浙江大学
生命演化研究中心

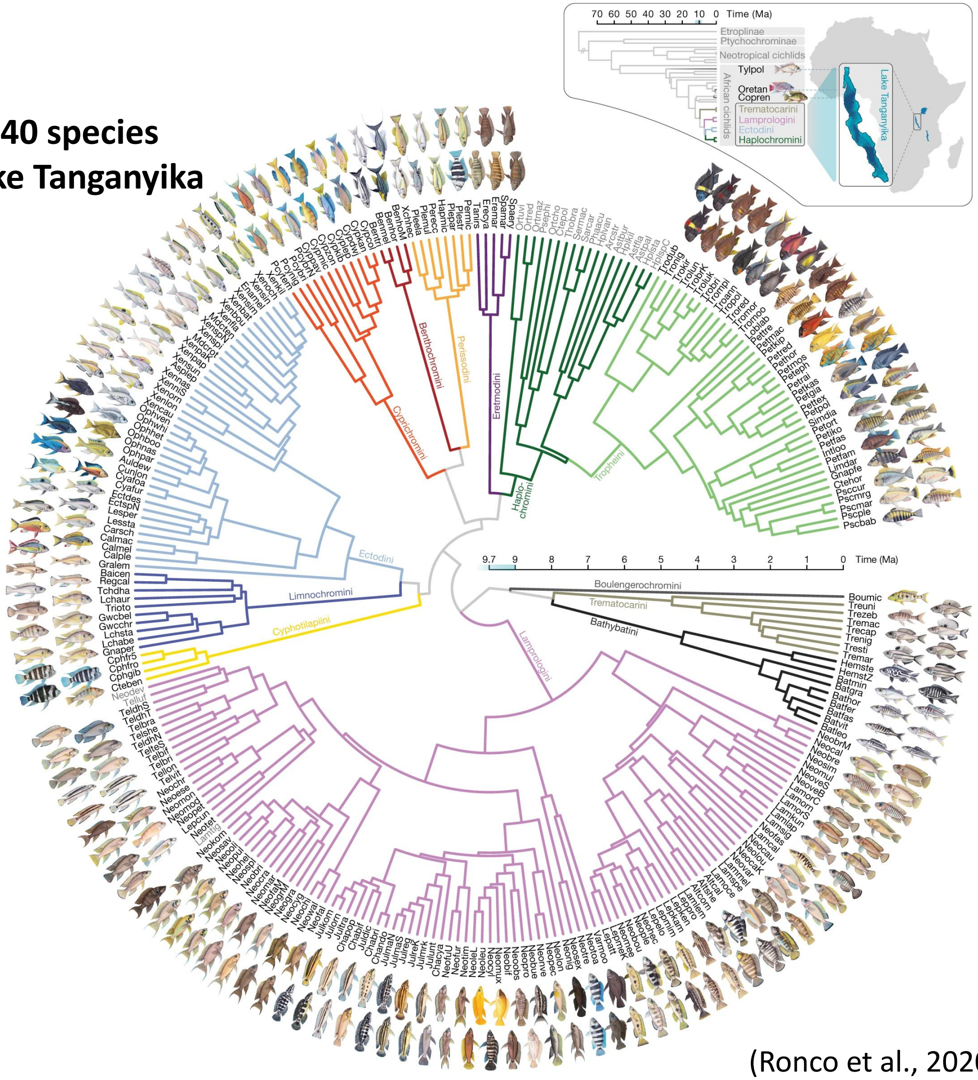
Adaptive Evolution in Vertebrates: From Genomics to Transcriptomics

Xiaoxu Xu

2026/6/26

Cichlid fish

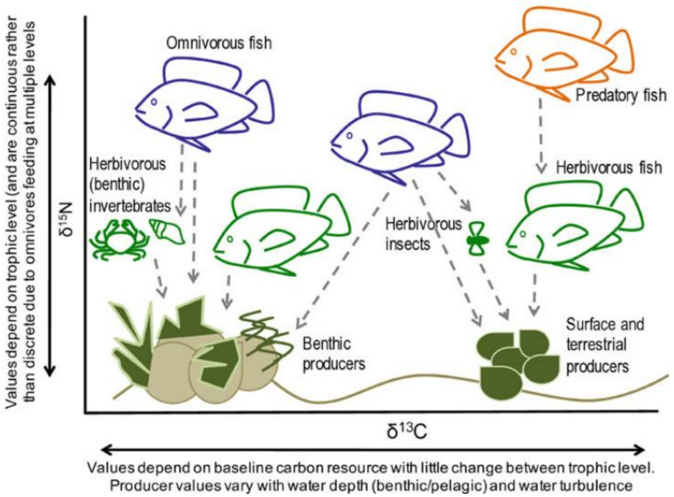
~240 species
in Lake Tanganyika



(Ronco et al., 2020)

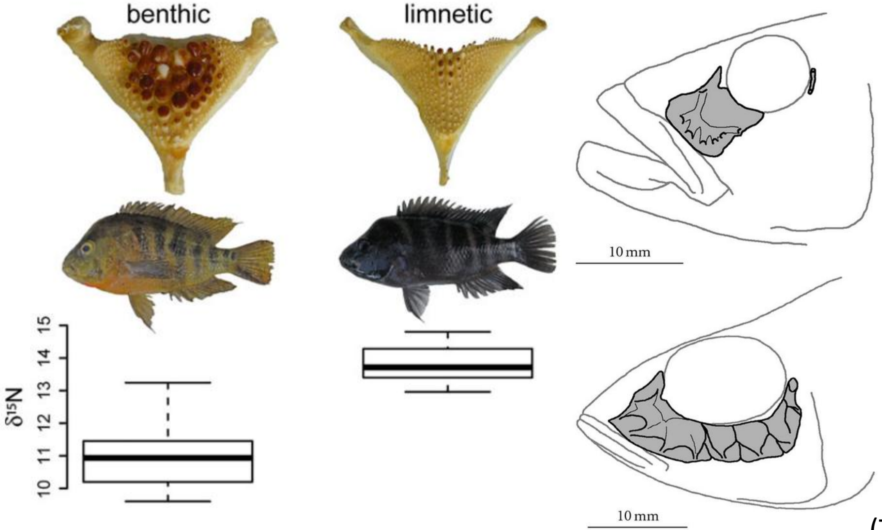
"the most outstanding example of adaptive radiation"

Cichlid fishes have evolved highly diverse diets.



(Noakes et al., 2021)

Predator 食肉动物
Herbivore 食草动物
Omnivore 杂食动物



How exactly does the digestive tract adapt to these completely different diets?

(Takahashi et al., 2011)

feeding apparatus responsible for the uptake and mastication of foods

Article

Adaptive cellular evolution in the intestine of hyperdiverse cichlid fishes

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Antoine Fages[1]✉, Maëva Luxey[1,2], Fabrizia Ronco[1], Charlotte E. T. Huyghe[1], Sabrina Fischer[1], Gudrun Viktorin[1], P. Navaneeth Krishna Menon[1], Adrian Indermaur[1], Walter Salzburger[1,3]✉ & Patrick Tschopp[1,3]✉

Walter Salzburger
University of Basel

What are the nature and extent of dietary adaptations in the digestive tract during adaptive radiations?

