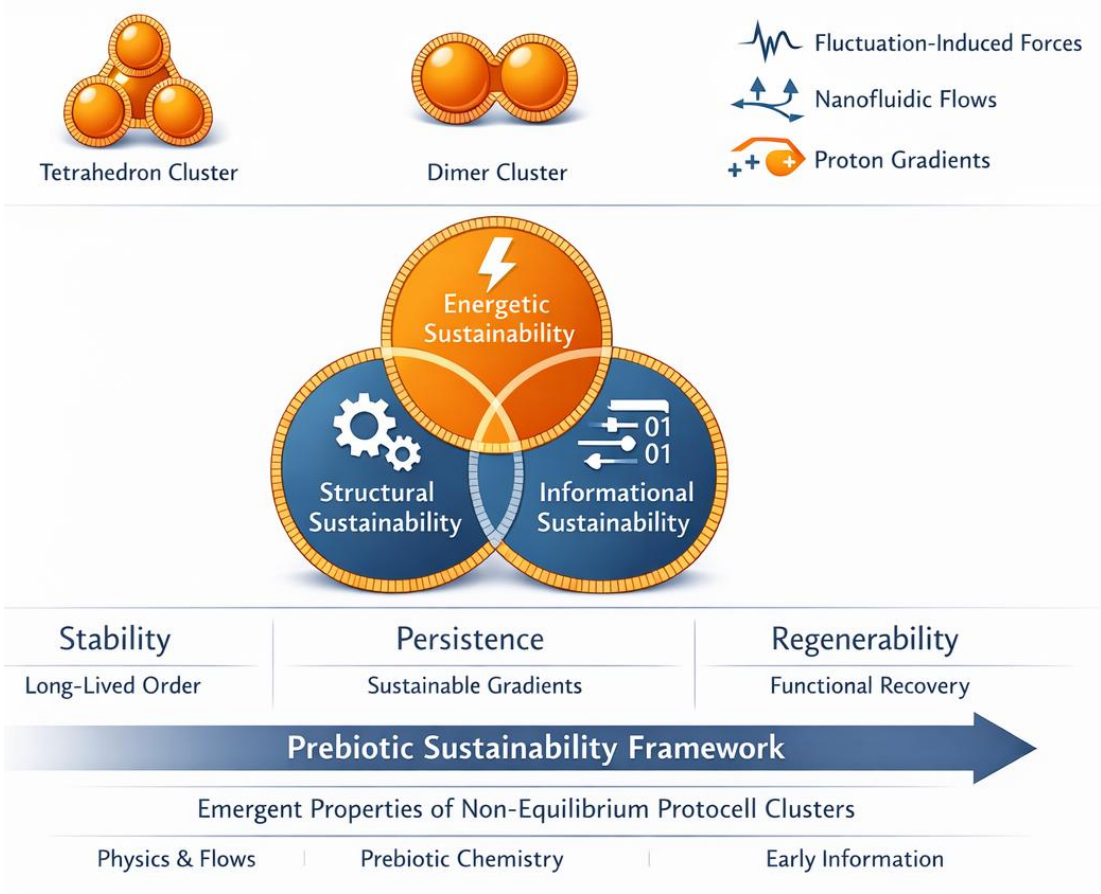
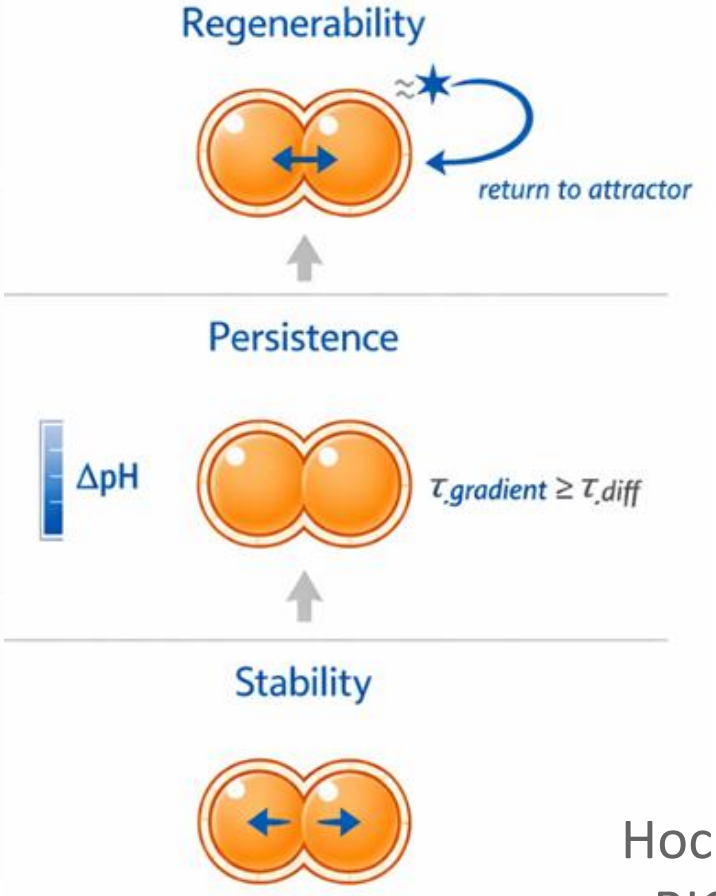
Prebiotic Sustainability in the Nanoworld: A Physical Framework for Early Protocell Cluster Stability





