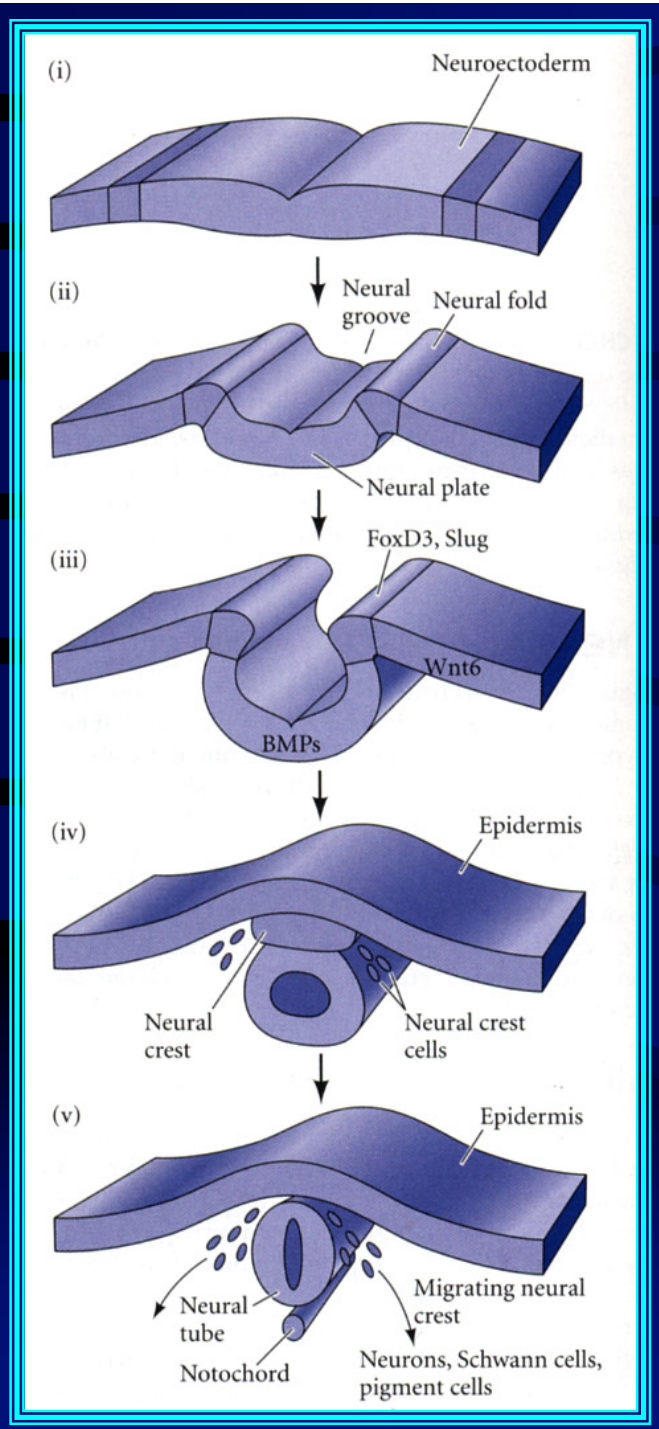
Development of the Enteric Nervous System

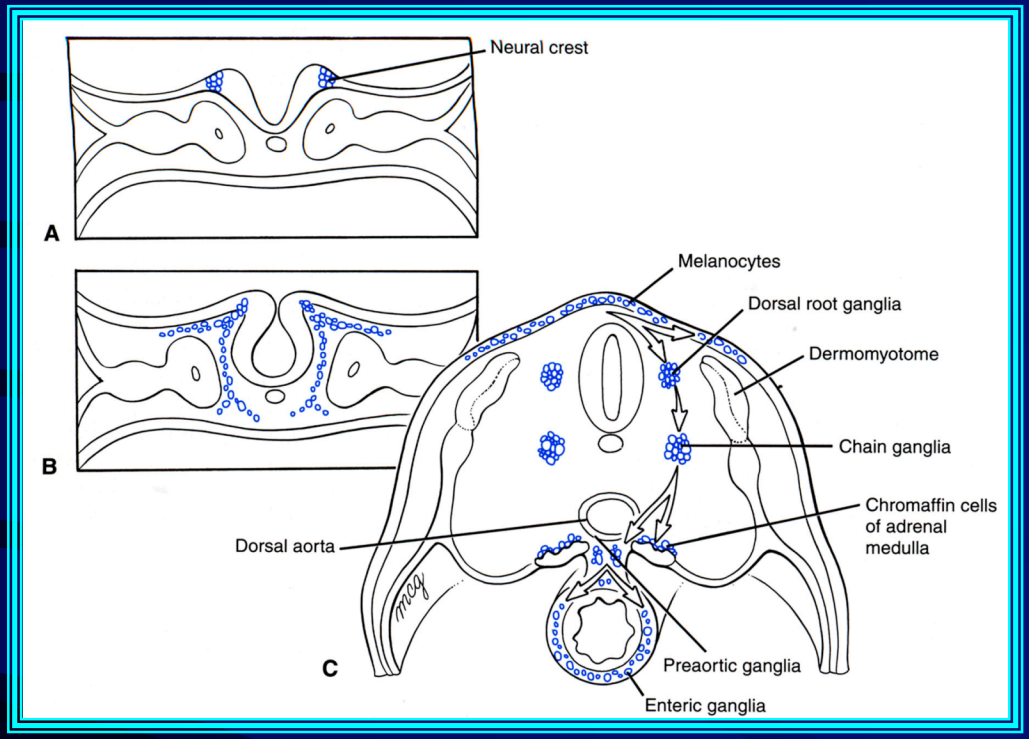
Mike Gershon



The neural crest delaminates from the closing neural tube

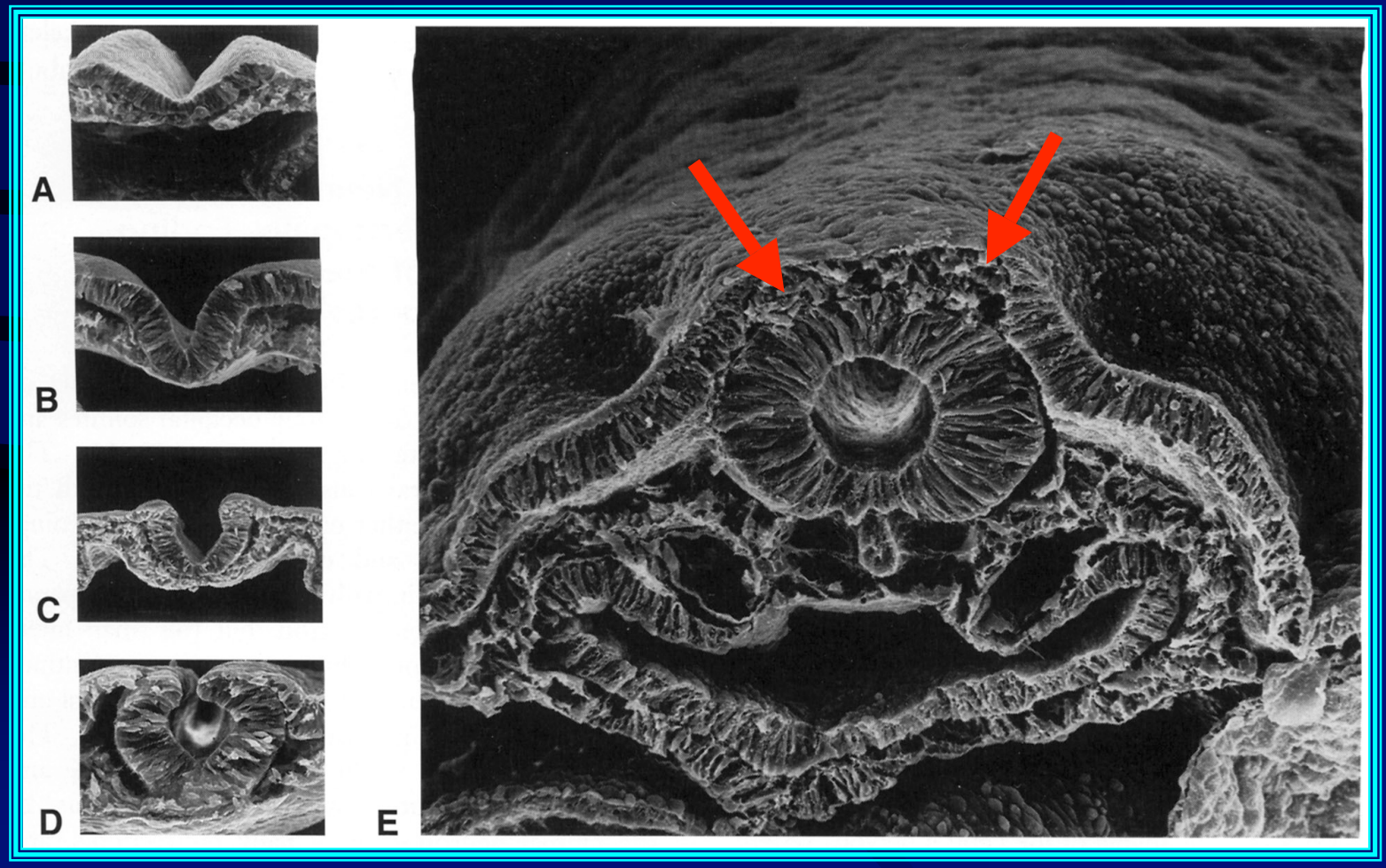
- The crest forms at the neural plate - epidermis boundary where moderate levels of paracrine factors are present.
  - BMPs (Neural plate), Wnt6 (Epidermis), FGFs
- Paracrine factors induce neural crest border specifiers.
  - Distalless-5, Pax3: Prevent region from becoming either neural plate or epidermis.
- Border specifiers induce neural crest specifiers.
  - FoxD3 specification of crest and Slug, epithelial-mesenchymal transformation

Neural crest arises at the lateral edges of the neural plate



- Crest-derived cells migrate either along dorsolateral (melanocytes) or ventral (ganglia, Schwann cells, ets.) pathways
- Developmental potential of crest cells is heterogeneous when they begin to migrate.
  - Some are committed, others are pluripotent

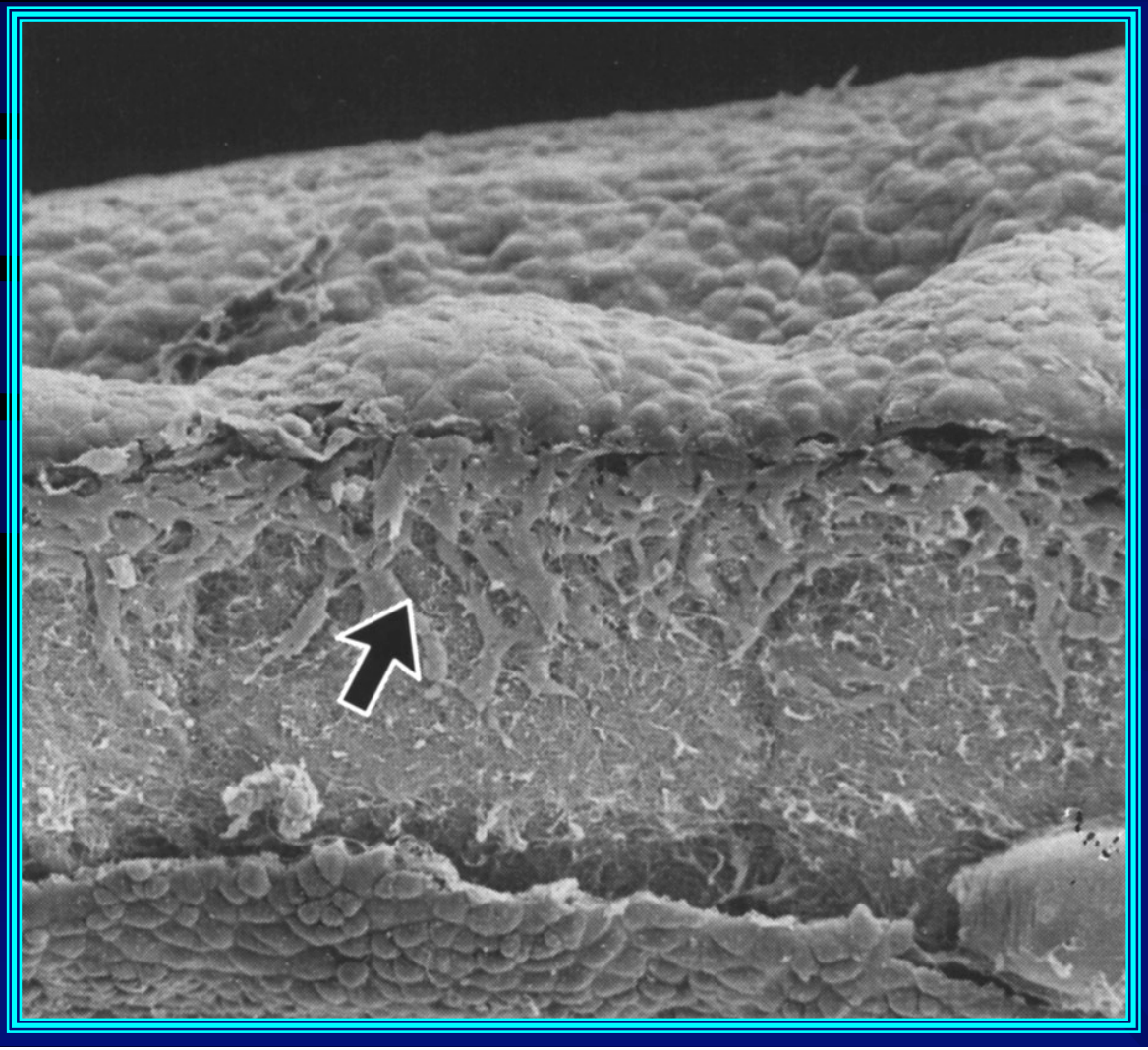
The neural crest forms during neurulation but is transient



Migration of crest is timed in a rostro-caudal sequence

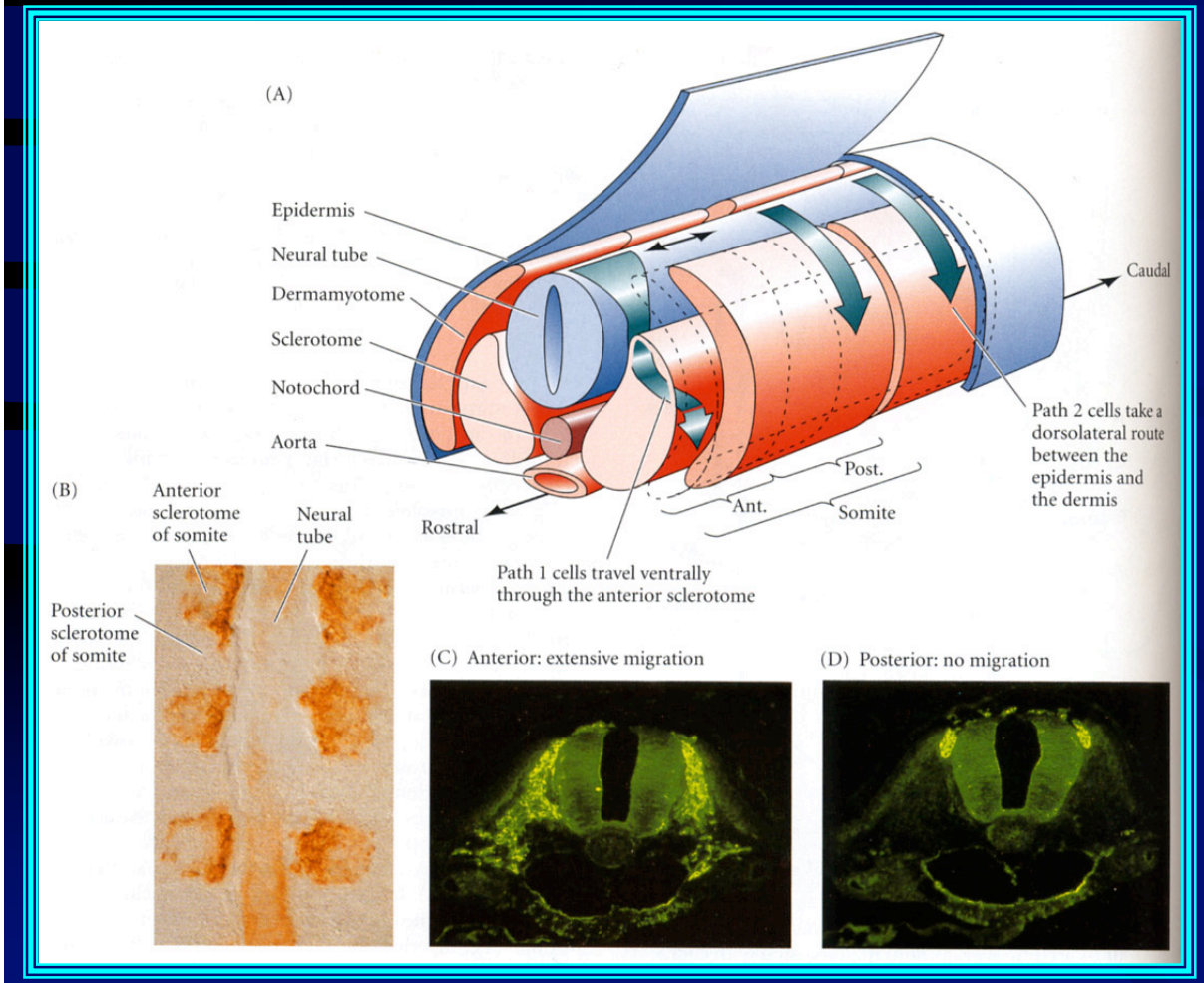
- Crest cells undergo an epithelial-mesenchymal transformation to delaminate and become migratory.
  - Lose junctional proteins and adhesion molecules

