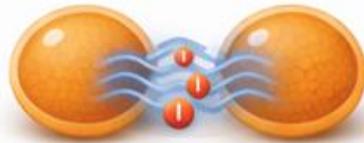


# Quantum Field-induced Proton $H^+$ Gradients in Prebiotic Protocell Clusters

Casimir-Lifshitz Attraction & Dynamic Matsubara Modes Lowered Vacuum Energy



Quantum Fluctuations

$H^+$  Enrichment

Dimers: 1-D Proton Channel

Linear Proton Flow



$H^+$  Transport

Proton Trap • Directed Flux

Tetrahedron: 3-D Proton Tunnel

Triangular Proton Flow



$H^+$  Concentration

Proton Funnel • Reaction Hub

Prebiotic Proton Gradients

Geometry & Quantum Fluctuations Create Energetic Reservoirs



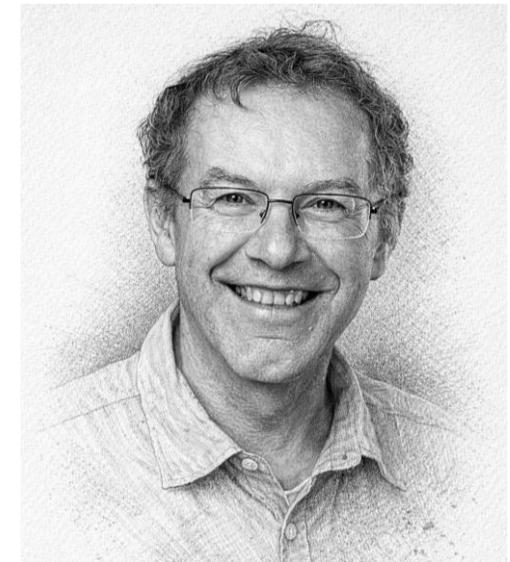
Local pH Centers



No Biological Pumps



Early Proto-Metabolic Activity



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BIOTECHNO-2026 | Valencia

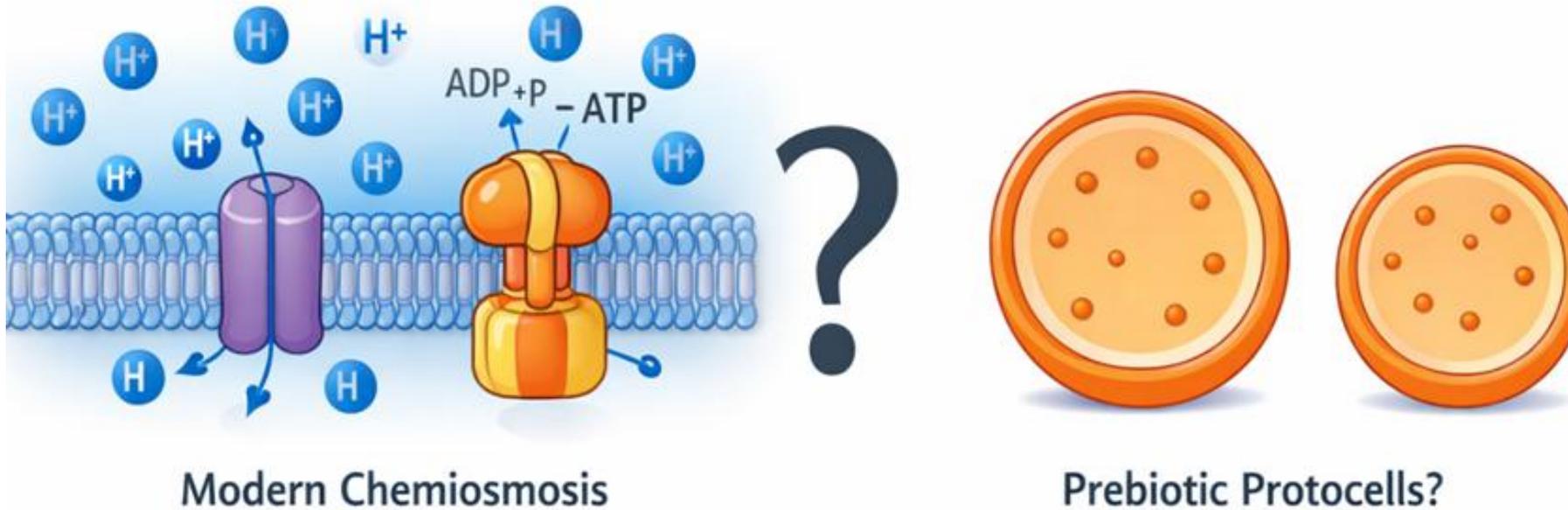
# Emergence path

A **Constructivist Proto-Bio-Information Theory**: *A Physically Grounded Nano-Systems Architecture for Prebiotic Emergence, Information, Proto-Semantic Function, and Sustainability of Protocell Aggregation and Cluster Formation*



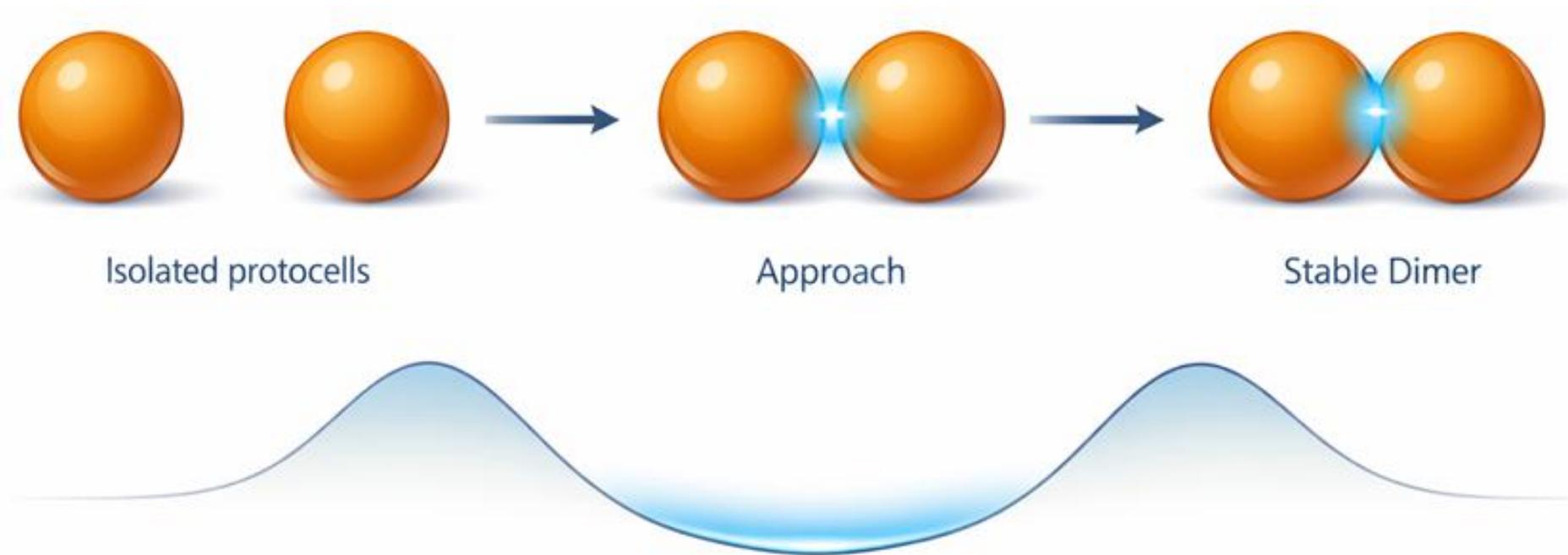
- **Papers 1–2:** CL coupling stabilizes dimers/tetrahedra (persistent geometries).
- **Papers 3–4:** those geometries define informational/meaning layers via tasks and  $\epsilon$ -machines.
- **Paper 5:** same geometries generate **energetic reservoirs: proton gradients** without pumps.