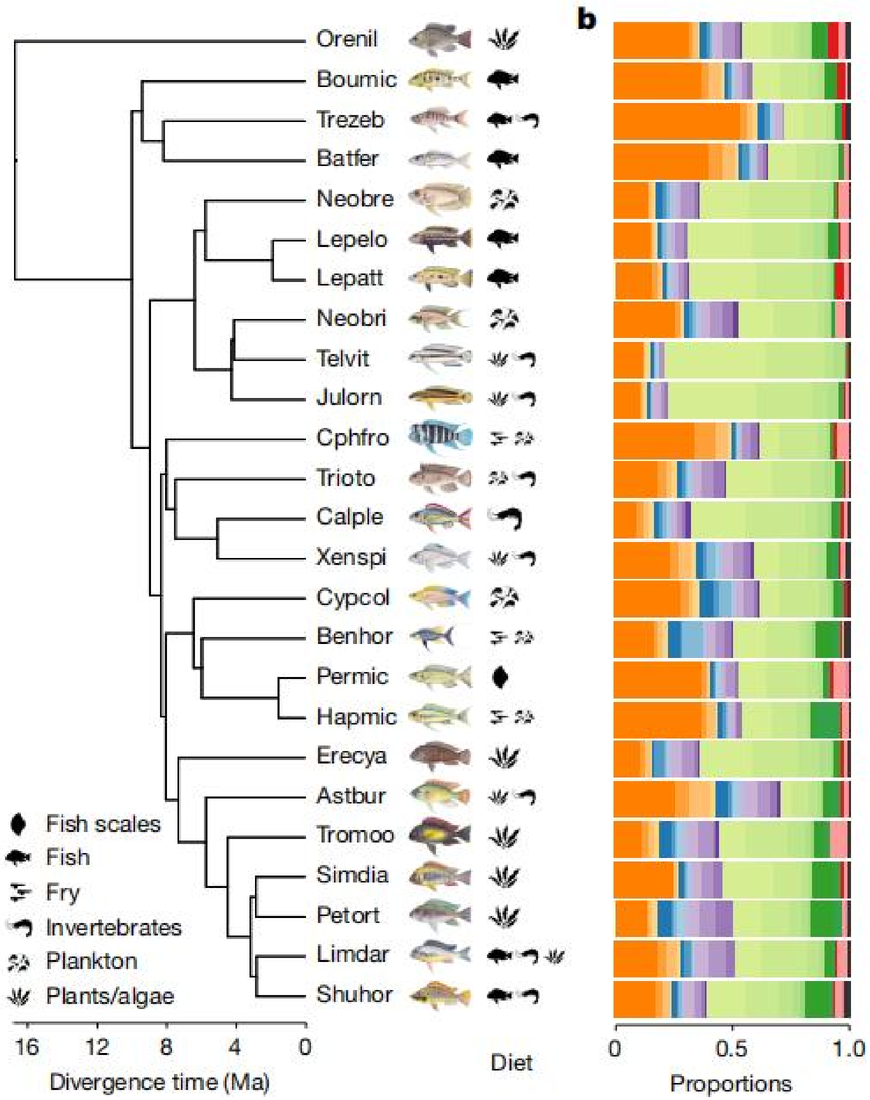
Antoine Fages
Postdoctoral researcher

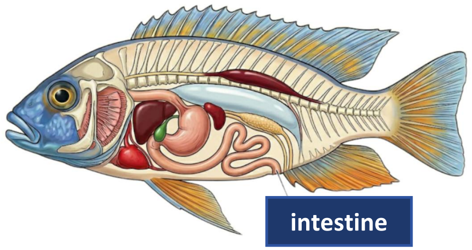
Patrick Tschopp
University of Basel

Fages, A., Luxey, M., Ronco, F. et al. Adaptive cellular evolution in the intestine of hyperdiverse cichlid fishes. Nature (2026).

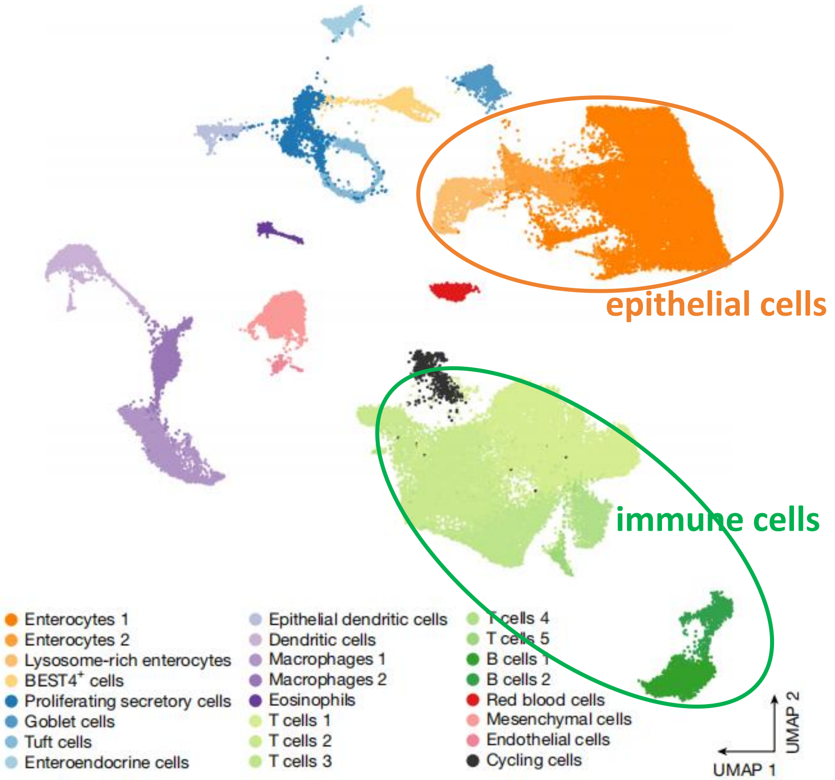
Cellular diversity in cichlid intestines

