Embryonic and post-embryonic hourglass patterns of plant development

Marcel Quint and and Ivo Grosse

Leibniz Institute of Plant Biochemistry
Martin Luther University Halle-Wittenberg
German Center of Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig

Quint Lab


Jana Gentkow


Julia Bellstädt


Kristian Ullrich


Usman Anwer

Grosse Lab


Alexander Gabel


Hajk-Georg Drost


Markus Bönn


Claus Weinholdt

Collaborators

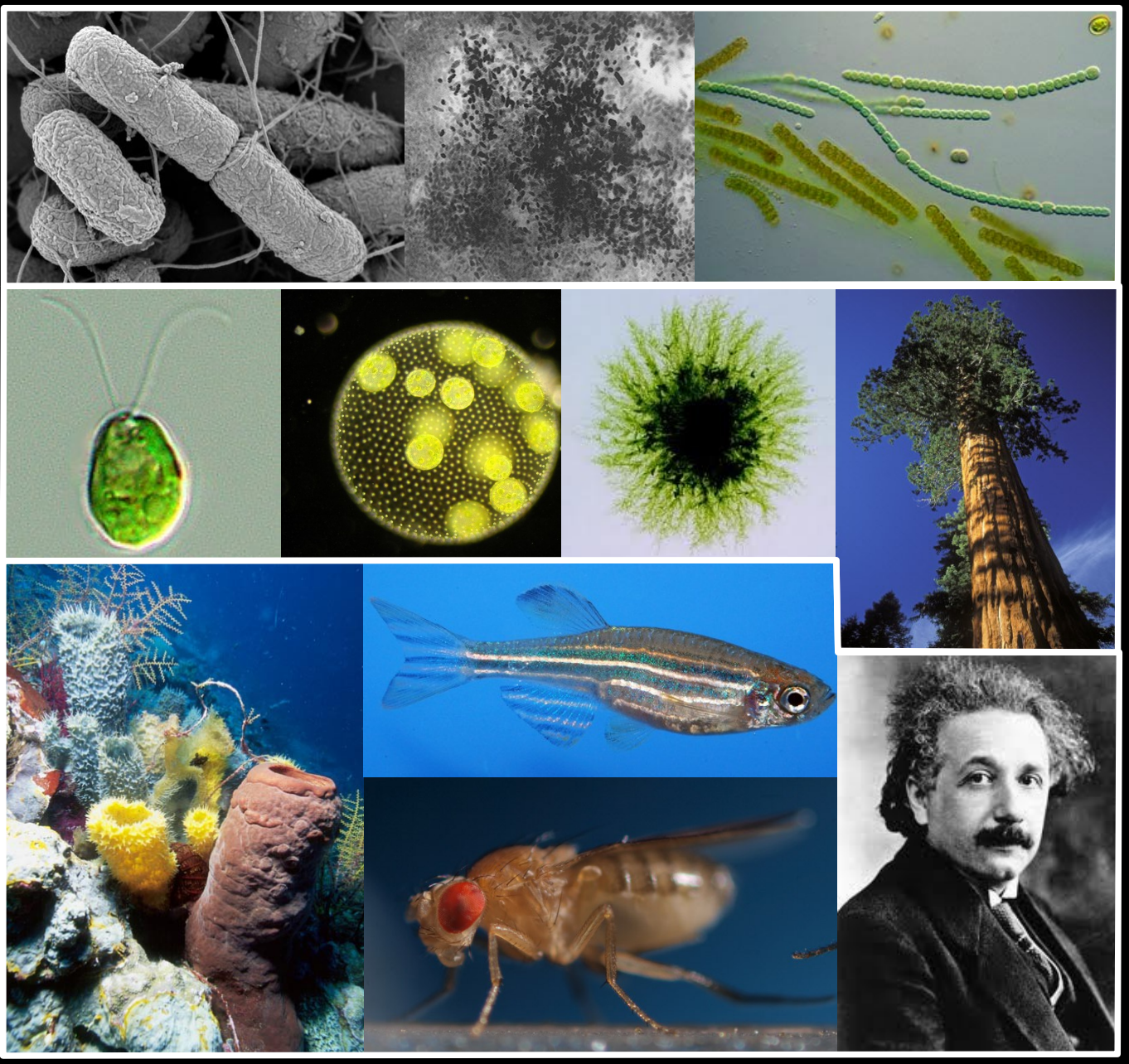
Wilco Ligterink, Anderson Silva, Leonie Bentsink, Bas Dekkers,
Wageningen University

Frank Wellmer, Pat Ryan, Diarmuid Ó'Maoiléidigh
Trinity College Dublin

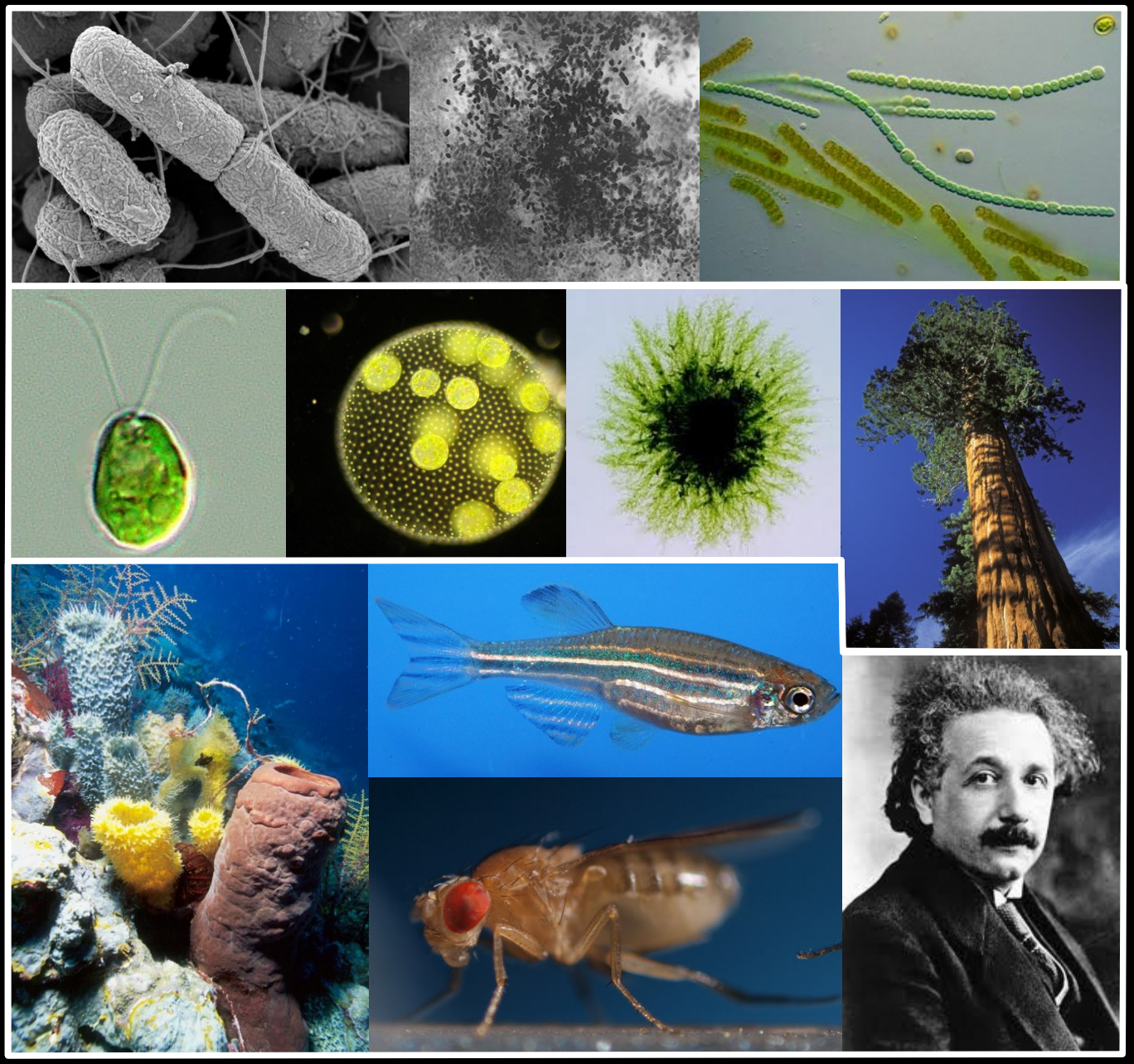
Dolf Weijers
Wageningen University

SPP 1530
Bernd Weisshaar, Uni Bielefeld
Siegbert Melzer, Christian Jung, Uni Kiel
Reinhard Töpfer, Siebeldingen

How did complex life emerge?



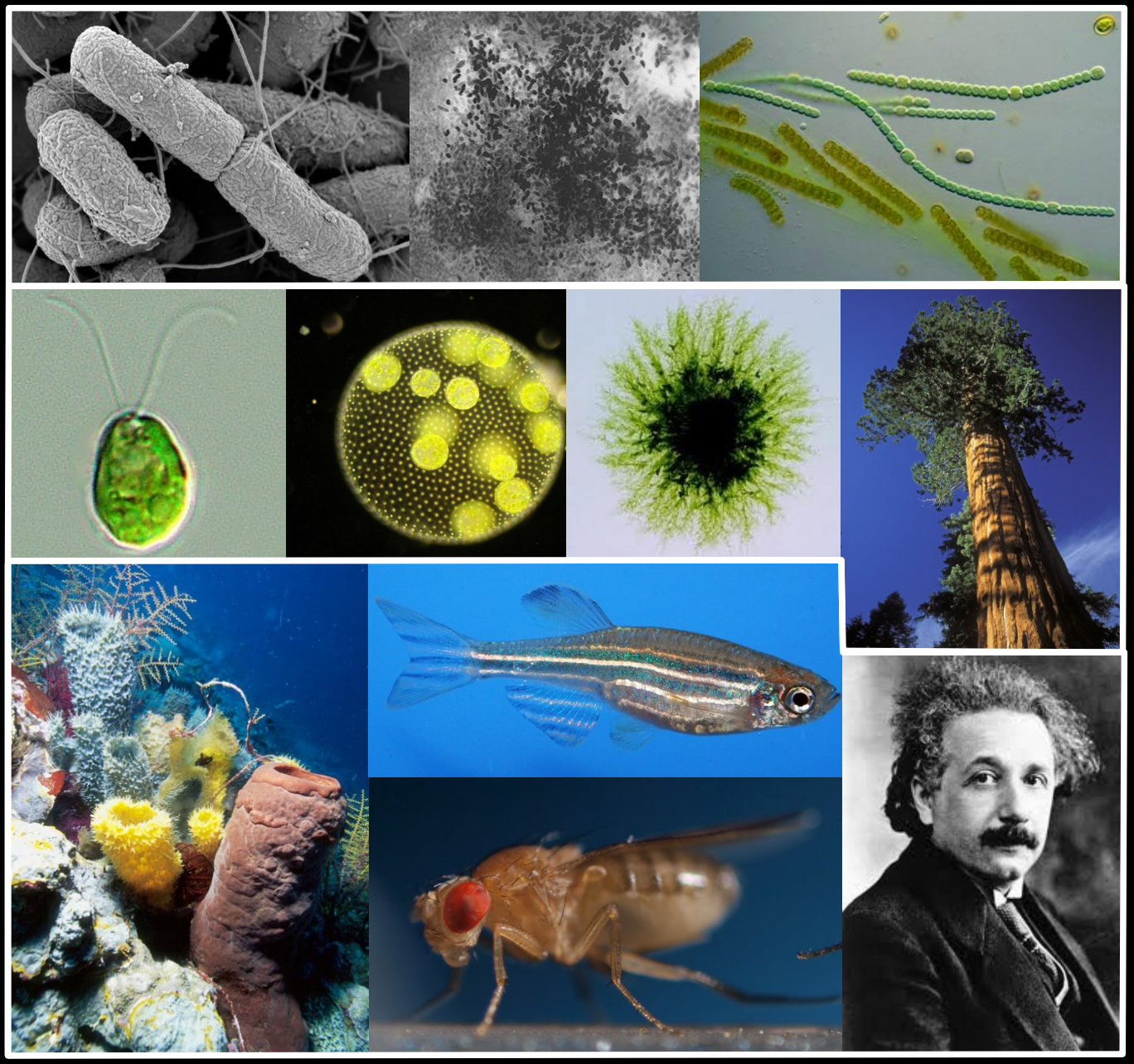
How did complex life emerge?



on the evolutionary level

on the developmental level

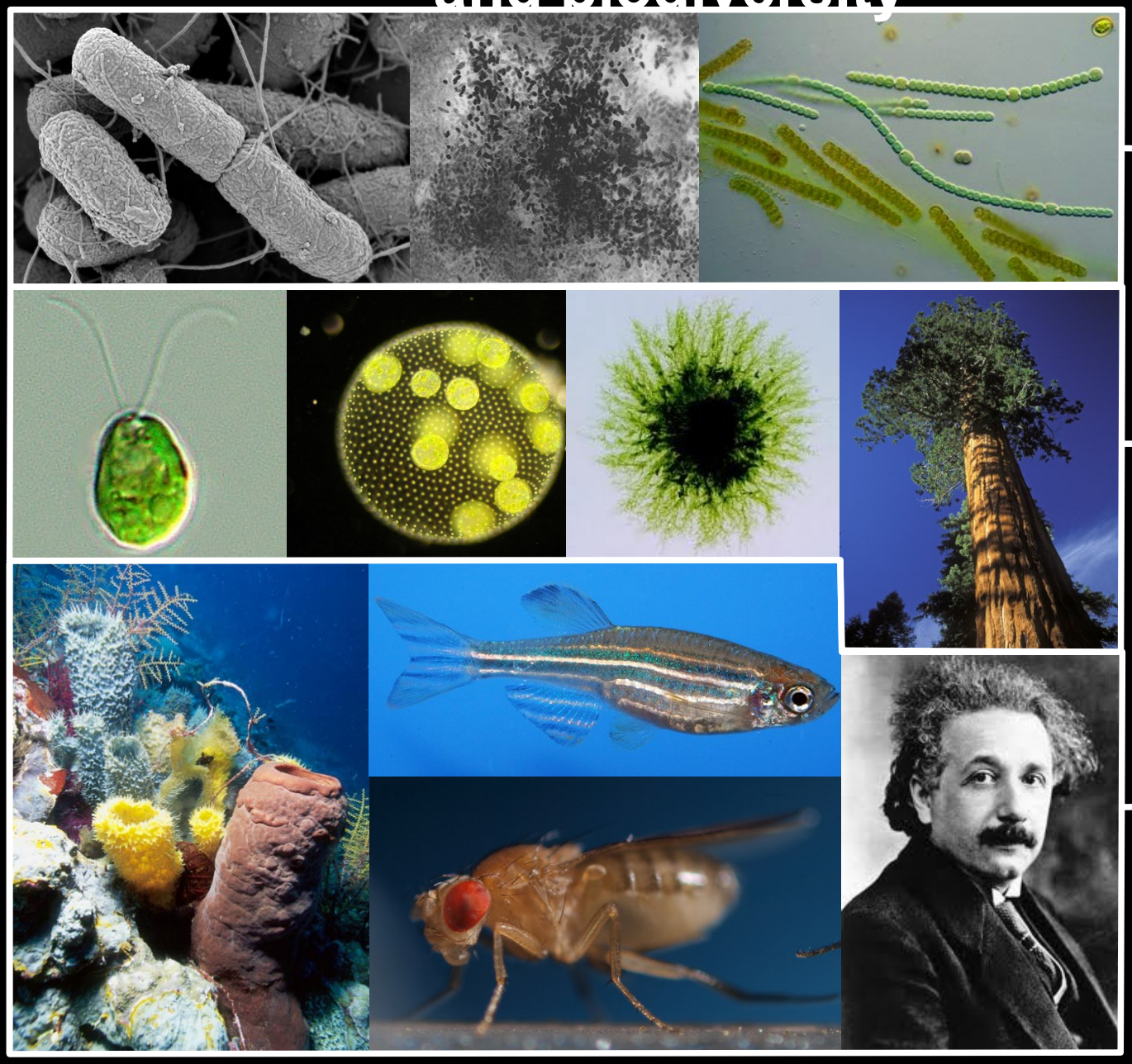
How did biodiversity emerge?



on the evolutionary level

on the developmental level

Gradual evolution of complex life and biodiversity

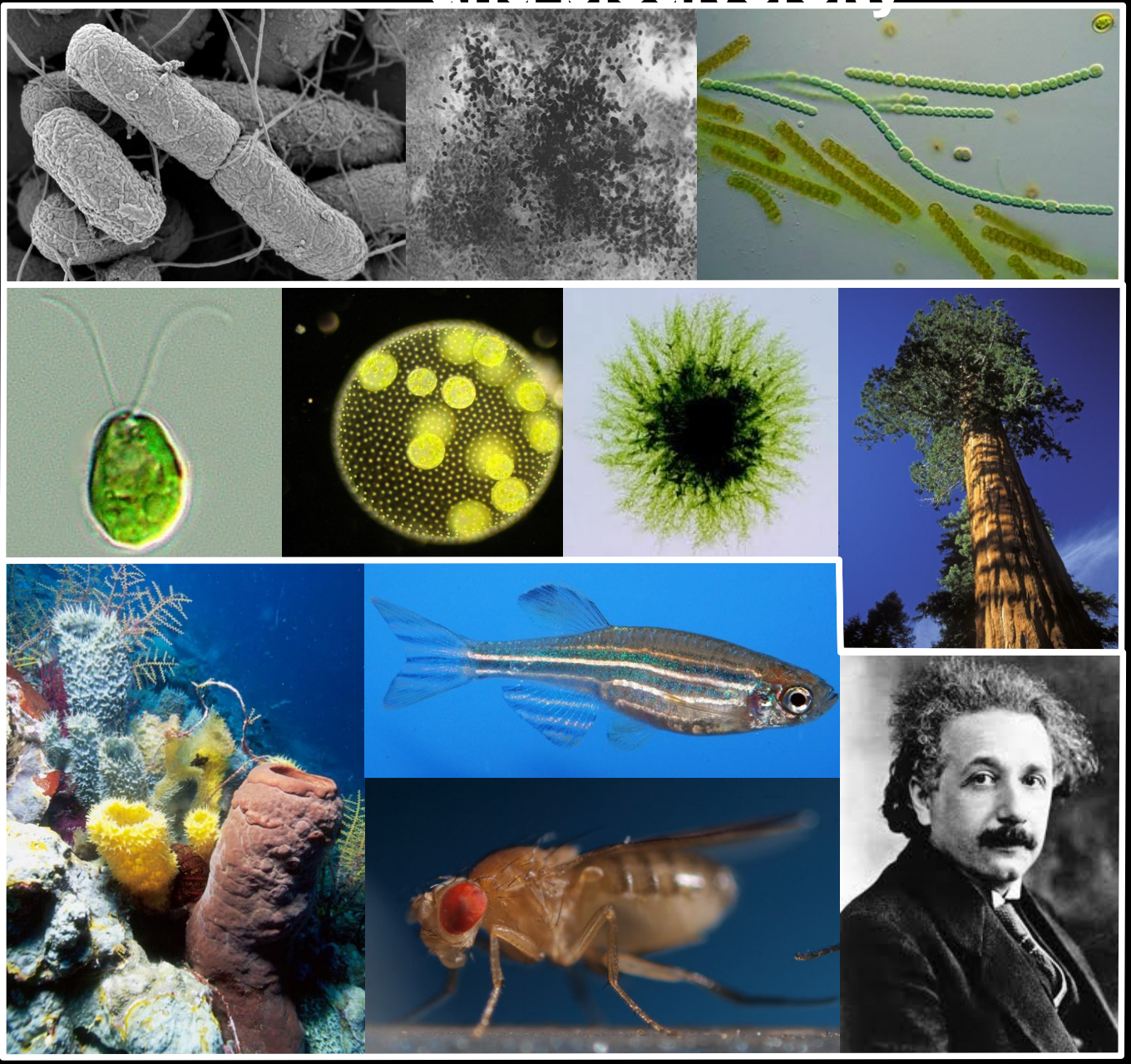


Gradual evolution of complex life and biodiversity

Bacteria

Plants

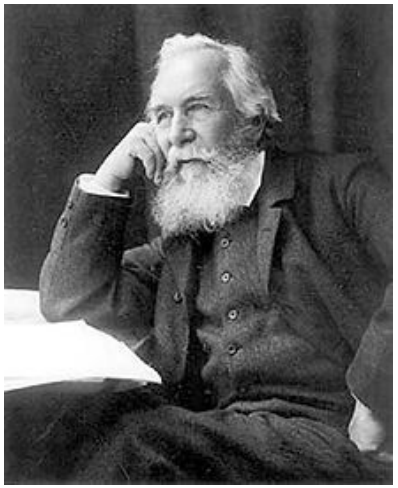
Animals



Comparative embryology

Evolutionary embryology

Evo-devo



Ernst Haeckel
1834 - 1919

Haeckel's biogenetic law (1866):

