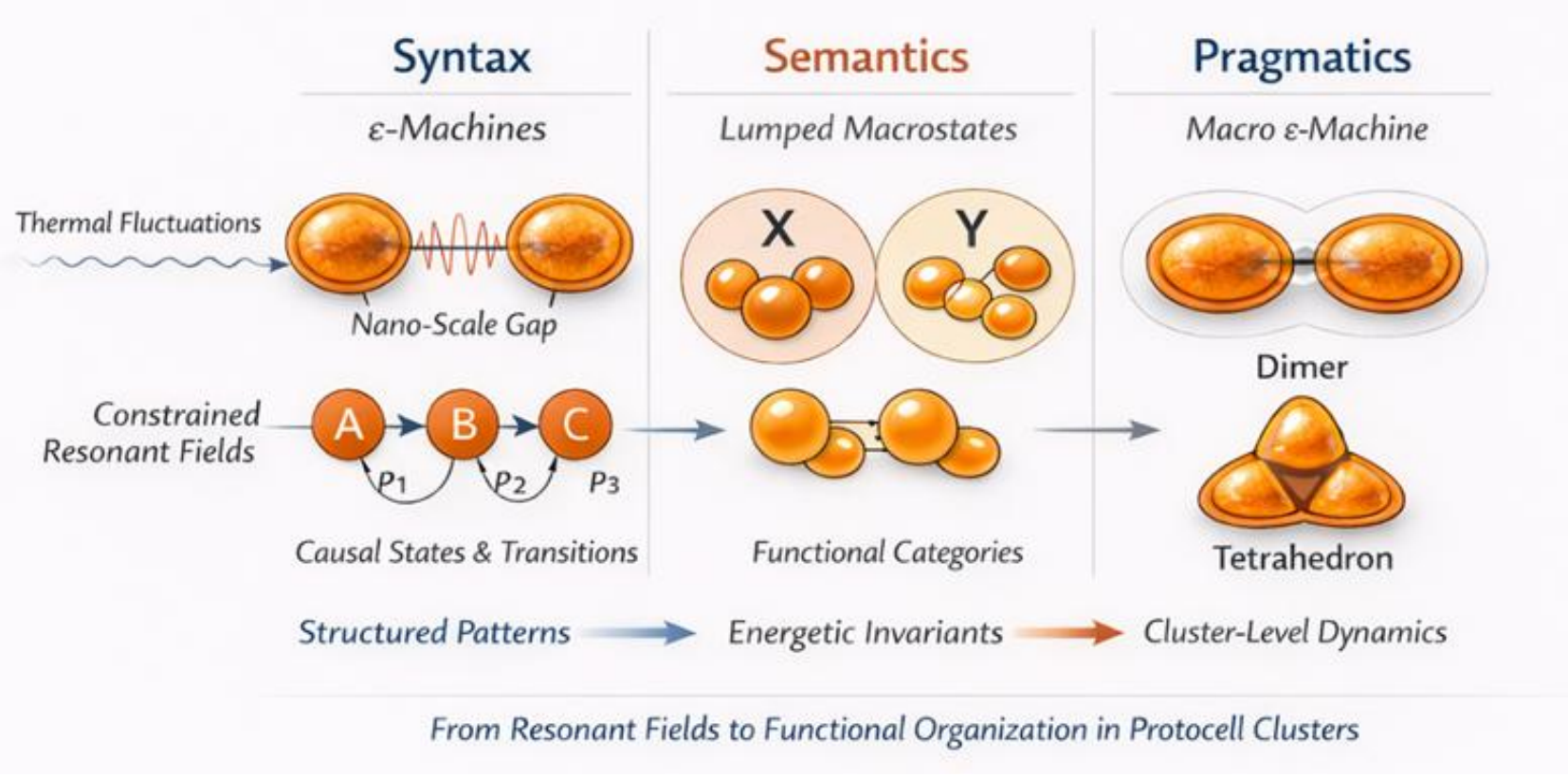
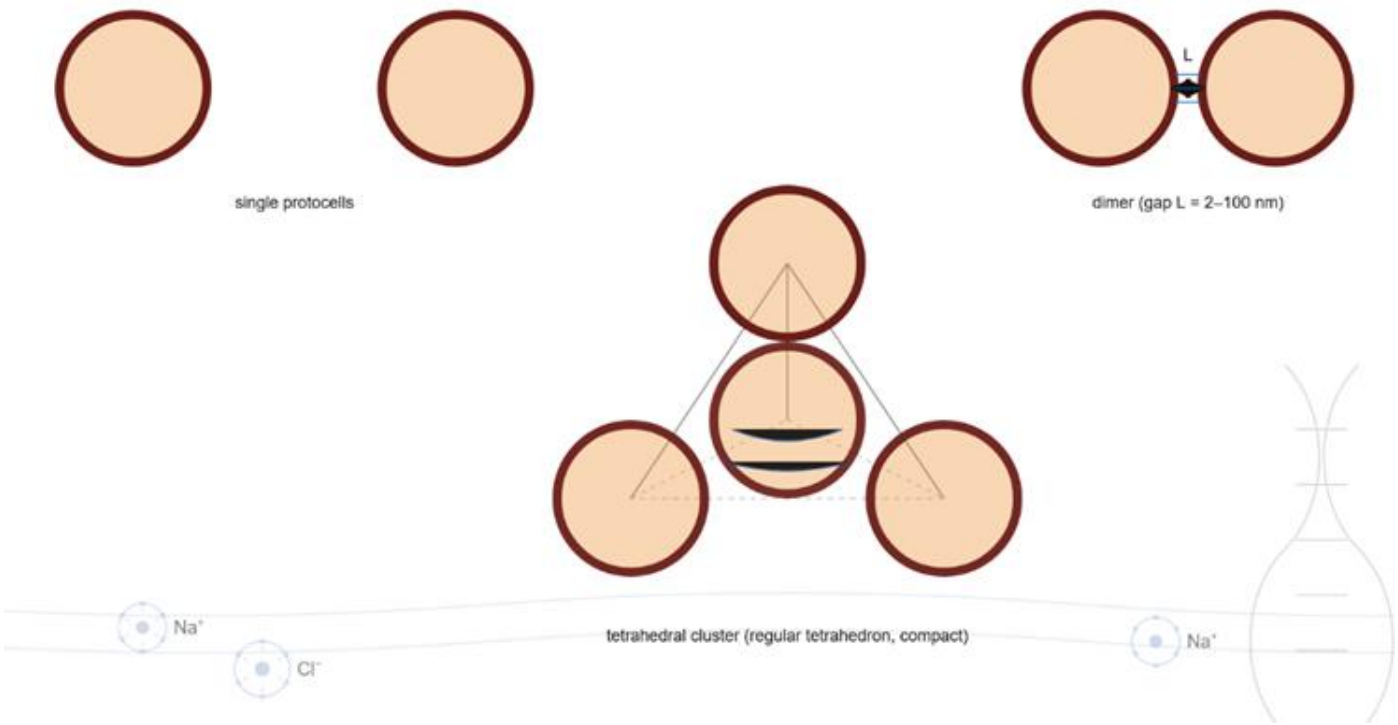
Physical Origin of Proto-Information: Syntax, Semantics and Pragmatic Emergence in Prebiotic Protocell Clusters



Michael Massoth
Hochschule Darmstadt (h_da)
BIOTECHNO-2026 | Valencia

Before RNA/DNA – what structured information?



