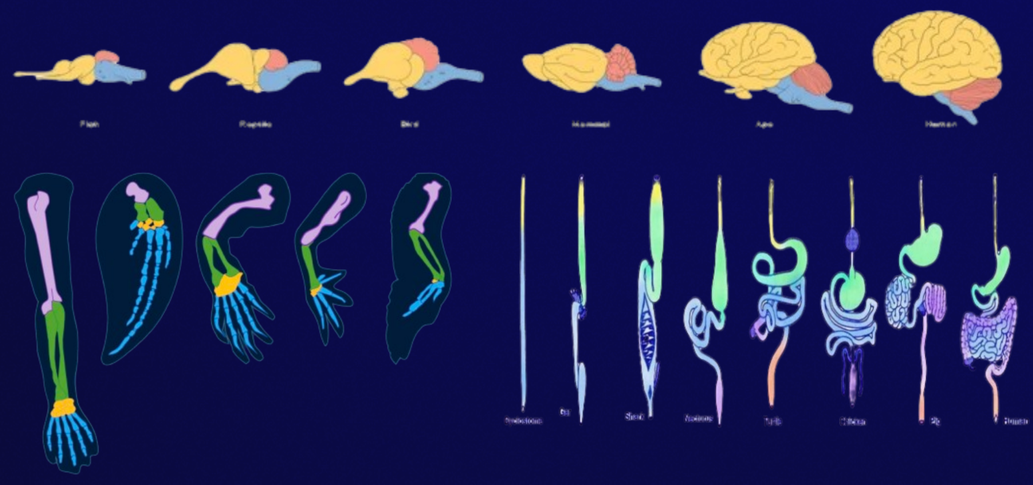
The molecular evolution of vertebrate organs

Journal Club of Zhang Lab

Guangji Chen 2026.04.03



Background

nature ecology & evolution

Review article

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The molecular evolution of vertebrate organs

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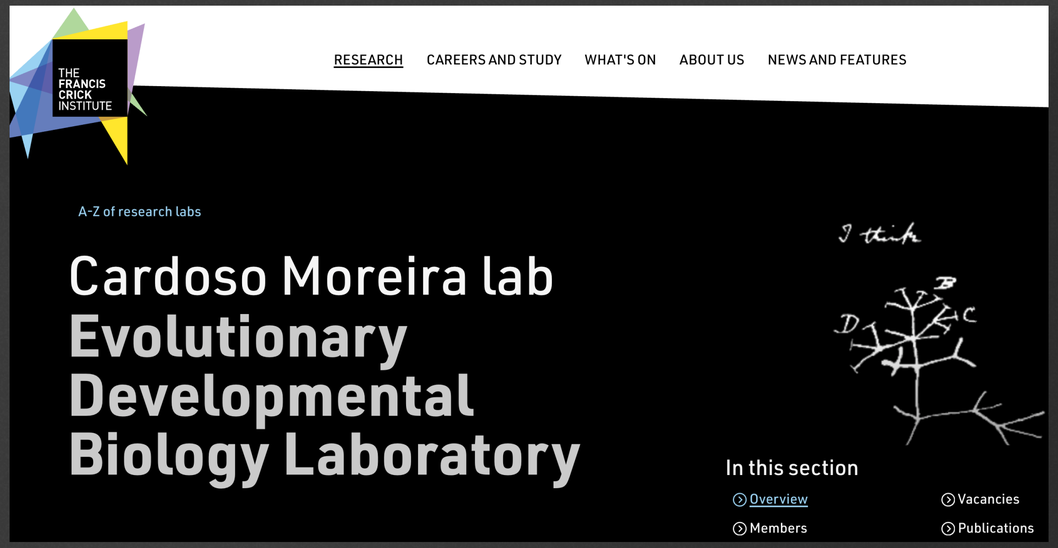
Margarida Cardoso-Moreira

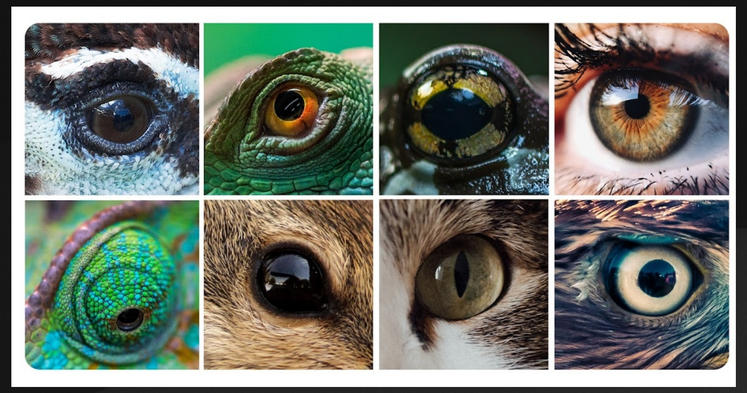
- **Review article**
- ***Nature ecology & evolution***
- Published online: 25th Feb 2026



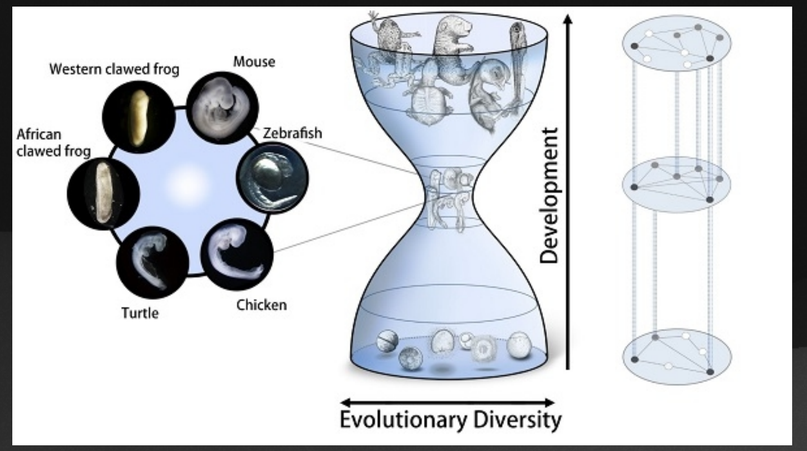
Evolutionary Developmental Biology Laboratory, The Francis Crick Institute, London, UK

