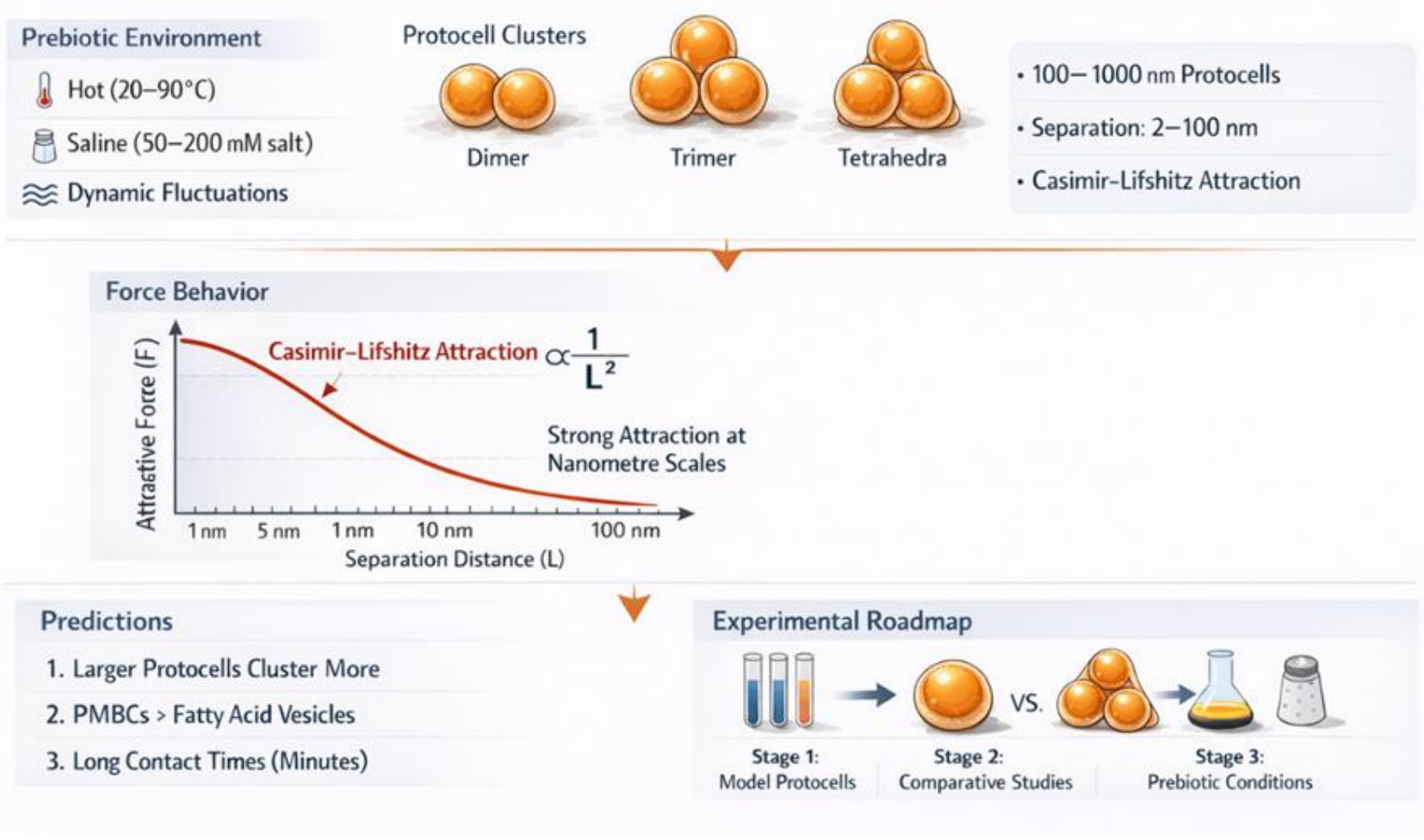
Attractive Casimir–Lifshitz Forces as a Universal Driver of Prebiotic Protocell Aggregation



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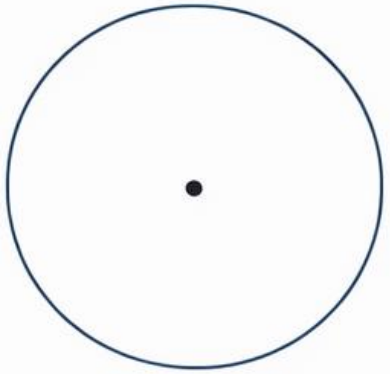
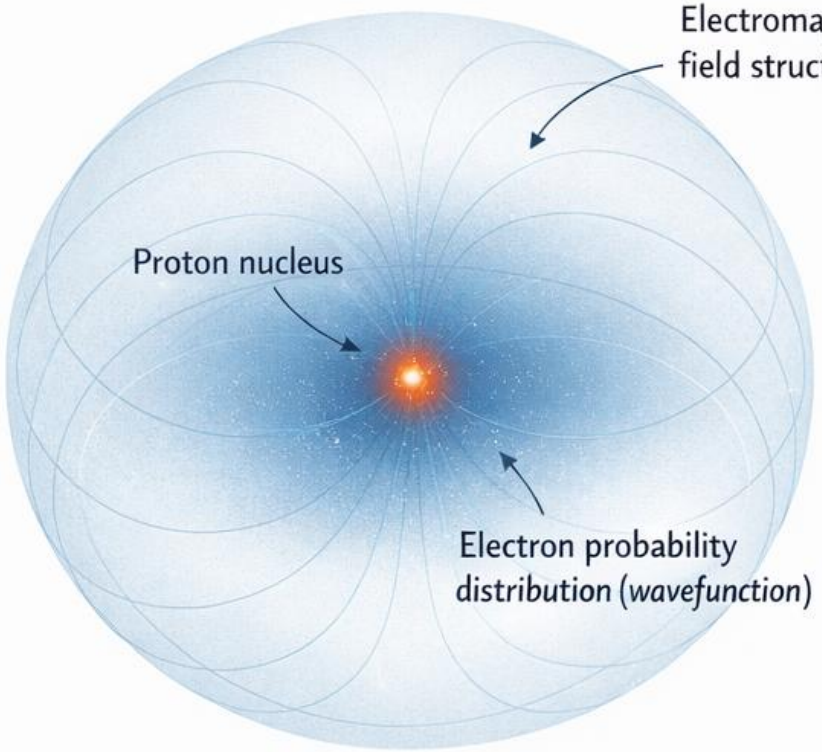
Prologue: What is real? Internal structure of H-Atom

Scale comparison:



Atomic diameter : Proton diameter
≈ 60,000 : 1



Hydrogen Atom Data:

Hydrogen atom diameter
$\approx 1.06 \times 10^{-10}$ m

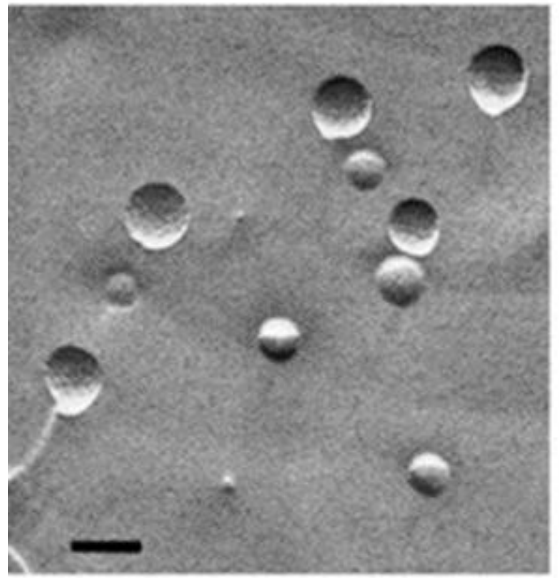
Proton diameter
$\approx 1.7 \times 10^{-15}$ m

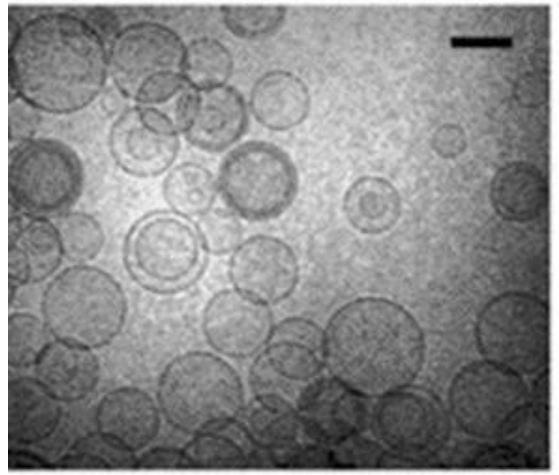
Empty space fraction
≈ 99.9999999999999 %

Most of the atom consists of space structured by fields and probability distributions.

At the atomic scale, physical reality appears as patterns of relations rather than solid substance.

