

Exploring Thylakoid Emergence: Evolution of Membrane Biogenesis in Early-diverging Cyanobacteria



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Context & Research Question

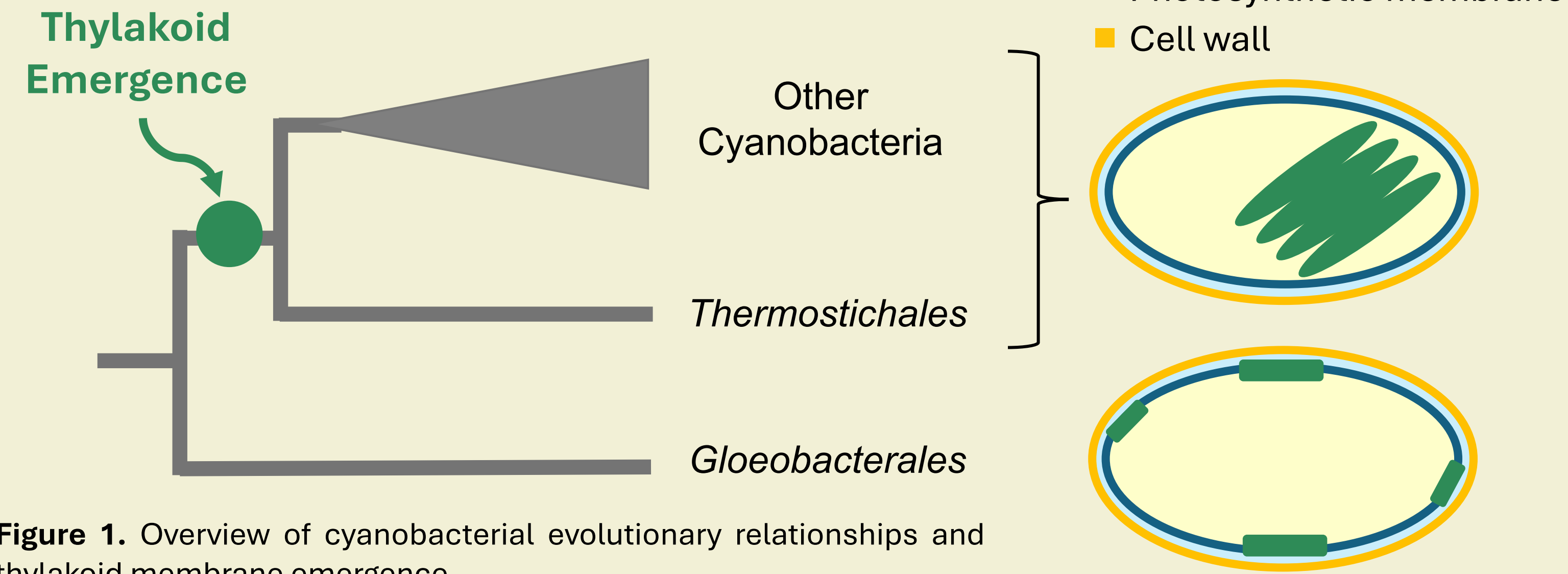
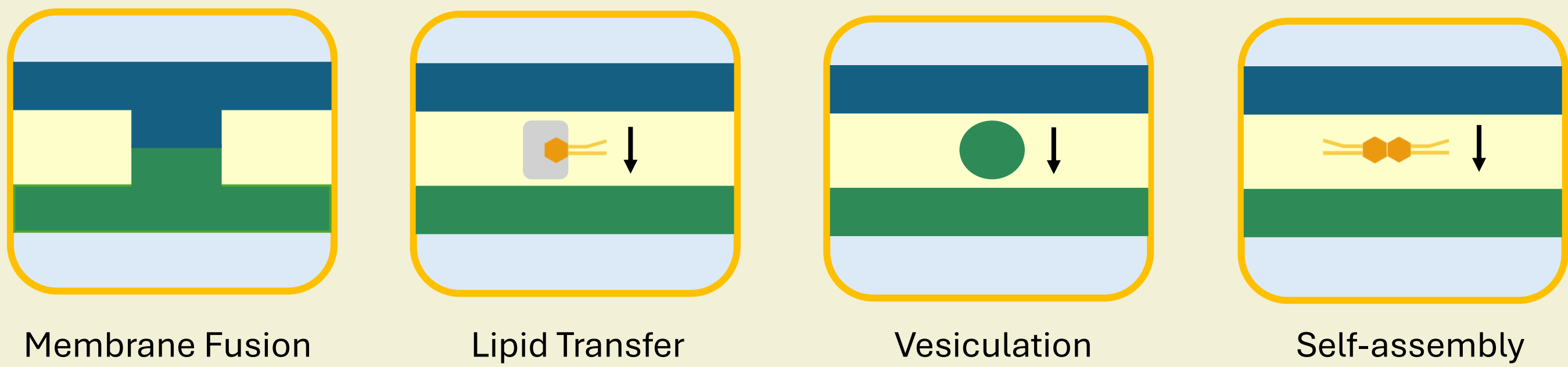