# The Origin-of-Life **Energy Problem**:



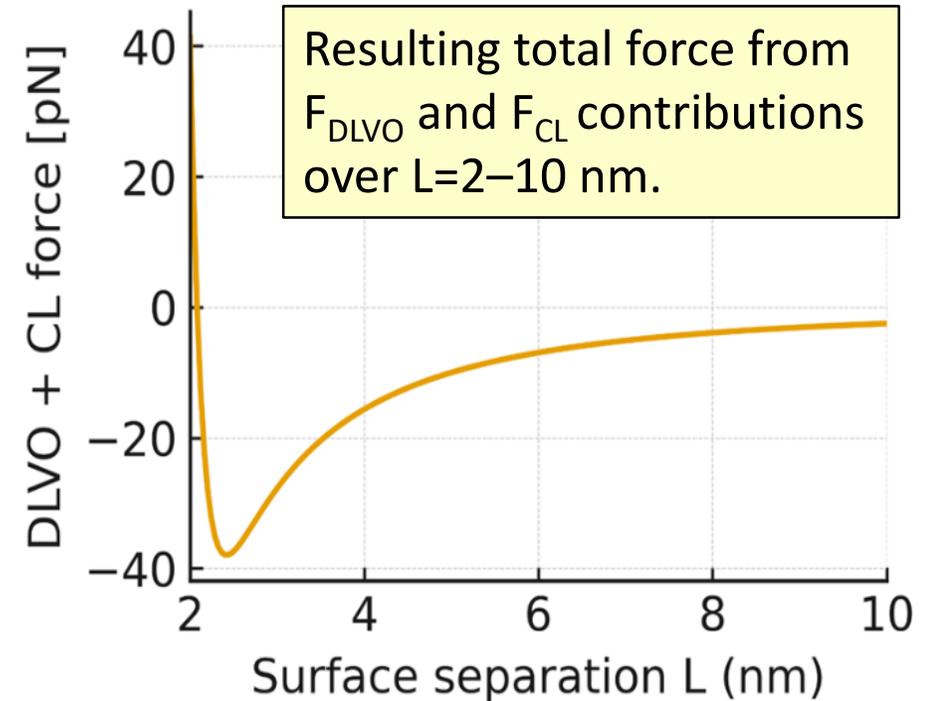
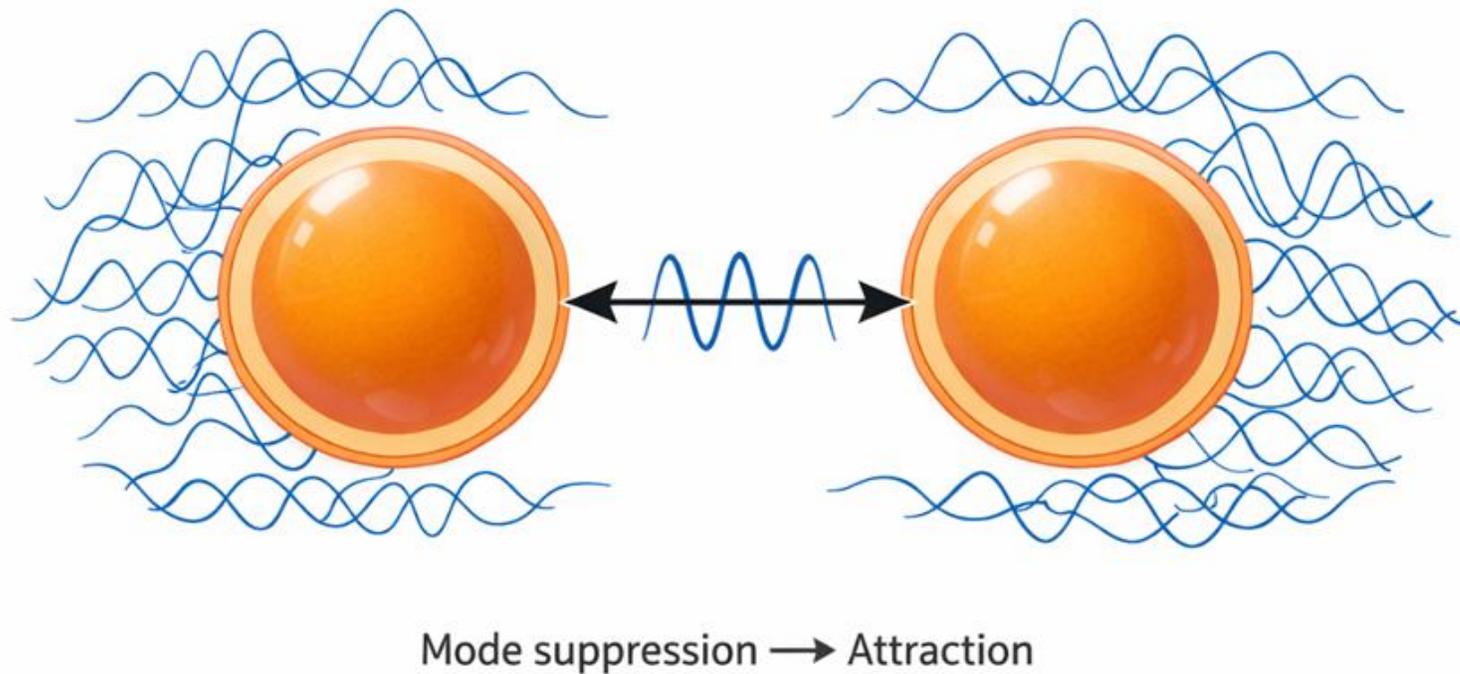
- **Life** universally uses **ion gradients** (especially **H<sup>+</sup>**) to do work.
- But before pumps/enzymes: where could the first **localized proton gradients** come from?
- **Hypothesis**: nanoscale protocell cluster gaps act as **quantum-geometric proton reservoirs**.

# Geometry: protocell dimer gap as a nanoscale cavity



- Two spheres with radii  $R_1$ ,  $R_2$  separated by gap  $L$  in saline water.
- Critical regime:  $L \approx 2\text{--}50$  nm (strong confinement, CL-stable).
- This gap is the '**cavity**' that shapes field modes and proton distributions.

