Hyperon Spin Correlations

(from realtime 1+1d QFT simulations)

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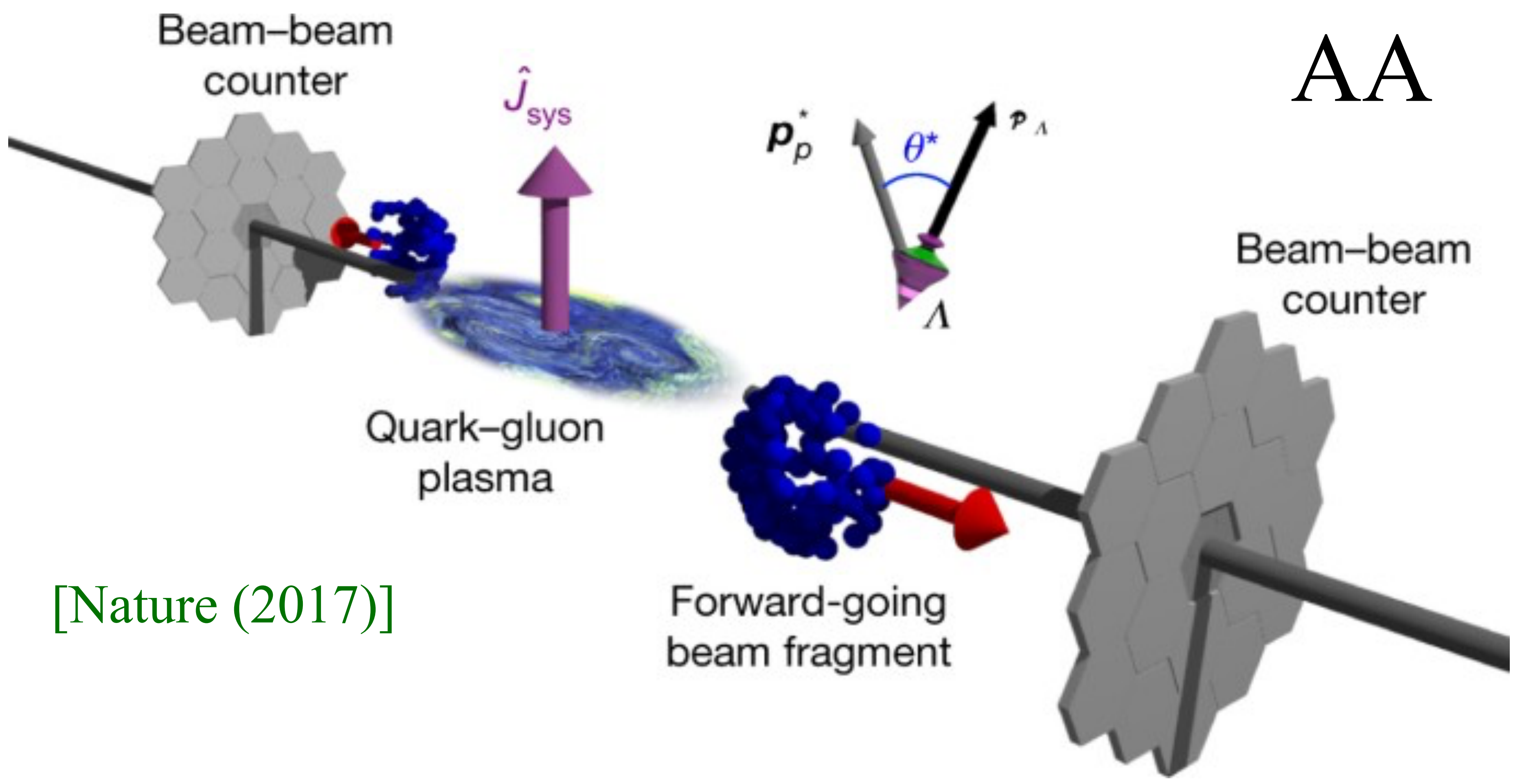
Based on: 2308.13596, with W. Gong (MIT) and R. Venugopalan (BNL)

Hyperon Spin correlations

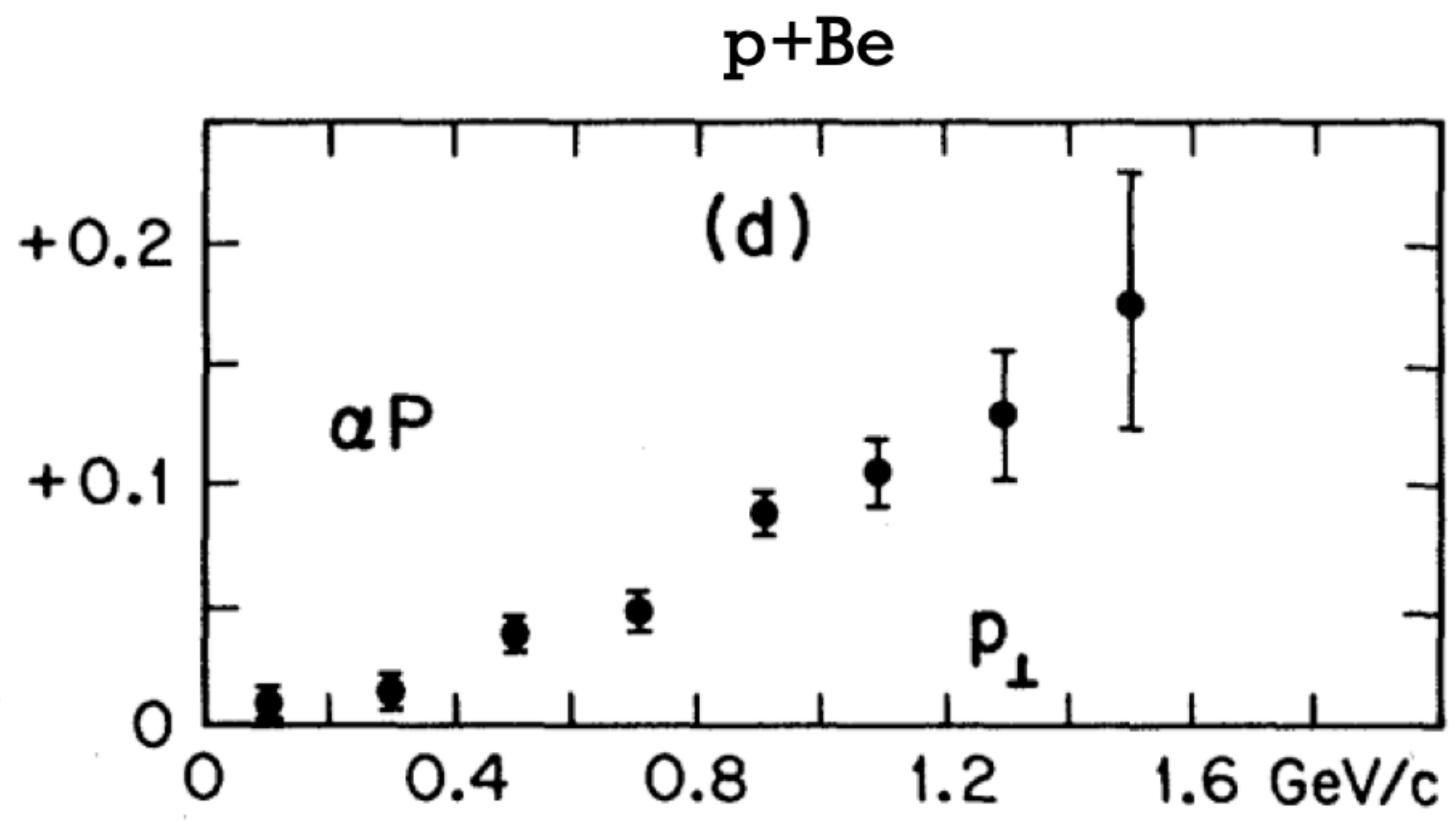
Λ= uds

A remarkable discovery: Λ hyperons get polarized in many (unpolarized) collision systems:

AA



[Nature (2017)]



[PRL (1976)]

So far there is no complete description for this phenomena:

AA : hyperons' spin aligns with angular momentum of (rotating) quark gluon plasma

Smaller systems : some models describe polarization, but not full events

Hyperon Spin correlations

Λ= uds

Spin-spin hyperon correlations can give important information about:

Initial state spin effects: extract hyperon polarization in polarized scattering experiments

Hadronization dynamics and fragmentation

How can spin correlations be washed away?

[Gong, Parida, Tu, Venugopalan, 2107.13007]