Scientific Motivation: Information before Genes

A fundamental question in **origin-of-life research** is:

How could information and meaning emerge before genes, enzymes, or metabolic networks existed?

Early protocells must already have exploited
reproducible physical differences and stable patterns.

Without such structures, biochemical evolution could not have begun.

Conceptual Framework

This work proposes a **physics-based model** for **proto-information** and **proto-meaning**.

Three conceptual layers:

- **Syntax** – structured physical patterns
- **Semantics** – functional categories
- **Pragmatics** – reproducible tasks

Together they form a **hierarchy of prebiotic information organization**.

Physical Mechanism: Casimir-Lifshitz Coupling

Casimir–Lifshitz interactions generate attraction between protocells in aqueous environments.

Nanometer-scale gaps between membranes shape electromagnetic fluctuation spectra.
The **physical driver** of the system:

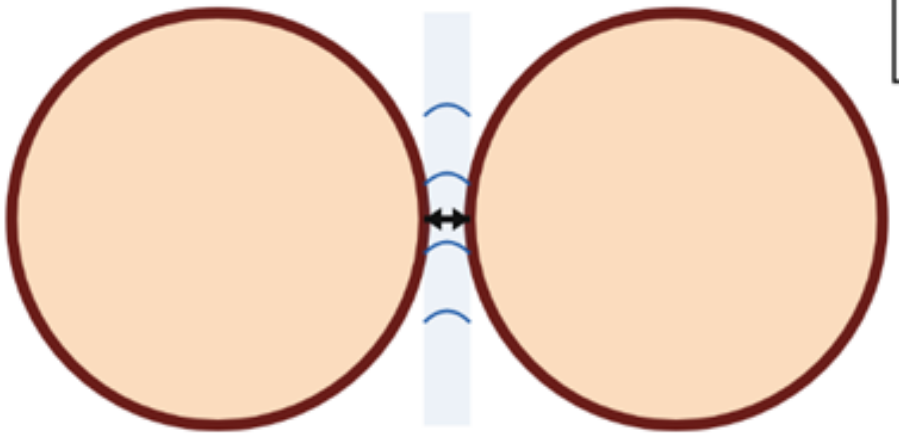
- fluctuation-induced forces
- nanometer membrane gaps
- structured electromagnetic mode spectra

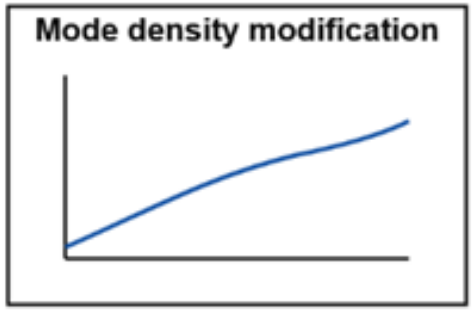
These structured fluctuations create reproducible physical configurations
that form **proto-informational states**.
These create stable protocell clusters and reproducible fluctuation patterns.

Casimir-Lifshitz Coupling

- Geometry-dependent attraction
- Not chemical bonding
- Fluctuation-mediated geometry selection