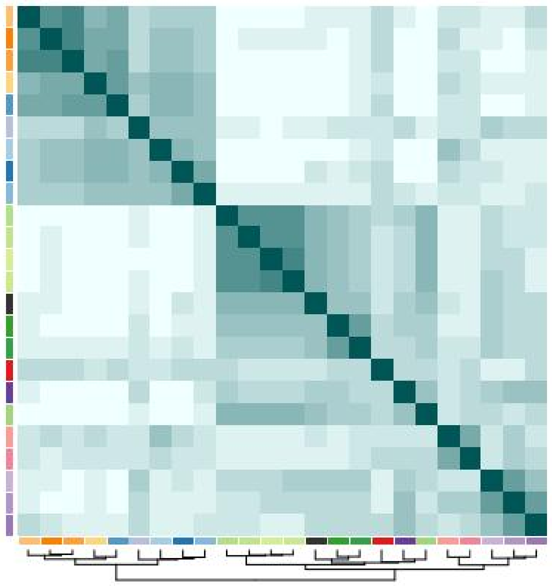
24 species, 13 clades

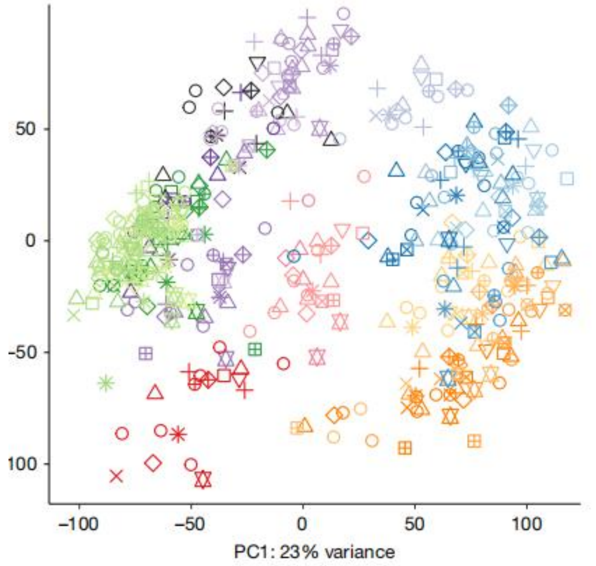




82,621 high-quality cells

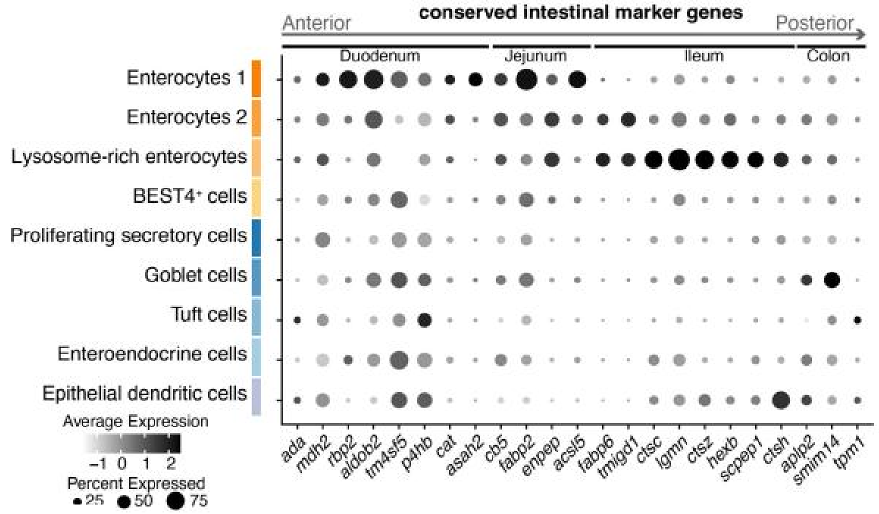


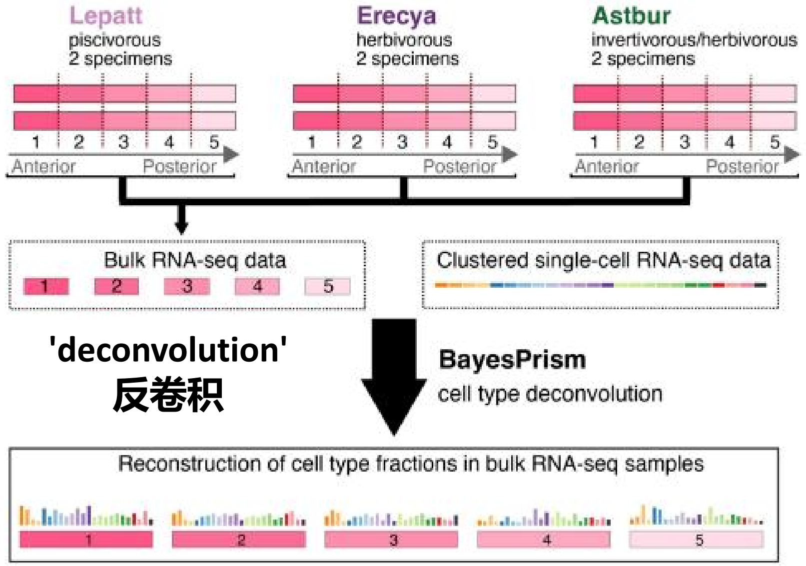




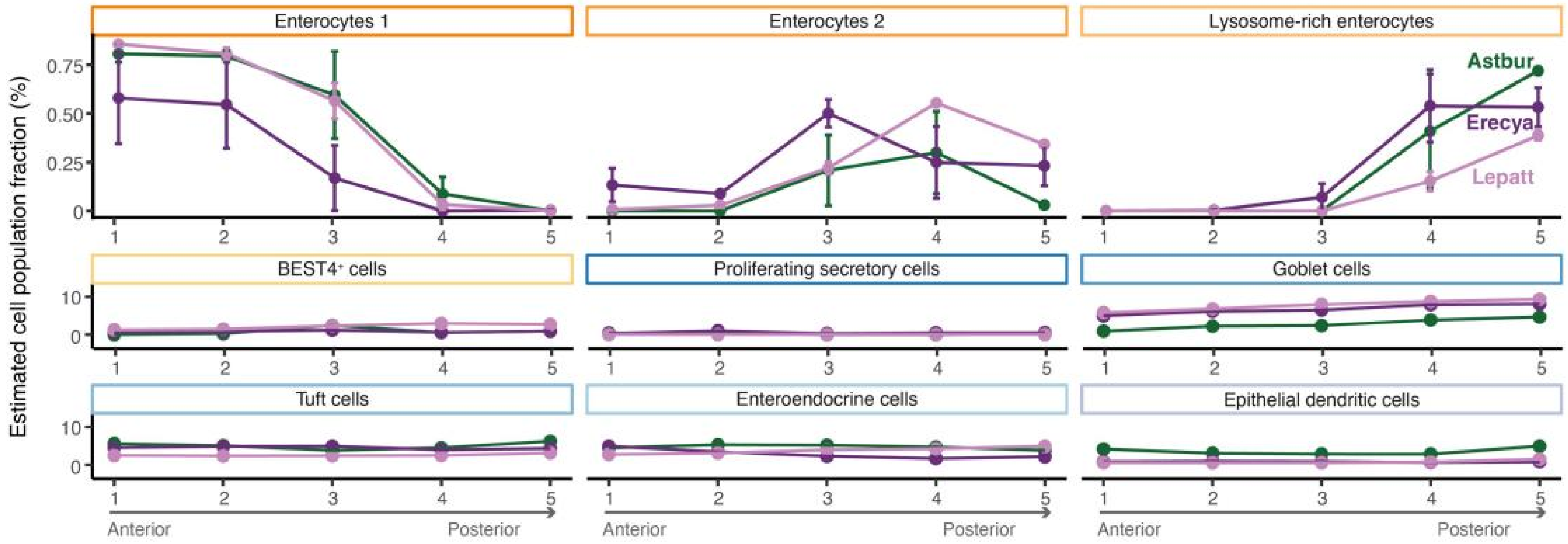
Cellular diversity in cichlid intestines

How are they spatially distributed?

