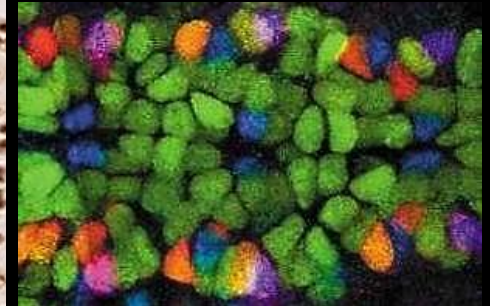
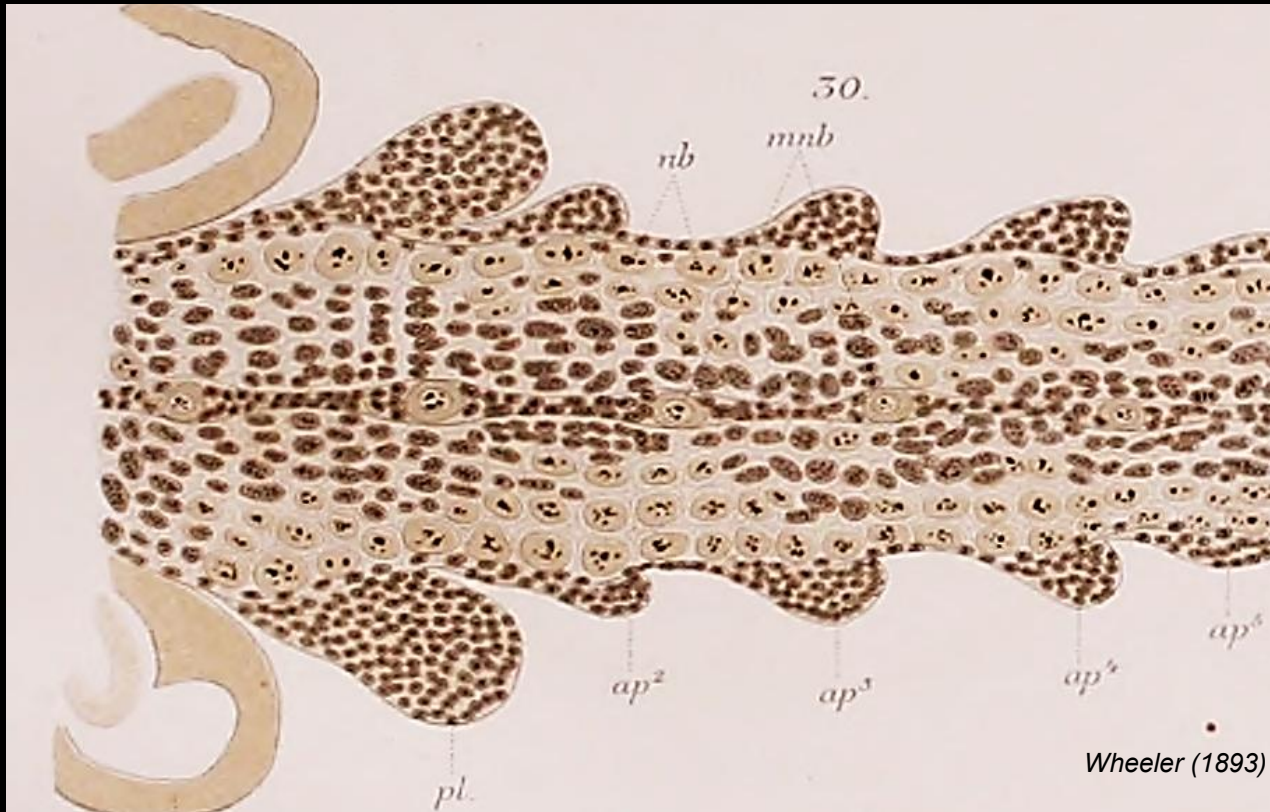


Study of early neurogenesis in insects: An epistemological view



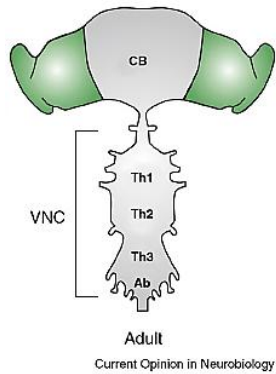
Wheeler (1893)

Nature Press

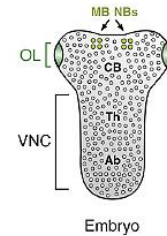
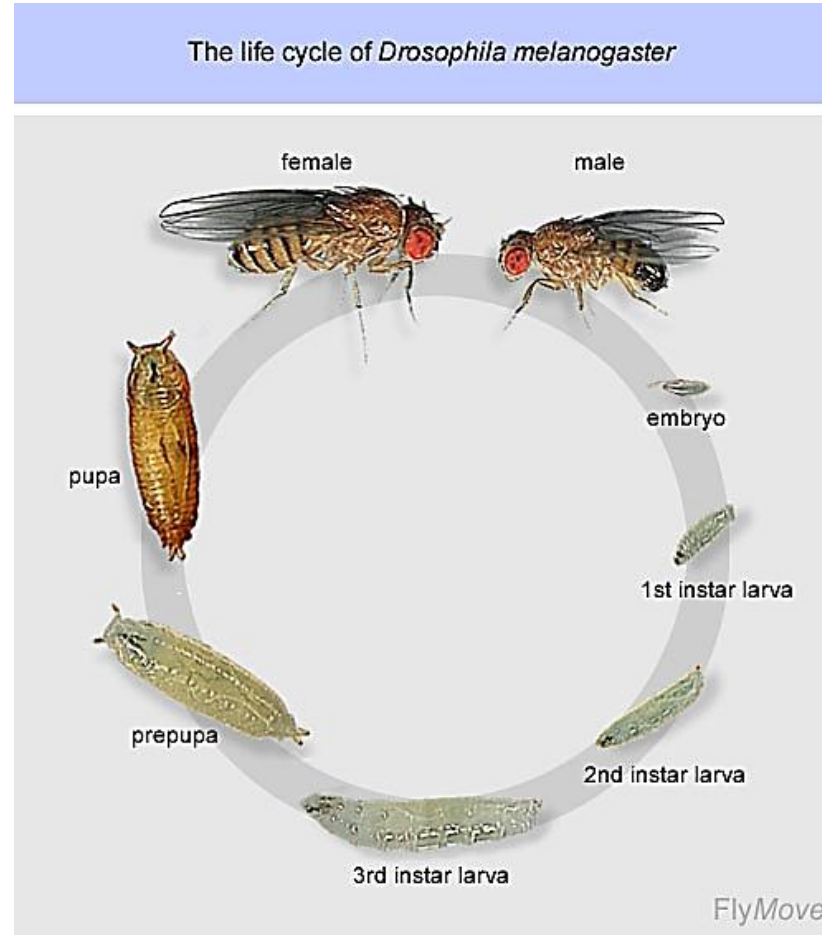
Sébastien SZUPLEWSKI

Holometabola development

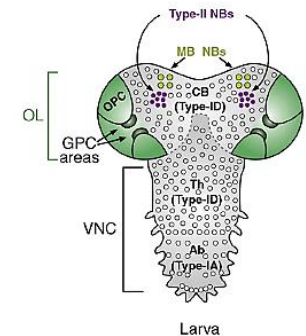
Two shapes, two lifestyles, two CNS & PNS



- Michel Gho (PNS)



- François Agnès (CNS)



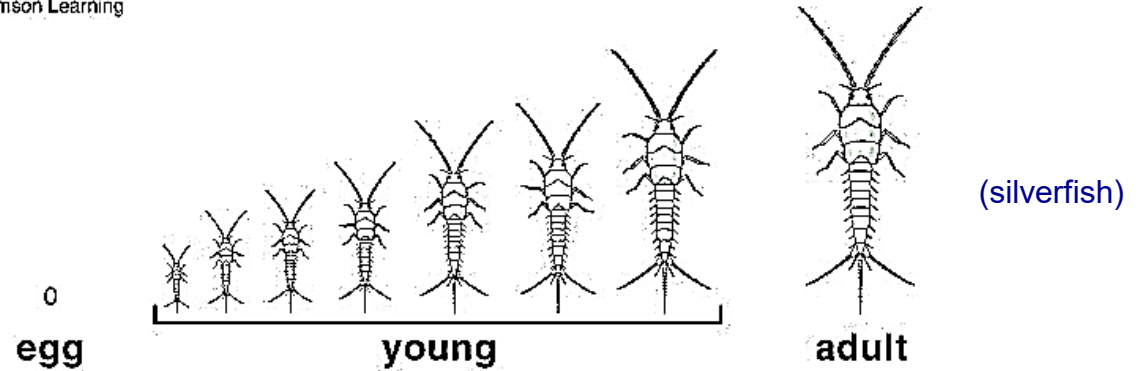
- Pauline Spéder (CNS)

Post-embryonic development & Ecdysis

© 2001 Brooks/Cole - Thomson Learning

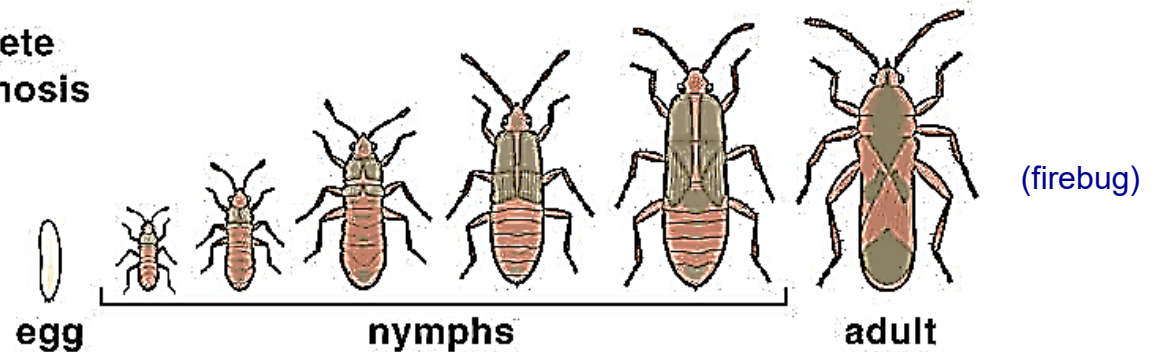
Ametabola

a Growth and molting



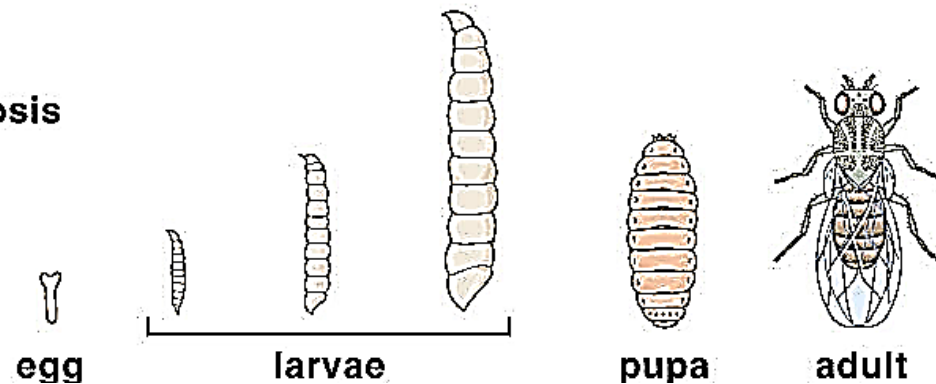
Heterometabola

b Incomplete metamorphosis

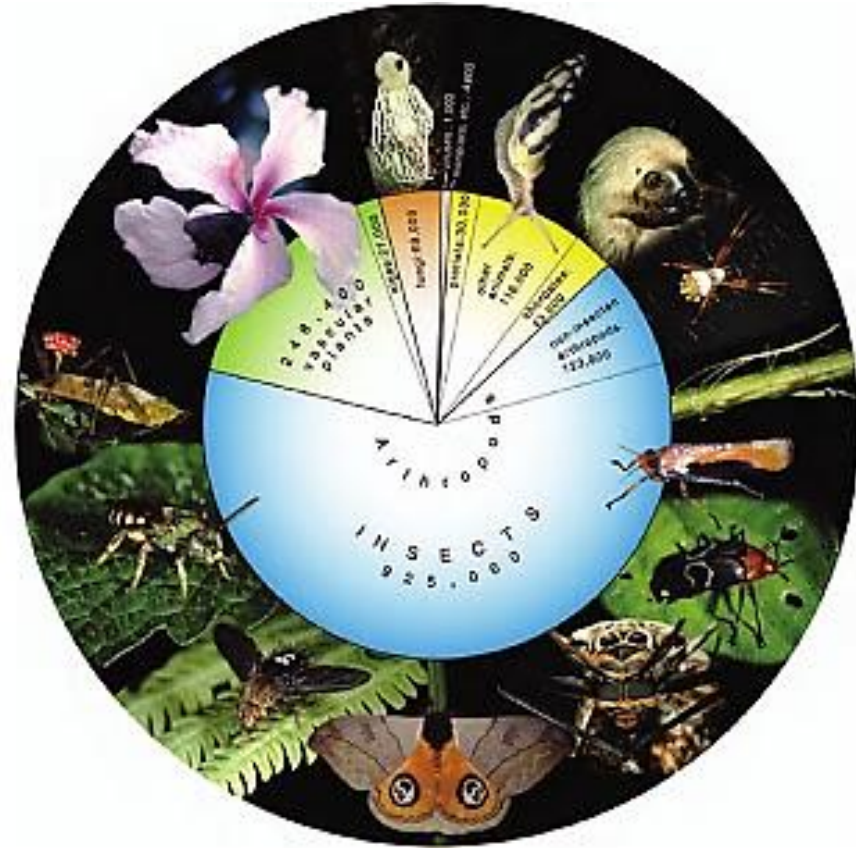
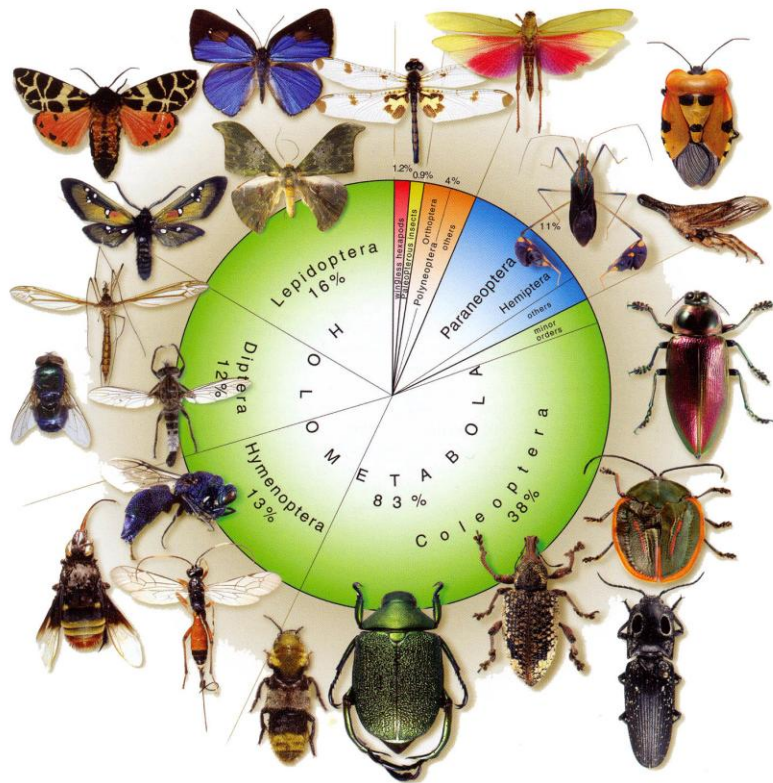


Holometabola

c Complete metamorphosis

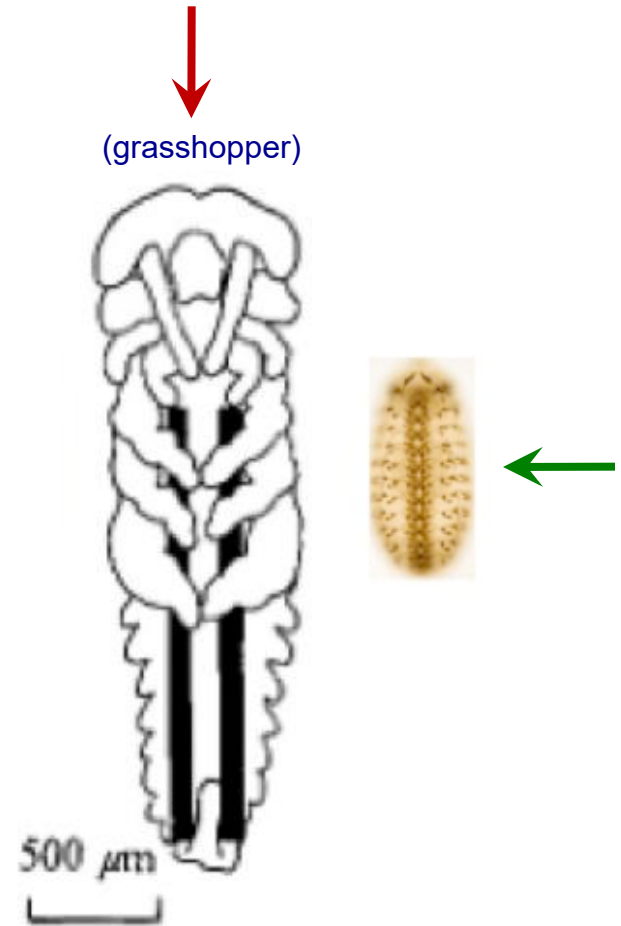
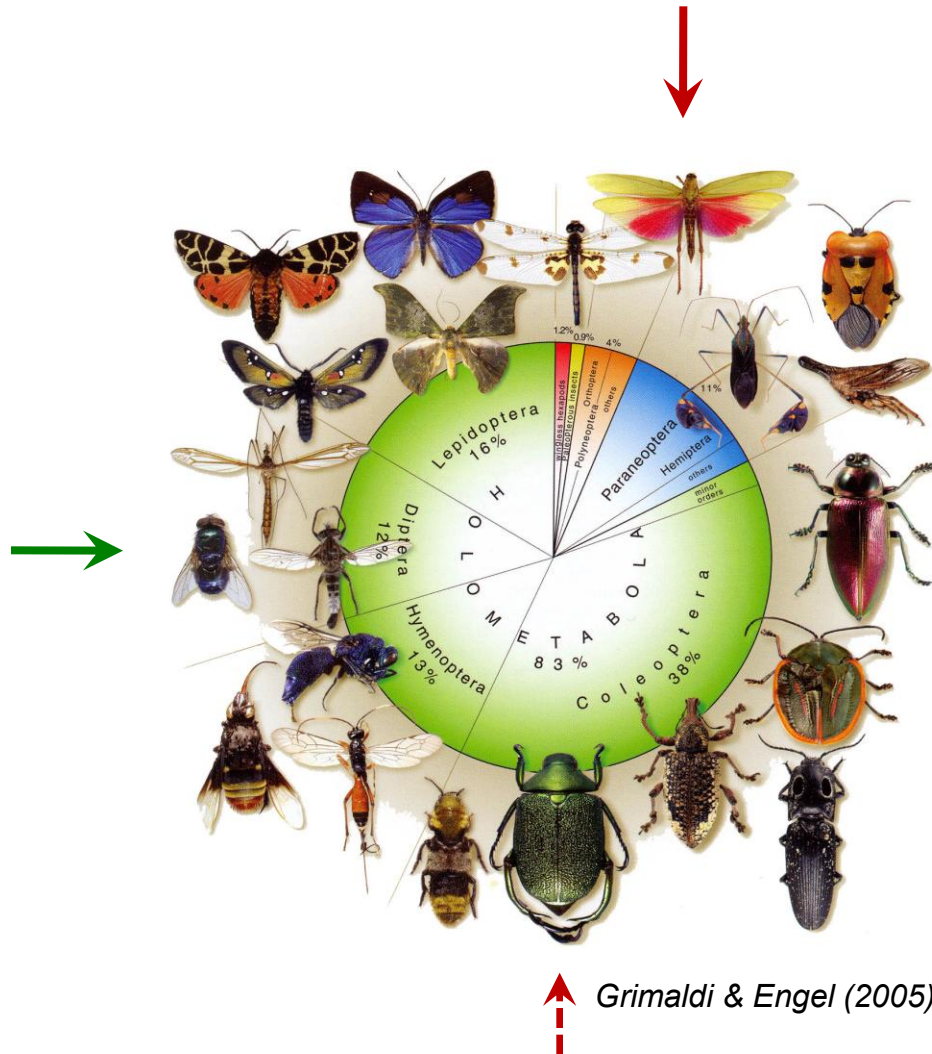


Champions of the biodiversity



Grimaldi & Engel (2005)

Choice of a model organism: size matters



Modified from
<http://amapress.gen.cam.ac.uk/?p=1326>

Choice of a model organism: major investigators



*William M.
Wheeler*



*Donald F.
Poulson*

1891

1937



*Michael
Bate*



*Corey S.
Goodman*



Chris Q. Doe



*José-Antonio
Campos-Ortega*

1980

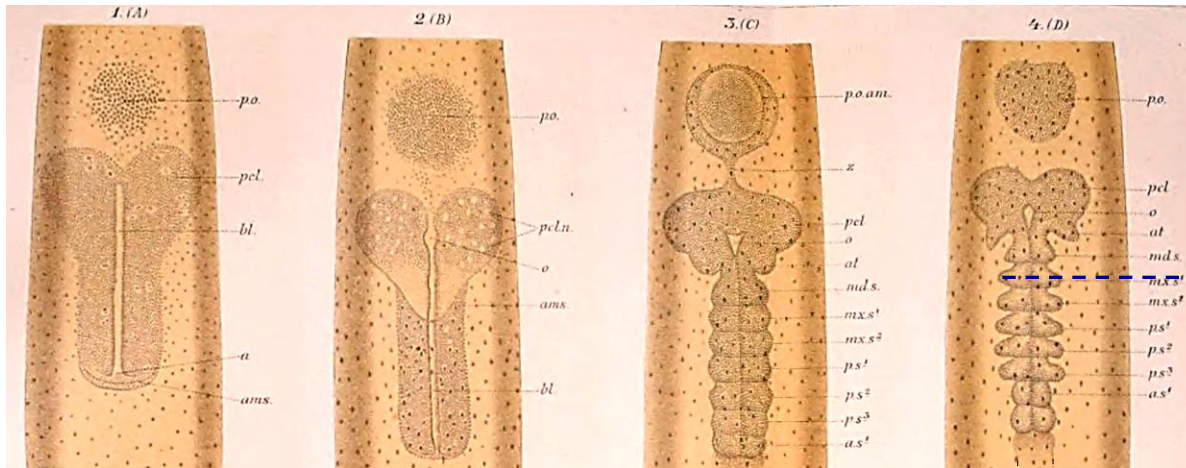
1990

2000

Development of *Orthoptera* ventral nerve cord

Wheeler (1891) *Neuroblasts in the arthropod embryo*. *J. Morph.* 4:337-343.