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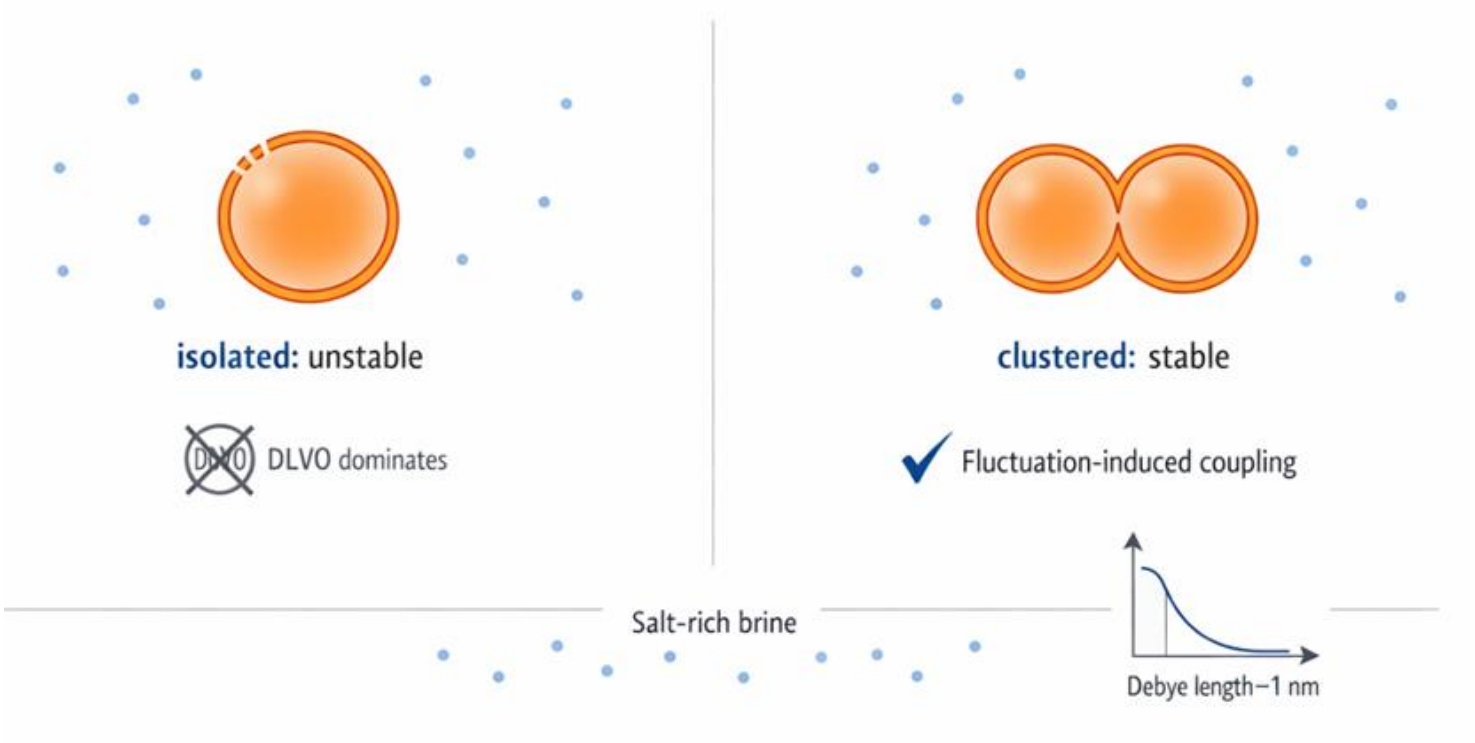
The Problem: Why Protocells Don’t Fall Apart in Brines



Prebiotic Sustainability in the Nanoworld

Identity-under-change in **open dissipative systems**:

- Entropy production continues (**$\sigma(t) > 0$**)
- Structural & functional identity remains within tolerance **δ**

Operational Metric:

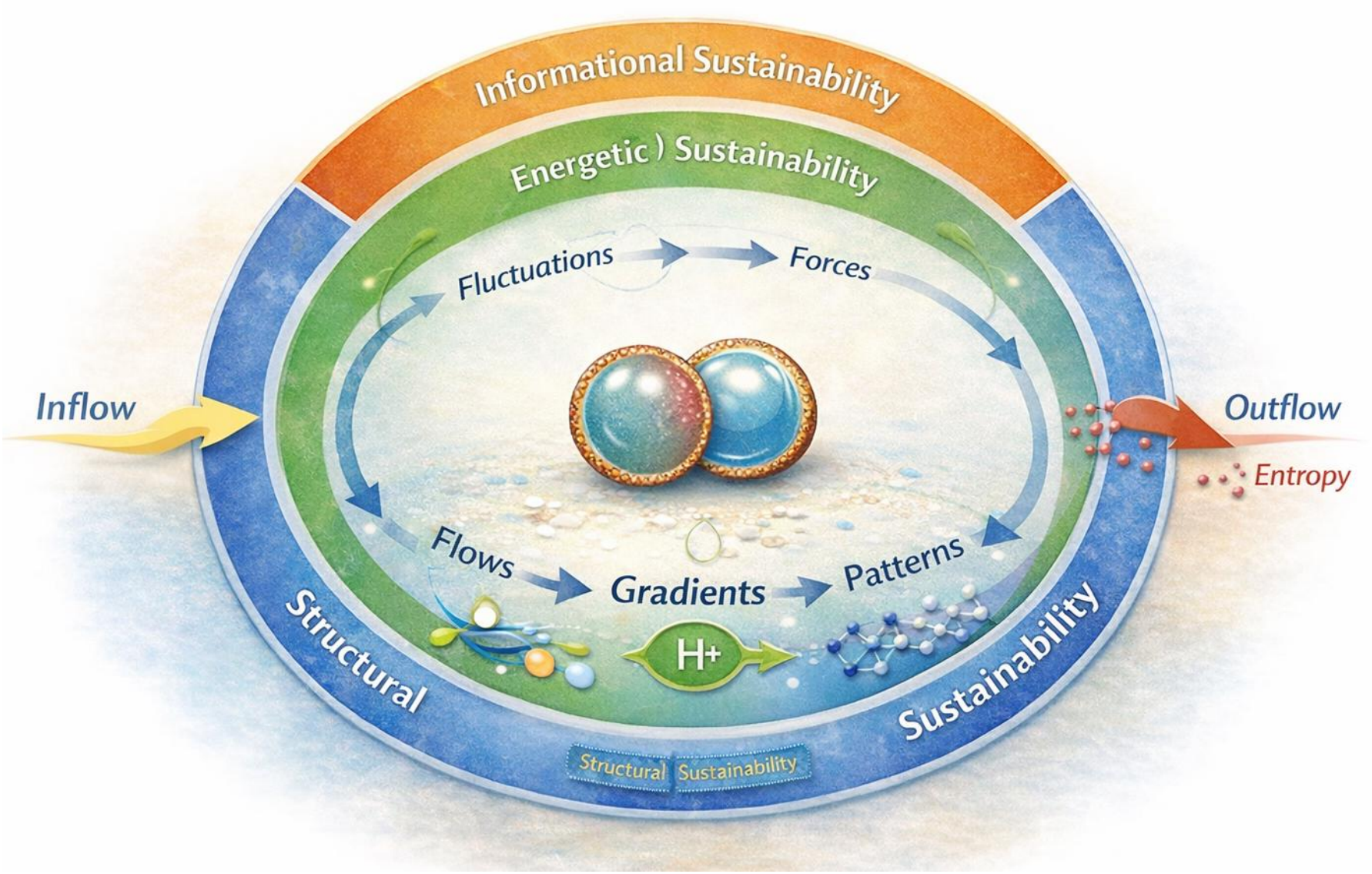
- Order parameters $\theta(t)$: geometry, gradients, recurrence
- Normalized drift $D(t,\Delta t)$ measures identity change
- Sustainable if: $\sigma(t) > 0$ and $D(t,\Delta t) < \delta$

Prebiotic Sustainability in the Nanoworld: Core Claim

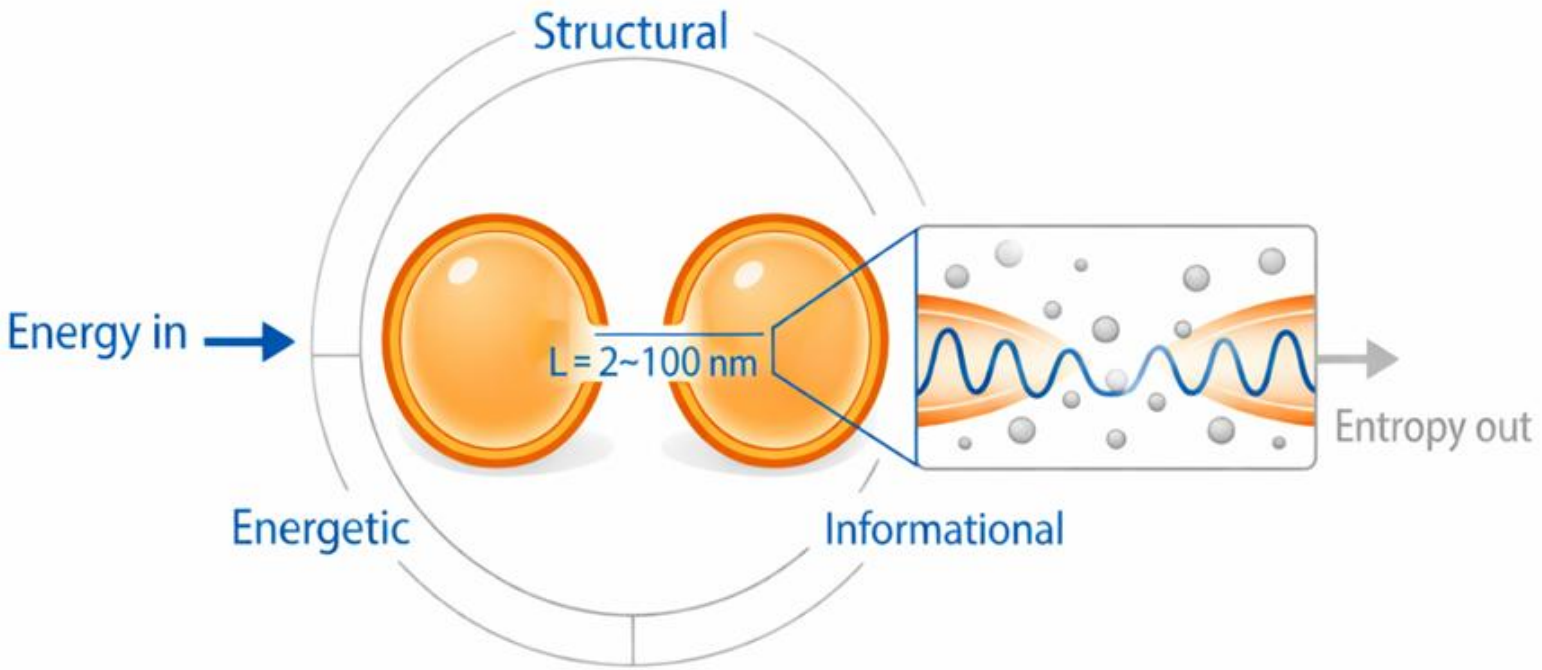
Sustainability emerges **in open non-equilibrium nanophysics**:

- Coupled pipeline: fluctuations → forces → flows → gradients → regeneration
- No genes or enzymes required

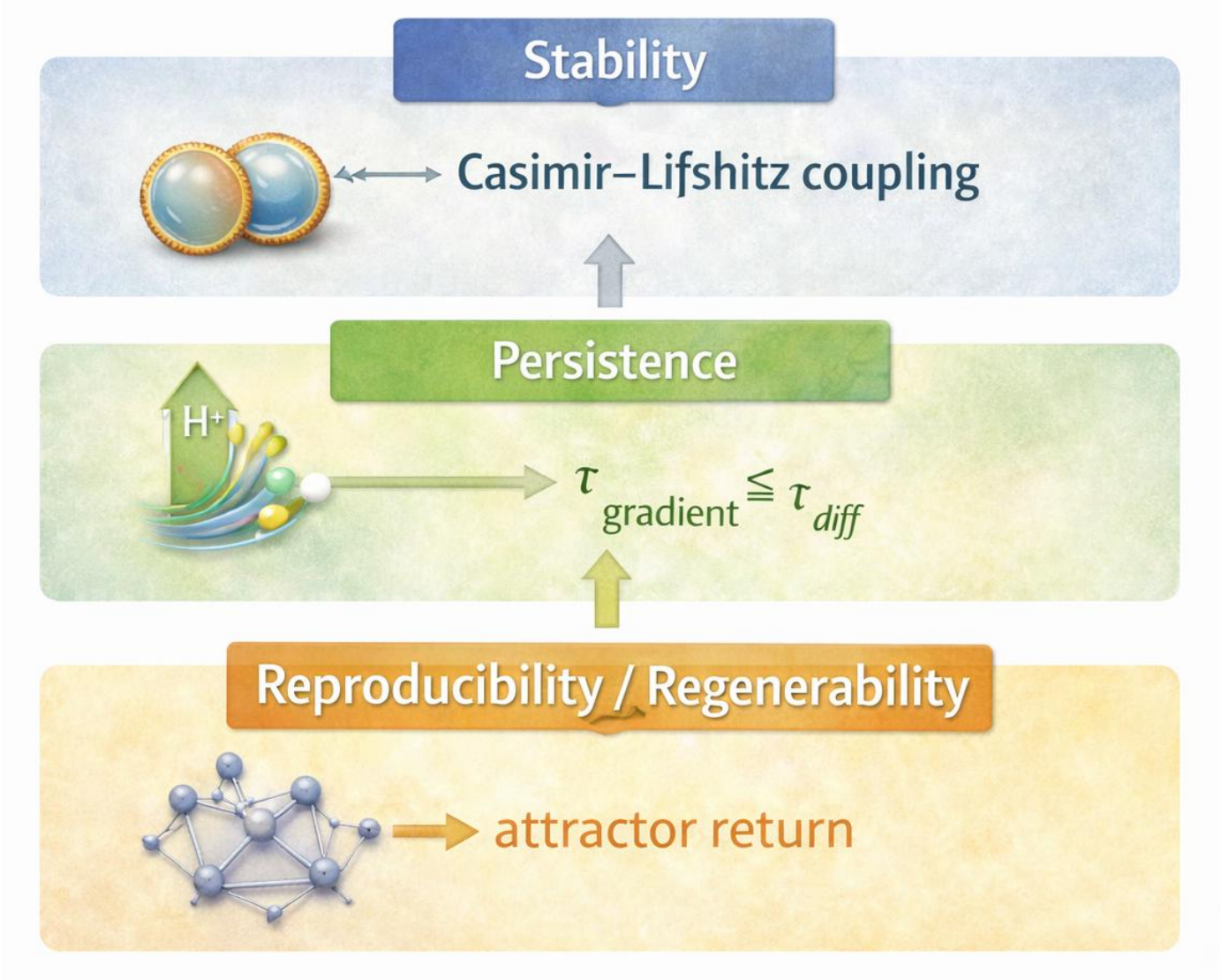
The Concept of Prebiotic Sustainability



Prebiotic Sustainability in the Nanoworld



Three-Level Sustainability Framework



Three-Dimensions Sustainability Framework (S-E-I)

Structural sustainability (S)

- membrane integrity
- cluster connectivity
- stable distances & contact graphs

Metrics: lifetime, breakup rate, $\langle k \rangle$, $\langle L\_nn \rangle$

Energetic sustainability (E)

- persistence of ion/proton gradients
- $\tau\_gradient \geq \tau\_diff$ as criterion
- ΔpH pockets as usable energy

Metrics: ΔpH, $\tau\_gradient$, heat proxy

Informational sustainability (I)