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

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

Haeckel, 1874

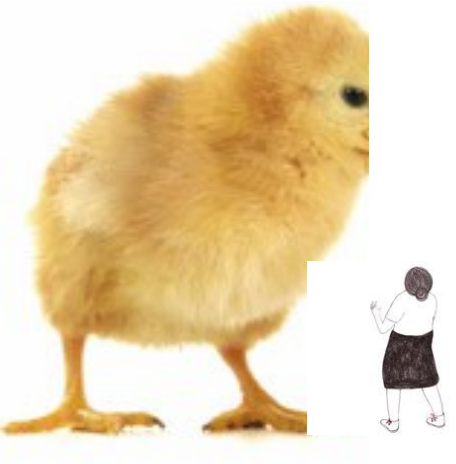
Comparative embryology - Baer's laws of embryology

Gedankenexperiment K.E. von Baer, 1828:

"*Stellen wir uns vor, dass Vögel ihre eigene Entwicklung studieren und dass sie es waren, die die Struktur adulter Säugetiere und des Menschen untersucht haben. Würden ihre Physiologiebücher nicht folgendes lehren?*

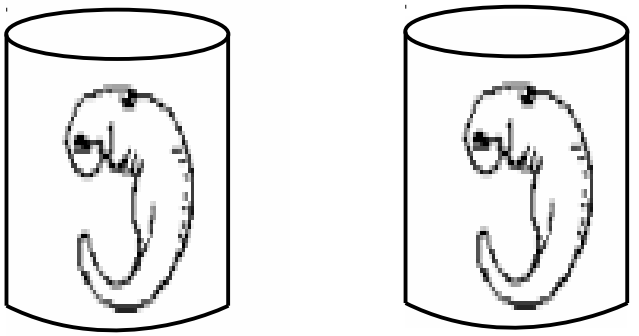
'Diese vierbeinigen Tiere weisen viele Ähnlichkeiten zu unseren eigenen Embryonen auf. Ihre Schädelknochen sind nur lose zusammengefügt und sie haben keinen Schnabel, genauso wie wir in den ersten fünf oder sechs Tagen unserer Brutzeit; ihre Extremitäten sind sich alle sehr ähnlich, so wie unsere in demselben Stadium; bis auf dünne Federschäfte haben sie keine wirklichen Federn an ihrem Körper, sodass wir als Küken im Nest bereits weiter entwickelt sind als sie es jemals sein werden … Darüber hinaus können sich diese Säugetiere noch lange nach der Geburt nicht selbständig ernähren, sie können sich niemals eigenständig von der Erde erheben und sehen sich selbst als weiter entwickelt als wir?' "

- von Baer, 1828, *Entwickelungsgeschichte der Thiere*



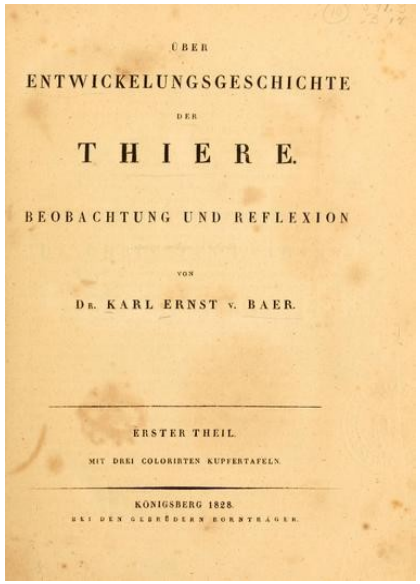
Comparative embryology - Baer's laws of embryology

Karl Ernst von Baer
1792-1876



„Ich besitze zwei kleine Embryonen in Weingeist, für die ich versäumt habe die Namen zu notieren, und ich bin jetzt durchaus nicht im Stande, die Klasse zu bestimmen, der sie angehören. Es können Eidechsen, kleine Vögel oder ganz junge Säugetiere seyn. So übereinstimmend ist die Kopf- und Rumpfbildung in diesen Thieren.“

- 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.
KONIGSBERG 1828.

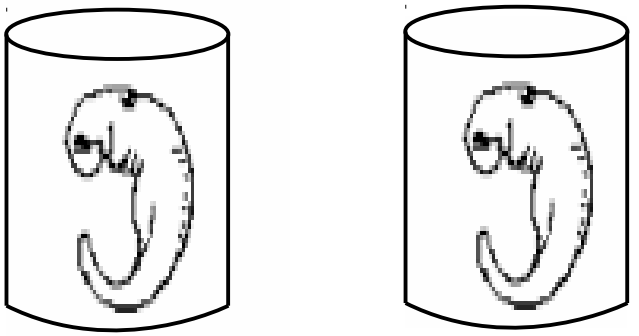
(1) General features of the embryo appear earlier than special features
(2) Special characters develop from general characters
(3) Embryos of different species progressively diverge from one another during ontogeny
(4) Embryos of one animal can never resemble the adult form of another animal, but only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

→ 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

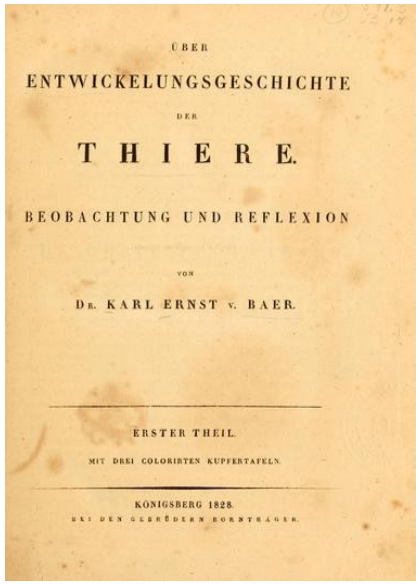
Comparative embryology - Baer's laws of embryology

Karl Ernst von Baer
1792-1876



„Ich besitze zwei kleine Embryonen in Weingeist, für die ich versäumt habe die Namen zu notieren, und ich bin jetzt durchaus nicht im Stande, die Klasse zu bestimmen, der sie angehören. Es können Eidechsen, kleine Vögel oder ganz junge Säugetiere seyn. So übereinstimmend ist die Kopf- und Rumpfbildung in diesen Thieren.“

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

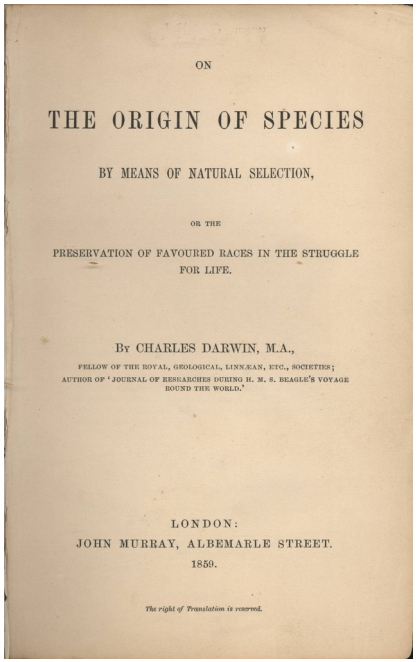

ÜBER
ENTWICKELUNGSGESCHICHTE
DER
THIERE.
BEOBACHTUNG UND REFLEXION
VON
DR. KARL ERNST v. BAER.
ERSTER THEIL.
MIT DREI COLORIRTEN KUPFERTAFELN.
KONIGSBERG 1828.

(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.

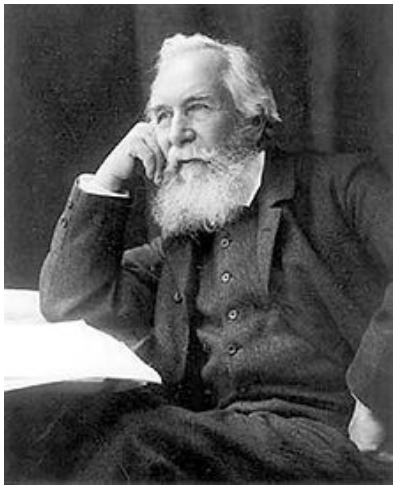
The right of Translation is reserved.

→ 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:

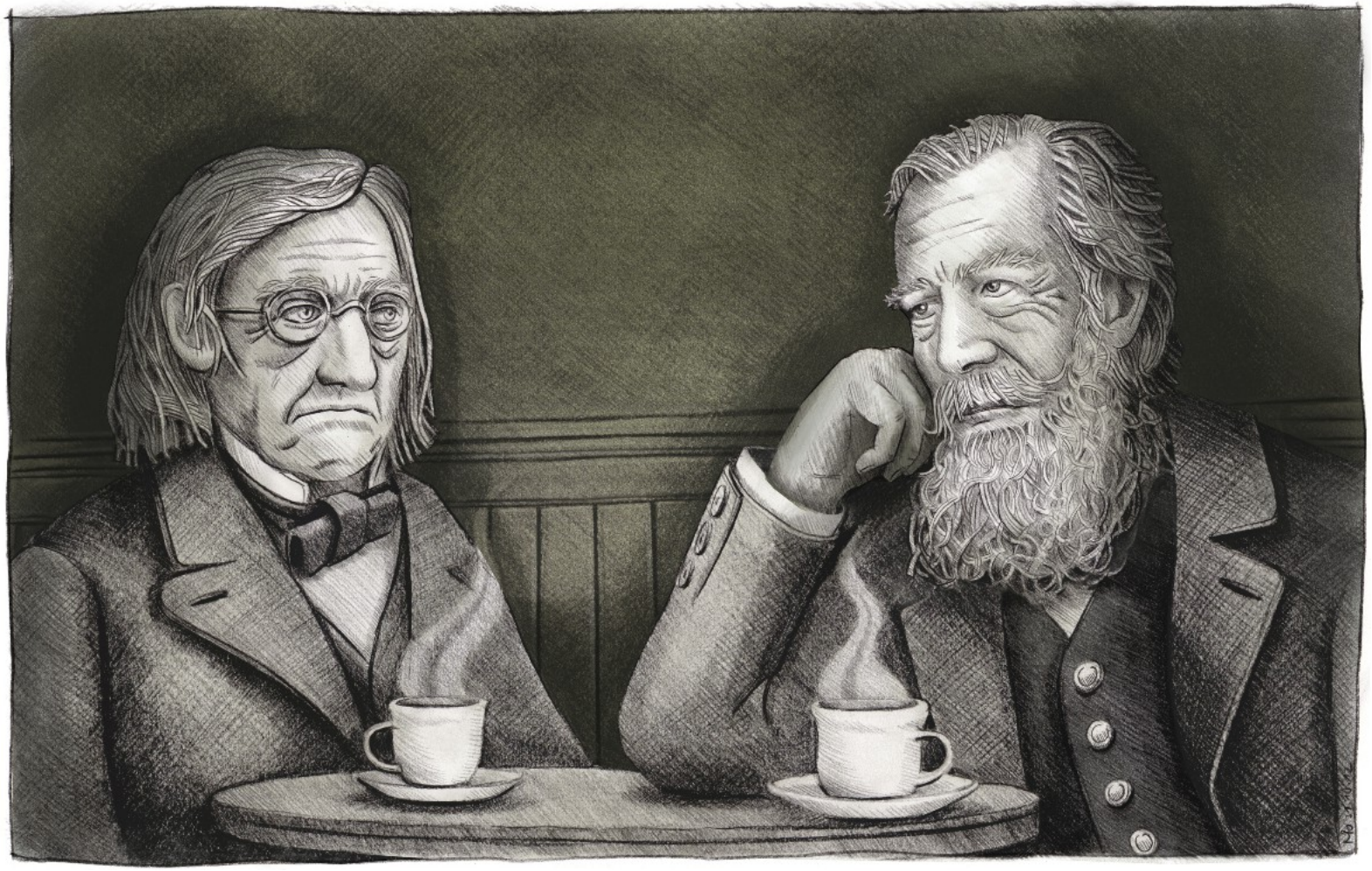
- Groundwork for social darwinism and nazi racial ideology

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



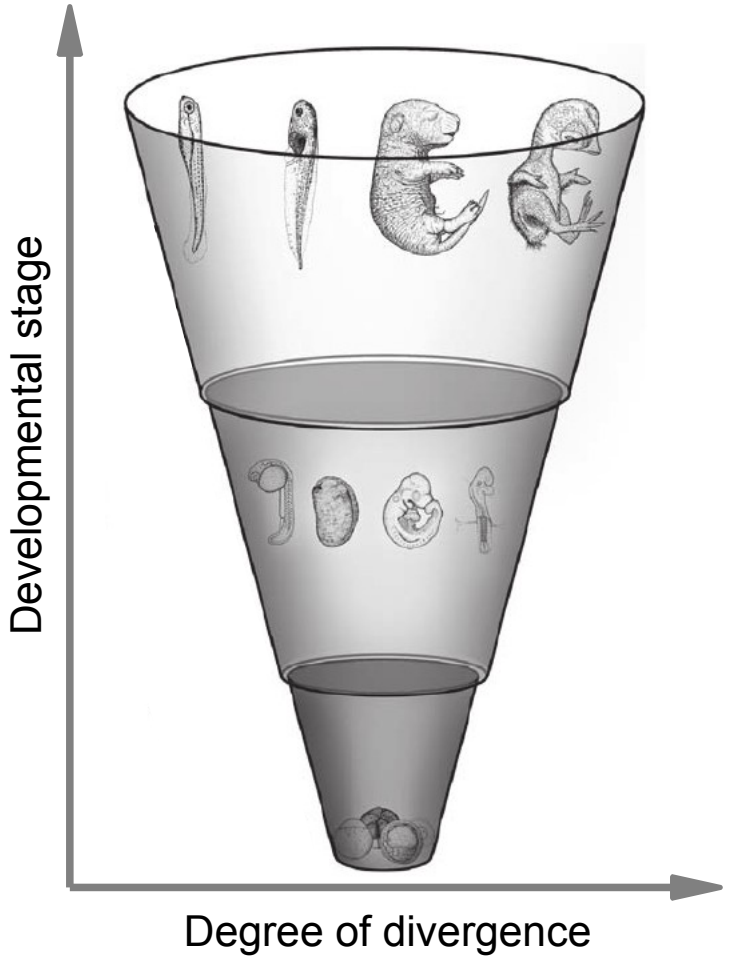
<u>von Baer's contribution</u>

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

<u>Haeckel's contribution</u>

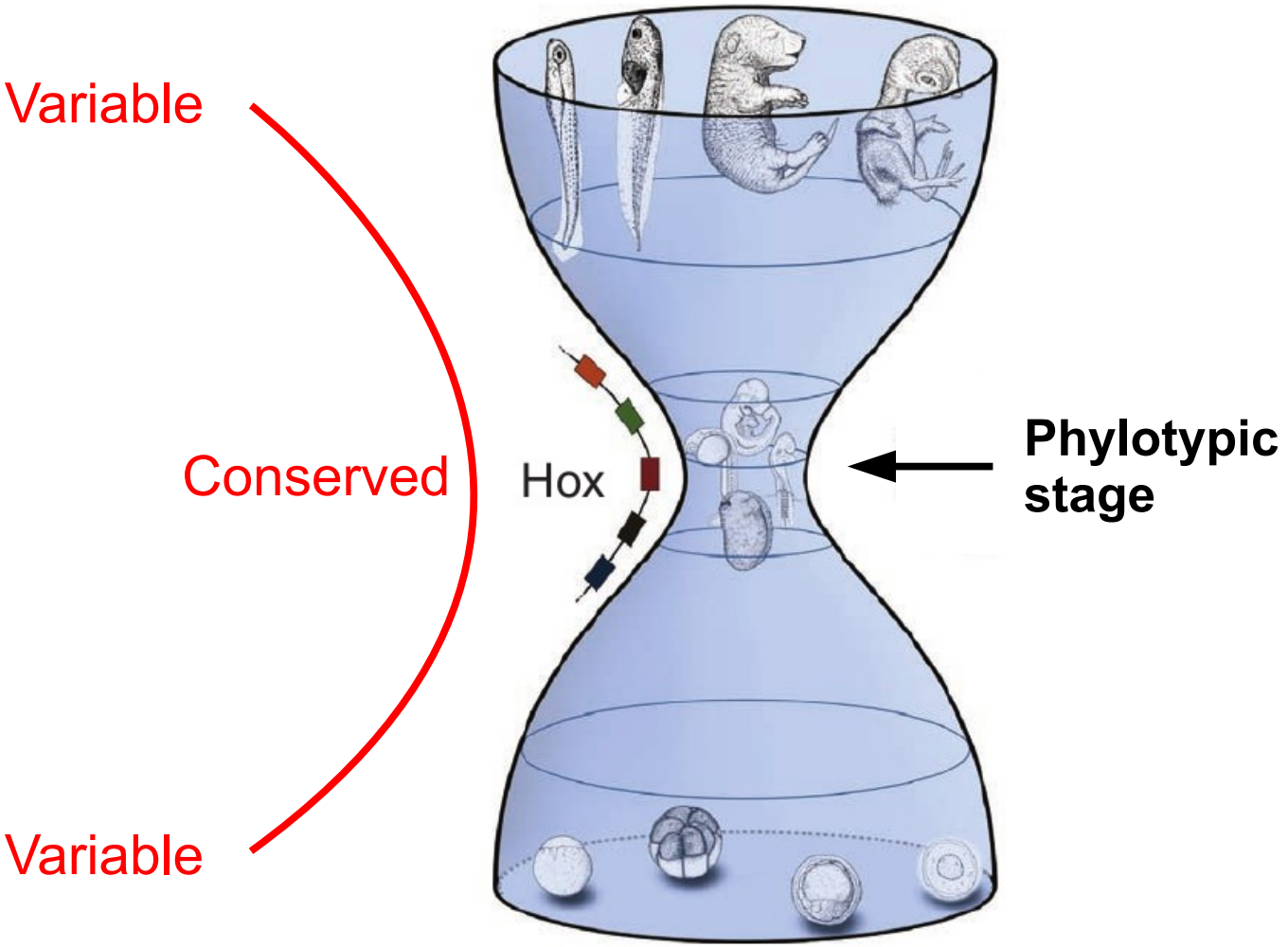
- Integration of different disciplines, such as taxonomy and embryology, into the then new Darwinian framework
- Use of such data for phylogeny reconstruction

Comparative embryology – The funnel model



Irie and Kuratani, 2011, *Nature Communications*

Comparative embryology – The hourglass model



Irie and Kuratani, 2011, *Nature Communications*

- **21**st century – the genomic level

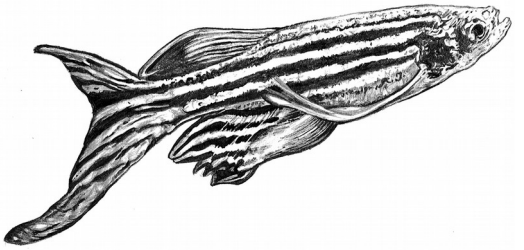
LETTER

doi:10.1038/nature09632

A phylogenetically based transcriptome age index mirrors ontogenetic divergence patterns

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

Nature (2010)



