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DYNAMICS ON AN OPEN SU(2) LATTICE GAUGE THEORY

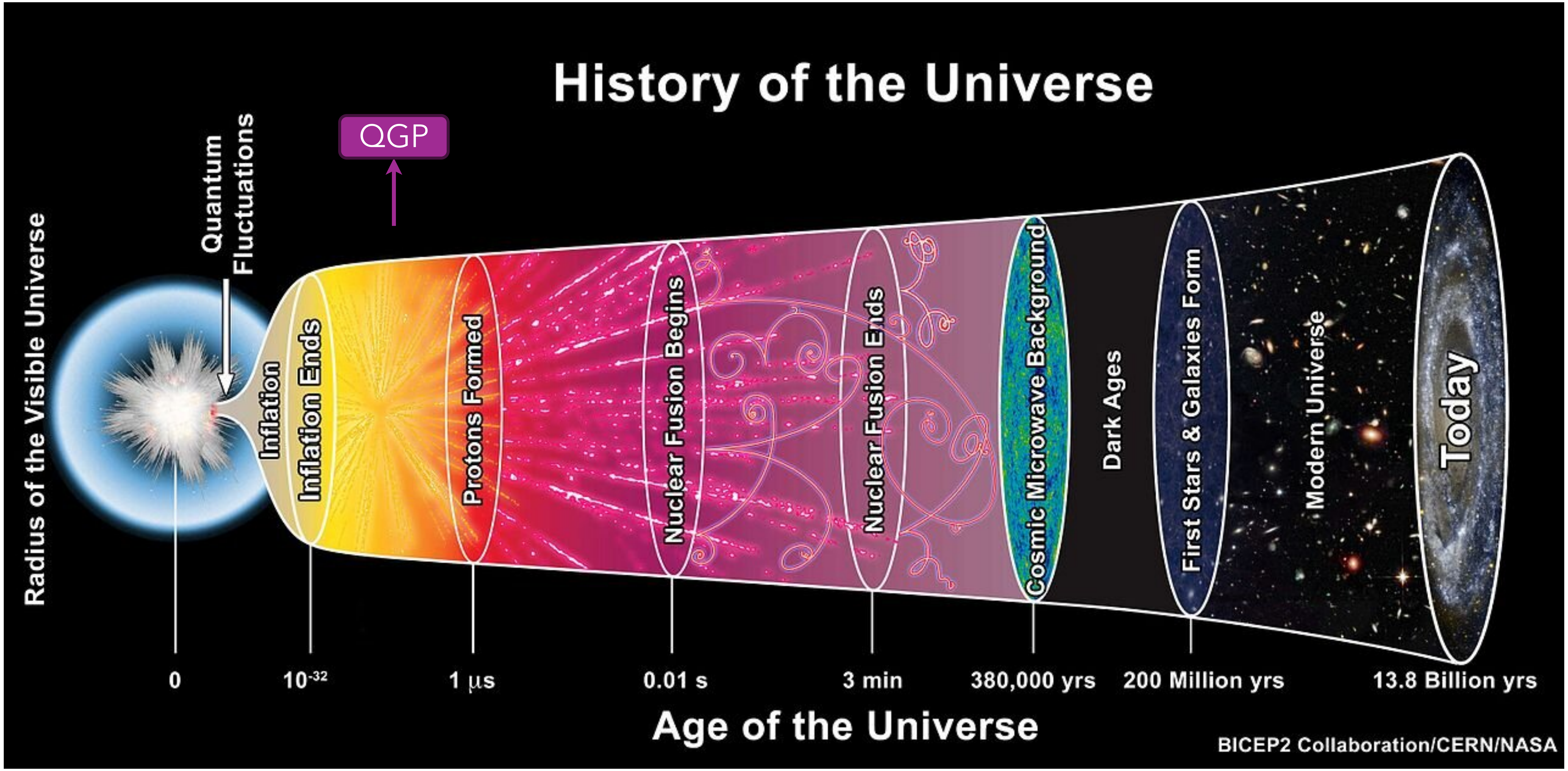
OPEN QUANTUM SYSTEMS: DISSIPATION AND DECOHERENCE FROM SUBATOMIC TO COSMIC SCALES

GIOVANNI CATALDI

MAINZ. 27/05/26

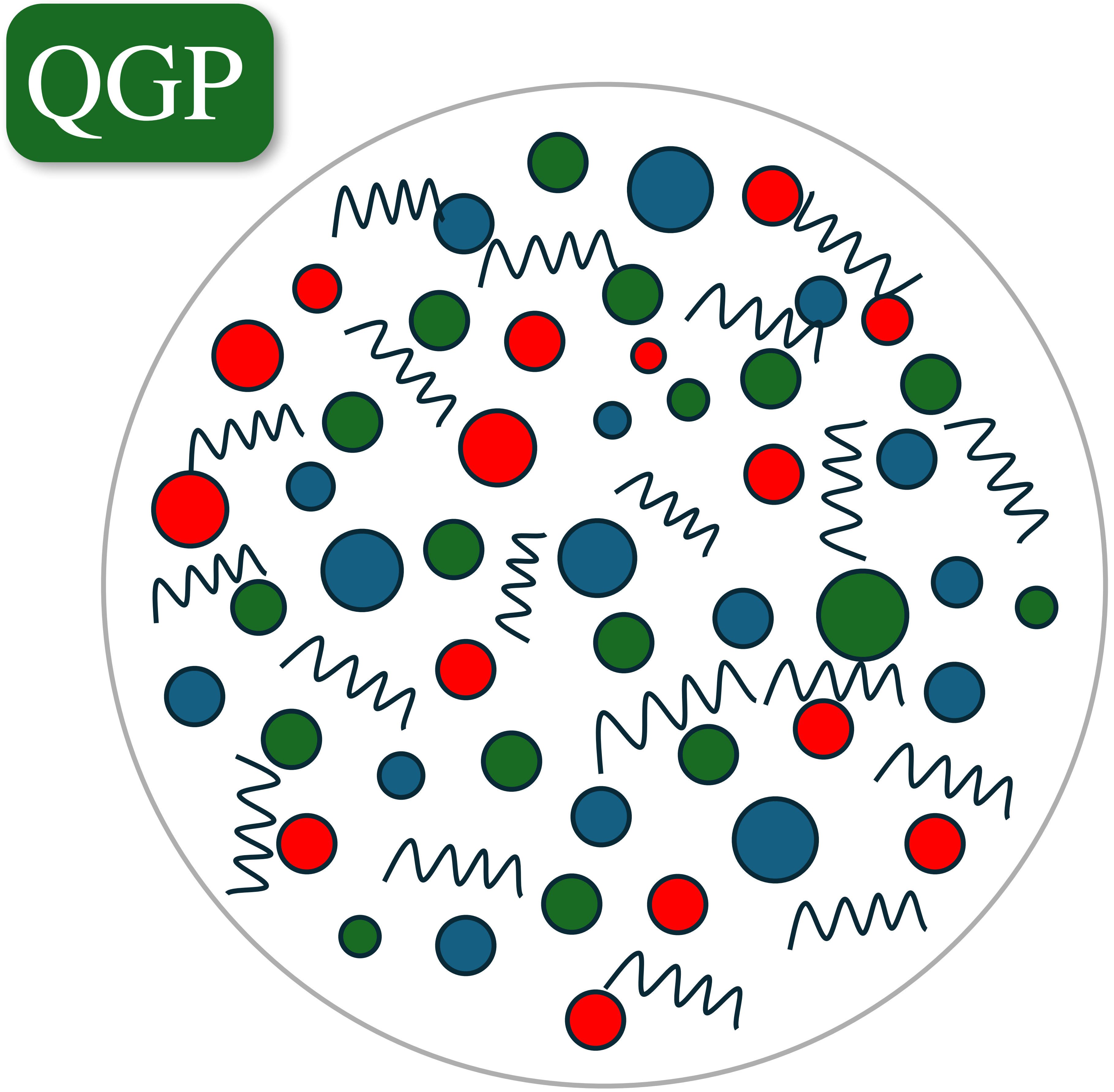
Mainz Institute for
Theoretical Physics

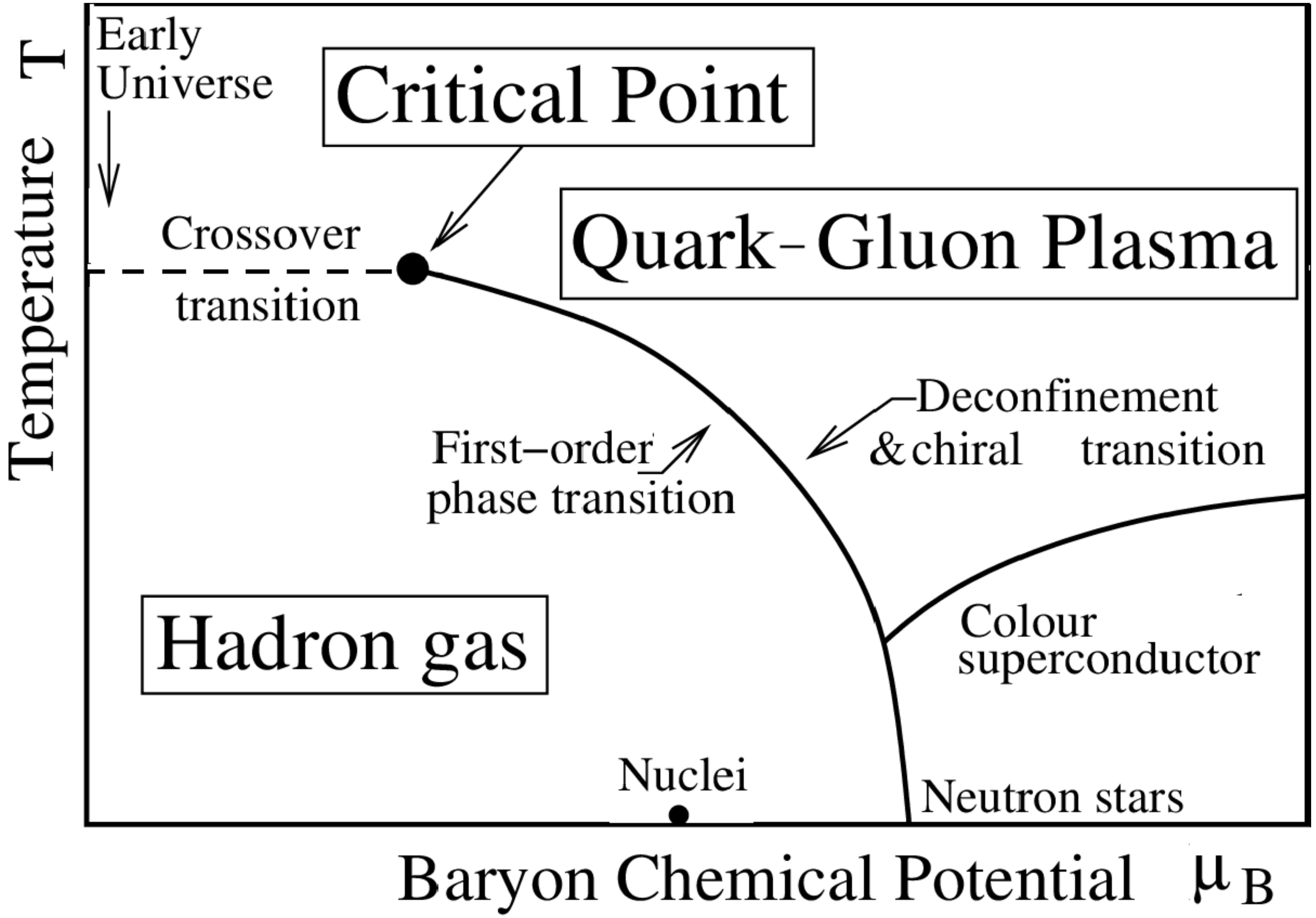
THE PROBLEM



BICEP2 Collaboration/CERN/NASA

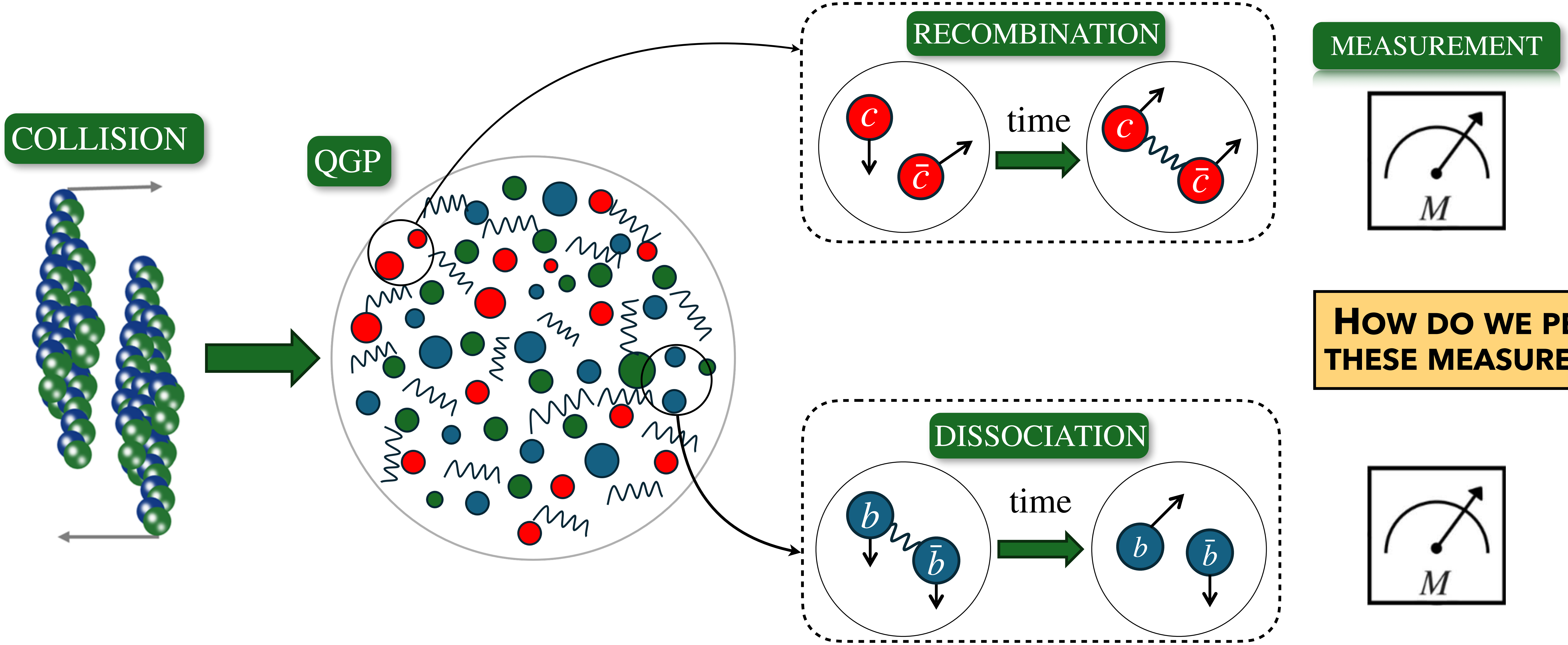
QUARK-GLUON PLASMA





PROBING QUARK–GLUON PLASMA

LOOKING AT HEAVY-ION COLLISIONS

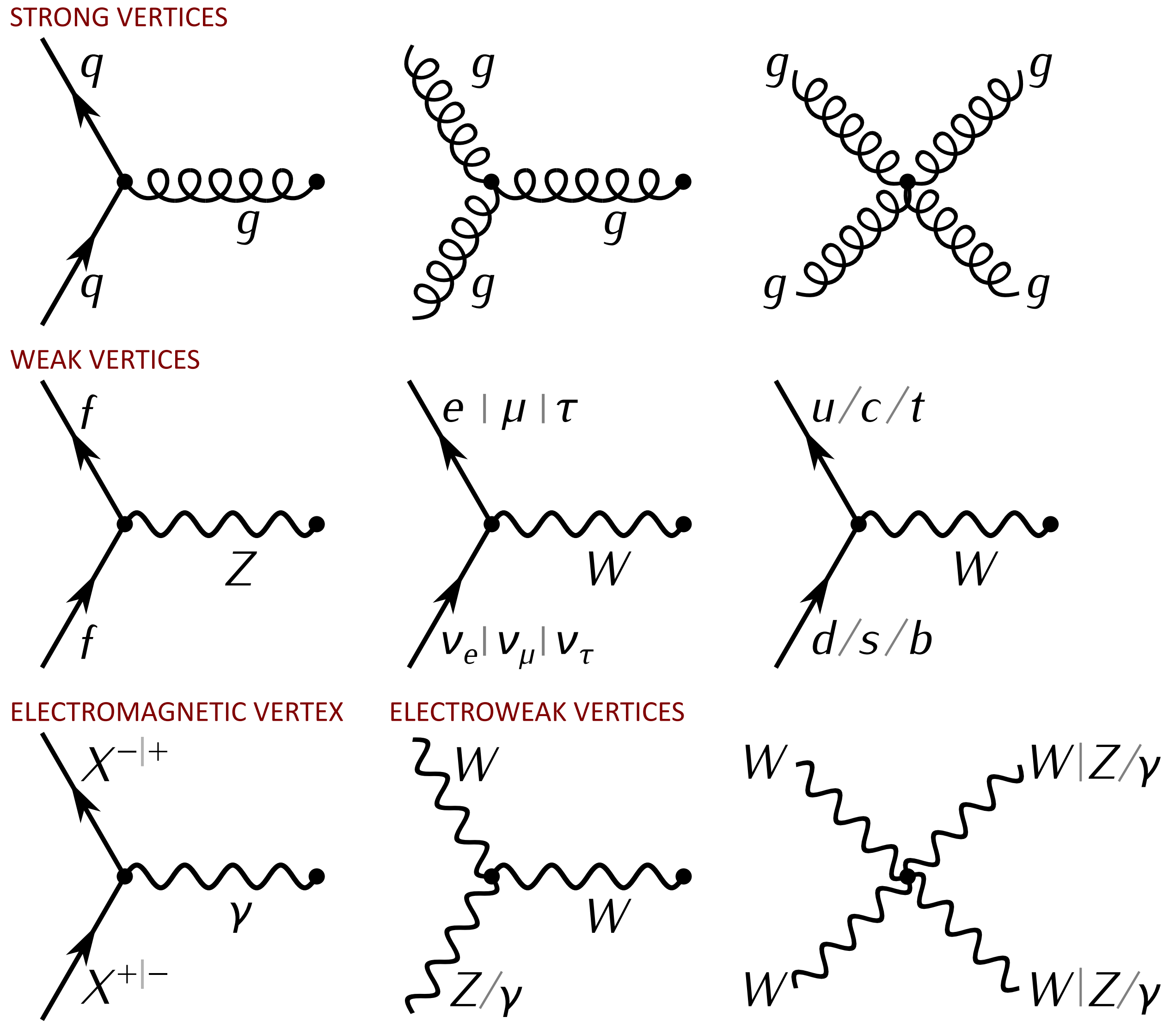


HOW DO WE PERFORM THESE MEASUREMENTS?

HOW TO STUDY GAUGE THEORIES

THEORETICAL PARTICLE PHYSICS

PERTURBATION THEORY VIA FEYNMAN DIAGRAMS



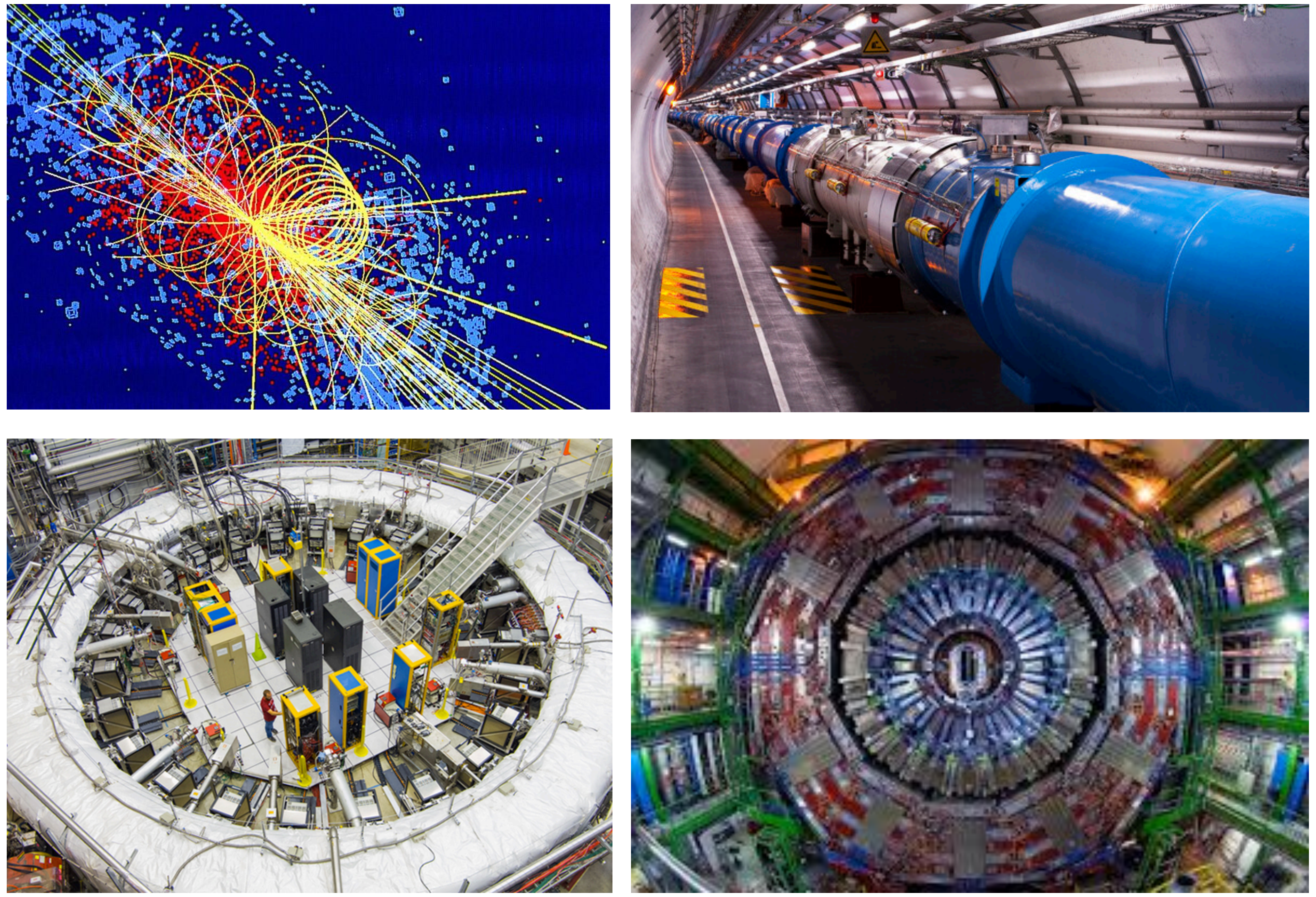
NUMERICAL SIMULATIONS

BEYOND EXPERIMENTAL AND PERTURBATIVE APPROACHES:

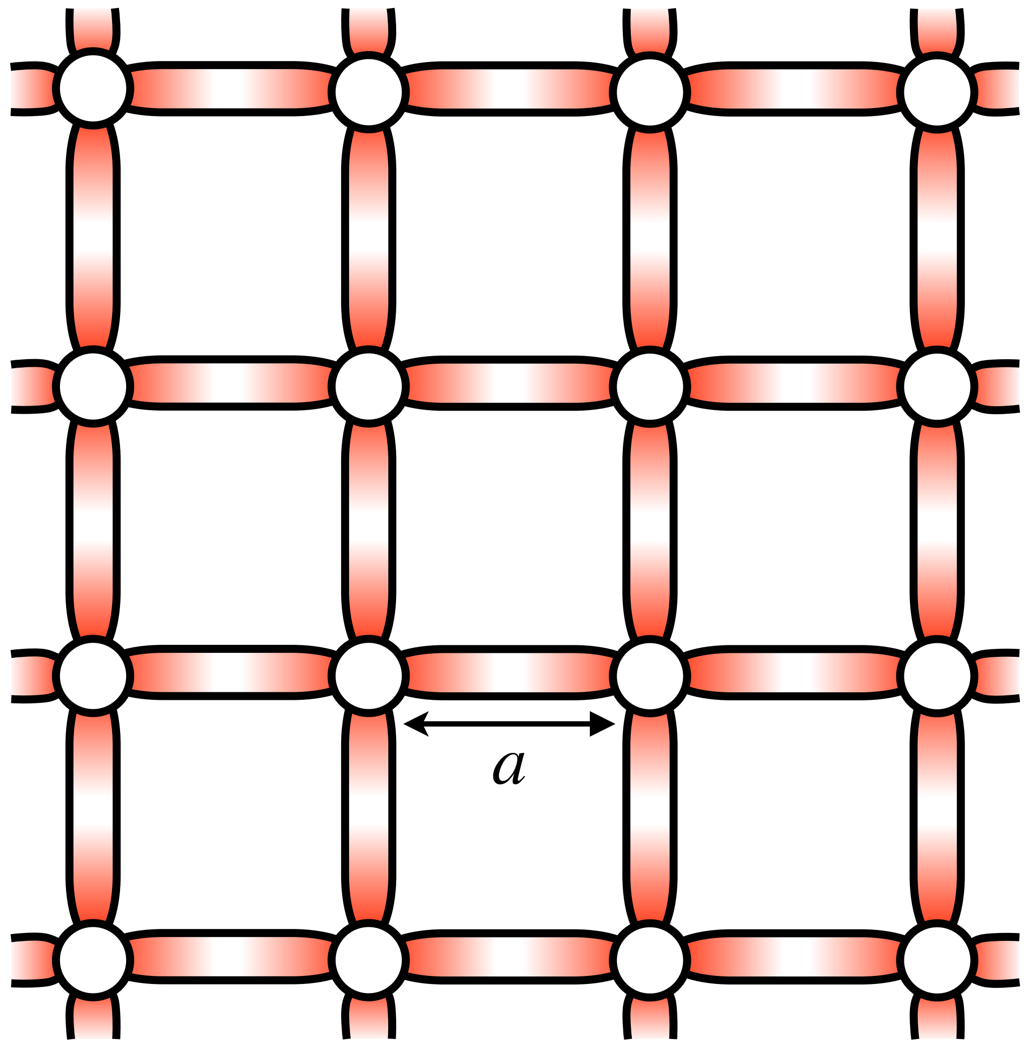
LATTICE GAUGE THEORIES

[Rothe, Lattice Gauge Theories (2012)]

EXPERIMENTAL PARTICLE PHYSICS



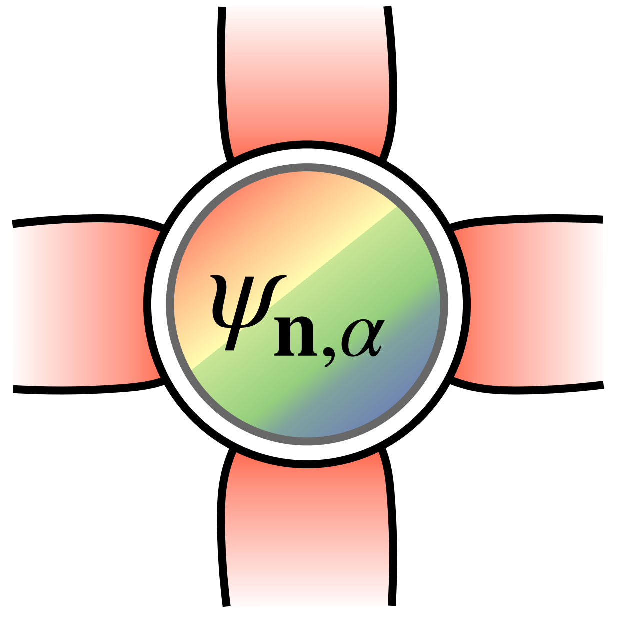
LATTICE GAUGE THEORY

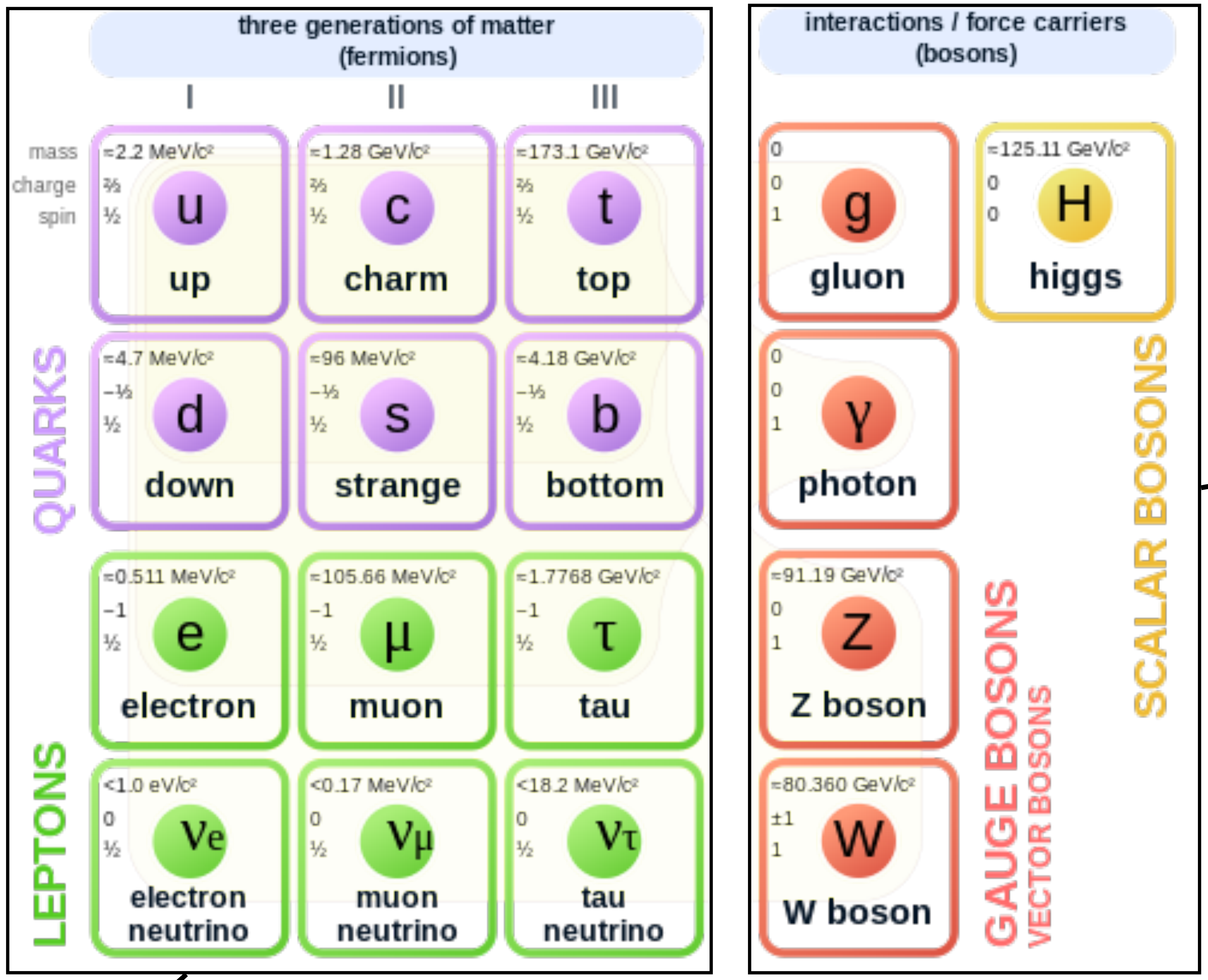


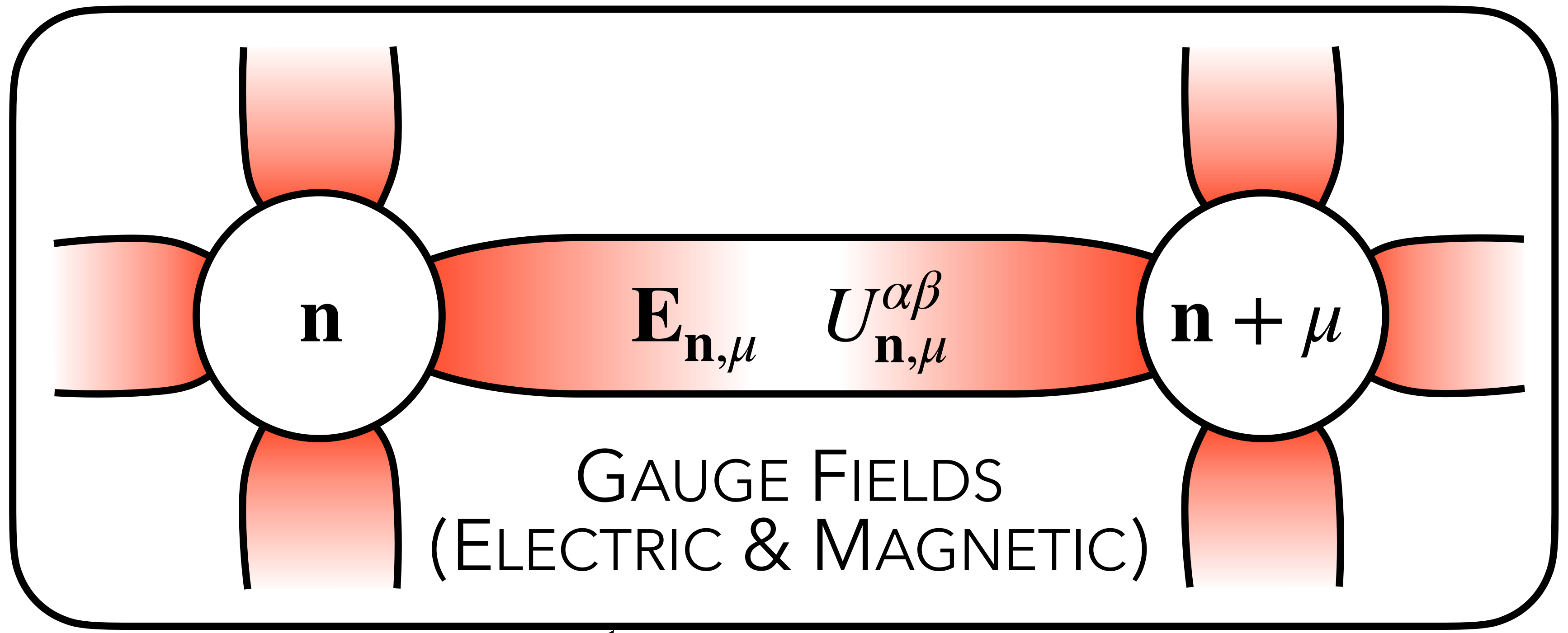
Hyper-cubic spatial Lattice Λ

MATTER FIELDS (FERMIONS)

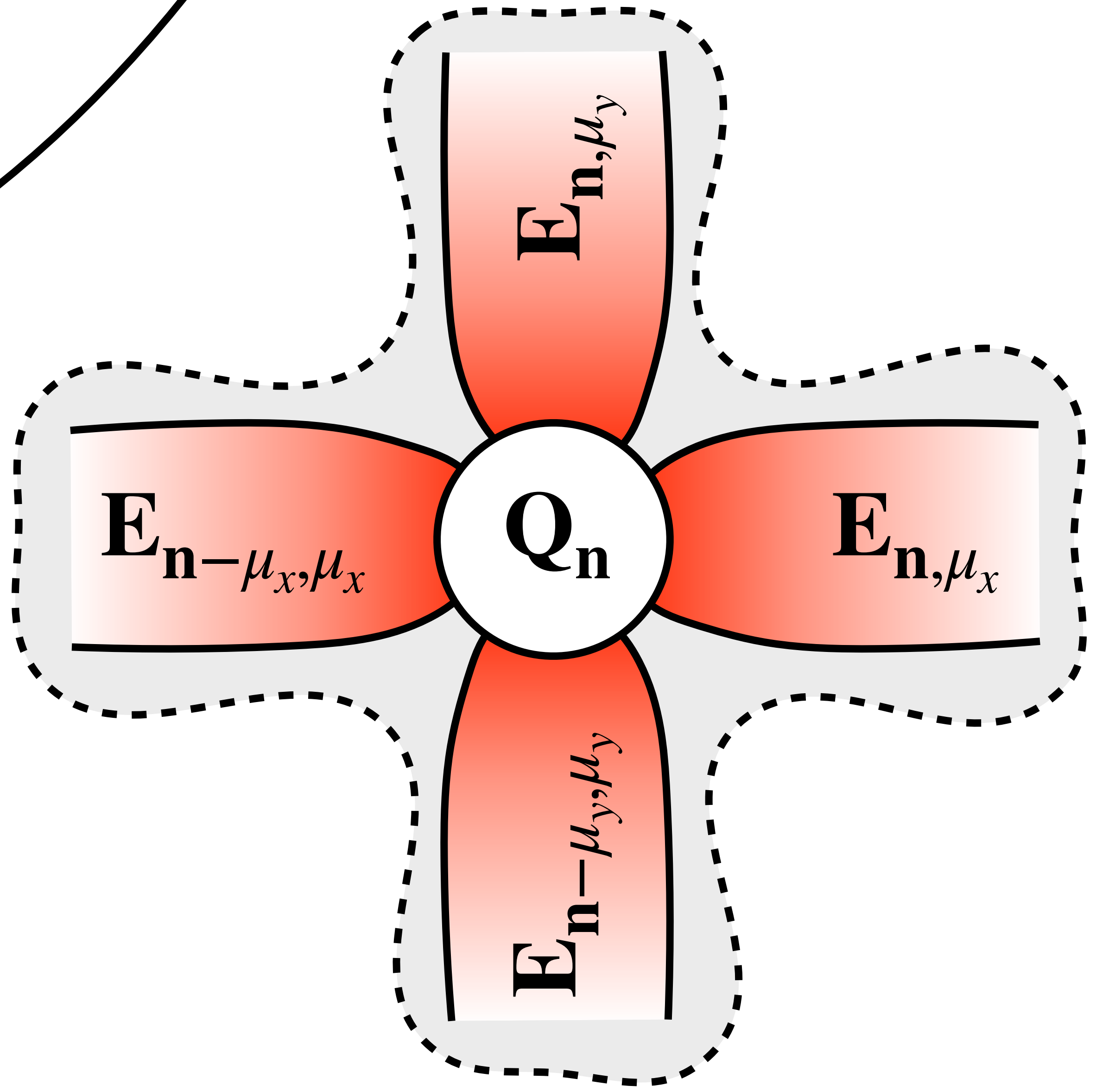
$\alpha \in \{$ 🔴🟢🔵 $\dots\}$







GAUGE FIELDS (ELECTRIC & MAGNETIC)



GAUSS LAW

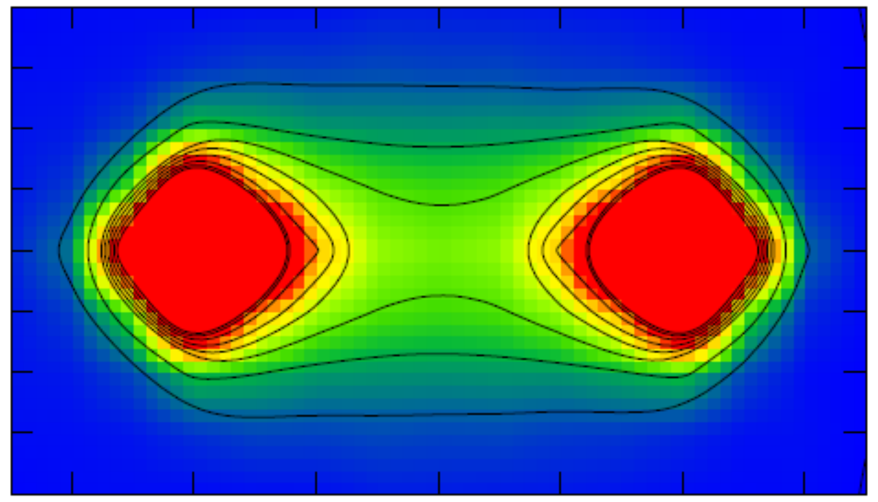
$$\nabla \cdot \mathbf{E}(\mathbf{r},t) - \rho(\mathbf{r},t) = 0$$

GAUSS LAW: $\mathbf{G}_{\mathbf{n}}\,|\psi\rangle = 0$

$$\mathbf{G}_{\mathbf{n}} = \sum_{k=x,y} \left[\mathbf{E}_{\mathbf{n}+\mu_k} - \mathbf{E}_{\mathbf{n}}\right] - Q_{\mathbf{n}}$$

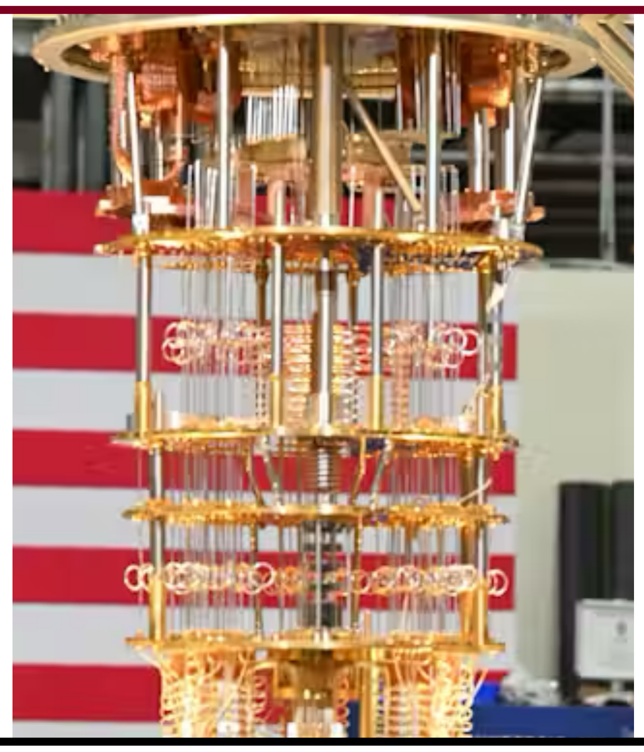
HOW TO SIMULATE LGTS?

MONTE CARLO SIMULATIONS

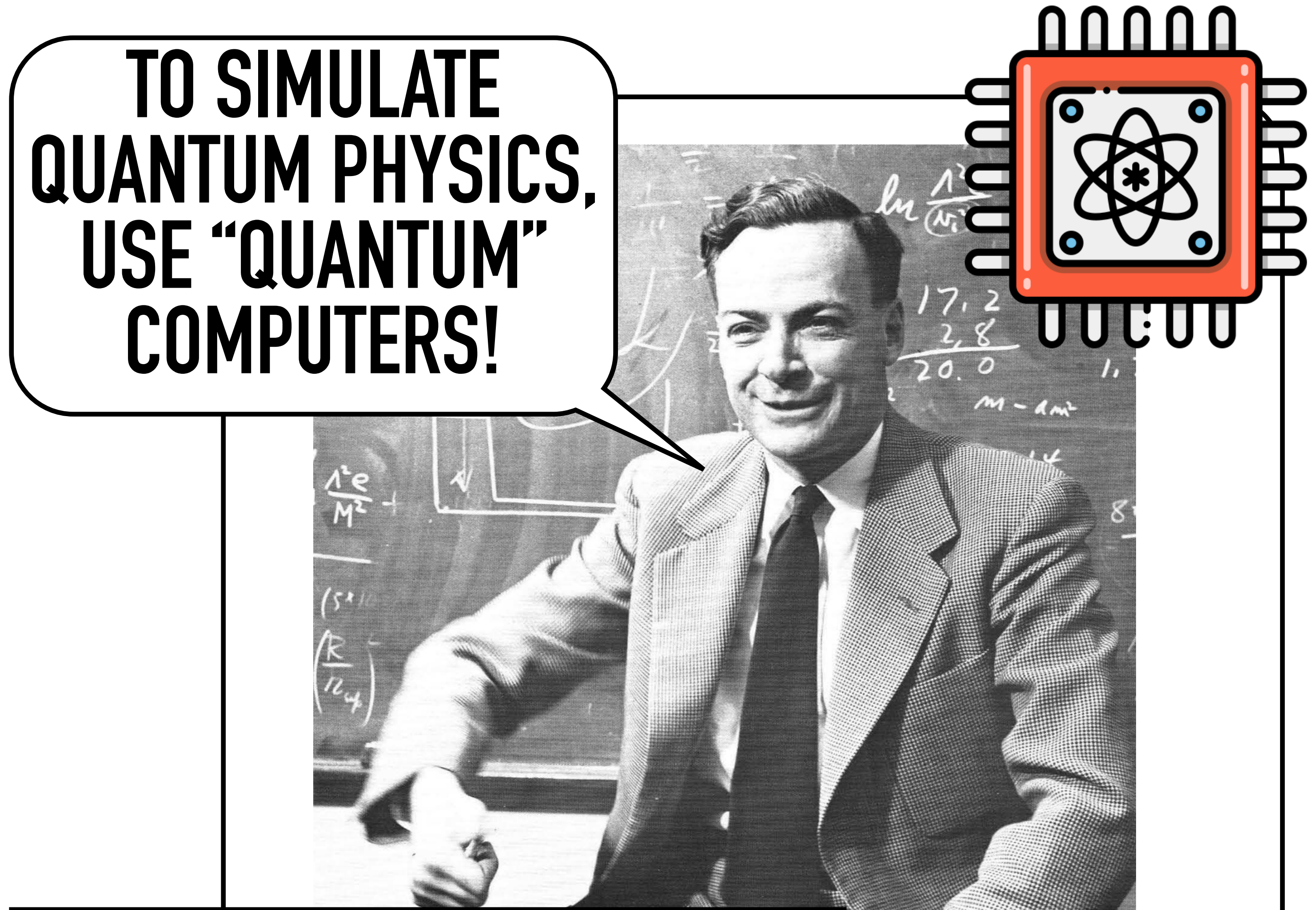


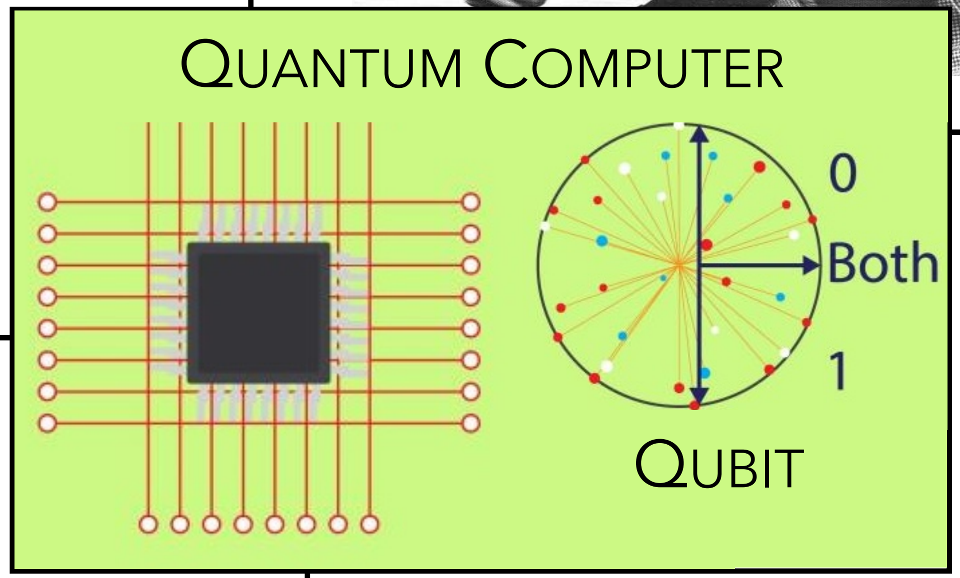
- LAGRANGIAN FORMALISM
- PARTITION FUNCTION
- GOOD RESULTS:
  CONFINEMENT, ✓
  HADRONIC SPECTRUM, ✓
  CHYRAL-SYMMETRY BREAKING ✓
- SIGN PROBLEM:
  REAL-TIME DYNAMICS, ✗
  FINITE DENSITY OR CHEMICAL POTENTIAL ✗