Crest-derived cells migrate preferentially through the rostral (anterior) halves of somites



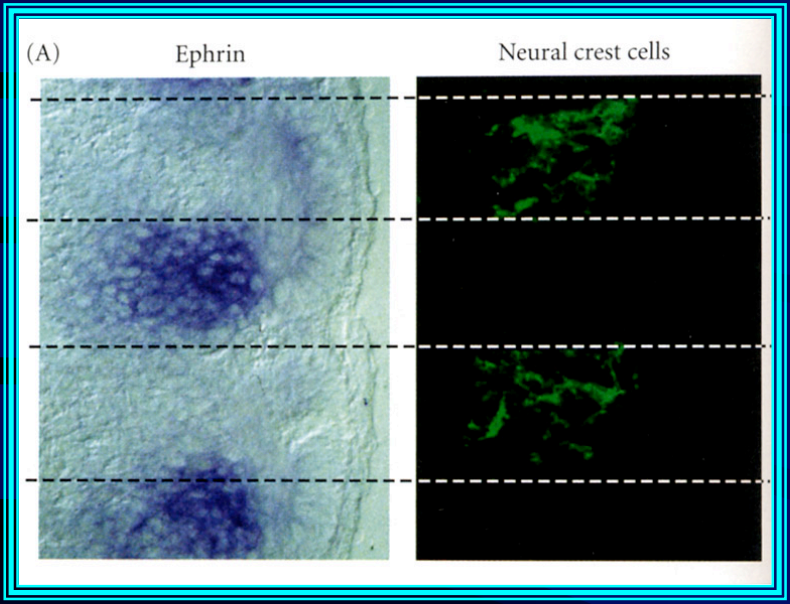
- Segmental pattern is the same as that later followed by spinal nerves.
- Gives rise to the segmentation of DRG.

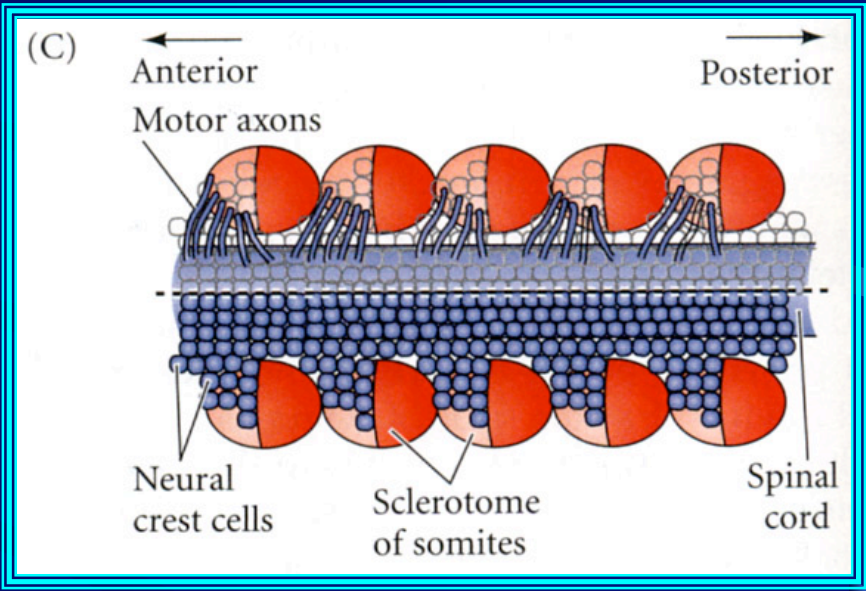
The ventral pathway leads through anterior somites



- Cells moving ventrally go through the anterior sclerotome to reach somites.
- Cells moving dorsally migrate beneath the epidermis and form melanocytes.

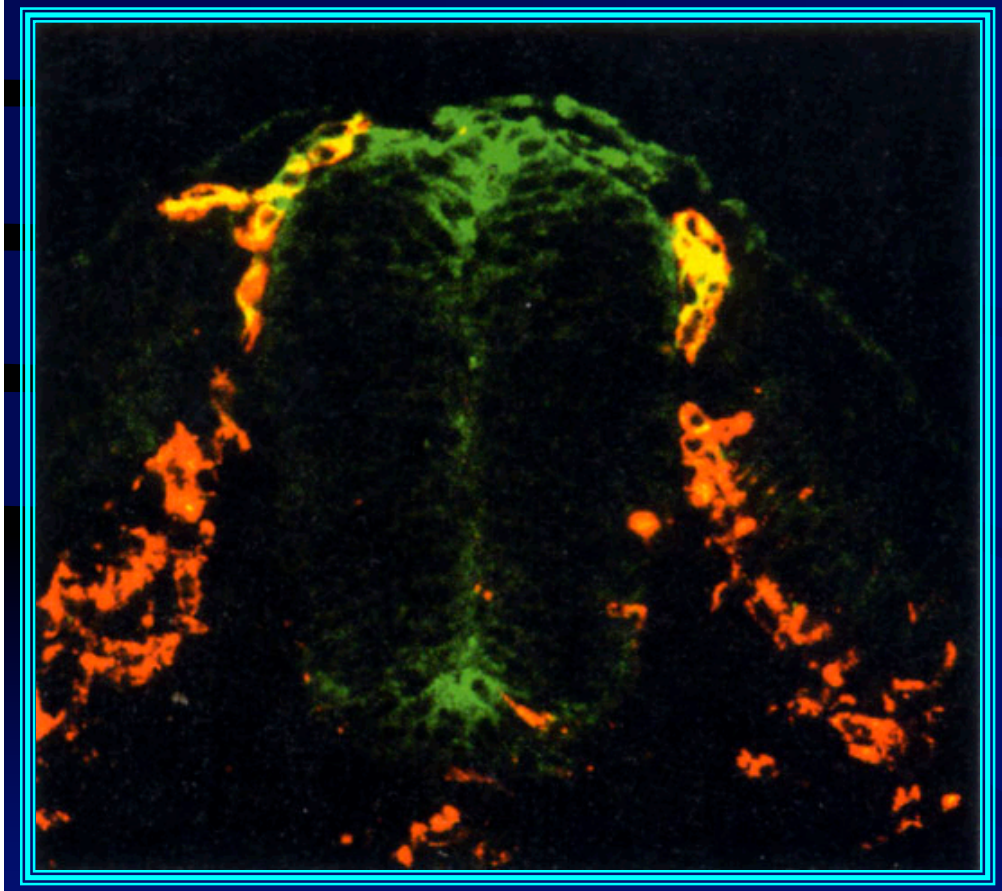
Ephrins help to prevent crest cells and spinal nerves from entering posterior half-somites





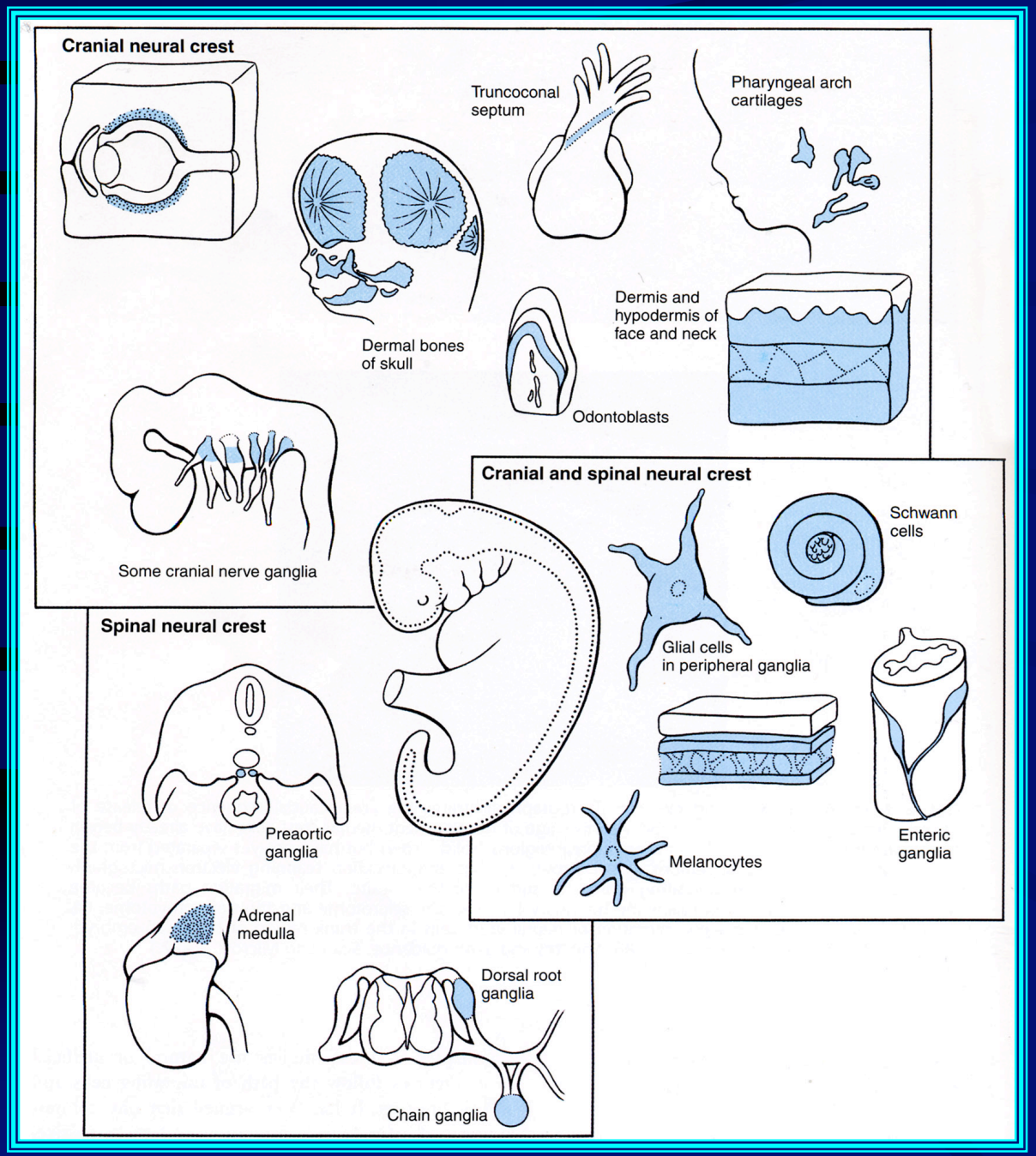
- Crest cells and axonal growth cones express Eph receptors and respond to ephrins in the ECM.
- Crest cells and axons respond to the same guidance cues as they leave the neuraxis.

Crest cells express RhoB as they begin to migrate



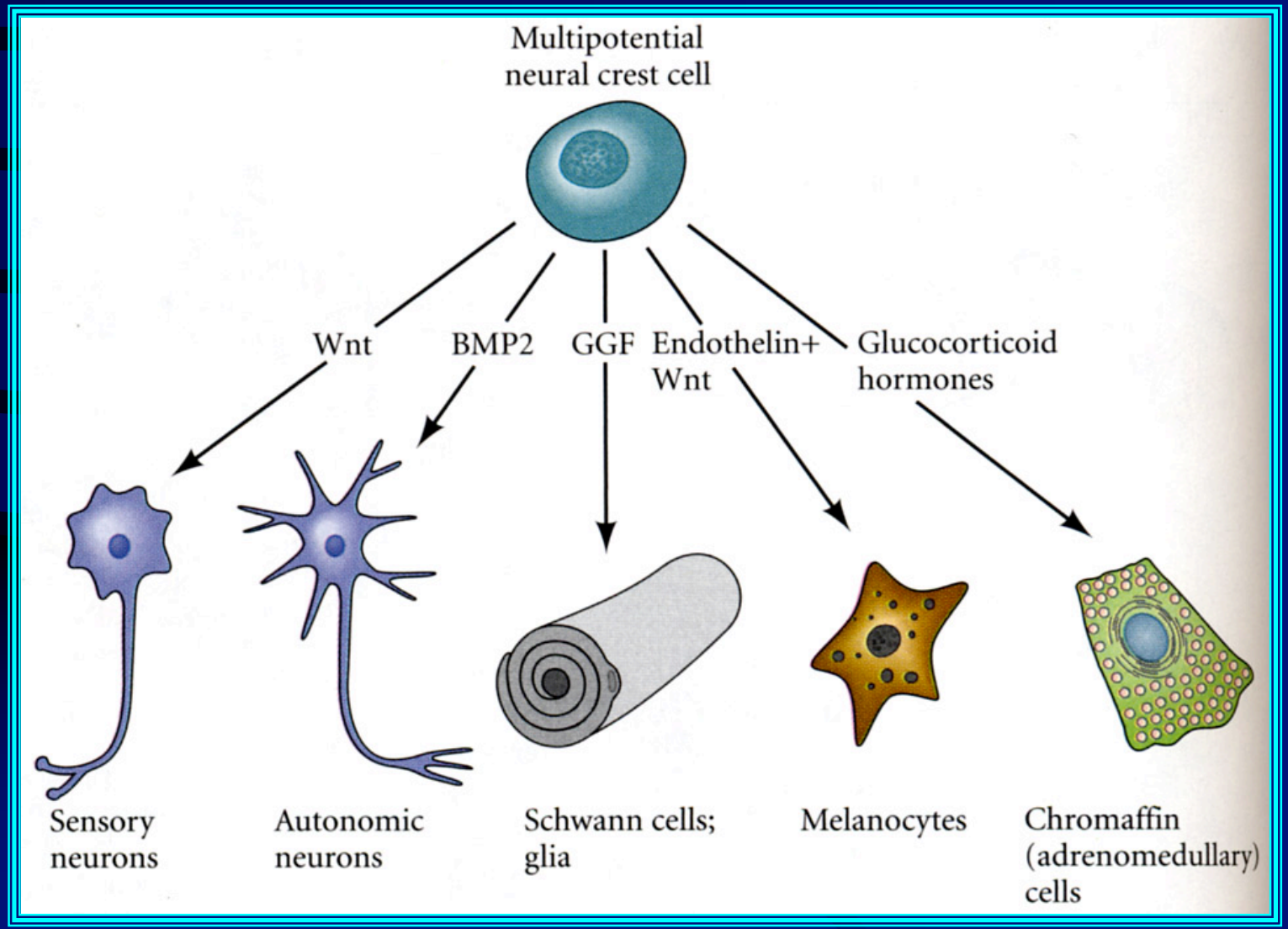
HNK-1 = crest

- RhoB establishes the cytoskeletal conditions that permit migration.
  - Promotes actin polymerization and insertion of microfilaments into membrane at focal adhesion juntions
- Slug helps dissociate the E-cadherins that hold epithelial cells together.