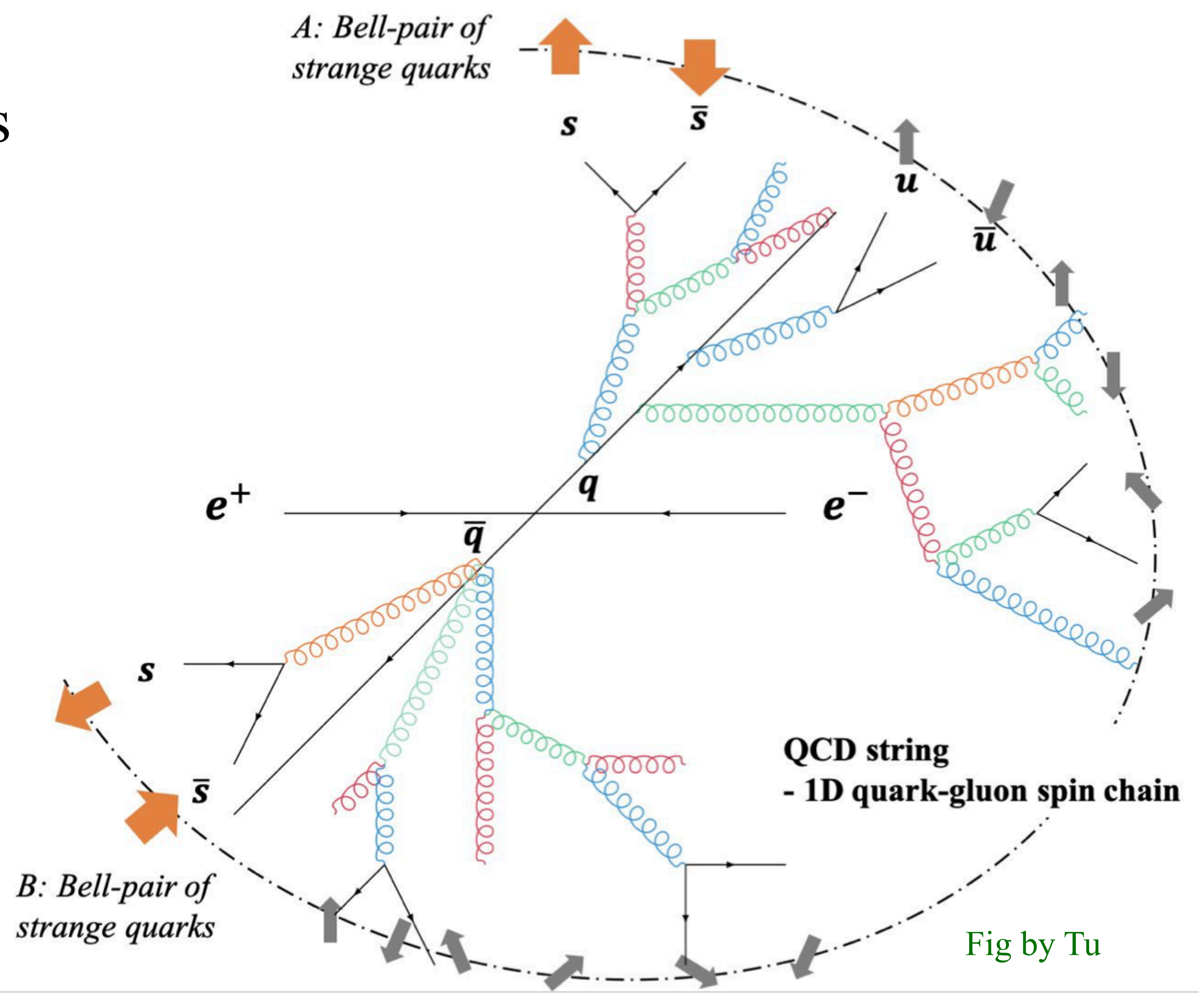


Fig by Tu

Hyperon Spin correlations

Λ= uds

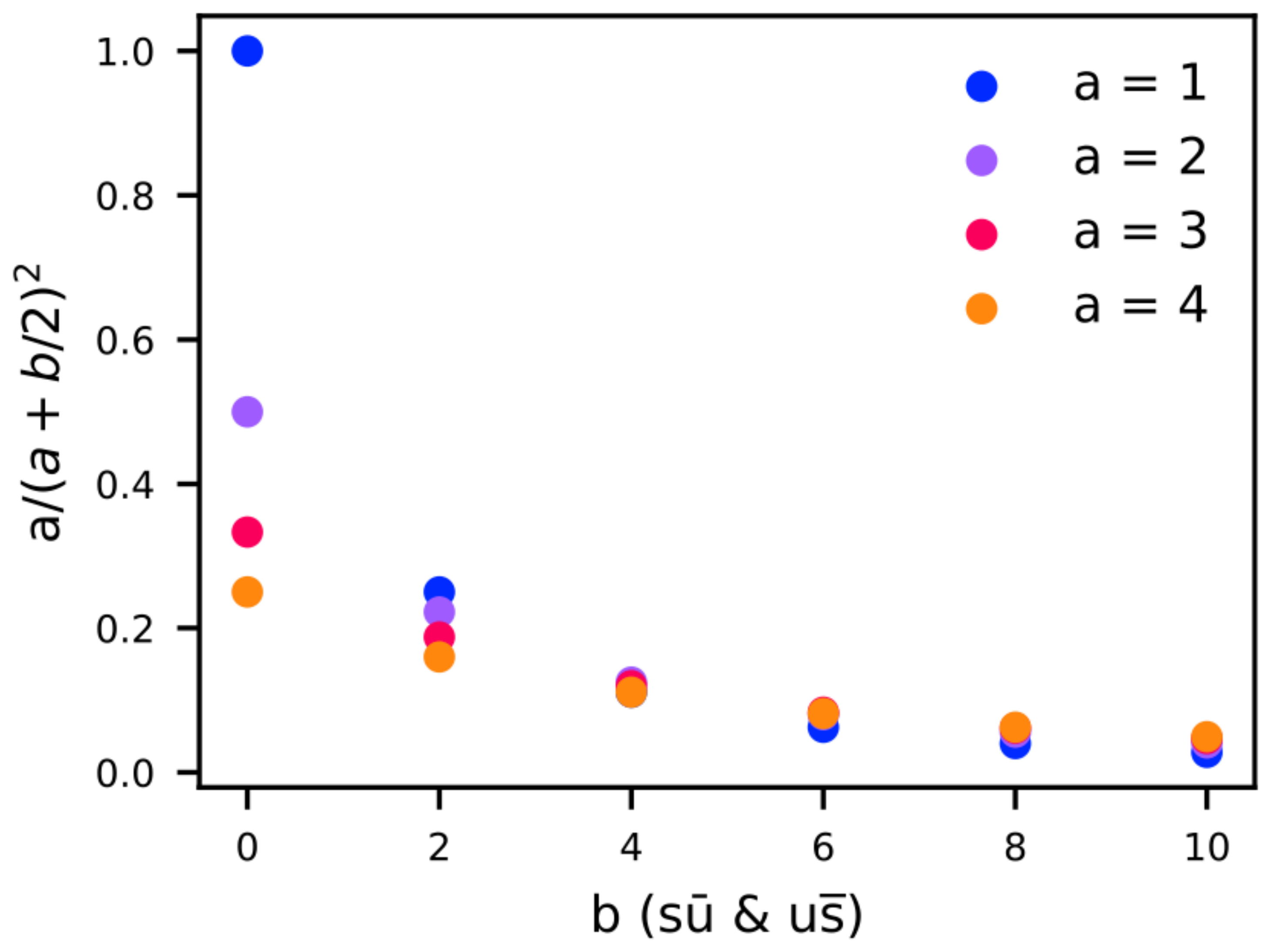
How can spin correlations be washed away?

[Gong, Parida, Tu, Venugopalan, 2107.13007]

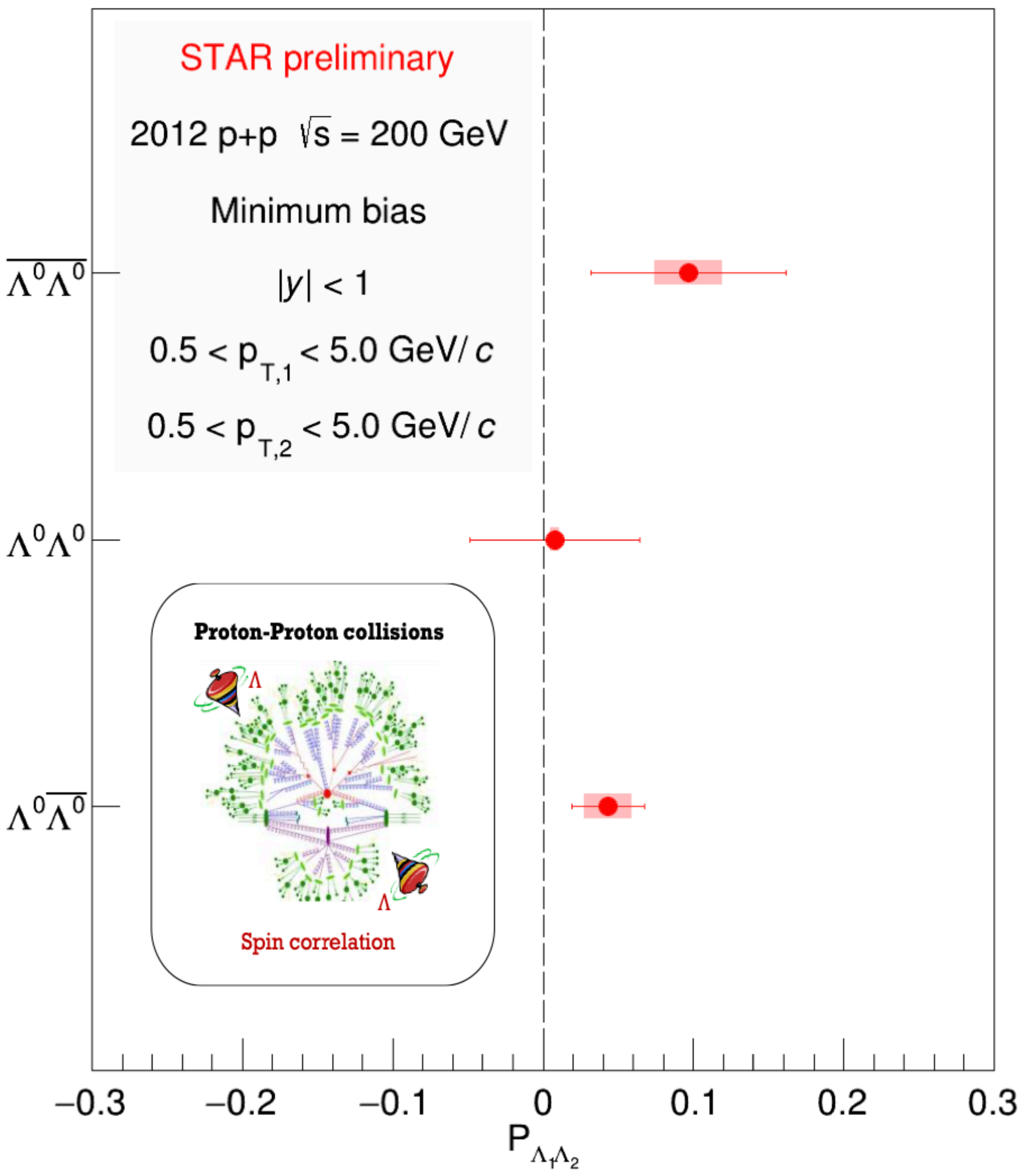
$$\frac{P(|\hat{n}_1\rangle, |\hat{n}_2\rangle)}{P(|\hat{n}_1\rangle)P(|\hat{n}_2\rangle)} = 1 - \frac{a}{(a+b/2)^2}\cos(\theta_2 - \theta_1)$$

a= # strange pairs b= # light quarks

Corollary 2. *If the magnitude of the coefficient of* $\cos(\theta_{ab})$ *in a symmetric rotationally invariant correlation function is* $> \frac{1}{2}$, *then the measured state* ρ_{ab} *is entangled.*



[from J. Vanek at SPIN 23]



Towards describing spin correlations from QFT

So far, description constrained to perturbative approaches or modeling of static strings

How to go beyond ?