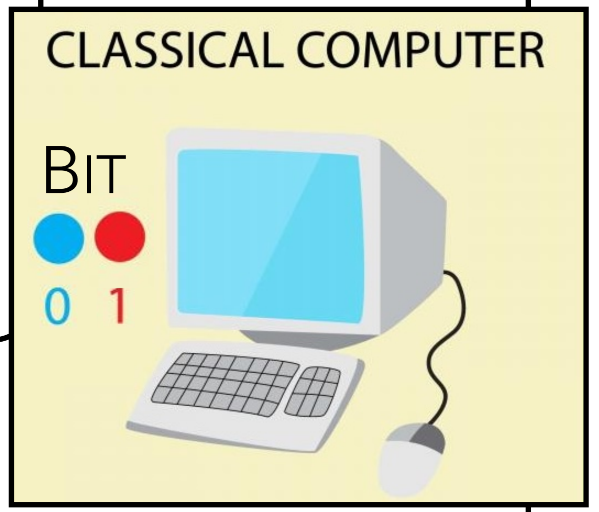
NOISY INTERMEDIATE SCALE QUANTUM ERA
Preskill, Quantum 2, 79 (2018)



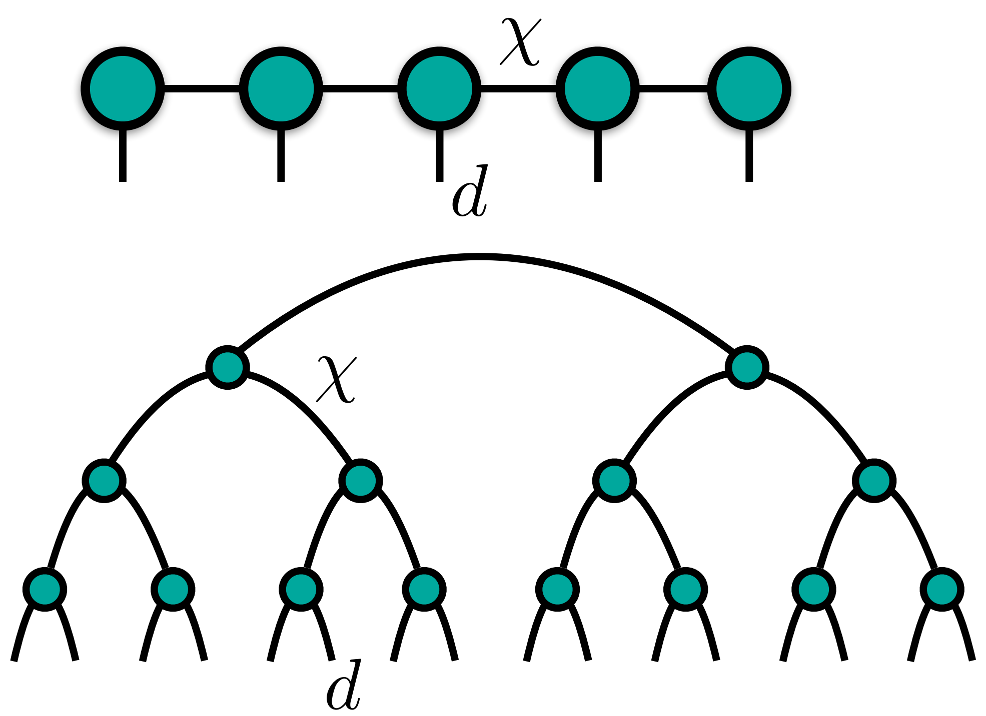
NOISE & SCALABILITY PROBLEMS:
NOT READY, BUT SOON …







TENSOR NETWORK METHODS

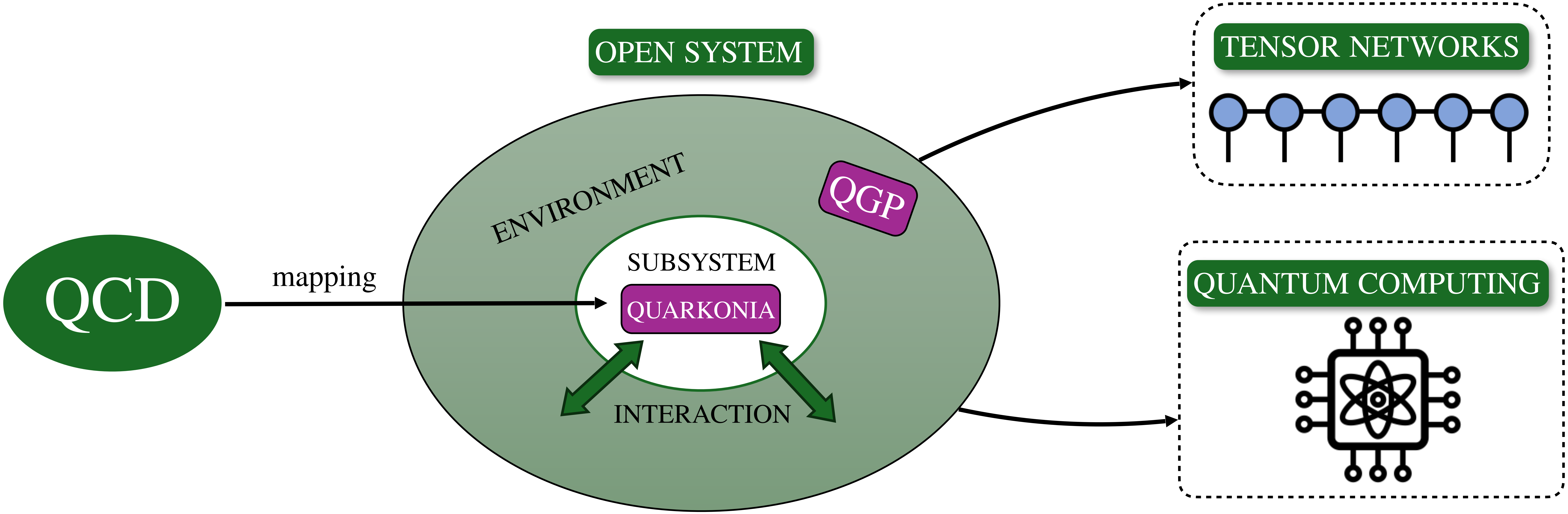


- HAMILTONIAN FORMALISM
- VARIATIONAL APPROACH
- SIGN PROBLEM FREE!
  REAL-TIME DYNAMICS ✓
  FINITE DENSITY ✓

[Cardoso et al, PRD 81, 034504 (2010)]

QGP IN LATTICE GAUGE THEORIES

SIMULATE THE LATTICE GAUGE THEORY AS AN OPEN QUANTUM SYSTEM



OPEN SYSTEM

QCD

mapping

ENVIRONMENT

QGP

SUBSYSTEM

QUARKONIA

INTERACTION

TENSOR NETWORKS

QUANTUM COMPUTING

SUBSYSTEM APPROXIMATION $(3+1)\text{D SU}(3) \longrightarrow (1+1)\text{D SU}(2)$

OVERVIEW

HAMILTONIAN LATTICE GAUGE THEORIES

- ✦ Kogut-Susskind formulation for SU(2) Yang-Mills
- ✦ Matter & Gauge SU(2) Hilbert space

OPEN QUANTUM SYSTEMS THEORY

- ✦ Linblad Master Equation
- ✦ Timescales and Brownian Limit
- ✦ Physics-informed approximations

TENSOR NETWORK SIMULATIONS

- ✦ Time evolution for open quantum systems

THERMALIZATION TIME

- ✦ Empirical vs Liouvillian
- ✦ Dependence on Environment, Temperature etc
- ✦ Comparison with other approaches (pNRQCD)
- ✦ Anomalies

ENTROPY

LOCAL OBSERVABLES

- ✦ Casimir evolution
- ✦ Matter production

OUTLOOK AND CONCLUSIONS

HAMILTONIAN LGTS: INGREDIENTS

$$H = \boxed{H_{\text{matter}}} + \boxed{H_{\text{gauge}}} + \boxed{H_{\text{interaction}}}$$

$$= \int \psi^\dagger \left[-i\vec{\gamma}\cdot\vec{\nabla} + \gamma^0 m\right]\psi - \int \left[\boxed{E^2} + \boxed{B^2}\right] + \int g\psi^\dagger i(\vec{\gamma}\cdot\vec{A})\psi$$

DIRAC HAMILTONIAN OF FREE FERMIONS

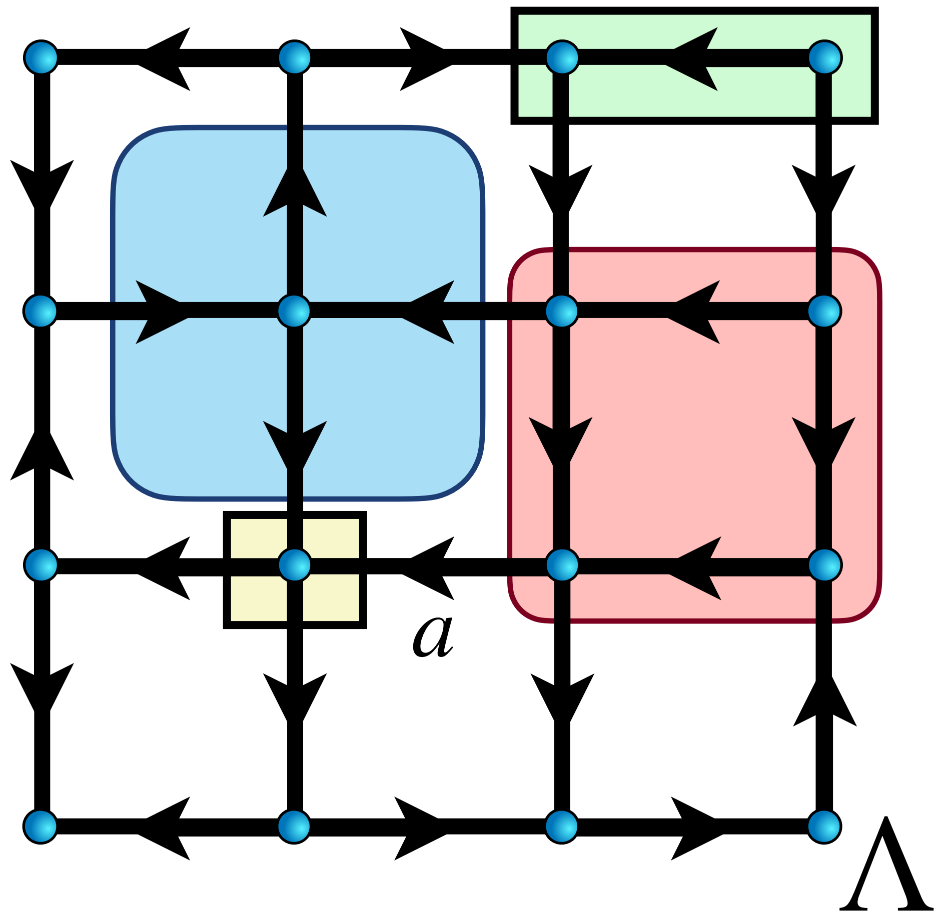
ELECTRIC CONTRIBUTION

MAGNETIC CONTRIBUTION

COVARIANT DERIVATIVE: $\partial_k \to \partial_k - gA_k$

SPATIAL DISCRETIZATION. TIME IS CONTINUOUS

PARALLEL TRANSPORTER $-i\psi^\dagger\gamma^k[\partial_k - gA_k]\psi \longrightarrow -i\psi^\dagger\gamma^k U_k\psi$



$$H = -\frac{1}{2a}\sum_{\mathbf{n},\mu}\left[\boxed{\psi_{\mathbf{n}}^\dagger U_{\mathbf{n},\mathbf{n}+\mu}\psi_{\mathbf{n}+\mu}} + \text{H.c.}\right] + \boxed{m\sum_{\mathbf{n}}\psi_{\mathbf{n}}^\dagger\psi_{\mathbf{n}}} + \boxed{H_{\text{Pure}}}$$

$$H_{\text{Pure}} = \boxed{\frac{g^2}{2a}\sum_{\mathbf{n},k}E^2_{\mathbf{n},\mu_k}} \boxed{-\frac{1}{2ag^2}\sum_{\square}\text{Tr}\left[\text{U}_\square + \text{U}_\square^\dagger\right]}$$

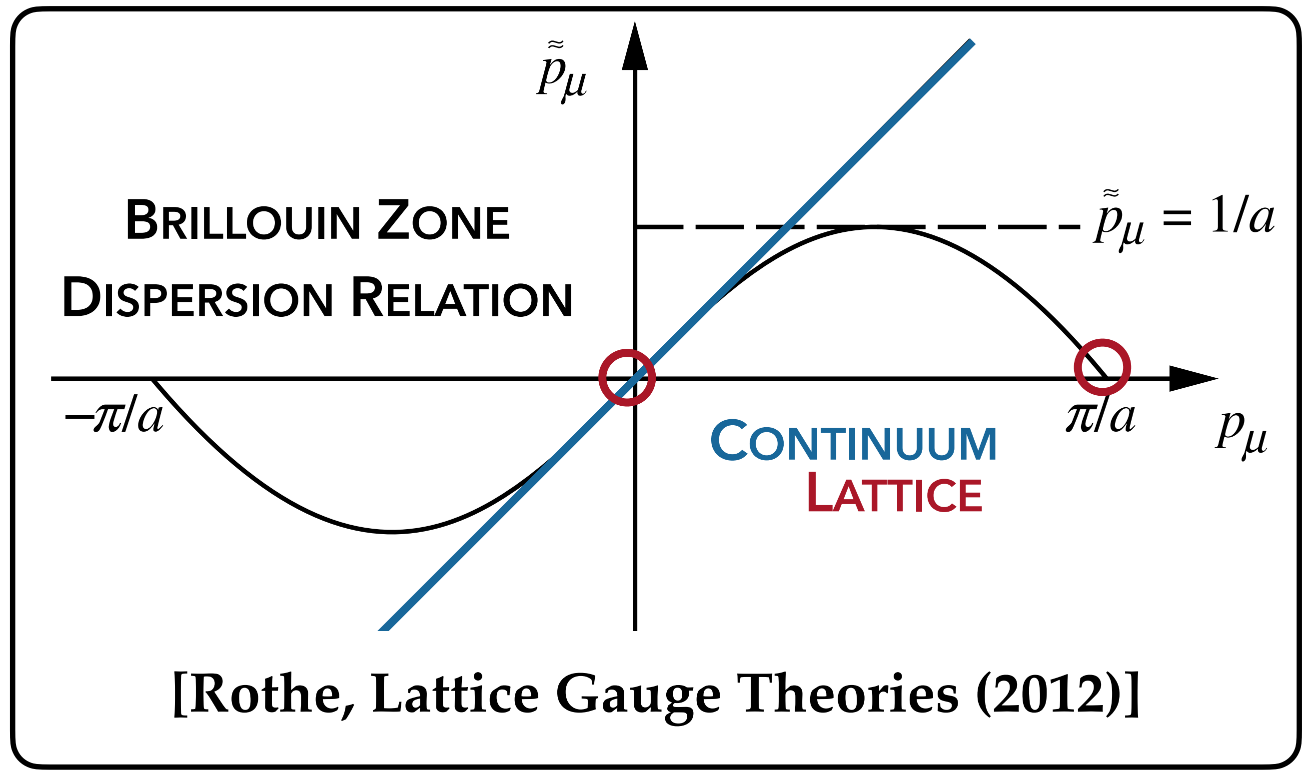
$$U_\square = \begin{array}{ccc} \ulcorner & U^\dagger & \urcorner \\ U^\dagger & & U \\ \llcorner & U & \lrcorner \end{array}$$

[Kogut & Susskind PRD 11, 395 (1975)] [Wilson PRD 10, 2445 (1974)]

MATTER HILBERT SPACE

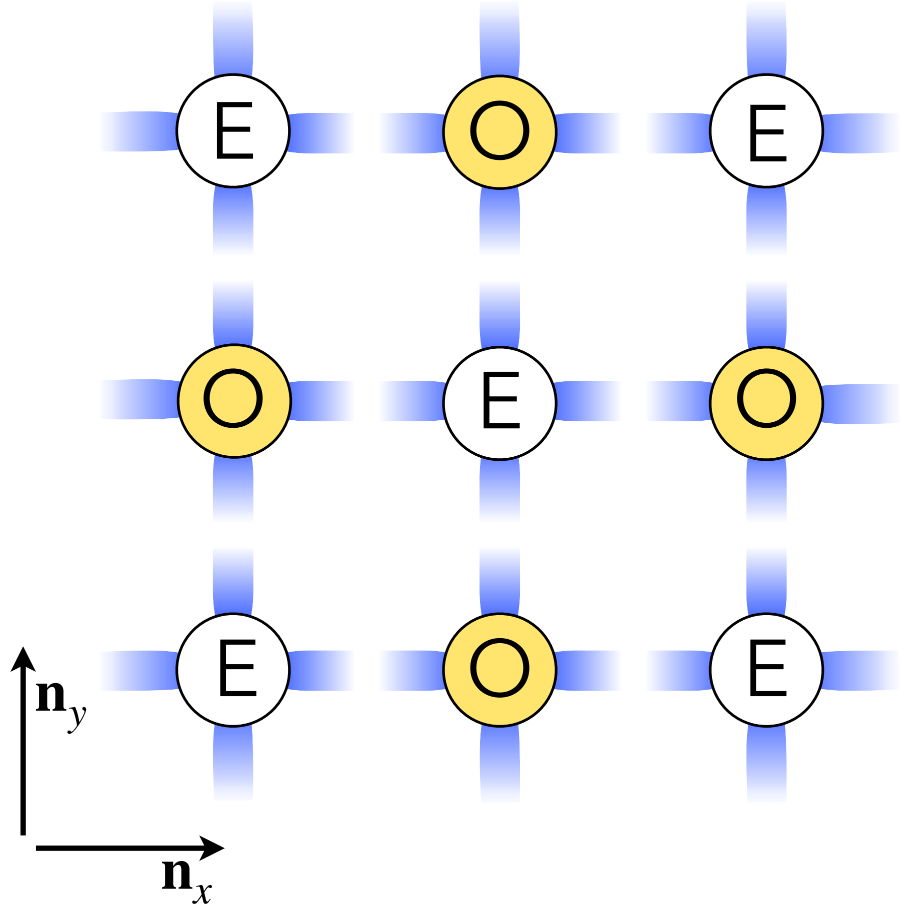
$$\mathscr{H} = \left[\mathscr{H}_{\text{matter}} \otimes \mathscr{H}_{\text{gauge}}\right]_{\text{Gauss Law}}$$

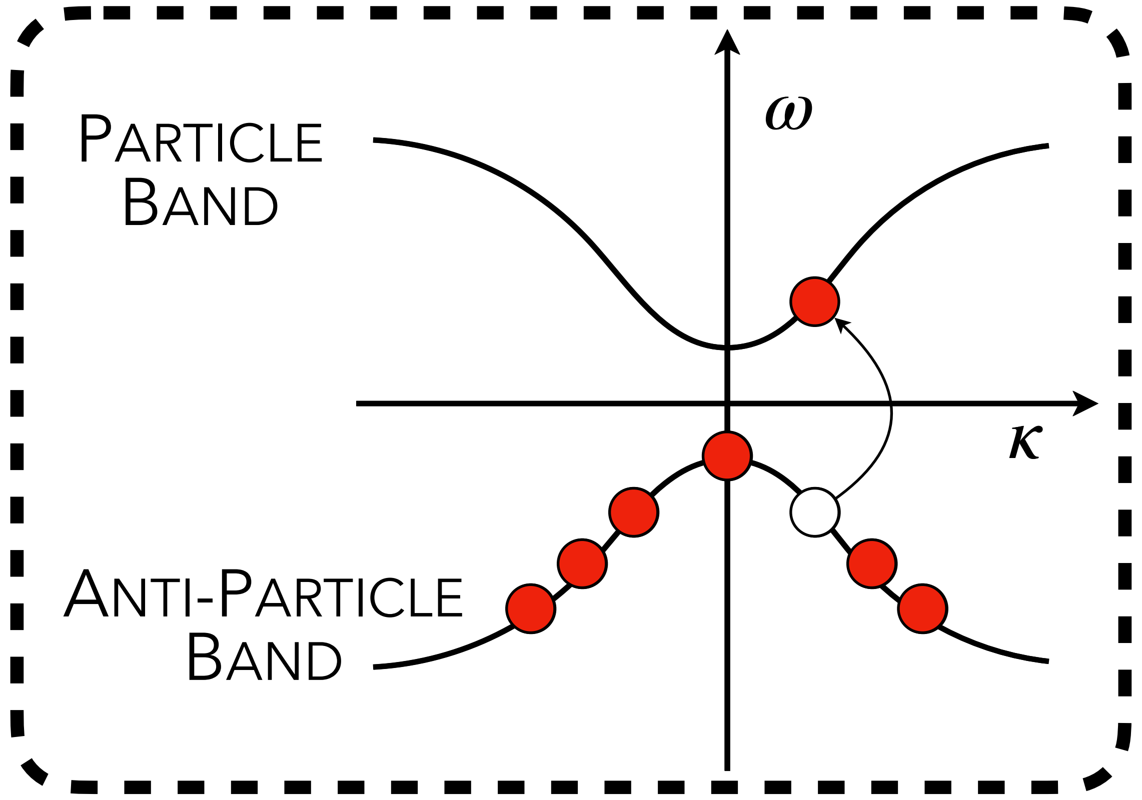
Studying Fermions on the Lattice is challenging [**Fermion Doubling Problem**]



[Rothe, Lattice Gauge Theories (2012)]

We use **Staggered Fermions** and **split spinor components** on sublattices





ABELIAN CASE: U(1)

