The future of quantum theory

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Causality in the quantum world
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Part I: Introduction

Storyline of quantum theory

The past		
Quantum mechanics of particles	1920s	Matrix/Wave Mechanics
The present		
Quantum theory of fields	1970s	Standard Model
The future?		
Quantum theory of correlations?	2020-	Quantum Gravity?

Surpass frameworks

For fundamental physics, we need good predictions.

General frameworks	Specific models/theories
QFT framework global state	QED, QCD, Higgs mechanism etc.
(Non-)relativistic QM framework wave function	Relativistic quantum particle $(\partial^a \partial_a - m^2)\psi = 0$ etc.
Quantum information framework	?

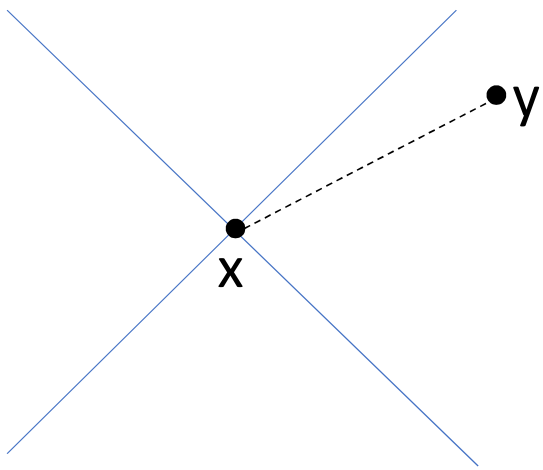
Maybe theories tell us what processes are allowed

Surpass wave function/particle

$$(\partial^a \partial_a - m^2)\psi = 0$$

$$\langle y|x\rangle \neq 0$$

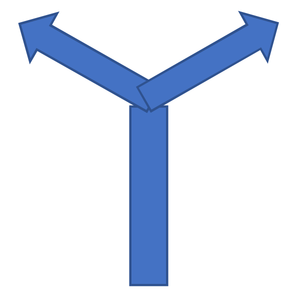
Causality issue



Spacelike correlations are perfectly fine

Field

Correlation



Particle/ wave function

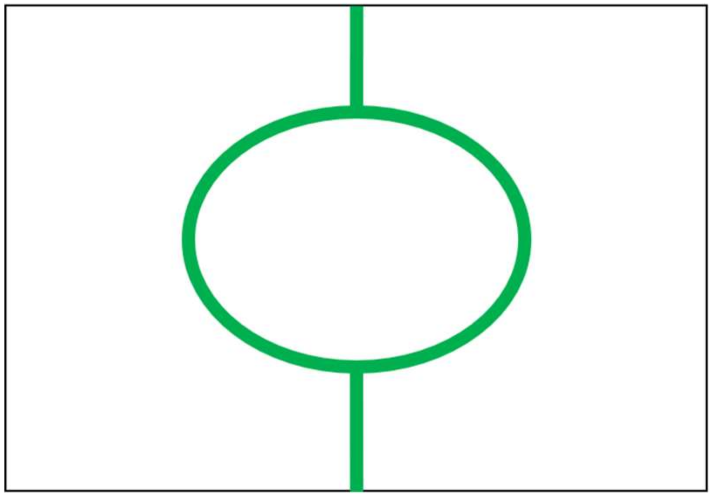
Challenges

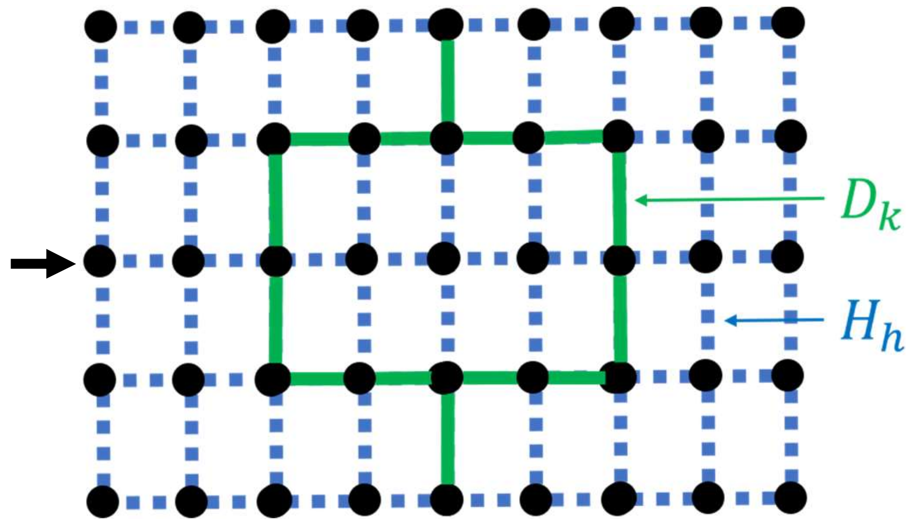
- Specific theories
- Relativity
- Quantum gravity

Proposals

1. Reformulate quantum field theory in terms of correlational quantum theory
2. New approach to QG (World Quantum Gravity)
   Idea: $g_{ab} \rightarrow \sigma(x, y)$

Main result – World Quantum Gravity (arXiv: 1909.05322)





$\sum_\Gamma \prod_i \int dx_i \frac{V[\Gamma]}{N[\Gamma]} \prod_{k\in\Gamma} G_k$

Non-perturbative, background independent

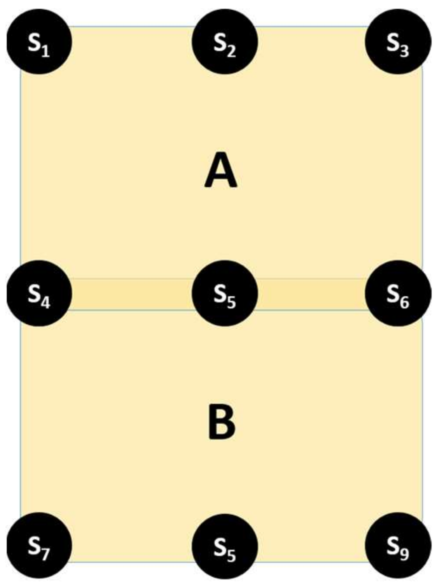
$$\boxed{\sum_\Gamma \sum_\sigma \frac{V[\gamma_\Gamma]}{N[\gamma_\Gamma,\sigma]} \prod_{h\notin\gamma_\Gamma} \underbrace{\Delta_h^{3\alpha_h \Delta_h^{-1}}}_{H_h} \prod_{k\in\gamma_\Gamma} \underbrace{\int \frac{dl_k}{(4\pi i l_k)^2} \Delta_k^{3C_k} \exp\left\{ i\frac{\sigma_k}{2l_k} - i m^2 l_k \right\}}_{D_k}}$$

Part II: Reformulate QFT

Hilbert space formalism

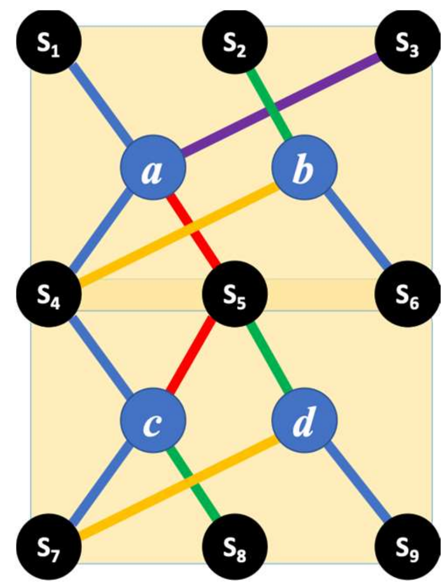
- Channels (Choi operators) A, B, C, …
- Composition $A*B:=\mathrm{Tr}_a[A^{T_a}B]$

Who correlates with whom?



