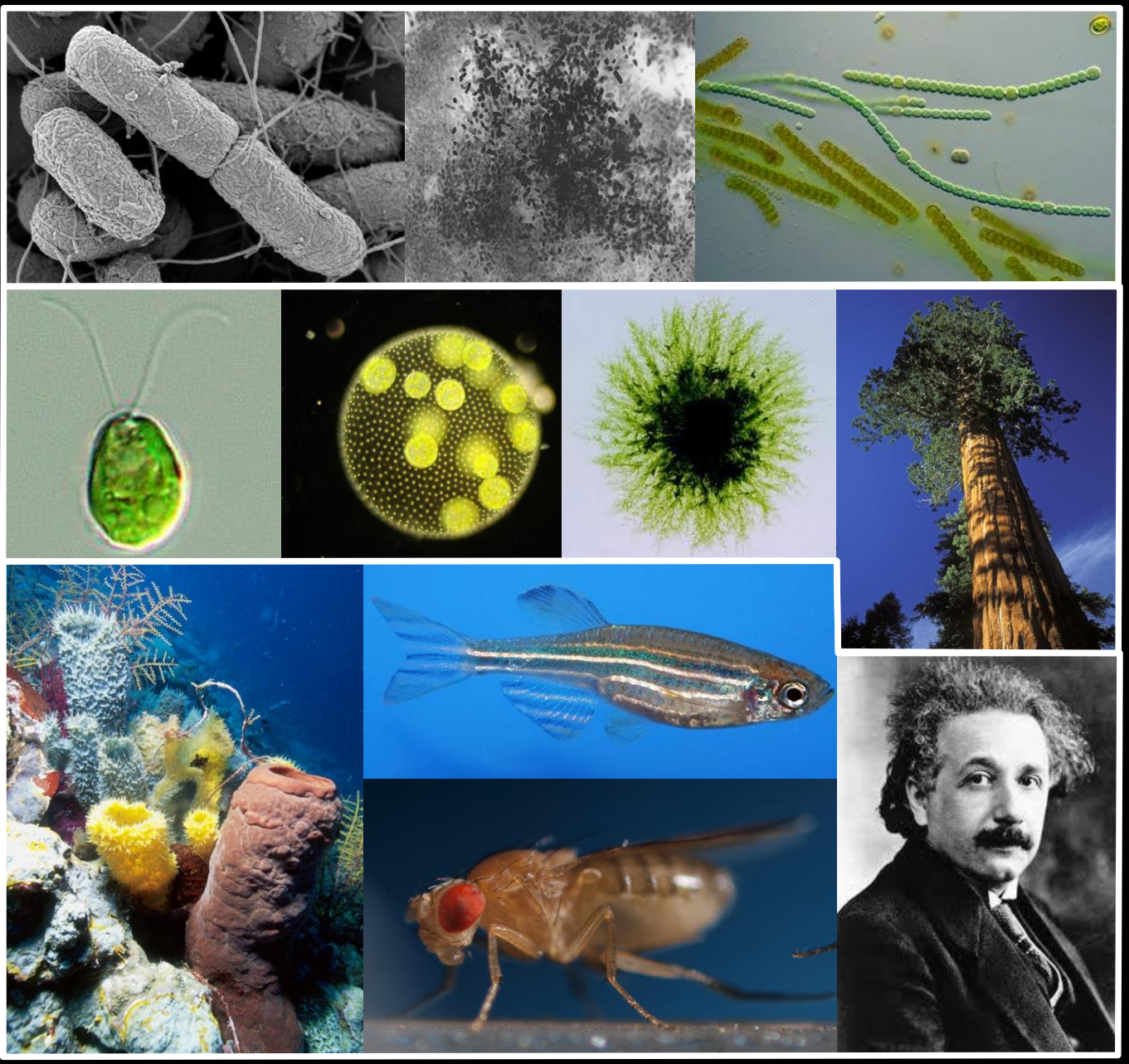
Phylotranscriptomic hourglasses of plant and animal embryogenesis

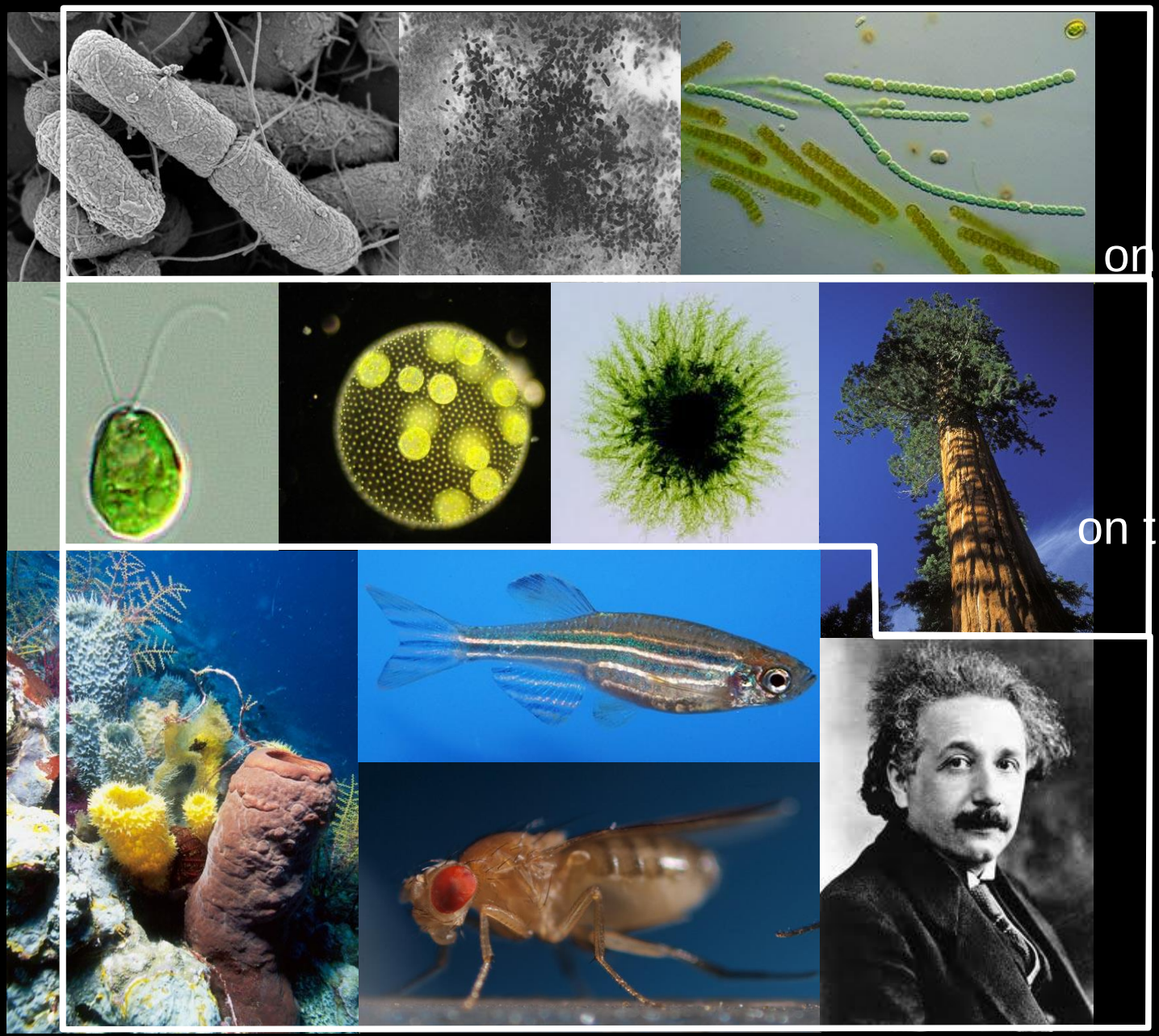
Marcel Quint, Hajk-Georg Drost, Alexander Gabel, Kristian Karsten Ullrich, Markus Boenn, and Ivo Grosse

Leibniz Institute of Plant Biochemistry
Institute of Computer Science at Halle University
German Center of Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig

How did complex life emerge?



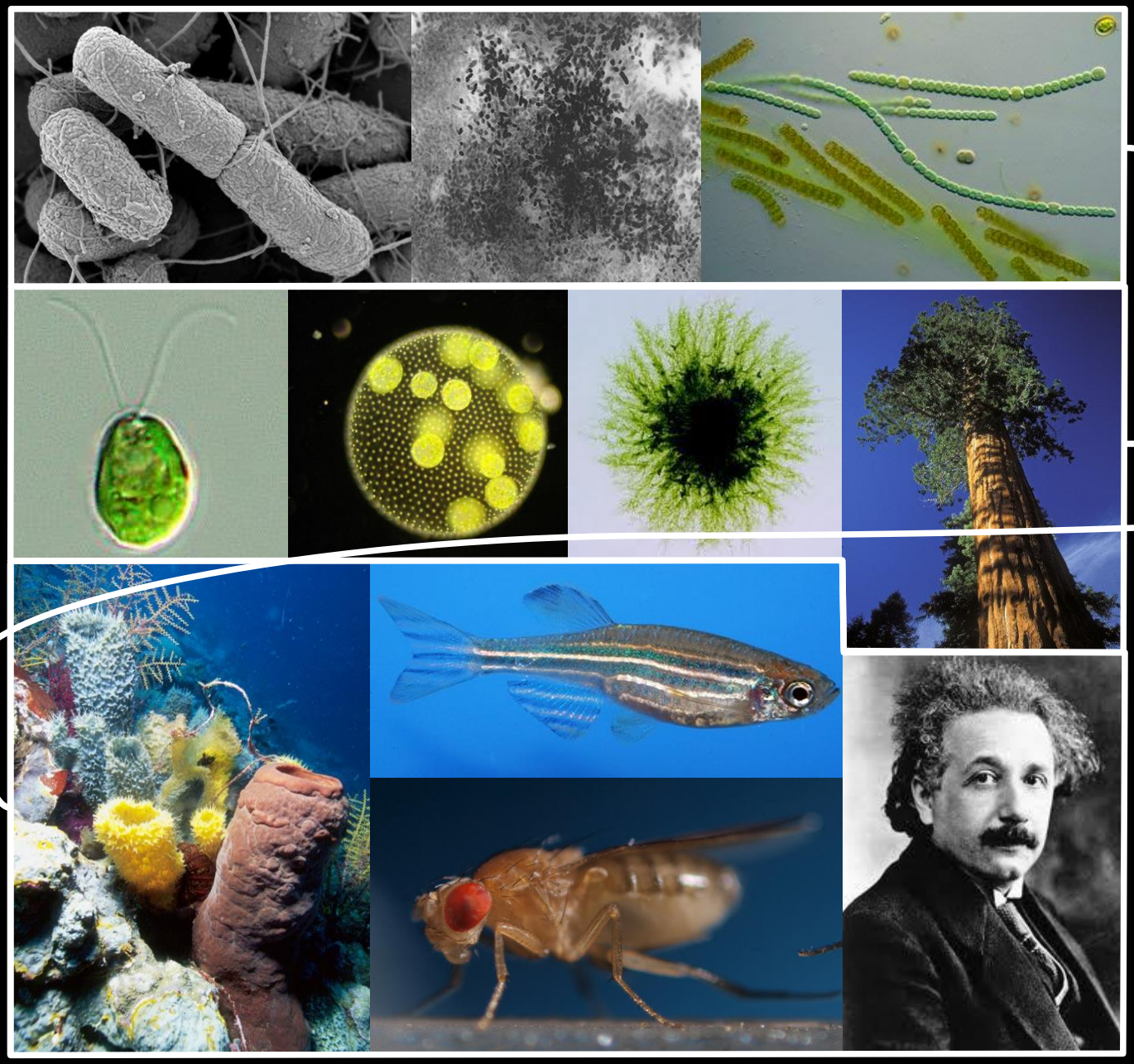
How did complex life emerge?



on the evolutionary lev

on the developmental le

Gradual evolution of complex life and biodiversity

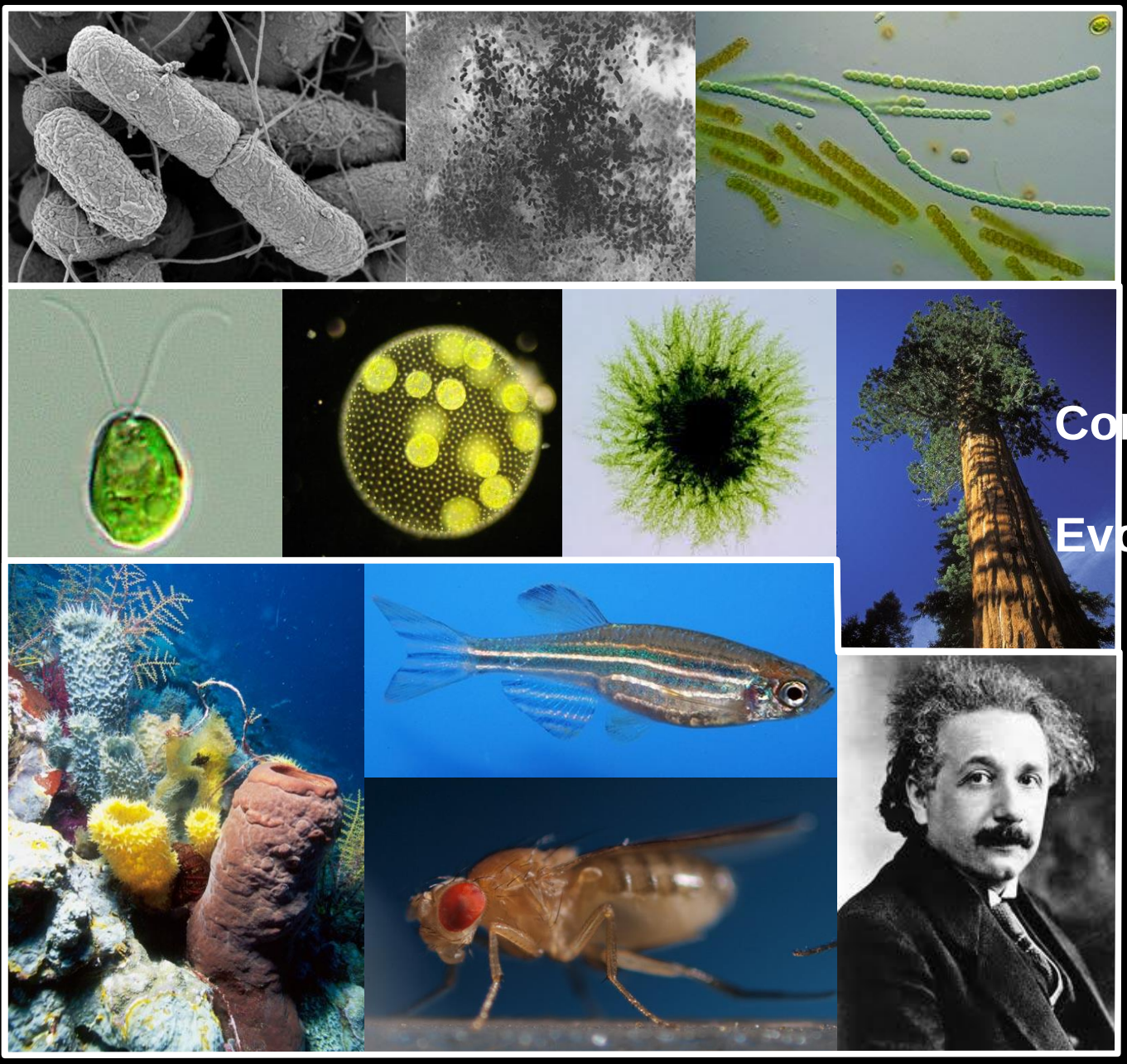


Gradual evolution of complex life and biodiversity

Bacteria

Plants

Animals



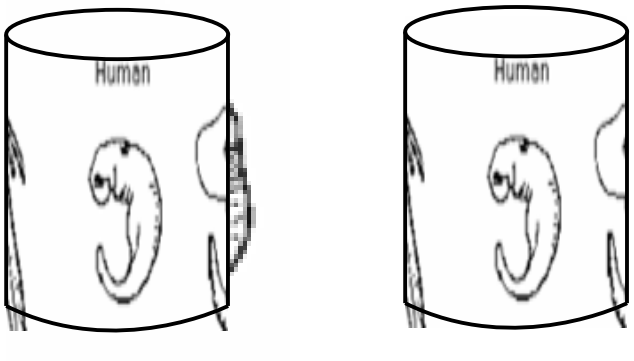
Comparative embryol

Evolutionary embryol

Evo-devo

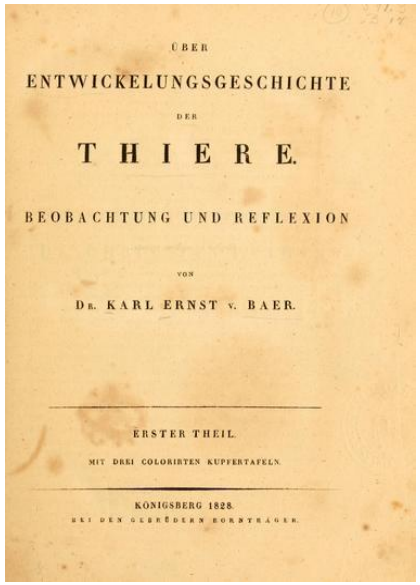
Comparative embryology - Baer's laws of embryology

Karl Ernst von Baer
1792-1876



„Ich besitze zwei kleine Embryonen in Weingeist, für die ich versäumt habe di

- K.E. von Baer, (**1828**), *Entwickelungsgeschichte der Thiere* (S. 221)


ÜBER
ENTWICKELUNGSGESCHICHTE
DER
THIERE.
BEOBACHTUNG UND REFLEXION
VON
DR. KARL ERNST v. BAER.
ERSTER THEIL.
MIT DREI COLORIRTEN KUPFERTAFELN.
KÖNIGSBERG 1828.
BEI DEN GEBRÜDERN BORNTRÄGER.

