Causality in QFT

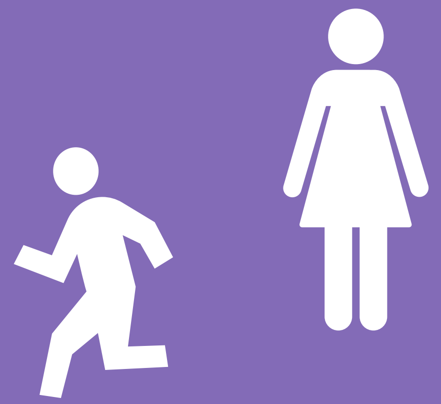
The scattering paradigm (and beyond…)

Maria Papageorgiou

ÖAW IQOQI Vienna

WINQ program- Informational Foundations for QFT , Nordita Stockholm, 20-24 May 2024

$\mathscr{E}[\rho]$



$-\mathrm{tr}(\rho \ln \rho)$

$\frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right)$

POVMs

Born's rule

Quantum interpretations?

Fundamental particles/ interactions

$\langle \hat{\Phi}(\mathrm{x}_1)\hat{\Phi}(\mathrm{x}_2)\ldots\hat{\Phi}(\mathrm{x}_n)\rangle$

Scattering amplitudes

$\mathscr{A}(O)$

Curved spacetimes?

Curved spacetimes?

$\mathscr{E}[\rho]$

Quantum interpretations?

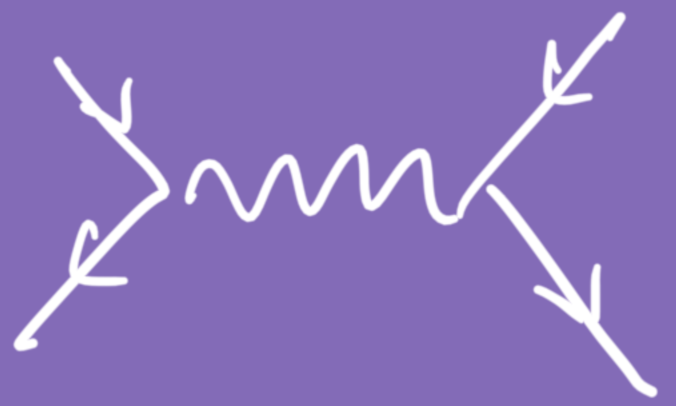
$-\mathrm{tr}(\rho \ln \rho)$

$\langle \hat{\Phi}(\mathsf{x}_1)\hat{\Phi}(\mathsf{x}_2)\ldots\hat{\Phi}(\mathsf{x}_n)\rangle$

Scattering amplitudes

$\mathscr{A}(O)$

$\frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right)$



Born's rule

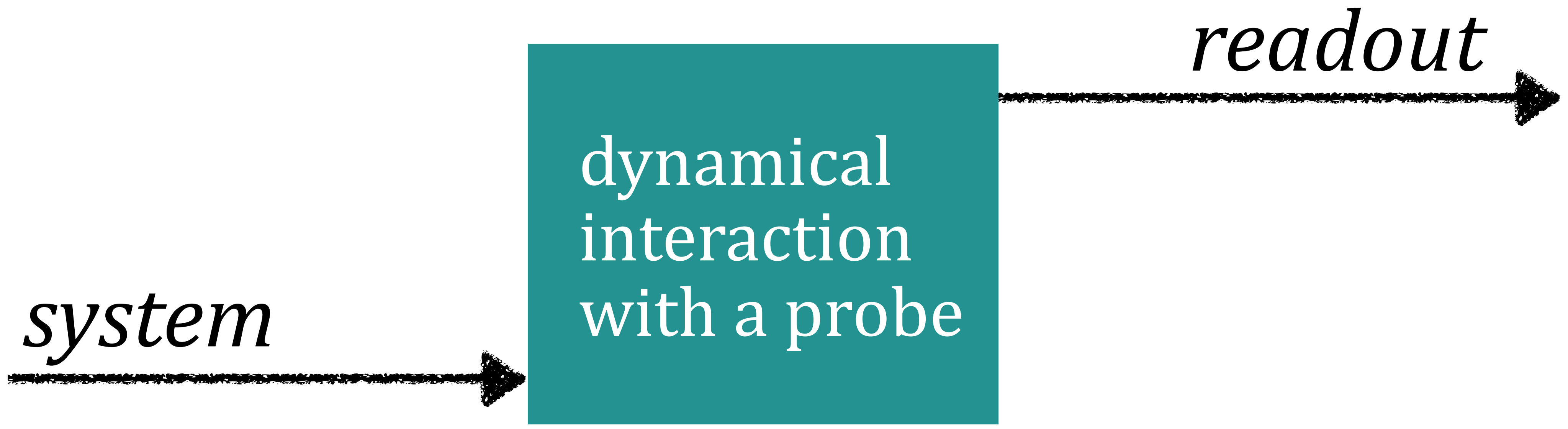
...

Overview

- The concept of quantum measurement is central in quantum information.
- **Developing a *local* measurement theory for QFT is essential for its informational foundation (currently several proposals!).**
- Of course, measurement is possible in QFT: standard predictions take the form of *asymptotic* scattering amplitudes. But, what about finite processes in space and time?
- **Existing frameworks for local measurements in QFT (that pass the causality tests) rely on a local version of scattering theory.**
- This talk is about causality in the (local vs asymptotic) scattering paradigm in QFT (and beyond?)

Standard measurement theory

The system (to be measured) must interact dynamically with another system (the probe/detector/apparatus).
By ‘reading out’ the apparatus one can infer the induced system observables.