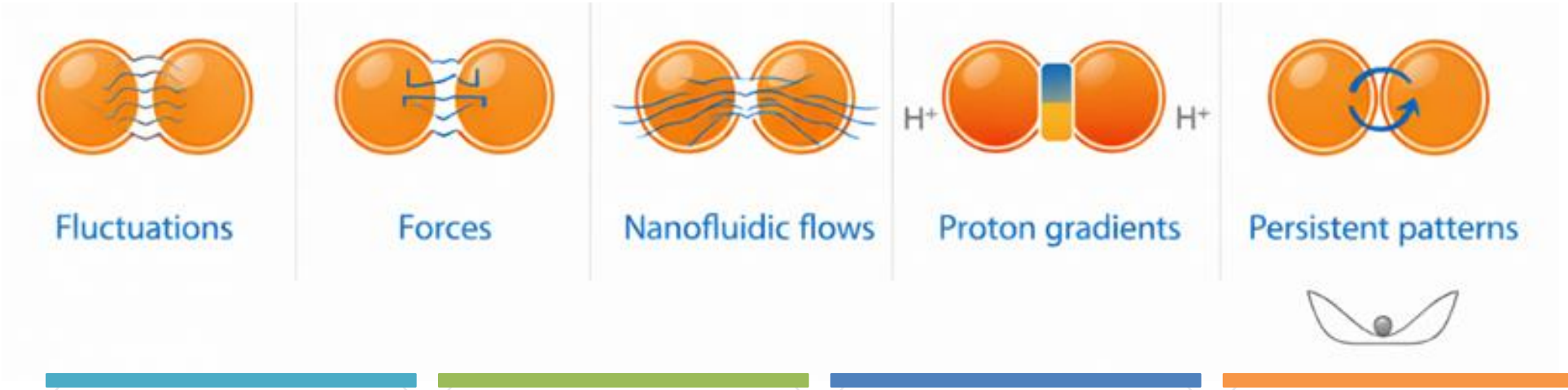
- recurrence of macrostates
- attractor return dynamics
- ε-machine stability of transitions

Metrics: P_return, T_return

Mapping of Prebiotic Sustainability Levels to Reliability Engineering Concepts

Prebiotic Sustainability Level	Reliability Engineering Analogon	Representative Measurement / Metric
Stability	Low hazard rate / high Mean Time To Failure (MTTF)	Cluster break-up rate; mean lifetime of dimer or cluster structures
Persistence	State retention time / operational availability	Ratio τgradient / τdiff; duration of stable ion or proton gradients
Regenerability	Mean Time To Recovery (MTTR) / recoverability	Reassembly time after perturbation; return probability to functional attractor state

Physical Pipeline: Fluctuations → Forces → Flows → Gradients → Patterns/Return dynamics



1. Confined fluctuations

EM mode filtering in nanoscale gaps

2. Coupling forces

Casimir–Lifshitz attraction ($\propto R_{eff}/L^2$)

3. Nanofluidic flows

Water expulsion + micro-advection

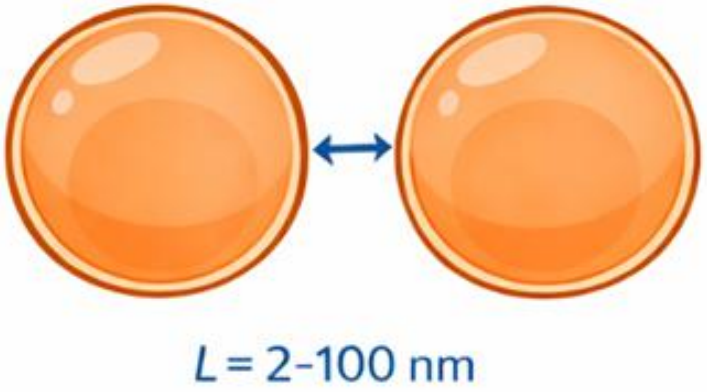
4. Proton gradients

CP potential wells → ΔpH pockets

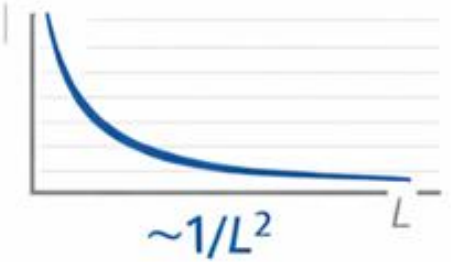
5. Return dynamics

Attractor-like recovery to functional states

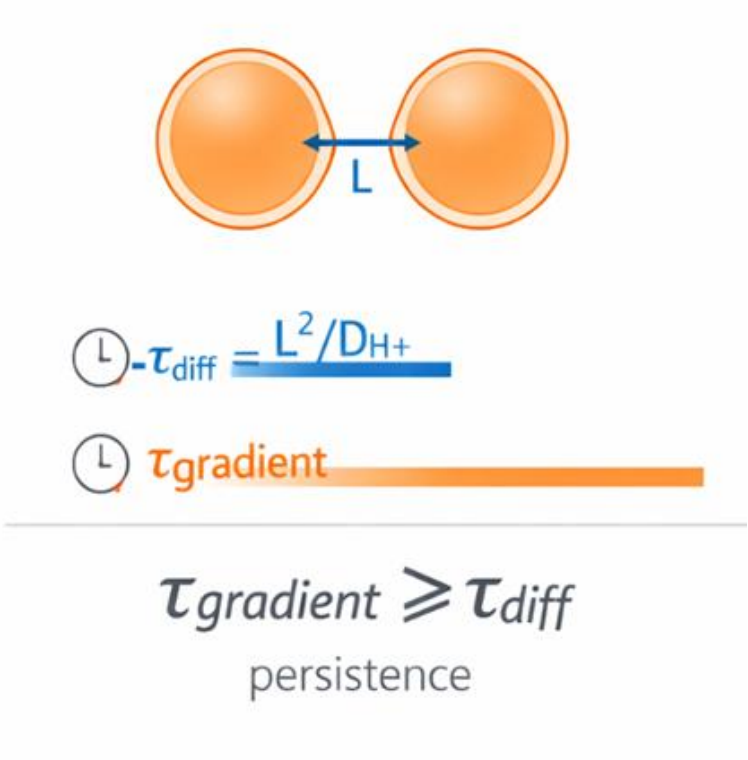
Casimir–Lifshitz Coupling in the L=2–100 nm Gap