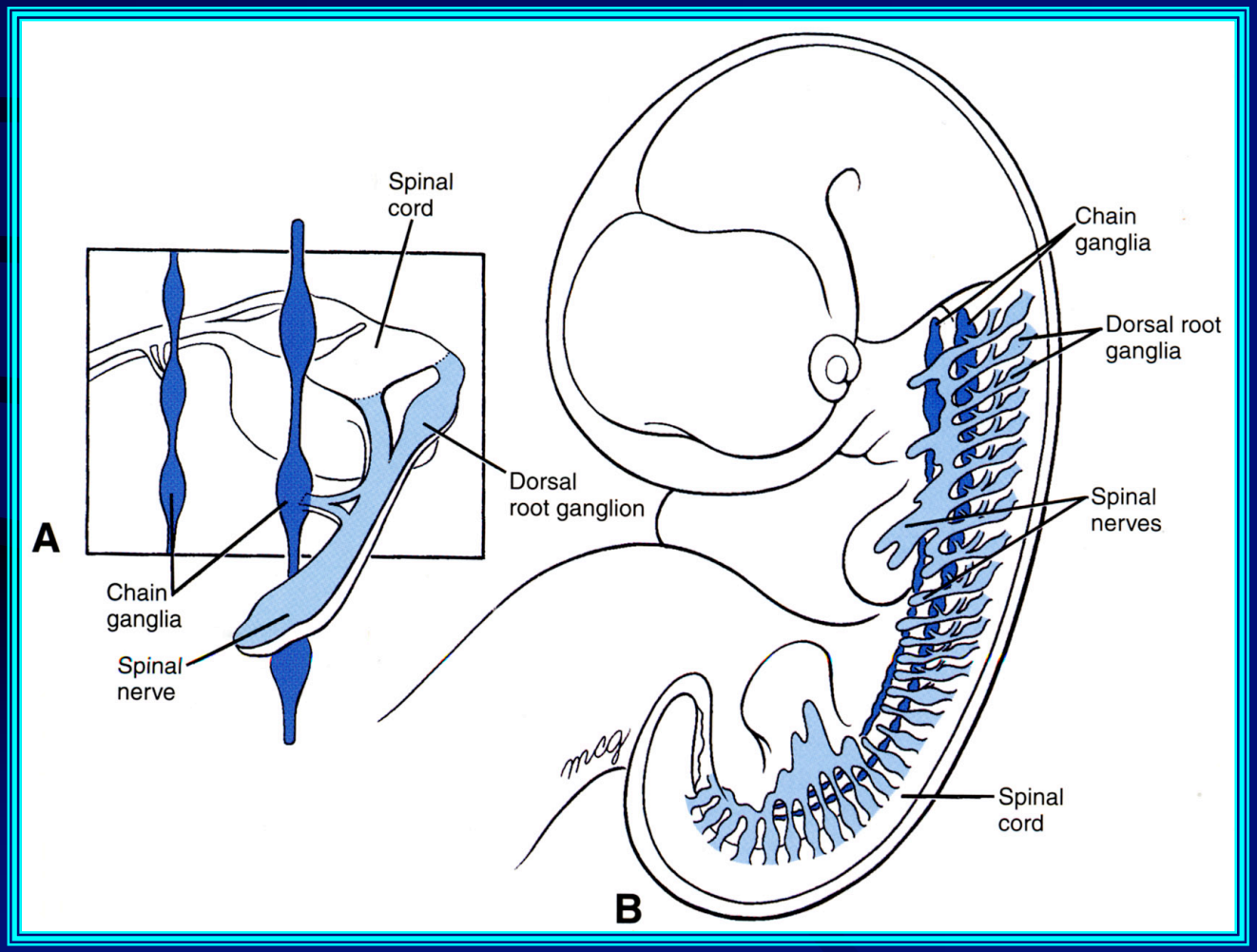


There are many derivatives of the neural crest

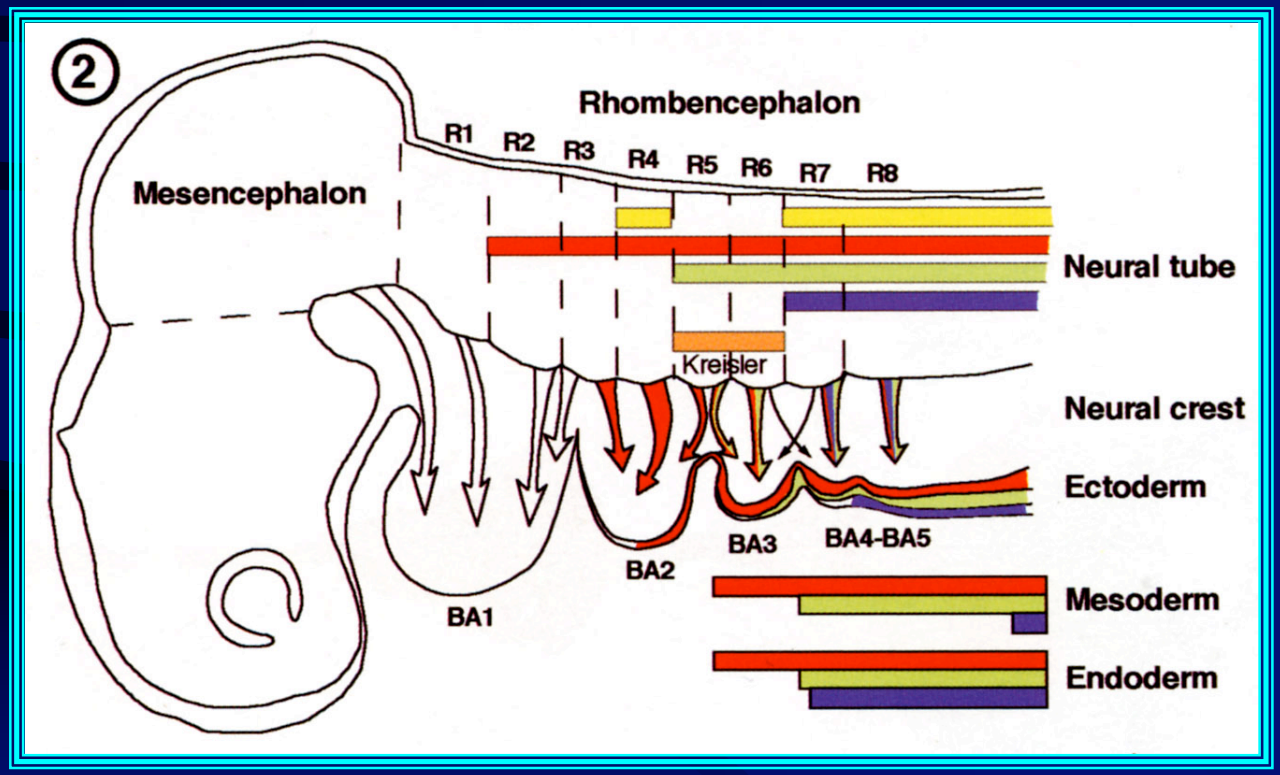
Microenvironmental paracrine factors help specify neural crest lineages



Crest gives rise to DRG and sympathetic chain ganglia at almost all levels



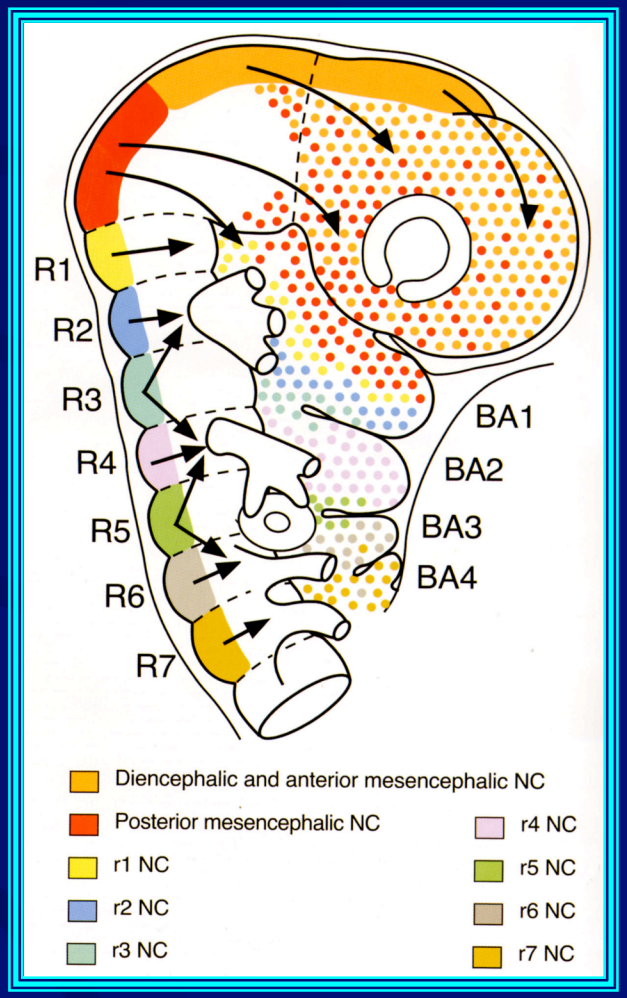
Different *Hox* genes are expressed by neural crest cells migrating into branchial arches



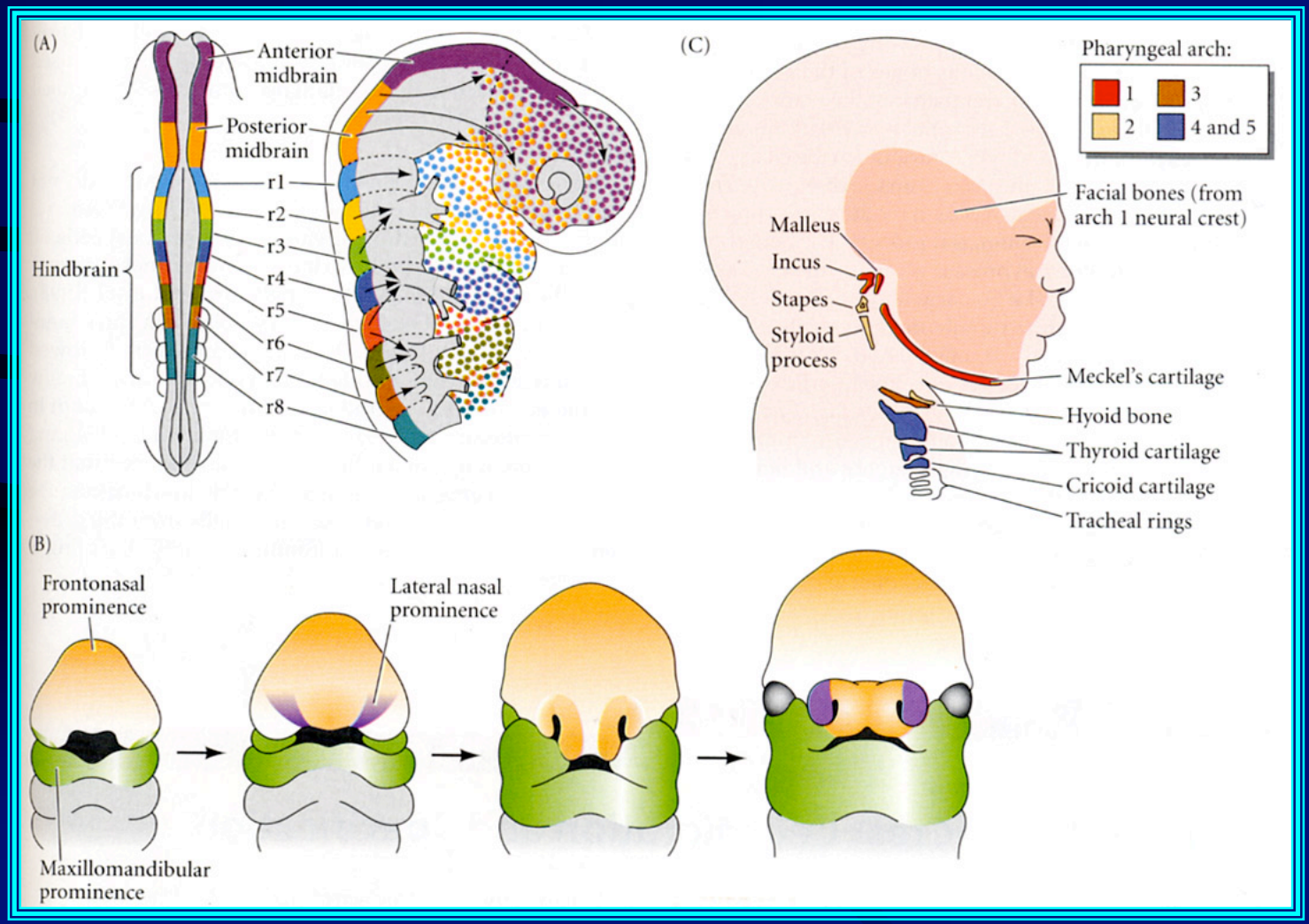
- These constitute a Hox gene code.

The connective tissue of the head and neck is largely derived from the neural crest

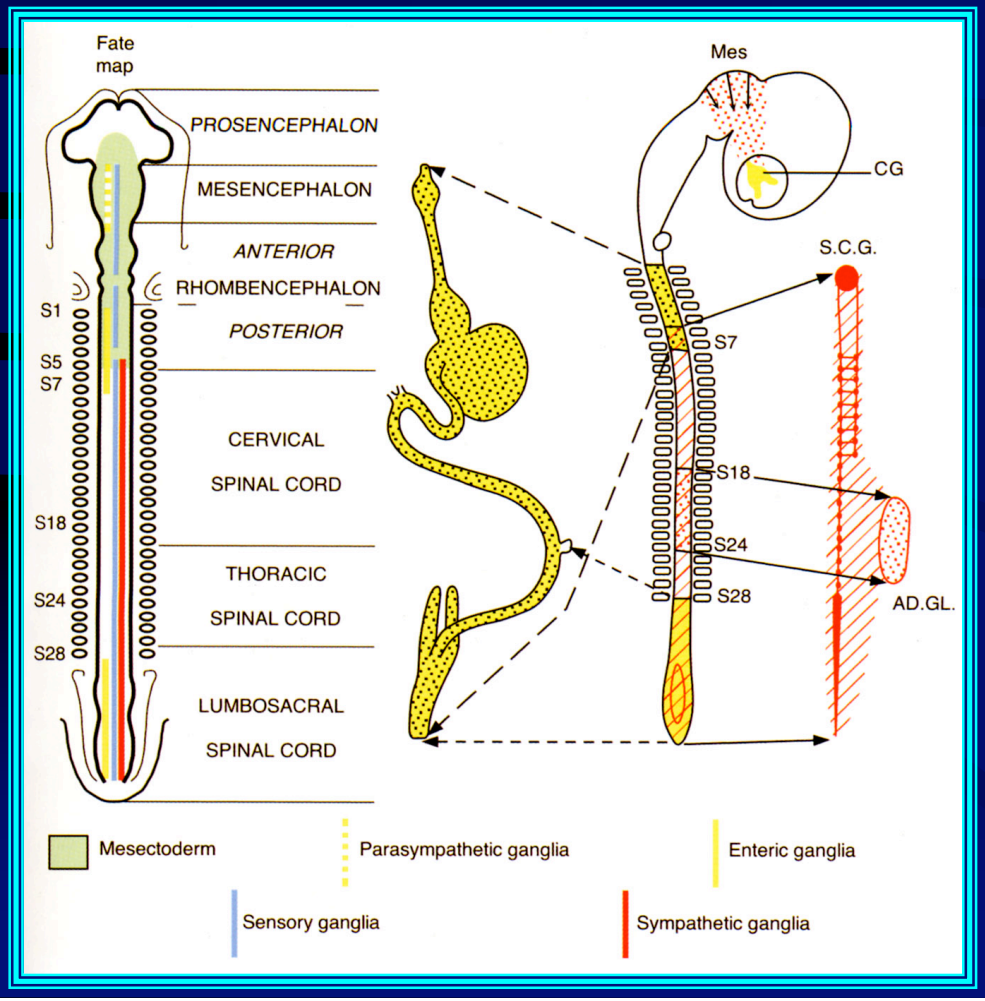
- These are called "mesectoderm".
- Specific regions of the crest colonize specific regions of the head and neck



Migratory pathways in the head channel crest cells from different regions to specific destinations



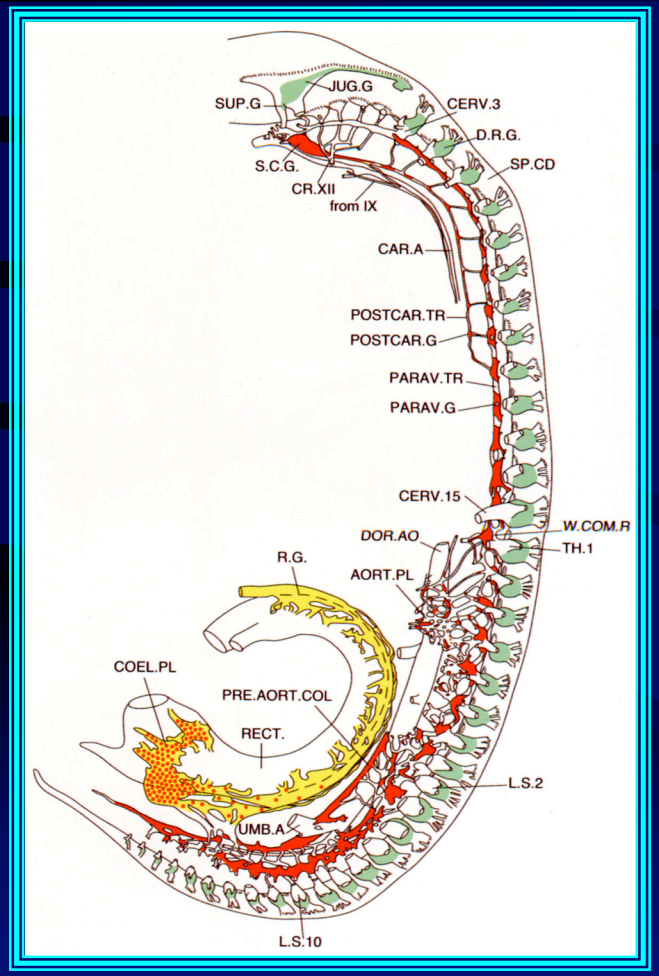
Sympathetic ganglia, the ENS, and the adrenal medulla arise from post-otic levels of the crest



