Towards an understanding of quantum field theory as time-symmetric statistical mechanics

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Overview

What I want to convince you of

Three claims, in increasing order of speculativeness:

- The quantum measurement problem is a serious problem, and single-world realism deserves to be taken seriously.
- The no-go theorems on “hidden variables” shouldn’t scare us off.
- There is a live programme (with Mritunjay Tyagi) for deriving quantum field theory as the statistical mechanics of a time-symmetric stochastic dynamics.

Overview

Motivation: The quantum measurement problem

Rough outline:

- Empirical checks of quantum theories involve detecting sharp values of dynamical variables (position, momentum, spin,...).
- But the assumption that (all? any?) dynamical variables have sharp values is difficult to reconcile with the quantum formalism.
- This makes it difficult to see how the world can possibly be such that quantum theory is as successful as it manifestly is.

More concretely

Consider a system prepared in a quantum state $|\psi\rangle$.

- Quantum theory does not specify any values of dynamical variables beyond (perhaps) those for which $|\psi\rangle$ is an eigenstate.
- But what if we measure a dynamical variable $\hat{A}$ for which $|\psi\rangle$ is not an eigenstate $|a_i\rangle$?
- We do obtain a sharp value; how does quantum theory account for it?
- Standard answer: "measurement collapse", $|\psi\rangle \mapsto |a_i\rangle$.

Problem: When and why does "collapse" occur? "Measurement" is an unsharp, anthropocentric notion, not a fundamental one.

Three types of reactions

Three broad families of interpretations can be distinguished:

- *Anti-realism:* statements about sharp values generally meaningless.
- *Many worlds:* quantum states are real and never collapse; sharp outcomes are perspectival, not objective.
- *Single-world realism:* many (all?) dynamical variables have sharp values after all.

Here: focus on exploring the options for single-world realism.

Einstein's expectation

The concrete inspiration:

> *[Q]uantum theory would, within the framework of future physics, take an approximately analogous position to the statistical mechanics within the framework of classical mechanics. I am rather firmly convinced that the development of physics will be of this type; but the path will be lengthy and difficult. (Einstein 1947)*

The measurement problem is purely quantum

Classical mechanics has no measurement problem:

- Any system has a sharp phase space location at any time.
- Dynamical variables are functions A on phase space, all sharp-valued.
- $\langle A \rangle = \int_\Gamma A(\mathbf{z})\, P(\mathbf{z})\, d\mathbf{z}$, with P broadly epistemic.

Conventional wisdom about quantum theory:

- Dynamical variables are self-adjoint operators $\hat{A}$.
- $\langle \hat{A} \rangle = \mathrm{Tr}(\hat{A}\hat{\rho})$.
- Not all (perhaps none) of the $\hat{A}$ simultaneously have sharp values.
- Classical A are "not even defined" in quantum theory.

Why not sharp values for all dynamical variables?

One standard answer: the Kochen–Specker theorem.

KS assumes, for any valuation v:

- KS1: $v(\hat{A}) \in \mathrm{spec}(\hat{A})$ (values are eigenvalues).
- KS2(a): $v(\hat{A} + \hat{B}) = v(\hat{A}) + v(\hat{B})$ (for commuting $\hat{A}, \hat{B}$).
- KS2(b): $v(\hat{A}\hat{B}) = v(\hat{A}) \cdot v(\hat{B})$ (for commuting $\hat{A}, \hat{B}$).

KS shows: no such valuation exists on Hilbert spaces of dim ≥ 3.

But: why should KS1, KS2(a), KS2(b) all hold?

A circularity in this reasoning

The conventional reading goes:

1. Dynamical variables *are* self-adjoint operators $\hat{A}$.
2. KS shows no consistent value-assignment on such operators.
3. Therefore not all dynamical variables have sharp values.

But step 1 presupposes that dynamical variables are operators, not phase space function.