Figure 1. Overview of cyanobacterial evolutionary relationships and thylakoid membrane emergence.

- Thylakoid membranes host the **photosynthetic machinery** in most **cyanobacteria** but are **absent in *Gloeobacterales***, the earliest-diverging lineage (Fig. 1).
- The mechanisms of **thylakoid membrane biogenesis** remain **unknown**, with **four current hypotheses** debating their origin, as shown in Figure 2:



What evolutionary changes in membrane biogenesis and protein integration explain this transition?

Methods

- Dataset Selection:** Curation of **950 Terrabacterial genomes** to sample a broad phylogenetic diversity of high-quality genomes from the GTDB and NCBI databases.
- Orthology Inference:** Identification of **orthologous groups** to track protein evolution across Cyanobacteria.
- Phylogenetic Reconstruction:** Construction of **Maximum Likelihood trees** to analyze the **taxonomic distribution** and **evolutionary history** of 36 proteins involved in photosystem II assembly and 13 proteins involved in membrane dynamics.
- Molecular Modeling structures:** **Multiple sequence alignment** and **3D structure prediction** (AlphaFold) to assess functional conservation and identify **key structural motifs**.

Results

1 Proteins involved in the integration of photosynthetic components

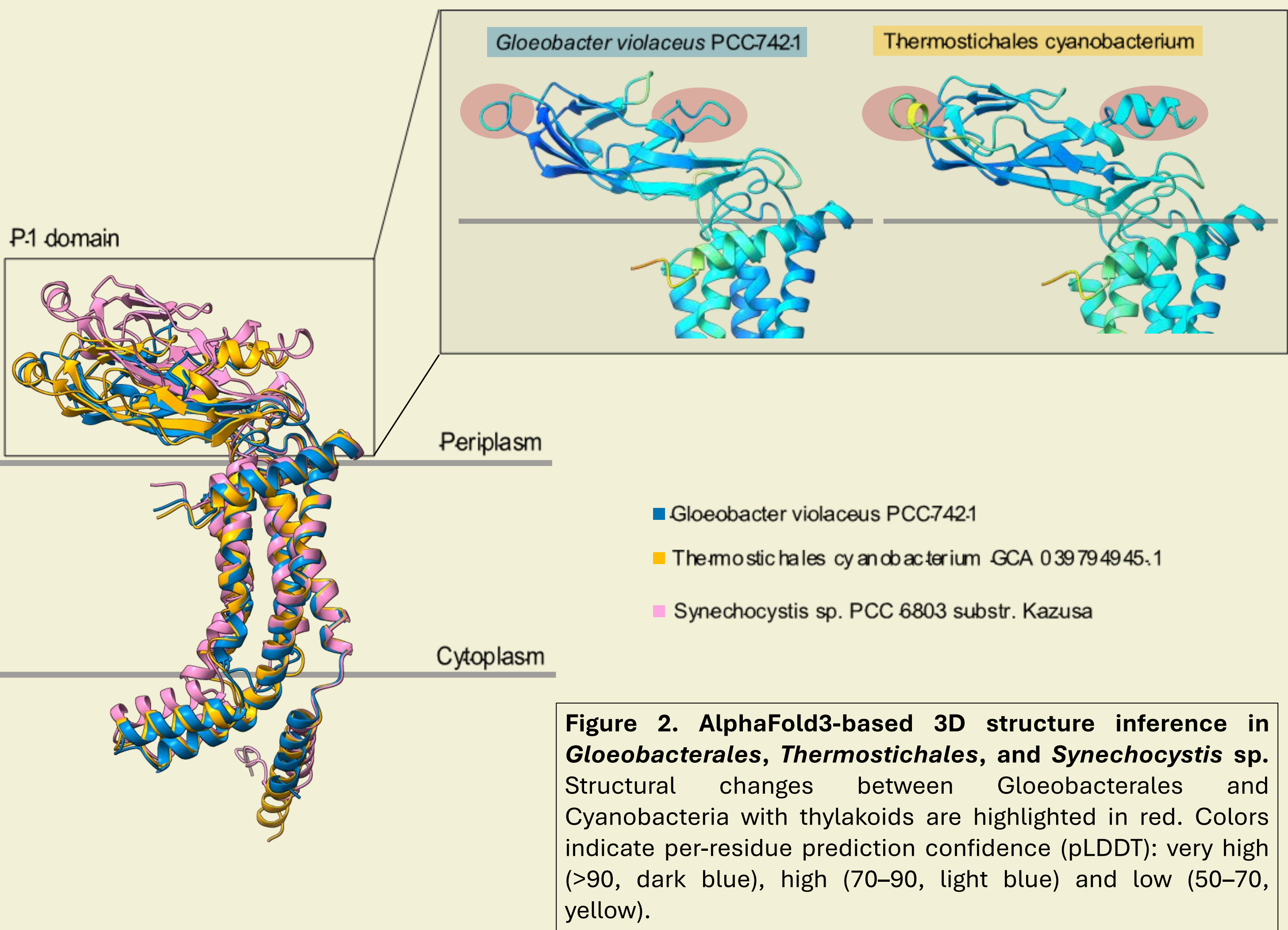


Figure 2. AlphaFold3-based 3D structure inference in *Gloeobacterales*, *Thermostichales*, and *Synechocystis* sp. Structural changes between *Gloeobacterales* and Cyanobacteria with thylakoids are highlighted in red. Colors indicate per-residue prediction confidence (pLDDT): very high (>90, dark blue), high (70–90, light blue) and low (50–70, yellow).

2 Proteins involved in membrane dynamics

	<i>Gloeobacterales</i>	Cyanobacteria with thylakoids	Evolutionary Insights
DedA			
Lipid transfer			
Vesicular trafficking			
Slr0232	Divergent	Conserved	Thylakoid-linked adaptation
Slr0305	Absent	Conserved	Thylakoid-linked presence
Slr0509	Poorly conserved	Poorly conserved	Low conservation
Prohibitins (SPFH family)			
Associated with lipid raft			
Slr1106	Absent	Conserved	Thylakoid-linked presence
Slr1768	Absent	Conserved	Thylakoid-linked presence
Basal Group I	Conserved	Conserved in basal clades	Early ancestral loss
Basal Group II	Conserved	Conserved in basal clades	Early ancestral loss

Tables 1 & 2. Comparative evolutionary distribution of DedA and prohibitin families indicates molecular basis of thylakoid acquisition.