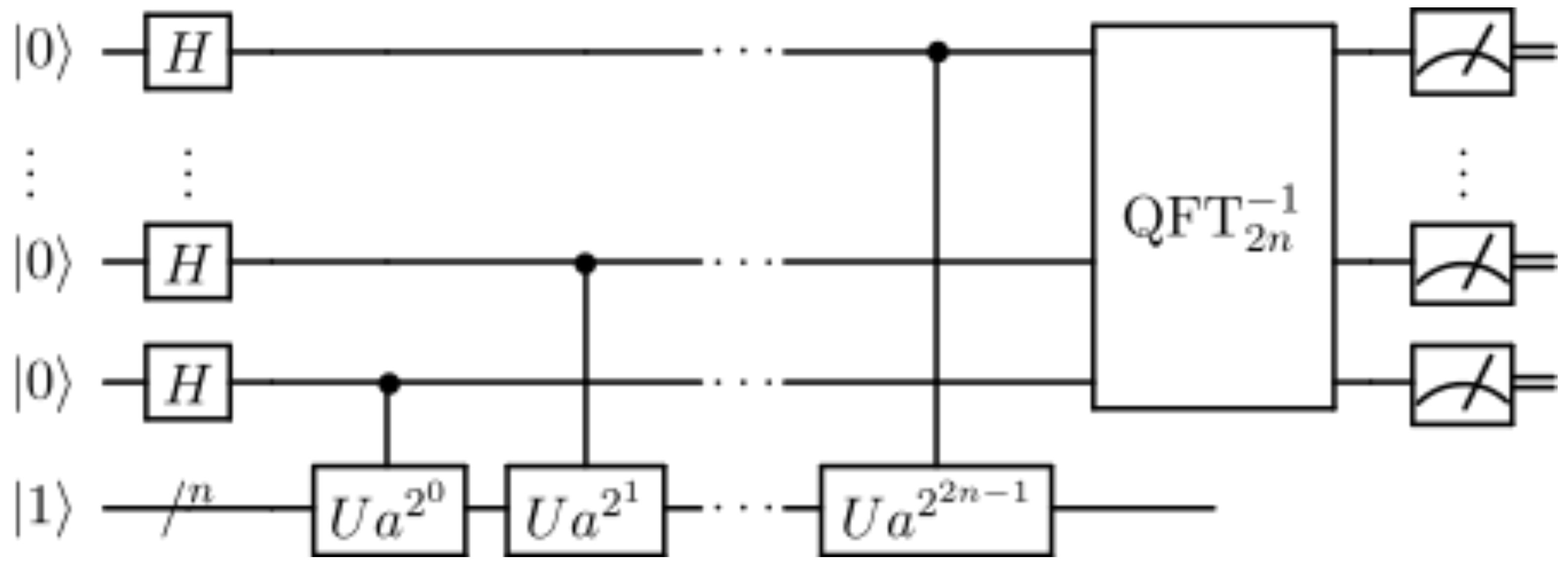
Euclidean Lattice QFT ✗

Well established non-perturbative QFT formulation

Hadronization and fragmentation are inherently Minkowski and thus one can not use traditional lattice

Minkowski Lattice QFT ✓

Requires quantum devices



Many caveats, so far no full scale machine exists

Description always in 1+d dimensions so no sign problem !

Massive Schwinger model and pair production

Working models mainly constrained to 1+1d, with the QCD analog being the Schwinger model

[Schwinger, 1951]

$$H_{\text{Schwinger}} = \int dx \, \frac{1}{2} E^2(x) + \sum_{f=1}^{N_f} \bar{\psi}_f(x)(-i\gamma^1\partial_1 + g\gamma^1 A_1(x) + m_f)\psi_f(x)$$

Shares many properties similar to QCD…

Chiral condensate

Confining fermion potential

… but also important differences

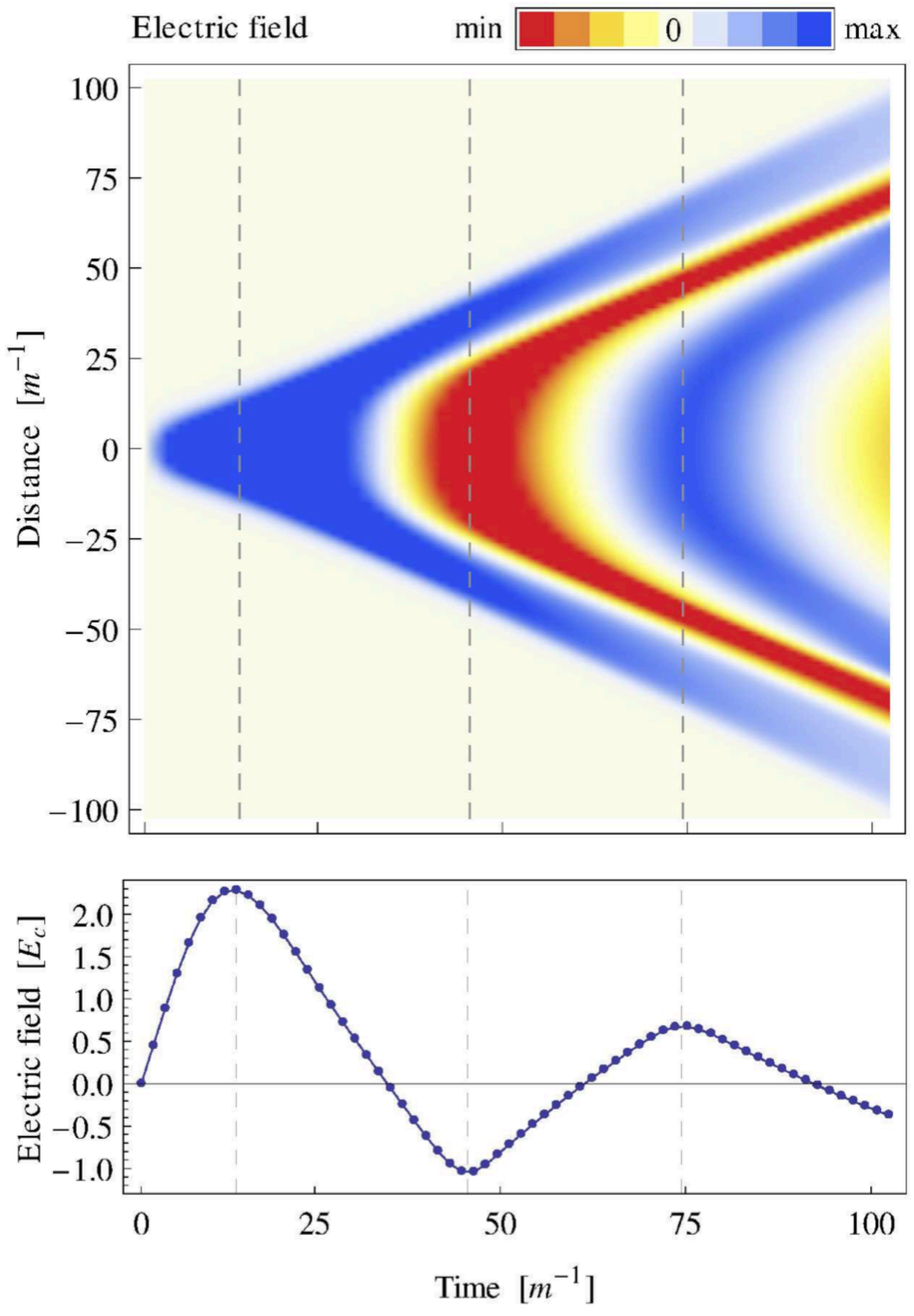
Integrable in the massless limit

No dynamical gauge fields

Massive Schwinger model and pair production

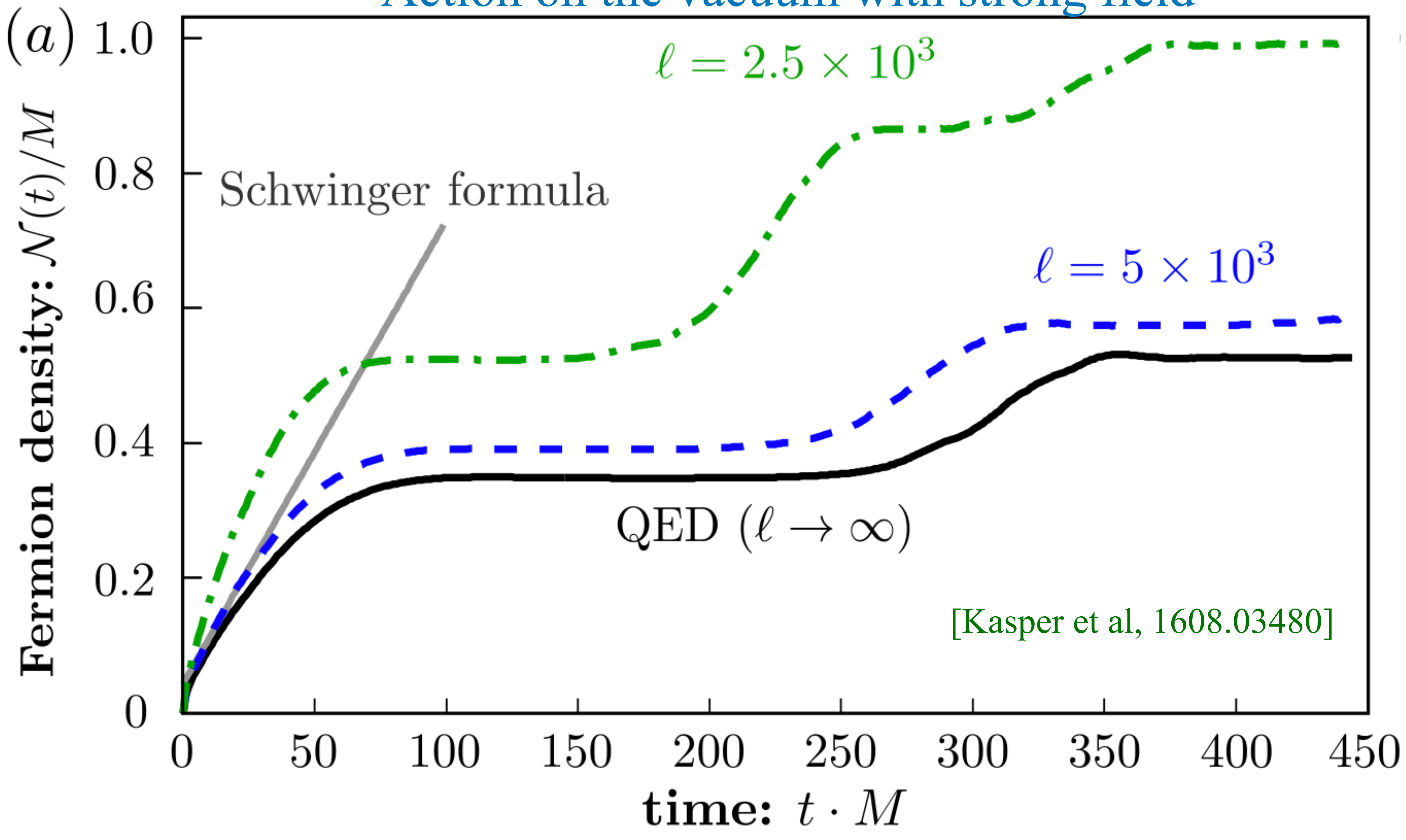
Schwinger effect: intense electric fields can lead to proliferation of particle pairs out of the vacuum