Shift the perspective: treat *classical phase-space functions* $A(\mathbf{z})$ as the dynamical variables. Then the question becomes: is there a quantization such that

$$\mathrm{Tr}(\hat{A}\hat{\rho}) \;=\; \int_\Gamma A(\mathbf{z})\,P(\mathbf{z})\,d\mathbf{z}$$

for some bona fide probability density P?

Mathematically, A *is* related to $\hat{A}$ by *quantization*:

$$Q: \; A(\mathbf{z}) \longmapsto \hat{A}\,.$$

- Quantization schemes are not unique: Weyl, Wick, Anti-Wick, Berezin–Toeplitz,. . .
- Different schemes give different operators for the same classical A.
- Key idea: A remains the dynamical variable. $\hat{A}$ merely *represents* it for calculations.

Observation: This makes Kochen–Specker obsolete...

KS2(b) — "$\hat{C} = \hat{A}\hat{B}$ implies $v(\hat{C}) = v(\hat{A}) \cdot v(\hat{B})$" — is implausible in light of quantization:

- If A, B, C are the dynamical variables rather than $\hat{A}$, $\hat{B}$, $\hat{C}$, we expect that $C = AB$ implies $v(C) = v(A) \cdot v(B)$.
- But quantizations do not preserve algebraic relations!
- For example $A(x, p) = B(x, p) = xp$ with Weyl operator $\hat{A} = \hat{B} = \frac{1}{2}(\hat{X}\hat{P} + \hat{P}\hat{X})$.
- Then $\hat{A}^2 = \hat{B}^2$ is *not* the Weyl operator of $(xp)^2$.
- Hence KS2(b) is not plausible to begin with.

An even simpler example: in coherent-state quantization, the operator representing x^2 is $\hat{X}^2 + \ell^2 \hat{I}$ for some length scale $\ell \neq 0$.

Details: Friederich & Tyagi, *Annals of Physics* **487** (2026), 170355.

Anti-Wick (Berezin–Toeplitz) quantization

Candidate scheme for the classical/quantum link:

$$A \longmapsto \hat{A} = \frac{1}{\pi} \int A(\mathbf{z})\, |\mathbf{z}\rangle\langle\mathbf{z}|\, d\mathbf{z}\,,$$

where $|\mathbf{z}\rangle$ are coherent states. $\hat{A}$ is a *Toeplitz operator*.

- Polynomial A are mapped to operators in anti-normal (Anti-Wick) order.
- Positive $A \geq 0$ are mapped to positive operators $\hat{A} \geq 0$ — unlike Weyl quantization.
- Natural home: the Segal–Bargmann space of holomorphic functions.

See Friederich, *Physics Letters A* **567** (2026), 131226.

What gets to be the probability density?

The *Husimi Q-function*:

$$Q(\mathbf{z}) \;=\; \frac{1}{\pi}\langle \mathbf{z}|\hat{\rho}|\mathbf{z}\rangle\,.$$

Indeed:

$$\begin{aligned}\mathrm{Tr}(\hat{\rho}\hat{A}) &= \mathrm{Tr}\left(\hat{\rho}\,\frac{1}{\pi}\int A(\mathbf{z})|\mathbf{z}\rangle\langle\mathbf{z}|\,d\mathbf{z}\right)\\ &= \int A(\mathbf{z})\,Q(\mathbf{z})\,d\mathbf{z}\,.\end{aligned}$$

Q has the formal features of a probability density: non-negative, normalized.

Empirical adequacy of treating Q as one: see Friederich 2024, *BJPS*.

Key question: Can we give a *trajectory interpretation* of the evolution of Q?

The goal:

- Quantum states/Husimi functions as "epistemic" probability distributions over sharp underlying phase-space values — not as physical quantities themselves.
- Collapse as Bayesian updating in the light of new evidence, not as a physical process.
- If achieved: no measurement problem to begin with. All dynamical variables have sharp (if imprecisely known) values at all times.

Concretely: look for a *stochastic* generalization of classical Hamiltonian mechanics, and check whether we recover QFT as its statistical mechanics.

