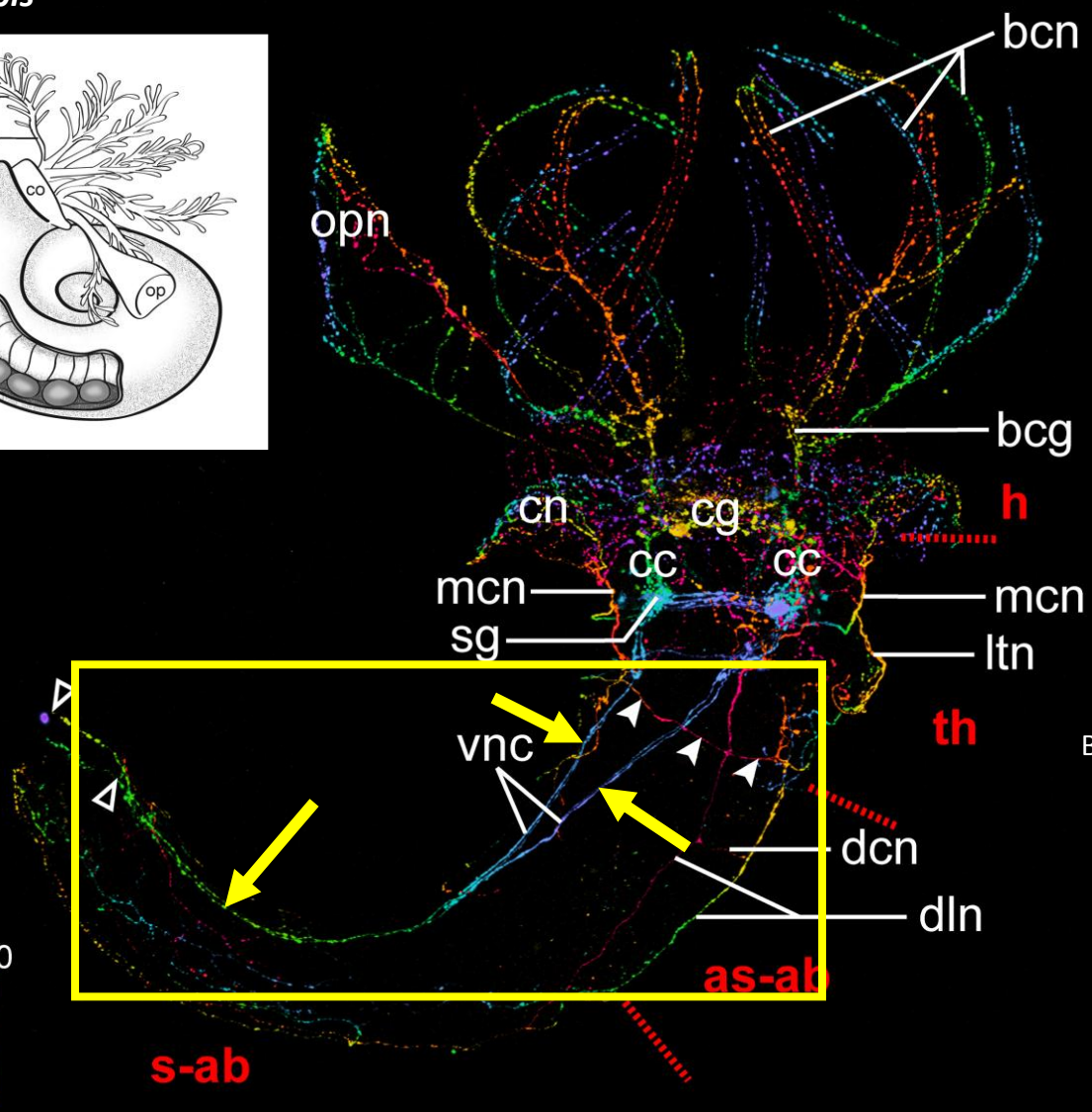


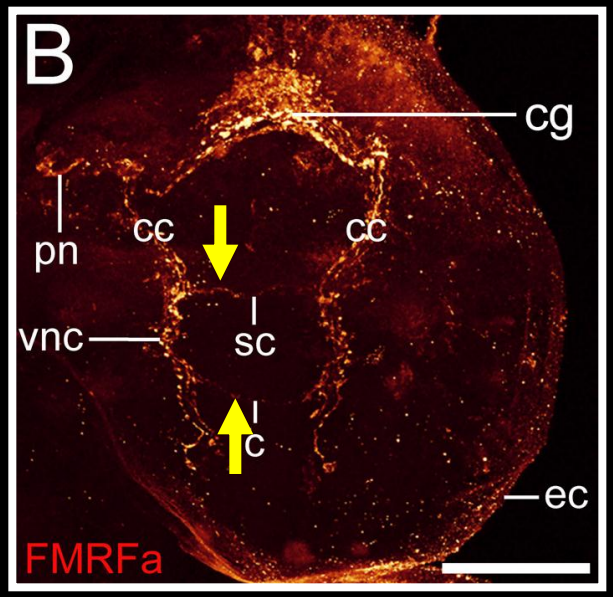
Müller: *Integr. Comp. Biol. (2006)*

Polychaete neurogenesis

Spirorbis

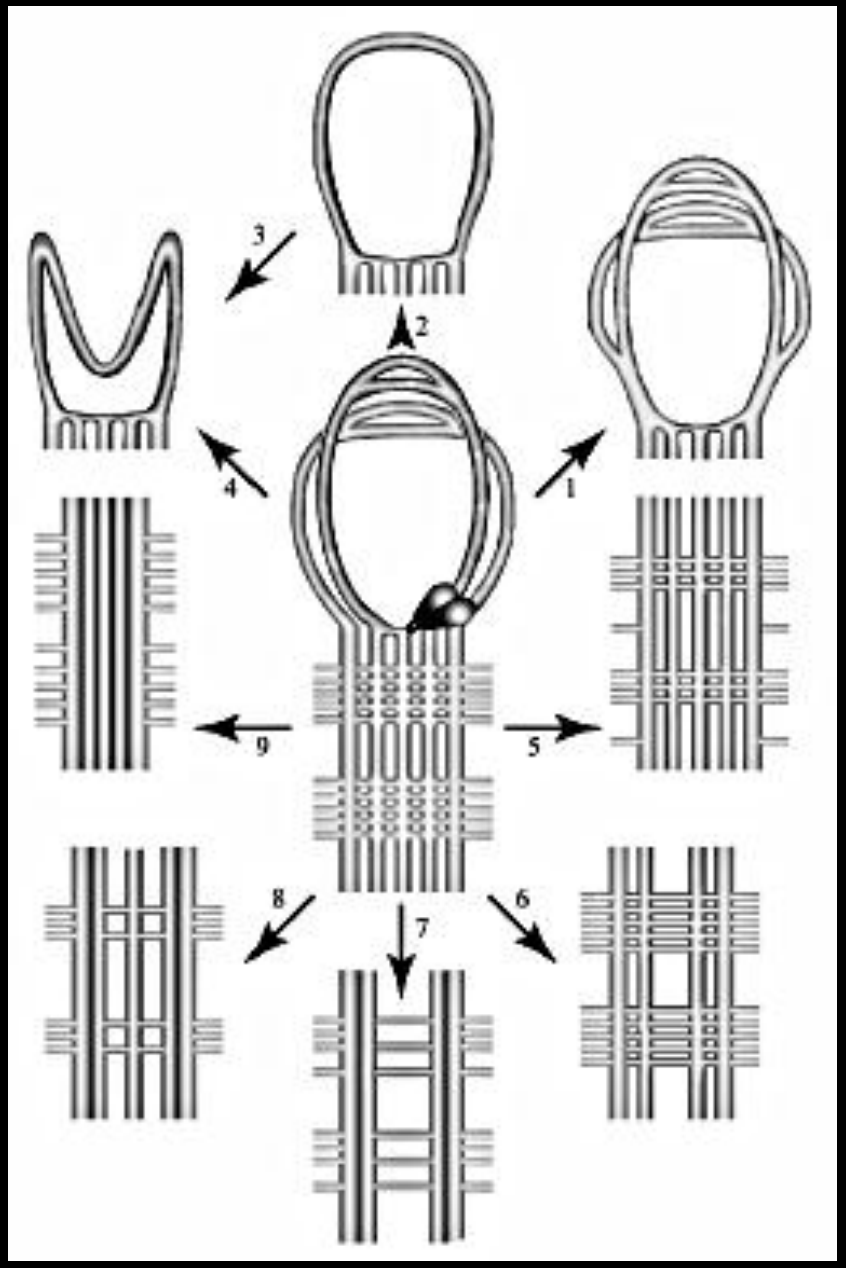






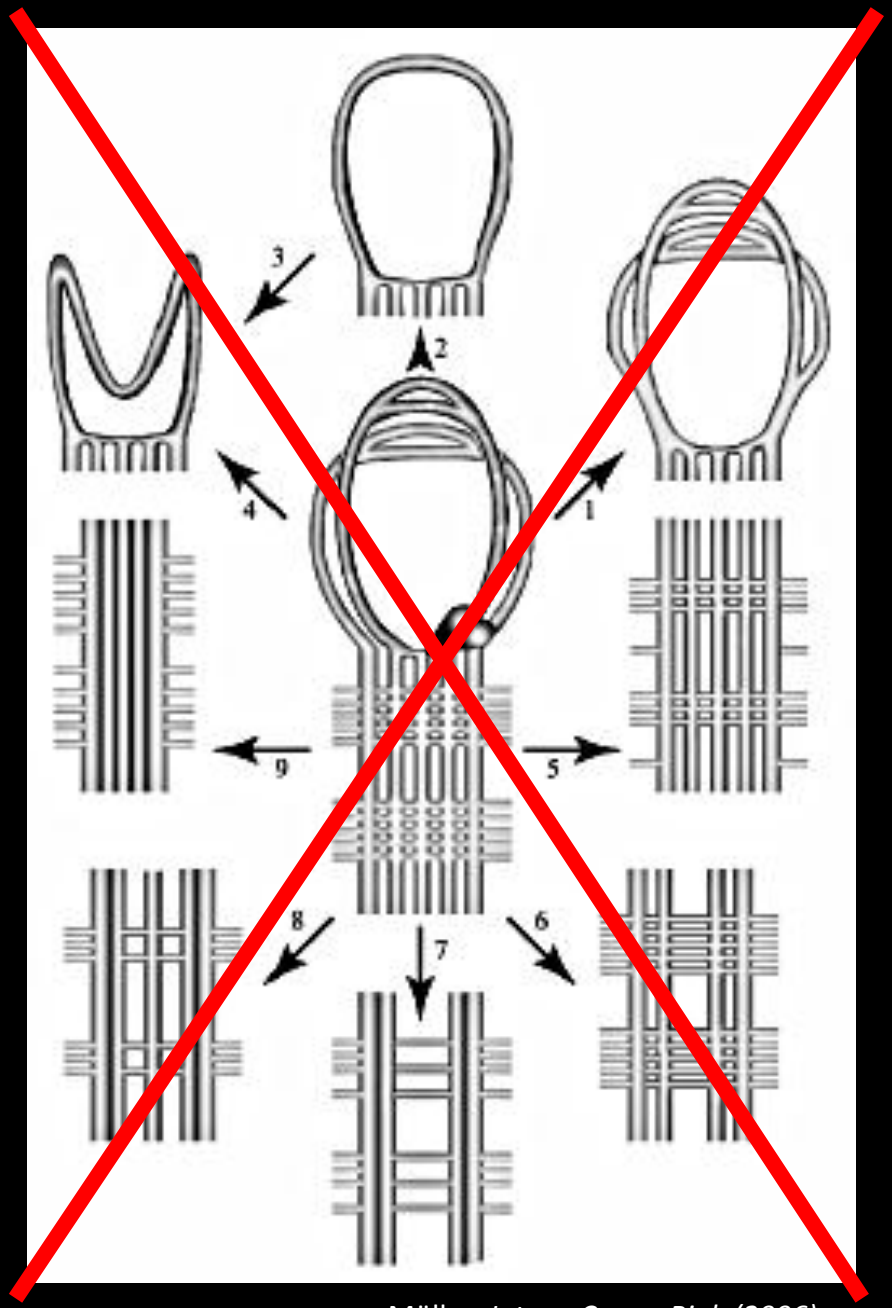
Brinkmann & Wanninger: *BMC Evol. Biol. (2009)*

Evolution of the annelid nervous system



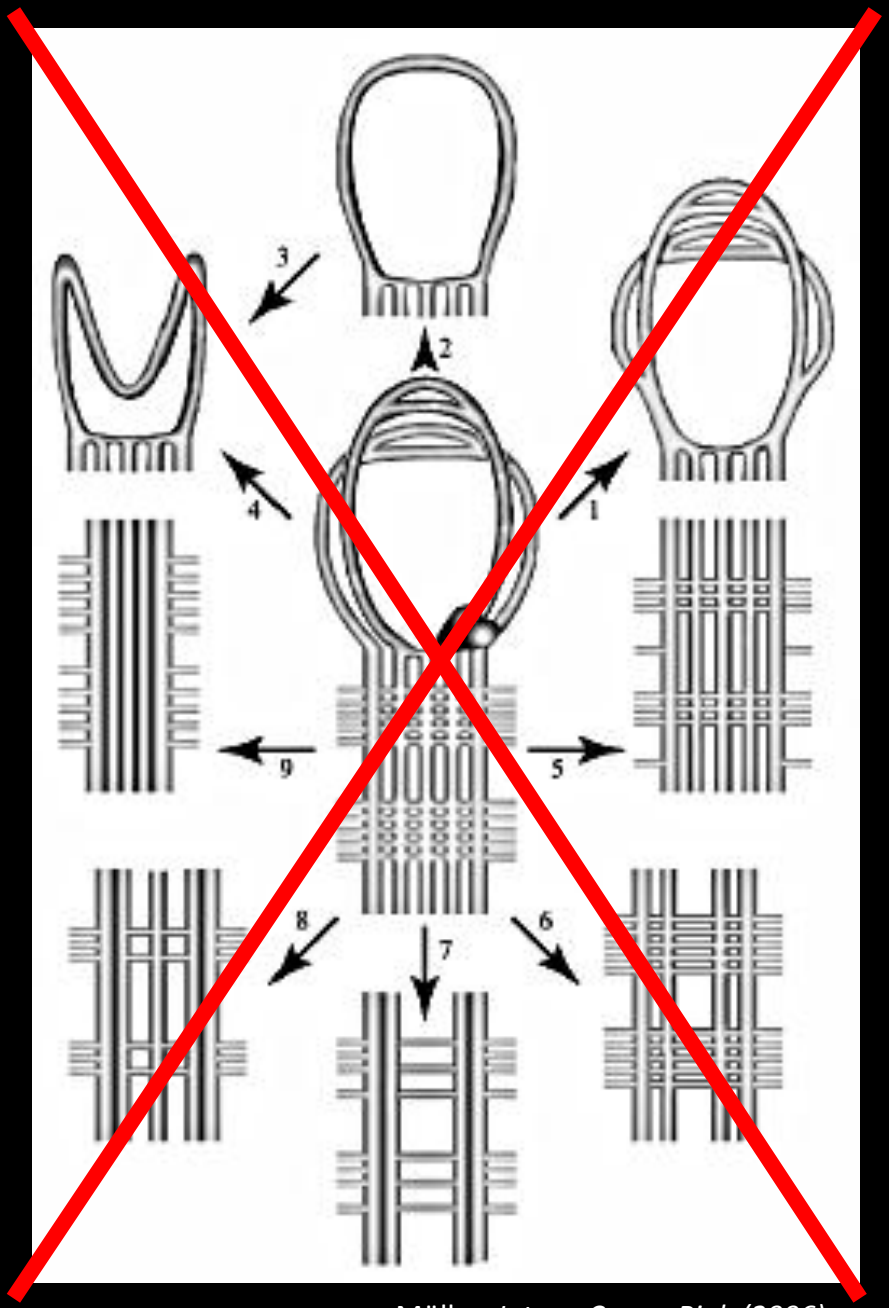
Müller: *Integr. Comp. Biol. (2006)*

Evolution of the annelid nervous system

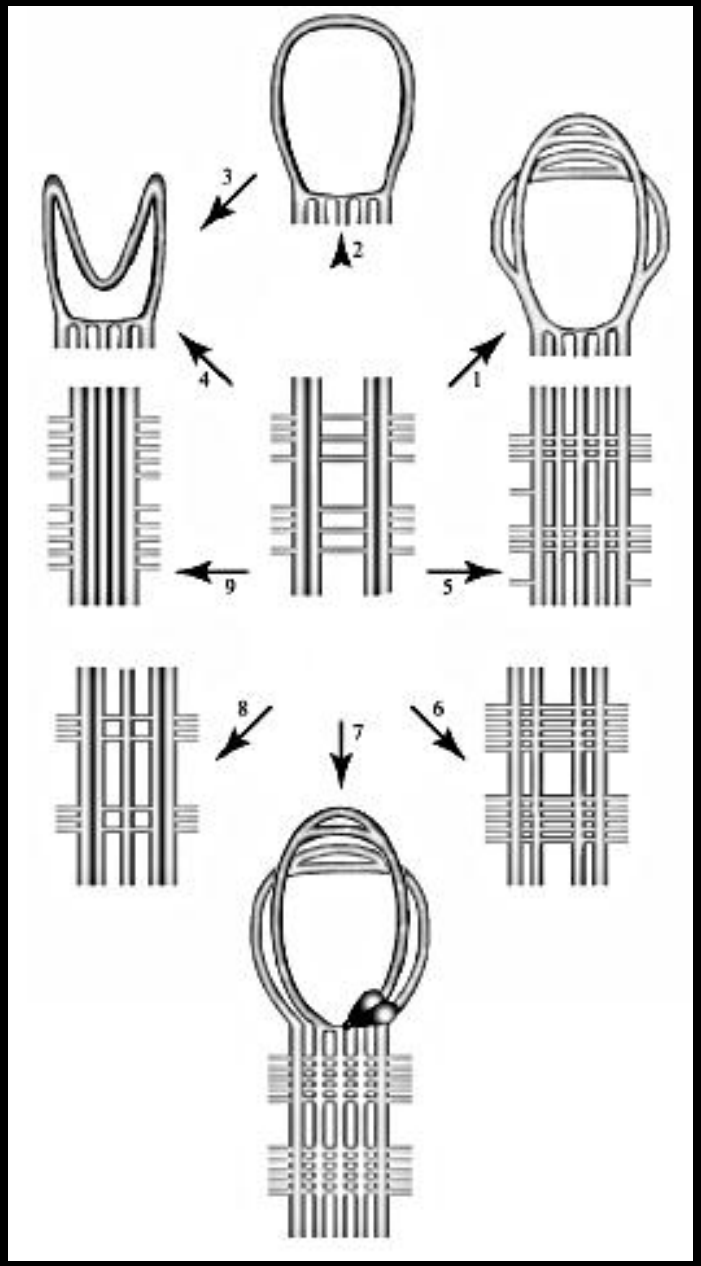


Müller: *Integr. Comp. Biol. (2006)*

Evolution of the annelid nervous system from a paired ventral nerve cord

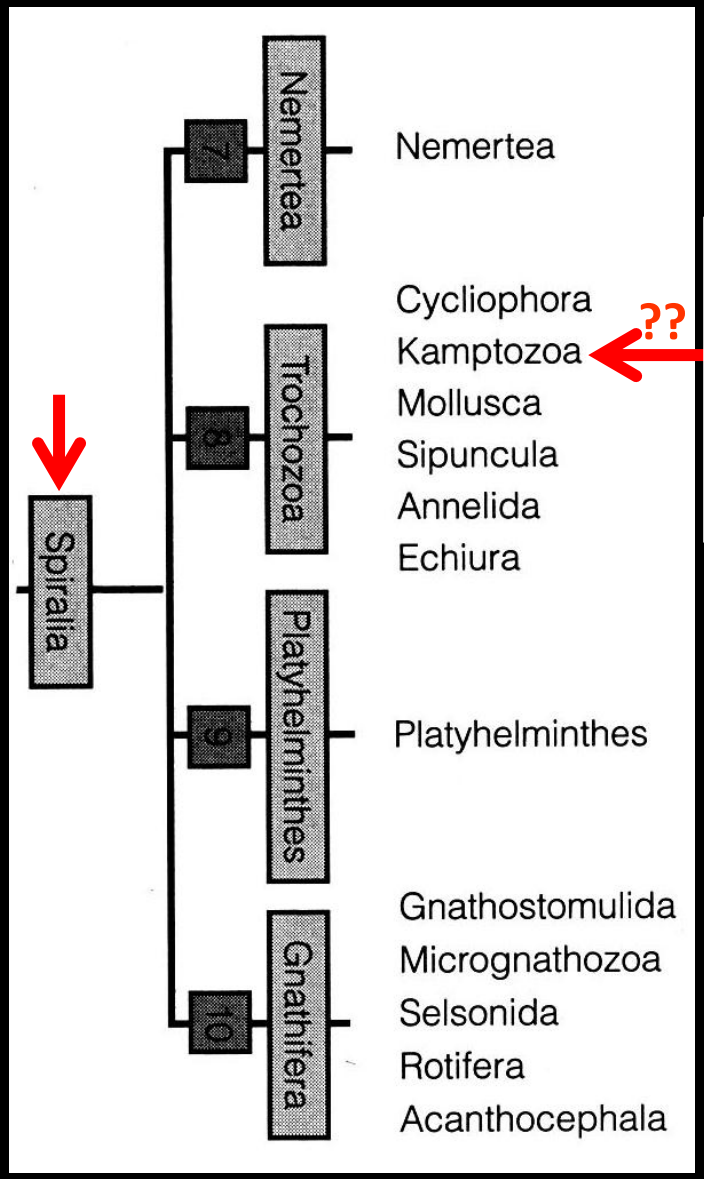


Müller: *Integr. Comp. Biol. (2006)*



Modified after Müller: *Integr. Comp. Biol. (2006)*

Neurogenesis & phylogeny



Ruppert, Fox & Barnes: *(2004)*

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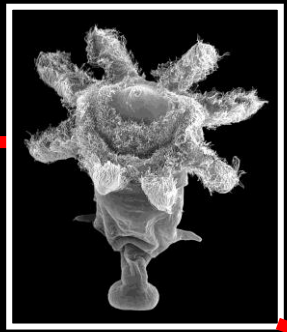
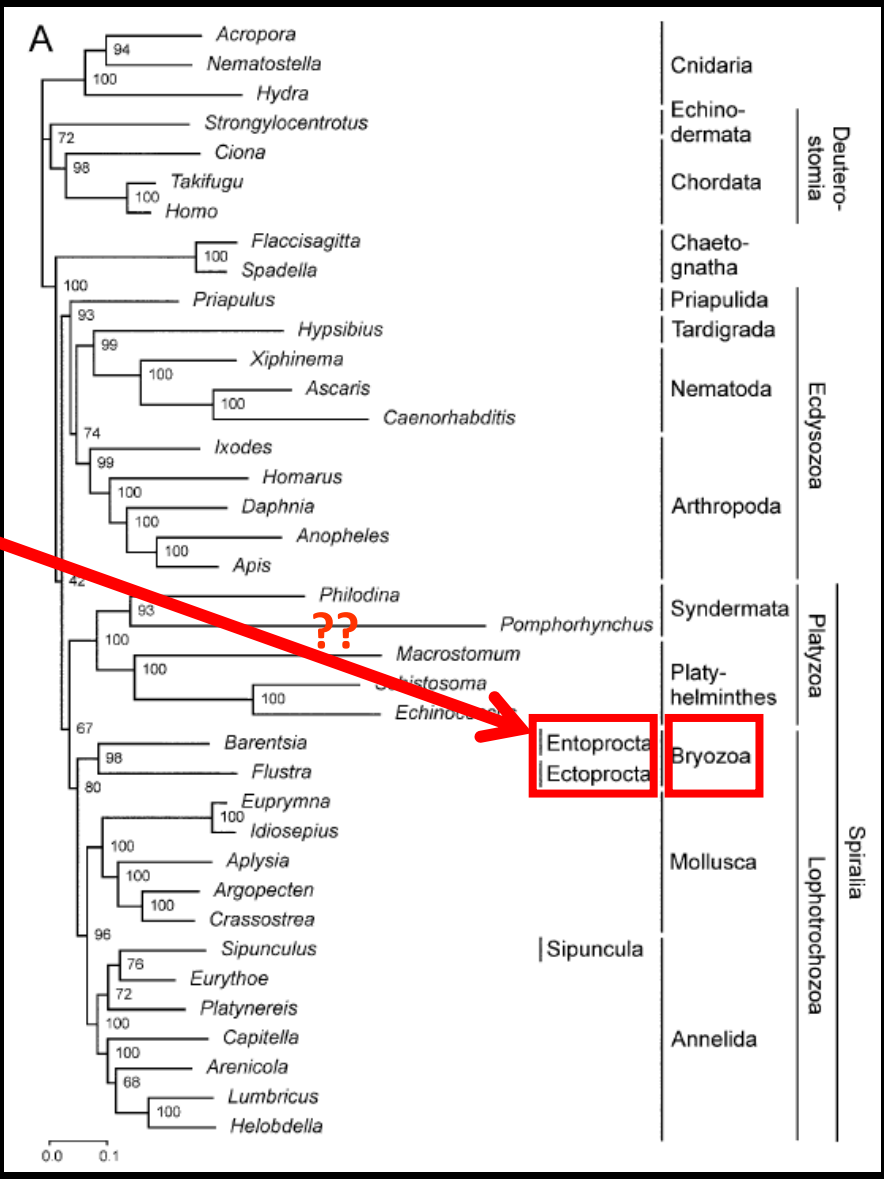
Entoprocta (Kamptozoa)

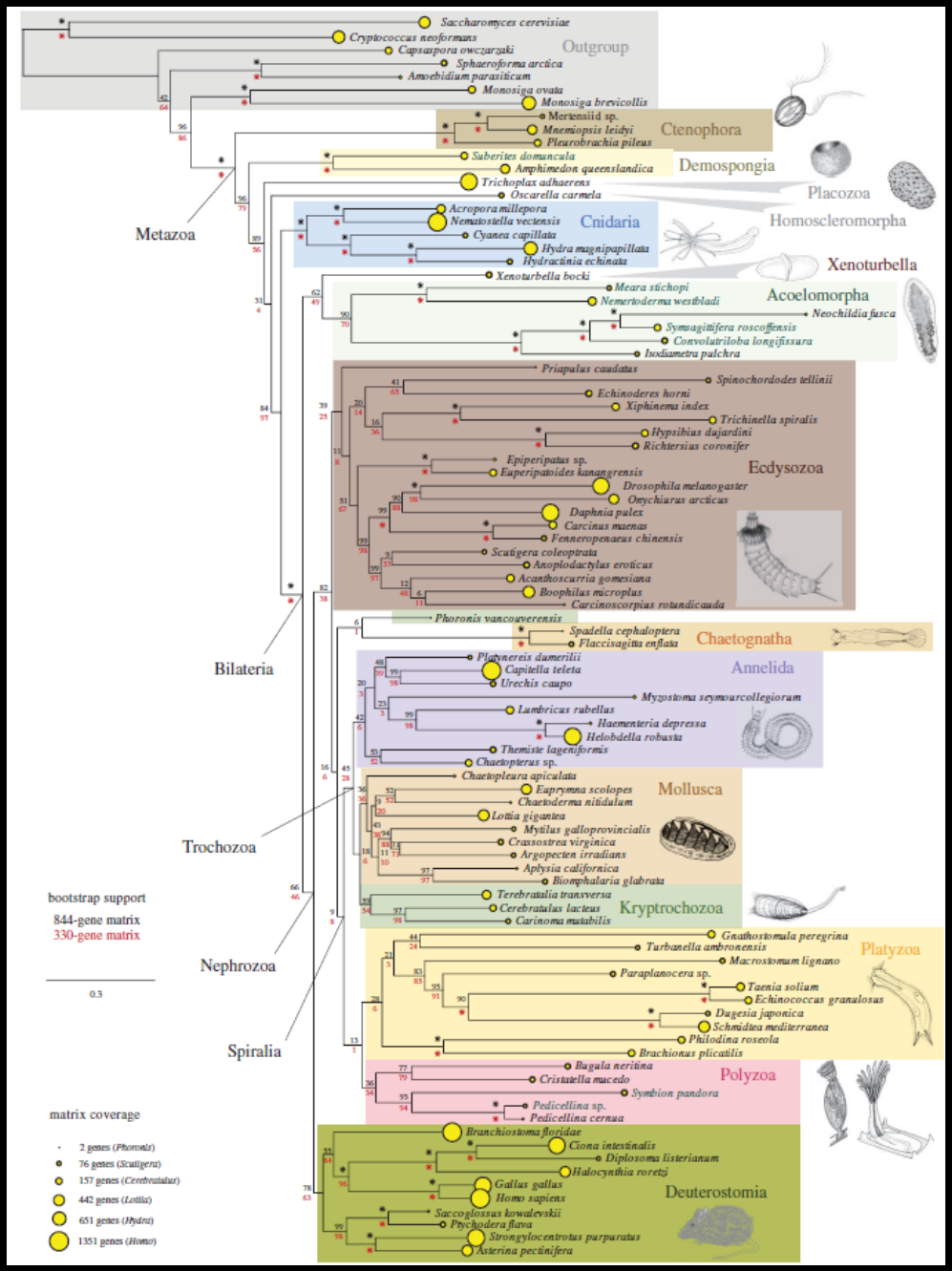


Ectoprocta (Bryozoa)



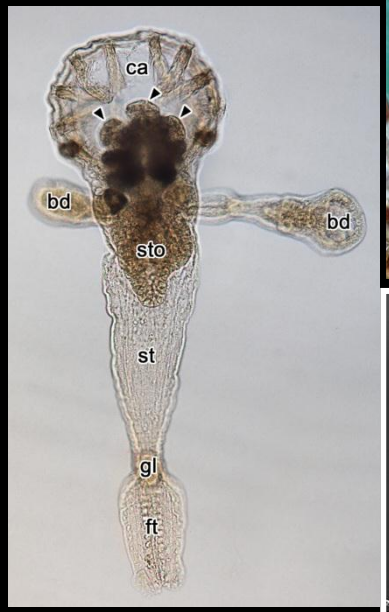
Hausdorf et al.: *Mol. Biol. Evol. (2007)*

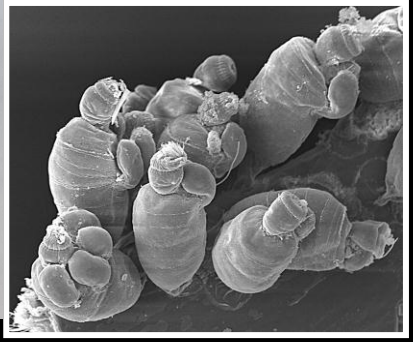
Neurogenesis & phylogeny

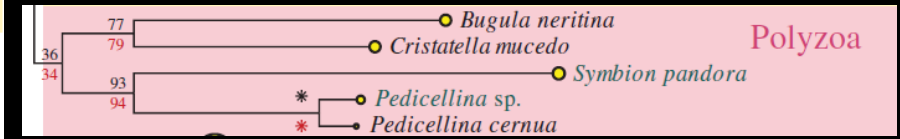


Polyzoa-hypothesis:

Ectoprocta + Entoprocta + Cycliophora

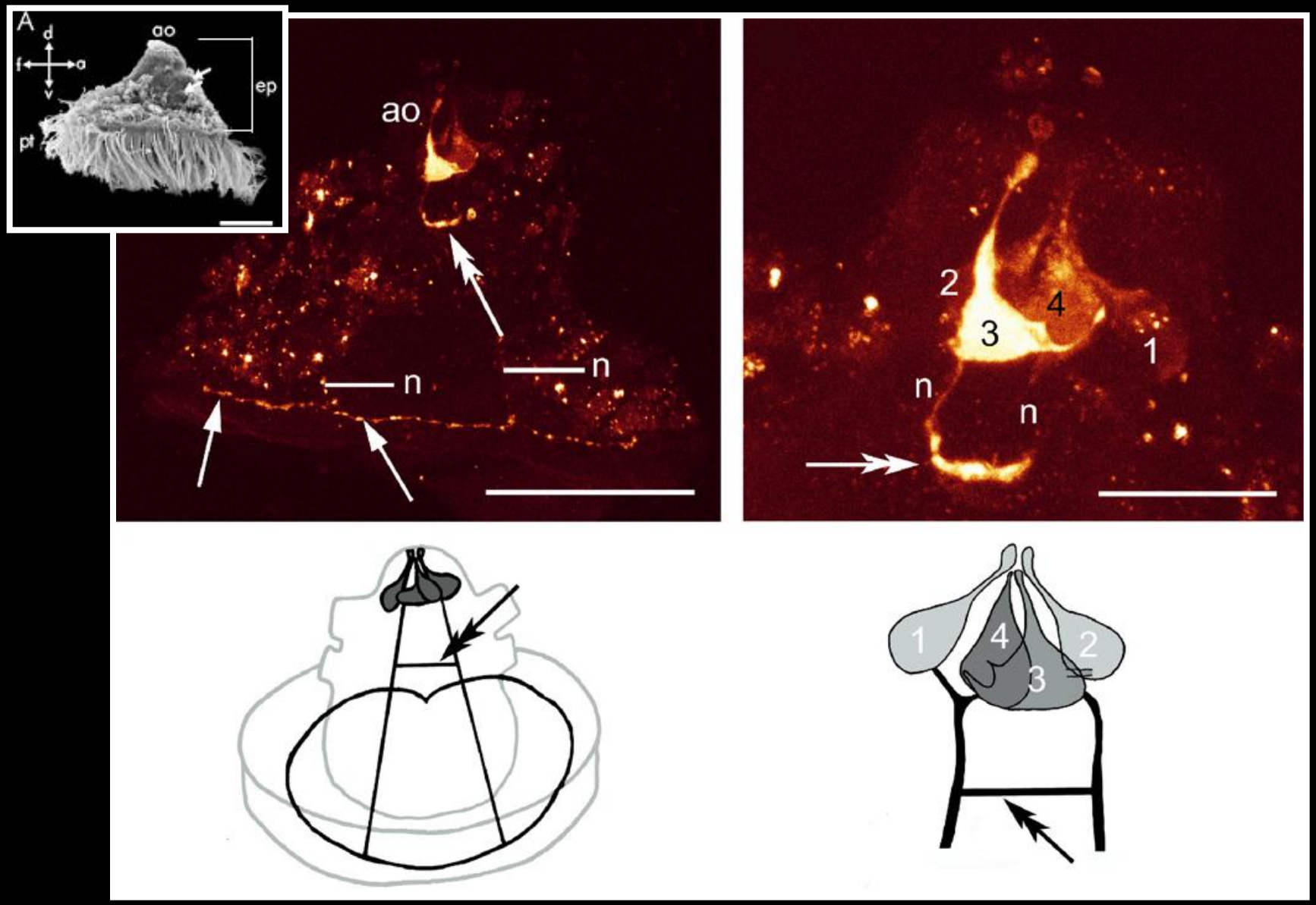






Neurogenesis & phylogeny

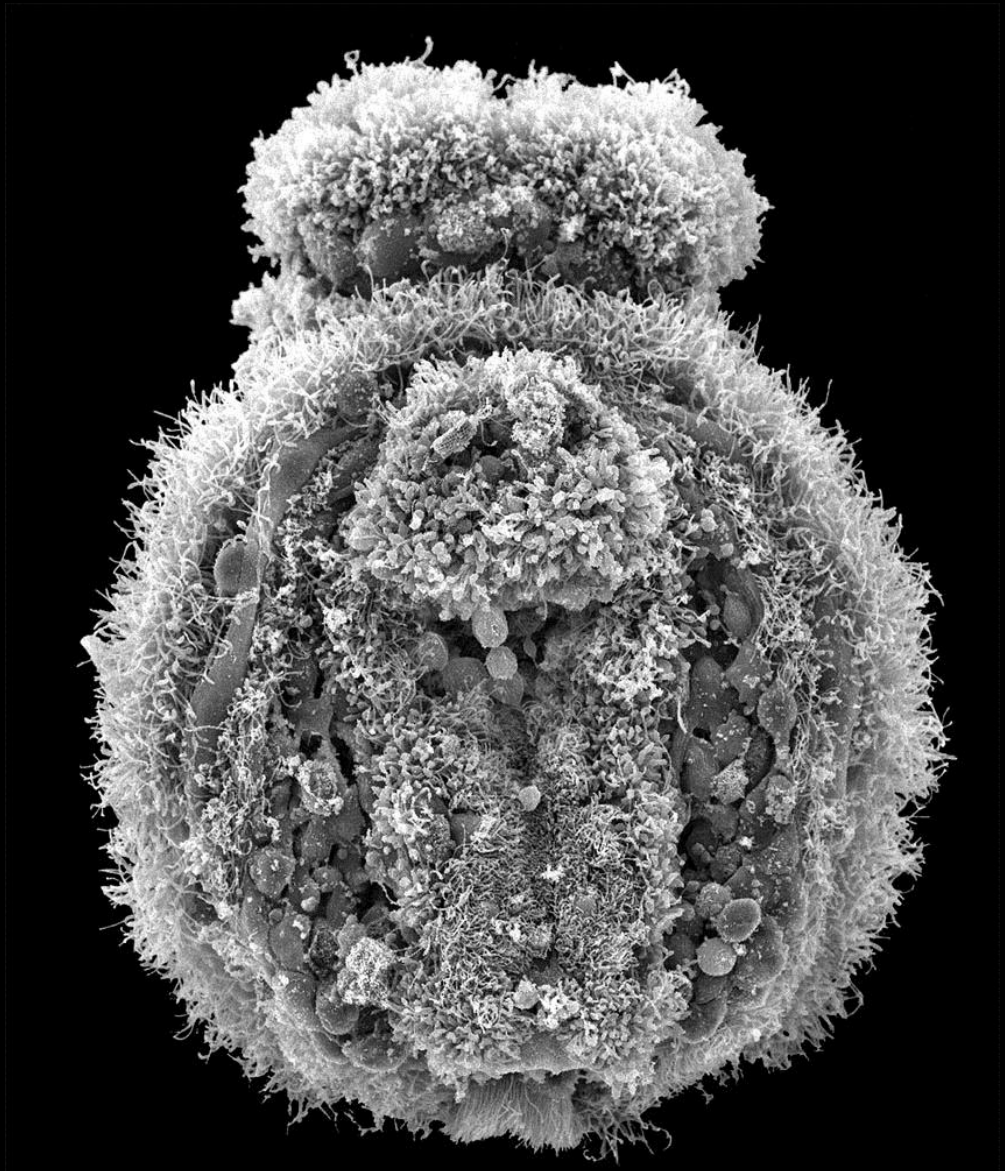
Kamptozoa (Entoprocta): nervous system of the swimming-type larva (derived!): simple, sterotypic for spiralian larvae