Correlation diagram formalism

- Correlation diagram
- Composition matching

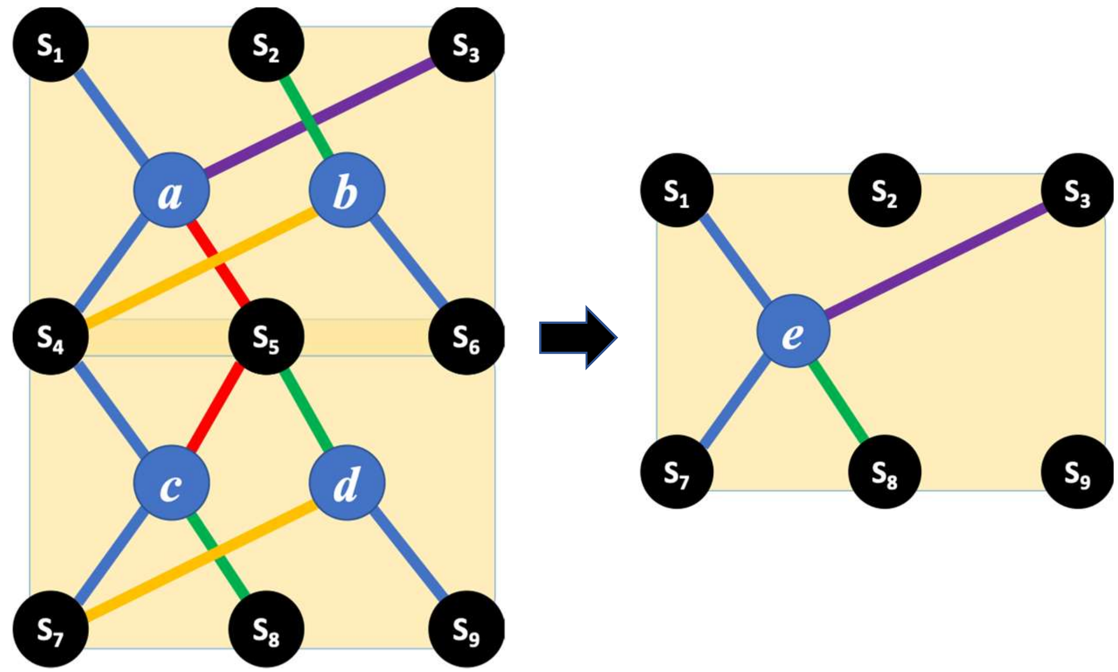


Correlation diagrams

- Correlation type decomposition (Oreshkov, Costa, Brukner; …)

$$A=\sum_{i,j,\ldots,k} \boxed{a_{ij\ldots k}}\, \sigma_i^{s_1} \otimes \sigma_j^{s_2} \ldots \otimes \sigma_k^{s_n}$$