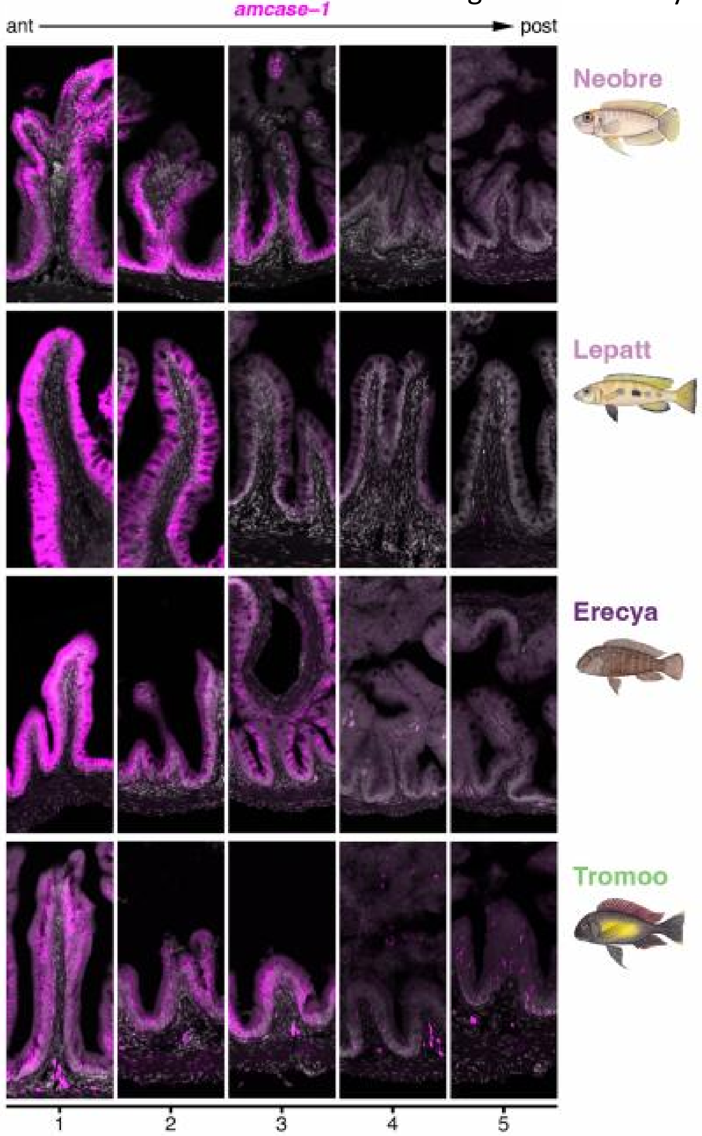




'deconvolution'
反卷积



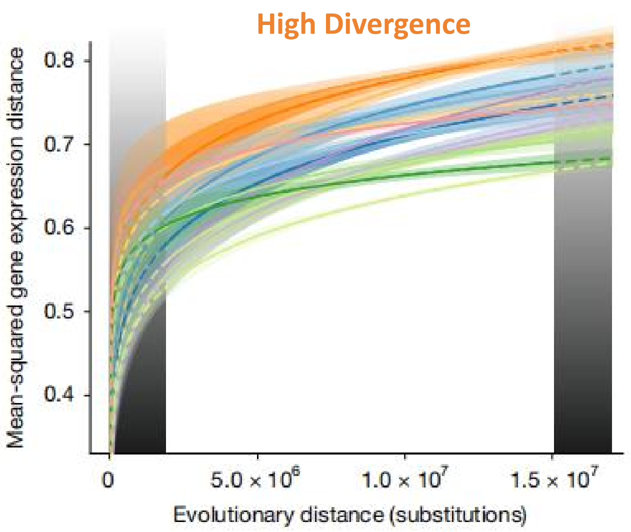
marker gene of Enterocytes 1

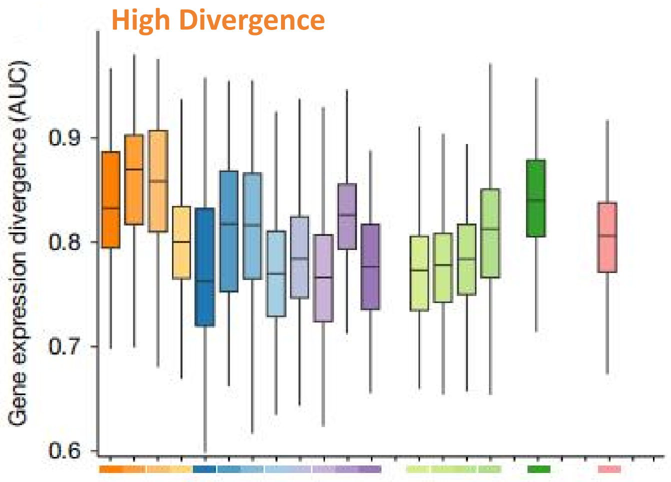


➢ “highly precise cellular and molecular sub-functionalization along the anterior-posterior axis”

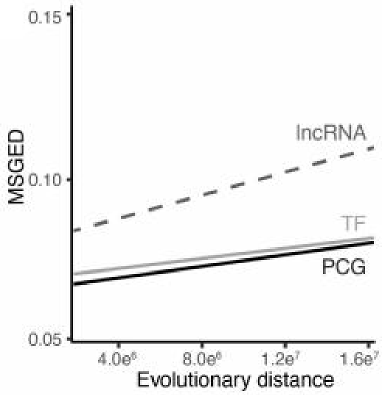
Transcriptome evolution in the intestine

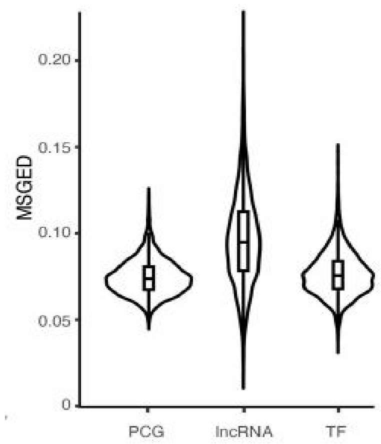
- **Gene expression divergence follows an Ornstein–Uhlenbeck (OU) model.**



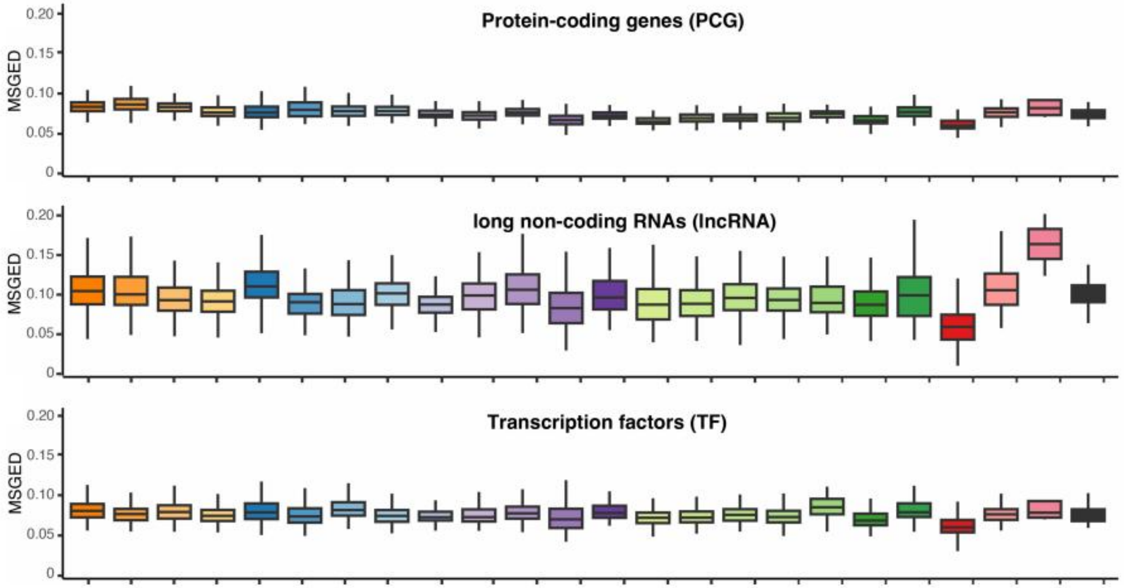


- **Long non-coding RNAs (lncRNAs) evolve faster and show higher divergence than PCGs and transcription factors.**