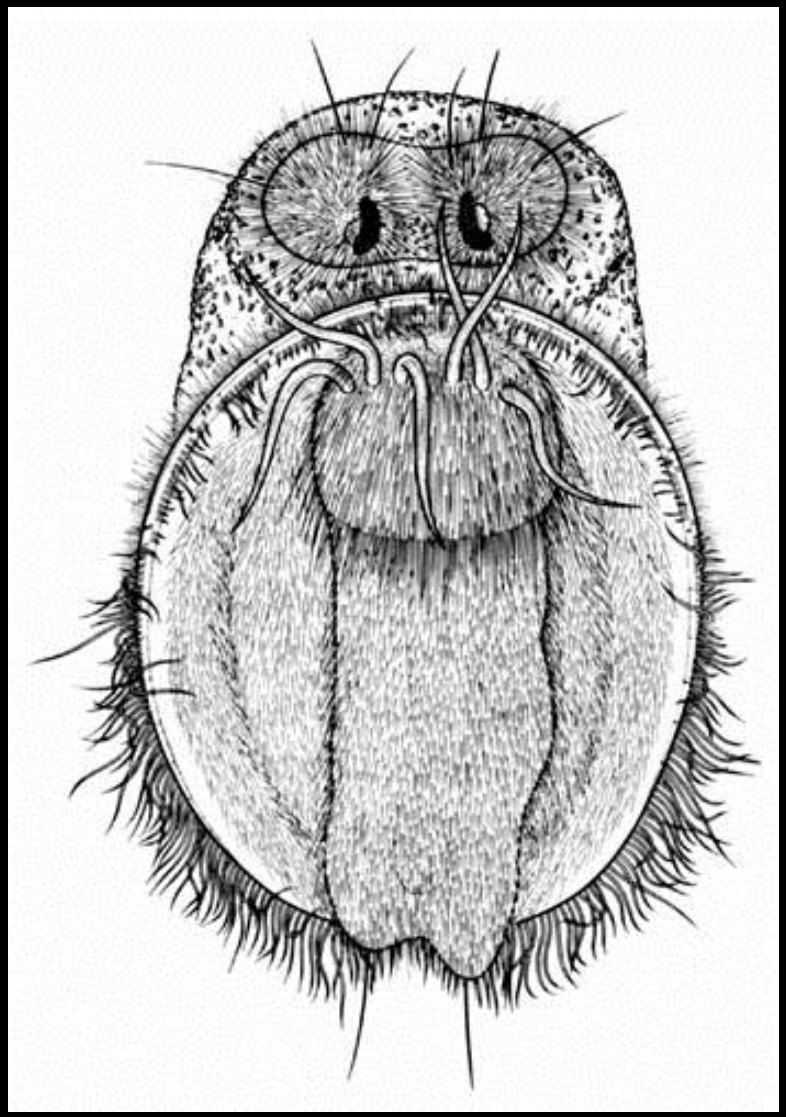
Fuchs & Wanninger: *Org. Divers. Evol. (2008)*

Neurogenesis & phylogeny

Kamptozoa (Entoprocta): creeping-type larva



Wanninger, Fuchs & Haszprunar: *Invertebr. Biol. (2007)*

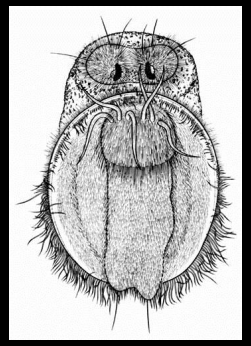


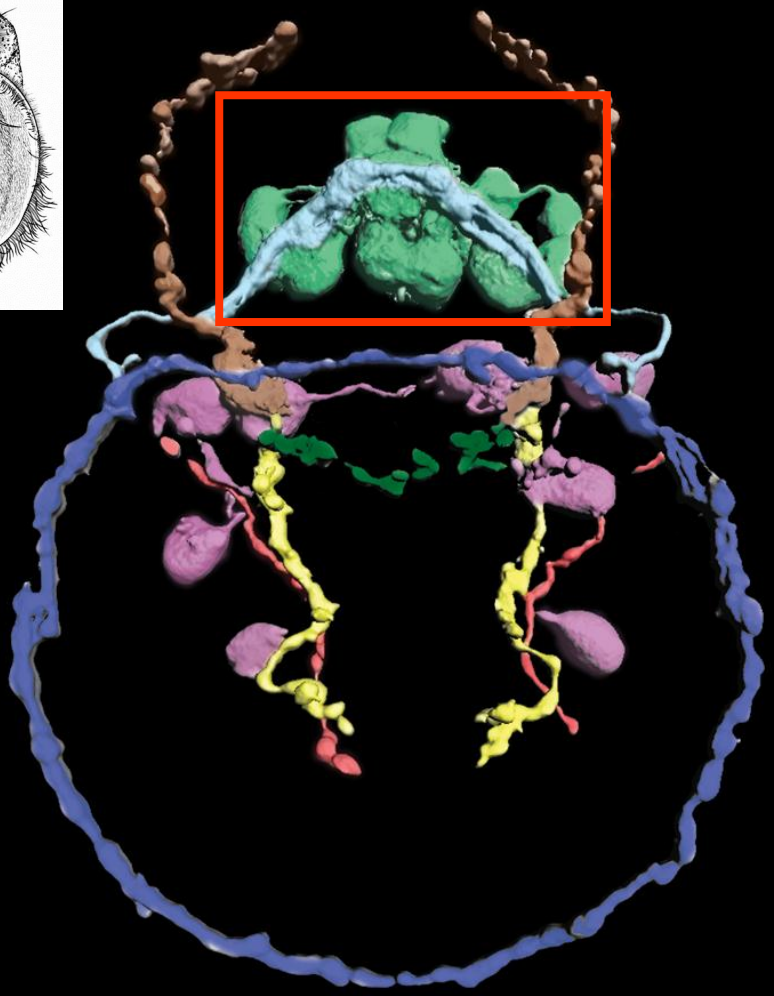
Nielsen: *Ophelia (1971)*

Neurogenesis & phylogeny

Creeping-type larva: nervous system with complex apical organ

Wanninger, Fuchs & Haszprunar: *Invertebr. Biol. (2007)*

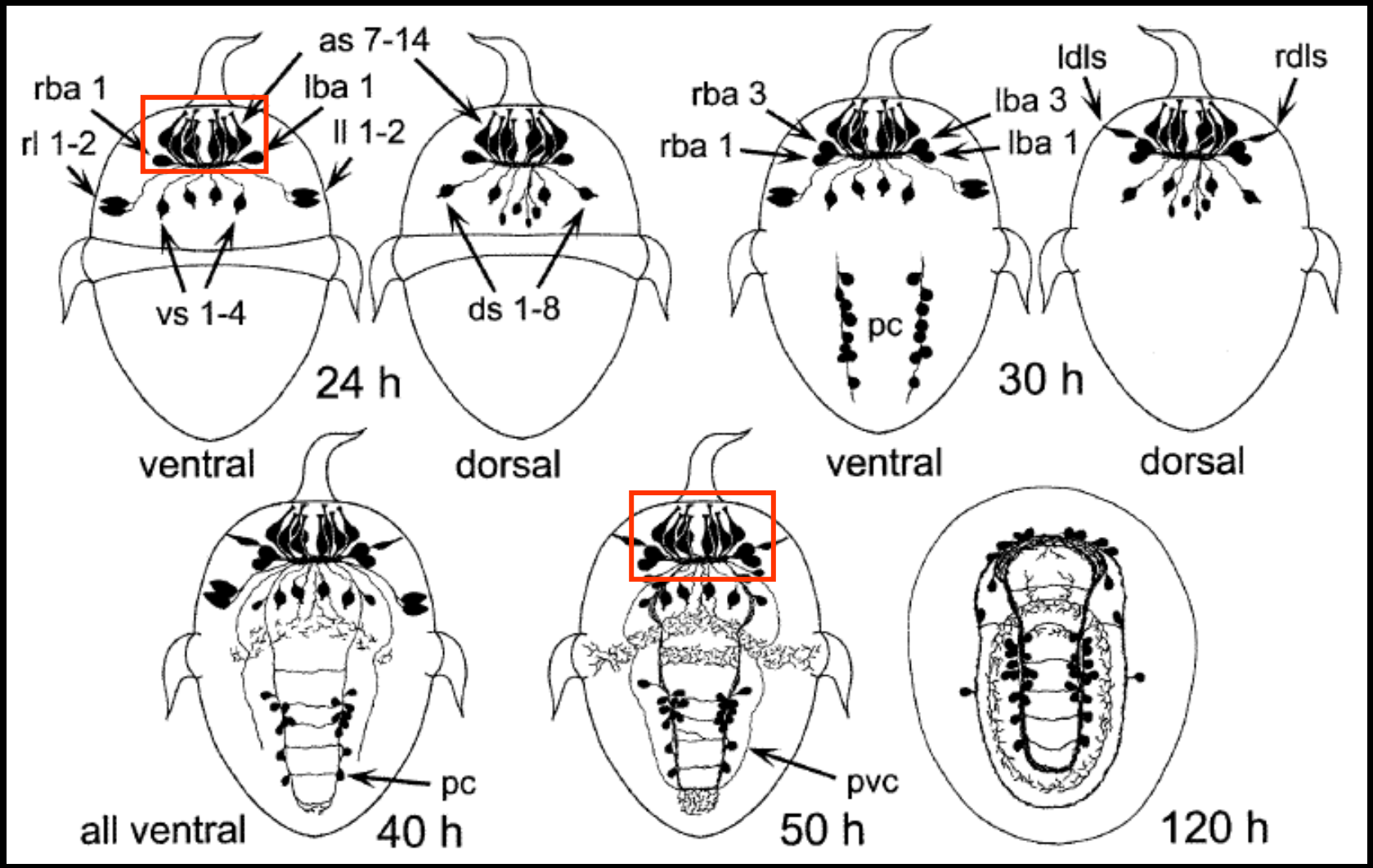




Wanninger: *Biol. Bull. (2009)*

Neurogenesis & phylogeny

Polyplacophora (*Ischnochiton hakodadensis*): neurogenesis (serotonin)

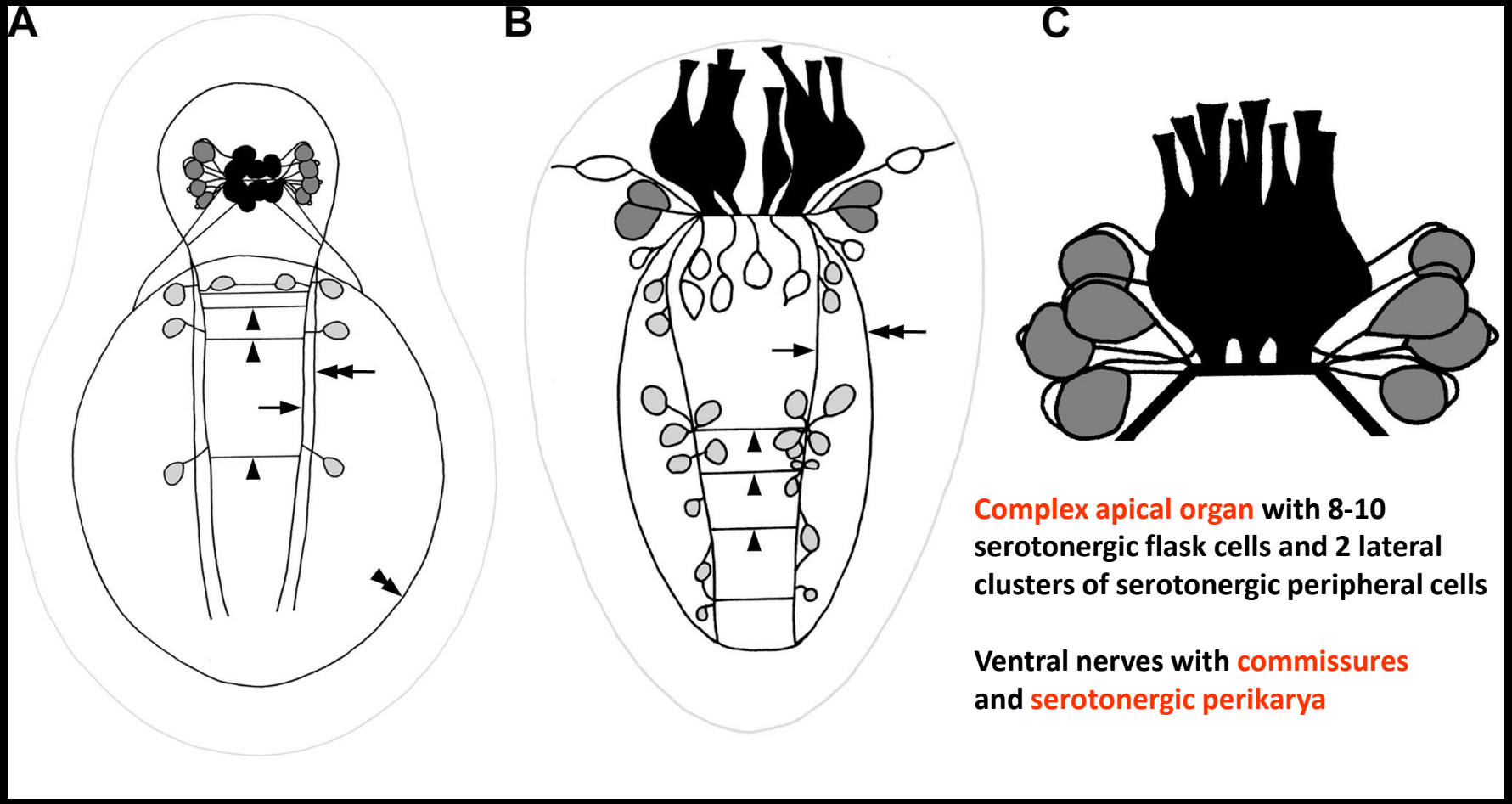


Voronezhskaya et al.: *J. Comp. Neurol. (2002)*

Neurogenesis & phylogeny

Creeping-type larva: nervous system as a **mosaic of larval and adult molluskan characters**

Kamptozoa **Polyplacophora** **apical organ**



Complex apical organ with 8-10 serotonergic flask cells and 2 lateral clusters of serotonergic peripheral cells

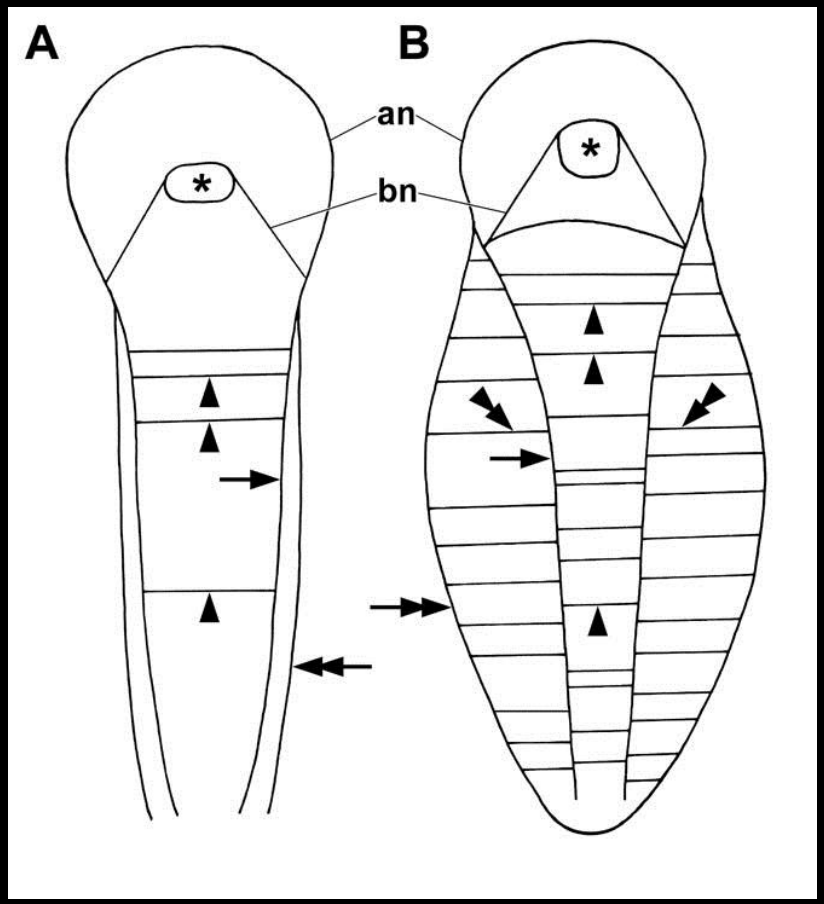
Ventral nerves with commissures and serotonergic perikarya

Wanninger, Fuchs & Haszprunar: *Invertebr. Biol. (2007)*

Neurogenesis & phylogeny

Creeping-type larva: nervous system as a mosaic of larval and adult molluskan characters

Kamptozoa **Polyplacophora**



Wanninger, Fuchs & Haszprunar: *Invertebr. Biol. (2007)*

Ventral nerves with commissures and serotonergic perikarya

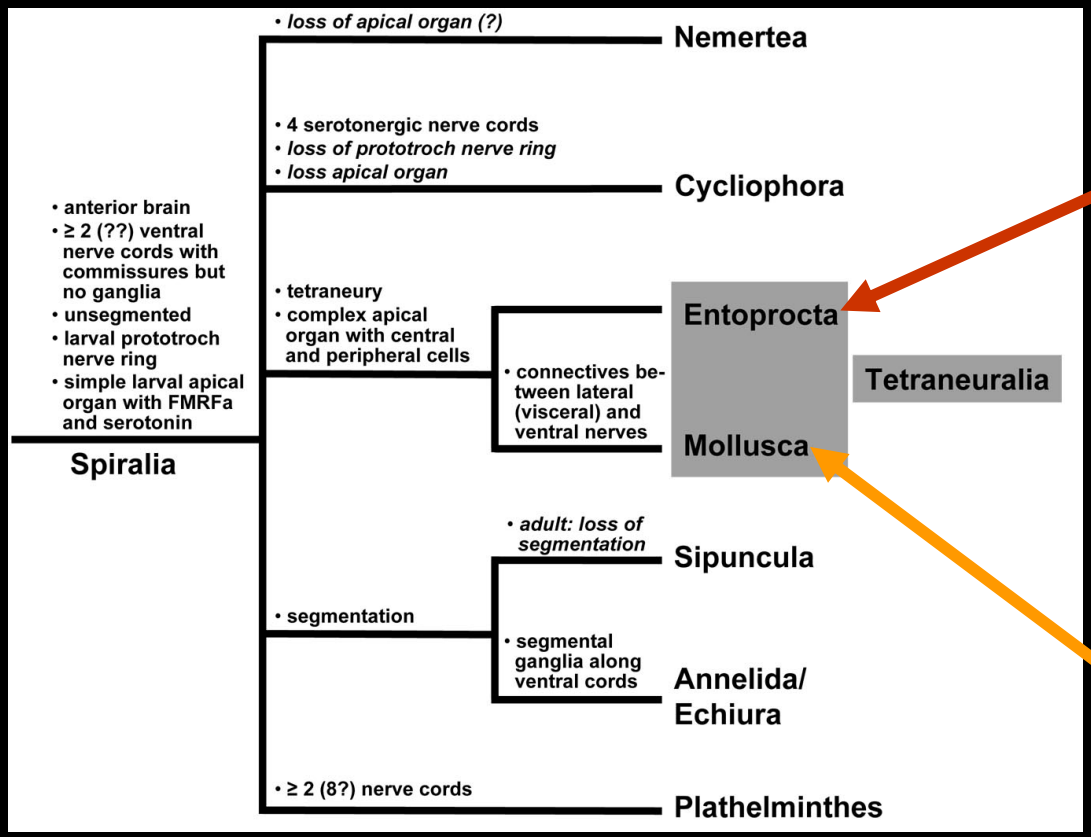
Complex apical organ with 8-10 serotonergic flask cells and 2 lateral clusters of serotonergic peripheral cells

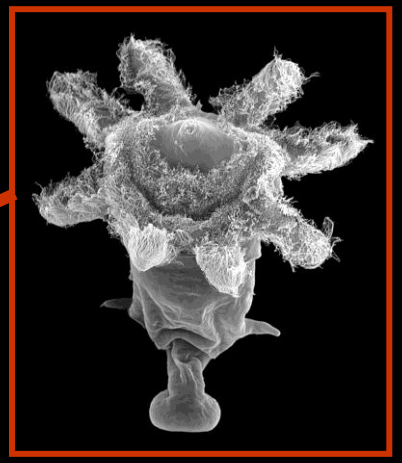
Tetraneury: 1 pair of ventral and 1 pair of visceral nerves cords

Pre-oral and circumoral nerve ring

Buccal nerves

Neurogenesis & phylogeny





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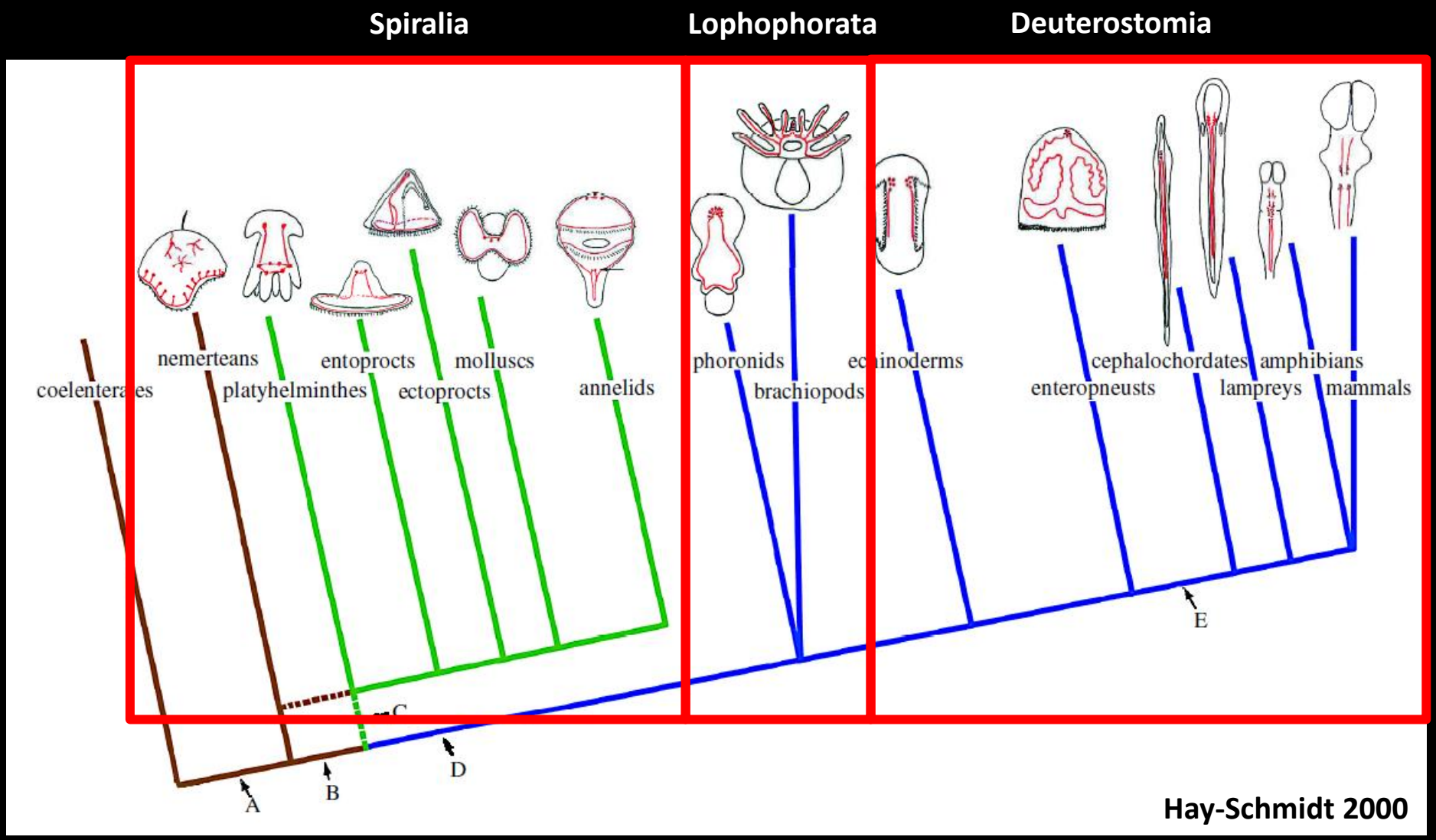
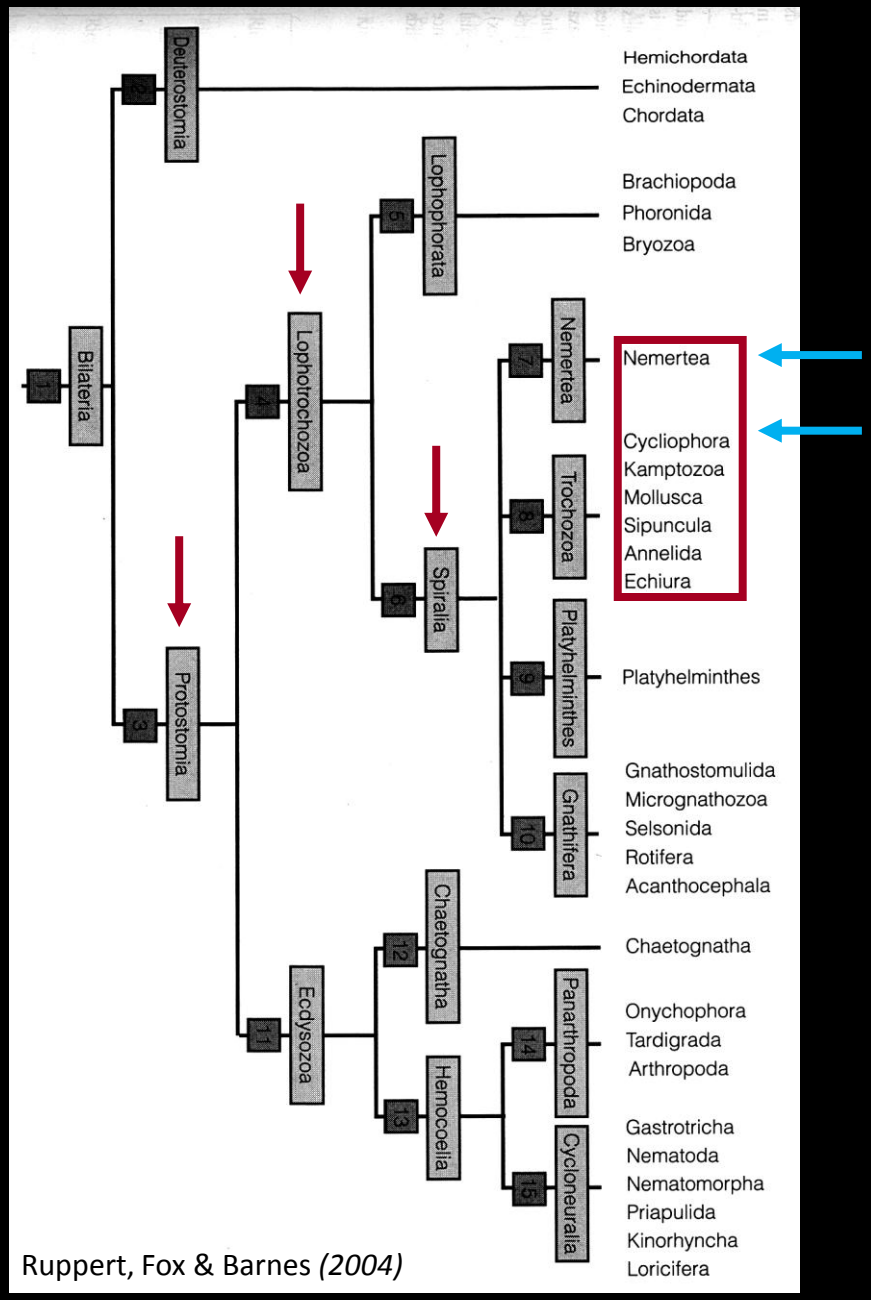
Invertebrate larval serotonergic nervous systems

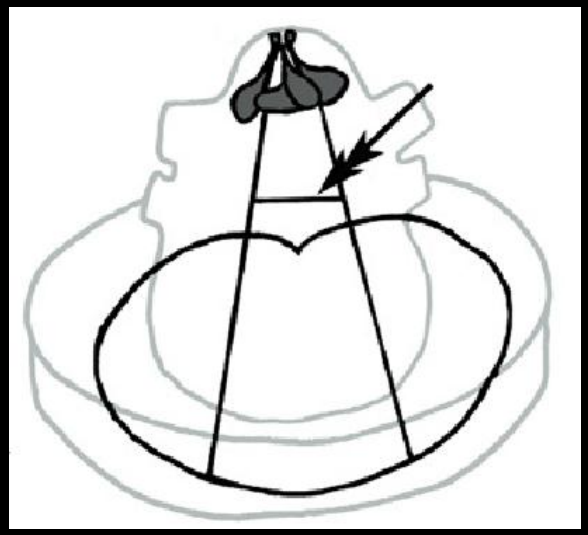


Hay-Schmidt 2000

Spiralian neurogenesis



Ruppert, Fox & Barnes *(2004)*



”Typical” spiralian (larval) nervous system:

Simple apical orgen with few (4?) serotonergic flask cells

Paired ventral nerve cord

Serotonergic prototroch nerve ring

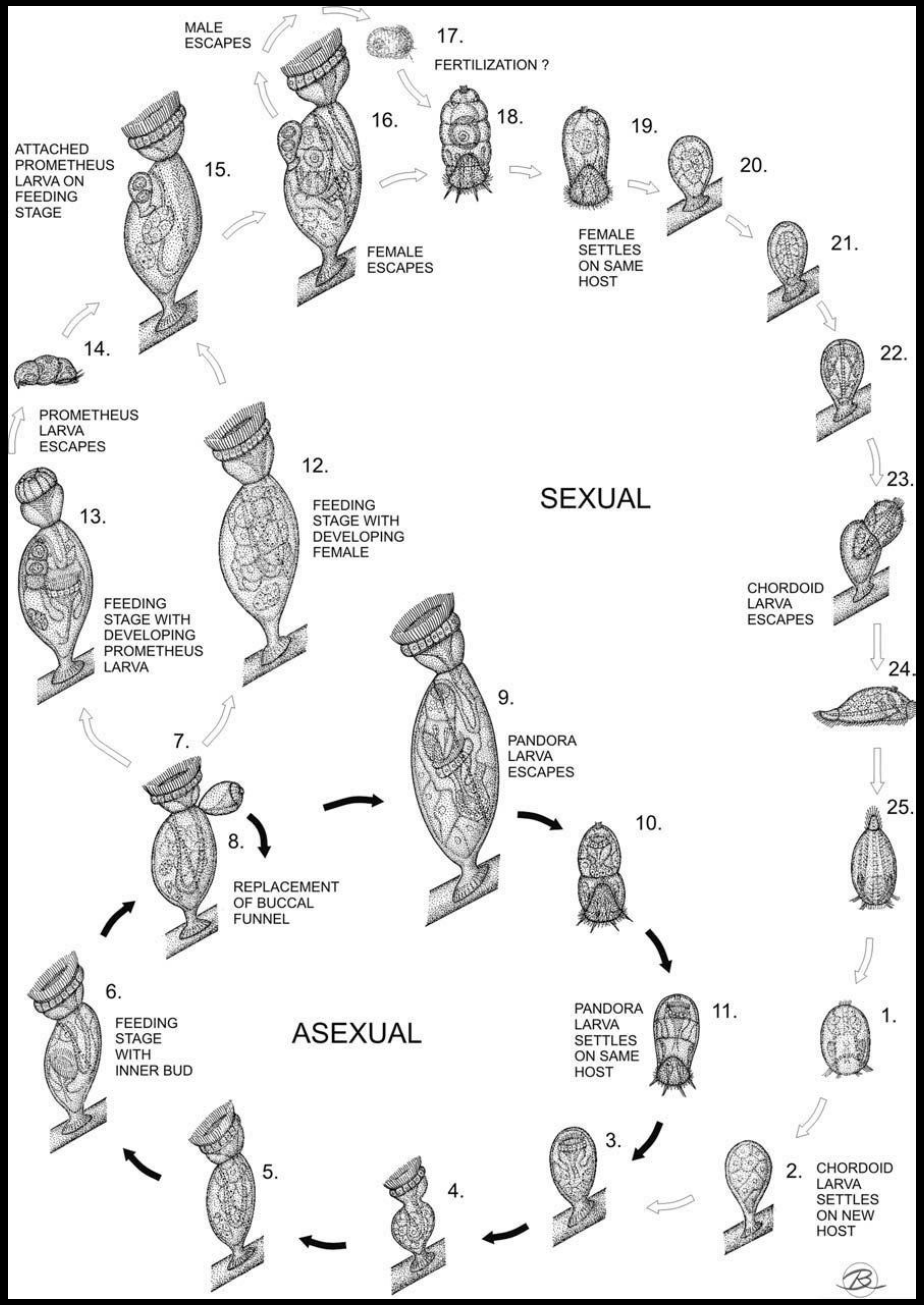
Cycliophora

Complex life cycle with 2 larval stages:

Pandora larva: settles on same host

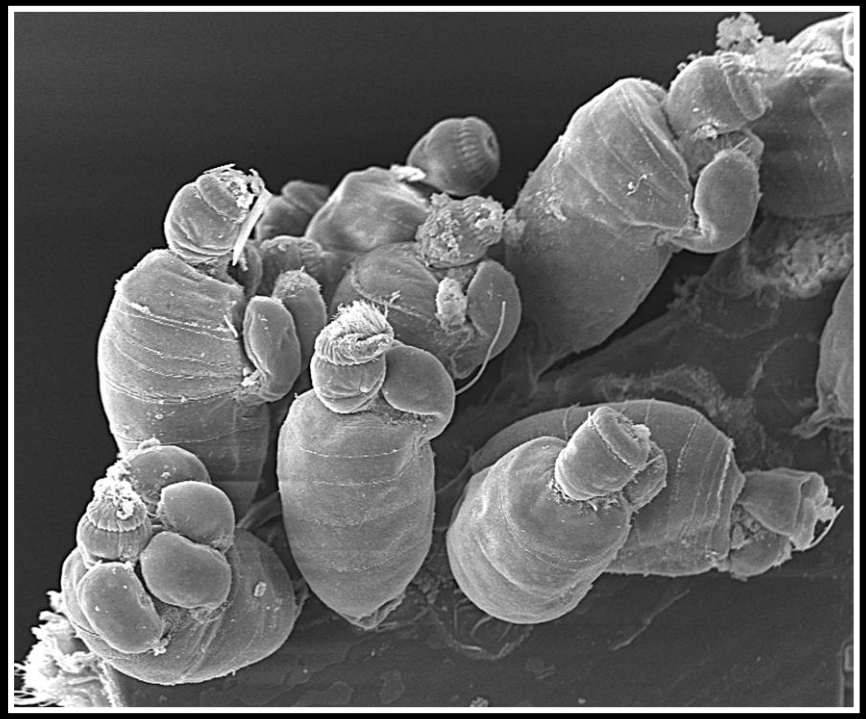
Chordoid larva: colonializes new host

Prometheus larva: settles on feeding stage and forms male

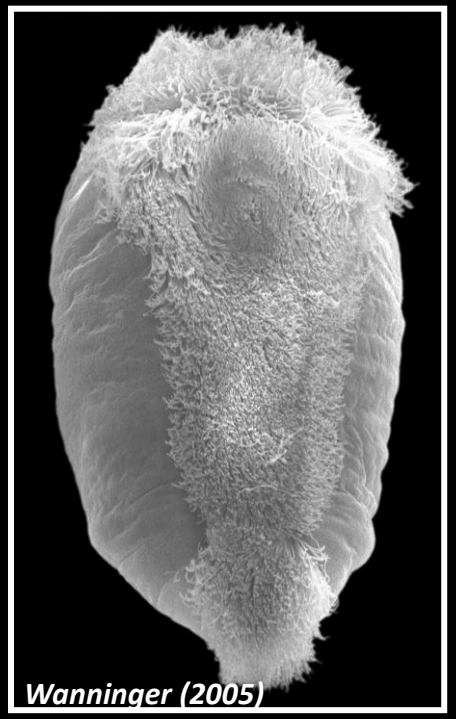


Cycliophora: larval neuroanatomy

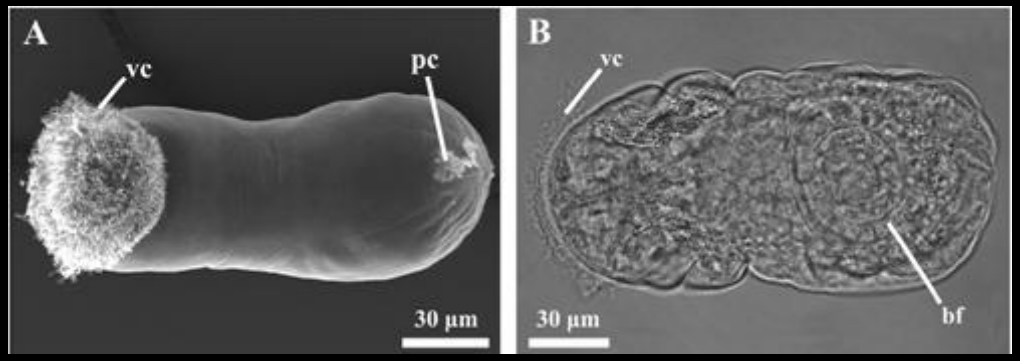
Feeding stage



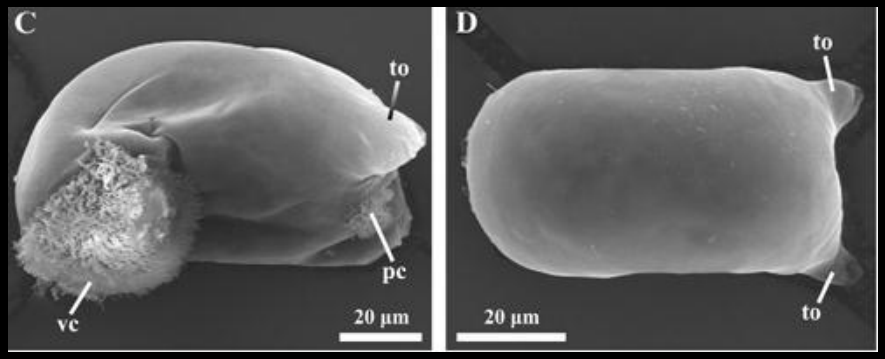
Chordoid larva



Pandora larva



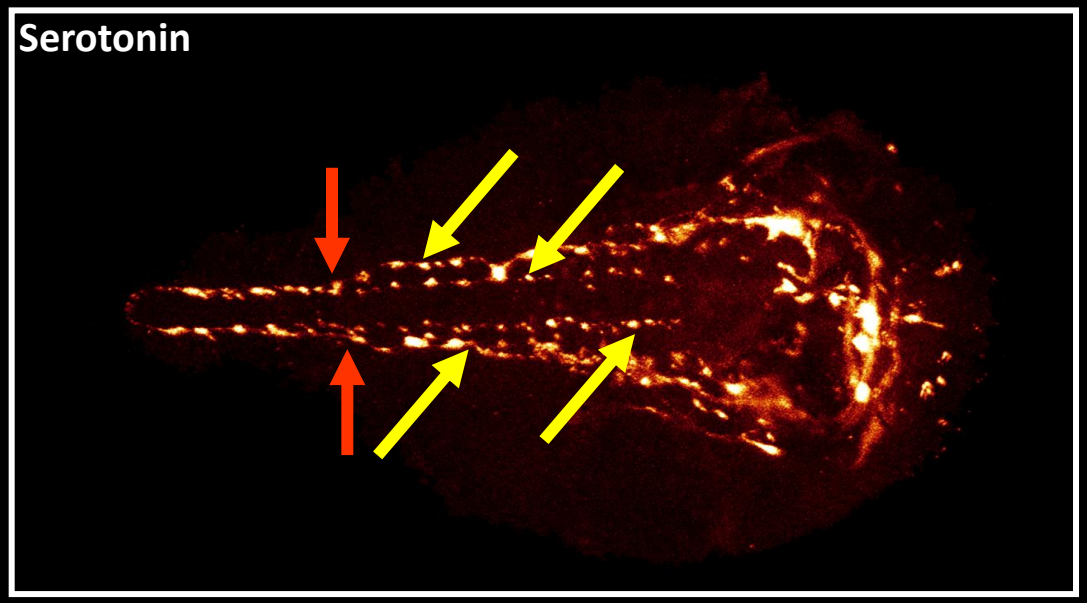
Prometheus larva

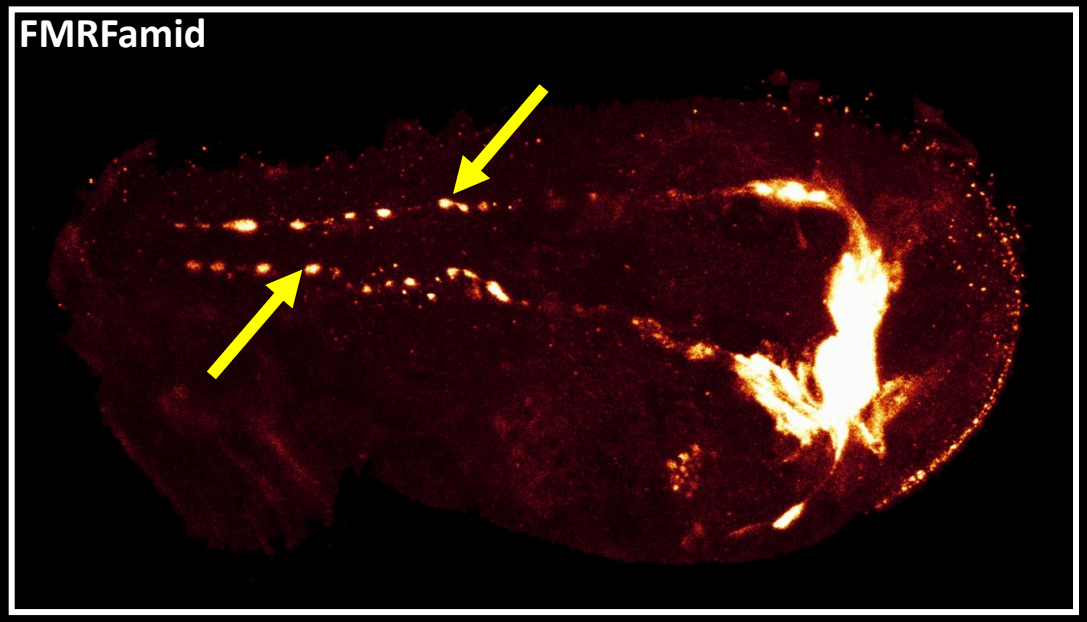


Neves, Kristensen & Wanninger (2010)

Cycliophora: larval neuroanatomy

Chordoid larva: no apical organ, no prototroch nerve, 4 (!) serotonergic ventral nerve cords; large brain

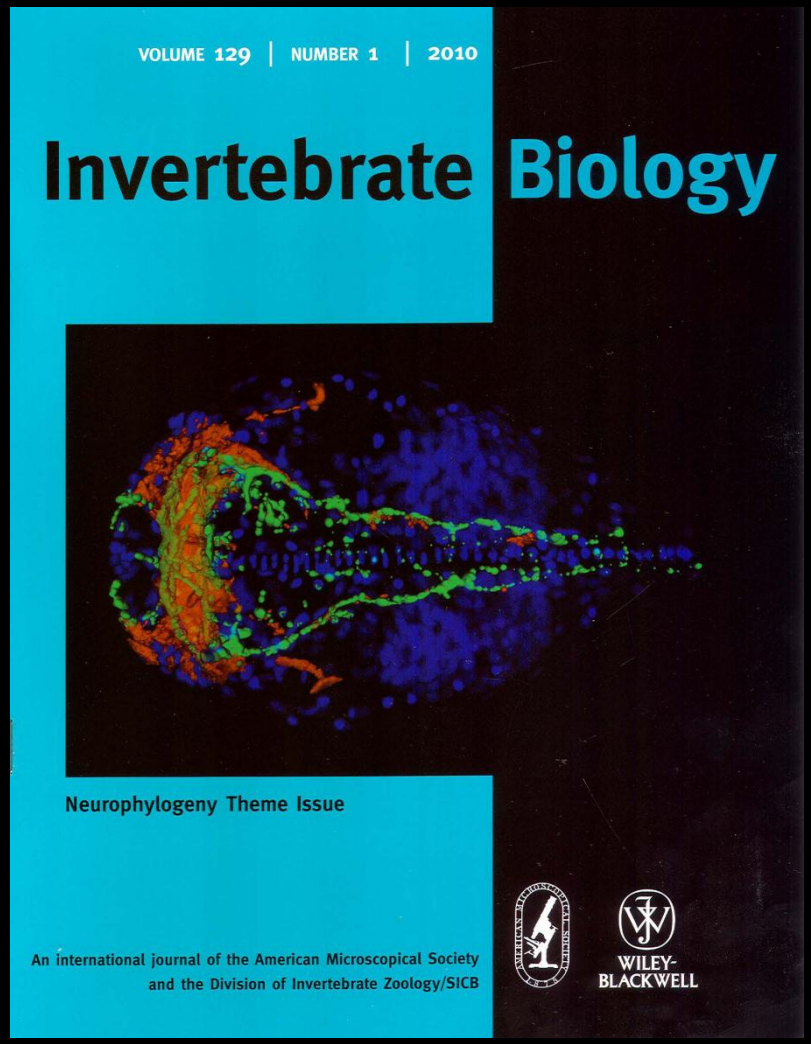


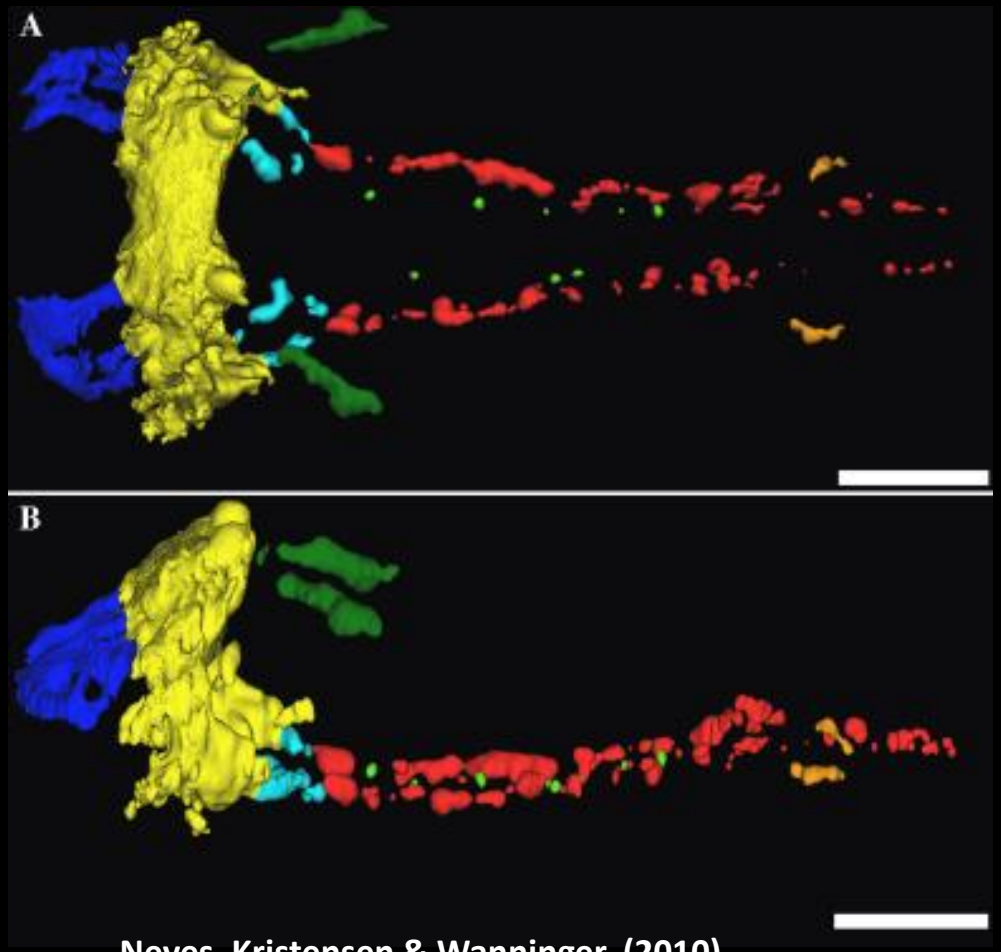


Wanninger (2005)

Cycliophora: larval neuroanatomy

Chordoid larva: 4 synapsinergic ventral nerve cords!

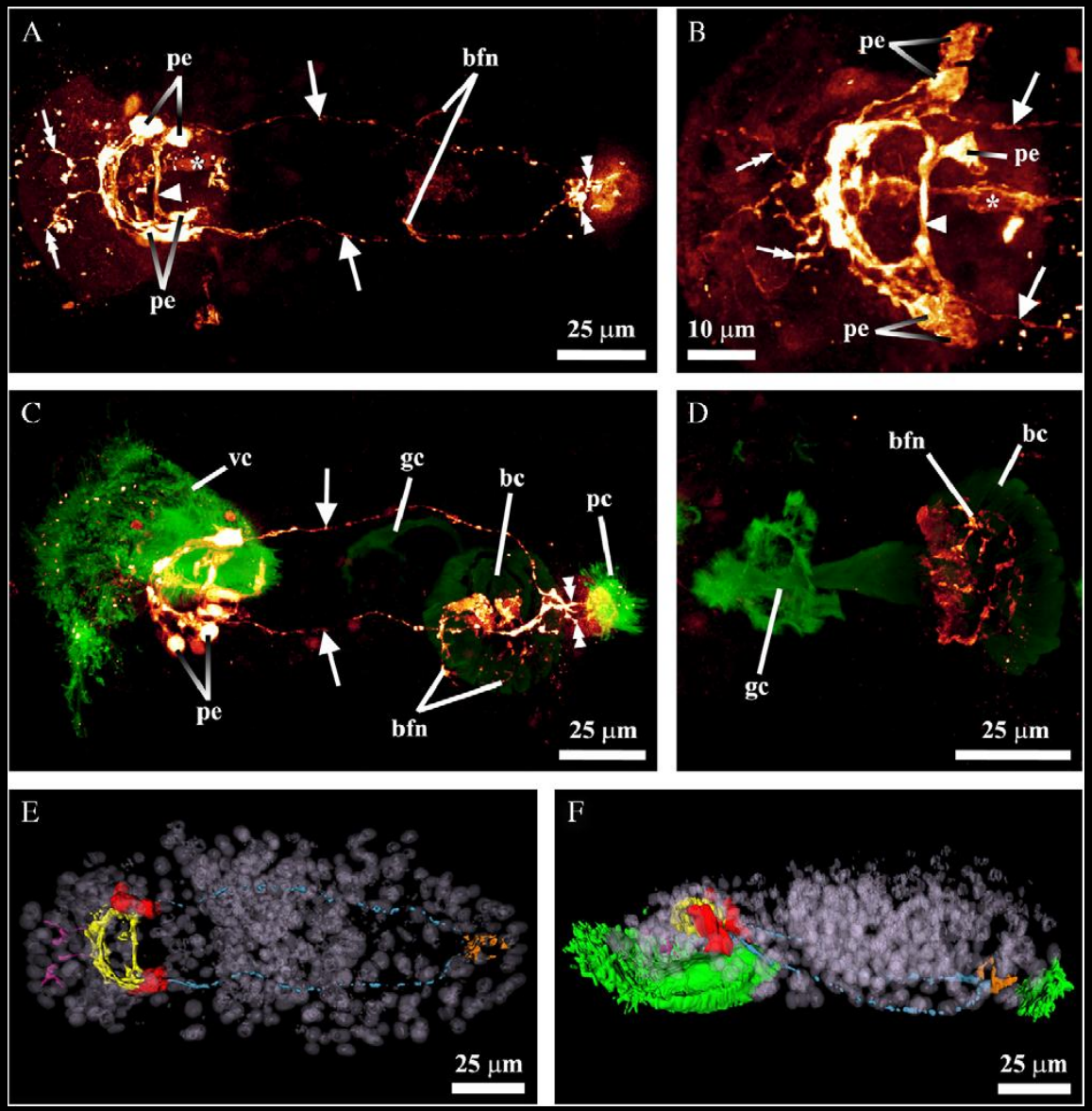




Neves, Kristensen & Wanninger (2010)

Cycliophora: larval neuroanatomy

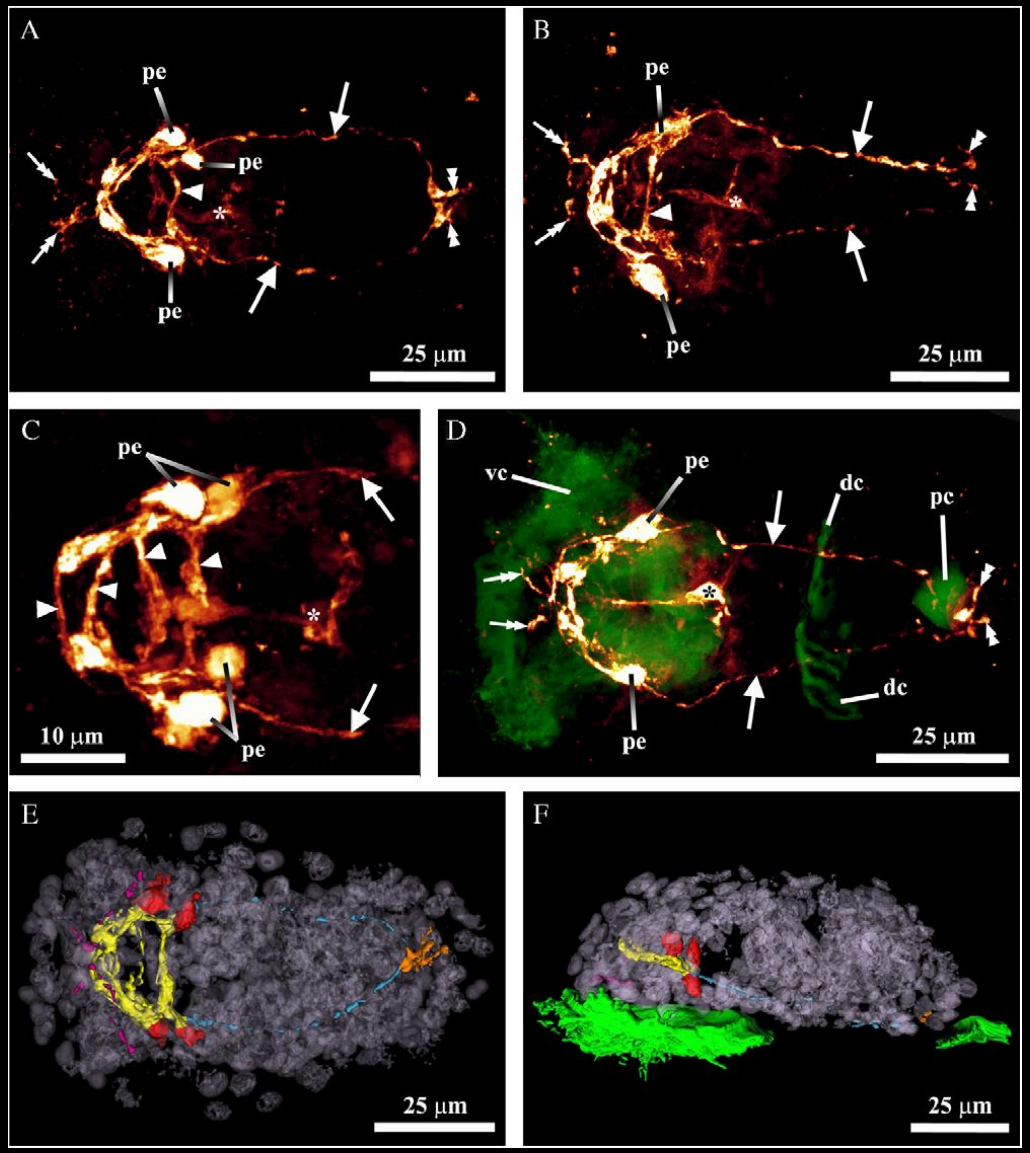
Pandora larva: brain, no apical organ, no prototroch nerve, 2 serotonergic ventral nerve cords



Neves, Kristensen & Wanninger (2010)

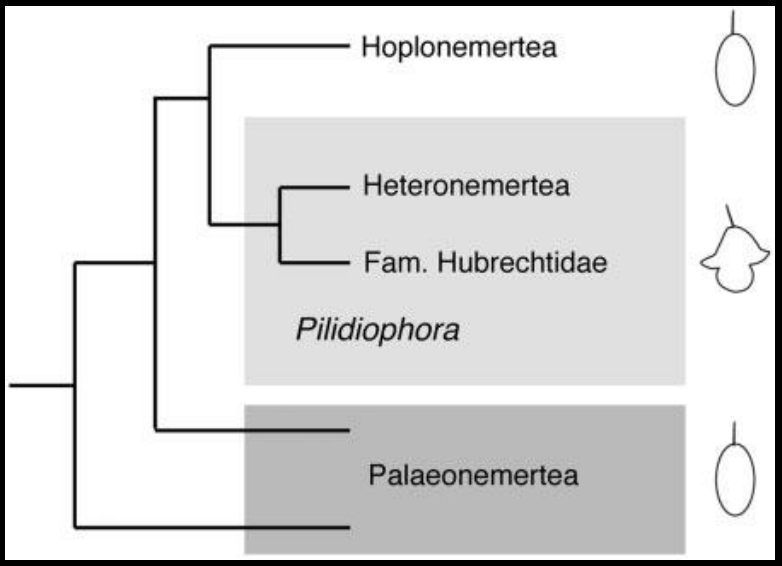
Cycliophora: larval neuroanatomy

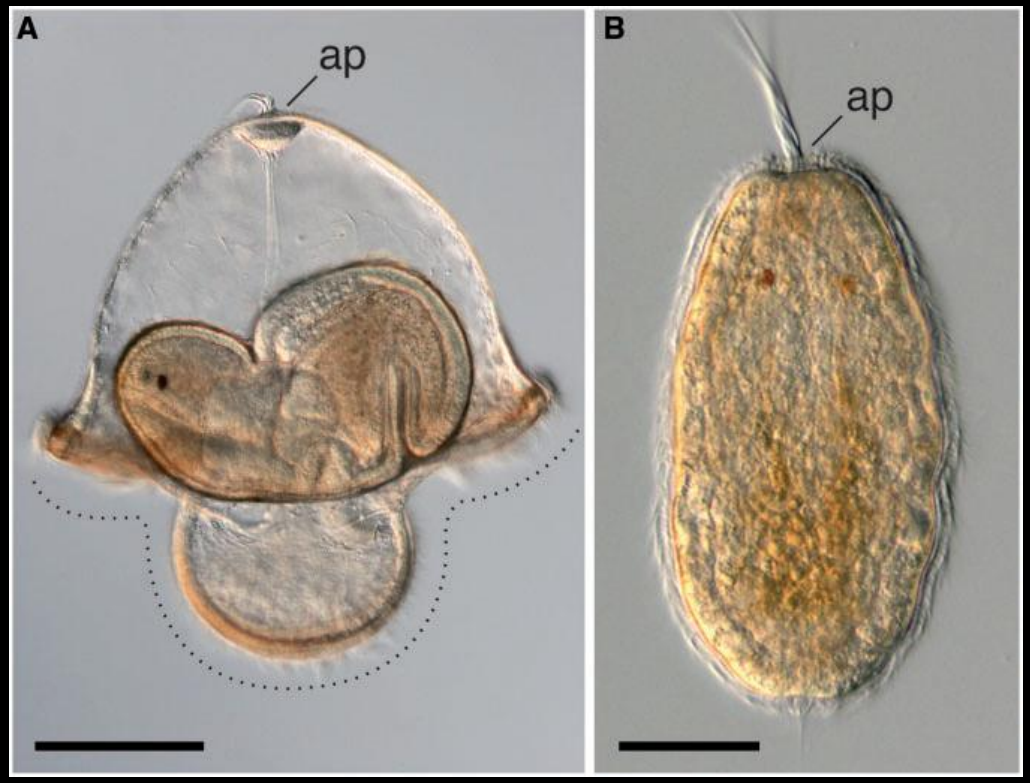
Prometheus larva: brain, no apical organ, no prototroch nerve, 2 serotonergic ventral nerve cords



Neves, Kristensen & Wanninger (2010)

Nemertea: larval neuroanatomy





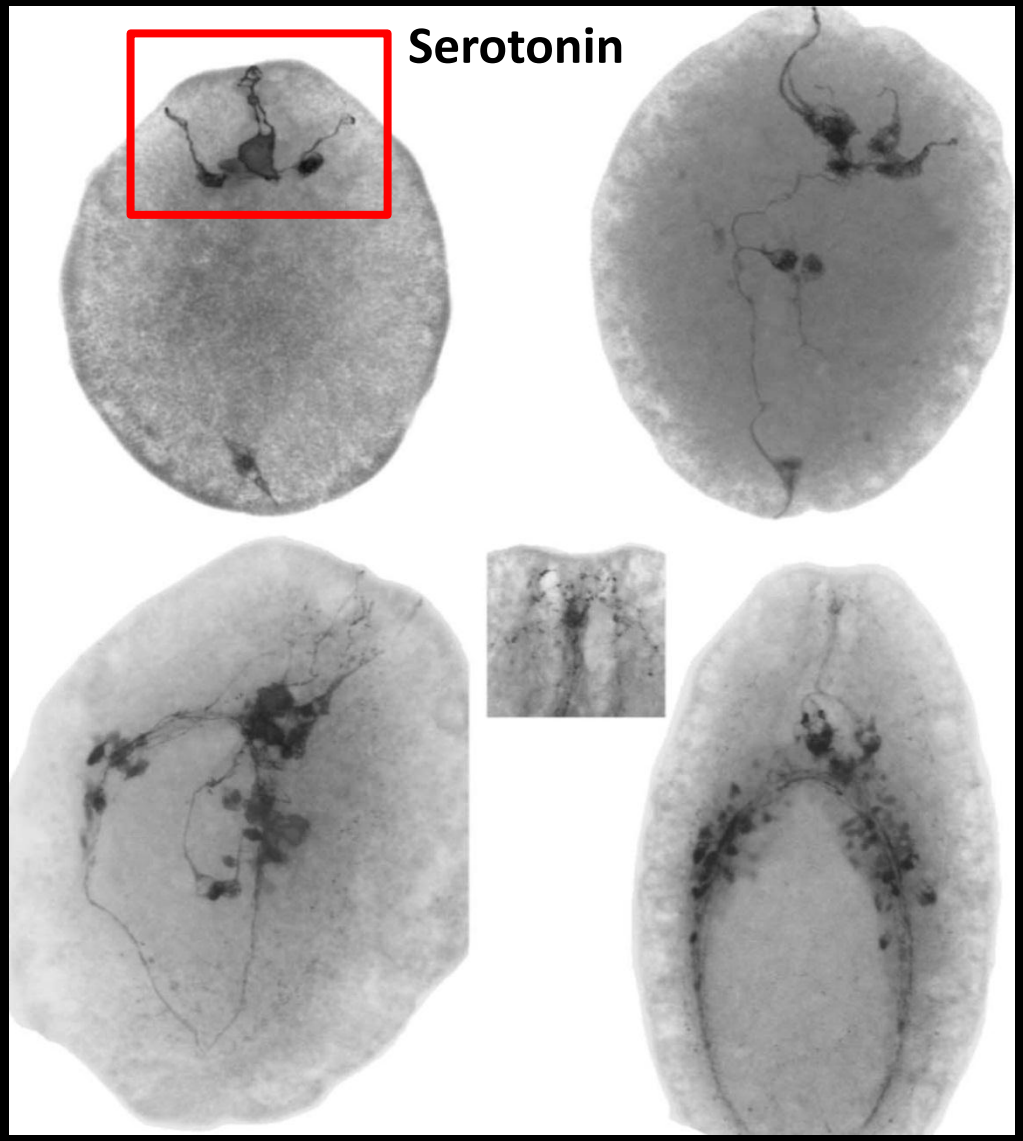
Maslakova: *Integr. Comp. Biol. (2010)*

Nemertea: larval neuroanatomy

Flask-shaped serotonergic cells in the apical organ of hoplonemertean larva!
Paired ventral nerve cord; no prototroch nerve