Choi coefficients types

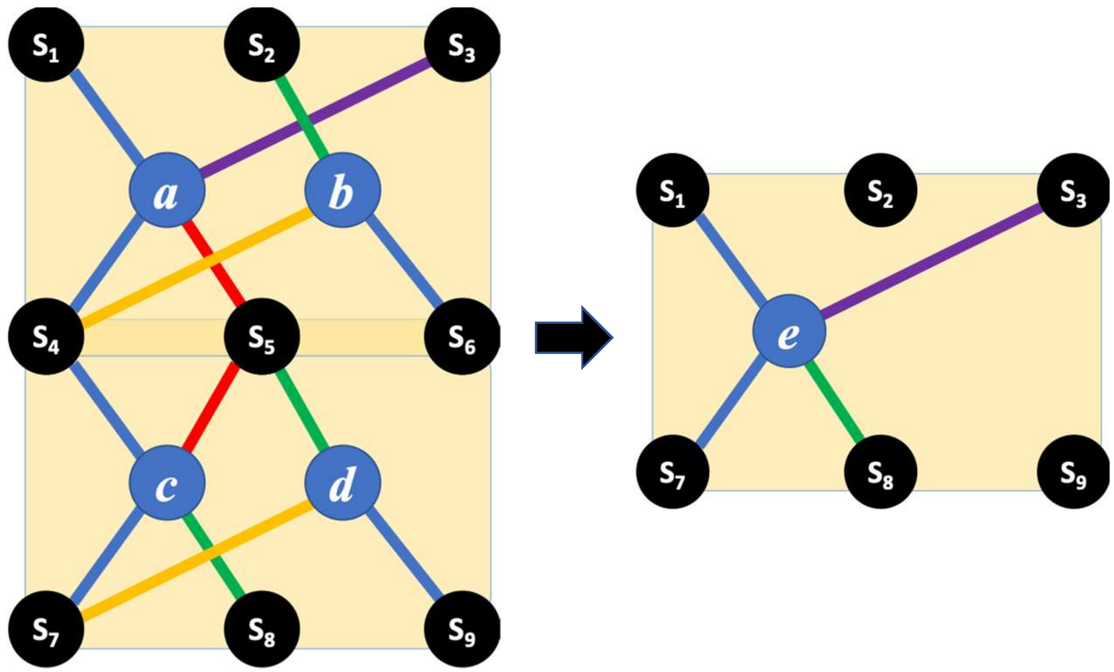


General correlation diagrams

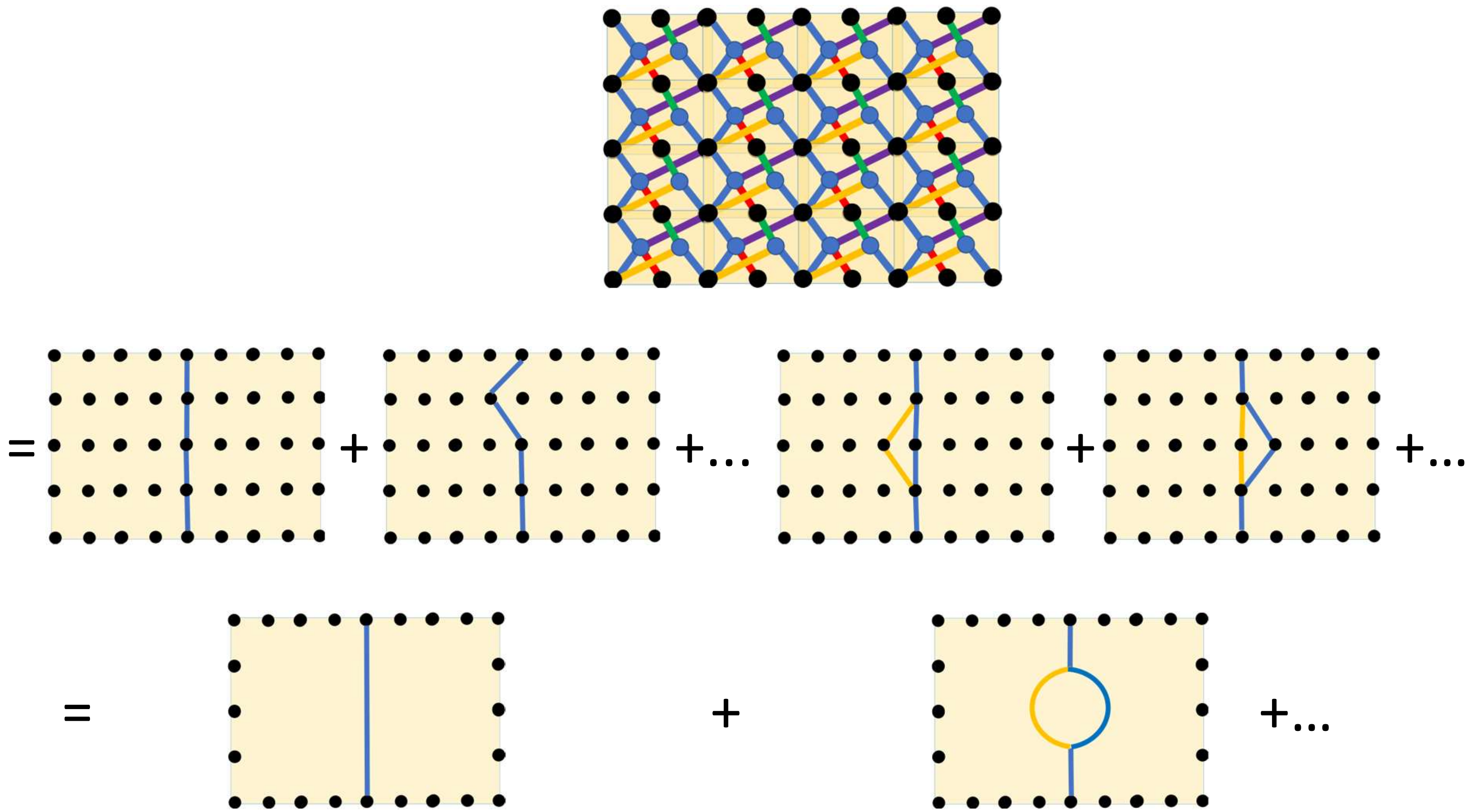
Idea: correlations are mediated

- Types and coefficients
- Composition by matching

A diagrammatic paradigm
for defining theories



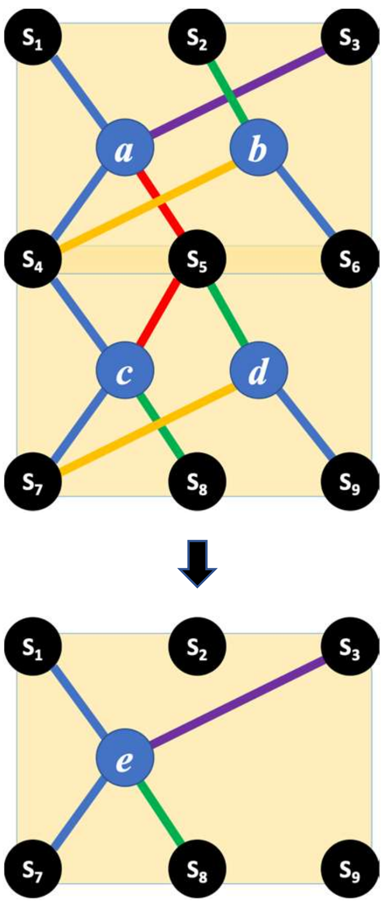
Feynman diagrams as topological classes



Correlation diagrams

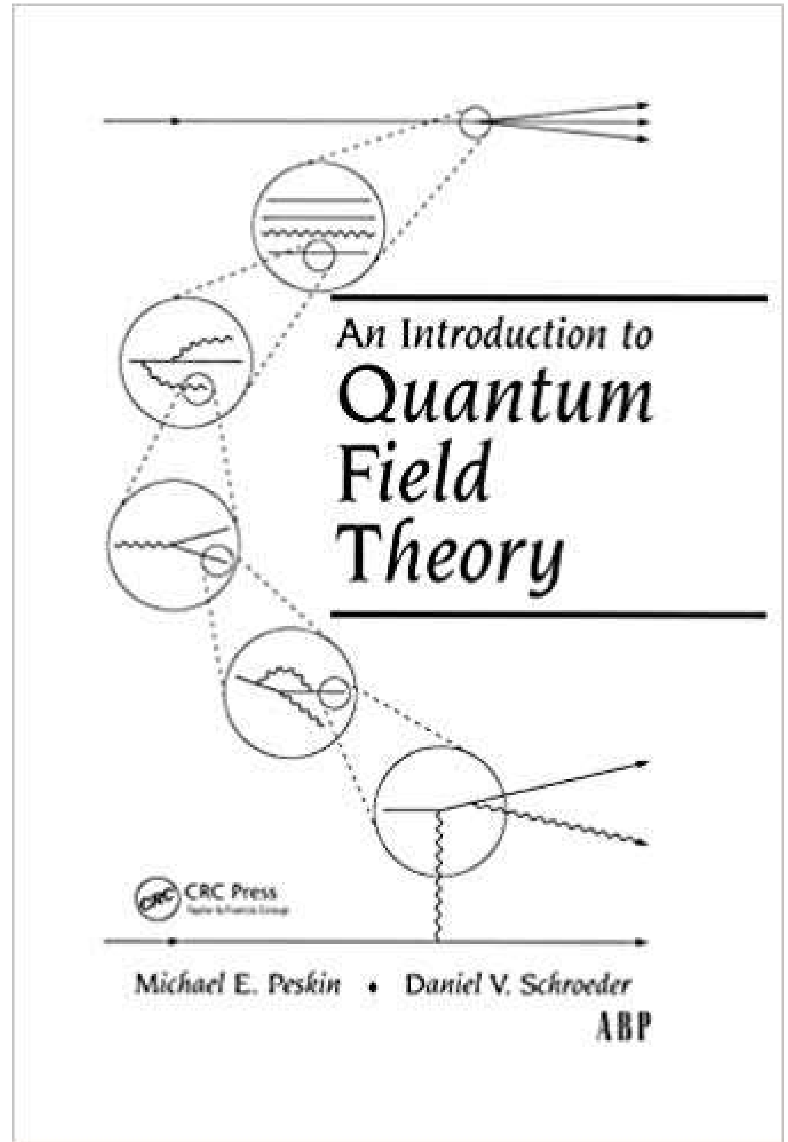
Feynman diagrams

QFT: arbitrary decomposition

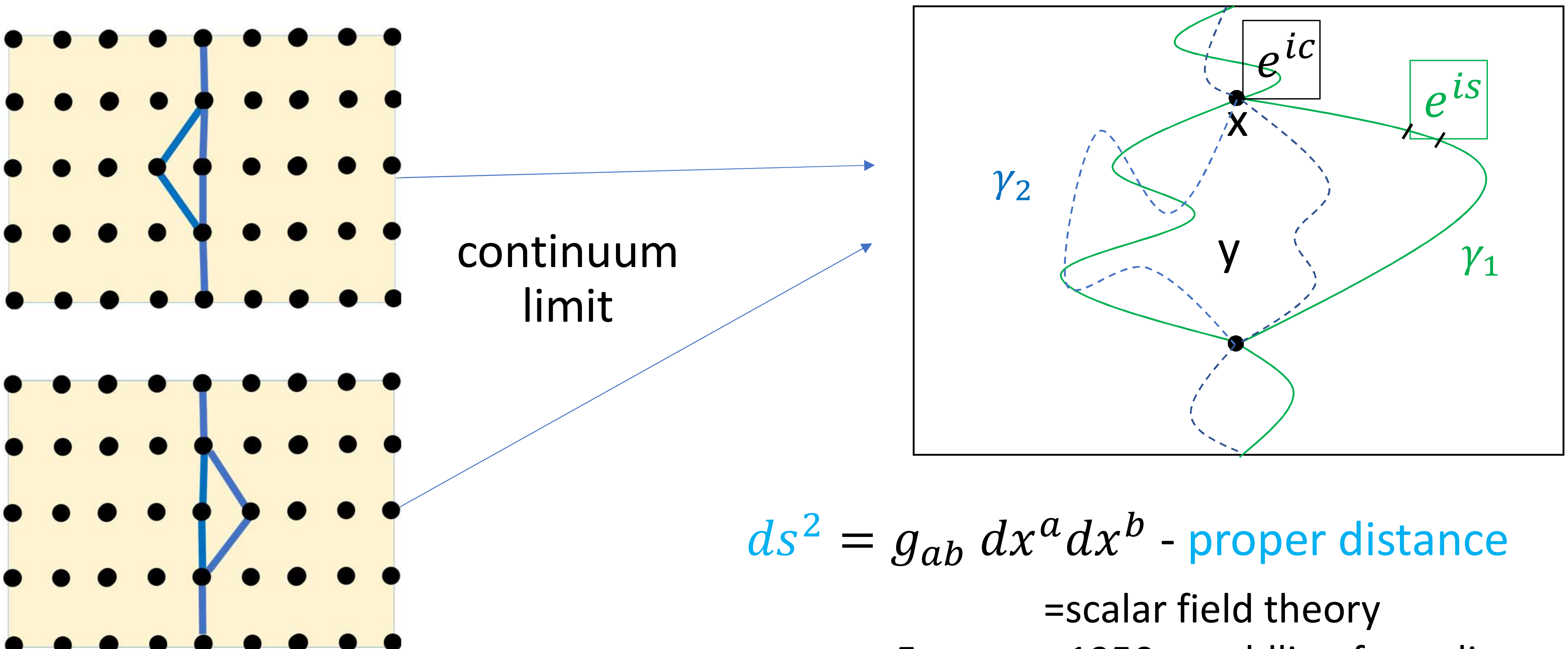


Reason:
Types and coefficients
specified at every point

specific theories



QFTs are simple!