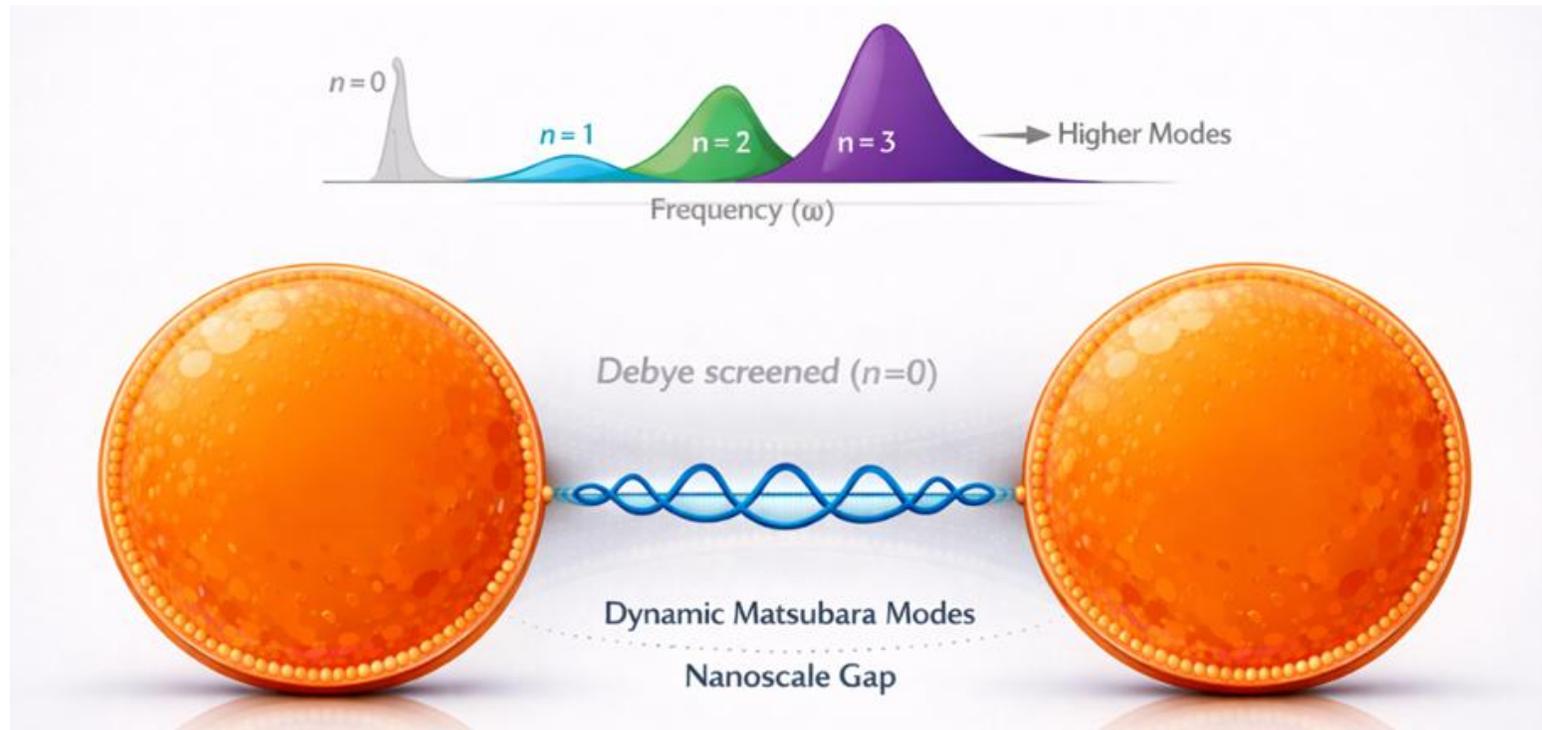
# The Casimir–Lifshitz Attraction Concept:



**Prerequisite: Protocell cluster must be mechanically stable**

- CL force scaling (PFA):  $F_{CL}(L) \approx -(A_{eff}/6) \cdot (R_{eff}/L^2)$ .
- Algebraic range enables long-lived dimers/tetrahedra in saline media.
- Those stable gaps allow time for proton equilibration into resonance minima.

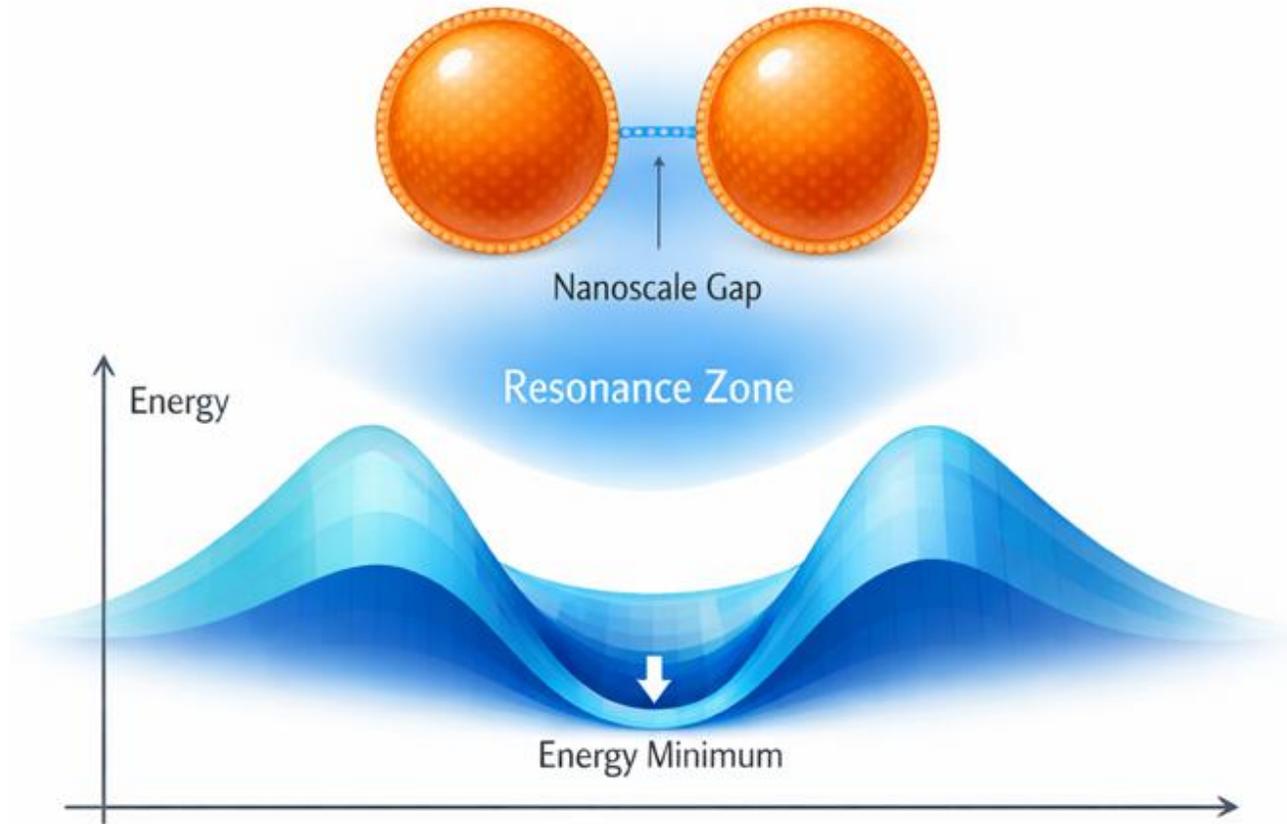
# Dynamic Matsubara Mode Selection in the Gap L



- Only  $n \geq 1$  modes contribute effectively in saline gaps.
- Matsubara frequencies:  $\xi_n = 2\pi n kBT / \hbar$ .
- Mode density  $f_n(z)$  varies with geometry  $\rightarrow$  spatially varying field energy.