First Protocells appeared 4.2 billion years ago

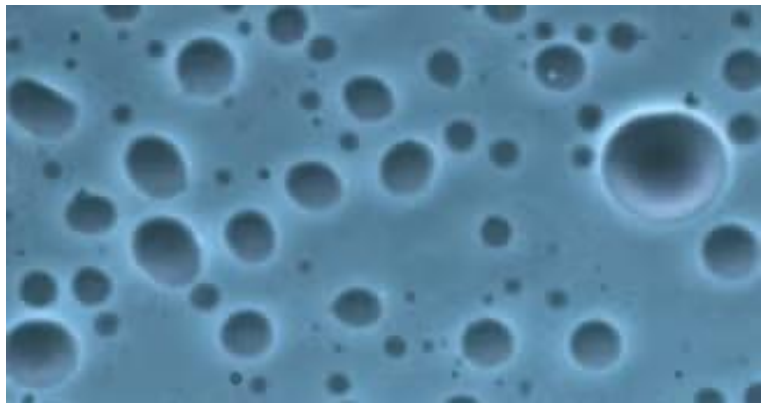


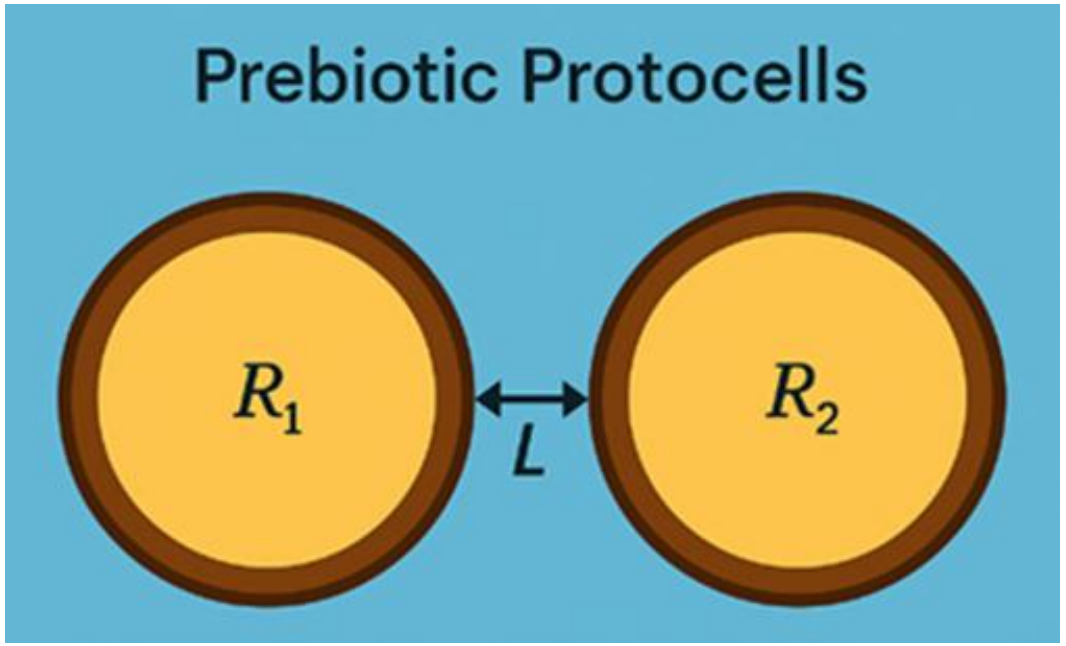


The research question and claim:

How could fragile, RNA-free, prebiotic protocells remain physically associated long enough for cooperation to emerge?

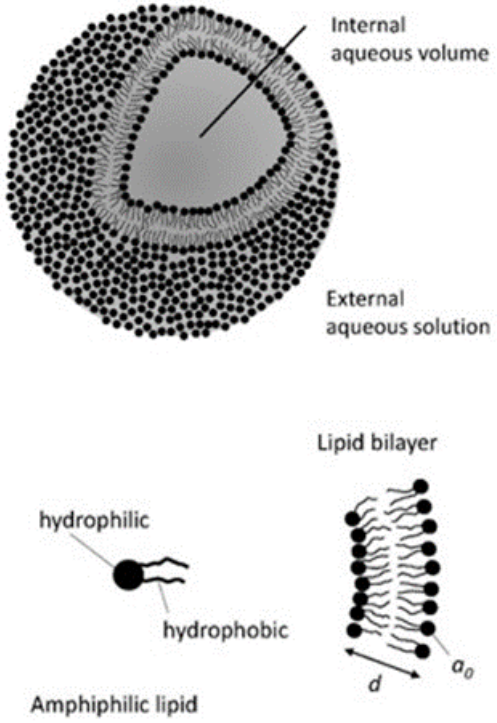
I will argue that **attractive Casimir–Lifshitz forces** provide an **universal** and **unavoidable physical coupling** mechanism in precisely the distance regime where classical explanations fail.

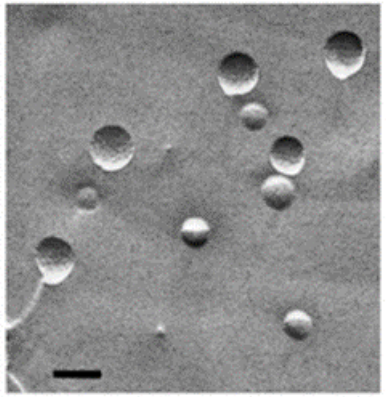


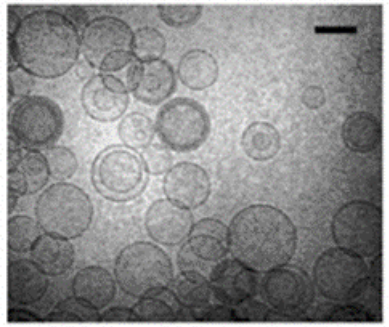


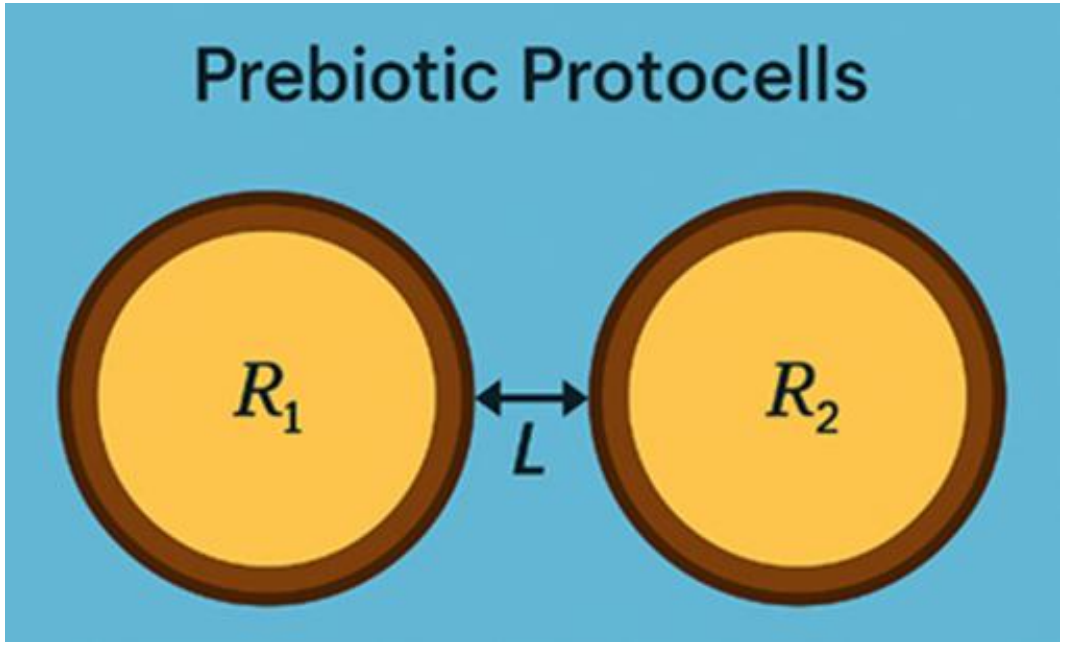
The unresolved problem:

- **How could fragile RNA-free protocells form stable clusters?**
- Prebiotic environments were hot, saline and fluctuating.
- DLVO + hydrophobic effects fail at 5–200 nm separation.

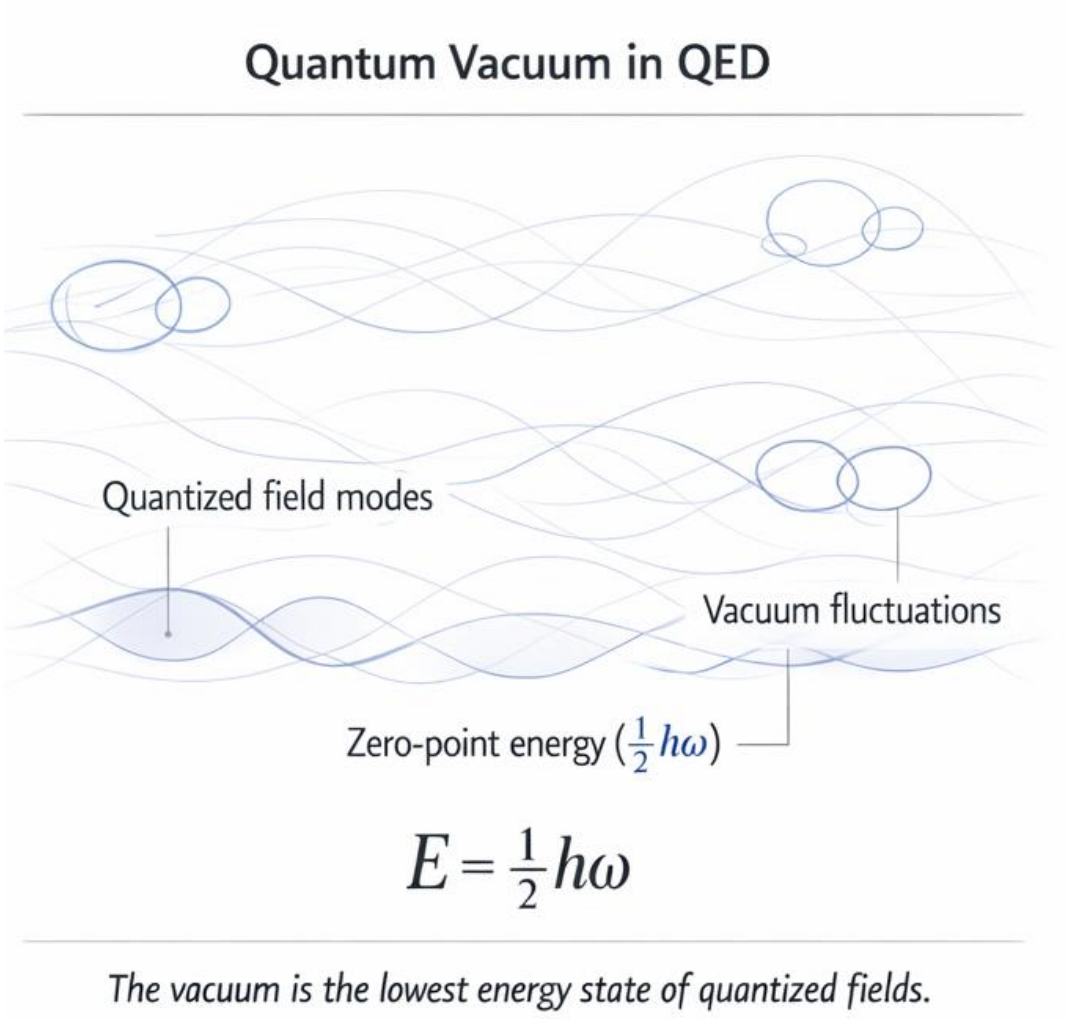








Some Physical Basics: The Quantum Vacuum in QED (1)