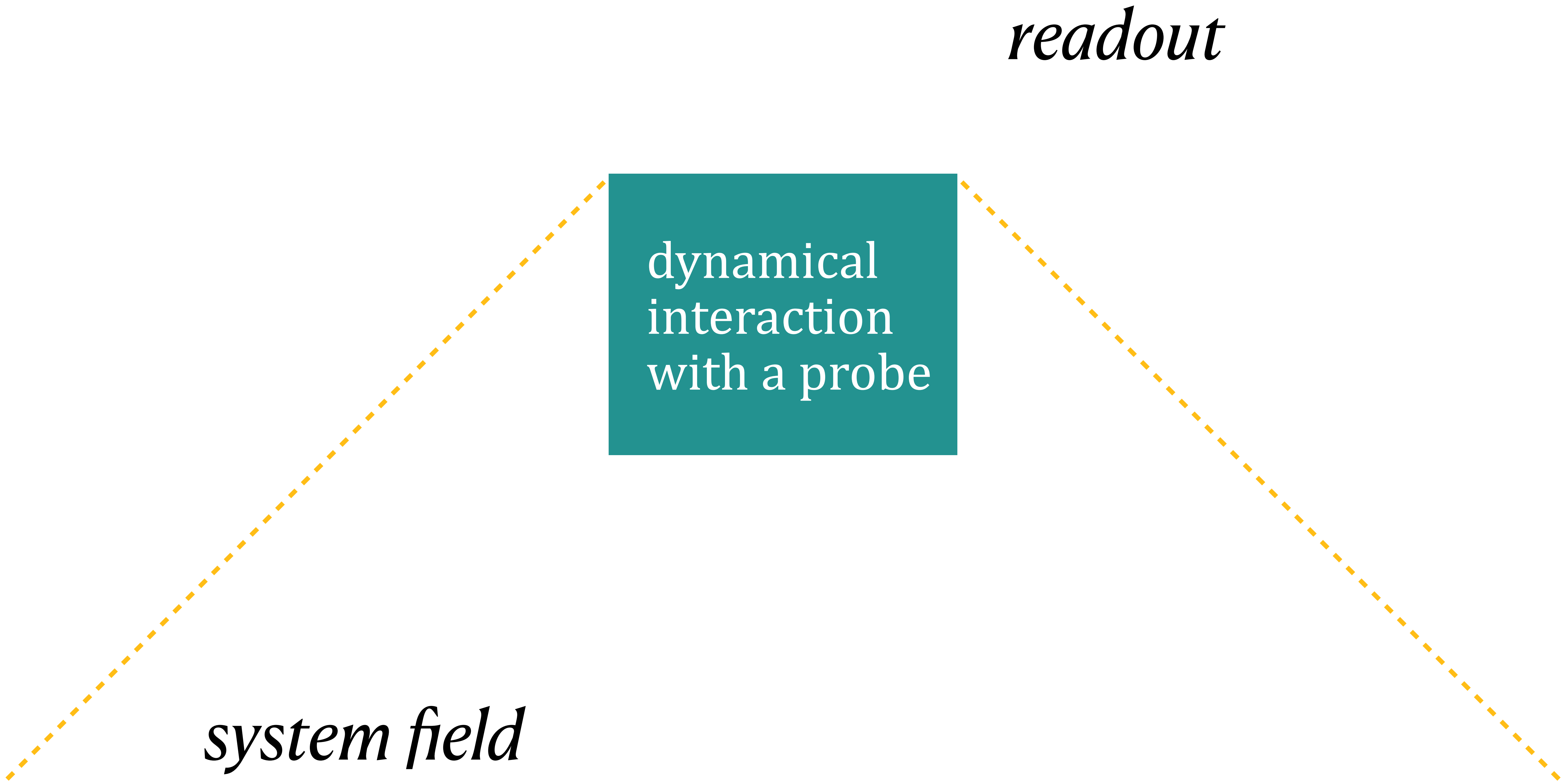


*von Neumann (1932) or Busch , Lahti and Mittelstaedt (1996)

Standard measurement theory

in QFT

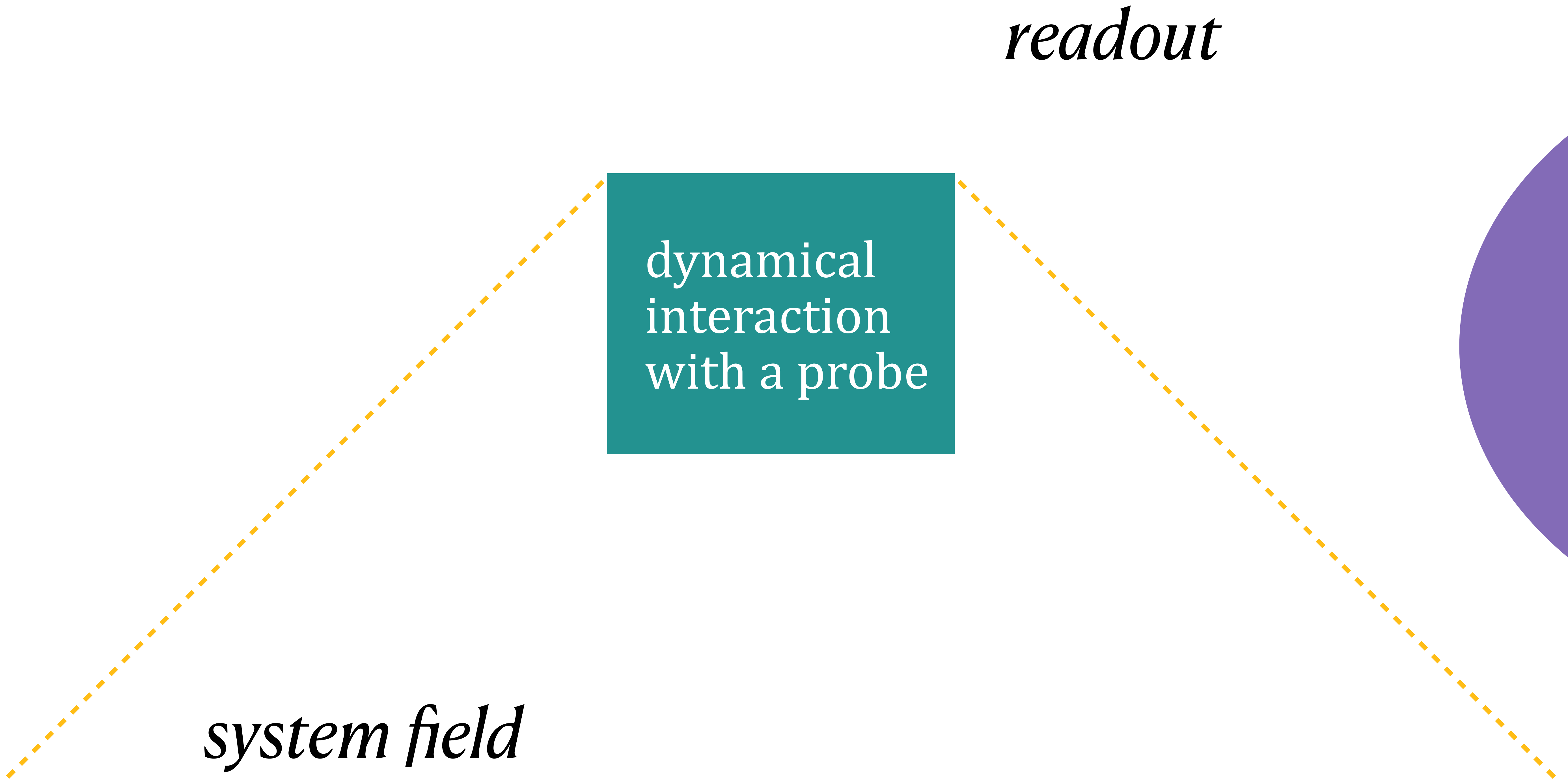
The system (to be measured) must interact dynamically with another system (the probe/detector/apparatus).
By ‘reading out’ the apparatus one can infer the induced system observables.



Standard measurement theory

in QFT

The system (to be measured) must interact dynamically with another system (the probe/detector/apparatus).
By ‘reading out’ the apparatus one can infer the induced system observables.