Two sides of the same problem:

- *From above:* find a stochastic generalization of classical mechanics whose statistical mechanics is (recognizably) quantum field theory.
- *From below:* find a trajectory interpretation of the Husimi evolution equation.

The dynamics we look for should:

- be time-symmetric,
- not make the quantum state itself a dynamical agent,
- admit a consistent (continuous) trajectory interpretation.

A challenge: stochasticity and time symmetry

Ordinary stochastic dynamics — diffusion, Fokker–Planck — is manifestly time-asymmetric.

A standard Fokker–Planck equation for diffusion

$$\partial_t \rho \;=\; -\partial_i (a^i \rho) \;+\; \tfrac{1}{2}\,\partial_i \partial_j (D^{ij} \rho)$$

has a clear forward-in-time character: D^{ij} is positive semi-definite.

The forward-conditional probability densities $\rho(x, t + \Delta t \mid x_0, t)$ (Green functions) are defined, the backward ones $\rho(x, t \mid x_0, t + \Delta t)$ aren't.

An important observation by Watanabe (1965): If forward-probabilities $P(x, t + \Delta t \mid x_0, t)$ are *law-like*, backward-probabilities generally aren't.

But the Schrödinger equation does *not* qualitatively distinguish time directions. So any stochastic underpinning of quantum mechanics must differ substantively from standard diffusion.

Husimi evolution, independently motivated

Part I (arXiv:2603.20399):

One can motivate an evolution equation for ρ that generalizes the classical Liouville equation directly from natural constraints:

- reduction to the classical Liouville equation in the appropriate limit,
- time-reversal invariance,
- preservation of non-negativity and normalization,
- Fokker–Planck form (up to higher derivatives).

Evolution equation in complex coordinates

$$\frac{\partial Q}{\partial t} = i \sum_i \left[\frac{\partial}{\partial \alpha_i}\Big(\frac{\partial H}{\partial \alpha_i^*}\, Q \Big) - \frac{\partial}{\partial \alpha_i^*}\Big(\frac{\partial H}{\partial \alpha_i}\, Q \Big) \right]$$

$$+ \frac{i\hbar}{2} \sum_{i,j} \left\{ \frac{\partial^2}{\partial \alpha_i \partial \alpha_j}\Big(\frac{\partial^2 H}{\partial \alpha_i^* \partial \alpha_j^*}\, Q \Big) - \frac{\partial^2}{\partial \alpha_i^* \partial \alpha_j^*}\Big(\frac{\partial^2 H}{\partial \alpha_i \partial \alpha_j}\, Q \Big) \right\}.$$

In dimensionless real phase space coordinates, the second term (the "diffusion" contribution) takes the form

$$\big(\partial_t Q\big)_{\mathrm{diff}} = \frac{1}{4\hbar} \sum_{a,b=1}^{2N} \tilde{\partial}_a \tilde{\partial}_b \Big(\big[\tilde{H}'',\, J\big]_{ab}\, Q \Big)\,.$$

The diffusion matrix $D \propto [\tilde{H}'', J]$ has zero trace, i.e. it is intrinsically indefinite.

It turns out: In some QFTs, this is the Husimi evolution equation.

Scope of the result:

- Applies to bosonic QFTs with at most density-density quartic interactions (e.g. Bose-Hubbbard).
- For beyond density-density quartic interaction, the Husimi function evolution has beyond-diffusion terms $O(\hbar^2)$.

Can we give a trajectory interpretation for the QFTs within the scope?

Why we need a (field) trajectory interpretation

Part II (arXiv:2603.28983):

A trajectory interpretation supplies, below the level of $Q(\mathbf{z}, t)$, a measure on *paths* $\phi(t)$ in phase space such that:

- $Q(\mathbf{z}, t)$ is the marginal of this path measure at time t,
- every individual system has a sharp phase-space location at every time.

The path measure encodes the microdynamics.

