The Frame–Budget Approach (FBA)

How time, dynamics, and geometry emerge from budget flows

An operational bridge between quantum mechanics and general relativity

Part V: Spacetime, Light Cones & Local Field Theory

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Part V

Spacetime, Light Cones & Local Field Theory

V.1 Introduction & Target Picture

V.1.1 Motivation

Part II showed how, in the FBA[1], a light-cone structure arises as an operational causal reference, in the flat reference limit of homogeneous budgets, from sequence, balance, and front calibration.[2] Parts III and IV fixed the kinematic operator language and admissible dynamics such that *open* quantum systems can be treated as CPTP and, respectively, GKLS processes.[3] What is still missing is the step that operationally brings both strands together: how does a globally formulated process description become a *local* structure in which operations have spatial support, signals propagate only within the cones, and field algebras are organized as nets over regions? Exactly this local translation is the task of this treatise.

V.1.2 Logical Path

We build the local QFT structure as a *systematic translation* of already fixed FBA primitives:

1. **Sequence:** minimal events provide an update-stable order of global frames.[4]
2. **Budget:** per update, a balance holds that separates internal, external, and irreversible contributions.[5]
3. **Calibration:** signal fronts fix the maximal slope c metrologically (not as a postulate).[6]
4. **Cone structure (reference):** in the flat reference limit, the budget quadric identifies its null directions as fronts and thus an operational causal reference.[7]
5. **Process locality:** composition and no-signalling classify admissible operations by support (local vs. disjoint), without introducing global inconsistencies.[8]
6. **Field structure (local organization):** from locally supported operations *under* cone restriction we formulate the algebraic core as a consistency structure: a net of local algebras over regions, microcausality as a condition under spacelike separation, and a cone-compatible (locally generated) dynamics in the GKLS limit. The operational

[1] An overview of all parts of the FBA treatise including download links can be found in Section V.8 of this document.

[2] See FBA Part II: Time, Proper Time & Minkowski Geometry, Secs. II.3–II.6 "Time from Difference, Calibration & Budget Quadric".

[3] See FBA Part IV: Dynamics & Measurement (GKLS), Secs. IV.3–IV.5 "CPTP Admissibility, Measurement as an Instrument & GKLS".

[4] See FBA Part I: FBA – Foundations, Sec. I.2 "Primitives & Axioms of the FBA".

[5] See FBA Part I: FBA – Foundations, Sec. I.3 "Budget Calculus per Step".

[6] See FBA Part I: FBA – Foundations, Sec. I.3 "Calibration and Front Costs".

[7] See FBA Part II: Time, Proper Time & Minkowski Geometry, Secs. II.5–II.7 "Front, Quadric & Light Cone".

[8] See FBA Part I: FBA – Foundations, Sec. I.6 "Composition, Locality & No-Signalling".

punchline is: "field" is the consistent localization of admissible operations *under* the already fixed causal order.

Why this order? Without (3), c is merely a convention and the cone order is not operationally fixed. Without (4), the robust distinction "causally reachable" vs. "spacelike separated" is missing. And without (5), "local" remains a geometric word without dynamical content, because it is unclear which process steps count as locally admissible. Only then does (6) become the consistent formulation of QFT structure in the FBA: as an algebraic organization of locality under cone restriction.

V.1.3 Scope and Delimitation

We work in the *flat, kinematic* reference limit: no curvature, no backreaction, local inertial language as working coordinates. Admissible dynamics is CPTP-conform and, in the Markov limit, GKLS-conform; locality is sharpened via composition, ancillary registers, and coarse-graining.[9] Gravity as a deviation from the homogeneous limit is derived only in Part VI from budget gradients.[10] Scale questions and renormalization, which are unavoidable for field theory, are bundled independently in Part VII.[11]

V.1.4 Contribution relative to standard QFT

Standard QFT typically starts with a given spacetime and then postulates microcausality and local fields as structural principles. In the FBA, these building blocks are decoupled in two steps and then brought together consistently: the cone structure is already calibrated as a budget limit (not postulated), and admissible dynamics is stable under composition as CPTP/GKLS (not freely choosable). This makes *microcausality* readable as a compatibility condition between locally supported dynamics and the cone order, and *local fields* appear as an algebraic representation of this compatibility. The additional gain is operational: because measurement and open dynamics are treated as channels from the outset, deviations from ideal locality can be formulated as protocol costs or as violations of the admissibility assumptions, rather than as a matter of interpretation.

V.1.5 Reading Guide

The Section order is chosen such that we (i) fix the reference notions "local" and "causal" cleanly, (ii) translate the already established spacetime and cone order as reference causality into regional notions and support, and (iii) only then formulate the local QFT structure (nets, microcausality, local dynamics) as a consistent organizational form.

Section V.2 - Foundations & Conventions: Import of the required building blocks and fixation of the notation. *Why first?* So that "region", "locally supported", and "spacelike" are not silently redefined later, but rest on the same reference assumptions (balance, front, quadric, composition).

[9] See FBA Part IV: Dynamics & Measurement (GKLS), Secs. IV.2–IV.5 "Admissibility, Instruments & GKLS".

[10] See FBA Part VI: Gravity & Geometry from Budget Flows, Secs. VI.1–VI.4 "Geometry/Gravitation from Budget Flows".

[11] See FBA Part VII: Constants, Scales & Renormalization, Secs. VII.2–VII.4 "Calibration/Scales & RG Flows".

Section V.3 - Spacetime as emergent structure: Translation of the global update order (minimal events) into an operational spacetime language. *Why here?* Only once "region" is understood as a substructure of the update/balance logic can "local" be more than a metaphor.

Section V.4 - Light cones as causal structure: Recapitulation of the cone order as reference causality from quadric and front calibration and its use to operationalize "spacelike" vs. "causally reachable". *Why afterwards?* Because microcausality and local dynamics require a clear meaning of "spacelike separated".

Section V.5 - Microcausality & nets of local algebras: Algebraic locality (microcausality) as a consistency condition from composition/no-signalling *under* cone restriction; construction of the Haag–Kastler core and cone-compatible local dynamics. *Why here?* Because "field" in the FBA is precisely the consistent localization of admissible operations *under* this causal order.

Section V.6 - FBA and local relativistic QFT: Placing the obtained structure within the standard framework of local relativistic QFT (symmetries, conservation laws, classical limit). *Why now?* Only after the local core is in place does the comparison "same prediction – different derivation" become genuinely transparent.

Section V.7 - Summary & Outlook: Condensation of the results, passages to scales/RG and backreaction/gravity, and translation into testable protocols. *Goal:* The transition to the next parts should proceed as an interface to clearly named structural elements (cone order, nets, local generators).