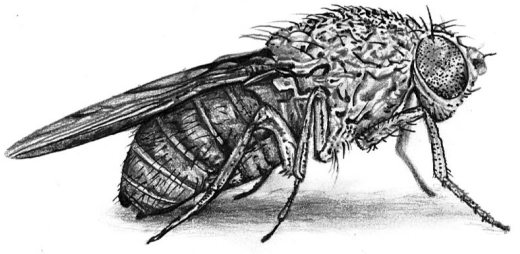
LETTER

doi:10.1038/nature09634

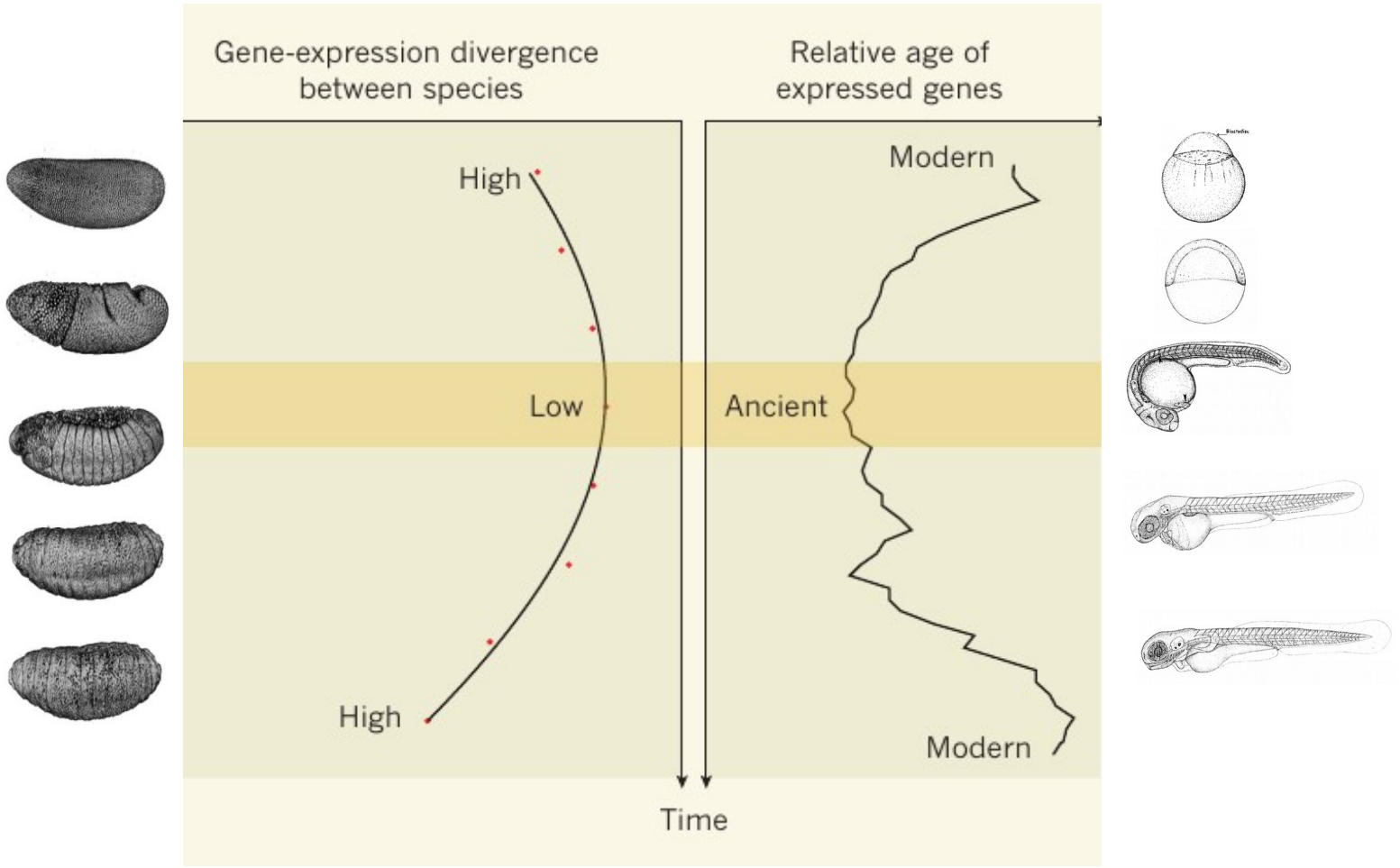
Gene expression divergence recapitulates the developmental hourglass model

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



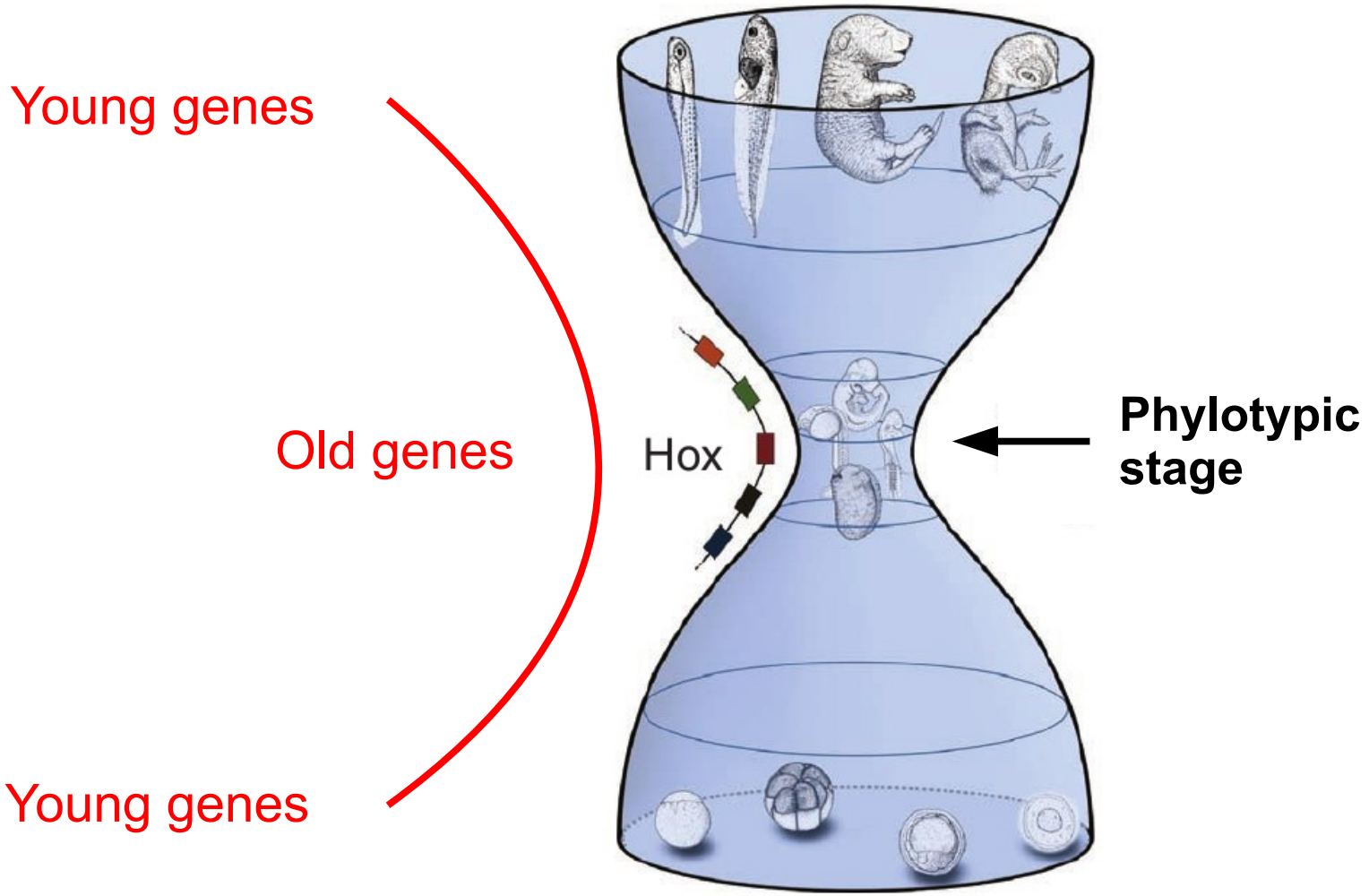
Drosophila

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

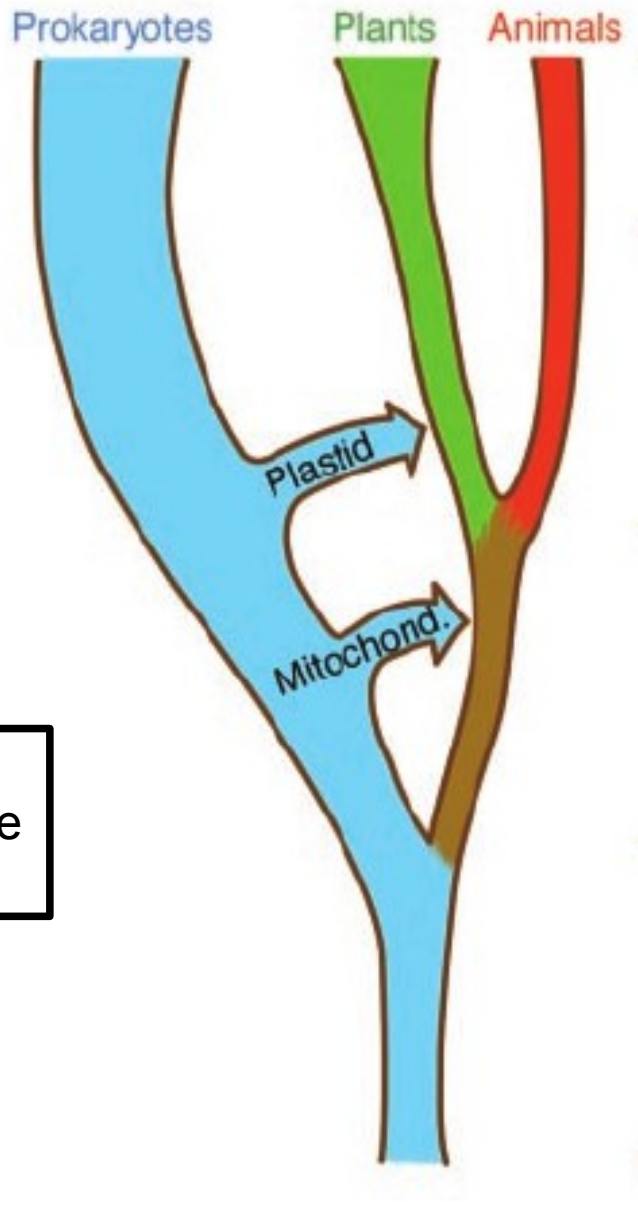


Irie and Kuratani, 2011, *Nature Communications*


ACGTACGTACGT

Evolution of embryogenesis

Unicellular life → Multicellular life → Embryogenesis → Complex life



← Embryogenesis

← Multicellularity (Eukaryotes)

← Last common ancestor: Unicellular

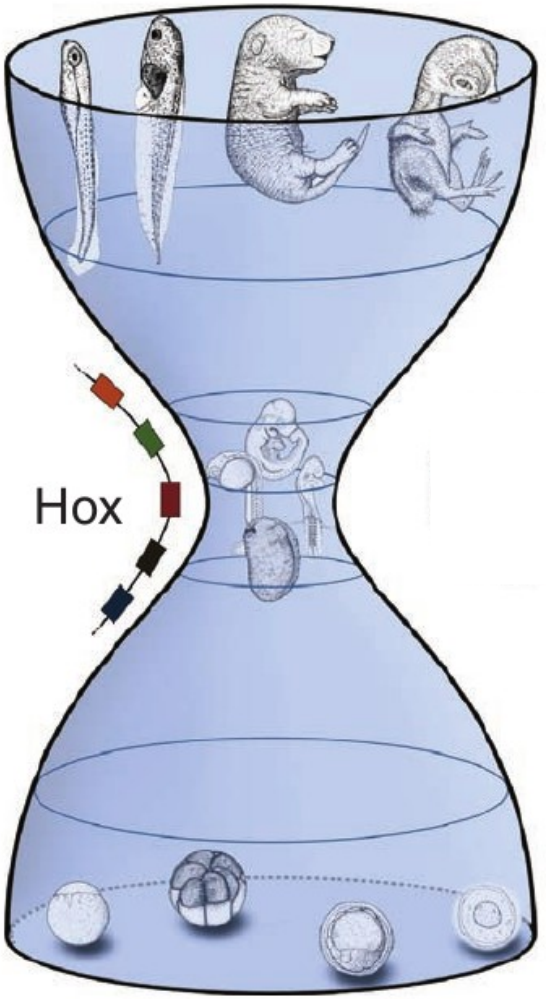
Embryogenesis evolved at least twice and independently

Meyerowitz, 2002, *Science*

What about plants?

- Is there a transcriptional hourglass in plants?

- Or any other pattern?



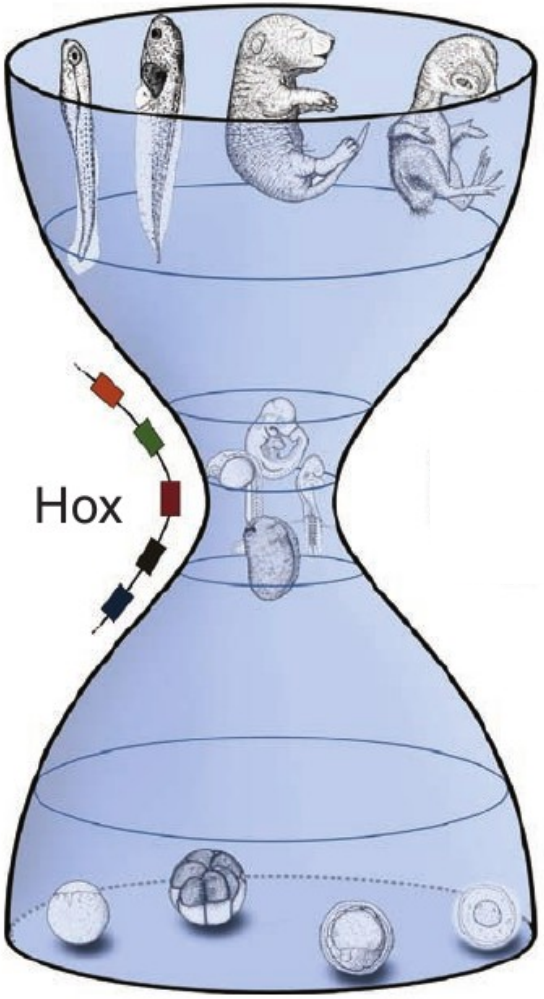
Irie and Kuratani, 2011, *Nature Communications*

What about plants?

Two pieces of information:

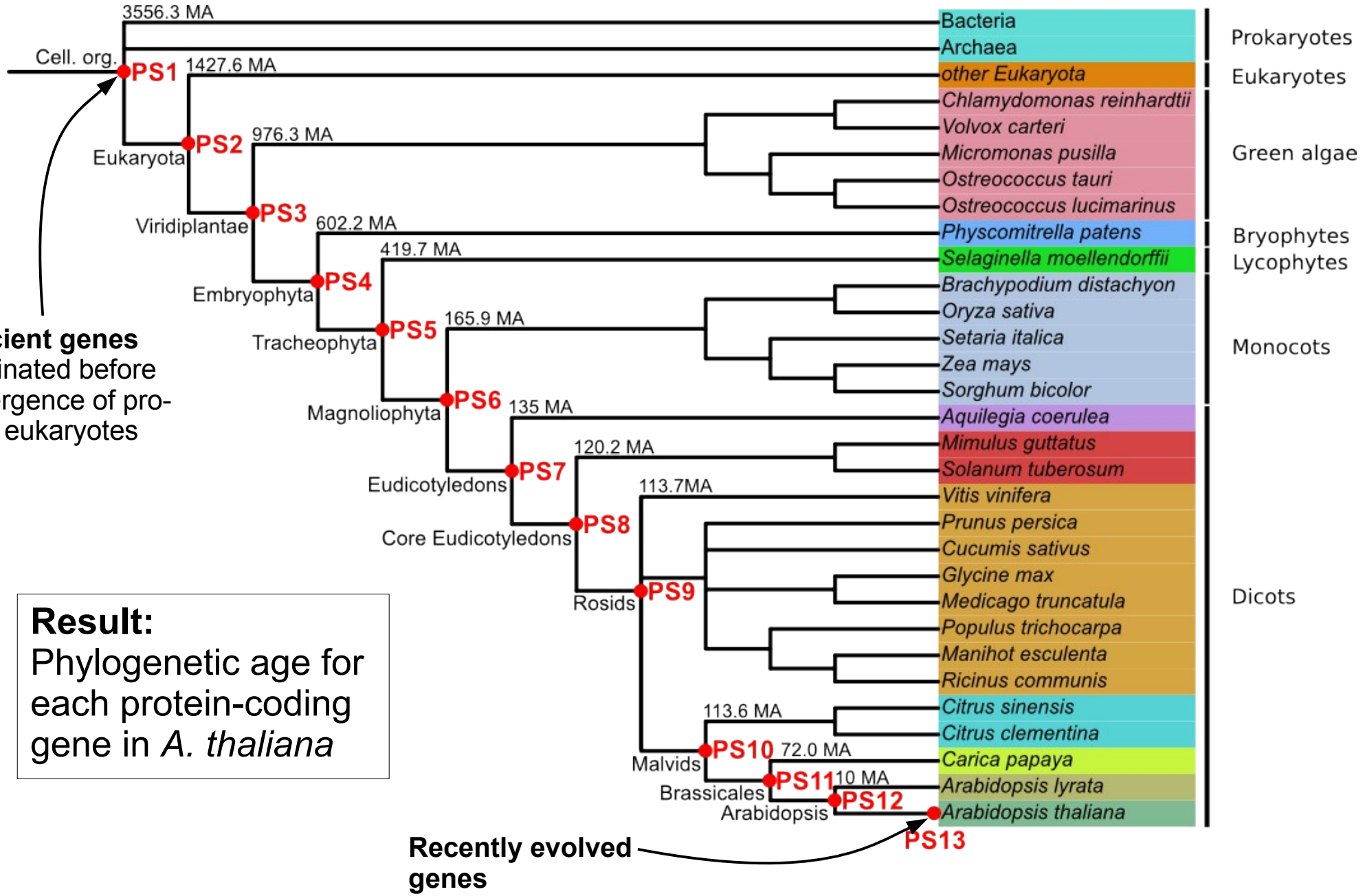
1. Evolutionary age for each gene

2. Transcriptomes of various embryo stages



Irie and Kuratani, 2011, *Nature Communications*

Phylostratigraphic map 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 phylogenetic age

↓

Sum over all genes

=

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

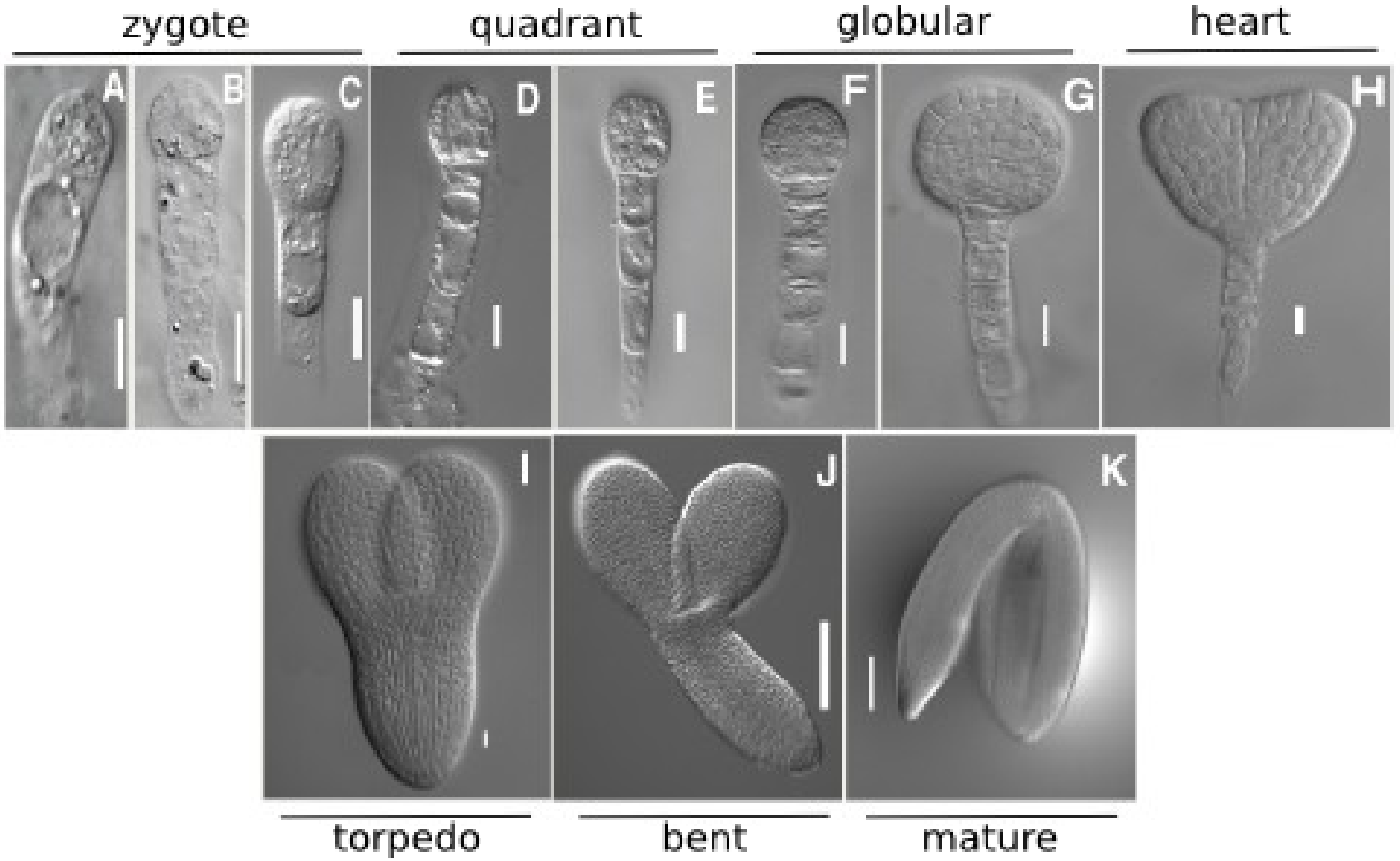
↓

Definition TAI:
The mean evolutionary age of a transcriptome, where the evolutionary age (PS) of each gene is weighted by its expression level.