L = 2–100 nm





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

$$R_{eff} = \left(R_1 \cdot R_2 \right) / \left(R_1 + R_2 \right)$$

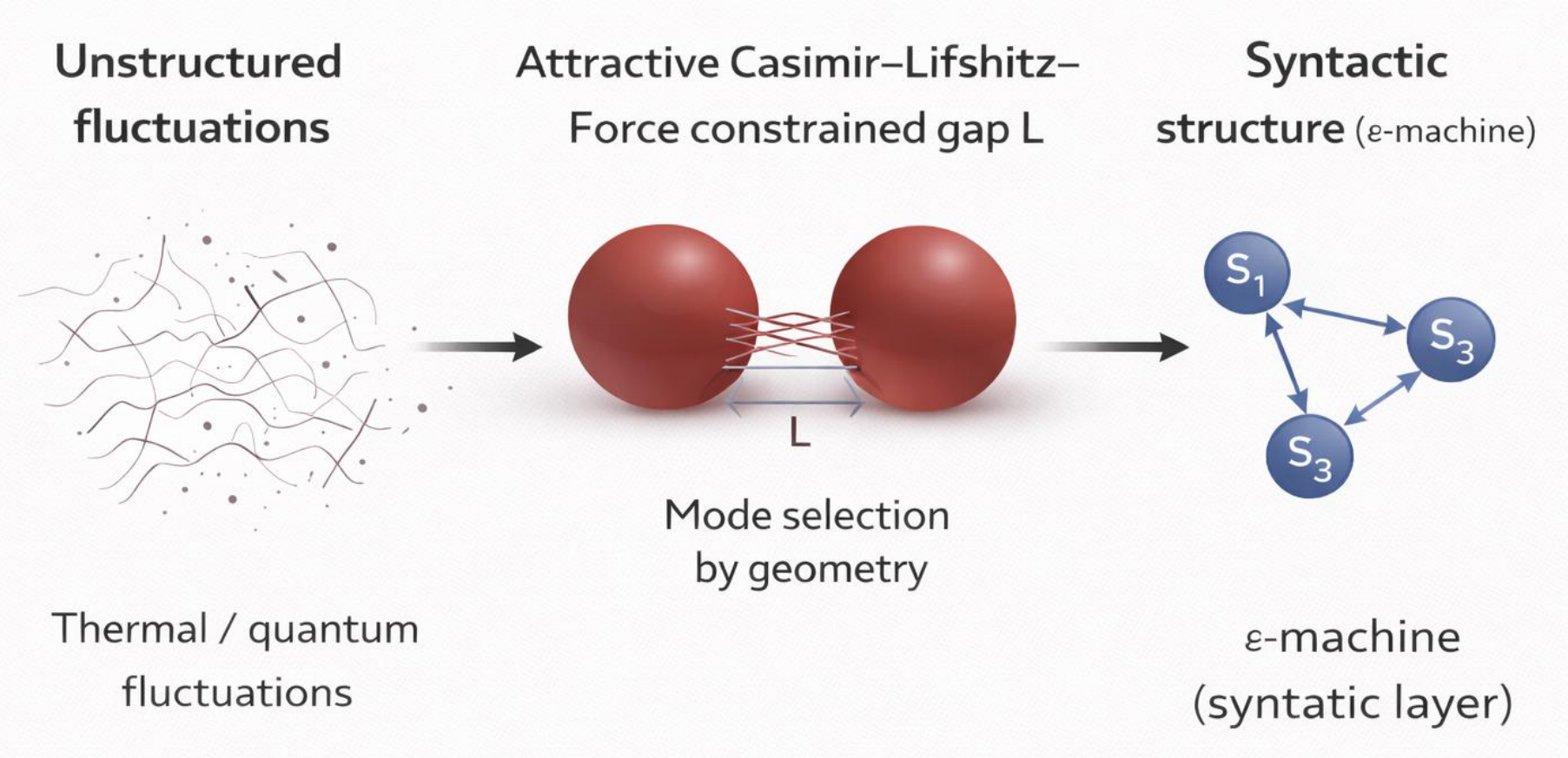
Syntax: Structured Patterns

Syntax corresponds to **reproducible physical patterns**.

Computational Mechanics describes these patterns using **ε-machines**.

ε-machines identify minimal predictive states that
capture causal structure in system dynamics.

Physical origin of syntactic structure in protocell clusters



ε-Machines as Physical Syntax

An **ε-machine** groups past histories that lead to identical future predictions.

ε-machines = **minimal predictive state models**
Each **equivalence class** defines a **causal state**.

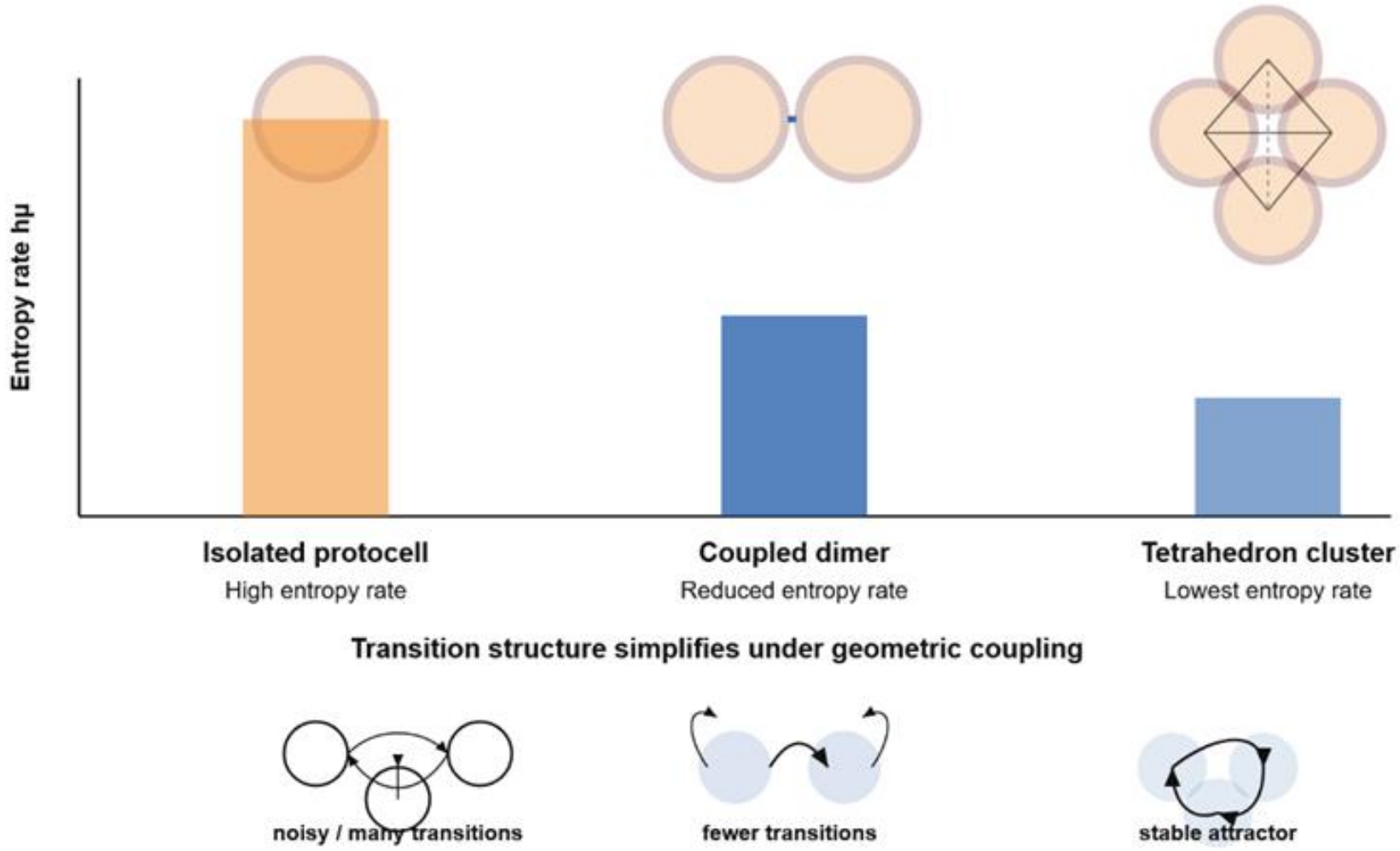
In protocell systems, observable variables include:

- inter-cell distances
- field intensities
- proton densities

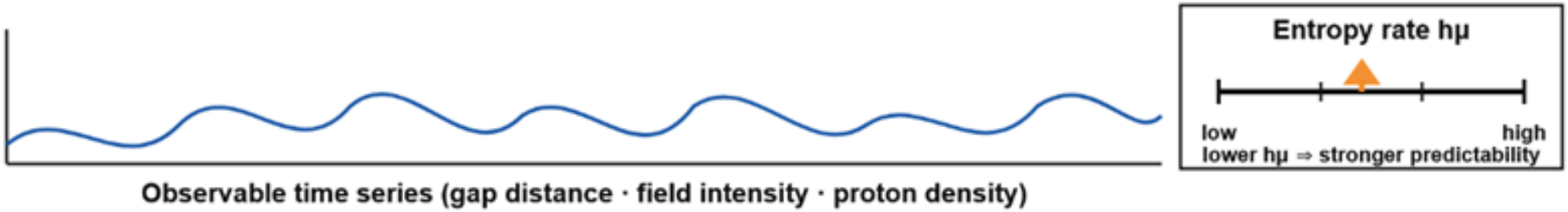
These represent **syntax of the system**.

These states form the **syntactic information layer**.