Margarida Cardoso-Moreira

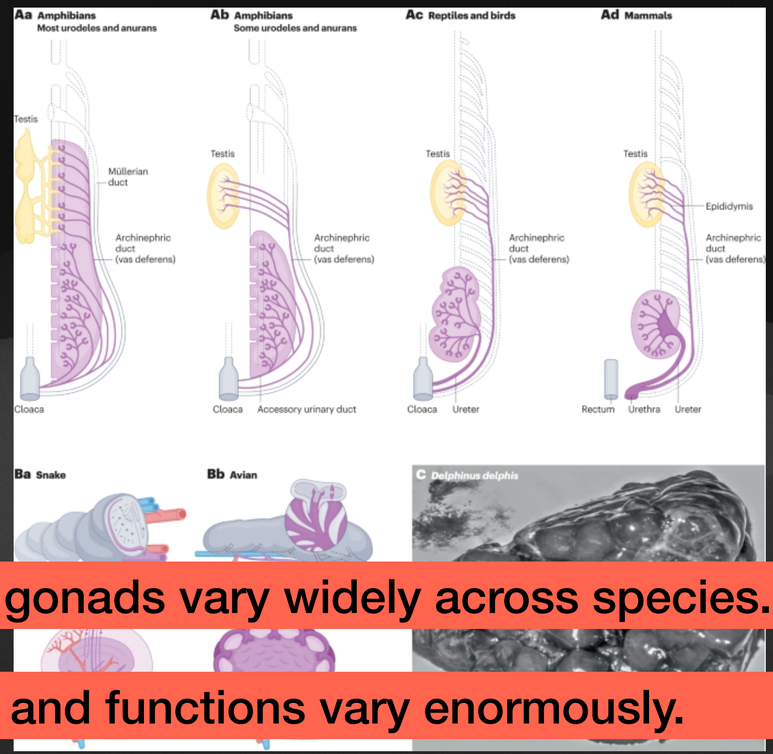
Vertebrate organs



Vertebrate eyes



Vertebrate *bodyplan*

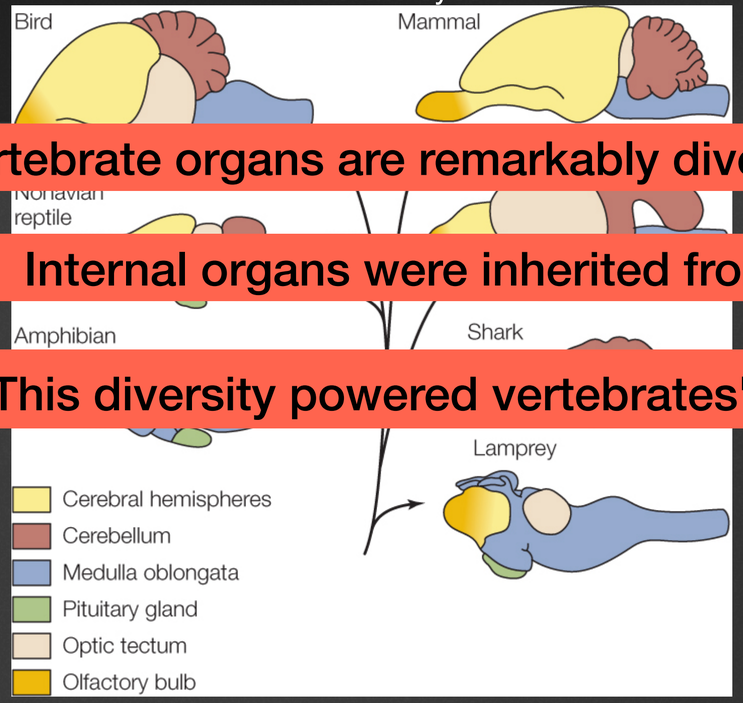


Vertebrate kidney

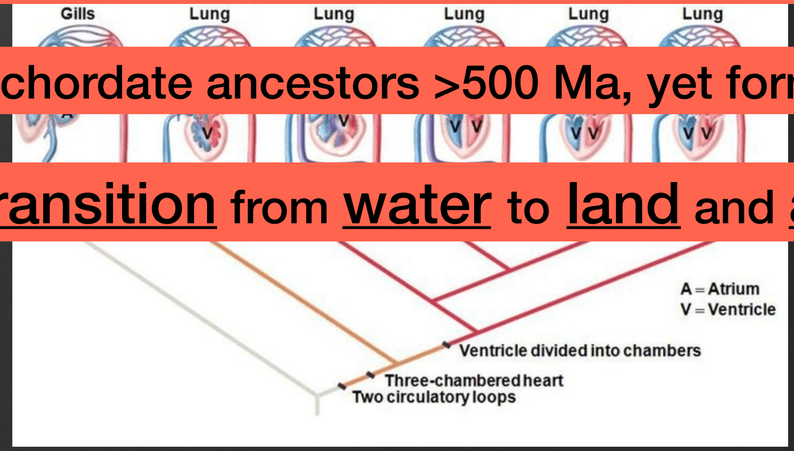
Vertebrate organs are remarkably diverse — brains, hearts, kidneys, livers, and gonads vary widely across species.

Internal organs were inherited from chordate ancestors >500 Ma, yet forms and functions vary enormously.

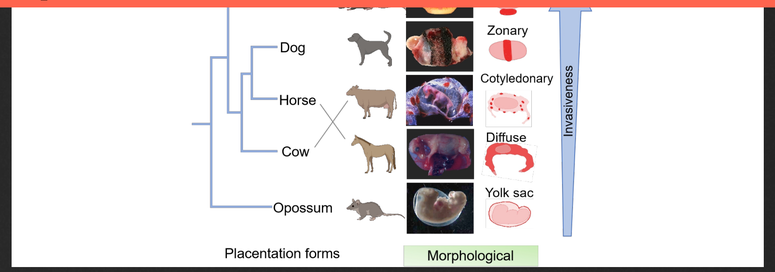
This diversity powered vertebrates' transition from water to land and adaptation to most environments.



Vertebrate brain



Vertebrate heart



Mammalian Placenta (@ Wang Lab)

Questions

- What molecular & developmental changes are responsible for the *origin* and *diversification* of *vertebrate organs*?
- What *evolutionary forces* drove these changes?
- How do new technologies (WGS, single-cell genomics, genome editing) *transform* our understanding?