Goal:
Compute TAI across multiple embryo stages

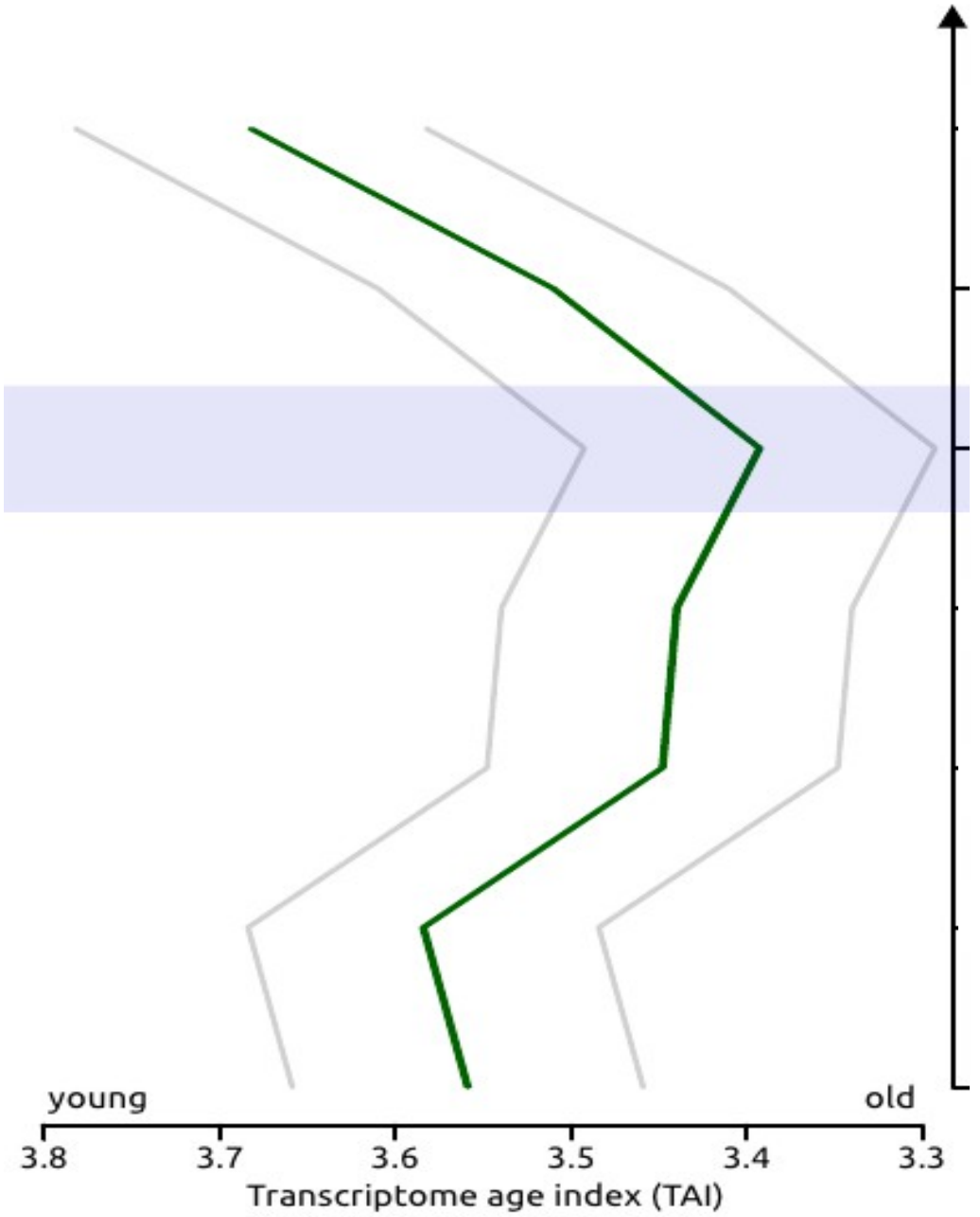
→ compare TAI profile to hourglass pattern

Embryogenesis in *Arabidopsis thaliana*



Xiang et al., 2011, *Plant Physiol*

TAI pattern of *A. thaliana* embryogenesis is reminiscent of the developmental hourglass