- In electrolyte: **Debye screening** suppresses quasi-static fields.
- **Static Matsubara mode ( $n=0$ )** is effectively removed for  $L \gg \lambda_D$  ( $\sim 1-2$  nm).
- Remaining dynamic modes ( $n \geq 1$ ) create geometry-dependent mode suppression  $\rightarrow$  **lowered vacuum energy zones.**

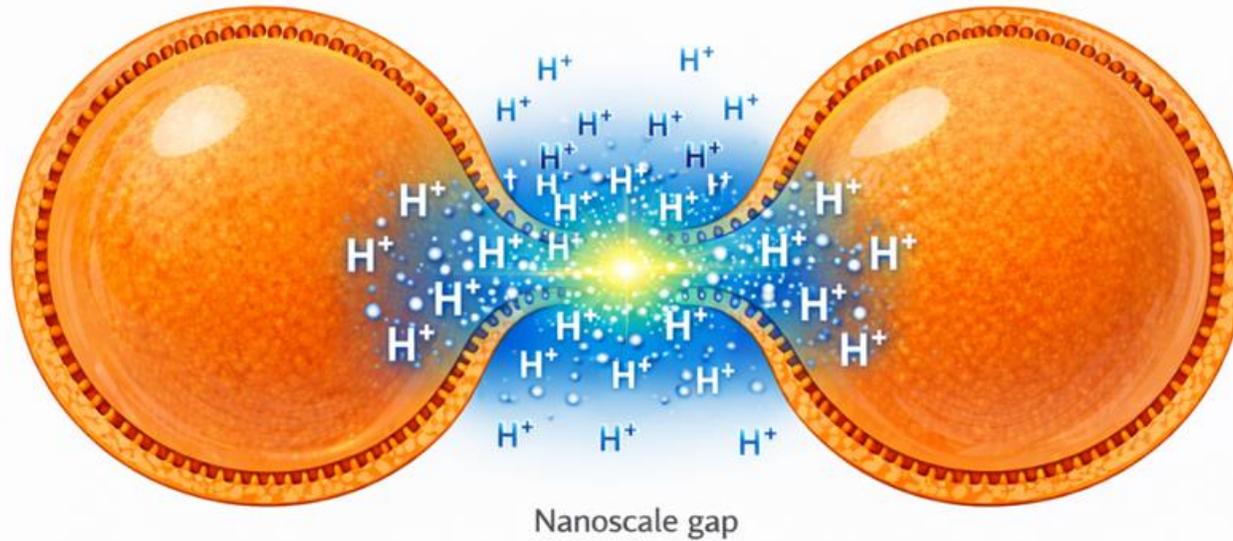
# Vacuum Energy Resonance Zone:



## Why hydrated protons accumulate:

- **Hydrated protons** are highly polarizable clusters in water.
- They couple to the modified electromagnetic mode density in the gap.
- **Casimir–Polder coupling** creates an **effective potential  $U_{CP}(z)$**  with **minima in resonance zones**.

# Proton Accumulation Mechanism:



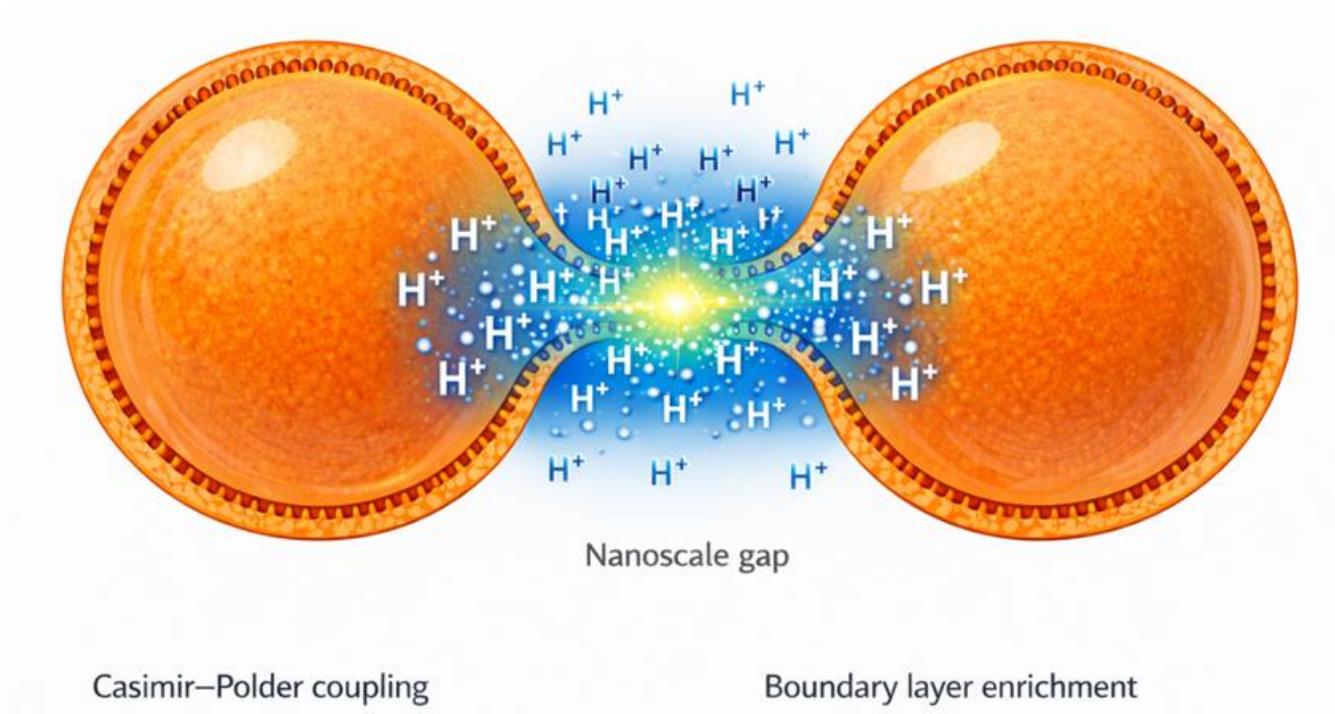
Casimir-Polder coupling

Boundary layer enrichment

Casimir-Polder potential  $\rightarrow$   
exponential enrichment in gap:

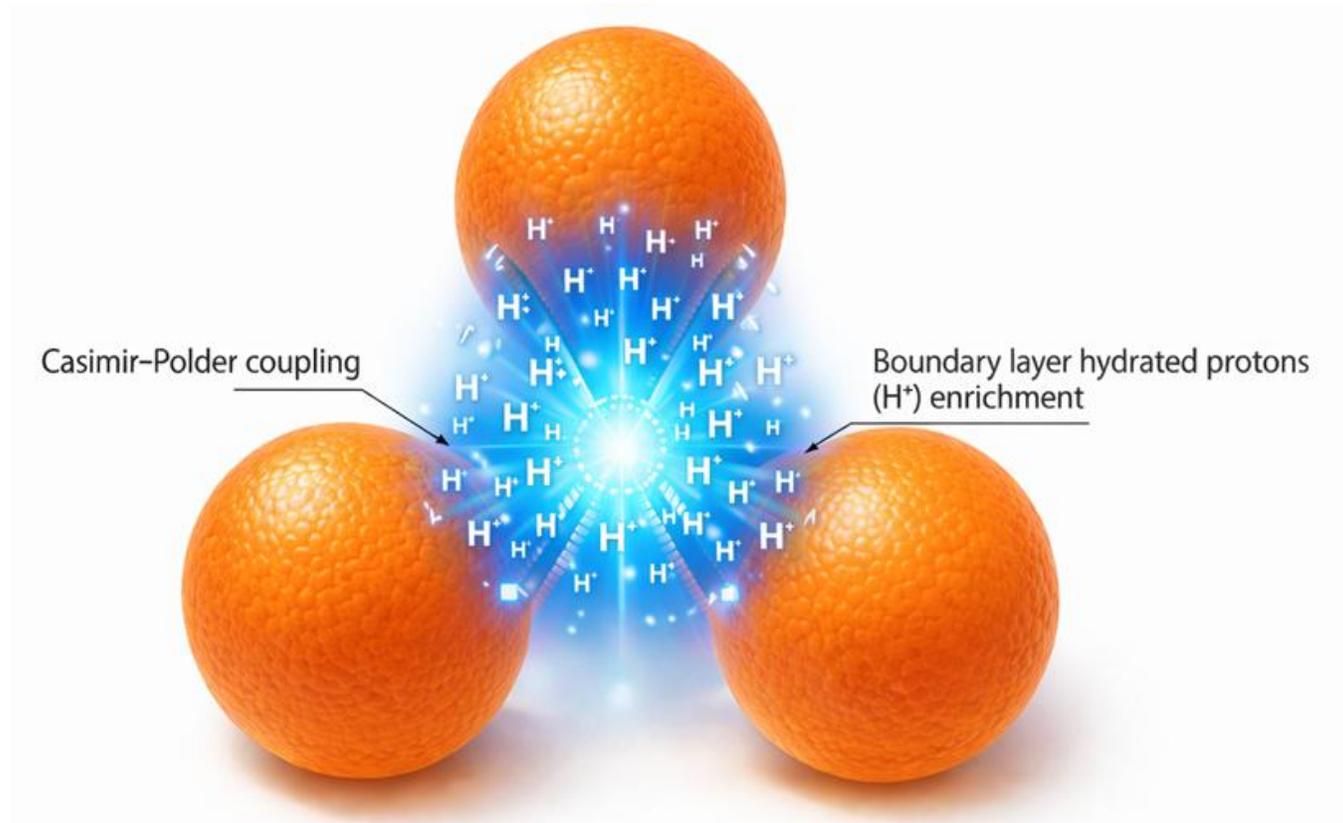
- Effective potential:  $U_{CP}(z) \sim (1/2) kBT \sum_{n \geq 1} \alpha(i\xi_n) f_n(z)$ .
- Proton distribution:  $P(z) \propto \exp[-U_{CP}(z)/kBT]$ .
- Even  $\Delta U$  of a few kBT gives orders-of-magnitude enrichment.

# Dimer: **one-dimensional proton channel** (nanoslit)



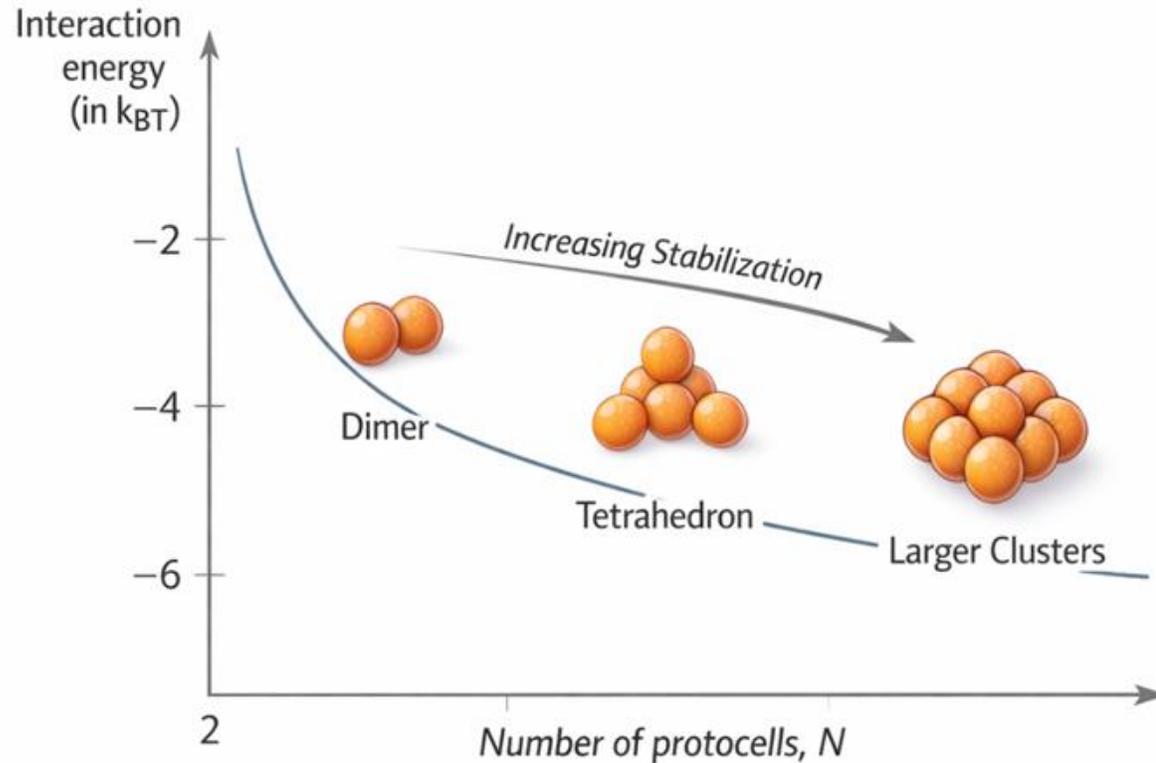
- Gap acts as a **nanoslit cavity** with a midline resonance minimum.
- Protons accumulate along the symmetry axis → a **proto-proton channel** without proteins.
- **Function:** directed H<sup>+</sup> guidance and local pH shift in the intermembrane region.

# Tetrahedral Protocell Cluster: **3D proton hub (funnel)**



- Four interfaces confine modes more strongly than a dimer.
- Multiple scattering produces a deep central resonance well.
- **Result: a 3D proton hub (funnel)** — a proto-chemiosmotic reservoir, mainly on the surfaces of the membranes.