Outlines

01 **Molecular Basis of Organ Evolution**
Types of molecular changes driving phenotypic diversity

02 **Organs & Cells Evolve at Different Rates**
Brain vs. testis; single-cell insights

03 **WGS & Ohnologues**
Ohno's hypothesis, ohnologues, and vertebrate innovations

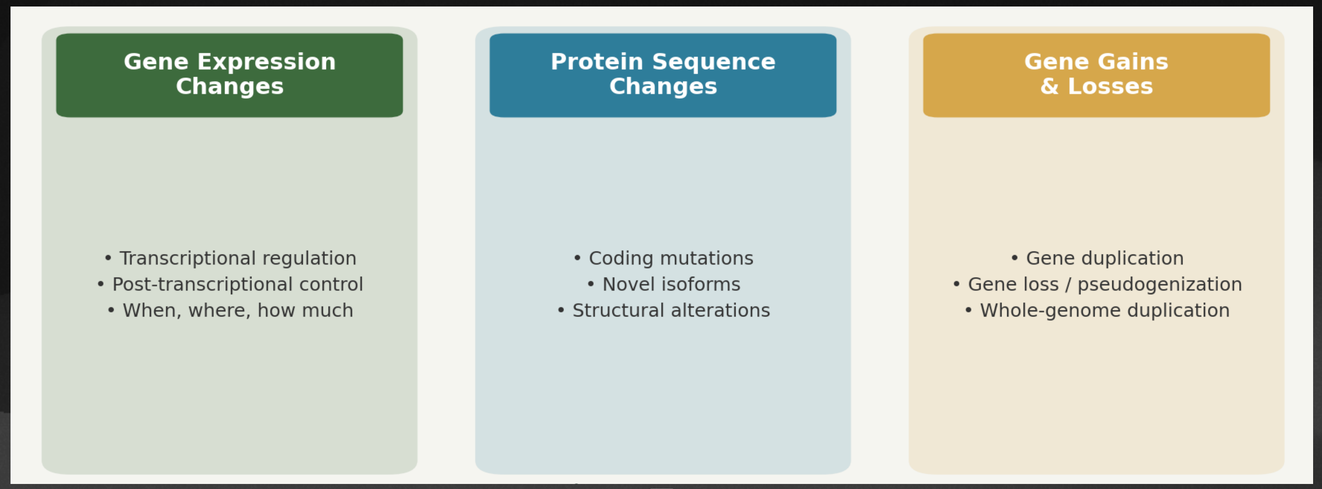
04 **Evolutionary Forces & Sex Differences**
Purifying selection, positive selection, and sex differences

05 **Evolution & Development**
Von Baer's law, hourglass model, pleiotropy

06 **Origin of Evolutionary Novelties**
New forms, cell types, and organ gains/losses

07 **Future Directions**
Golden period for organ evolution research

01. Molecular Basis of Organ Evolution



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Phenotypic Diversification of Vertebrate Organs

Questions Remain

- **Morphology** changes driven by gene expression?
- **Physiology** changes driven by protein sequence?

- Are gene expression changes the most common driver?
- Mutations in regulatory elements tend to be less pleiotropic?
- Can transposable elements rapidly rewire gene networks?

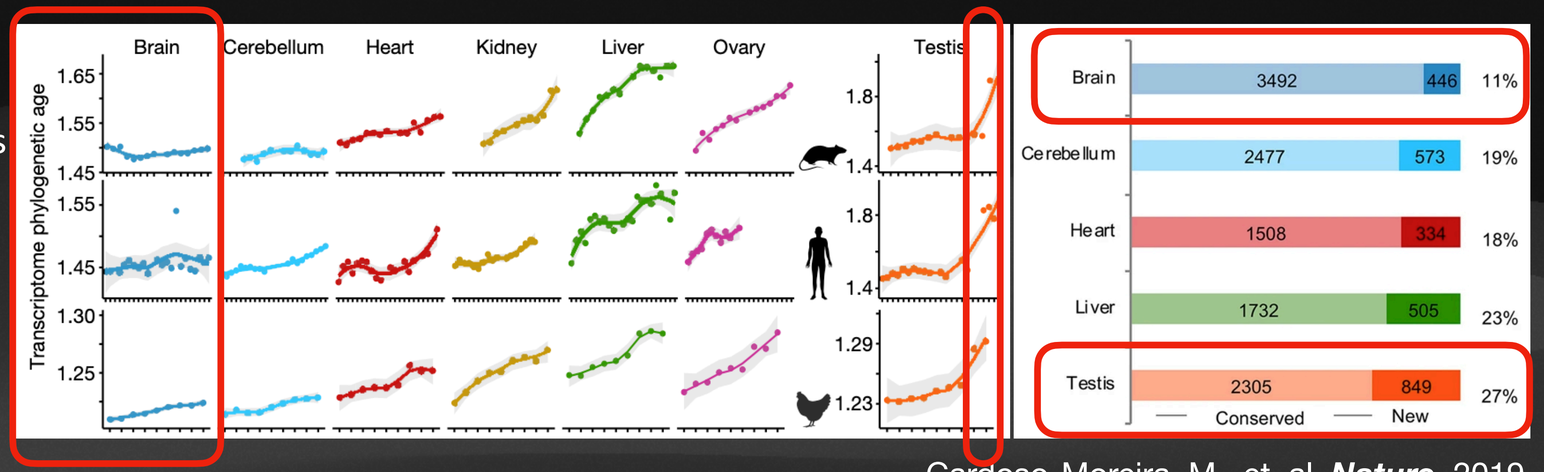
Identifying genetic basis of organ evolution remains challenging, due to the most traits emerge from many genetic changes over millions of years.

02. Organs & Cells Evolve at Different Rates

Organs Evolve at Different Rates

Brain — Slowest Evolving

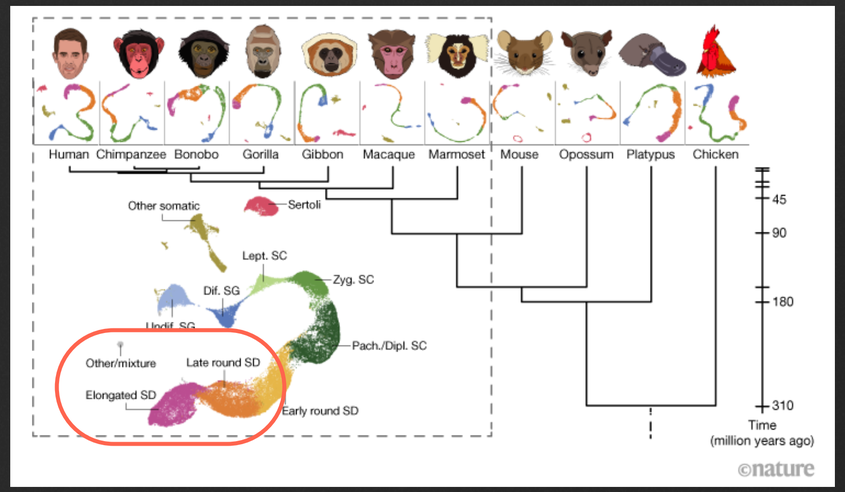
- Genes expressed in brain differ least across species
- Consistent across all vertebrate lineages studied
- Strongest purifying (stabilizing) selection



Cardoso-Moreira, M., et. al. ***Nature***. 2019

Testis — Fastest Evolving

- Sperm competition, sexual conflict, and meiotic drive all proposed as drivers
- When organs evolve faster, they do so through multiple molecular change types in parallel
- Ovary evolves considerably slower than testis
- Weaker purifying selection, especially in late-spermatogenic [生精晚期] cells



The rapid evolution of the testis mostly to late spermatogenic (post-meiotic) cells.