Pair-production rate computed in the semi-clasical limit (no back-reaction) [Schwinger, 1951]



[Hebenstreit, Berges, Gelfand, 1307.4619]

Action on the vacuum with strong field



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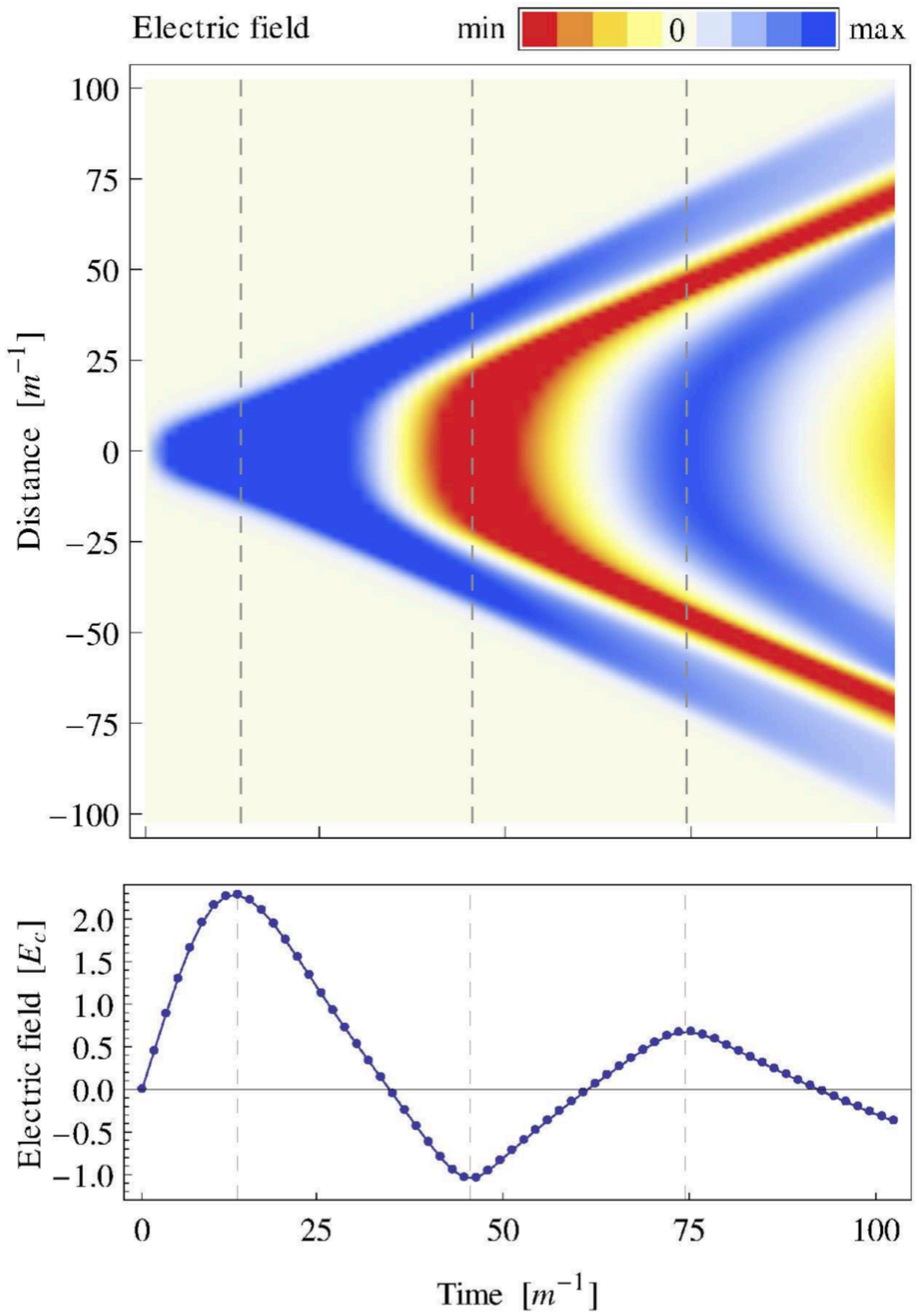
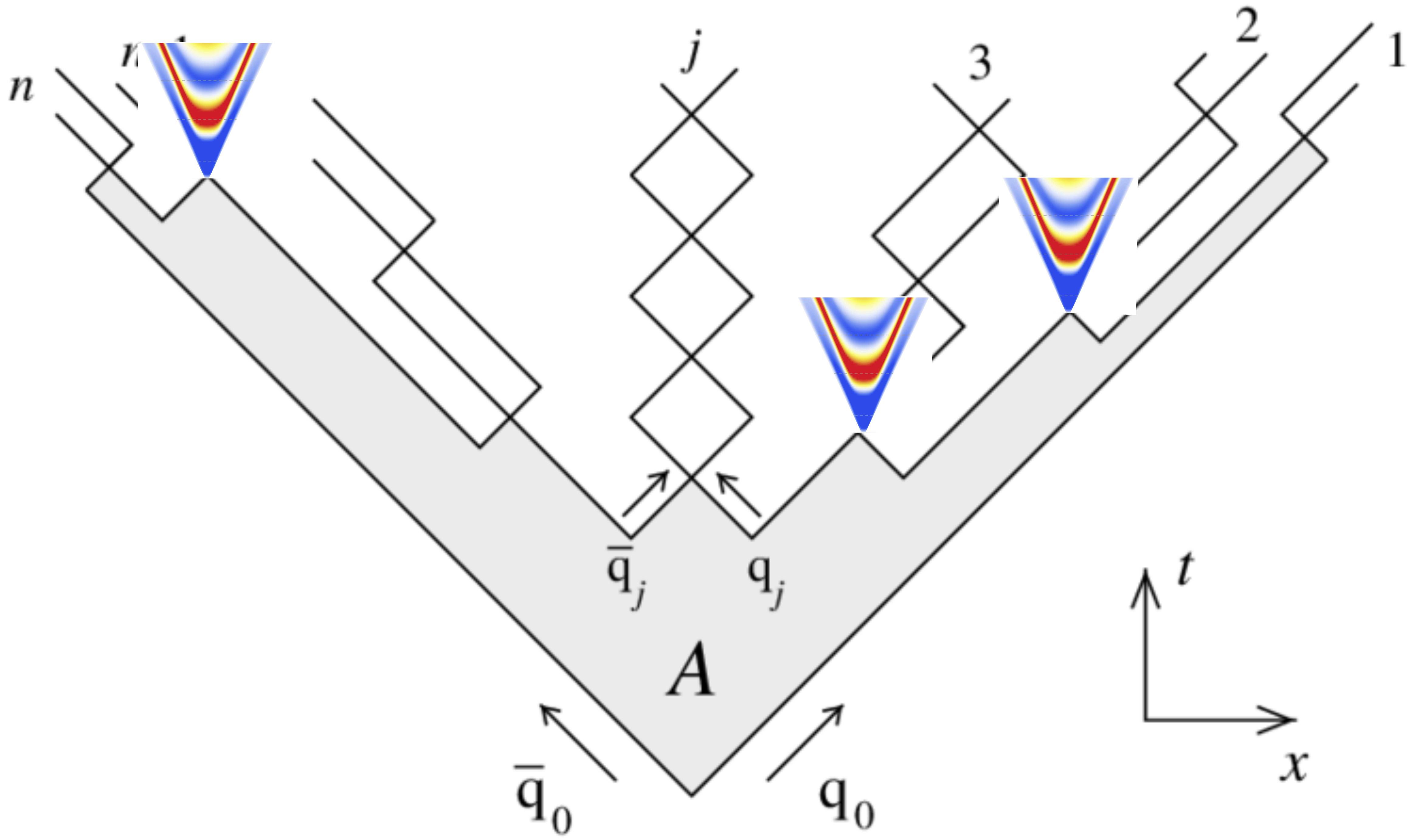


[Hebenstreit, Berges, Gelfand, 1307.4619]

Qualitatively very close to standard hadronization picture !



A 1+1d toy model: Hamiltonian

Since there is no true notion of spin in 2d, we consider the following toy theory