Wheeler (1893) *A contribution to insect embryology*. *J. Morph.* 8:1-160.



Transverse sections

1st maxillary segment



D
↑
↓
V

Abdominal segment



- Two cell populations:

+ dermatoblasts

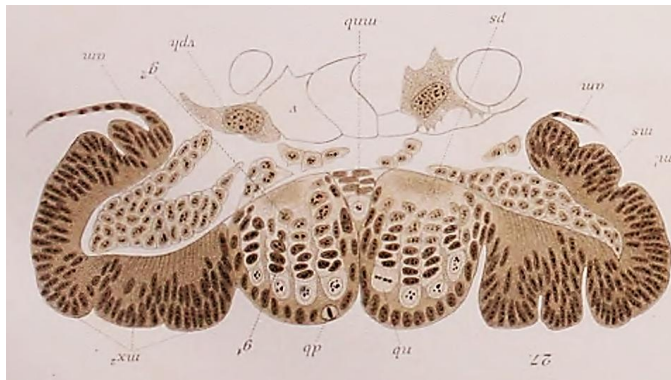
+ neuroblasts

(Whitman, 1878 (leech embryo))

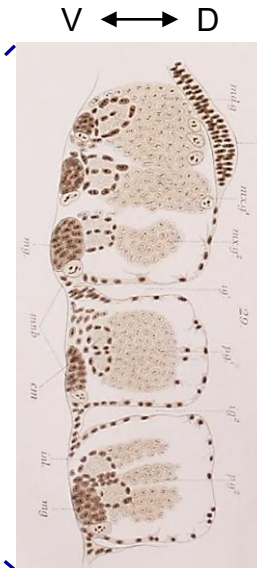
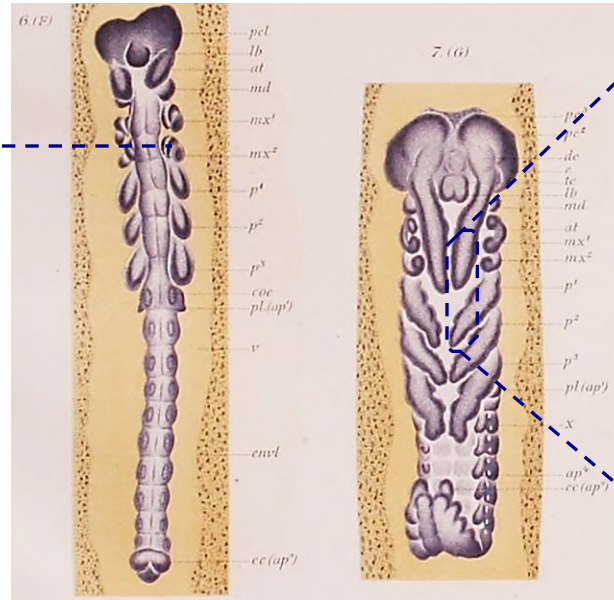
The neuroblasts

Wheeler (1891) **Neuroblasts** in the arthropod embryo. J. Morph. 4:337-343.

Wheeler (1893) A contribution to insect embryology. J. Morph. 8:1-160.



Transverse section
2nd maxillary segment



Sagittal section



- Neuroblast divisions

- + likely the only dividing cells
- + in waves

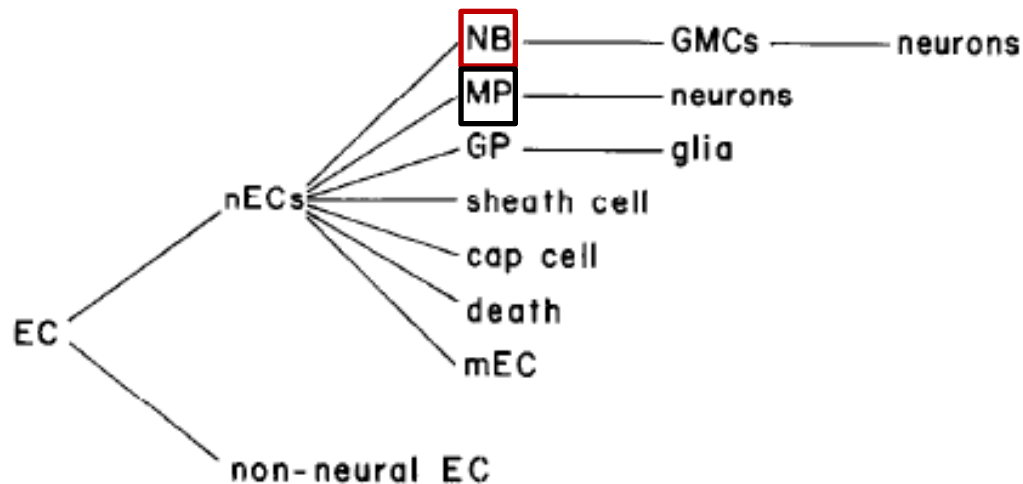
- Daughter cells

- + smaller and more stained
- + form some clusters
- + become «ganglionic cells»

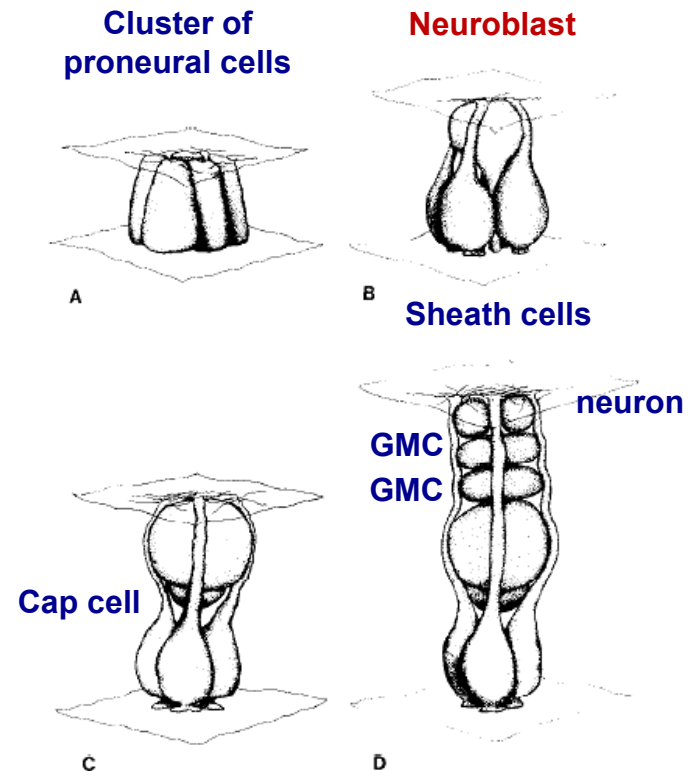
Revisiting *Orthoptera* early neurogenesis

Doe & Goodman (1985) *Early events in insect neurogenesis. I. Development and segmental differences in the pattern of neuronal precursor cells.* Dev Biol. 111:193-205.

Lucifer Yellow injection



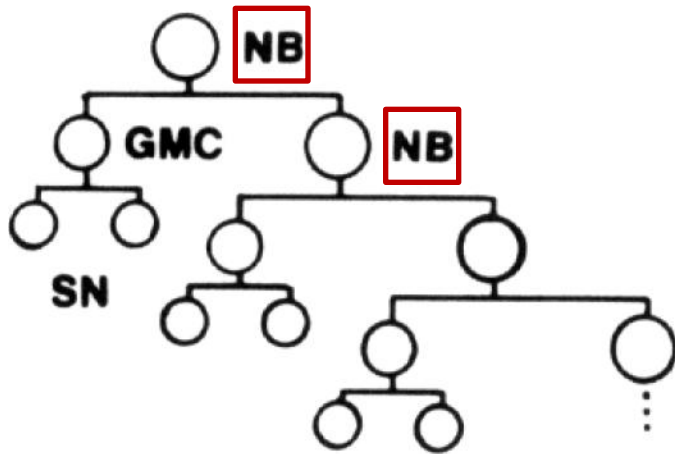
Live cell observation
with Nomarski optics



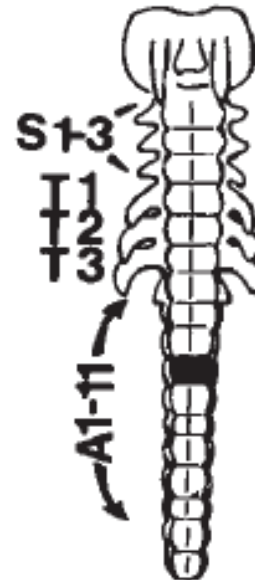
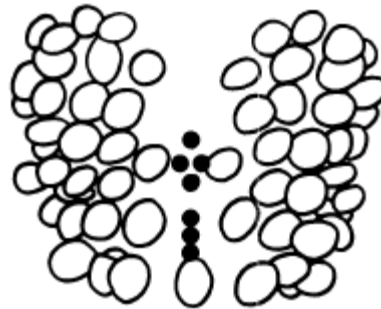
Revisiting *Orthoptera* early neurogenesis

Bate & Grunewald (1981) Embryogenesis of an insect nervous system II: A second class of neuron precursor cells and the origin of the intersegmental connectives. J Embryol Exp Morphol. 61:317-330.

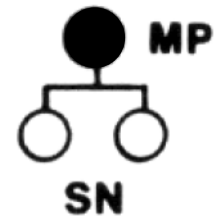
Live cell observation
with Nomarski optics



**Asymmetric
divisions**



Median line
precursors

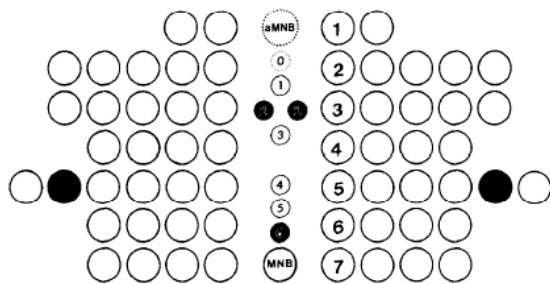


**Symmetric
divisions**

Revisiting *Orthoptera* early neurogenesis

Bate (1976) *Embryogenesis of an insect nervous system. I. A map of the thoracic and abdominal neuroblasts in Locusta migratoria. J Embryol Exp Morphol.* 35:107-123.

Live cell observation
with Nomarski optics

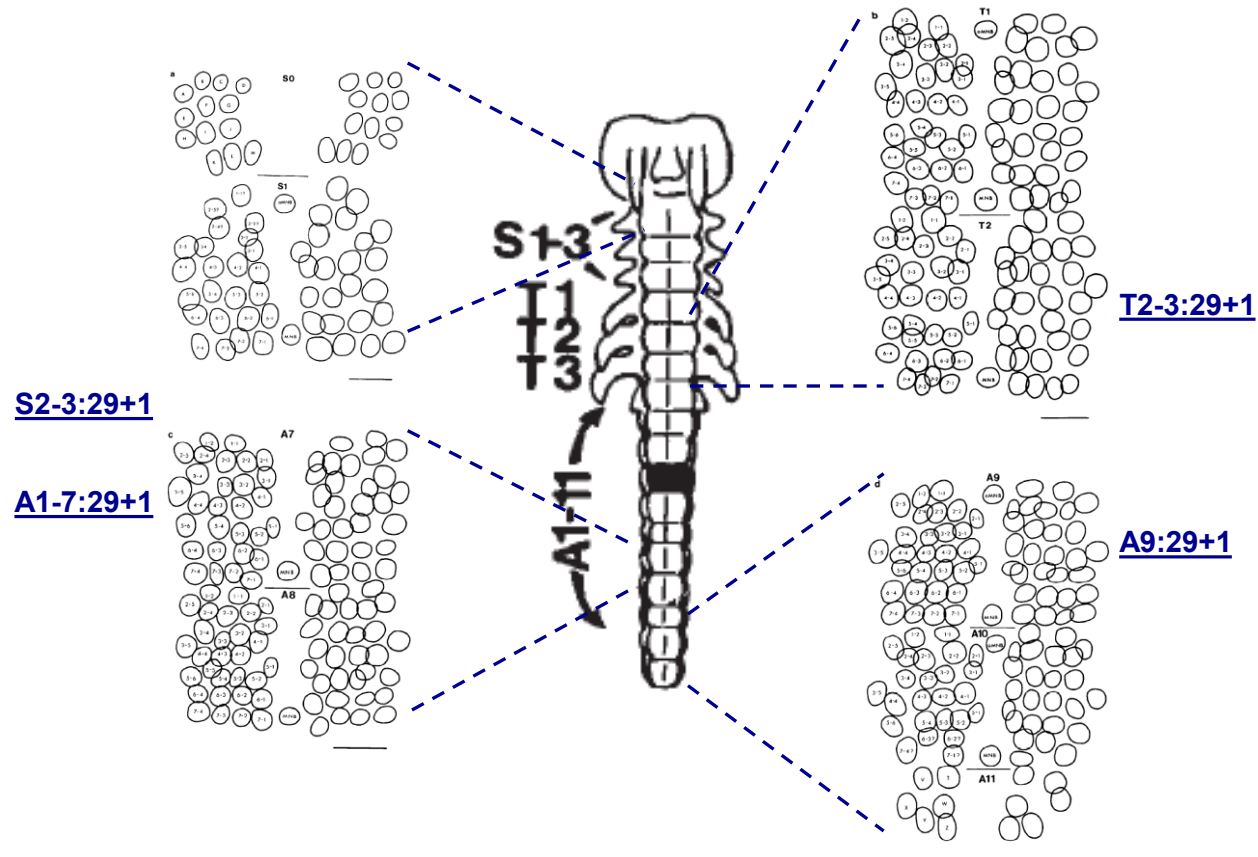


Doe & Goodman (1985)

Reproducible pattern

**29 Neuroblasts /
hemineuromeres**

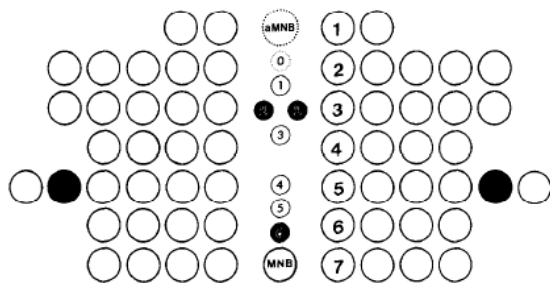
+ 1 median neuroblast



Revisiting *Orthoptera* early neurogenesis

Bate (1976) *Embryogenesis of an insect nervous system. I. A map of the thoracic and abdominal neuroblasts in Locusta migratoria*. *J Embryol Exp Morphol*. 35:107-123.

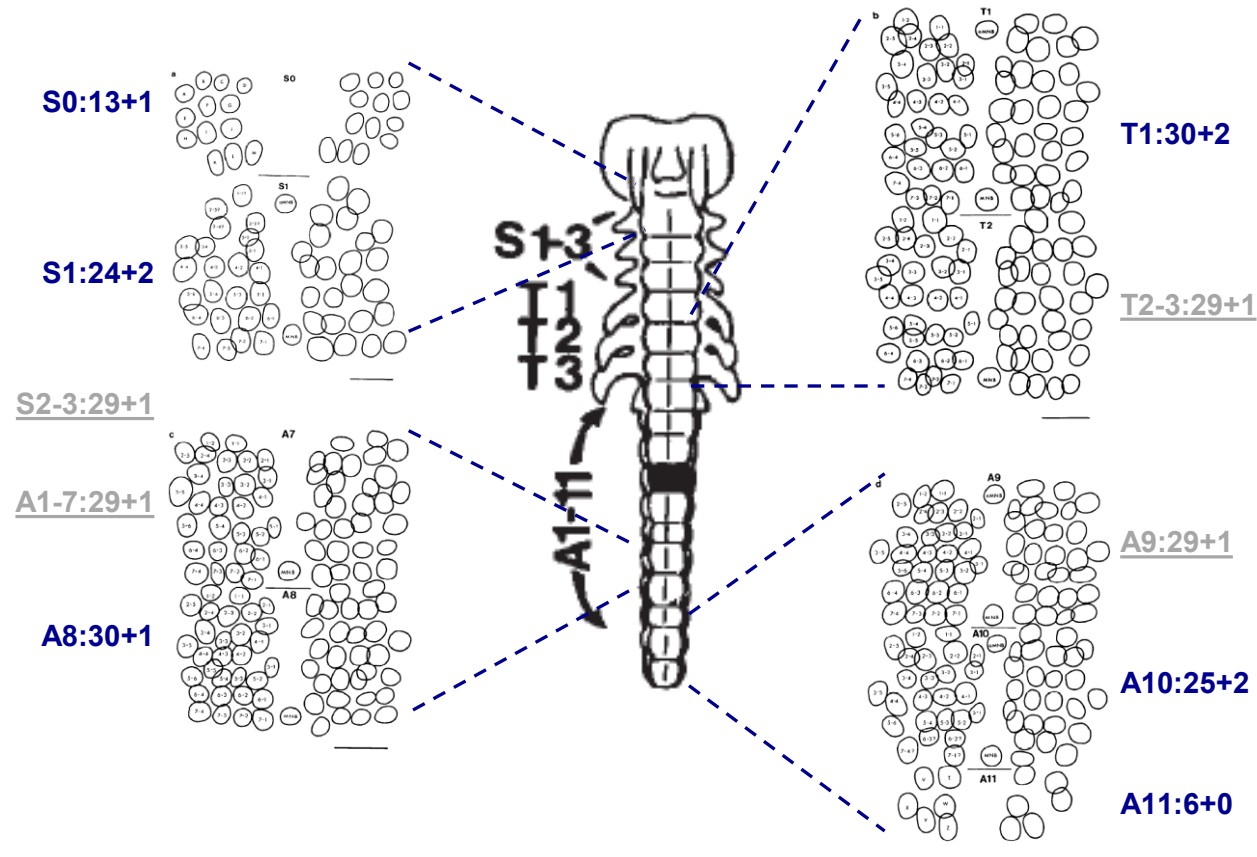
Live cell observation
with Nomarski optics