- ENS: somites S1-7; 28-
  - Vagal
  - Sacral
- Sympathetic S6-
- Adrenal S18-24

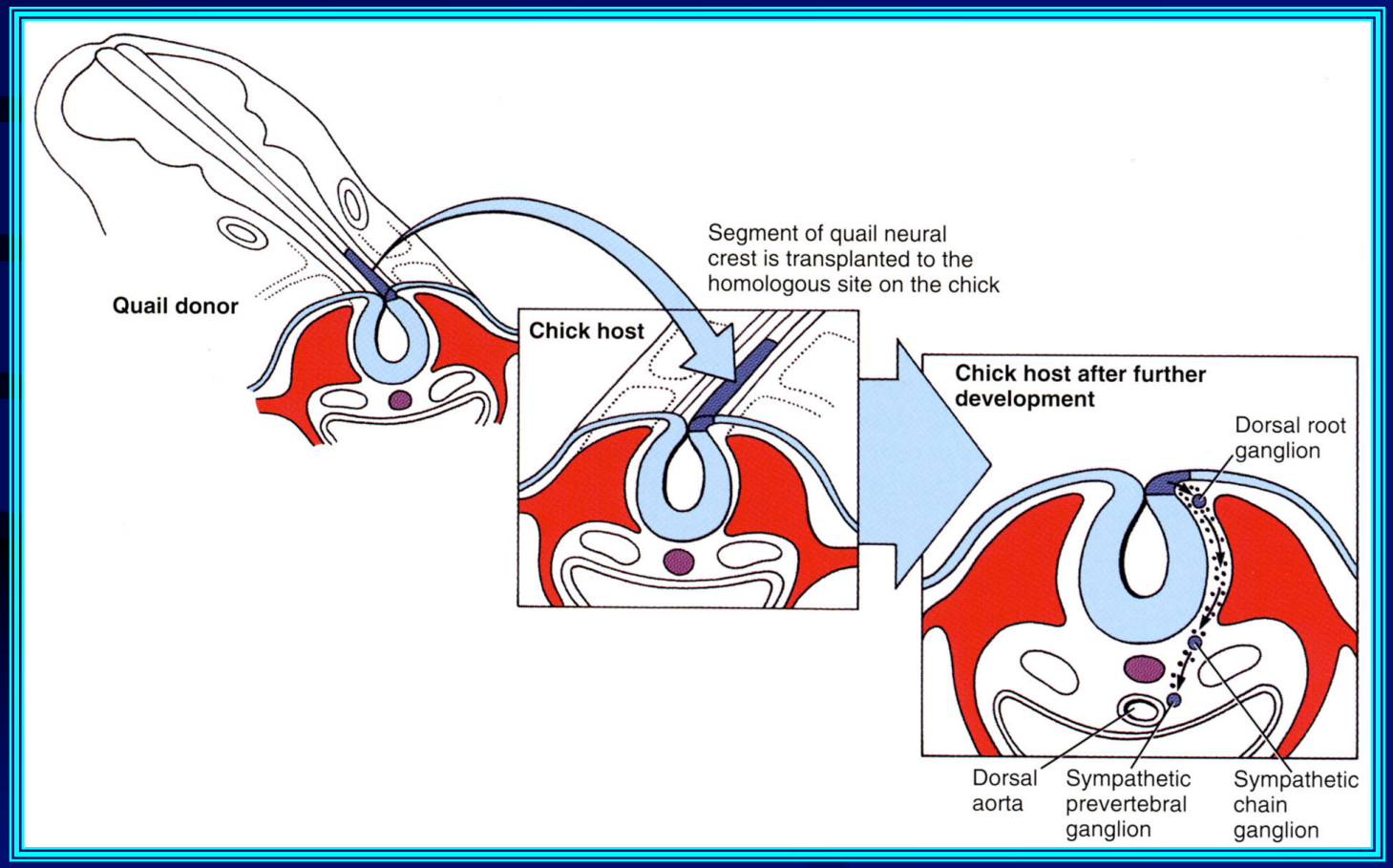
- The cardiac outflow tract is also derived from the neural crest (called the cardiac crest- levels overlap with vagal crest)

Crest-derived ganglia in a chick embryo

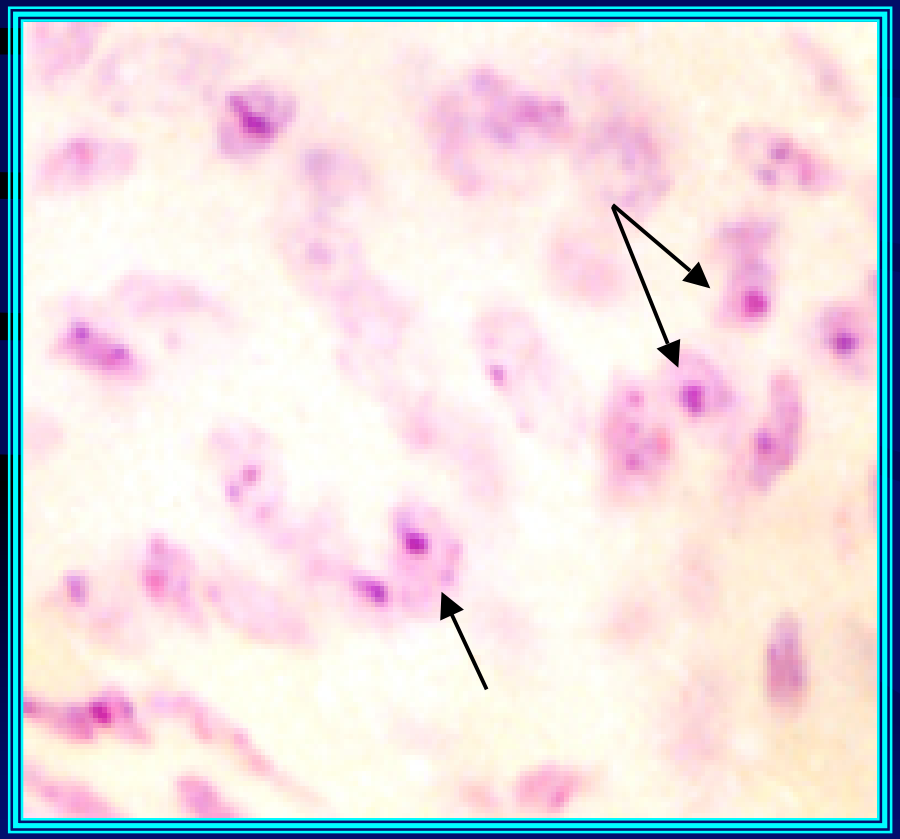


- DRG ganglia are crest derivatives
- Some cranial ganglia are crest-derivatives
  - Some are mixed, placodes and crest
- Parasympathetic ganglia are crest-derived
- ENS is crest-derived.

Crest cells are traced by using quail-chick interspecies chimeras

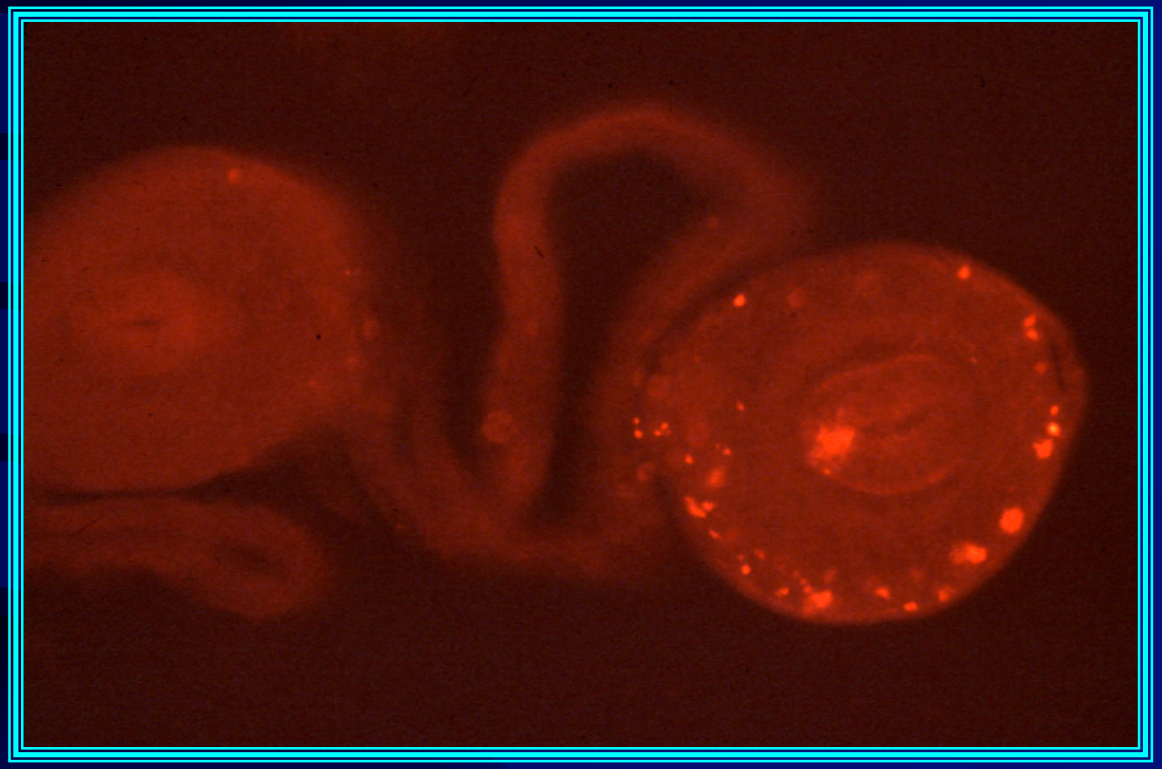


Quail-chick interspecies chimeras reveal the migration pathways of crest-derived cells



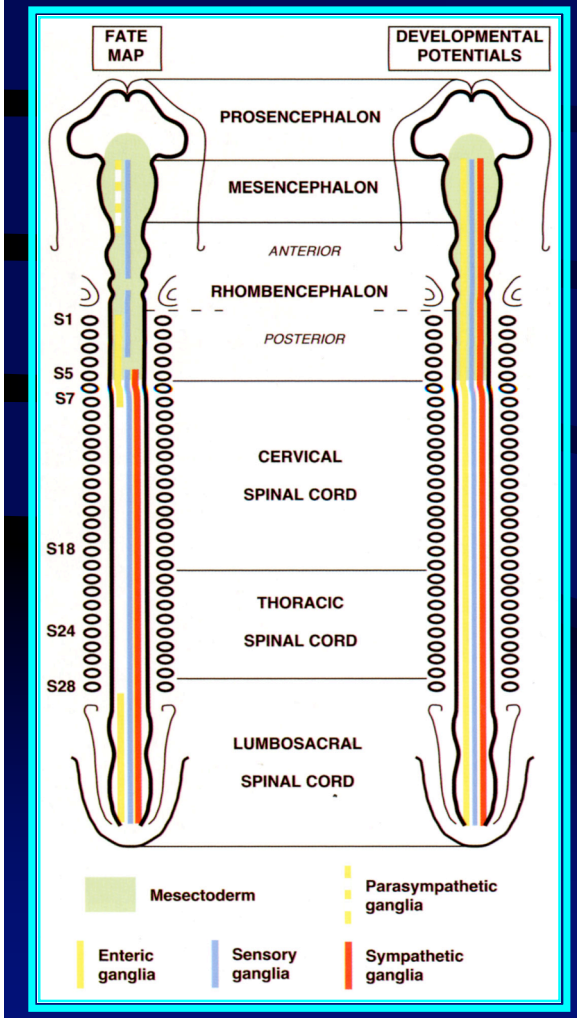
- Chick crest is removed before migration begins.
- Replaced with a graft of quail crest.
  - Quail crest cells migrate in host.
- Quail crest cells are stably marked by their distinctive nucleolus-associated heterochromatin.
- Location of quail cells reveals destinations reached by migrating crest-derived cells.

DiI-labeled sacral crest cells colonize the post-umbilical bowel



- DiI was injected into neural crest of a chick embryo caudal to somite 28.

Fates of crest cells varies with their axial level but developmental potential is broader

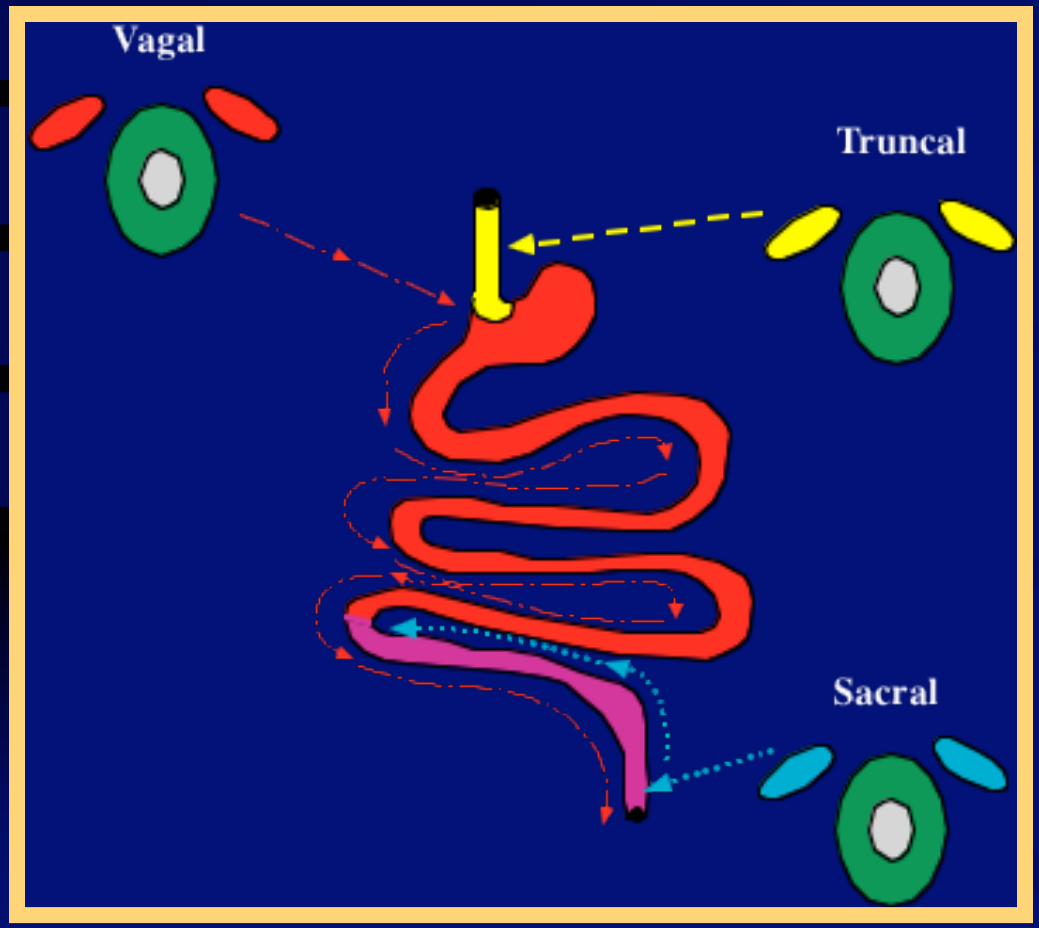


- Defined migratory pathways lead crest-derived cells to their ultimate destinations.
  - Cells thus may not realize their developmental potential
  - Fates are shaped by cues delivered in the migratory pathway or in the target organ.
- Many levels can give rise to sensory ganglia, sympathetic ganglia, and ENS, but only S1-7 and caudal to S28 do give rise to ENS in situ.

The ENS is a unique part of the nervous system

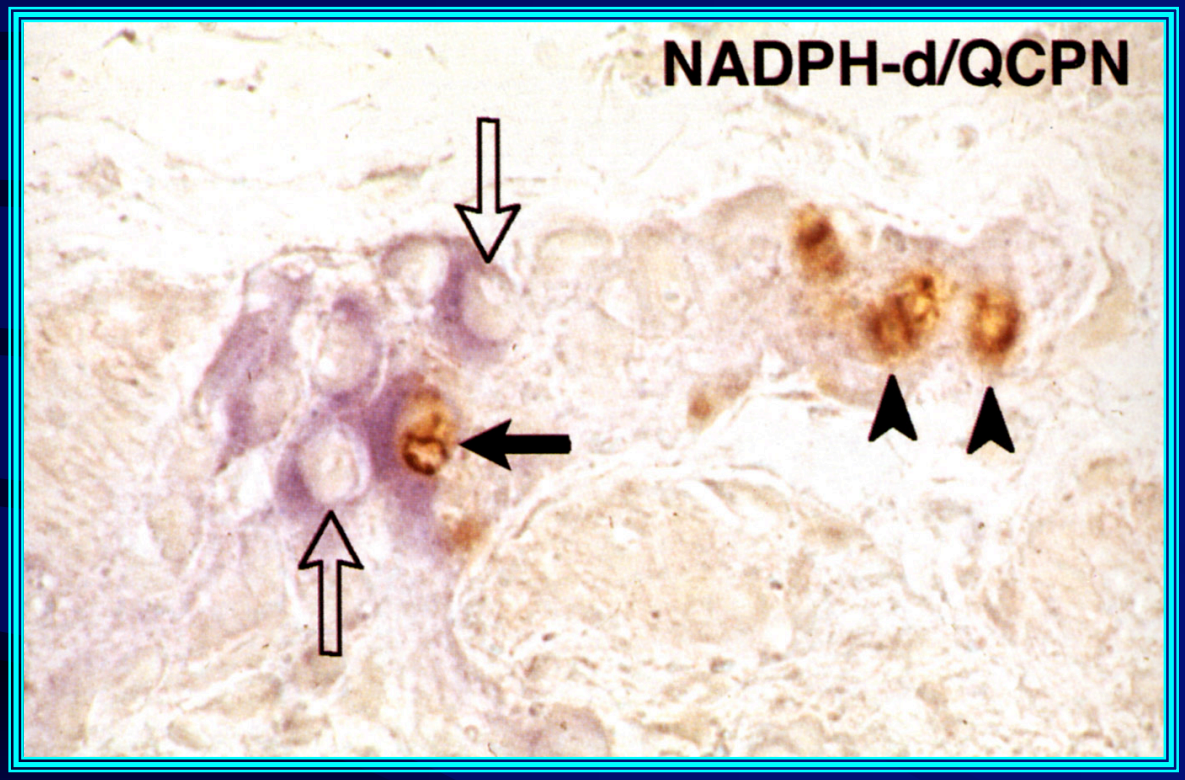
- Mediates behavior of gut in absence of input from CNS.
  - Most neurons not connected to CNS
- Lacks internal collagen
- Support from enteric glia
- Many neurons and many types of neuron
  - Every class of neurotransmitter found in CNS is also in ENS
  - More neurons than spinal cord
  - More neurons than remainder of PNS
  - Greatest phenotypic diversity in PNS

The gut is colonized by precursors that migrate from the neural crest.