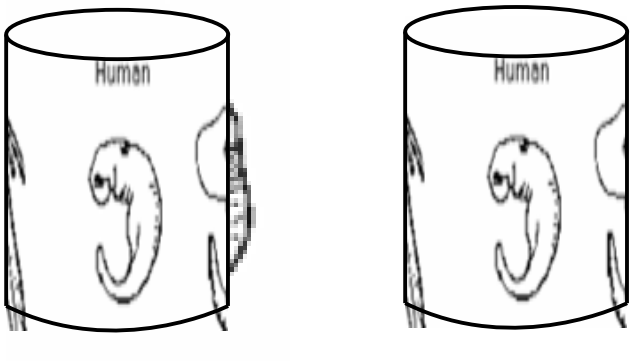
(1) General features of the embryo appear earlier than special features
(2) Special characters develop from general characters
(3) Embryos of different species progressively diverge from one another during ontogeny
(4) Embryos of one animal can never resemble the adult form of another animal, but only its embryo

→ Existence of a stage in which embryos of different vertebrate species could not be distinguished
→ One of the milestone discoveries in developmental biology!

http://upload.wikimedia.org/wikipedia/de/0/08/VonBaer.jpg

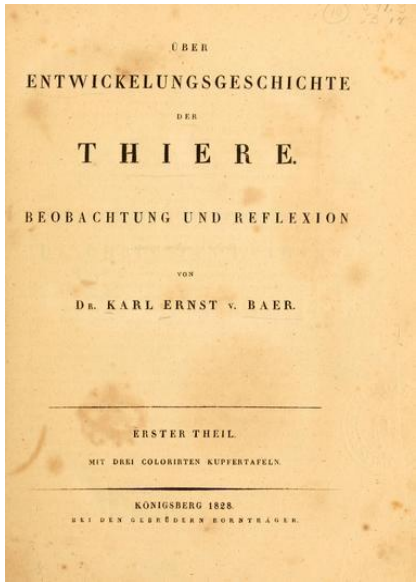
Comparative embryology - Baer's laws of embryology

Karl Ernst von Baer
1792-1876



„*Ich besitze zwei kleine Embryonen in Weingeist, für die ich versäumt habe di*

- K.E. von Baer, (**1828**), *Entwickelungsgeschichte der Thiere* (S. 221)

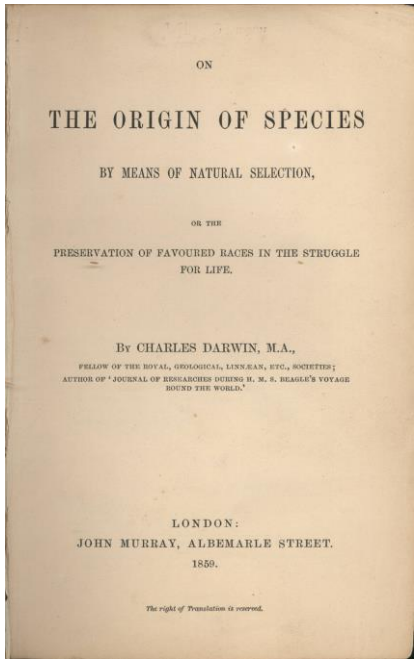

ÜBER
ENTWICKELUNGSGESCHICHTE
DER
THIERE.
BEOBACHTUNG UND REFLEXION
VON
DR. KARL ERNST v. BAER.
ERSTER THEIL.
MIT DREI COLORIRTEN KUPFERTAFELN.
KÖNIGSBERG 1828.

(1) General features of the embryo appear earlier than special features
(2) Special characters develop from general characters
(3) Embryos of different species progressively diverge from one another during ontogeny
(4) Embryos of one animal can never resemble the adult form of another animal, but only its embryo

→ Pre-Darwin → no connection to Darwinian evolution

http://upload.wikimedia.org/wikipedia/de/0/08/VonBaer.jpg

Post-Darwin



ON

THE ORIGIN OF SPECIES

BY MEANS OF NATURAL SELECTION,

OR THE

PRESERVATION OF FAVOURED RACES IN THE STRUGGLE FOR LIFE.

By CHARLES DARWIN, M.A.,

FELLOW OF THE ROYAL, GEOLOGICAL, LINNÆAN, ETC., SOCIETIES;
AUTHOR OF 'JOURNAL OF RESEARCHES DURING H. M. S. BEAGLE'S VOYAGE ROUND THE WORLD.'

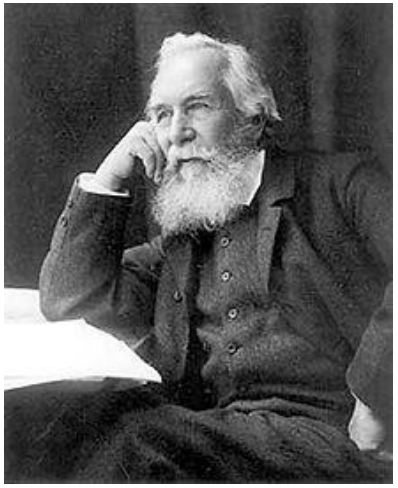
LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1859.

→ Darwin delivered the connection of:
- Theory of evolution
- Common origin of species

} Mechanism:
Natural Selection

Connection between origin / descent, systematics, and ontogeny?

Post-Darwin - Ernst Haeckel



Ernst Haeckel
1834 - 1919

Haeckel's biogenetic law (1866):

"*Die Ontogenesis ist die kurze und schnelle Recapitulation der Phylogenesis*"

- Mostly wrong and based on purposely falsified data:

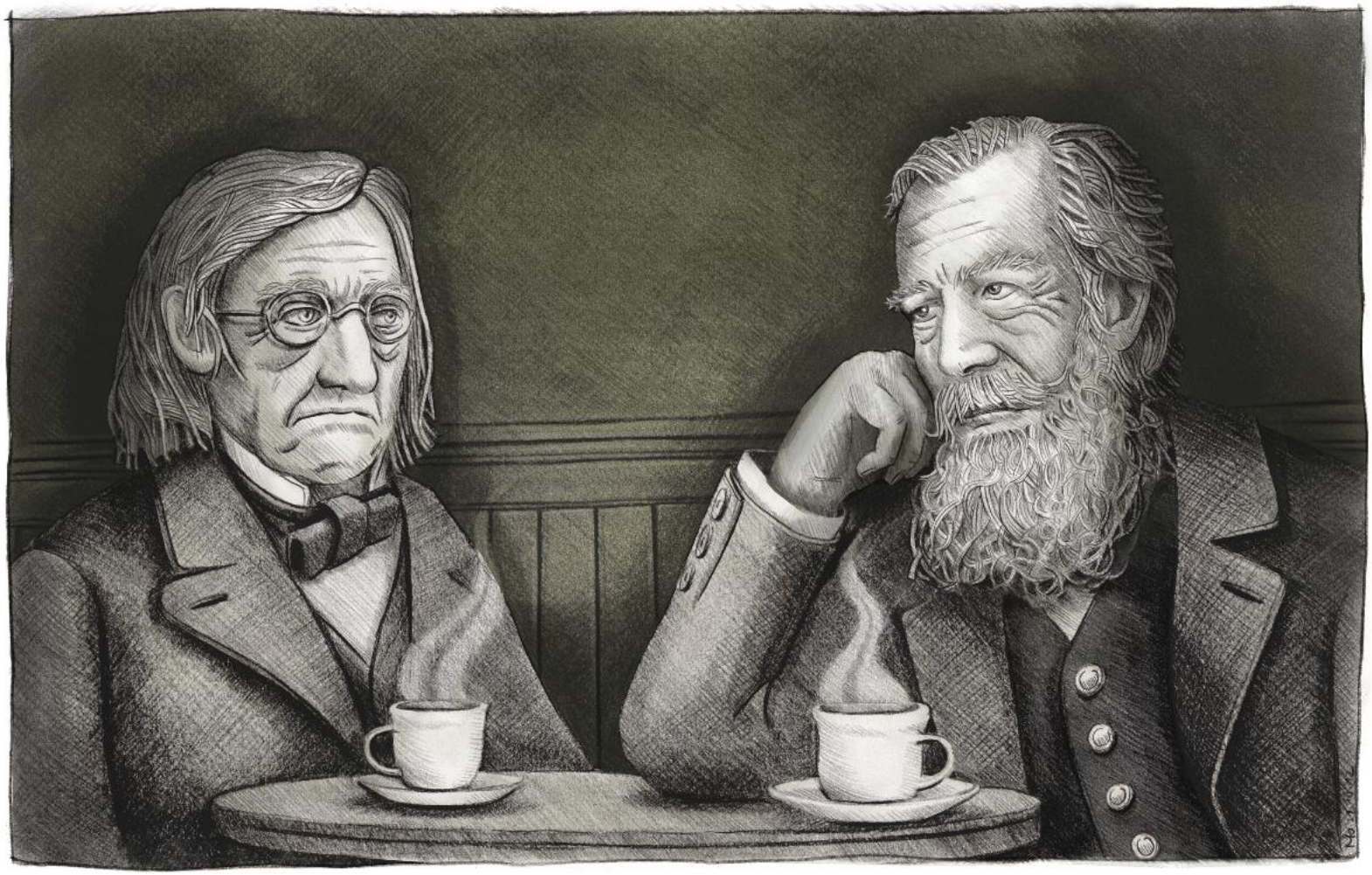
- Groundwork for social darwinism and nazi racial ideology

BUT: for the first time approaching developmental biology from an evolutionary perspective

http://upload.wikimedia.org/wikipedia/commons/thumb/2/2f/Ernst_Haeckel_2.jpg/220px-Ernst_Haeckel_2.jpg

Haeckel, 1874

Comparative embryology – **19**th century



<u>von Baer's contribution</u>

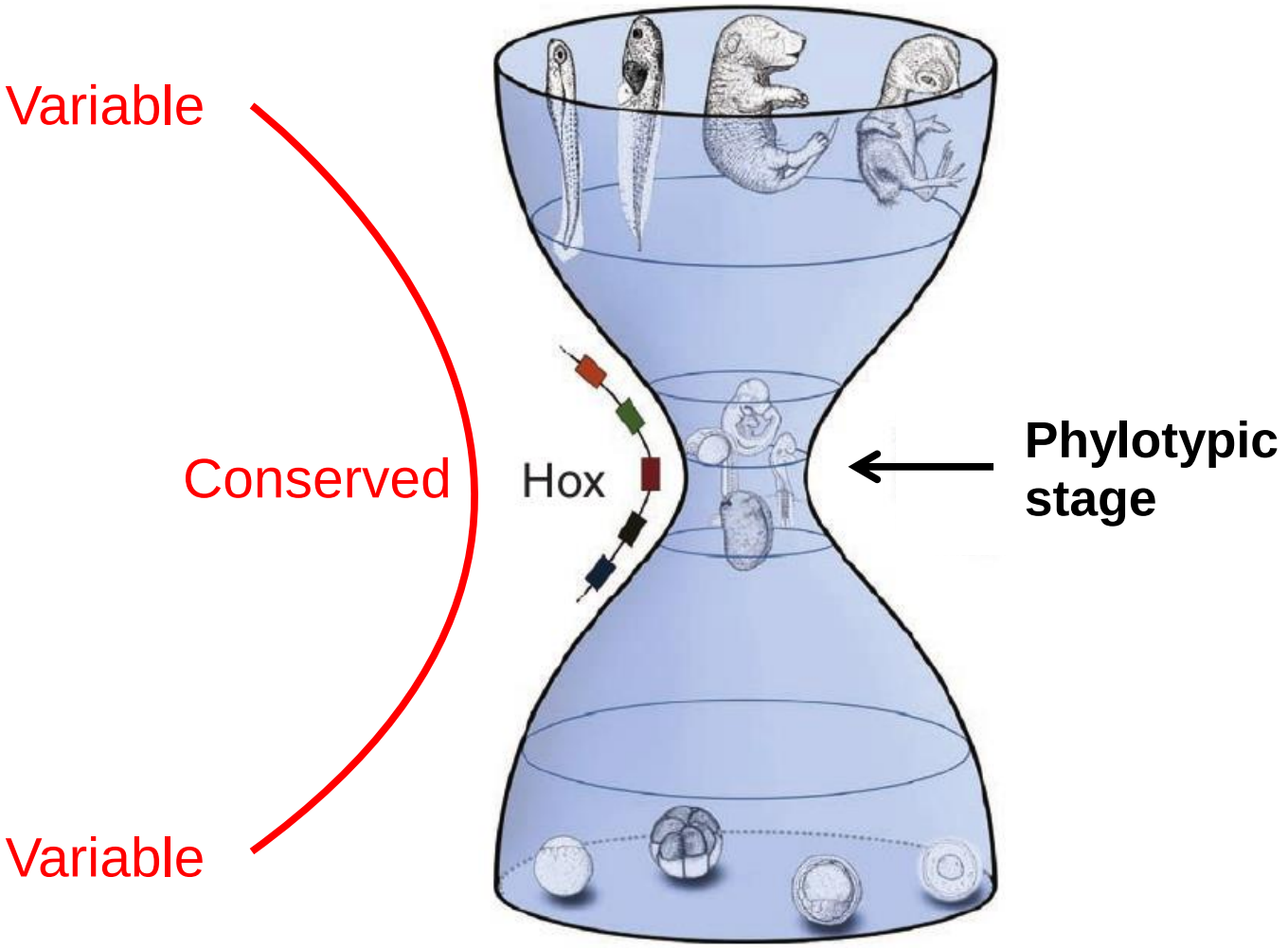
- Existence of a stage of max. morphological conservation during embryogenesis of different vert

<u>Haeckel's contribution</u>

f different disciplines, such as taxonomy and embryology, into the then new Darwinian framework

- Use of such data for phylogeny reconstruction

Comparative embryology – The hourglass model



Irie and Kuratani, 2011, *Nature Communications*

.21st century – the genomic level

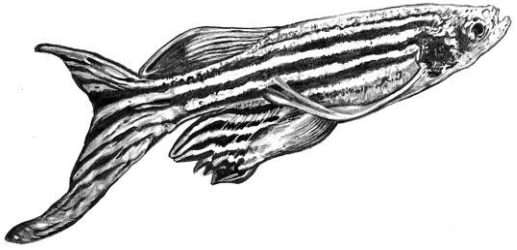
LETTER

doi:10.1038/nature09632

A phylogenetically based transcriptome age index mirrors ontogenetic divergence patterns

Tomislav Domazet-Lošo[1,2] & Diethard Tautz[1]

Nature (2010)



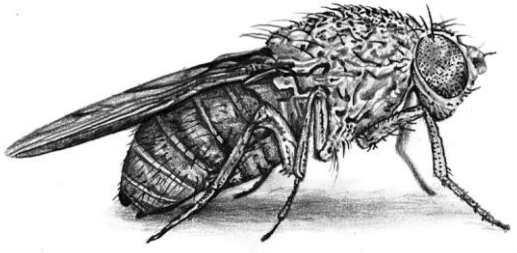
LETTER

doi:10.1038/nature09634

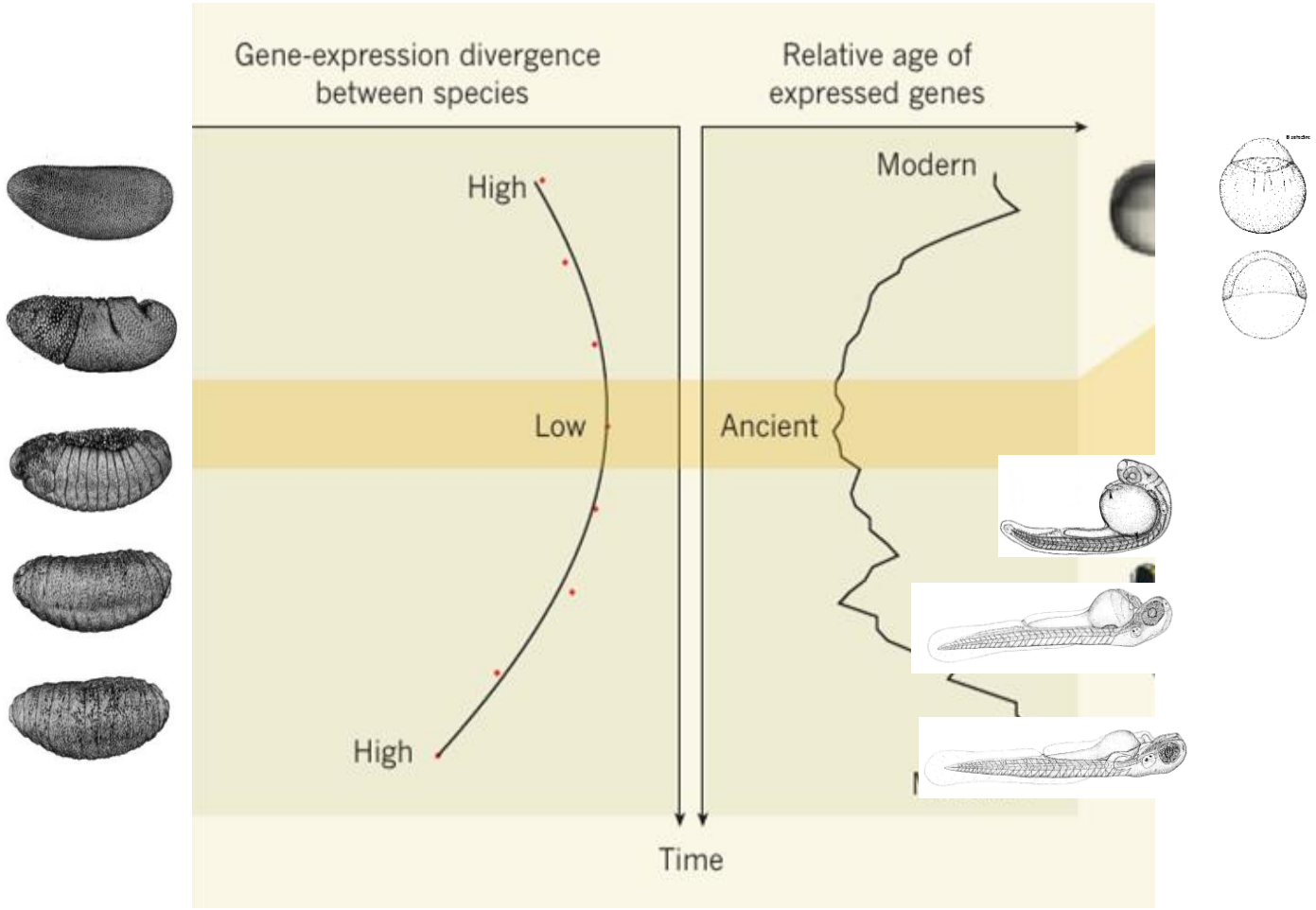
Gene expression divergence recapitulates the developmental hourglass model