Compare: So far, we have the equivalent of the Liouville equation. We are missing the equivalent of Newton's law/Hamilton's equations.

Drummond's construction (2021)

Drummond develops a path measure for the bosonic QFTs where the Husimi evolution has Fokker-Planck form. In coordinates $\phi = (\mathbf{x}, \mathbf{y})$ in which the traceless diffusion is diagonal:

$$\mathbf{x}(t) = \mathbf{x}_0 + \int_{t_0}^{t} \mathbf{a}^x(\phi(t'))\, dt' + \int_{t_0}^{t} d\mathbf{w}^x\,,$$
$$\mathbf{y}(t) = \mathbf{y}_f + \int_{t_f}^{t} \mathbf{a}^y(\phi(t'))\, dt' + \int_{t_f}^{t} d\mathbf{w}^y\,.$$

Mixed-time boundary conditions $(\mathbf{x}_0, \mathbf{y}_f)$. The path probability is given by a *real* action:

$$\mathbb{P}[\phi(\cdot) \mid \mathbf{x}_0, \mathbf{y}_f] \;\propto\; \exp\bigl(-S[\phi]\bigr)\,.$$

This gives a genuine trajectory measure, with $\mathbf{x}$ fixed an the beginning and $\mathbf{y}$ at the end.

Three levels of ensembles:

- E_1: an ensemble of trajectories from fixed boundary data $(\mathbf{x}_0, \mathbf{y}_f)$.
- E_2: a mixture $\rho(\phi, t) = \int G(\phi, t \mid \phi_{\mathrm{IN}})\, P(\phi_{\mathrm{IN}})\, d\phi_{\mathrm{IN}}$ over boundary data.
- E_3: an E_2-ensemble *conditioned* on an initial Q-function.

Drummond shows that every E_1- and E_2-ensemble satisfies the generalized Fokker–Planck equation. Every Husimi Q-function satisfies it too.

Does it follow that every Q-function is an E_2-ensemble? Unfortunately not! ("Affirming the consequent").

The central mathematical challenge:

- We want: every Husimi Q-function is representable as the marginal of a Drummond-type path measure, for some boundary distribution $P(\phi_{\mathrm{IN}})$.
- We have: this is true only for a restricted class of Q-functions (E_2-representable).
- General Q-functions require E_3-conditioning, which disrupts the Drummond measure.

Closing this gap is an open technical problem of the programme.

Current direction (speculative): **Schrödinger bridges**. Construct a path measure by fixing the phase space configuration at both endpoints.

Current limitations

- **Representability gap:** still open whether every Q admits a trajectory measure.
- **Scope:** Hamiltonians with at most density-density quartic interactions .
- **No fermions:** the construction is bosonic; fermionic phase space would need anticommuting variables.
- **No manifest Lorentz covariance:** the stochastic dynamics is currently set up in a preferred foliation. Whether it is *compatible* with relativistic covariance at the statistical level is a separate, unresolved question.
- **No gauge fields (yet).**

The dynamics is non-Markovian

Drummond's explicit dynamics — the one concrete case we have — is *non-Markovian*:

$$P(\mathbf{z}_3 \mid \mathbf{z}_2, \mathbf{z}_1) \neq P(\mathbf{z}_3 \mid \mathbf{z}_2)\,.$$

The factorization is mixed, with forward-evolving **x** and backward-evolving **y** components coupling non-locally in time, the dynamics-encoding probabilities are:

$$P(\mathbf{x}_2, \mathbf{y}_1 \mid \mathbf{y}_2, \mathbf{x}_1)$$

Conditioned on boundary data the process satisfies the *Bernstein property* (Markov when pinned at both ends) — but the unconditional dynamics is genuinely non-Markovian.

Conjecture: this feature is non-accidental. A more versatile trajectory construction — even one resolving the representability gap — will inherit it.