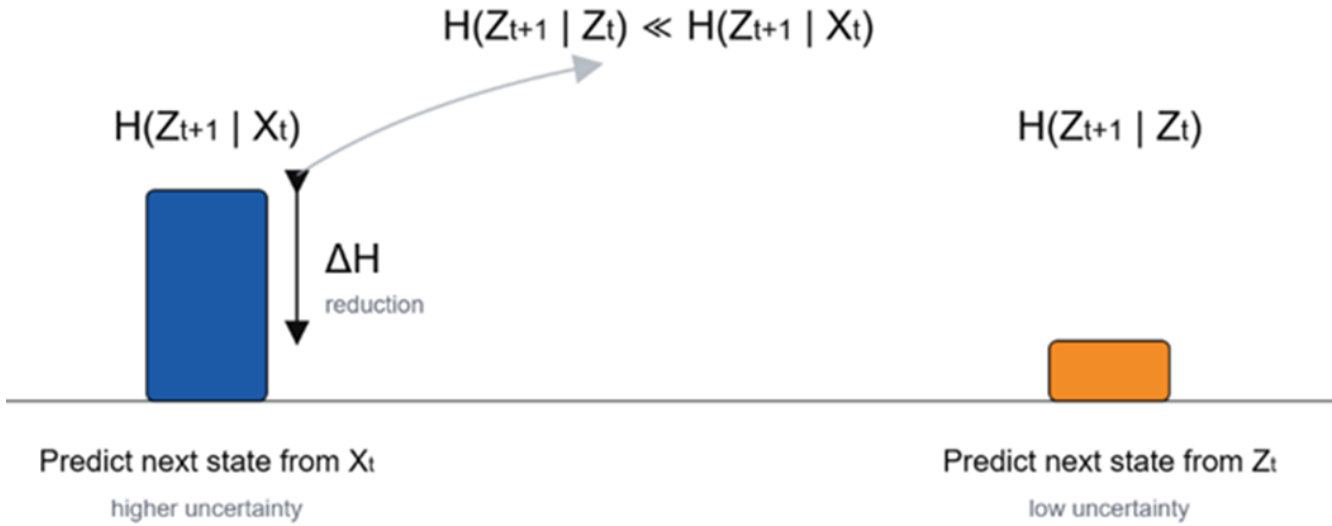
From Noise to Causal States



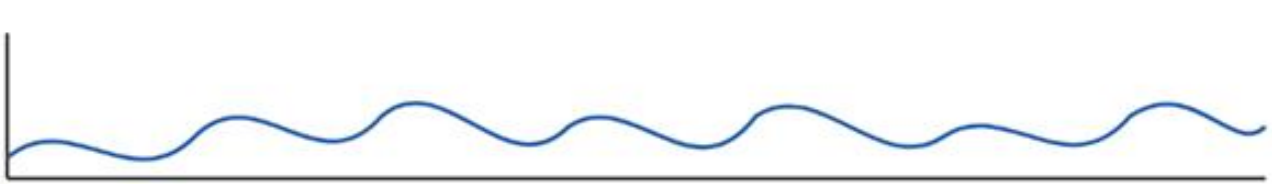
Quantifying syntactic order: entropy rate hμ



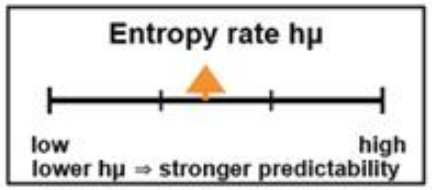
- **Entropy rate: hμ = H [X_t | S_t]** (residual unpredictability given syntactic state).
- **CL coupling** reduces accessible fluctuation space → **lower hμ** than isolated vesicles.
- **Prediction:** clusters show compressible, state-dependent time series.



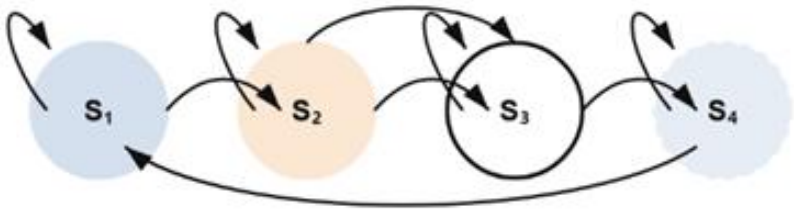
Syntax via ε-Machines



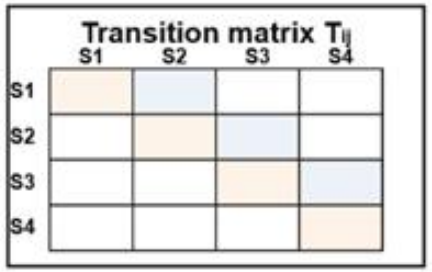
Observable time series (gap distance · field intensity · proton density)



Histories lump into causal states with identical future distributions



Finite causal states · Transition probabilities · Entropy rate hμ



Semantics: Functional Categories

Semantics emerges when different syntactic states produce the same physical effect.

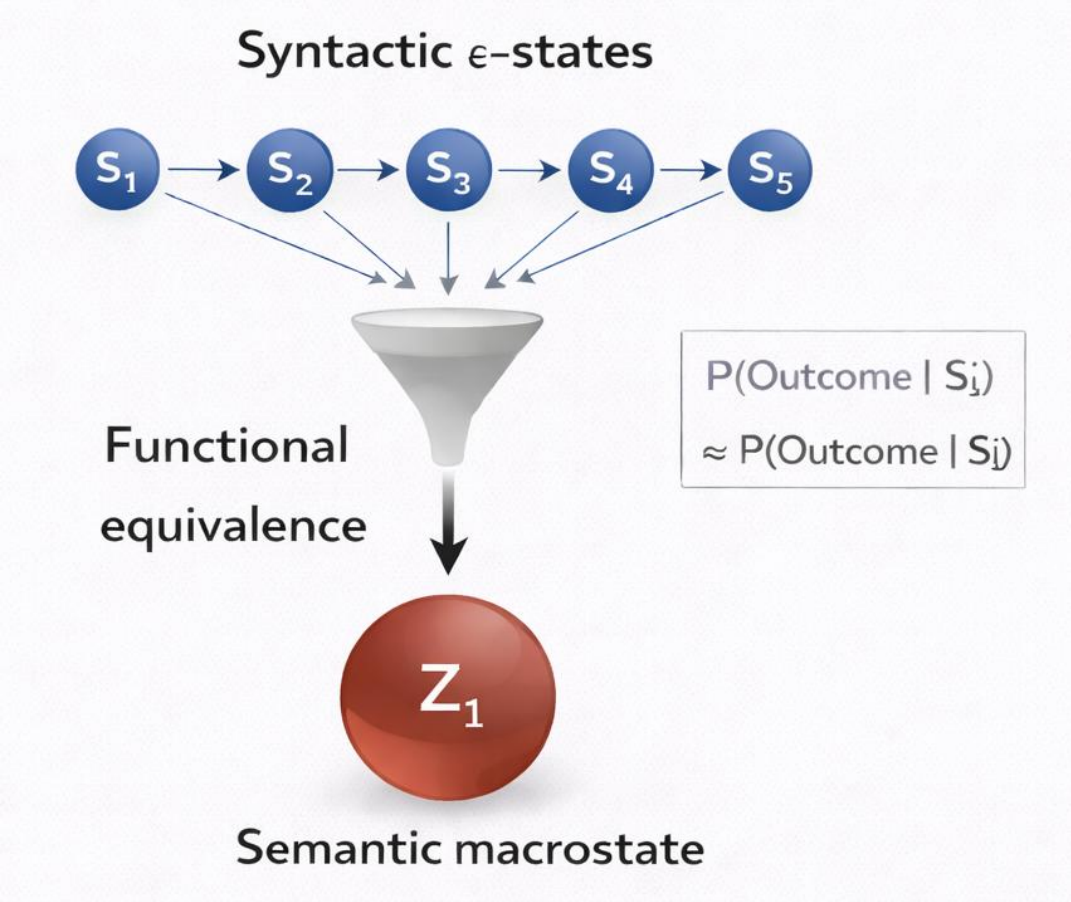
Key idea: different syntactic states produce the **same physical effect**
→ grouped into **semantic macrostates** via **lumping** (dt. Zusammenfassung, es. Agrupamiento)
Through **functional lumping**, **multiple ε-states** become **semantic macrostates**.