Doe & Goodman (1985)

Reproducible pattern

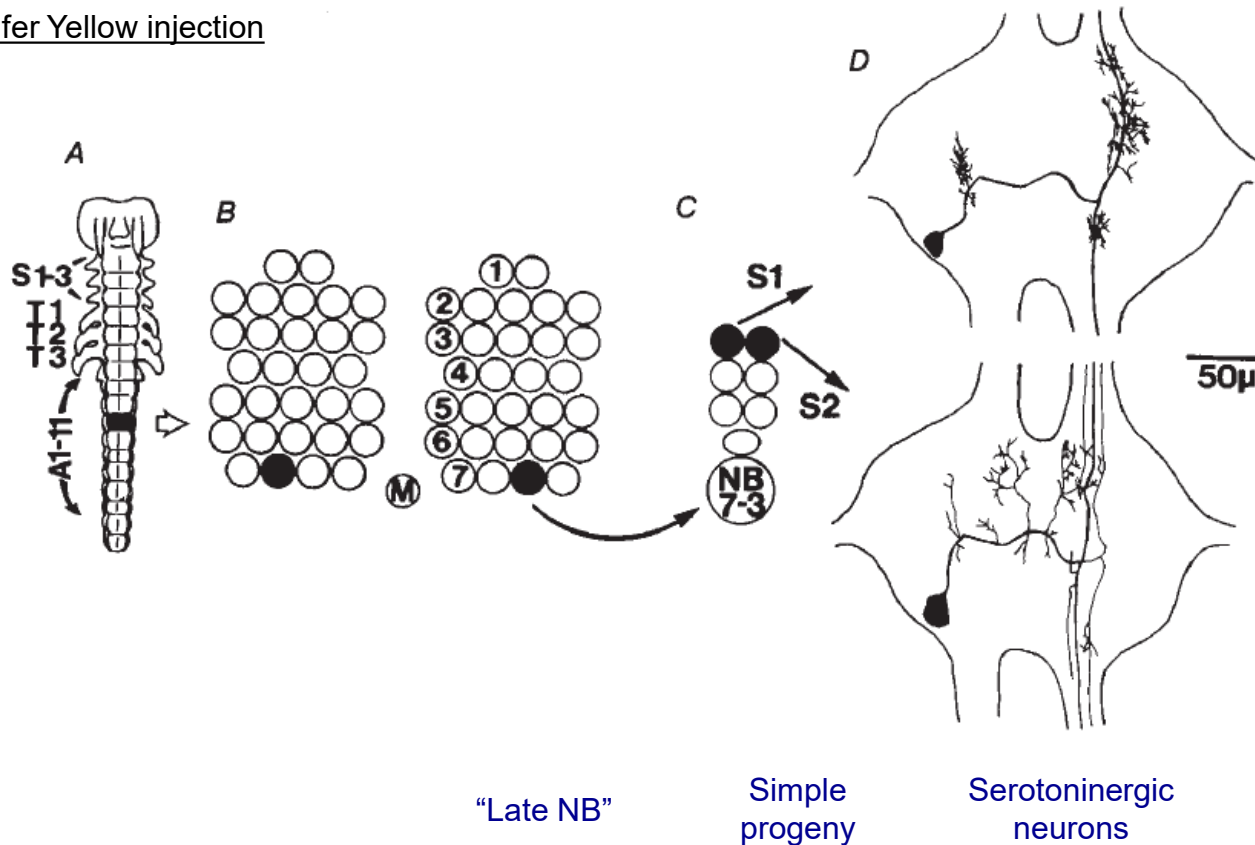
but segment specific



Revisiting *Orthoptera* early neurogenesis

Taghert et al. (1984) Cell determination and regulation during *development of neuroblasts and neurones in grasshopper embryo*. *Nature* 307:163-165.

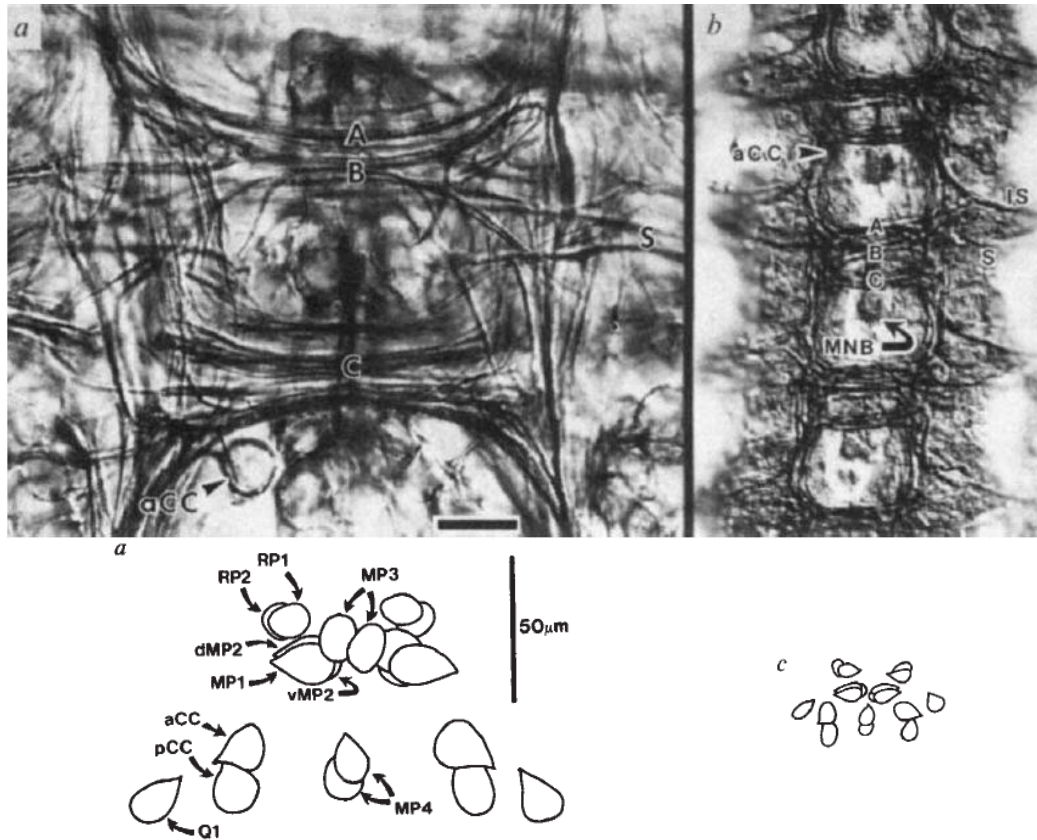
Lucifer Yellow injection



Sequential neuroblasts production and thus of neurons

Similarities between *Drosophila* and Orthoptera CNS

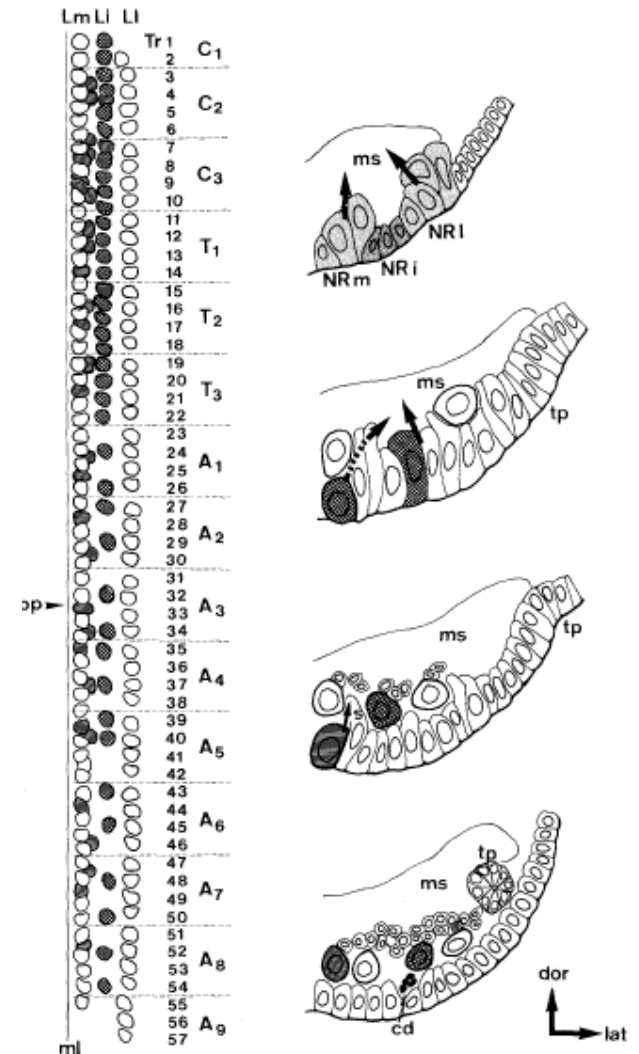
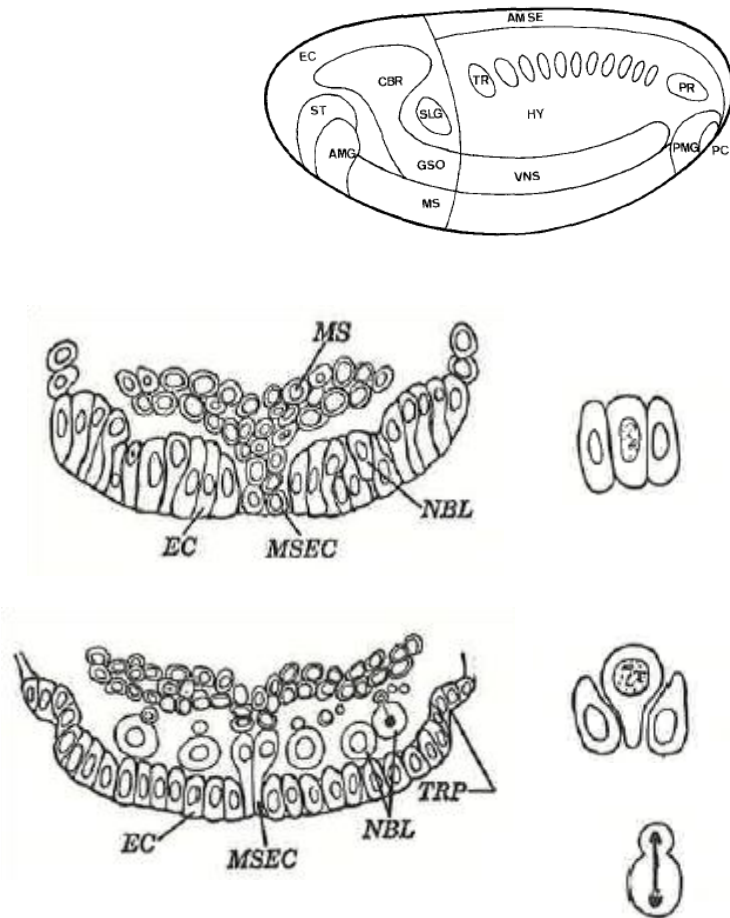
Thomas et al. (1984) *From grasshopper to Drosophila: a common plan for neuronal development.* Nature 310:203-207.



Thomas et al. (1984)

Development of *Drosophila* ventral nerve cord

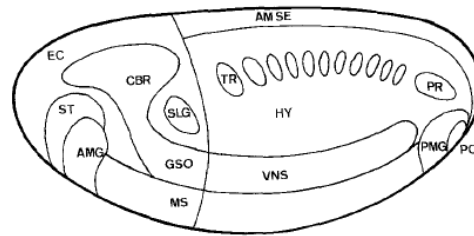
Poulson (1937) *The embryonic development of Drosophila melanogaster*. *Actualités sci. et ind.* 498:1-51.



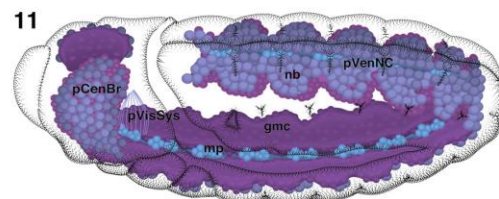
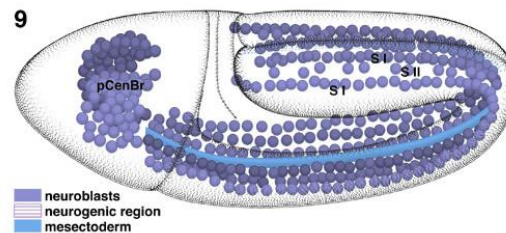
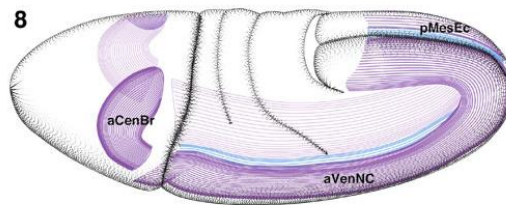
Adapted from Poulson (1950)

Hartenstein & Campos-Ortega (1984)

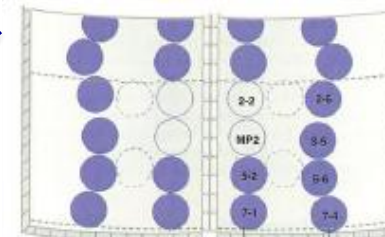
Revisiting *Drosophila* early neurogenesis



Doe (1992) Thoracic

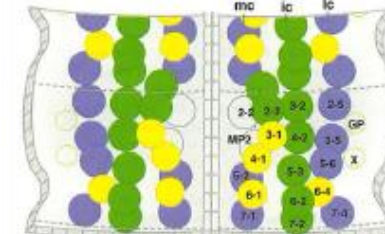


Hartenstein (1993)



Stade 9

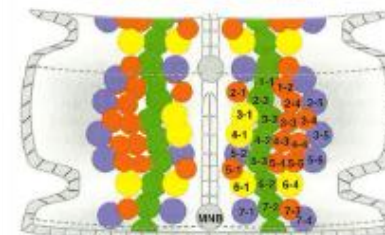
SI



Stade 10

SII

SIII

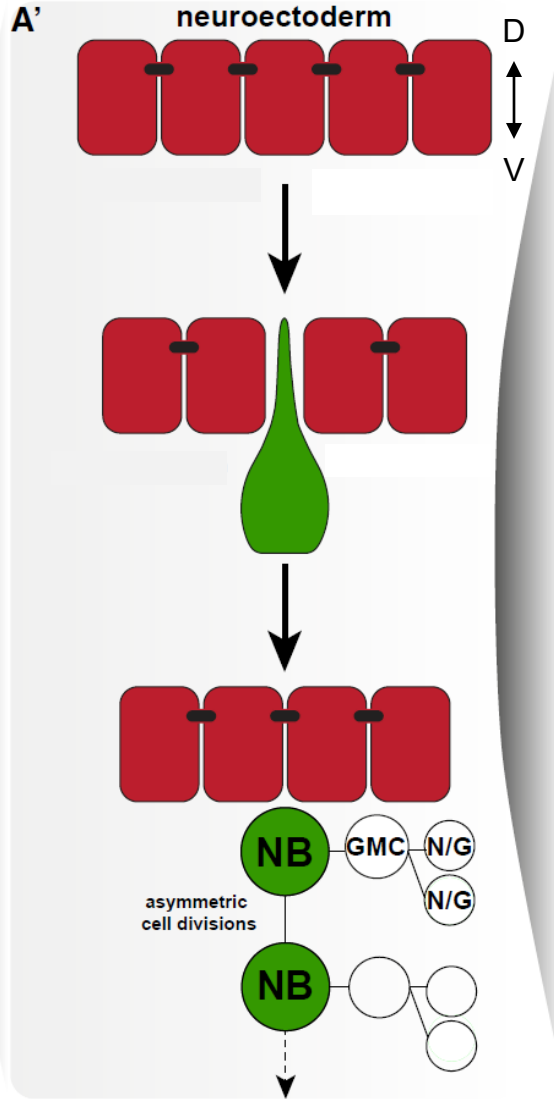
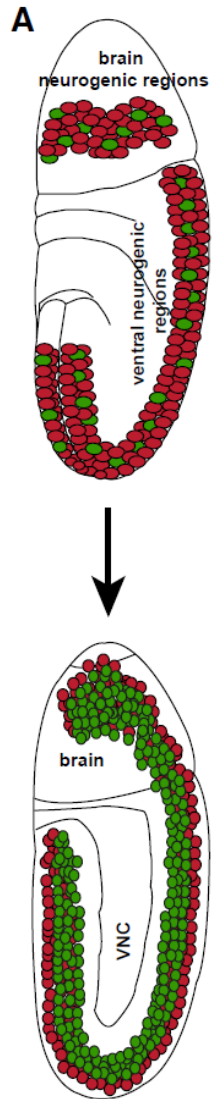


Stade 11

SIV-SV

Campos-Ortega & Hartenstein (1997)

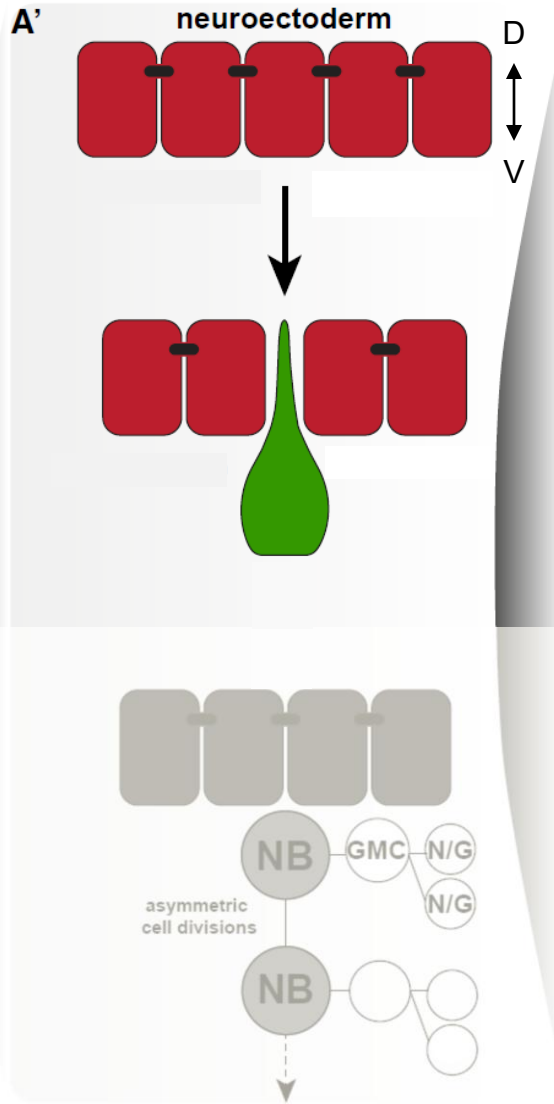
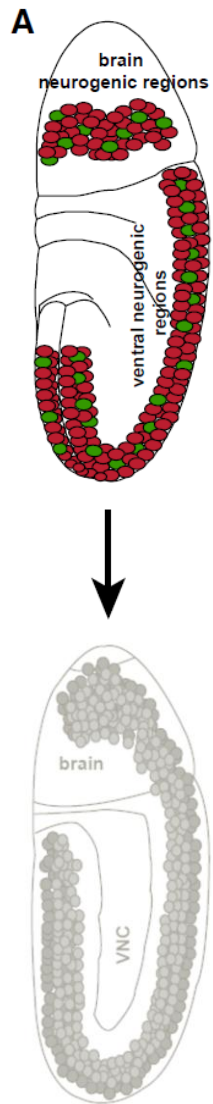
Some questions



➤ Neuroblast determination ?

➤ Neuronal diversity ?

Some questions



➤ Neuroblast determination ?