$$H = H_{\text{Schwinger}} + H_{\text{spin}}$$

where the first term is the 4 flavor Schwinger model

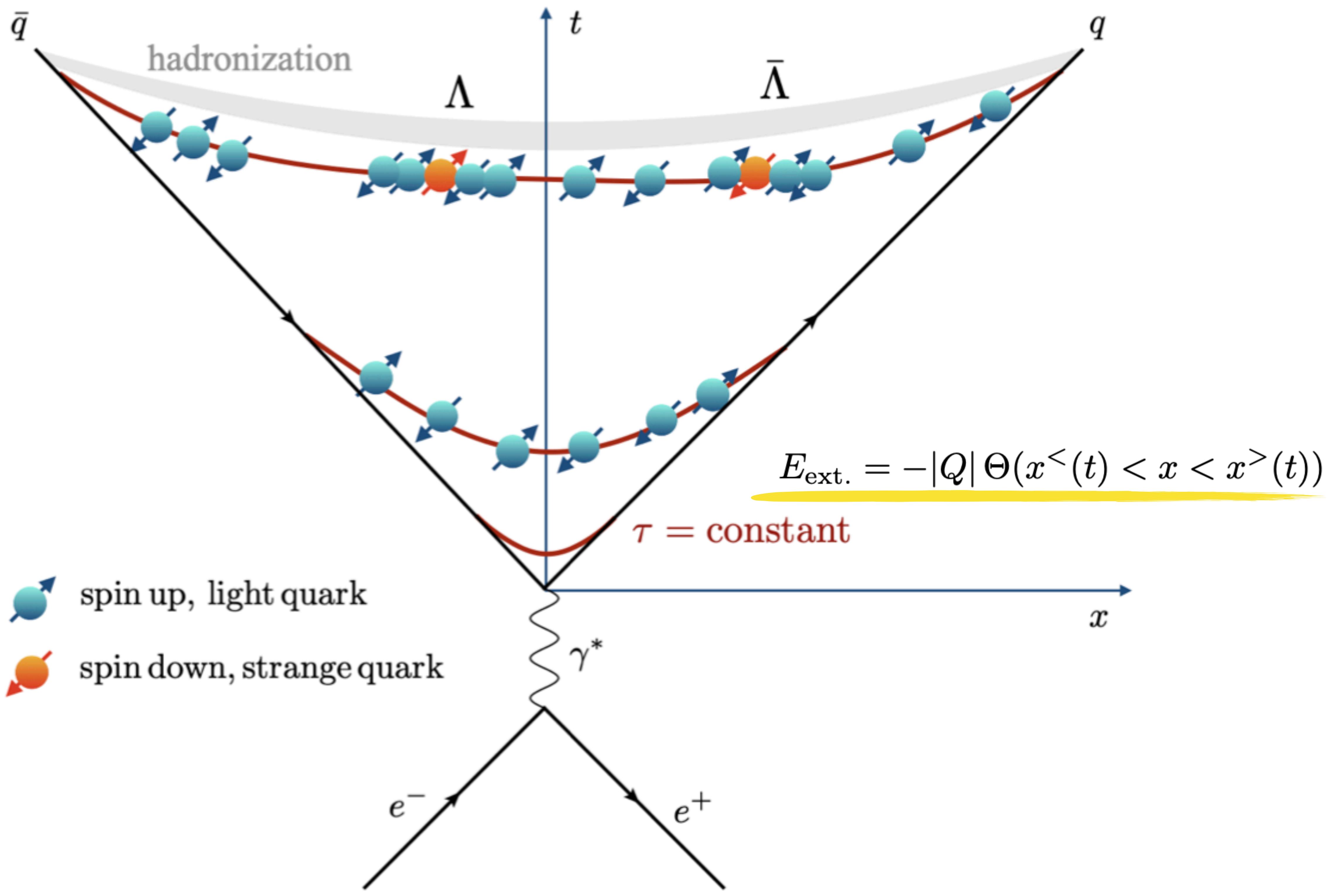
$$H_{\text{Schwinger}} = \int dx\, \frac{1}{2}E^2(x) + \sum_{f=1}^{N_f} \bar{\psi}_f(x)(-i\gamma^1\partial_1 + g\gamma^1 A_1(x) + m_f)\psi_f(x)$$

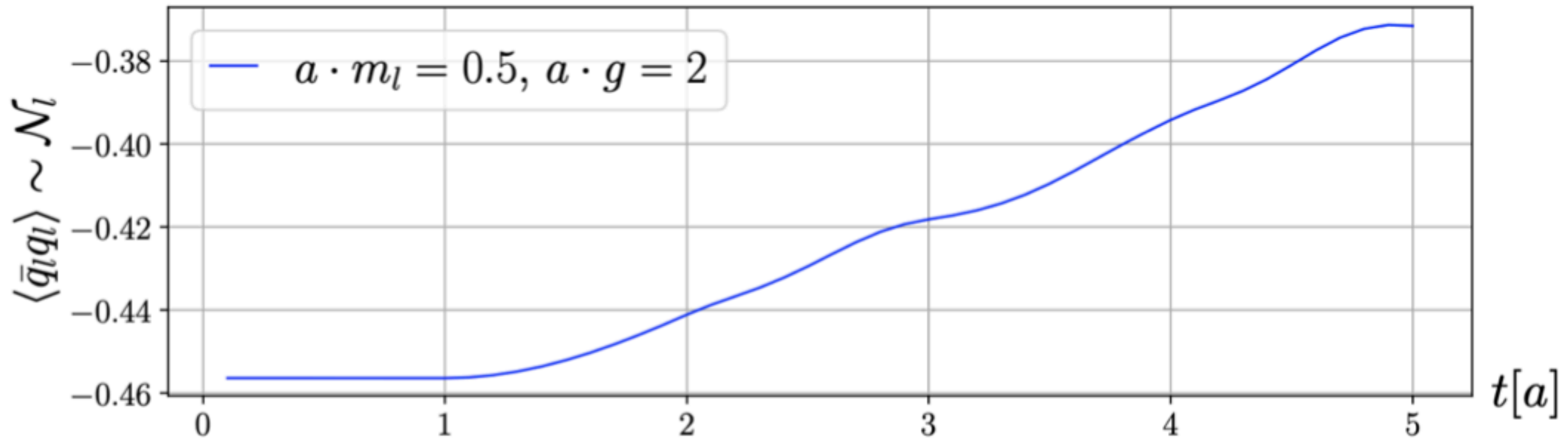
We take the mapping

$$1 \to (h,\uparrow)\ ;\ 2 \to (h,\downarrow)\ ;\ 3 \to (l,\uparrow)\ ;\ 4 \to (l,\downarrow)$$

Spin flips between different species are induced by the term

$$\begin{aligned} H_{\text{spin}} = {} & g^0_{ll}(\bar{\psi}_{l,\uparrow}\gamma^0\psi_{l,\downarrow} + h.c.) \\ & + g^1_{ll}(\bar{\psi}_{l,\uparrow}\psi_{l,\downarrow} + \text{h.c.}) \\ & + g^0_{l,h}(\bar{\psi}_{h,\uparrow}\gamma^0\psi_{l,\downarrow} + \bar{\psi}_{h,\downarrow}\gamma^0\psi_{l,\uparrow} + \text{h.c.}) \\ & + g^1_{l,h}(\bar{\psi}_{h,\uparrow}\psi_{l,\downarrow} + \bar{\psi}_{h,\downarrow}\psi_{l,\uparrow} + h.c.) \end{aligned}$$





A 1+1d toy model: simulation

Given this model, the spin Hamiltonian is obtained by

Introducing lattice Kogut-Susskind fermions:

$$\psi_f(na) \to \frac{1}{\sqrt{a}} \begin{pmatrix} \chi_f(2n) \\ \chi_f(2n+1) \end{pmatrix}$$

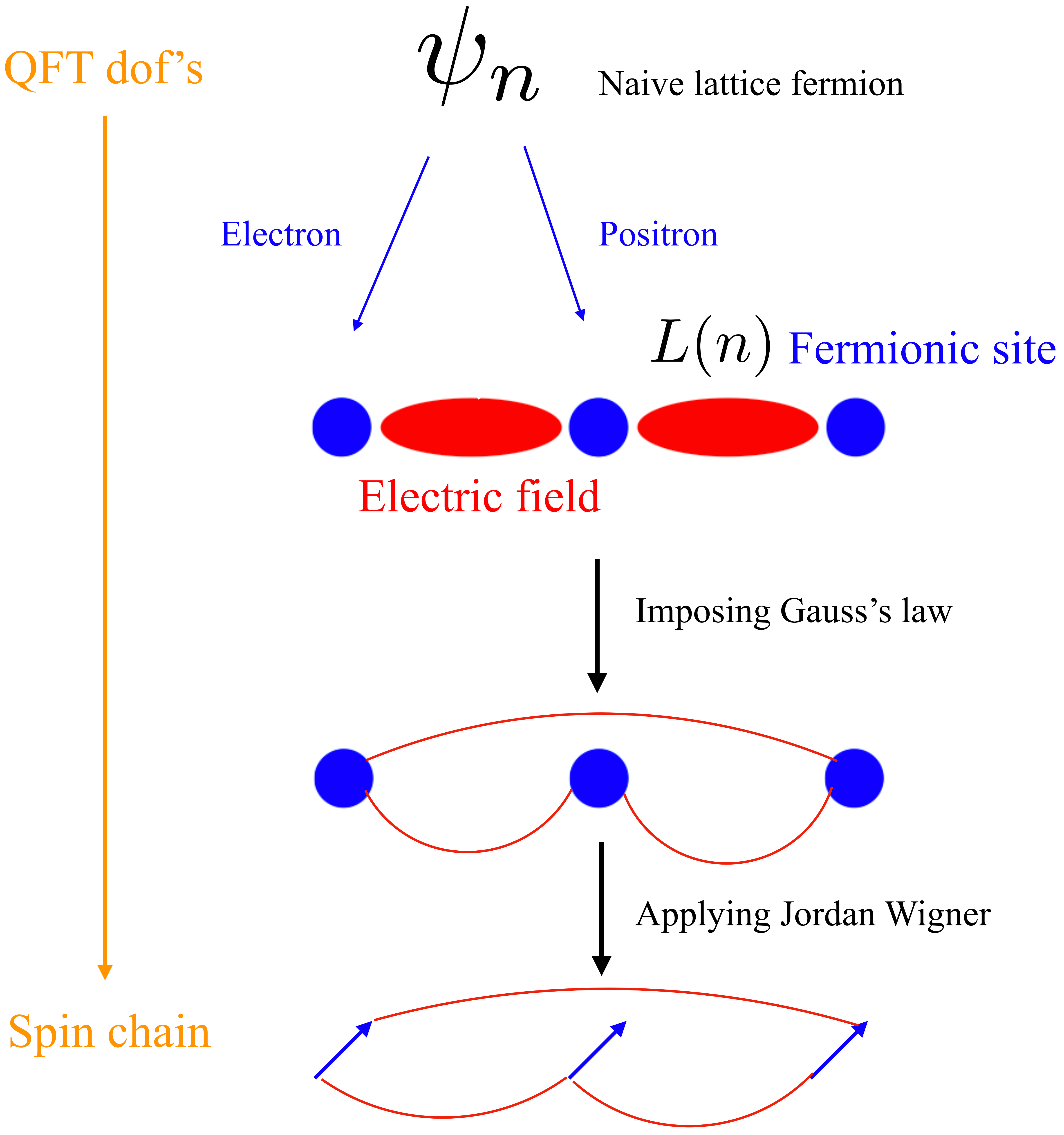
Performing a Jordan-Wigner transformation, e.g.:

$$\chi_{h,\uparrow}(\tilde{n}) = S(\tilde{n})\sigma^{-}_{h,\uparrow}(\tilde{n})$$

Integrating out the gauge field using Gauss' law:

$$G(n)\,|\psi\rangle = 0$$

$$G(n) = L(n) - L(n-1) - \sum_f \left(\chi_f^\dagger(n)\chi_f(n) - \frac{1}{2}(1-(-1)^n) \right)$$