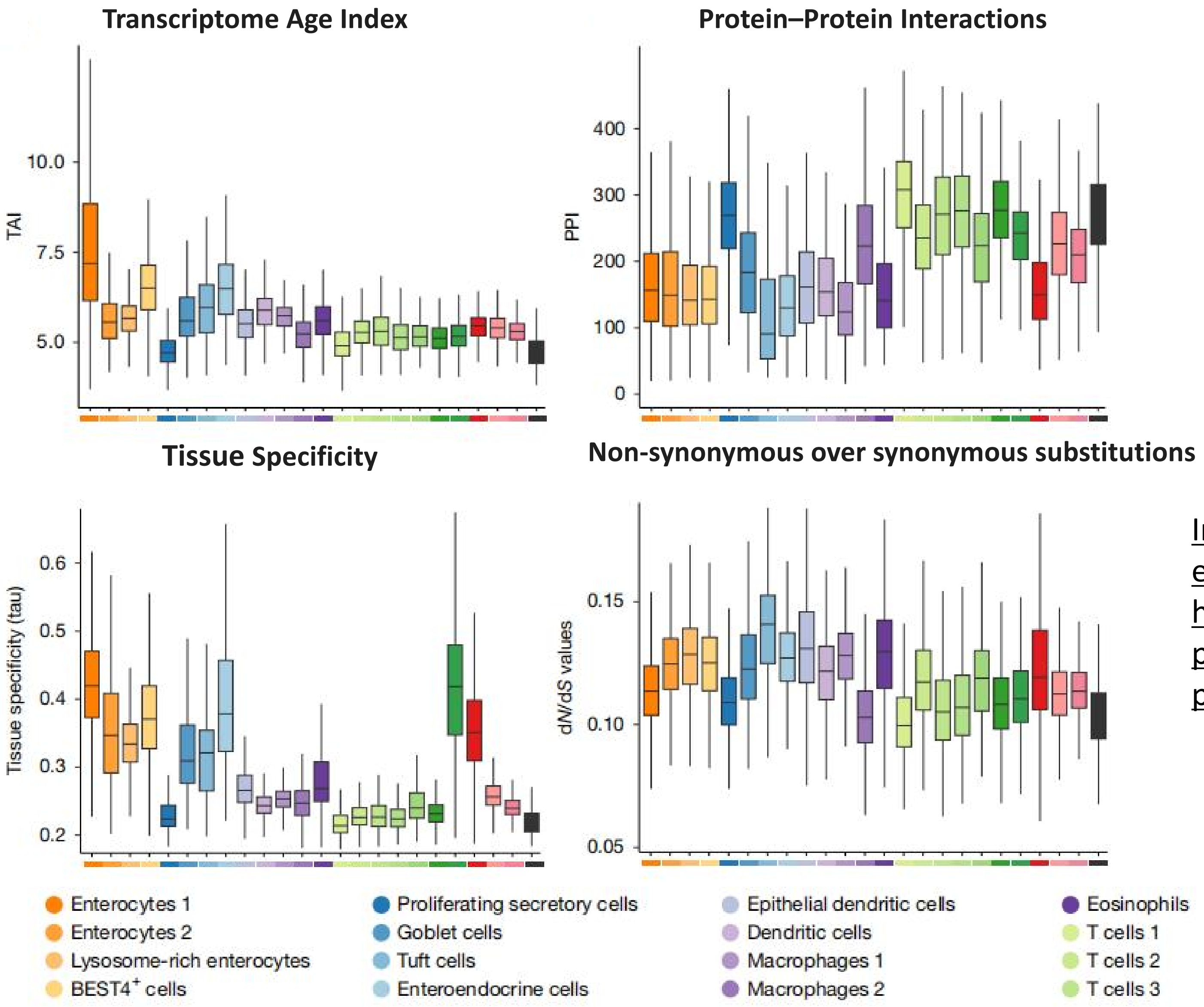
- **The pronounced divergence in absorptive cells is primarily driven by protein-coding genes (PCGs).**



- Enterocytes 1
- Enterocytes 2
- Lysosome-rich enterocytes
- BEST4⁺ cells
- Proliferating secretory cells
- Goblet cells
- Tuft cells
- Enteroendocrine cells
- Epithelial dendritic cells
- Dendritic cells
- Macrophages 1
- Macrophages 2
- Eosinophils
- T cells 1
- T cells 2
- T cells 3
- T cells 4
- T cells 5
- B cells 1
- B cells 2
- Red blood cells
- Mesenchymal cells
- Endothelial cells
- Cycling cells

Transcriptome evolution in the intestine

Why do absorptive cells evolve so fast and diverge so much?

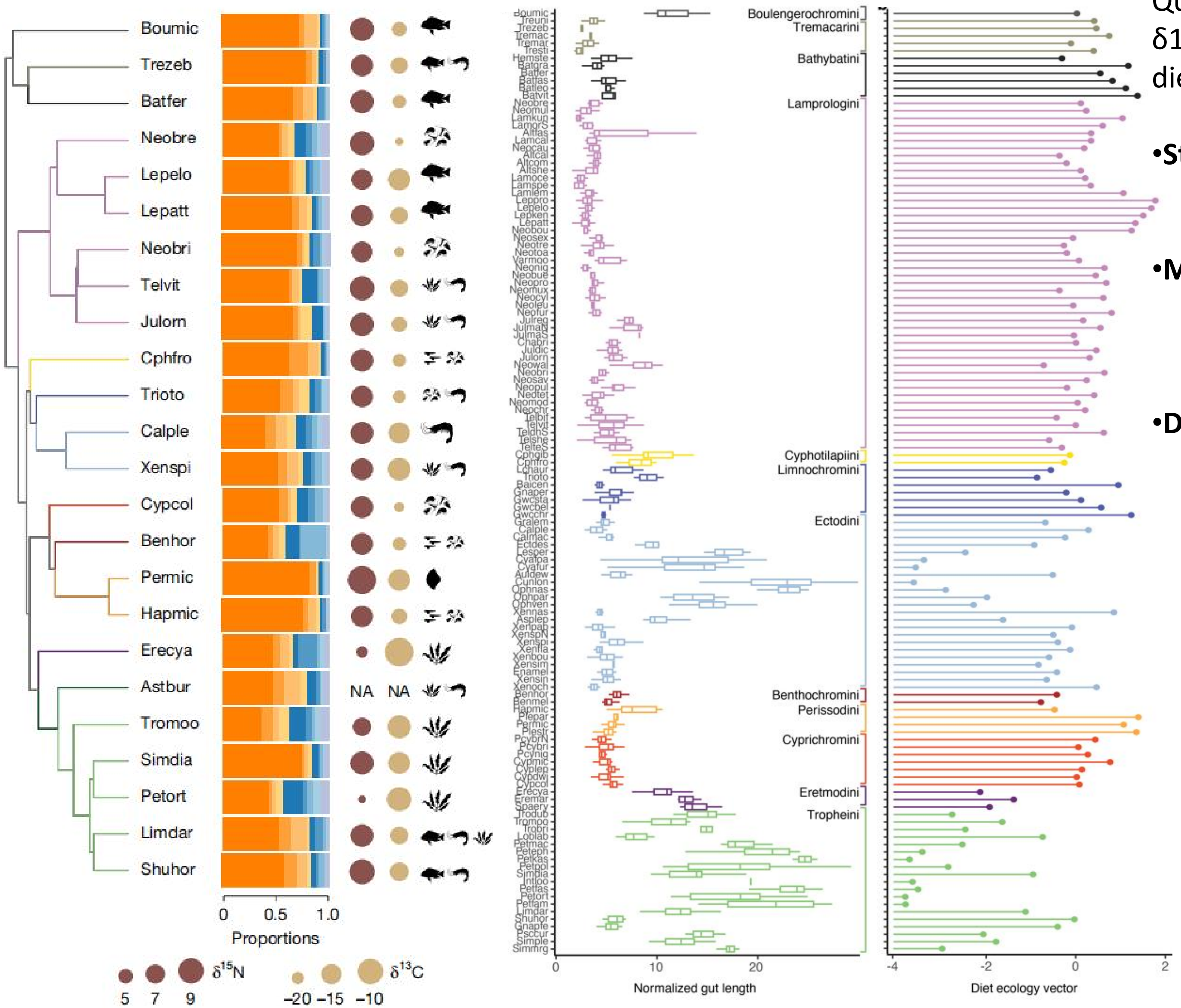


- Absorptive cells express evolutionarily "younger" genes, indicating **reduced phylogenetic constraints**.
- High tissue specificity and fewer protein-protein interactions (PPIs) in absorptive cells reflect **relaxed pleiotropic constraints**.
- Elevated dN/dS ratios in epithelial cells demonstrate **reduced selective pressures** on their protein-coding sequences.