V.2 Preliminary Foundations & Conventions (Import from Part I: FBA – Foundations)

Why an import? In Part V we do not want to introduce *local* structure as an additional axiom, but as a systematic translation of already fixed building blocks: (1) sequence and balance provide the update structure; (2) calibration and quadric provide the cone order as reference causality; (3) CPTP/GKLS under composition provides the admissible dynamics class that remains stable under ancillary registers and coarse-graining. Once these three points are in place, a "local field" is no longer a free choice, but the algebraic formulation of which operations are compatible with the cone order and no-signalling. So that the line of argument here does not collapse into repetition, we adopt the primitives from Part I unchanged.[12] The derivation of the cone structure itself is used as a reference from Part II and is not carried out anew here.[13]

Reading-guide note. Part V assumes that "causal" has already been fixed operationally (front calibration, quadric) and that "admissible" has been specified as a process class (CPTP/GKLS, instruments).[14] What is new here is the local translation: we make precise how to define regions, causal complements, and nets of algebras from these inputs, so that microcausality becomes visible as a consistency condition and operationally testable.

[12]See FBA Part I: FBA – Foundations, Secs. I.2–I.6 "Sequence, Budget, Calibration, Composition & Admissibility".

[13]See FBA Part II: Time, Proper Time & Minkowski Geometry, Secs. II.5–II.7 "Front, Quadric & Light Cone".

[14]See FBA Part IV: Dynamics & Measurement (GKLS), Secs. IV.2–IV.5 "Admissibility, Measurement as an Instrument & GKLS".

Imported building blocks (unchanged)

- **Sequence of global states & minimal events:** frame sequence, minimal event, as well as co-actuality and refinement invariance.[a]
- **Difference function & operational minimal difference:** operational difference measure as the basis of refinement-stable orders.[b]
- **Budget calculus (internal/external/irreversible) & balance:** one-step budget, balance equations, and refinement invariance.[c]
- **External calibration & front:** calibration, front bound, and signal front as the reference structure for c.[d]
- **Proper time & aging, Minkowski limit:** proper time, aging, Minkowski limit, and time dilation as the flat reference limit.[e]
- **Admissible dynamics (CPTP/GKLS), DPI/Spohn:** CPTP, Kraus/Stinespring, measurement as CPTP, GKLS generators, Spohn monotonicity, semigroup budget, DPI arrow, and no-recovery.[f]
- **Composition, locality & no-signalling:** symmetric-monoidal structure, budget additivity, no-wire inflation and local operations, causal cones and local GKLS.[g]

[a] See FBA Part I: FBA – Foundations, Sec. I.2.
[b] See FBA Part I: FBA – Foundations, Sec. I.2.
[c] See FBA Part I: FBA – Foundations, Sec. I.3.
[d] See FBA Part I: FBA – Foundations, Sec. I.3.
[e] See FBA Part I: FBA – Foundations, Sec. I.4.
[f] See FBA Part I: FBA – Foundations, Sec. I.5.
[g] See FBA Part I: FBA – Foundations, Sec. I.6.

What exactly are these imports used for in Part V? The points above fix the two things we absolutely need for a local field structure: a *reference causality* (cones from quadric/front) and a *stable process class* (CPTP/GKLS under composition). Only then can one meaningfully formulate what it means that an operation "acts only in a region", and why spacelike separated operations must not influence each other.

Notation & conventions

- **Discrete vs. continuum:** step index $n \in \mathbb{Z}$ for successive frames; $\Delta(\cdot)$ for discrete increments, $d(\cdot)$ for differential quantities in the limit.
- **Budget decomposition (reference):** per step $\delta b_{\rm int}$, $\delta b_{\rm ext}$, $\delta b_{\rm irr}$ (internal/external/irreversible). *Aging* $dA \equiv db_{\rm irr} \geq 0$. *Geometric proper time* $d\tau_{\rm geo} \equiv db^{\rm rev}_{\rm int}$. *Total proper time* $d\tau_{\rm tot} = d\tau_{\rm geo} + dA$.
- **Calibration and cone reference:** c remains explicit (no $c = 1$ units). We use coordinates $(t, \mathbf{x}) \in \mathbb{R} \times \mathbb{R}^3$ and the flat reference quadric

$$ds^2 \;=\; -c^2\, dt^2 + d\mathbf{x}^2.$$

  Equivalently, in $x^0 \equiv ct$, we have $ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu$ with $\eta = \mathrm{diag}(-1, 1, 1, 1)$. This Minkowski notation is *reference language* here; its justification as the flat reference limit follows from Part II.[a] The light cone is given by $ds^2 = 0$.
- **Spacetime regions and causal hulls:** spacetime points p, q; regions $\mathcal{O} \subset \mathbb{R}^{1,3} \cong \mathbb{R} \times \mathbb{R}^3$. Causal future/past $J^{\pm}(\mathcal{O})$, causal closure $J(\mathcal{O}) = J^+(\mathcal{O}) \cup J^-(\mathcal{O})$. Spacelike complement $\mathcal{O}^{\perp}$ (all points that are spacelike separated from *all* points in $\mathcal{O}$).
- **Local algebras and local operations:** $\mathcal{A}(\mathcal{O})$ denotes the (e. g. C*- or von Neumann-) *algebra of observables localized in $\mathcal{O}$. The commutator for observables is $[A, B] = AB - BA$. Microcausality will later be formulated as $[A, B] = 0$ for $A \in \mathcal{A}(\mathcal{O}_1)$, $B \in \mathcal{A}(\mathcal{O}_2)$ with $\mathcal{O}_1 \subset \mathcal{O}_2^{\perp}$. Separately, we write $\mathrm{Chan}(\mathcal{O})$ for the class of admissible (CPTP) operations supported in $\mathcal{O}$ (a precise definition follows in the local dynamics/nets Section).
- **Fields and smearing (if operator-valued):** symbolic expressions like $\phi(x)$ are (where used) to be read as shorthand for smeared $\phi(f)$ with test functions $f \in C_c^\infty(\mathcal{O})$. Statements such as microcausality are then formulated support-based (spacelike separated supports), not pointwise.
- **Channels and pictures:** CPTP channels Φ in the Schrödinger picture: $\rho \mapsto \Phi(\rho)$. Adjoint Heisenberg picture Φ^* with $\mathrm{Tr}(\Phi(\rho)E) = \mathrm{Tr}(\rho\, \Phi^*(E))$.
- **Composition/locality:** parallel composition $\otimes$; serial composition $\circ$. Local CPTP operations respect no-signalling and budget additivity.[b]
- **Sign conventions:** vector norms $\|\cdot\|$; Euclidean inner products $\cdot$ in space. expectations $\mathbb{E}[\cdot]$; supremum sup.