readout

dynamical interaction with a probe

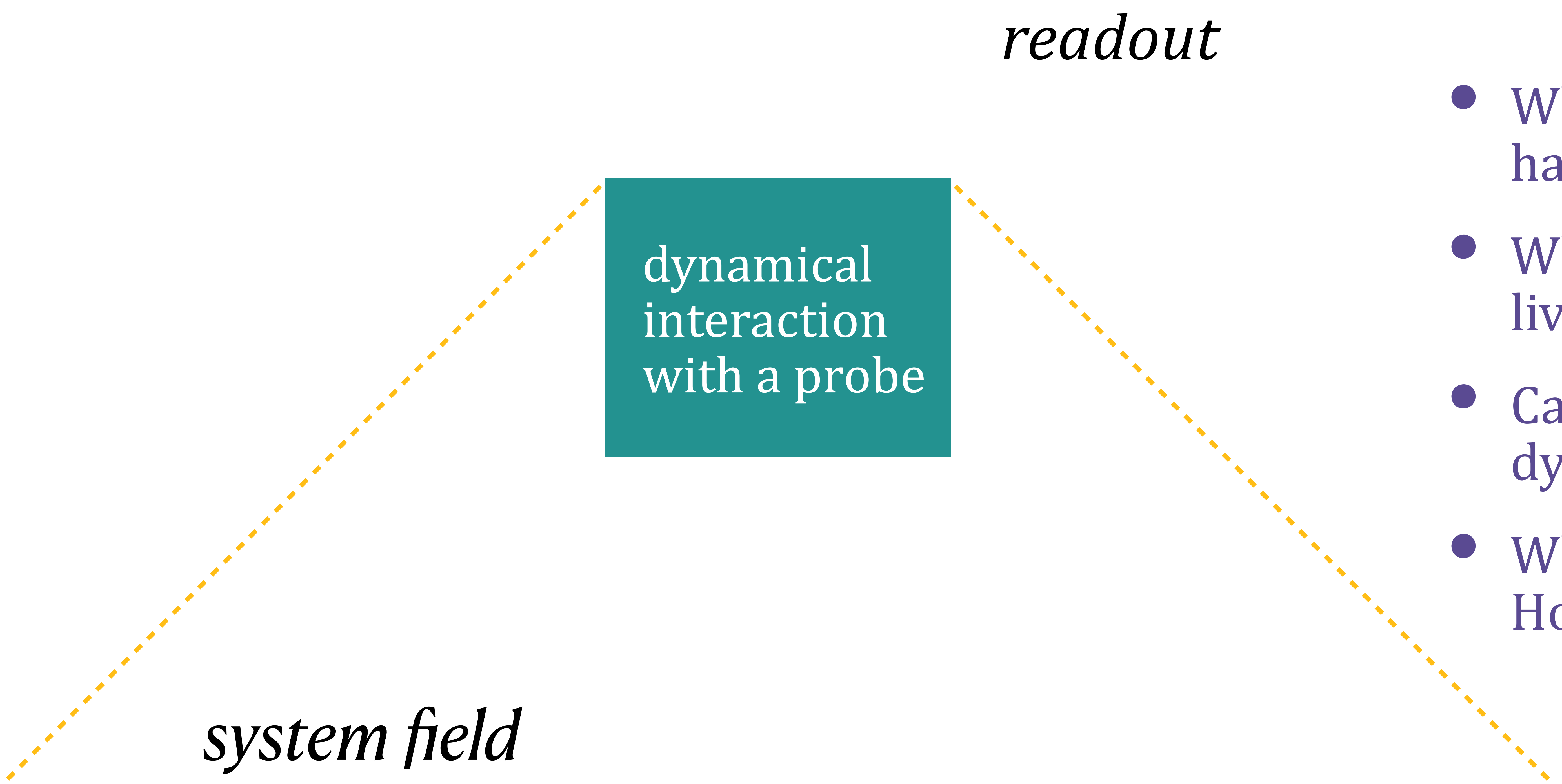
system field

Standard measurement theory within QFT= (local) scattering maps

Standard measurement theory

in QFT

The system (to be measured) must interact dynamically with another system (the probe/detector/apparatus). By ‘reading out’ the apparatus one can infer the induced system observables.



readout

dynamical interaction with a probe

system field

- When/where the does the readout happen?
- Where do the induced observables live in spacetime?
- Causality for multiple detector-field dynamical interactions?
- What is a ‘good’ detector for QFT? How to detect e.g. ‘particles’?

In sum

- Measurement process in (local) QFT is a (local) scattering process (modulo interpretation!).

$$\mathscr{F} \otimes \mathscr{P} \xrightarrow[\hat{S}]{} \text{readout}$$

- Causality can be analysed by means of the properties of *local* scattering maps (causality considerations are 'washed away' in asymptotic treatments.)
- **Interesting historical questions about the 'convergence' of standard measurement theory with scattering theory.**

*'Eliminating the 'Impossible': Recent Progress on Local Measurement Theory for Quantum Field Theory' **MP**, D. Fraser, Found Phys 54, 26 (2024)

*`Measurement in Quantum Field Theory', C. Fewster, R. Verch, Encyclopedia of Mathematical Physics, Elsevier (2024)

Historical interlude

Based on ‘Note on episodes in the history of modeling measurements in local spacetime regions using QFT’ D. Fraser, **MP**, EPJ H 48, 14 (2023).

Quantum measurement theory:

Established with the work of von Neumann (1932)

1930s .... **Quantum measurement theory for QFT today**

Local measurements in QFT:

Debate on quantum field measurability

(e.g. Bohr and Rosenfeld 1933)

Quantum measurement theory:

Established with the work of von Neumann (1932)

1930s ……

Quantum measurement theory for QFT today

Local measurements in QFT:

Debate on quantum field measurability

(e.g. Bohr and Rosenfeld 1933)

Establishment of QFT as a theory about scattering!

The scattering paradigm

- **Is QFT a theory about scattering?** In fact, standard (very successful!) predictions take the form of asymptotic scattering amplitudes.
- **How did QFT get established as a theory about asymptotic scattering?**
- Blum describes the 'paradigm shift' from instantaneous or stationary states (QM) to asymptotic scattering amplitudes (QFT).

``But the striking fact that (relativistic) QFT is so readily formulated as a theory of scattering, and that the discovery of this reformulation was so important for the development of the theory, even for its acceptance as a consistent physical theory, calls for an explanation. In what sense is QFT really a theory of scattering processes, and in what sense is the prevalence of scattering problems merely a historical contingency and an effect of good ol' American pragmatism?''

`The state is not abolished, it withers away: How quantum field theory became a theory of scattering', A. S. Blum,
Studies in History and Philosophy of Modern Physics 60:46-80 (2017).

Interesting to revisit historical episodes on modeling local (rather than asymptotic) measurements, from the early history of QFT in the 1930s until today.

- Bohr and Rosenfeld (1933) and (1950)
- Algebraic tradition of operationalism in 1950s and 1960s
- Hellwig and Kraus circa 1970
- Developments in QFTCS (1980s) and (relativistic) quantum information
- Sorkin 1993 `impossible measurements on quantum fields'
- …….

Which *local* operations/measurements are possible in QFT?

‘Note on episodes in the history of modeling measurements in local spacetime regions using QFT’ D. Fraser, **MP**, EPJ H 48, 14 (2023).

Quantum field measurability

The ‘small war of Copenhagen’

The debate about quantum field measurability in the 1930s was centered around the uncertainty principle/complementarity.

- <u>Heisenberg (1930)</u> attempted to extend the uncertainty principle to a relativistic set up to argue that the limitations on quantum field measurements are analogous to the ones in non-relativistic quantum mechanics.
- <u>Landau and Peierls (1931)</u> argued that the limitations on quantum measurement are more severe in QFT than in quantum mechanics, challenging the physical basis of the theory.
- <u>Bohr and Rosenfeld (1933)</u> responded to their argument, challenging their assumption of electrically charged pointlike particles as test bodies. They argue that one must consider spatially extended (macroscopic!) charged test bodies, whose atomistic structure can be ignored and whose charge density can be adjusted.
- <u>Bohr and Rosenfeld ‘vs’ von Neumann notion of measurement</u> (macroscopic vs microscopic apparatus, measurement outcomes: epistemology, thermodynamics vs consciousness…)

*’Uses and Appropriations of Niels Bohr’s Ideas About Quantum Field Measurement’ T. Hartz, O. Freire, 1930–1965 vol. 1, pp. 397–418 (2015)

(Fast forward to Sorkin 1993 ‘impossible measurements’)

- Sorkin suggests that Bohr and Rosenfeld's proposal for measuring smeared-field amplitudes might provide a testing ground for his claim that there are ideal measurement scenarios in QFT in which superluminal signalling is predicted to occur.