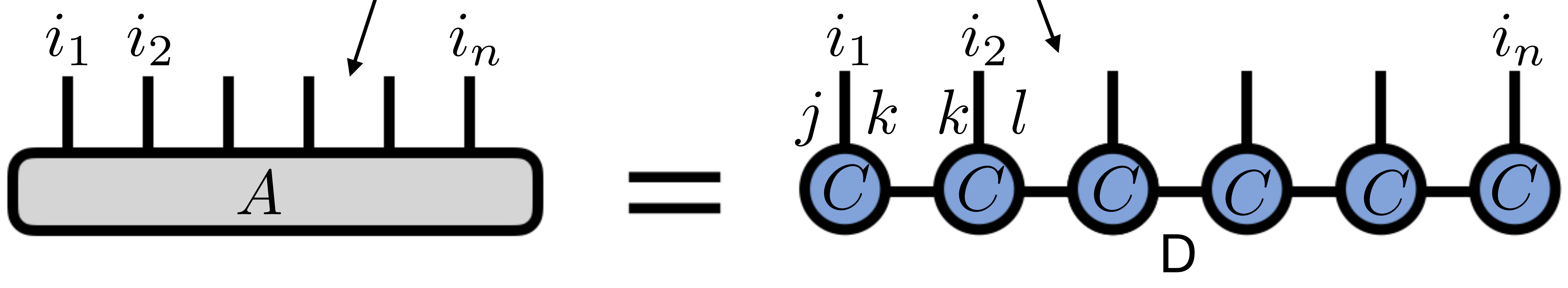


Numerically evolving the system: tensor networks

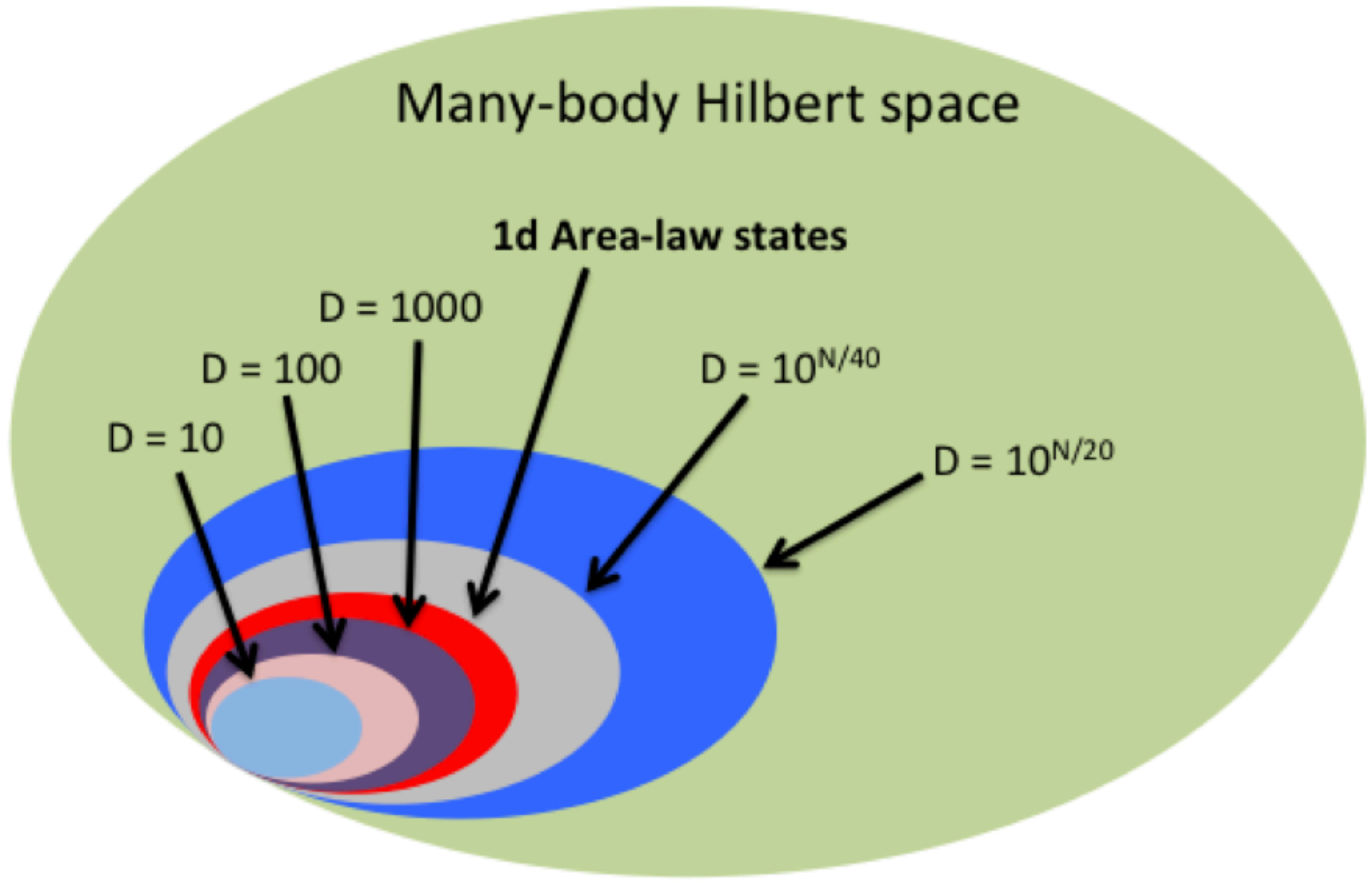
Basic idea: Lowest states of a gapped local Hamiltonian obey the area-law for entanglement entropy
i.e. they are highly constrained by locality

$$|\psi\rangle = \sum_{i_j} A_{i_1 i_2 \cdots i_n} |i_1\rangle |i_2\rangle |i_3\rangle \cdots |i_n\rangle$$