[a] See FBA Part II: Time, Proper Time & Minkowski Geometry, Sec. II.6 “Budget Quadric & Minkowski Limit”.

[b] See FBA Part I: FBA – Foundations, Sec. I.6 “Composition, No-Wire Inflation & Local Operations”.

Consequence. With these imports and conventions, in the following Sections we can use the cone order as an operational causal structure, make “local support” of operations precise, and from this consistently *formulate and develop* nets of local algebras together with microcausality and local dynamics – without hidden notation shifts or implicit additional postulates.

V.3 Spacetime as an Emergent Structure from FBA

Up to this point, two things are already firmly anchored: first, there is an update-stable order of global frames via minimal events.[15] Second, in the flat reference limit an operationally calibrated cone structure is available as a reference (fronts fix c, and the budget quadric determines the null directions).[16] What is still missing is the translation of this global structure into a language in which "region", "locally supported", and "causally reachable" are not merely geometric metaphors, but statements about which operations are mutually compatible. We need exactly this translation in order to define local field algebras as nets over regions in the following Sections.

V.3.1 Translating the spacetime reference structure from sequence, balance, and calibration

Minimal events provide not only an ordering, but an operational notion of when two global frames are "neighboring": they differ minimally in the sense of the difference function.[17] The budget balance makes this neighborhood compatible with a consistent resource flow per update.[18] And calibration via signal fronts finally provides a metrological fixation of the maximal propagation rate c, so that "as fast as possible" becomes a reproducible bound.[19] The actual cone/quadric structure is adopted *as a reference* from Part II; here we translate it into notions that will later carry regionality and support of operations.[20]

V.3.2 Access to spacetime via minimal events and cone order

The time scale introduced in Part II is a strictly increasing embedding of the frame sequence, whose unit is fixed only by front calibration.[21] At the discrete level this means: a transition $F_n \to F_{n+1}$ is an elementary update step, and causal relations between such steps are controlled by whether a connection can be realized within the front bound. In the continuum limit of refinement, we recapitulate this reference causality as the cone order of the Minkowski shorthand notation, with the Minkowski language explicitly being only shorthand for the already derived reference limit.[22] This order is decisive: only calibration turns the sequence into a comparable spacetime structure, so that "outside the cone" becomes an operationally robust statement.

V.3.3 Spacetime patches as local substructures

We understand local spacetime regions or patches as sub-sequences of the global updates that are connected by causal relations. For "local" to be more than a geometric label, this patch formation must be compatible with the admissible process class: operations on disjoint

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[15] See FBA Part I: FBA – Foundations, Sec. I.2 "Global States, Frame Sequence, and Minimal Event (ME)".

[16] See FBA Part II: Time, Proper Time & Minkowski Geometry, Secs. II.5–II.7 "Calibration, Budget Quadric & Minkowski Limit".

[17] See FBA Part I: FBA – Foundations, Sec. I.2 "Difference Function & Operational Minimal Difference".

[18] See FBA Part I: FBA – Foundations, Sec. I.3 "One-Step Budget & Balance Equations".

[19] See FBA Part I: FBA – Foundations, Sec. I.3 "Calibration and Front Costs".

[20] See FBA Part II: Time, Proper Time & Minkowski Geometry, Secs. II.5–II.7 "Calibration, Budget Quadric & Minkowski Limit".

[21] See FBA Part II: Time, Proper Time & Minkowski Geometry, Sec. II.3 "Time from a Sequence of Minimal Differences".

[22] See FBA Part II: Time, Proper Time & Minkowski Geometry, Sec. II.6 "Budget Quadric and Minkowski Limit".

supports must not influence each other (no-signalling), and the dynamics must remain stable under ancillary registers and coarse-graining.[23] This is exactly where the process principles fixed in Part IV bite: admissible local updates are CPTP, and in the Markov limit locally supported GKLS flows arise.[24] A patch is therefore not an isolated entity, but a slice of the global bookkeeping whose internal dynamics respects the same closure rules as the theory as a whole.

V.3.4 Interim summary and transition to local fields

In the FBA, spacetime emerges as a reference structure from (i) the sequence of minimal differences, (ii) the budget balance per update, and (iii) front calibration, which fixes c metrologically.[25] Local patches are the substructures of this global order that are compatible with composition, no-signalling, and admissible dynamics. This sets the stage for defining "local fields" in the following Sections as nets of algebras over regions, whose microcausality becomes visible not as an additional postulate but as a consistency condition of cone order and process class.

[23] See FBA Part I: FBA – Foundations, Sec. I.6 "Composition, Locality & No-Signalling".

[24] See FBA Part IV: Dynamics & Measurement (GKLS), Secs. IV.3–IV.5 "Admissible Processes, Measurement as an Instrument & GKLS".

[25] See FBA Part II: Time, Proper Time & Minkowski Geometry, Secs. II.5–II.7 "Calibration, Quadric & Cone Structure".

V.4 Light Cones as a Causal Structure

V.4.1 Null structure of the budget quadric: the light cone is not an additional assumption

As derived in Part II, the operational causal structure in the FBA is fixed in the *flat reference limit* by the *budget quadric*: from balance, refinement, and front calibration one obtains a quadratic line element whose null directions describe the signal fronts, and whose continuous limit can be written in Minkowski form.[26] What matters here is the status statement: the Minkowski notation is *shorthand* for this reference limit, not an additional postulate.

Formula Box V.4.1.1: Light cone from quadric and front calibration

In the flat, kinematic reference limit we write, for calibrated increments $dx^\mu = (dt, \mathrm{d}\mathbf{x})$, the line element as

$$\eta_{\mu\nu}\, dx^\mu dx^\nu \;=\; -c^2\, dt^2 + \|\mathrm{d}\mathbf{x}\|^2.$$

The null structure

$$\eta_{\mu\nu}\, dx^\mu dx^\nu = 0 \qquad \Longleftrightarrow \qquad \|\mathrm{d}\mathbf{x}\| = c\,|dt|$$

characterizes the *light-cone directions* and is saturated by signal fronts. For future-directed increments ($dt > 0$) this is equivalent to $\|\mathrm{d}\mathbf{x}\|/dt = c$. [a] [b]

[a]See FBA Part I: FBA – Foundations, Sec. I.3 “Calibration and Front Costs”.
[b]See FBA Part I: FBA – Foundations, Sec. I.3 “Front Bound/Signal Front”.

V.4.2 Causal order as the reference notion for “local”, “spacelike”, and “reachable”

Since c is fixed metrologically in the FBA via fronts, “inside/outside the cone” is not a free convention, but the operational reference statement relative to which we define “causally reachable” and “spacelike separated” (cf. notation & conventions in Section V.2).