``specifically, one can ask whether they actually measure the field averages they claim to, and whether the probabilities of the different possible outcomes are those predicted by the quantum formalism (with special reference to the use of the projection postulate after the first measurement, since its effect could only be seen in a full quantum treatment)."

- Essentially, Sorkin is calling for Bohr and Rosenfeld's models to be modified to fit into the framework for modeling measurements that was introduced by von Neumann.

‘’It would of course be very interesting to try to construct models within quantum field theory, to see what goes wrong, but I will not attempt such a von-Neumann-like analysis here.’’

---

*’ Impossible measurements on quantum fields’ R. Sorkin, In: Directions in General Relativity: Proceedings of the 1993 International Symposium, Maryland, vol. 2, pp. 293–305 (1993)

Algebraic operationalism?

- One might think that algebraic QFT would have been a context in which the representation of local measurements in QFT was worked out long ago because Haag and others adopted an operational interpretation of the local algebras.

Haag, Kastler 1964: ‘We must turn now to the physical interpretation [of the local algebras] i.e., to the following question: Suppose a specific operation (or state) is defined in terms of a laboratory procedure. How do we find the corresponding element in the mathematical description? For the ‘’operations" the question is partially answered by the assertion: An operation in the space-time region O corresponds to an element from $\mathscr{A}(O)$.’

- This operational interpretation is an abstract schema: particular local operators are not associated with particular concrete measurement operations carried out in a local laboratory.
- In fact, standard rules for measurement (Born’s rule, state update) are not part of the axioms in algebraic QFT.

Algebraic operationalism?

- In its early history, AQFT is *not* connected to predictions via the direct interpretation of local algebras in terms of laboratory procedures. Instead, the connection to predictions is still made through (asymptotic) scattering theory.
- Haag's theorem raised the problem of how to formulate collision theory in a mathematically consistent way. Haag-Ruelle scattering theory was regarded by Haag as the most satisfactory answer to this problem.

Haag and Kastler 1964: ‘observables that can be measured in a spacetime region [are linked to the calculation of] quantities of direct physical interest such as masses of particles and collision cross sections [by appeal to Haag-Ruelle scattering theory’ (footnote: at the present stage this claim is an overstatement…)

*’Perturbative expansions and the foundations of quantum field theory’ J. Fraser, K. Rejzner, EPJ H 49, 10 (2024)

State update in relativity?

Attempts of relativistic generalisations of the state update rule:

- Hellwig and Kraus (1970) propose an ad hoc modification of Lueders' rule for state update for ideal measurements that is manifestly Lorentz covariant and satisfies the microcausality assumption.
- In other two papers by Hellwig and Kraus (1969, 1970) an operation—a change of state that is brought about by an (external) physical apparatus acting on the system—is modeled using a unitary, finite-time S-matrix interaction S between the apparatus and system!
- They emphasise that their result concerns mathematically possible operations, and that a physical approach would also consider physical restrictions on the initial state of the apparatus, measurable properties of the apparatus, and the interactions between system and apparatus. They also argue that Haag and Kastler (1964) can be used to formulate within AQFT the physical requirement that an operation be local (indeed! [Fewster, Verch 2020]).

Particle detector models in QFTCS and RQI

- In the 1970s, the Unruh (1976) and Hawking (1977) effects focused attention on the thermal states of quantum fields and the exploration of the more exotic settings of curved spacetime and black holes. Particle detectors were introduced to extract particle phenomenology from QFT models.
- Recently, a lot of work on the foundations of detector models in QFTCS and RQI (causality, signalling, covariance, induced field observables, non-perturbative arguments, relativistic extensions, connection to formal approaches…).
- Just one comment about particle detection 'beyond' perturbation theory: 'clean' particle detection through resonance of the relativistic Breit-Wigner form arises in *solvable models* in the long-time limit (switching→ 1).

*'Particle-field duality in QFT measurements', **MP,** J. de Ramón, and C. Anastopoulos, Phys. Rev. D 109, 065024 (2024).

Summary and contemporary questions

- Initial Bohr Rosenfeld papers were influential (contrary to what is commonly believed) but not always in the spirit of the initial debate (Sorkin's seminal paper as an example).

*What other (e.g. thermodynamical?) arguments can play a role in quantum field measurability?

- The role of scattering also dominant in the 'operationalist' tradition to AQFT.

*What does it take for a physical theory to be 'operational'? Is scattering 'operational'?

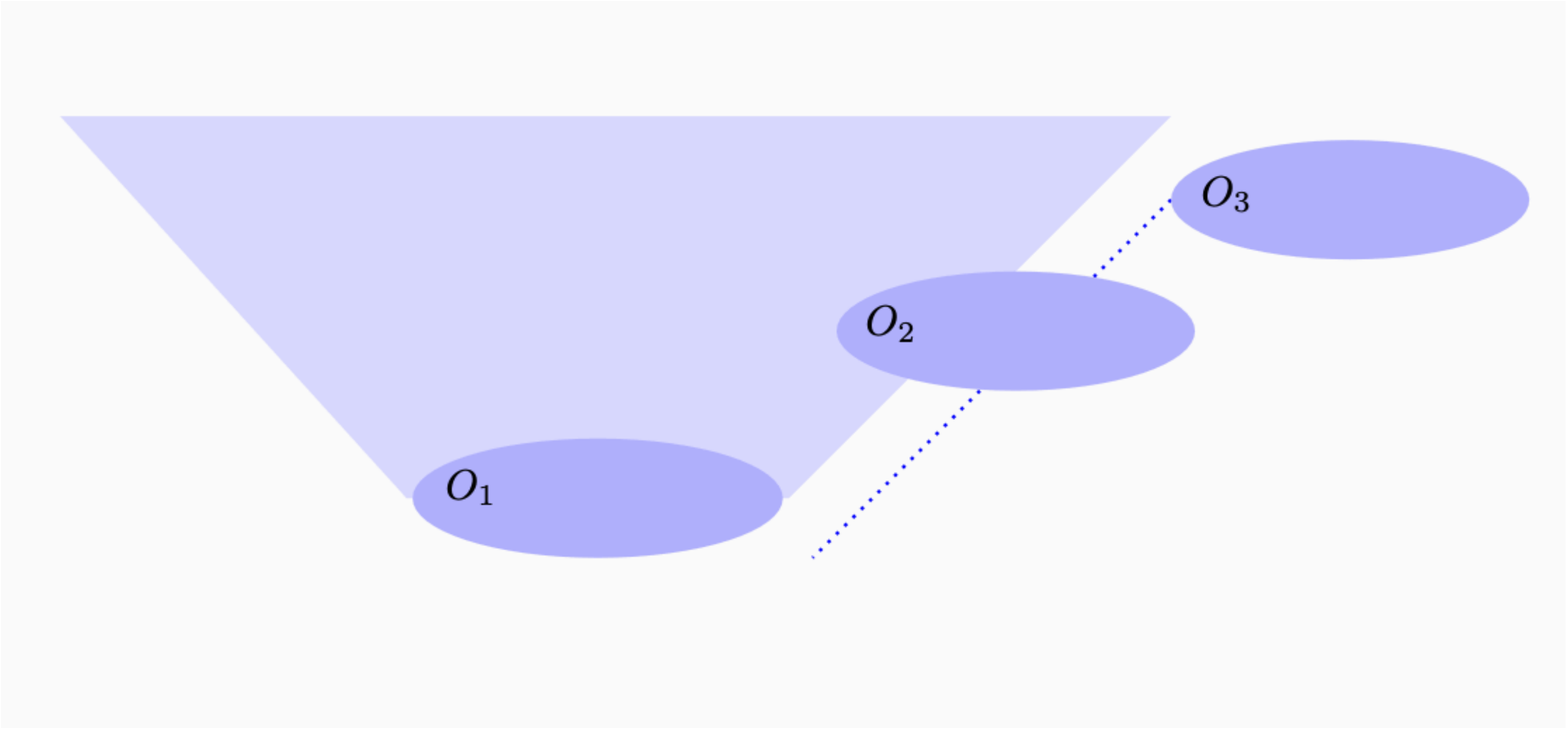
- Hellwig and Kraus first tried to bring measurement axioms into QFT through an S-matrix approach. These measurements are (by definition) not ideal.