# Energy Scaling of Cluster Stability:

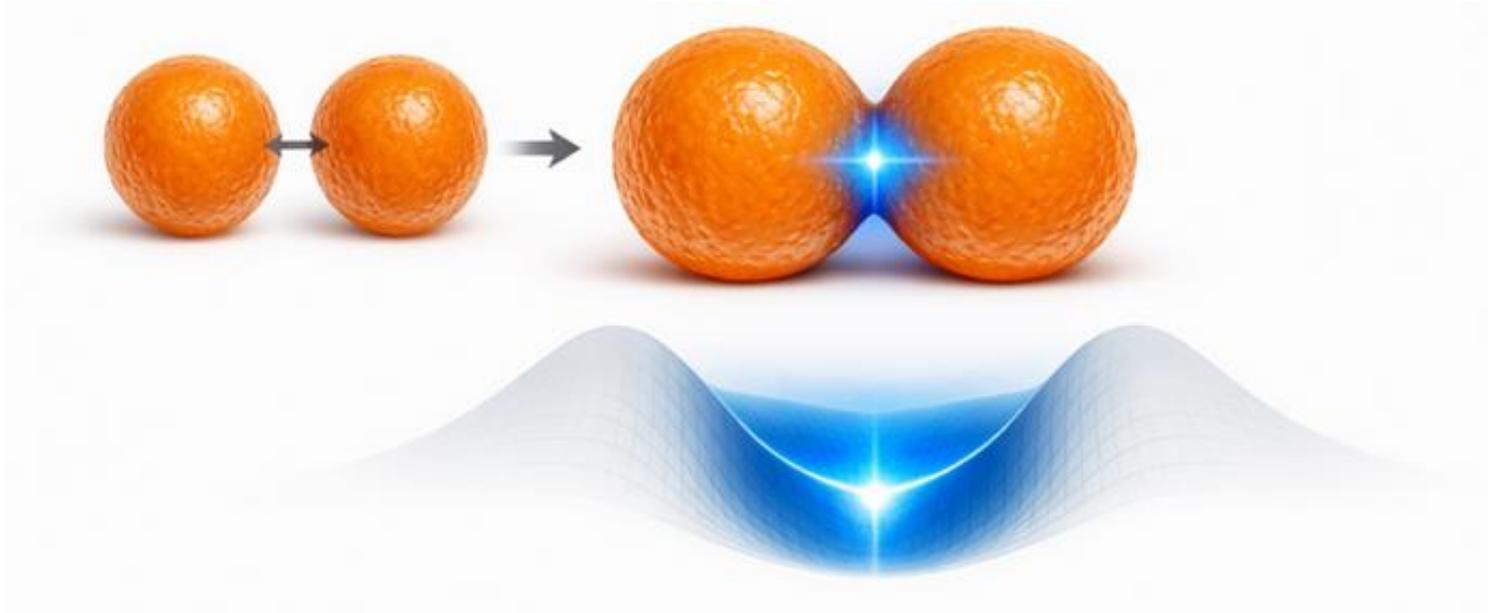


$N$	<u>Protocell Structure</u>	$N_{\text{bonds}}$	$E_N/k_B T \approx$
2	Dimer	1	-5.1
3	<u>Triangularer Trimer</u>	3	-15.2
4	<u>Tetrahedron</u>	6	-30.5
6	<u>Oktahedron</u>	12	-61.0
7	<u>Pentagonal Bipyramid</u>	15	-76.2
13	<u>Icosahedral 13-Cluster</u>	42	-213.4

## Why tetrahedra matter: Bonds amplify persistence

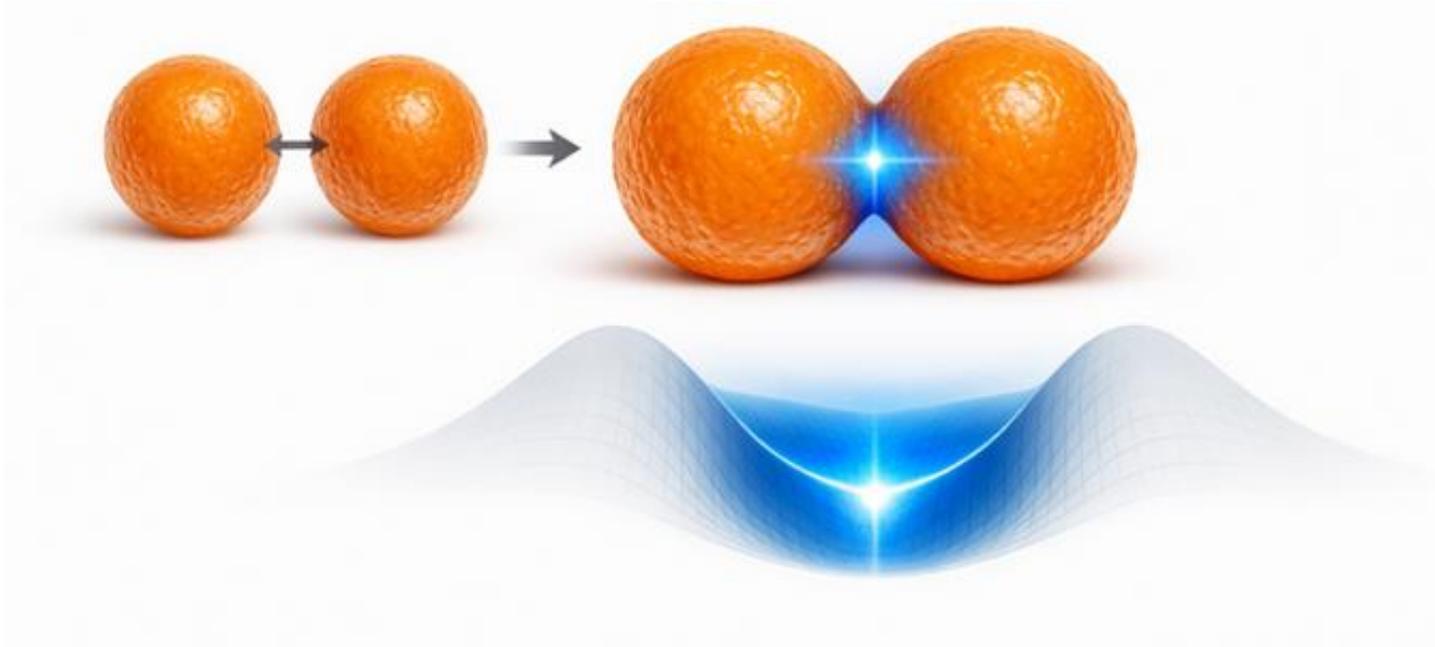
- More bonds  $\rightarrow$  longer-lived geometry  $\rightarrow$  **more persistent resonance zones.**
- Energetic reservoirs are therefore strongest in highly stable cluster motifs.