Alex T. Kalinka[1]*, Karolina M. Varga[1]*†, Dave T. Gerrard[2], Stephan Preibisch[1], David L. Corcoran[3], Julia Jarrells[1], Uwe Ohler[3], Casey M. Bergman[2] & Pavel Tomancak[1]

Nature (2010)



21st century – the genomic level



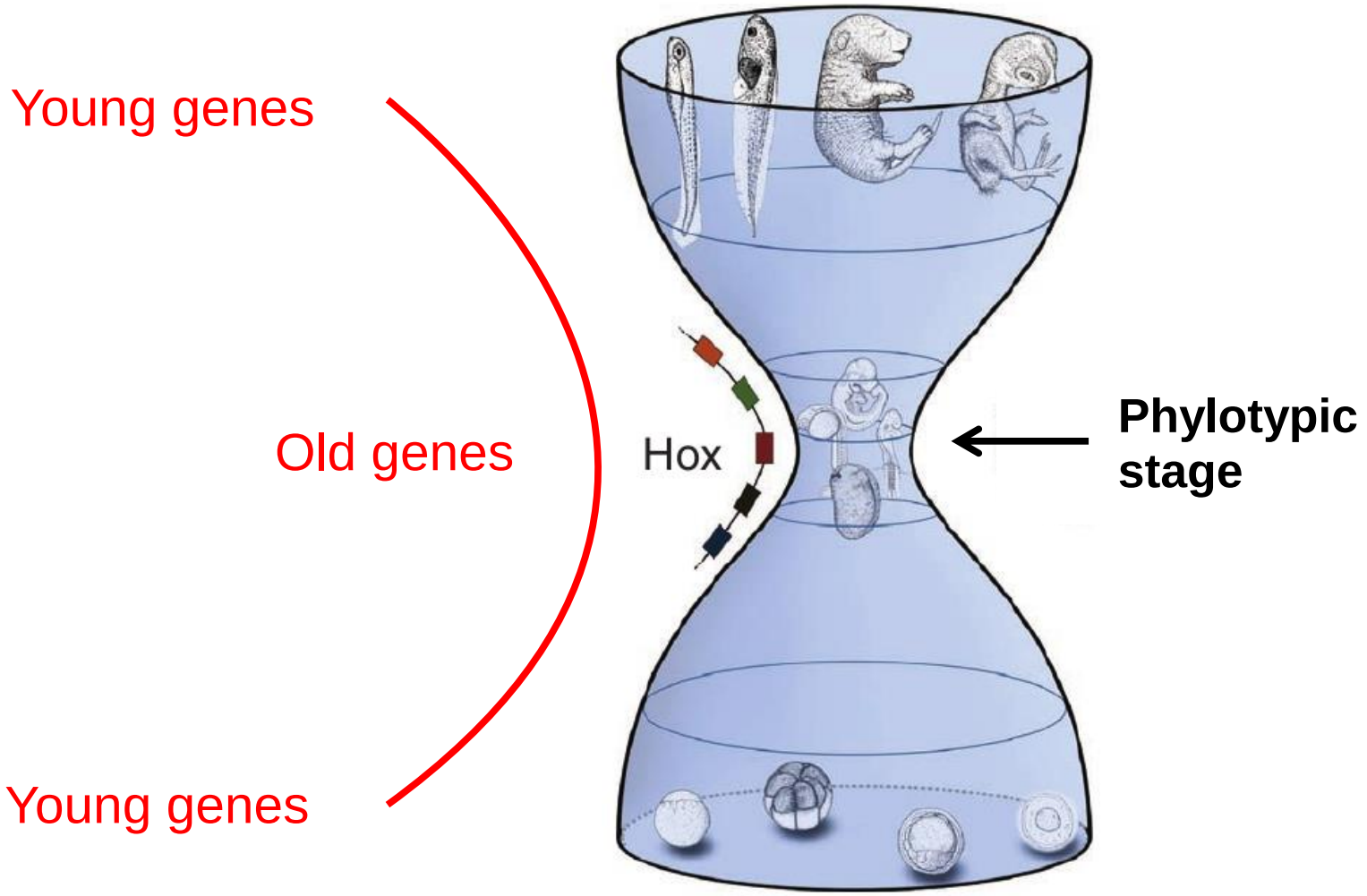
Drosophila

Zebrafish

1. Morphology AND transcriptomes follow an hourglass pattern!
2. Max. conservation of the transcriptomes observed at the morphological phylotypic stage!

Prud'homme and Gompel, 2010, *Nature* (referring to Domazet-Loso and Tautz, 2010, *Nature*, and Kalinka et al., 2010, *Nature);* http://www.neuro.uoregon.edu

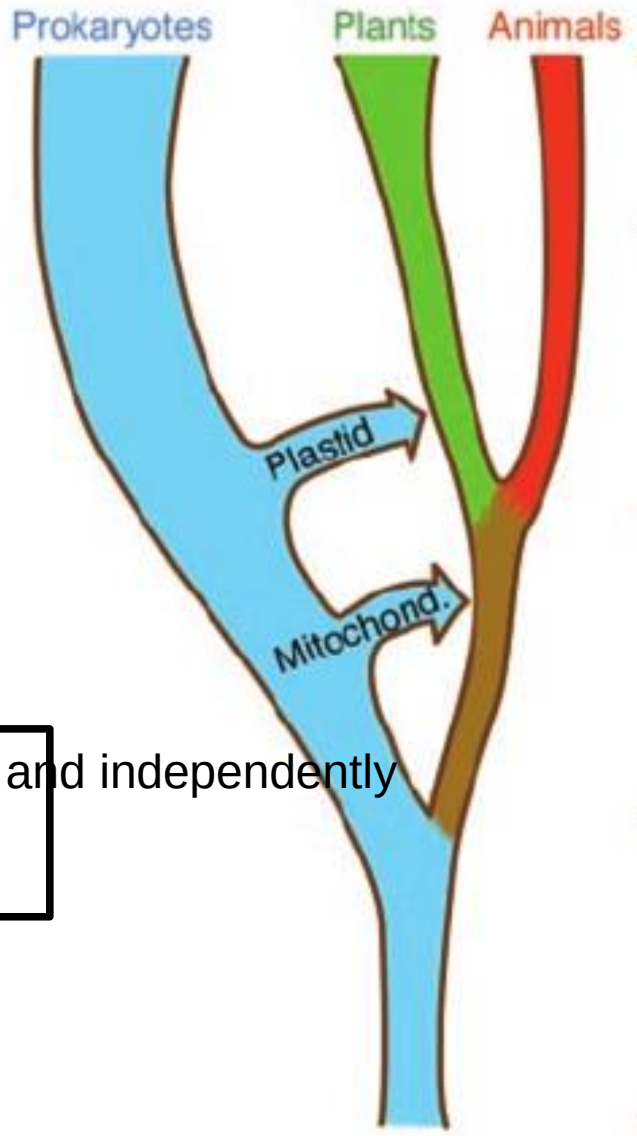
21st century – the genomic level



Irie and Kuratani, 2011, *Nature Communications*

Evolution of embryogenesis

Unicellular life ⟶ Multicellular life ⟶ Embryogenesis ⟶ Complex life



← Embryogenesis

← Multicellularity (Eukaryotes

← Last common ancestor: Unicellular

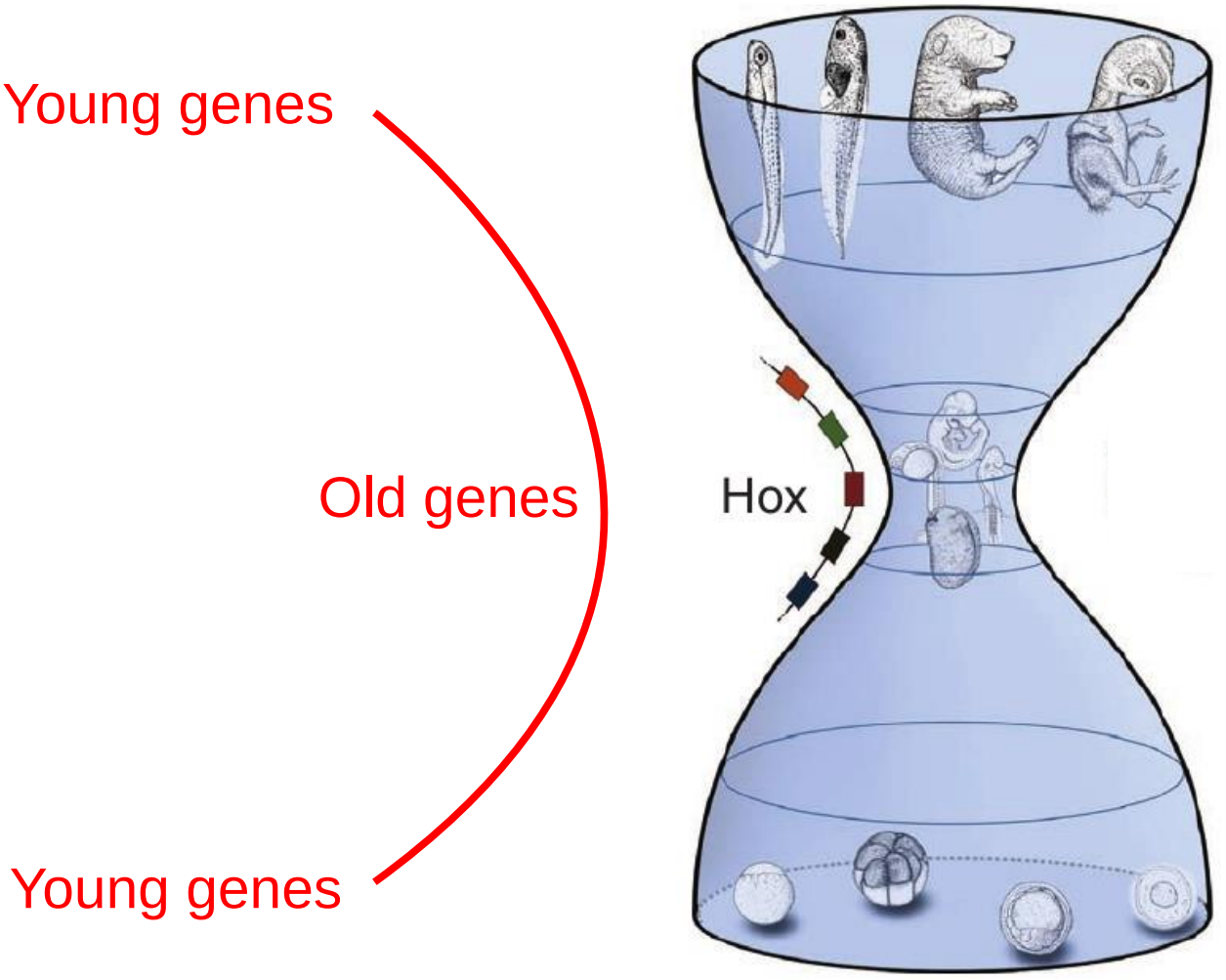
esis evolved at least twice and independently

Meyerowitz, 2002, *Science*

What about plants?

- Is there a transcriptional hourglass in plants?

- Or any other pattern?



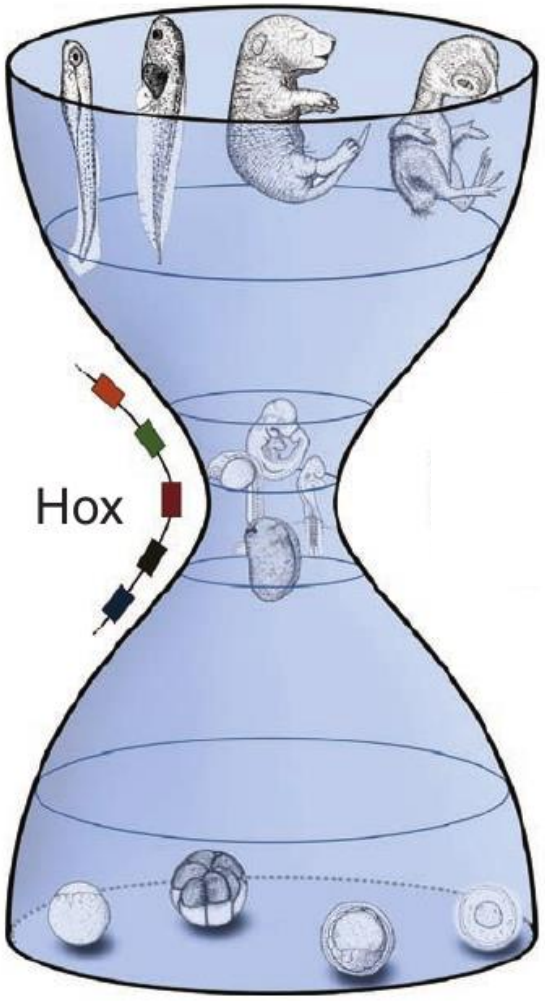
Irie and Kuratani, 2011, *Nature Communications*

What about plants?