<u>Intestinal cell populations have evolved under strong evolutionary constraints, absorptive epithelial cells show higher cross-species gene expression divergence, relaxed phylogenetic, pleiotropic constraints and reduced selective pressures.</u>

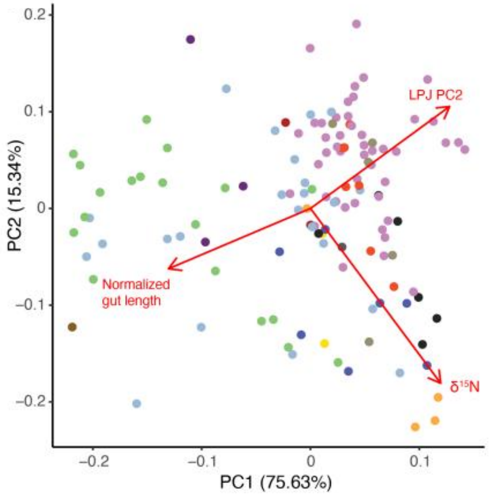
Adaptive cellular evolution in cichlids

Whether or not this variation adaptive—i.e., directly related to what the cichlids eat?



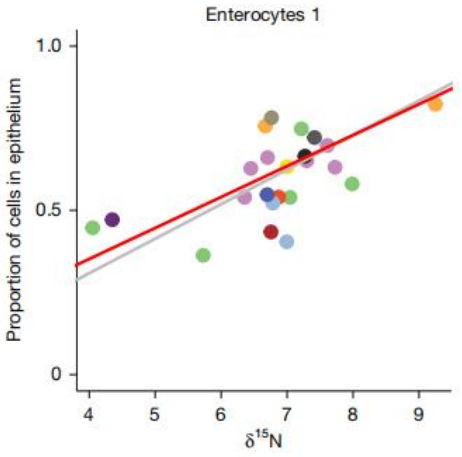
Quantitative ecological traits =
δ13C values + δ15N values + normalized gut length + diet ecology vector + Oral jaw + LPJ

- **Stable Isotopes** *(Gold standard)* **食肉动物 食草动物**
  - ◦δ15N: Reflects trophic level (Carnivores > Herbivores).
  - ◦δ13C : Reflects food source origin (Benthic > Pelagic).
- **Morphological Traits** **底栖动物 浮游动物**
  - ◦Standardized gut length (longer in herbivores).
  - ◦Lower Pharyngeal Jaw (LPJ) morphology.
  - ◦Oral Jaw
- **Dietary Ecological Vector**
  - ◦A mathematical summary combining the above traits to represent overall dietary inclination.



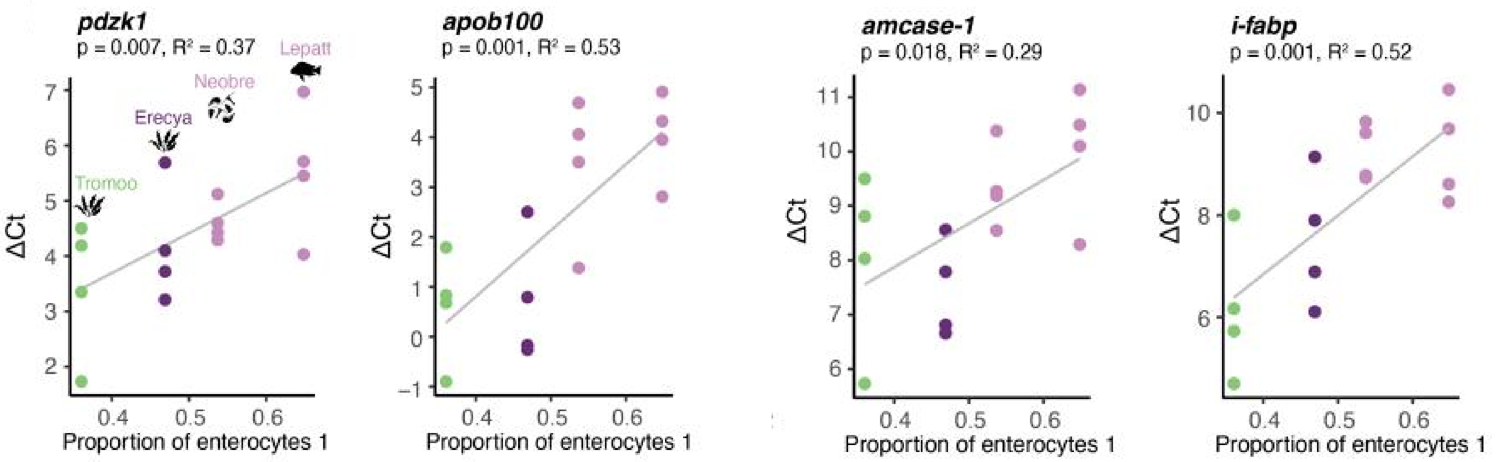
Adaptive cellular evolution in cichlids

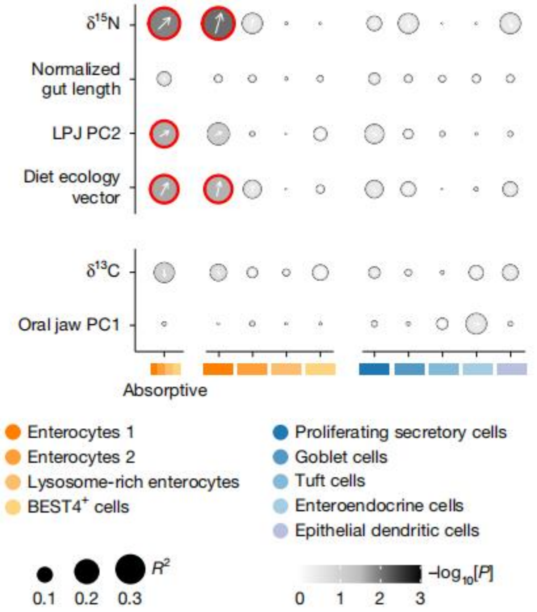
Does diet really dictate what cells grow and what genes are expressed in the intestine?