*How close can one go to ideal measurements without violating causality?

- Current proposals for measurement theory in QFT heavily rely on local scattering theory.

* Proposals beyond scattering theory? For problems like particle detection through resonance, histories-based formulations, continuous-time field measurements… Which notions of causality are available beyond scattering?

Scattering, causality and the ‘impossible’



Based on work with Jose de Ramon Rivera, Eduardo Martin-Martinez, Doreen Fraser, Robin Simmons…

Relativistic causality

- Many different notions of relativistic causality in QFT [Earman, Valente 2014]. Perhaps the most famous: microcausality condition

$$[\hat{\Phi}_1, \hat{\Phi}_2] = 0 \text{ if } O_1, O_2 \text{ spacelike separated.}$$

- **In which situations microcausality implies no superluminal signalling?** 1. when cluster decomposition of many interactions (asymptotic, not directly linked to stat. independence). 2. Two fully spacelike separated probes interacting with the quantum field…

*'Relativistic causality in detector models:…', J. De Ramon Rivera, **MP,** E. Martin, Martinez, Phys. Rev. D 103, 085002 (2021)

Relativistic causality

- Many different notions of relativistic causality in QFT [Earman, Valente 2014]. Perhaps the most famous: microcausality condition

$$[\hat{\Phi}_1, \hat{\Phi}_2] = 0 \text{ if } O_1, O_2 \text{ spacelike separated.}$$

- **In which situations microcausality implies no superluminal signalling?** 1. when cluster decomposition of many interactions (asymptotic, not directly linked to stat. independence). 2. Two fully spacelike separated probes interacting with the quantum field…

WE WILL SEE:

- Non-perturbative argument: microcausality ⇒ **causal factorisation** of two (causally orderable) detector field interactions ⇒ no superluminal signalling and retrocausation.
- Microcausality/causal factorisation is *not* sufficient for blocking impossible measurements. Need to impose extra condition on the scattering maps.

*'Relativistic causality in detector models:…', J. De Ramon Rivera, **MP,** E. Martin, Martinez,Phys. Rev. D 103, 085002 (2021)

Unruh DeWitt-type detector-field interactions

- State update and induced observables.
- Causal factorisation of the local scattering maps.
- Extra condition for the induced update map (no impossible measurements).
- In this context: impossible measurements= impossible dynamics.
- Interpretation and open questions.

*’Relativistic causality in detector models:…’, J. De Ramon Rivera, **MP,** E. Martin, Martinez,Phys. Rev. D 103, 085002 (2021)

State update and induced observables for UDW

- The updated state of the field given that the detector yields outcome i:

$$\rho'_\phi(i) = \frac{\hat{M}_{i,\psi}\rho_\phi\hat{M}^\dagger_{i,\psi}}{\mathrm{tr}_\phi\left(\rho_\phi\hat{M}_{i,\psi}\hat{M}^\dagger_{i,\psi}\right)} \quad \text{where} \quad \hat{M}_{i,\psi} := \langle i\,|\,\hat{S}\,|\,\psi\rangle.$$

where ψ the initial state of the detector, and $\hat{S}_{int} = \mathscr{T}\exp[-i\hat{H}_{int}]$.

*'A detector-based measurement theory', J. Polo Gomez, L. J. Garay, E. Martin, Martinez, Phys. Rev. D 105, 065003 (2022).

State update and induced observables for UDW

- The updated state of the field given that the detector yields outcome i:

$$\rho'_\phi(i) = \frac{\hat{M}_{i,\psi}\rho_\phi\hat{M}^\dagger_{i,\psi}}{\mathrm{tr}_\phi\left(\rho_\phi\hat{M}_{i,\psi}\hat{M}^\dagger_{i,\psi}\right)} \quad \text{where} \quad \hat{M}_{i,\psi} := \langle i\,|\,\hat{S}\,|\,\psi\rangle.$$

where ψ the initial state of the detector, and $\hat{S}_{int} = \mathscr{T}\exp[-i\hat{H}_{int}]$.

- For *non-selective* measurements (summing over all possible outcomes)*:

$$\rho'_\phi(ns) = \sum_i \hat{M}_{i,\psi}\rho_\phi\hat{M}^\dagger_{i,\psi} = tr_d\left(\hat{S}(\,|\psi\rangle\langle\psi|\otimes\rho_\phi)\hat{S}^\dagger\right) := \mathscr{E}[\rho_\phi].$$

---

*'A detector-based measurement theory', J. Polo Gomez, L. J. Garay, E. Martin, Martinez, Phys. Rev. D 105, 065003 (2022).

State update and induced observables for UDW

- The updated state of the field given that the detector yields outcome i:

$$\rho'_\phi(i) = \frac{\hat{M}_{i,\psi}\rho_\phi\hat{M}^\dagger_{i,\psi}}{\mathrm{tr}_\phi\left(\rho_\phi\hat{M}_{i,\psi}\hat{M}^\dagger_{i,\psi}\right)} \quad \text{where} \quad \hat{M}_{i,\psi} := \langle i\,|\,\hat{S}\,|\,\psi\rangle.$$

where ψ the initial state of the detector, and $\hat{S}_{int} = \mathscr{T}\exp[-i\hat{H}_{int}]$.

- For *non-selective* measurements (summing over all possible outcomes)*:

$$\rho'_\phi(ns) = \sum_i \hat{M}_{i,\psi}\rho_\phi\hat{M}^\dagger_{i,\psi} = tr_d\left(\hat{S}(\,|\psi\rangle\langle\psi|\otimes\rho_\phi)\hat{S}^\dagger\right) := \mathscr{E}[\rho_\phi].$$

The non-selective state-update map $\mathscr{E}$ depends only on (ψ and) the scattering map!

*'A detector-based measurement theory', J. Polo Gomez, L. J. Garay, E. Martin, Martinez, Phys. Rev. D 105, 065003 (2022).

Causal factorisation of the dynamics

- Causal factorisation is a property of the joint scattering map

  $$\hat{S}_{A+B} = \mathcal{T} exp[-i \int dt(\hat{H}_A(t) + \hat{H}_B(t))] \quad \text{where} \quad \hat{H}_\nu(t) = \lambda \int dx \Lambda_\nu(\mathsf{x}) \hat{J}_\nu(\mathsf{x}) \otimes \hat{\phi}(\mathsf{x})$$

  and $O_\nu = \text{supp}\Lambda_\nu(\mathsf{x}), \nu = A, B$, the two interaction regions.