Electrons q, Positrons $\bar{q}$

$(-1)^{\mathbf{n}_x+\mathbf{n}_y} = +1$	○	∅
	◉	q
$(-1)^{\mathbf{n}_x+\mathbf{n}_y} = -1$	◉	∅
	○	$\bar{q}$

Despite these strategies, Fermions are still problematic [Anti-Commute]

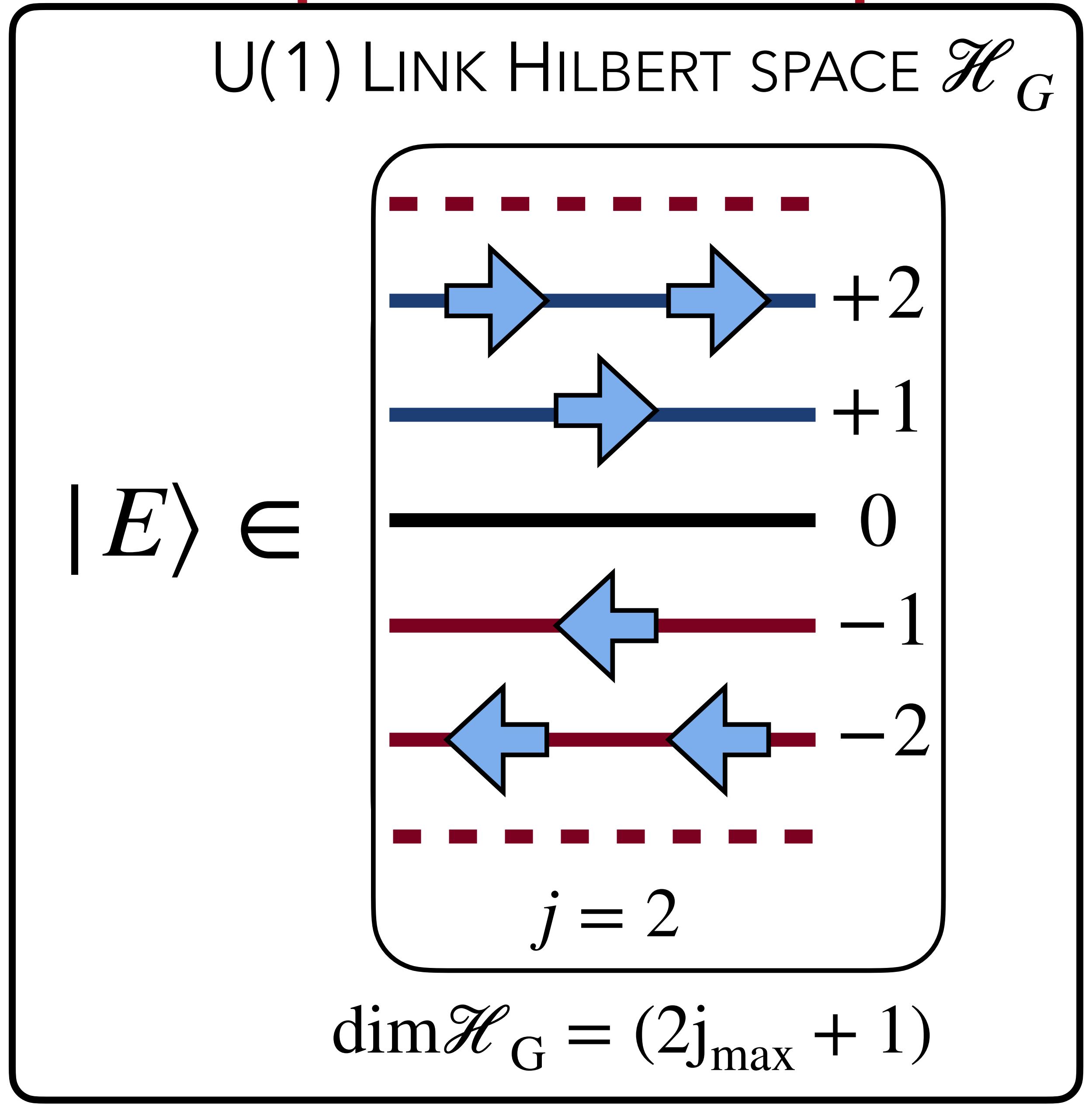
[Susskind, PRD 16 - 3031 (1977)]

GAUGE LINK HILBERT SPACE

FOR A **CONTINUOUS GAUGE GROUP** [U(1), SU(2), SU(3)]
THE CORRESPONDING **HILBERT SPACE IS INFINITE**: IT MUST BE TRUNCATED!

- QUANTUM LINK MODELS
  [Chandrasekharan et al, Nucl.Phys B 492, 1-2 (1997)]
- USE FINITE SUBGROUPS $(\mathbb{Z}_N, D_6)$
  [Ercolessi et al, PRD 98, 074503 (2018)]
- ALGEGRA DEFORMATION
  [Zache et al, PRL 131, 171902 (2023)]
- INTRODUCE AN ENERGY CUTOFF

ABELIAN CASE



CORE IDEA

USE SPIN-LIKE OPERATORS IN THE j-IRREP. EXAMPLE: QED
$(E, U, U^\dagger) \rightarrow (S^z, S^+, S^-)$

ABELIAN CASE: (1+1)D U(1) LGT, SCHWINGER MODEL

$$\hat{H}^{\mathrm{U}(1)} = -\frac{1}{2}\sum_{\mathbf{n}}\left[i\hat{\psi}^\dagger_{\mathbf{n}}\hat{S}^+_{\mathbf{n},+\mu}\hat{\psi}_{\mathbf{n}+\mu} + \mathrm{H.c.}\right] + m\sum_{\mathbf{n}}(-1)^{\mathbf{n}}\hat{\psi}^\dagger_{\mathbf{n}}\hat{\psi}_{\mathbf{n}} + \frac{g^2}{2}\sum_{\mathbf{n}}\left(\hat{S}^z_{\mathbf{n},+\mu}\right)^2$$

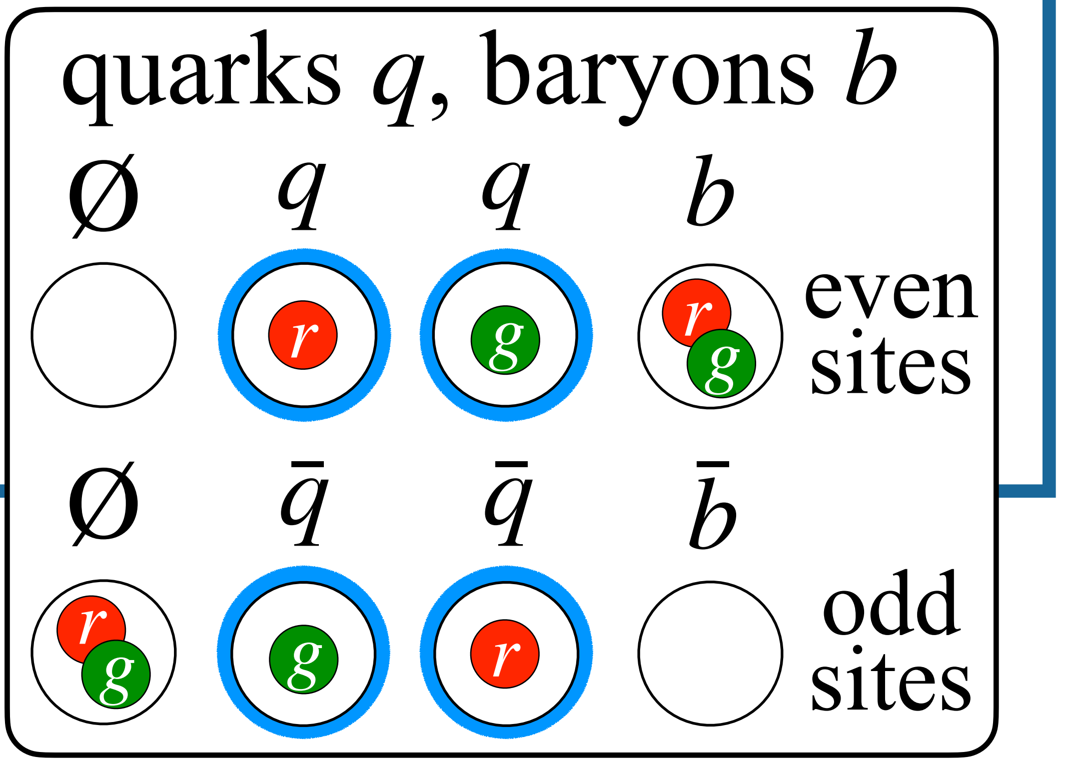
(1+1)D SU(2) YANG–MILLS LGT

$$\hat{H}^{\mathrm{SU(2)}} = -\frac{1}{2}\sum_{\mathbf{n}}\sum_{\alpha,\beta}\left[i\hat{\psi}^{\dagger}_{\alpha,\mathbf{n}}\hat{U}^{\alpha,\beta}_{\mathbf{n},+\mu}\hat{\psi}_{\beta,\mathbf{n}+\mu} + \text{H.c.}\right] + m\sum_{\mathbf{n}}(-1)^{\mathbf{n}}\sum_{\alpha}\hat{\psi}^{\dagger}_{\alpha,\mathbf{n}}\hat{\psi}_{\alpha,\mathbf{n}} + \frac{g^{2}}{2}\sum_{\mathbf{n}}\hat{E}^{2}_{\mathbf{n},+\mu}$$

MATTER HILBERT SPACE

STAGGERED
FLAVORLESS
SU(2) COLOR
FERMION FIELDS

4 matter states



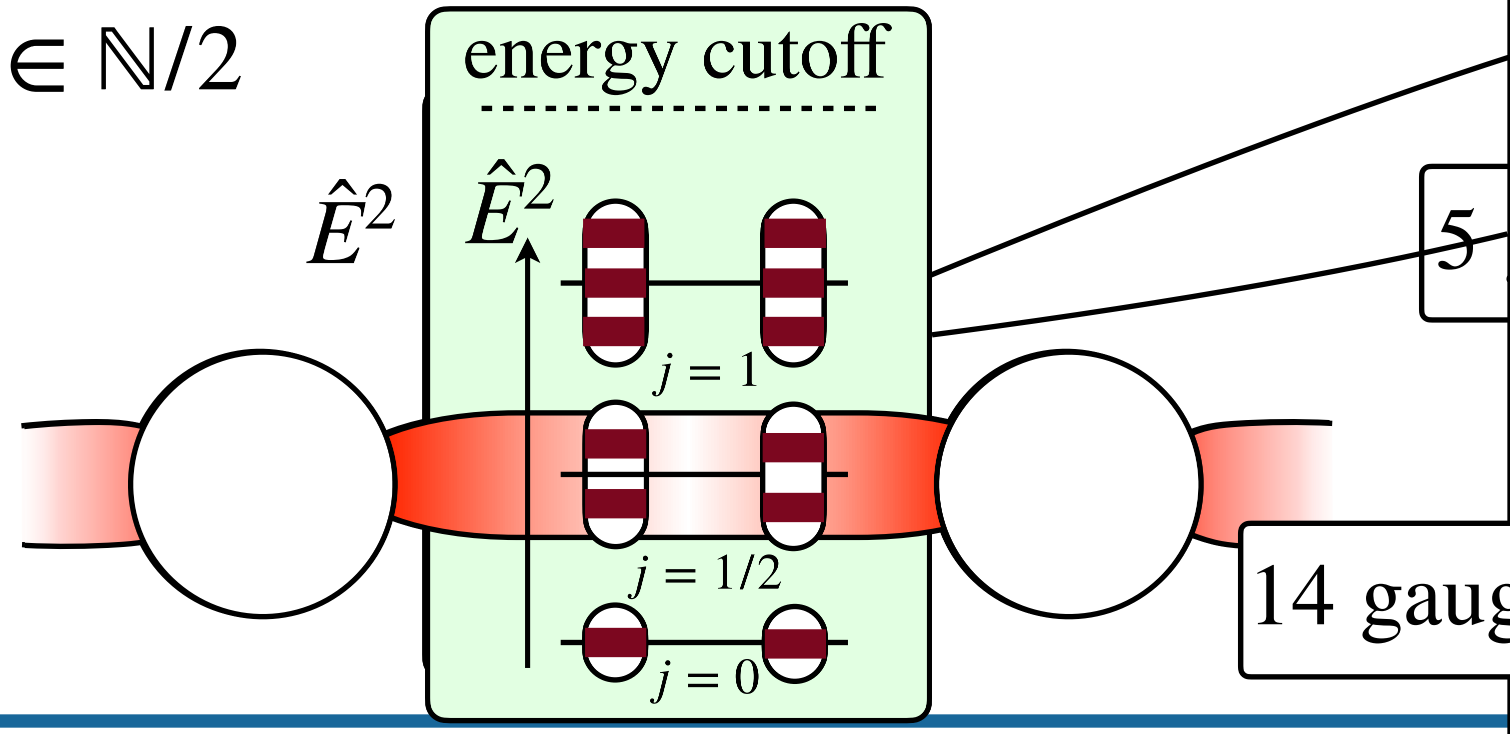
$$\mathscr{H} = \mathscr{H}_{\text{matter}} \otimes \mathscr{H}_{\text{gauge}}\Big|_{\text{Gauss Law}}$$

GAUGE HILBERT SPACE

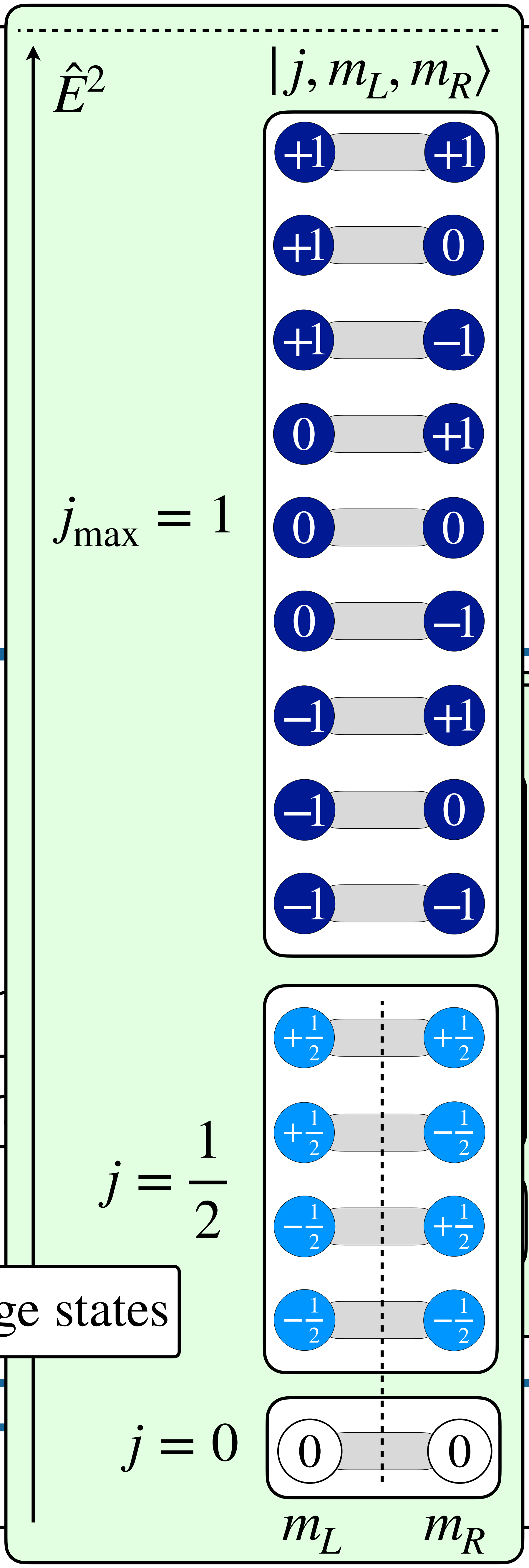
infinite in the Electric basis

$$\hat{E}^2\,|j,m_L,m_R\rangle = j(j+1)\,|j,m_L,m_R\rangle$$

$j \in \mathbb{N}/2$

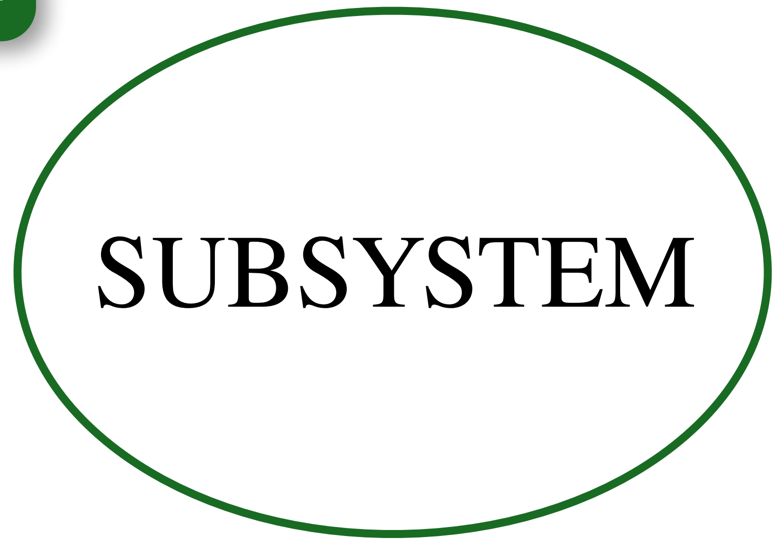


14 gauge states



OPEN SYSTEM VS CLOSED SYSTEM

CLOSED SYSTEM

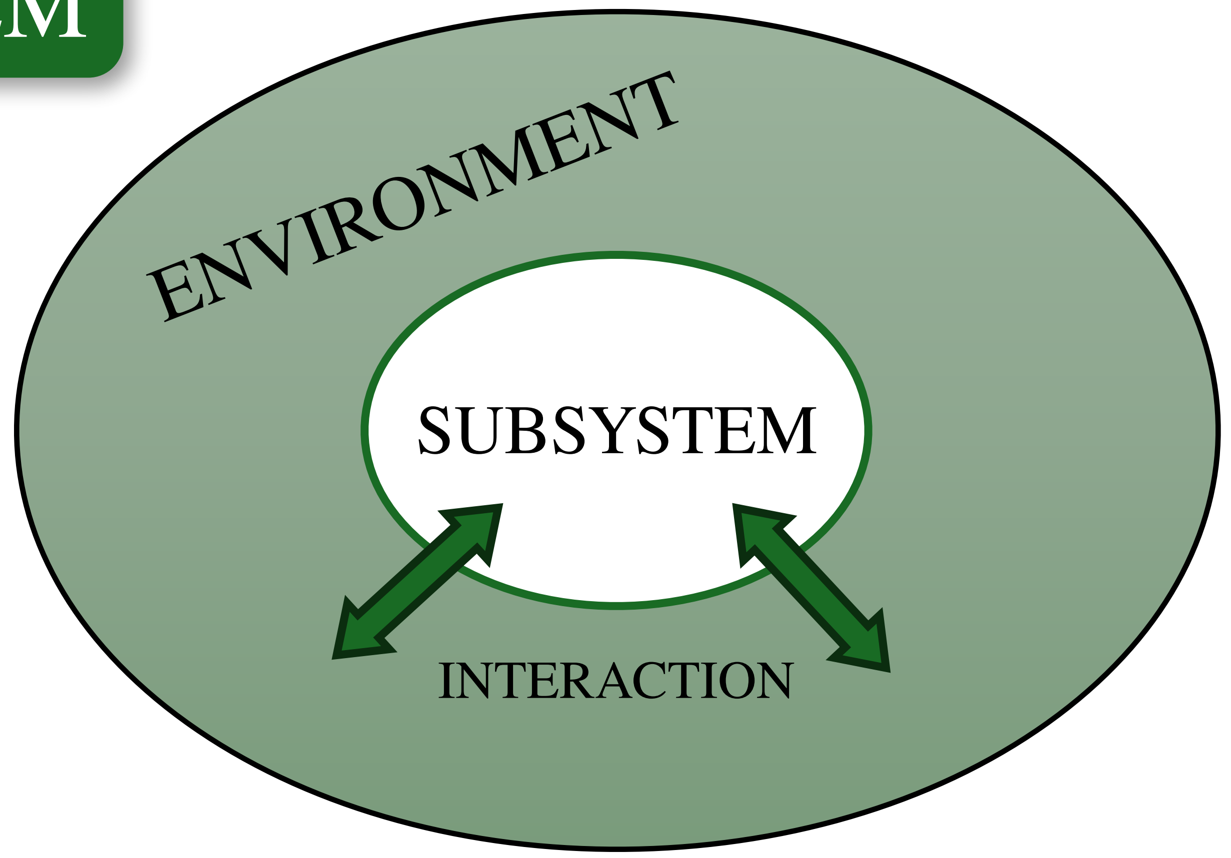


$$\hat{H}_{\text{tot}} = \hat{H}_S$$

VON NEUMANN EQUATION

$$\frac{d\hat{\rho}(t)}{dt} = -i\left[\hat{H}, \hat{\rho}(t)\right]$$

OPEN SYSTEM



$$\hat{H}_{\text{tot}} = \hat{H}_S + \hat{H}_E + \hat{H}_I$$

LINBLAD MASTER EQUATION

$$\frac{d\hat{\rho}_S(t)}{dt} = -i\left[\hat{H}_S + \Delta\hat{H}_S, \hat{\rho}_S(t)\right] +$$

$$\sum_{\mathbf{n}_1,\mathbf{n}_2} D_{\mathbf{n}_1,\mathbf{n}_2}(\omega = 0)\left(\tilde{O}_{\mathbf{n}_2}\hat{\rho}_S(t)\tilde{O}^\dagger_{\mathbf{n}_1} - \frac{1}{2}\left\{\tilde{O}^\dagger_{\mathbf{n}_1}\tilde{O}_{\mathbf{n}_2}, \hat{\rho}_S(t)\right\}\right)$$