Two pieces of information:

1. Evolutionary age for each gene

2. Transcriptomes of various embryo stages



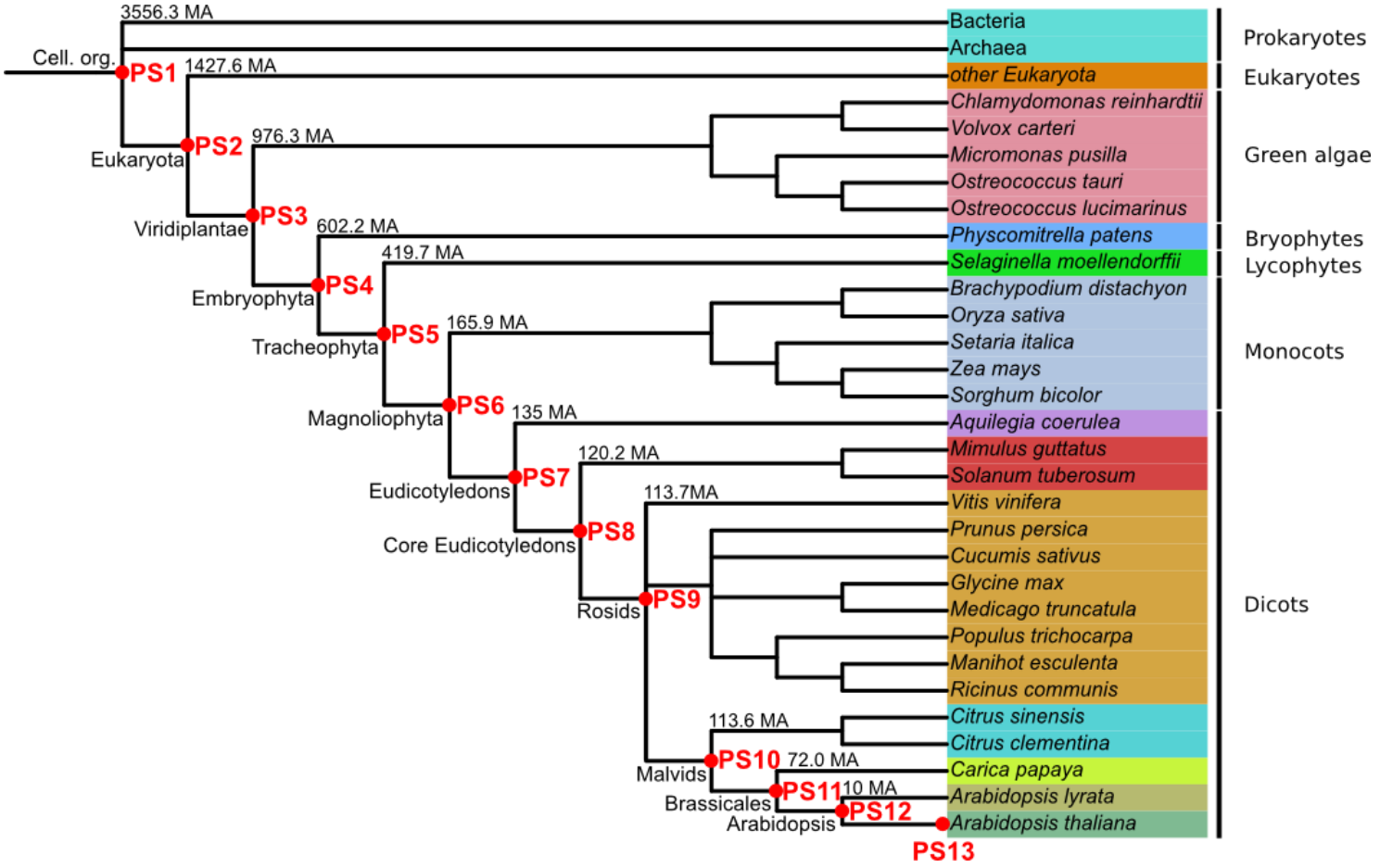
Irie and Kuratani, 2011, *Nature Communications*

Step 1: Phylogenetic information for each gene - Phylostratigraphy

Domazet-Lošo et al., 2007, *Trends Genet*

Reconstruct the phylogeny of *the species of interest* along the tree of life
→ restricted to completely sequenced organisms

Categorize each new node/branch point in the phylogeny to a **phylostratum**
→ from young to old



Step 1: Phylogenetic information for each gene - Phylostratigraphy

Domazet-Lošo et al., 2007, *Trends Genet*

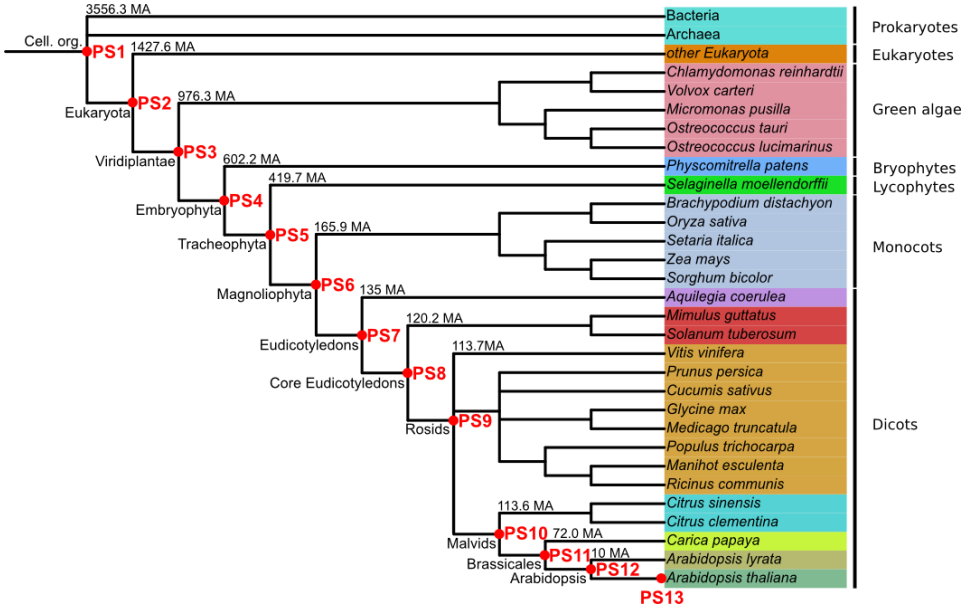
Reconstruct the phylogeny of *the species of interest* along the tree of life
→ restricted to completely sequenced organisms

Categorize each new node/branch point in the phylogeny to a **phylostratum**
→ from young to old

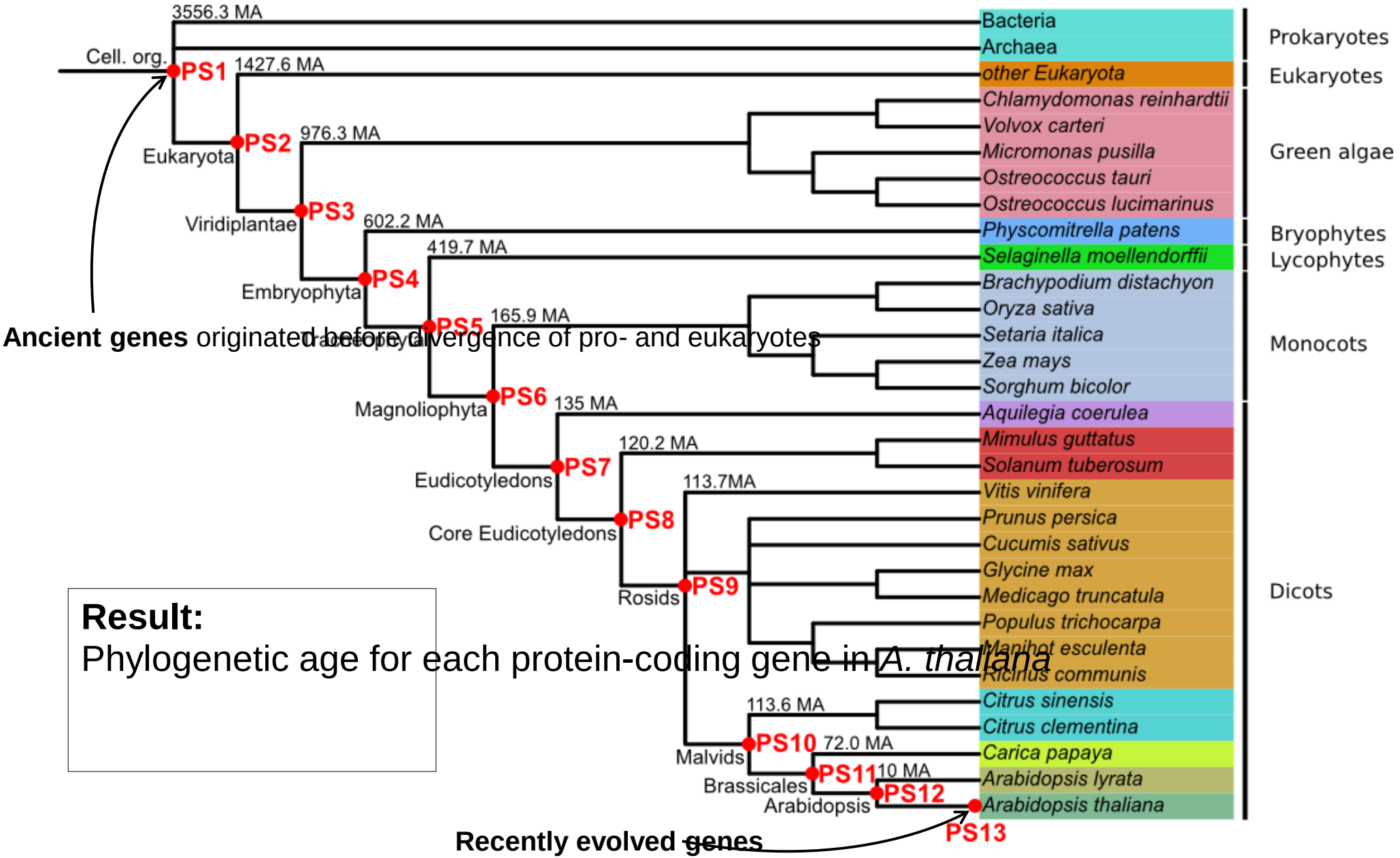
Construct a database with all sequenced genomes in the phylogeny

Blast each gene/protein of *the species of interest* to this database

Sort genes into phylostrata (PS1 through PSn)



Reconstructed phylogeny of *A. thaliana*



Ancient genes originated before divergence of pro- and eukaryotes

Result:
Phylogenetic age for each protein-coding gene in *A. thaliana*

Recently evolved genes

- based on completely sequenced species (n = 1452)

Step 2: How can we apply phylostratigraphy to transcriptional data?

adapted from Domazet-Lošo and Tautz, 2010, *Nature*

Introduce expression intensity of a gene as a weight for its phylogenet

Sum over all genes

=

Transcriptome **A**ge **I**ndex (TAI)

Definition TAI:

The mean evolutionary age of a transcriptome, where the evolutionary age (PS) of each gene is weighted

Step 2: How can we apply phylostratigraphy to transcriptional data?

adapted from Domazet-Lošo and Tautz, 2010, *Nature*

Introduce expression intensity of a gene as a weight for its phylogenet

Sum over all genes

=

Transcriptome **A**ge **I**ndex (TAI)

Definition TAI:

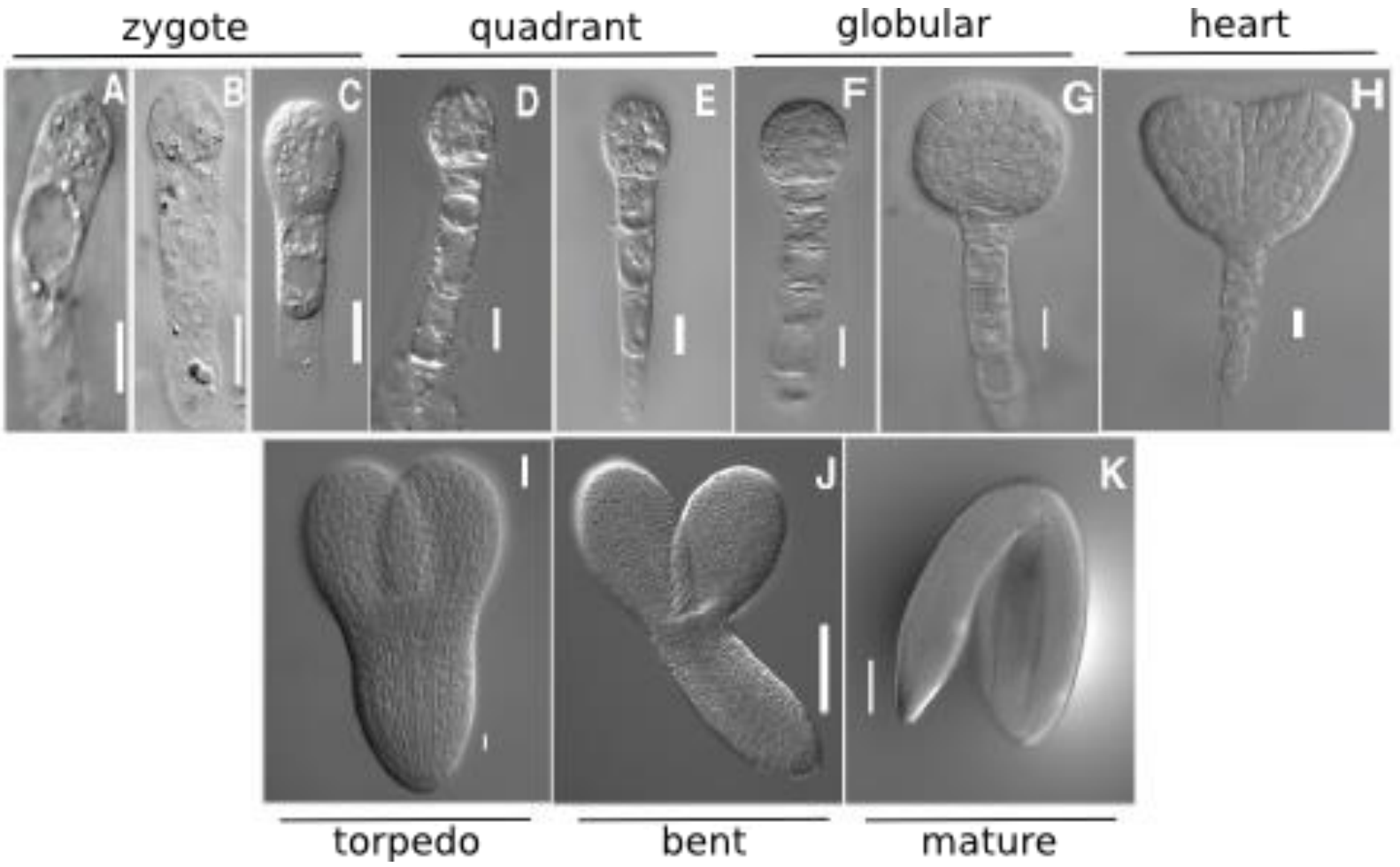
The mean evolutionary age of a transcriptome, where the evolutionary age (PS) of each gene is weighted

Goal:

Compute TAI across multiple embryo stages

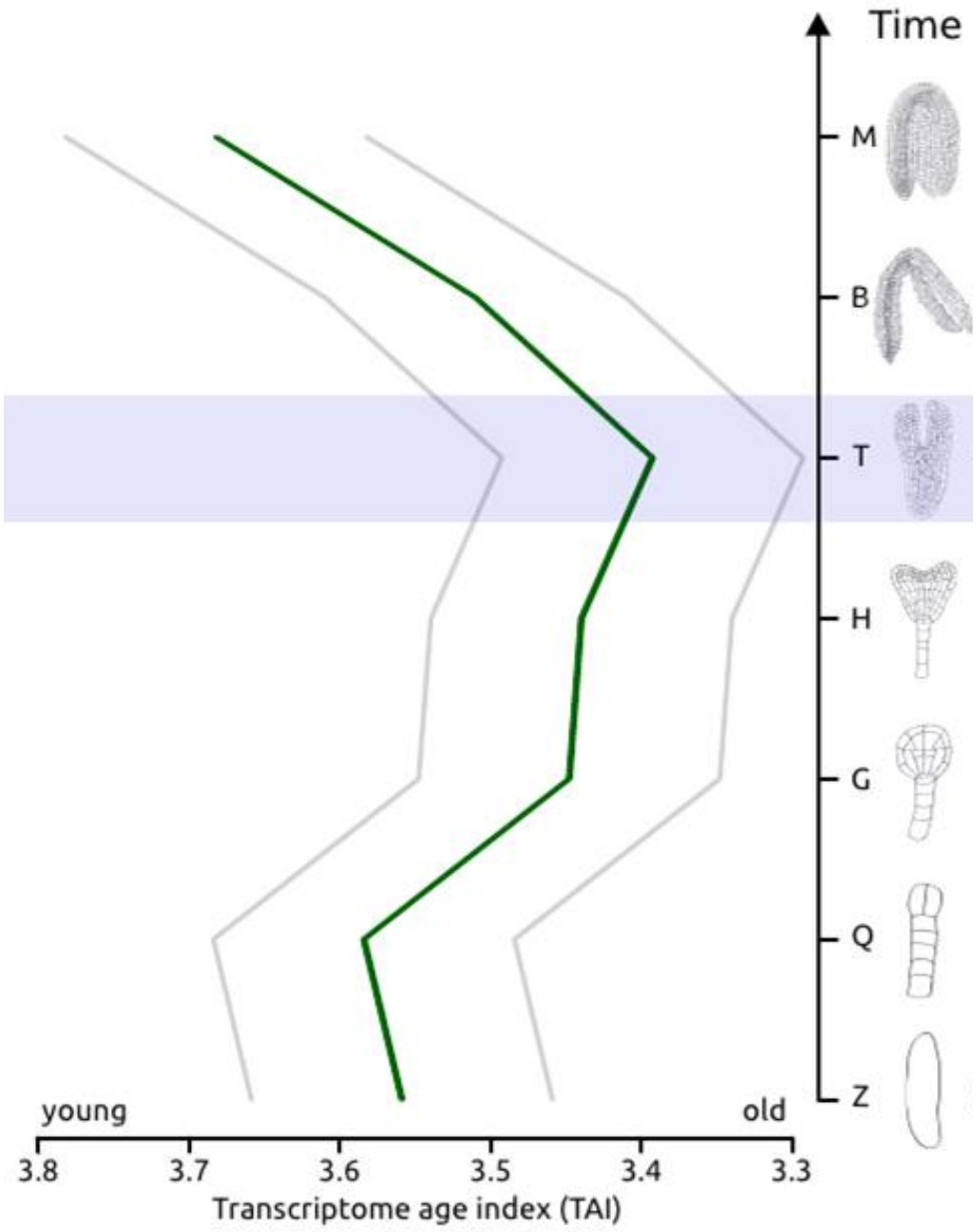
→ compare TAI profile to hourglass pattern