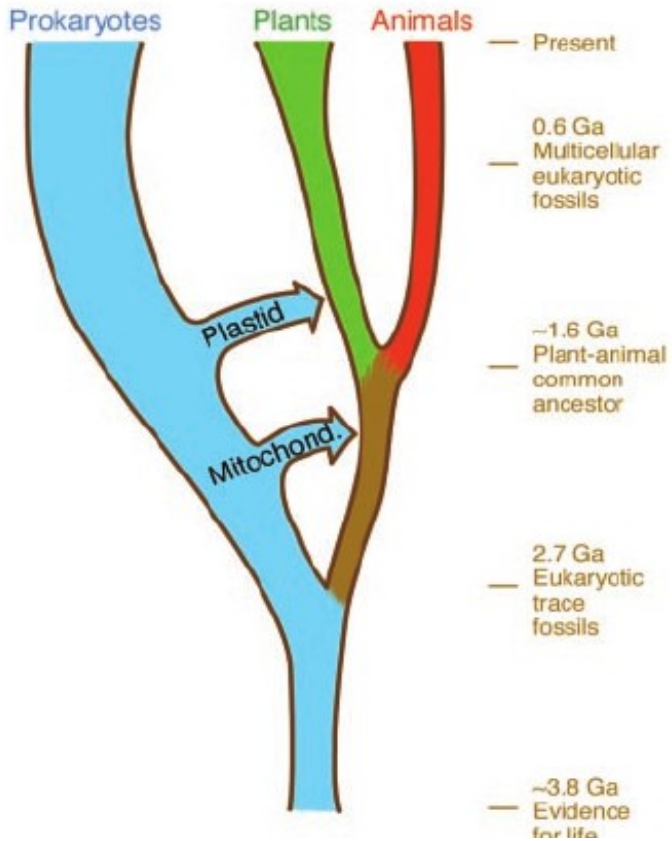


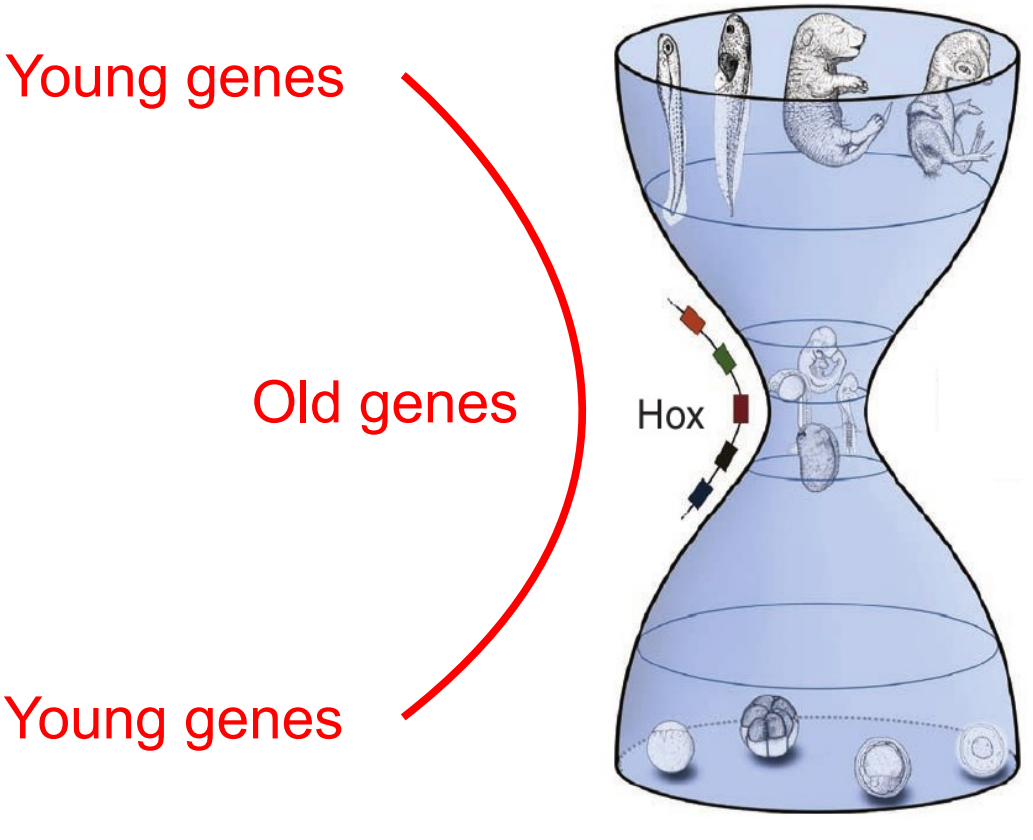
Intermediate conclusions

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



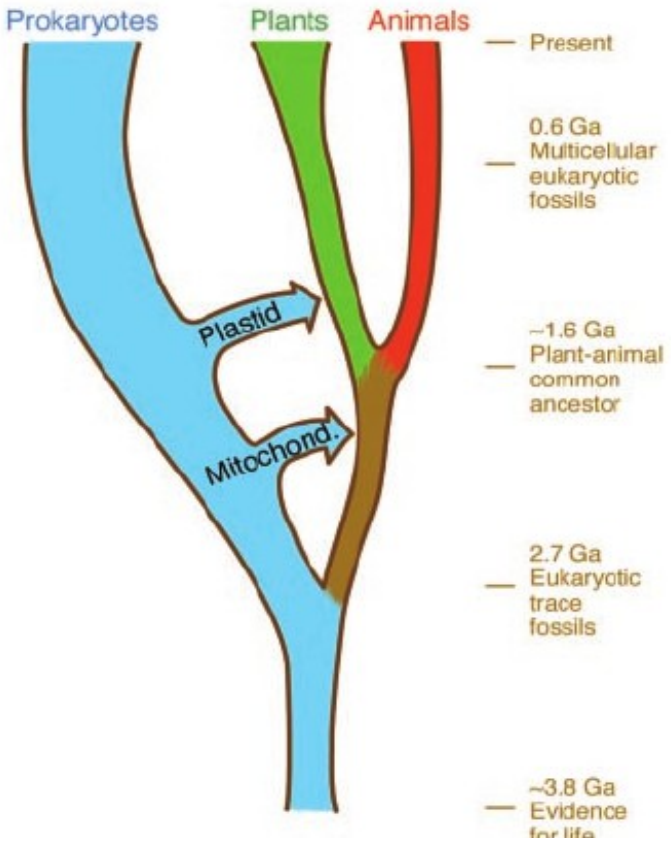


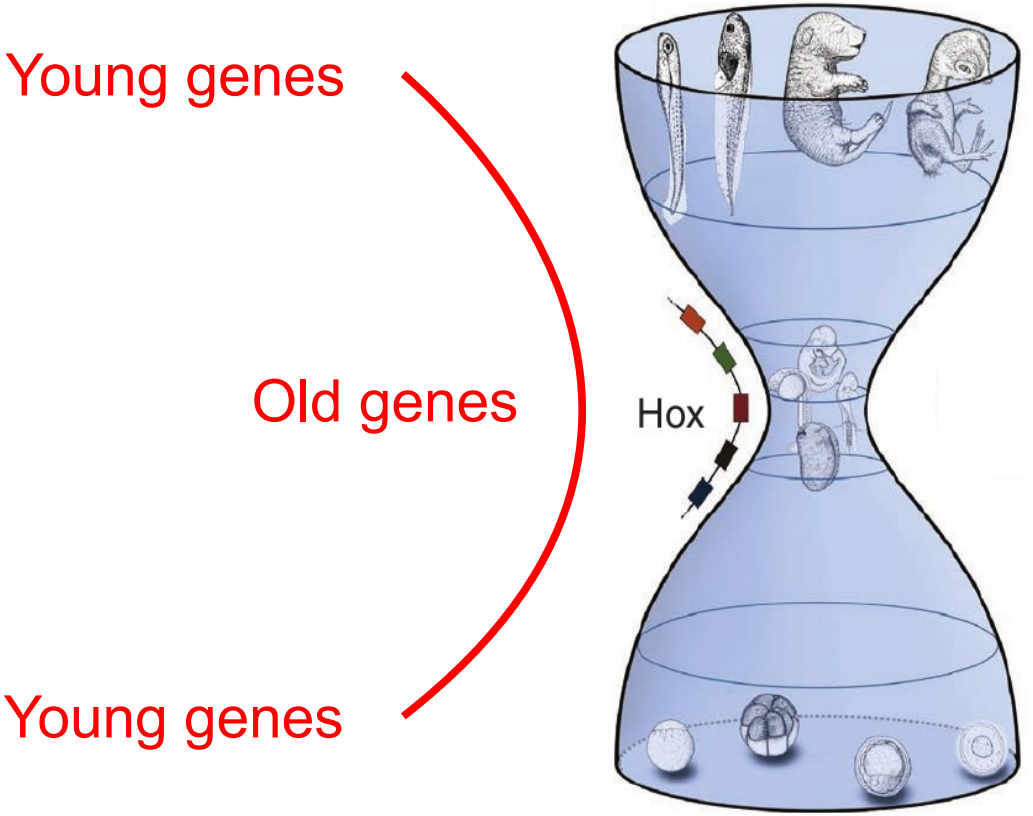
Fundamental question

Is the hourglass pattern

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

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





Transcriptome divergence index - TDI

TDI based on sequence divergence

↓

Sequence 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

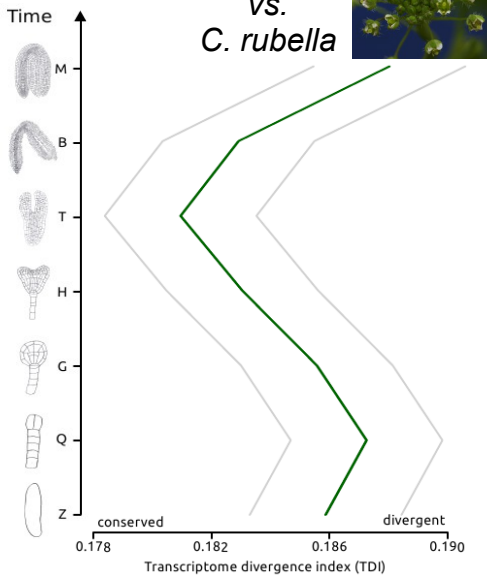
TDI patterns

TDI – 5 Mio years*

A. thaliana
vs.
A. lyrata

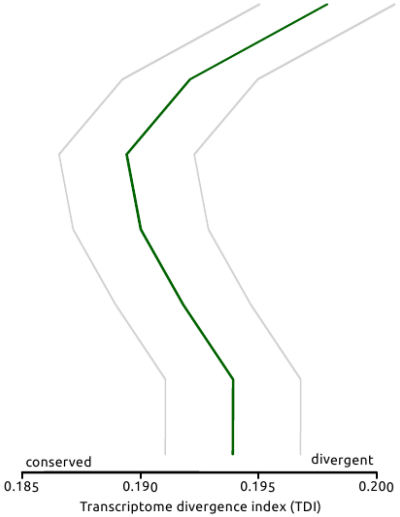
TDI – 10 Mio years*

A. thaliana
vs.
C. rubella



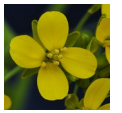
TDI – 12 Mio years**

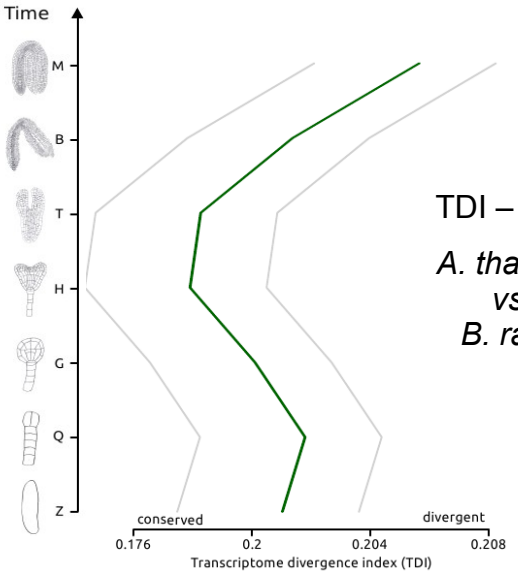
A. thaliana
vs.
T. halophila



TDI – 16 Mio years*

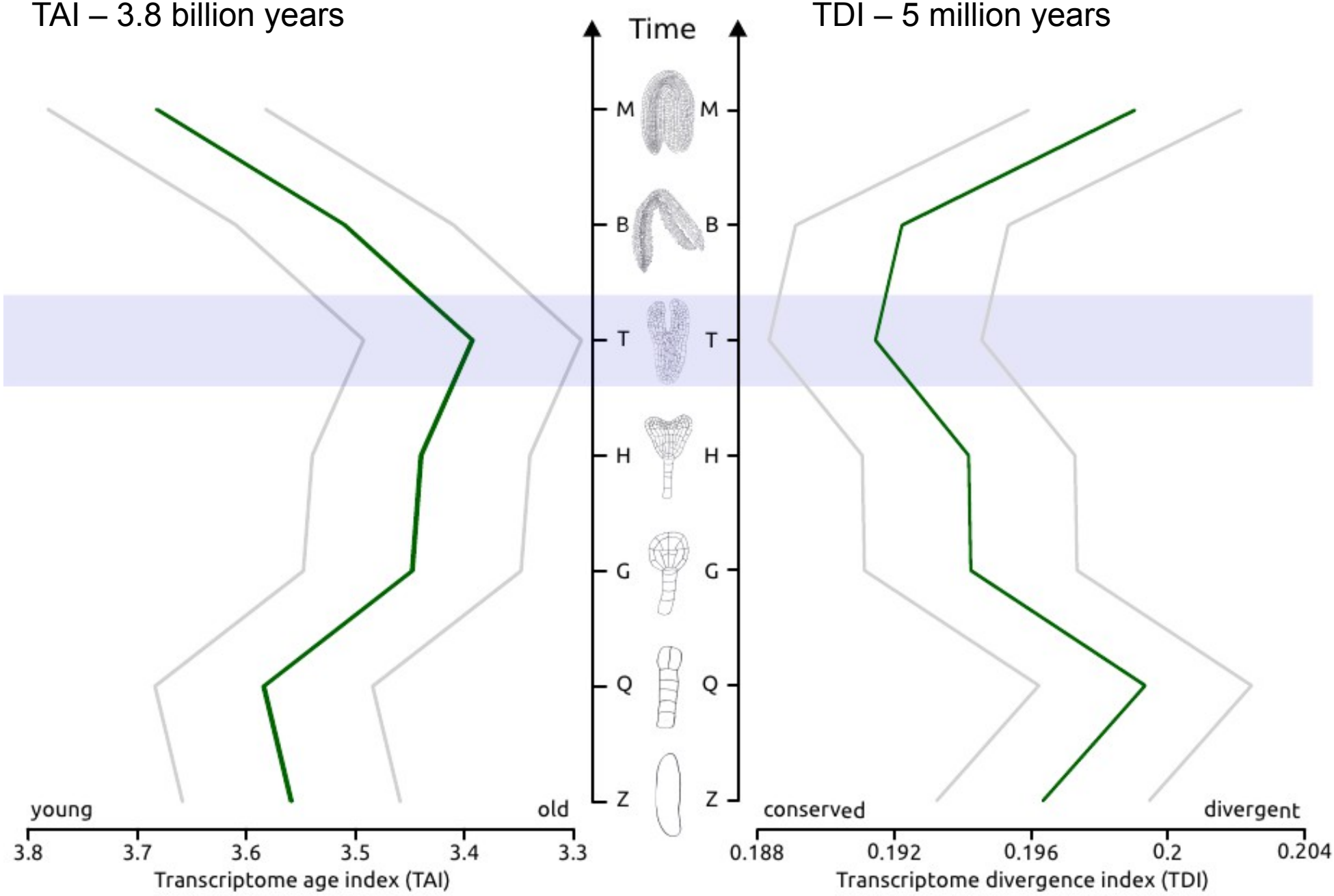
A. thaliana
vs.
B. rapa



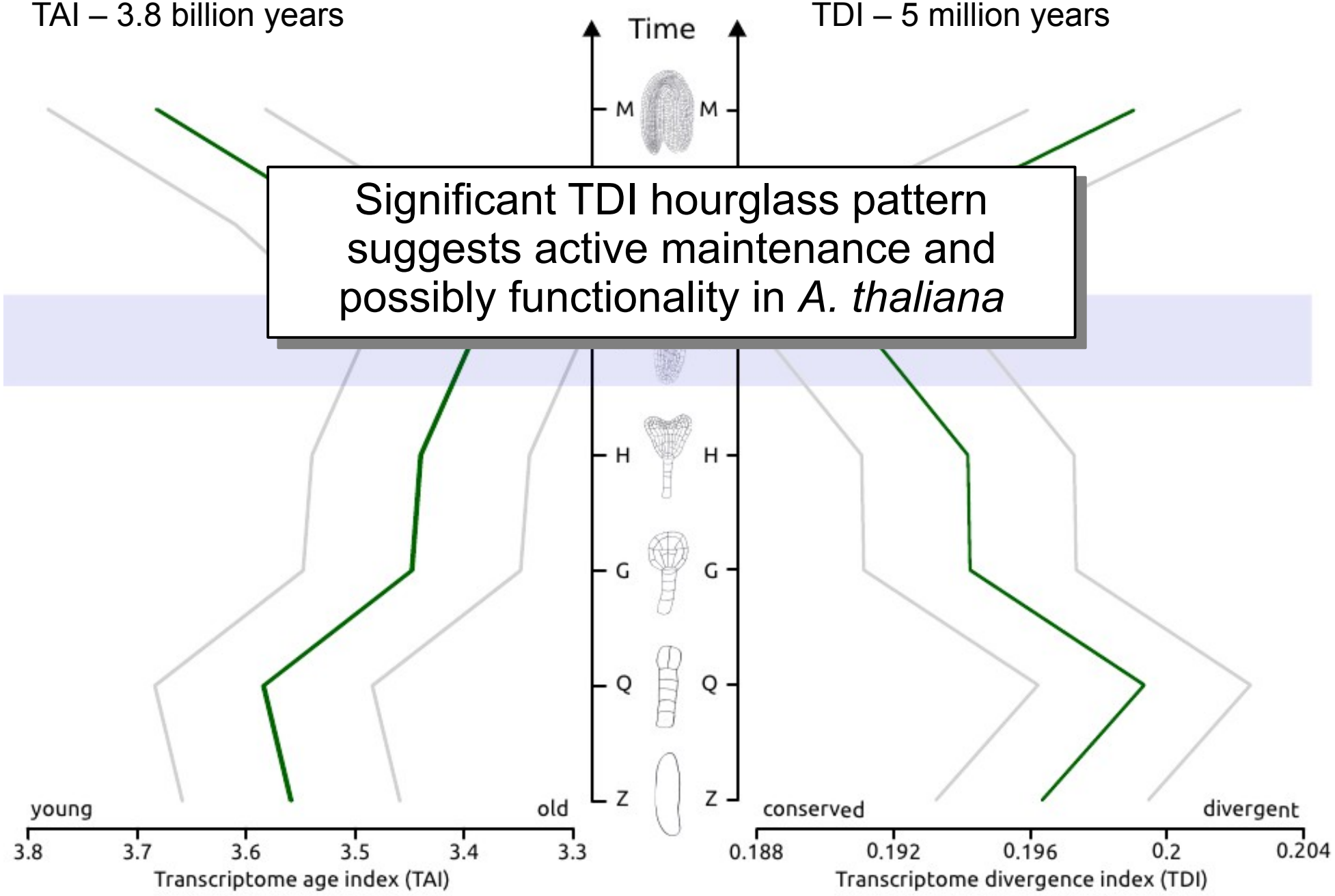


*Divergence times from timetree.org **Divergence times from Oh et al., 2010, *Plant Phys*

Developmental hourglass for *A. thaliana* embryogenesis

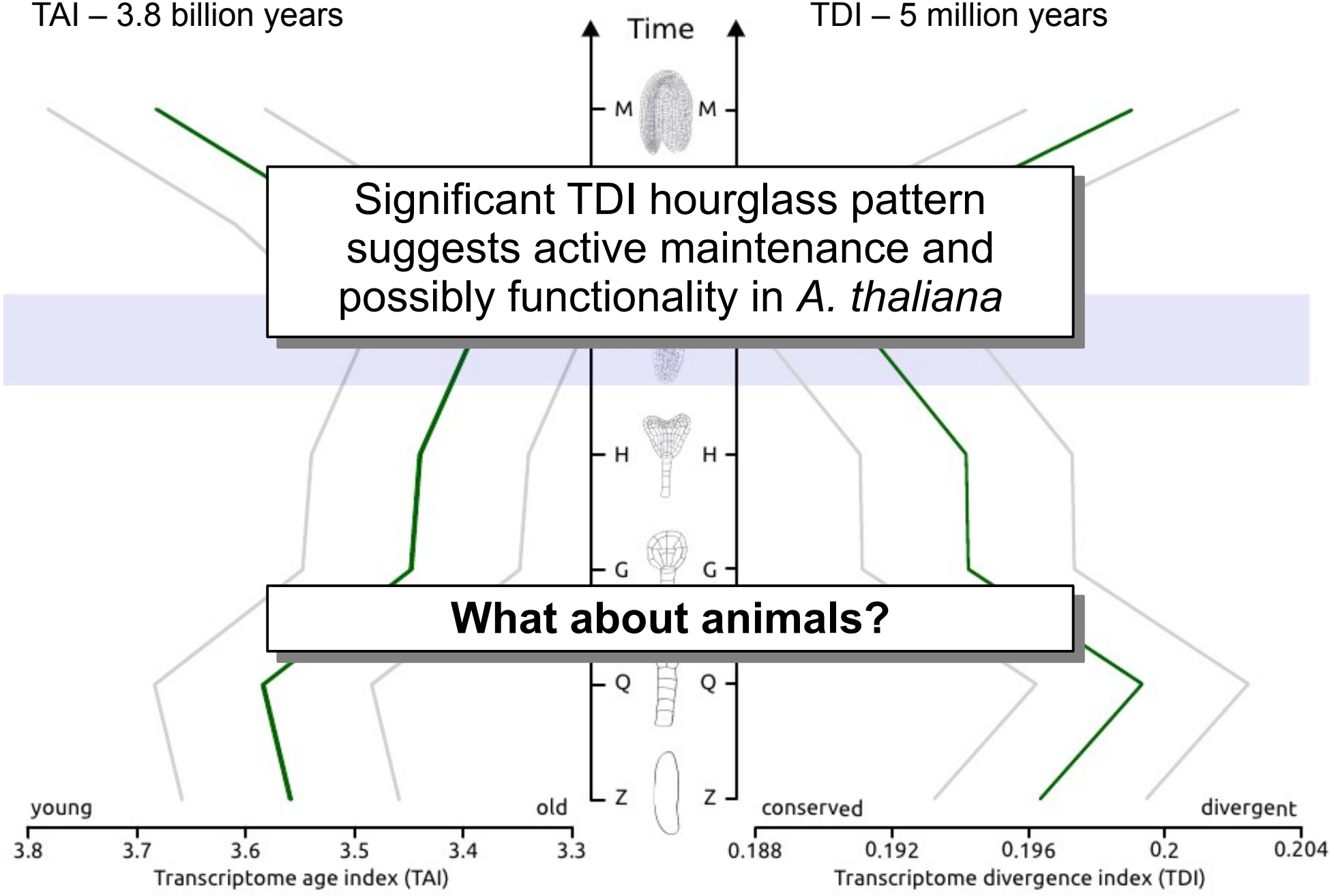


Developmental hourglass for *A. thaliana* embryogenesis



Significant TDI hourglass pattern suggests active maintenance and possibly functionality in *A. thaliana*

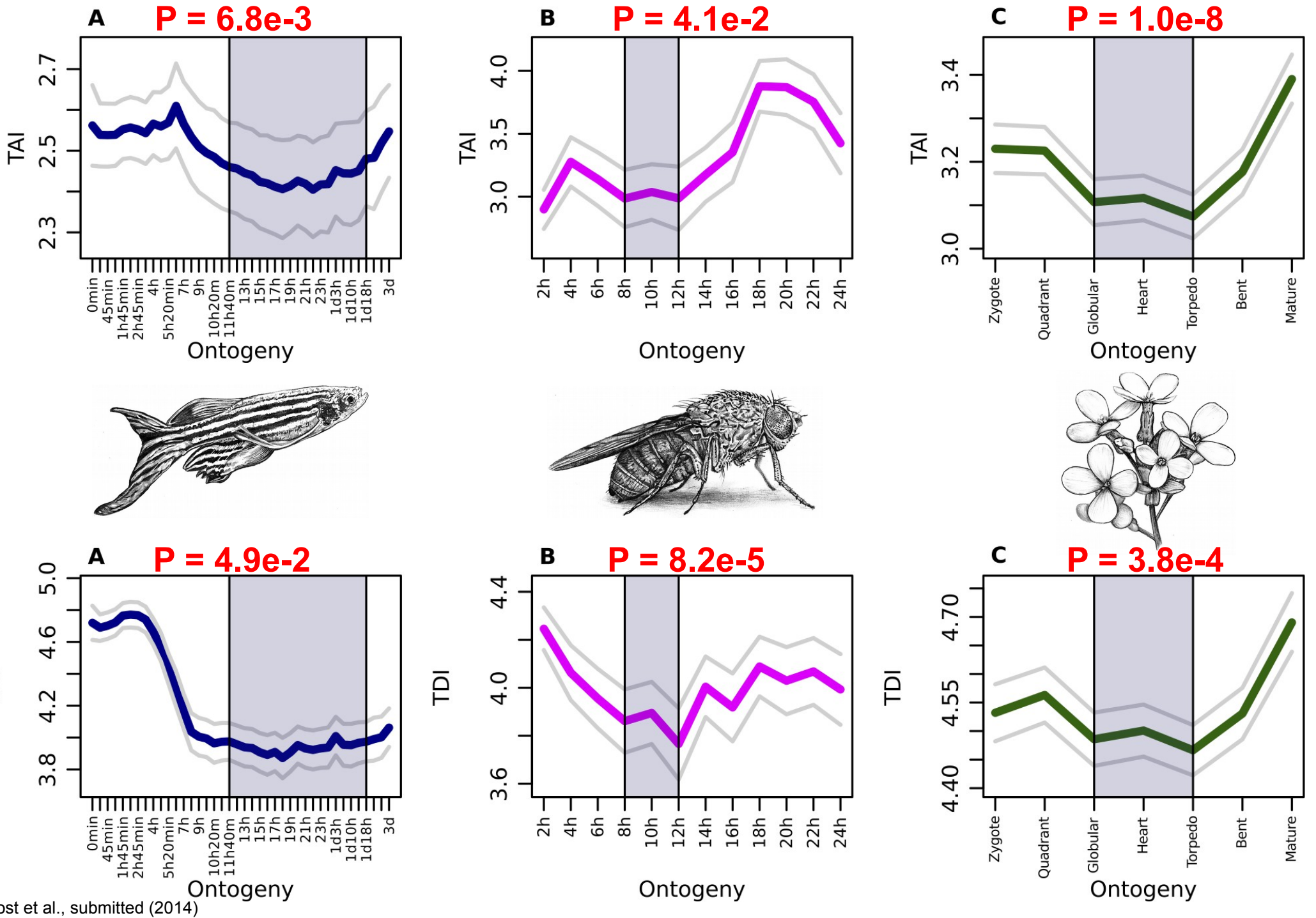
Developmental hourglass for *A. thaliana* embryogenesis



Significant TDI hourglass pattern suggests active maintenance and possibly functionality in *A. thaliana*

What about animals?

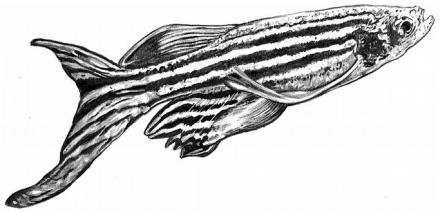
TAI and TDI for embryonic transcriptomes across kingdoms

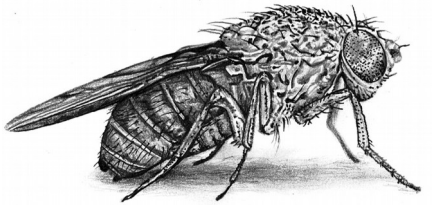


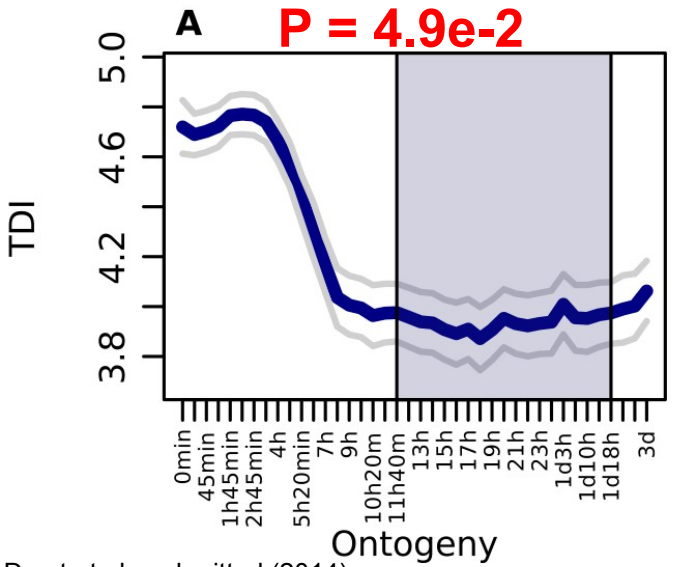
Drost et al., submitted (2014)

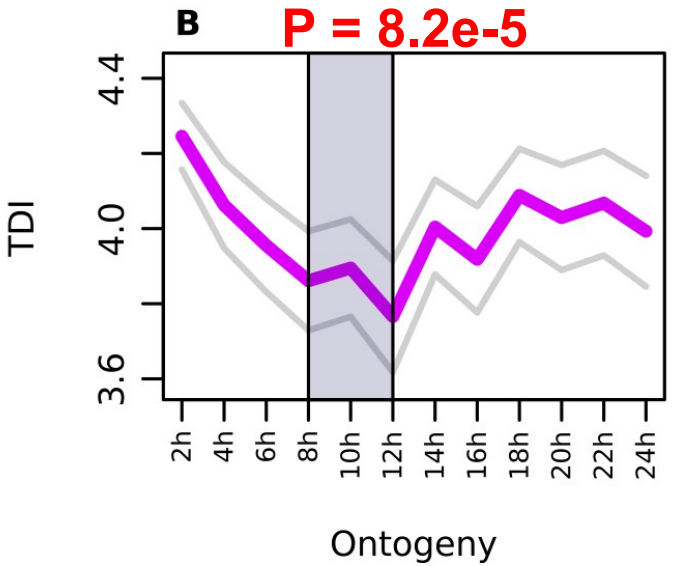
TAI and TDI for embryonic transcriptomes across kingdoms

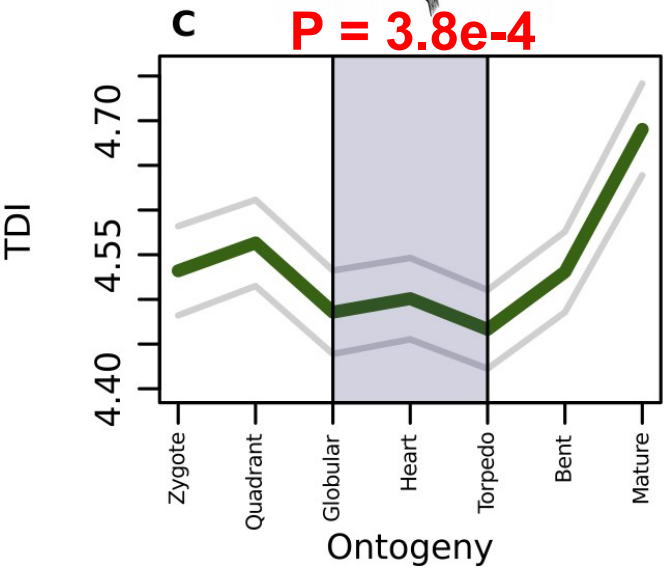
Significant TDI hourglass patterns suggest active maintenance and possibly functionality in both animals and plants







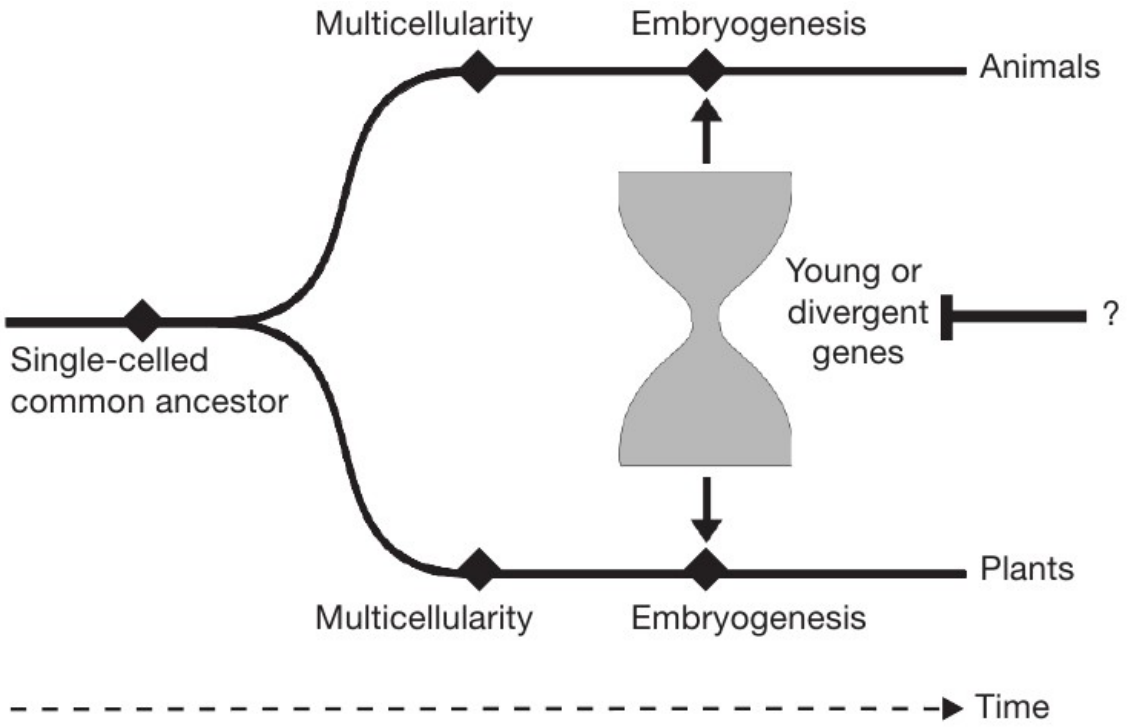




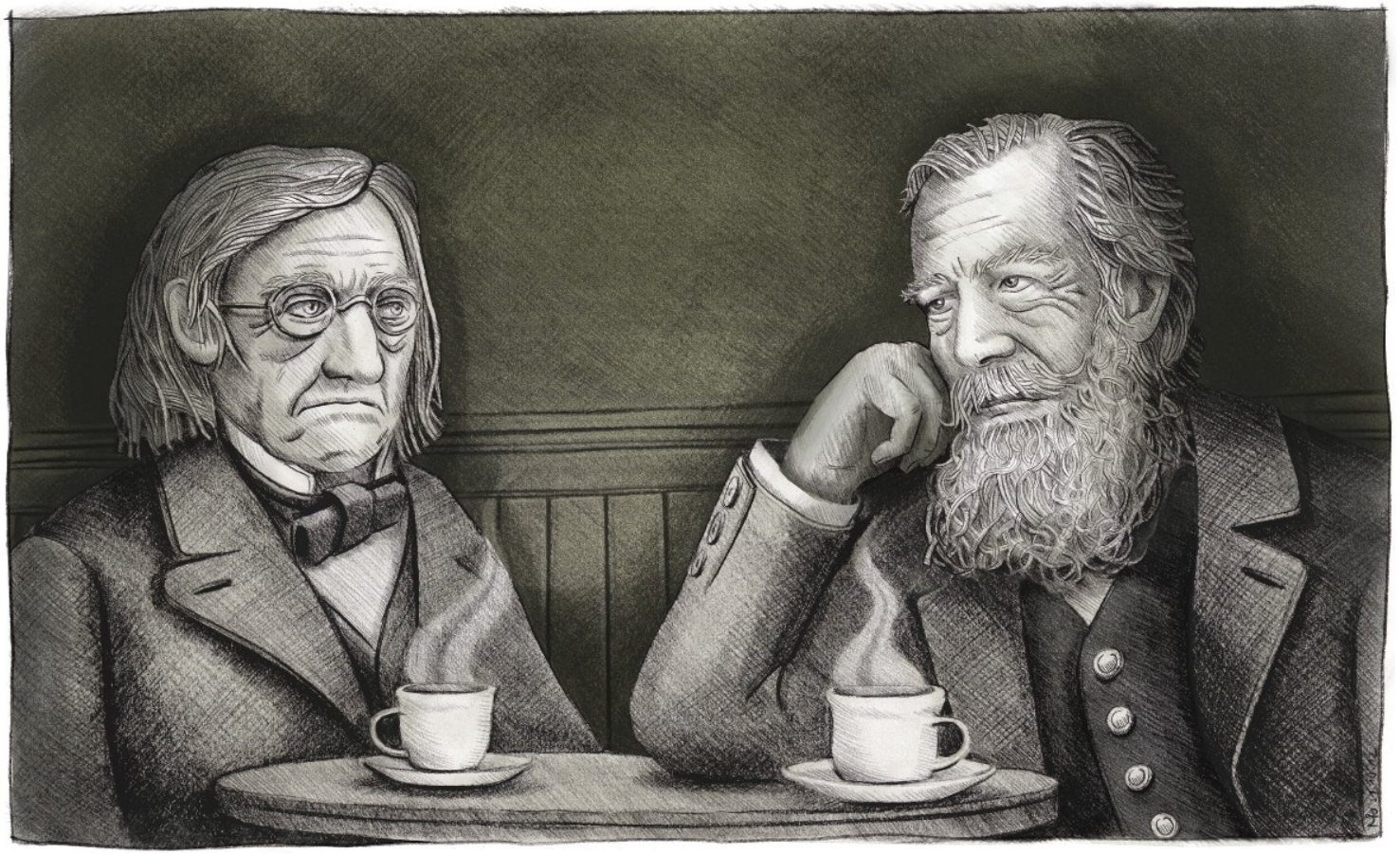
Drost et al., submitted (2014)