$$F_{CL}(L) = -\frac{A_{eff}}{6} \cdot \frac{R_{eff}}{L^2}$$



Proton Gradient Persistence: $\tau_{gradient}$ vs τ_{diff}

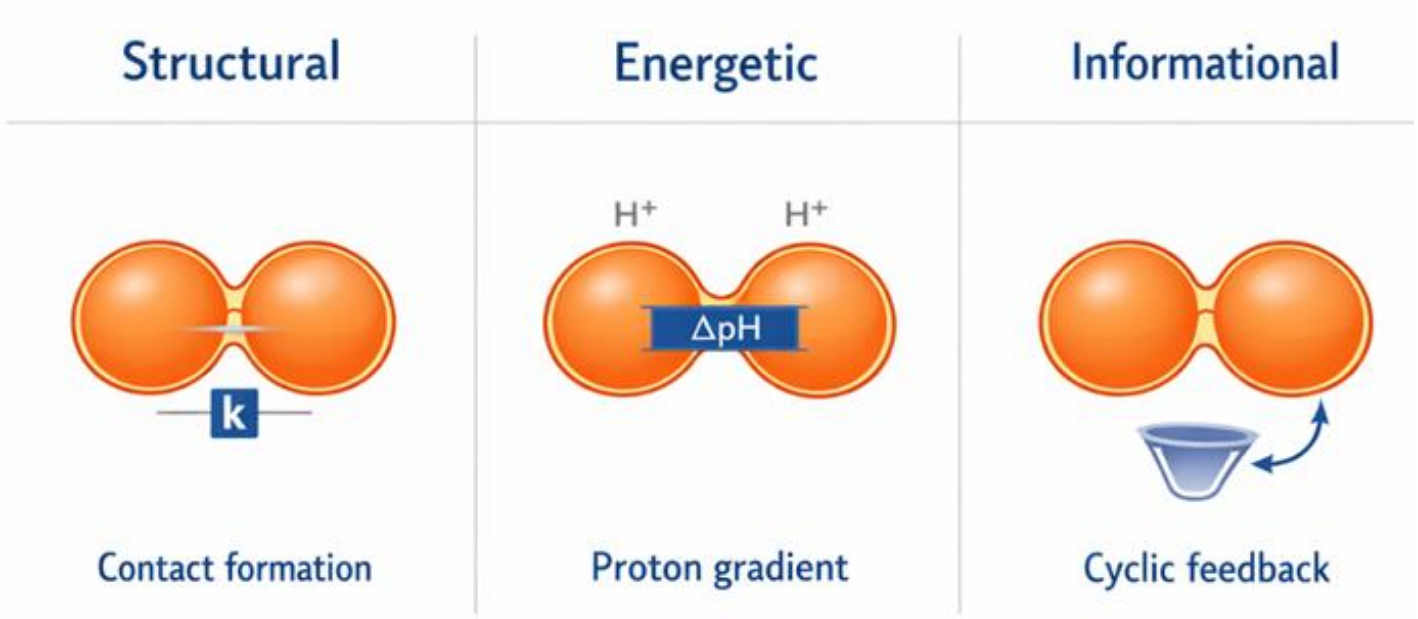


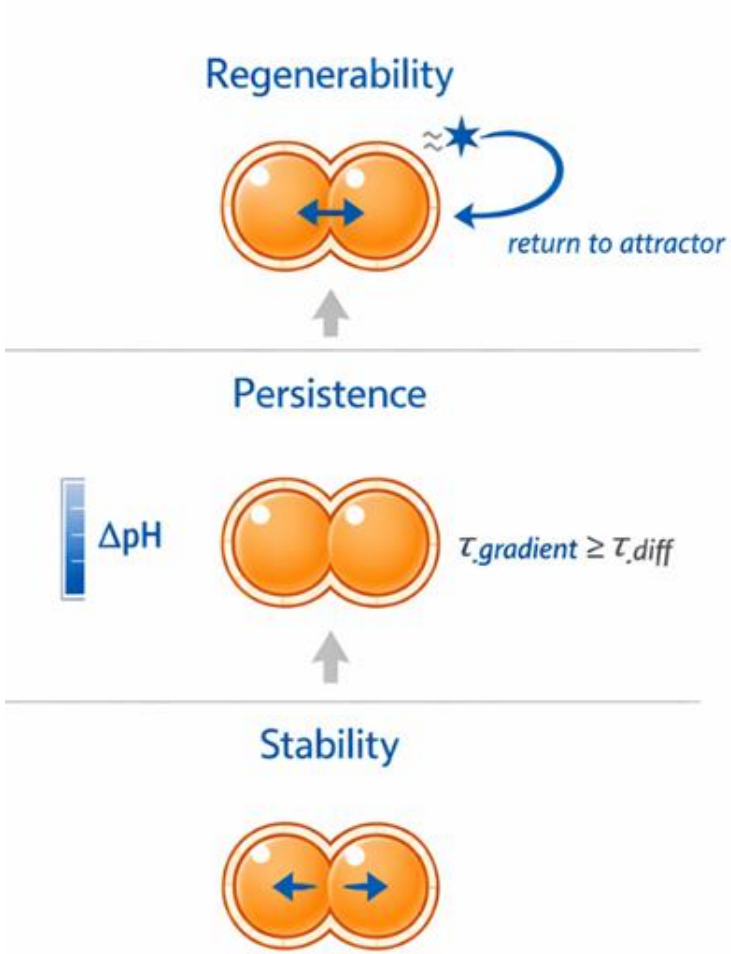
Diffusion time: $\tau\_diff \approx L^2 / D\_H+$

Requirement: **τ_gradient ≥ τ_diff**

If fulfilled → gradients become functionally relevant

Three Dimensions of Sustainability (Structural / Energetic / Informational)