- **Vagal level: whole gut. Anterior → posterior**
- **Truncal level: rostral foregut (Esophagus).**
- **Sacral level: postumbilical gut. Posterior → anterior**

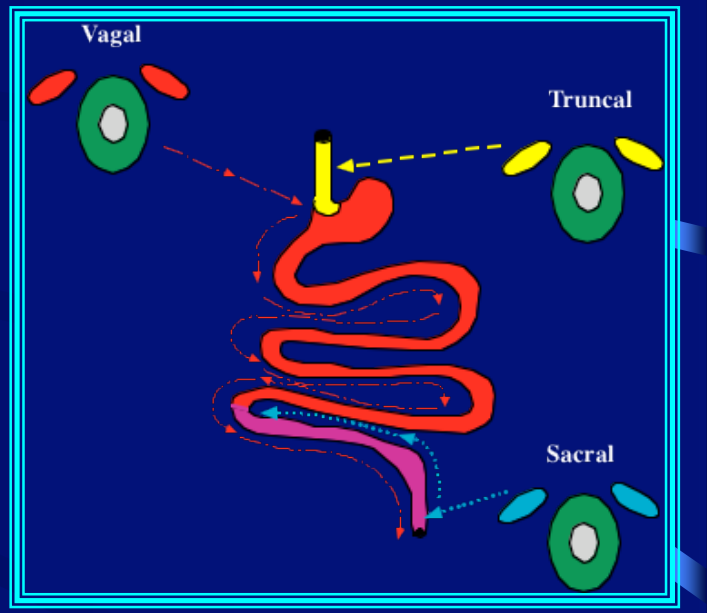
Sacral crest contributes enteric neurons

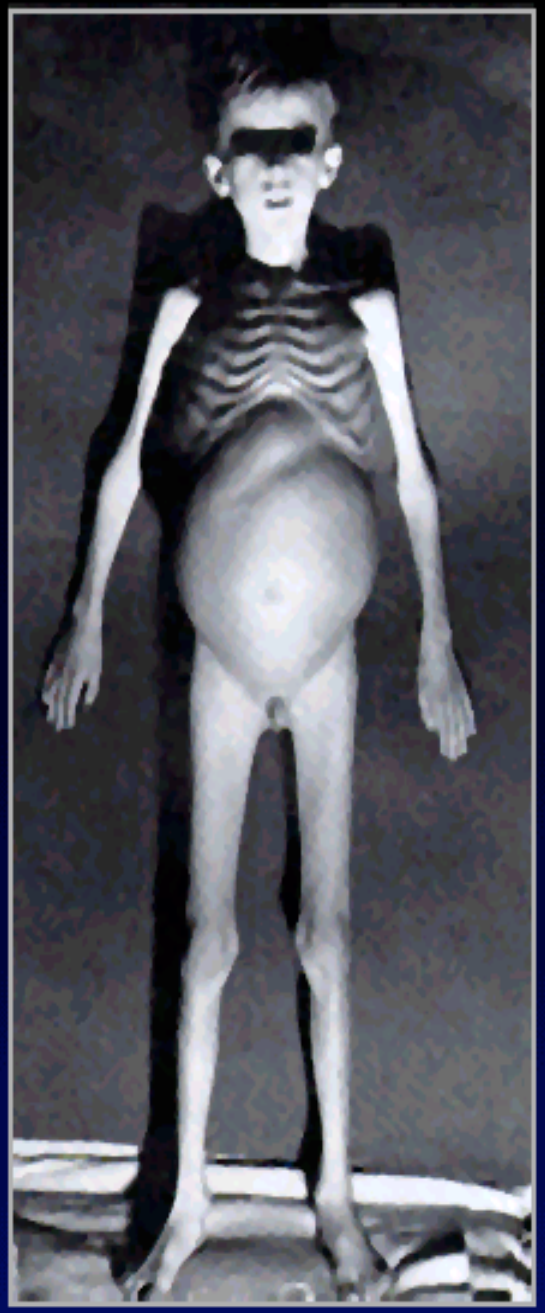


- Demonstrated with quail chick-chimeras
  - NADPH-d (purple) marks enteric neurons
    - NADPH-d = NOS
  - QCPN (antibodies to quail) marks quail cells

Microenvironmental signals determine the fates of crest-derived cells

- Signals from the environment received by crest cells regulate their:
  - migratory paths
  - proliferation
  - restriction of developmental potential
  - survival
  - formation of terminally differentiated derivatives.
- As crest-derived cells migrate they change:
  - cell surface receptors
  - intracellular transduction mechanisms.
- Postmigratory cells in the gut are thus different from their premigratory precursors in the neural crest.





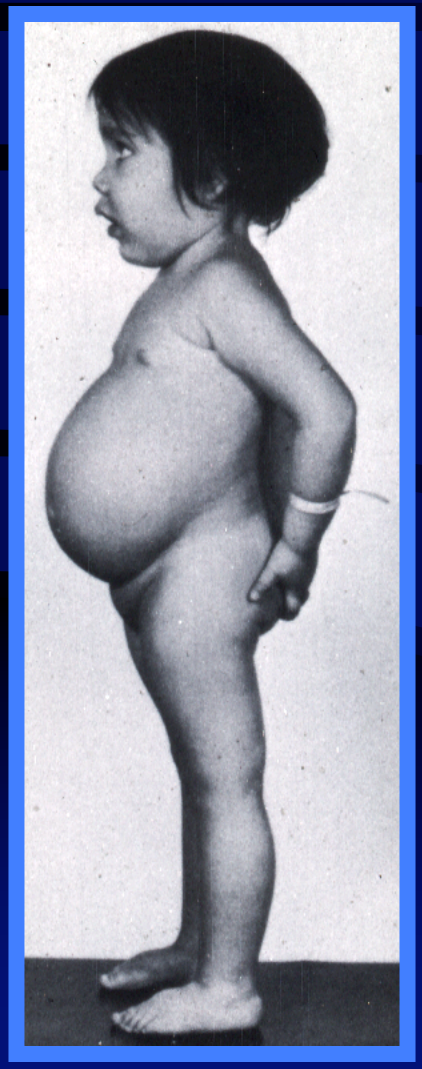
Harald Hirschsprung

1830-1916

Figure 31

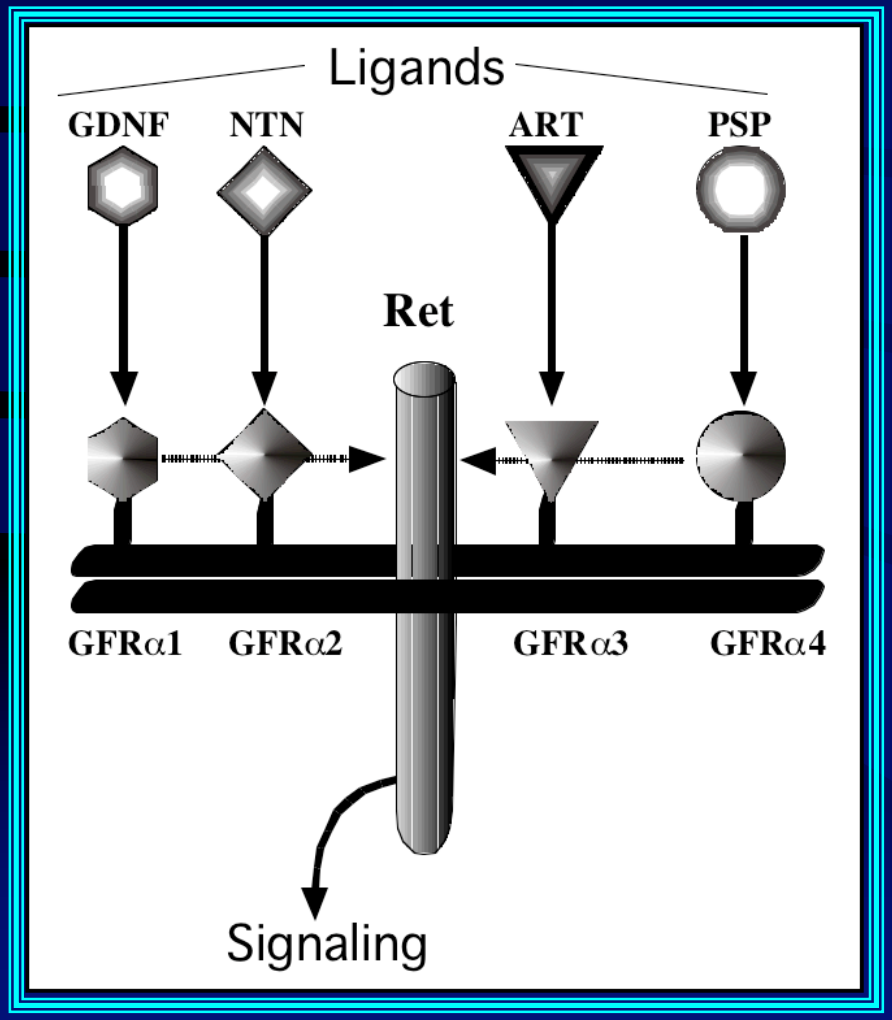
Wood-232.TC

Congenital aganglionosis causes pseudoobstruction



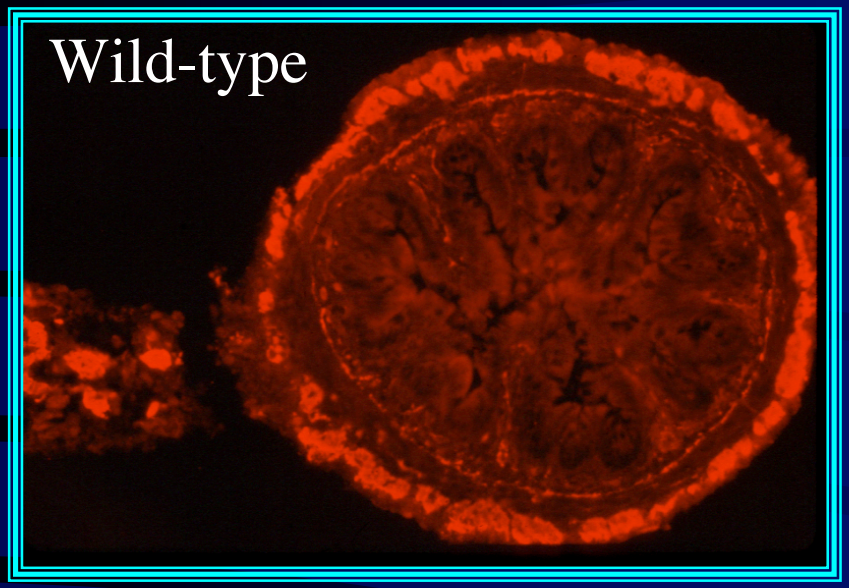
- Hirschspung's disease results from aganglionosis of the terminal colon.
- Associated with the development of megacolon.
- Relatively common disease
  - 1/5000 births in general population
  - 1/500 births in Mennonites (due to inbreeding
- Most commonly due to defect in RET > EDNRB.

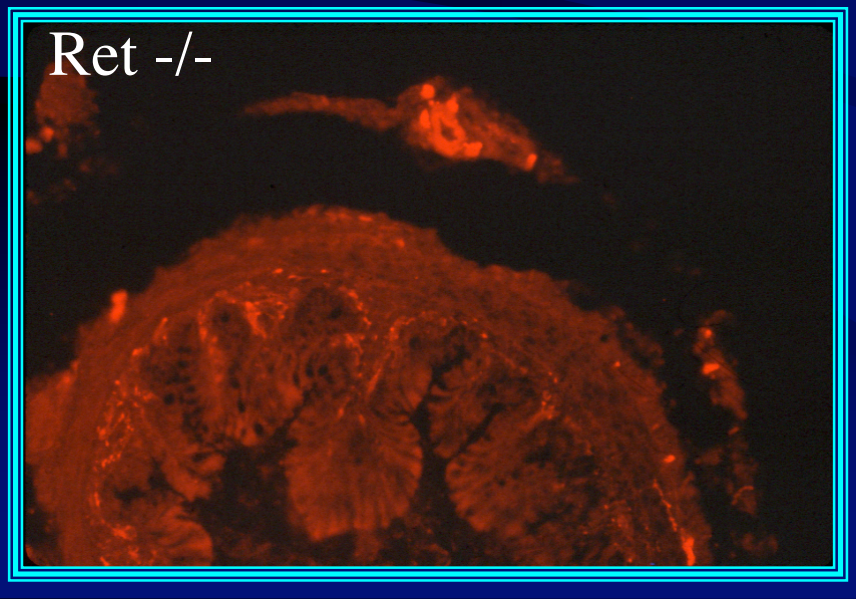
The GDNF family of growth factors activate Ret



- Ret is a receptor tyrosine kinase that is expressed in the gut only by crest-derived cells.
- Activated by ligands that bind to co-receptors
- Ret stimulates proliferation early in development, is a chemoattractant for migrating crest-derived cells, and supports survival.