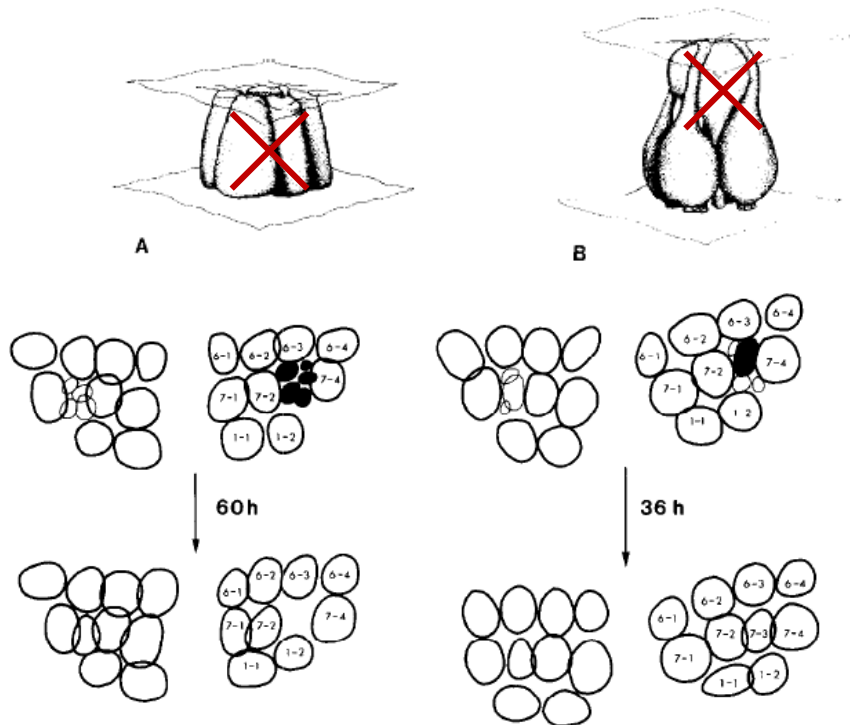
➤ Neuronal diversity ?

Orthoptera neuroblast determination

Taghert et al. (1984) *Cell determination and regulation during development of neuroblasts and neurones in grasshopper embryo*. Nature 307:163-165.

Doe and Goodman (1985) *Early events in insect neurogenesis II. The role of cell interactions and cell lineage in the determination of neuronal precursor cells*. Dev. Biol 111:206-219.

Cell ablation with a laser microbeam



Doe & Goodman (1985)

- Lineage determination

- A single neural cell is not determined

- Cluster determination

- Constitutes an equivalence group

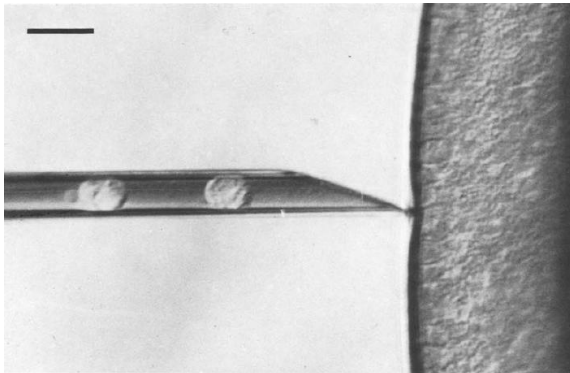
- Local inhibition - Lateral inhibition

Cell interactions ?

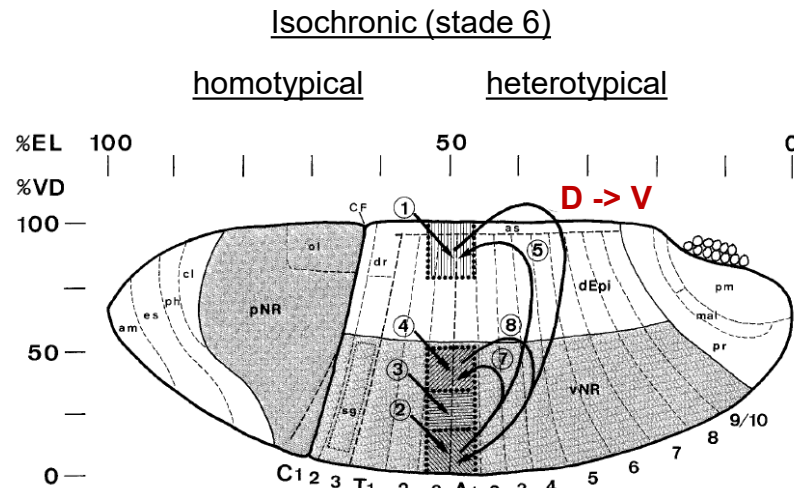
Cell determination in *Drosophila* embryos

Technau & Campos-Ortega (1986) Lineage analysis of *transplanted* individual cells in embryos of *Drosophila melanogaster* II. *Commitment* and proliferative capabilities of neural and epidermal cell progenitors. *Roux's Arch Dev Biol* 195:445-454.

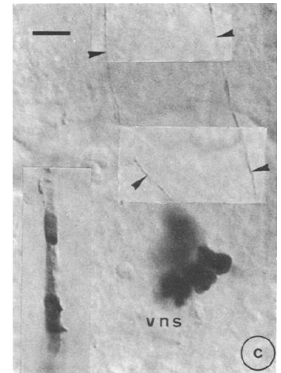
Individual transplantations
of marked cells (HRP)



Technau (1986)



Technau & Campos-Ortega (1986)



- **Determination : . positional** (D/V)



**Positional
information**

. **non-cell-autonomous**

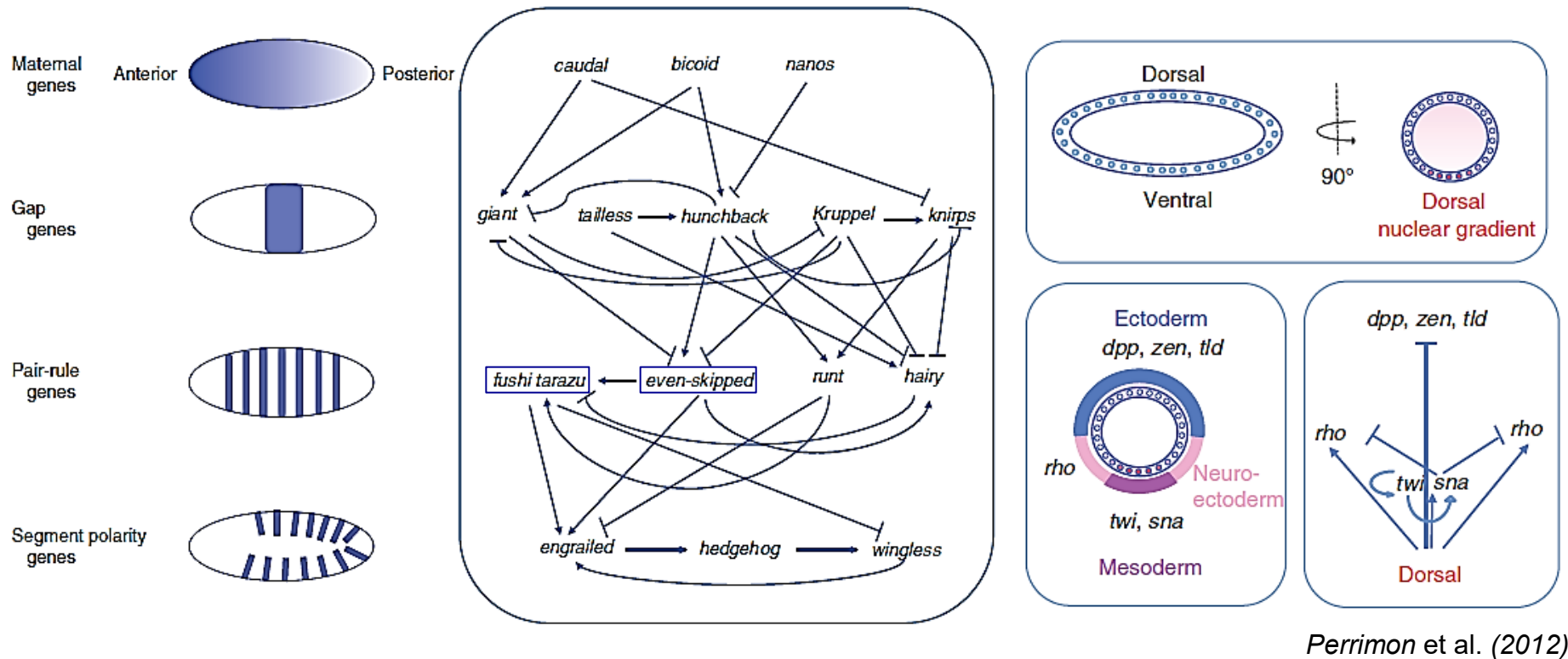


Cell interactions

Genetics of *Drosophila* embryogenesis

Zalokar & Erk (1977) Phase-partition fixation and staining of *Drosophila* eggs. *Stain Technol.* 52:89-95.

*Nüsslein-Vohldard & Wieschaus (1980) Mutations affecting segment number and polarity in *Drosophila*. *Nature* 287:795-801.*



Perrimon et al. (2012)

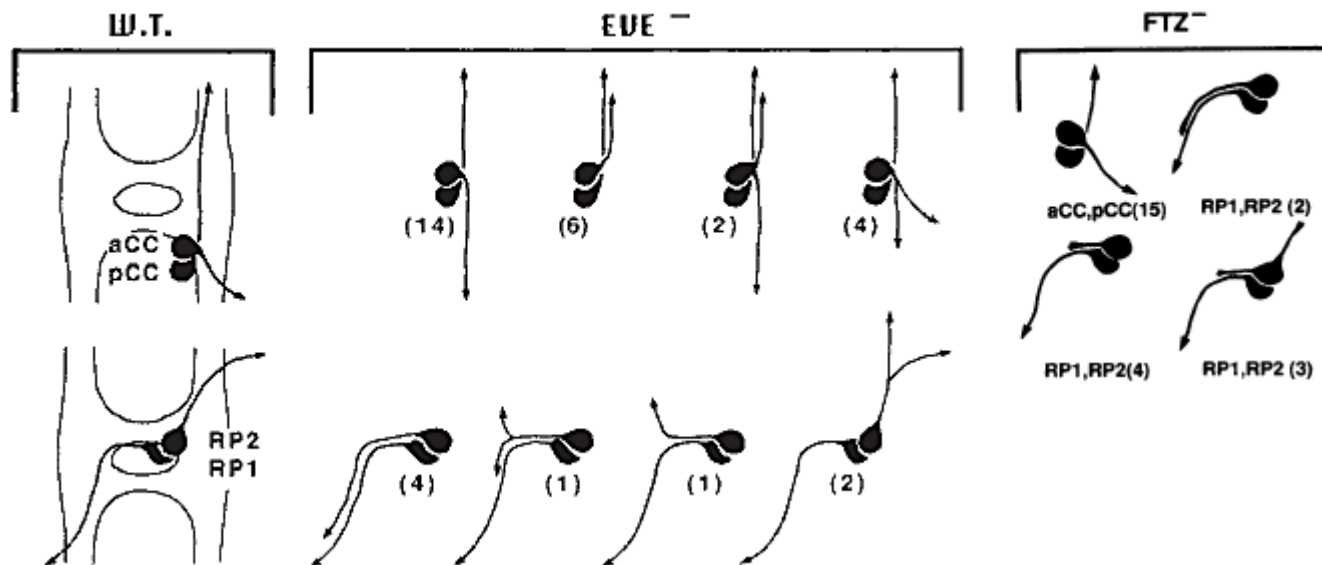
➤ Row

➤ Column

Drosophila neurogenetics

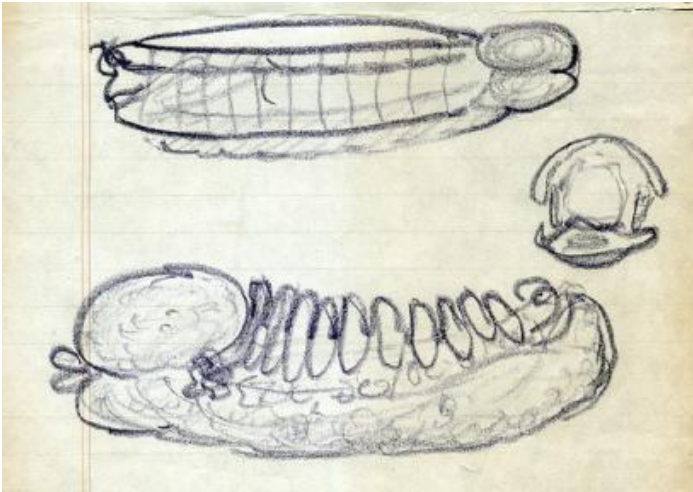
Doe, Smouse & Goodman (1988) Control of neuronal fate by the *Drosophila* segmentation gene even-skipped. *Nature* 333:376-378.

Doe et al. (1988) Expression and function of the segmentation gene fushi tarazu during *Drosophila* neurogenesis. *Science* 239:170-175.

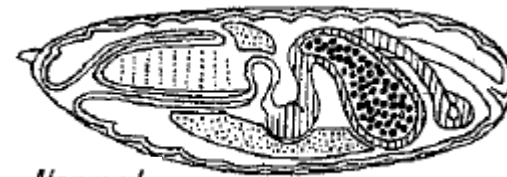


Drosophila neurogenetics

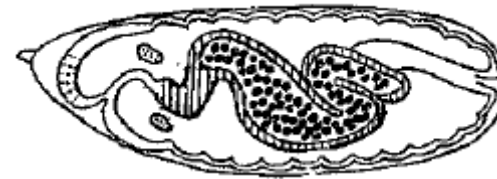
Ede (1956) Studies on the effects of some *genetic* lethal factors on the embryonic *development* of *Drosophila melanogaster*. IV. An analysis of the mutant X 20. Roux's Arch. Dev. Biol. 149:101-114.



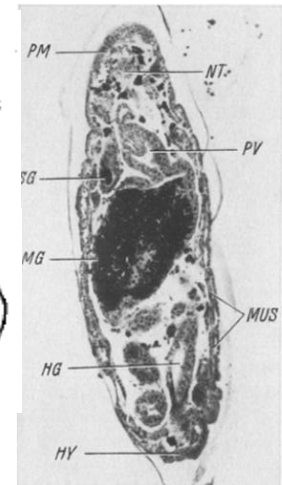
Knust & Hertel (2009)



Normal



Mutant X20 type II.



Ede (1956)

- CNS hyperplasia
- Epidermis hypoplasia

[neurogenic]

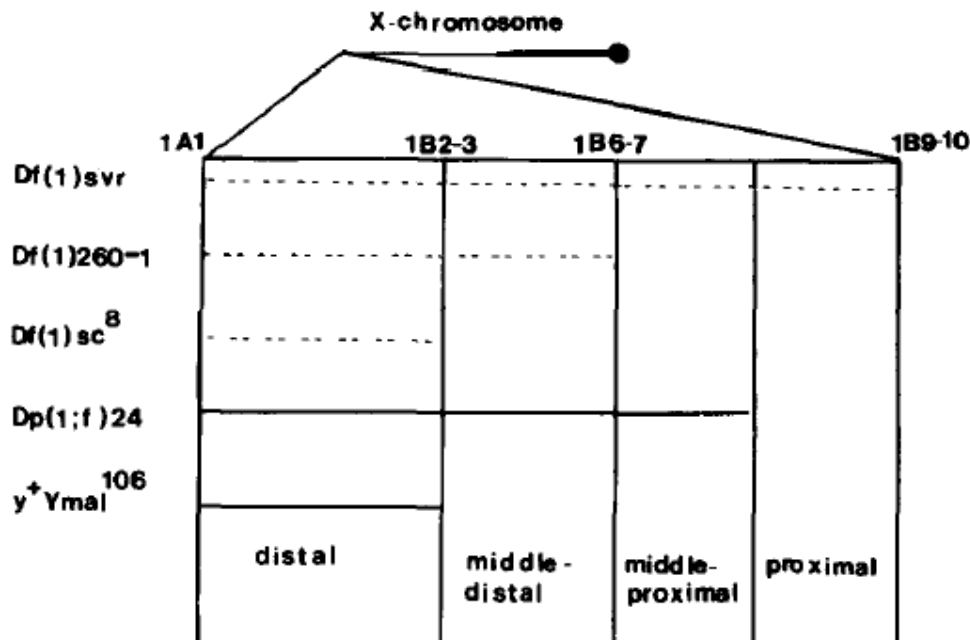
- CNS hypoplasia
- Epidermis hyperplasia

[proneural]

An interesting genomic region

Jimenez & Campos-Ortega (1979) A region of the *Drosophila* genome *necessary for CNS development*. *Nature* 282:310-312.

White (1980) *Defective neural development in Drosophila melanogaster embryos deficient for the tip of the X Chromosome*. *Dev. Biol.* 80:332-344.



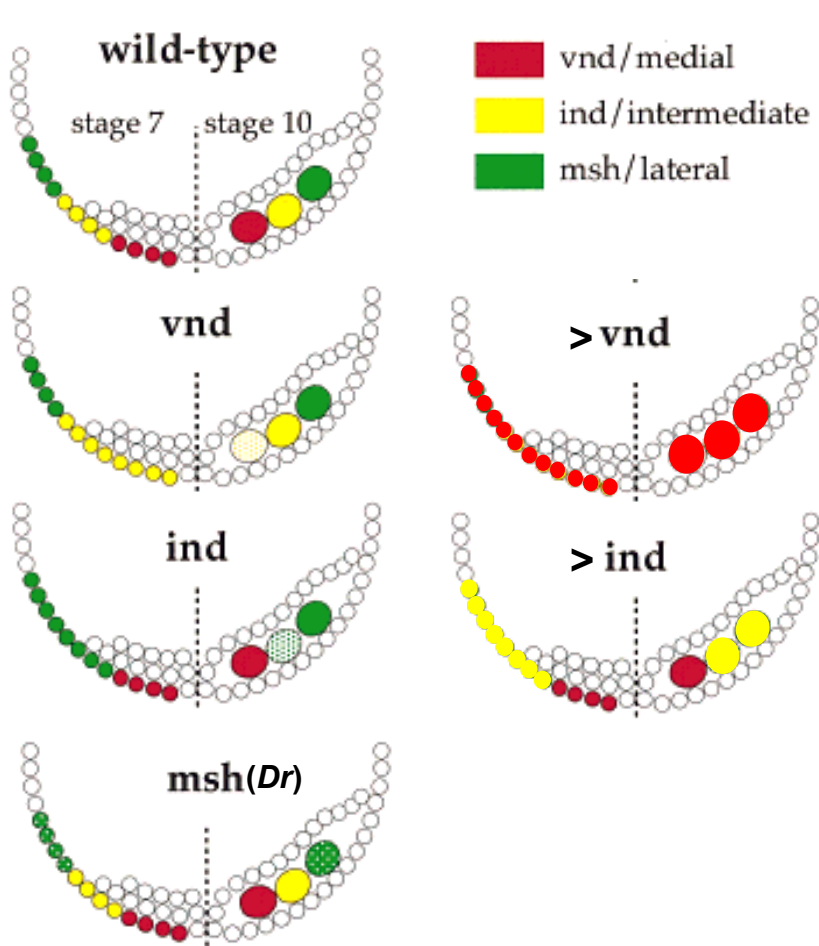
White (1980)

Jimenez & Campos-Ortega (1979)