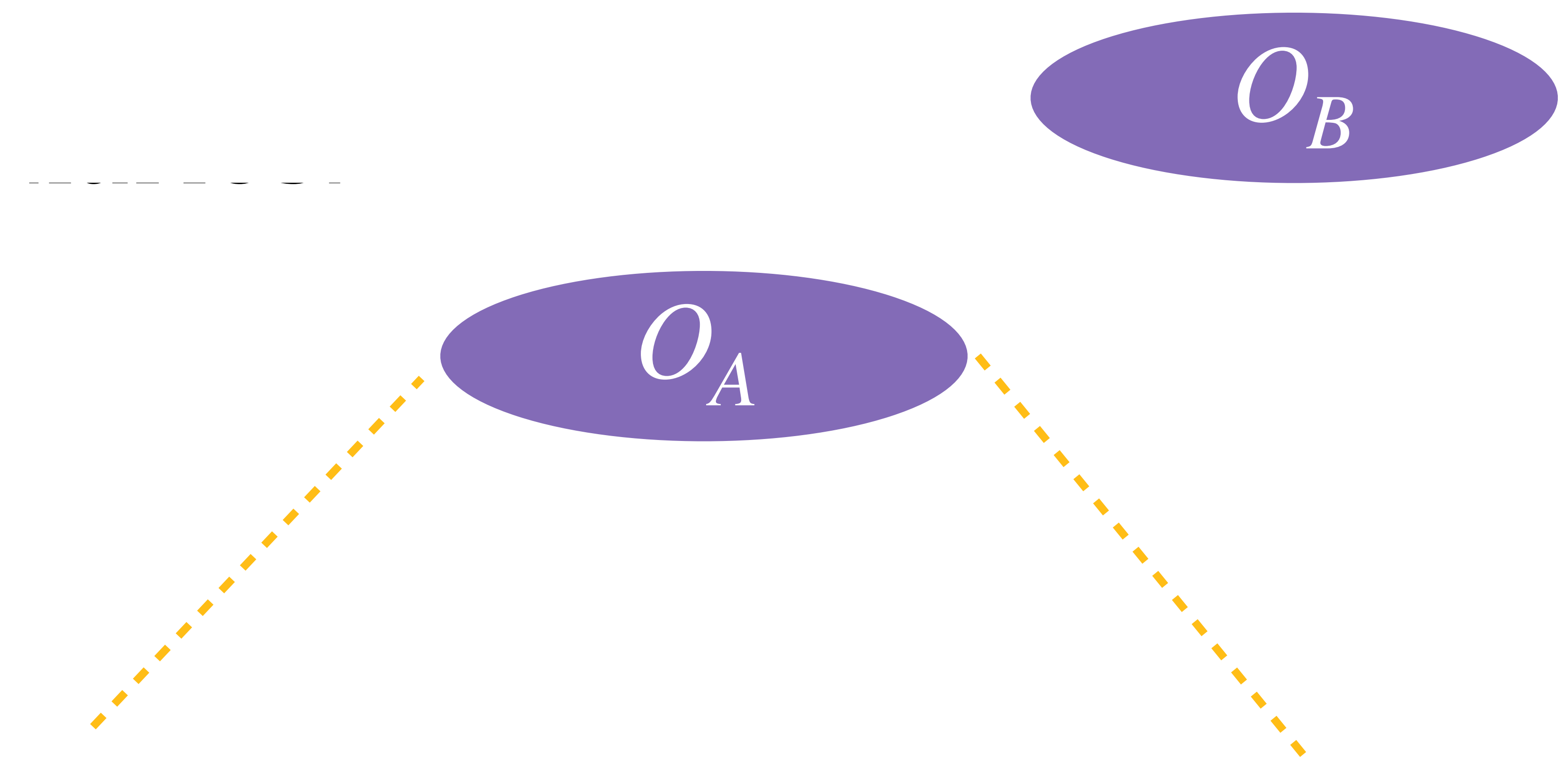
*’Relativistic causality in detector models:…’, J. De Ramon Rivera, **MP,** E. Martin, Martinez, Phys. Rev. D 103, 085002 (2021)

Causal factorisation of the dynamics

- Causal factorisation is a property of the joint scattering map

$$\hat{S}_{A+B} = \mathcal{T}exp[-i\int dt(\hat{H}_A(t) + \hat{H}_B(t))] \quad \text{where} \quad \hat{H}_\nu(t) = \lambda\int dx\Lambda_\nu(\mathsf{x})\hat{J}_\nu(\mathsf{x}) \otimes \hat{\phi}(\mathsf{x})$$

and $O_\nu = \text{supp}\Lambda_\nu(\mathsf{x}), \nu = A, B$, the two interaction regions.



*'Relativistic causality in detector models:…', J. De Ramon Rivera, **MP,** E. Martin, Martinez,Phys. Rev. D 103, 085002 (2021)