# Order-of-magnitude: $\Delta U \rightarrow$ proton enrichment $\rightarrow \Delta pH$



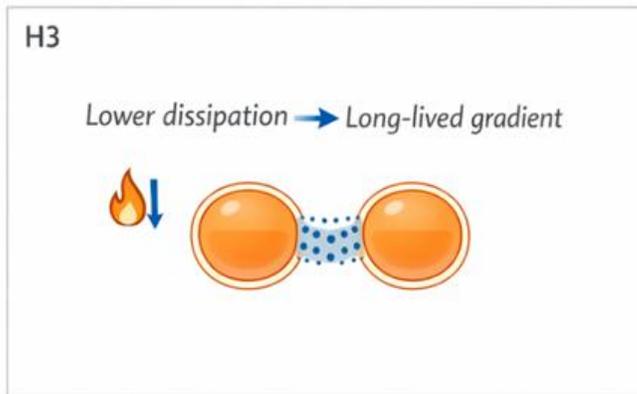
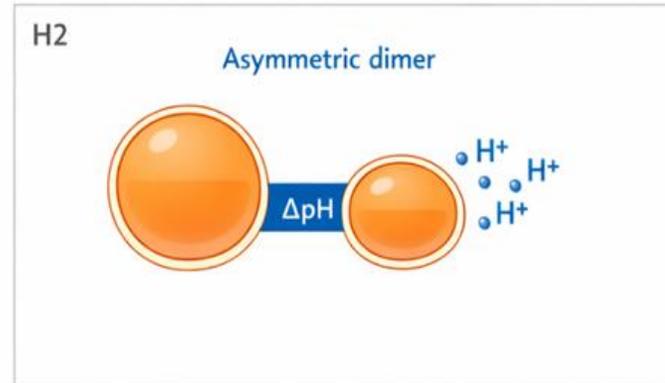
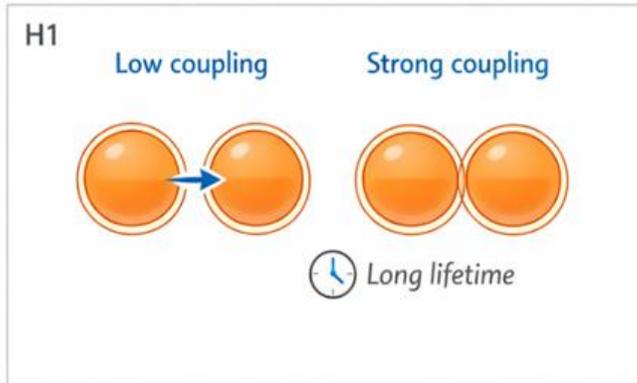
- **Expected well depths:** dimers  $\Delta U \sim 1\text{--}5$  kBT; tetrahedra  $\Delta U \sim 3\text{--}8$  kBT (geometry-dependent).
- **Enrichment:**  $P_{\text{local}}/P_{\text{bulk}} \approx \exp(\Delta U/kBT) \rightarrow \sim 10^0\text{--}10^2$  (dimer) and  $\sim 10^1\text{--}10^3$  (tetra).
- **Implied local shifts:**  $\Delta pH \sim 0.5\text{--}2$  (dimer) and  $\sim 1\text{--}3$  (tetra) in favorable gaps.

# $\Delta U \rightarrow$ proton enrichment $\rightarrow \Delta pH \rightarrow$ Implications



- **H<sup>+</sup> reservoirs** can act as stable analog 'state variables' in cluster dynamics.
- They couple **energy + geometry**: a functional signal embedded in physical structure.
- This supports earlier layers: semantics/pragmatics can be anchored to measurable energetic differences.

# Experimental Roadmap H1–H4:

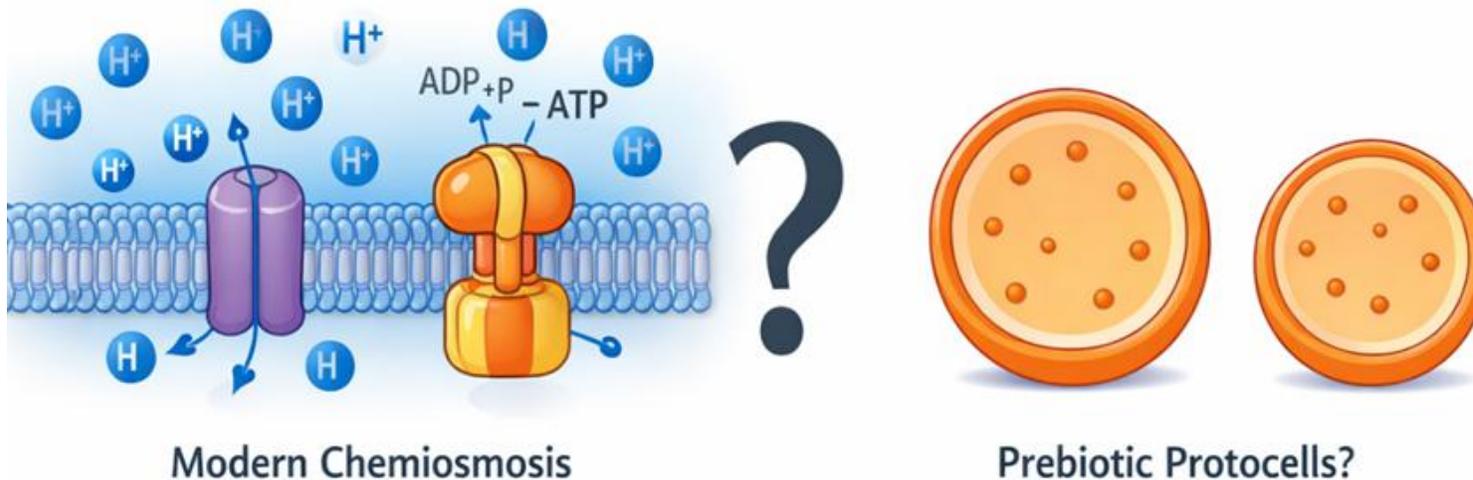


## How to test this (experimentally):

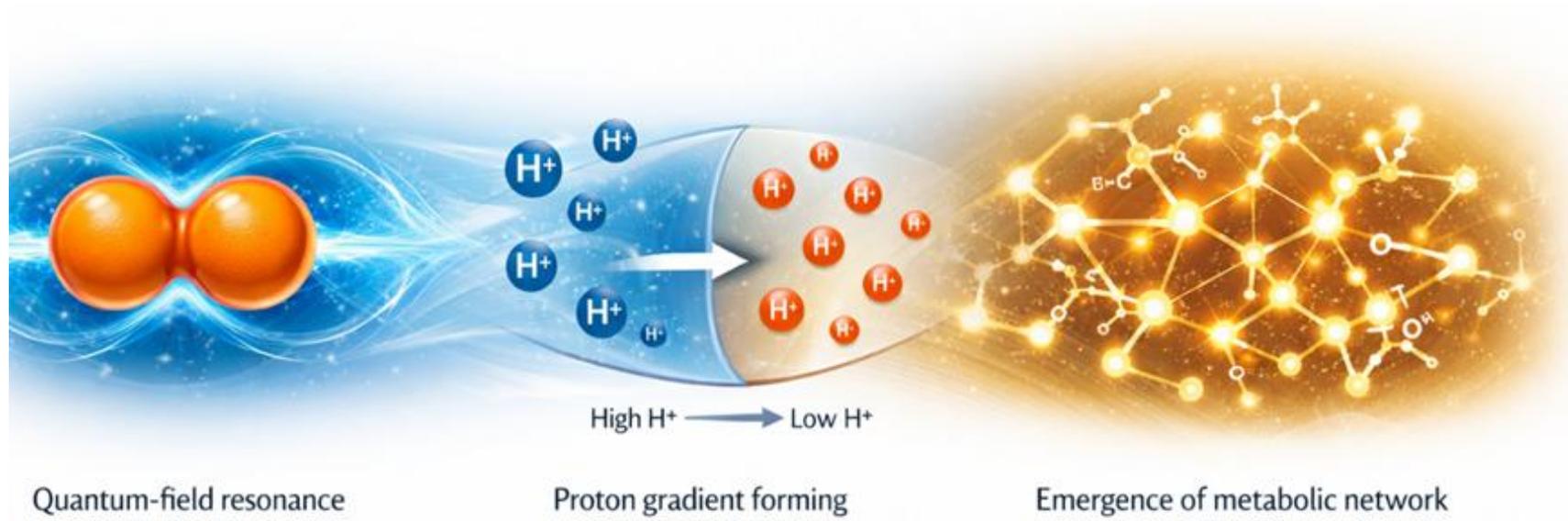
- Create controlled dimers/tetrahedra in microfluidics ( $L \approx 2\text{--}50\text{ nm}$ ).
- Measure pH/proton profiles with nanosensors or fluorescence reporters.
- Use THz/IR spectroscopy as a proxy for mode selection in confined gaps.
- Compare against controls where gaps/geometry are disrupted.