Quasitetrastemma stimpsoni

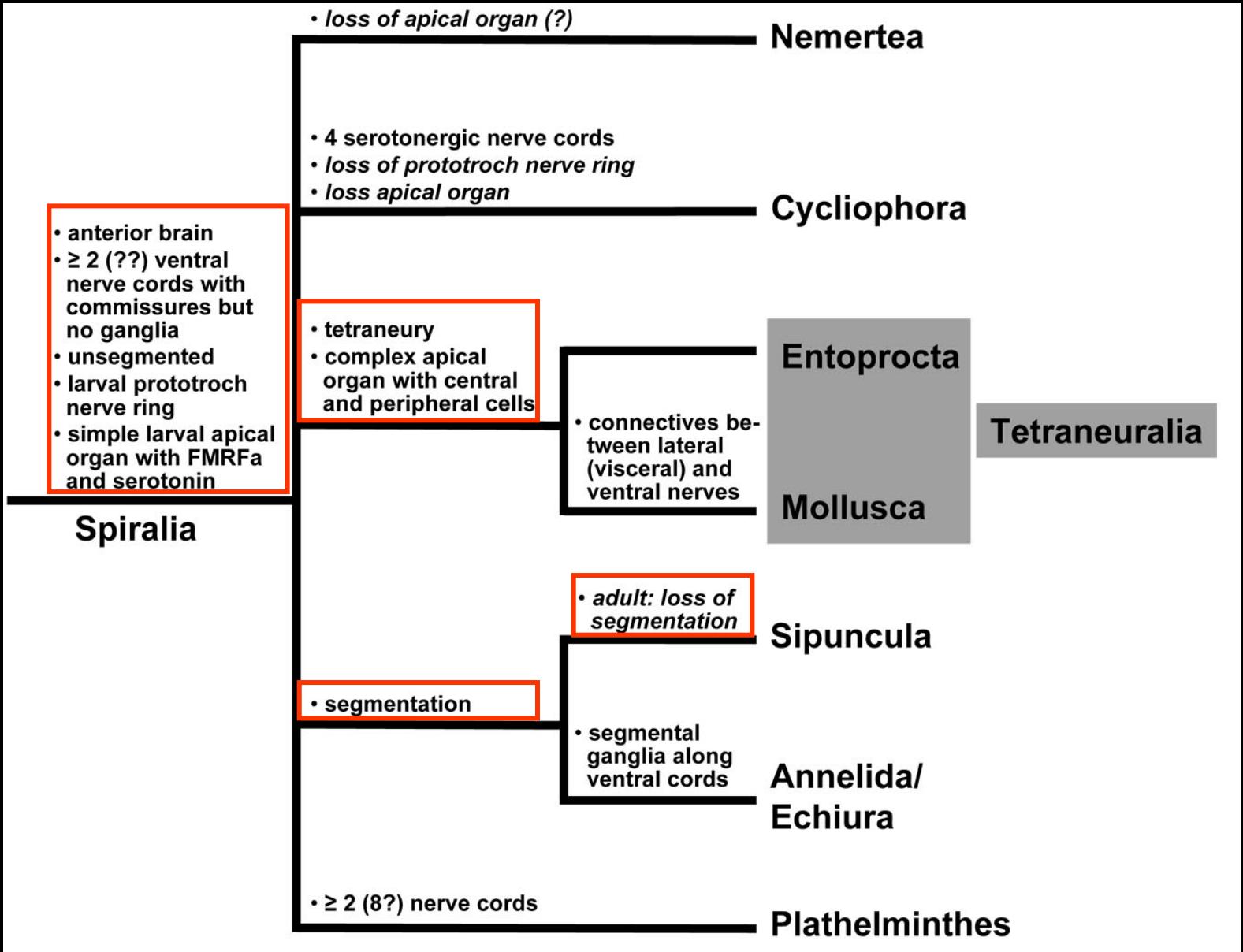
Maslakova: *Integr. Comp. Biol. (2010)*



Chernyshev & Magarlamov : *Dokl. Biol. Sci. (2010)*

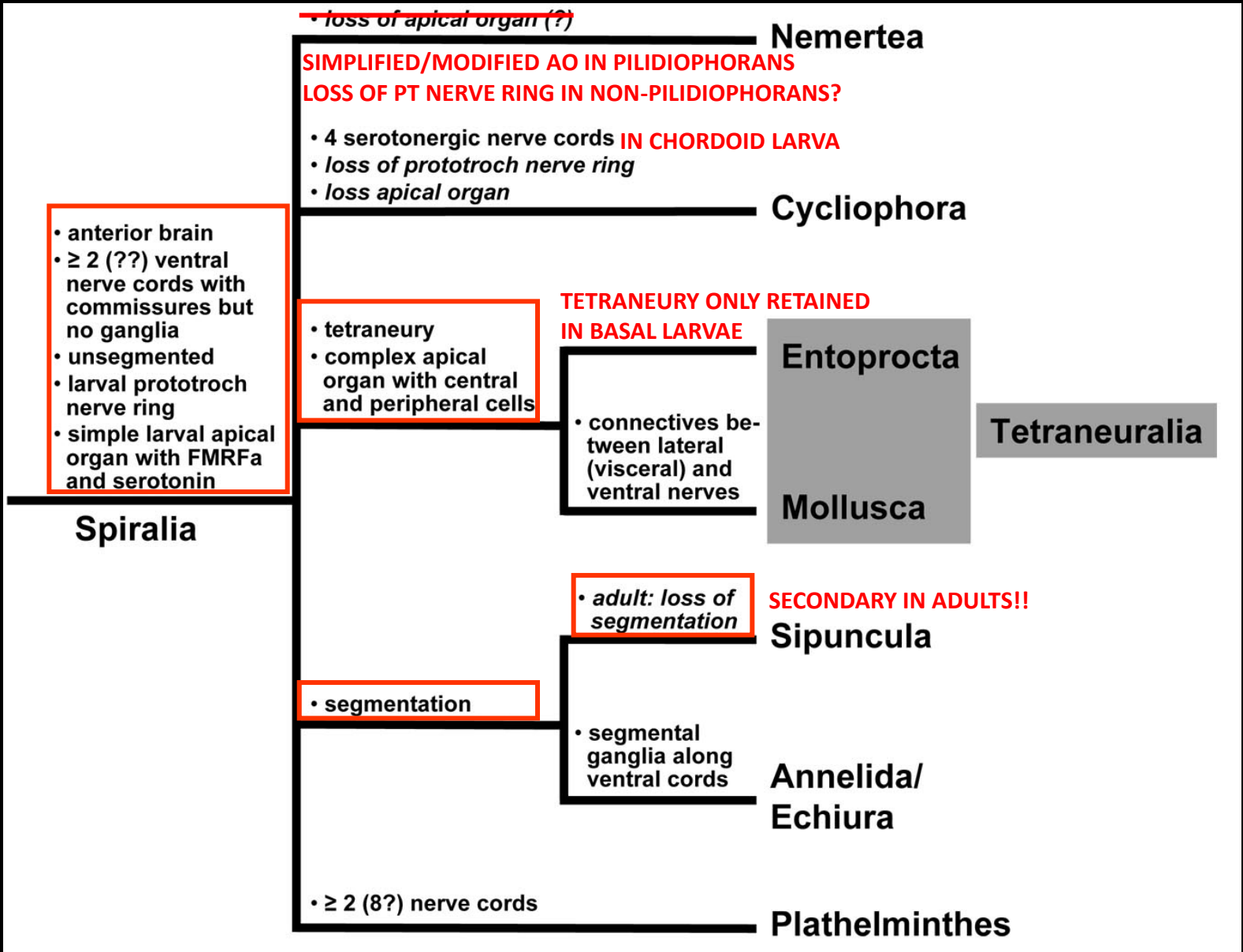
Nervous system evolution in Spiralia

Wanninger: *Biol. Bull. (2009):*

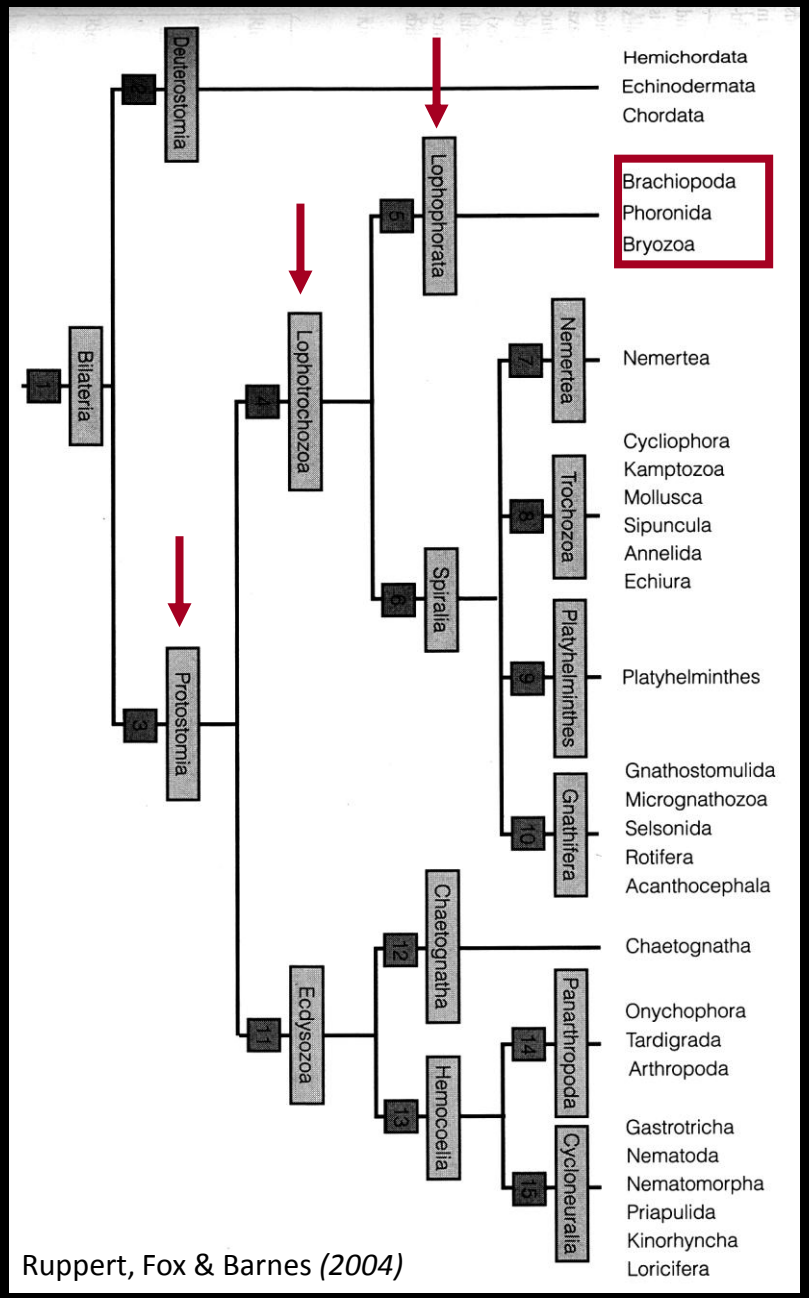


Nervous system evolution in Spiralia

Wanninger: *unpublished (2012):*

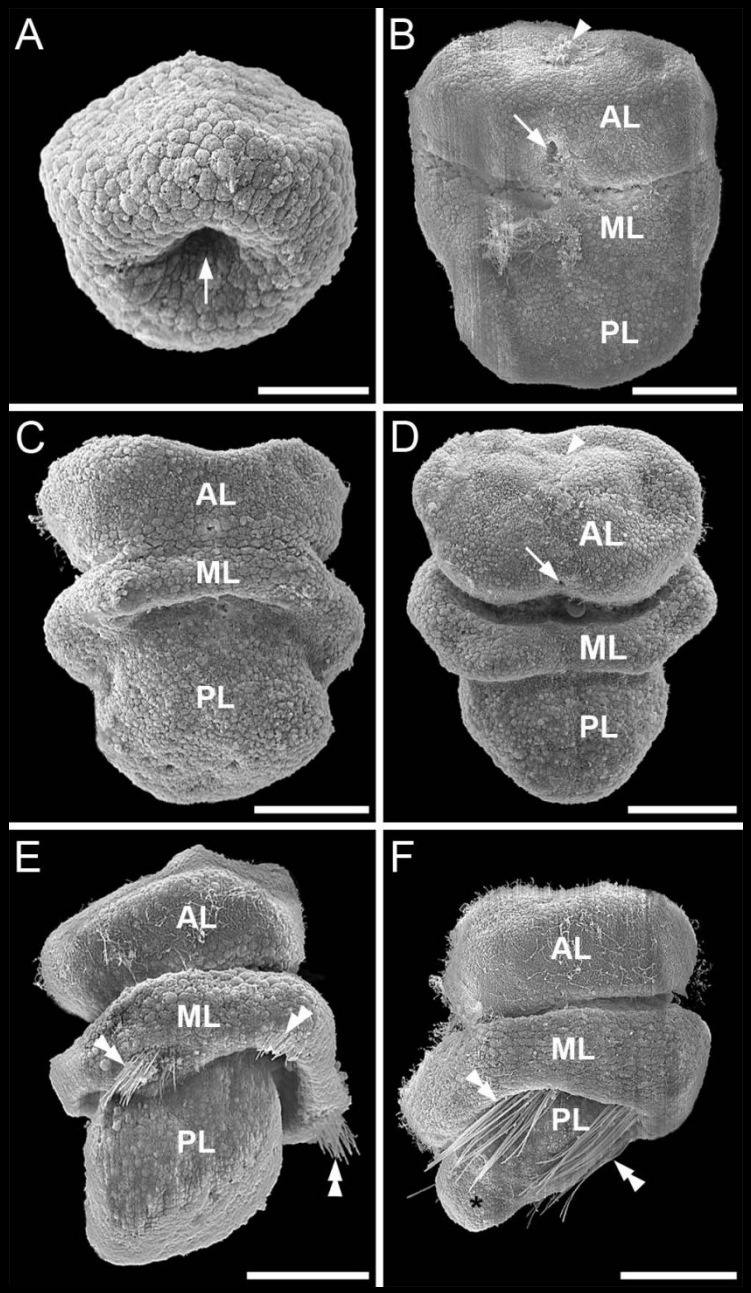


Lophophorate neurogenesis



Ruppert, Fox & Barnes *(2004)*

Brachiopoda: neurogenesis

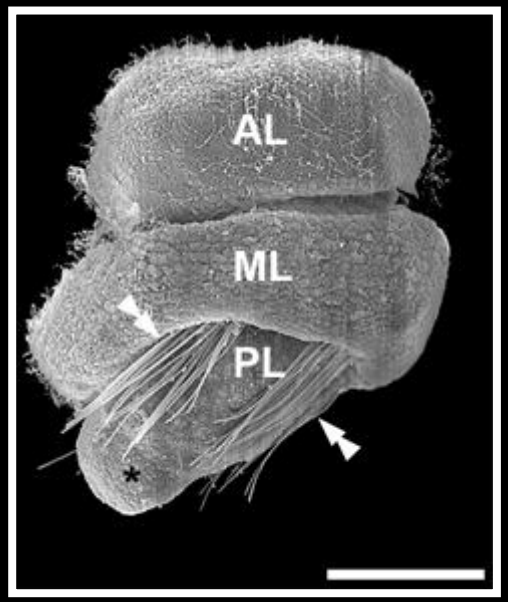


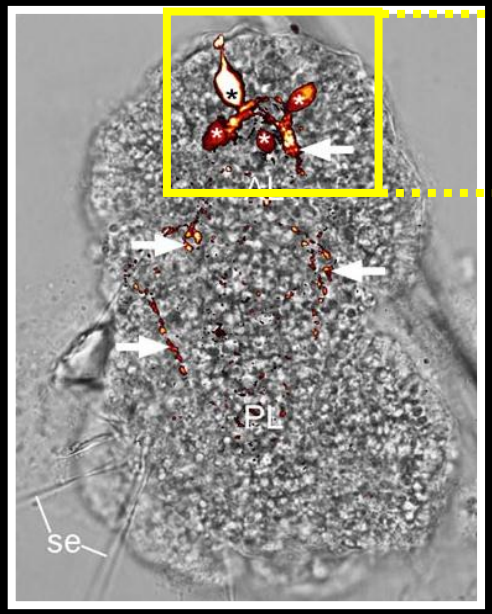
Altenburger & Wanninger: Front. Zool. (2009)

Brachiopoda: neurogenesis

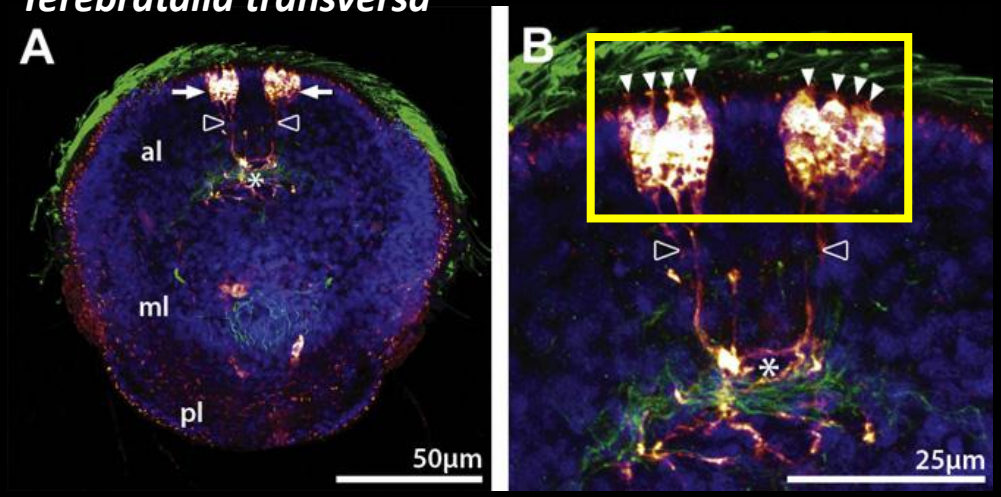
Simple apical organ with 4 or 2x4 serotonergic flask cells in lecithotrophic larvae;
No prototroch nerve

Novocrania anomala





Terebratalia transversa



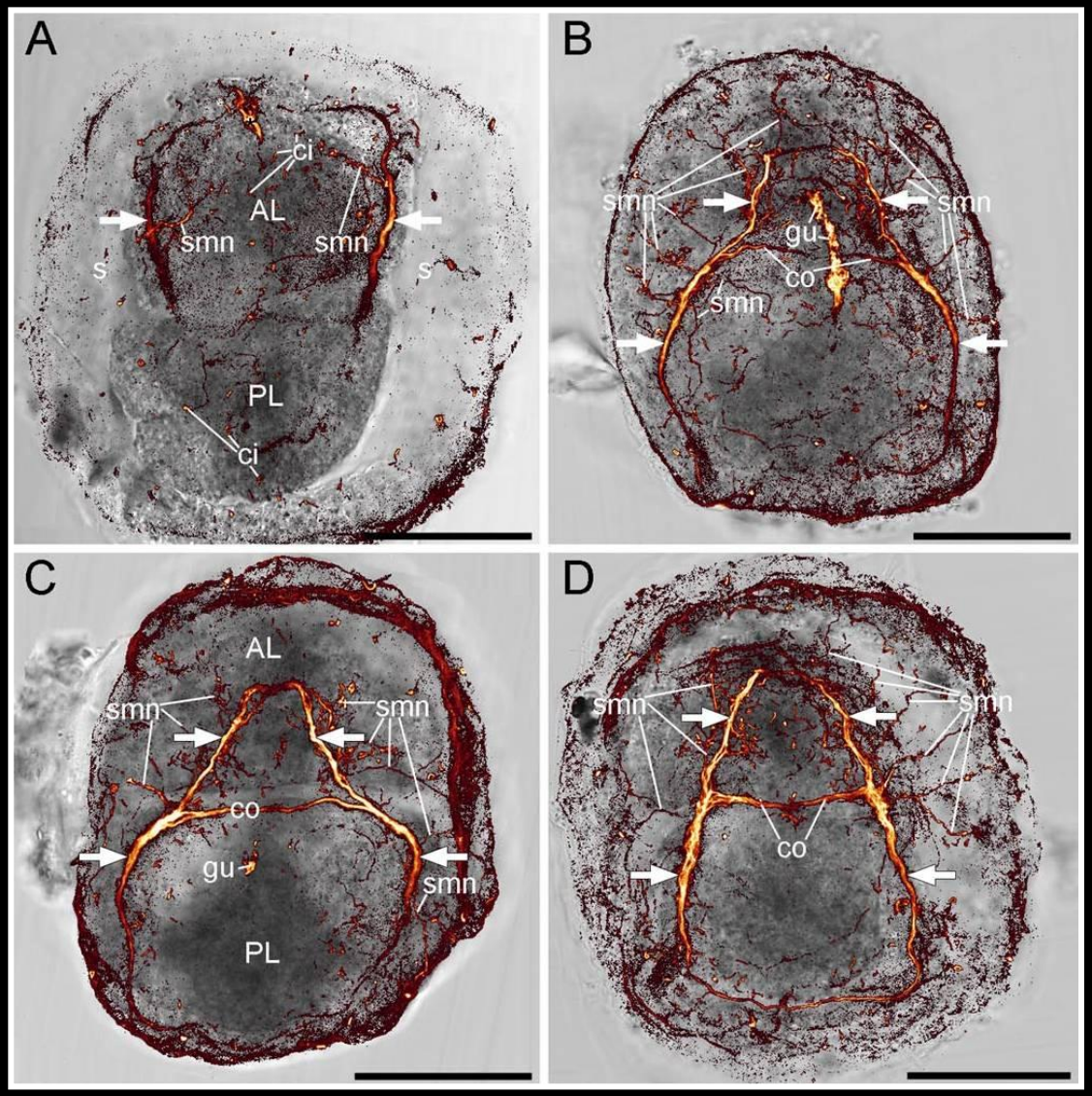
Altenburger & Wanninger: Evol. Dev. (2010)

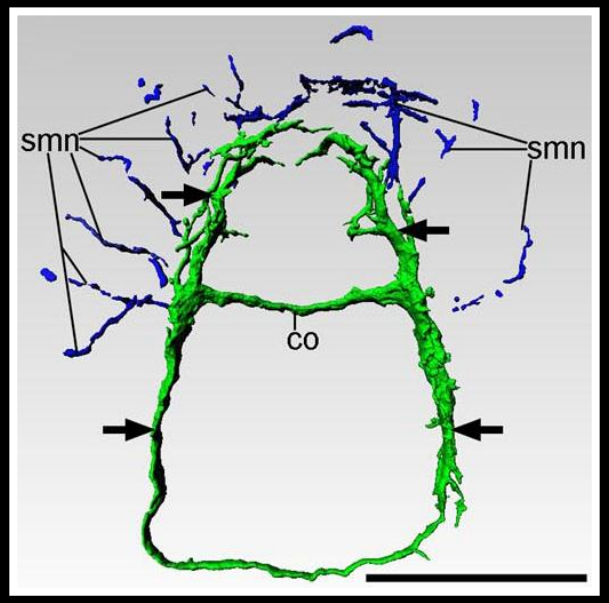
Altenburger, Martinez & Wanninger: Gene Exp. Patt. (2011)

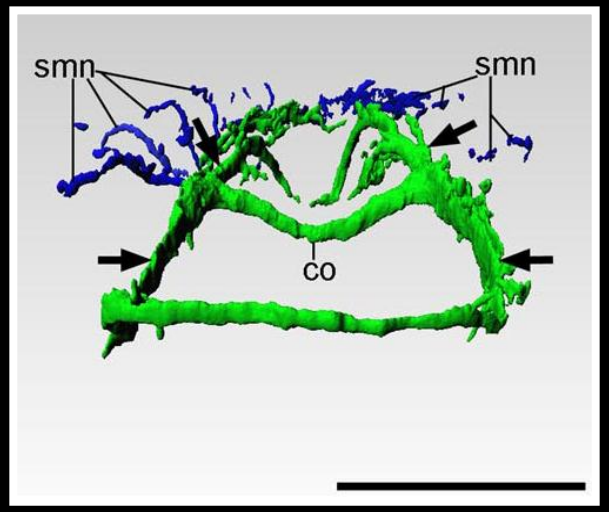
Brachiopoda: neurogenesis

Loss of apical organ and formation of paired ventral nerve cord with commissures

Novocrania anomala



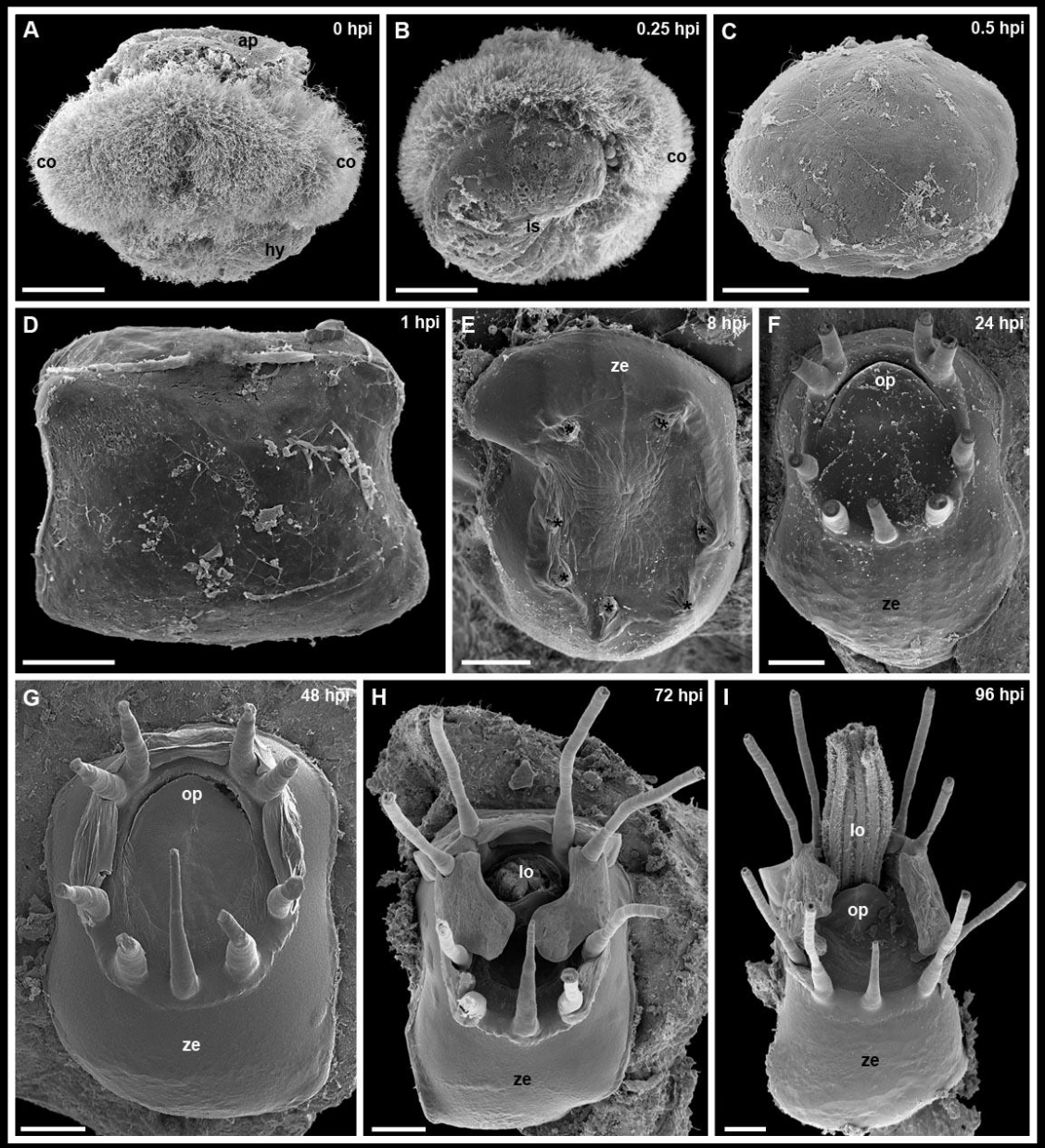




Altenburger & Wanninger : Evol. Dev. (2010)

Ectoprocta

Catastrophic metamorphosis, very rapid, complete loss of all larval structures

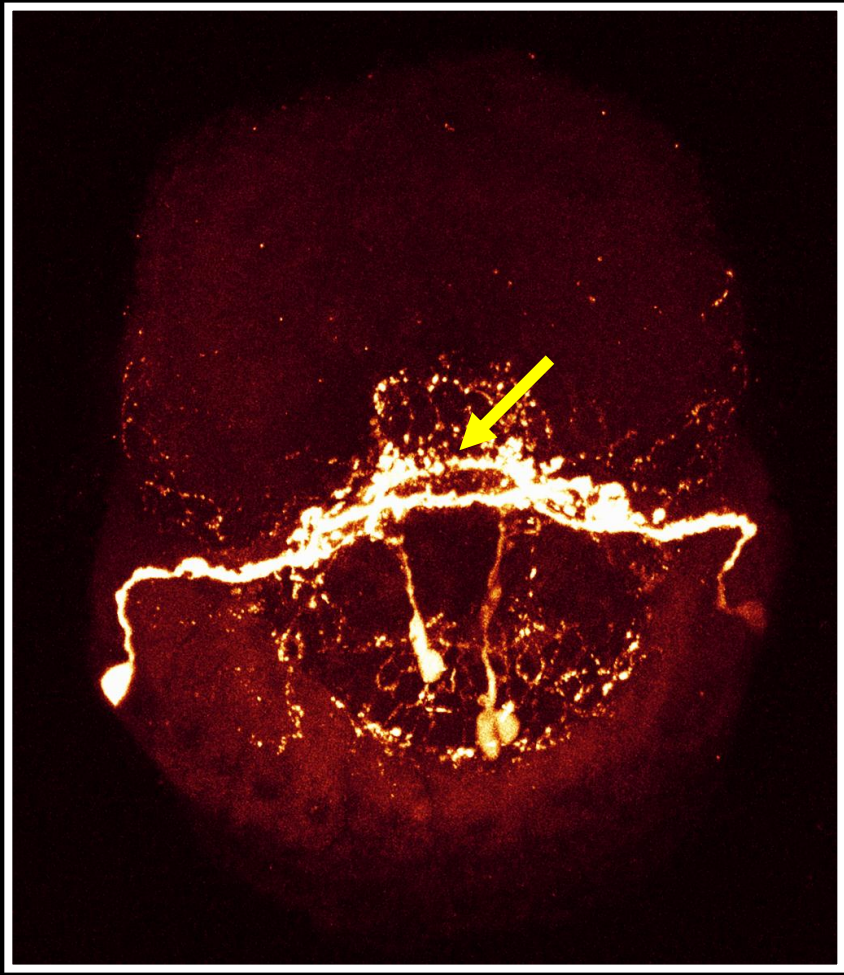


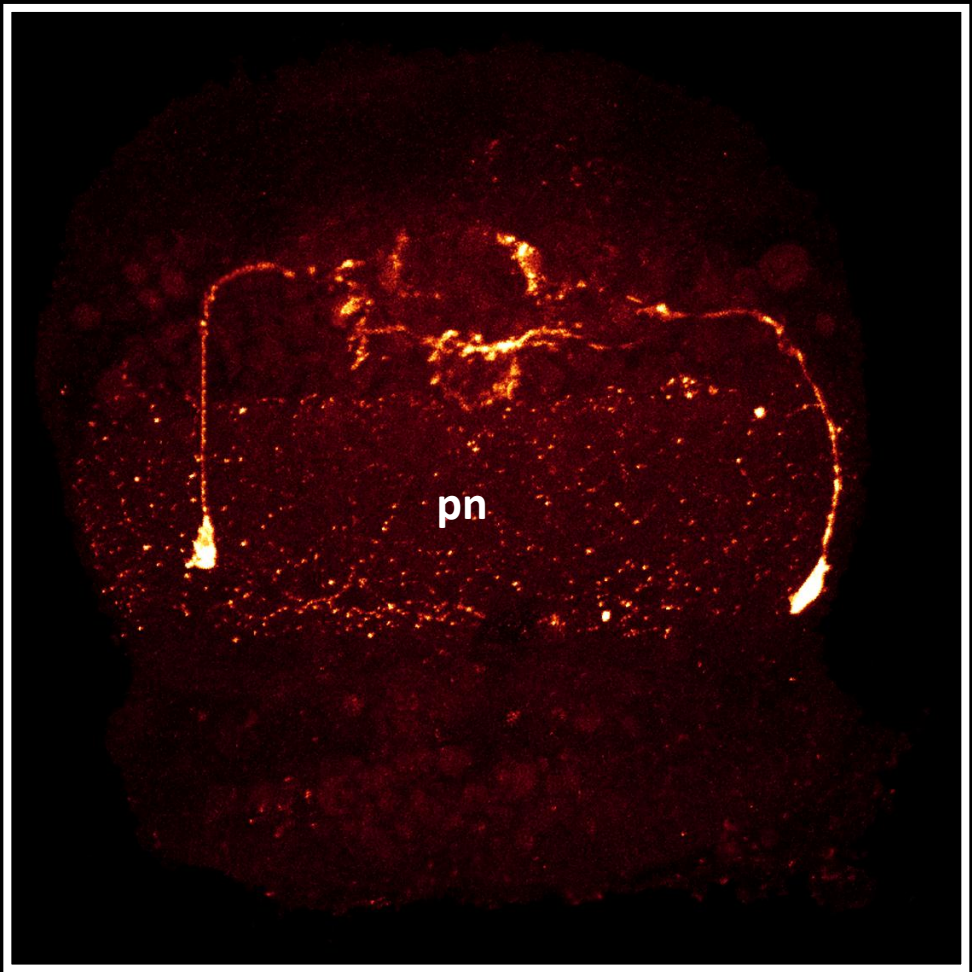
Wanninger et al. 2005

Ectoprocta: larval serotonergic nervous system

No distinct apical organ (serotonergic apical nerve ring), but **prototrochal nerve net**

Triphyllozoon



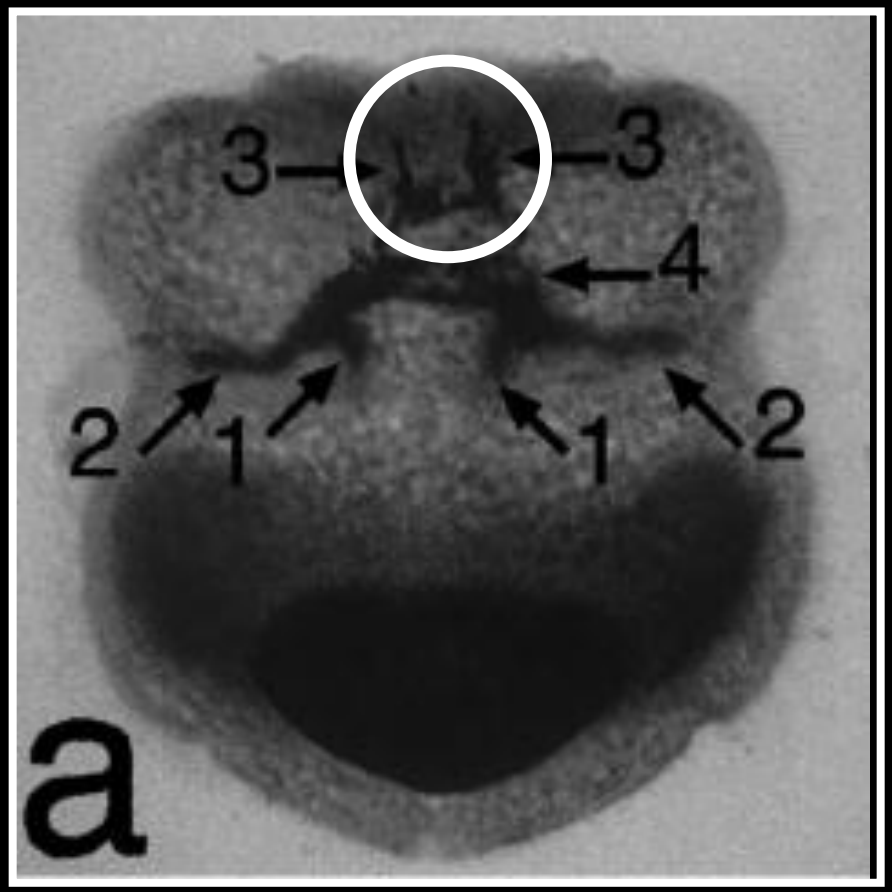


Wanninger, Koop & Degnan (2005)

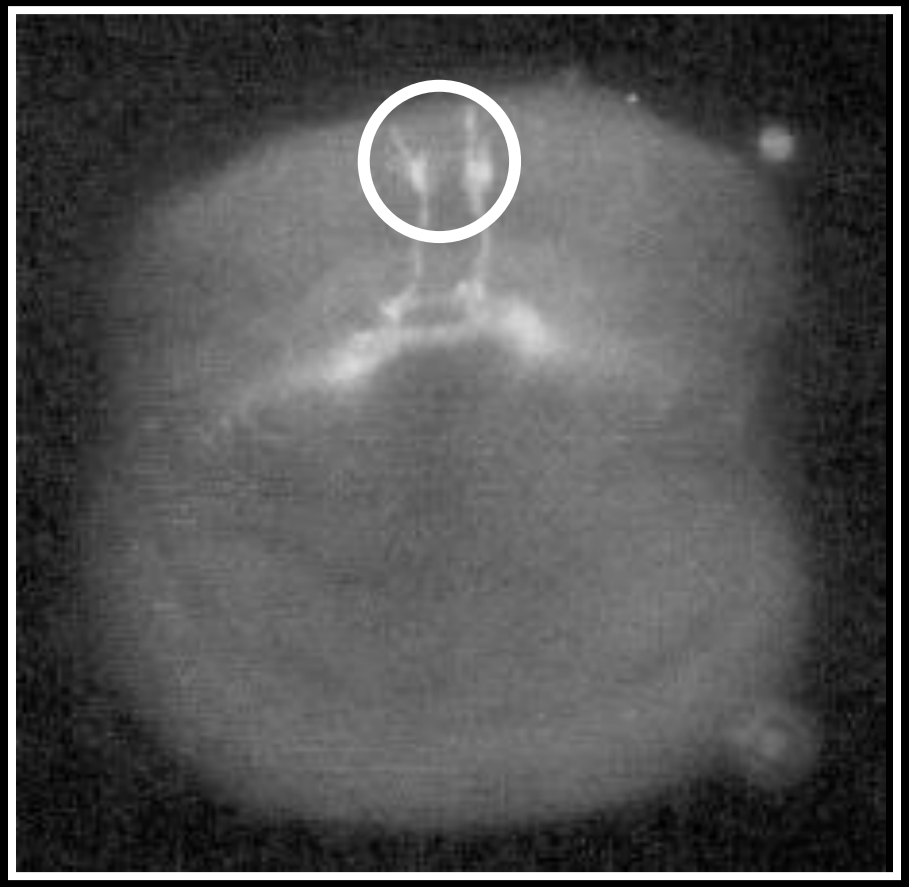
Ectoprocta: larval serotonergic nervous system

Apical organ with 2 serotonergic flask-shaped cells

Bugula



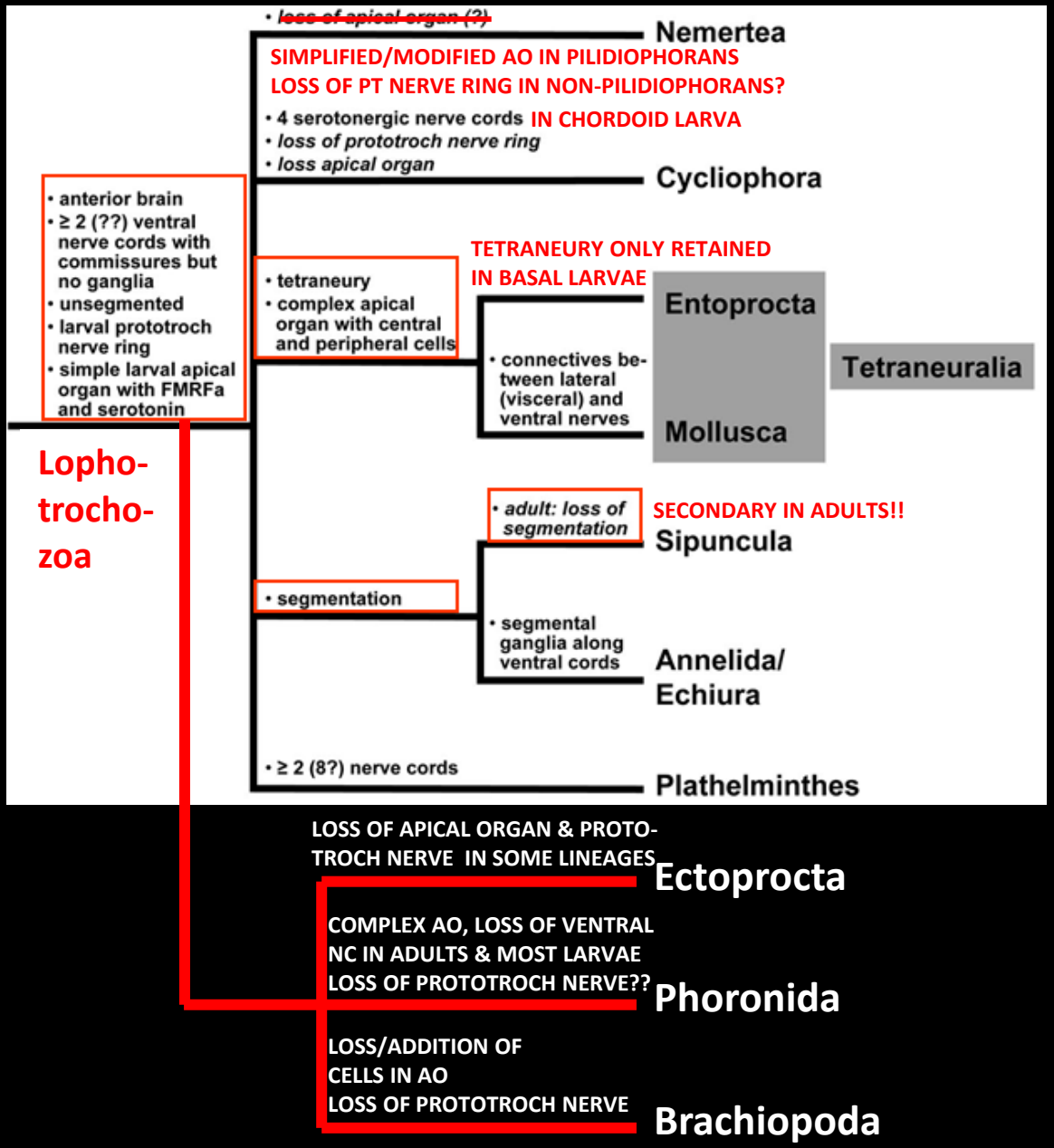
Pires & Woollacott (1997)



Shimizu et al. (2000)

Nervous system evolution in Lophotrochozoa

Wanninger: *unpublished (2012):*



Evolution of the lophotrochozoan NS from Urbilateria with direct development and non-centralized, plexus-like NS included evolution of:

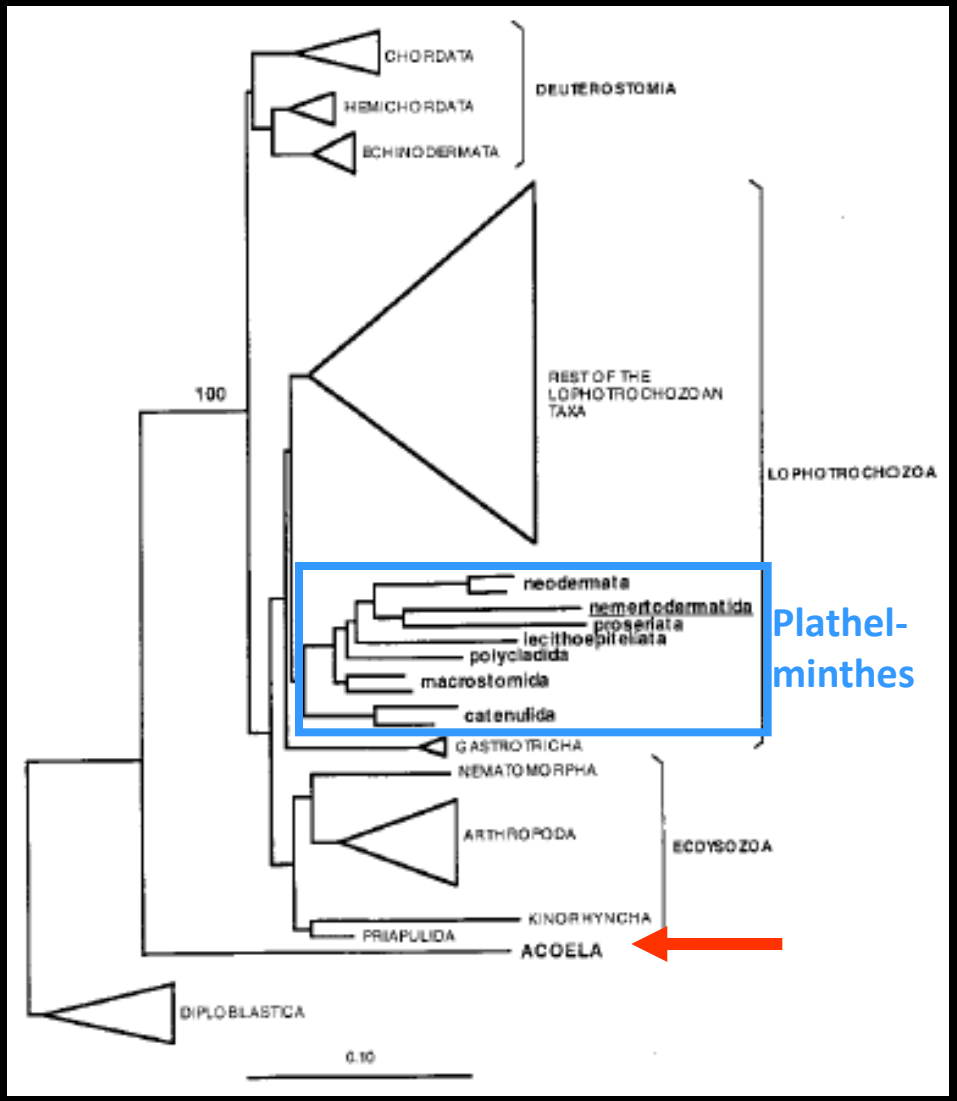
- **Simple larval apical organ** with 4 serotonergic flask cells

- **Serotonergic prototroch nerve ring**

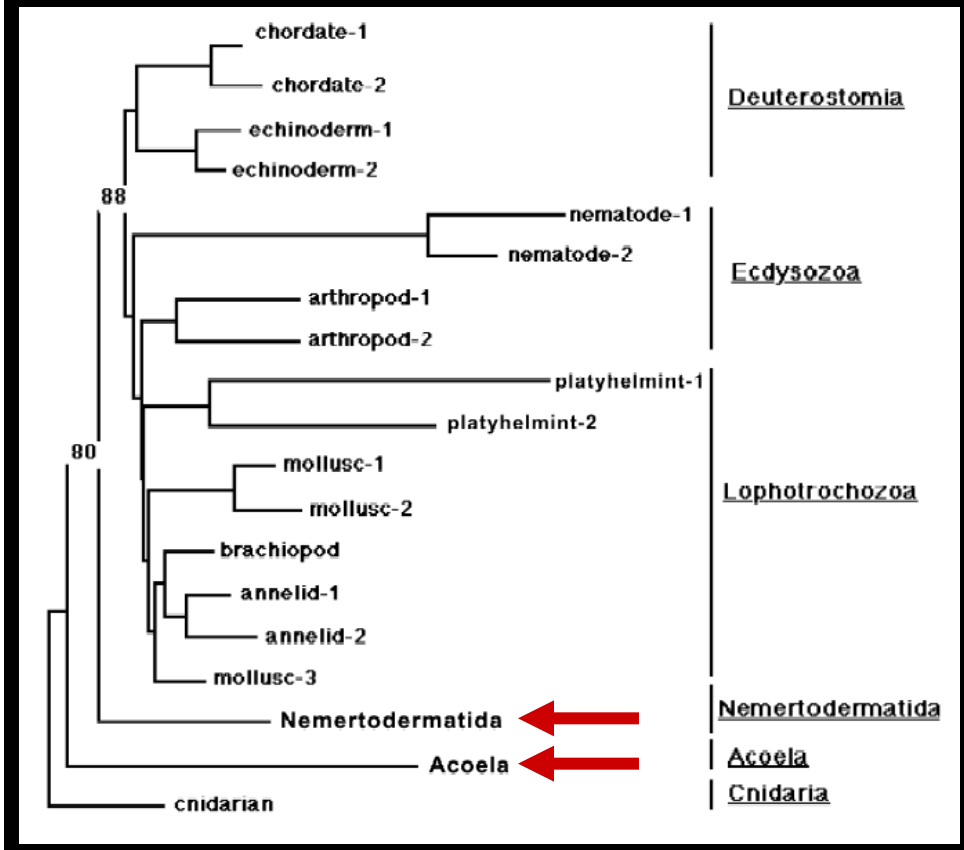
- Anterior **brain**

- Reduction of **longitudinal nerve cords to 2** (maybe only after the split of Plathelminthes from remaining lophotrochozoans; phylogeny?)