Examples:

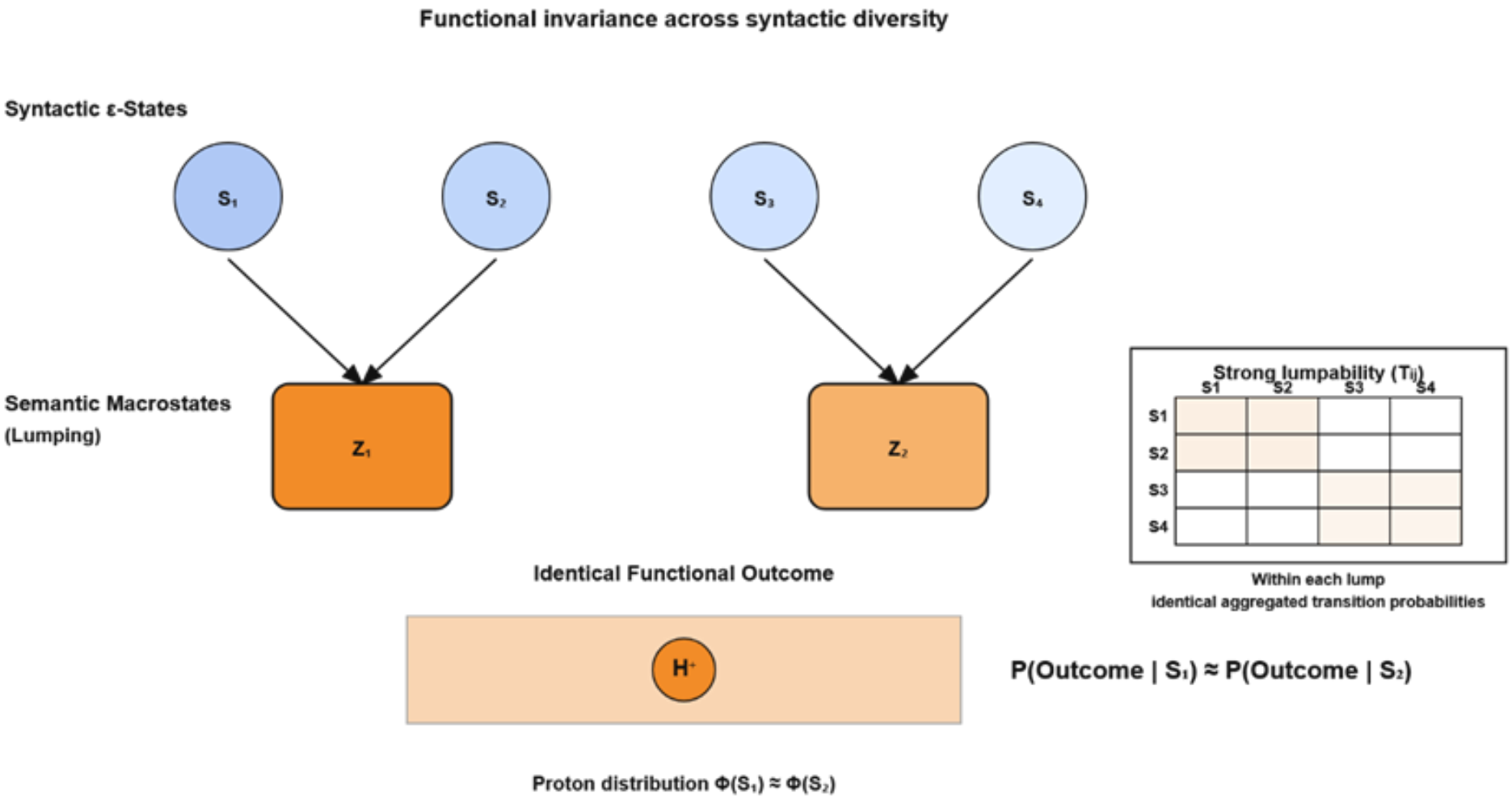
- proton focusing
- adsorption enhancement
- permeability changes

Meaning emerges as **functional invariance** **across patterns.**

Semantic macrostates emerge by functional lumping of syntax



From Syntax to Semantics



Proto-Semantic Alphabet

Structured functional category system — Syntax → Semantic Equivalence → Functional Task Potential