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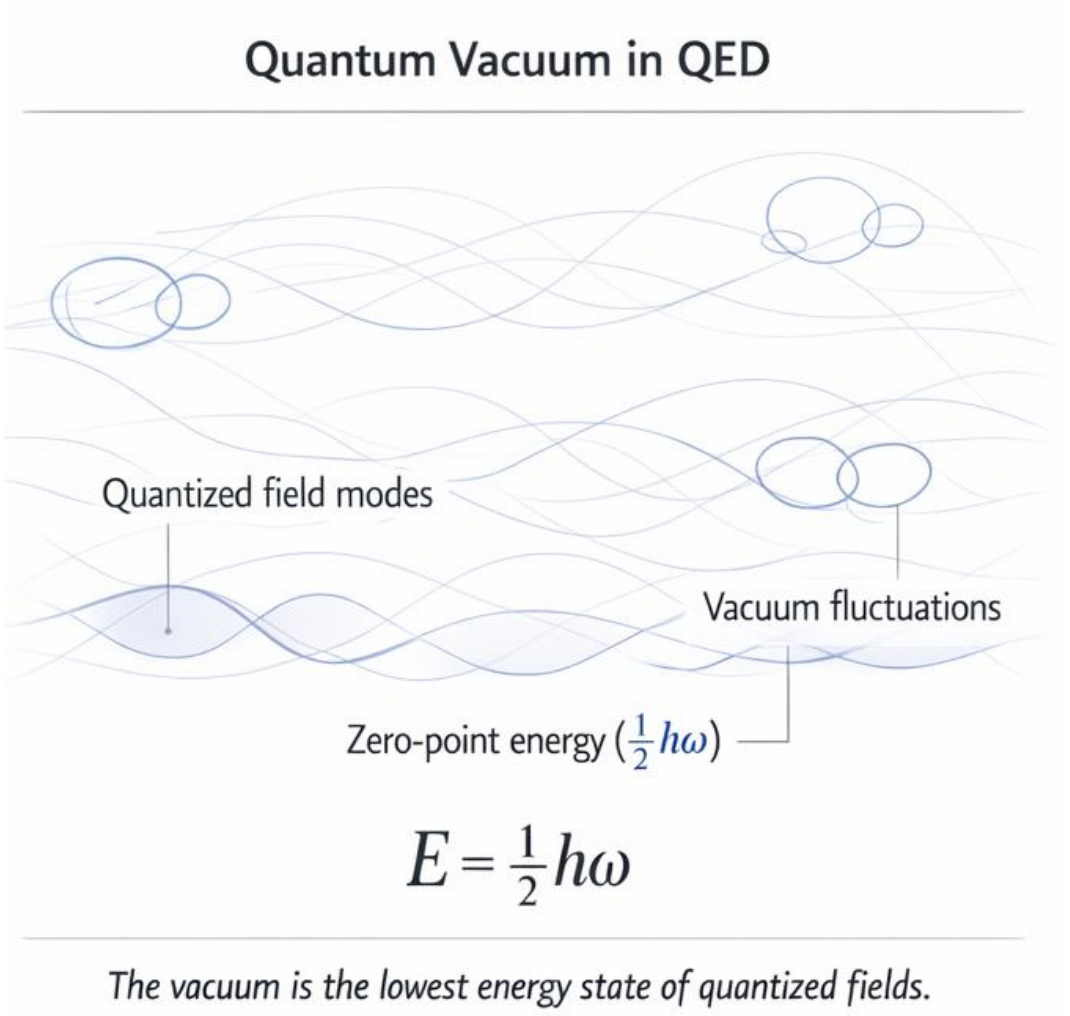
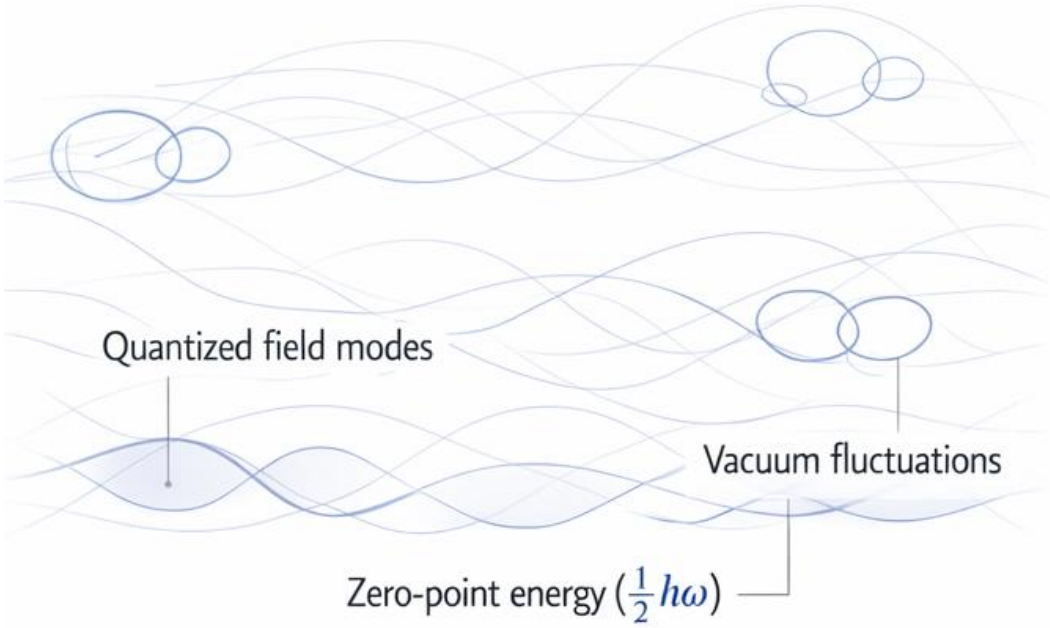


- Free of particles.
- The vacuum is not "nothingness," but rather the state of **lowest energy state** of quantised fields.
- According to **Heisenberg's uncertainty principle**, a quantum oscillator can never come to a complete rest. It always vibrates.
  → **Vacuum fluctuations**.

Some Physical Basics: The Vacuum & Casimir-Effect (2)

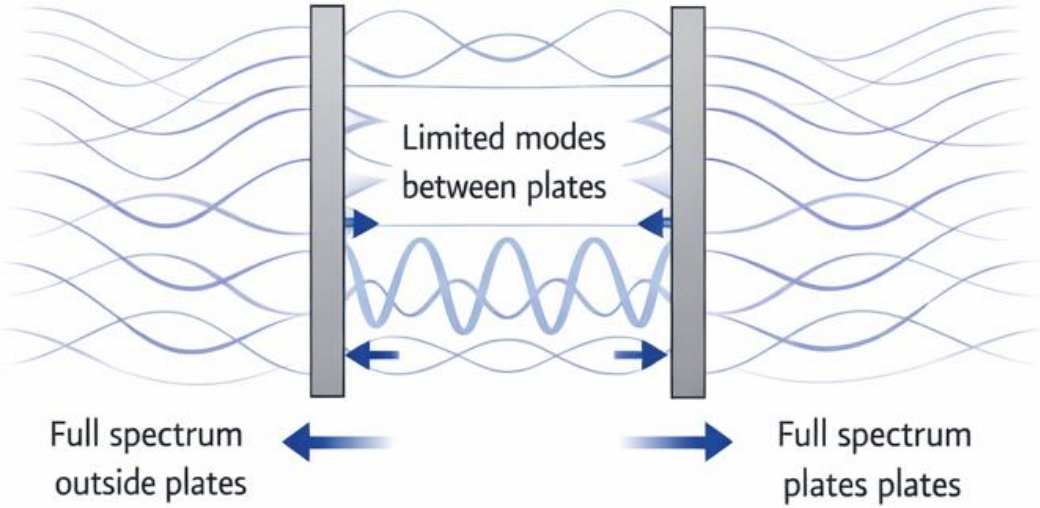
Quantum Vacuum in QED



$$E = \frac{1}{2}h\omega$$

The vacuum is the lowest energy state of quantized fields.