$$A_{i_1 i_2 \cdots i_n} = C^{jk}_{i_1} C^{kl}_{i_2} \cdots$$



$S \sim \log D$

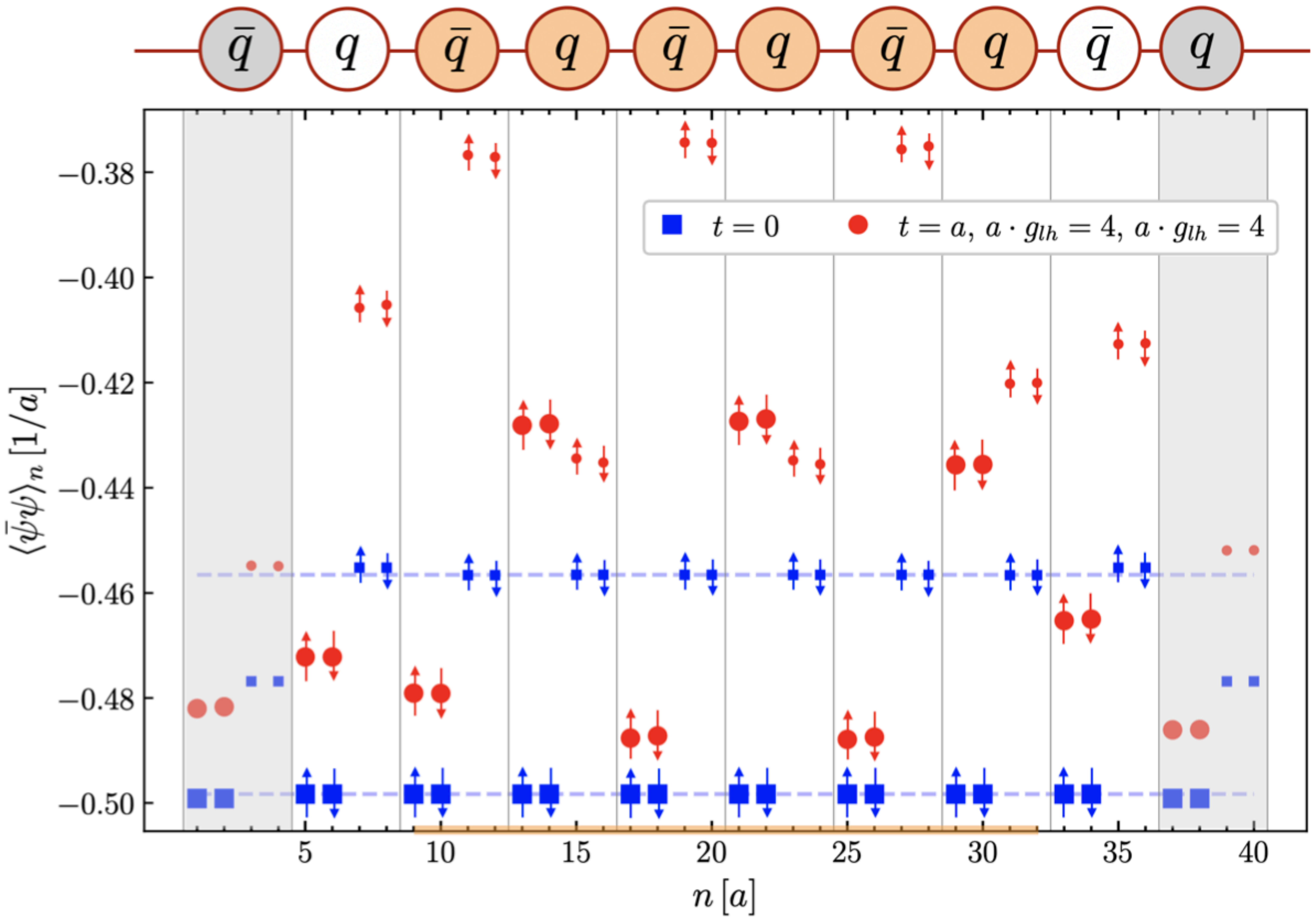


Powerful classical correspondent of quantum computers in 2d

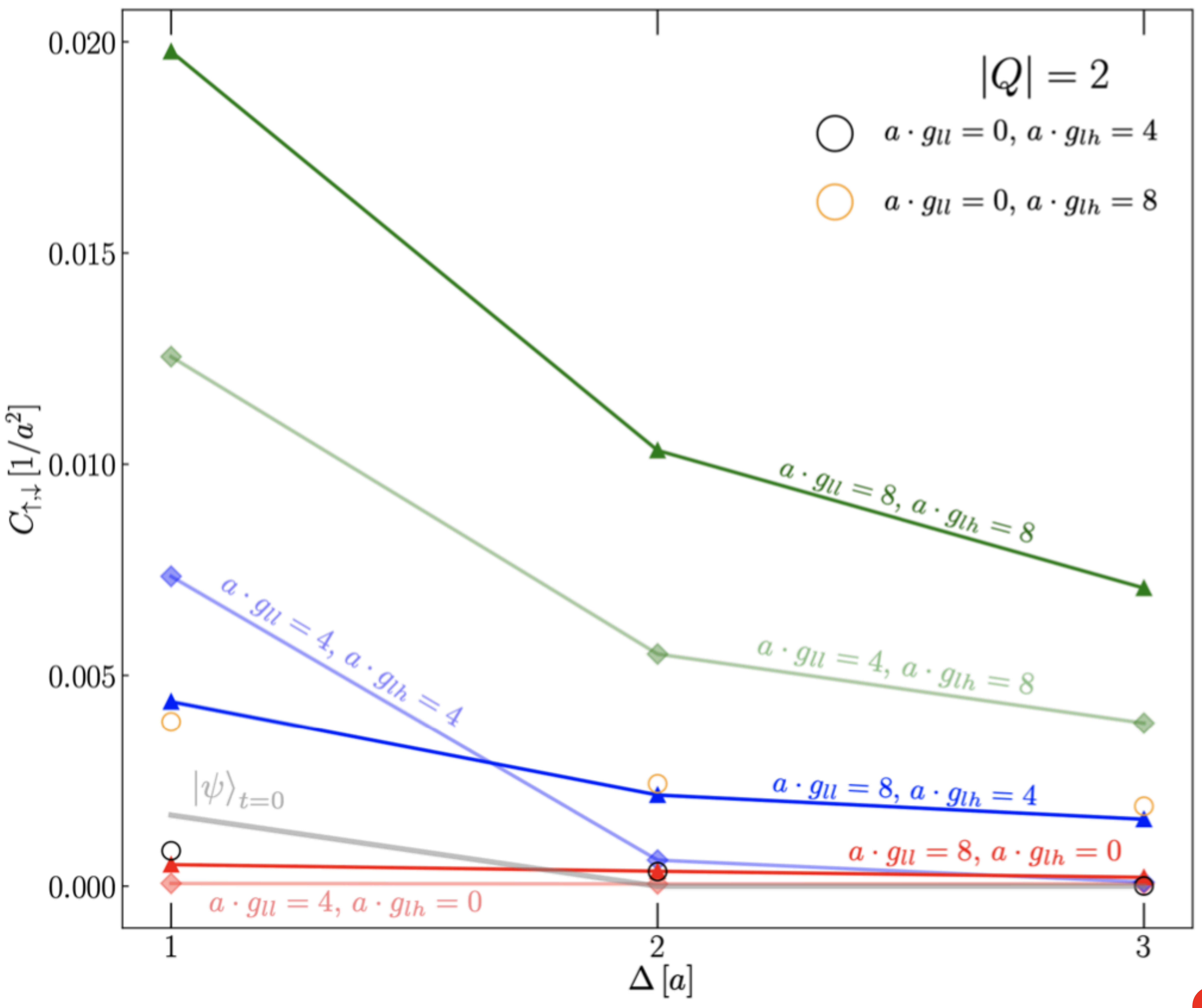
Fails when: Long time evolution Near critical points

Numerical results: quark bilinear

Time evolved state shows residual spin symmetry left after explicitly breaking the SU(4) flavor group



Numerical results: heavy spin-spin correlator



We consider the heavy fermionic correlator

$$C_{\sigma,\sigma'}(\Delta) \equiv \frac{\sum_{\tilde{n},\tilde{m}} \langle \hat{c}_\sigma(\tilde{n}) \hat{c}_{\sigma'}(\tilde{m}) \rangle_{\text{conn.}}\, \delta_{\Delta,\tilde{n}-\tilde{m}}}{\sum_{\tilde{n},\tilde{m}} \delta_{\Delta,\tilde{n}-\tilde{m}}}$$

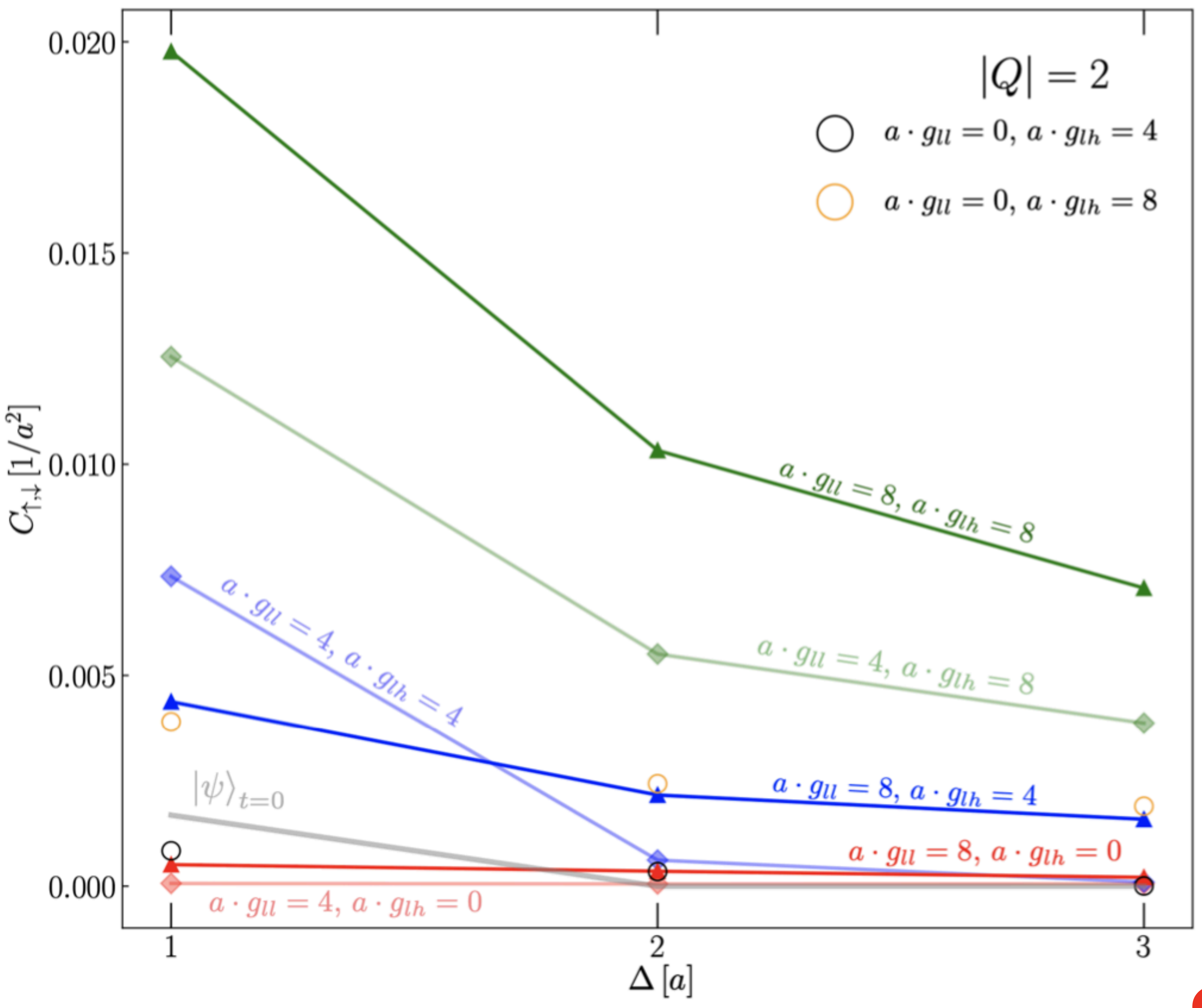
$$\hat{c}_\sigma(\tilde{n}) = \bar{\psi}_{h,\sigma}\psi_{h,\sigma} - \langle \bar{\psi}_{h,\sigma}\psi_{h,\sigma} \rangle_{|\psi\rangle_{t=0}}$$

Larger h-l and l-l : larger correlations

Only Larger h-l : smaller correlations

Only Larger l-l : small difference to initial condition

Numerical results: heavy spin-spin correlator



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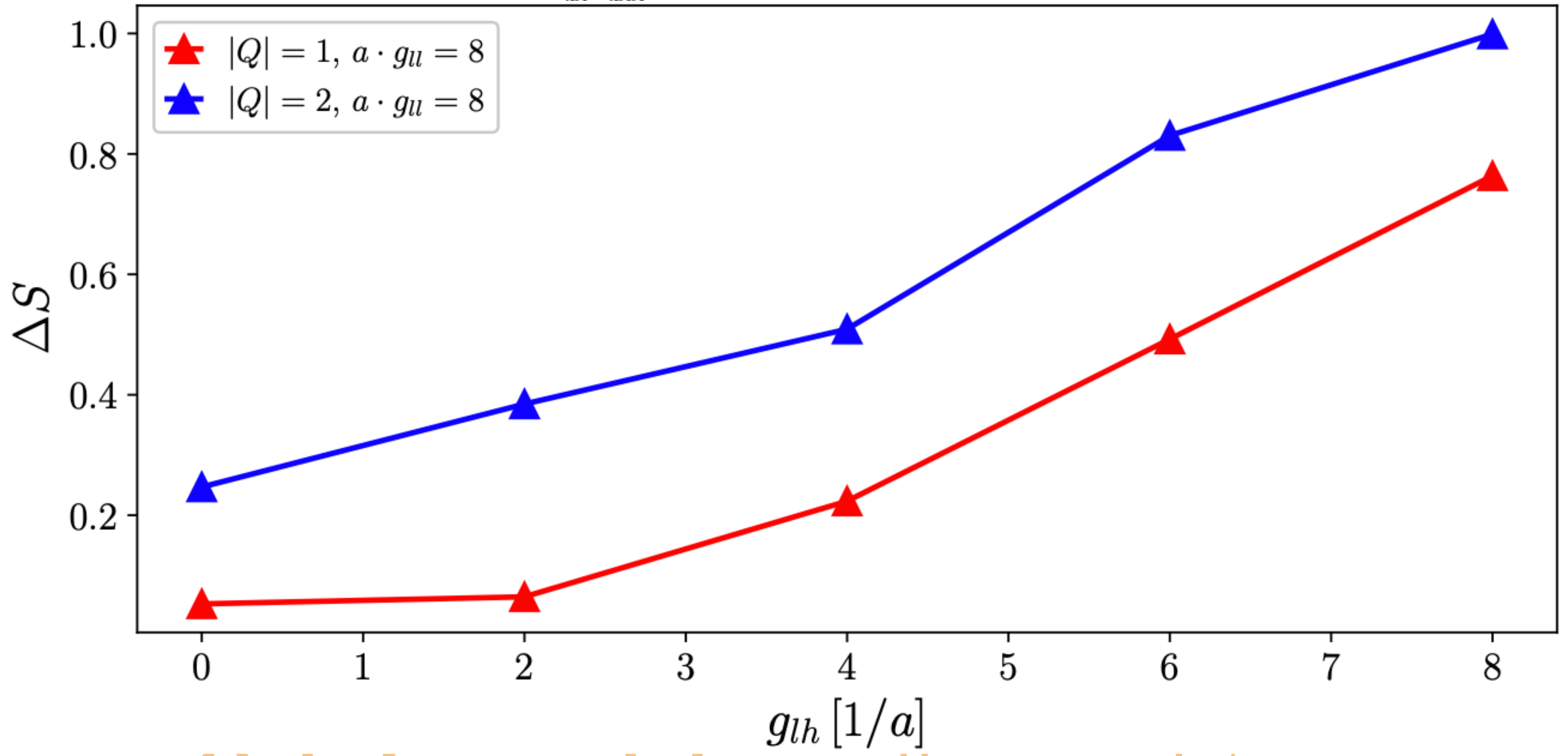
$$\sum_{\tilde{n},\tilde{m}} \langle \hat{c}_\sigma(\tilde{n}) \hat{c}_{\sigma'}(\tilde{m}) \rangle_{\text{conn.}}\, \delta_{\Delta,\tilde{n}-\tilde{m}}$$