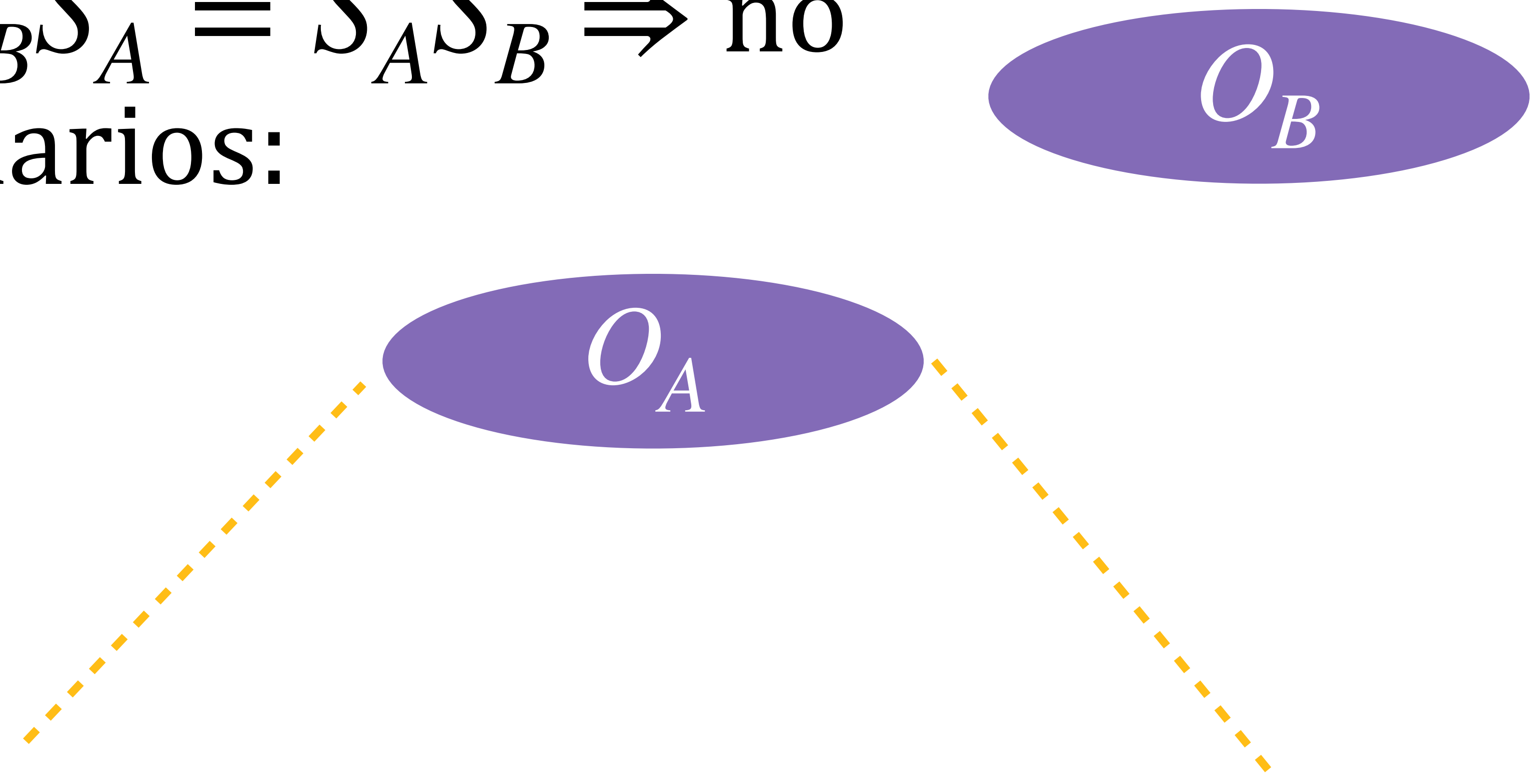
Causal factorisation of the dynamics

- Causal factorisation is a property of the joint scattering map

$$\hat{S}_{A+B} = \mathscr{T} exp[-i\int dt(\hat{H}_A(t) + \hat{H}_B(t))] \quad \text{where} \quad \hat{H}_\nu(t) = \lambda \int dx \Lambda_\nu(\mathsf{x})\hat{J}_\nu(\mathsf{x}) \otimes \hat{\phi}(\mathsf{x})$$

and $O_\nu = \text{supp}\Lambda_\nu(\mathsf{x}), \nu = A, B$, the two interaction regions.

- It follows from microcausality that for causally orderable compactly supported interaction regions $\hat{S}_{A+B} = \hat{S}_B\hat{S}_A$. In spacelike separation $\hat{S}_B\hat{S}_A = \hat{S}_A\hat{S}_B \Rightarrow$ no superluminal signaling and retrocausation in bipartite scenarios:

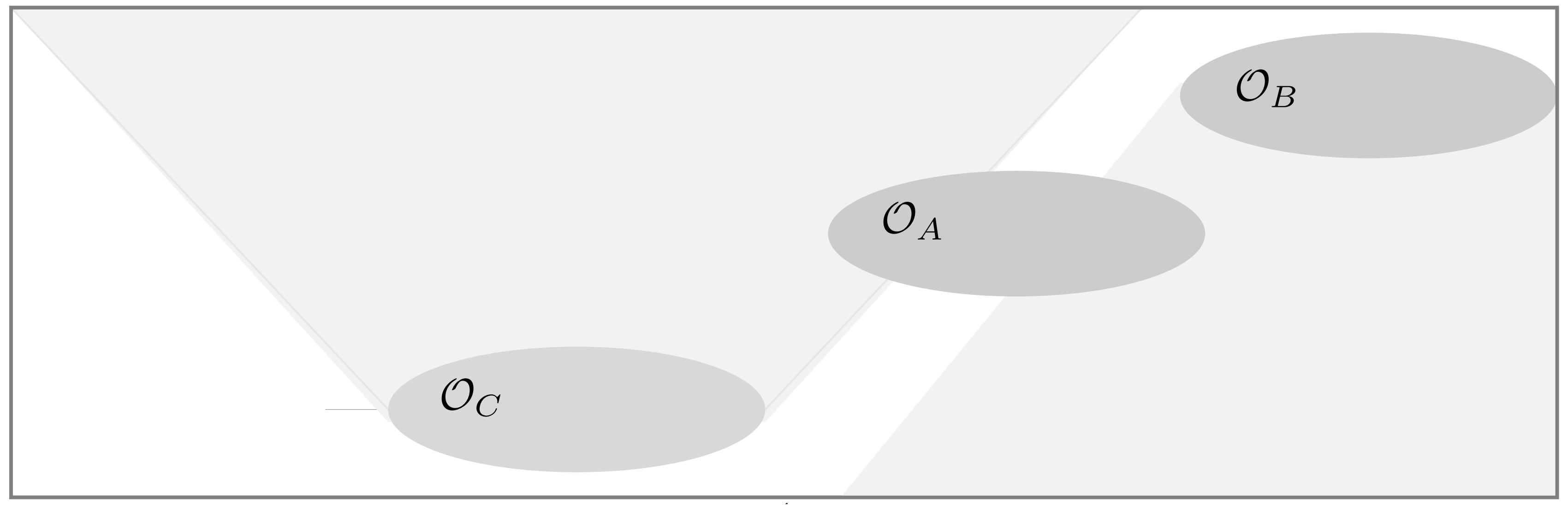


$$\hat{\rho}_A = \text{tr}_{B,\phi}(\hat{S}_A\ \hat{\rho}_{\text{initial}}\ \hat{S}_A^\dagger \hat{S}_B^\dagger \hat{S}_B) = \text{tr}_{B,\phi}(\hat{S}_A\ \hat{\rho}_{\text{initial}}\ \hat{S}_A^\dagger)$$

*'Relativistic causality in detector models:…', J. De Ramon Rivera, **MP,** E. Martin, Martinez, Phys. Rev. D 103, 085002 (2021)

Analysis of impossible measurements

Not sufficient that expectation values are unaffected in spacelike separation, but that a 'local kick' on C cannot be propagated through A to B!



- **Additional condition on the scattering maps:** for the expectation value of an observable $\hat{D}_B \in \mathscr{B}(\mathscr{H}_D)$ to not depend on $\hat{U}_c \in \mathscr{B}(\mathscr{H}_F)$ it should hold that

  $[\hat{S}_A^\dagger \hat{S}_B^\dagger \hat{D}_B \hat{S}_B \hat{S}_A, \hat{U}_C] = 0$ (condition S).