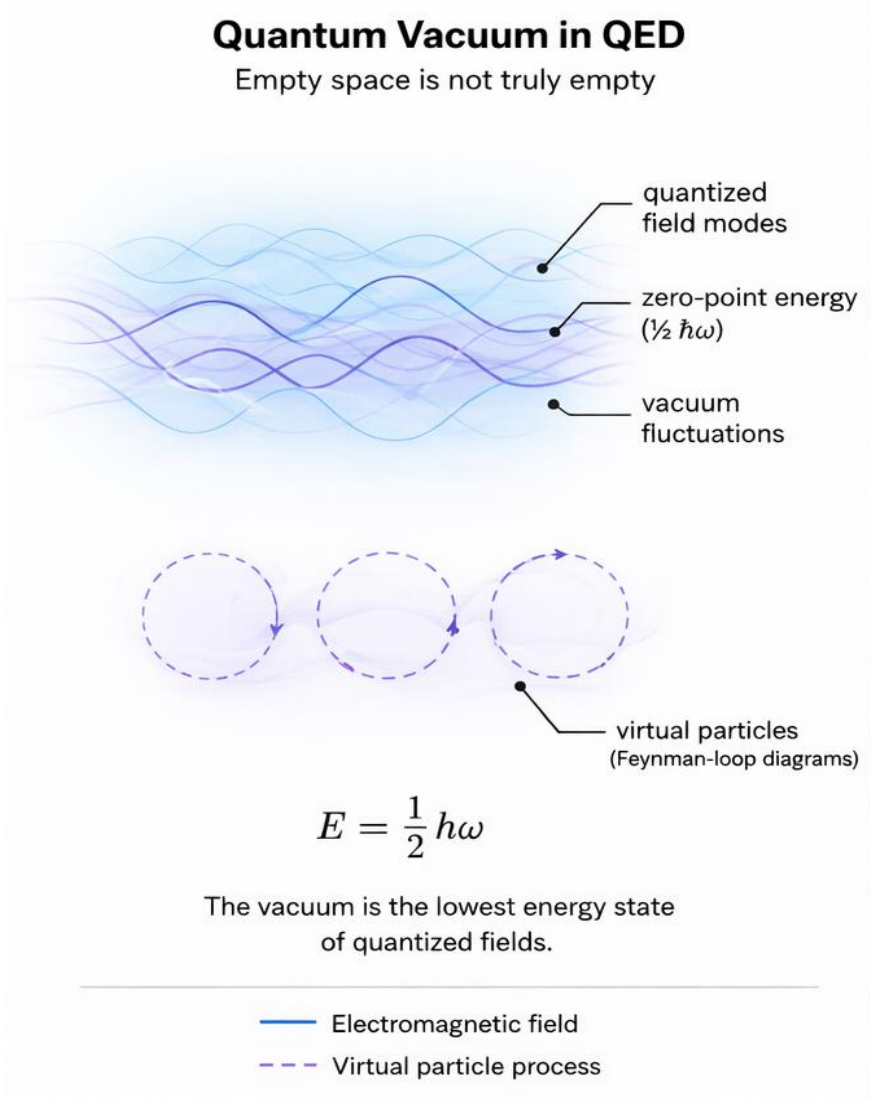
Casimir Effect

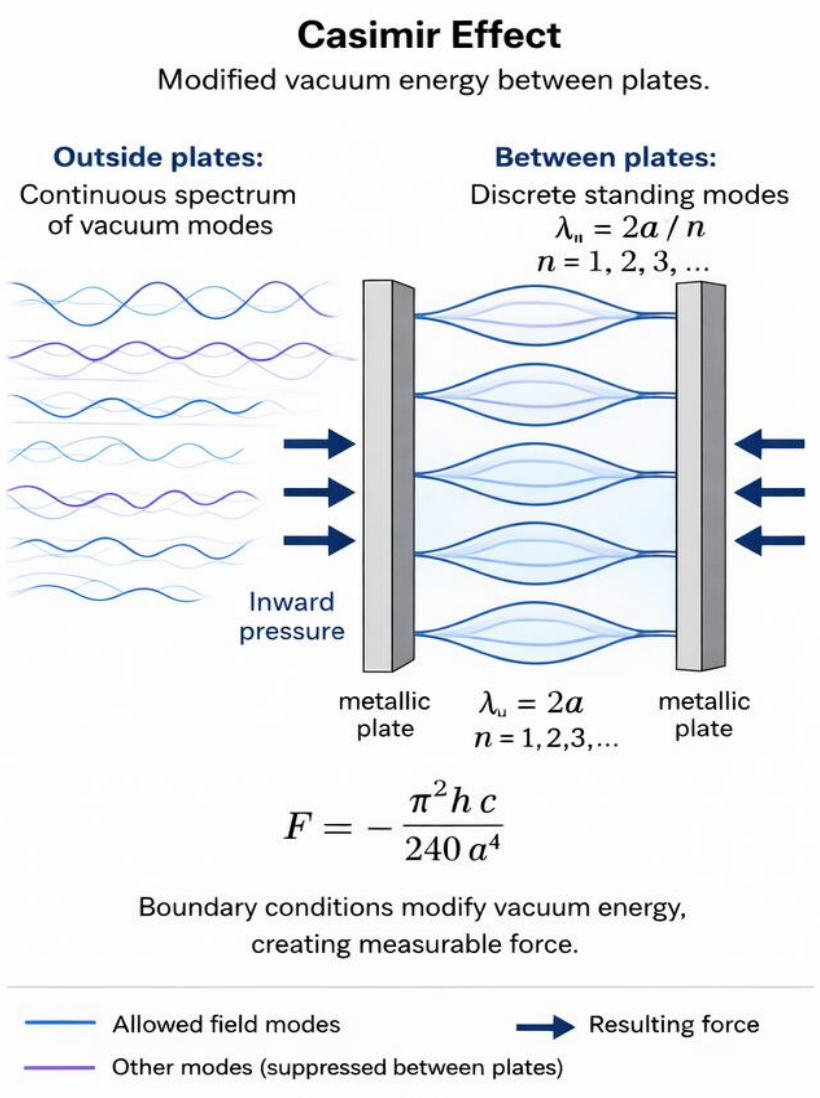


$$F = \frac{-\pi^2 hc}{240\,a^4}$$

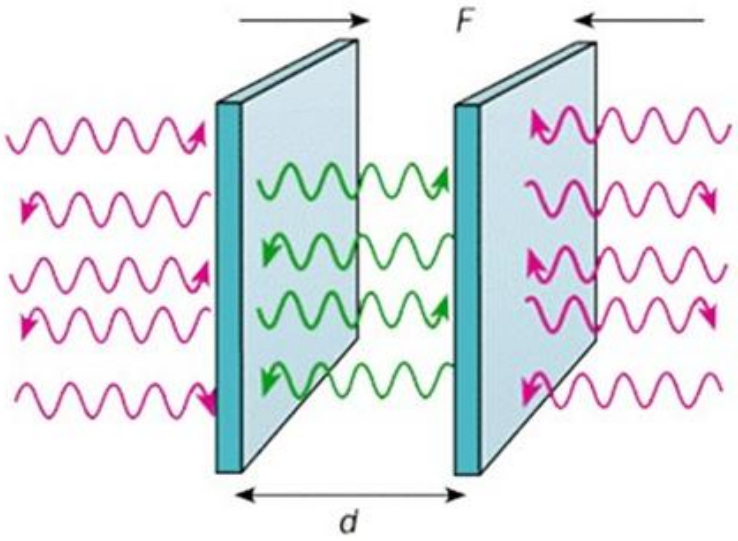
Boundary conditions modify vacuum energy, creating measurable force.

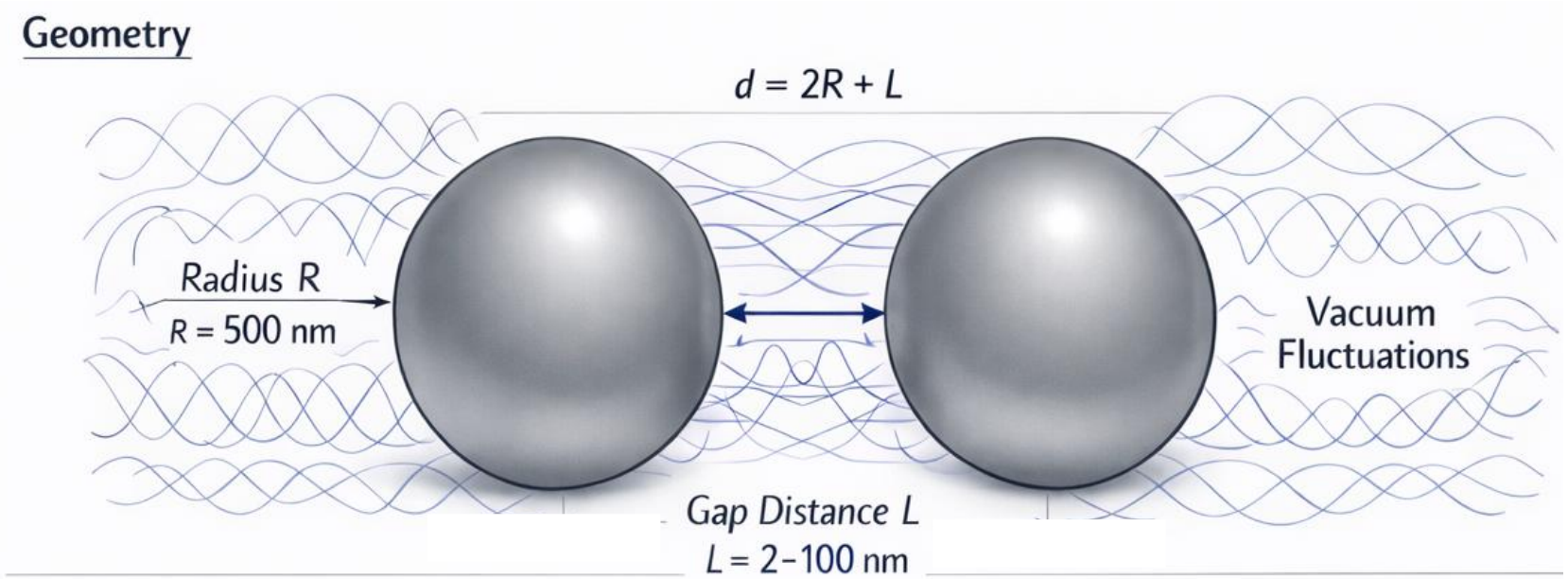
Some Physical Basics: The Vacuum & Casimir-Effect (3)