Acoel(omorph)a as basal Bilateria: implications for nervous system evolution

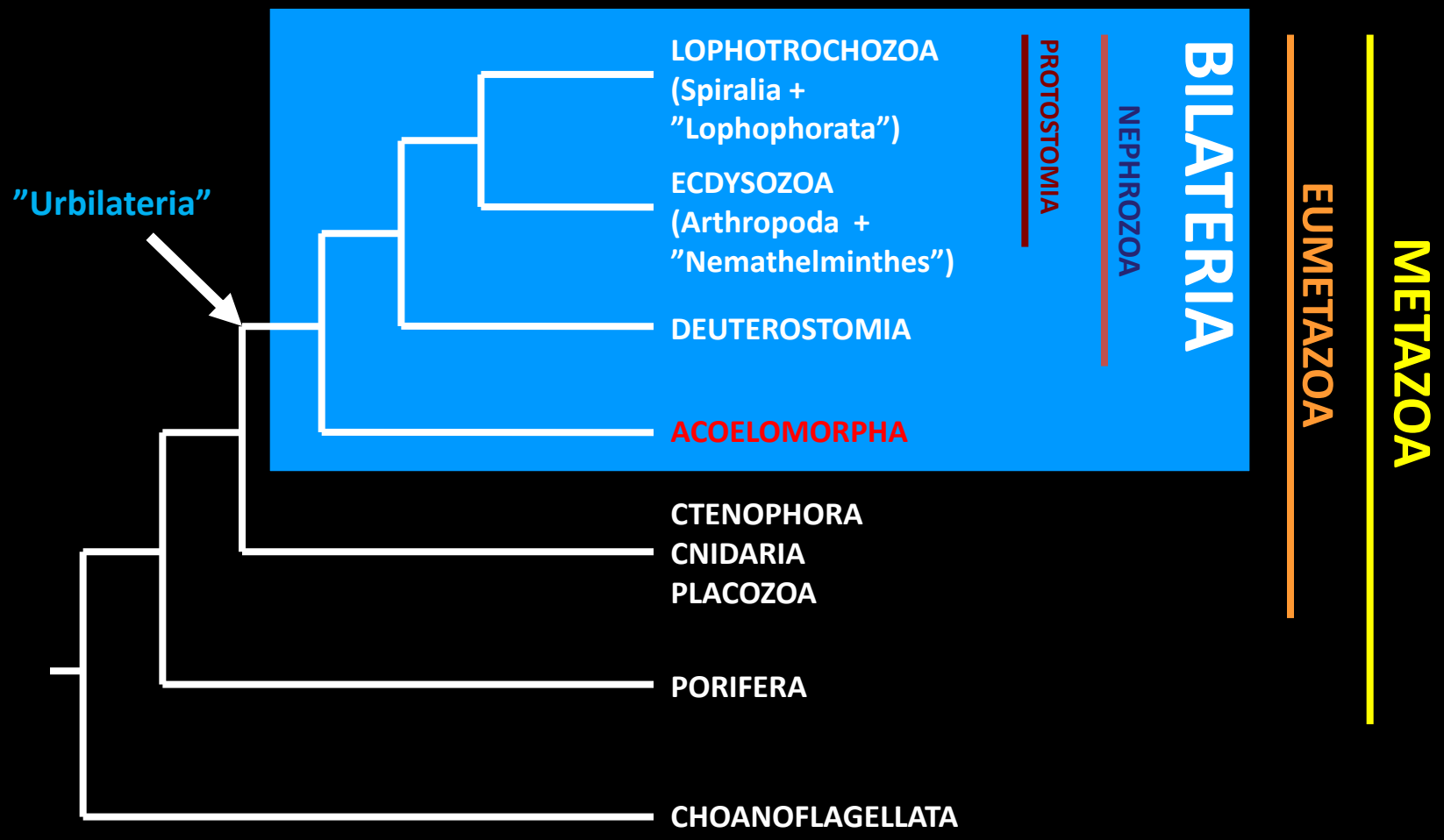


Ruiz-Trillo et al.: *Science (1999)*

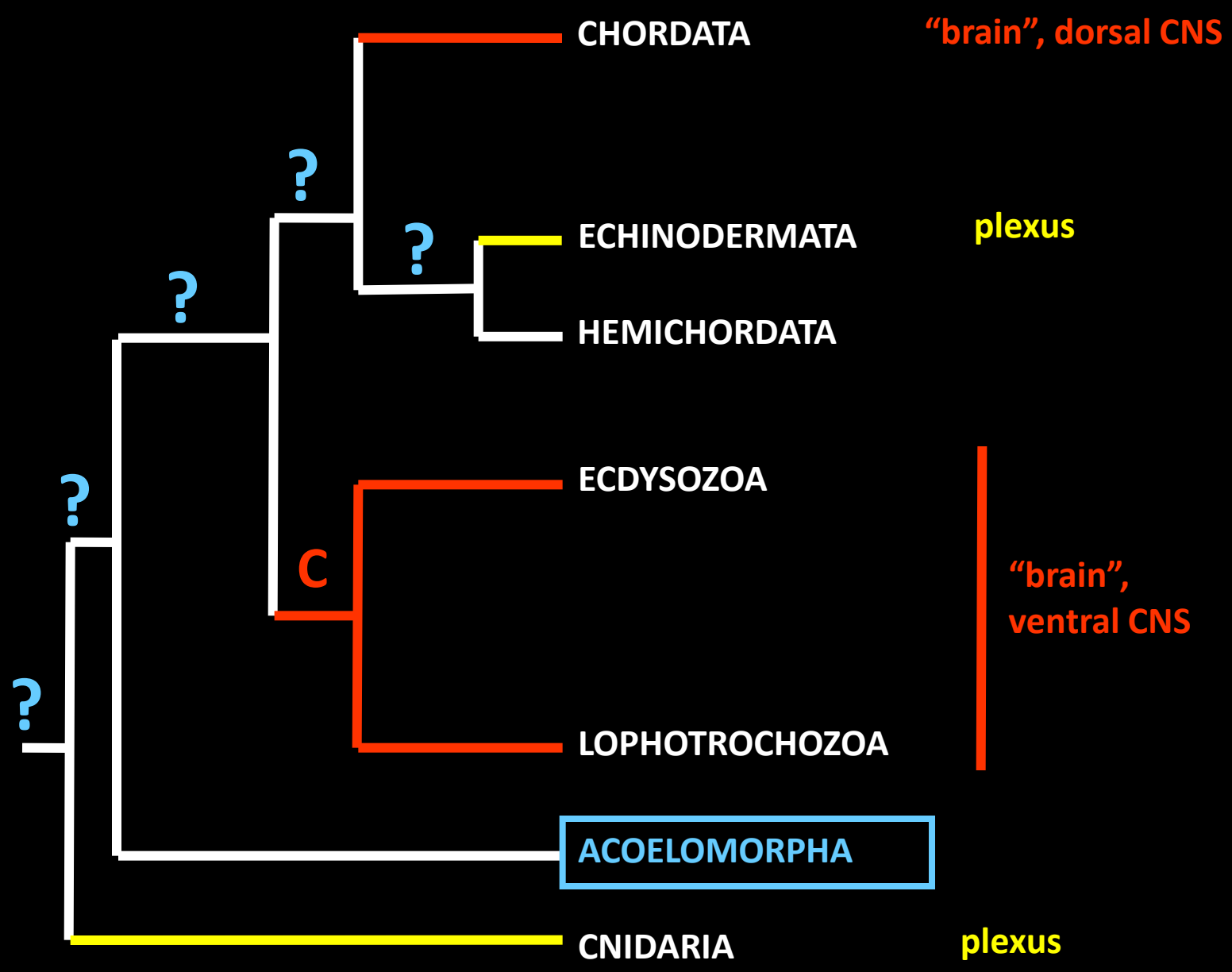


Jondelius et al.: *Zool. Scr. (2002)*

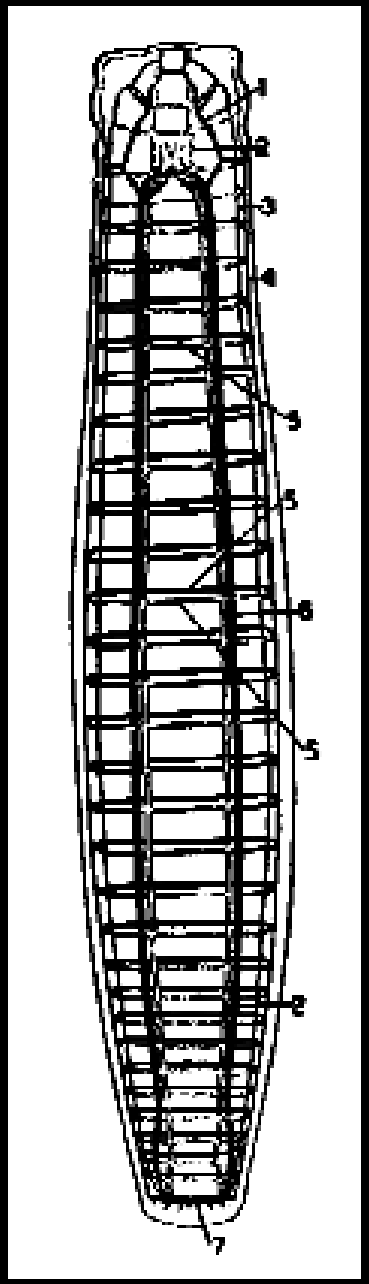
Bilateria

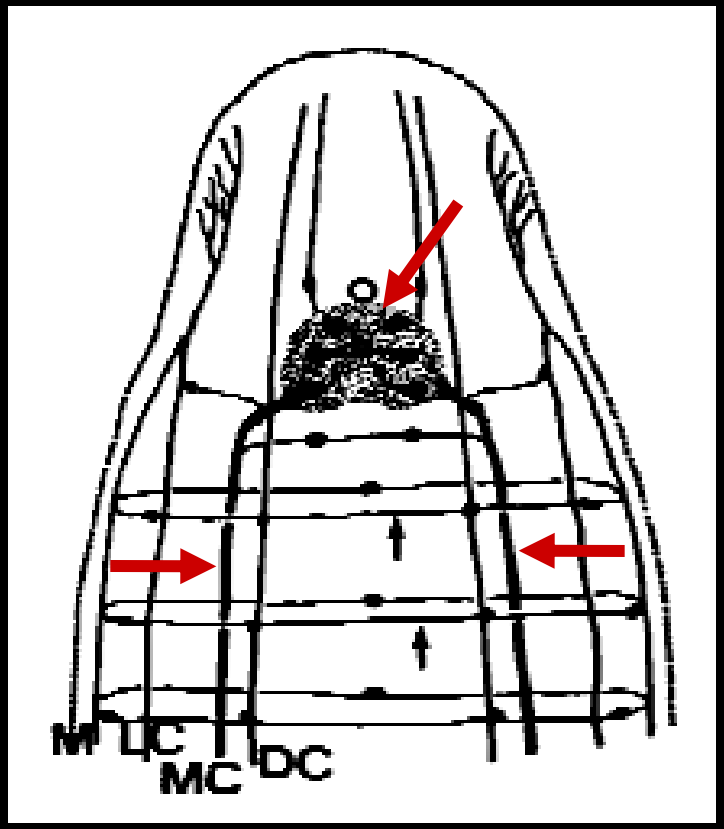

”Urbilateria”
LOPHOTROCHOZOA
(Spiralia +
”Lophophorata”)
ECDYSOZOA
(Arthropoda +
”Nemathelminthes”)
DEUTEROSTOMIA
ACOELOMORPHA
CTENOPHORA
CNIDARIA
PLACOZOA
PORIFERA
CHOANOFLAGELLATA
PROTOSTOMIA
NEPHROZOA
BILATERIA
EUMETAZOA
METAZOA

Nervous system evolution in Bilateria



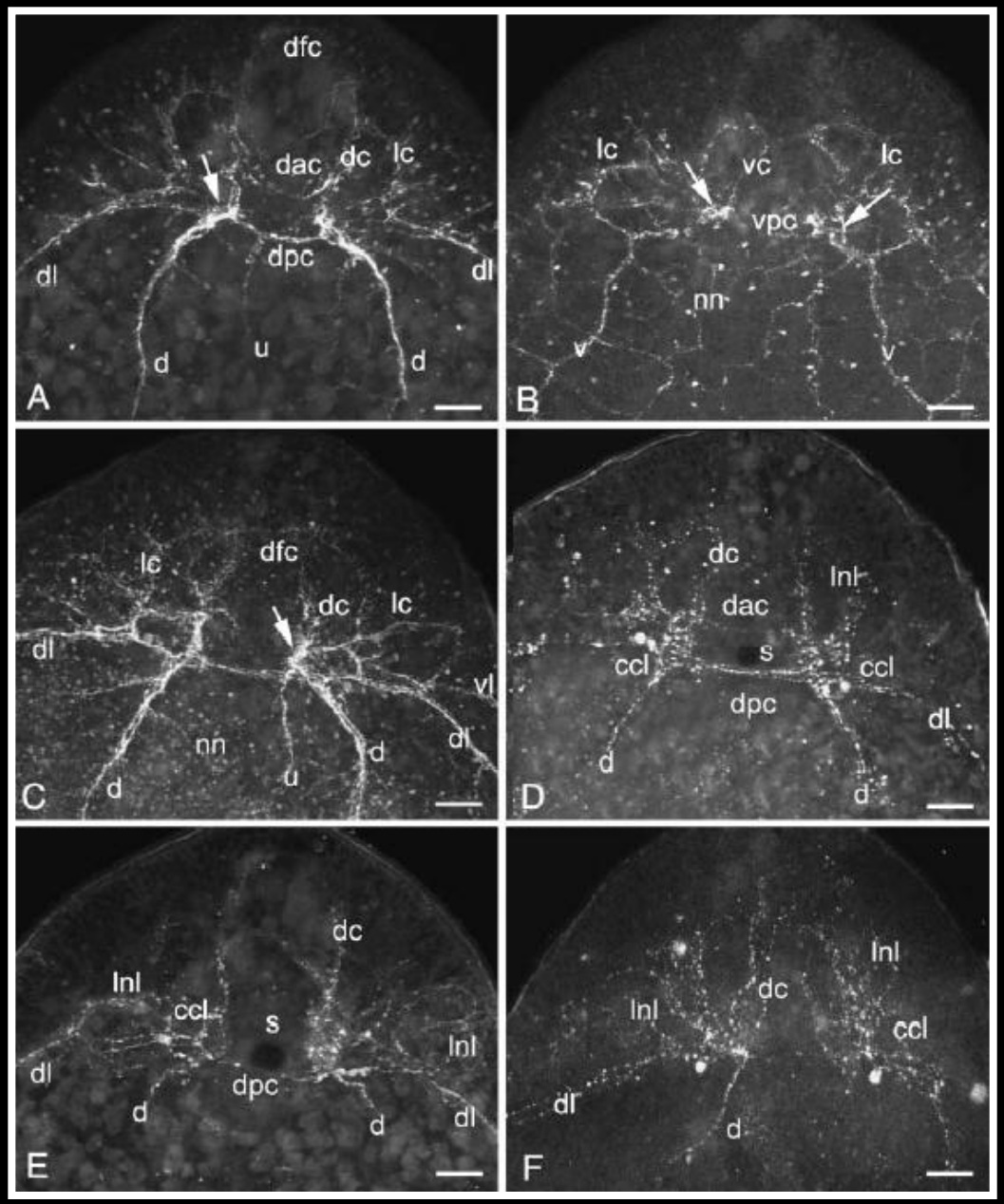
Nervous system of Plathelminthes: “orthogon” with anterior brain





From Reuter et al. 1998

Acoela: Adult serotonergic nervous system

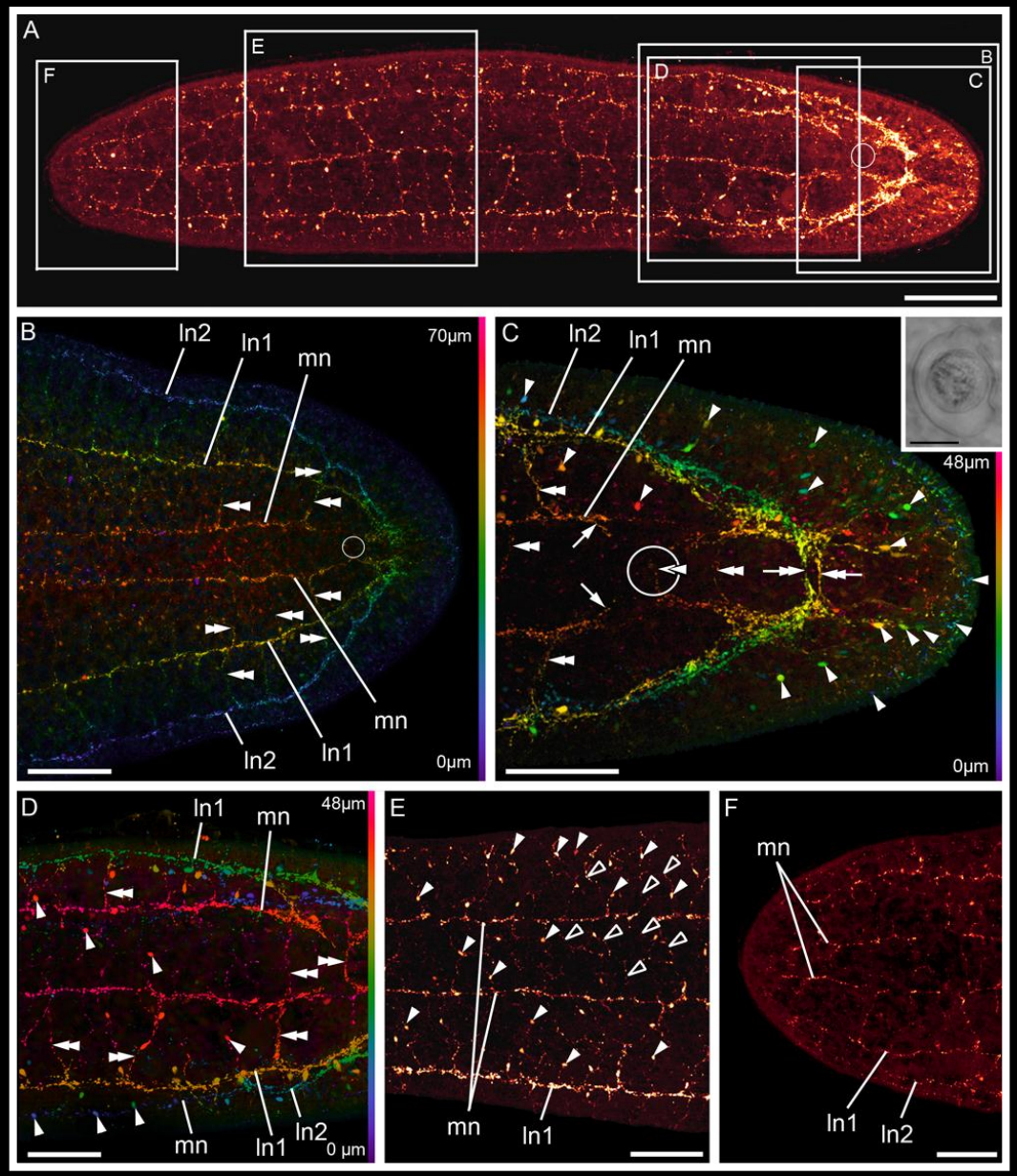


Raikova et al. *(2004)*

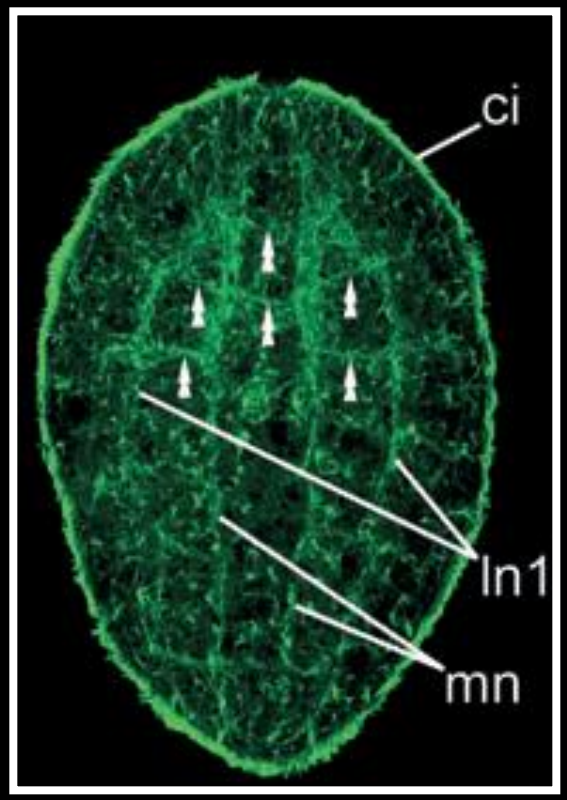
Acoela: neurogenesis

Symsagittifera roscoffensis

Serotonin

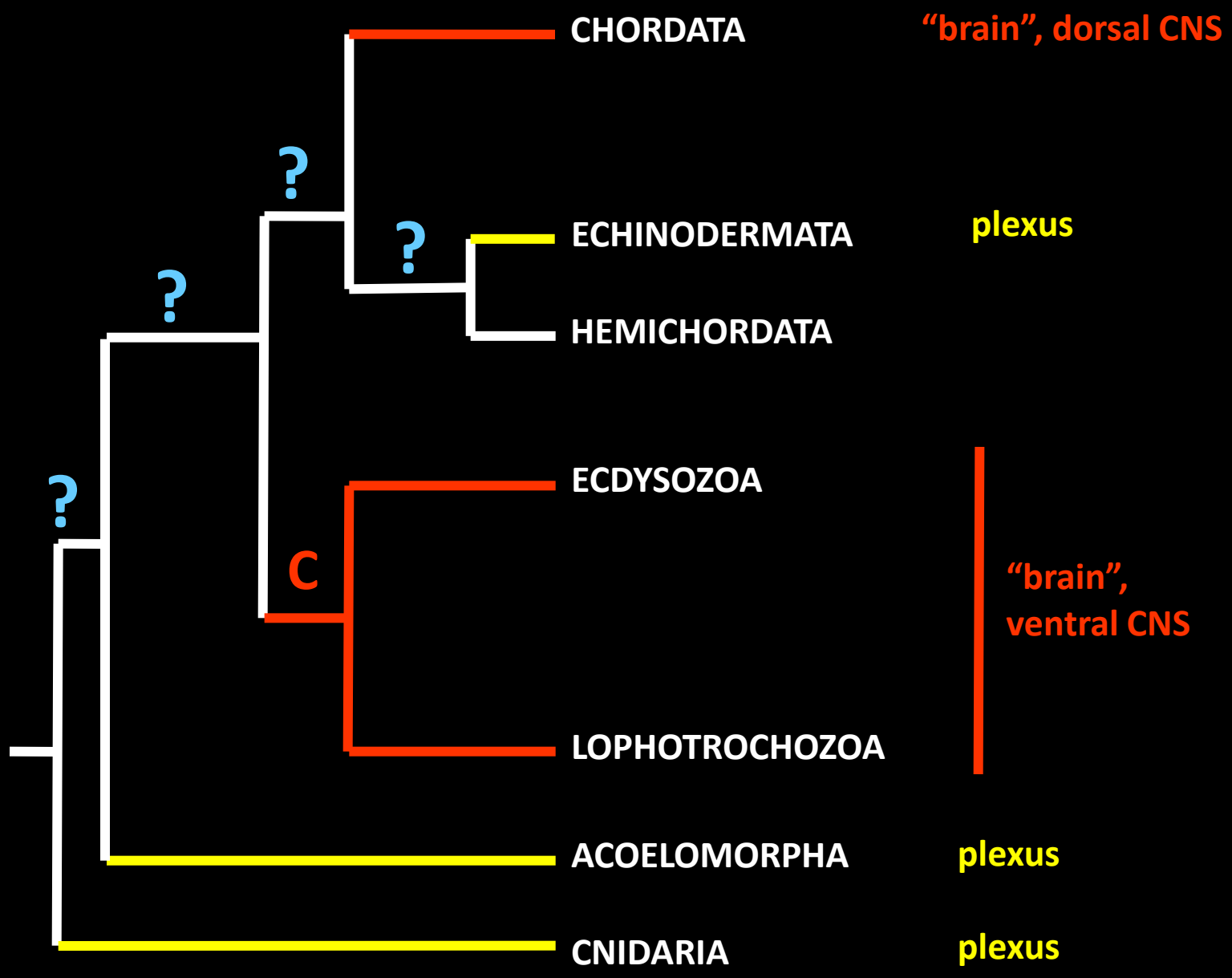


Tubulin

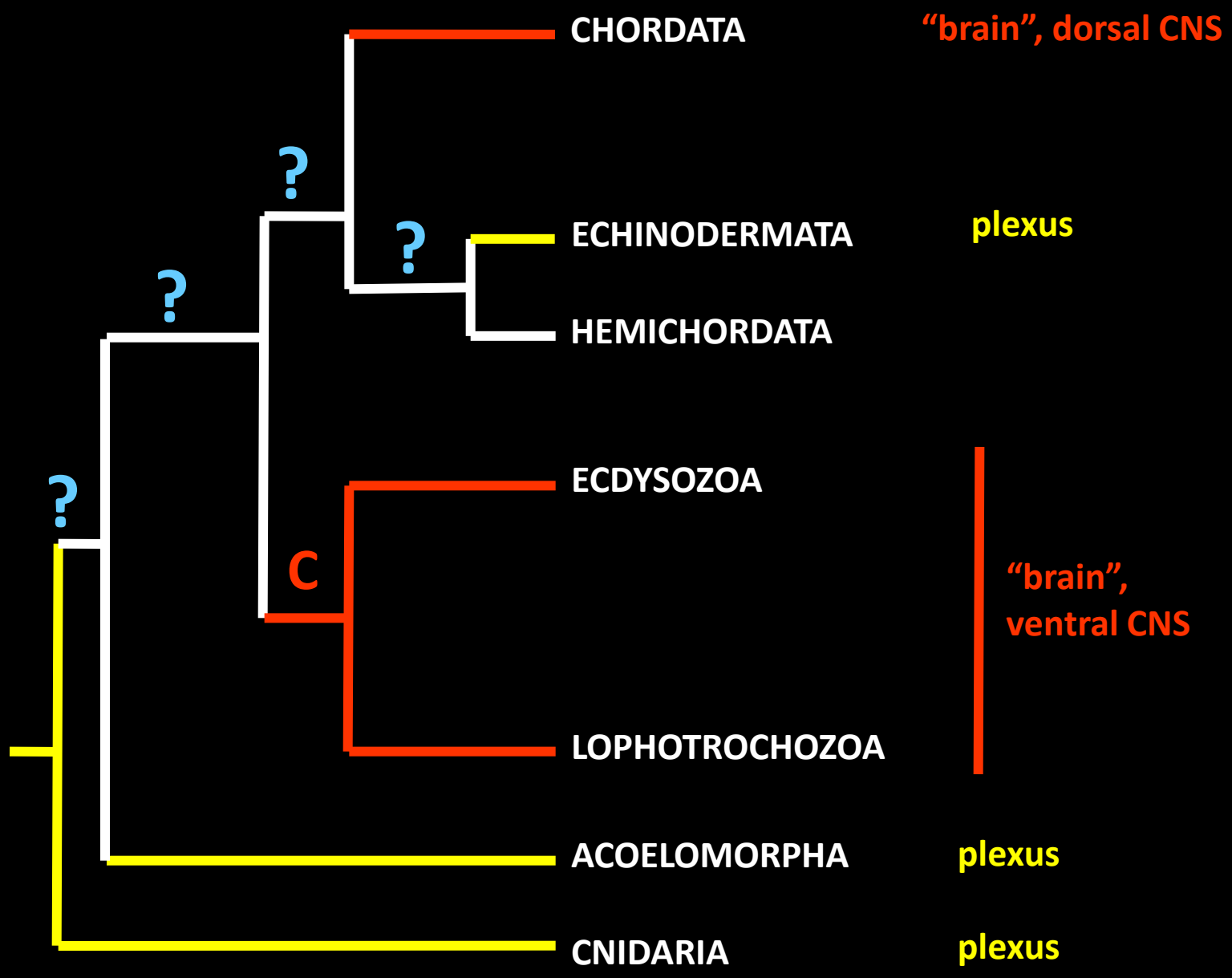


Semmler, Choidin, Bailly, Martinez & Wanninger: *Dev. Growth Diff. (2010)*

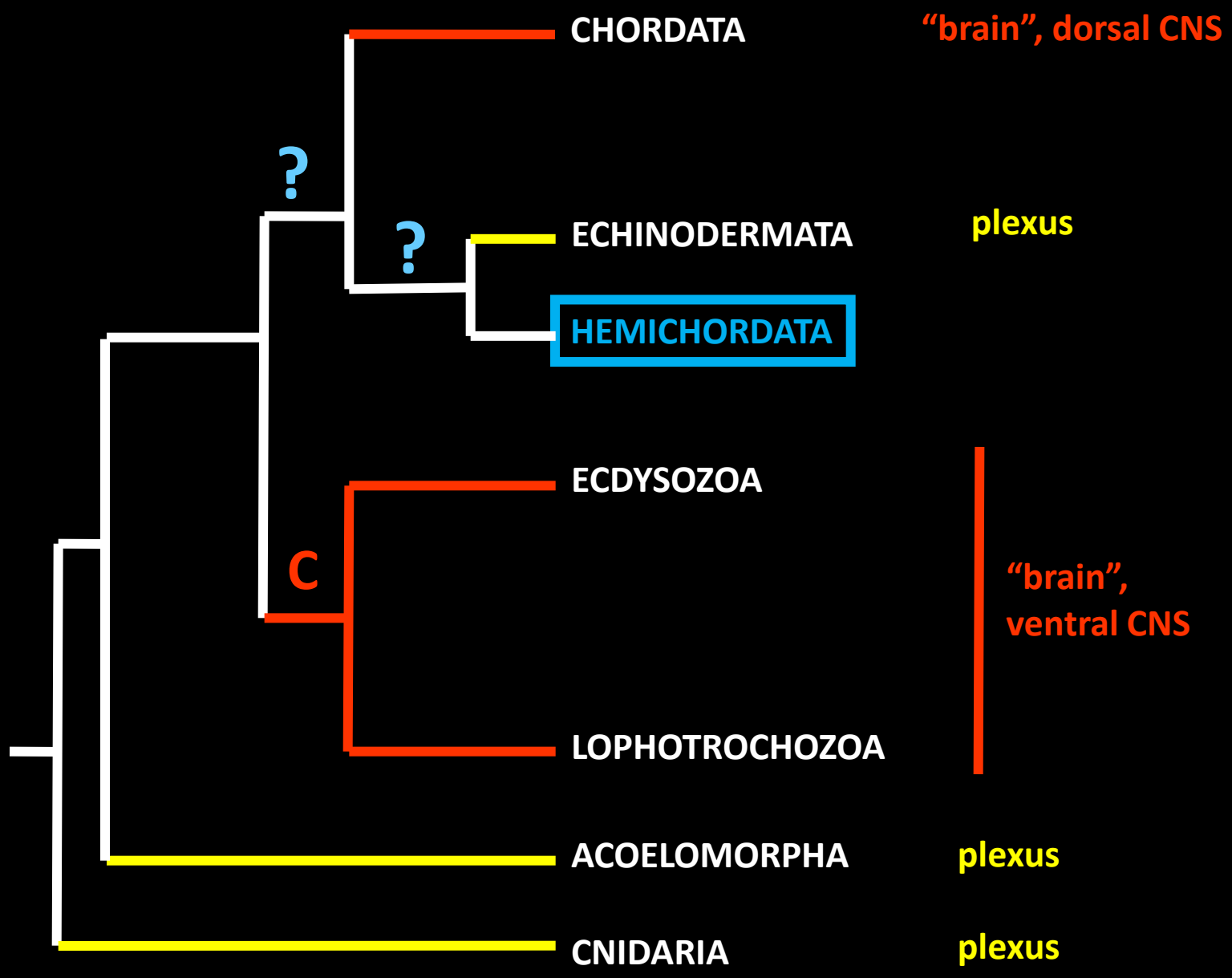
Nervous system evolution in Bilateria



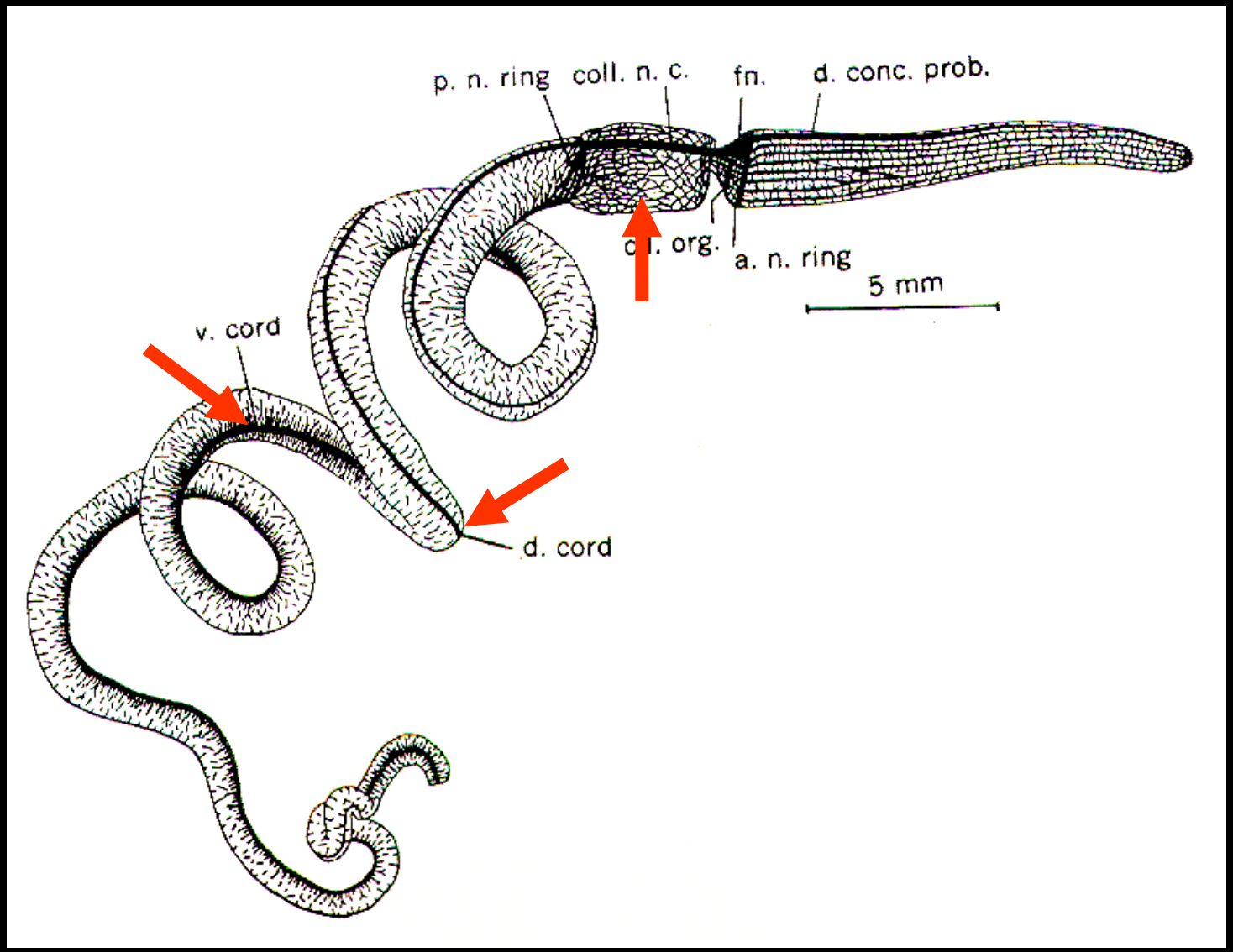
Nervous system evolution in Bilateria



Nervous system evolution in Bilateria



Enteropneusta (Hemichordata): nervous system anatomy & development

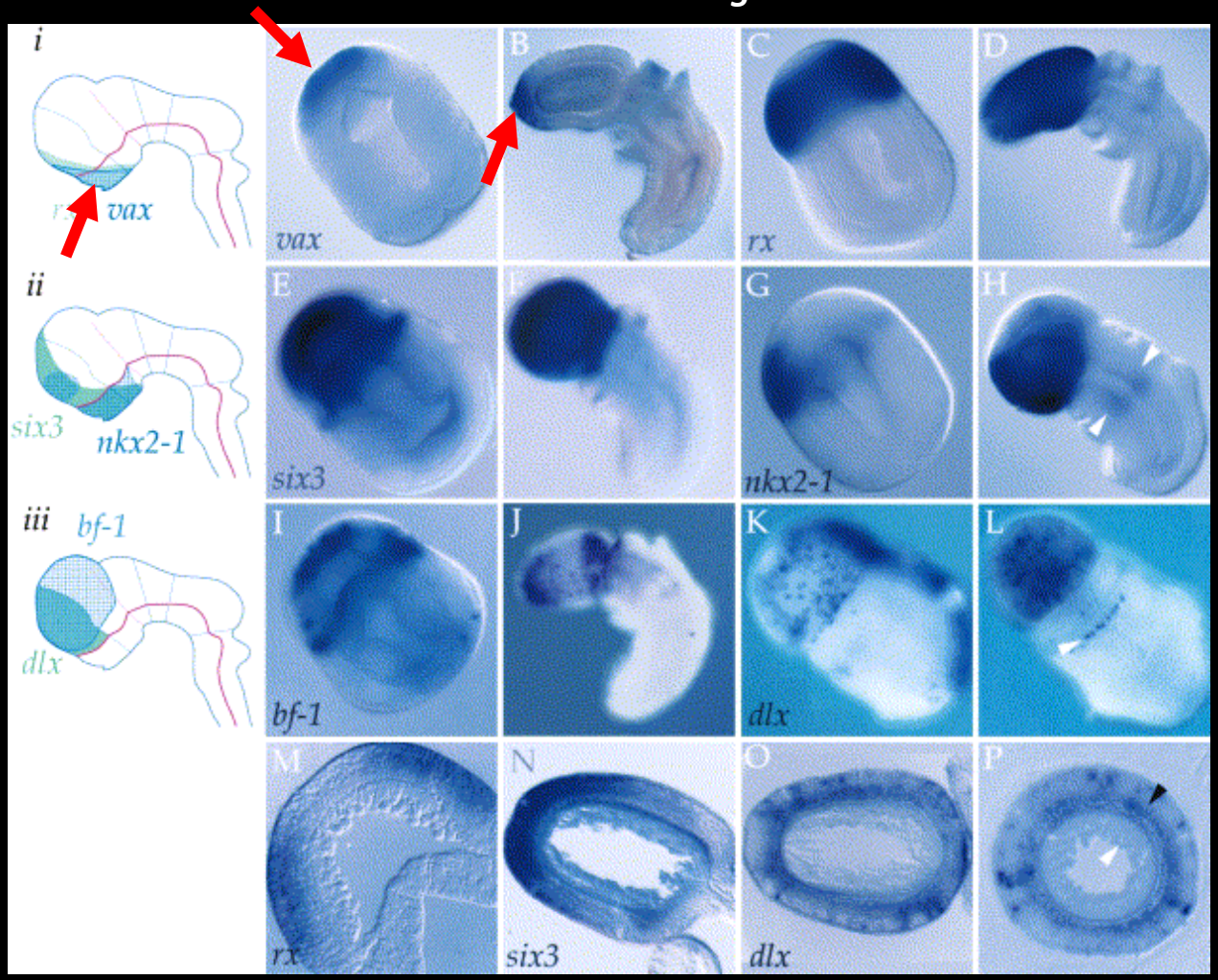


Bullock & Horridge: *(2003)*

Enteropneusta (Hemichordata): nervous system anatomy & development

1. Genes that are involved in forebrain formation in mouse are expressed in the ectoderm of the prosome in *Saccoglossus*