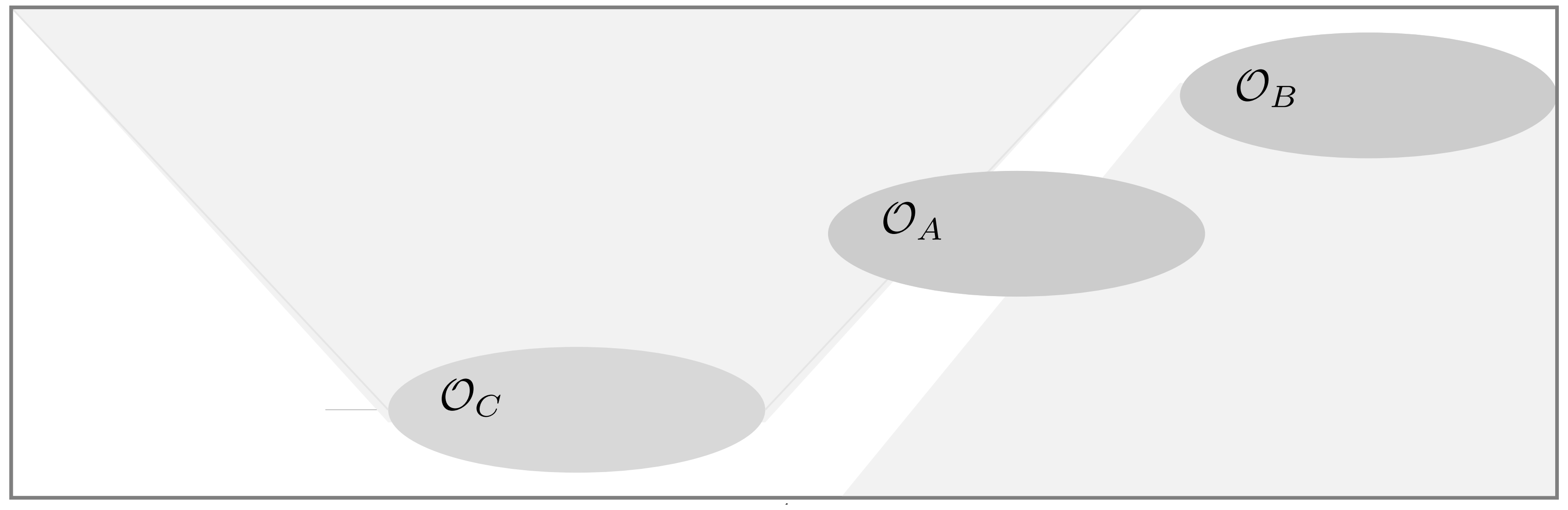
Dynamical requirement that fails when the dynamical current $\hat{J}_A$ is not microcausal:

$[\hat{J}_A(\mathsf{x}), \hat{J}_A(\mathsf{x}')] \neq 0$ for for spacelike separated $\mathsf{x}, \mathsf{x}' \in O_A$.

- The point like model is free from this problem. Advantage of detector model approach: can quantify the causality dilation based on the relevant physical scales (on a case-by-case basis).

*'Relativistic causality in detector models:…', J. De Ramon Rivera, **MP,** E. Martin, Martinez,Phys. Rev. D 103, 085002 (2021)
* 'Quantum information processing and relativistic quantum fields', D. Benincasa, L. Borsten, M. Buck, F. Dowker,Class. Quantum Grav. **31** 075007 (2014)

Making sense of (condition S)



- (S) can be rewritten as the (weaker) condition:

  $[\mathscr{E}_A^*(\hat{\Phi}_B), \hat{U}_C] = 0$ (condition S') where

  $\hat{\Phi}_B := \mathrm{tr}_B\left(\hat{S}_B^\dagger \hat{D}_B \hat{S}_B \rho_B\right)$ the induced field observable and

  $\mathscr{E}_A^*(\hat{\Phi}_B) := \mathrm{tr}_A\left(\hat{S}_A^\dagger \hat{\Phi}_B \hat{S}_A \rho_A\right)$ the (dual) state update map.

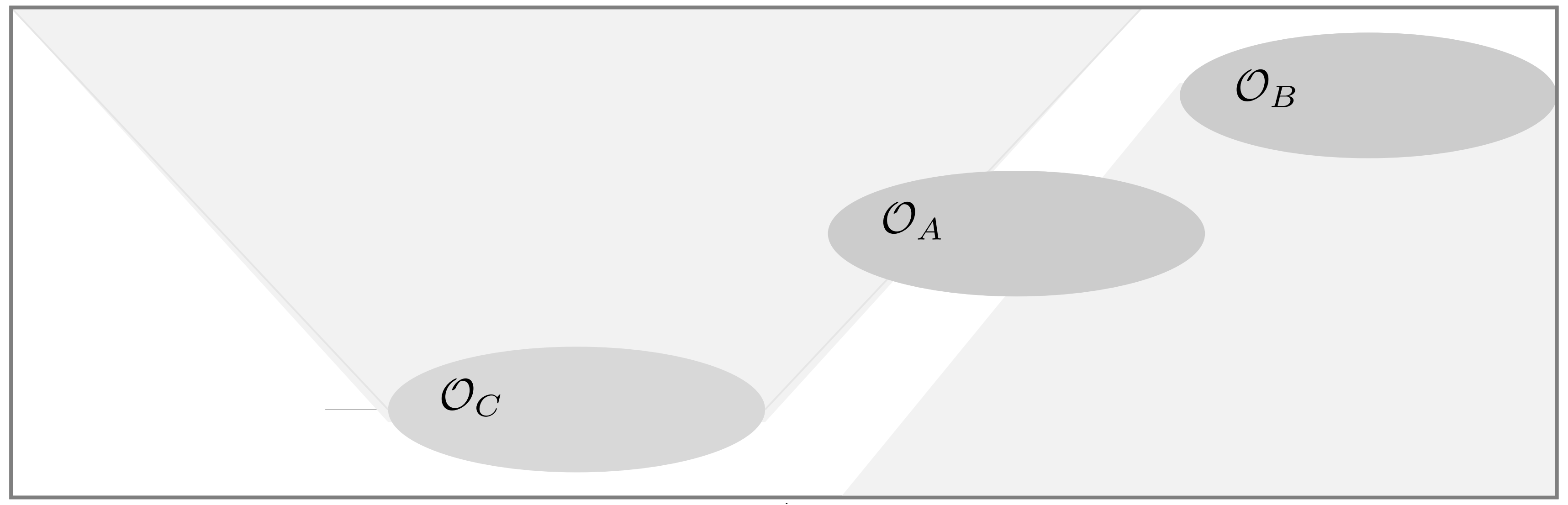
- The violation of (S') in this context shows that, due to the non-local dynamics, the (dual) state update map $\mathscr{E}_A^*$ does not define an observable in the causal complement of O_C.

*'Eliminating the 'Impossible': Recent Progress on Local Measurement Theory for Quantum Field Theory' **MP**, D. Fraser, Found Phys 54, 26 (2024)

*'Impossible measurements revisited' L. Borsten, I. Jubb, G. Kells, Phys. Rev. D 104, 025012 (2021)

Making sense of (condition S)

- Interesting observation (by Robin Simmons): If we actually model the 'local kick' $\hat{U}_c$ with another scattering map $\hat{S}_c$, (condition S) follows from the following condition from causal perturbation theory: $\hat{S}_{A+B} = \hat{S}_{C+A}\hat{S}_A^{-1}\hat{S}_{A+B}$ for all A (condition S'')



- If (condition S'') satisfied =>no impossible measurements!
- Properties of successive (non-selective) measurements sufficiently constrained by the causal properties of the scattering maps!

Moral

- Local measurements in QFT can be modelled as local scattering processes.
- Causality is ensured by (non-obvious!) properties of the scattering maps.
- In fact, Sorkin's impossible measurements have found partial (or exact!next talk:) resolutions within the scattering paradigm.
- At least in the scattering paradigm: impossible measurements= impossible dynamics.

*interesting to investigate the connection to formal approaches to perturbation theory (causal perturbation theory…)

Beyond?

- Histories-based approaches? (Advocated by Sorkin, see Isham 1994…Fuksa 2021 and Albertini, Jubb 2023).
- Problems with underlying relativistic classical field theory? (Much, Verch 2023).
- Problems with non-relativistic measurement theory? (Gisan, de Santo 2024).
- Philosophical implications for the QFT measurement problem? (Grimmer 2022, Adlam 2023, Fraser upcoming!).

“Once you eliminate the impossible,
whatever remains,
no matter how improbable,
must be the truth.”
- Sherlock Homes

Thank you!