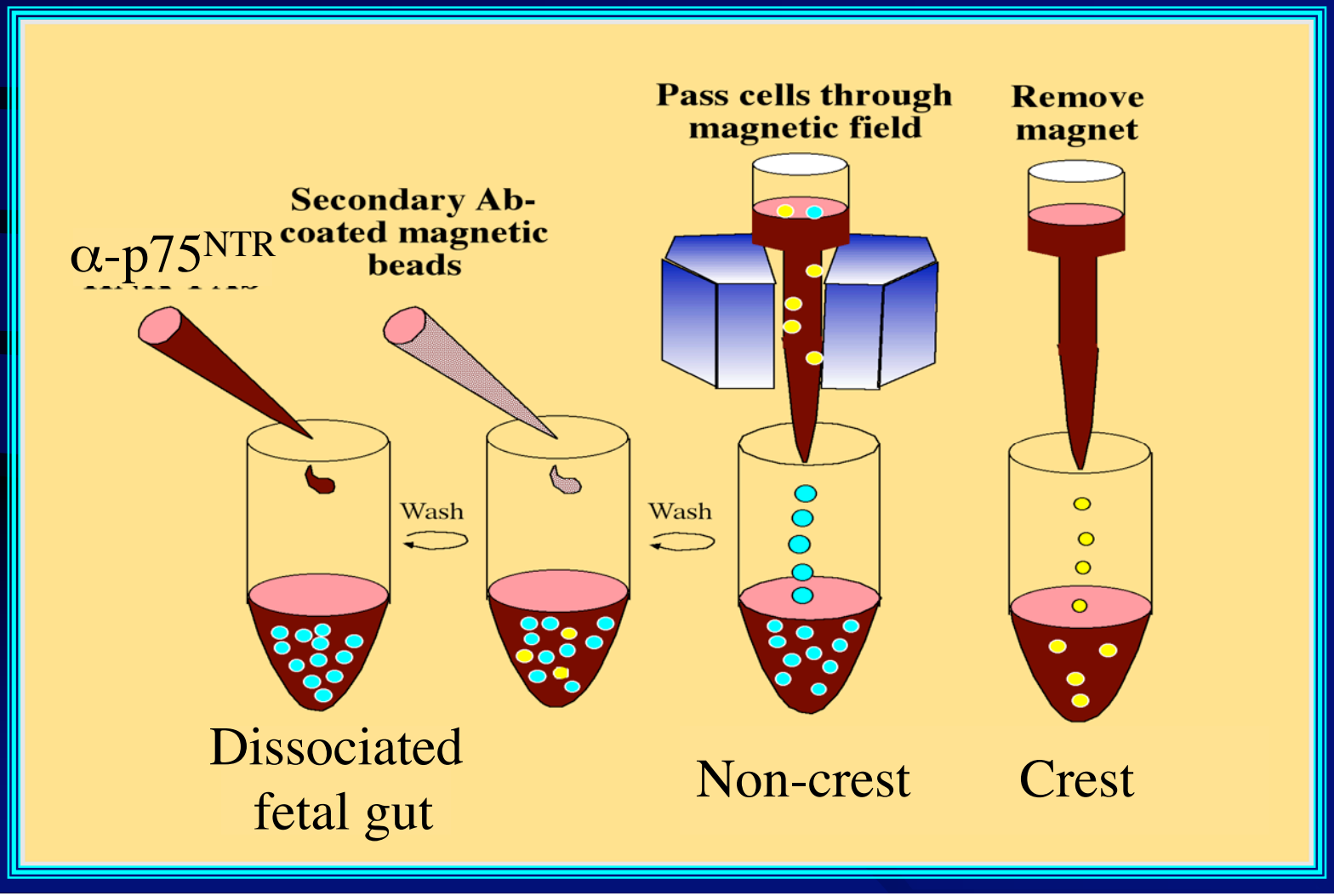
Enteric neurons are Ret-dependent



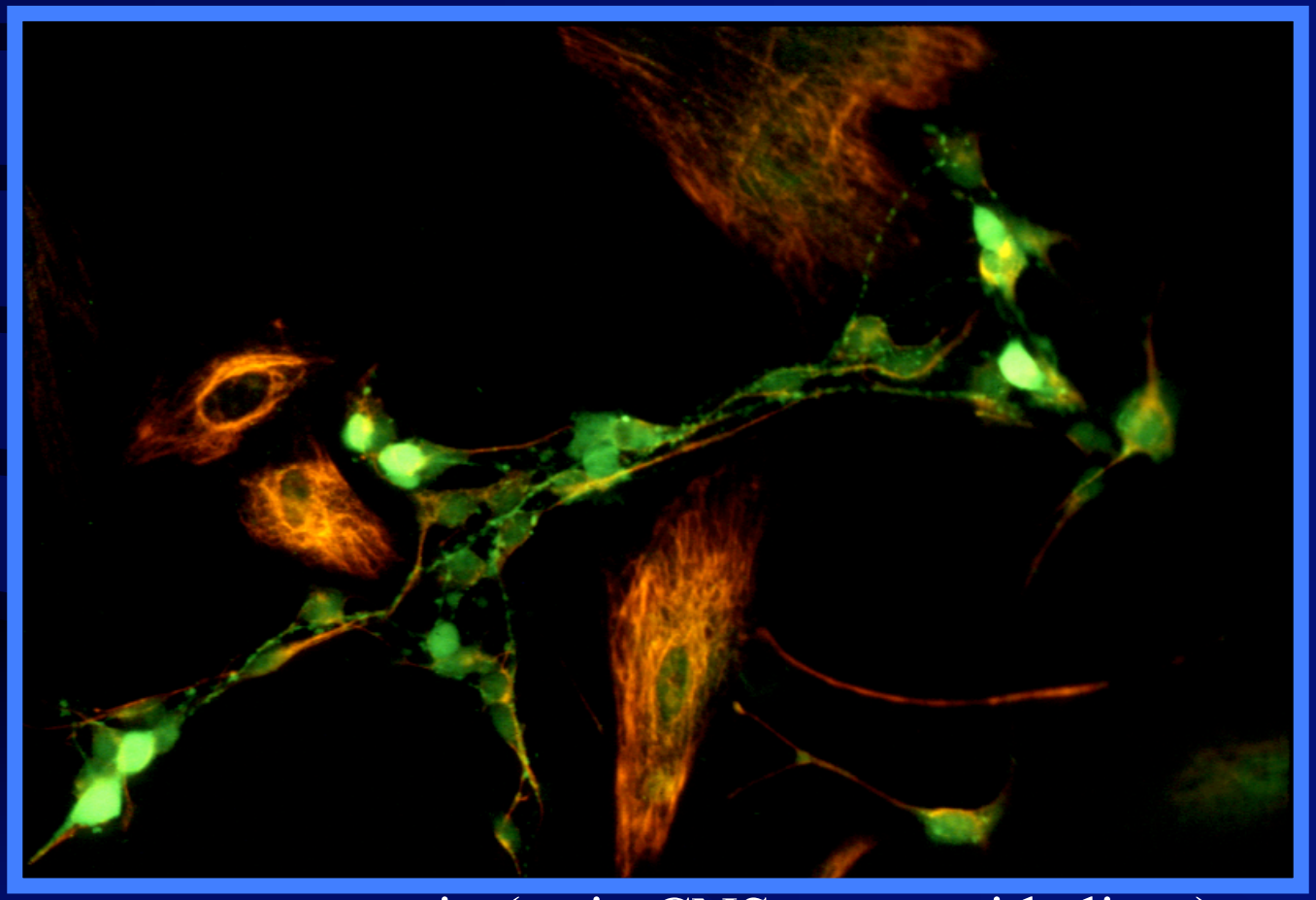


- GDNF binds to GRFα1 and stimulates Ret.
- Mice that lack Ret (or GDNF or GFRα1) lack enteric neurons below the level of the esophagus.
- Loss of function mutations in *RET, GDNF, or GFRα1* are associated with Hirschsprung's disease

Crest-derived cells are isolated by immunoselection.



Neurons develop in cultures of isolated crest-derived cells.

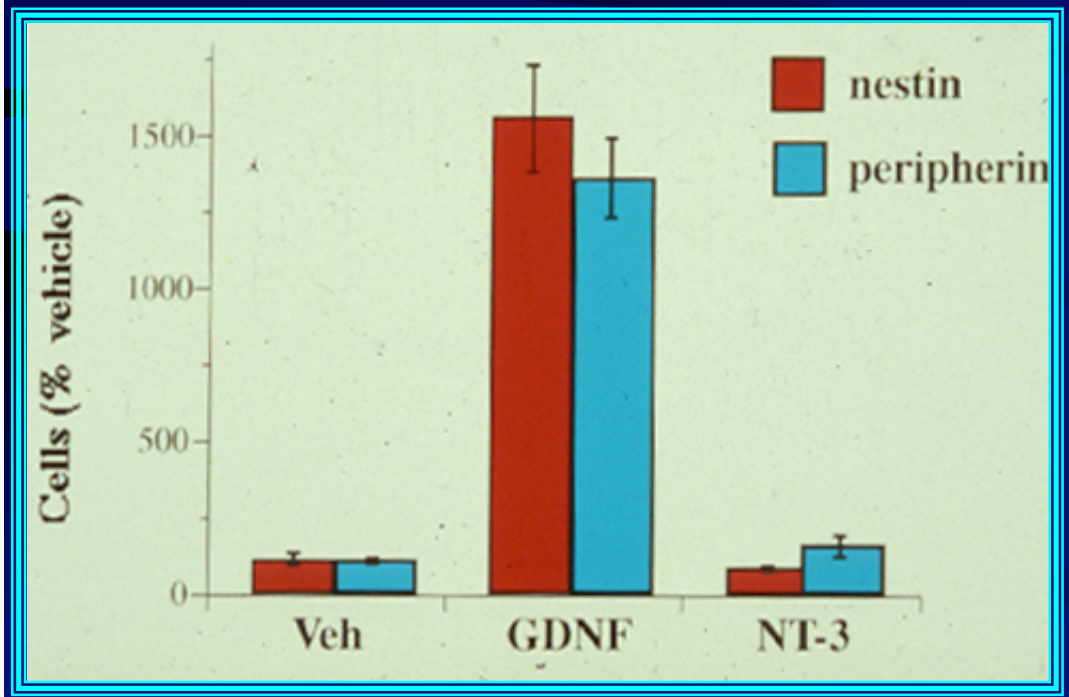


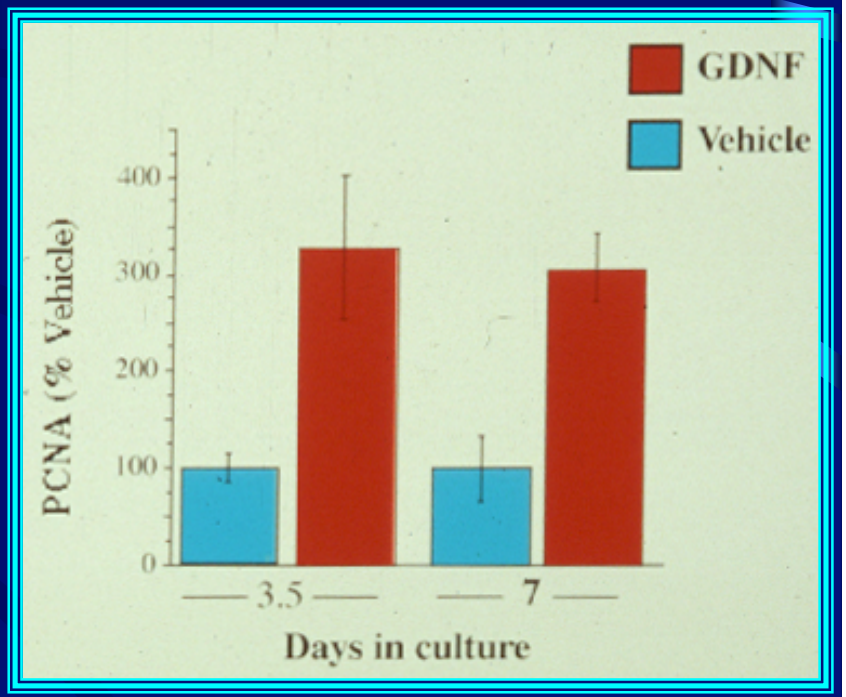
- Precursors express nestin (as in CNS neuroepithelium)
- Neurons express PGP9.5 (a neuronal form of ubiquitin hydrolase).

GDNF is mitogenic and promotes neurogenesis at E12

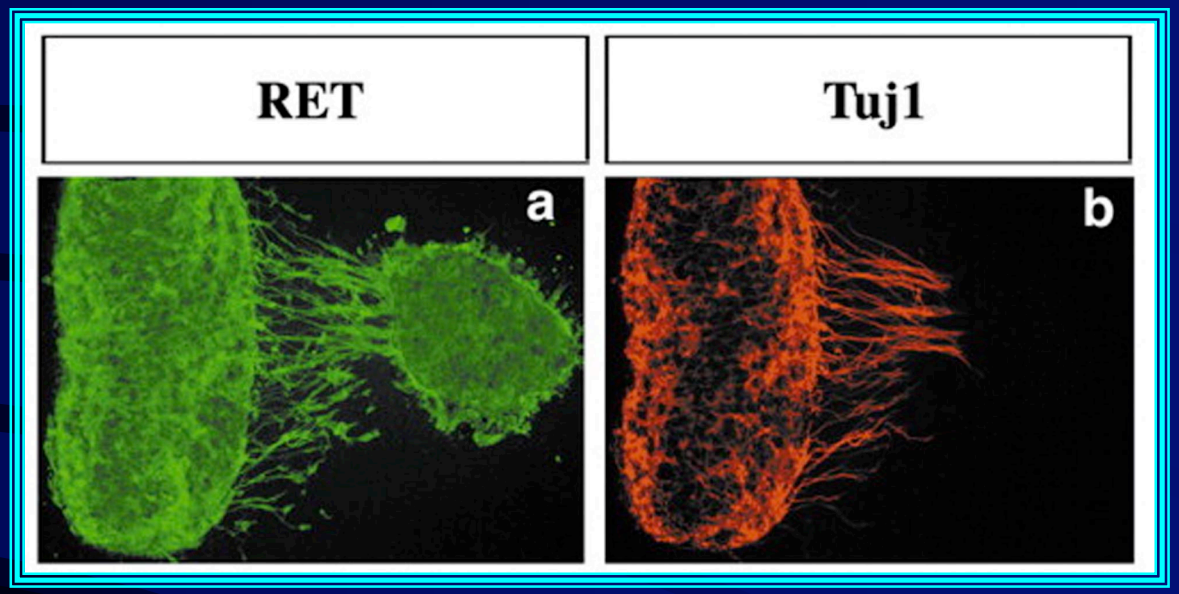
- GDNF increases precursors (**nestin**) and neurons (**peripherin**)
- NT-3 affects neither.

- **GDNF** increases proliferating (PCNA-expressing) cells .



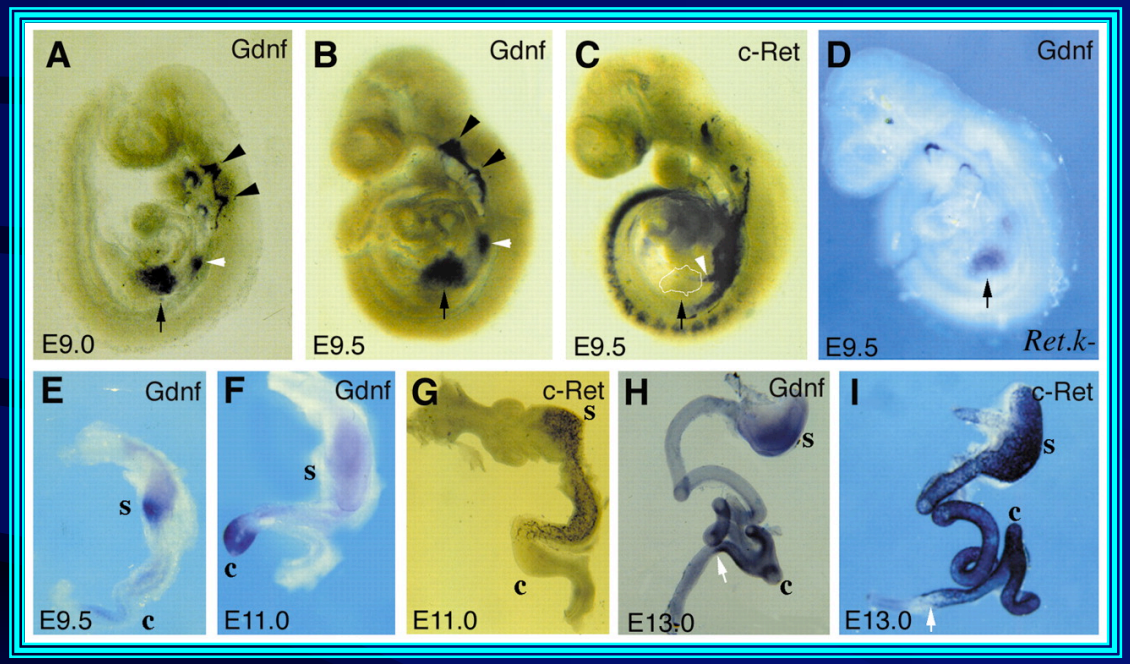


GDNF attracts enteric crest-derived cells



- Cos cells expressing GDNF attract Ret expressing cells from gut explants.
- These cells give rise to neurons (Tuj1).

GDNF is express first in stomach then in cecum



- Ret-expressing crest-derived cells follow GDNF gradient, but how do they get past the cecum?

GDNF/GFRα1/Ret is required to

- 1. Expand the population of crest-derived émigrés sufficiently to colonize the gut.
  - Stimulates mitosis of early precursors.
- 2. Provide a chemoattractive force that directs the proximo-distal migration of crest-derived cells
  - But other factor must break in to limit the proliferation of precursor and allow them to escape the trap of the cecum where GDNF expression is highest.
- 3. If Ret is inadequate: the terminal bowel (last colonized) becomes aganglionic and Hirschsprung's disease results.

Crest-derived cells require Edn3 (ET-3) and Ednrb (ET_B) to complete their colonization of the gut

- The endothelins are vasoactive peptides
  - edn1 (ET-1), edn2 (ET-2), edn3 (ET-3)
- Big endothelins are secreted and converted in tissues to active peptides by endothelin converting enzymes (1 and 2).
- There are 2 endothelin receptors.
- Ednra (ET_A) and Ednrb (ET_B).
  - edn1 and edn2 stimulate both
  - edn3 only activates Ednrb.
    - ENS development requires edn3 and ednrb.