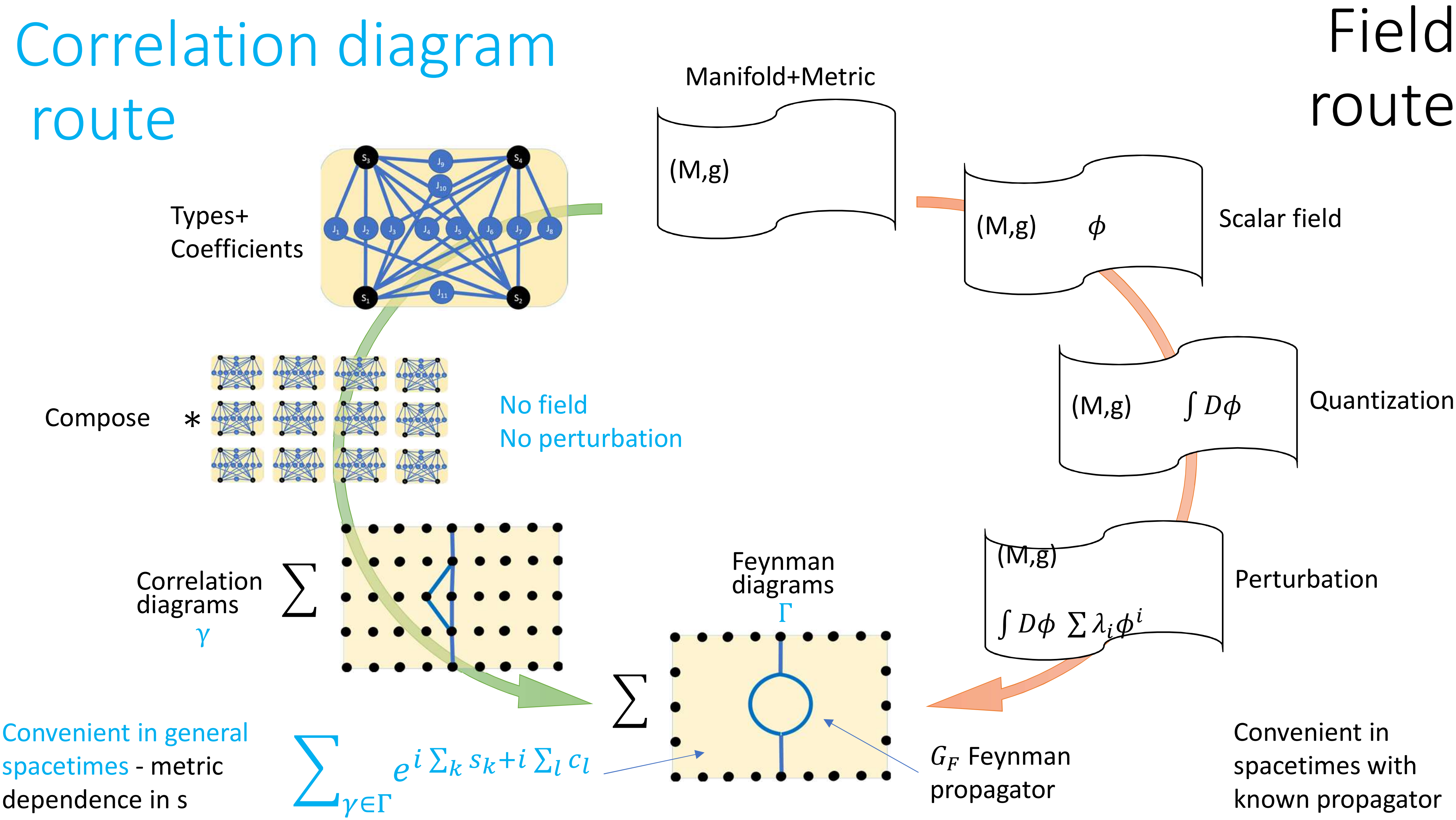


$ds^2 = g_{ab}\, dx^a dx^b$ - proper distance

=scalar field theory

Feynman 1950; worldline formalism

Higher spin through internal dof



Correlation diagram route
Field route
Manifold+Metric
(M,g)
(M,g) ϕ
Scalar field
(M,g) $\int D\phi$
Quantization
(M,g)
$\int D\phi \sum \lambda_i \phi^i$
Perturbation
Types+ Coefficients
Compose
$*$
No field
No perturbation
Correlation diagrams
γ
$\sum$
Feynman diagrams
Γ
$\sum$
Convenient in general spacetimes - metric dependence in s
$\sum_{\gamma\in\Gamma} e^{i\sum_k s_k + i\sum_l c_l}$
G_F Feynman propagator
Convenient in spacetimes with known propagator

How is this possible?

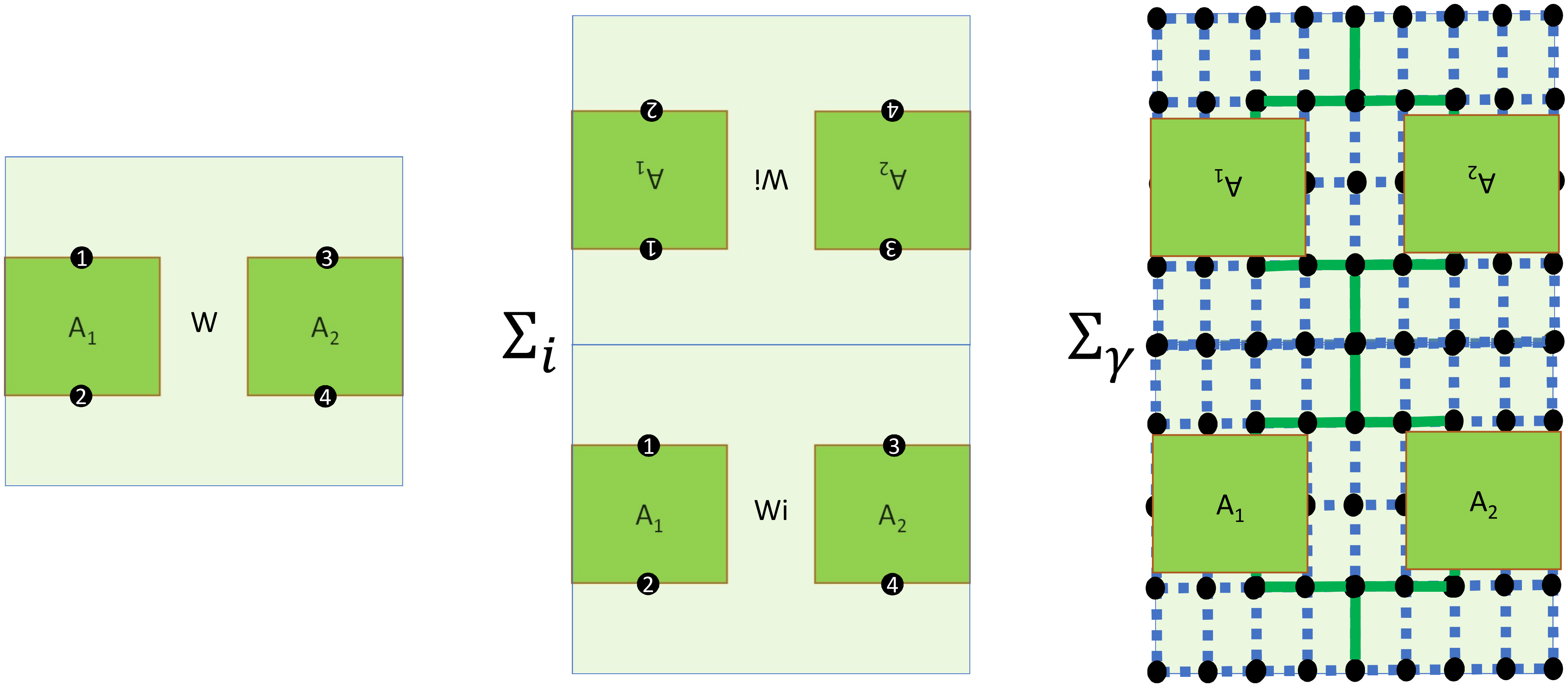
- Essence of QFT: correlations mediated in ST
- Reason for Feynman diagrams: correlation topology classes
- Quantum fields not necessary to capture the mediation of correlations
- Haag's perspective: fields are coordinates (Borcher classes)

$$x \to x'; \phi \to \phi'$$

- "Coordinate-free" description

Part III: World Quantum Gravity

$$N : \rho \sum_i \mapsto K_i \rho K_i^{\dagger}$$



probability amplitude theory

Idea: $g_{ab} \rightarrow \sigma(x,y)$

Path integral approach

$$A = \sum_{g} A_{QG}[g] \sum_{m} A_{M}[g, m]$$

World Quantum Gravity (WQG)

QFT

$$A = \int Dg_{ab}\ e^{iS_{EH}[g_{ab}]} \int D\phi\ e^{iS_M[g_{ab},\phi]}$$

$$A = \sum_{\sigma} A_{QG}[\sigma] \sum_{\gamma} A_{M}[\sigma, \gamma]$$

Van Vleck-Morette determinant

Worldline formalism

What is σ?

$$\boxed{\sigma(x,y) = \frac{\pm 1}{2} s(x,y)^2 \text{ - Synge world function}}$$

$$\sigma(x,y) = \tfrac{1}{2}\eta_{ab}(y-x)^a(y-x)^b$$

$$g_{ab}(x) = -\lim_{y\to x} \frac{\partial}{\partial x^a}\frac{\partial}{\partial y^b}\sigma(x,y)$$

Why σ?