Embryogenesis in *Arabidopsis thaliana*



Xiang et al., 2011, *Plant Physiol*

ttern of *A. thaliana* embryogenesis is reminiscent of the developmental hou

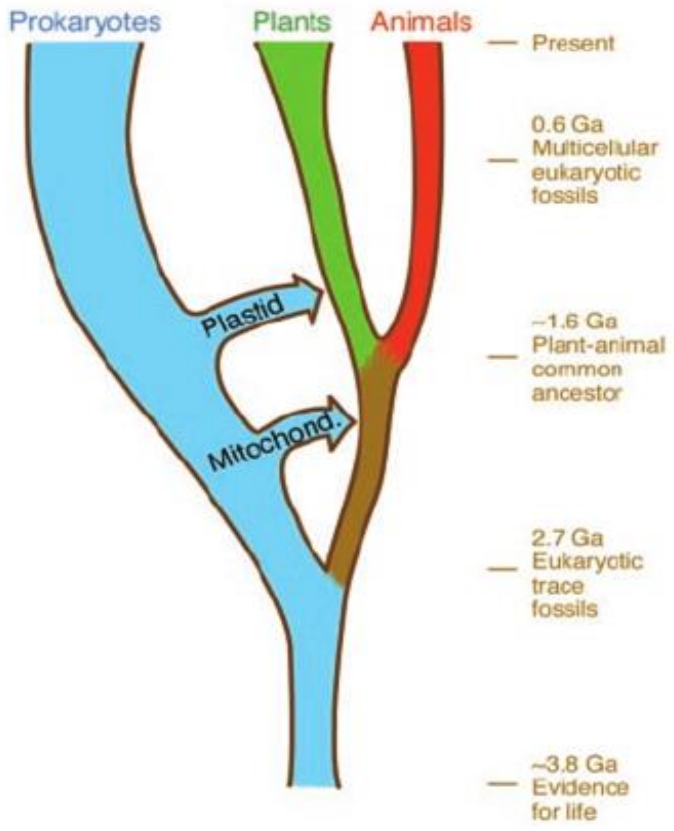


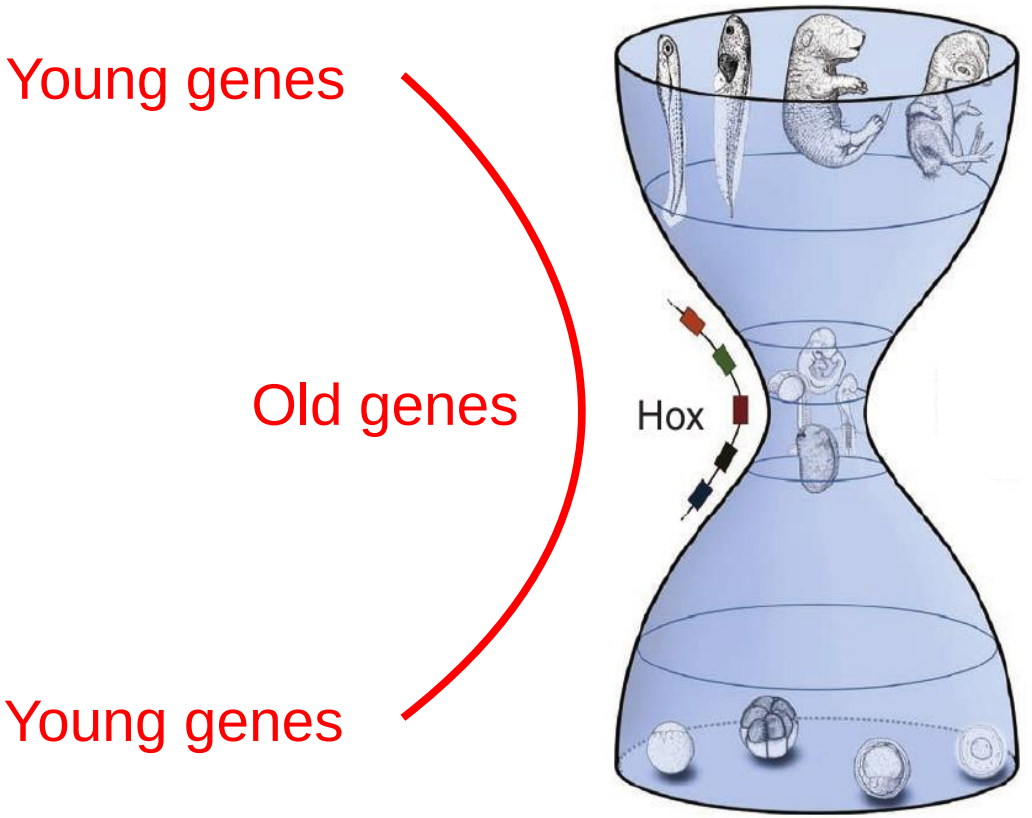
Intermediate conclusions

Embryogenesis evolved twice and independently in animals and plants

Embryogenesis morphologically and genetically different in animals and plants

But transcriptomes of animals and plants show the same hourglass pattern



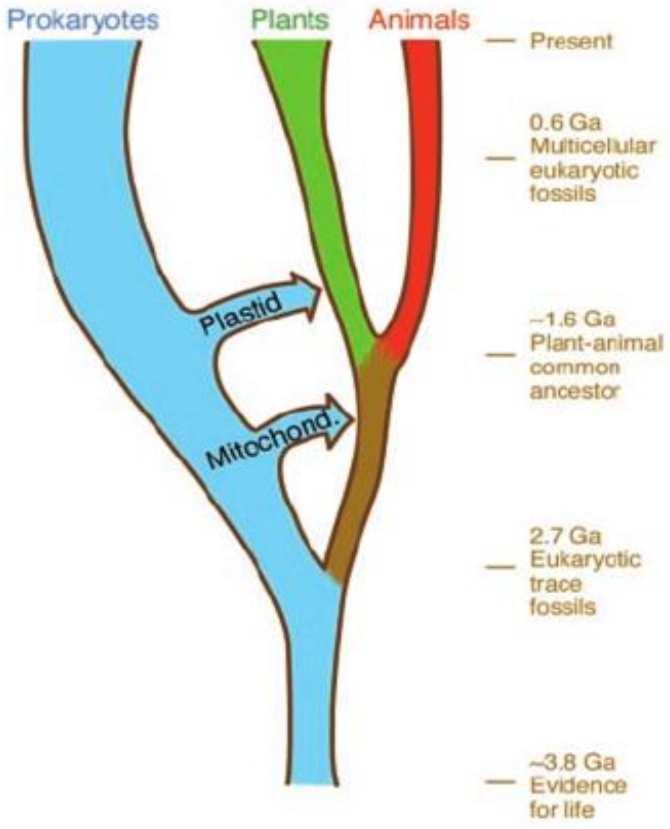


Fundamental question

Is the hourglass pattern

- **an evolutionary relic** and possibly not functional anymore**?**

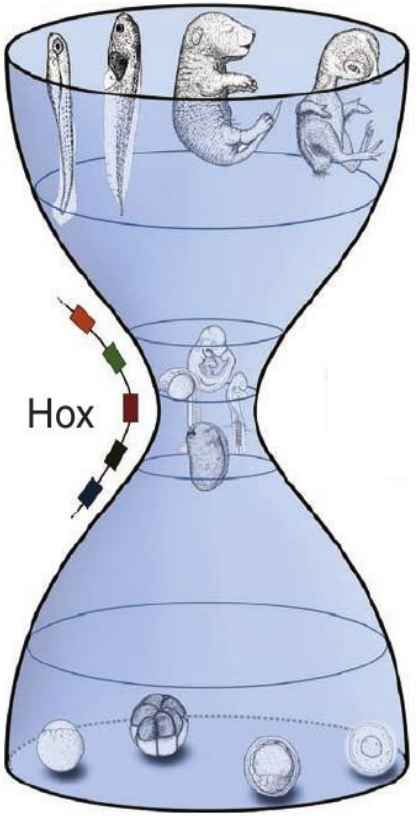
- **or actively maintained** and possibly still functional**?**



Young genes

Old genes

Young genes



Transcriptome divergence index - TDI

TDI based on sequence divergence

↓

equence comparison of orthologous genes in related species

↓

Sequence divergence = Ka/Ks → Evolutionary conserved genes
→ sequence divergence small

Ka = nonsyn. mutations
Ks = syn. mutations

Evolutionary variable genes
→ sequence divergence large

↓

Genome-wide → Ka/Ks ratios for all orthologous ~~gene pairs~~ → *A. thaliana vs. A. lyrata*

Ka/Ks instead of PS

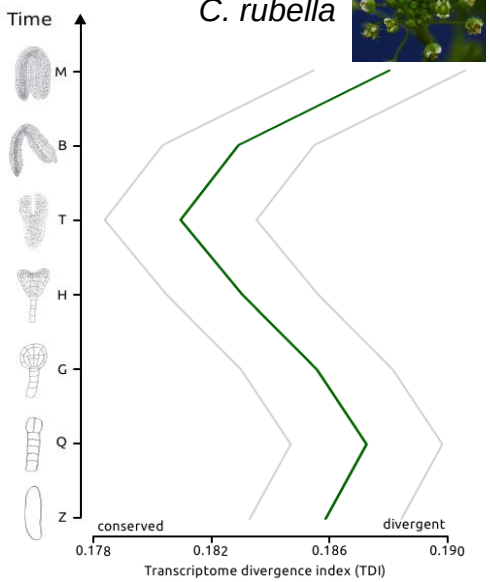
TDI patterns

TDI – 5 Mio years*

A. thaliana vs. A. lyrata

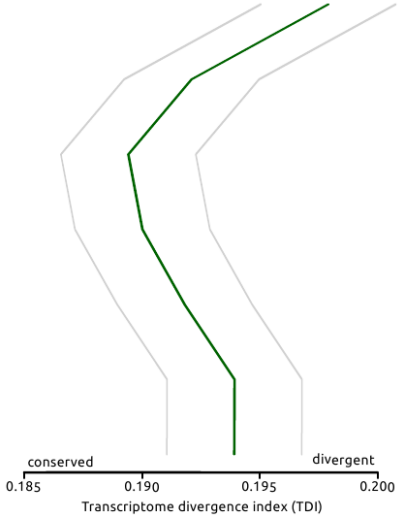
TDI – 10 Mio years*

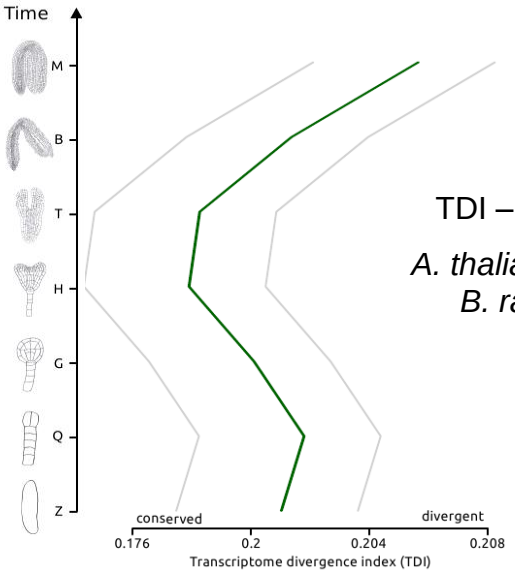
A. thaliana vs. C. rubella



TDI – 12 Mio years**

A. thaliana vs. T. halophila



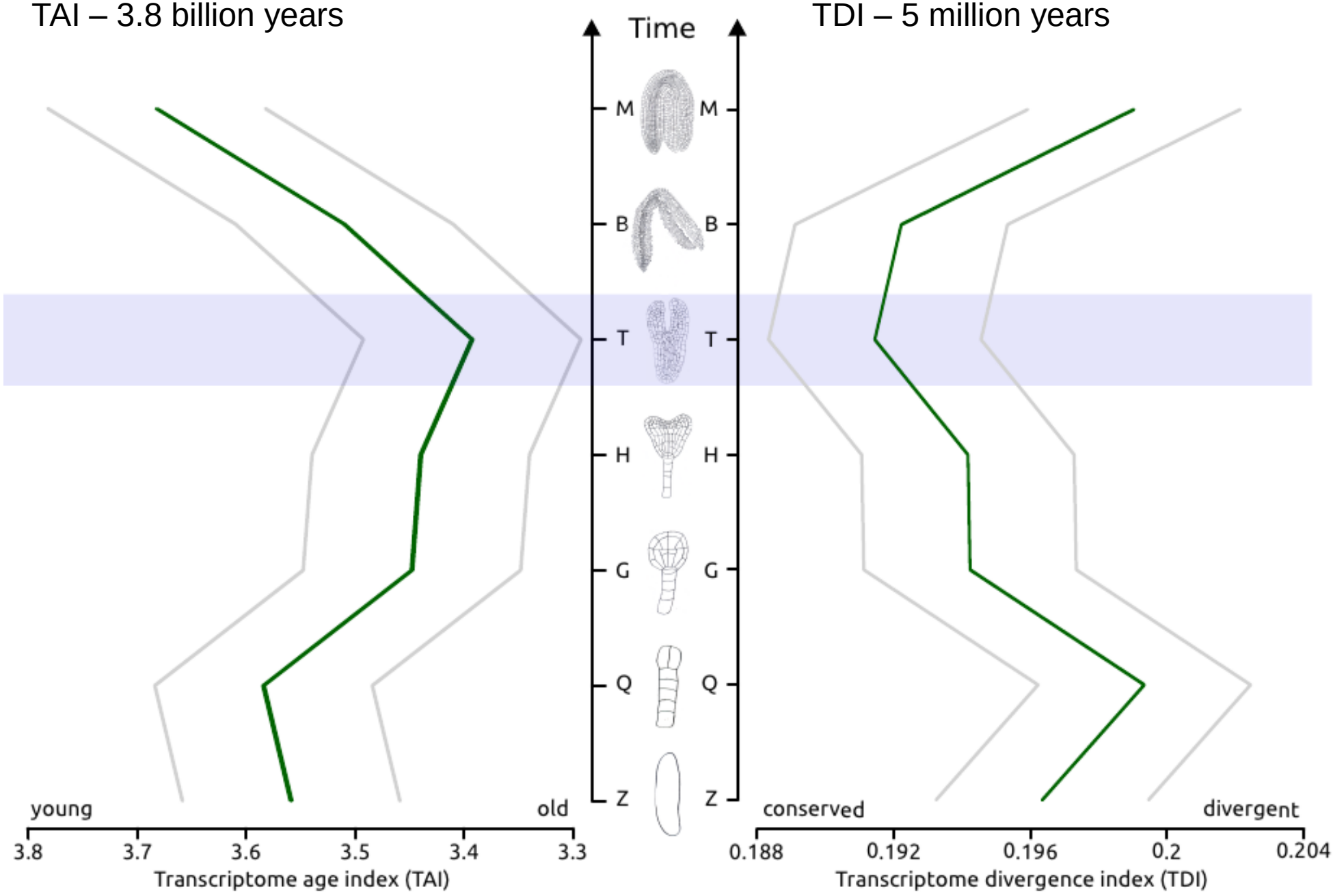


TDI – 16 Mio years*

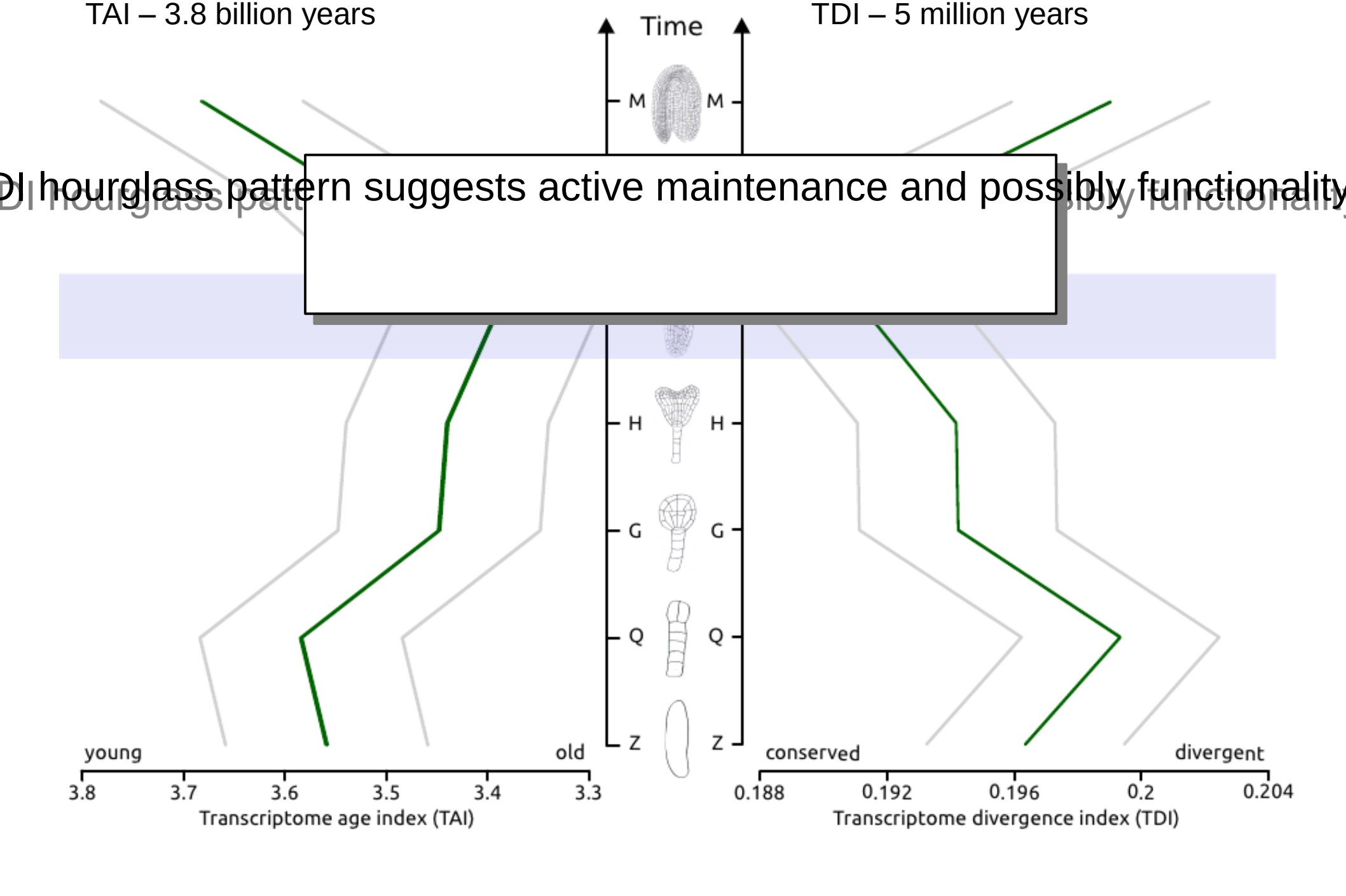
A. thaliana vs. B. rapa

*Divergence times from timetree.org **Divergence times from Oh et al., 2010, *Plant Phys*