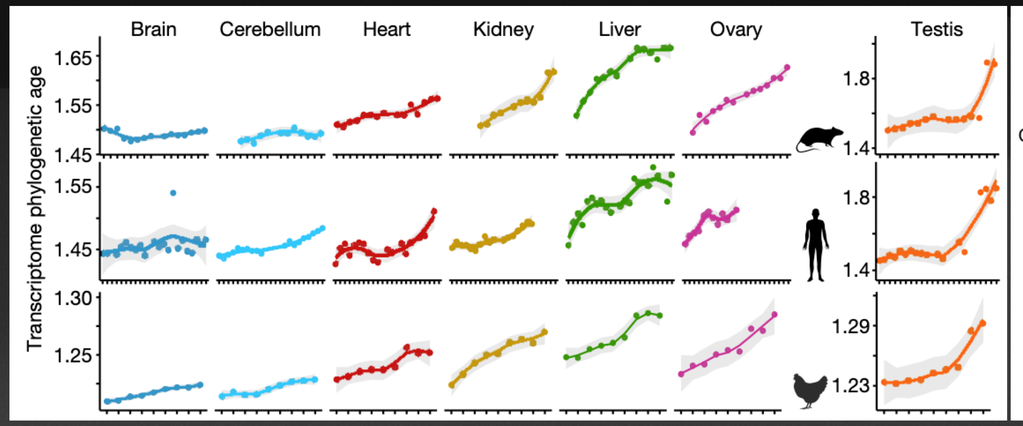
Florent, M., et al., ***Nature***. 2022

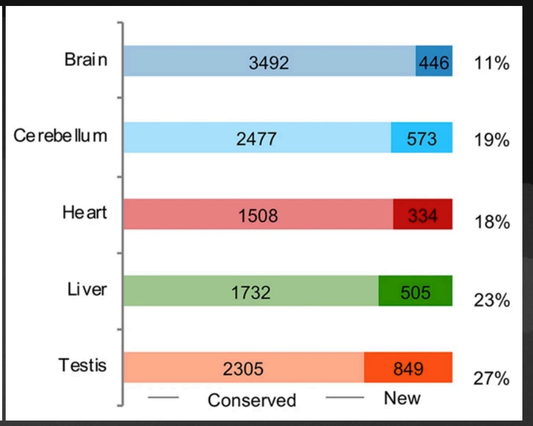
02. Organs & Cells Evolve at Different Rates

Organs Evolve at Different Rates

Alternative Splicing

- More prominent in brain and heart evolution
- Extensive in neurons and cardiomyocytes
- Species differences in splicing timing (heterochrony) common in ovary and testis





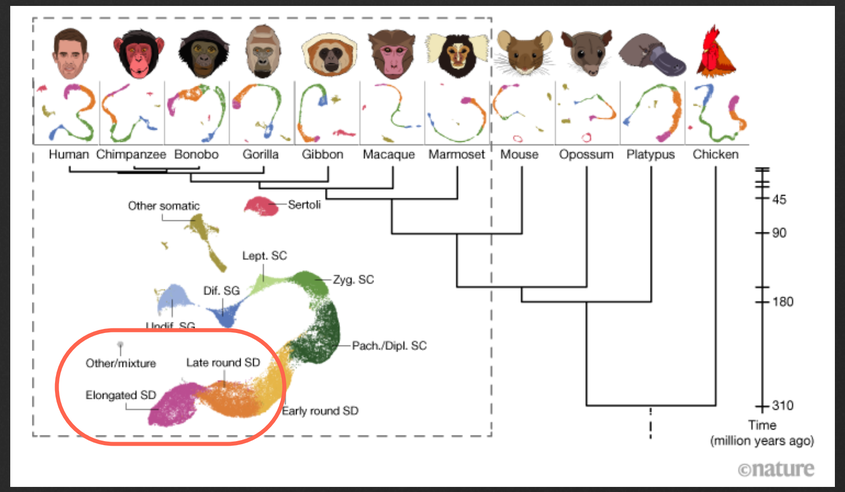
Cardoso-Moreira, M., et. al. ***Nature***. 2019

Gene Expression

- Changes in expression levels and timing are widespread
- Newly evolved enhancers near positively selected genes (liver)
- Organs with most expression divergence show more positive selection

Transposable Elements

- Add new exons and genes to genomes
- Can 'rewire' entire gene regulatory networks
- Disproportionately contribute to fast-evolving organs: testis, blood, immune, placenta



The rapid evolution of the testis mostly to late spermatogenic (post-meiotic) cells.

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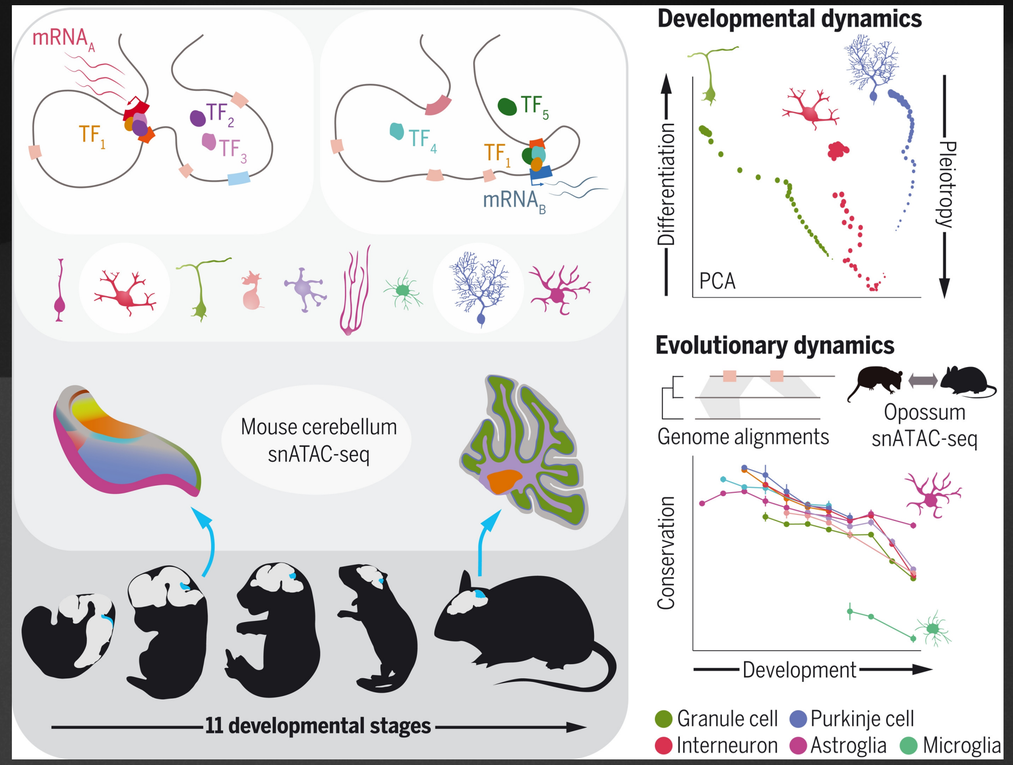
02. Organs & Cells Evolve at Different Rates