Intermediate conclusions

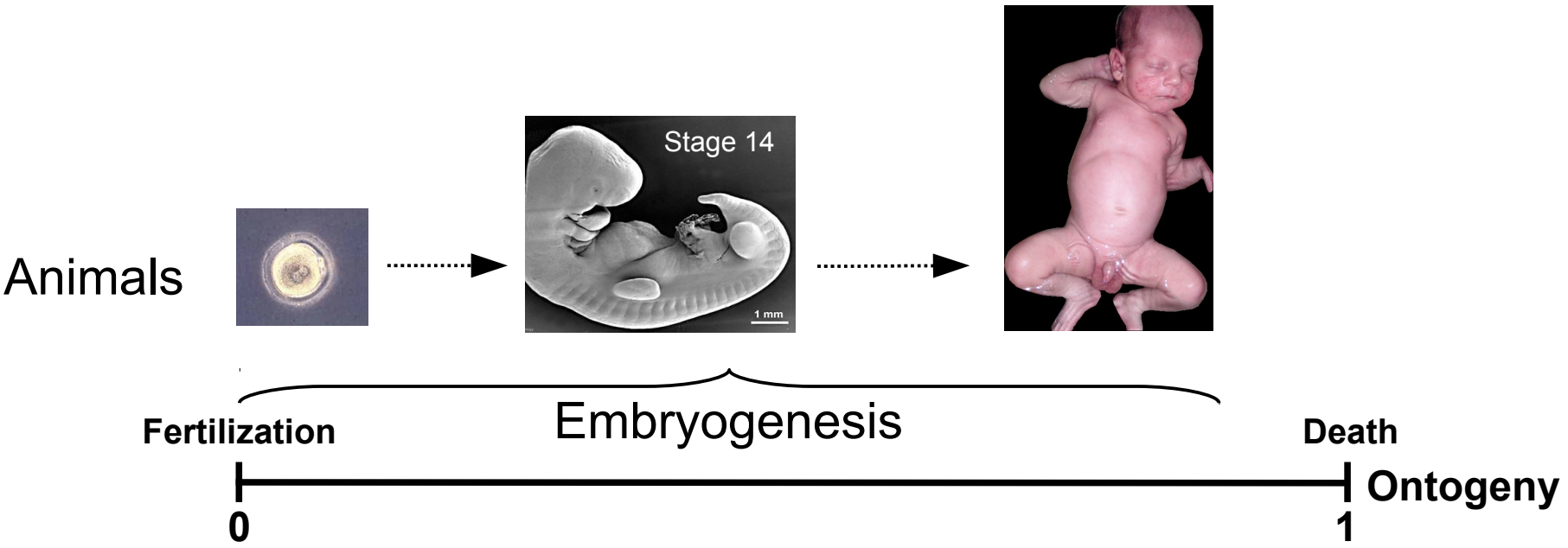
- Nature invented embryogenesis twice and independently
- Embryogenesis very different in plants and animals
- Developmental hourglass seems to be
  - essential
  - actively maintained
  - possibly still functional?



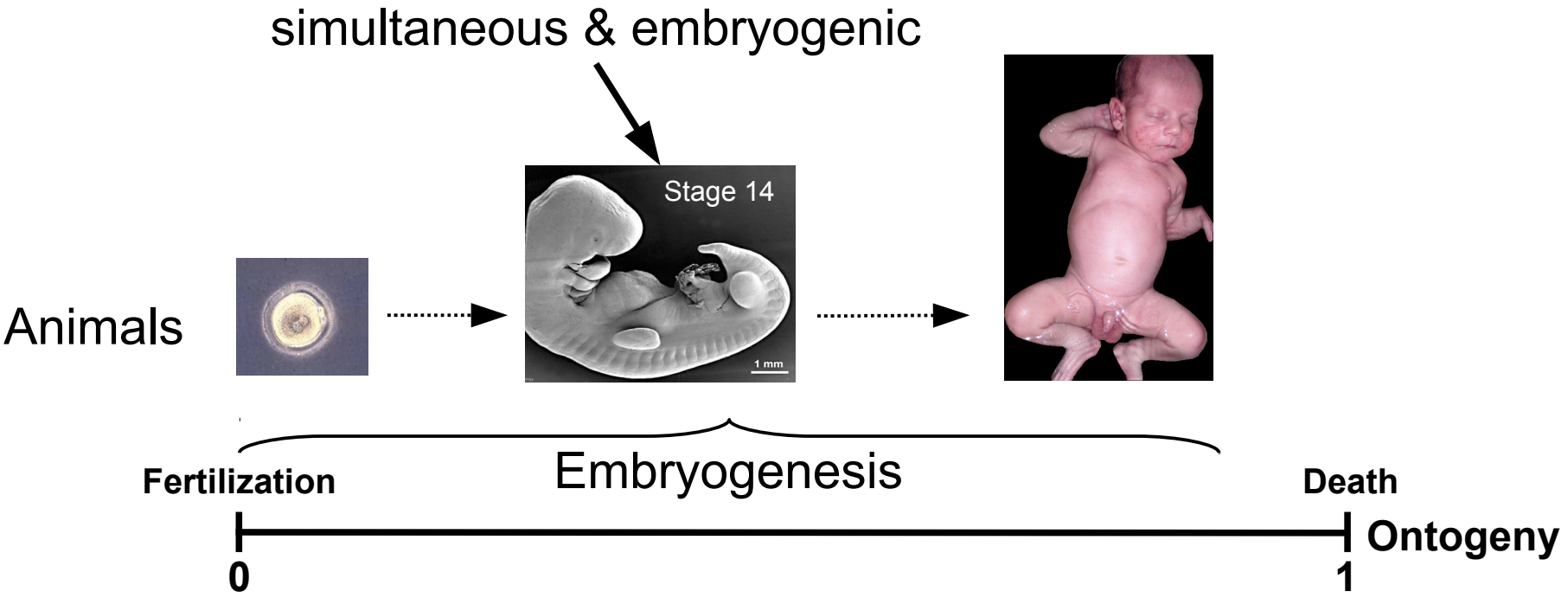
Is the hourglass pattern specific for embryogenesis?



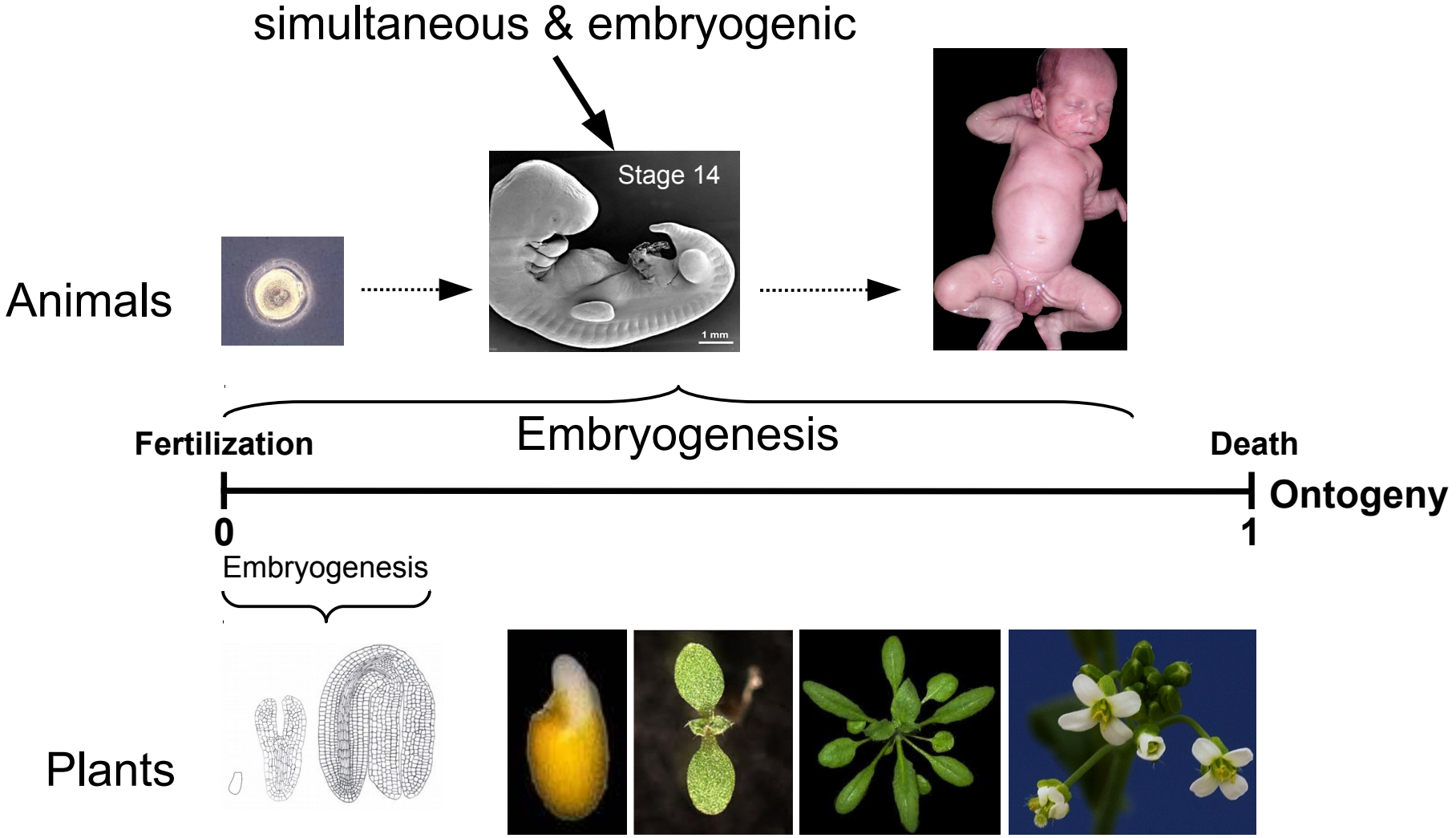
Ontogeny / organ development: animals vs. plants



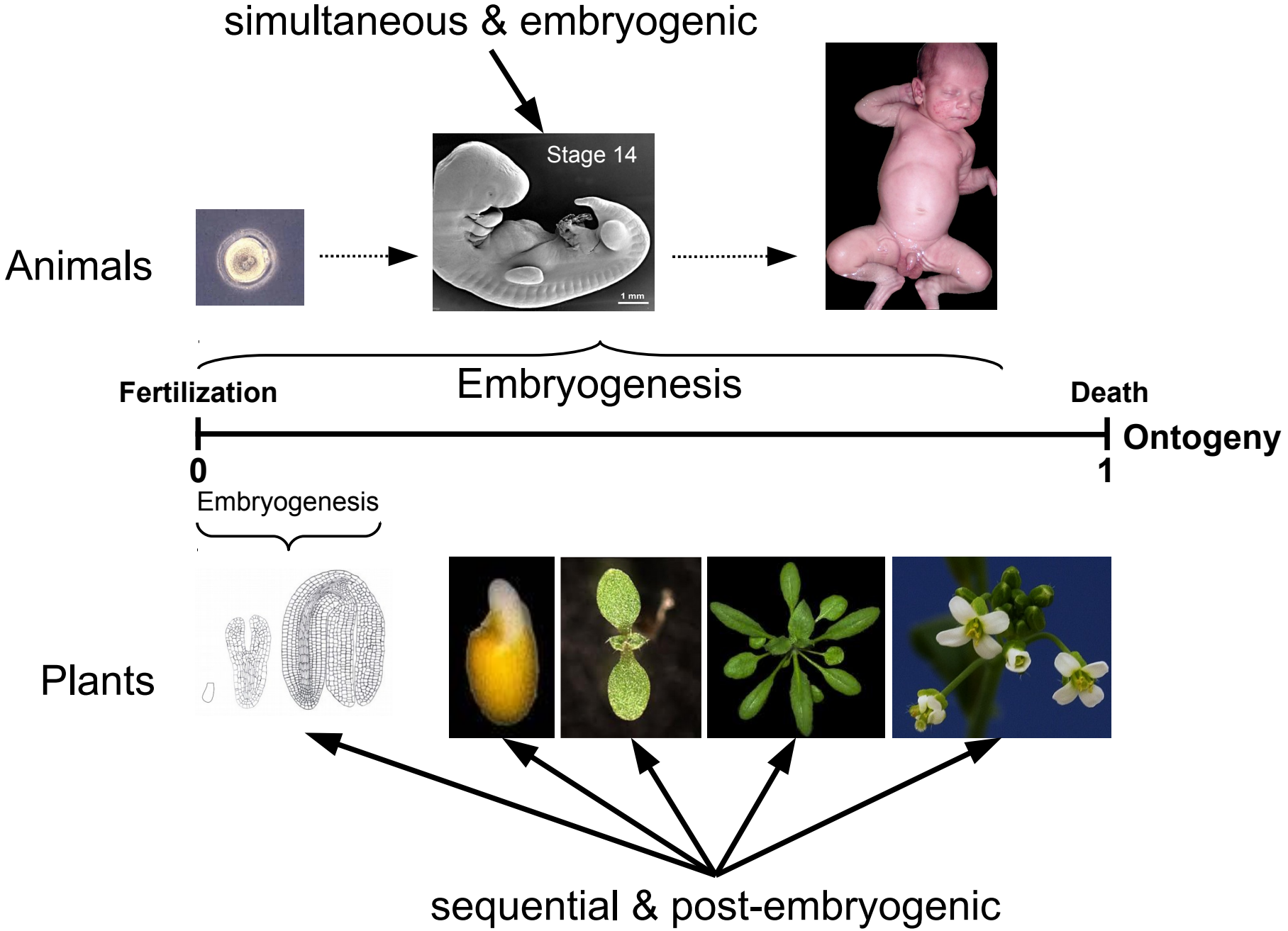
Ontogeny / organ development: animals vs. plants



Ontogeny / organ development: animals vs. plants



Ontogeny / organ development: animals vs. plants



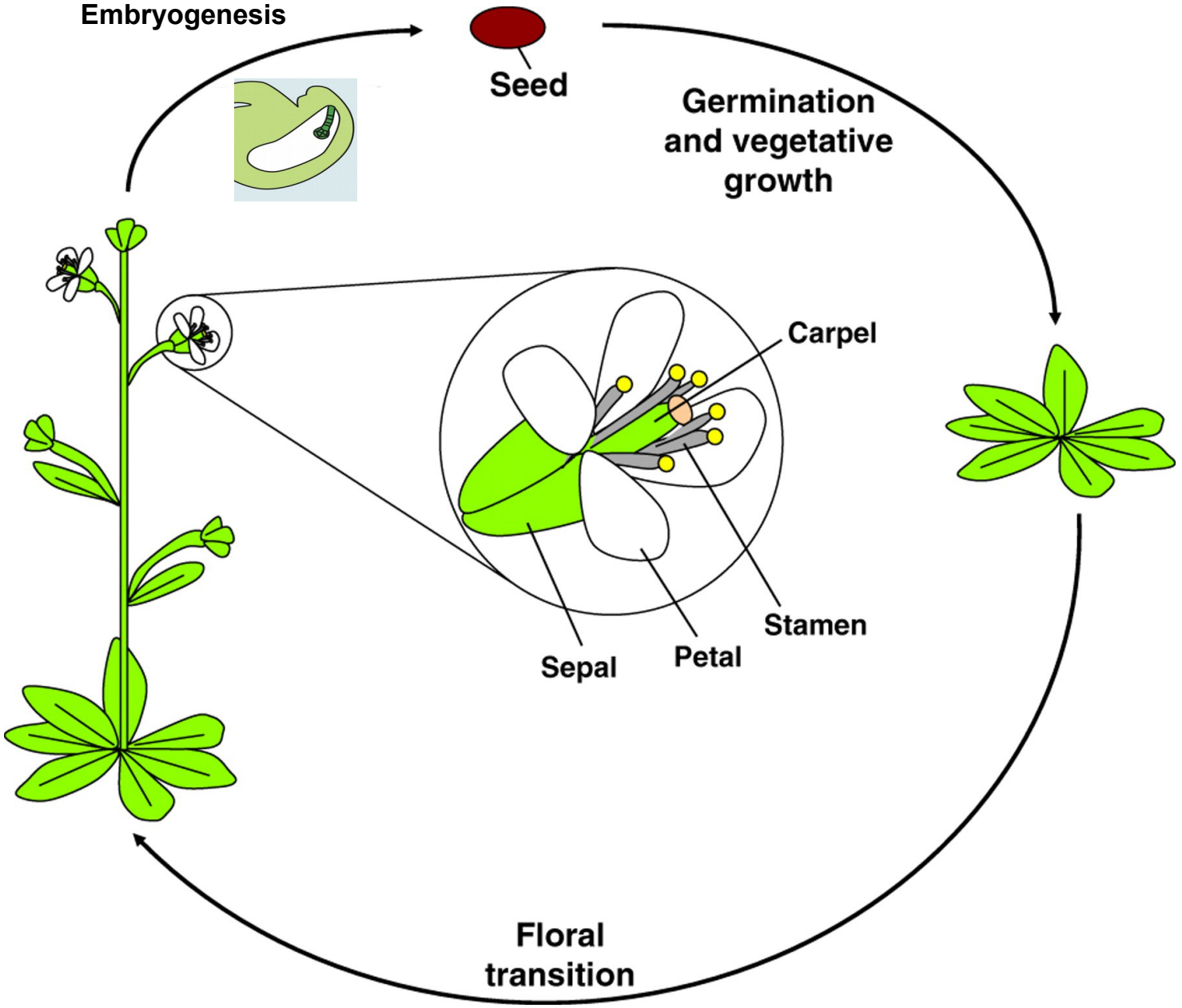
Are transcriptomic hourglasses unique to embryogenesis?

Are they possibly a general feature of developmental transitions?