ASSUMPTIONS

RELEVANT TIMESCALES

RELAXATION TIME

$$\tau_R \sim \frac{T}{\left(H_I^{(\mathrm{int})}\right)^2}$$

SUBSYSTEM TIMESCALE

$$\tau_S \sim \frac{1}{H_S}$$

ENVIRONMENT CORRELATION TIME

$$\tau_E \sim \frac{1}{T}$$

BROWNIAN MOTION LIMIT

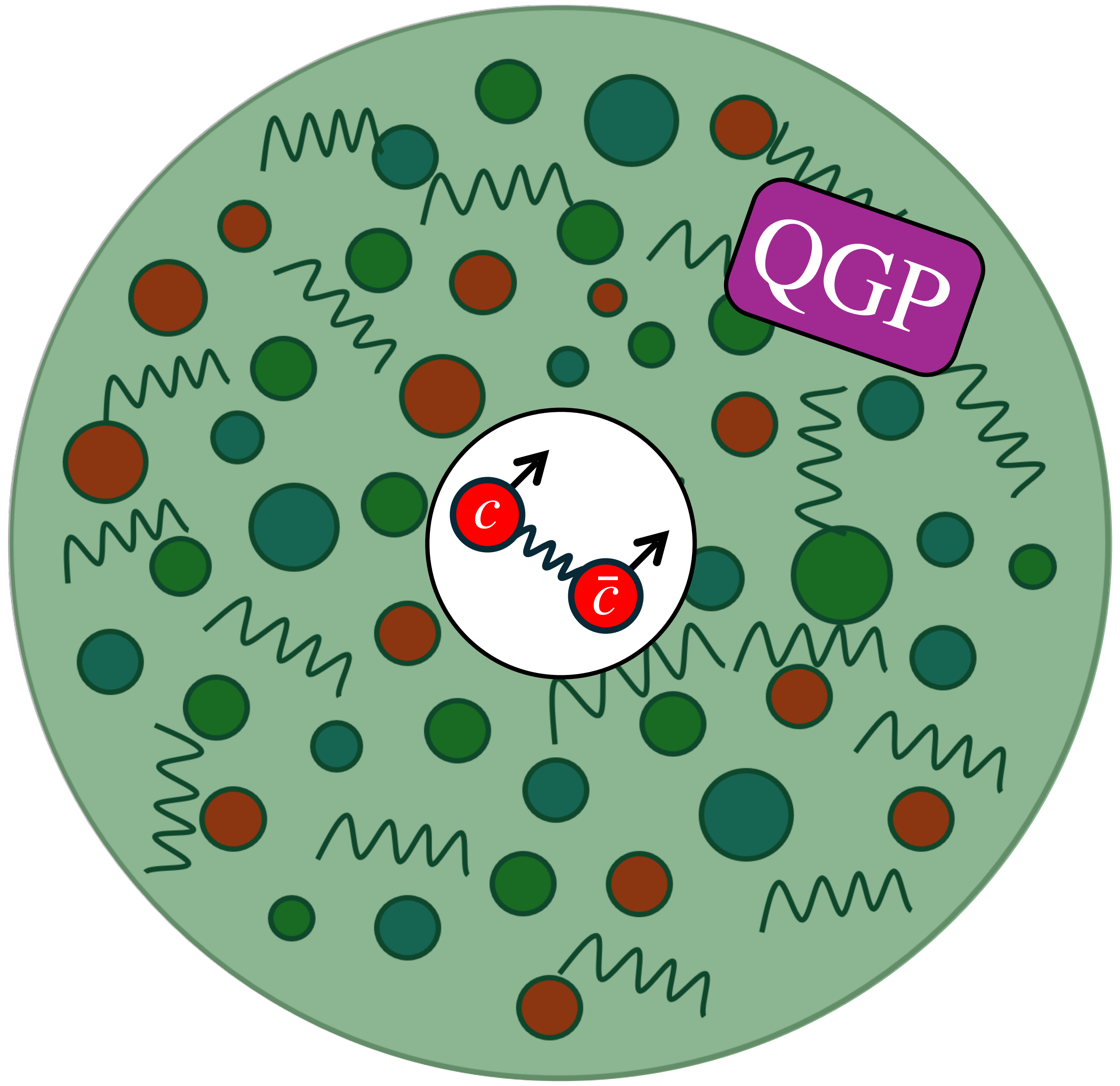
$$\tau_R \gg \tau_E$$
$$\tau_S \gg \tau_E$$

WEAK COUPLING LIMIT

$$\hat{\rho}(t) = \hat{\rho}_S(t) \otimes \hat{\rho}_E$$

BROWNIAN MOTION LIMIT

$$T \gg H_I^{(\mathrm{int})}$$
$$T \gg H_S$$

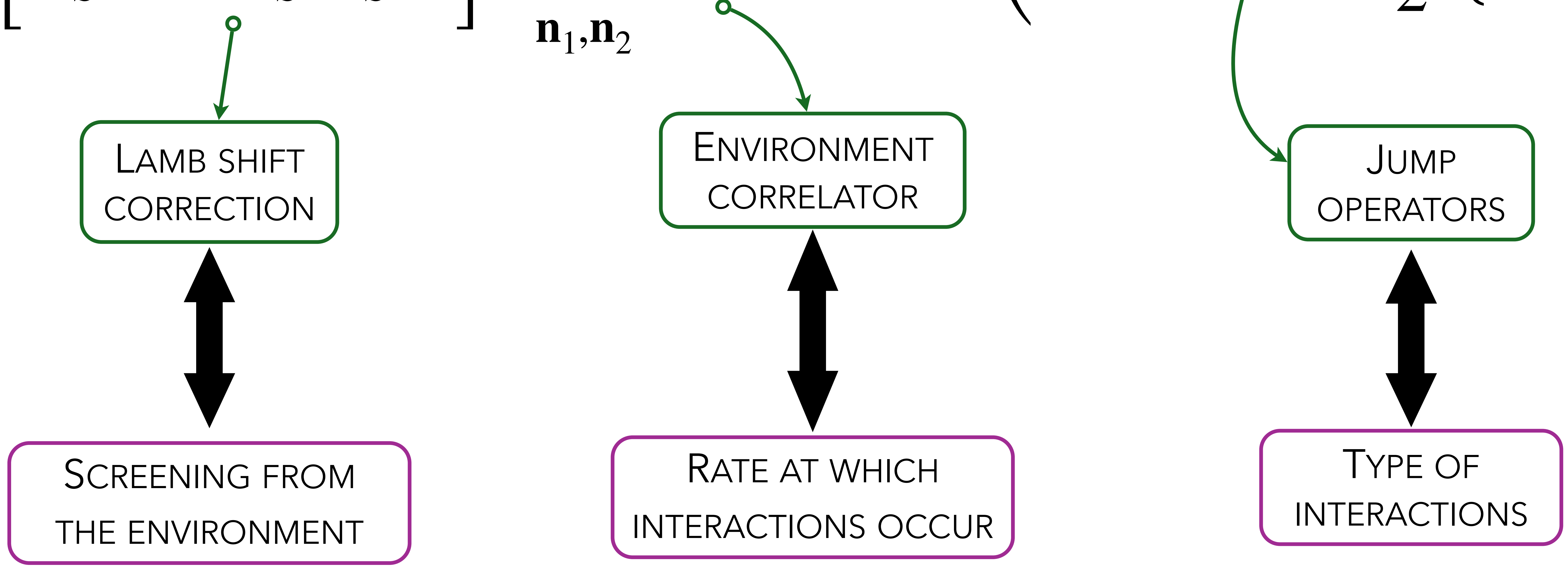


$$T \sim 10^{12}\,[\mathrm{Kelvin}]$$

TIME EVOLUTION EQUATION

LINBLAD MASTER EQUATION IN THE BROWNIAN MOTION LIMIT

$$\frac{d\hat{\rho}_S(t)}{dt} = -\,i\left[\hat{H}_S + \Delta\hat{H}_S, \hat{\rho}_S(t)\right] + \sum_{\mathbf{n}_1,\mathbf{n}_2} D_{\mathbf{n}_1,\mathbf{n}_2}(\omega = 0)\left(\tilde{O}_{\mathbf{n}_2}\hat{\rho}_S(t)\tilde{O}^\dagger_{\mathbf{n}_1} - \frac{1}{2}\left\{\tilde{O}^\dagger_{\mathbf{n}_1}\tilde{O}_{\mathbf{n}_2}, \hat{\rho}_S(t)\right\}\right)$$



Lamb shift correction

Screening from the environment

Environment correlator

Rate at which interactions occur

Jump operators

Type of interactions

X. Yao, Int. J. Mod. Phys. A 36, 2130010 (2021)

INTERACTION TYPE & LAMB SHIFT

YUKAWA POTENTIAL

$$\hat{H}_I = \lambda \sum_{n,\alpha} (-1)^n \hat{\phi}_{n,\alpha} \hat{\psi}^\dagger_{n,\alpha} \hat{\psi}_{n,\alpha}$$

➡

JUMP OPERATOR

$$\hat{O}_n = (-1)^n \hat{\psi}^\dagger_{n,\alpha} \hat{\psi}_{n,\alpha}$$

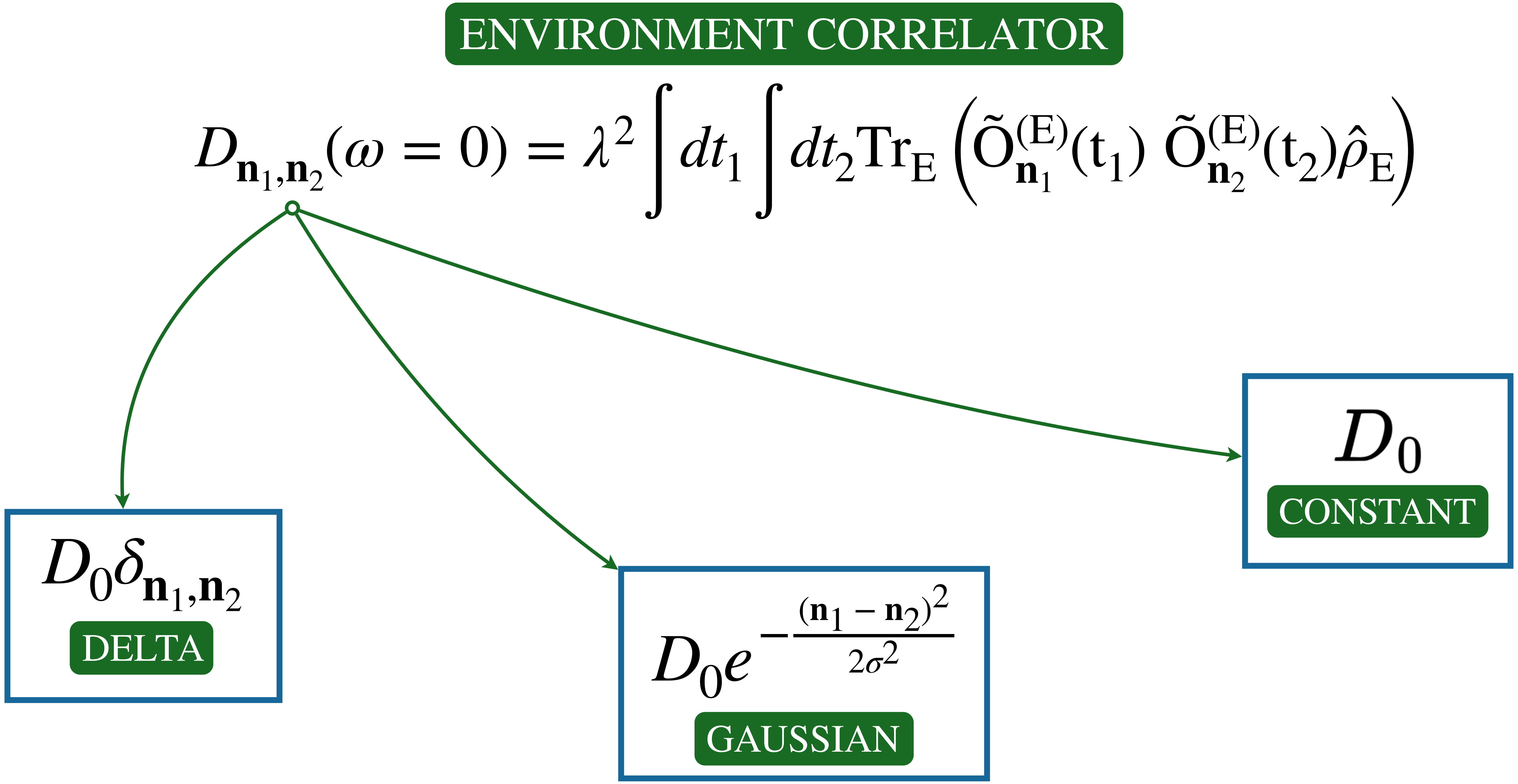
$$\Delta \hat{H}_S = \sum_{\alpha,\beta} S_{\alpha\beta} \hat{O}^{(S)}_\alpha \hat{O}^{(S)}_\beta + \frac{i}{8T} \sum_{\alpha,\beta} D_{\alpha,\beta} \left\{ \hat{O}^{(S)}_\alpha, \left[H_S, \hat{O}^{(S)}_\beta \right] \right\}$$

LAMB SHIFT

PHENOMENOLOGICALLY EXPECTED TO BE IRRELEVANT:

X. Yao, Int. J. Mod. Phys. A 36, 2130010 (2021)
Lee et al., PRD 108, 094518 (2023)
Angelides et al., JHEP 04, 195 (2025)

ENVIRONMENT CORRELATORS



ENVIRONMENT CORRELATOR

$$D_{\mathbf{n}_1,\mathbf{n}_2}(\omega = 0) = \lambda^2 \int dt_1 \int dt_2 \mathrm{Tr}_{\mathrm{E}} \left(\tilde{\mathrm{O}}^{(\mathrm{E})}_{\mathbf{n}_1}(\mathrm{t}_1)\ \tilde{\mathrm{O}}^{(\mathrm{E})}_{\mathbf{n}_2}(\mathrm{t}_2) \hat{\rho}_{\mathrm{E}} \right)$$

$$D_0 \delta_{\mathbf{n}_1,\mathbf{n}_2}$$

DELTA

$$D_0 e^{-\frac{(\mathbf{n}_1 - \mathbf{n}_2)^2}{2\sigma^2}}$$

GAUSSIAN

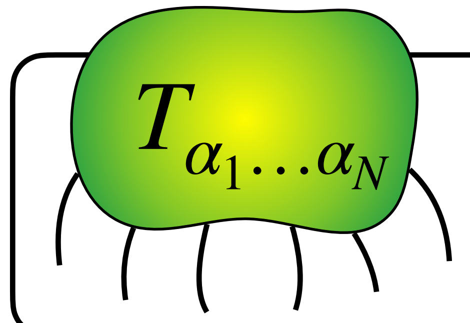
$$D_0$$

CONSTANT

Y. Akamatsu, Prog. Part. Nucl. Phys. 123, 103932 (2022)

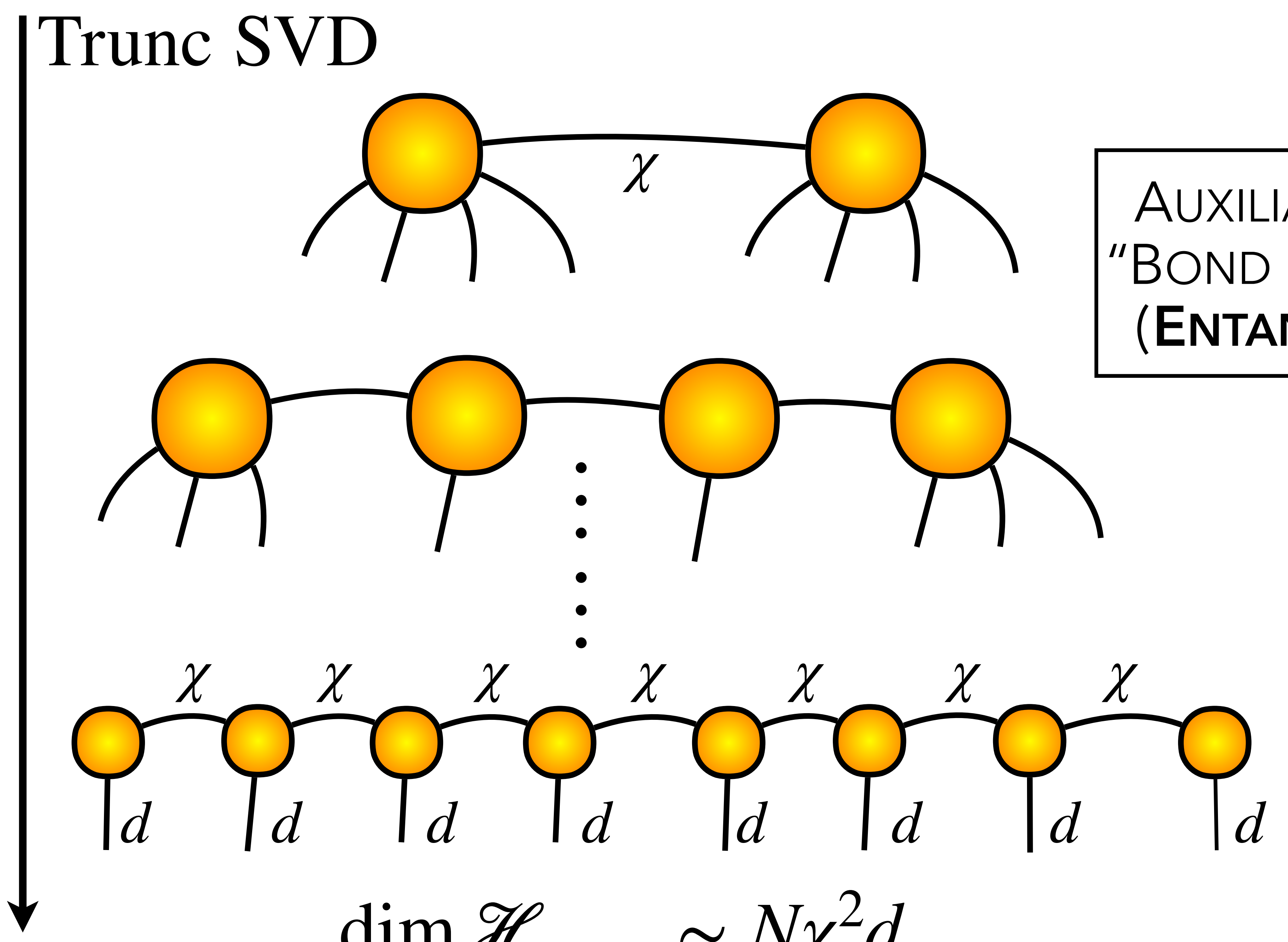
TENSOR NETWORK METHODS

The Hilbert space of N-Body Systems *grows exponentially*. Exact Diagonalization (ED) is not sustainable for large N



$$|\Psi_{\text{QMB}}\rangle = \sum_{\alpha_1 \dots \alpha_N} T_{\alpha_1 \dots \alpha_N} |\alpha_1 \dots \alpha_N\rangle$$

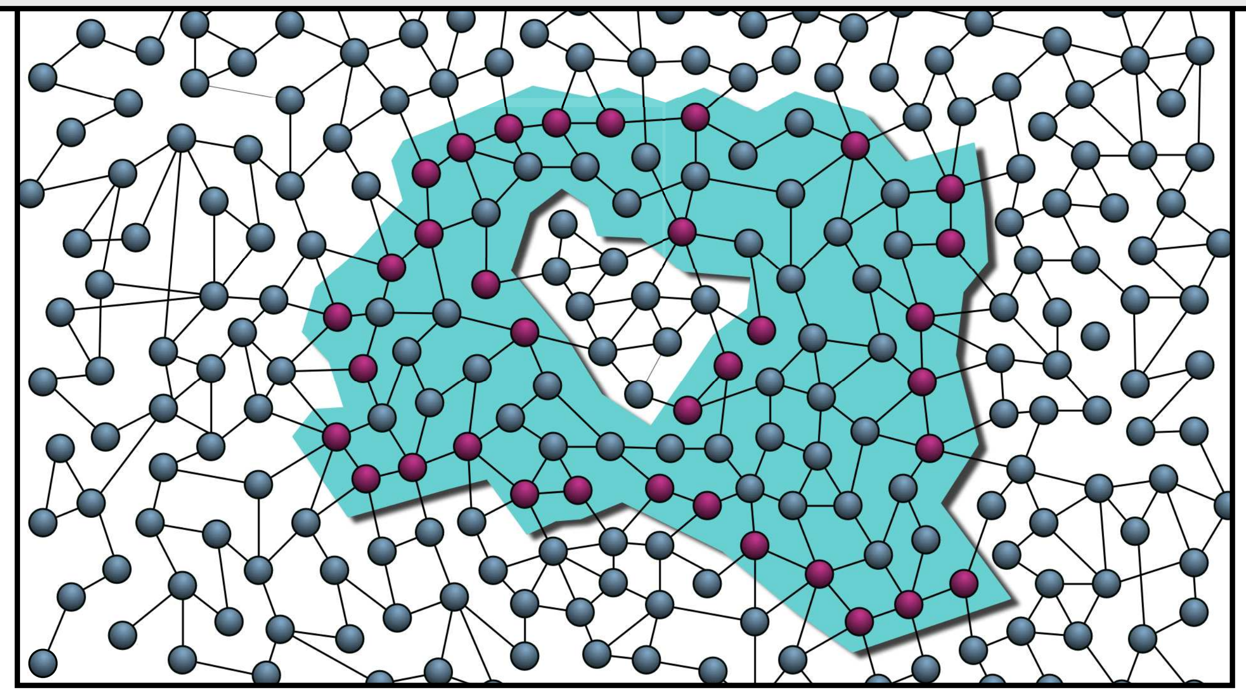
$$\dim \mathscr{H} = d^N$$



$$\dim \mathscr{H}_{\text{trunc}} \sim N\chi^2 d$$

AUXILIARY LINKS χ
"BOND DIMENSION"
(**ENTANGLEMENT**)

FOR GROUND STATES, THERE IS AREA LAW!