- Simple

$$\sigma(x,y) = \sigma(x',y')$$

- Matter-friendly

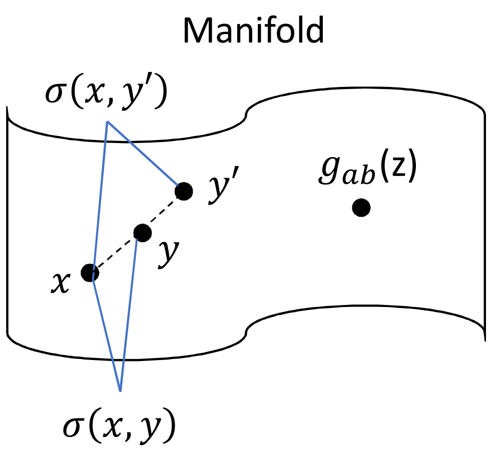
$$A_M \to e^{i\sigma/2l - im^2 l}$$

- Causal structure manifest

$$\sigma \quad =,<,> \quad 0$$

I. Topological setup (the case of local relational variables)

g_{ab}(x) – pointwise defined

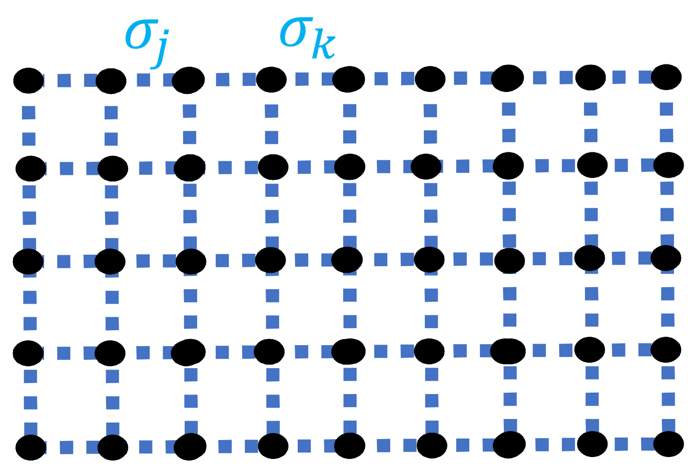


$$\boxed{\sigma(x,y) = \frac{1}{2}(l_y - l_x) \int_{l_x}^{l_y} g_{ab}(z) \frac{dz^a}{dl} \frac{dz^b}{dl} dl}$$

pairwise defined
relational

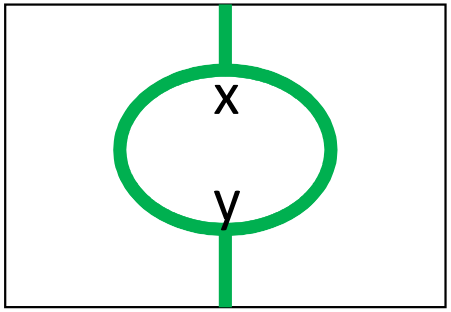
Integral expression
local

Skeleton graph
Hypercube
(for concreteness)



Algorithmic discreteness,
not necessarily fundamental!

II. Matter amplitude (Feynman diagrams are topological classes)



Γ Feynman diagrams

$$(\Box + m^2 + \xi R)\phi(x) = 0$$

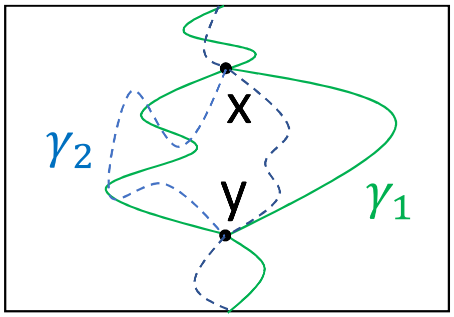
Scalar field is not just for scalar field!

Feynman, DeWitt, Parker…

"Worldline formalism":

External, spacetime dof in worldline location;

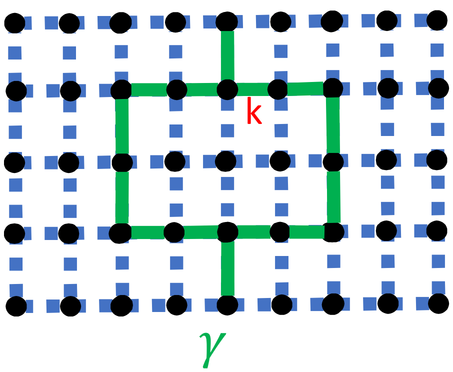
internal dof in Grassman variables



γ correlation diagrams

$$G(x,y) = i\int_0^\infty \langle x, l | y, 0\rangle\, e^{-im^2 l} dl$$

$$\langle x, l | y, 0\rangle = \int d[x(l')] \exp\Big\{ i\int_0^l dl' [\tfrac{1}{4} g_{ab} \tfrac{dx^a}{dl'} \tfrac{dx^b}{dl'} - (\xi - \tfrac{1}{3}) R(l')] \Big\}$$



$$A_M[k \in \gamma, g] = \int \frac{dl_k}{(4\pi i l_k)^2} \exp\Big\{ i\frac{\sigma_k}{2l_k} - i(\xi - \frac{1}{3}) R_k l_k - im^2 l_k \Big\}$$

$$A_M[\gamma, g] = \prod_{k\in\gamma} A_M[k \in \gamma, g] V[\gamma]$$

III. Gravity amplitude (Parker's magic)

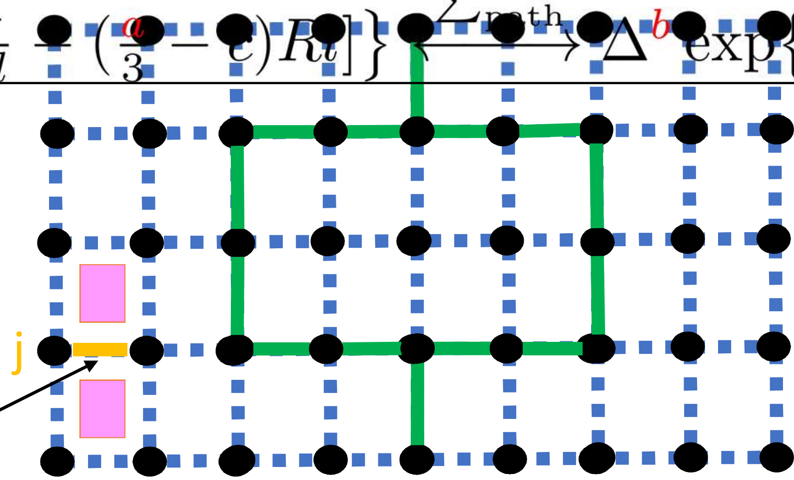
(Parker 1979, Bekenstein & Parker 1981)

$$\exp\{i(\tfrac{\sigma}{2l}+clR)\} \xleftrightarrow{\sum_{\text{path}}} (\Delta[\sigma])^{3c}\exp\{i\tfrac{\sigma}{2l}\}$$

$$\Delta^{a}\exp\{i[\tfrac{\sigma}{2l}-(\tfrac{a}{3}-c)Rl]\} \xleftrightarrow{\sum_{\text{path}}} \Delta^{b}\exp\{i[\tfrac{\sigma}{2l}-(\tfrac{b}{3}-c)Rl]\}$$

$$c_j \to \alpha_j \Delta_j^{-1}$$

$$l_j \to s_j$$



$$\boxed{\exp\{i\alpha_j s_j \Delta_j^{-1} R_j\}}$$

$$\alpha_j = \alpha\sum_{\{k,m,n\}} s_k s_m s_n$$

$$\exp\{i\bar{\alpha} d^4x_j\sqrt{-g_j}R_j\}$$

Van Vleck-Morette determinant:

$$\boxed{\Delta = C\exp\{-\textstyle\int \theta ds'\}/s^{-d}}$$

1. Meaning: Measures curvature by geodesic (de)focusing
(Visser 1993)

curved spacetime geodesic density / Flat spacetime geodesic density

2. World function $\boxed{\Delta = \Delta[\sigma]}$

$$s = |2\sigma|^{1/2} \qquad \theta(x) = \frac{\sigma^{a}{}_{a}(x,y)-1}{s}$$

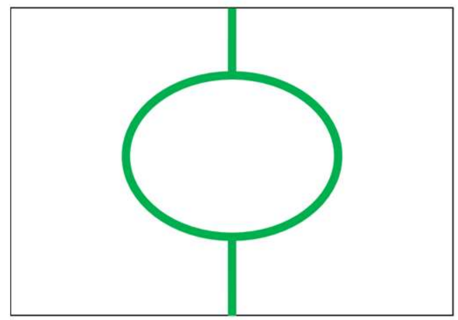
3. Wilson line $\mathcal{P}\exp\{\int A_a dx^a\}$

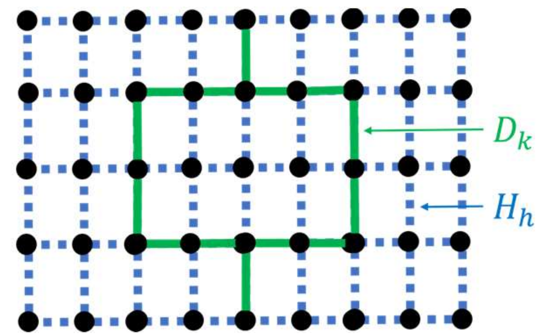
IV. Main formula (breaking up propagators into modified pieces)

$$\sum_\Gamma \prod_i \int dx_i \frac{V[\Gamma]}{N[\Gamma]} \prod_{k\in\Gamma} G_k$$