Reliability Engineering Mapping Table

Sustainability level	Reliability analog	Representative metric
Stability	MTTF / Low hazard	Cluster break-up rate
Persistence	State retention / Availability	$\tau_{gradient} / \tau_{diff}$
Regenerability	MTTR / Recoverability	Reassembly time / Return probability

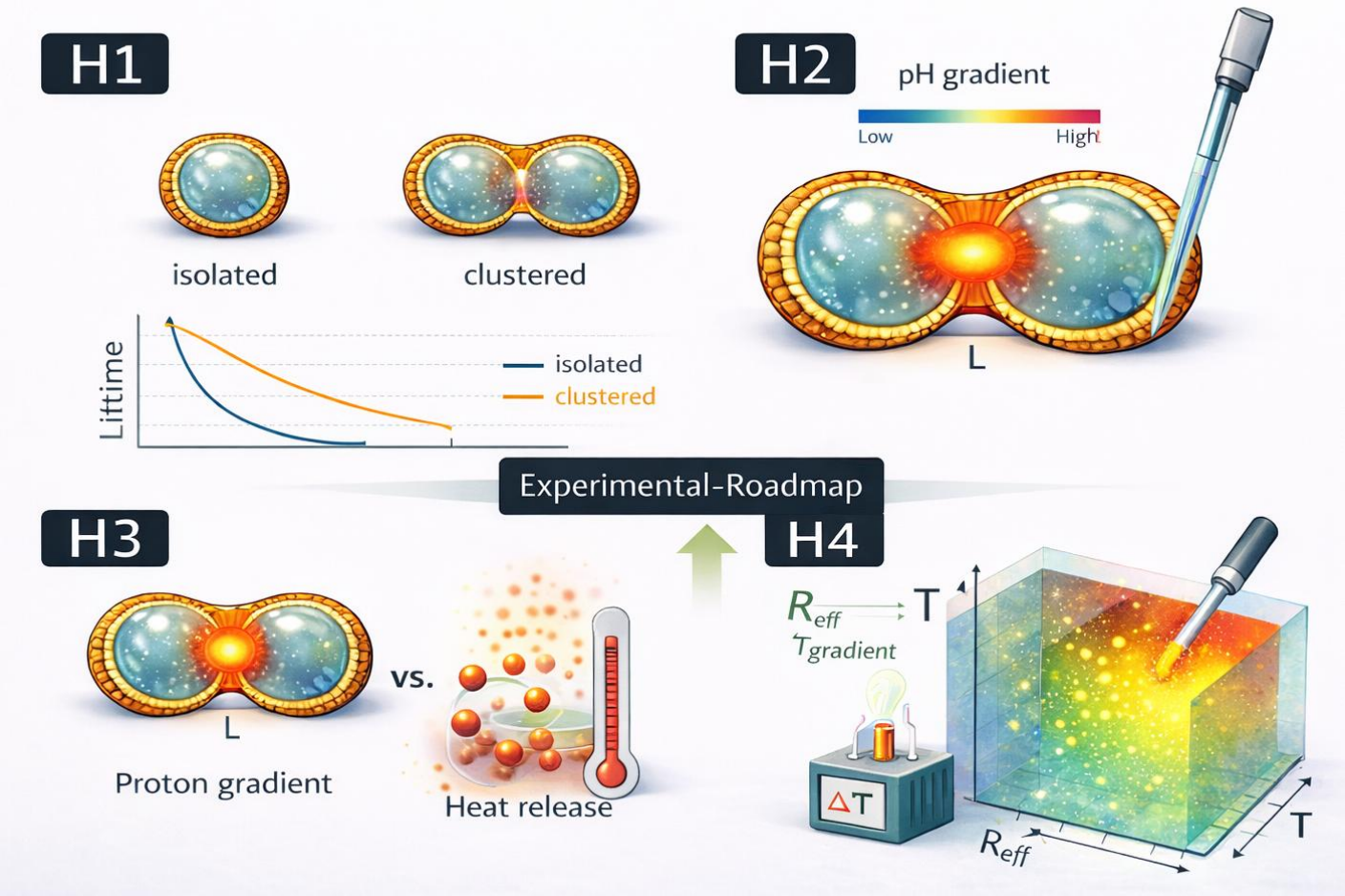
Structural Distance D(t,Δt) from Order-Parameter Vector θ(t)

$\theta(t)$

- $\langle L_{nn} \rangle$
- $\sigma(L_{nn})$
- $N\_cluster$
- $\langle k \rangle$
- $f\_cluster$
- $\langle \Delta pH\_gap \rangle$
- $\sigma(\Delta pH\_gap)$
- $\tau\_gradient$
- T_return

$$D(\text{Struktur}, t + \Delta t \mid t) = \left(\sum_{i=1}^{n} w_i \left[\frac{\theta_i(t + \Delta t) - \theta_i(t)}{\theta_{i,\text{ref}}} \right]^2 \right)^{1/2}$$

Experimental Roadmap Hypothesis H1–H4



H1 – Structural Sustainability:
Protocell clusters outlive isolated vesicles because fluctuation-induced forces stabilize their collective structure.

H2 – Asymmetry and Ion Gradients:
Asymmetric vesicle pairs generate measurable proton and ion gradients in the gap region through geometry, fluctuations, and flow alone.

H3 – Energetic Sustainability and Entropy Production:
Protocell configurations with long-lived ion gradients exhibit lower entropy production per time and volume than configurations with short-lived gradients.

H4 – Sustainability and the Three-Layer Framework:
Observable dynamics can be statistically grouped into the three sustainability levels—stability, persistence, and regenerability. Cluster dynamics can be classified via low/medium/high D regimes.