[Eisert et al, Rev. Mod. Phys. 82, 277 (2010)]

FOR TIME EVOLUTION

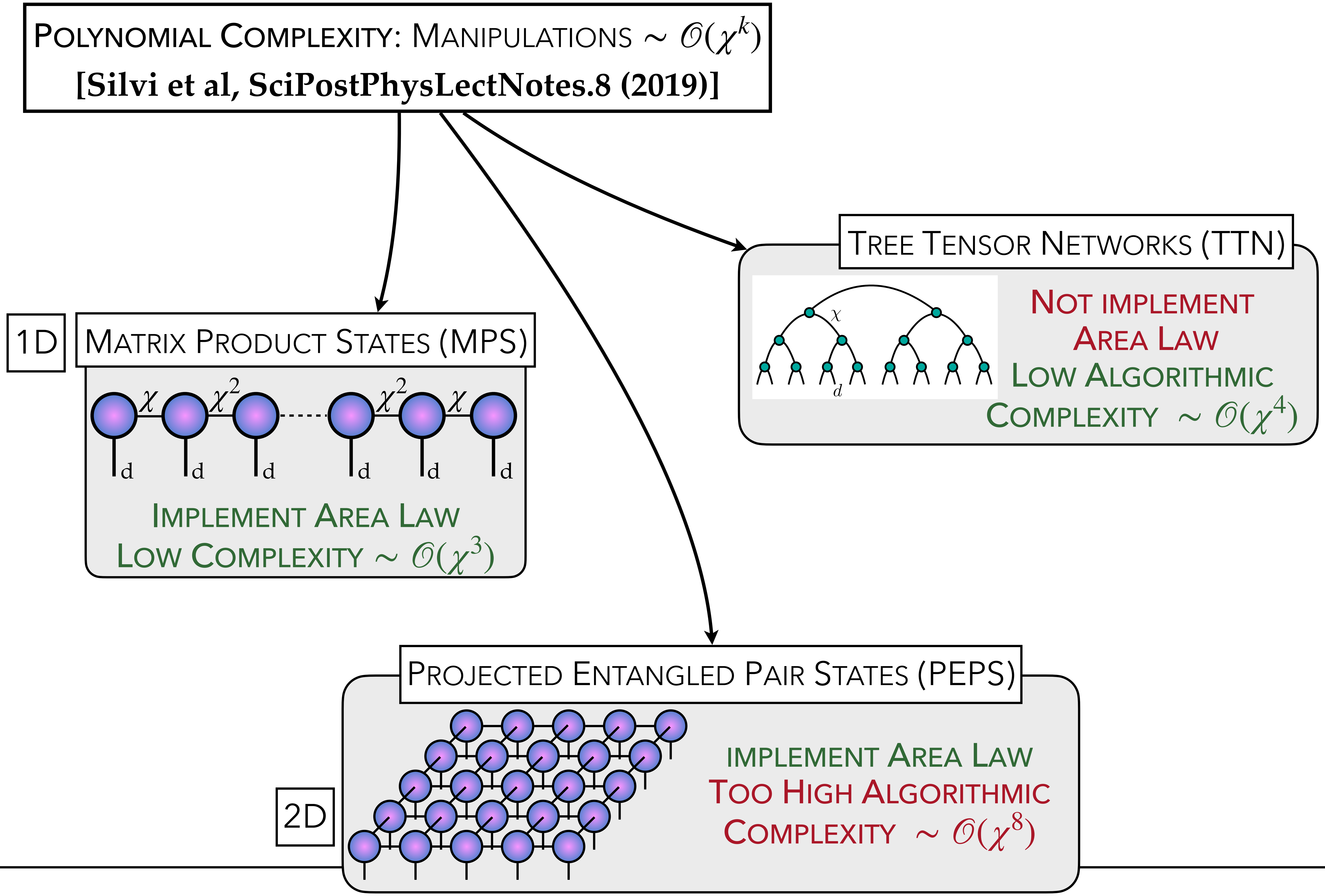
TIME-EVOLVING BLOCK DECIMATION (TEBD)

[G. Vidal, PRL 93,040502 (2004)]

TIME-DEPENDENT VARIATIONAL PRINCIPLE (TVDP)

[J. Haegeman et al, PRL 107, 070601 (2011)]

TENSOR NETWORK ANSÄTZE



Polynomial Complexity: Manipulations $\sim \mathcal{O}(\chi^k)$
[Silvi et al, SciPostPhysLectNotes.8 (2019)]

1D Matrix Product States (MPS)

Implement Area Law
Low Complexity $\sim \mathcal{O}(\chi^3)$

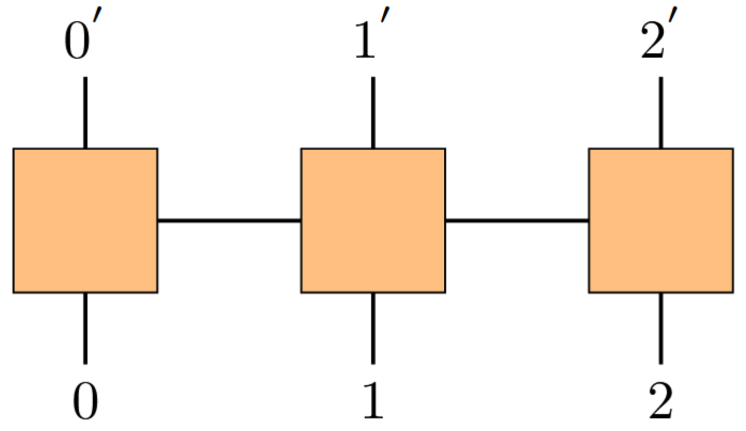
Tree Tensor Networks (TTN)

Not implement Area Law
Low Algorithmic Complexity $\sim \mathcal{O}(\chi^4)$

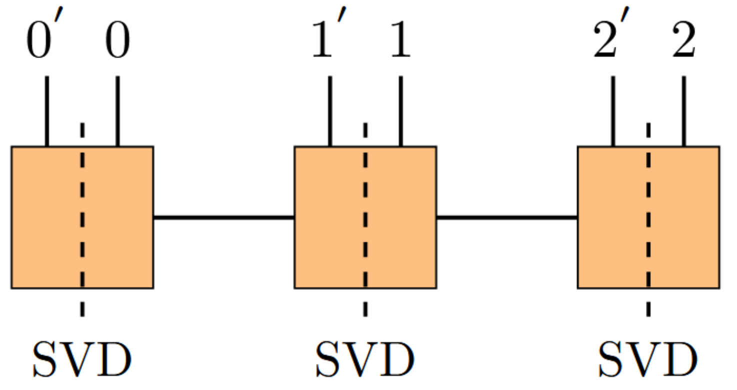
2D Projected Entangled Pair States (PEPS)

Implement Area Law
Too High Algorithmic Complexity $\sim \mathcal{O}(\chi^8)$

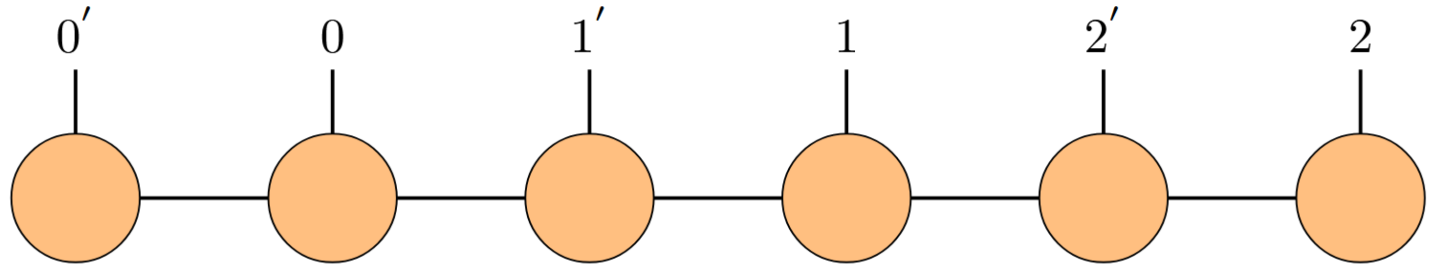
MPS for Open Quantum Many-Body Systems



(a) Initial MPO representing ρ_S.



(b) Separating the legs on each site with SVD.



(c) MPS representing ρ_S equivalent to the initial MPO in (a).

Angelides et al., JHEP 04, 195 (2025)

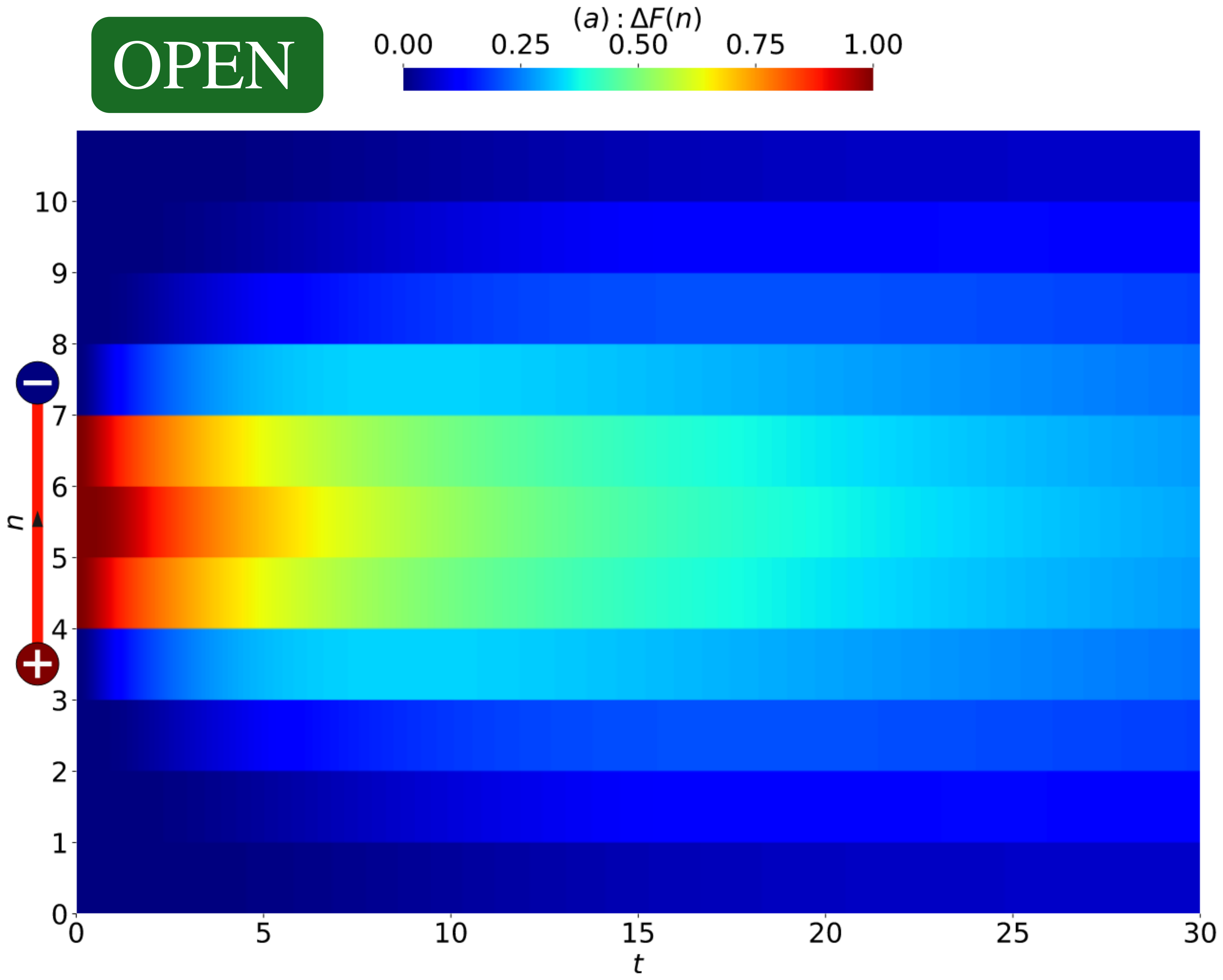
TENSOR NETWORKS FOR OPEN SYSTEMS

(1 + 1)D U(1) LGT

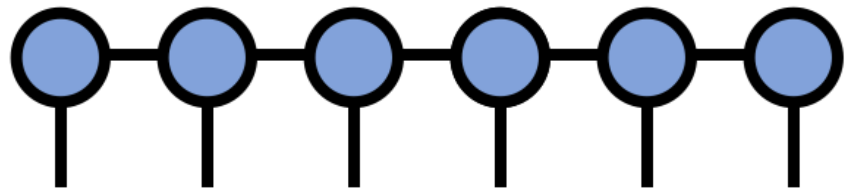
DELTA CORRELATOR

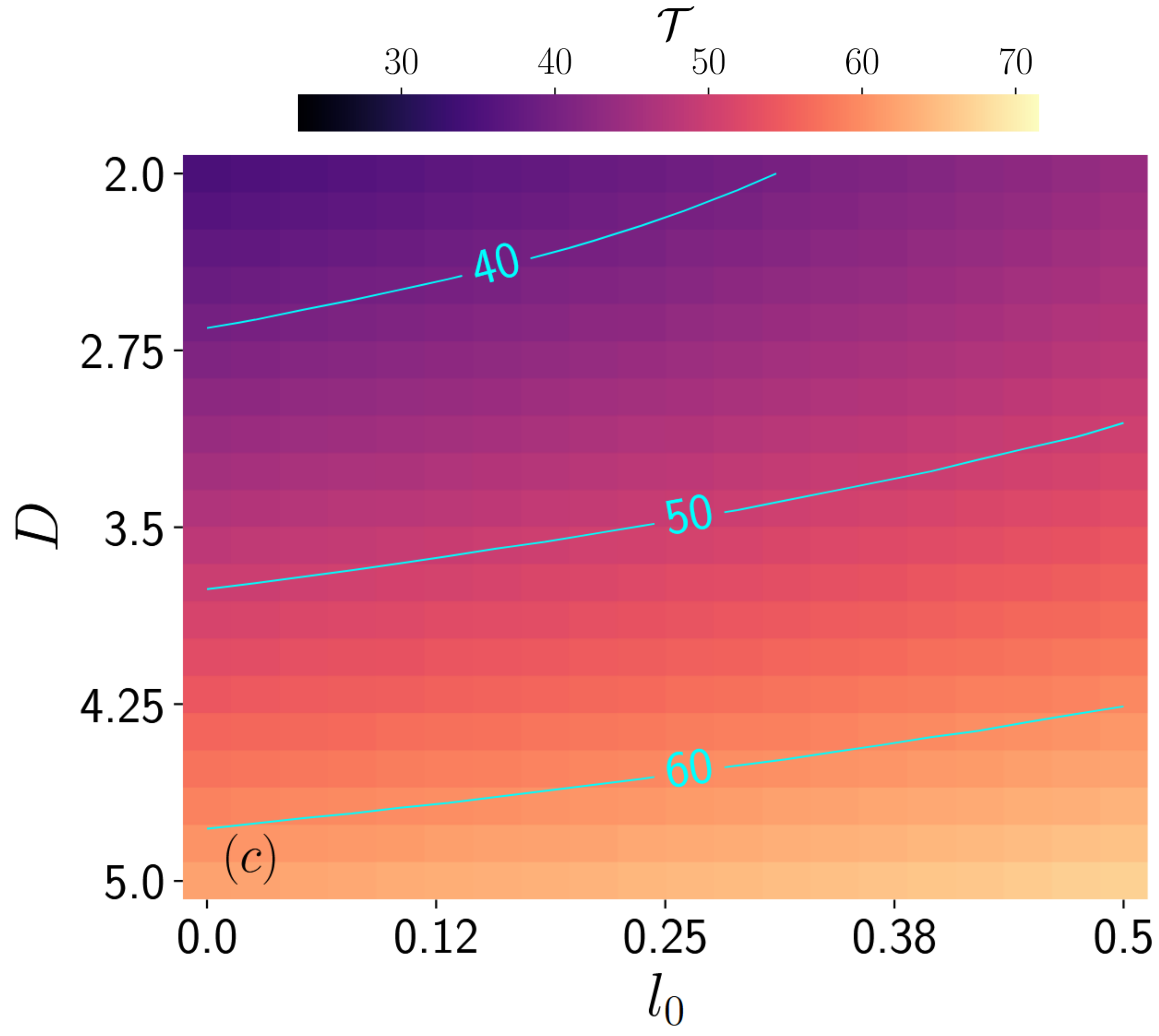
$$D_{\alpha,\beta}(\omega = 0) = D\delta_{\alpha,\beta}$$

OPEN



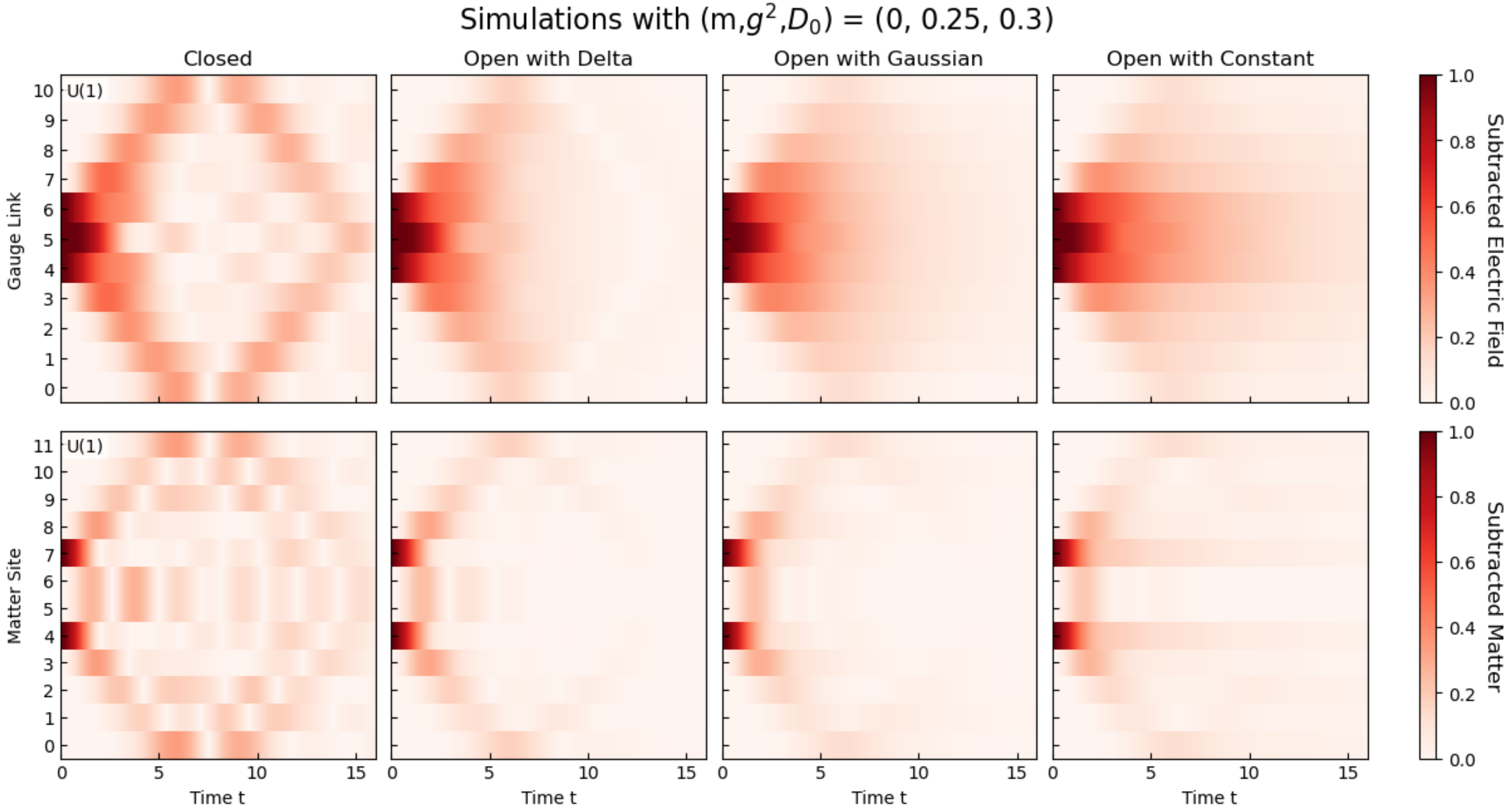
MATRIX PRODUCT STATES





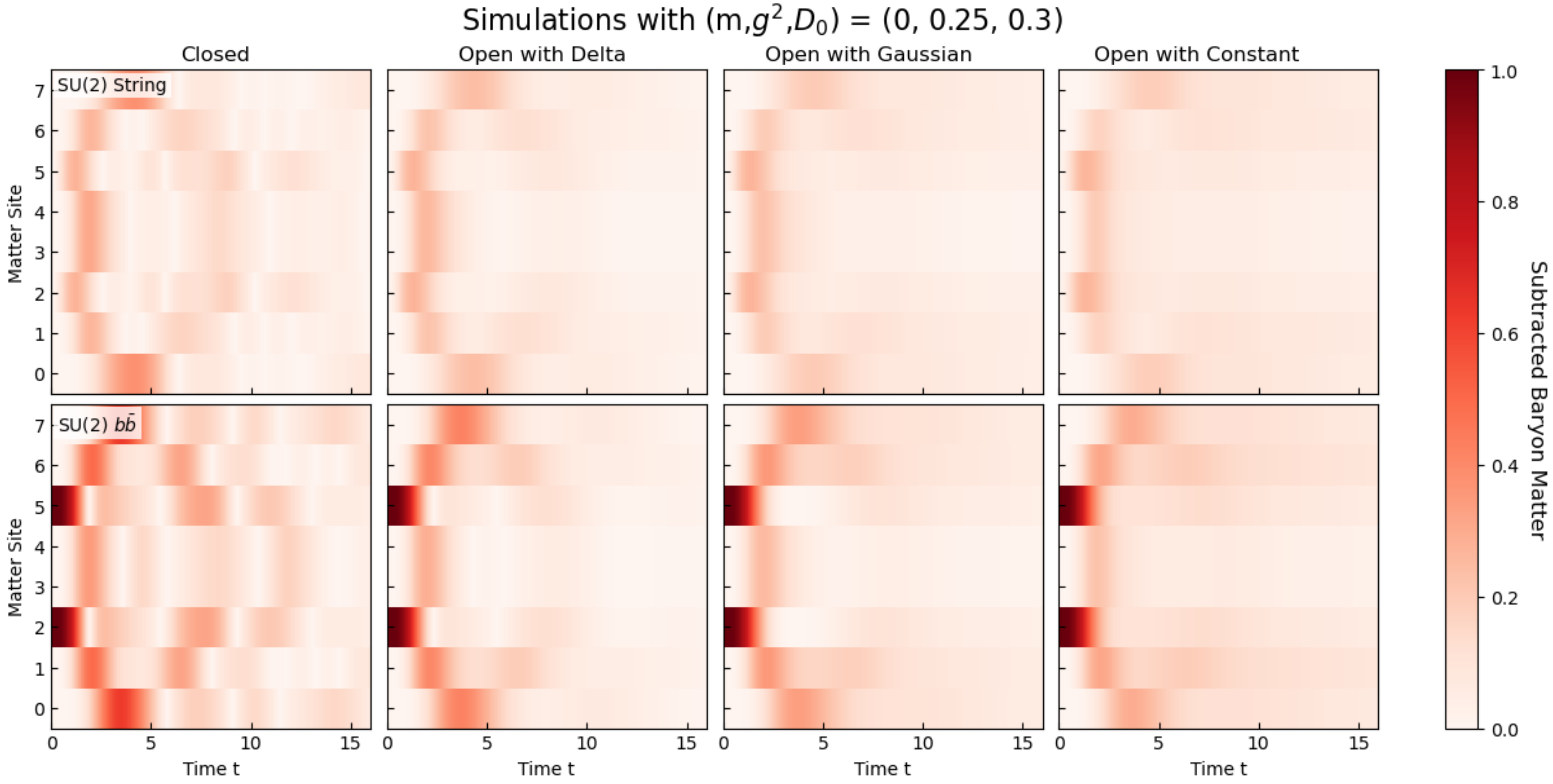
Angelides et al., JHEP 04, 195 (2025)