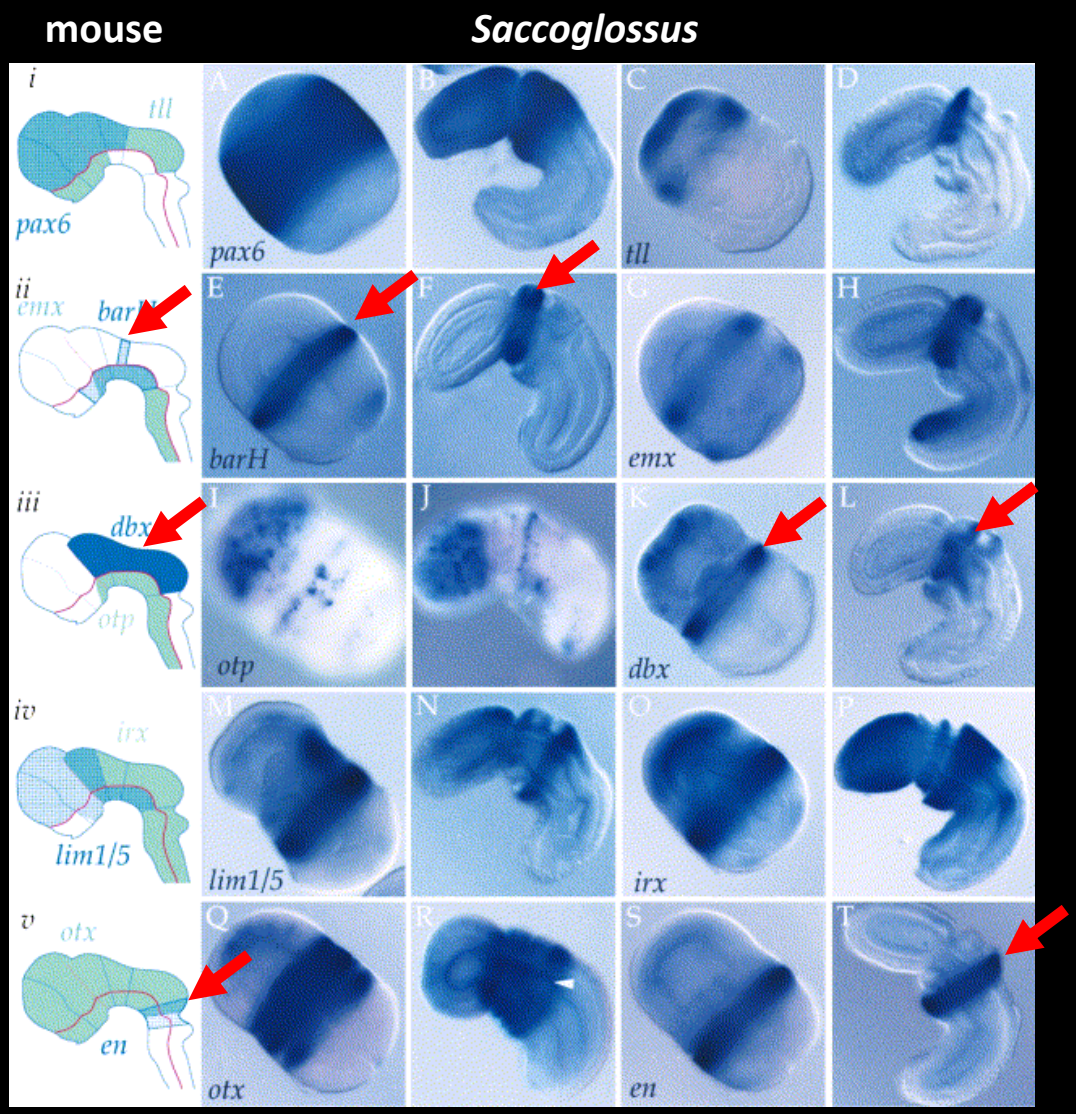
mouse ***Saccoglossus***



Lowe et al.: *Cell (2003)*

Enteropneusta (Hemichordata): nervous system anatomy & development

2. Genes that are involved in midbrain formation in mouse are expressed in the ectoderm of the mesosome and the anterior metasome in *Saccoglossus*



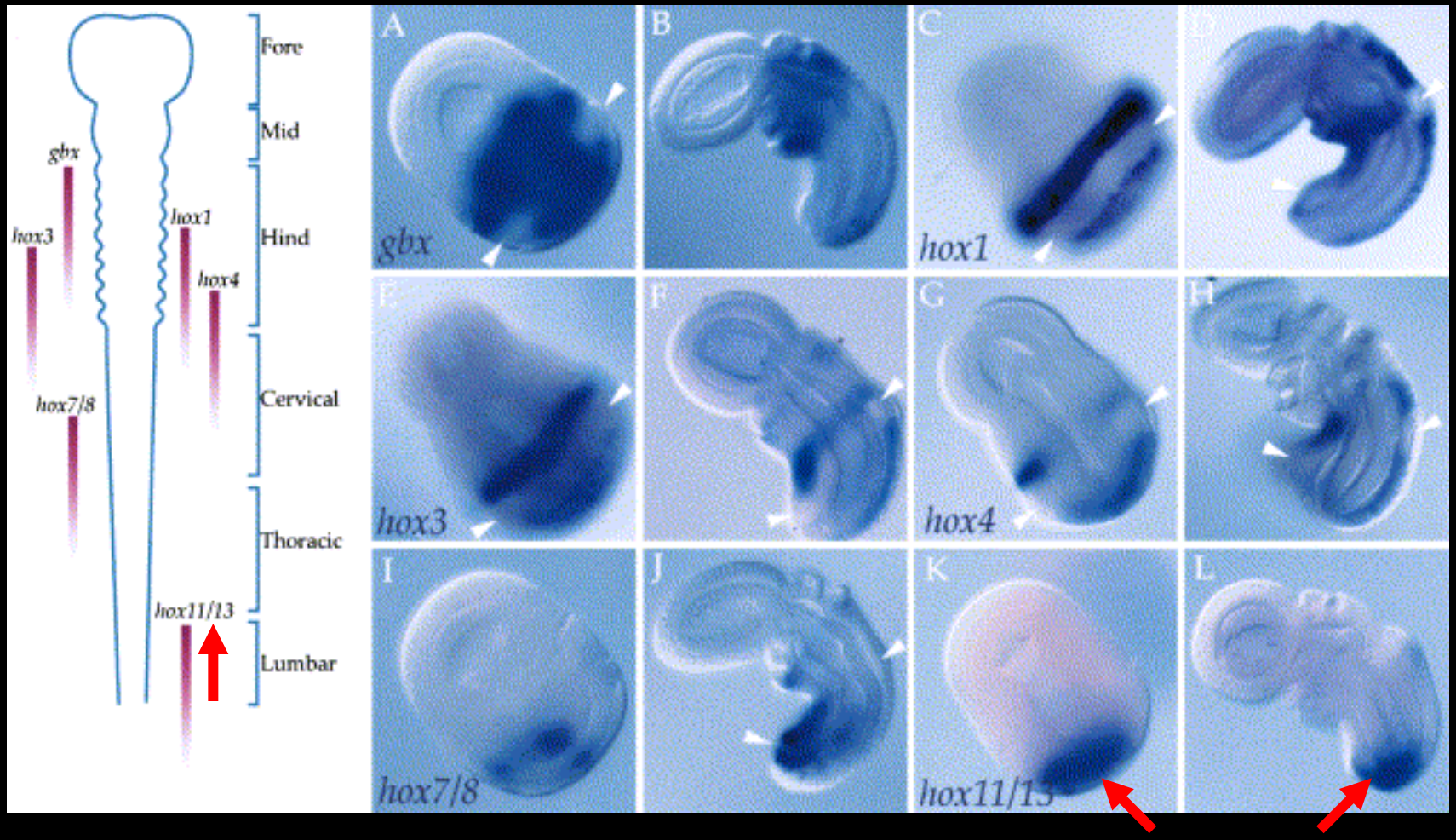
Lowe et al.: *Cell (2003)*

Enteropneusta (Hemichordata): nervous system anatomy & development

3. Genes that are expressed in the hindbrain and the spinal cord in mouse are expressed in the posterior metasome of *Saccoglossus*