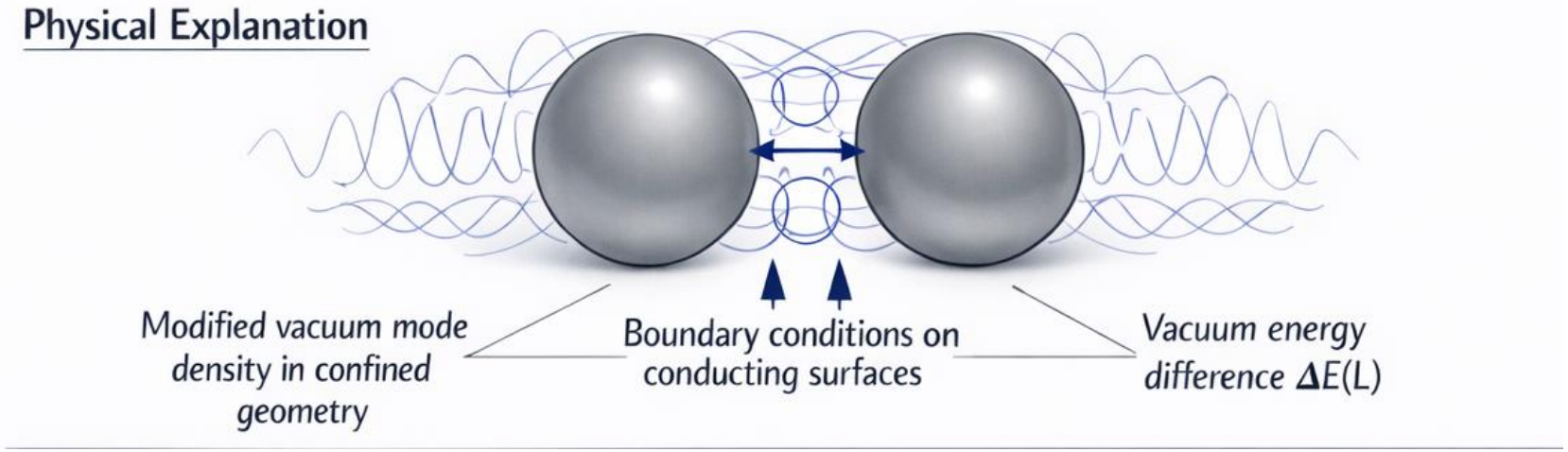




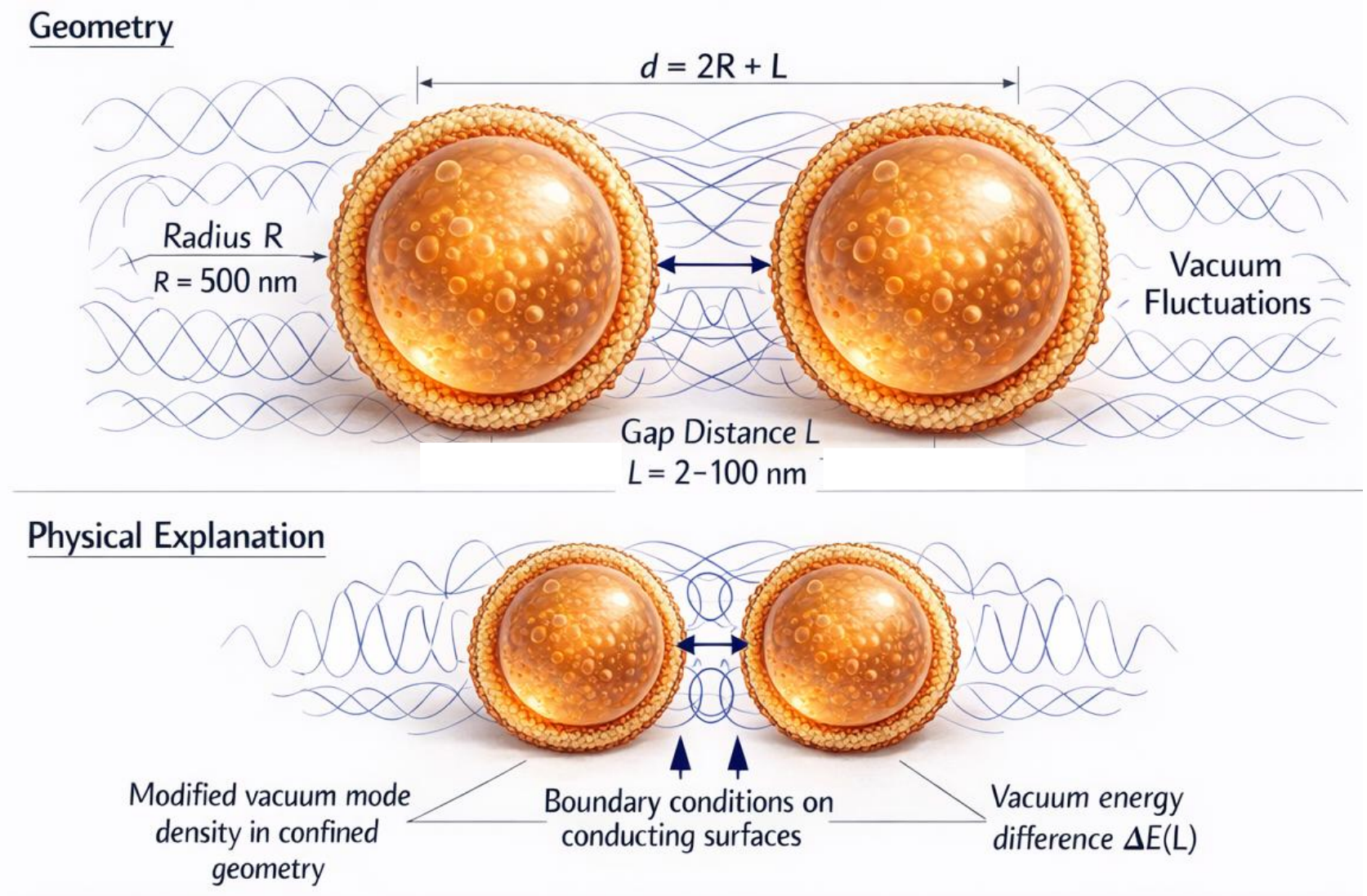
Casimir-Effect between two metallic Spheres (4)



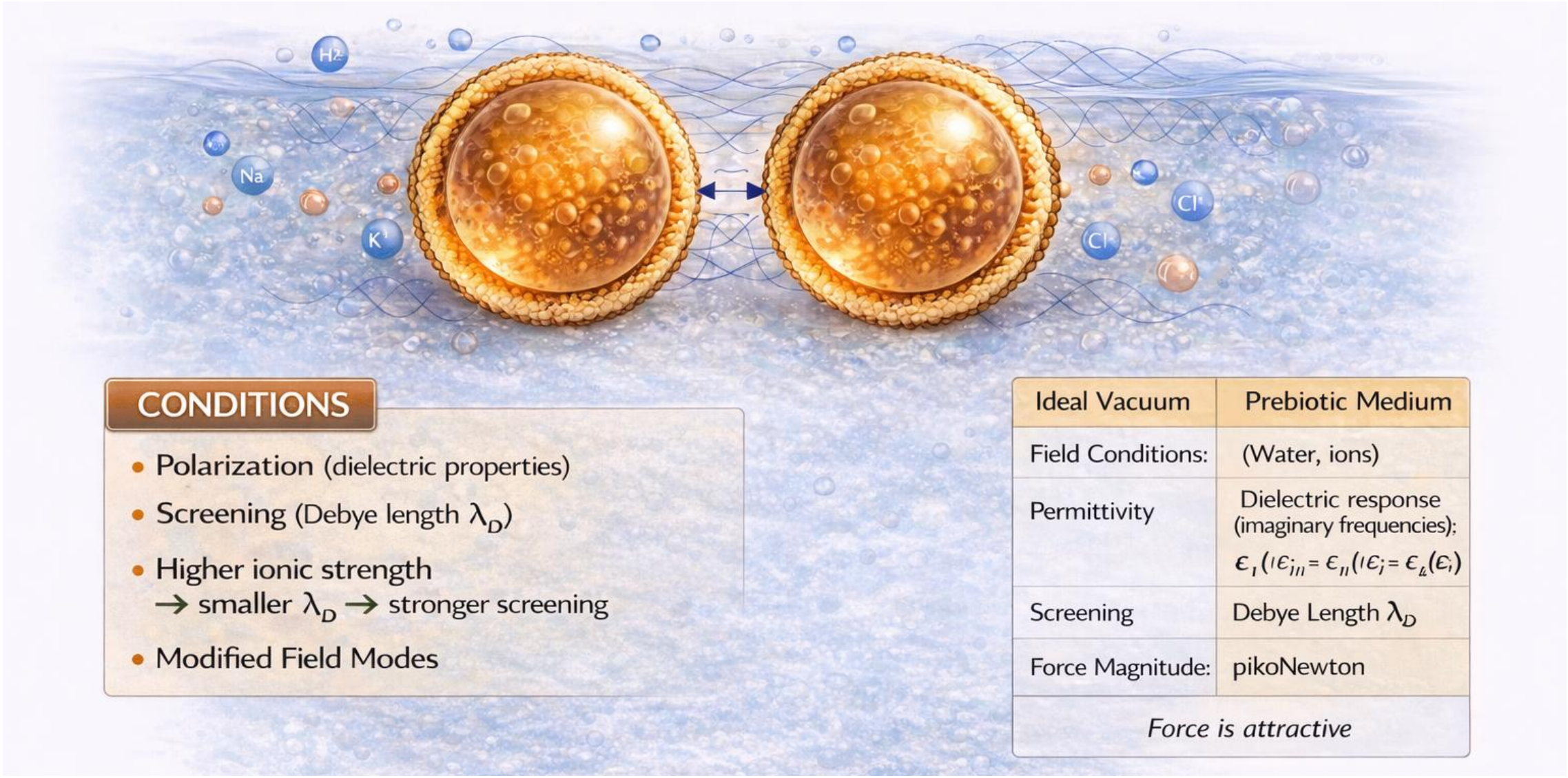




Casimir-Effect between two Protocells (5)



Casimir-Lifshitz-interactions in primordial soup (6)



CONDITIONS

- Polarization (dielectric properties)
- Screening (Debye length λ_D)
- Higher ionic strength
  → smaller λ_D → stronger screening
- Modified Field Modes

Ideal Vacuum	Prebiotic Medium
Field Conditions:	(Water, ions)
Permittivity	Dielectric response (imaginary frequencies): $\epsilon_1(i\xi_{jn}) = \epsilon_{II}(i\xi_j) = \epsilon_4(\epsilon_i)$
Screening	Debye Length λ_D
Force Magnitude:	pikoNewton
Force is attractive	

Harsh environment in the primordial soup: Prebiotic Parameter Window

thermal agitation

high ionic strength

constant fluctuations

- R = 200–1000 nm.
- L = 2–100 nm.
- T = 20–80 °C.
- Salt = 50–200 mMol.