①Difference: Sum over geometry

$$\sum_{[\sigma]} \sum_{\sigma\in[\sigma]}$$





③ Matter: Propagators broken into pieces

$$\boxed{\sum_\Gamma \sum_\sigma \frac{V[\gamma_\Gamma]}{N[\gamma_\Gamma,\sigma]} \prod_{h\notin\gamma_\Gamma} \underbrace{\Delta_h^{3\alpha_h\Delta_h^{-1}}}_{H_h} \prod_{k\in\gamma_\Gamma} \underbrace{\int \frac{dl_k}{(4\pi i l_k)^2}\Delta_k^{3C_k} \exp\left\{ i\frac{\sigma_k}{2l_k} - im^2 l_k \right\}}_{D_k}}$$

$$C_k = \left(\frac{1}{s_k} + \frac{1}{l_k}\right)\left[\alpha_k s_k \Delta_k^{-1} - \left(\xi - \frac{1}{3}\right) l_k\right]$$

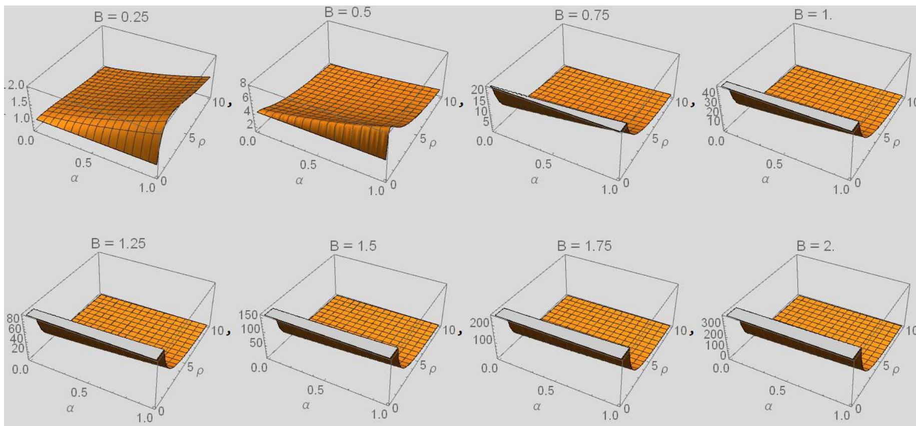
②Gravity: Non-perturbative treatment

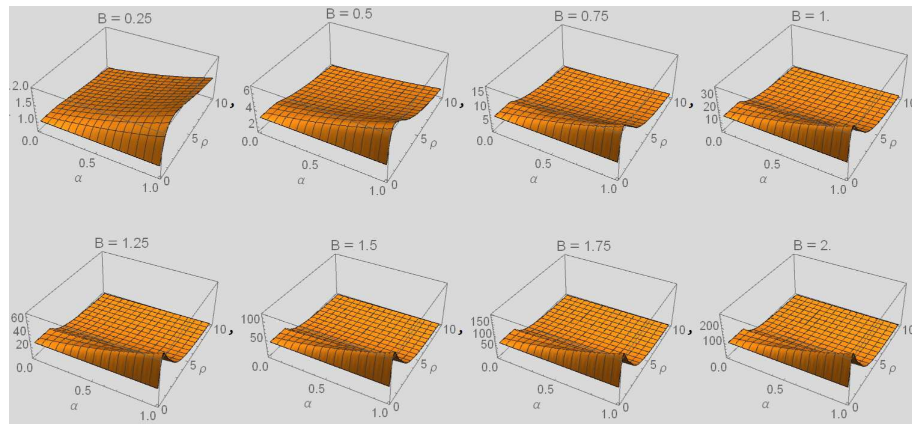
Preliminary numerical analysis

$$\boxed{\sum_\Gamma \sum_\sigma \frac{V[\gamma_\Gamma]}{N[\gamma_\Gamma,\sigma]} \prod_{h\notin\gamma_\Gamma} \underbrace{\Delta_h^{3\alpha_h\Delta_h^{-1}}}_{H_h} \prod_{k\in\gamma_\Gamma} \underbrace{\int \frac{dl_k}{(4\pi i l_k)^2}\Delta_k^{3C_k}\exp\left\{i\frac{\sigma_k}{2l_k} - i m^2 l_k\right\}}_{D_k}}$$

$$\Delta(s,\rho) = \left[\sqrt{\tfrac{\rho}{3}}\; s\; \csc\left(s\sqrt{\tfrac{\rho}{3}}\right)\right]^3 \qquad \int d\rho_h \int d\sigma_h \Delta_h^{3\alpha_h\Delta_h^{-1}} B^{s_h}$$

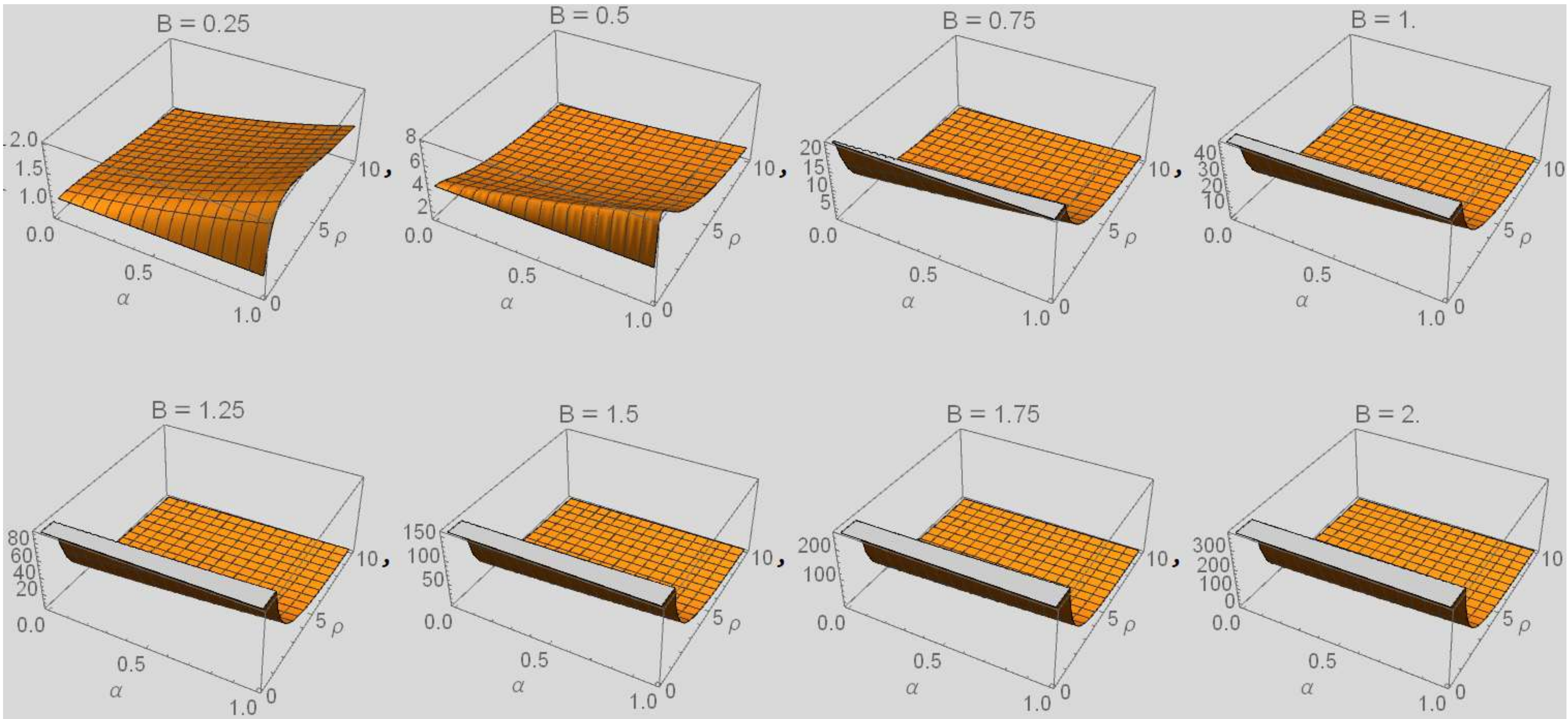
$$\boxed{\int_{-a^2/2}^{a^2/2} d\sigma \Delta^{3\alpha\Delta^{-1}} B^s = 2\int_0^a ds\; s\Delta^{3\alpha\Delta^{-1}} B^s}$$