SITE-RESOLVED U(1) DYNAMICS



A CONSTANT ENVIRONMENT TRIES TO KEEP THE MATTER WHERE IT BEGAN MOST

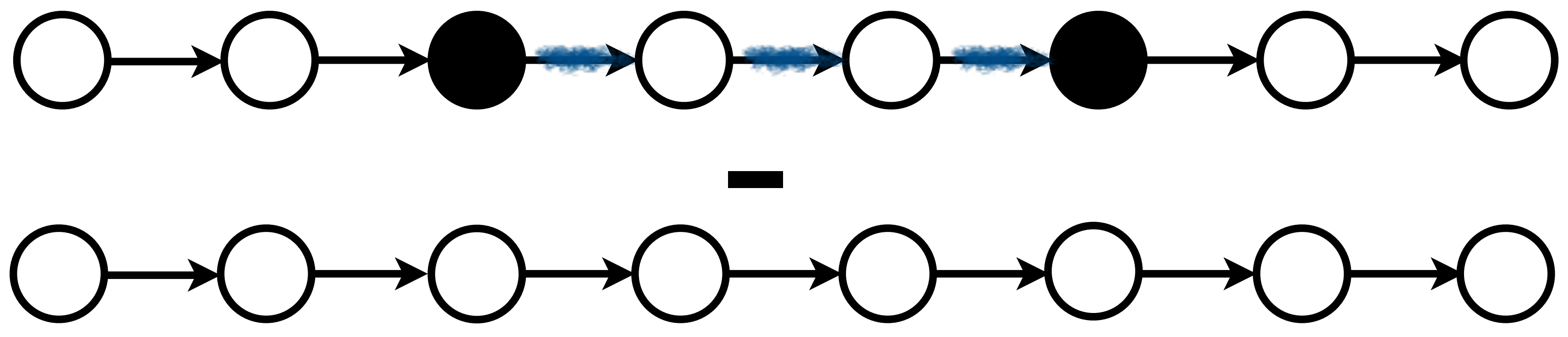
SITE-RESOLVED SU(2) DYNAMICS



EMPIRICAL THERMALIZATION TIME

EMPIRICAL THERMALIZATION TIME

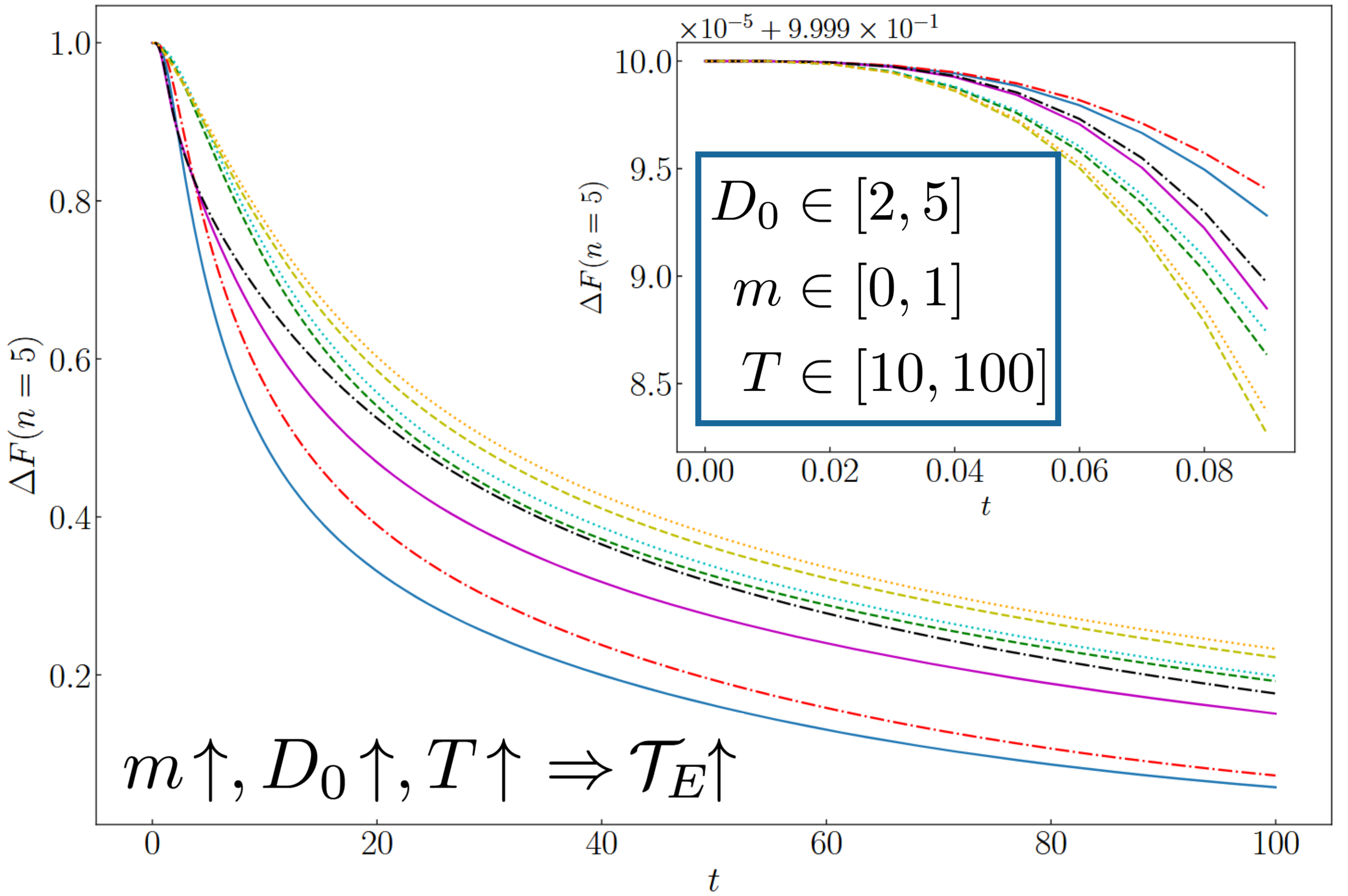
$\mathscr{T}_{\mathrm{E}} =$ Time for SEF in the central gauge link to decrease by a given %



SEF

Subtracted Electric Field = String – Vacuum

(1 + 1)D U(1) LGT



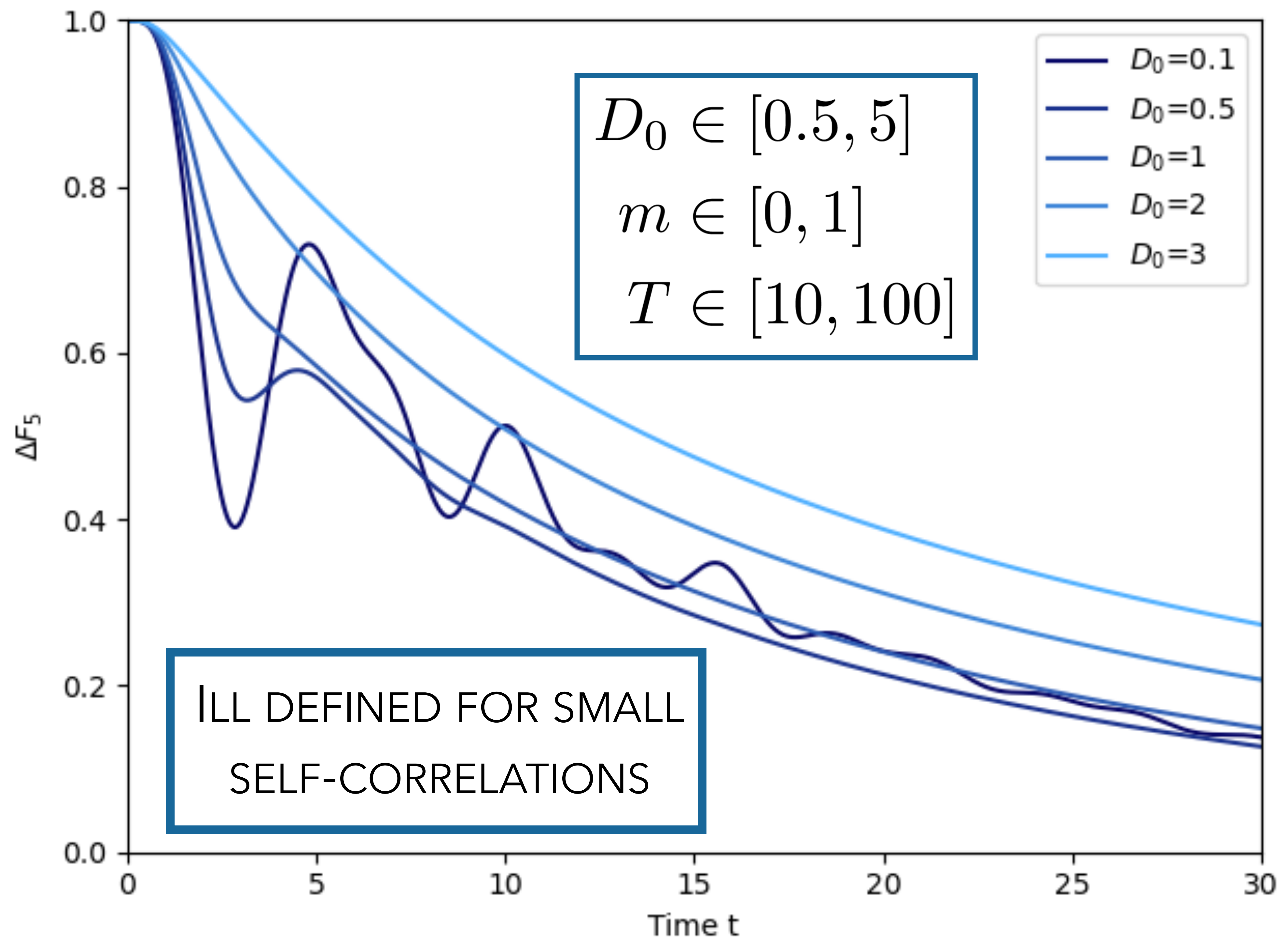
$D_0 \in [2, 5]$

$m \in [0, 1]$

$T \in [10, 100]$

$m\uparrow, D_0\uparrow, T\uparrow \Rightarrow \mathcal{T}_E\uparrow$

Angelides et al., JHEP 04, 195 (2025)



$D_0 \in [0.5, 5]$

$m \in [0, 1]$

$T \in [10, 100]$

Ill defined for small self-correlations

LIOUVILLIAN THERMALIZATION TIME

$$\frac{d\hat{\rho}}{dt} = \mathcal{L}\hat{\rho} \Rightarrow \hat{\rho}(t) = e^{\mathcal{L}t}\hat{\rho}(0)$$

THE LIOUVILLIAN IS **NOT-HERMITIAN**!

LIOUVILLIAN DIAGONALIZATION

$\hat{r}_k$ = Right Eigenvectors

$\hat{\ell}_k$ = Left Eigenvectors

λ_k = Eigenvalues

$\lambda_0 = 0$
steady state

$\mathrm{Re}(\lambda_k) < 0 \ \forall k > 0$
decay mode

$$\hat{\rho}(t) = \hat{\rho}_{ss} + \sum_k e^{\lambda_k t} C(\hat{\ell}_k^\dagger)\hat{r}_k$$

$$= \hat{\rho}_{ss} + e^{\lambda_1 t} C(\hat{\ell}_1)\hat{r}_1 + \mathcal{O}(e^{\lambda_2 t})$$

ASSUMPTION

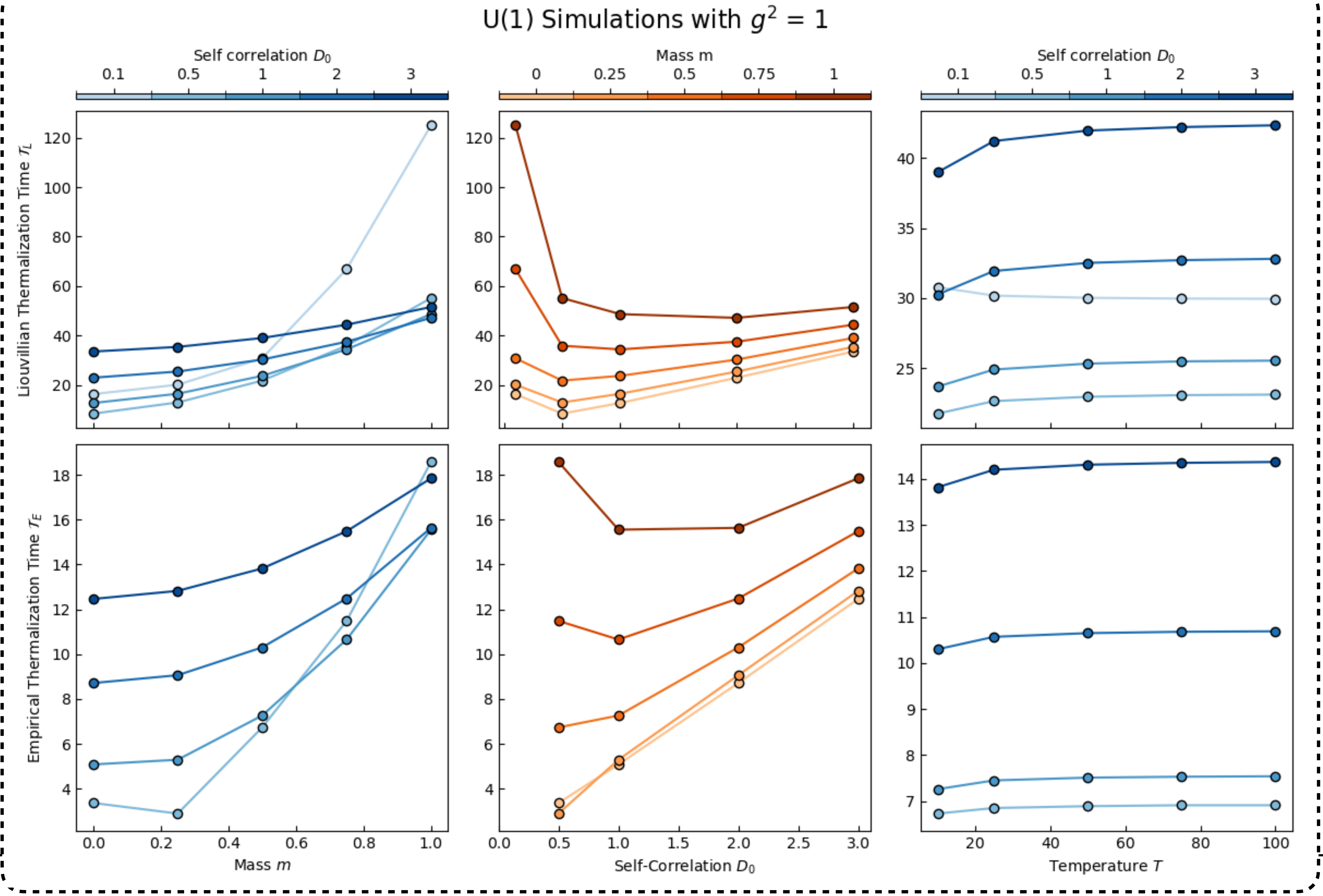
iff $\mathrm{Re}(\lambda_1) \gg \mathrm{Re}(\lambda_{k>1}) \forall k$

LIOUVILLIAN THERMALIZATION TIME

$$\mathcal{T}_L = \frac{1}{|\mathrm{Re}(\lambda_1)|}$$

INVERSE OF THE REAL PART OF THE FIRST NON-ZERO EIGENVALUE OF THE LIOUVILLIAN

U(1) THERMALIZATION



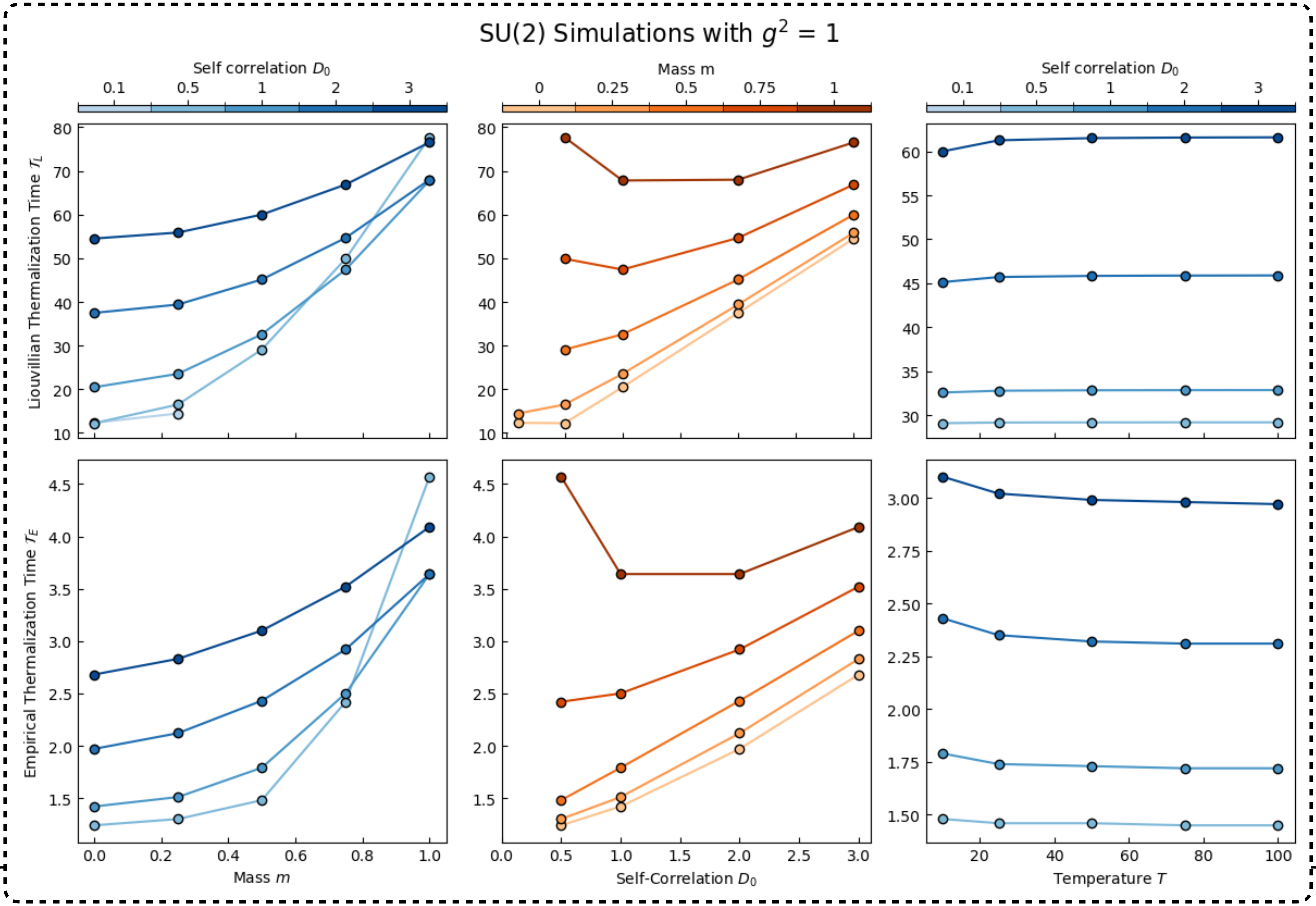
U(1)

$(D_0 \sim 1)$

$$[T\uparrow, D_0\Uparrow] \rightarrow \mathcal{T}_E\uparrow$$

Angelides et al., JHEP 04, 195 (2025)

SU2 THERMALIZATION



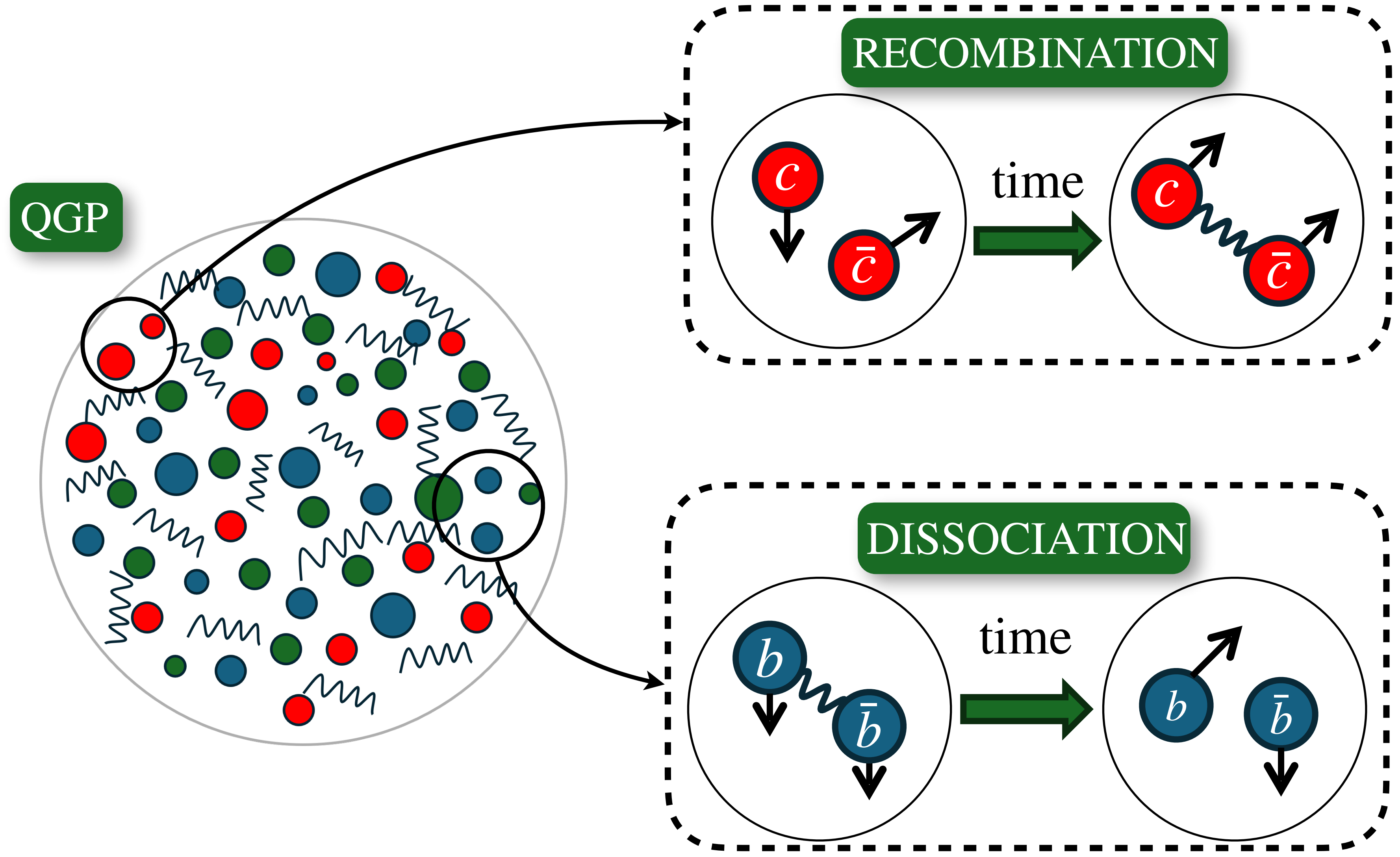
SU(2)

$(D_0 \ll 1)$

$$[T\uparrow, D_0\uparrow] \rightarrow \mathcal{T}_E\downarrow$$

POTENTIAL NON-RELATIVISTIC QCD

Brambilla et al., arXiv:2508.11743 (2025)