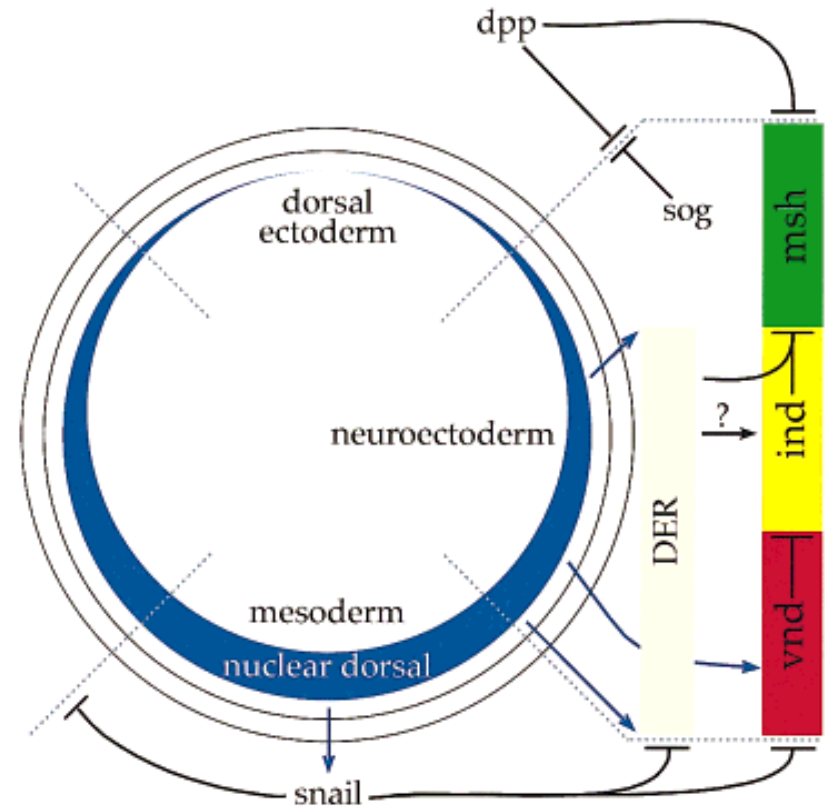
vnd

ventral nervous system defective

Columnar patterning

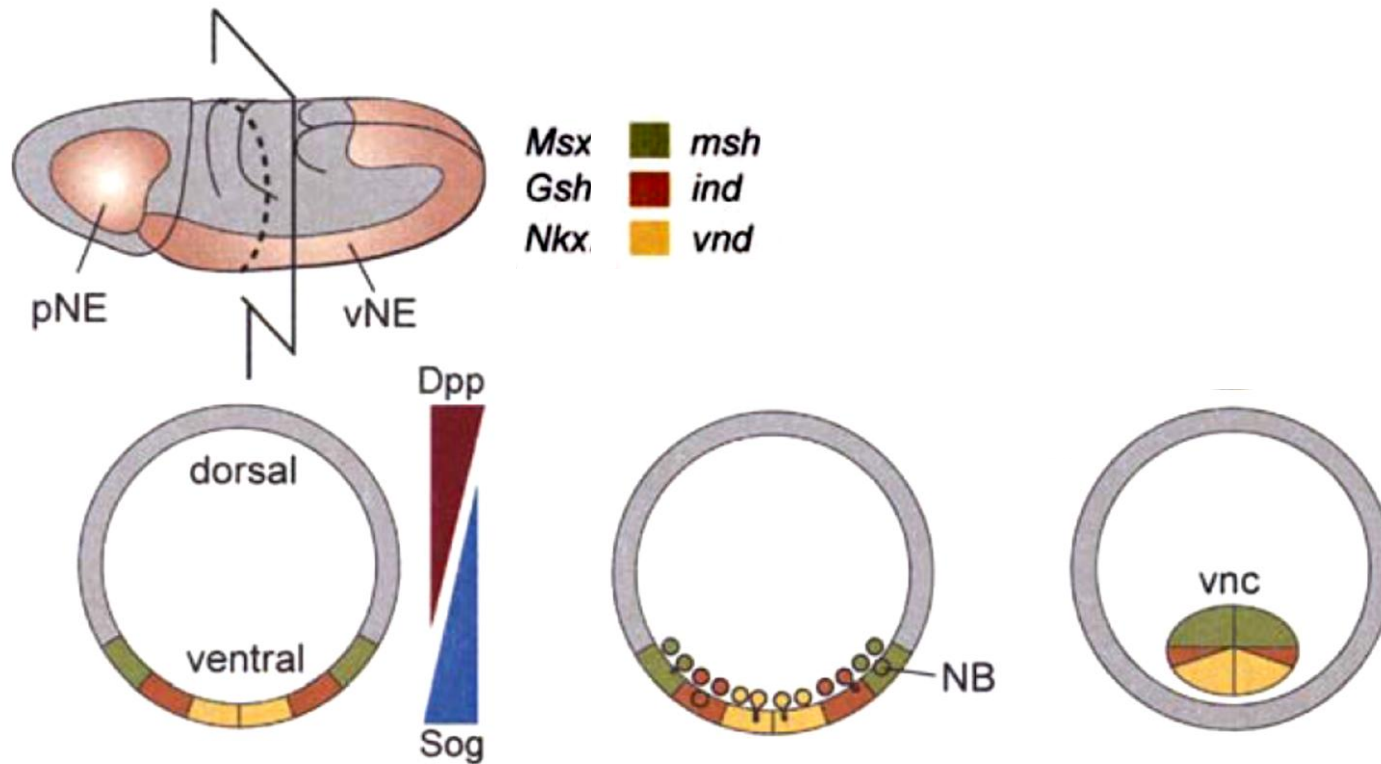


Adapted from Skeath (1999)



Skeath (1999)

Columnar patterning



Adapted from Urbach & Technau (2008)

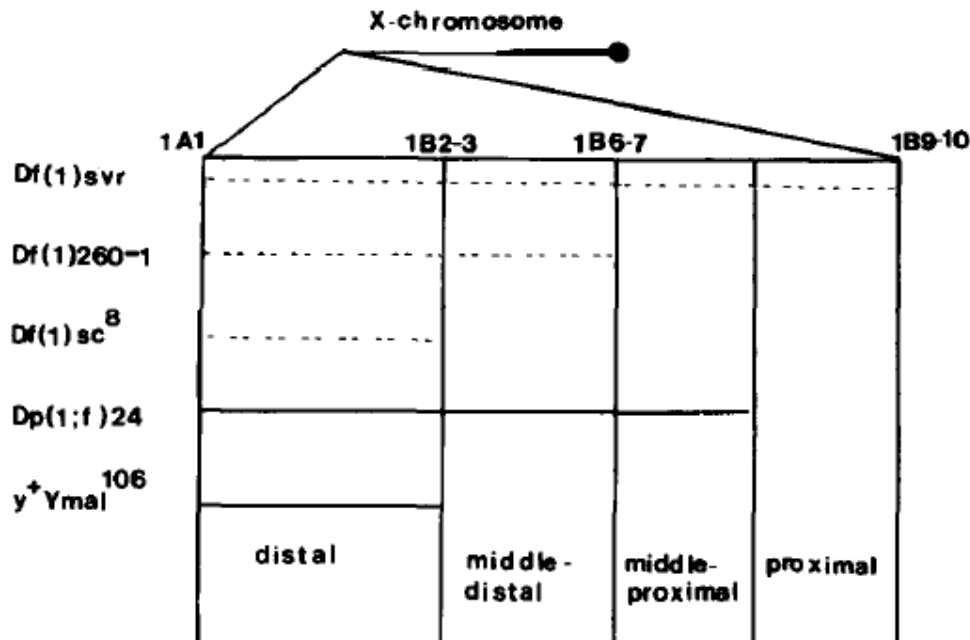


Positional information

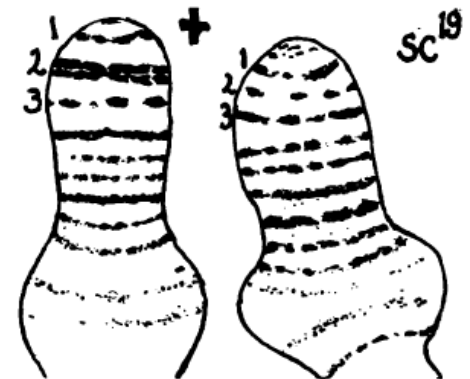
The *achaete-scute* (AS-C) gene complex

Jimenez & Campos-Ortega (1979) A region of the *Drosophila* genome *necessary for CNS development*. *Nature* 282:310-312.

White (1980) *Defective neural development in Drosophila melanogaster embryos deficient for the tip of the X Chromosome*. *Dev. Biol.* 80:332-344.



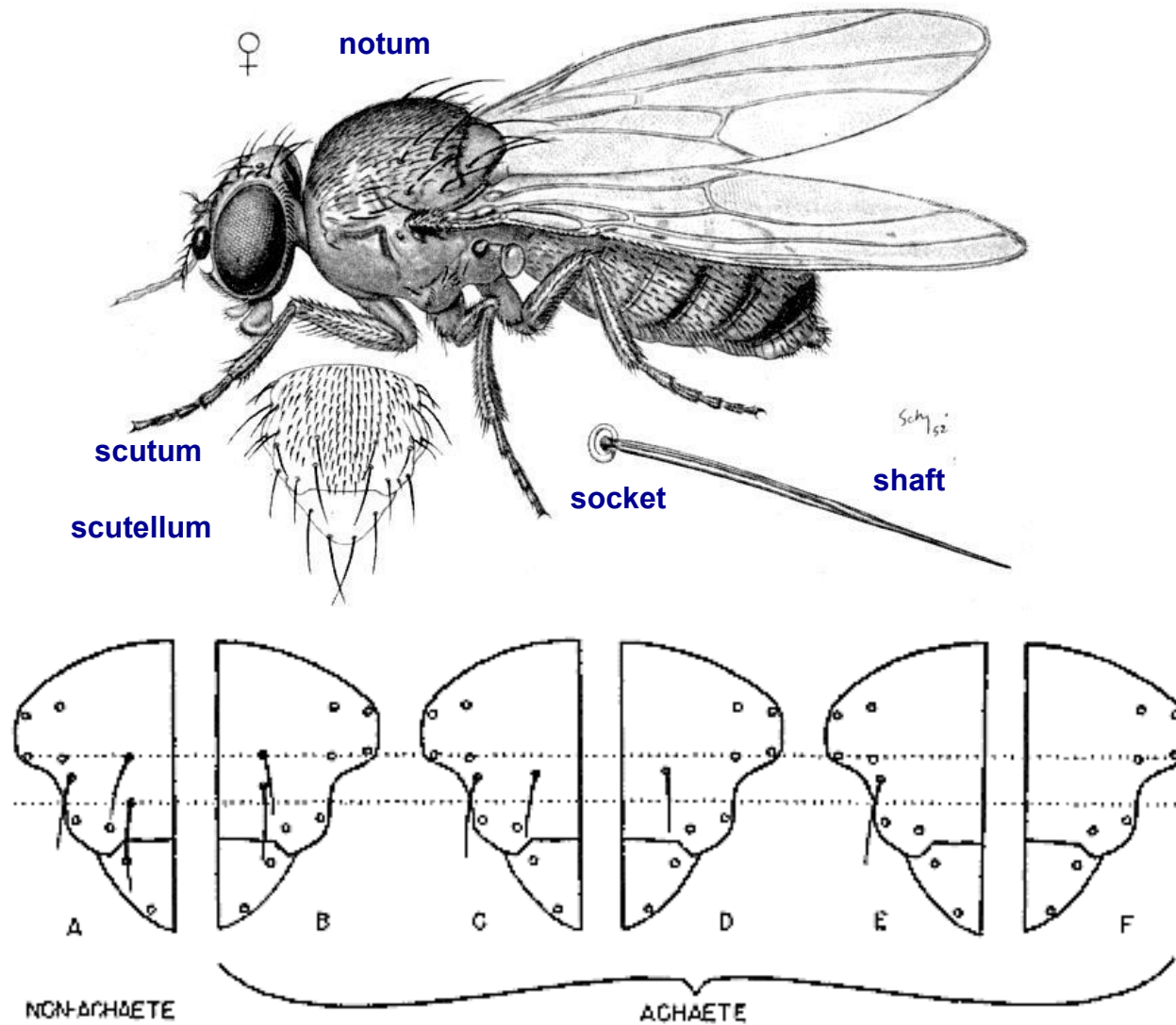
White (1980)



Müller & Prokofyeva (1935)

**achaete
- scute**

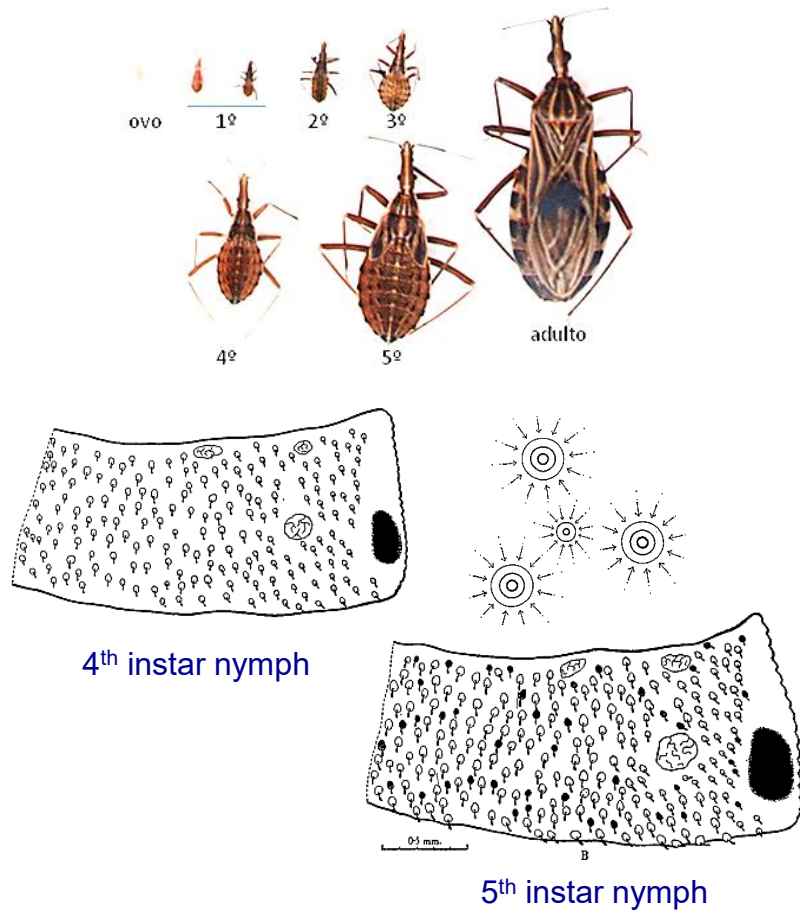
The *achaete-scute* (AS-C) gene complex



Similarities between PNS & CNS

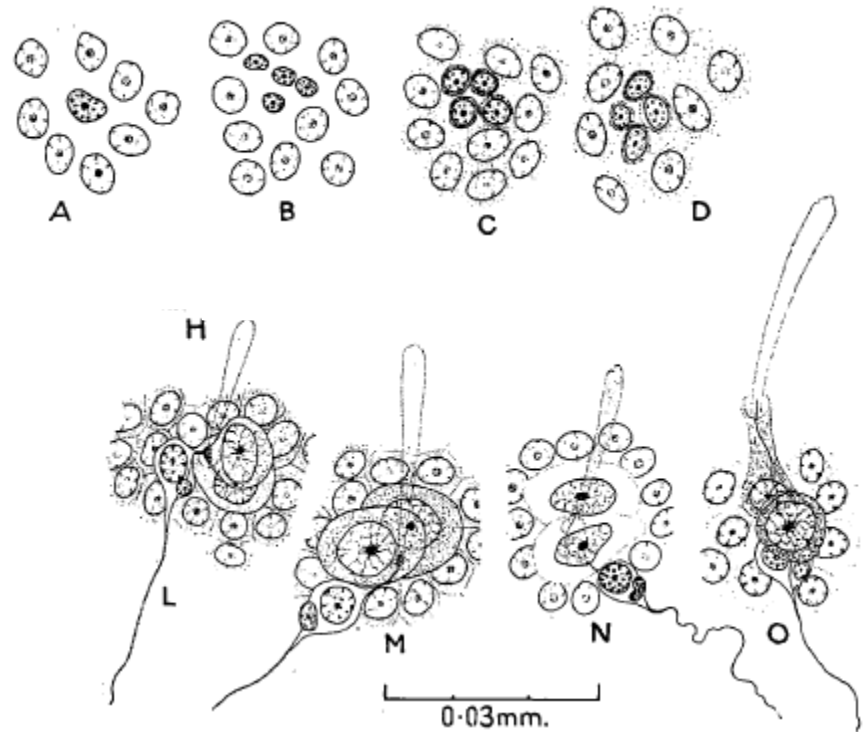
Wigglesworth (1940) *Local and general factors in the development of "pattern" in Rhodnius prolixus (Hemiptera).* *J.Exp. Biol.* 17:180-200.

- Lateral inhibition**



Adapted from Wigglesworth (1940)

- A single precursor cell per organ (equivalence groupe)**



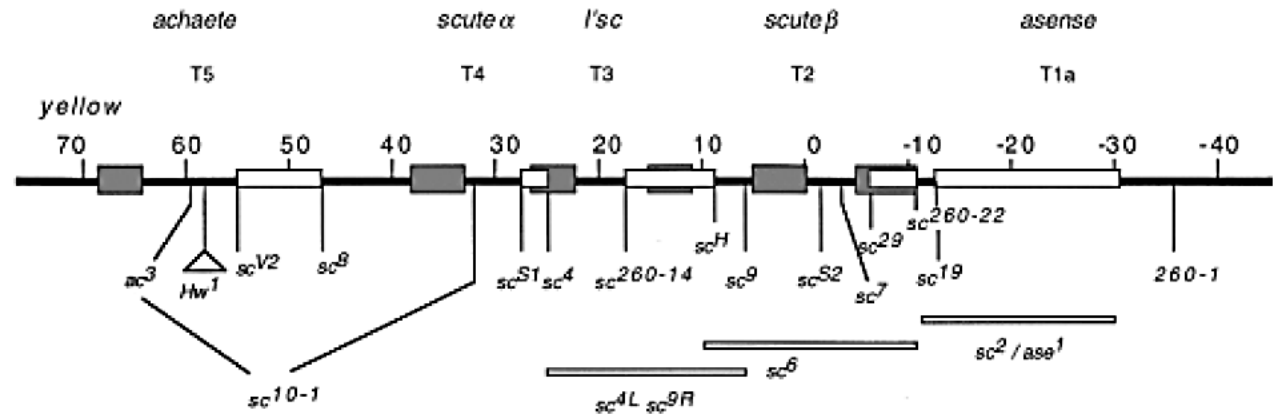
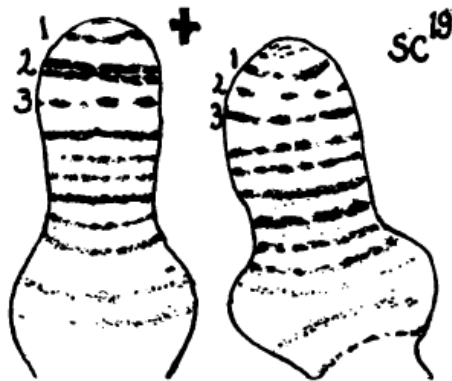
Adapted from Wigglesworth (1953)

Cloning of the *achaete-scute* gene complex

Carramolino et al. (1982) *DNA map of mutations at the scute locus of Drosophila melanogaster*. *Cell* 40:327-338.

Campuzano et al. (1985) *Molecular genetics of the achaete-scute gene complex of D. melanogaster*. *Cell* 40:327-338.

Positional cloning & Chromosomal walk



Müller & Prokofyeva (1935)

cDNA libraries screening & Sequencing

Campos-Ortega (1998)

Villares & Cabrera (1987) *The achaete-scute gene complex of Drosophila melanogaster: conserved domains in a subset of genes required for neurogenesis and their homology to myc*. *Cell* 50:415-424.

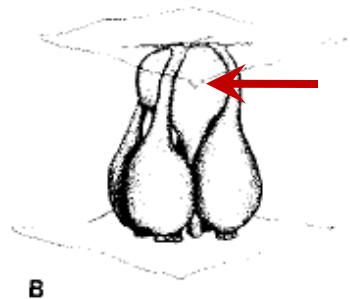
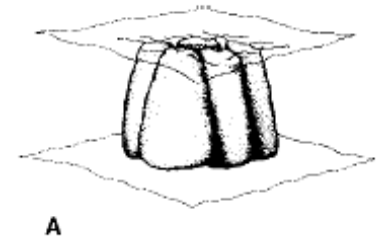
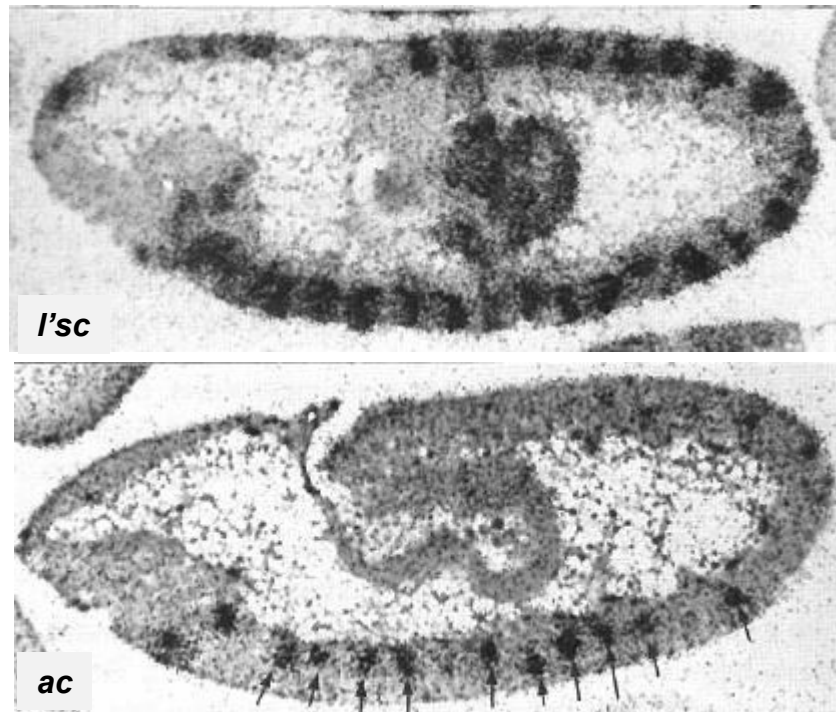
Alonso & Cabrera (1988) *The achaete-scute gene complex of Drosophila melanogaster comprises four homologous genes*. *EMBO J.* 7:2585-2591.

basic Helix-Loop-Helix (bHLH) transcription factors

Expression of AS-C genes

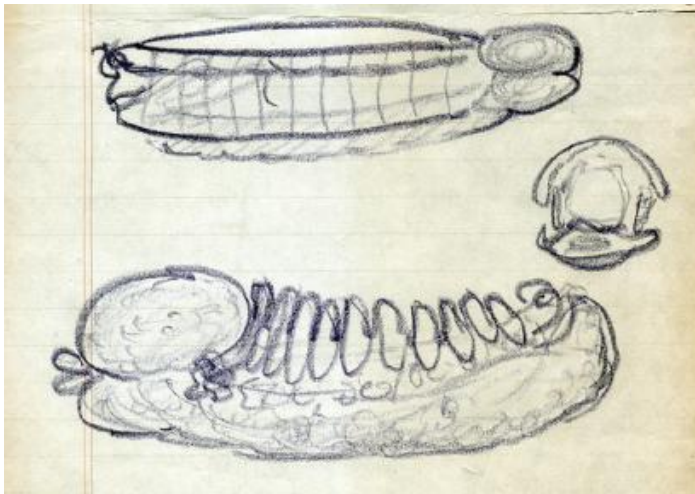
Cabrera et al. (1987) *The expression of three members of the achaete-scute gene complex correlates with neuroblast segregation in Drosophila. Cell 50:425-433.*

In situ hybridization of sections with radioactive probes



Expression in neurogenic genes ?