# Clarifications and Limitations: What this mechanism is (and isn't)

- Not full transmembrane chemiosmosis (no ATP synthase).
- It is a **local, geometry-bound reservoir** that can bias reactions and coupling.
- A **plausible physical precursor** — a **scaffold/functional pattern** on which biological pumps could later evolve.



# Bridge: From **Physics** and **Proton Gradients** to **Sustainability** & **Proto-Liveliness**:



- **Paper 6:** how clusters maintain structure + energy + information over time (sustainability).
- **Paper 7:** quantify proto-liveliness in S–E–I space and define a life–death threshold.
- **$H^+$  reservoirs** are the **energetic axis** that enables S–E–I feedback loops.

# Take-Home Message:

## Prebiotic Proton Gradients

Geometry & Quantum Fluctuations Create Energetic Reservoirs



Local pH Centers



No Biological Pumps

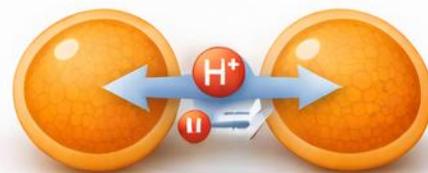


Early Proto-Metabolic Activity

- In saline media, static fields are screened; dynamic Matsubara modes remain and are geometry-sensitive.
- Mode suppression in nanoscale gaps creates resonance minima of vacuum energy.
- Hydrated protons accumulate via Casimir–Polder coupling → exponential enrichment.
- Dimers form 1D proton channels; tetrahedra form 3D proton funnels/reservoirs.
- These reservoirs are plausible physical precursors to chemiosmotic gradients and early energetic coupling.

### Dimers: 1-D Proton Channel

Linear Proton Flow

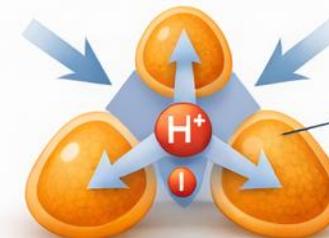


H<sup>+</sup> Transport

Proton Trap • Directed Flux

### Tetrahedron: 3-D Proton Tunnel

Triangular Proton Flow

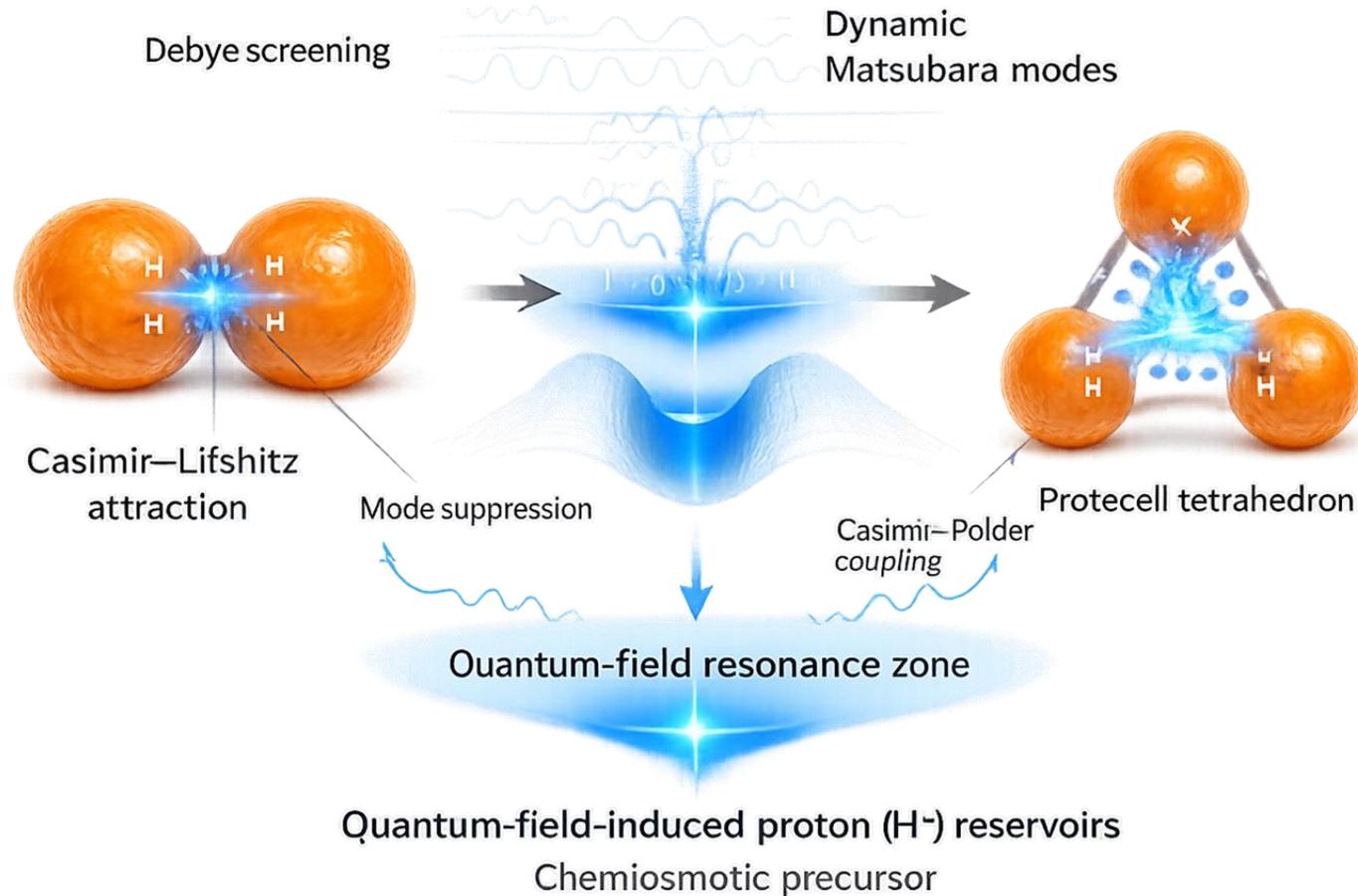


H<sup>+</sup> Concentration

Proton Funnel • Reaction Hub

# Thank you very much for your attention.

## Are there any questions?



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