mouse

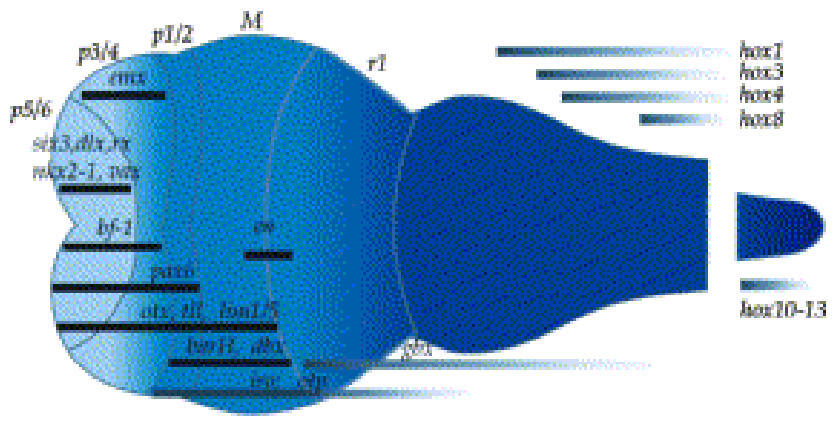
Saccoglossus



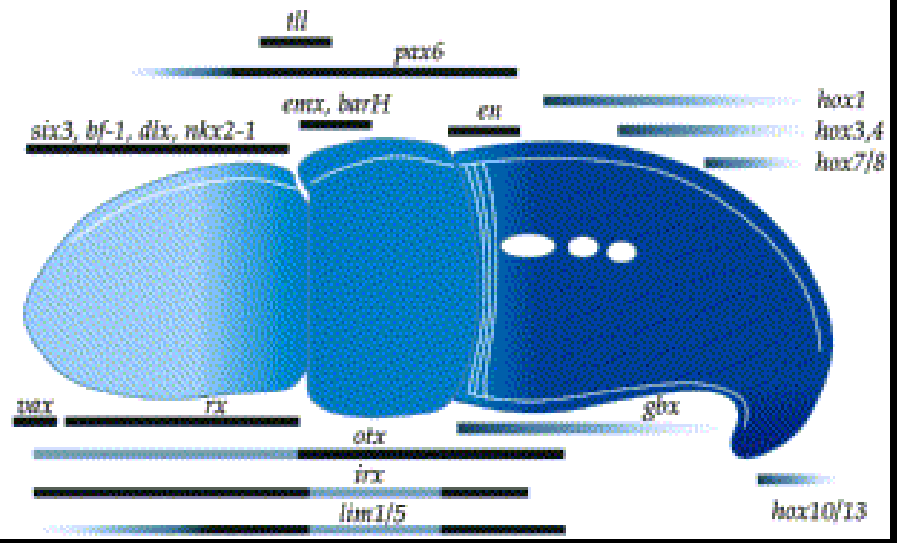
Lowe et al.: *Cell (2003)*

Expression of neurogenesis genes in chordates and hemichordates

mouse: brain

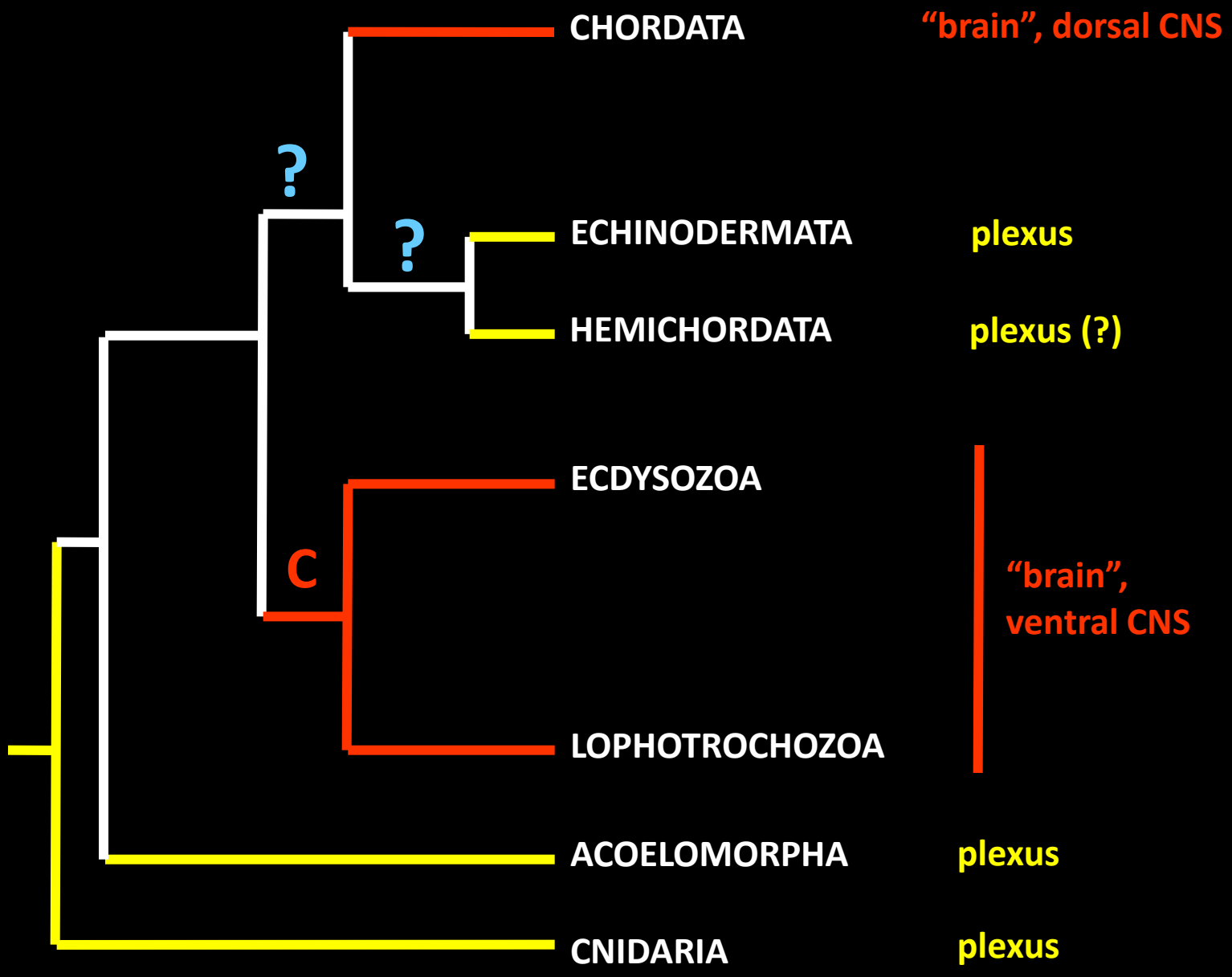


***Saccoglossus*: ectoderm**

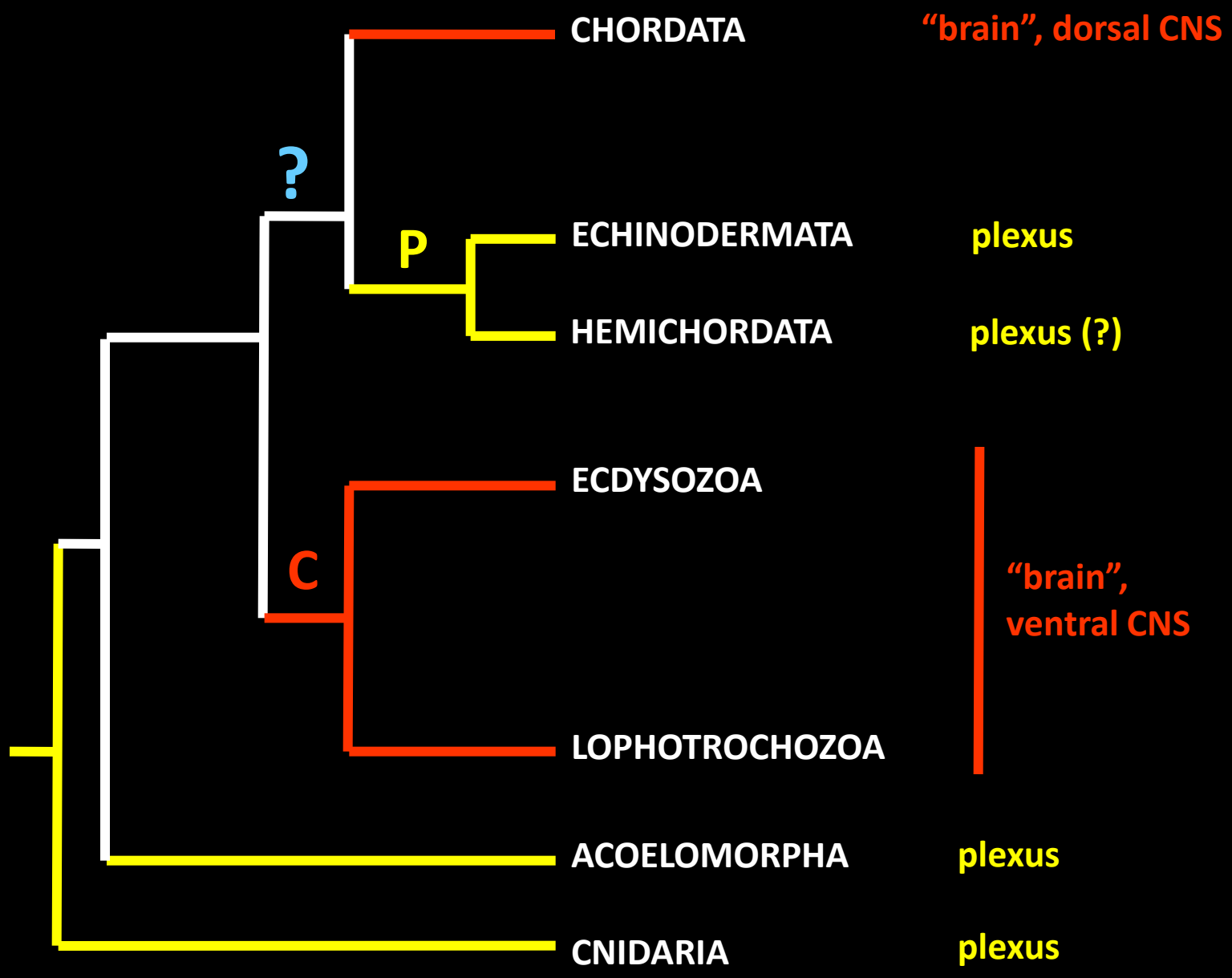


Lowe et al.: *Cell (2003)*

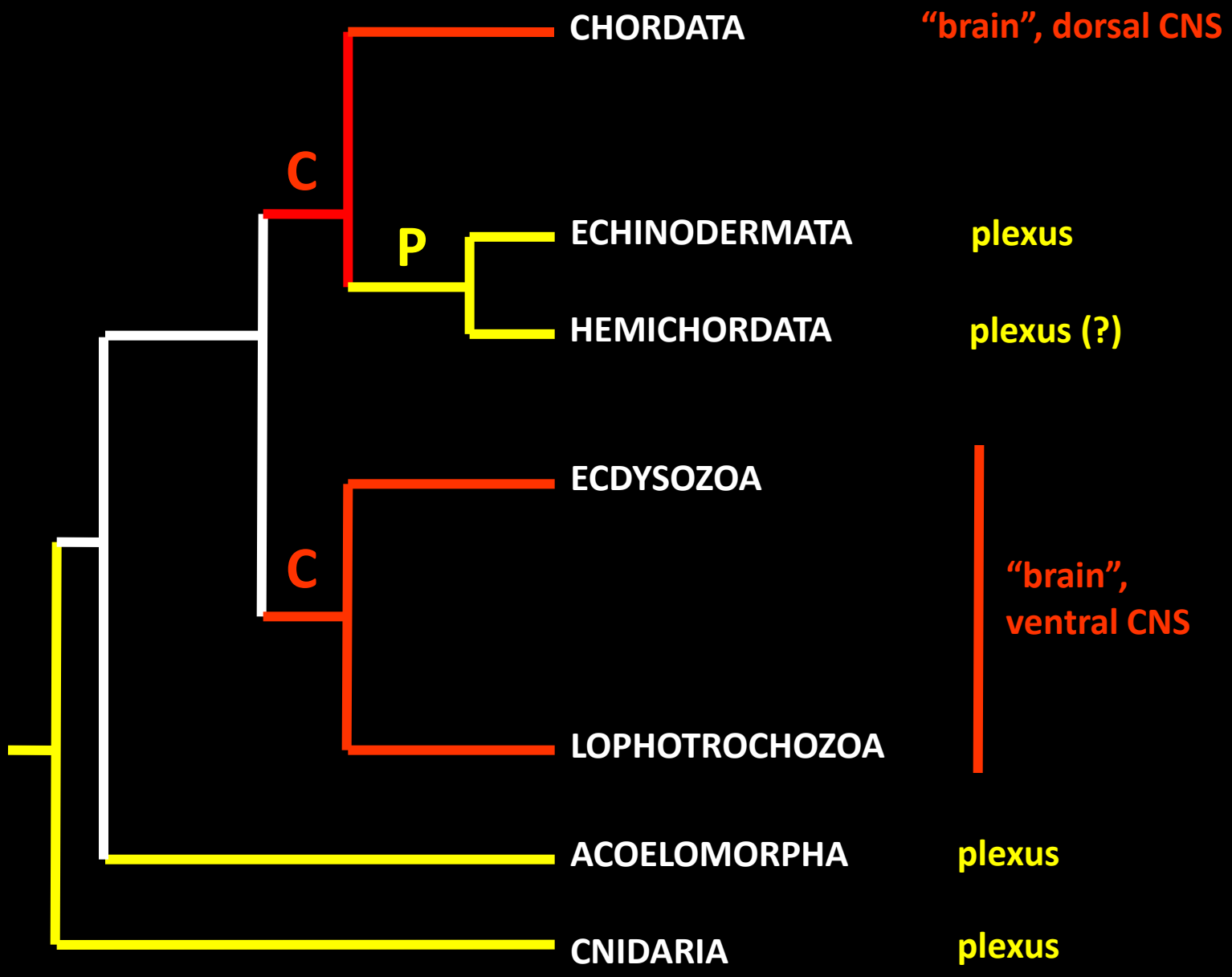
Nervous system evolution in Bilateria



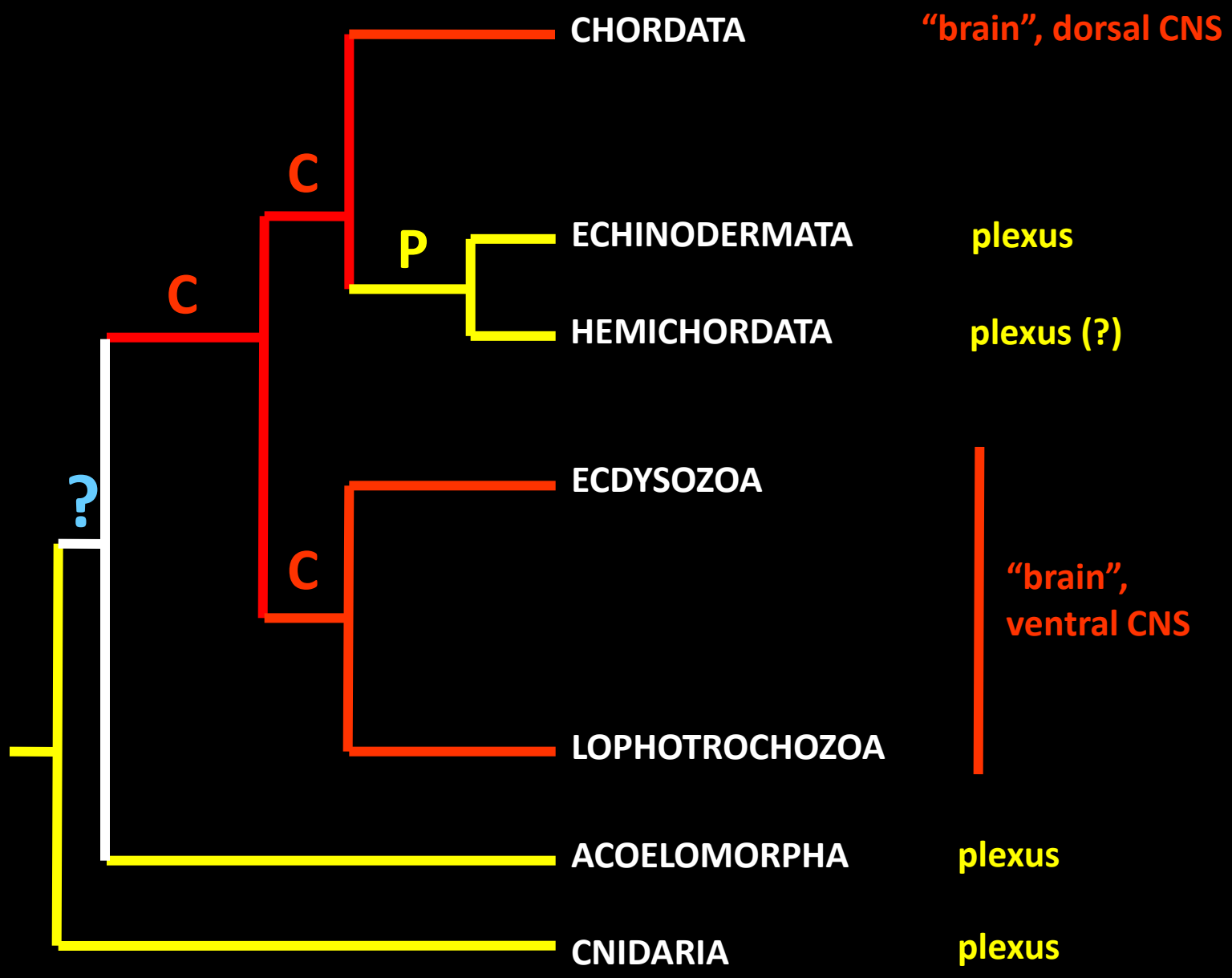
Nervous system evolution in Bilateria



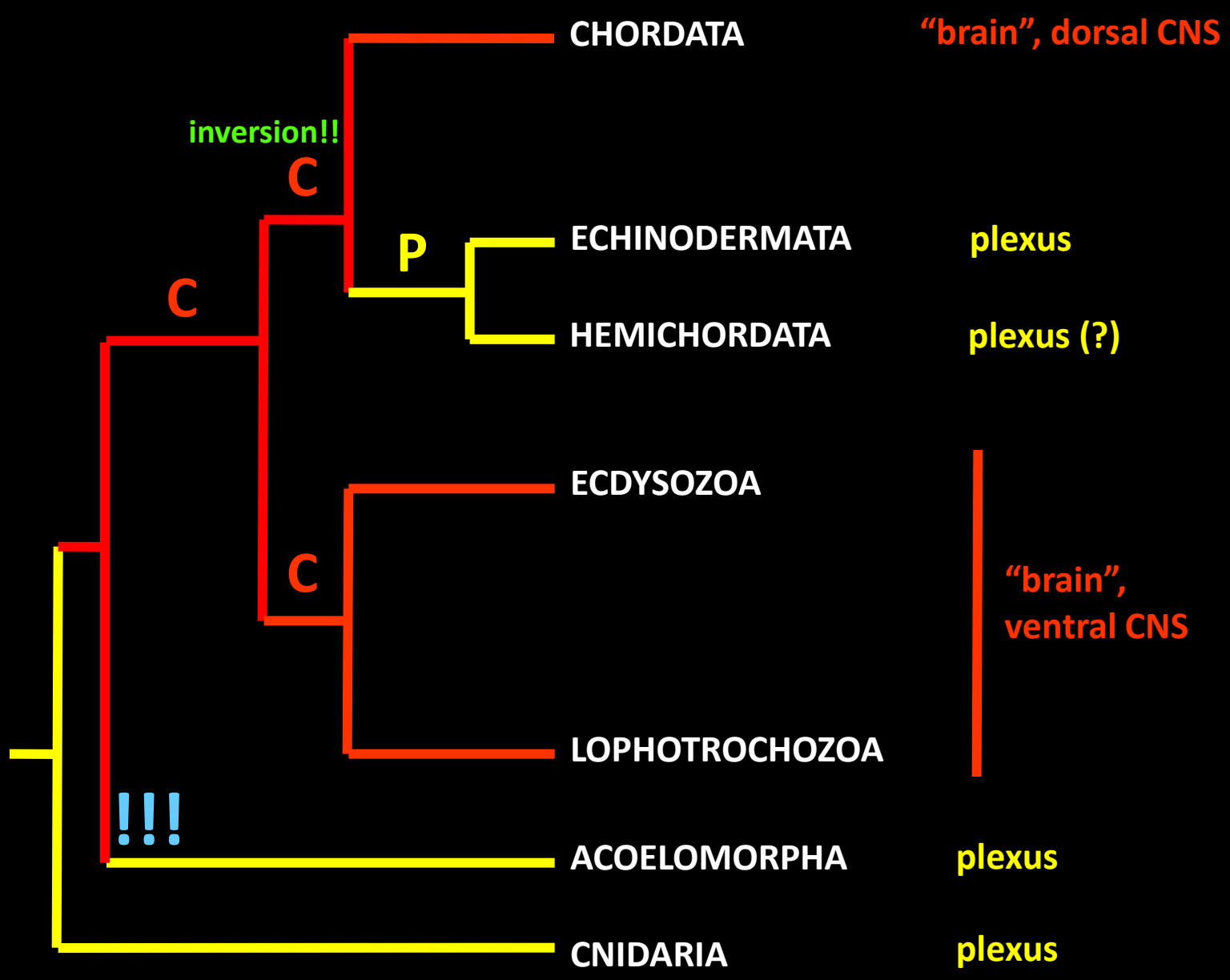
Nervous system evolution in Bilateria



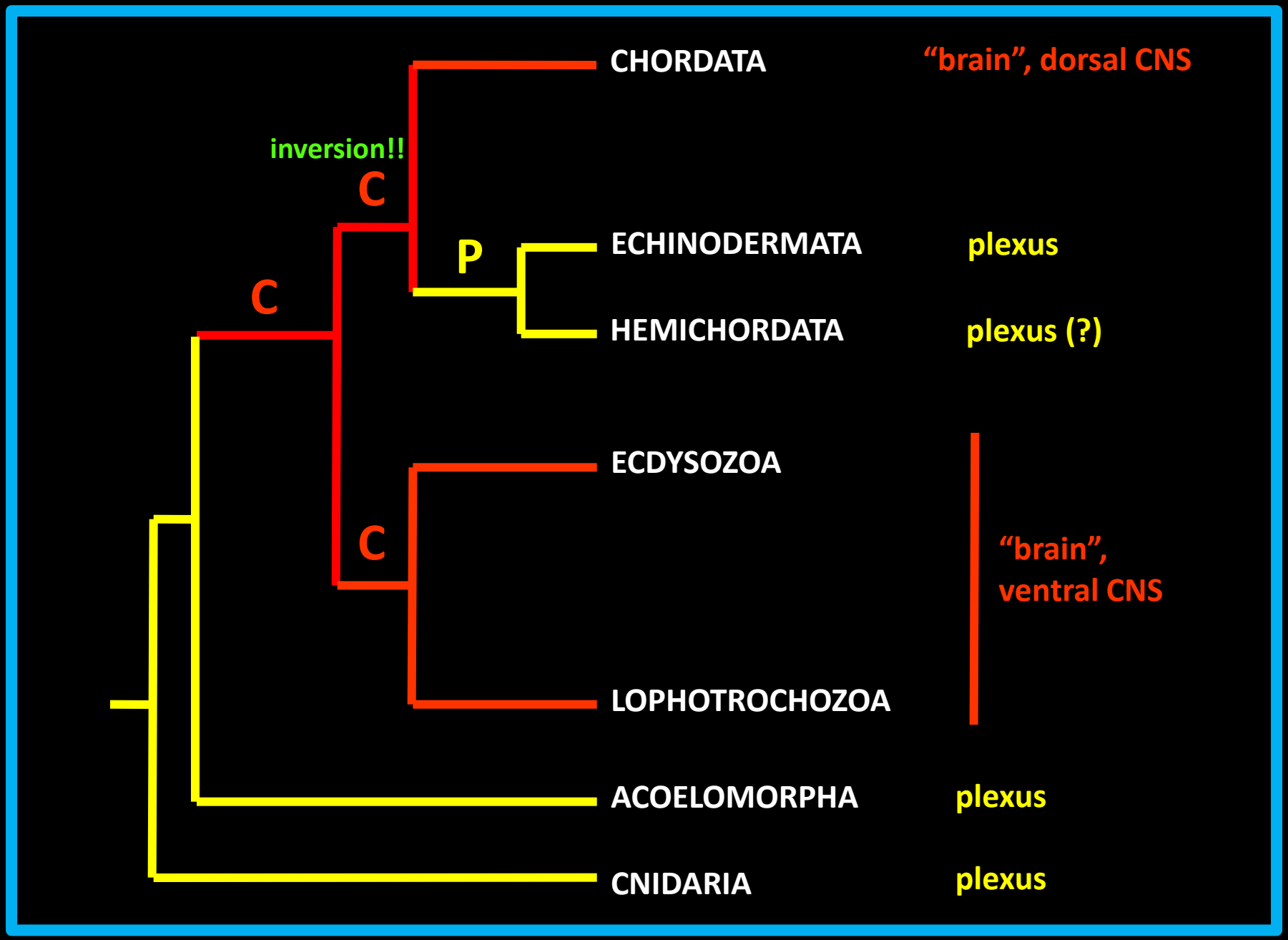
Nervous system evolution in Bilateria



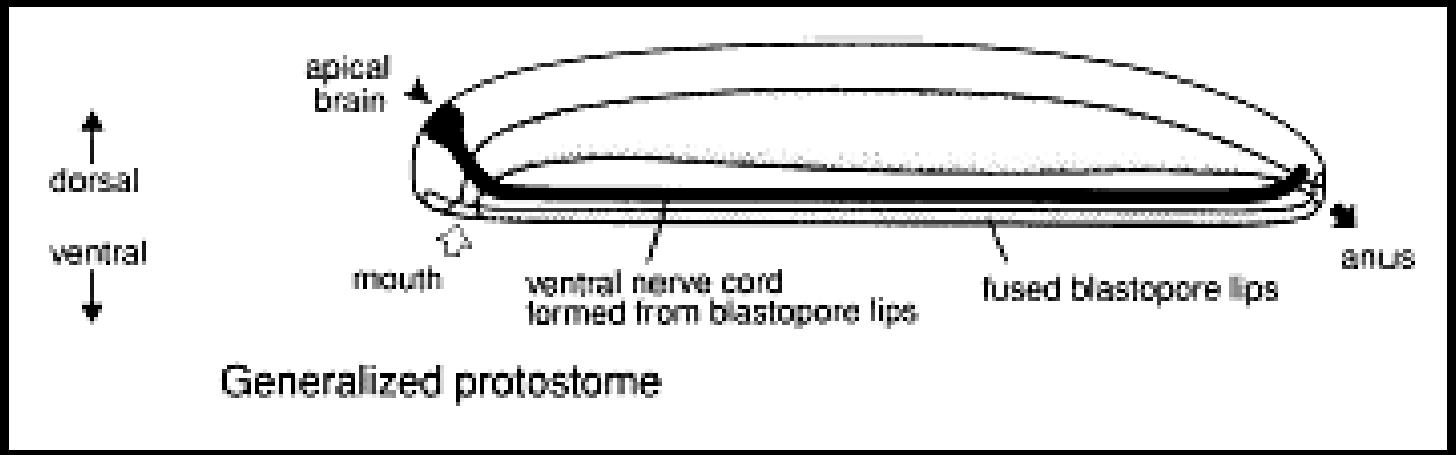
Nervous system evolution in Bilateria

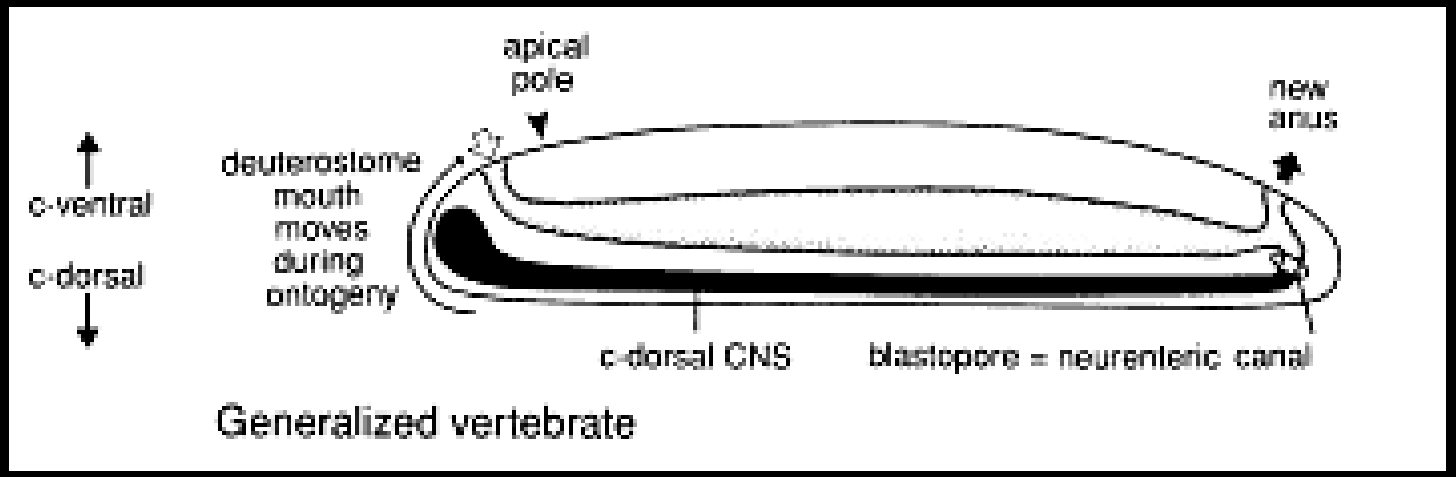


Nervous system evolution in Bilateria



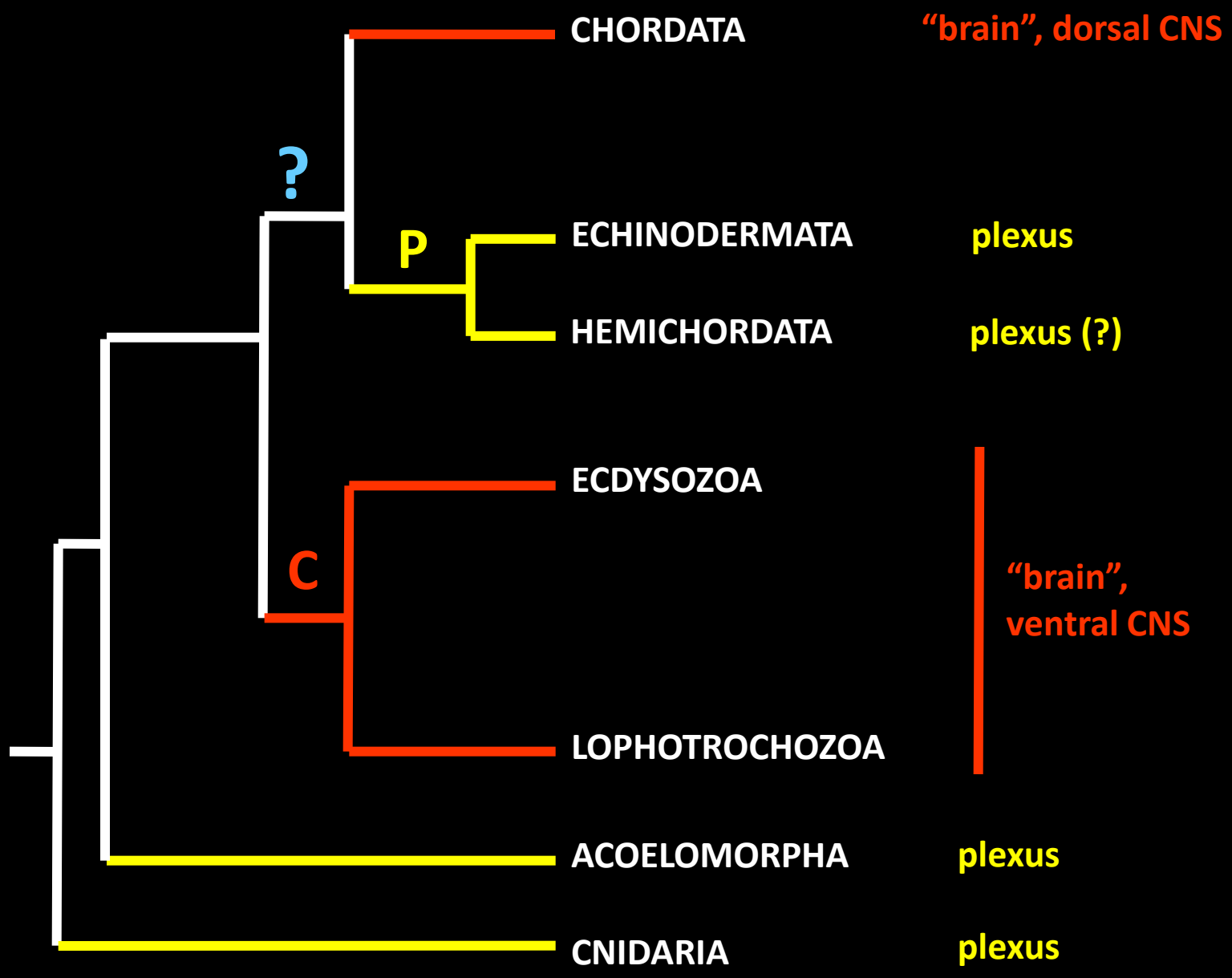
Nervous system evolution in Bilateria



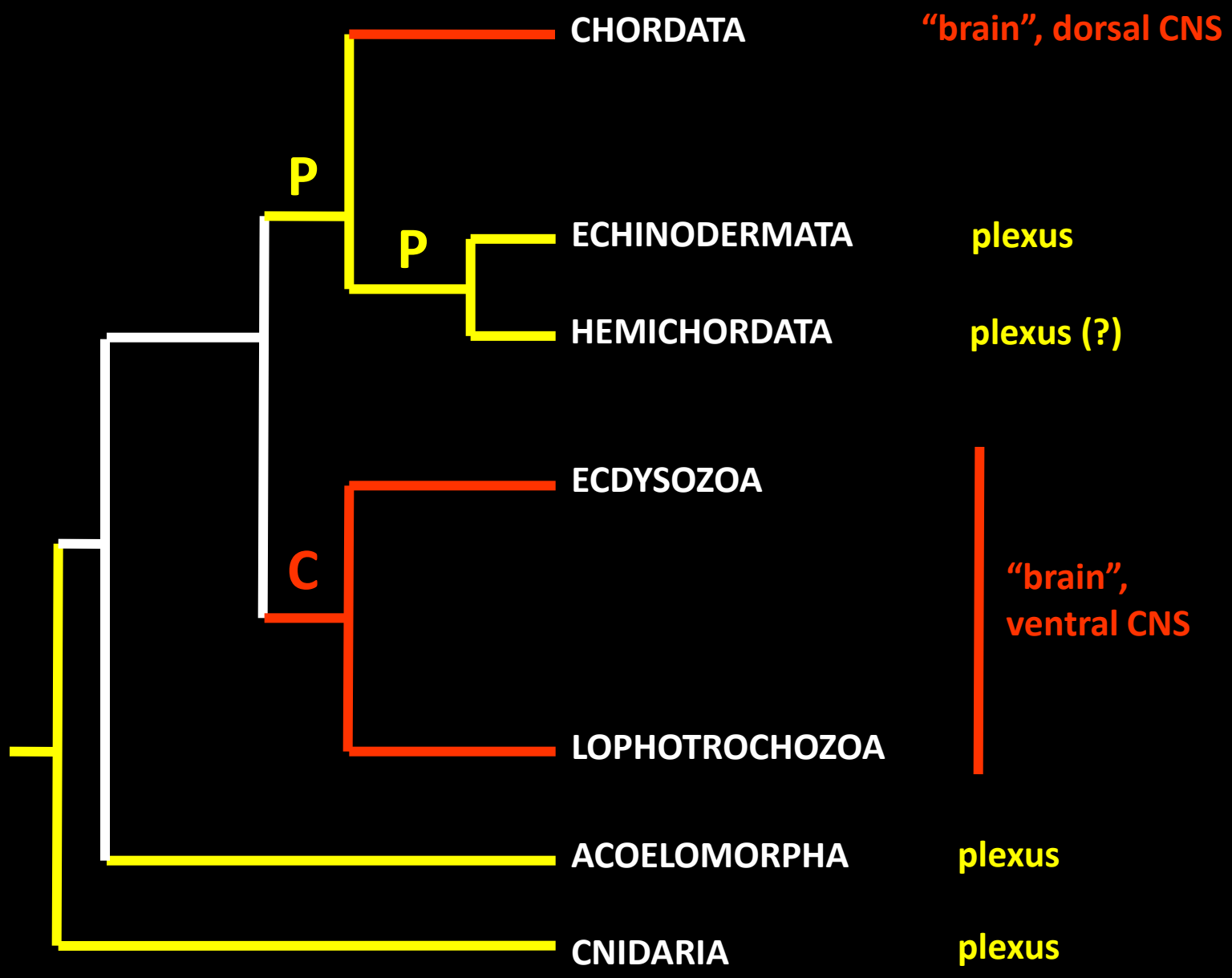


Nielsen: *(1999)*

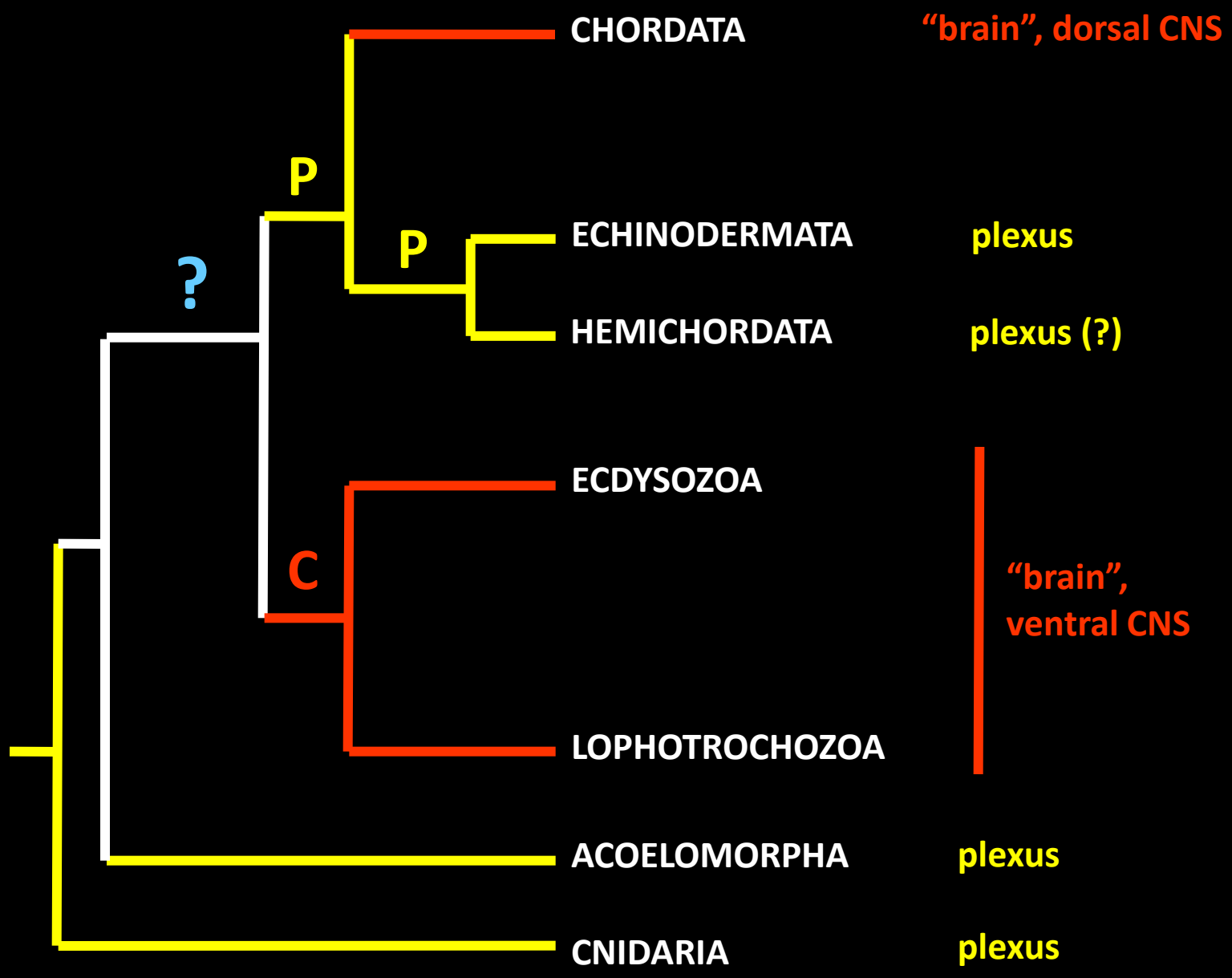
Nervous system evolution in Bilateria



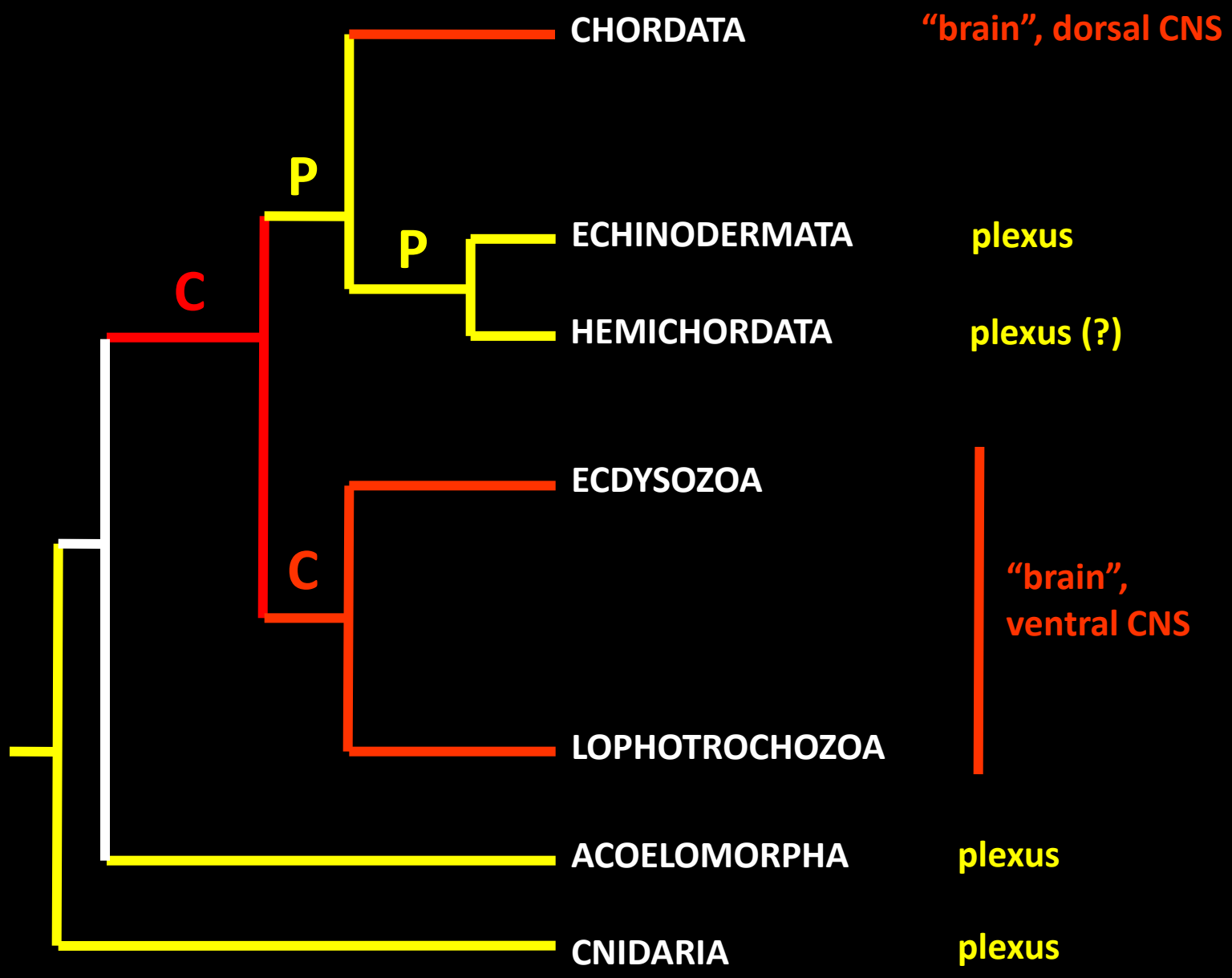
Nervous system evolution in Bilateria



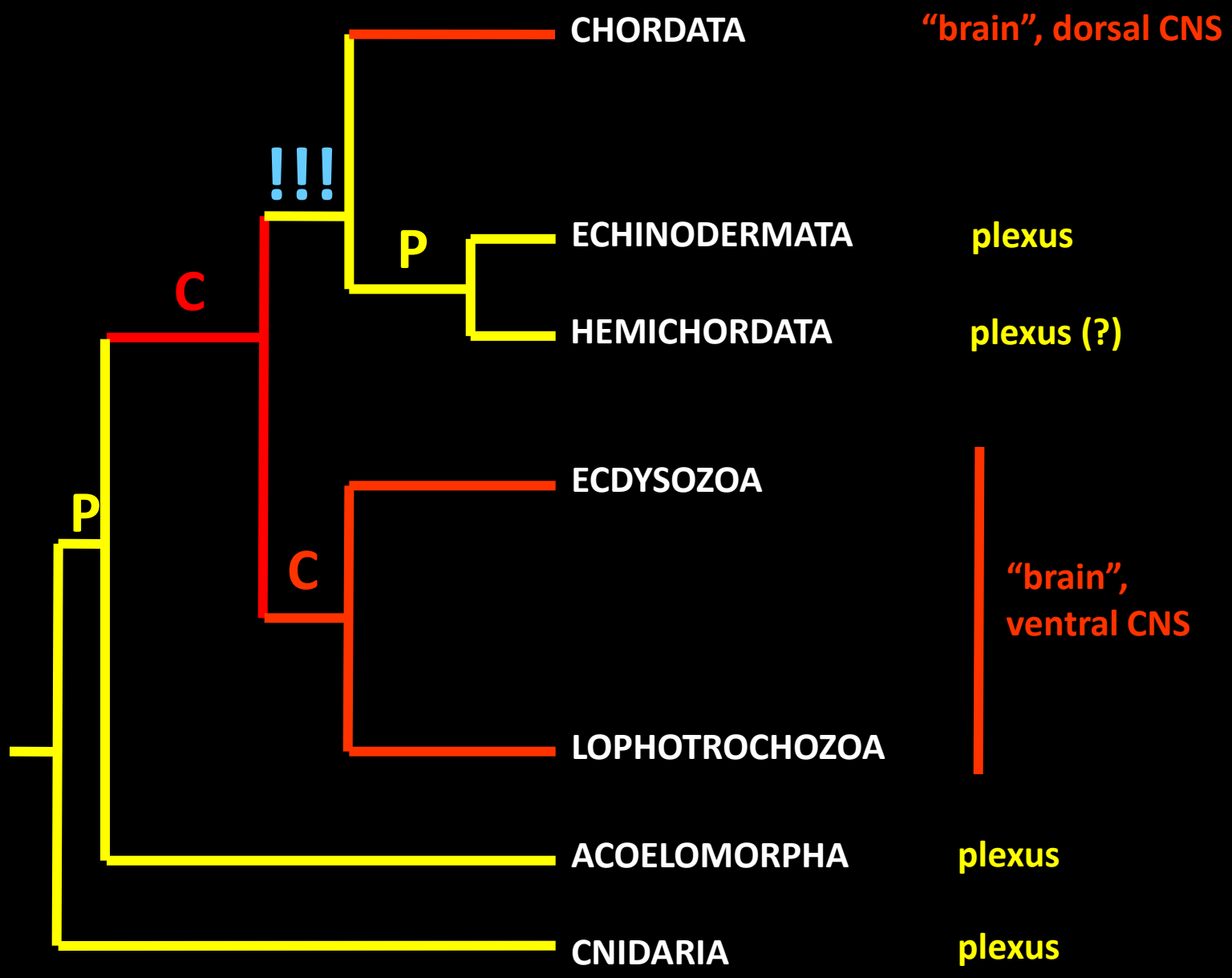
Nervous system evolution in Bilateria



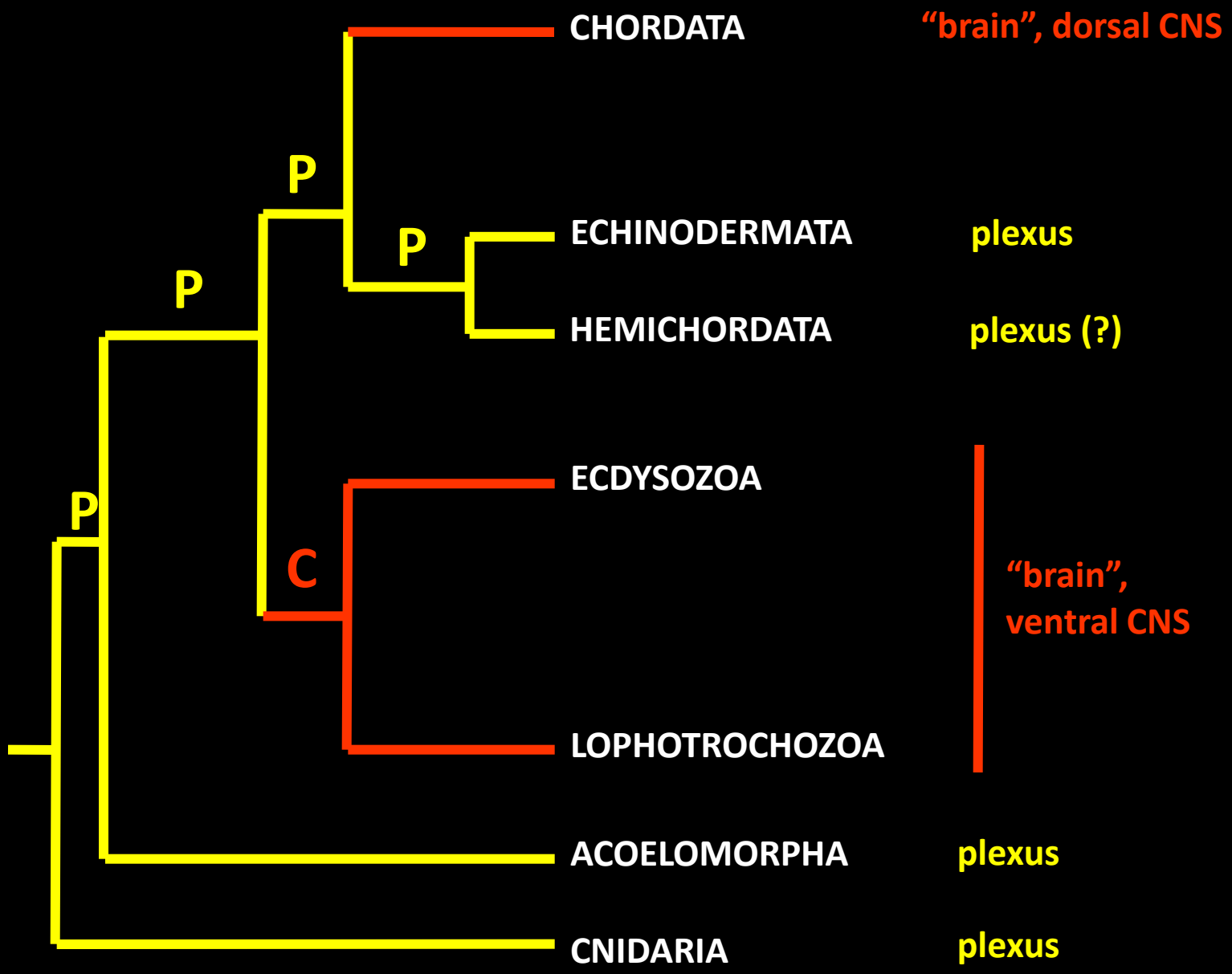
Nervous system evolution in Bilateria



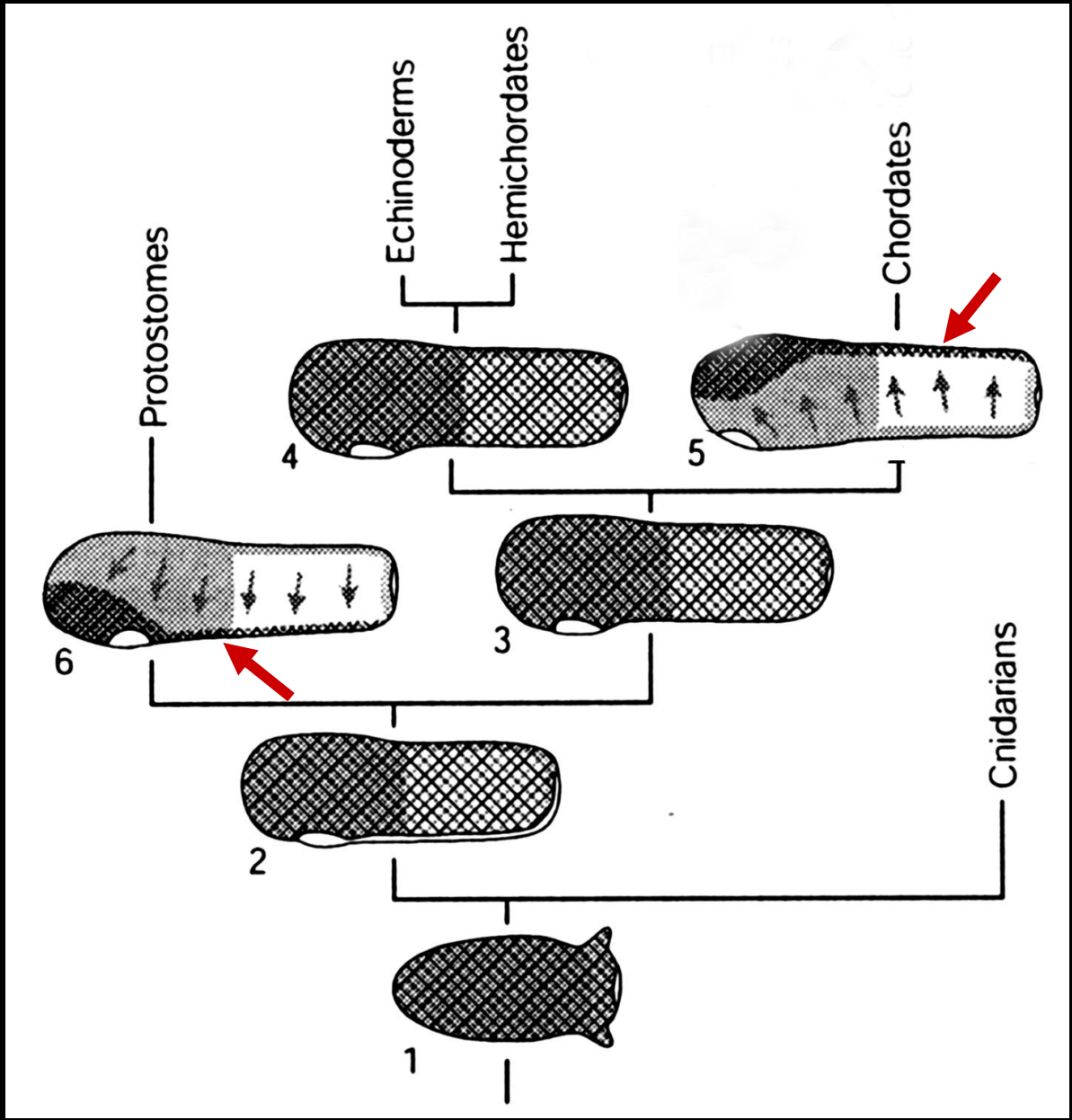
Nervous system evolution in Bilateria



Nervous system evolution in Bilateria



Nervous system evolution in Bilateria



After Holland: *Nat. Rev. Neurosci. (2003)*

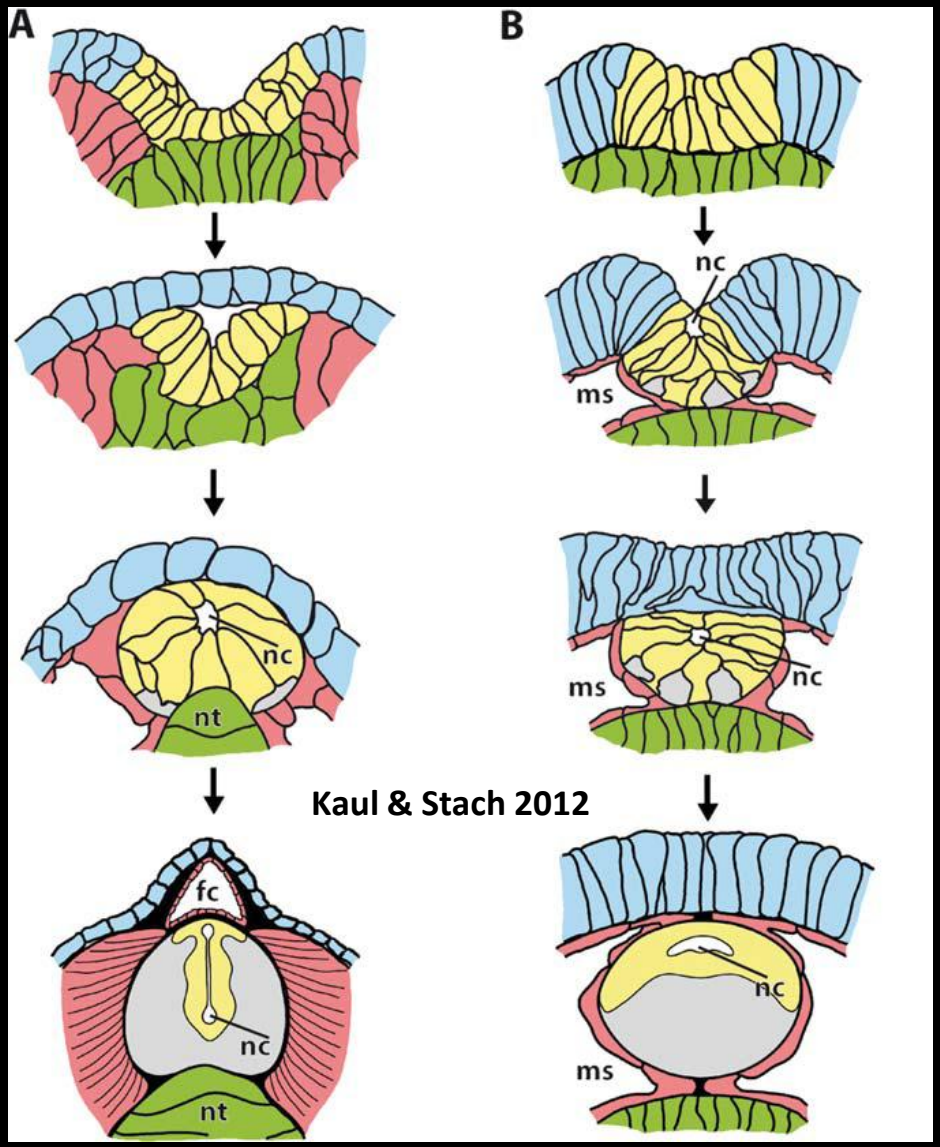
BUT...

Neurulation process in enteropneusts and chordates is highly similar!

Neurulation in enteropneusts and chordates homologous?

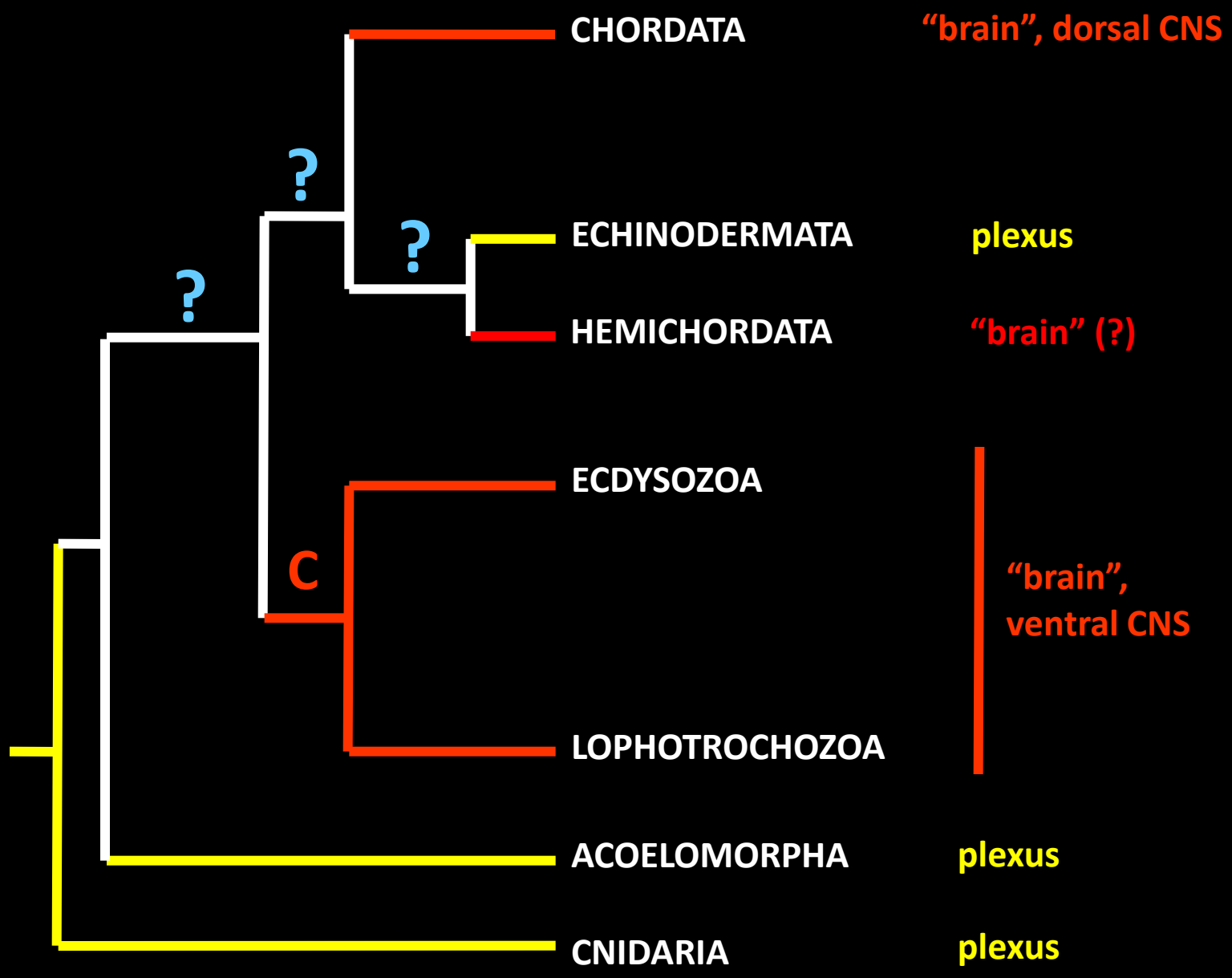
Hemichordates/enteropneusts sister group to chordates?