Developmental hourglass for *A. thaliana* embryogenesis

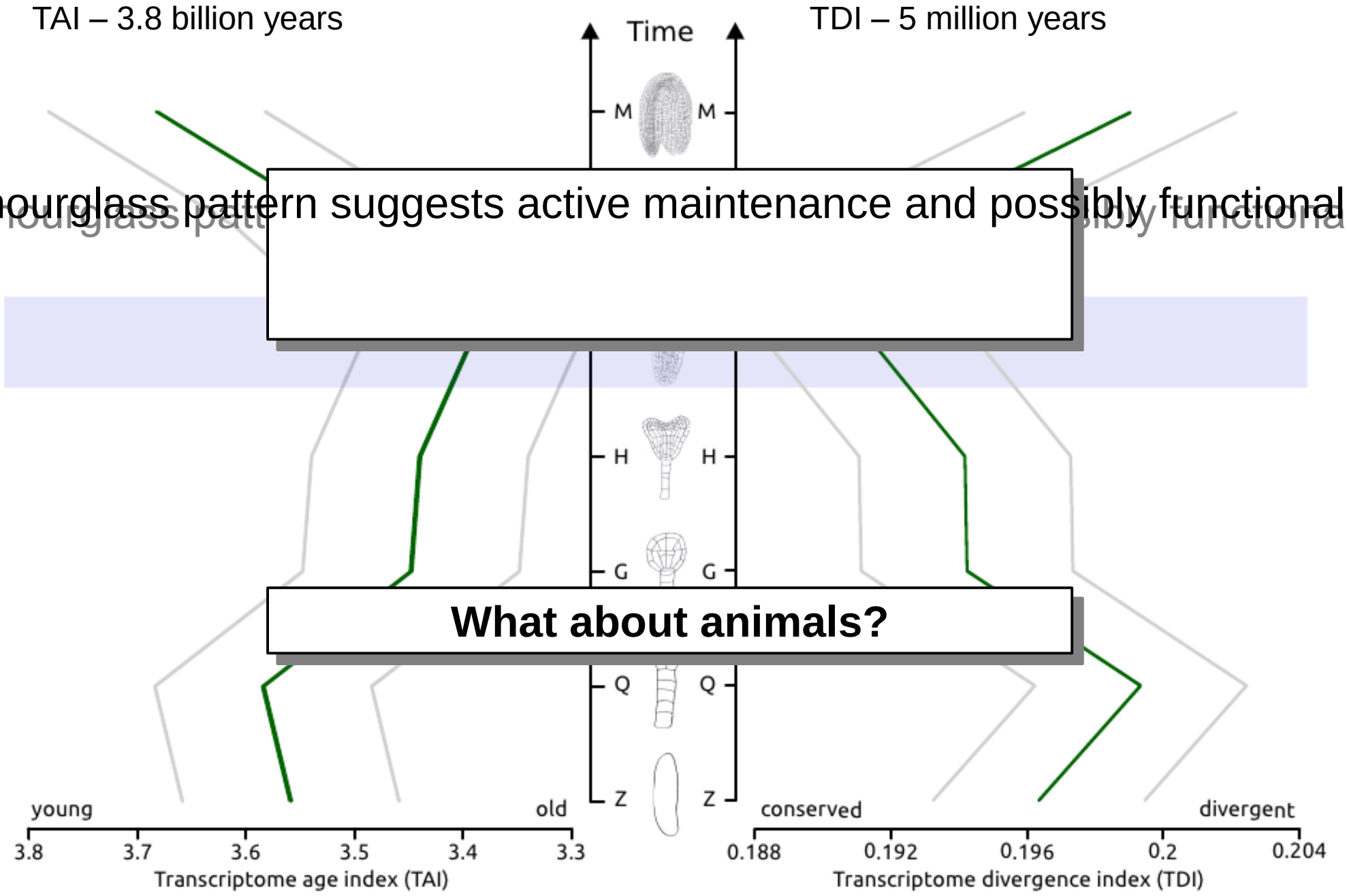


Developmental hourglass for *A. thaliana* embryogenesis



DI hourglass pattern suggests active maintenance and possibly functionality

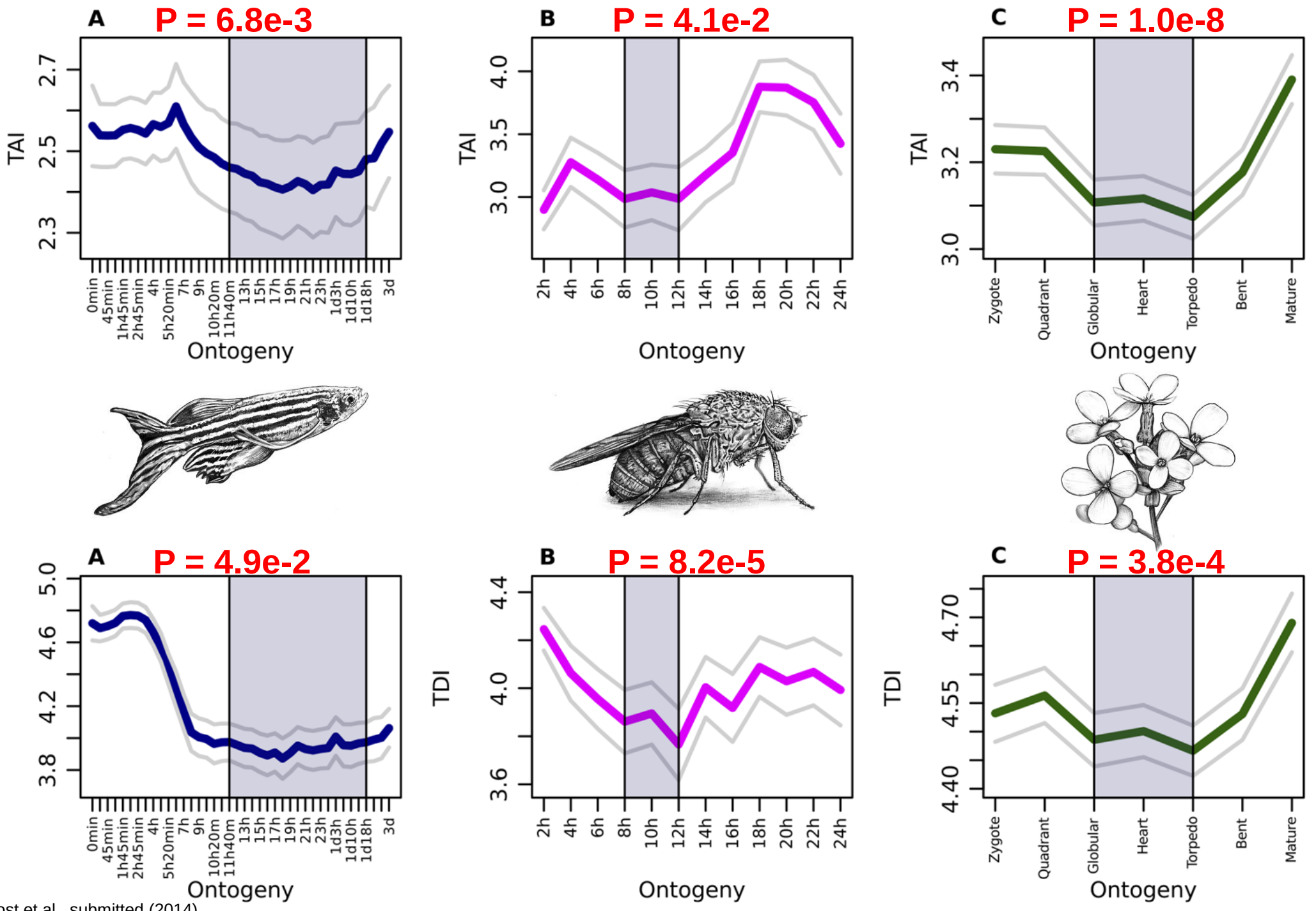
Developmental hourglass for *A. thaliana* embryogenesis



TDI hourglass pattern suggests active maintenance and possibly functionality

What about animals?

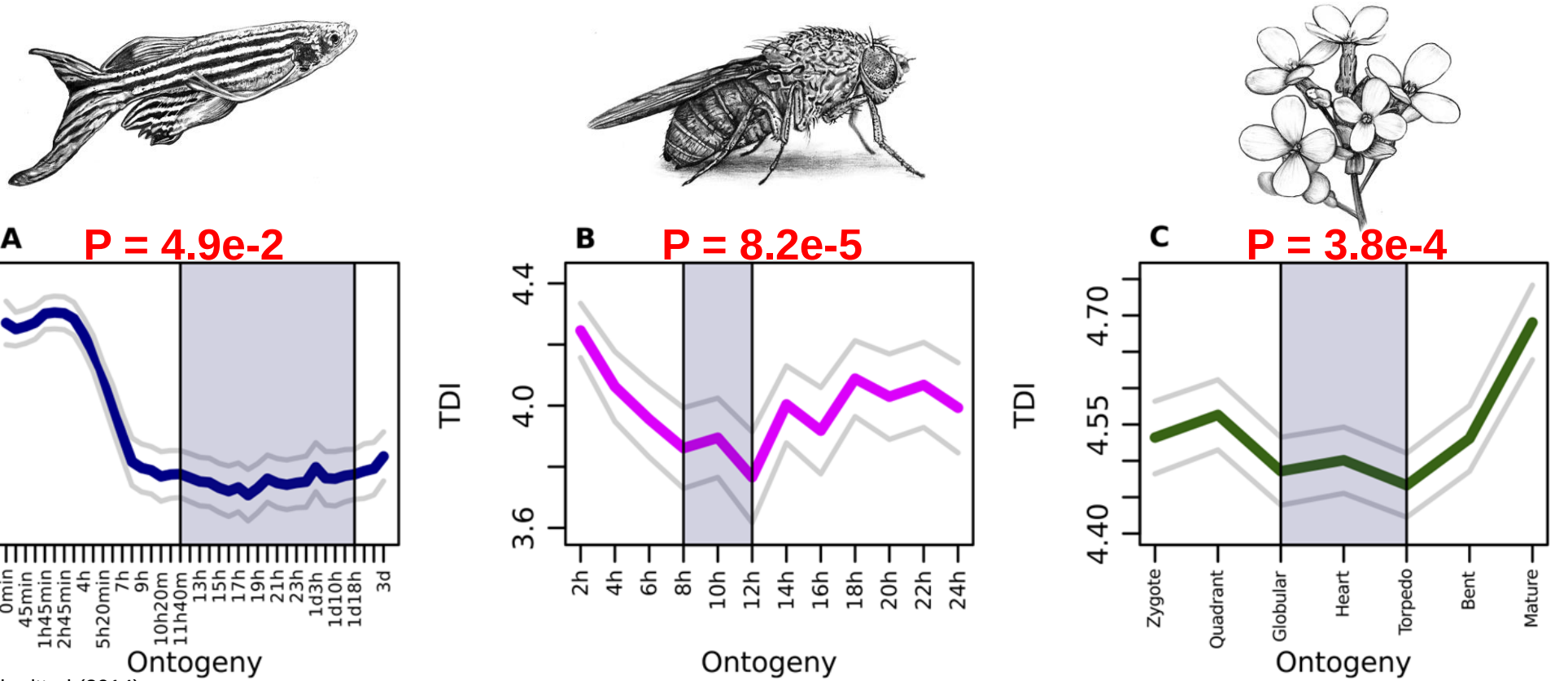
TAI and TDI for embryonic transcriptomes across kingdoms



Drost et al., submitted (2014)

TAI and TDI for embryonic transcriptomes across kingdoms

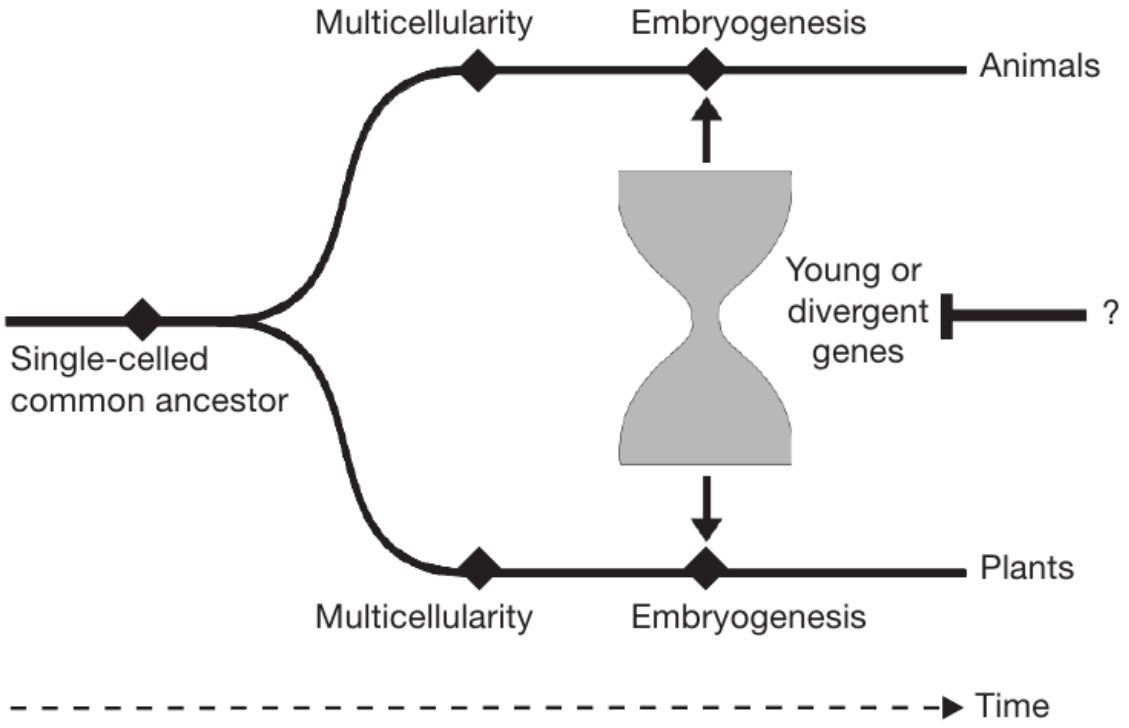
glass patterns suggest active maintenance and possibly functionality in both



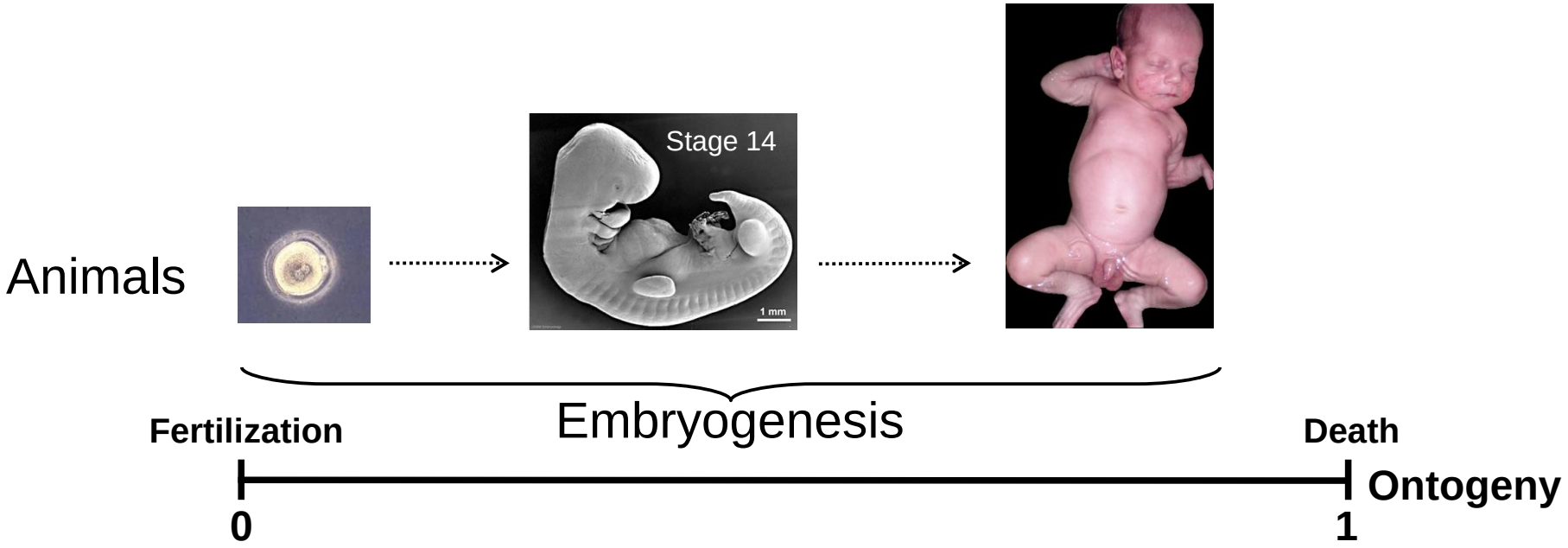
Drost et al., submitted (2014)