Lipid Packing Density

Activation mode

Resonant Modes

Adsorption enhancement

Field Gradients

Proton transfer

Energetic Wells

Transfer windows

Synchronization

Cluster stability

Interference Patches

Reaction zones

Pragmatics: Cluster-Level Tasks

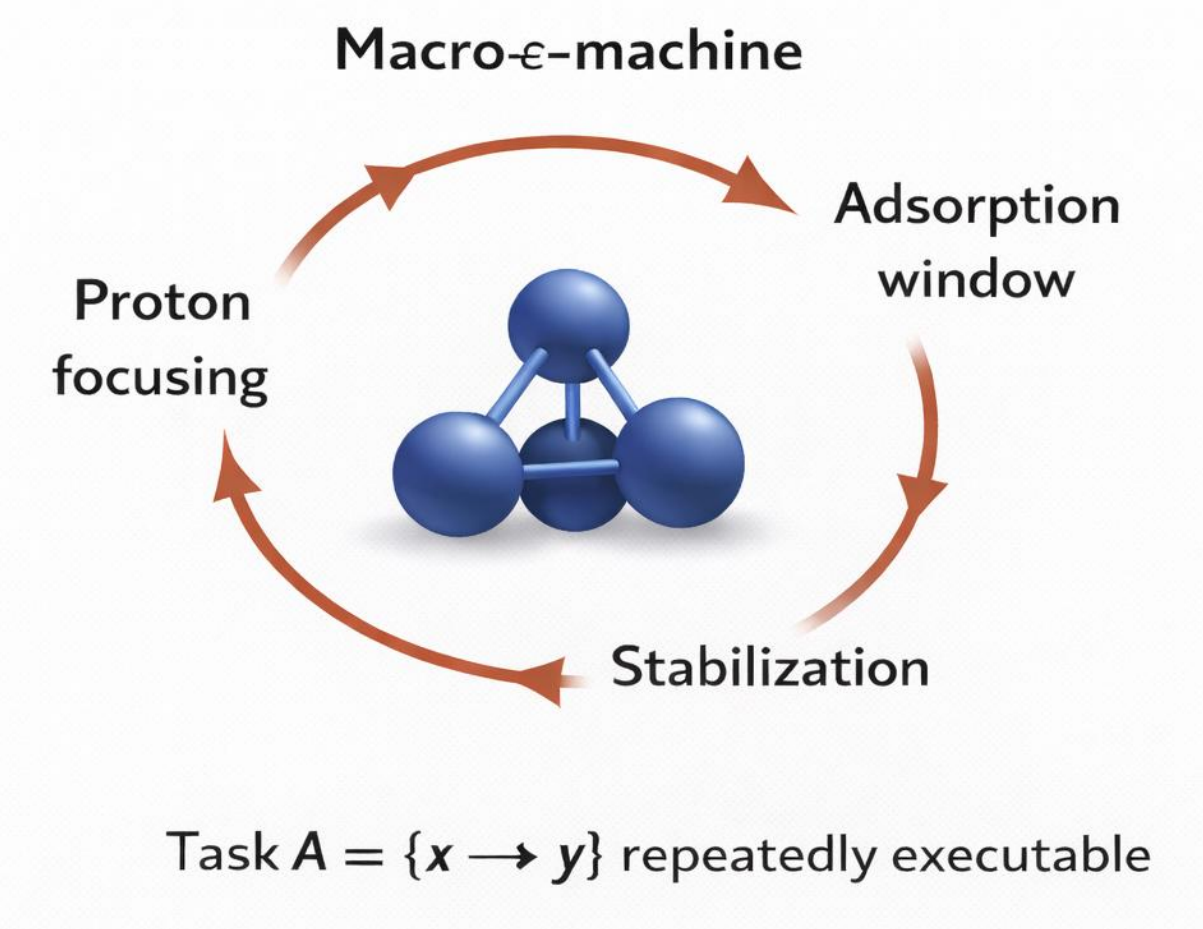
Pragmatics appears when clusters perform **reproducible physical tasks**.

Examples include:

- proton focusing in nanogaps
- adsorption windows
- exchange channels
- geometric stabilization

Clusters behave as **macro-ε-machines**.
These clusters act as **prebiotic partial constructors**.

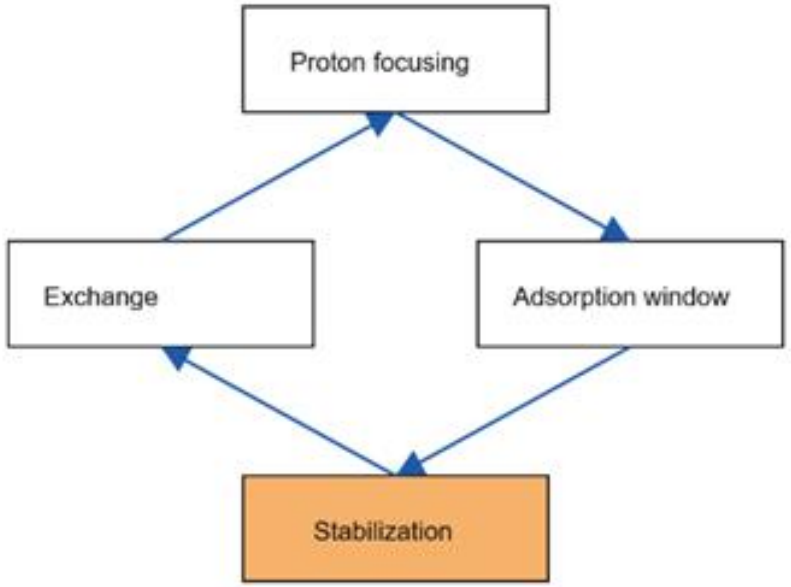
Macro-ε-machines implement repeatable prebiotic functional tasks → Pragmatics



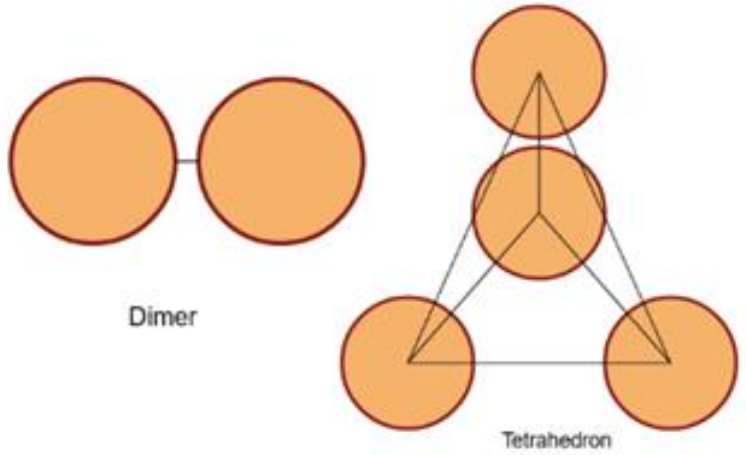
Proto-Constructors

Emergent macro-ε-machine task loops in protocell clusters

Closed Task Loop



Macro-State Geometries



Meaning: Stable macro-structure performing recurrent physical tasks

Proto-Pragmatic Functional Meaning

Functional meaning arises when a structure reliably performs a task.

Examples:

- resonant modes → adsorption enhancement
- field gradients → proton transfer
- energetic wells → molecular exchange
- synchronized modes → cluster stability

Meaning emerges from **physical task structures**.