Why this matters: no-go theorems

Most no-go theorems (Bell, PBR, Spekkens contextuality/negativity) rely on λ-*mediation*:

$$P_{M,R}(x_i \mid \lambda) \; = \; P_M(x_i \mid \lambda)\,,$$

i.e. outcome probabilities conditional on the ontic state λ are independent of the preparation R.

In our non-Markovian setting, the natural time-oriented conditional

$$P_R(\phi_2 \mid \phi_1) \; = \; P(\mathbf{x}_2, \mathbf{y}_1 \mid \mathbf{y}_2, \mathbf{x}_1) \cdot \frac{P_R(\mathbf{y}_2, \mathbf{x}_1)}{P_R(\phi_1)}$$

depends on R in a non-trivial way. λ-mediation fails.

Conclusion: Bell, PBR, Spekkens do not apply to this approach. The no-go theorems are not the real obstacle.

What has been achieved:

- A principled response to Kochen–Specker: KS2(b) is implausible in light of quantization. Anti-Wick quantization supports sharp values for all dynamical variables.
- The Husimi-Q evolution is recovered as the statistical mechanics of a time-symmetric stochastic dynamics, for certain bosonic systems.
- Non-Markovianity of the underlying dynamics means standard no-go theorems (Bell, PBR, Spekkens) do not apply.

What remains open:

- The representability gap — does every Q admit a path-measure realization?
- Generic QFTs, Lorentz covariance.

References

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Backup slides

Backup: The generalized Fokker–Planck equation

The time-symmetric evolution for Q is

$$\partial_t Q \;=\; -\partial_i(a^i Q) \;+\; \tfrac{1}{2}\,\partial_i\partial_j(D^{ij} Q) \;+\; \text{(higher derivatives)}\,,$$

where the diffusion matrix

$$D \;=\; \tfrac{1}{2\hbar}\,[\tilde{H}'', J]$$

is a commutator of the Hessian of the Anti-Wick symbol of H with the symplectic form. It is *traceless* — hence indefinite — hence not a standard positive-semi-definite diffusion.

For Hamiltonians with up to density-density quartic interactions, the higher derivatives vanish and the equation closes at the Fokker–Planck order.

Backup: Bernstein property

A process $\{\phi_t\}_{t\in[s,u]}$ conditioned on ϕ_s, ϕ_u has the *Bernstein property* if, for $s \le t_1 < t_2 < t_3 \le u$,

$$P(\phi_{t_1}, \phi_{t_3} \mid \phi_{t_2}, \phi_s, \phi_u) = P(\phi_{t_1} \mid \phi_{t_2}, \phi_s) \cdot P(\phi_{t_3} \mid \phi_{t_2}, \phi_u)\,.$$

Equivalently: conditioned on both endpoints, the process is Markov.

But this is not ordinary Markovianity. The factor $P(\phi_{t_3} \mid \phi_{t_2}, \phi_u)$ depends on the future endpoint. The unconditional dynamics remains non-Markovian.

Backup: Anti-Wick vs. Weyl

For a classical polynomial $A(x, p)$, different quantizations give different operators:

- *Weyl* (symmetric ordering): $xp \mapsto \frac{1}{2}(\hat{X}\hat{P} + \hat{P}\hat{X})$.
- *Anti-Wick* (coherent-state / Berezin–Toeplitz): $xp \mapsto$ Toeplitz operator with symbol xp, equal to anti-normal-ordered $\hat{P}\hat{X}$ (shifted by a constant).

Crucially: Anti-Wick maps $A \geq 0$ to $\hat{A} \geq 0$. Weyl does not.

For us, the positivity-preserving property is what makes Anti-Wick the natural candidate for linking classical phase-space variables to their quantum counterparts.

Backup: The GHZ case and single-world realism

One might worry: doesn't GHZ show that no value-assignment to x_i, y_i can reproduce the quantum correlations?

Response: GHZ rules out *forward-nomic* value assignments. With backward-nomic value assignments, GHZ correlations can be reproduced.

See Friederich, "Reproducing EPR correlations without superluminal signalling," *EPL* 150 (2025), 40001.