Only Larger h-l : smaller correlations

Only Larger l-l : small difference to initial condition

Numerical results: ongoing

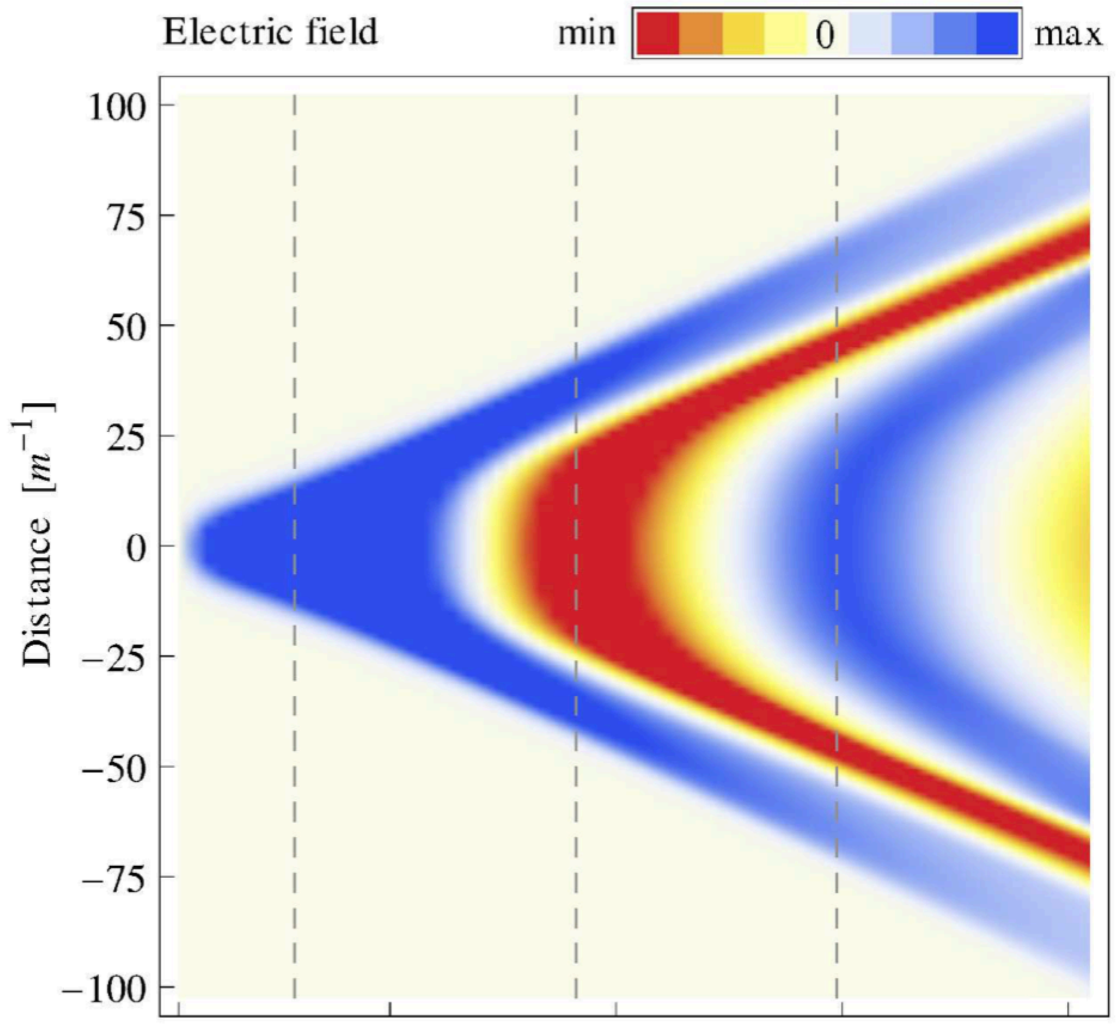
Main shortcomings tied to limitations of long time evolutions for TNs; some ways to move forward:

Integrate out light fermions

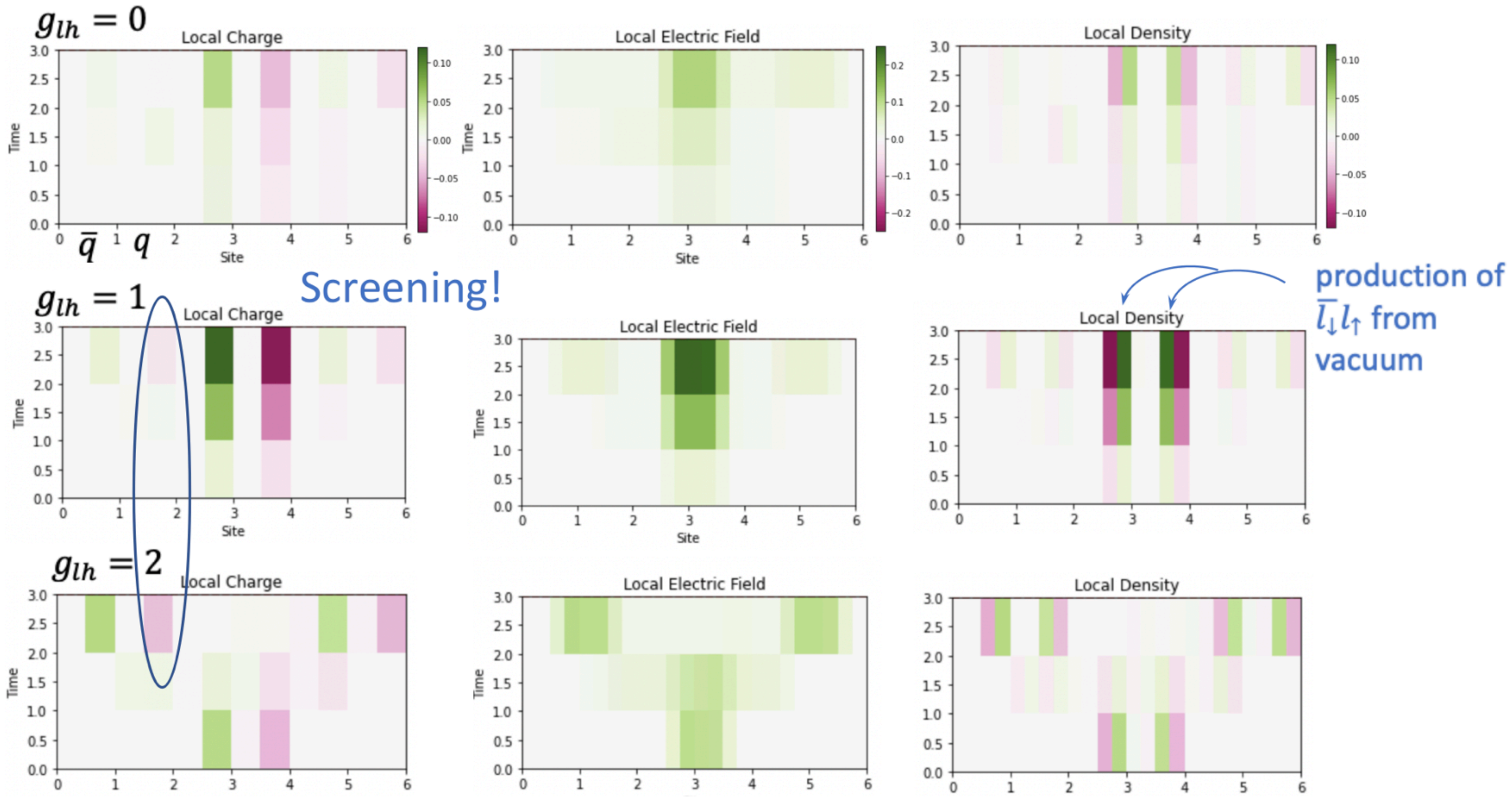
$$H_{\text{eff}} = H_0^h + g_h \sum_n (-1)^n \chi^\dagger_{h,\uparrow}(n)\chi_{h,\downarrow}(n)$$

$$+ g_h^2 \sum_n \chi^\dagger_{h,\uparrow}(n)\chi_{h,\downarrow}(n)\chi^\dagger_{h,\downarrow}(n)\chi_{h,\uparrow}(n) + \text{h.c.} + \mathcal{O}(g_h^3)$$

Classical stat. simulations



Exact diagonalisation



Conclusion

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- Lambda spin correlations offer the opportunity to study initial and final state effects. Such studies can be ideally performed at the EIC.

- Final state effects might give access to non-perturbative final state dynamics. Their current theoretical understanding is limited.

- New quantum technologies are ideally posed to study realtime non-perturbative dynamics

- We propose a simple toy model to capture the time evolution of hyperon spin correlations in a QCD string-like environment.

- Exploratory numerical results agree with naive physical picture: higher fermion density leads to a growth of correlations.