Force Comperison: Hydrophobic vs. DLVO vs. CL

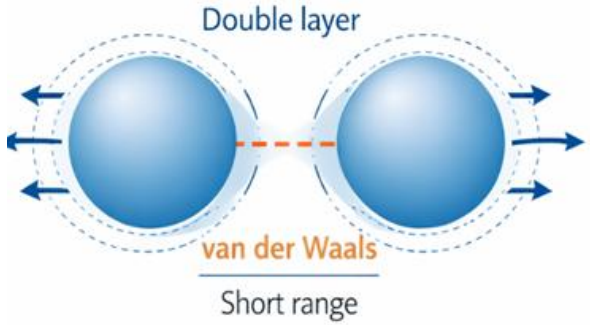
Physical vs. Chemical Interaction Landscape

Interaction	Range	Salt sensitivity	Chemistry required
Hydrophobic	< 1 nm	–	yes
DLVO	< 2 nm	high	yes
Casimir–Lifshitz	2–100 nm	low	no

Derjaguin–Landau–Verwey–Overbeek (DLVO)

DLVO Limitations:

- Electrostatic term decays exponentially with Debye length.
- λD ≈ 0.7–1.4 nm at 50–200 mMol salt.
- No mesoscale stabilization beyond few nm.

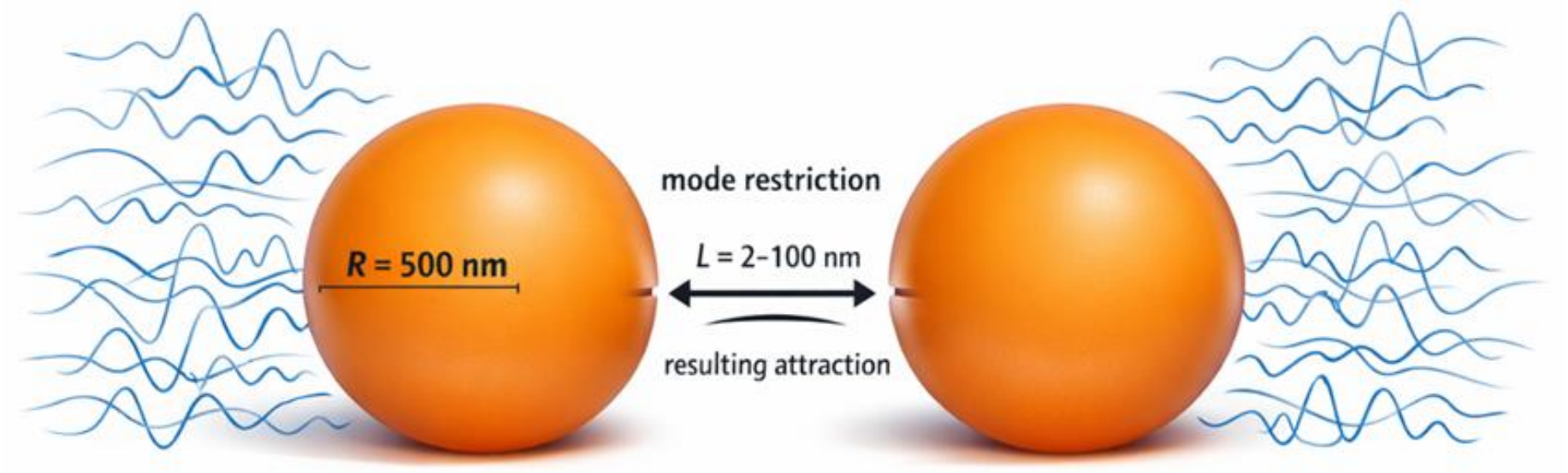


Classical DLVO Interactions

in the Primordial Soup

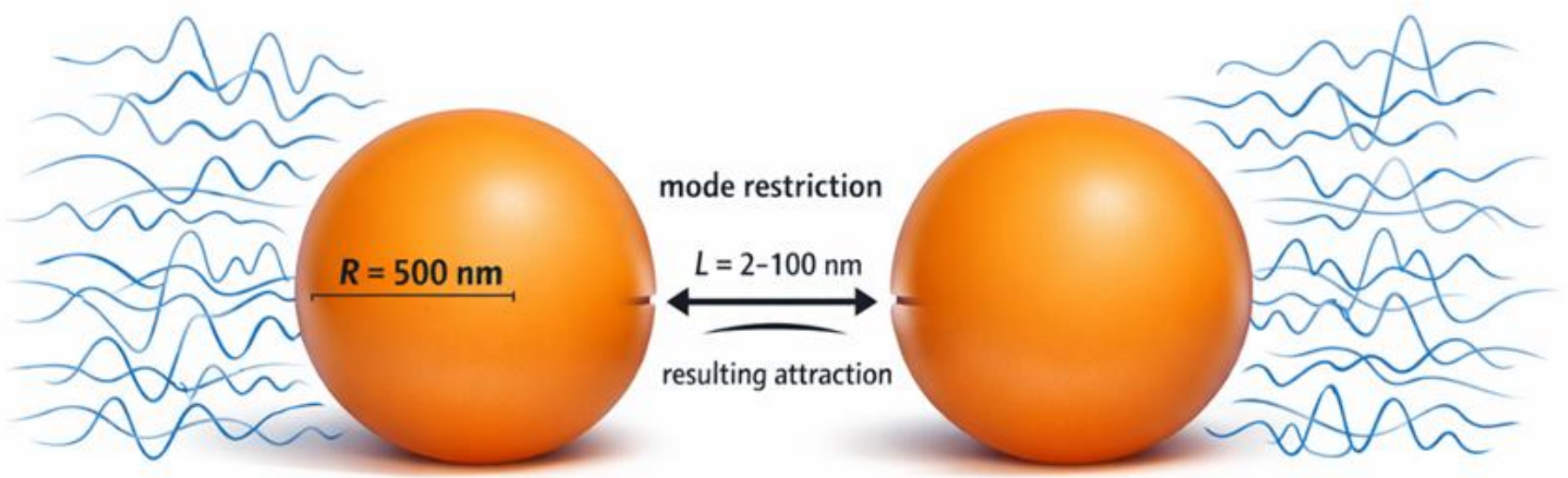
Strongly suppressed and screened
by 50–200 mMol ions

Casimir–Lifshitz Physics (1):



- Field-theoretic fluctuation-induced interaction.
- Depends on dielectric contrast ε(iξ).
- Persists 2–100 nm without exponential collapse.

Casimir–Lifshitz Physics (2):

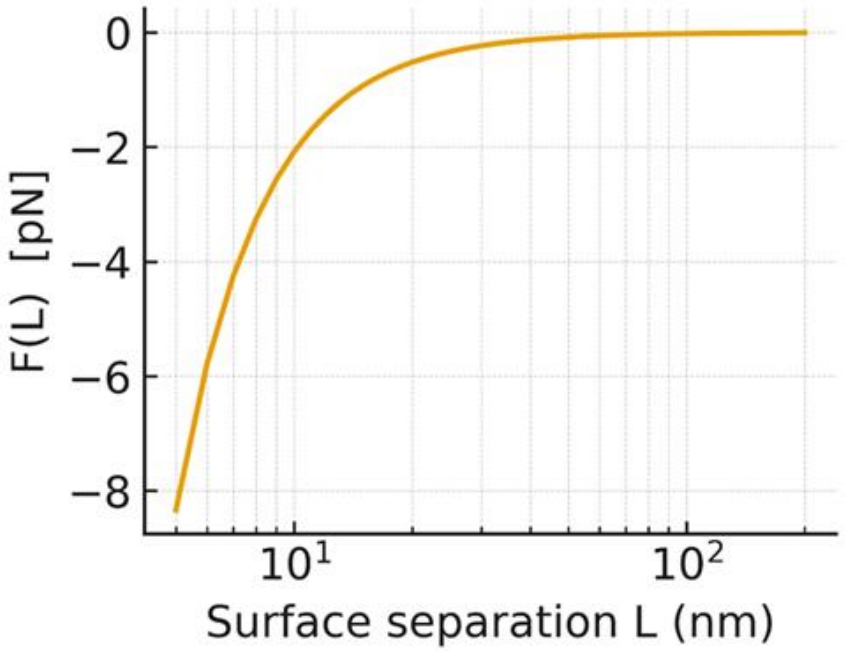


$$F_{CL}(L) \approx -\frac{A_{eff}}{6} \cdot \frac{R_{eff}}{L^2}$$

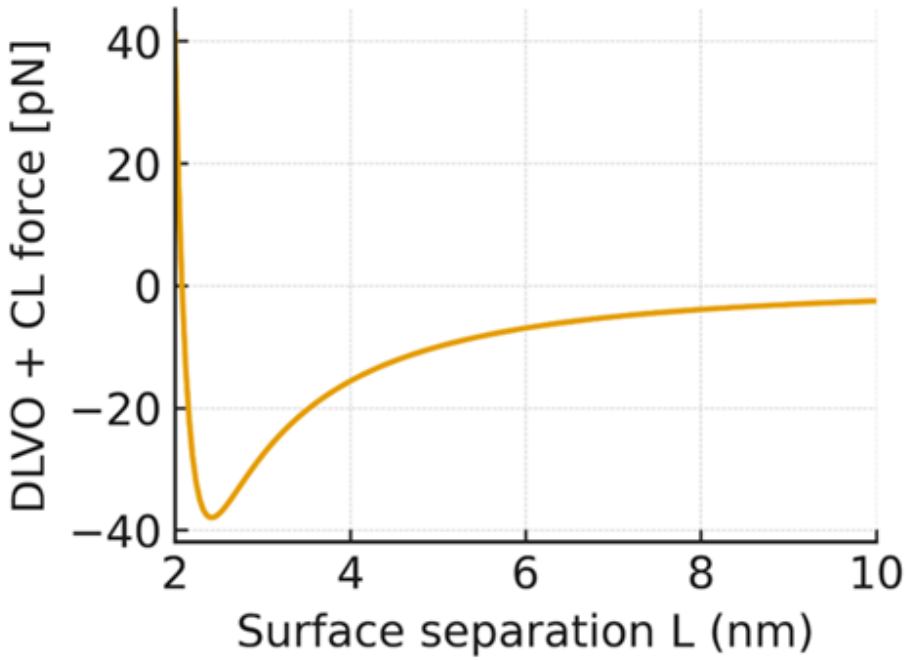
$$\text{with } R_{eff} = \frac{R_1 \cdot R_2}{R_1 + R_2}$$

A_{eff} = *effective Hamaker constant* $\approx 5 \times 10^{-21}$ Joule.