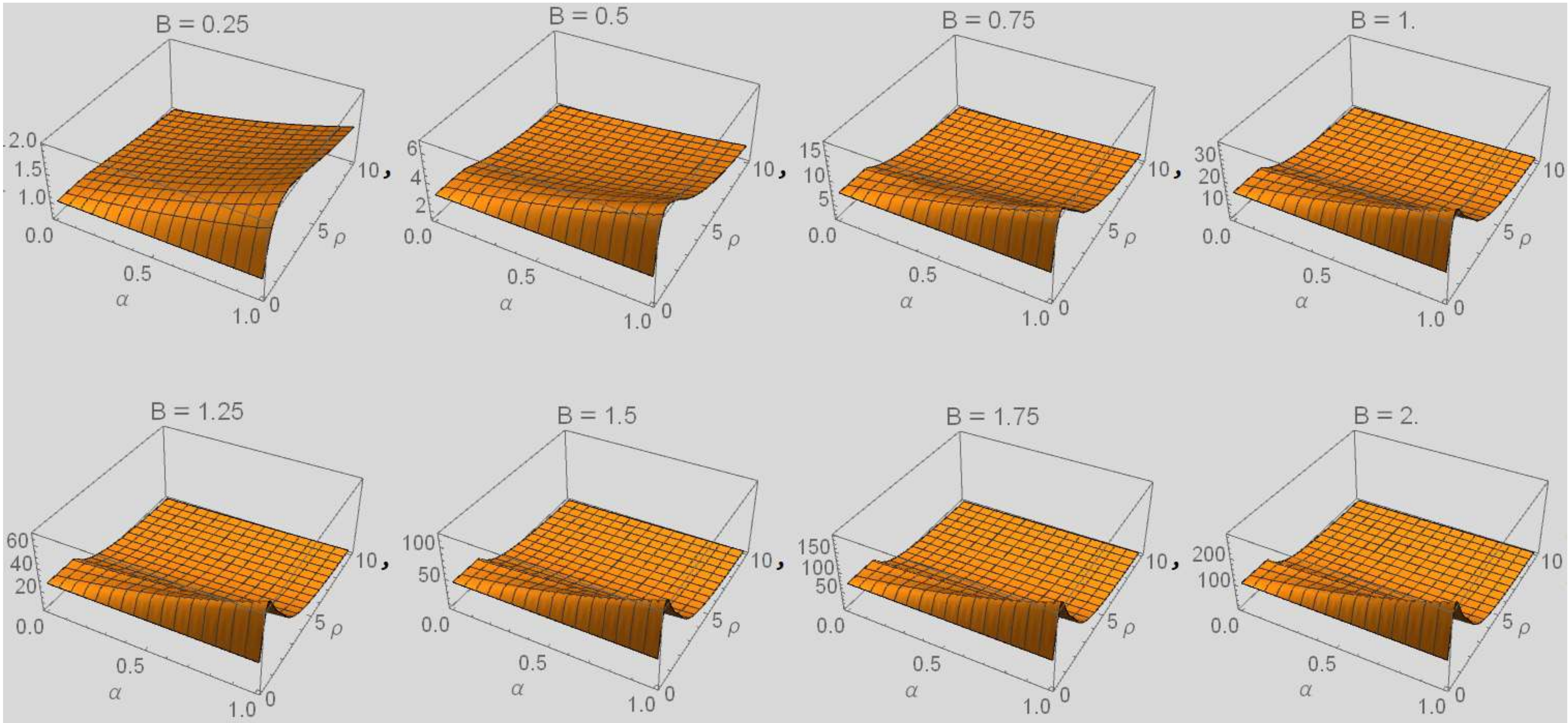


$$\boxed{\int_0^\infty d\rho \int_{-a^2/2}^{a^2/2} d\sigma \Delta^{3\alpha\Delta^{-1}} B^s}$$

B \ α	0.	0.2	0.4	0.6	0.8	1.
0.25	4348.37	4814.91	5326.67	5932.13	6650.38	7510.03
0.5	4388.28	4858.77	5375.17	5986.14	6710.92	7578.33
0.75	4430.65	4905.33	5426.67	6043.47	6775.17	7650.82
1.	4481.73	4961.46	5488.75	6112.63	6852.69	7738.29
1.25	4545.96	5032.04	5566.83	6199.53	6950.14	7848.2
1.5	4627.45	5121.55	5665.88	6309.83	7073.77	7987.72
1.75	4730.38	5234.71	5791.02	6449.14	7229.86	8163.81
2.	4870.94	5376.13	5947.45	6623.36	7425.16	8384.1