Difficult to address in most animals
→ development largely embryonic

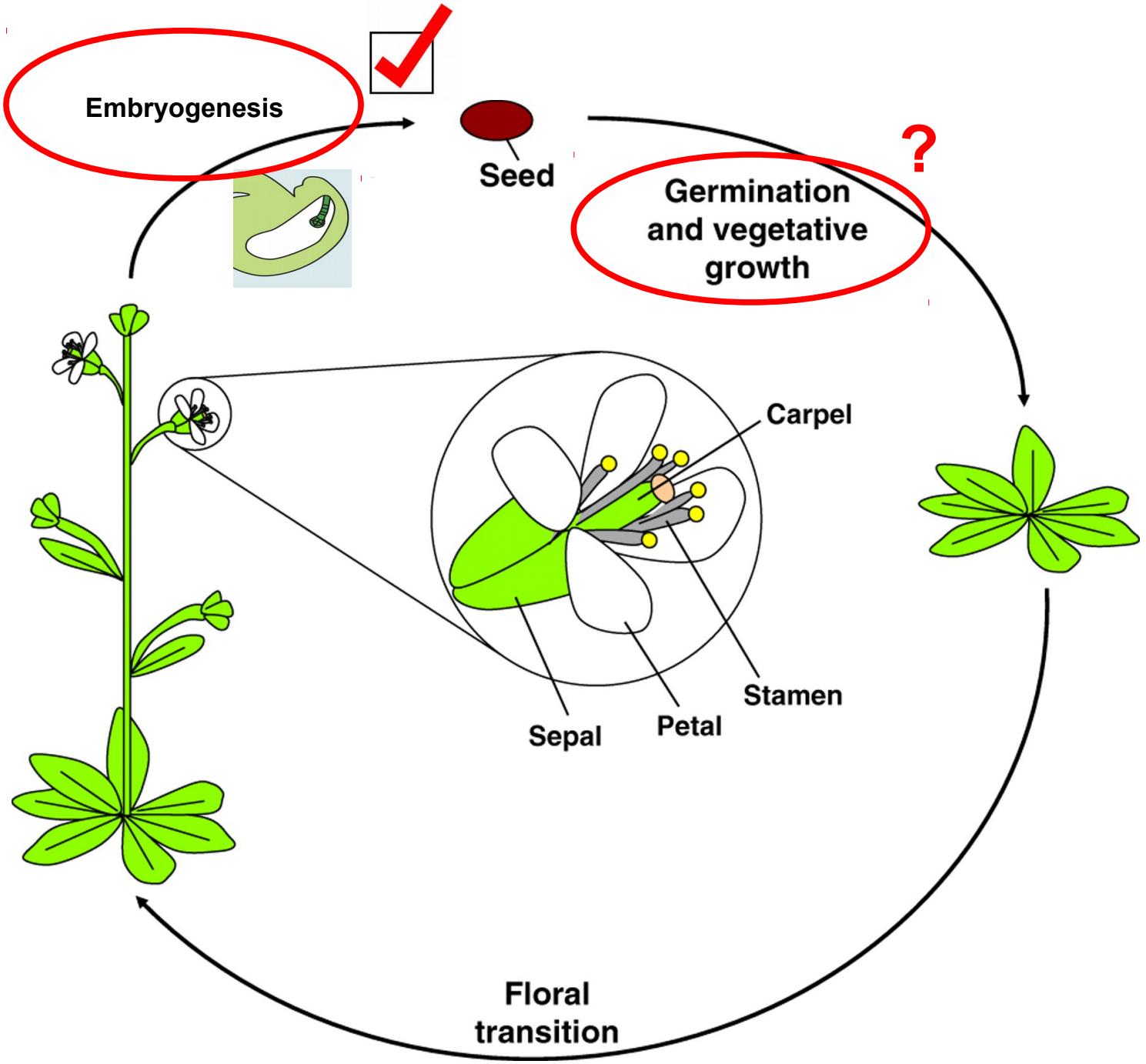
Straight-forward to address in plants
→ development largely post-embryonic

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



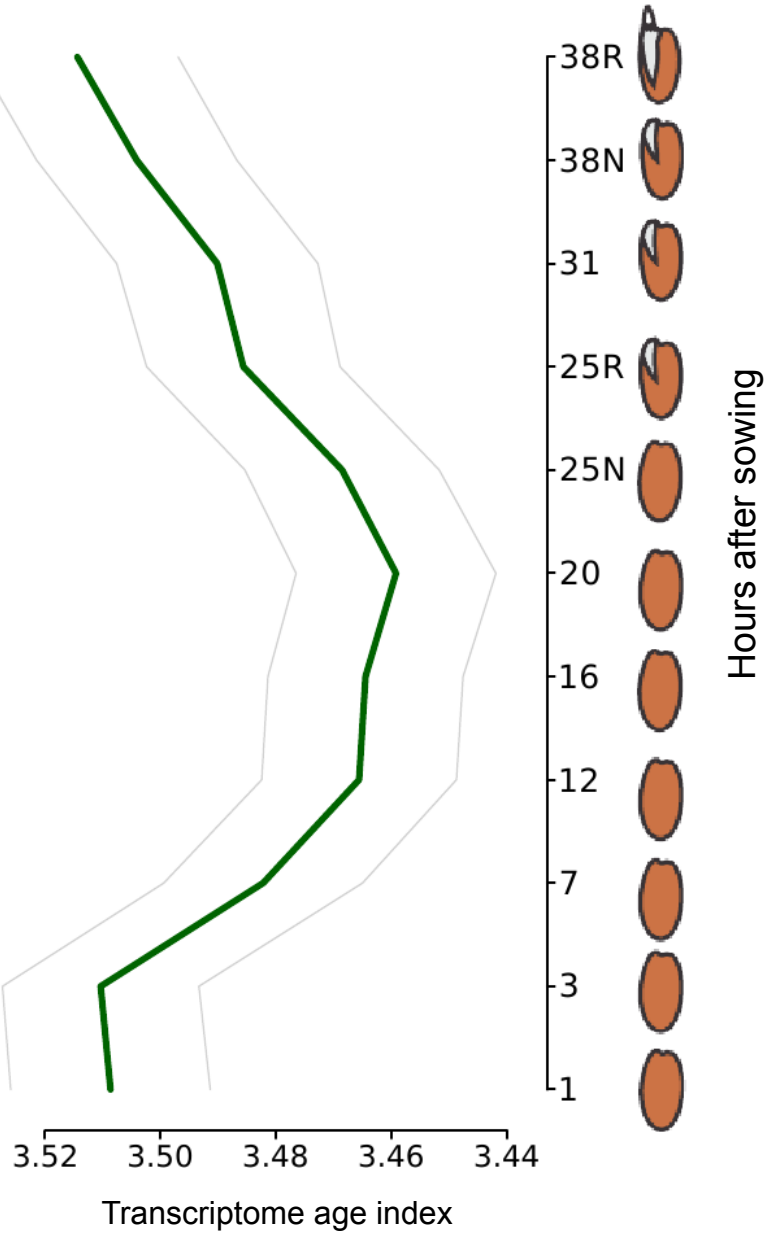
Liu et al., *Development* (2009)

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



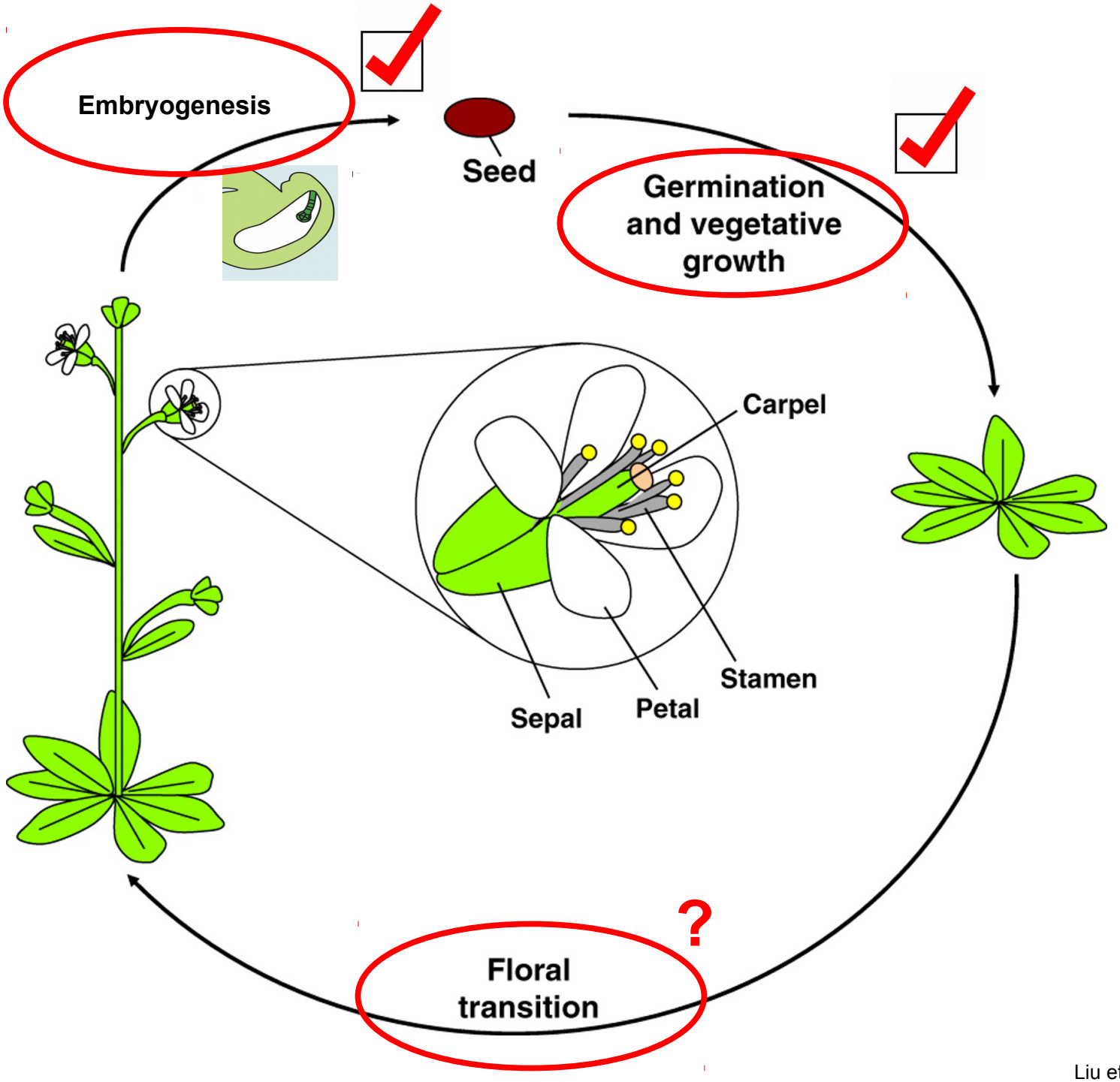
Liu et al., *Development* (2009)

A developmental hourglass for germination



collaboration with Wilco Lighterink, Wageningen University

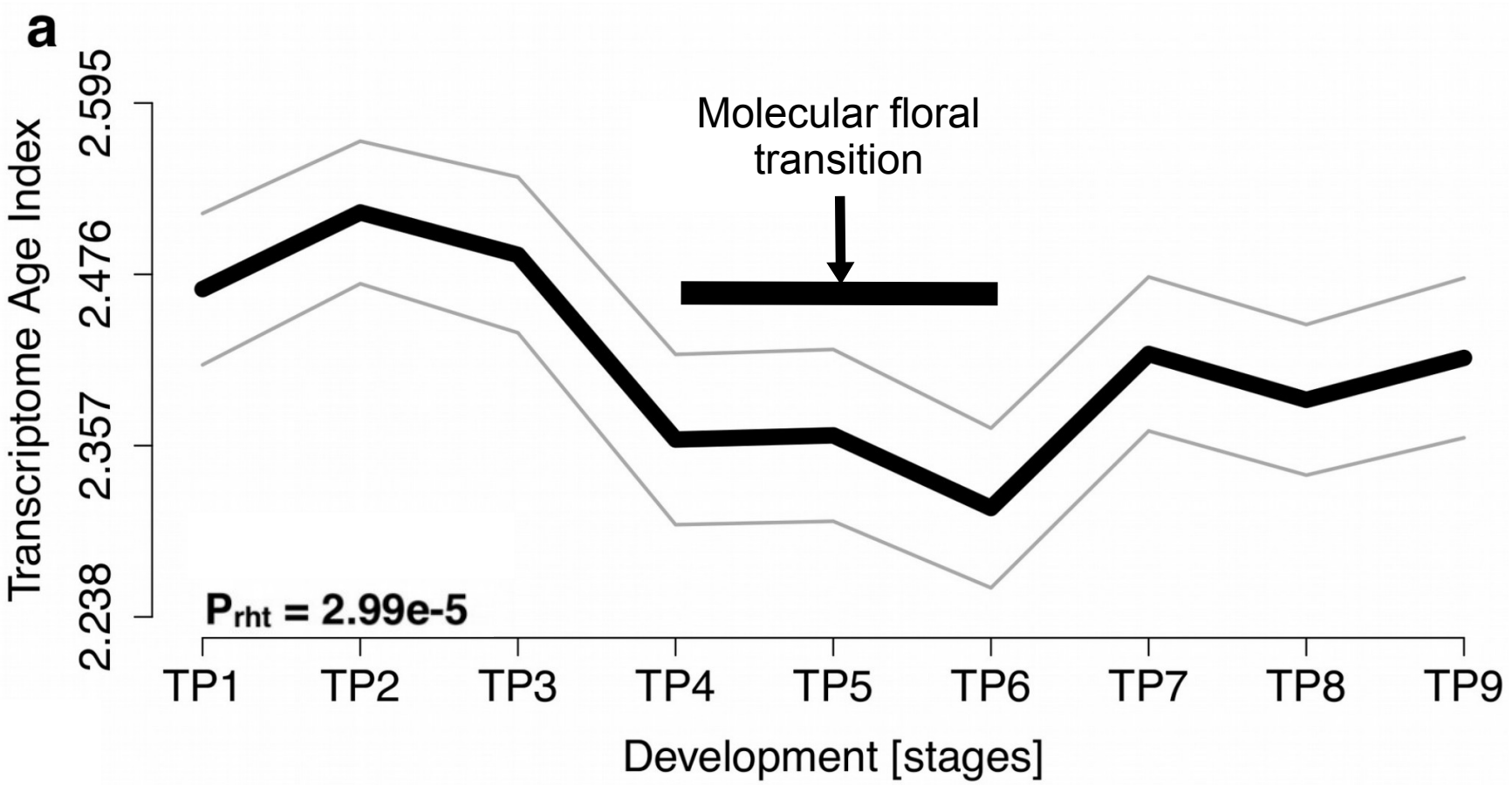
Major developmental transitions in the *A. thaliana* life cycle



Liu et al., *Development* (2009)

Vegetative to reproductive transition aka floral transition

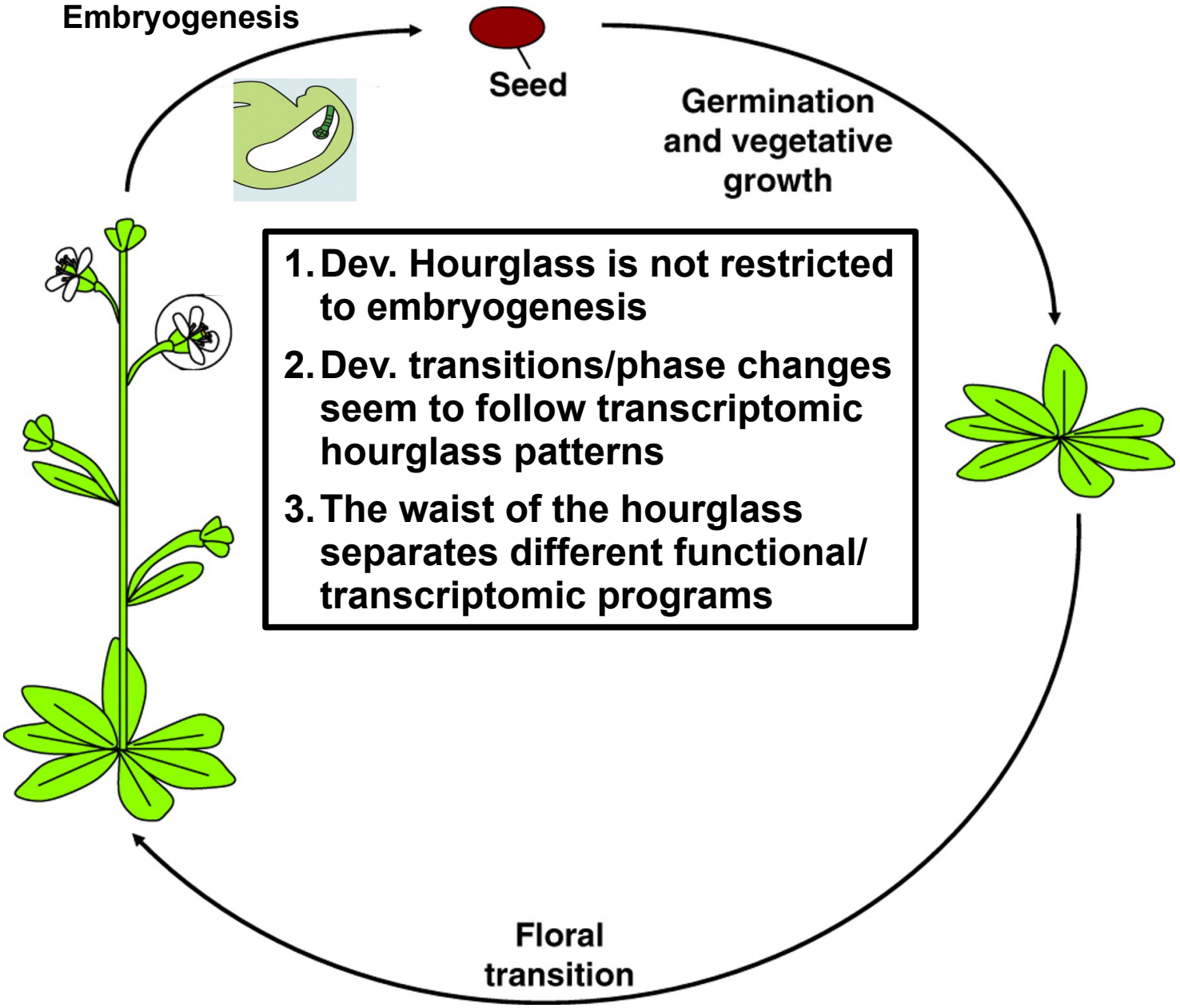
- SPP1530 – PP24, Quint, Grosse, Weisshaar



- Highly significant TAI hourglass for vegetative-reproductive phase change
- Waist of the hourglass pattern marks molecular floral transition
- TAI pattern separates two transcriptional programs

Drost et al., 2016, submitted (preprint at *bioRxiv* http://dx.doi.org/10.1101/035527)

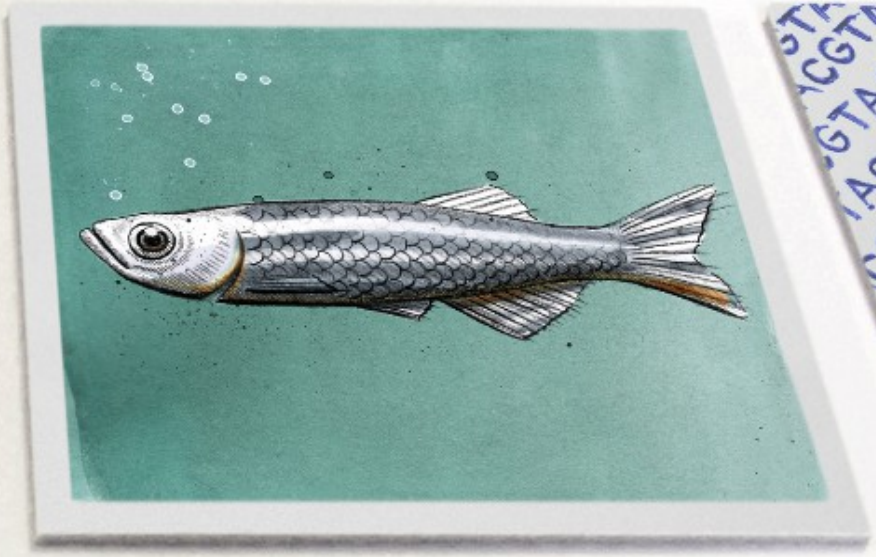
Conclusions and outlook so far



Liu et al., *Development* (2009)

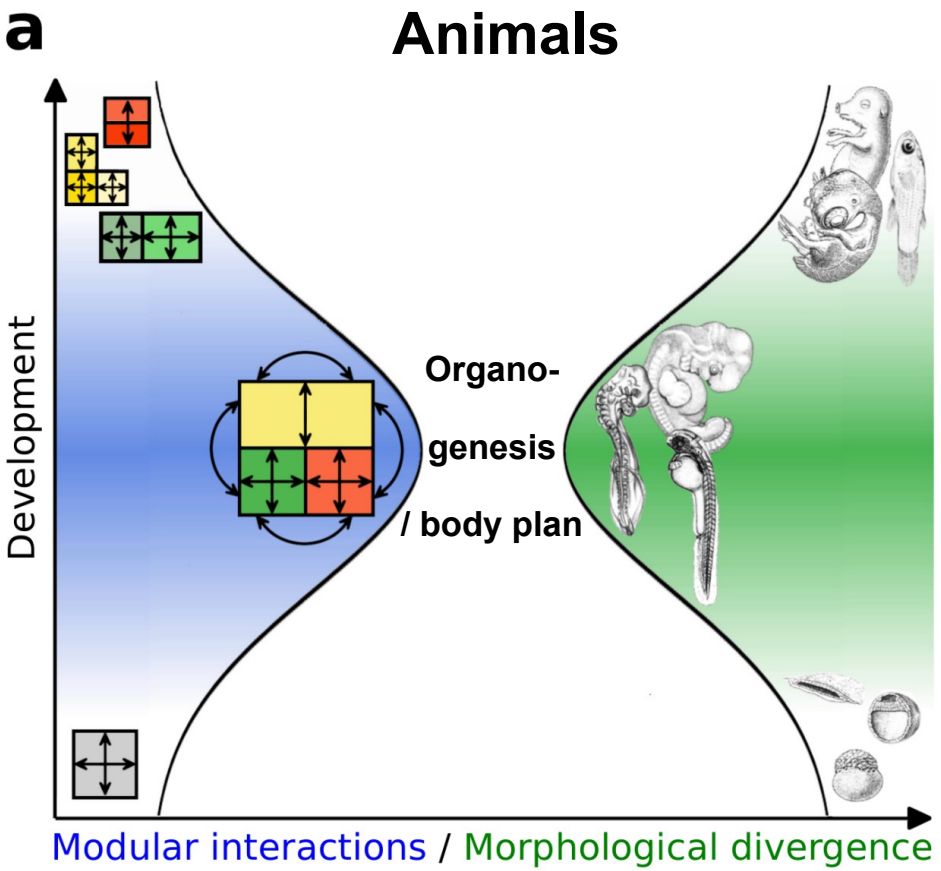
1. Developmental hourglass specific for animals?