Intermediate conclusions

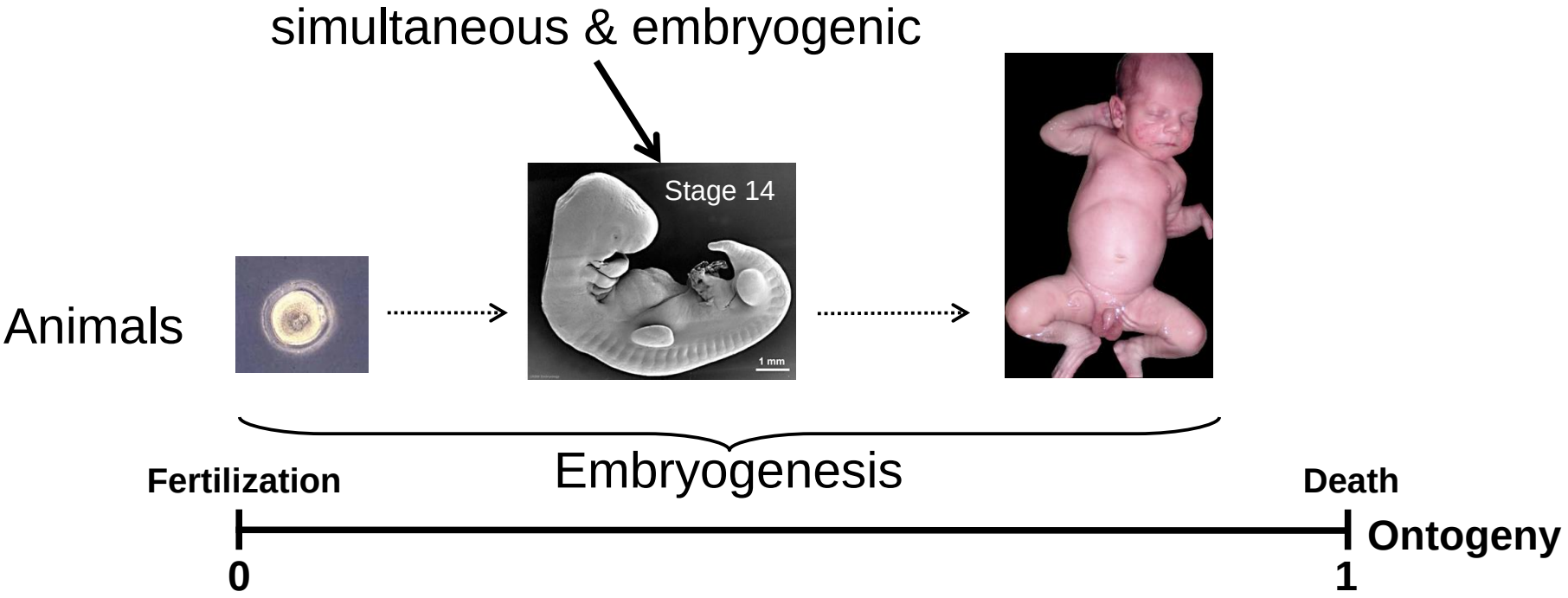
- Nature invented embryogenesis twice and independently
- Embryogenesis very different in plants and animals
- Developmental hourglass seems to be
- essential
- actively maintained
- possibly still functional?



Ontogeny / organ development: animals vs. plants



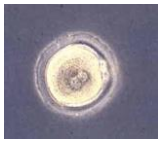
Ontogeny / organ development: animals vs. plants

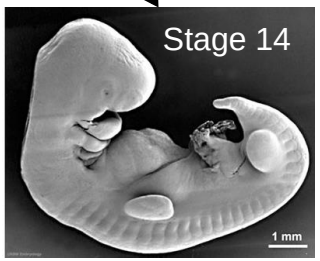


Ontogeny / organ development: animals vs. plants

simultaneous & embryogenic

Animals





Embryogenesis

Fertilization **Death**

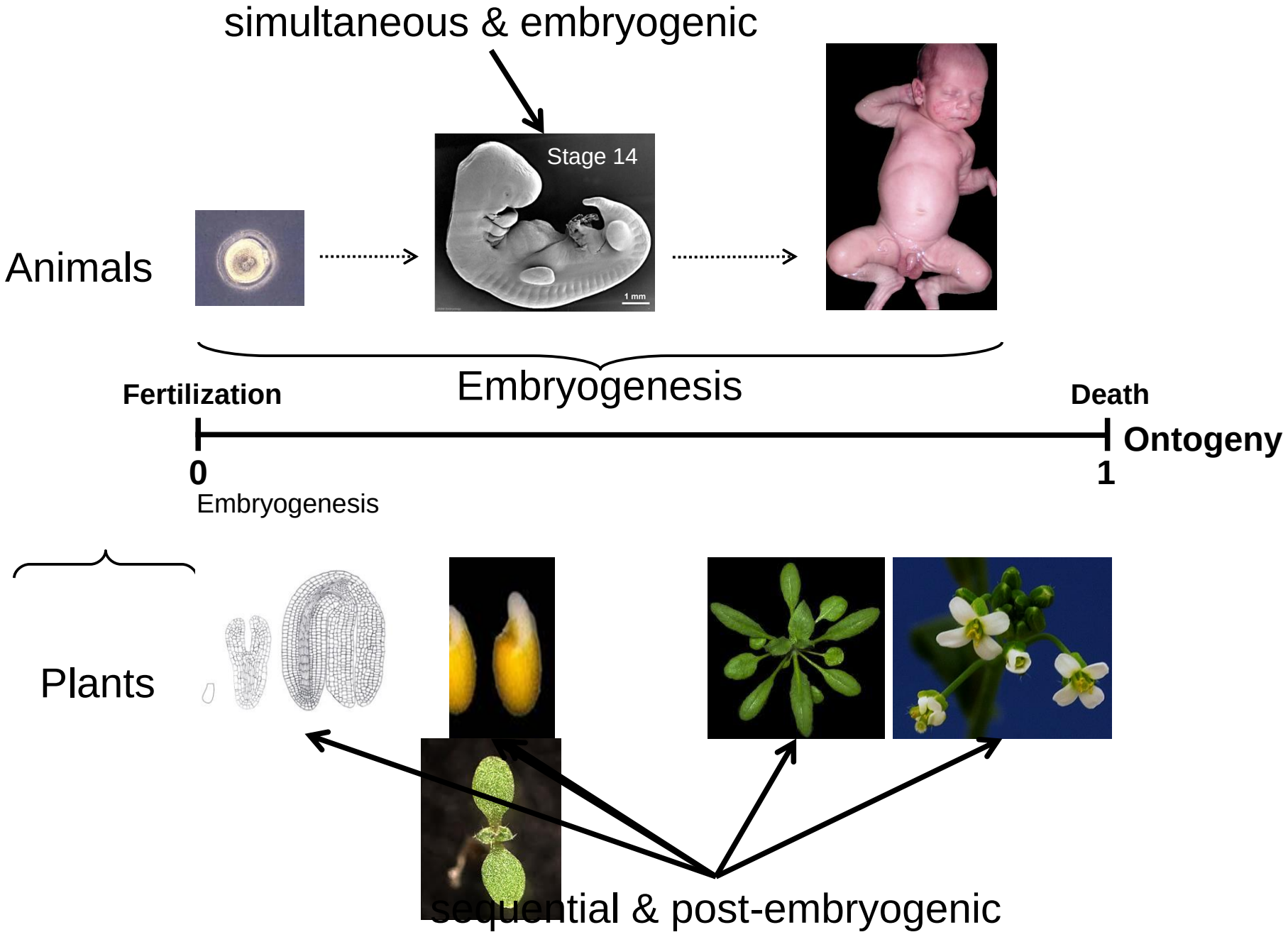
Ontogeny

0 **1**

Embryogenesis

Plants

Ontogeny / organ development: animals vs. plants



Are transcriptomic hourglasses unique to embryogenesis?

Are they possibly a general feature of developmental transitions?

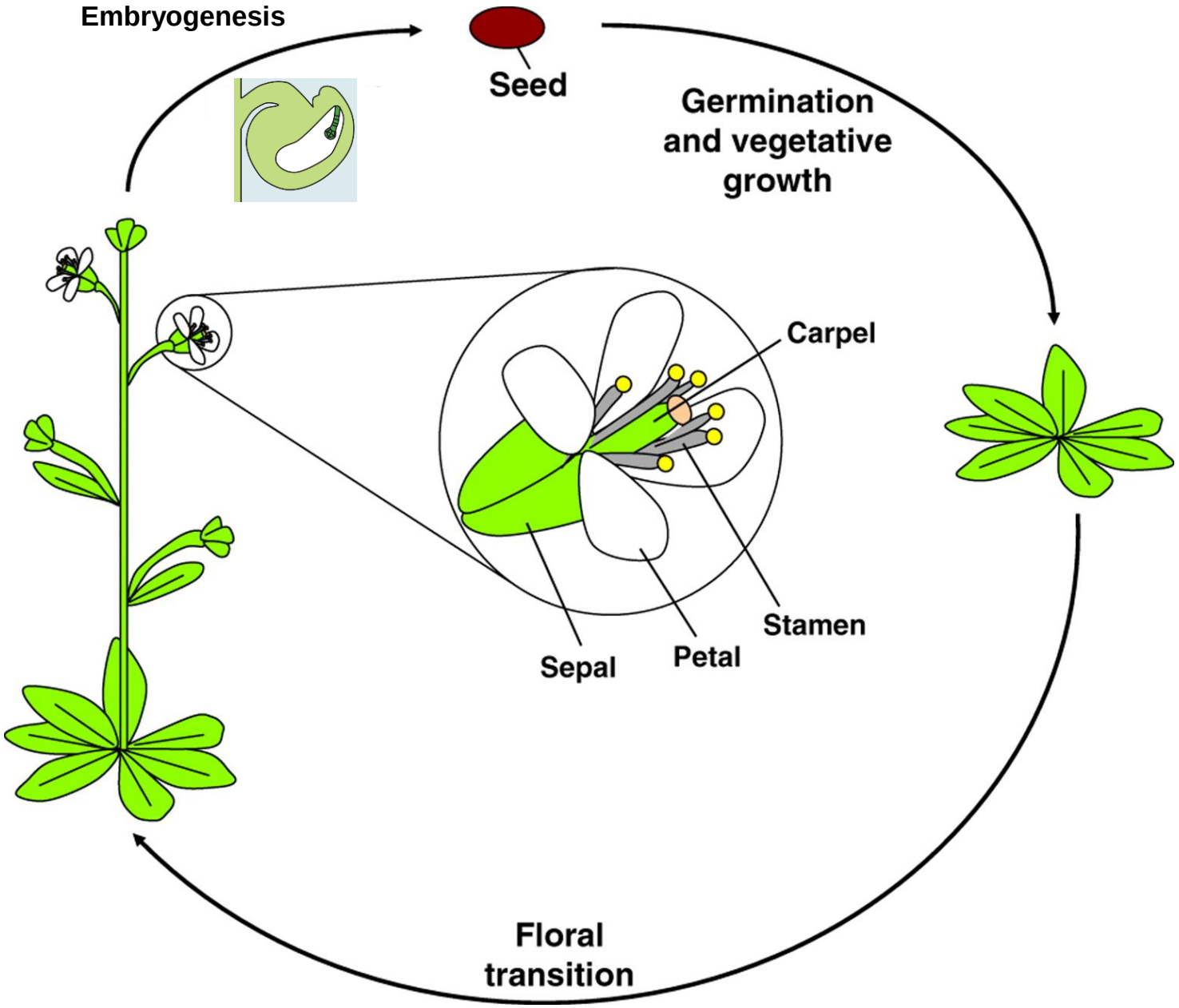
↓

Difficult to address in most animals → development largely embryonic

↓

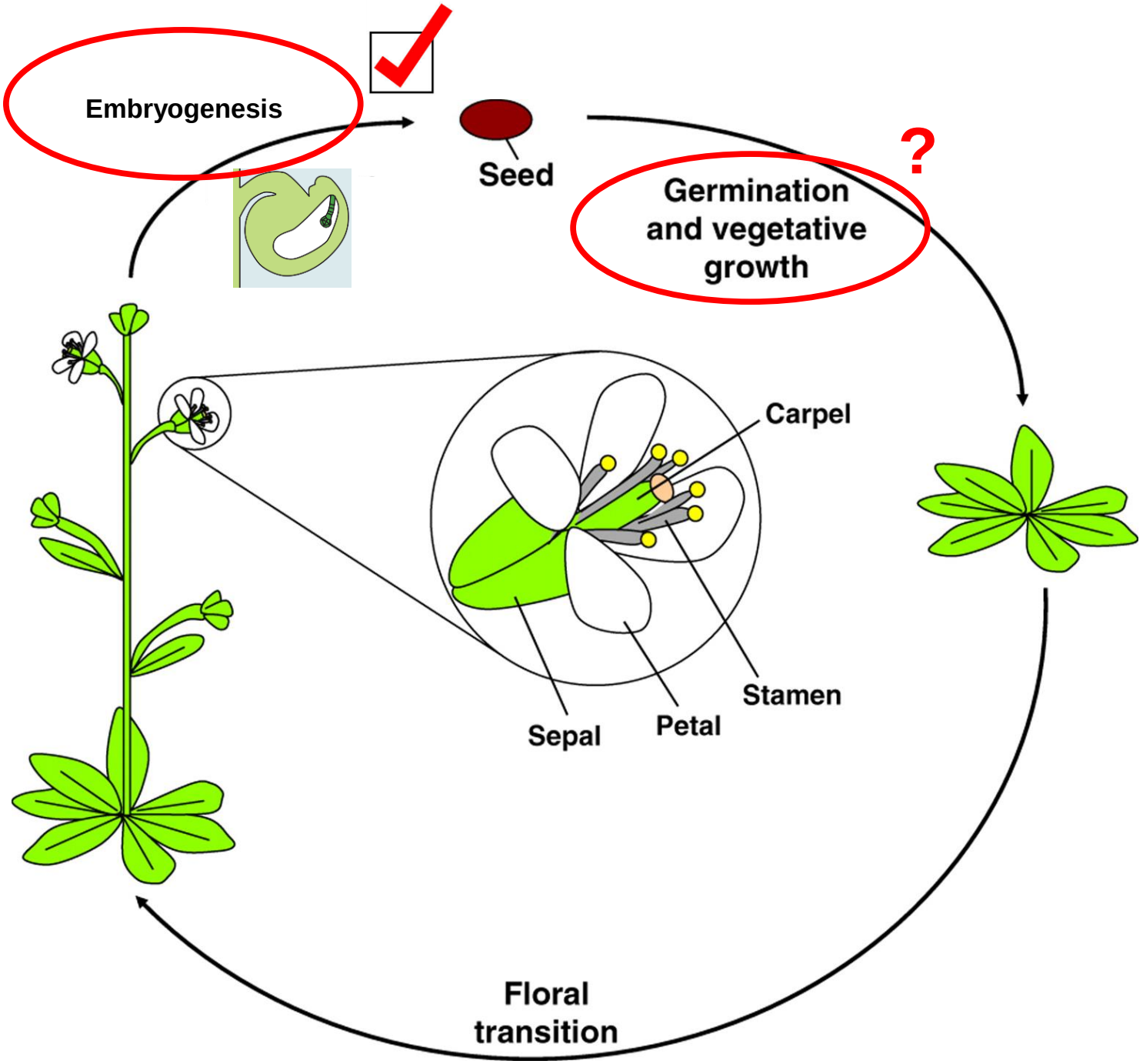
Straight-forward to address in plants
→ development largely post-embryonic