[26]See FBA Part II: Time, Proper Time & Minkowski Geometry, Sec. II.6 “Budget Quadric and Minkowski Limit”.

Definition V.4.2.1: Causal order from the light cone

We use the coordinates $(t, \mathbf{x})$ and thus the signature $\eta = \mathrm{diag}(-c^2, 1, 1, 1)$ for $dx^\mu = (dt, d\mathbf{x})$. A piecewise smooth curve γ is called *causal* if its tangent vector is everywhere timelike or lightlike: $\eta_{\mu\nu}\dot\gamma^\mu\dot\gamma^\nu \le 0$. It is called *future-directed* if along the parametrization $dt/d\lambda \ge 0$ holds. Then for a region $\mathcal{O} \subset \mathbb{R}^{1,3}$ we define:

$$J^+(\mathcal{O}) \;=\; \{\, q \,|\, \exists\, p \in \mathcal{O} \text{ and a future-directed causal curve from } p \text{ to } q \,\},$$

$$J^-(\mathcal{O}) \;=\; \{\, q \,|\, \exists\, p \in \mathcal{O} \text{ and a past-directed causal curve from } p \text{ to } q \,\},$$

$$J(\mathcal{O}) = J^+(\mathcal{O}) \cup J^-(\mathcal{O}).$$

The *spacelike complement* is

$$\mathcal{O}^\perp \;=\; \mathbb{R}^{1,3} \setminus J(\mathcal{O}),$$

i. e. the set of all points that are spacelike separated from *all* points in $\mathcal{O}$. [a]

[a] See FBA Part II: Time, Proper Time & Minkowski Geometry, Sec. II.6 “Budget Quadric and Minkowski Limit”.

V.4.3 Signal limitation: the front bound as the operational form of “inside the cone”

In the FBA, the light-cone structure is not merely “geometry language”, but the direct translation of a calibration and admissibility statement: a *realizable* signal respects the bound fixed by fronts.

Lemma V.4.3.1: Signal limitation as a front bound

Under correct front calibration, for every realized information transfer (signal) between spatially separated events with $\Delta t > 0$ one has:

$$\frac{\|\Delta\mathbf{x}\|}{\Delta t} \le c,$$

and equality occurs only in the limiting case of signal fronts.[a] Thus the light-cone structure is the operational translation of front admissibility: “signal admissible” implies “inside the cone”.

[a] See FBA Part I: FBA – Foundations, Lemma/Corollary I.3 “Front Bound/Signal Front”.

V.4.4 Positioning relative to Special Relativity: same flat predictions, different derivation logic

In Special Relativity, Minkowski structure is typically formulated as a kinematic starting point.[1, 2] In the FBA, the same structure appears as a *limiting form* of an invariant notion obtained from balance, calibration, and refinement: the quadric yields the cones (null directions), the fronts fix c, and the Lorentz group is the symmetry group of this quadric in the flat reference limit.[27] [28] The difference thus does not lie in the flat predictions, but in the *derivation logic*: in the FBA, causality is a consequence of budget admissibility and metrological calibration, not an independent postulate.

[27]See FBA Part II: Time, Proper Time & Minkowski Geometry, Sec. II.6 “Budget Quadric and Minkowski Limit”.

[28]See FBA Part II: Time, Proper Time & Minkowski Geometry, Sec. II.10 “Comparison & Placement within Special Relativity”.

V.5 Microcausality and nets of local field algebras

From *composition/locality* and *no-signalling* (import), together with the flat reference limit (budget quadric ⇒ light cones), an operational causal structure is available as a reference.[29] [30] [31] Building on this we formulate (i) microcausality as algebraic independence under spacelike separation, (ii) a local net $\mathcal{O} \mapsto \mathcal{A}(\mathcal{O})$ of C*-algebras (Haag–Kastler language),[3, 4] and (iii) cone compatibility of locally generated (GKLS) dynamics as an explicit compatibility requirement.[32] States/effects come from the kinematics.[33]

Note on language. $\mathcal{A}(\mathcal{O})$ is the *algebra of locally accessible observables/effects* in the region $\mathcal{O}$. *Operations* in $\mathcal{O}$, by contrast, are described as CP maps in the Heisenberg picture acting on $\mathcal{A}$ (e. g. as $\Phi^*_{\mathcal{O}}$). Unselected dynamics (CPTP in the Schrödinger picture) corresponds to CP-*unital* maps in the Heisenberg picture; selective instrument branches are in general CP-*subunital* (the sum is unital). This distinction prevents a category mistake.

Step 1: We fix the *algebraic* content of "spacelike separated does not influence each other": microcausality is the condition under which the order of spacelike separated local interventions makes no observable difference whatsoever.[4]

Formula Box V.5.1: Microcausality (algebraic formulation)

Let $\mathcal{O}_1, \mathcal{O}_2 \subset \mathbb{R}^{1,3}$ be open, bounded regions with spacelike separation $\mathcal{O}_1 \subset \mathcal{O}_2^{\perp}$ (definition via the reference causality/light-cone order).[a] Then *bosonic locality* reads:

$$[A, B] = 0 \qquad \forall\, A \in \mathcal{A}(\mathcal{O}_1),\ \forall\, B \in \mathcal{A}(\mathcal{O}_2).$$

For $\mathbb{Z}_2$-*graded* (fermionic) sectors with parity $|\cdot| \in \{0, 1\}$, *graded locality* holds:

$$[A, B]_{\mathrm{gr}} \;\equiv\; AB - (-1)^{|A||B|} BA \;=\; 0, \qquad A \in \mathcal{A}(\mathcal{O}_1),\ B \in \mathcal{A}(\mathcal{O}_2).$$

In particular, odd–odd operators anticommute under spacelike separation: $\{A, B\} = 0$ for $|A| = |B| = 1$.

[a] See FBA Part II: Time, Proper Time & Minkowski Geometry, Sec. II.6 "Budget Quadric and Minkowski Limit".

Reading. Formula Box V.5.1 is not meant here as an "additional field axiom", but as a *minimal form* of operational independence: if interventions in $\mathcal{O}_1$ and $\mathcal{O}_2$ truly allow no mutual influence, then the "order" of their implementation must not become measurable. The dividing line matters: *no-signalling* alone is a marginal statement; for microcausality one needs the stronger requirement of *order unobservability* of spacelike separated interventions.

[29] See FBA Part I: FBA – Foundations, Sec. I.6 "Symmetric-Monoidal Structure, No-Wire Inflation & Local Operations".