Organs & Cell-Level Evolutionary Rates



- Most brain cell types is slow-evolving.
- The fastest cell type in brain is microglia, which is one of the immune cells (generally fast-evolving).
- But the microglia is the slow-evolving cell type among the immune cells.

The fastest cell type in brain is microglia[小神经胶质细胞].

Shared cell types (eg. immune cells) evolve at rates reflecting their organ-specific neighbors.

04. Evolutionary Forces & Sex Differences

Except the neutral processes, there are …

Claude Generated

Evolutionary Forces

- Purifying selection: pervasive across all organs, but strength differs — strongest in brain, weakest in testis
- Positive selection: amplifies differences between organs (liver, immune organs, and testis are frequent targets)

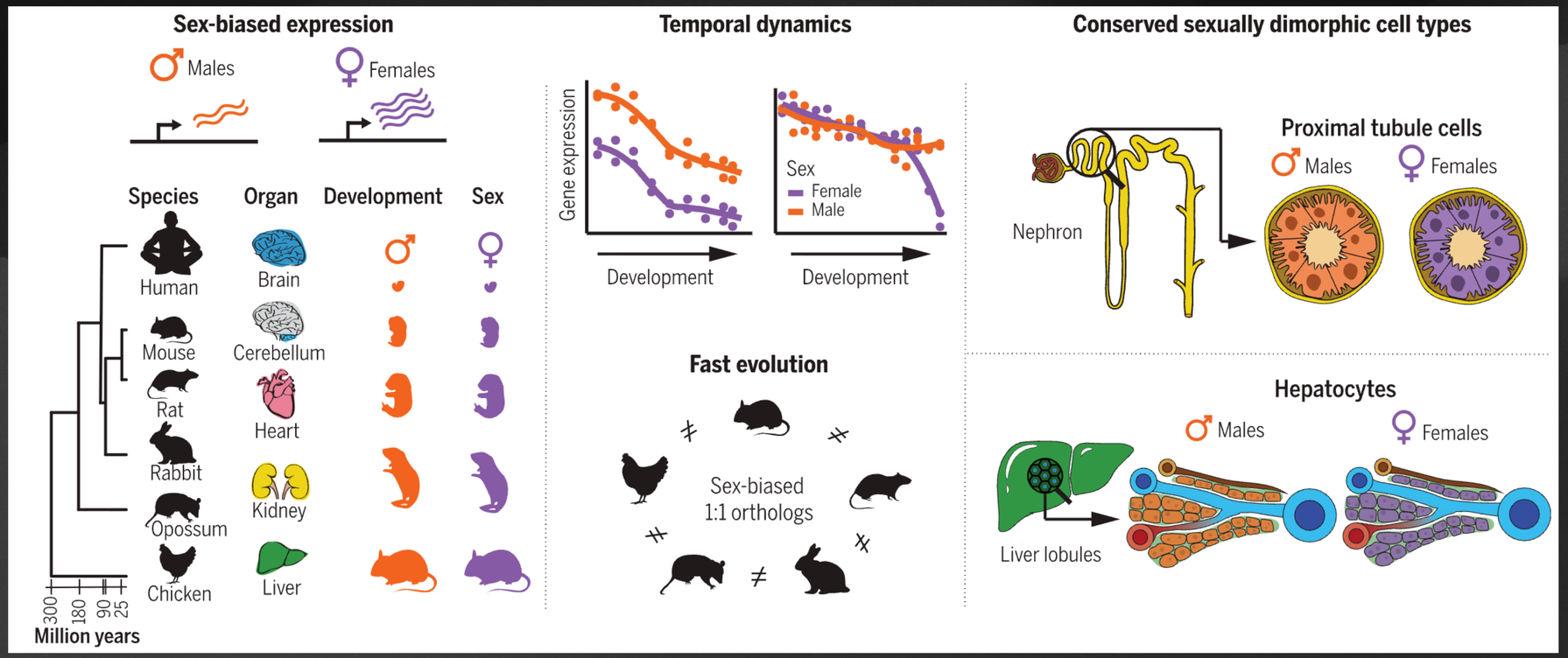
- Both forces work together to create the pattern of differential evolutionary rates

04. Evolutionary Forces & Sex Differences

Sex Differences (sex-biased expression)

An area of increasing interest is the evolution of sex differences, particularly sex-biased gene expression

Different genes but the same organ!



Rodríguez-Montes, L., et. al. ***Science***. 2023

Why do organ sex differences evolve so fast?