Major developmental transitions in the *A. thaliana* life cycle



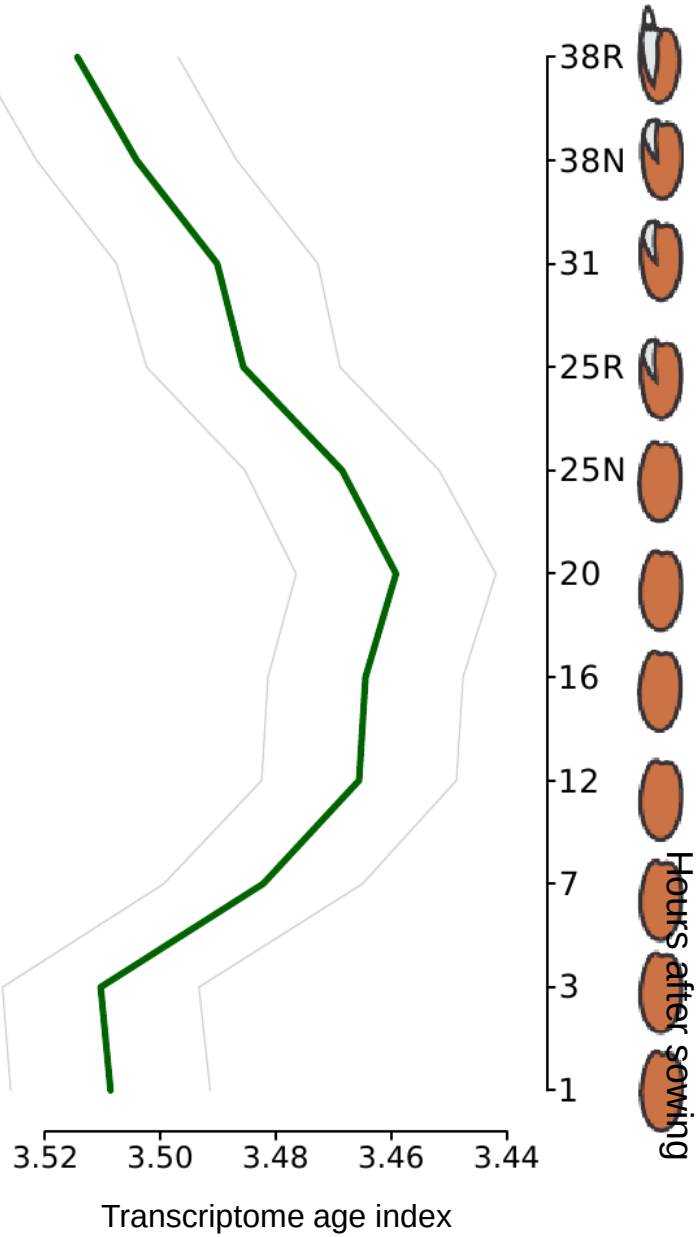
Liu et al., *Development* (2009)

Major developmental transitions in the *A. thaliana* life cycle



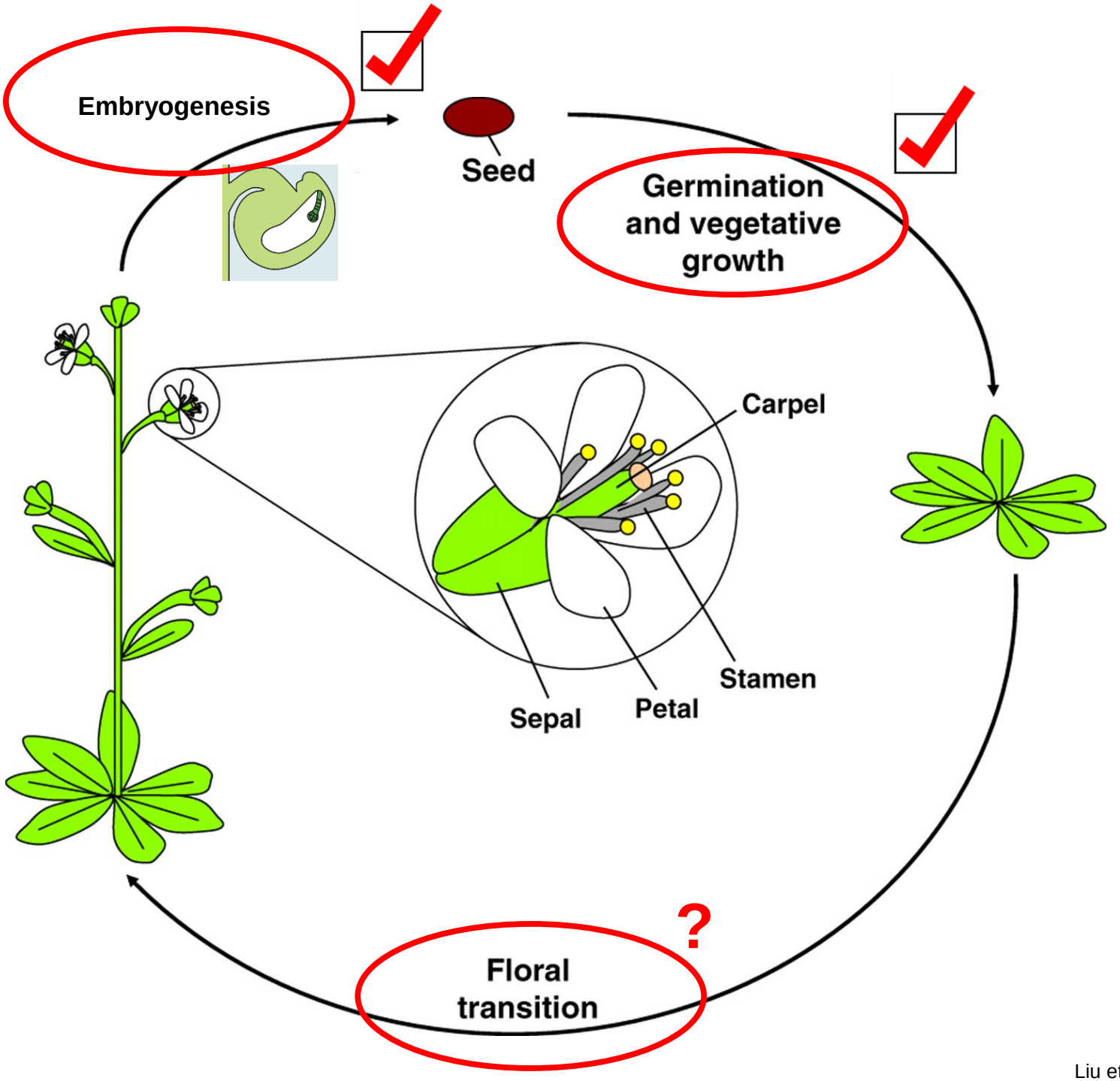
Liu et al., *Development* (2009)

A developmental hourglass for germination



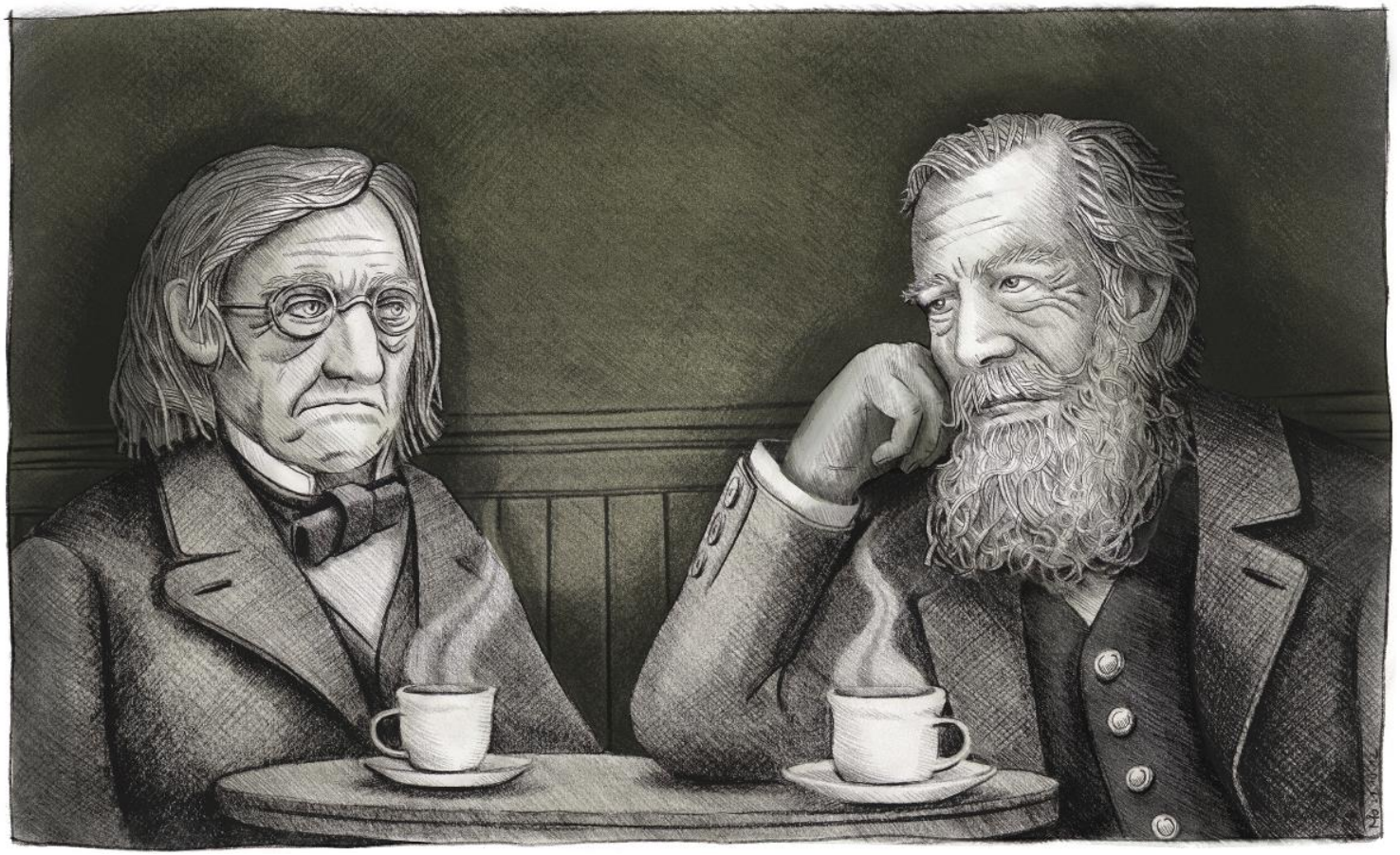
collaboration with Wilco Lighterink, Wageningen University

Major developmental transitions in the *A. thaliana* life cycle

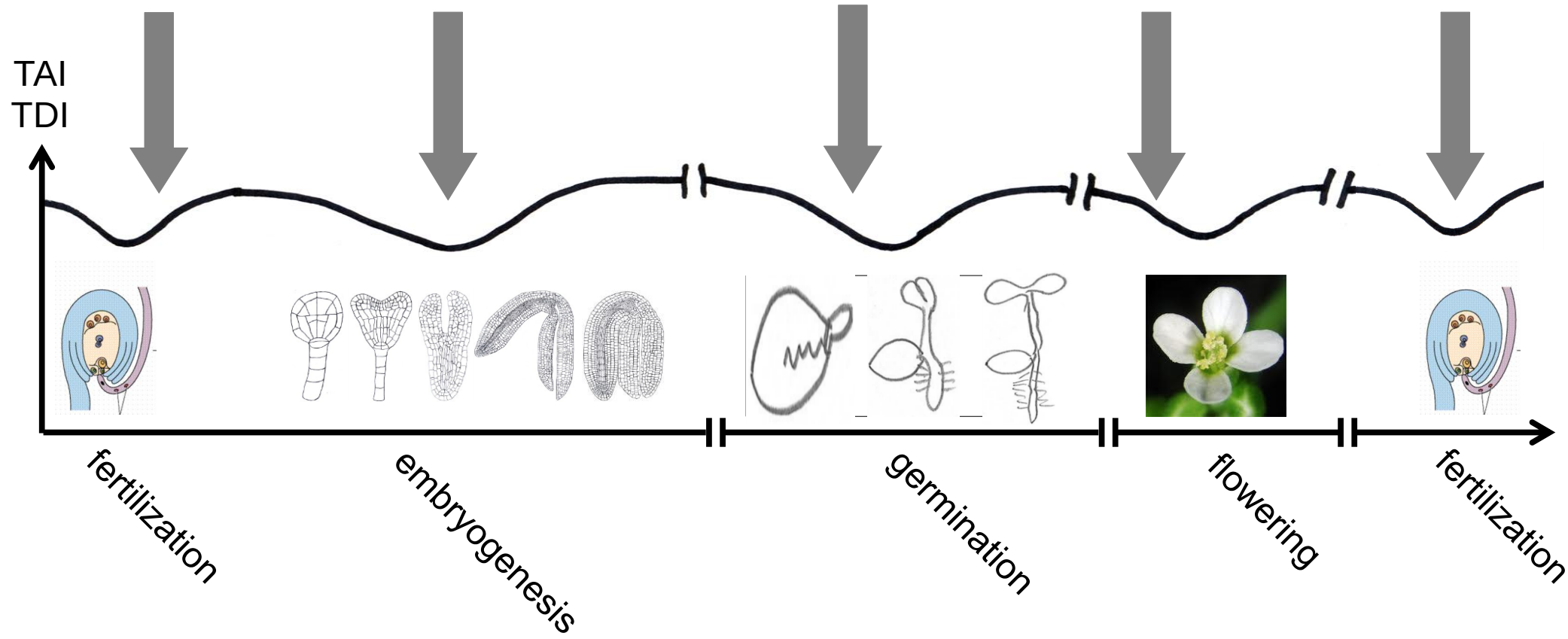


Liu et al., *Development* (2009)

Many hourglasses?



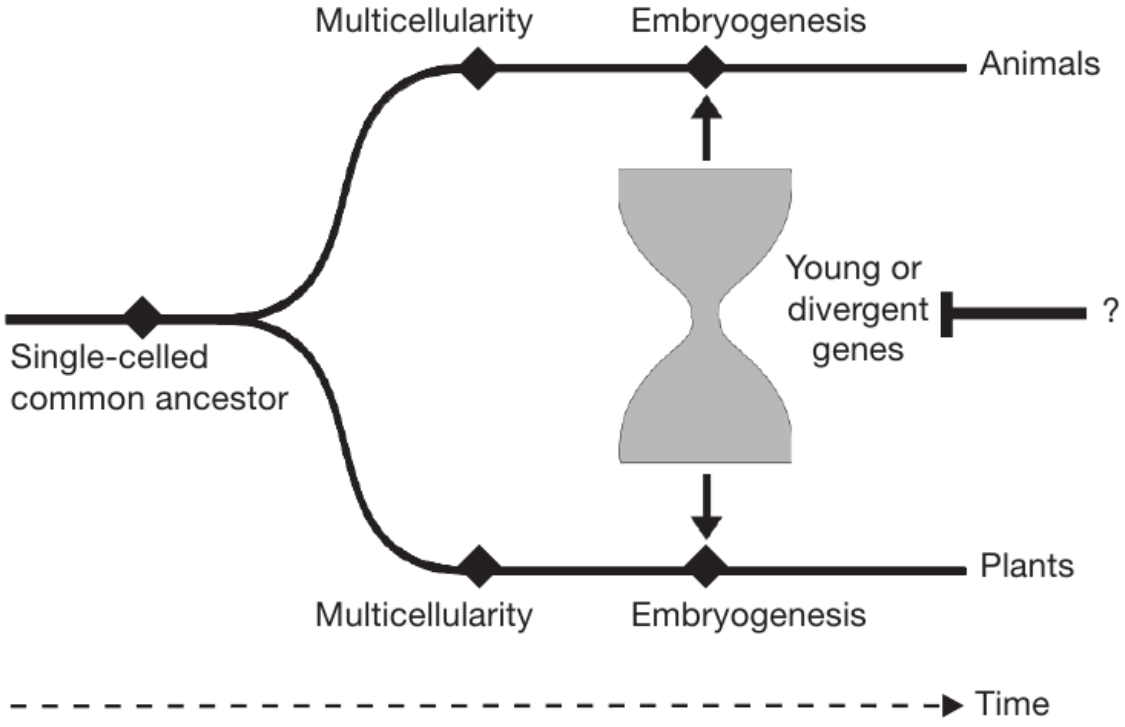
Many hourglasses?
Checkpoint hypothesis

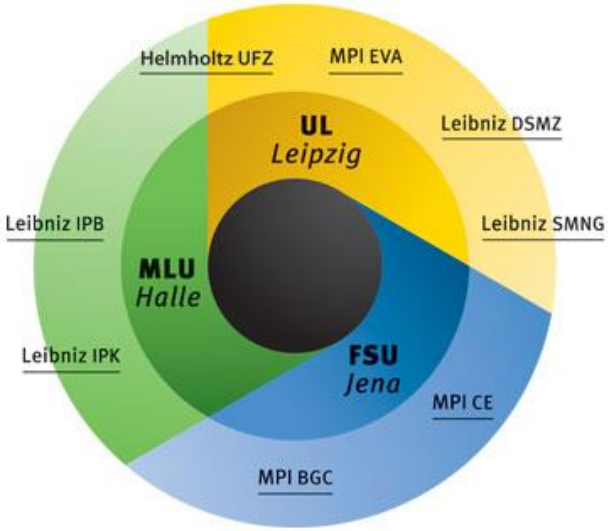


http://www.emc.maricopa.edu; http://www.greenhousecanada.com; http://plantdev.bio.wzw.tum.de; http://www.angenetik.fu-berlin.de

Conclusions

- Nature invented embryogenesis twice and independently
- Embryogenesis very different in plants and animals
- Developmental hourglass seems to be
- essential
- actively maintained
- possibly still functional?
- Postembryonic hourglasses in plants in germination and floral transition
- Existence of a universal logic that coordinates (i) embryogenesis in both kingdoms





Conclusions

- Nature invented embryogenesis twice and independently
- Embryogenesis very different in plants and animals
- Developmental hourglass seems to be
- essential
- actively maintained
- possibly still functional?
- Postembryonic hourglasses in plants in germination and floral transition
- Existence of a universal logic that coordinates (i) embryogenesis in both kingdoms