[30] See FBA Part II: Time, Proper Time & Minkowski Geometry, Sec. II.6 "Budget Quadric and Minkowski Limit".

[31] See FBA Part II: Time, Proper Time & Minkowski Geometry, Sec. II.7 "Relativity & Lorentz Symmetries from the Quadric".

[32] See FBA Part IV: Dynamics & Measurement (GKLS), Secs. IV.3–IV.5 "Admissible Processes, Measurement Instruments & GKLS".

[33] See FBA Part III: Quantum Kinematics & CPTP Channels, Secs. III.3–III.5 "States, POVMs & Operator Language".

Why additional operational assumptions appear here. For "order is unobservable" to actually imply an *algebra statement* like $[A, B] = 0$, the theory must be locally "rich" enough: if an observable/effect is locally accessible, it should (at least infinitesimally) also be usable as a reversible local intervention. Without this minimal control assumption, there could be mathematically noncommuting candidates that are never operationally visible as an order signature.

Lemma V.5.1: Order unobservability (under operational completeness) ⇒ microcausality (operator representation)

Assume:

(i) Local interventions on disjoint supports are well defined under parallel composition and budget-additive (symmetric-monoidal structure).[a]

(ii) Spacelike separated regions satisfy no-signalling (no change of observable marginals) as a basic consistency condition.[b]

(iii) **Operational order unobservability:** For *every* choice of local interventions in $\mathcal{O}_1$ and $\mathcal{O}_2$, all *unselected* observable statistics are invariant under swapping the implementation order (no measurable "order signature").

(iv) **Operational separation (standard representation):** The set of locally accessible states/effects separates the locally relevant part of the algebra/map actions: equality of all expectation values for all locally accessible tests implies equality of the corresponding algebra elements/maps (no "invisible" differences in the physically relevant part of $\mathcal{A}(\mathcal{O}_1 \cup \mathcal{O}_2)$).[c]

(v) **Operational completeness (local reversible control):** For every region $\mathcal{O}$, sufficiently small reversible "kicks" from $\mathcal{A}(\mathcal{O})$ are locally realizable: for every self-adjoint $a \in \mathcal{A}(\mathcal{O})$ and sufficiently small ε there exists an unselected, locally implementable intervention in $\mathcal{O}$ whose Heisenberg action (possibly approximately) realizes the inner automorphism

$$A \mapsto e^{i\varepsilon a} A \, e^{-i\varepsilon a}$$

(and analogously, in the $\mathbb{Z}_2$-graded case, compatible with the grading).

Then, in a standard operator representation, the local algebras are (bosonically or graded) local under spacelike separation, i. e. they satisfy Formula Box V.5.1.[d]

[a] See FBA Part I: FBA – Foundations, Sec. I.6 "Symmetric-Monoidal Structure".
[b] See FBA Part I: FBA – Foundations, Sec. I.6 "No-Wire Inflation & Causal Cones & Local GKLS".
[c] See FBA Part III: Quantum Kinematics & CPTP Channels, Secs. III.3–III.5 "Operator Language, States & Tests".
[d] See FBA Part III: Quantum Kinematics & CPTP Channels, Secs. III.3–III.5 "Operator Representation & Heisenberg Picture".

The structural results established in Parts I, III, and IV (composition, ancillary registers, Stinespring/Kraus, instruments) provide the technical backbone; here the point is the idea of *which* operational fact motivates microcausality: the unobservability of order.[34] [35] [36] The next box summarizes this "idea chain" compactly.

Proof Sketch V.5.1: Idea chain

(1) Order unobservability ⇒ commuting Heisenberg actions (on observable tests). For locally supported *unselected* interventions (CPTP in the Schrödinger picture) $\Phi_{\mathcal{O}_1}, \Phi_{\mathcal{O}_2}$, the adjoint maps $\Phi^*_{\mathcal{O}_i}$ act CP-unital on $\mathcal{A}$. Assumption (iii) means: for all locally accessible tests C (in particular $C \in \mathcal{A}(\mathcal{O}_1 \cup \mathcal{O}_2)$) and all admissible states ρ, expectation values are invariant under swapping,

$$\mathrm{Tr}\big(\rho\, \Phi^*_{\mathcal{O}_1}(\Phi^*_{\mathcal{O}_2}(C))\big) = \mathrm{Tr}\big(\rho\, \Phi^*_{\mathcal{O}_2}(\Phi^*_{\mathcal{O}_1}(C))\big).$$

With (iv) (separation) this becomes equality of the actions on the physically relevant part:

$$\Phi^*_{\mathcal{O}_1} \circ \Phi^*_{\mathcal{O}_2} \;=\; \Phi^*_{\mathcal{O}_2} \circ \Phi^*_{\mathcal{O}_1} \quad \text{(on the locally accessible part of } \mathcal{A}(\mathcal{O}_1 \cup \mathcal{O}_2)).$$

(2) Noncommutativity ⇒ an order signature (contradiction to (iii)). Assume for contradiction that there exist $A = A^\dagger \in \mathcal{A}(\mathcal{O}_1)$ and $B = B^\dagger \in \mathcal{A}(\mathcal{O}_2)$ with $[A, B] \neq 0$.

By (v), for small ε the local reversible "kicks" $\mathrm{Ad}_{e^{-i\varepsilon A}}$ in $\mathcal{O}_1$ and $\mathrm{Ad}_{e^{-i\varepsilon B}}$ in $\mathcal{O}_2$ are admissible as unselected interventions (Heisenberg picture: conjugation).

Then the composed action is in general order-dependent:

$$\mathrm{Ad}_{e^{-i\varepsilon A}} \circ \mathrm{Ad}_{e^{-i\varepsilon B}} \;\neq\; \mathrm{Ad}_{e^{-i\varepsilon B}} \circ \mathrm{Ad}_{e^{-i\varepsilon A}} \quad \text{if } [A, B] \neq 0,$$

and (with a suitable choice of a locally accessible test C) a measurable order signature arises in expectation values/statistics. This contradicts (iii). Hence $[A, B] = 0$ must hold (or, in the fermionic case, the graded commutator must vanish).

(3) Fermionic sectors. With $\mathbb{Z}_2$ grading, "commutativity" is replaced by the graded commutator; odd–odd operators anticommute without violating operational consistency (CAR structure as a consistent realization).

Step 2: Microcausality is thus fixed as *local independence*. To obtain a field-theory language from this, we need a systematic organization: which observables belong to which region? This is provided by a *net* $\mathcal{O} \mapsto \mathcal{A}(\mathcal{O})$, which encodes local accessibility as an algebra assignment.

[34] See FBA Part I: FBA – Foundations, Secs. I.5–I.6 "Ancillary Registers/Composition".