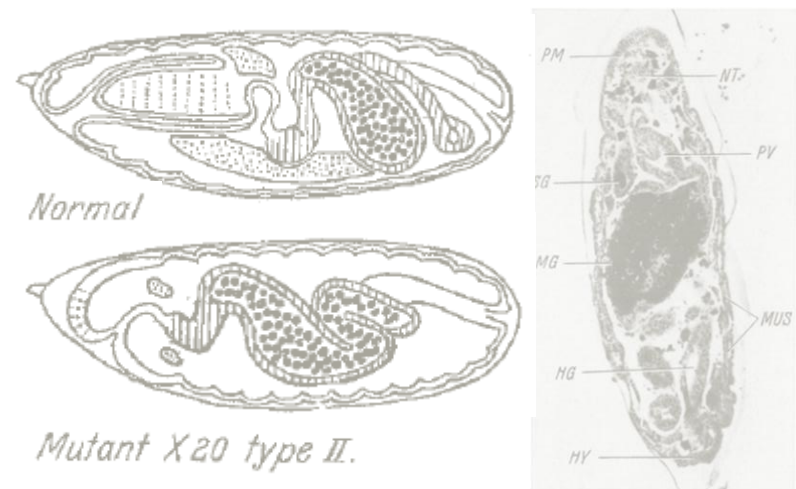
Poulson (1937) *Chromosomal deficiencies and the embryonic development of Drosophila melanogaster*.
Proc. Natl Acad. Sci. USA 23:133-137.



Knust & Hertel (2009)

- CNS hyperplasia
- Epidermis hypoplasia

[neurogenic]



Ede (1956)

- CNS hypoplasia
- Epidermis hyperplasia

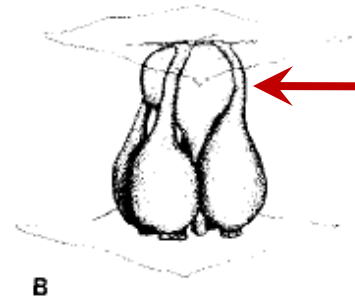
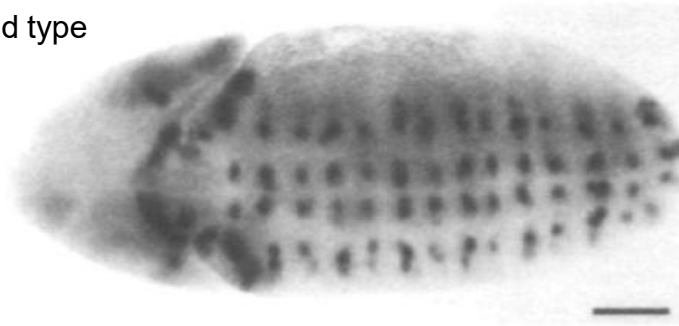
[proneural]

Regulation of the AS-C expression by neurogenic genes ?

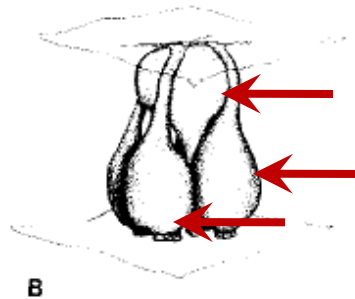
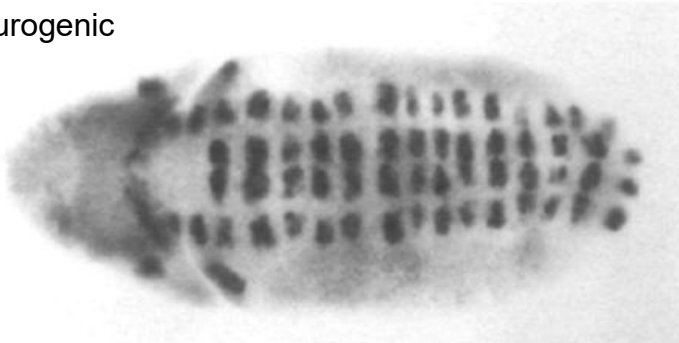
Skeath & Carroll (1992) *Regulation of proneural gene expression and cell fate during neuroblast segregation in the Drosophila embryo. Development* 50:939-946.

Immunodetections anti-Ac

Wild type



neurogenic



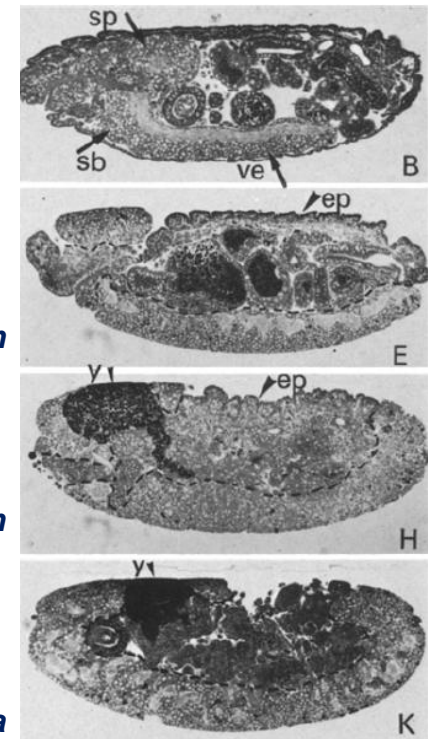
The neurogenic genes

Lehmann et al. (1981) *Mutations of early neurogenesis in Drosophila*.
Roux's Arch. Dev. Biol. 190:226-229

Lehmann et al. (1983) *On the phenotype and development of mutants of early neurogenesis in Drosophila melanogaster*. Wilhelm Roux's Archives 192:62-74

	Complementation groups	Extreme phenotype
(Poulson)	Notch (<i>N</i>)	FX1,FX2,FX3,FX4,FX5,FX6,FX7,FX8,FX9,FE1,FE2,8,264-39,264-40,264-105,264-47,69h9,55e11
(1983)	almondex (<i>amx</i>)	1
	big brain (<i>bib</i>)	
	master mind (<i>mam</i>)	
	neuralised (<i>neu</i>)	IF65,IIIA83,IN94,11B116,9L119,12H56
	Delta (<i>DI</i>)	9P39,IL79N,9D27,5F102,9M46,ru-41,E50-2,FE1,FE2,FE3,FE7,FE9,FE17,FE26,FX1,FX4,FX5,FX6,XTÜ1,X43,PX,FX2,FX3,FX7,roeXM3,X18,FX8,roe,6B37 (at 29° C)
(1983)	Enhancer of split <i>E(spl)</i>	R1,R2,R3

Lehmann et al. (1983)



Notch

big brain

Delta

Lehmann et al., 1981

(Wieschaus, Nüsslein-Vohldard, EMS)

The *Enhancer of split* locus

Knust et al. (1987) *The Enhancer of split locus and neurogenesis in Drosophila melanogaster*.
Dev. Biol. 122:262-273.

Gain of function allele of *E(spl)*

[proneural]

Cell autonomous
dermoblast



Adapted from de la Concha et al. (1988)

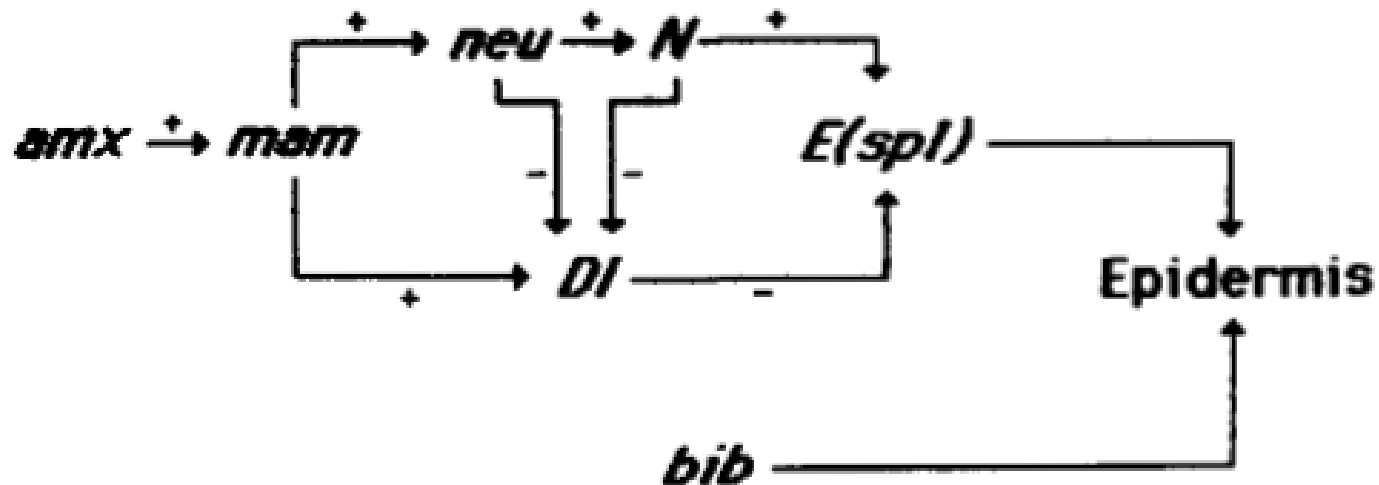
Epistasis of neurogenic genes

de la Concha et al. (1988) *Functional interactions of neurogenic genes of Drosophila melanogaster*.
Genetics 118:499-508.

(Dp, homozygous mt)

Non-cell autonomous
neuroblast

Cell autonomous
dermoblast



Adapted from de la Concha et al. (1988)

➤ Lateral inhibition signaling pathway

Notch cloning

Positional cloning & Chromosomal walk

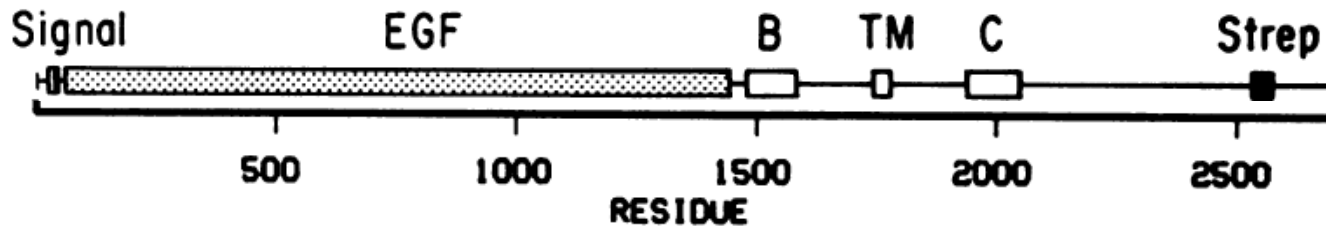
Artavanis-Tsakonas et al. (1983) *Molecular cloning of Notch, a locus affecting neurogenesis in Drosophila. Proc. Natl Acad. Sci. USA 80:1977-1981.*

Kidd et al. (1983) *The Notch locus of Drosophila melanogaster. Cell 34:421-433.*

cDNA libraries screening & Sequencing

Wharton et al. (1985) *Nucleotide sequence from the neurogenic locus Notch implies a gene product that shares homology with proteins containing EGF-like repeats. Cell 43:567-581.*

Kidd et al. (1987) *Sequence of the Notch locus of Drosophila melanogaster: relationship of the encoded protein to mammalian clotting and growth factors. Mol. Cell. Biol. 6:3094-3108.*



Kidd et al. (1987)

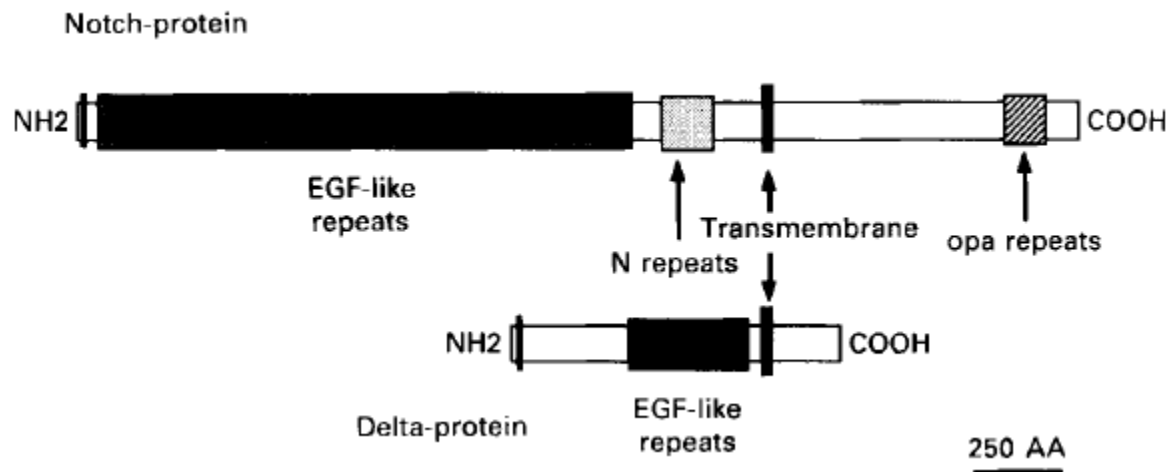
Delta cloning

Vässin et al. (1987) *The neurogenic gene Delta of Drosophila melanogaster is expressed in neurogenic territories and encodes a putative transmembrane protein with EGF-like repeats.* EMBO J. 6:3431-3440.

Kopczynski et al. (1988) *Delta, a Drosophila neurogenic gene, is transcriptionally complex and encodes a protein related to blood coagulation factors and epidermal growth factor of vertebrates.* Genes Dev. 2:1723-1735.

Positional cloning & Chromosomal walk

cDNA libraries screening & Sequencing



Knust & Campos-Ortega (1989)

➤ **extracellular interactions**

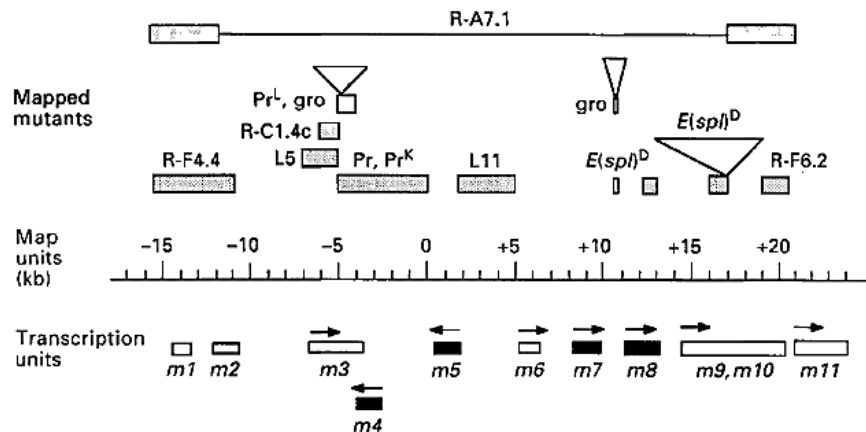
***E(spl)* complex cloning**

Knust et al. (1987) Molecular analysis of the neurogenic locus Enhancer of split of Drosophila melanogaster. EMBO J. 6:4113-4123.

Preiss et al. (1988) The molecular genetics of Enhancer of split, a gene required for embryonic neural development in Drosophila. EMBO J. 7:3917-3927.

Hartley et al. (1988) A deduced gene product from the Drosophila neurogenic locus, Enhancer of split, shows homology to mammalian G-protein beta subunit. Cell 55:785-795.

Klämbt et al. (1989) Closely related transcripts encoded by the neurogenic gene complex Enhancer of split of Drosophila melanogaster. EMBO J. 8:203-210.