Constructor Theory x Proto-Pragmatics Tasks

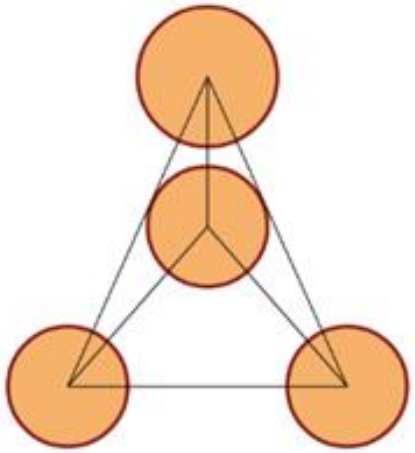
Tasks, constructors, and macro-ε-machines over cluster geometries

Constructor-theoretic tasks

$A = \{ x \rightarrow y \}$

$A(t : 0, +\infty) : (x, C) \rightarrow (y, C)$

A possible $\Leftrightarrow \exists$ constructor C



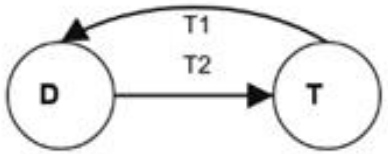
Proto-pragmatic task set

T1 : proton focusing

T2 : adsorption in gap

T3 : regulated exchange

Macro-ε-machines (cluster geometries)



Unified Architecture (1)

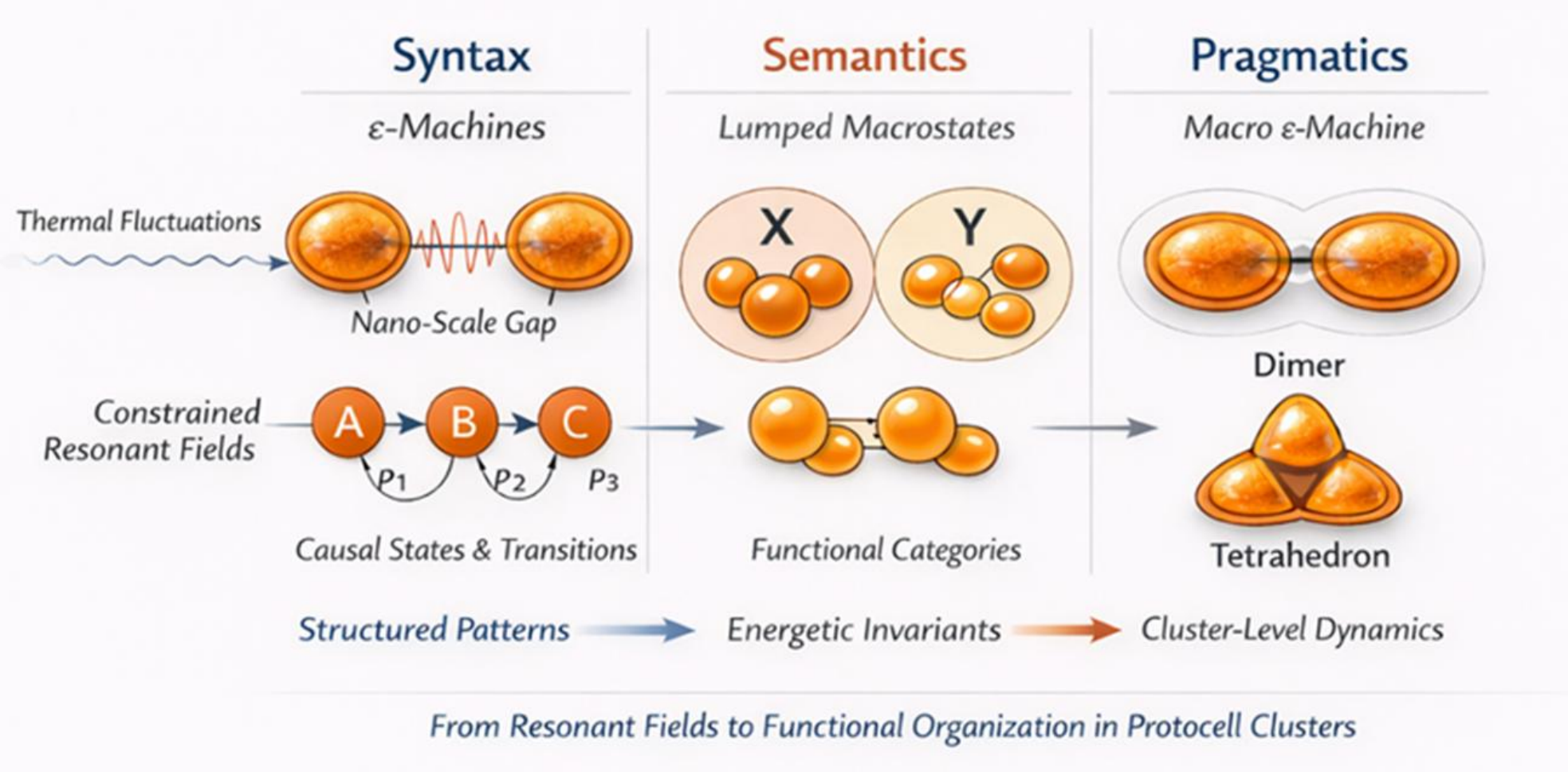
Pragmatics (=Tasks or actions enabled by those states)
Macro-ε-machines implement repeatable tasks

Semantics (=Functional meaning of those states)
Functional lumping of syntactic states

Syntax (=Structure of patterns or states)
ε-Machines causal states

Physics
Casimir-Lifshitz coupling structures fluctuation spectra

Unified Architecture (2)