[35] See FBA Part III: Quantum Kinematics & CPTP Channels, Secs. III.3–III.5 "Kraus/Stinespring, Instruments".

[36] See FBA Part IV: Dynamics & Measurement (GKLS), Secs. IV.3–IV.4 "Admissibility & Instruments".

Definition V.5.1: Net of local C*-algebras (Haag–Kastler core)

An assignment $\mathcal{O} \mapsto \mathcal{A}(\mathcal{O}) \subset \mathcal{A}$ is called a *local net.*[3, 4] If:

- *Isotony:* $\mathcal{O}_1 \subseteq \mathcal{O}_2 \Rightarrow \mathcal{A}(\mathcal{O}_1) \subseteq \mathcal{A}(\mathcal{O}_2)$.
- *(Graded) locality:* $\mathcal{O}_1 \subset \mathcal{O}_2^{\perp} \Rightarrow \mathcal{A}(\mathcal{O}_1)$ and $\mathcal{A}(\mathcal{O}_2)$ satisfy Formula Box V.5.1.
- *Covariance (Minkowski reference limit; additional assumption):* There exists a representation $U(\Lambda, a)$ of the Poincaré group with $U(\Lambda, a)\,\mathcal{A}(\mathcal{O})\,U(\Lambda, a)^\dagger = \mathcal{A}(\Lambda\mathcal{O} + a)$.[a]
- *Time-slice (additional assumption):* Let Σ be a Cauchy surface and $D(\Sigma)$ its causal development (domain of dependence). For every relatively compact neighborhood $N(\Sigma)$ of Σ one has
$$\mathcal{A}(N(\Sigma)) \;=\; \mathcal{A}(D(\Sigma)).$$
Operational connection via causal cones and local generators.[b][4]

[a]See FBA Part II: Time, Proper Time & Minkowski Geometry, Sec. II.7 "Relativity & Lorentz Symmetries from the Quadric".
[b]See FBA Part I: FBA – Foundations, Sec. I.6 "Causal Cones & Local GKLS".

Step 3: A net alone is still kinematical. For it to become "dynamical", open flows (GKLS) must act in a way that does not destroy localization: locally supported generators must not create effects outside the causal closure. We now formulate exactly this cone compatibility in the Heisenberg picture as a compatibility requirement.

Formula Box V.5.2: Local GKLS dynamics on the net (Heisenberg picture)

In the flat, kinematic limit, unselected open dynamics is formally described by a CP-unital semigroup $\{\alpha_t\}_{t\geq 0}$ on $\mathcal{A}$ (Heisenberg picture) with generator $\mathcal{L}^*$ in GKLS form:[5–7]

$$\frac{d}{dt}\,\alpha_t(A) = \mathcal{L}^*(\alpha_t(A)), \qquad \mathcal{L}^*(A) = i[H, A] + \sum_\ell \Big(L_\ell^\dagger A L_\ell - \tfrac{1}{2}\{L_\ell^\dagger L_\ell, A\}\Big).$$

As *cone compatibility (localization requirement)* we demand: if the generator data are localized to a region $\mathcal{O}$ (e. g. $H \in \mathcal{A}(\mathcal{O})$ and $L_\ell \in \mathcal{A}(\mathcal{O})$ for all ℓ), then for all $t \geq 0$,

$$\alpha_t(\mathcal{A}(\mathcal{O})) \subseteq \mathcal{A}(J(\mathcal{O})),$$

where $J(\mathcal{O})$ is the causal closure.[a] [b]

[a]See FBA Part I: FBA – Foundations, Sec. I.6 "Causal Cones & Local GKLS".
[b]See FBA Part IV: Dynamics & Measurement (GKLS), Sec. IV.5 "GKLS Equation".

Status of the result. With Definition V.5.1 and Formula Box V.5.2, the local operator language is formulated as a consistent framework that brings together (i) the cone order as reference causality and (ii) the process class (CPTP/GKLS) as the admissibility core. This is exactly the point at which one recognizes the usual local QFT structure as an *organizational form* (not merely as a postulate).

Corollary V.5.1: Embedding into the local QFT framework (kinematical core)

The structure in Definition V.5.1 provides isotony and (graded) locality; together with the additional assumptions "covariance" and "time-slice" this corresponds to the usual Haag–Kastler core.[3, 4]

Spectrum, vacuum, and renormalization assumptions are dynamical add-ons and are deferred to later parts (scales/RG, backreaction).

Remark V.5.1: Fermionic sectors & grading

For fermionic fields, locality is implemented via the $\mathbb{Z}_2$-graded commutator in Formula Box V.5.1. The line of argument remains unchanged once local interventions (channels/instruments) respect the grading (e. g. local parity selection as superselection).

Positioning. (i) Microcausality appears here as the operational form of the unobservability of the order of spacelike separated interventions.[37] [38] (ii) The net $\mathcal{O} \mapsto \mathcal{A}(\mathcal{O})$ is the carrier on which states/POVMs and admissible dynamics (CPTP/GKLS) can be formulated simultaneously.[39] [40] (iii) This yields the kinematical core of local relativistic QFT in the FBA as an *emergent* structure: a consistent organization of local accessibility, stable under composition, coarse-graining, and cone order.

[37] See FBA Part I: FBA – Foundations, Sec. I.6 "Composition/Locality/No-Signalling".
[38] See FBA Part II: Time, Proper Time & Minkowski Geometry, Secs. II.6–II.7 "Quadric & Lorentz".
[39] See FBA Part III: Quantum Kinematics & CPTP Channels, Secs. III.3–III.5 "States & POVMs".
[40] See FBA Part IV: Dynamics & Measurement (GKLS), Secs. IV.3–IV.5 "Admissible Processes & GKLS".

V.6 FBA and local relativistic QFT

Up to this point we have made the *kinematical core* of local relativistic field theory in the FBA formalism visible: light cones as reference causality from the quadric/front (Section V.4), microcausality as the operational form of *order unobservability* of spacelike separated interventions (in a standard operator representation; Section V.5), and from this a net of local algebras $\mathcal{O} \mapsto \mathcal{A}(\mathcal{O})$, supplemented by the (*additional*) covariance and time-slice assumptions customary in the standard framework (Section V.5).[4] [41][42]

This Section now explains how exactly this structure is to be read as *local relativistic QFT*: not as a new postulate, but as an *identification* of the nets/flows already obtained with the standard framework (*Haag–Kastler* / algebraic), and which *additional assumptions* (choice of state, spectrum, vacuum, regularity, possibly implementation of symmetries) are needed to pin down the *dynamical* content.