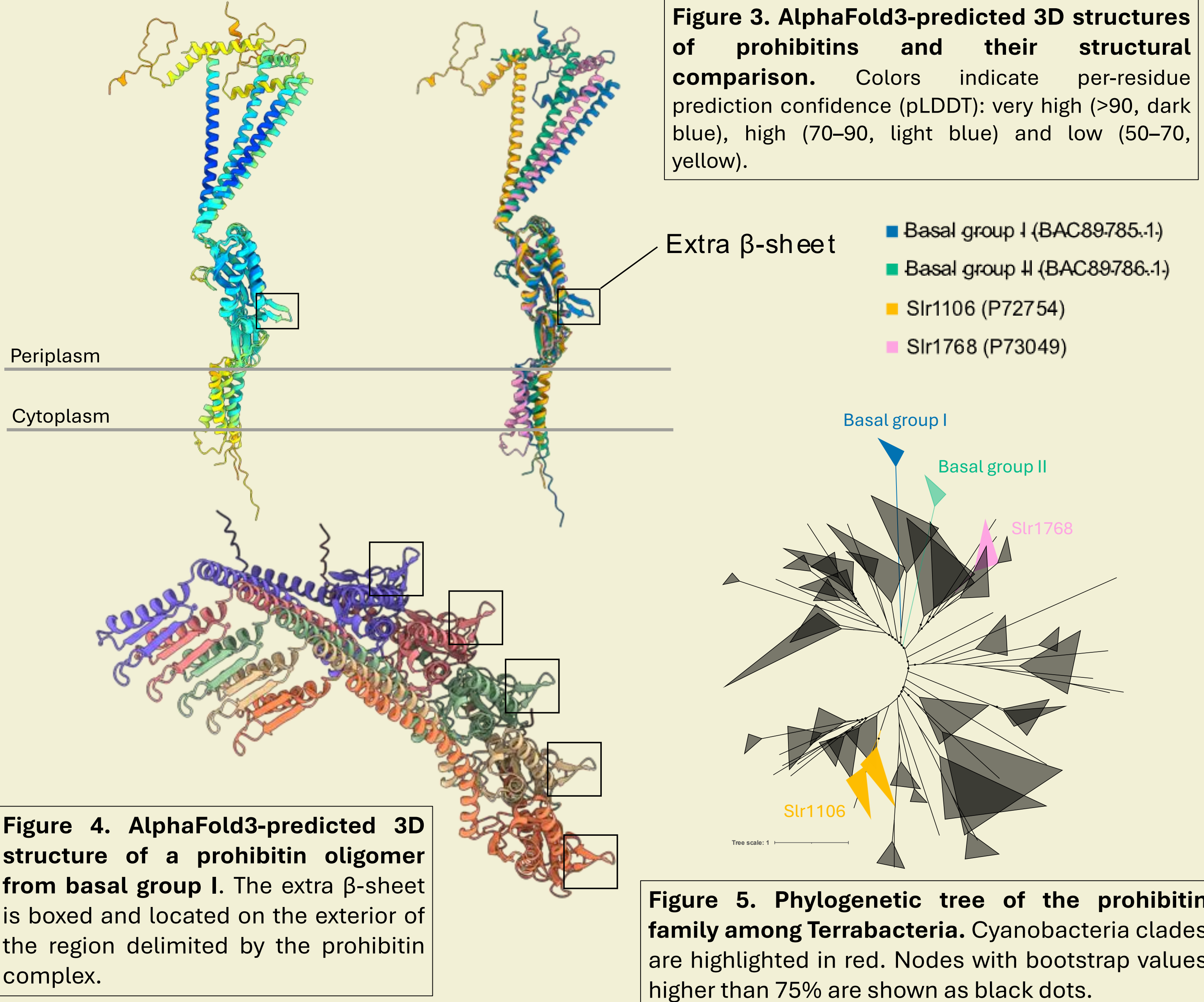


Figure 3. AlphaFold3-predicted 3D structures of prohibitins and their structural comparison. Colors indicate per-residue prediction confidence (pLDDT): very high (>90, dark blue), high (70–90, light blue) and low (50–70, yellow).

Figure 4. AlphaFold3-predicted 3D structure of a prohibitin oligomer from basal group I. The extra β -sheet is boxed and located on the exterior of the region delimited by the prohibitin complex.

Figure 5. Phylogenetic tree of the prohibitin family among Terrabacteria. Cyanobacteria clades are highlighted in red. Nodes with bootstrap values higher than 75% are shown as black dots.

Conclusion

- Our phylogenomic analysis reveals specific **divergences in the periplasmic domains of YidC (Fig. 2)** that coincide with the emergence of thylakoids.
- Evolutionary patterns** of DedA and prohibitin families (Tables 1 & 2), together with specific prohibitin groups in basal cyanobacteria (Figs. 3–5), suggest that the **transition** from *Gloeobacter*-like ancestors to thylakoid-bearing Cyanobacteria involved the emergence of **specialized membrane domains**, potentially precursors of thylakoid membranes via **vesiculation (Fig. 2)**.

Open Questions

- What is the specific function of the **periplasmic domains** of YidC (Fig. 2) in coordinating membrane protein insertion within Cyanobacteria?
- Do **SPFH and DedA proteins** act as "scaffolds" to stabilize **photosynthetic active domains** in *Gloeobacterales* (which lack thylakoids) (Tables 1 & 2)?
- Could the **specialization** of the DedA and prohibitin families be the missing link that allowed the **relocation** from the **plasma membrane** to **thylakoids**?

Selected References

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- Research:** Evolutionary genomics of thylakoid membranes in cyanobacteria
- Focus:** Thylakoid biogenesis, protein insertion and targeting, and assembly of the photosynthetic electron transport chain
- Goal:** Understanding how membrane organization (e.g. lipid domains) contributed to the emergence of thylakoid membranes

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