Own Numerical Calculations:

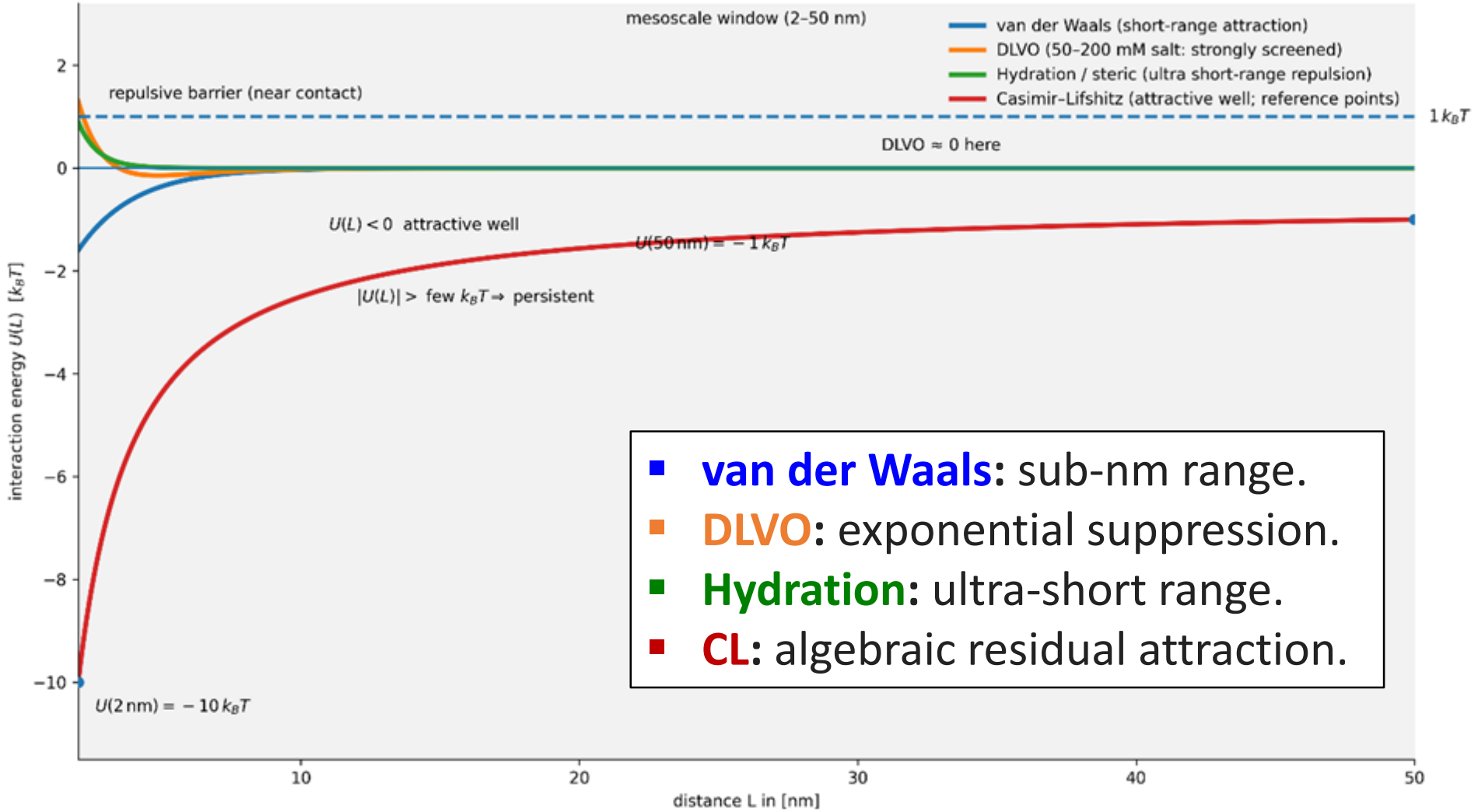


Attractive Casimir–Lifshitz force $F_{CL}(L)$ between two PMBC-like protocells (R_1=R_2=500 nm) as a function of separation L.



Resulting total force from F_{DLVO} and F_{CL} contributions over L=2–10 nm.

Force Comperison: CL vs. DLVO vs. van-der-Waals

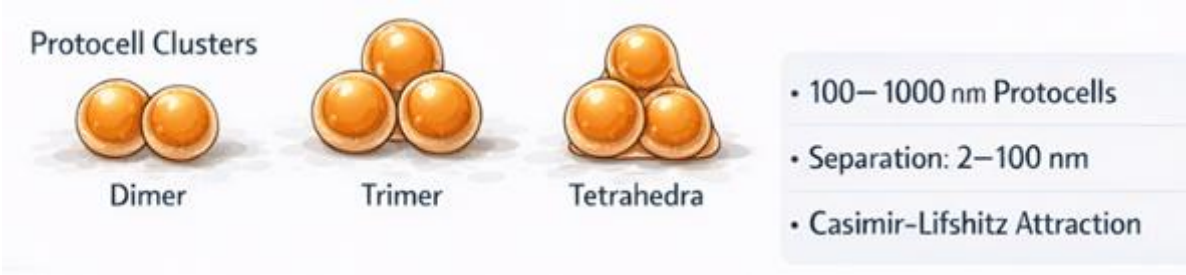


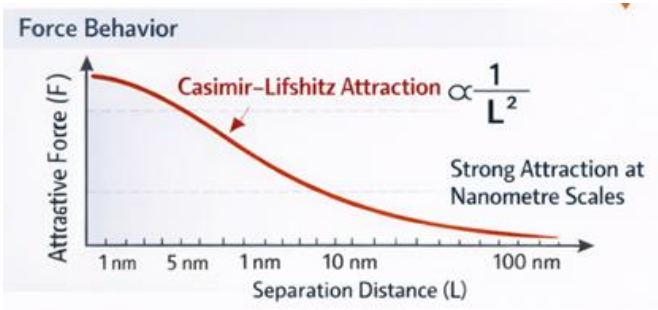
- **van der Waals**: sub-nm range.
- **DLVO**: exponential suppression.
- **Hydration**: ultra-short range.
- **CL**: algebraic residual attraction.

Main Results of Casimir-Lifshitz Coupling

Sensitivity Analysis:
- Strongest dependence on separation L.
- Linear size scaling via R_eff.
- Weak sensitivity to ionic strength.

Radius-Dependent Adhesion:
- **Larger protocells couple more strongly.**
- Enhanced contact persistence.
- Testable via particle tracking.

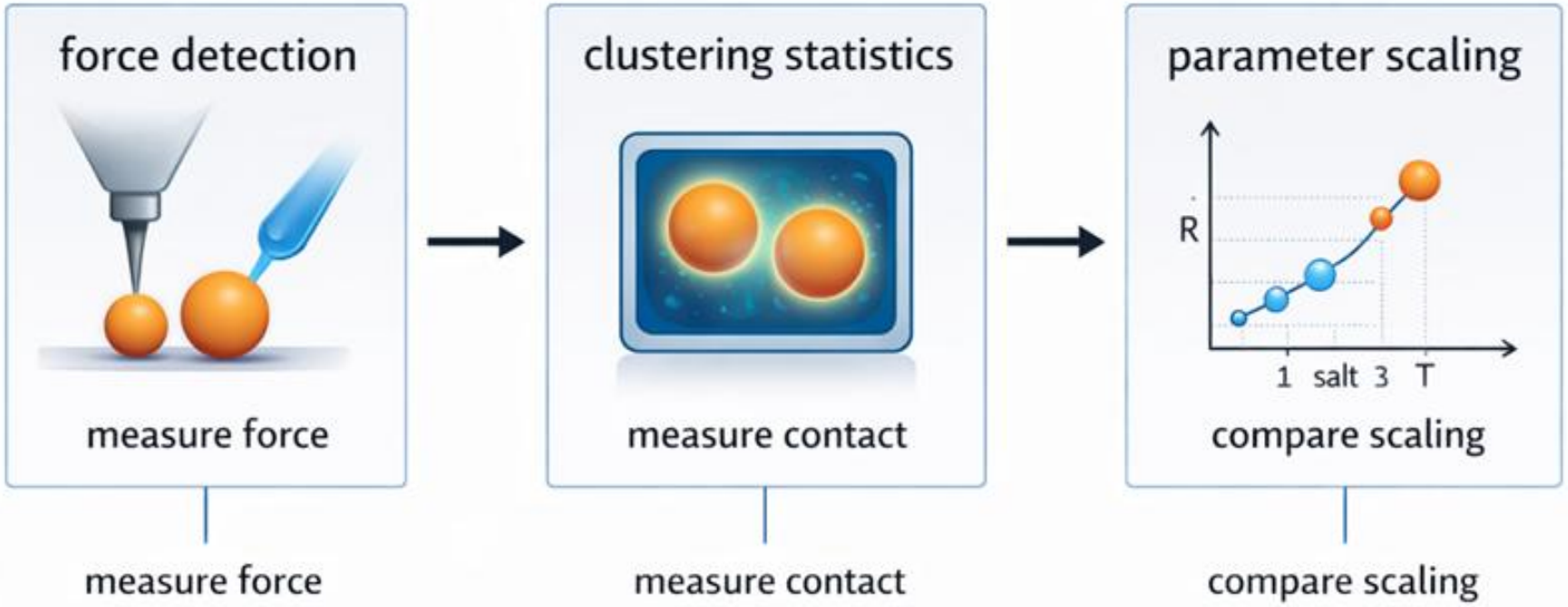




Material Predictions:
- **Protein-Based Membrane Compartments** (**PMBCs**) will show more attraction than **fatty-acid vesicles**.
- Higher polarizability → deeper wells.
- Experimentally measurable clustering difference.