Working principle. We consistently separate (i) the *kinematical core* (net, locality, covariance, time-slice) from (ii) *dynamical add-ons* (vacuum/spectrum, concrete field coordinatization, renormalization, backreaction). This separation is particularly natural in the FBA, because (i) follows from the process class and causal order as a *reference structure*, whereas (ii) touches scale/RG and geometry questions and therefore belongs in later parts.

V.6.1 From the FBA net to algebraic QFT: what is "the field"?

In algebraic QFT the primary object is not $\phi(x)$ as an operator-valued distribution, but the *net* of local observable algebras.[3, 4] Exactly this net has already been constructed: $\mathcal{A}(\mathcal{O})$ encodes which *observables/effects* are locally accessible in a region $\mathcal{O}$, and microcausality is the algebraic form of "spacelike separated does not influence each other" (Section V.5). *Operations* in $\mathcal{O}$ appear in this language as CP maps in the Heisenberg picture acting on $\mathcal{A}$. What matters is: unselected dynamics (CPTP in the Schrödinger picture) corresponds to CP-*unital* maps in the Heisenberg picture, whereas selective instrument branches are in general CP-*subunital* (the sum is unital).

Thus the transition in the FBA is:

$$\text{local QFT} \;\widehat{=}\; (\mathcal{O} \mapsto \mathcal{A}(\mathcal{O})) \;+\; \text{choice of state} \;+\; \text{dynamics/regularity.}$$

The first summand is given by Section V.5; the other two determine *which* physics (vacuum/spectrum, thermal states, particle content, correlations) the net carries.

V.6.2 Symmetries: Lorentz/Poincaré covariance, generators, and conservation laws

In the FBA, the relativistic reference structure comes together from two sources: (1) the cone order (quadric/front) fixes Lorentz-compatible causal structure in the flat limit,[43] (2) the local process class (CPTP/GKLS) plus microcausality ensures that locally supported dynamics does

[41] See FBA Part I: FBA – Foundations, Sec. I.6 "Composition, No-Wire Inflation & Local Operations".

[42] See FBA Part II: Time, Proper Time & Minkowski Geometry, Secs. II.6–II.7 "Budget Quadric, Minkowski Limit & Lorentz".

[43] See FBA Part II: Time, Proper Time & Minkowski Geometry, Secs. II.6–II.7 "Budget Quadric, Minkowski Limit & Lorentz".

not violate this causal structure (Section V.5).[44] *Poincaré covariance* (including translations) is, in the standard framework, an additional symmetry assumption of the homogeneous reference limit and is implemented in the algebraic language via a (projective) unitary representation $U(\Lambda, a)$ that transforms the net correctly (cf. the covariance requirement in the net definition in Section V.5).

Definition V.6.2.1: Conservation laws from symmetries (under representation assumptions)

Under the assumption that the translation subgroup $a \mapsto U(\mathbb{I}, a)$ is unitary and strongly continuous, Stone's theorem yields self-adjoint generators $P_\mu = P_\mu^\dagger$ with

$$U(\mathbb{I}, a) = e^{ia^\mu P_\mu},$$

where the sign convention is purely definitional.[8] Translation invariance of the relevant states/dynamics then leads in the usual way to conservation statements (energy/momentum) *in the sense of the respective representation*; identifying them with local densities (stress-energy) requires further regularity.

Positioning. The FBA does not shift the content here, but the logic: the Lorentz/cone structure is obtained as a reference from quadric/calibration, and covariance/generators are the standard follow-up of this structure *under* representation and regularity assumptions.

V.6.3 Classical connection: from nets and GKLS to effective field equations

The classical (or semiclassical) connection follows the same separation logic: kinematically the net is retained (local observables remain local), while dynamically certain states/scalings in a suitable limiting regime appear as classical field quantities or transport equations. In the FBA this step is transparent because continuum and continuity limits are already read as controlled limiting forms of the update/process structure (refinement $\Rightarrow$ continuum; Markov/continuity $\Rightarrow$ GKLS).[45]

Definition V.6.3.1: Classical limit of QFT (as a controlled limiting regime)

The classical (or semiclassical) limit in the FBA is a limiting regime in which (i) refinement carries the discrete update structure into an effective continuum description and (ii) suitable states/scalings lead to field observables being described by classical quantities (expectation values, Wigner/phase-space limits, effective transport equations). In this sense, classical field equations appear as effective dynamics of the underlying net.

Summary. Local relativistic QFT is, in the FBA, not an additional layer but the standard reading of the already derived structure: light cones $\Rightarrow$ reference causality, operational order unobservability under spacelike separation $\Rightarrow$ microcausality, net of local algebras + (possibly covariance) + time-slice $\Rightarrow$ Haag–Kastler core (Sections V.4 and V.5). Symmetries

[44] See FBA Part IV: Dynamics & Measurement (GKLS), Secs. IV.3–IV.5 "Admissible Processes, Measurement Instruments & GKLS".

[45] See FBA Part IV: Dynamics & Measurement (GKLS), Secs. IV.4–IV.5 "Markov Semigroups & GKLS".

and conservation laws follow as usual *under* representation/continuity assumptions (Definition V.6.2.1), and the classical connection is a controlled limiting regime of the same structure (Definition V.6.3.1). This places the QFT side in the FBA precisely as an *organizational form of admissible, locally causal process structures.*

V.7 Summary and Outlook

V.7.1 Recap: What has been established in Part V?

We have made the *local, relativistic kinematical core* in the FBA precise as a *derived* structure:

- **Spacetime as a reference structure from updates.** Spacetime patches arise as local substructures of the global update order via minimal events and refinement (Section V.3); Minkowski language serves as shorthand for the flat reference limit (see conventions in Section V.2).
- **Light cones as the null structure of an invariant.** The operational causal order is fixed via the quadric and front calibration: light cone = null set of the line element, signal fronts saturate the bound (Section V.4, Formula Box V.4.1.1, Lemma V.4.3.1, and Definition V.4.2.1).
- **Local fields as nets, not as an additional postulate.** Microcausality is formulated as the algebraic form of operational *order unobservability* of spacelike separated local interventions (in a standard operator representation; Section V.5, Lemma V.5.1, and Formula Box V.5.1). Building on this, one obtains a net of local C*-algebras $\mathcal{O} \mapsto \mathcal{A}(\mathcal{O})$ with (graded) locality as well as (under additional assumptions) covariance and time-slice (Definition V.5.1 and Corollary V.5.1).
- **Open local dynamics is cone-consistent.** Unselected processes appear as CP-unital semigroups (Heisenberg picture) with local GKLS structure, compatible with the causal closure $J(\mathcal{O})$ (Section V.5 and Formula Box V.5.2).