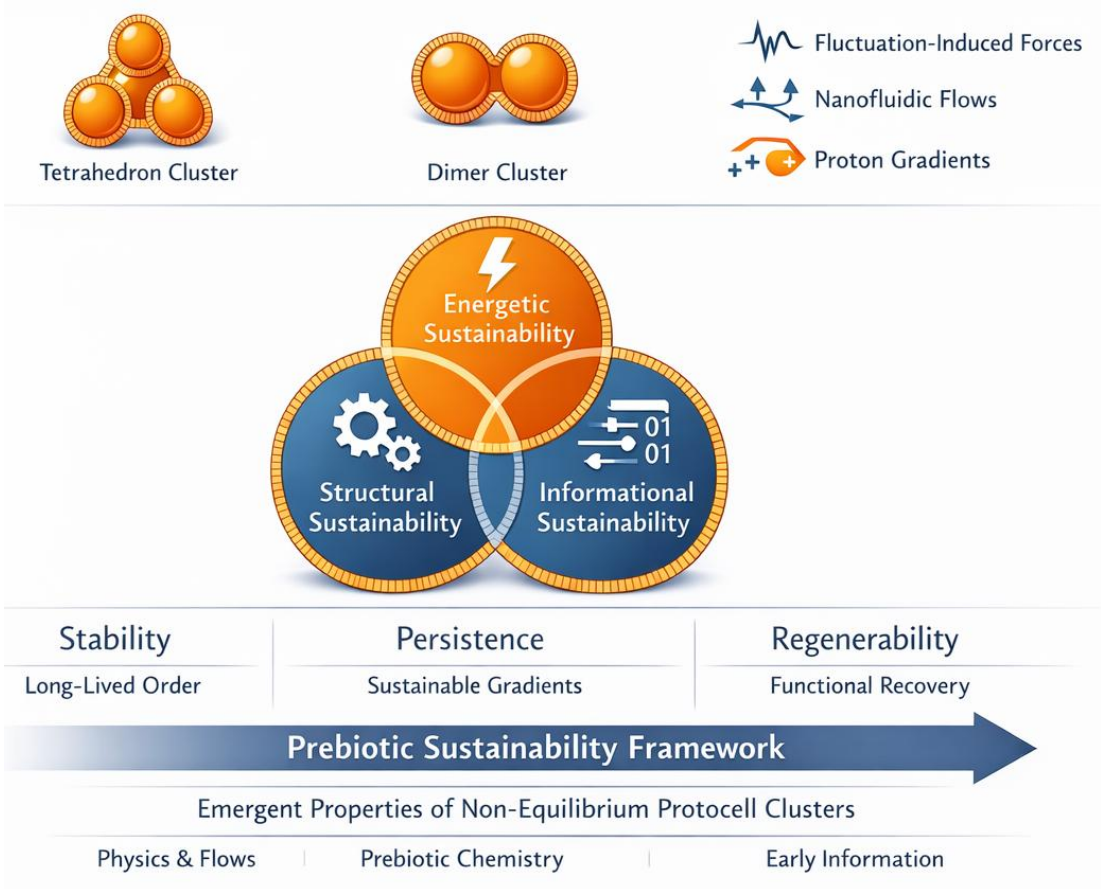
Take-Home message:

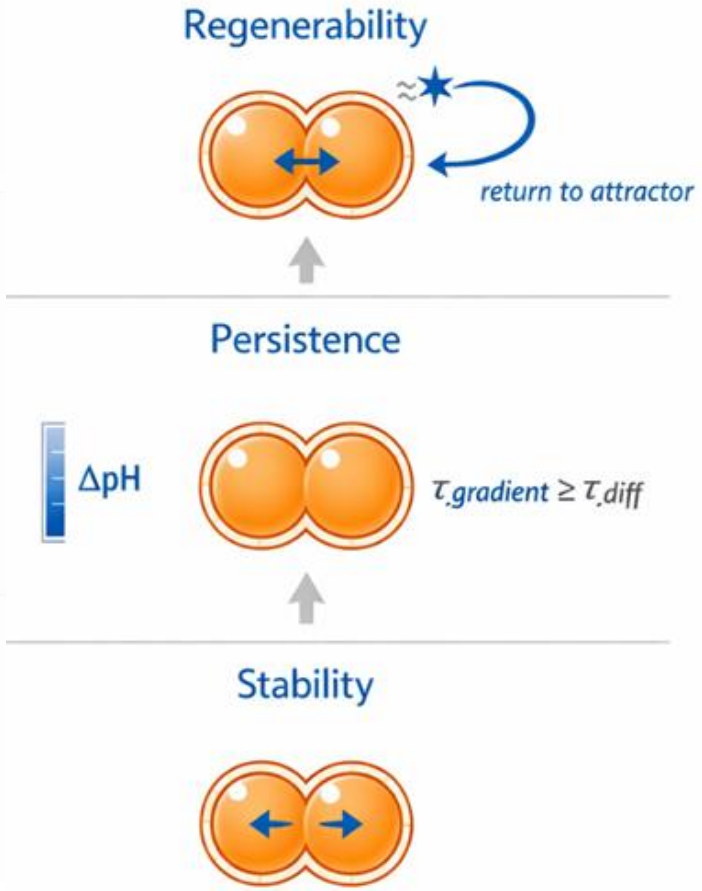
Sustainability can emerge from nanophysics alone:

- 3 dimensions (S/E/I) + 3 levels (Stability/Persistence/Regenerability)
- Measurable, testable, experimentally operational

Thank you very much for your attention.

Are there any questions?





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