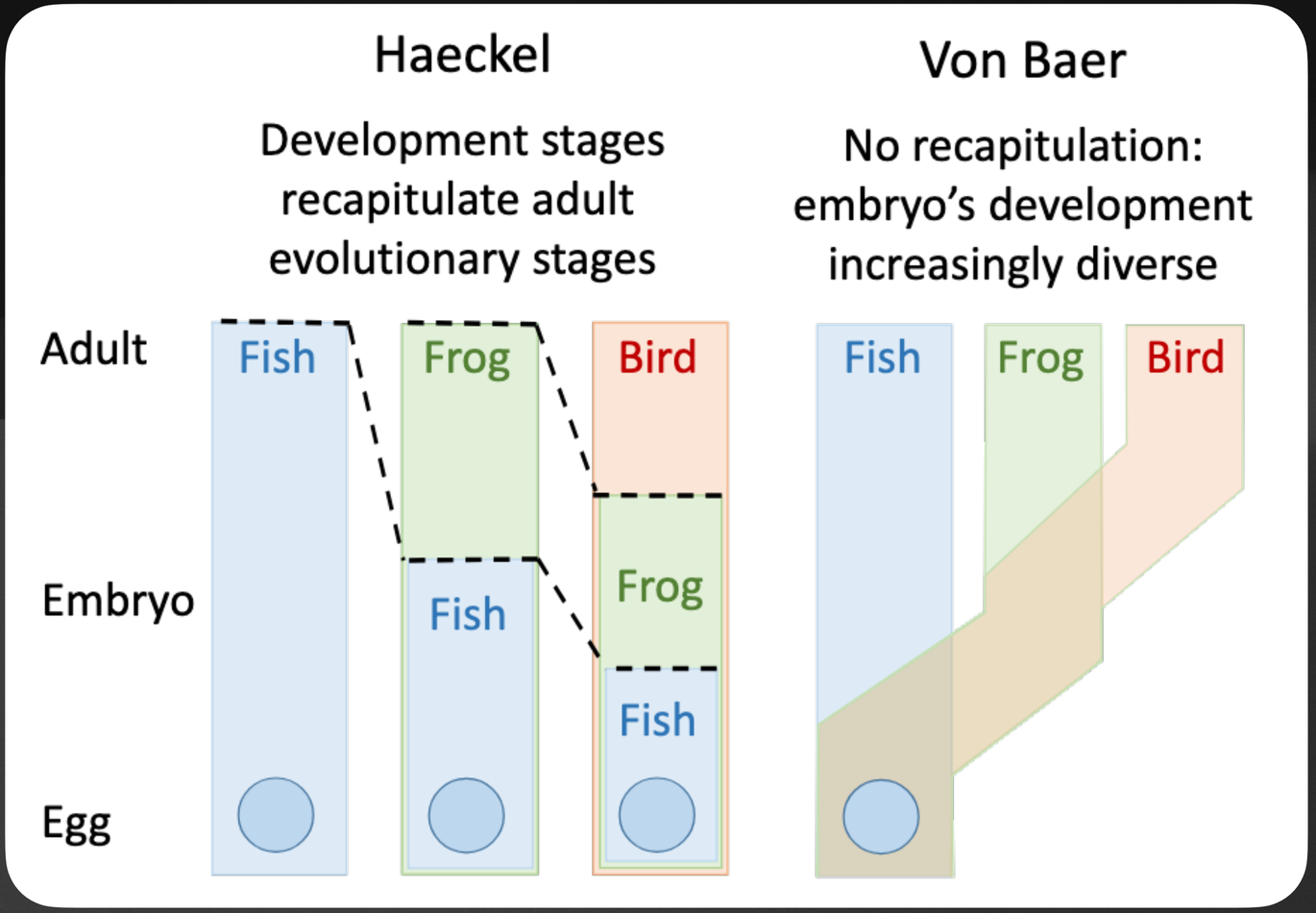
- it is probably because of the combination of strong sexual and natural selection and a simple genetic basis.
- In mammals, sex differences are mostly under **hormonal control** (changes in binding sites in TF).

05. Evolution & Development

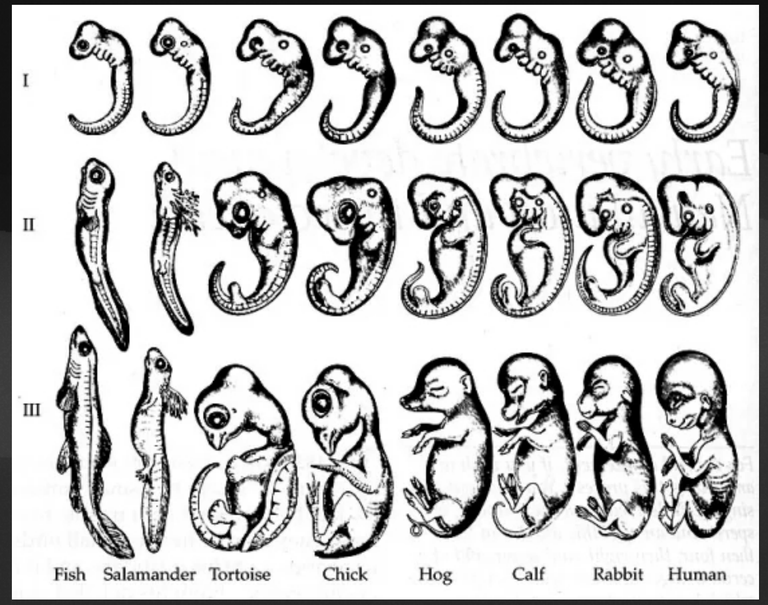
Von Baer's Law

@Xupeng Bi

@Xulan, Kezhi, Qisan



[胚胎重演] [胚胎发育增加多样性]