B = 0.25
B = 0.5
B = 0.75
B = 1.
B = 1.25
B = 1.5
B = 1.75
B = 2.
α
ρ



B = 0.25
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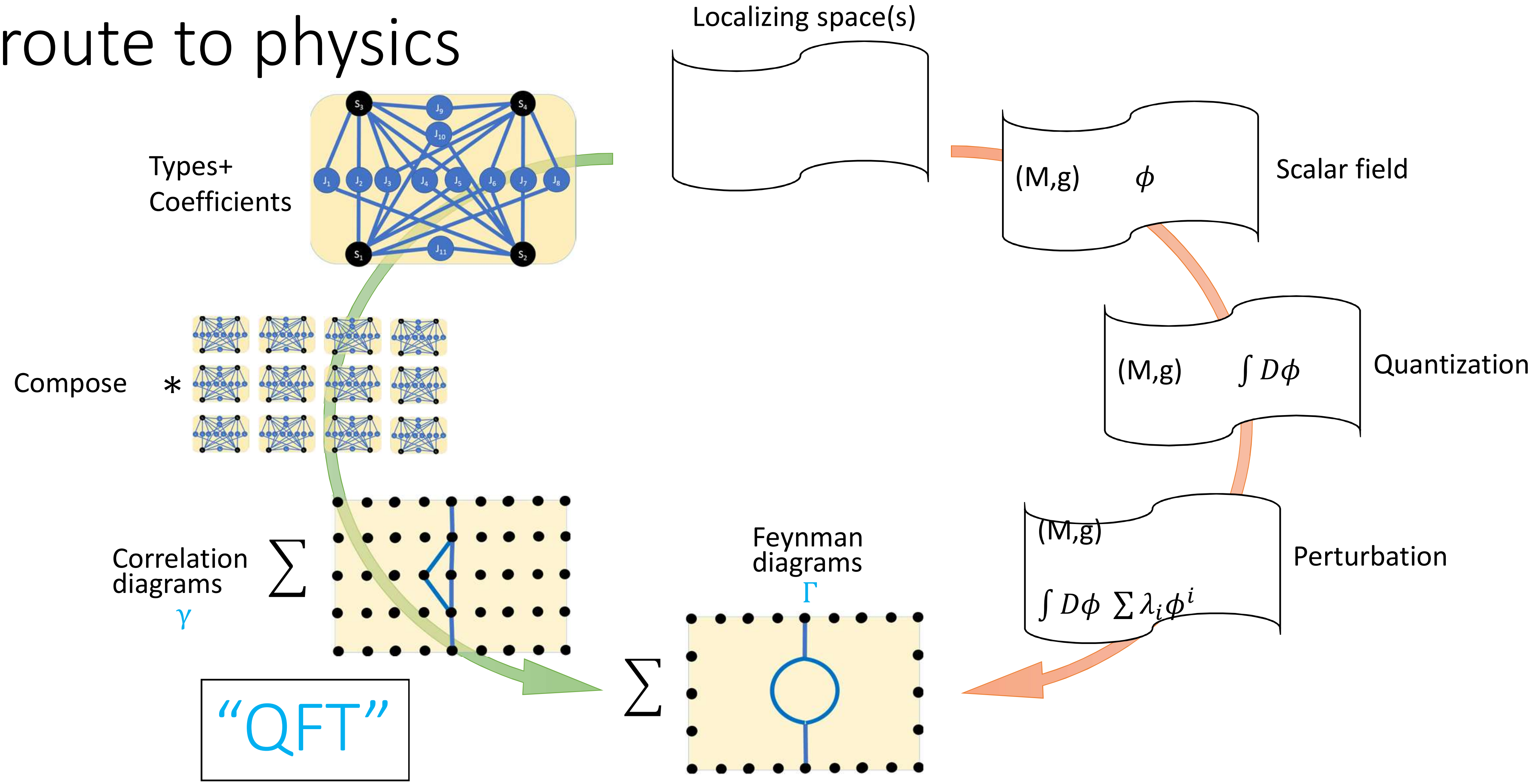
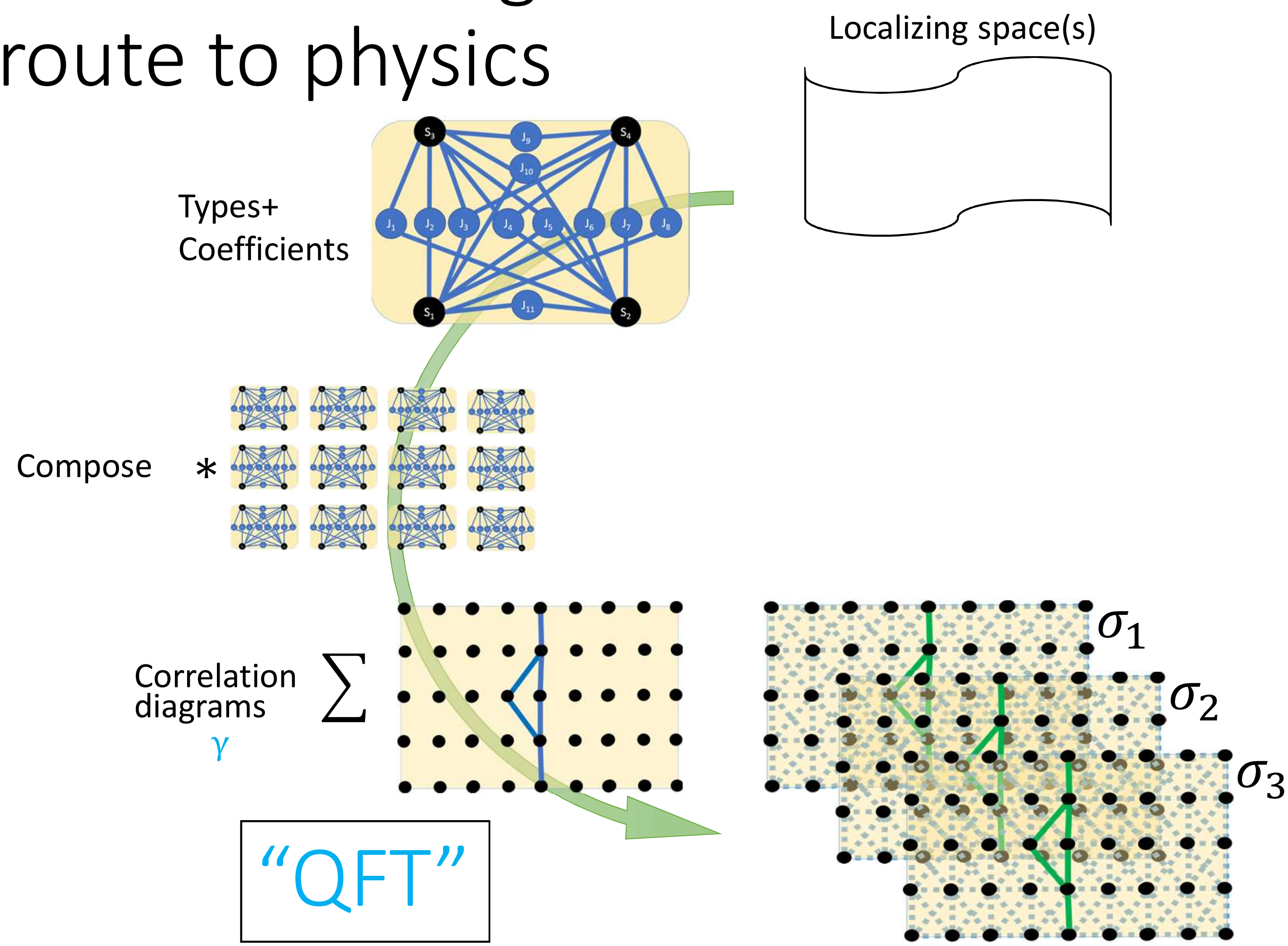
B = 1.25
B = 1.5
B = 1.75
B = 2.
α
ρ

Correlation diagram route to physics

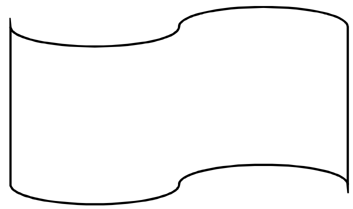


Correlation diagram route to physics

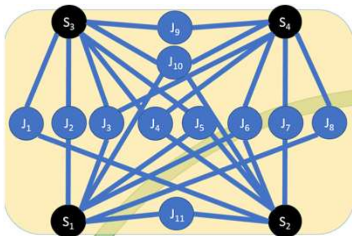


Correlation diagram route to physics

Localizing space(s)



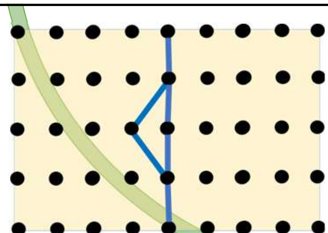
Types+
Coefficients

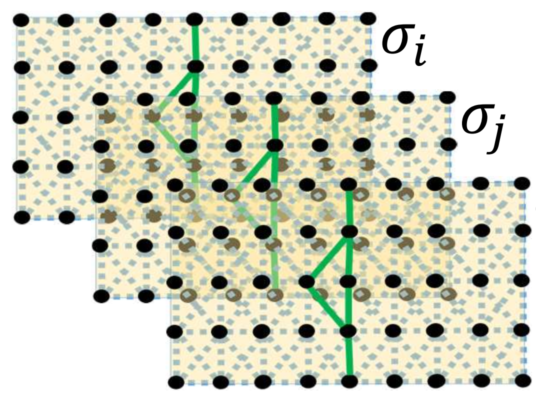


$$\sum_{\Gamma} \sum_{\sigma} \frac{V[\gamma_{\Gamma}]}{N[\gamma_{\Gamma},\sigma]} \prod_{h\notin\gamma_{\Gamma}} \underbrace{\Delta_h^{3\alpha_h \Delta_h^{-1}}}_{H_h} \prod_{k\in\gamma_{\Gamma}} \underbrace{\int \frac{dl_k}{(4\pi i l_k)^2} \Delta_k^{3C_k} \exp\left\{ i\frac{\sigma_k}{2l_k} - im^2 l_k \right\}}_{D_k}$$

Correlation
diagrams
γ

$\sum$



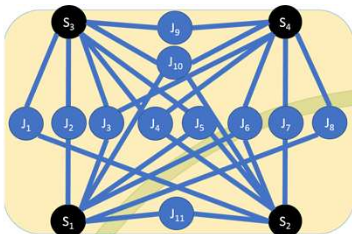


“QFT”

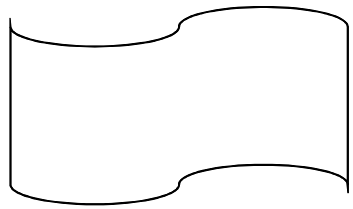
“QFT”+QG

Correlation diagram route to physics

Types+ Coefficients



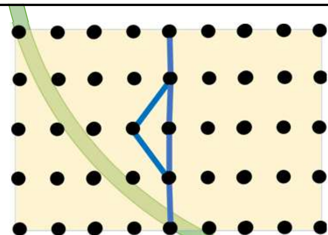
Localizing space(s)



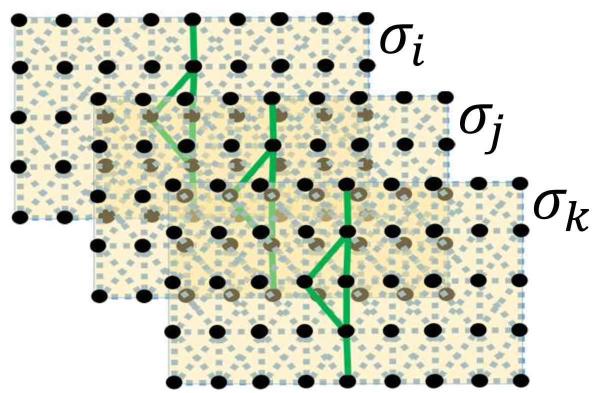
Thank you!

$$\sum_\Gamma \sum_\sigma \frac{V[\gamma_\Gamma]}{N[\gamma_\Gamma,\sigma]} \prod_{h\notin\gamma_\Gamma} \underbrace{\Delta_h^{3\alpha_h\Delta_h^{-1}}}_{H_h} \prod_{k\in\gamma_\Gamma} \underbrace{\int \frac{dl_k}{(4\pi i l_k)^2}\Delta_k^{3C_k}\exp\left\{i\frac{\sigma_k}{2l_k} - im^2 l_k\right\}}_{D_k}$$

Correlation diagrams γ $\sum$



“QFT”



“QFT”+QG