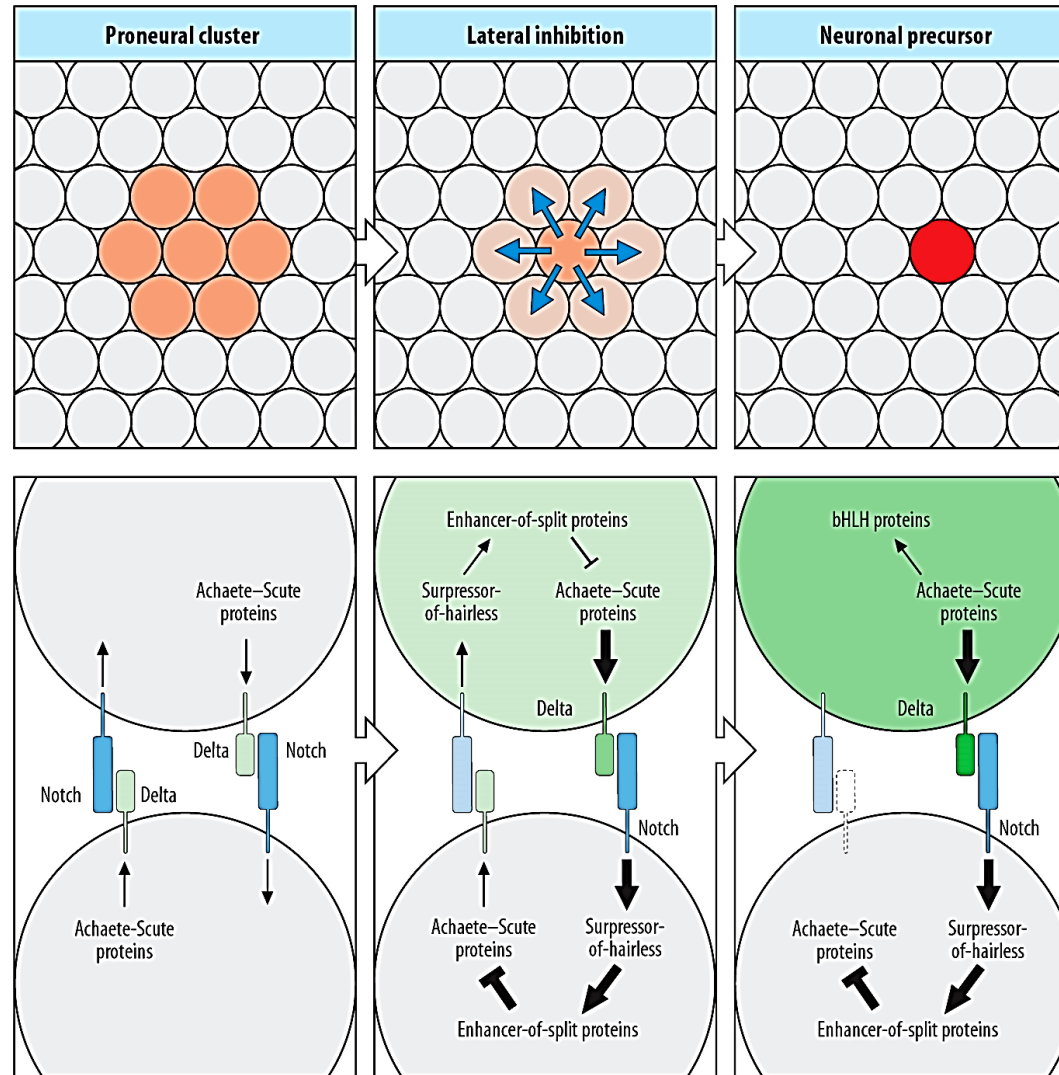
***m3, m5, m7, m8*
encode**

bHLH transcription factors

Knust & Campos-Ortega (1989)

Notch signaling pathway & lateral inhibition

Stochastic event



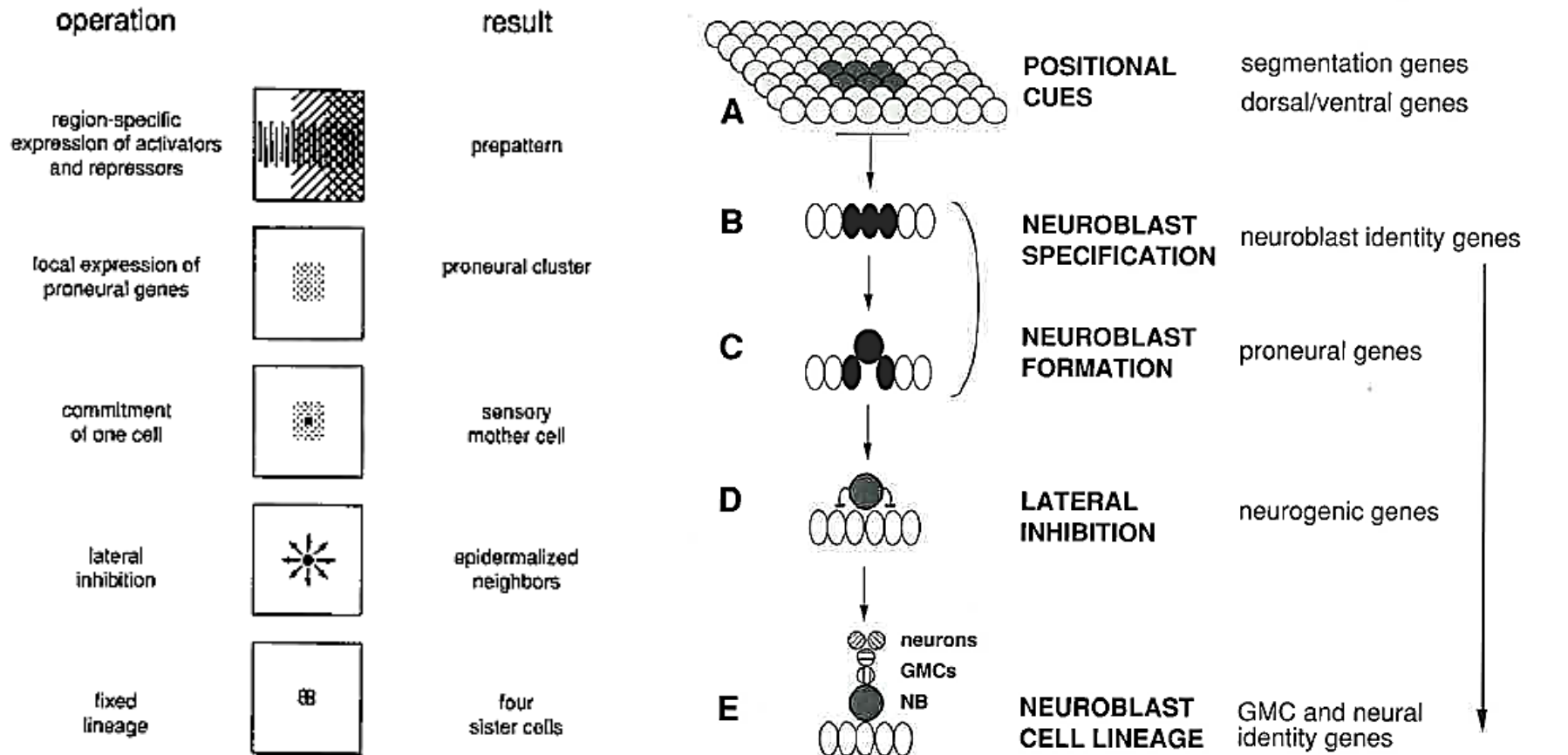
Notch OFF

Notch ON

Wolpert (2002)

A common model for *Drosophila* neurogenesis

Ghysen & Dambly-Chaudiere (1989) *Genesis of the Drosophila peripheral nervous system*.
Trends Genet. 5:251-5.



Ghysen & Dambly-Chaudiere (1989)

Goodman & Doe (1993)

A revised model for embryonic neurogenesis

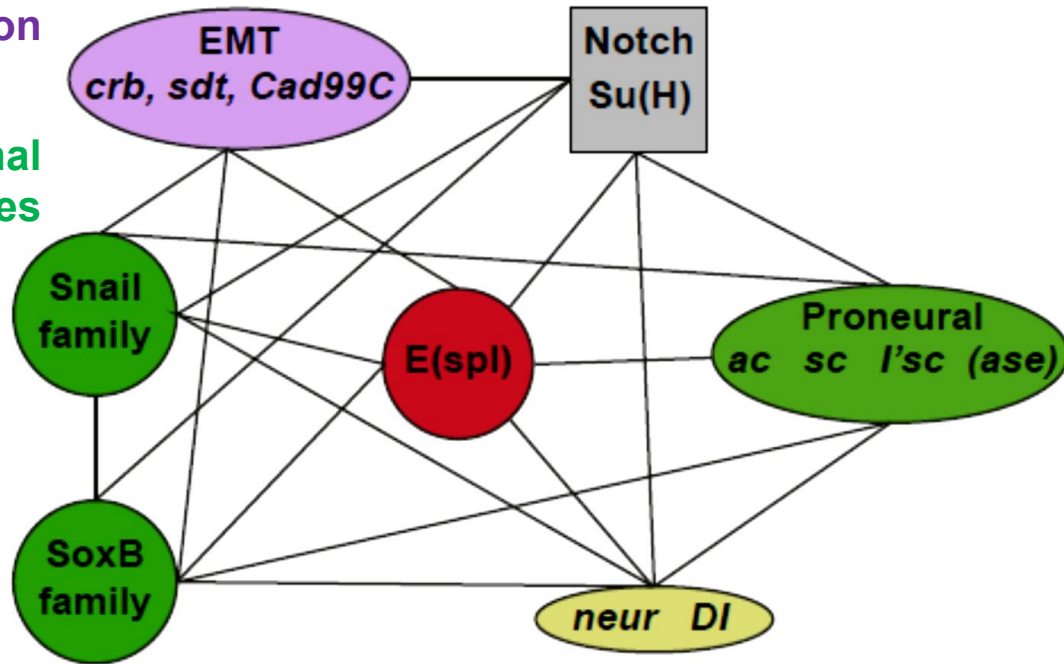
expanded interactions based upon
DNA-binding and transcriptome

Epithelial-mesenchymal
transition

Additional
proneural genes

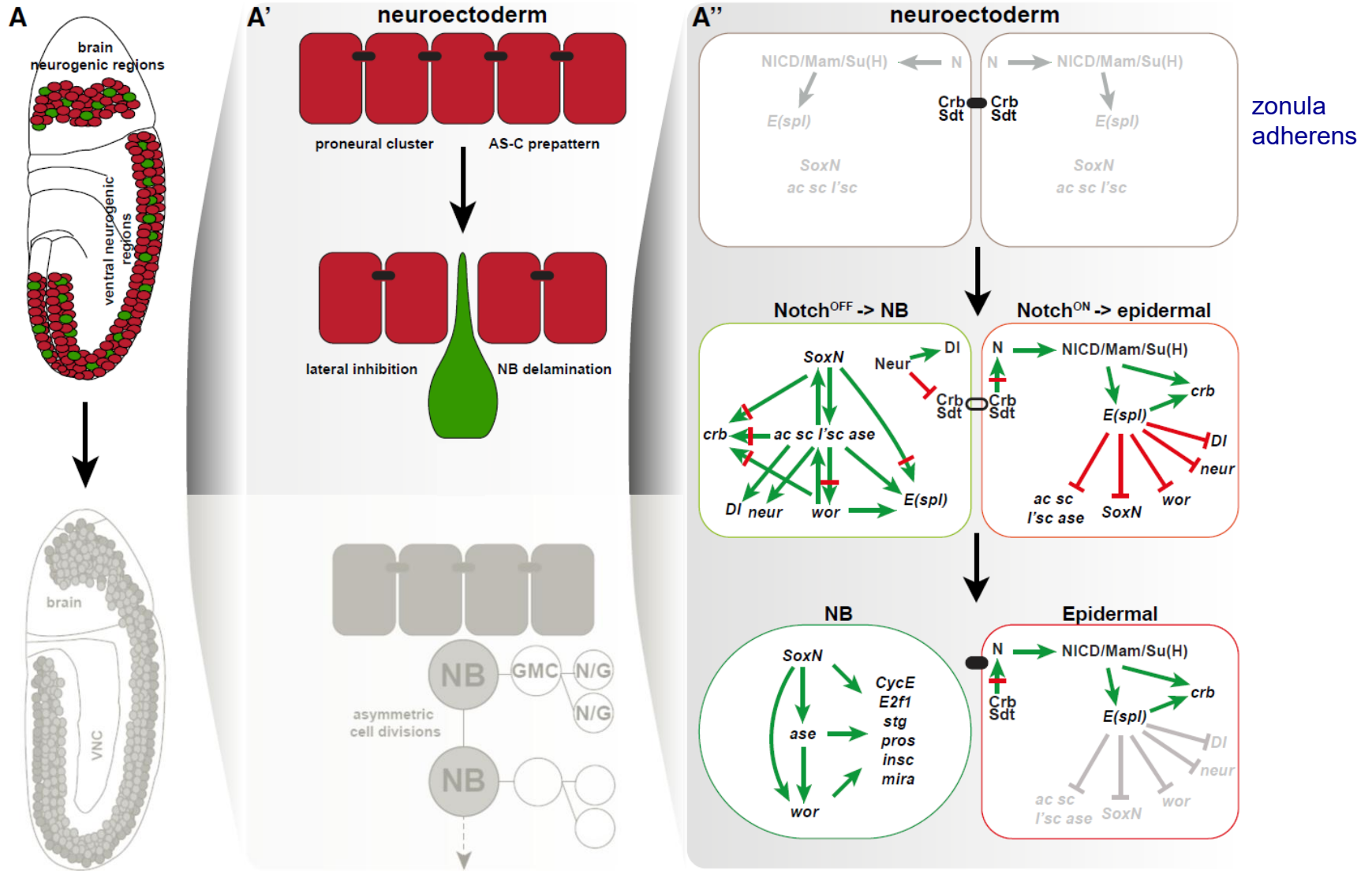
Worniu

Sox-Neuro

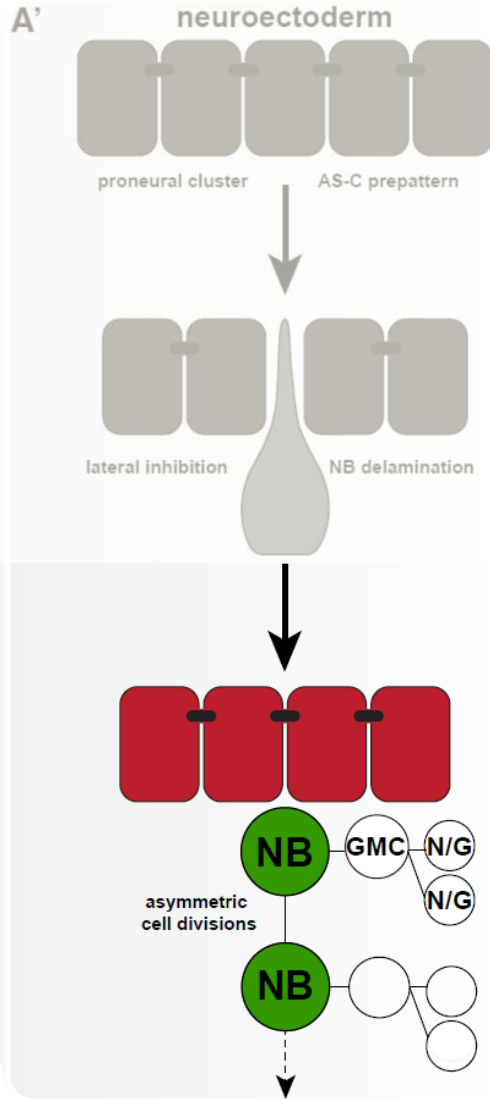
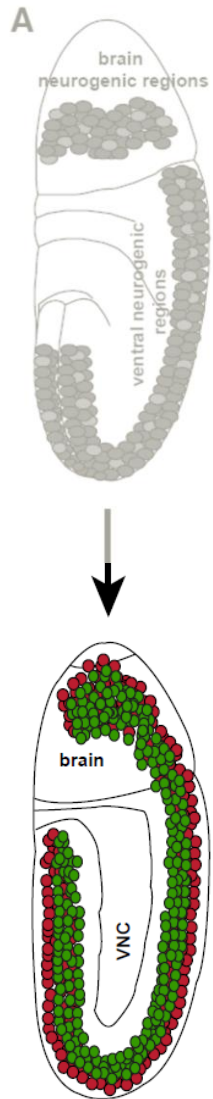


Arefin et al. (2019)

A revised model for embryonic neurogenesis



Some questions



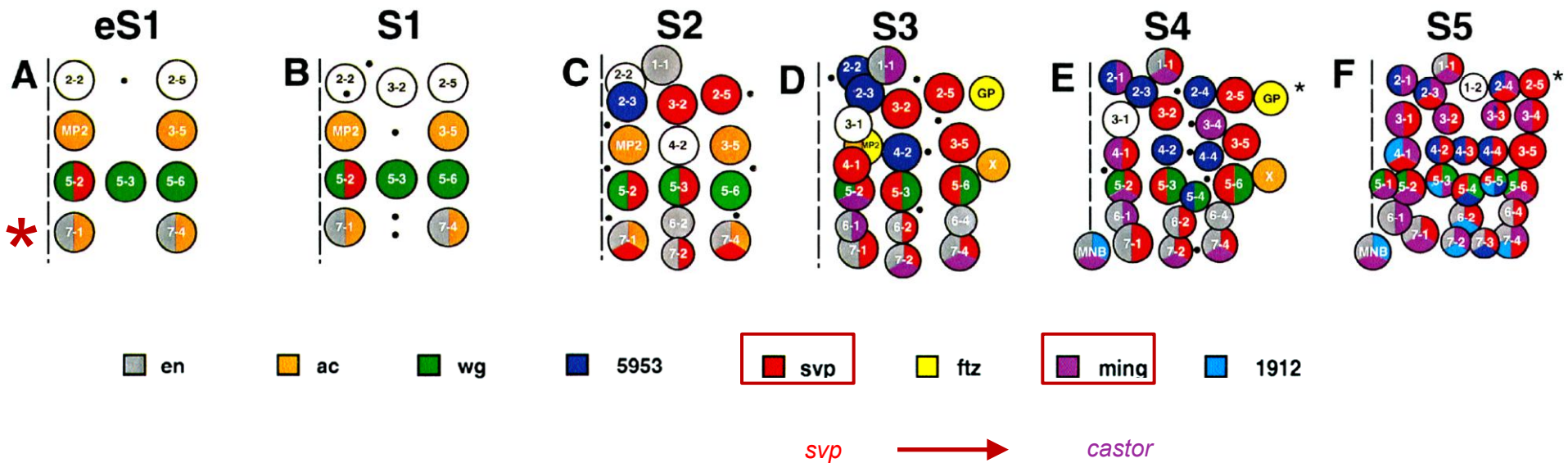
Arefin et al. (2019)

➤ Neuroblast determination ?

➤ Neuronal diversity ?

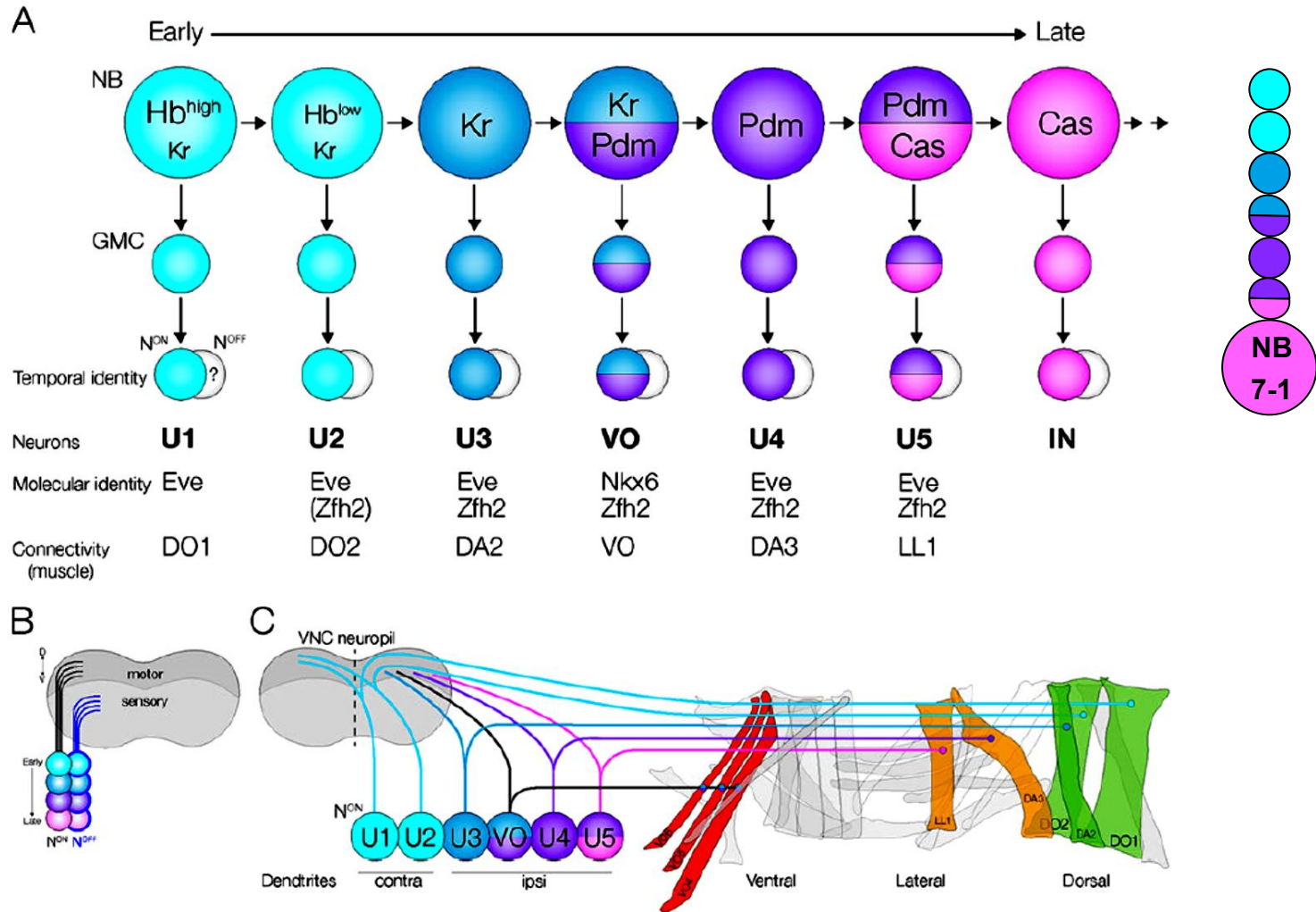
A molecular map

Doe (1992) Molecular markers for identified neuroblasts and ganglion mother cells in the Drosophila central nervous system. Development 116, 855-863.