Experimental Accessibility

Physical observables and falsifiable predictions in structured protocell systems

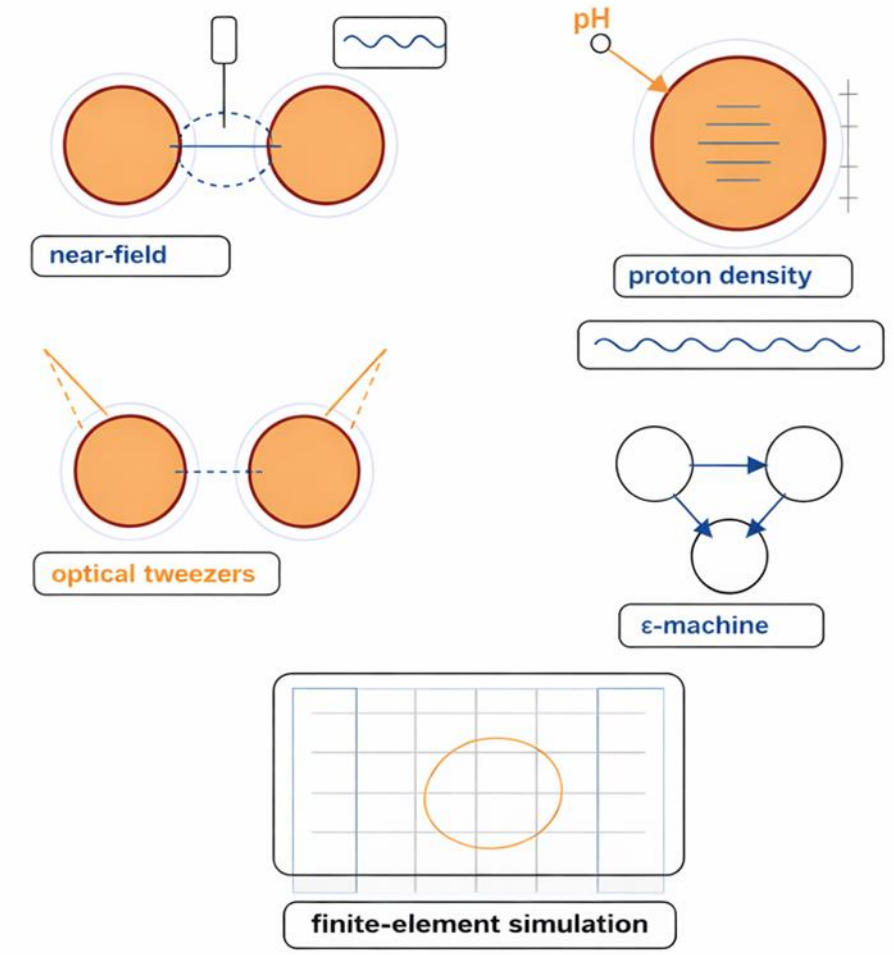
Experimental Methods

- Measure near-field fluctuations
- Track proton density with pH probes
- Optical tweezers assemble dimers
- Reconstruct ε-machines from time series
- Finite-element simulation of Casimir forces

Predictions

- Entropy reduction in coupled vesicles
- Stable proton funnels in tetrahedra
- Repeatable adsorption enhancement

This framework generates falsifiable claims.



Implications for Origin of Life

Protocell clusters may support a **hierarchical information architecture**:

Syntax: ordered fluctuation patterns

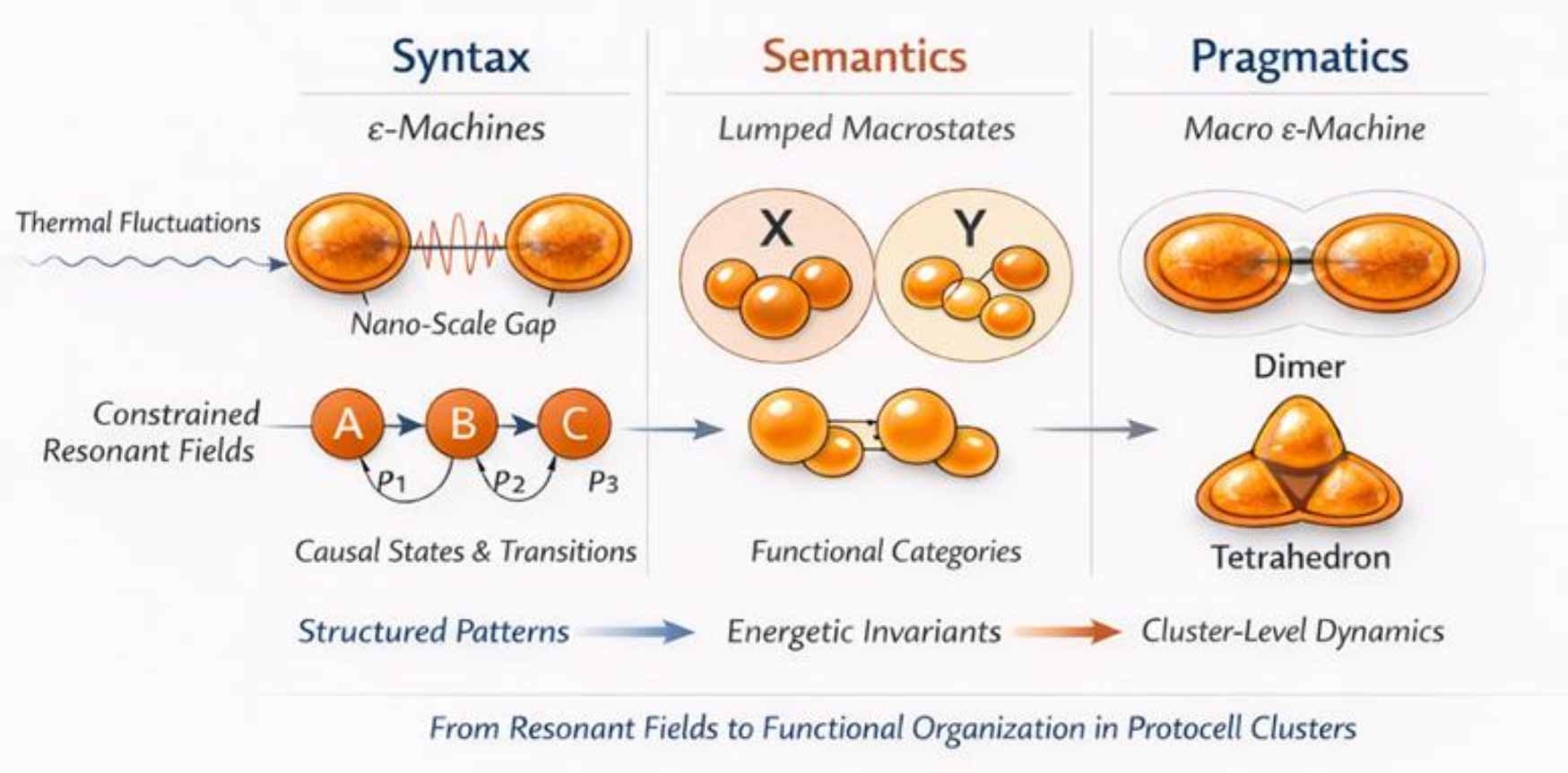
Semantics: functional invariances

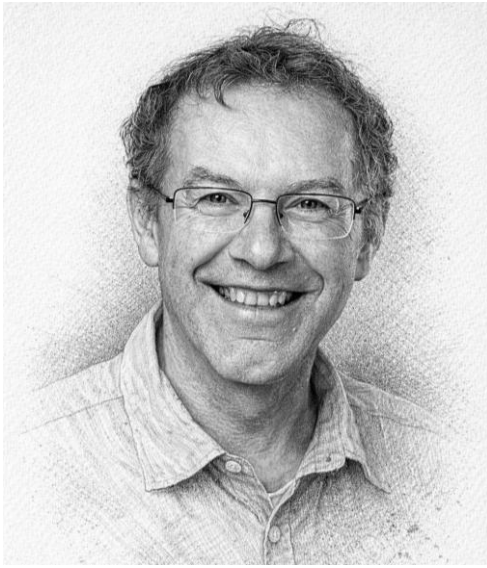
Pragmatics: cluster-level task execution

Information and **meaning** may emerge before genetic systems exist.

Thank you very much for your attention.

Are there any questions?





Michael Massoth
Contact:
michael.massoth@h-da.de