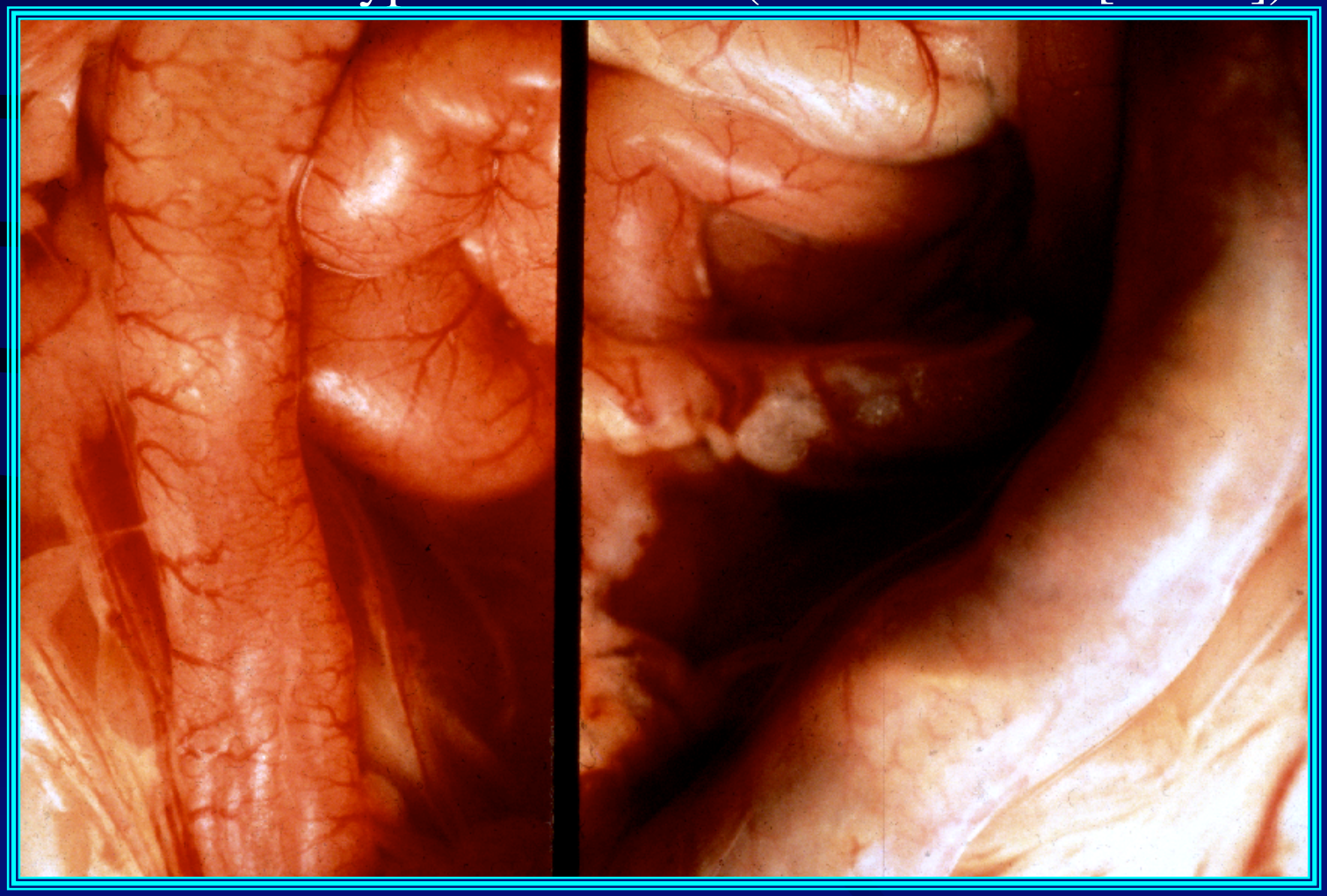
Ret and Ednrb interact in humans and in mice (mice tested to verify human data)

d

	male	female
mean length of aganglionosis (cm)	2.6	1.0
range (cm)	1.7–4.0	0.2–2.0

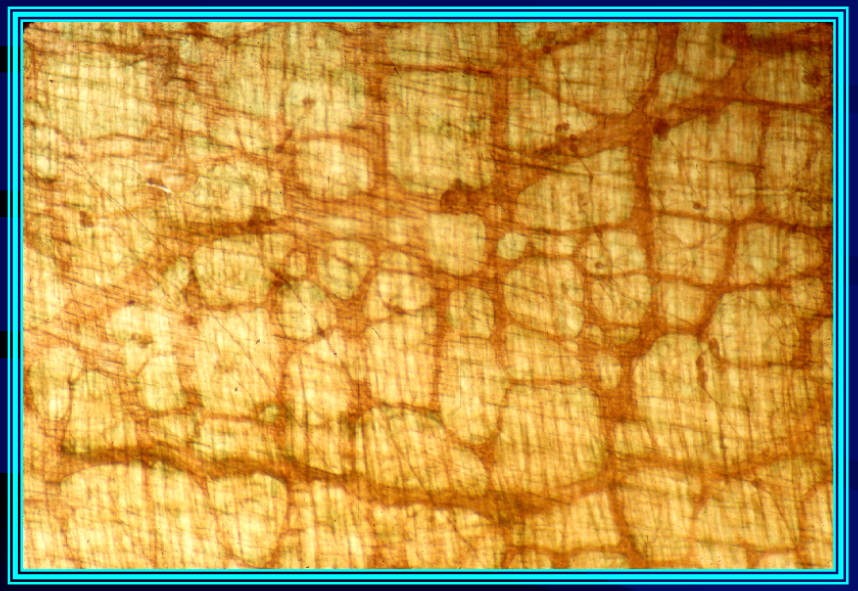
Megacolon occurs in mice that lack edn3 (ET-3)

Wild-type *ls/ls* (edn3-deficient [$edn3^{ls}$])

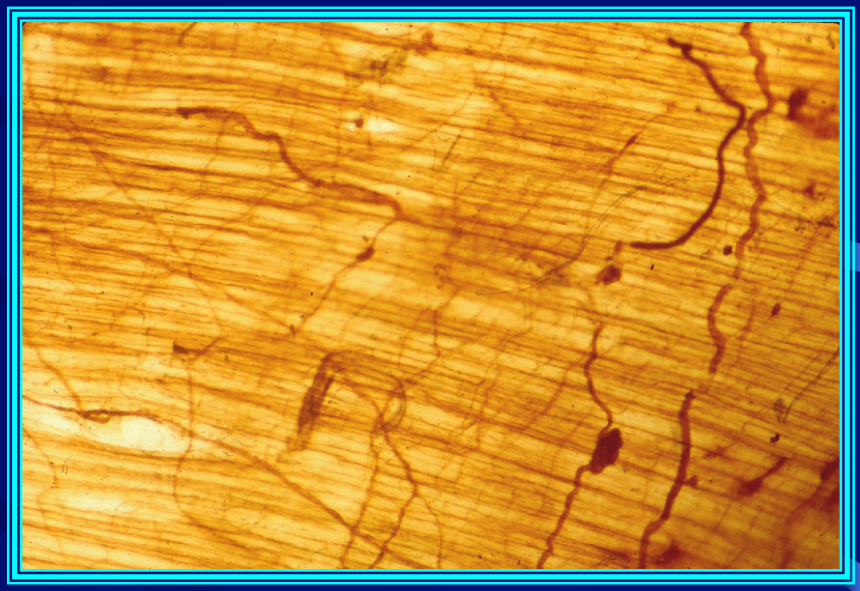


The terminal colon of ET-3-deficient mice is aganglionic

Wild-type



end3^{ls}



- The aganglionic bowel is not denervated.
  - It contains large nerve trunks containing extrinsic axons and projections from the proximal hypoganglionic bowel.

Co-cultured sources of crest fail to colonize presumptive *end3^{ls}* gut

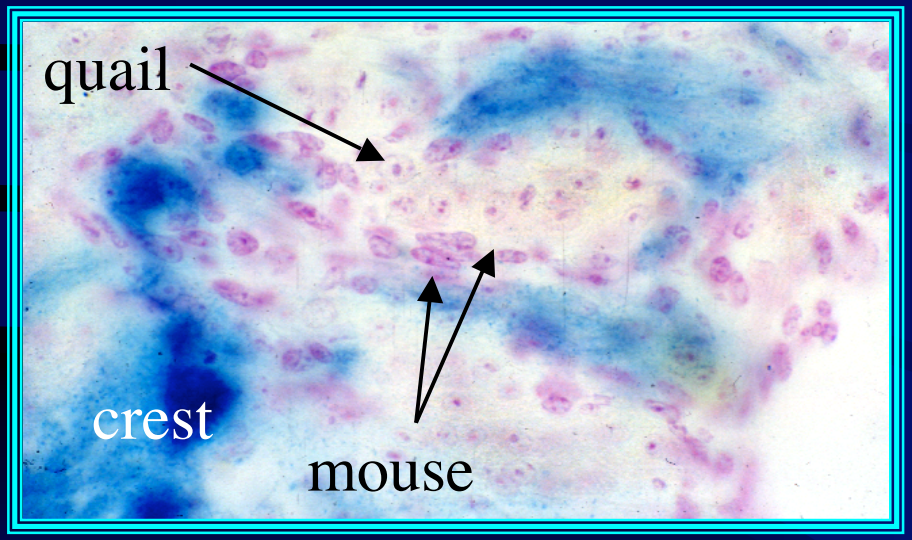
Wild-type mouse colon

***edn3^{ls}* mouse colon**

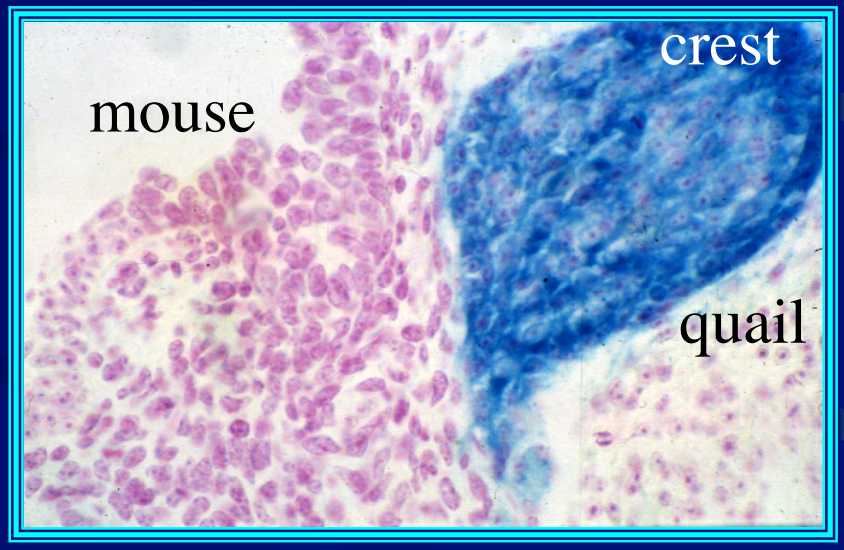
- Donor neurons marked by AChE activity.
- Donor neurons enter wild-type mouse colon but not *end3^{ls}* colon.

Presumptive aganglionic gut from *edn3*^{ls} mice cannot be entered by quail crest cells

Wild-type mouse colon

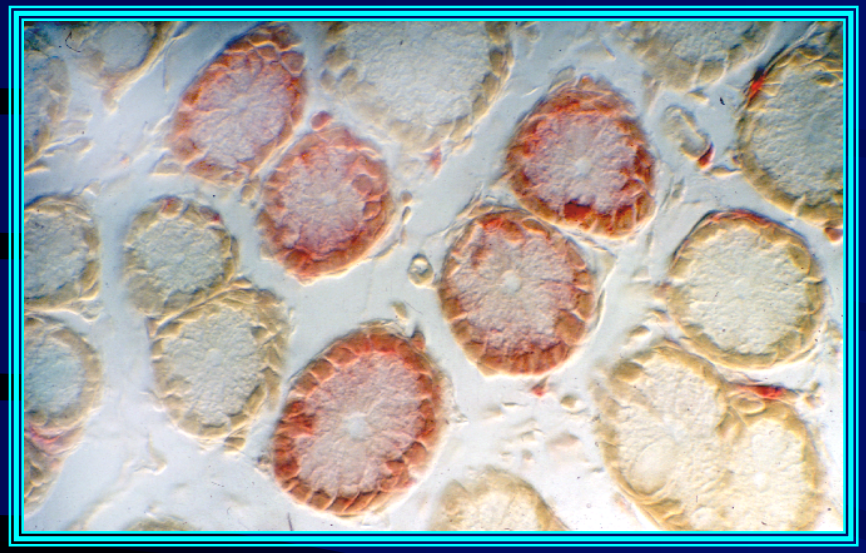


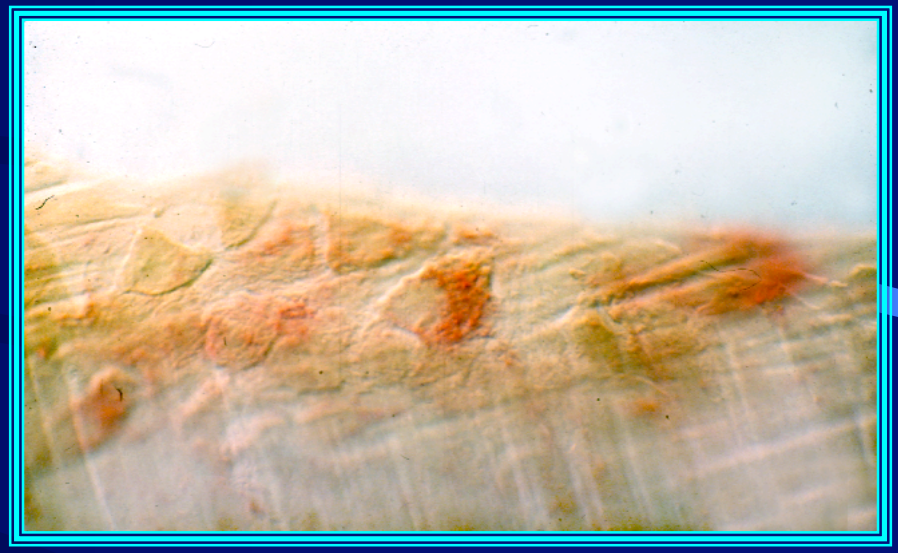
***edn3*^{ls} mouse colon**



- Mouse colon was grafted into a quail crest migration pathway.
- Crest is immunostained blue (HNK1).
- Mouse nuclei are different from those of quail, enabling a graft of mouse gut to be recognized in a quail host.

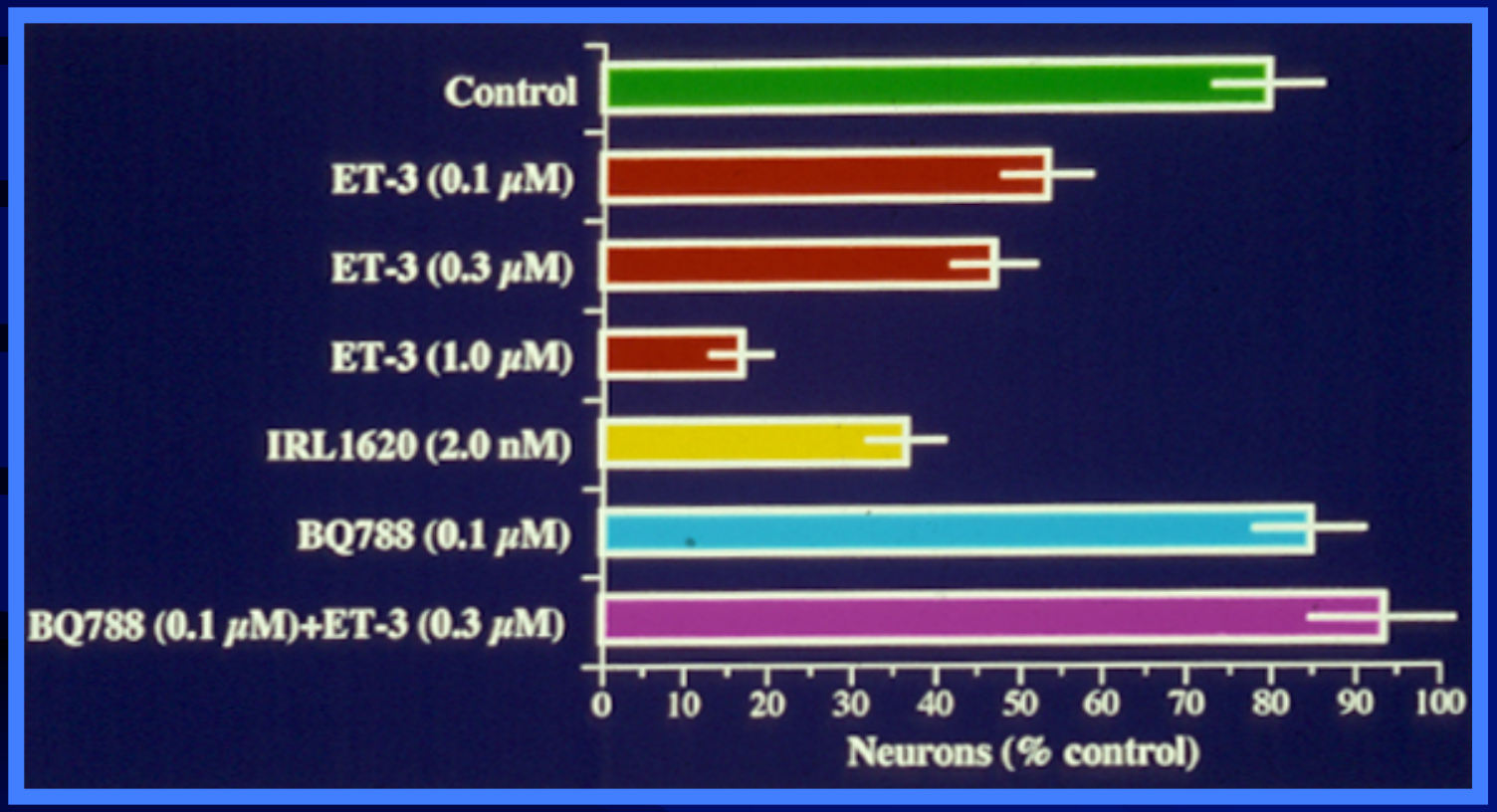
The terminal colon is normally colonized in *end3^{ls}* <> WT chimeric mice