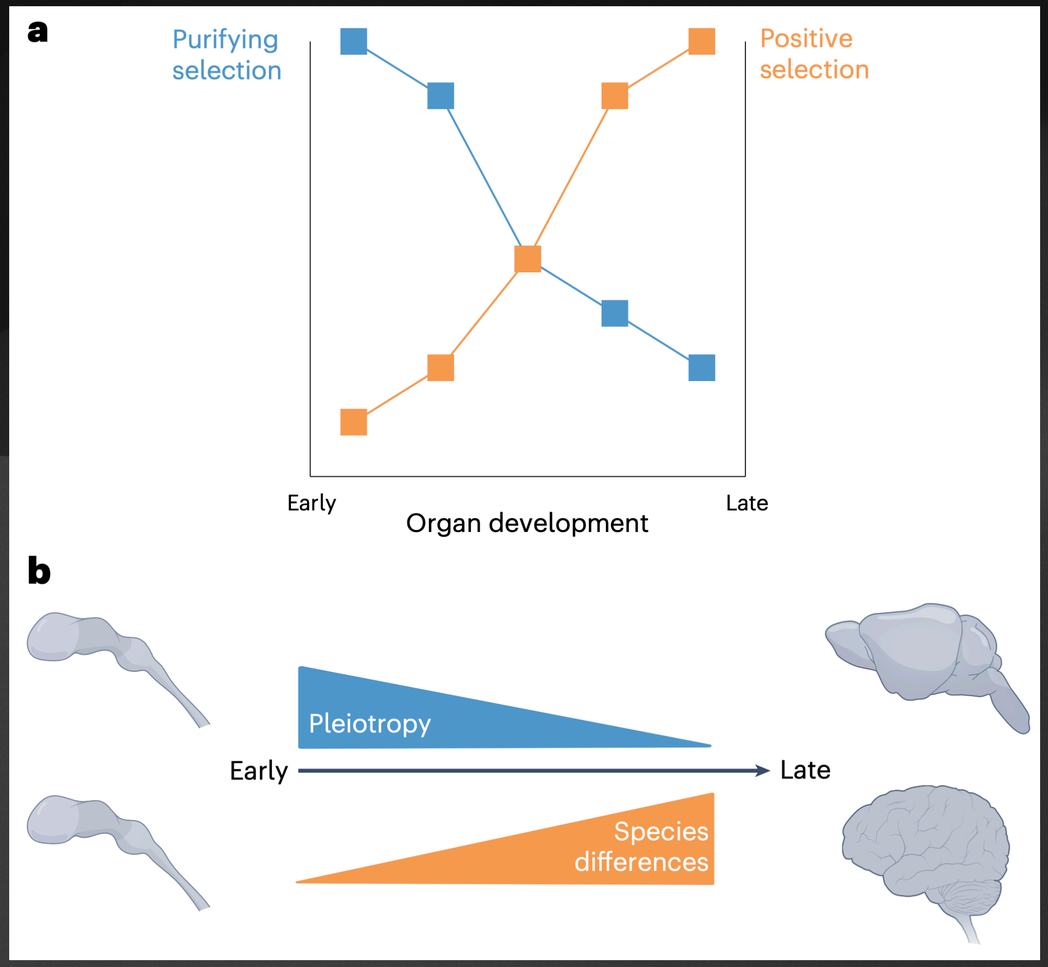


Von Baer's Law

- *Early vertebrate embryos exhibit features common to the entire subphylum.*
- *As development progresses, embryos become recognizable as members of their class, their order, their family, and finally their species.*

1. *The more general characters of a large group appear earlier in the embryo than the more special characters.*
2. *From the most general forms, the less general are developed, and so on, until finally the most special arises.*
3. *Every embryo of a given animal form, instead of passing through the other forms, rather becomes separated from them.*
4. *The embryo of a higher form never resembles any other form, but only its embryo.*

05. Evolution & Development



Evidence & Pleiotropy

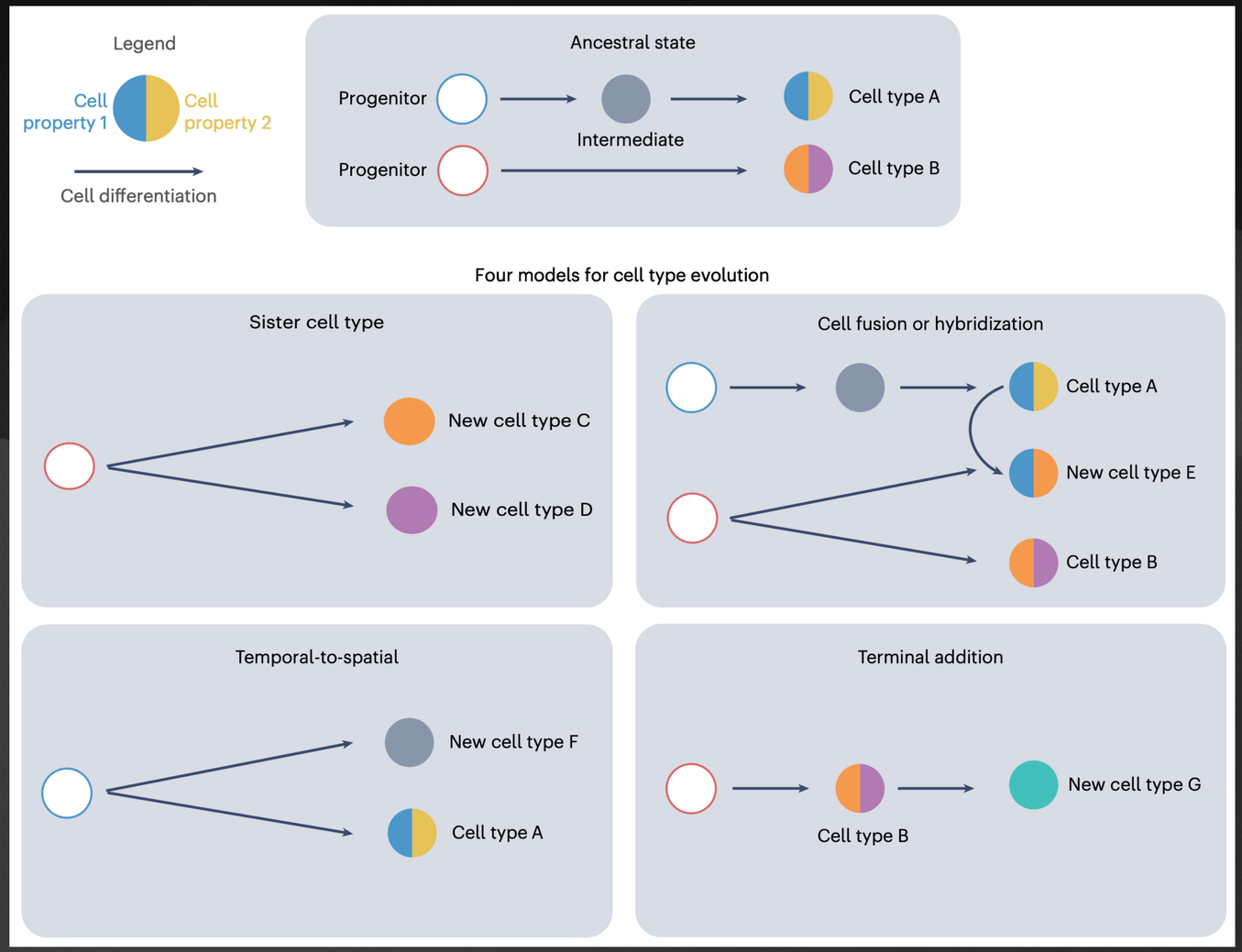
- As cells differentiate, species differences increase in gene expression and regulation increase.
- Pleiotropy: (early stage) more pleiotropic genes → stronger purifying selection
- Mutations with few pleiotropic effects are more likely to underlie adaptation
- Both stronger functional constraints early & increased adaptation later ('von Baerian' pattern)

Von Baer's Law — Molecular Confirmation

- Early embryos of different species are morphologically similar (phylotypic period)
- As development progresses, species differences emerge (confirmed at the molecular level)
- Purifying selection stronger early in development; positive selection increases later
- Pleiotropy of expressed genes decreases over development

06. Origin of Evolutionary Novelties

Models of New Cell Type Evolution



1. Sister Cell Type

Multifunctional cell segregates functions into two daughter types (division of labour).

E.g. neurons, photoreceptors, oligodendrocytes.

2. Cell Fusion

Transcription factors from different cell types co-expressed in same cell → new combined cell type.

E.g. defensive glands in beetles.

3. Temporal → Spatial

Programs that were sequentially activated become simultaneously active in different locations.

E.g. epitheliomuscular cells (photosensitive and contractile) in cnidarians.

4. Terminal Addition

New cell type via transdifferentiation of a terminally differentiated cell.