Markers of absorptive cell

Markers of enterocyte 1

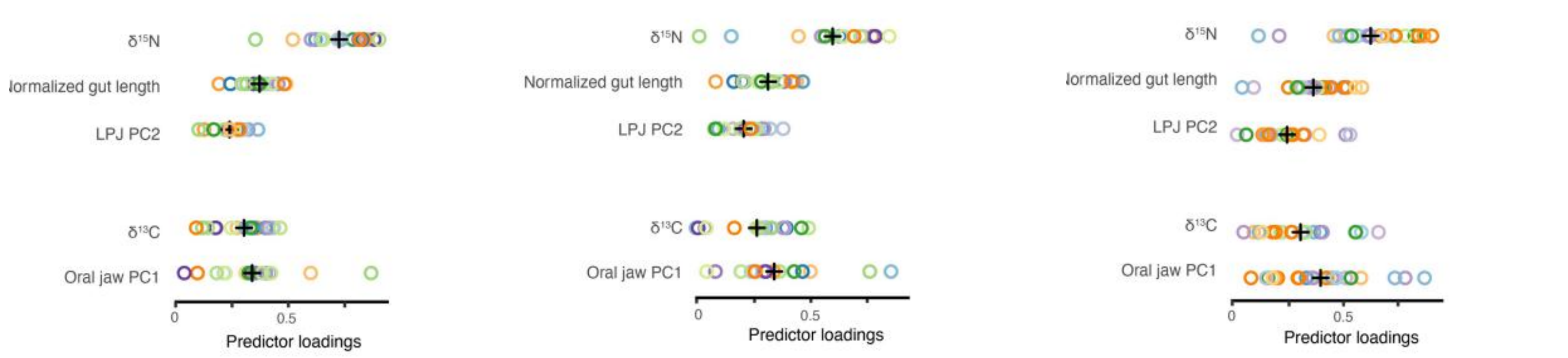




Genes expressed in at least 20% cells

Cell population-specific genes

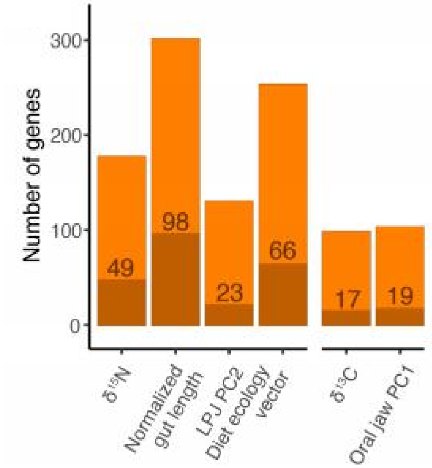
Genes in scWGCNA co-expressed modules



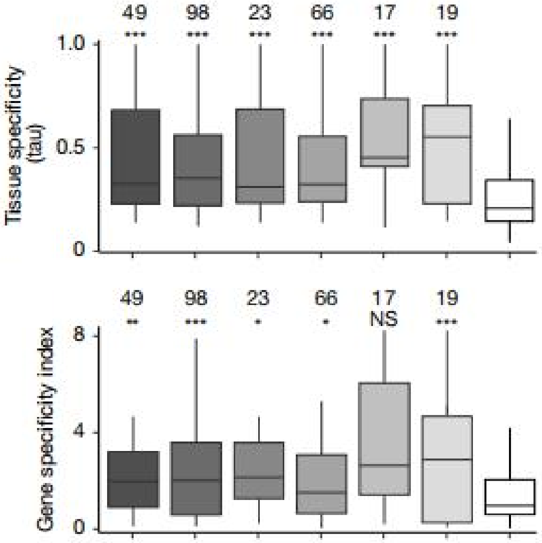
- ➢ Cichlids adapt to dietary niches by adjusting the relative abundance of absorptive cells in their intestine and rewriting the specific gene expression levels within their cells.

Molecular basis of dietary adaptations

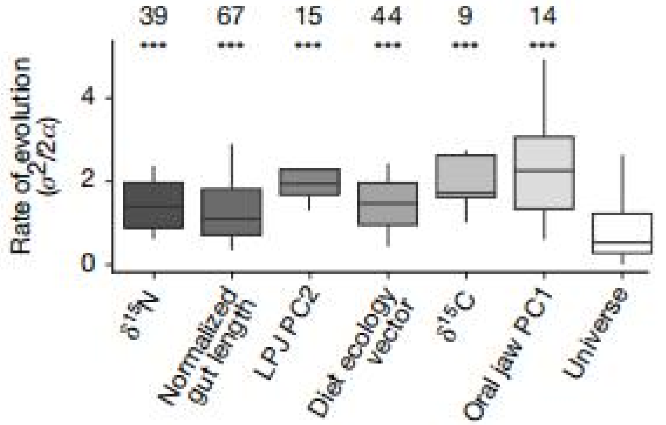
- 23-98 genes associated with each dietary predictor



- higher tissue specificity & gene specificity indices

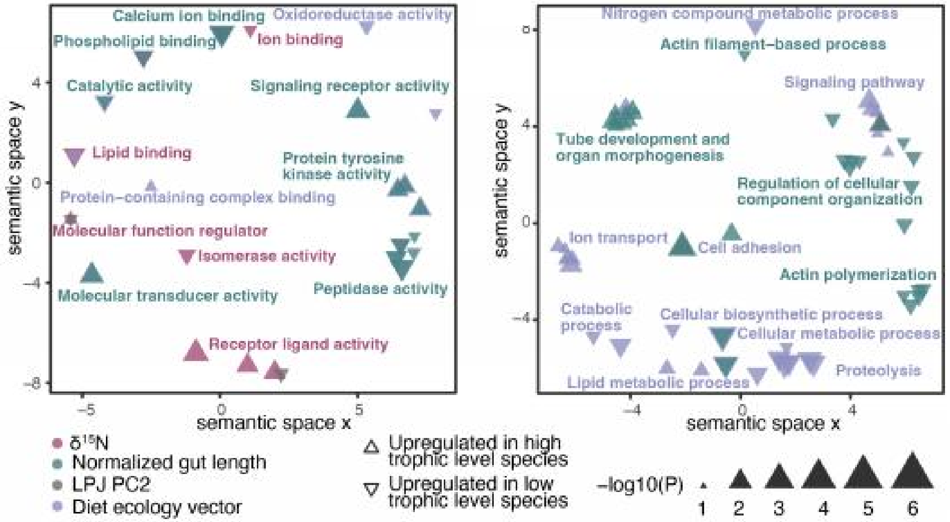


- The evolution of the expression of most genes was better captured by an OU model than by BM

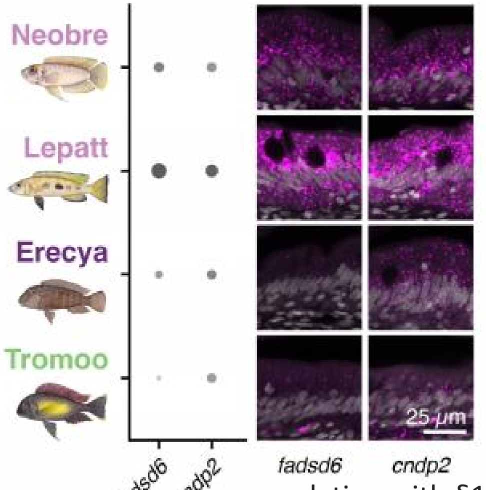


▲ breakdown and absorption of fats and proteins

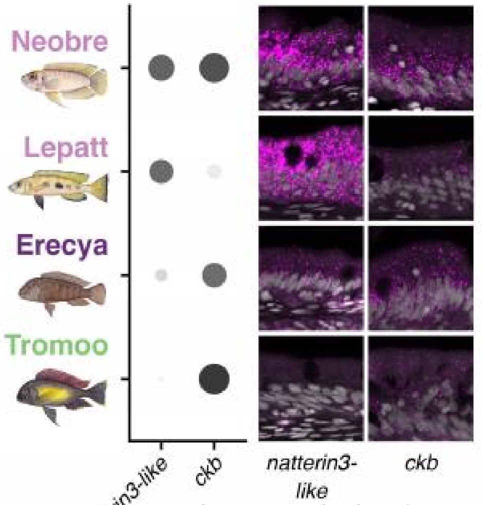
▼ epithelial cell maintenance and ion balance



- Ecologically relevant genes showed high interspecific variability in expression confirmed by ISH