Loss of neurulation in echinoderms?



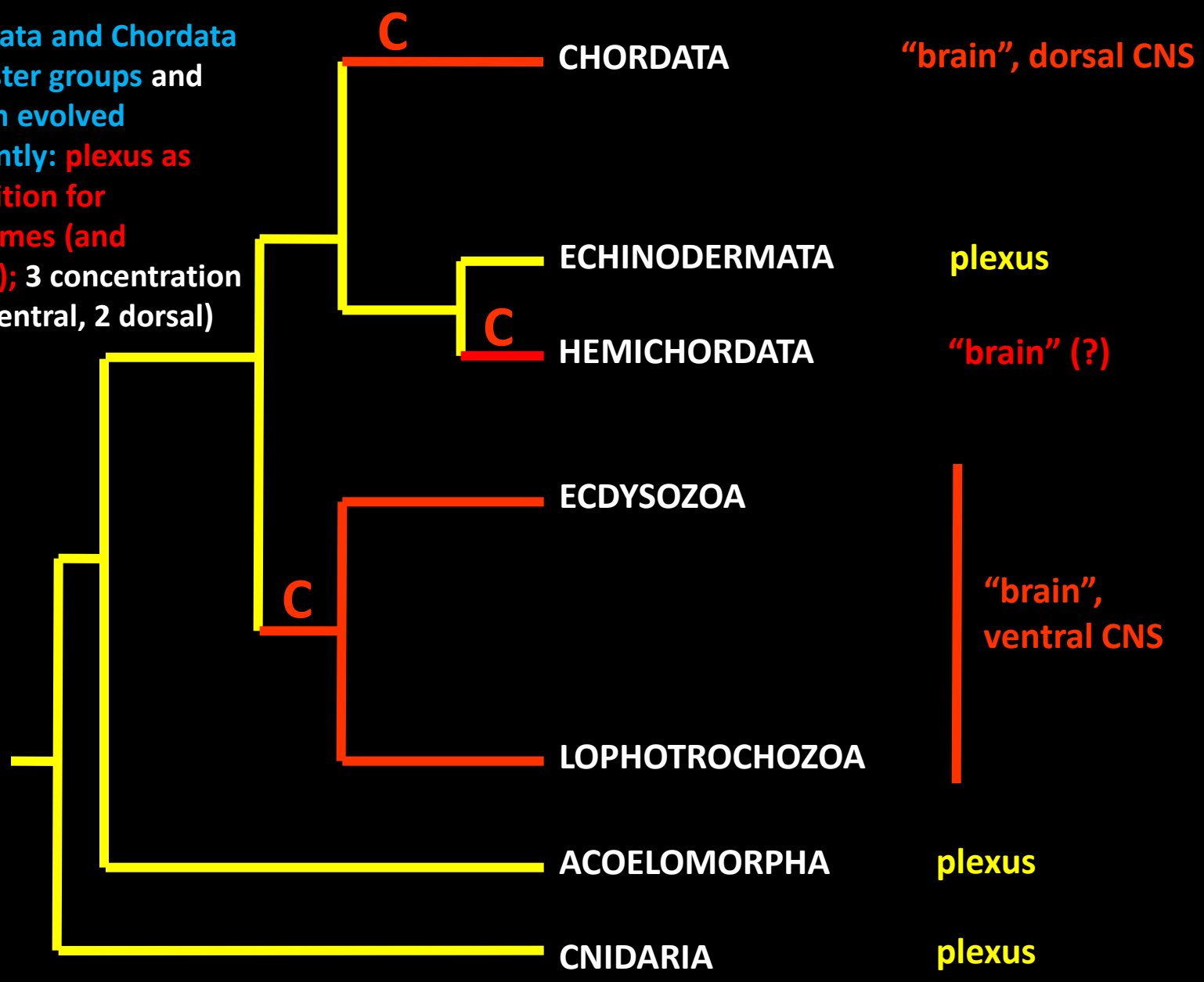
Kaul & Stach 2012

Nervous system evolution in Bilateria



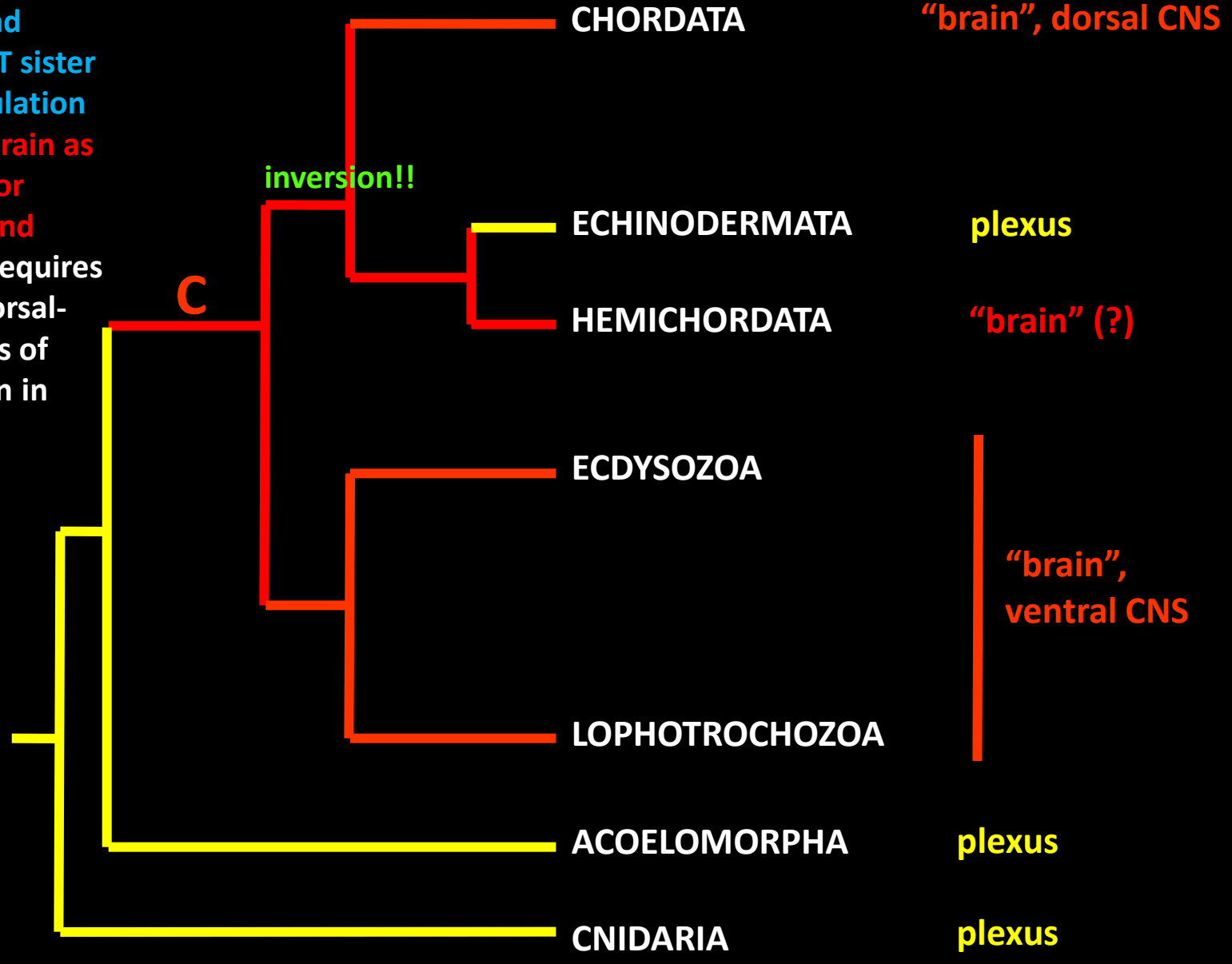
Nervous system evolution in Bilateria

Scenario 1:
Hemichordata and Chordata are NOT sister groups and **neurulation evolved independently: plexus as basal condition for deuterostomes (and Nephrozoa);** 3 concentration events (1 ventral, 2 dorsal)



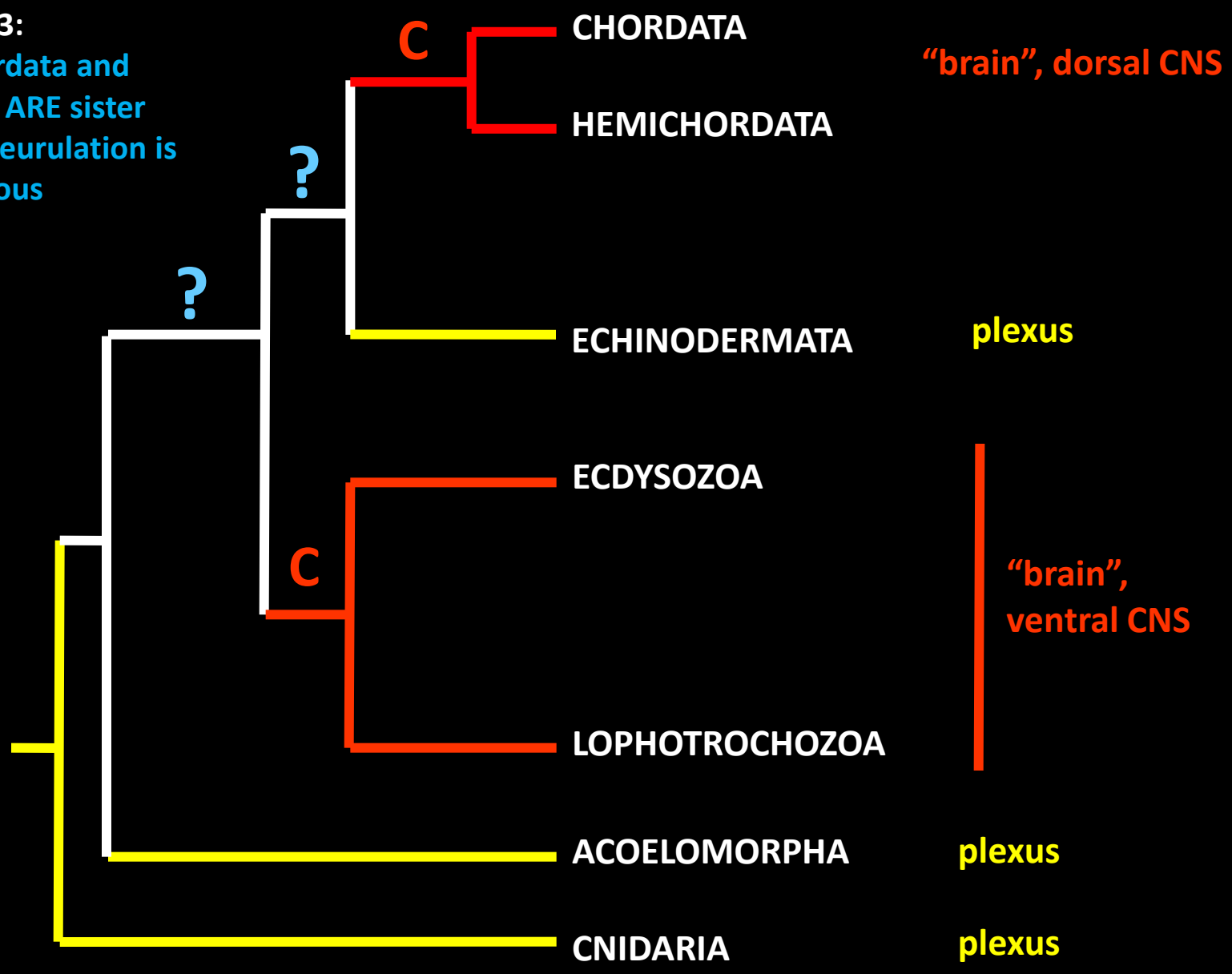
Nervous system evolution in Bilateria

Scenario 2:
Hemichordata and Chordata are NOT sister groups but neurulation is homologous: brain as basal condition for deuterostomes and Nephrozoa, but requires axis inversion (dorsal-ventral NC) & loss of brain/neurulation in Echinodermata



Nervous system evolution in Bilateria

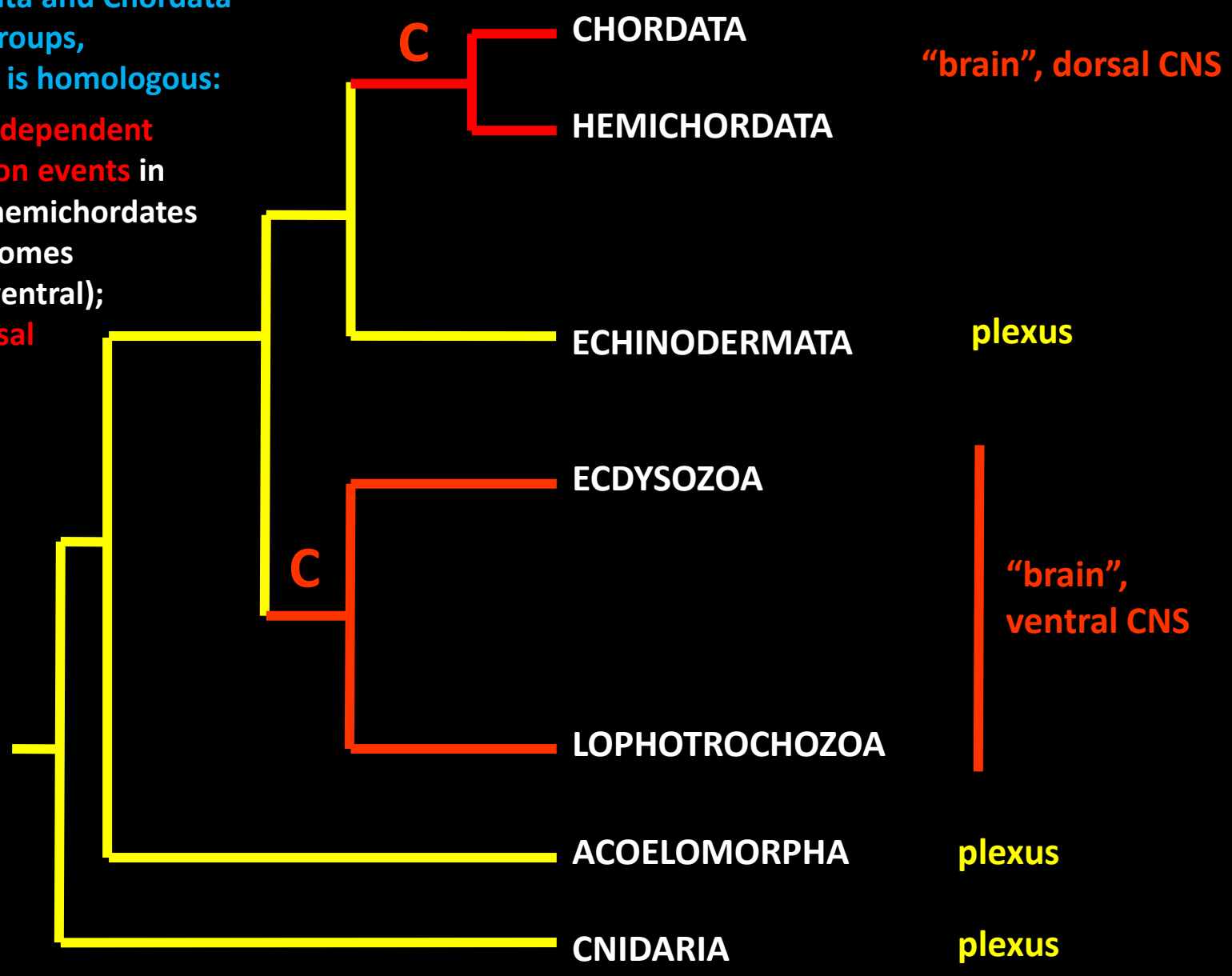
Scenario 3:
Hemichordata and Chordata ARE sister groups, neurulation is homologous



Nervous system evolution in Bilateria

Scenario 3:
Hemichordata and Chordata ARE sister groups, neurulation is homologous:

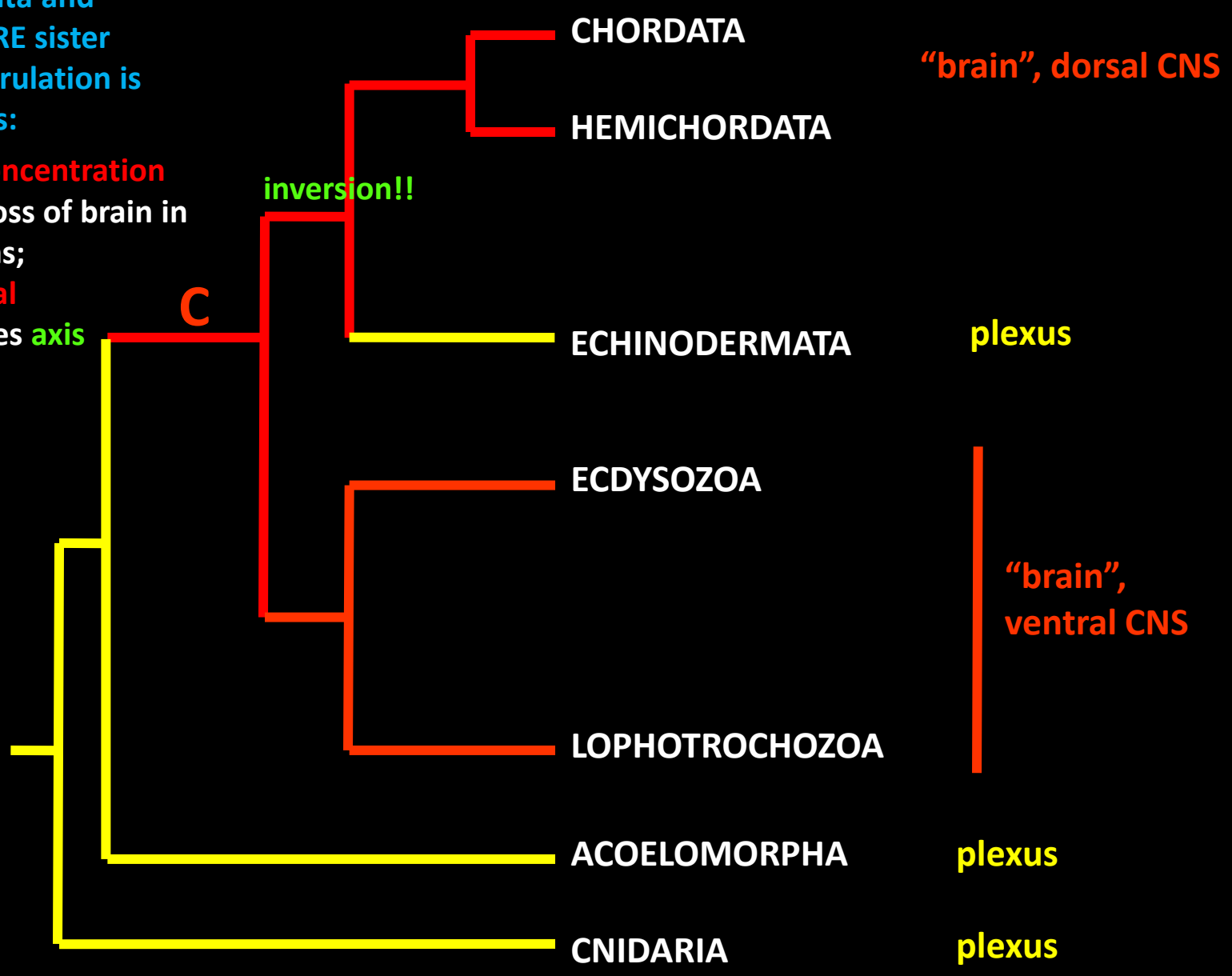
EITHER: independent concentration events in chordates/hemichordates and protostomes (dorsal vs. ventral); plexus is basal



Nervous system evolution in Bilateria

Scenario 3:
Hemichordata and Chordata ARE sister groups, neurulation is homologous:

OR: one concentration event and loss of brain in echinoderms; brain is basal
BUT: requires axis inversion!!

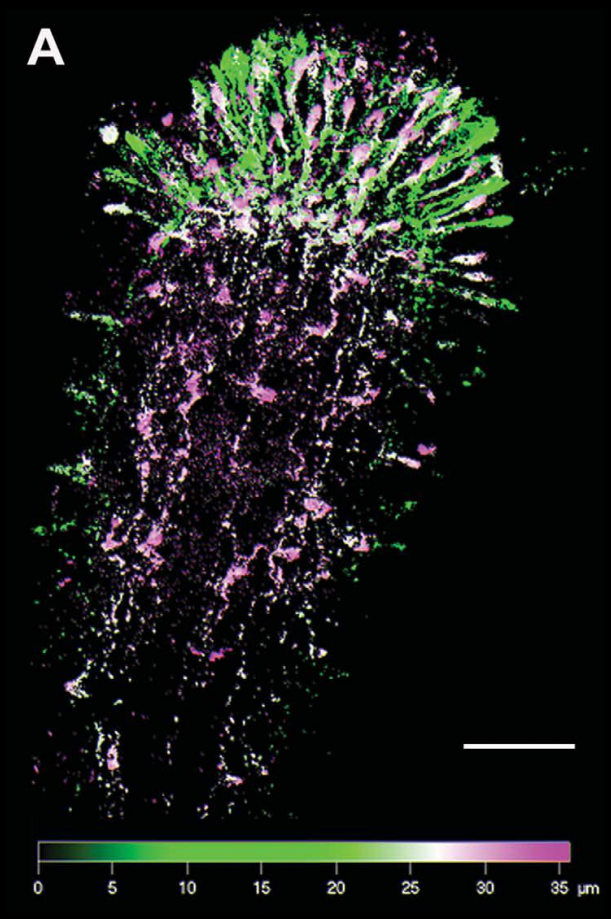


BUT...

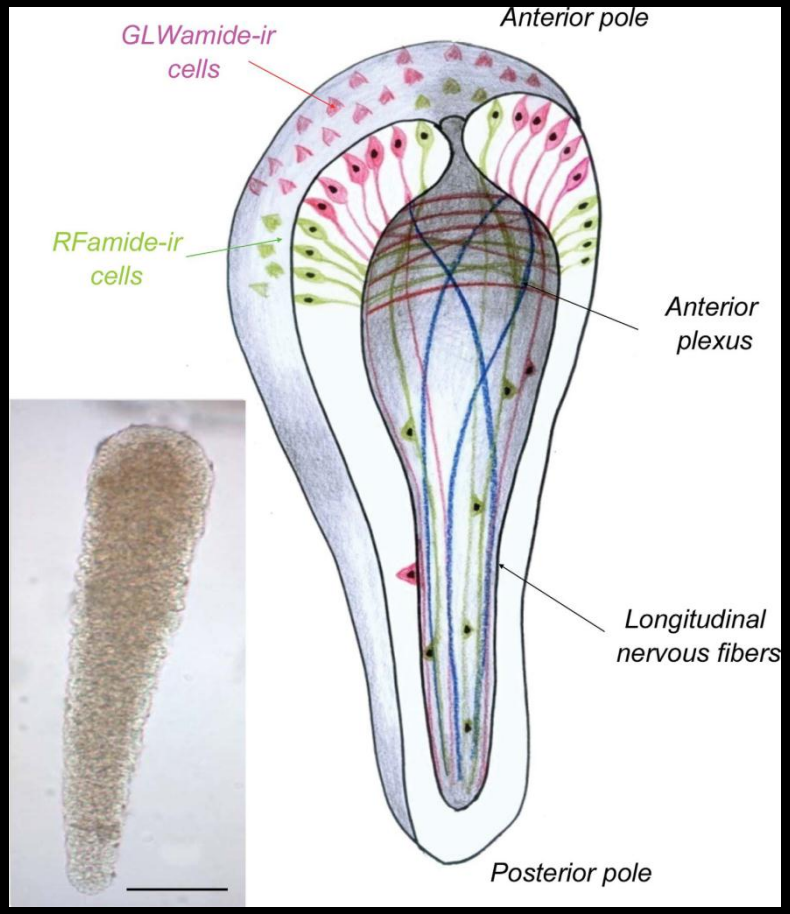
Cnidarian ancestor had a concentrated NS? Secondary simplifiacation?

Clava multicornis **(Cnidaria: Hydrozoa): neuroanatomy of planula larva**

GLWamide



RFamide



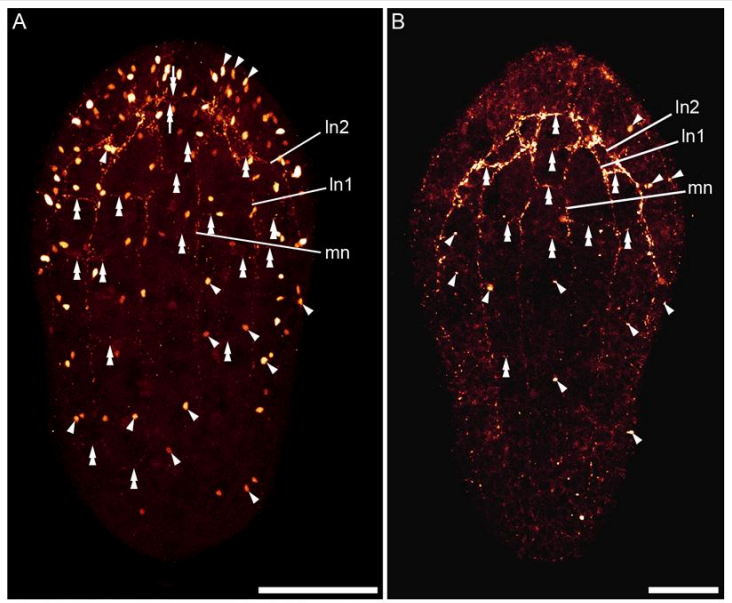
Piraino et al.: *J. Comp. Neurol. (2011)*

AND…

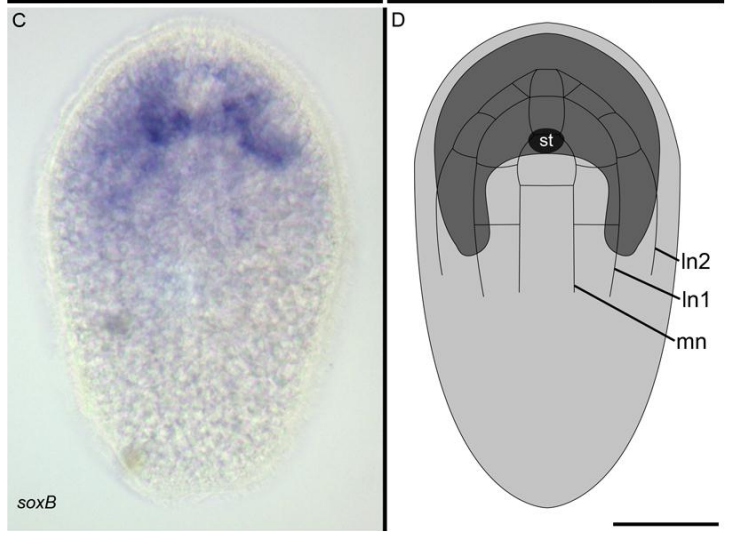
Acoelomorph ancestor had a concentrated NS? Secondary simplifiacation?

Symsagittifera roscoffensis

Serotonin

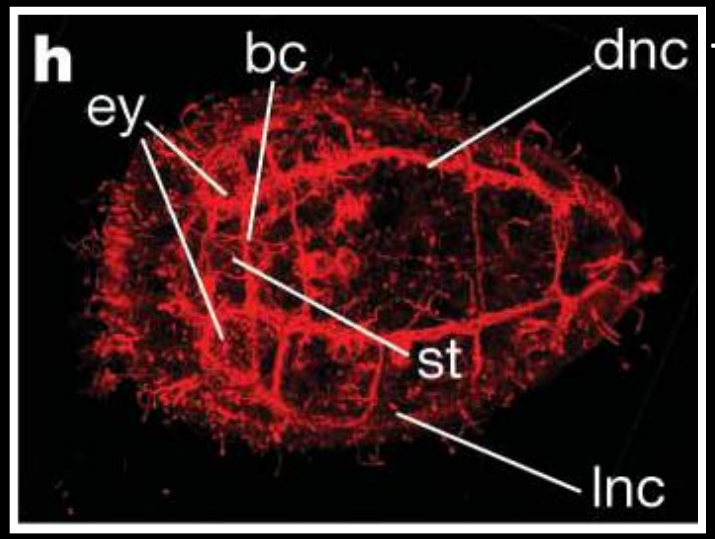


SoxB



Semmler, Choidin, Bailly, Martinez & Wanninger: *Dev. Growth Diff. (2010)*

Convolutriloba longifissura



Tubulin

cdx

Hejnol & Martindale: *Nature (2008)*

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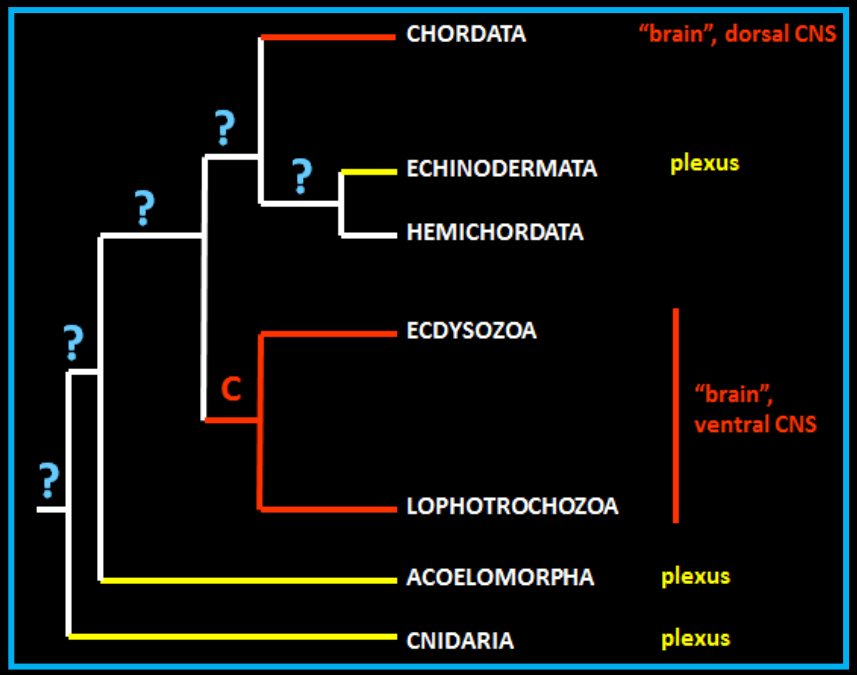

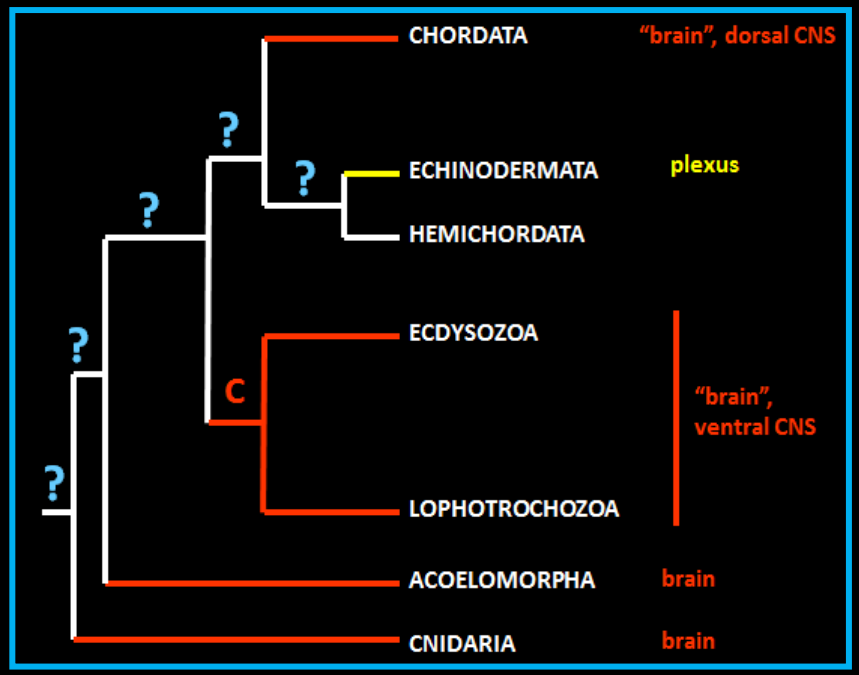

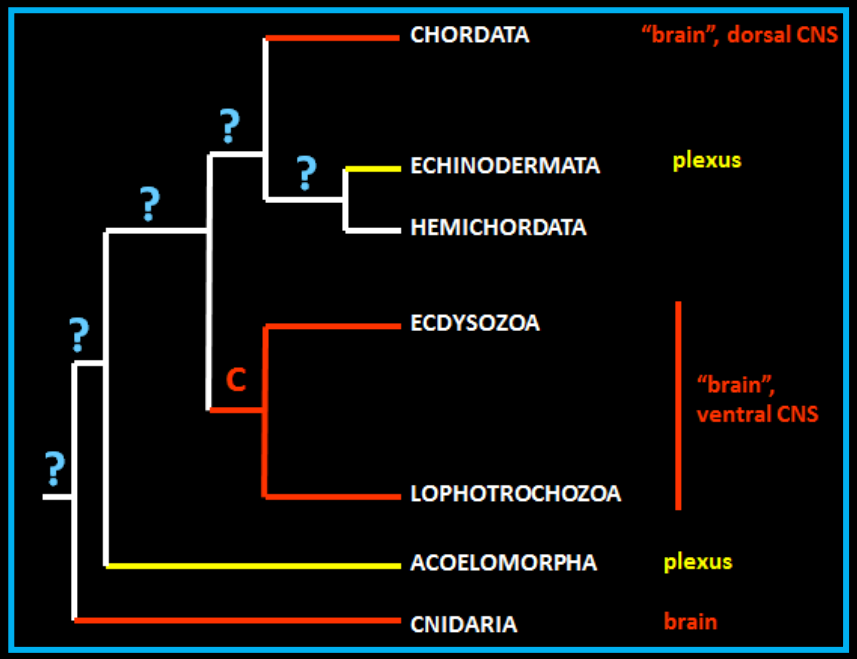

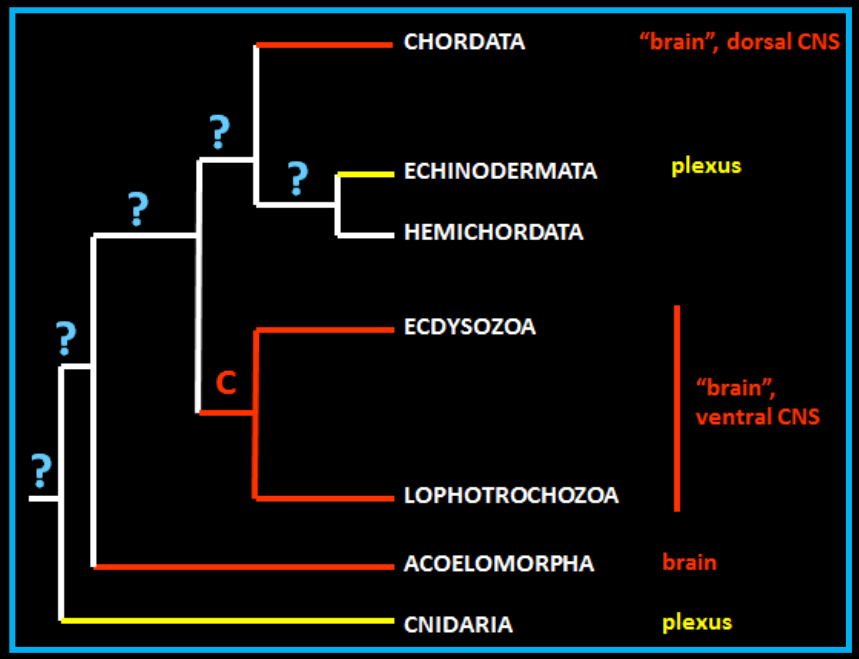

Nervous system evolution in Bilateria