Core point (flat/kinematical)
The local relativistic structure (light cones, microcausality, local nets, local open dynamics) is in the FBA *not an independent axiom*, but the consistent translation of front calibration/quadric (reference causality) and the process class under composition (CPTP/GKLS).

V.7.2 Connection to standard QFT: same framework, different derivation logic

With Section V.6, the transition to (algebraic) QFT is explicit: the net $\mathcal{O} \mapsto \mathcal{A}(\mathcal{O})$ is the primary object; "fields" are representations/coordinatizations of this net. *Poincaré* covariance (in particular translations) is formulated, in the flat homogeneous reference limit, as a *standard additional assumption*; conservation laws follow in the usual way *once* a sufficiently regular representation (strong continuity of the symmetry implementation) is chosen (Definition V.6.2.1). The classical/semiclassical connection is formulated as a limiting regime of the same structure (Definition V.6.3.1).

V.7.3 What is (still) not being claimed here?

This part works *flat and kinematically*: we have extracted the local relativistic *core*, but have made *no* full dynamical specification of a concrete QFT (spectrum/vacuum, concrete field generators, renormalization, interaction models). Likewise, gravity/backreaction is not implemented here, but reserved as a later program step.[46] Precisely this separation is conceptually useful: causal order and locality are already fixed, whereas scale/RG and backreaction are the *dynamical* add-ons.[47]

V.7.4 Outlook: next steps and test paths

The following development directions are natural in the FBA and at the same time empirically addressable:

1. **Choice of state, spectrum, particle content.** Construction of concrete models via additional, testable assumptions (e.g. spectrum condition, vacuum structure, thermal states) on top of the already fixed net core (Definition V.5.1 and Corollary V.5.1).
2. **Scales, renormalization, effective theories.** Making precise how refinement/coarse-graining appears in the FBA as an RG flow on nets/generators, and which invariants remain robust (in particular cone structure and locality).[48]
3. **Backreaction and dynamical geometry.** Extension beyond the flat reference limit: if budget flows influence the reference structure itself, "causal order" becomes locally dynamical. The goal is a controlled bridge to curved, locally causal descriptions without giving up microcausality and no-signalling.[49]
4. **Falsifiability at the local QFT core.** Concrete fail paths already arise at the kinematical level: (i) violation of the front bound despite correct calibration (Lemma V.4.3.1), (ii) *observable* order dependence of spacelike separated local interventions (operational breakdown of order unobservability; in an operator representation, breakdown of (graded) locality according to Formula Box V.5.1), (iii) inconsistencies between local GKLS dynamics and causal closure (Formula Box V.5.2).

Concluding remark. Part V thus provides the *local-relativistic field stage* in the FBA: cone order, microcausality, and net structure are available as derived consistency conditions. The subsequent work now shifts from "Which local structure is forced?" to "Which dynamical add-ons select the actually realized physics?" – in particular scales/RG, state spectra, and (later) backreaction/gravity.

[46] See FBA Part VI: Gravity & Geometry from Budget Flows, Secs. VI.1–VI.4 "Geometry/Gravitation from Budget Flows".

[47] See FBA Part VII: Constants, Scales & Renormalization, Secs. VII.2–VII.4 "Calibration/Scales & RG Flows".

[48] See FBA Part VII: Constants, Scales & Renormalization, Secs. VII.2–VII.4 "Calibration/Scales & RG Flows".

[49] See FBA Part VI: Gravity & Geometry from Budget Flows, Secs. VI.1–VI.4 "Geometry/Gravitation from Budget Flows".

V.8 Appendix: Overview of the FBA Series (Parts I–X)

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1. ***Part I*: FBA-Foundations: Ordering, Budget, Proper Time & Arrows.** *Goal:* Provide the base layer: ordering, budget, proper time/aging, front and the operational arrow of time (DPI); Minkowski limit from the budget quadric; admissible dynamics and locality/no-signalling. *Import:* – (reference for all subsequent parts). *Extension:* interface contracts, pass/fail checklists, reading guide.
2. ***Part II*: Time, Proper Time & Minkowski Geometry.** *Goal:* Capture proper time/quadric operationally and derive geodesics. *Import:* foundations (ordering, budget, proper time, front/DPI). *Extension:* smooth limit, variational principle on worldlines, calibration κ_τ.
3. ***Part III*: Quantum Kinematics & CPTP Channels.** *Goal:* State spaces and channels (CPTP) including composition. *Import:* foundations (budget, channel viewpoint, composition). *Extension:* concrete divergences/cost functionals $\mathcal{C}$, measurements, and classical registers.
4. ***Part IV*: Dynamics, Measurement & GKLS (Open Systems).** *Goal:* Continuous open dynamics (GKLS) and the operational arrow of time. *Import:* channels/DPI. *Extension:* Spohn monotonicity, stationary/NESS references, flows $b^{\mathrm{rev}}, b^{\mathrm{irr}}, b^{\mathrm{ext}}$.
5. ***Part V*: Spacetime, Light Cones & Local Field Theory.** *Goal:* Local field equations under front/locality. *Import:* front, composition, no-signalling. *Extension:* local GKLS generators, Lieb–Robinson-type bounds, effective light cones.
6. ***Part VI*: Gravity & Geometry from Budget Flows.** *Goal:* Geometrization of budget flows. *Import:* budget quadric/proper time. *Extension:* effective metrics from calibrations (κ_t, κ_x) and internal stresses; coupling to curvature.
7. ***Part VII*: Constants, Scales & Renormalization.** *Goal:* Scale running of the calibration theorems. *Import:* $c = \kappa_t/\kappa_x$, κ_τ. *Extension:* flow equations for $\kappa_t, \kappa_x, \kappa_\tau$; stability of c.
8. ***Part VIII*: Classical Limit, Thermodynamics & Aging.** *Goal:* Macroscopic behavior from $A[\gamma]$ (aging) and DPI. *Import:* proper time/aging, Spohn. *Extension:* entropy production, Euler–Lagrange forms for irreversible flows, effective transport equations.
9. ***Part IX*: Cosmic Dynamics, Time Dilation & Inflation (TDI).** *Goal:* Cosmic ordering & calibration flow. *Import:* budget, proper time/front. *Extension:* budget equations on large-scale slices; time-dilation inflation as calibration dynamics.
10. ***Part X*: Predictions, Falsifiability & Bridge FBA → QM ↔ GR.** *Goal:* Testable differences and bridges FBA ↔ QM/GR. *Import:* all foundational building blocks. *Extension:* protocols, limiting-case tests, overdetermined consistency relations (pass/fail).

All parts of the FBA series are available in both English and German at

https://www.frame-budget-approach.eu

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