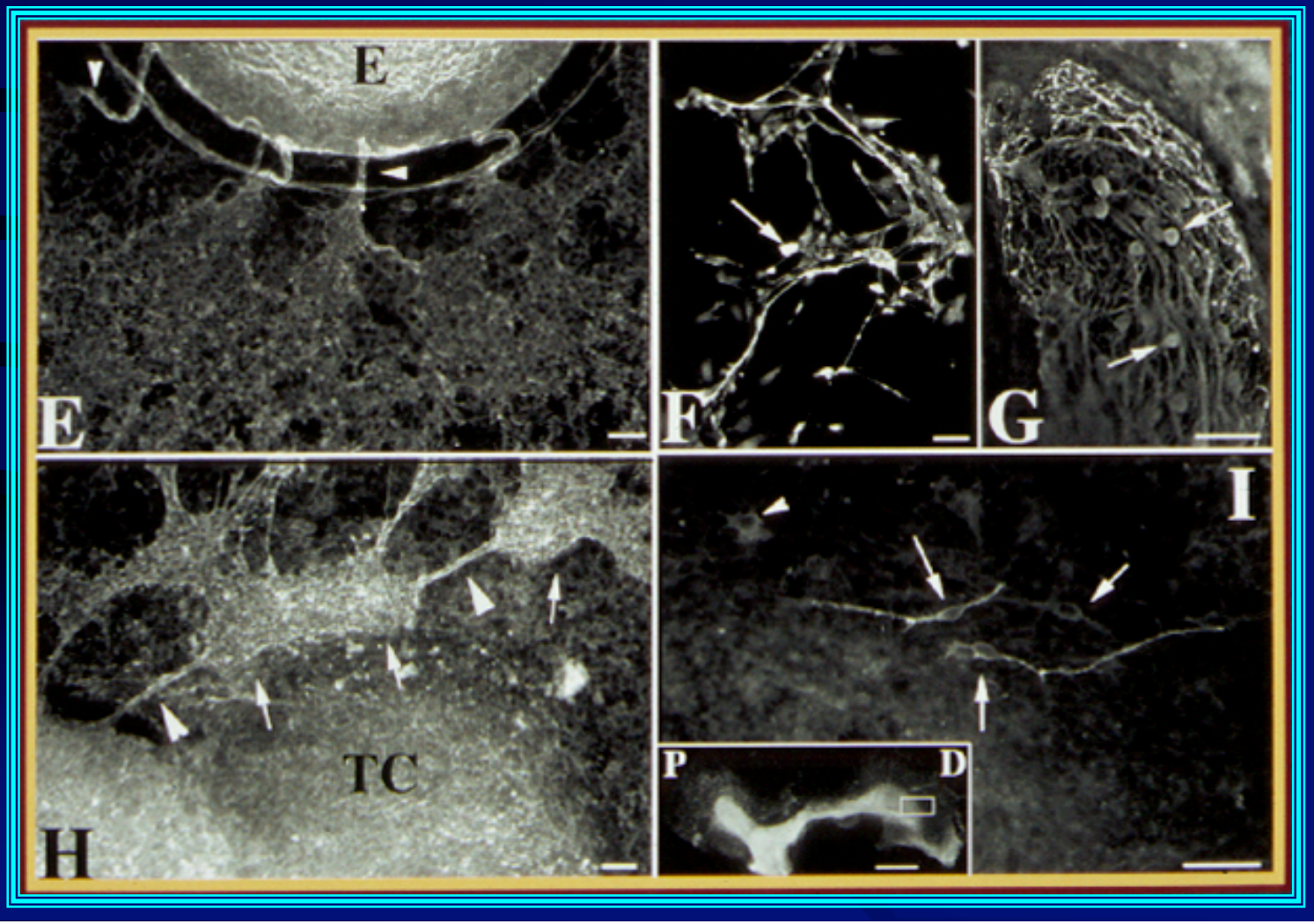
- Cells of WT mice have low and *end3^{ls}* mice have high levels of β-glucuronidase
- Crypts are clonal in origin.
- Neurons and connective tissue cells are either WT or *edn3^{ls}*.
- *Edn3^{ls}* neurons are found in the terminal colon.

Edn3 inhibits the development of neurons from crest-derived precursors

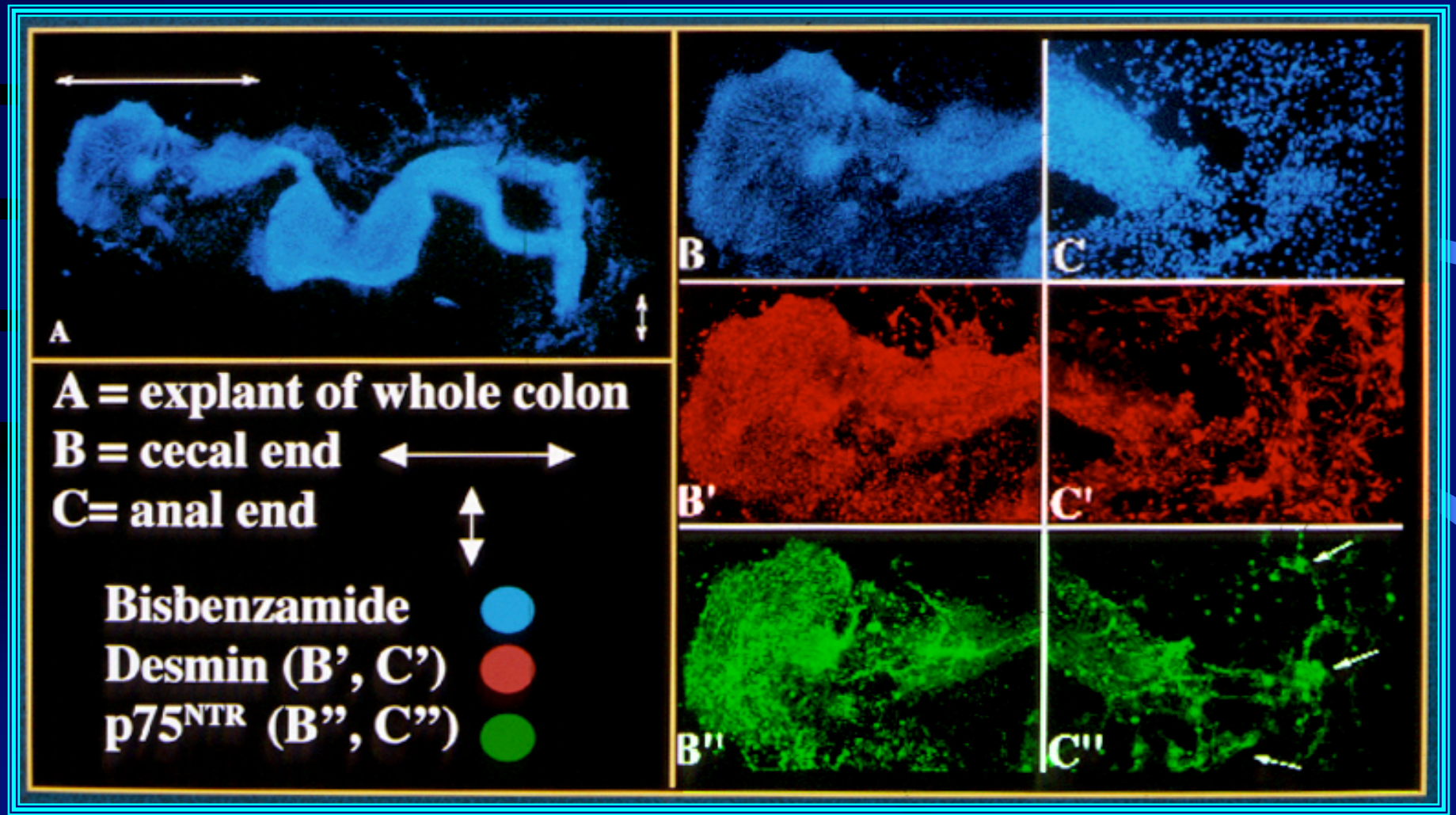


- Edn3 effects are mimicked by the ETB agonist, IRL1620 and blocked by the antagonist BQ788, but neurons develop in the presence of BQ788. Edn3 is not required for neural development.

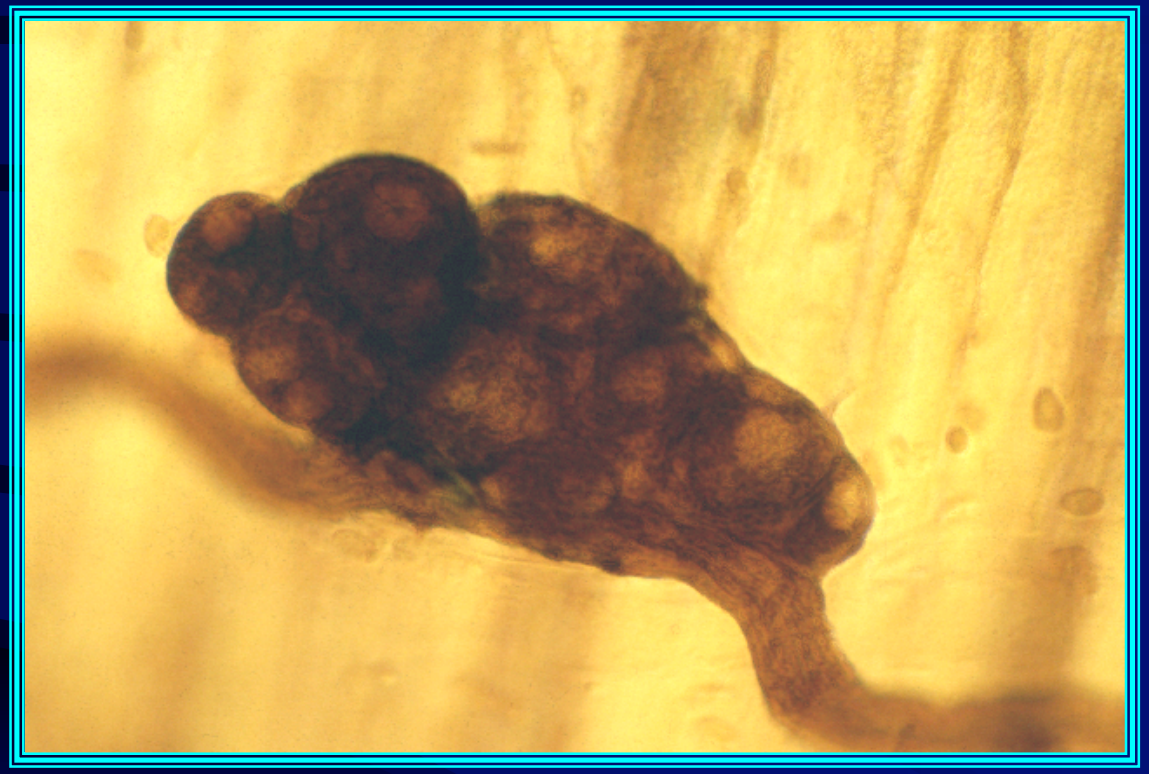
Exogenous Edn3 enables crest-derived cells to enter the terminal colon of Edn3-deficient mice



Exogenous ET-3 allows crest-derived cells to colonize the entire colon *in vitro*

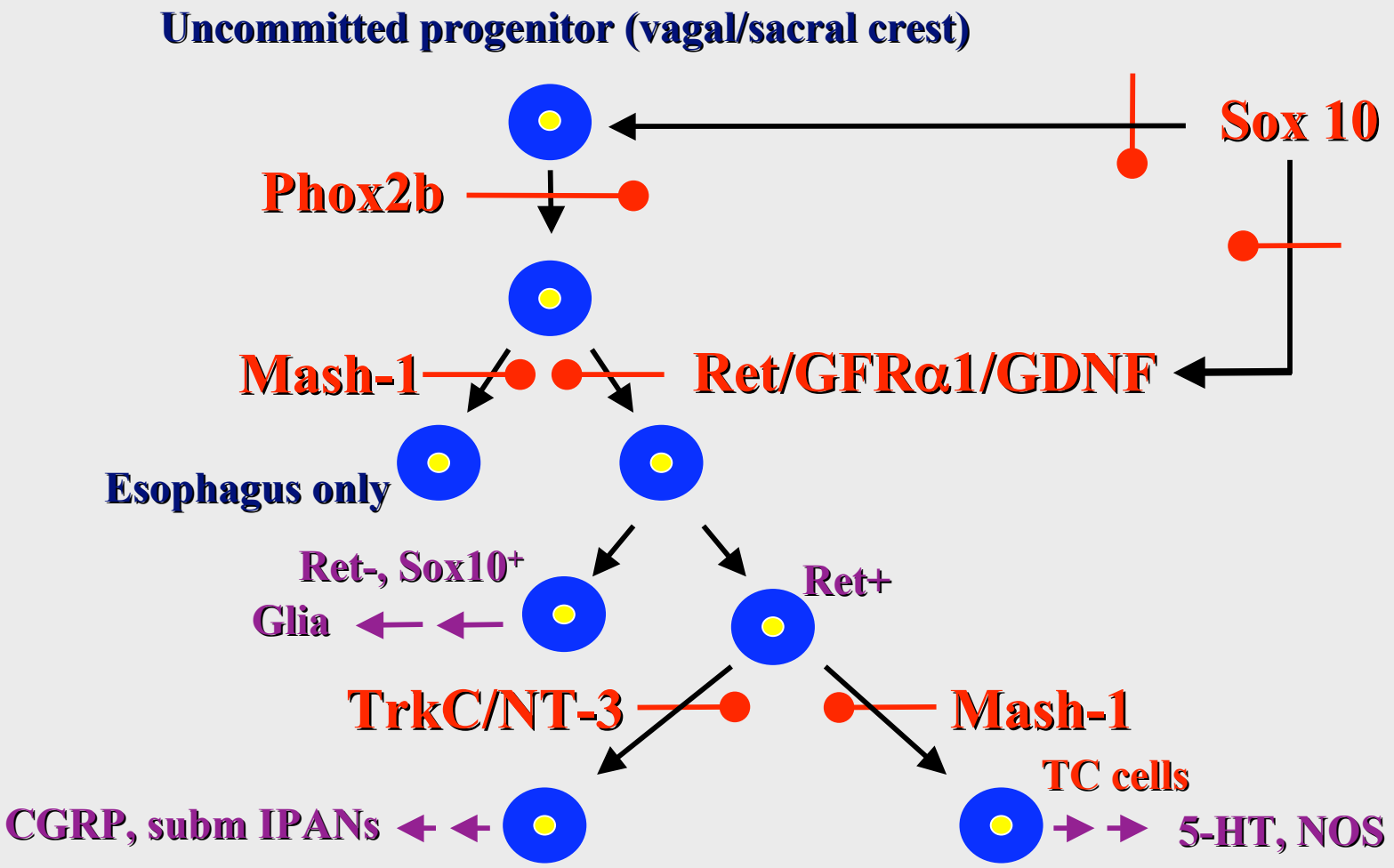


Ectopic ganglia develop in the pelvis of *end*^{ls} mice



- Structure is that of peripheral nerve, not ENS.
- Thought to be derived from sacral crest cells that have stopped migrating before reaching the gut.

Specific transcription and growth factors define stages in ENS development



The earlier a gene acts in development, the more massive the defect that follows its deletion

- Genes that lead to complete aganglionosis when knocked out
  - Phox2b
  - Sox10
  - Ret/GDNF;GFRα1 (below esophagus)
- Genes that lead to limited lesions when knocked out
  - Mash-1
  - Edn3/Ednrb
  - NTN/GFRα2
  - NT-3/TrkC

Genes associated with Hirschsprung's disease

- Phox2b: Transcription factor expressed by the most primitive of the crest-derived cells that colonize the gut.
- Sox10: Transcription factor: required early in development.
- Ret, its co-receptors, and ligands: Receptor tyrosine kinase activated first by GDNF, and then NTN.
- EDN3 and EDNRB: collaborates with Ret and needed by non-crest-derived cells of colon
- SIF1: Encodes Smad protein, involved in BMP signaling

Summary & Conclusions

- Intrinsic properties and microenvironmental signals (paracrine factors; ECM) determine the fates of crest-derived cells.
  - The ENS is derived from a multipotent set of precursors that migrate to the bowel from the neural crest.
  - Signals from the migratory and enteric microenvironments determine the fates of the crest-derived ENS precursors.
- Developmental potential is restricted and commitment increases as development proceeds.
  - Stages in development can be recognized by the dependence of cells on a succession of essential transcription factors, growth factors and their receptors.
    - Early factors include Phox2b, Sox10, Ret/GFRa1/GDNF
    - Later factors include Mash-1, EDNRB/EDN3, NT-3/TRkC