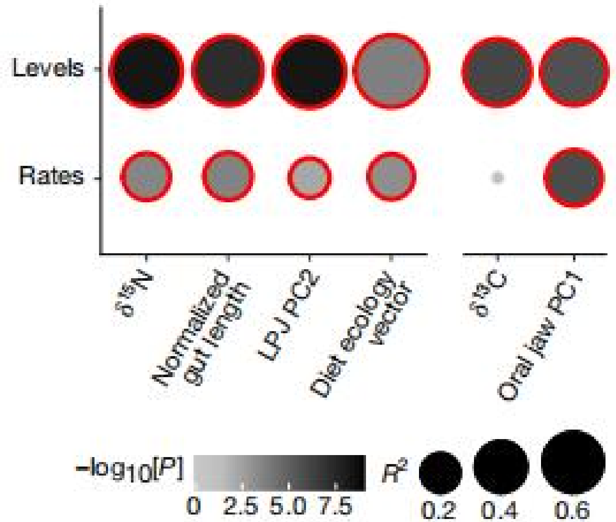


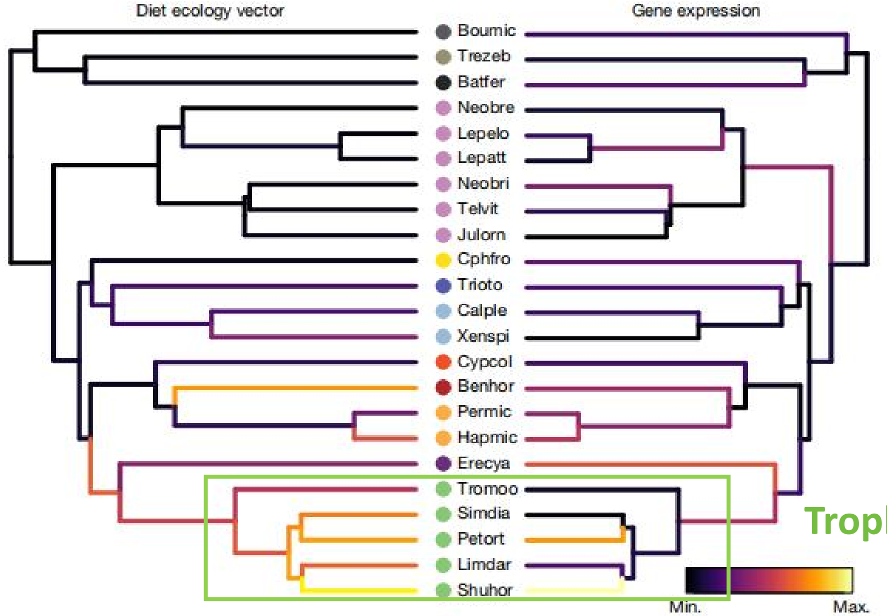
correlating with δ15N values



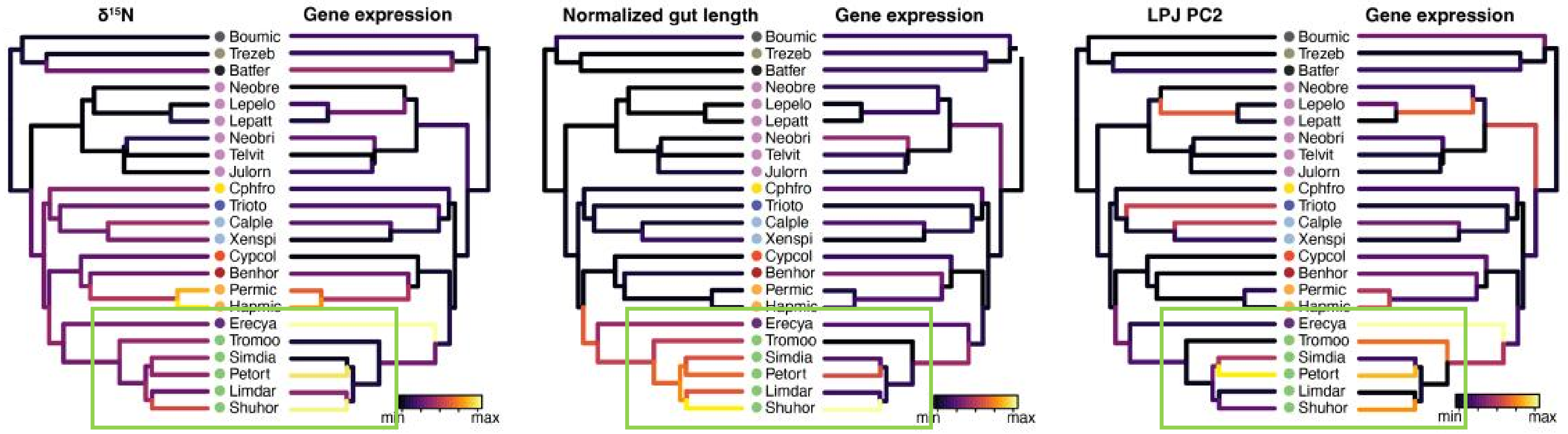
correlating with the diet ecology vector

Molecular basis of dietary adaptations





Tropheini(rapid trophic transitions)



- Rapid, cell-type-specific gene expression changes within anterior enterocytes directly facilitated specific diets, ultimately speeding up the formation of new species later in the radiation.

Takeaways & Limitations

- Anterior enterocytes (Enterocyte 1) are the core cellular targets for dietary adaptation.
- Trophic niche divergence directly drives quantitative changes in intestinal cellular composition.
- Fast-evolving, cell-population-specific genes form the molecular basis of dietary adaptation.
- Adaptive evolution occurs across multiple levels of biological organization.

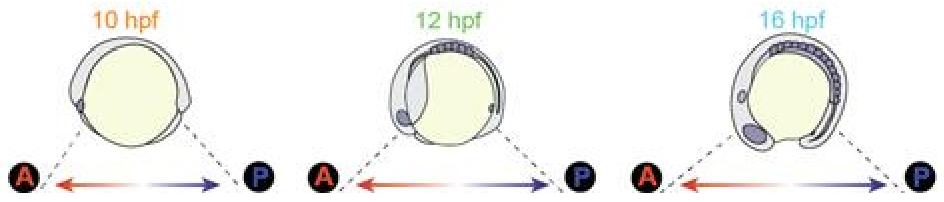
- **Single replicate per species**
  One individual per species — within-species variation unquantified.
- **Correlation ≠ causation**
  Cannot determine whether diet drives cell composition or vice versa.
- **Adult-only snapshot**
  No ontogenetic time series — unclear when cell-ratio differences are established
  Cell fate specification vs. progenitor pool expansion remains unresolved

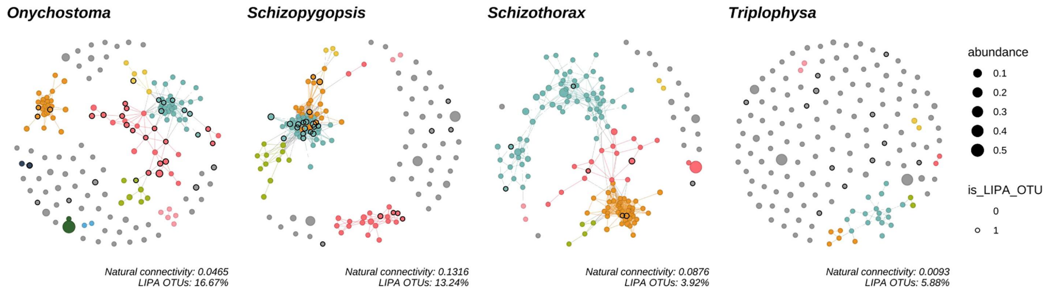
Future Directions

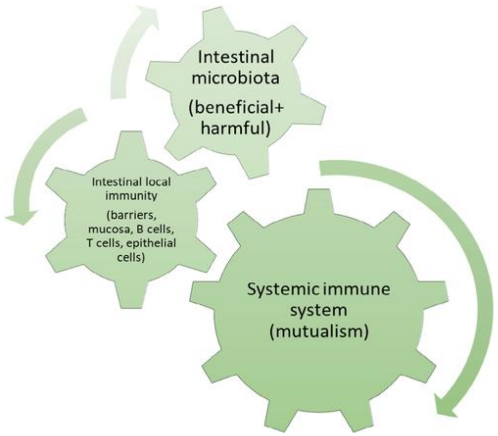
- **Ontogenetic Time-Series Analysis**
  Determine the underlying molecular and temporal dynamics of epithelial cell fate specification.
  Track progenitor pool expansion from embryonic to adult stages.

- **Host-Microbiome Interactions**
  Investigate how varying intestinal microbial landscapes influence epithelial cell specification.
  Assess the microbiome's impact on overall intestinal architecture and function.

- **Immune System Crosstalk**
  Explore the extent to which immune system activities shape diet-related cellular adaptations.







Q & A

Xiaoxu Xu

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