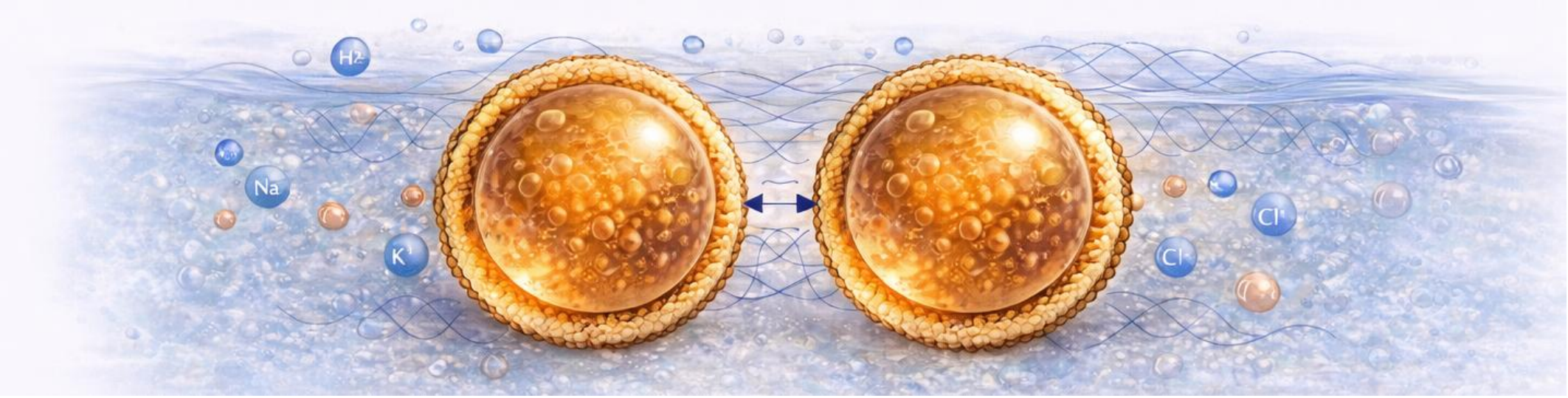
Prebiotic Parameter Window:
- R = 200–1000 nm.
- L = 2–100 nm.
- T = 20–80 °C.
- Salt = 50–200 mMol.

Experimental pipeline linking force measurements to observable clustering and quantitative scaling:

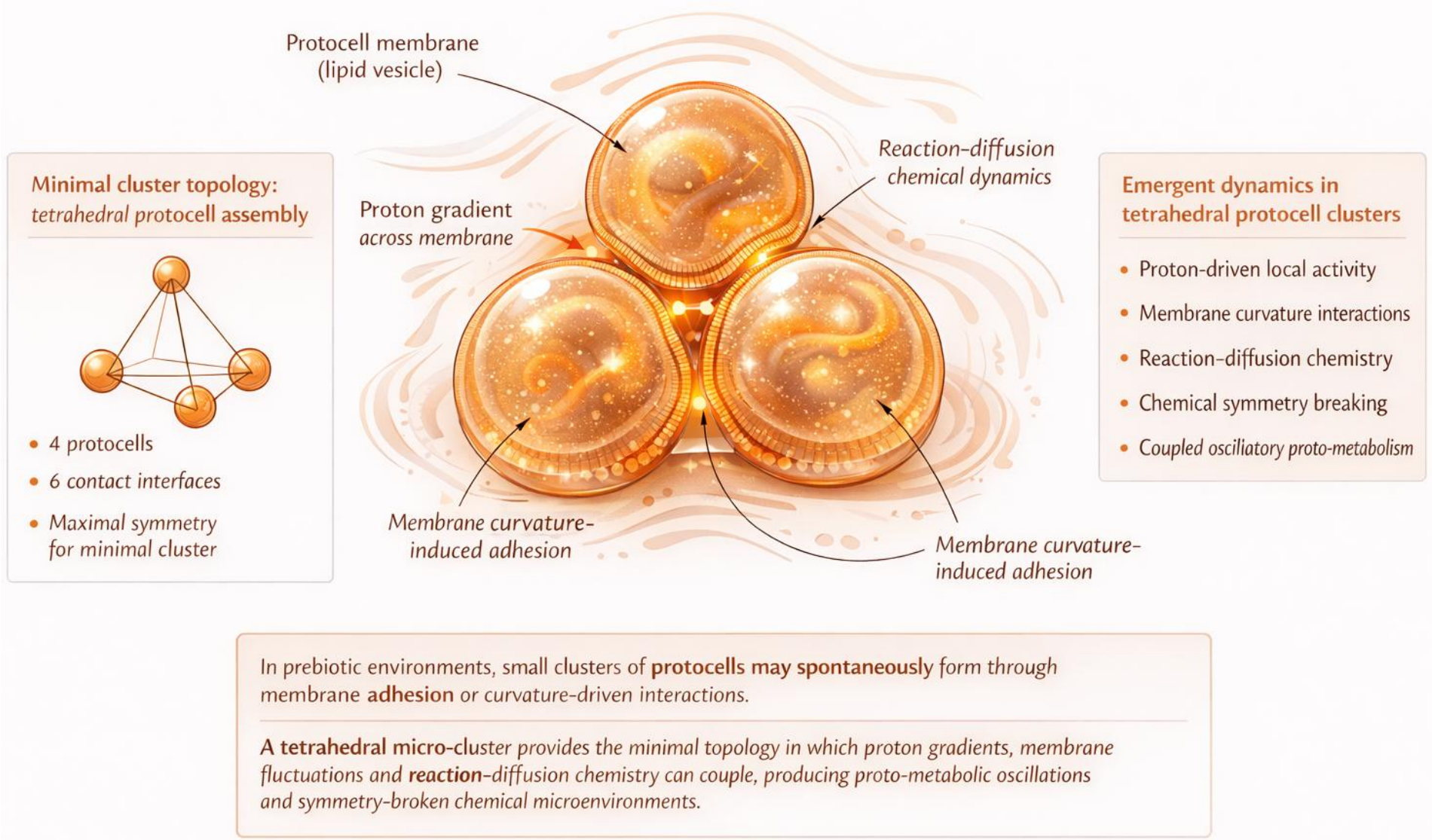


Take-Home message:

- **Casimir-Lifshitz forces** are physically unavoidable.
- They dominate where DLVO fails (for L=2-80 nm).
- They enable non-chemical mesoscale aggregation.
- **Next:** From physical clustering → information emergence.

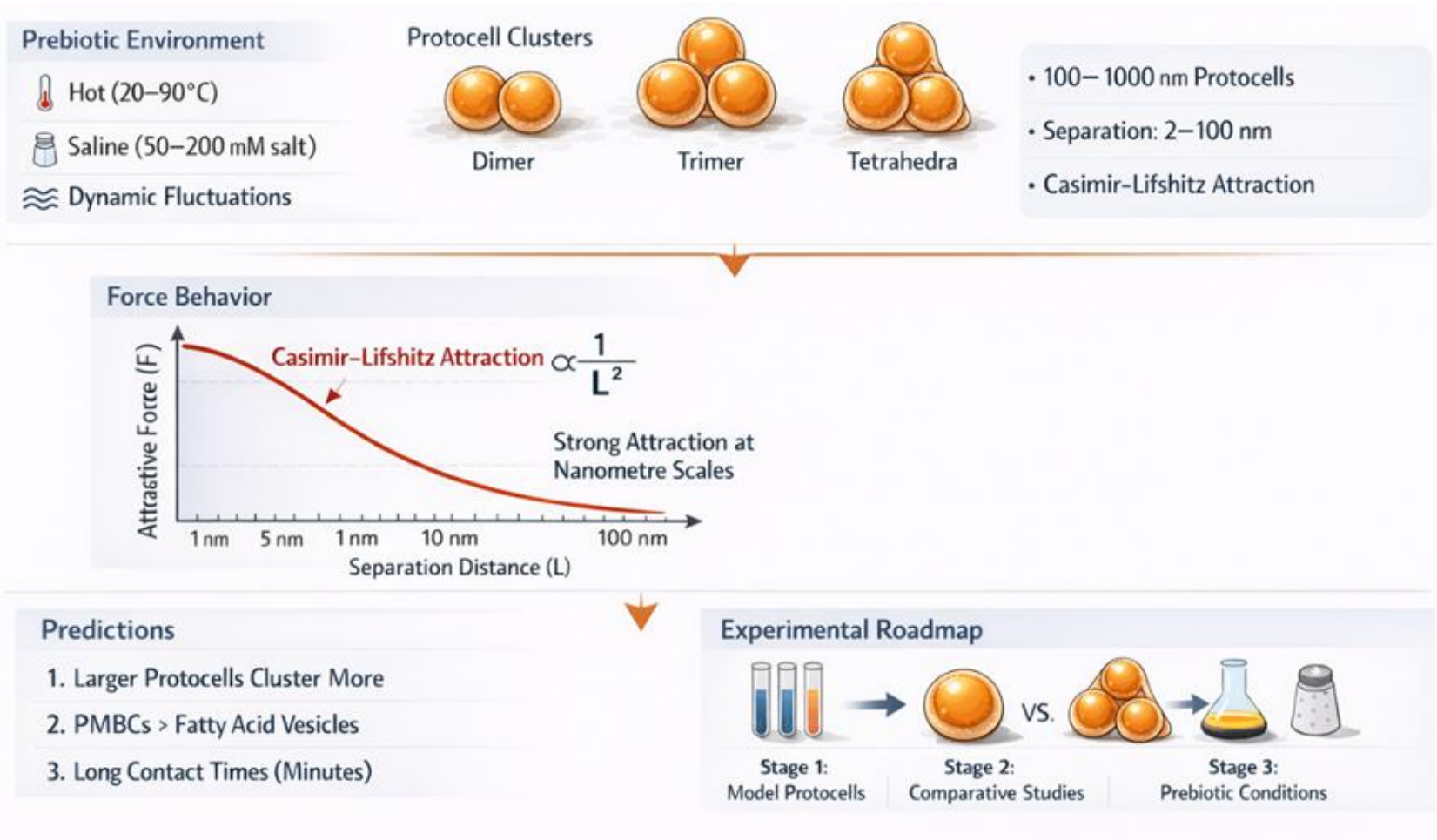


Outlook and future work: Local Activity Principle



Thank you very much for your attention.

Are there any questions?



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