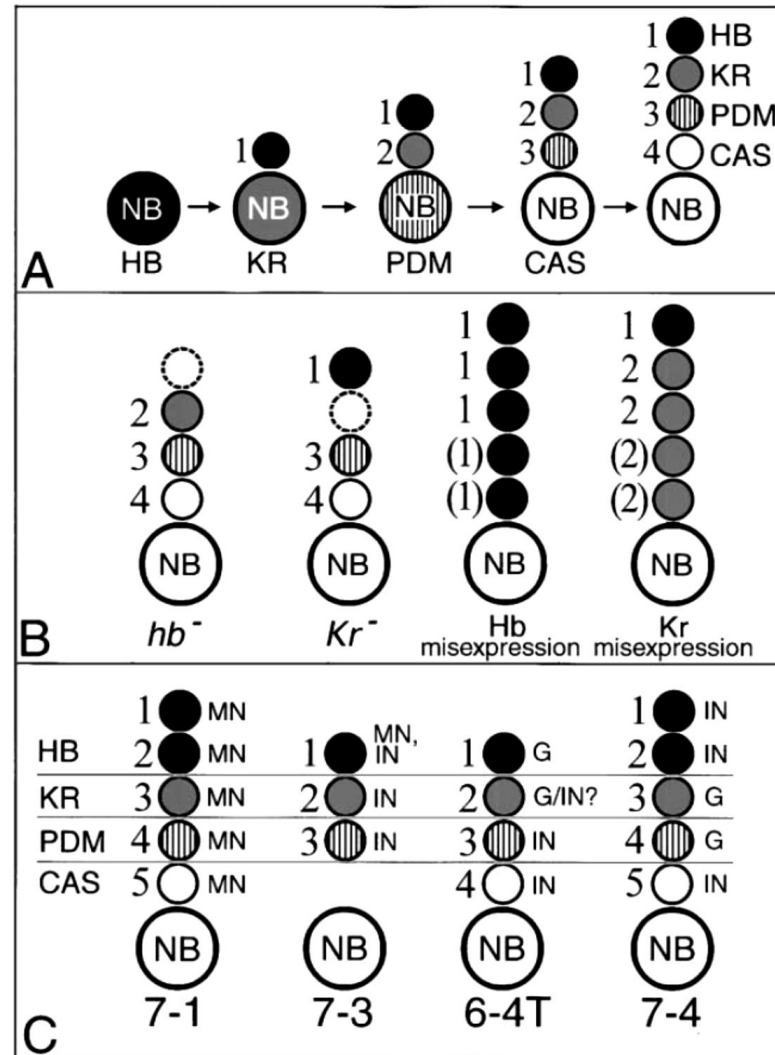
A temporal patterning

Isshiki et al. (2001) *Drosophila* neuroblasts *sequentially* express transcription factors which specify the *temporal identity* of their neuronal progeny. Cell 106, 511–521.

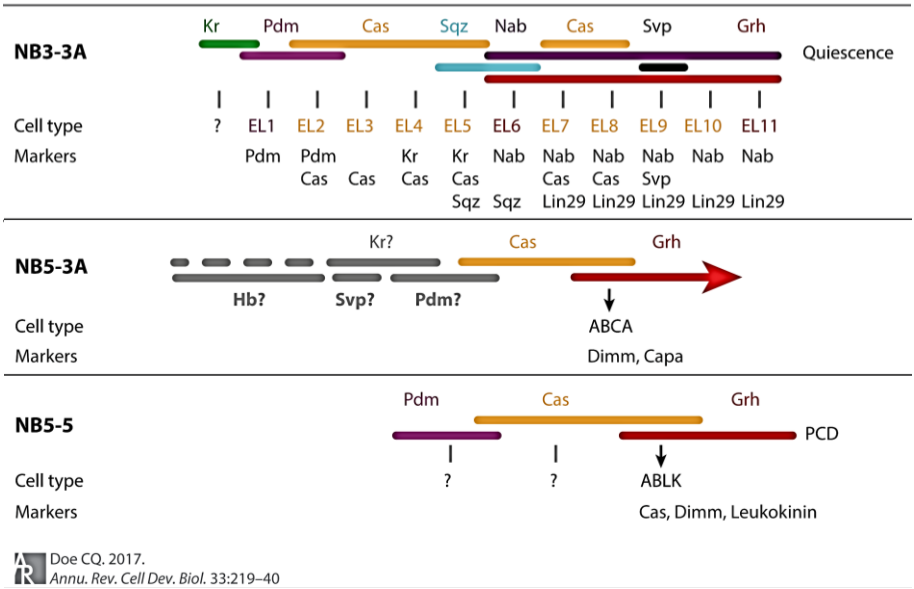
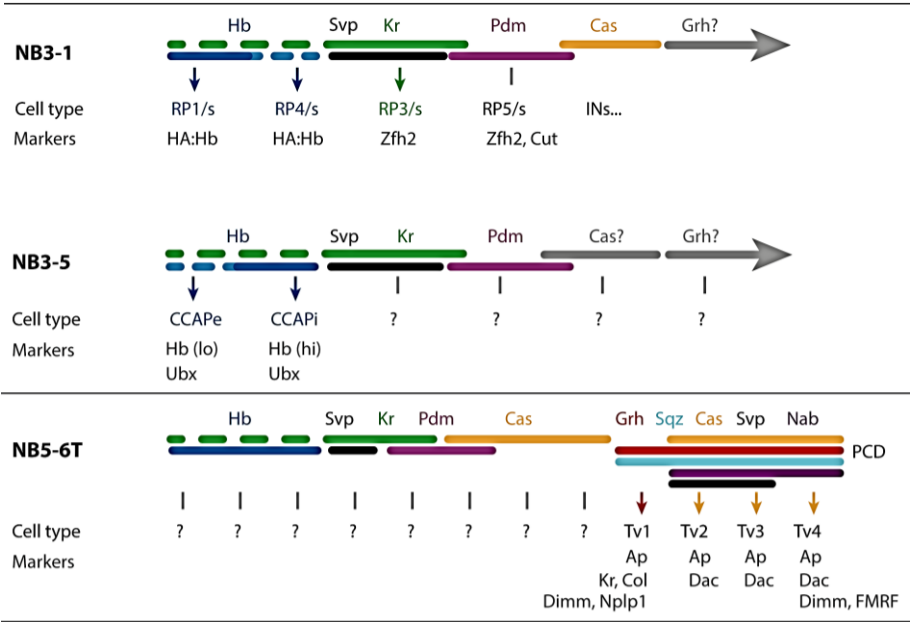


A temporal patterning

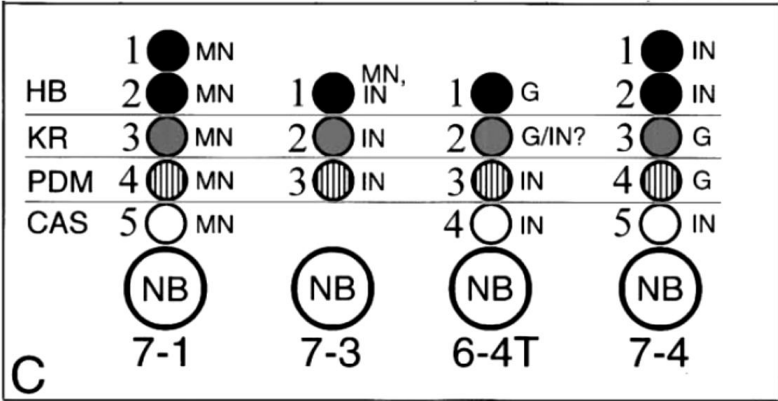
Isshiki et al. (2001) *Drosophila* neuroblasts *sequentially* express transcription factors which specify the *temporal identity* of their neuronal progeny. Cell 106, 511–521.



Some temporal patternings



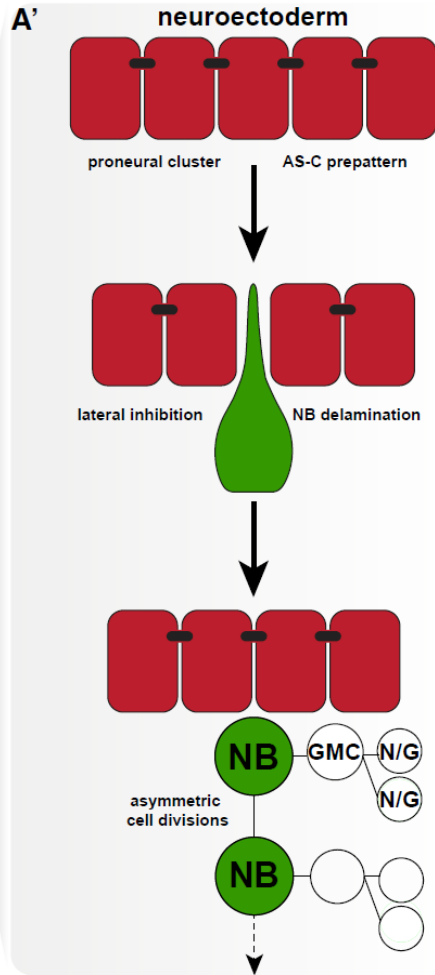
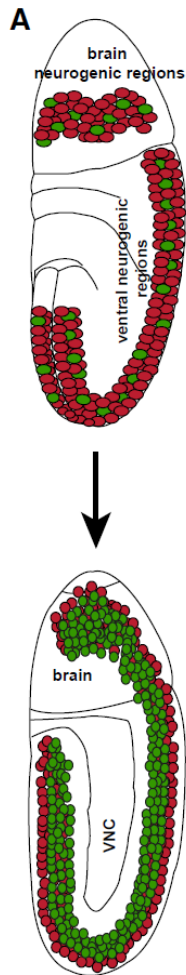
Doe (2017)



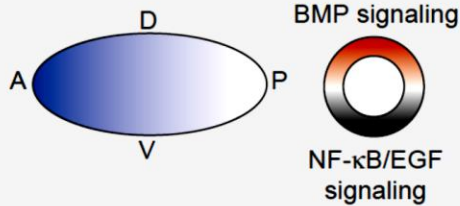
Isshiki et al. (2001)

In summary:

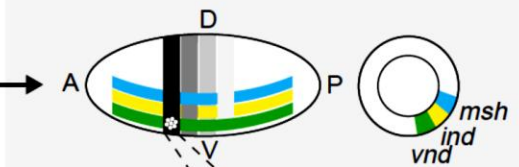
Ventral nerve cord development of *Drosophila* embryos



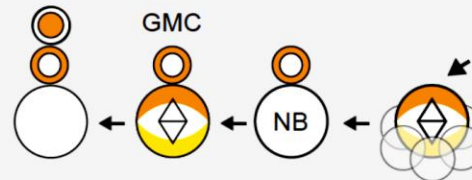
(a) AP and DV patterning



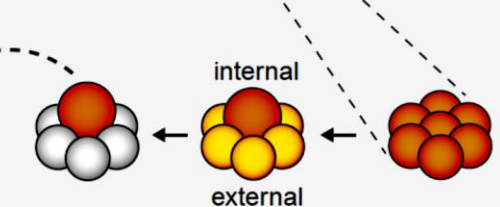
(b) Segmental/Columnar patterning



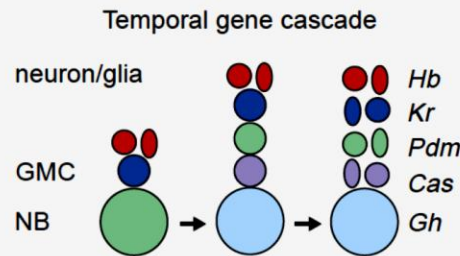
(d) Asymmetric NB divisions



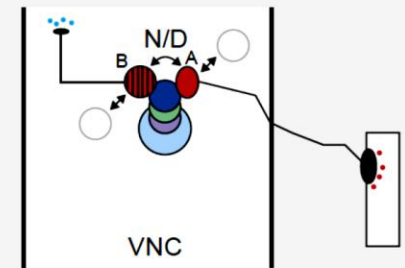
(c) NB formation and specification



(e) Specification of GMCs



(f) Asymmetric GMC division, specification of neurons/glia



Current Opinion in Neurobiology

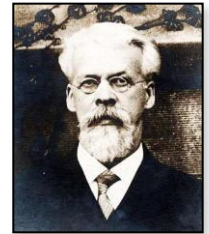
Arefin et al. (2019)

Skeath & Thor (2003)

Complements

- *Hartenstein & Wodarz (2013) Initial neurogenesis in Drosophila WIRE Dev. Biol. 2:701–721.*
- *Hartenstein & Stollewerk (2015) The evolution of early neurogenesis Dev. Cell 32(4):390-407.*
(leech development & neuroblast name)

Origin of the neuroblast name

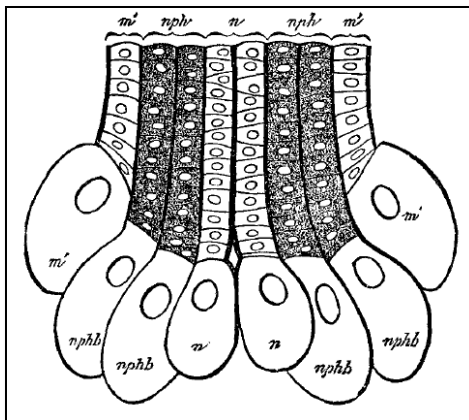
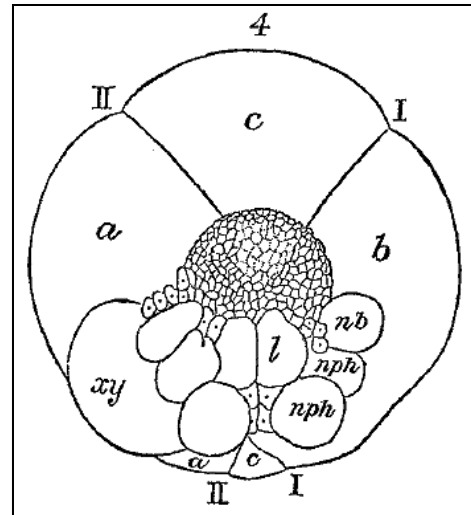


Whitman (1878) The embryology of Clepsine. Quar. Journ. Micr. Sci. 18:215-315.

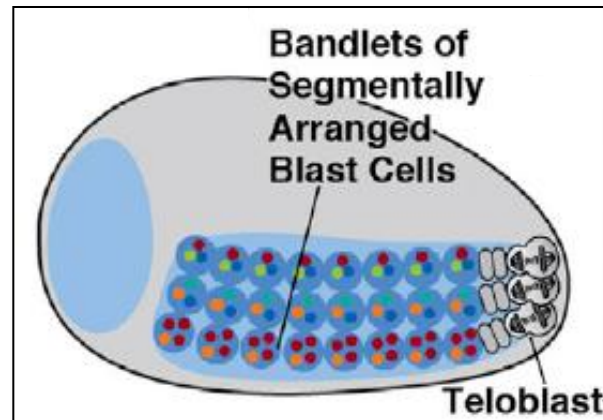
Leech (Annelid-Lophotrochozoan)



<http://www.ecosystema.ru/>



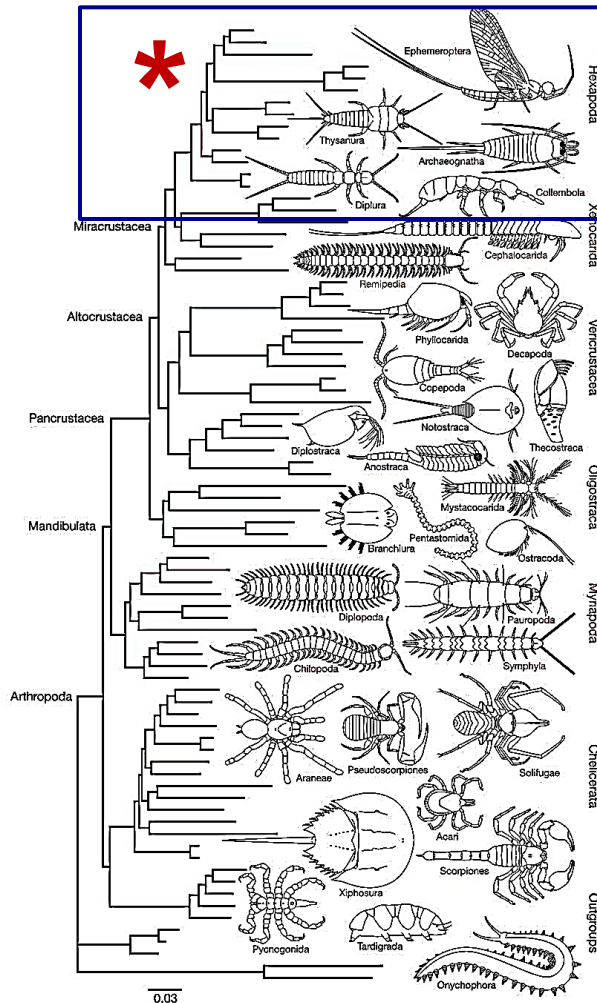
Whitman (1887)



Hartenstein & Stollewerk (2015)

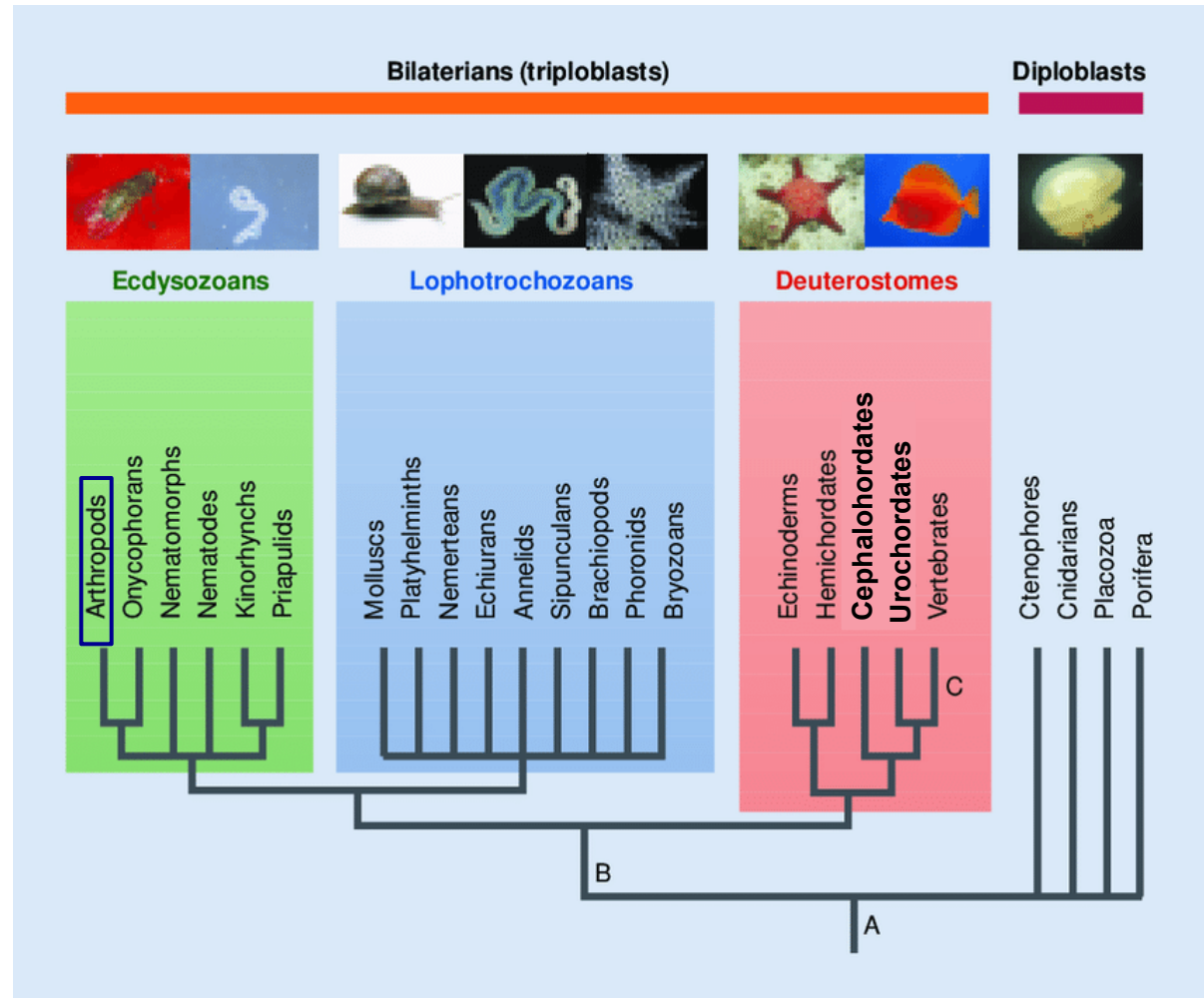
Phylogenetic position

Insects - Hexapods



Regier et al. (2010)

Arthropods - Ecdysozoans - Bilaterians - Animal



Modified from Holland (1999)