2. … specific for embryogenesis?

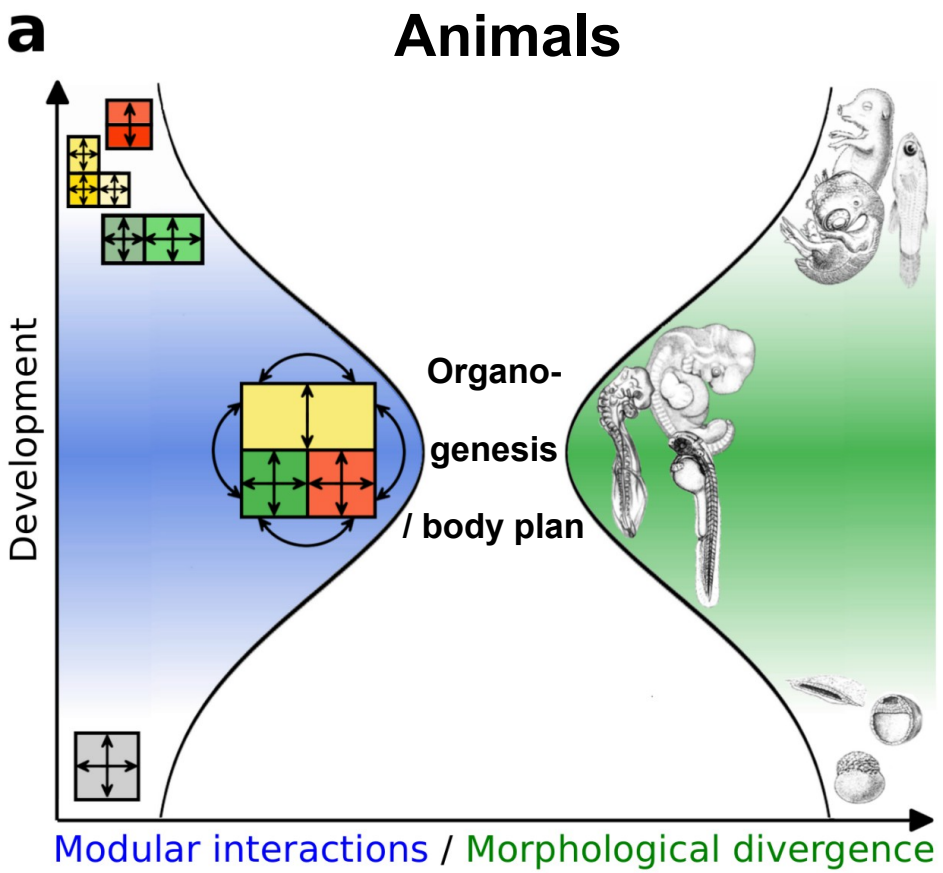


3. … related to organogeneis?

Concurrence of plant hourglass patterns with organogenesis hypothesis



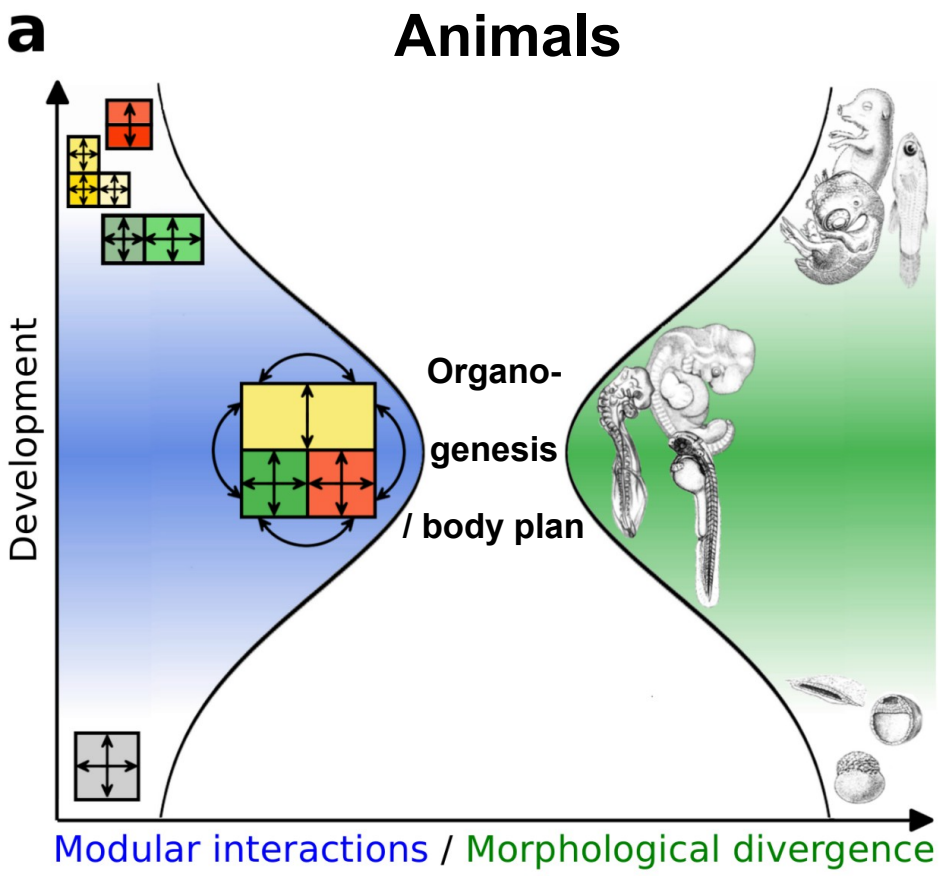
Concurrence of plant hourglass patterns with organogenesis hypothesis



Plants

Hourglass for:	Organogenesis?
• Embryogenesis	• Yes
• Germination	• Hardly
• Floral transition	• No

Concurrence of plant hourglass patterns with organogenesis hypothesis

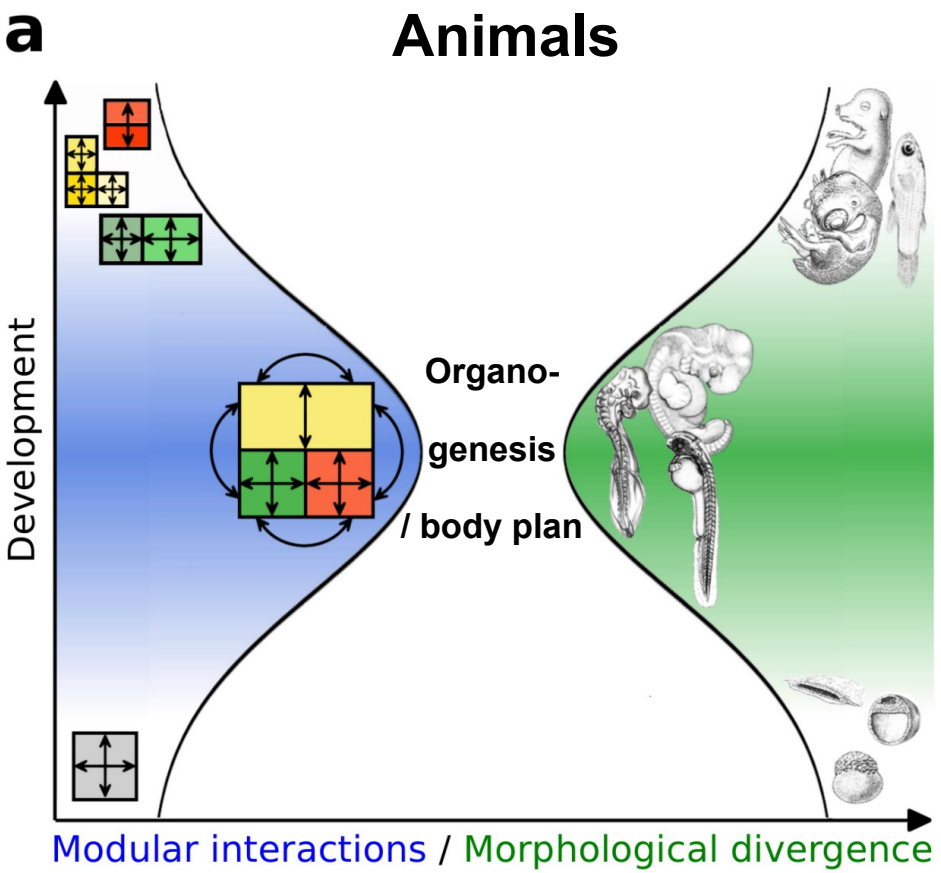


Plants

Hourglass for:	Organogenesis?
• Embryogenesis	• Yes
• Germination	• Hardly
• Floral transition	• No

Data largely disagree with the favored explanation for animal hourglass patterns

Concurrence of plant hourglass patterns with organogenesis hypothesis



Plants

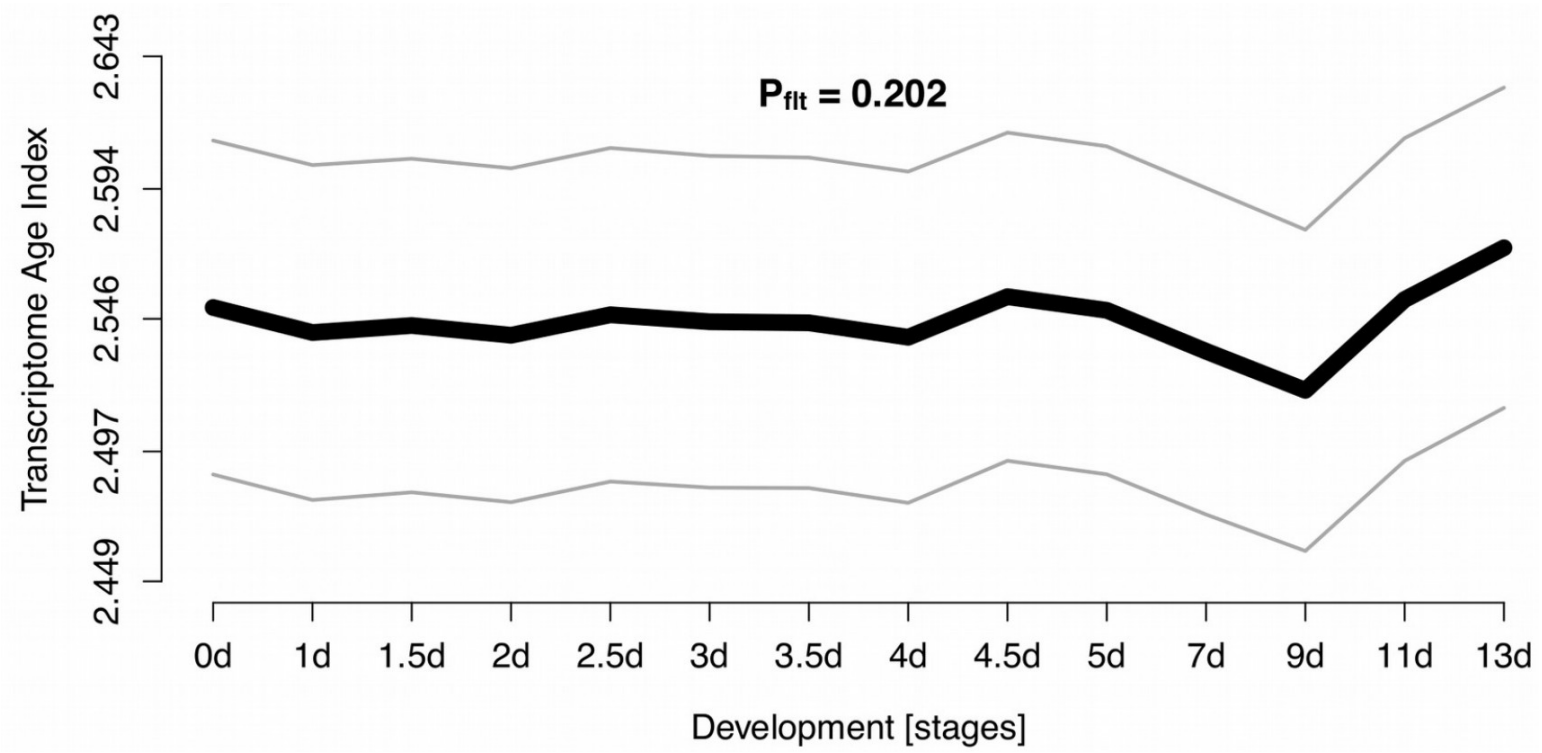
Hourglass for:	Organogenesis?
• Embryogenesis	• Yes
• Germination	• Hardly
• Floral transition	• No

Data largely disagree with the favored explanation for animal hourglass patterns

Negative control:
→ Flower development

Flower development as negative control

- Collaboration with Frank Wellmer, Dublin

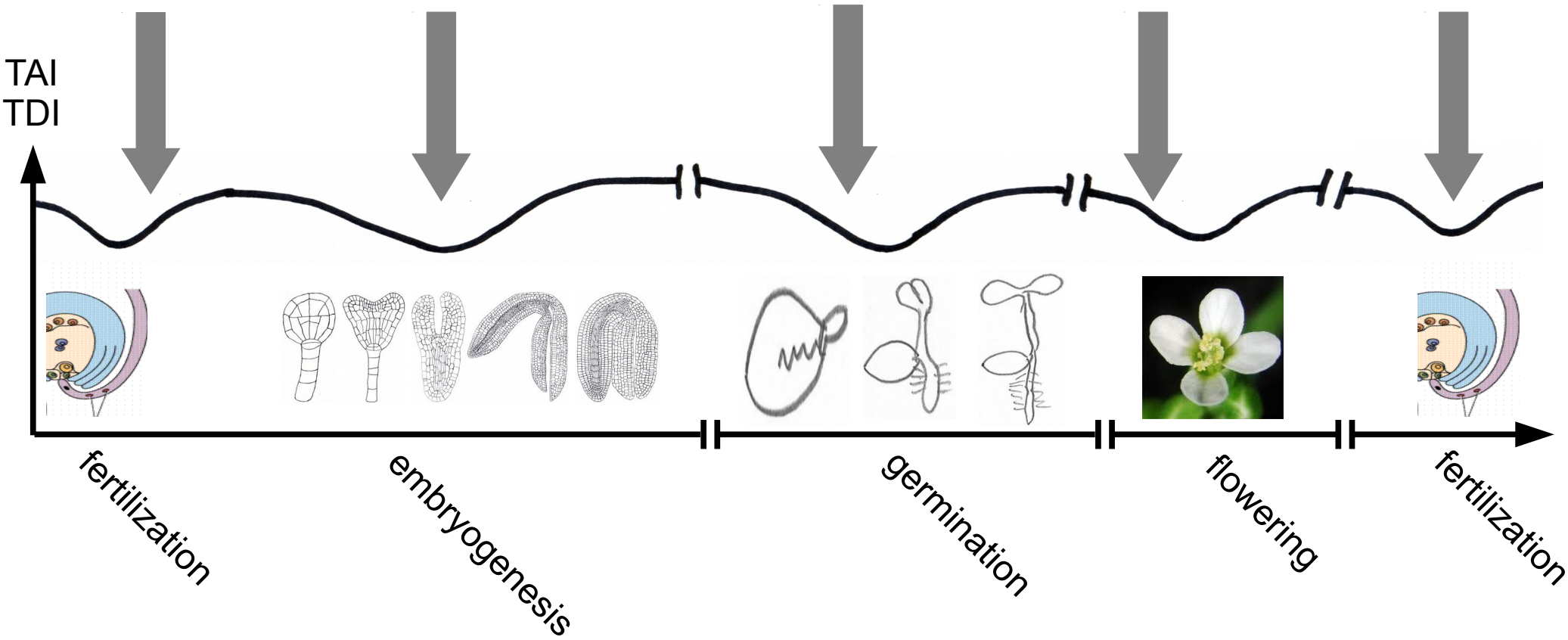


Organogenesis

The absence of conserved transcriptomes during organogenesis stages of flower development further refutes the association of organogenesis as the driving force of the developmental hourglass

Ryan et al., 2015, *BMC Genomics*; Drost et al., 2016, submitted (preprint at *bioRxiv* http://dx.doi.org/10.1101/035527)

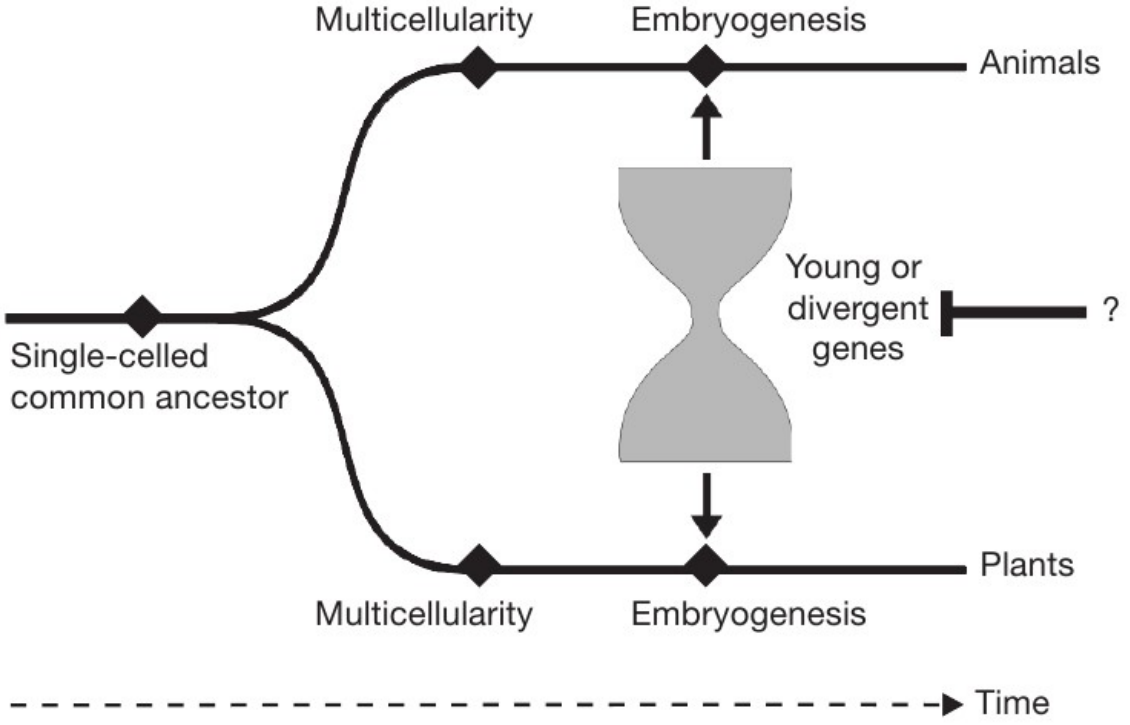
Many hourglasses?
Checkpoint hypothesis

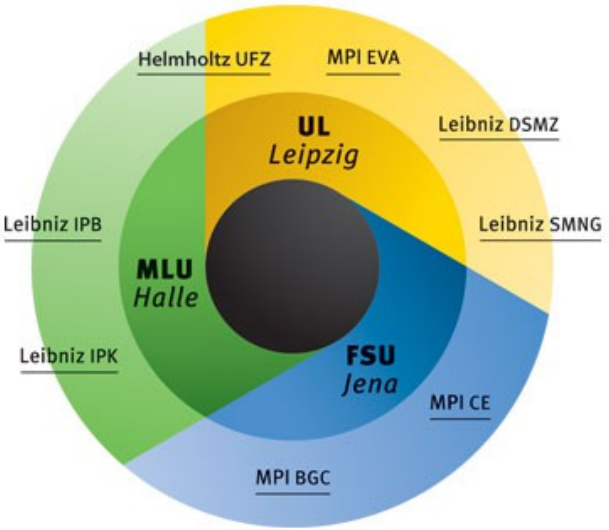


http://www.emc.maricopa.edu; http://www.greenhousecanada.com; http://plantdev.bio.wzw.tum.de; http://www.angenetik.fu-berlin.de

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 and (ii) several developmental proceses in plants, governing the emergence of complex life and biodiversity on our planet?





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 and (ii) several developmental proceses in plants, governing the emergence of complex life and biodiversity on our planet?