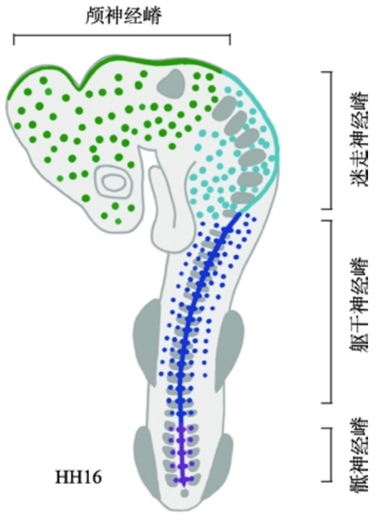
E.g. black → white pigment cells in zebrafish.

06. Origin of Evolutionary Novelties

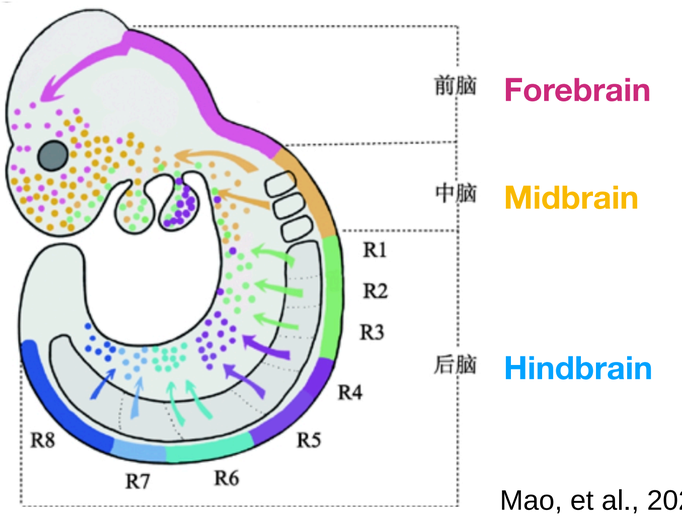
Vertebrate-Defining Cell Innovations

Neural crest

- Cranial neural crest 颅神经嵴
- Vagus neural crest 迷走神经嵴
- Trunk neural crest 躯干神经嵴
- Sacral neural crest 骶神经嵴



“New Head” hypothesis



Mao, et al., 2022.

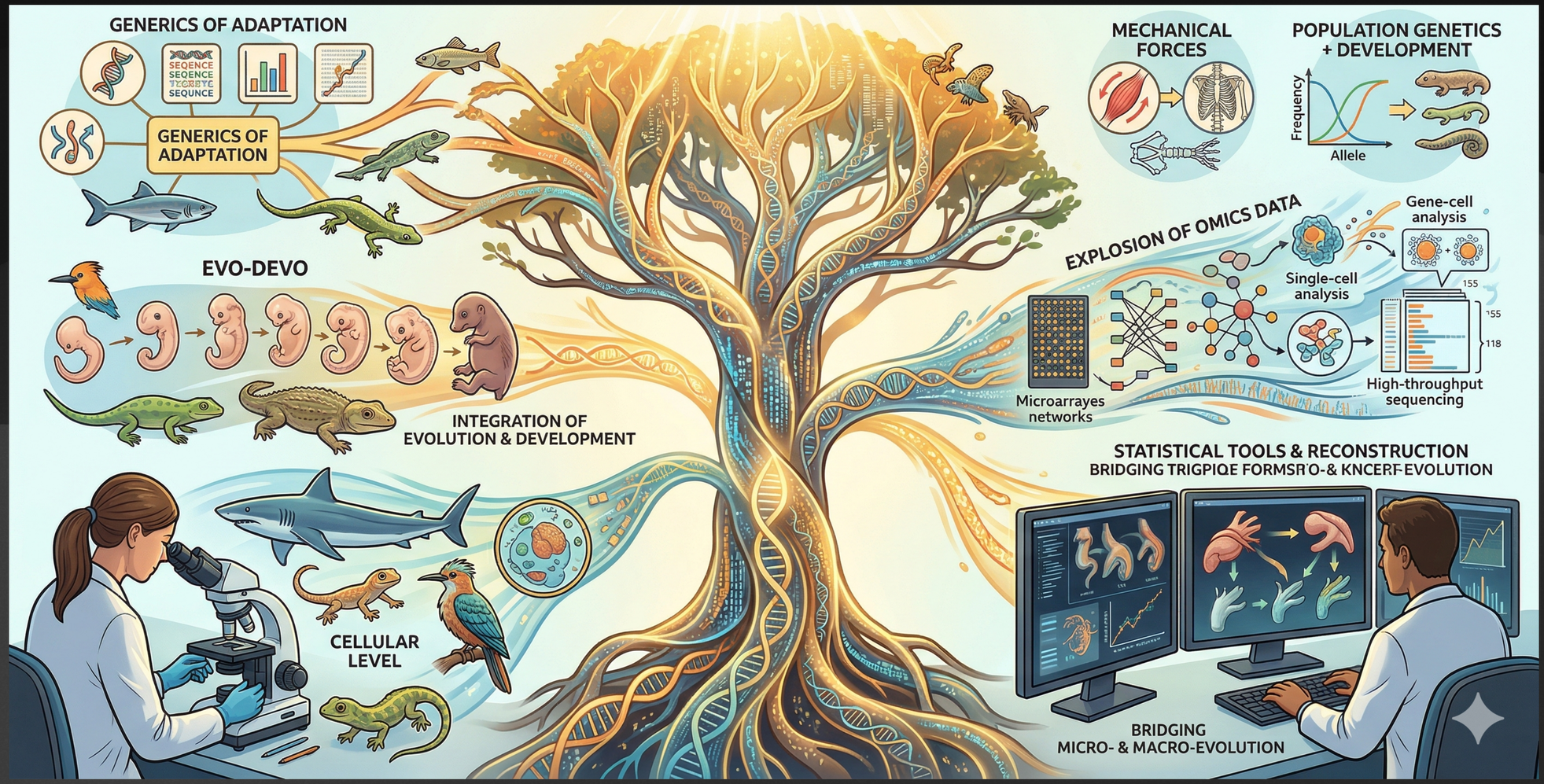
Neural Crest Cells [神经嵴细胞]

- Differentiate into bone, cartilage, smooth muscle, peripheral nerves, pigment cells
- Sensory neurons crucial for water-to-land transition are neural crest-derived

Cranial Placodes [颅板]

- Form inner ear, nose, lens, cranial sensory ganglia
- Together with neural crest: reshaped the vertebrate head, heart, and sensory systems

07. Future Directions



Golden Age of Organ Evolution Research (*Gemini Generated*)

Thanks for your attention!
Q & A

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