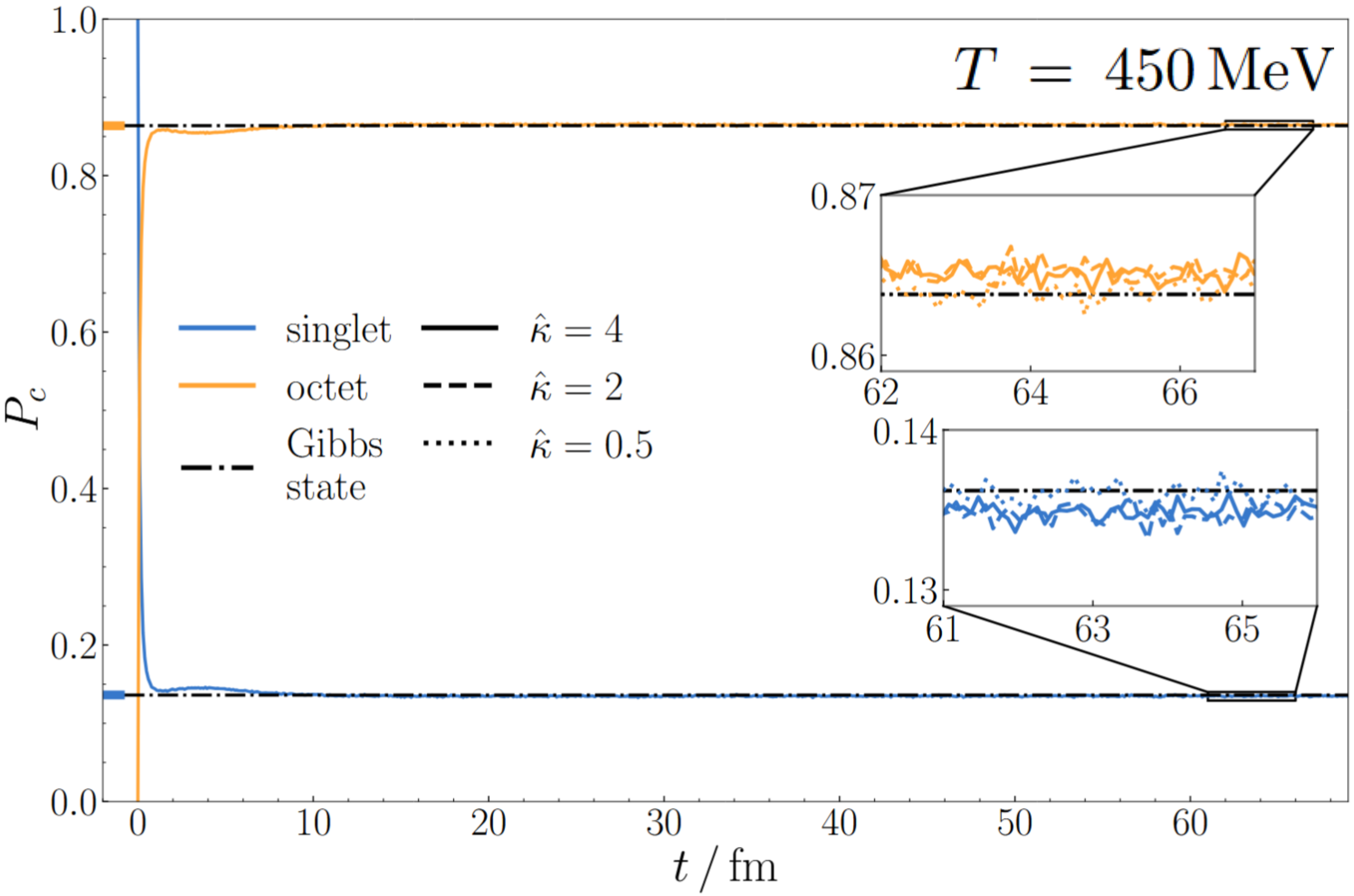


🟧 octet P_{octet} = Free quark

🟦 singlet $P_{singlet}$ = Quarkonia

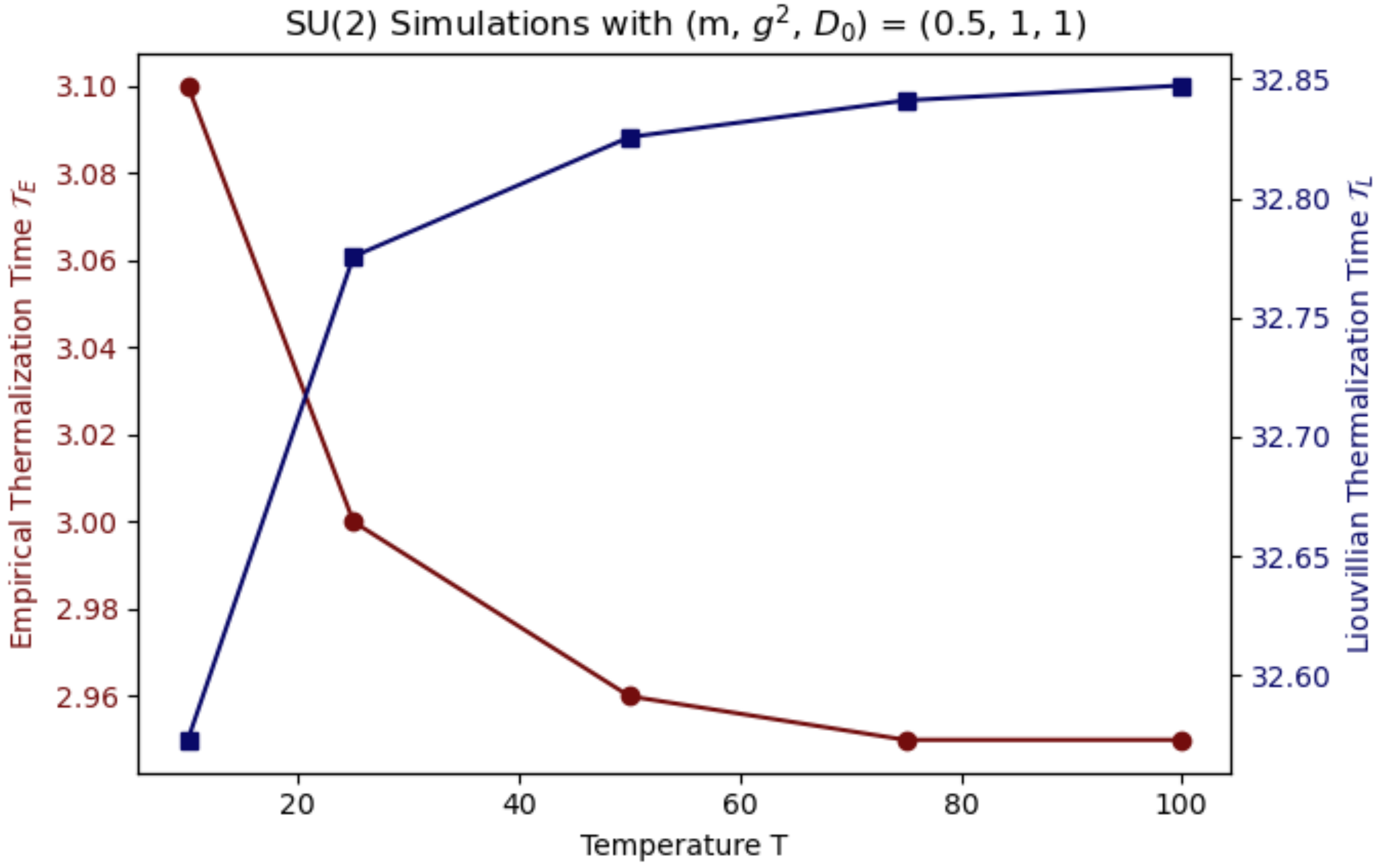
M

How? $\hat{\rho}_{ss}$ vs. $\hat{\rho}_{Gibbs} = \frac{1}{Z} e^{-\beta \hat{H}_S}$



TEMPERATURE DEPENDENT CONSTANT CORRELATOR $D_{n,m} = \hat{\kappa} T^3$

DISCREPANCIES



THERMALIZATION TIME DEPENDS:

1. ON DEFINITION (EMPIRICAL VS LIOUVILLIAN)
2. ON PARAMETER REGIMES (m, g, T, D_0)
3. ON THE LATTICE GAUGE THEORY

U(1) $(D_0 \sim 1)$

$$[T\uparrow, D_0\uparrow] \rightarrow \mathcal{T}_E\uparrow$$

Angelides et al., JHEP 04, 195 (2025)

SU(2) $(D_0 \ll 1)$

$$[T\uparrow, D_0\uparrow] \rightarrow \mathcal{T}_E\downarrow$$

PNRQCD $(D_0 \propto T)$

$$[T\uparrow, D_0\uparrow] \rightarrow \mathcal{T}_E\downarrow$$

Brambilla et al., arXiv:2508.11743 (2025)

QUESTION: WHICH BEHAVIOUR IS EXPECTED IN QGP PHYSICS?

SUMMARY

EMPIRICAL THERMALIZATION TIME

$\mathscr{T}_{\mathrm{E}} =$ TIME IT TAKES FOR SEF IN THE CENTRAL GAUGE LINK TO DECREASE BY A GIVEN%

PRO:

- EXPERIMENTALLY FRIENDLY
- TENSOR NETWORK FRIENDLY

CONS:

- MANY POSSIBLE ARBITRARY DEFINITIONS
- OBSERVABLE DEPENDENT
- ILL DEFINED IN CERTAIN PARAMETER REGIONS

LIOUVILLIAN THERMALIZATION TIME

$$\mathscr{T}_L = \frac{1}{|\mathrm{Re}(\lambda_1)|}$$

INVERSE OF THE REAL PART OF THE FIRST NON-ZERO EIGENVALUE OF THE LIOUVILLIAN

PRO:

- OBJECTIVE/UNIVERSAL PROBE
- WELL BEHAVED IN ALL PARAMETER SPACE
- INDEPENDENT TO THE INITIAL STATE

CONS:

- DIFFICULT WITH TENSOR NETWORK
- DIFFICULT WITH EXPERIMENTS
- SUBJECT TO ANOMALIES

QUESTION: WHICH ONE IS MORE RELEVANT TO QUARKONIA IN QGP?

ANOMALOUS THERMALIZATION TIME

LIOUVILLIAN DIAGONALIZATION

$\hat{r}_k$ = Right Eigenvectors

$\hat{\ell}_k$ = Left Eigenvectors

λ_k = Eigenvalues

$$\hat{\rho}(t) = \hat{\rho}_{ss} + \sum_k e^{\lambda_k t} C(\hat{\ell}^{\dagger}_k)\hat{r}_k$$

$$= \hat{\rho}_{ss} + e^{\lambda_1 t} C(\hat{\ell}_1)\hat{r}_1 + \mathcal{O}(e^{\lambda_2 t})$$

LIOUVILLIAN THERMALIZATION TIME IS RELIABLE

$$\mathcal{T}_L = \frac{1}{|\mathrm{Re}(\lambda_1)|}$$

$$\text{iff } \lambda_1 \gg \lambda_{k>1} \forall k$$

ANOMALIES

QUANTUM MPEMBA EFFECT

THE FIRST C_k ARE SMALL

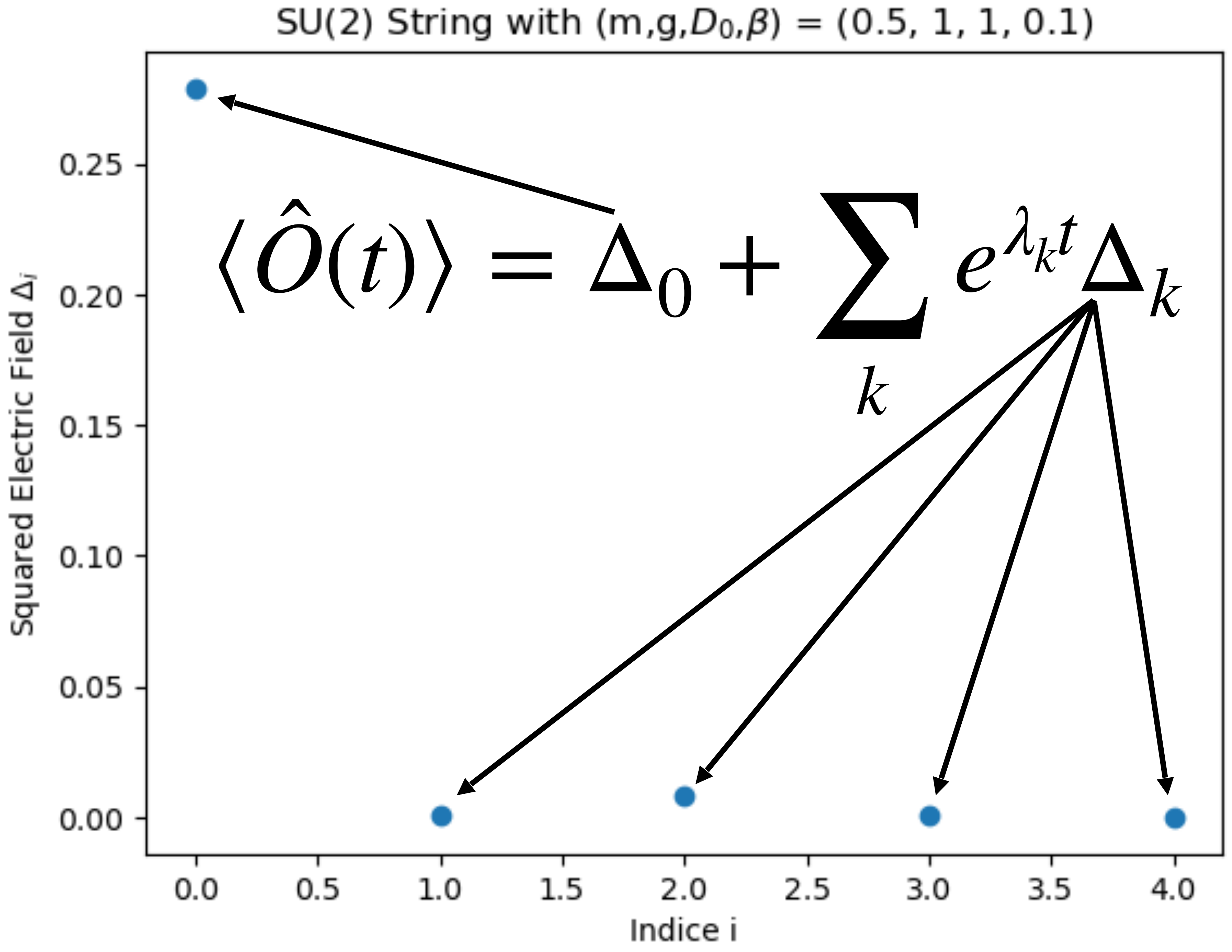
SUPER-EXPONENTIAL DECAY MODE

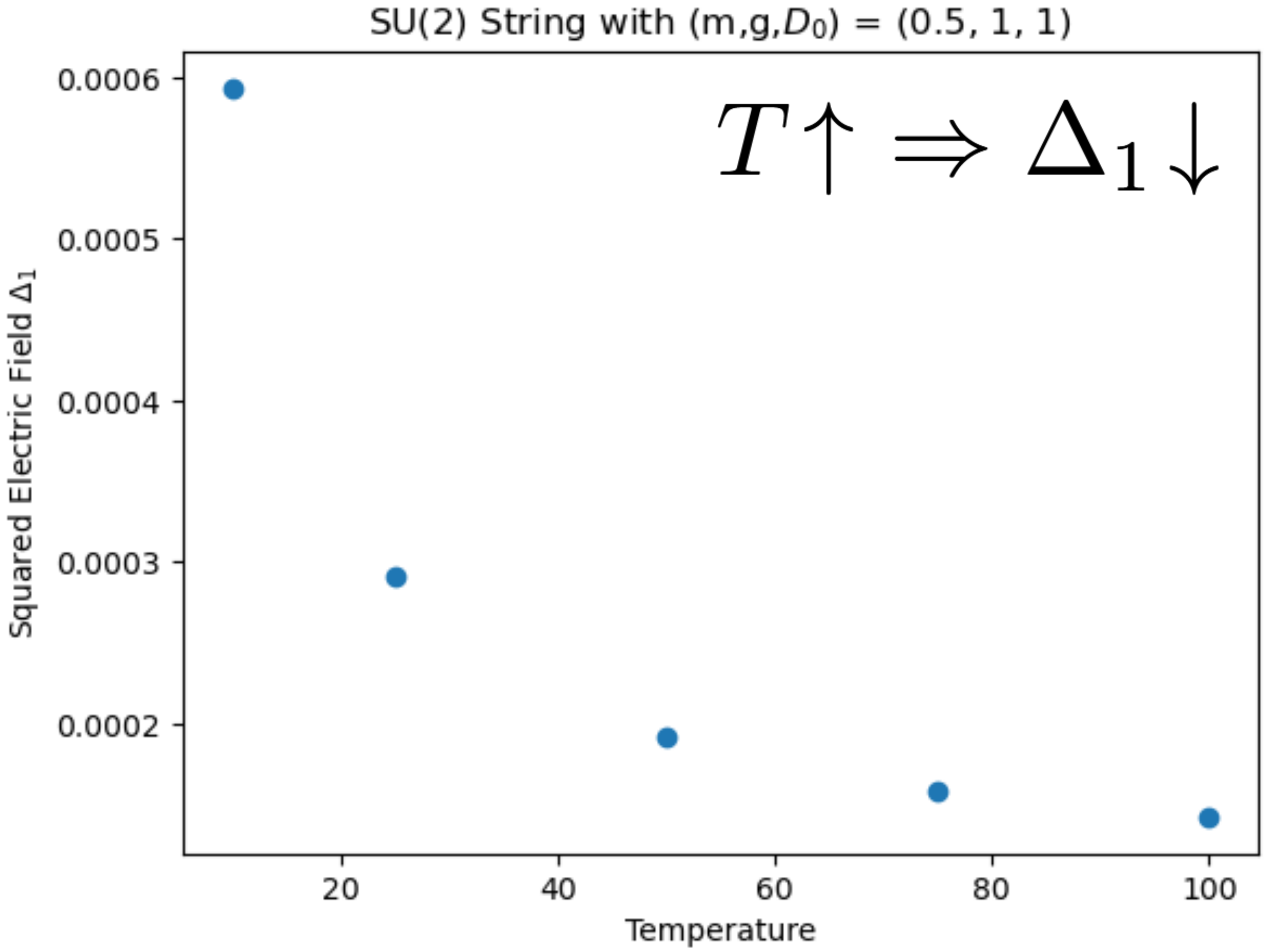
MANY LARGE C_k ARRIVES LATER

EFFECTS ON LOCAL OBSERVABLES

THESE ANOMALIES CAN BE OBSERVABLE DEPENDENT

$$\langle \hat{O}(t) \rangle = \Delta_0 + \sum_k e^{\lambda_k t}\, \mathrm{Tr}(\hat{O}^\dagger \hat{r}_k) C_k = \Delta_0 + \sum_k e^{\lambda_k t} \Delta_k$$





REAL-TIME DYNAMICS OF ENTROPY

VON NEUMANN ENTROPY

$$S_{v\mathrm{N}} = -\,\mathrm{tr}(\rho \log(\rho))$$

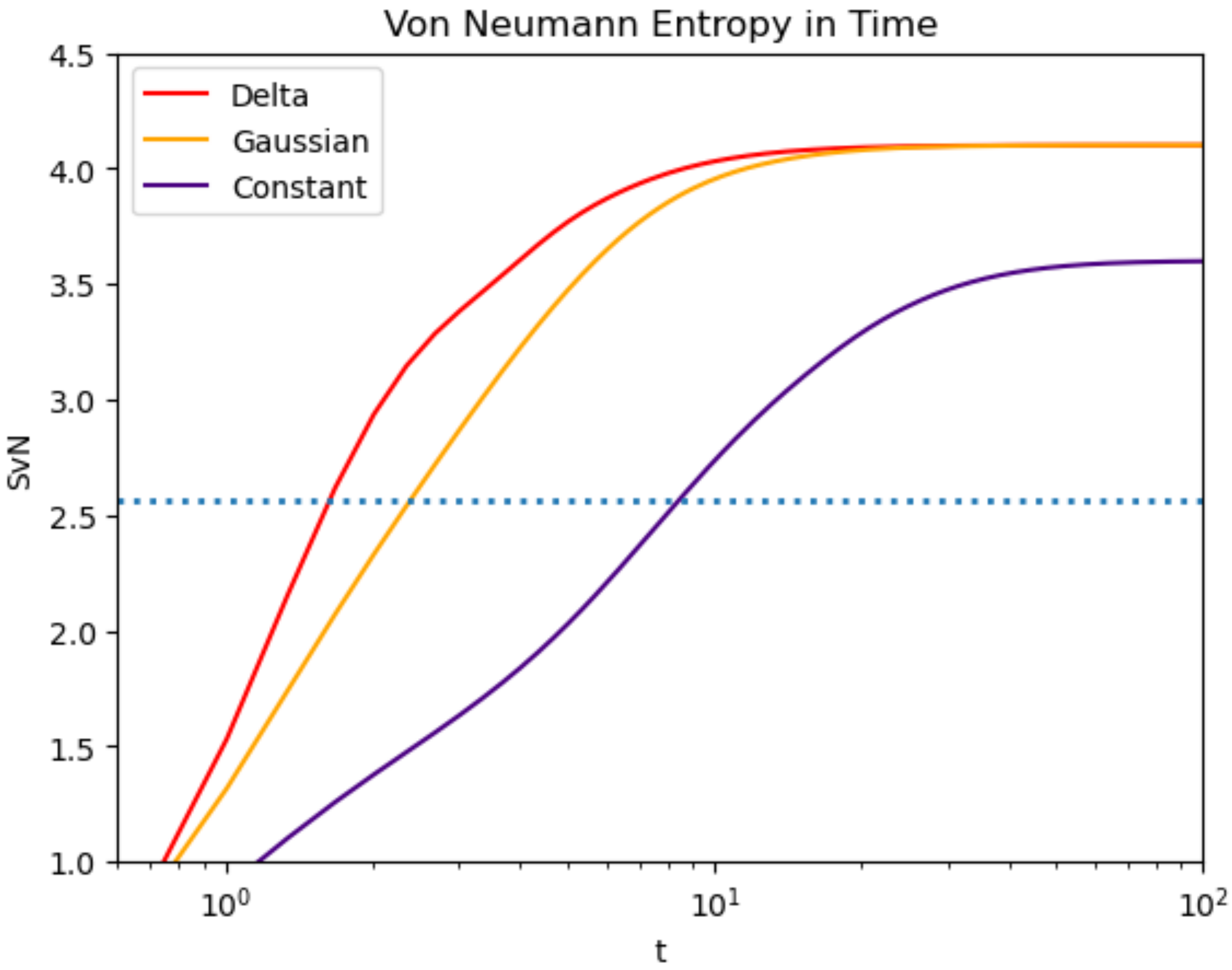
IS BOUNDED BY:

$$0 \leq S_{v\mathrm{N}} \leq \log d$$

IN THE LIMIT OF INFINITE TEMPERATURE, THE ENTROPY GOES TO

$$S_{v\mathrm{N}} \to \log d$$

IN THE STEADY STATE.

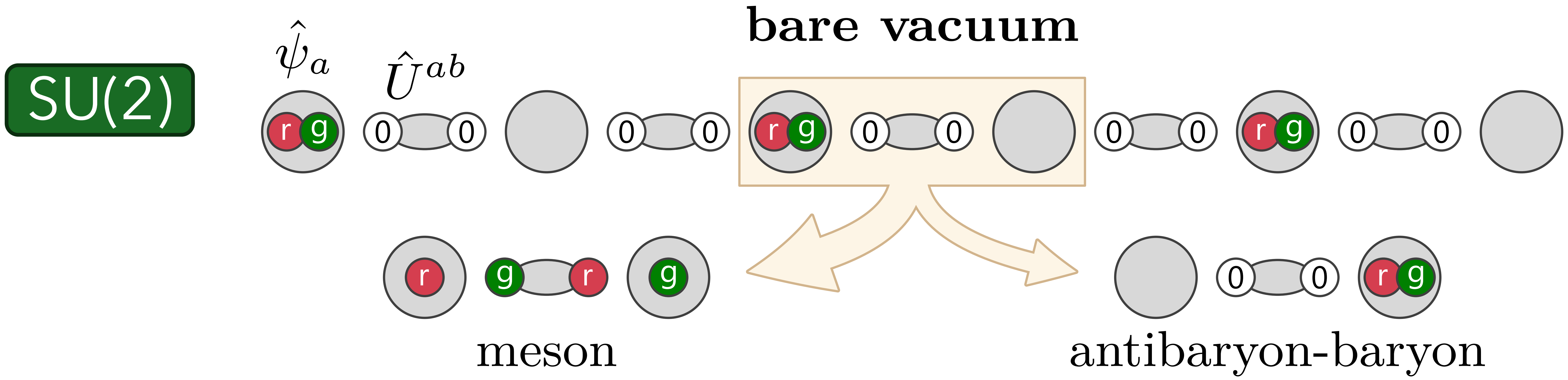


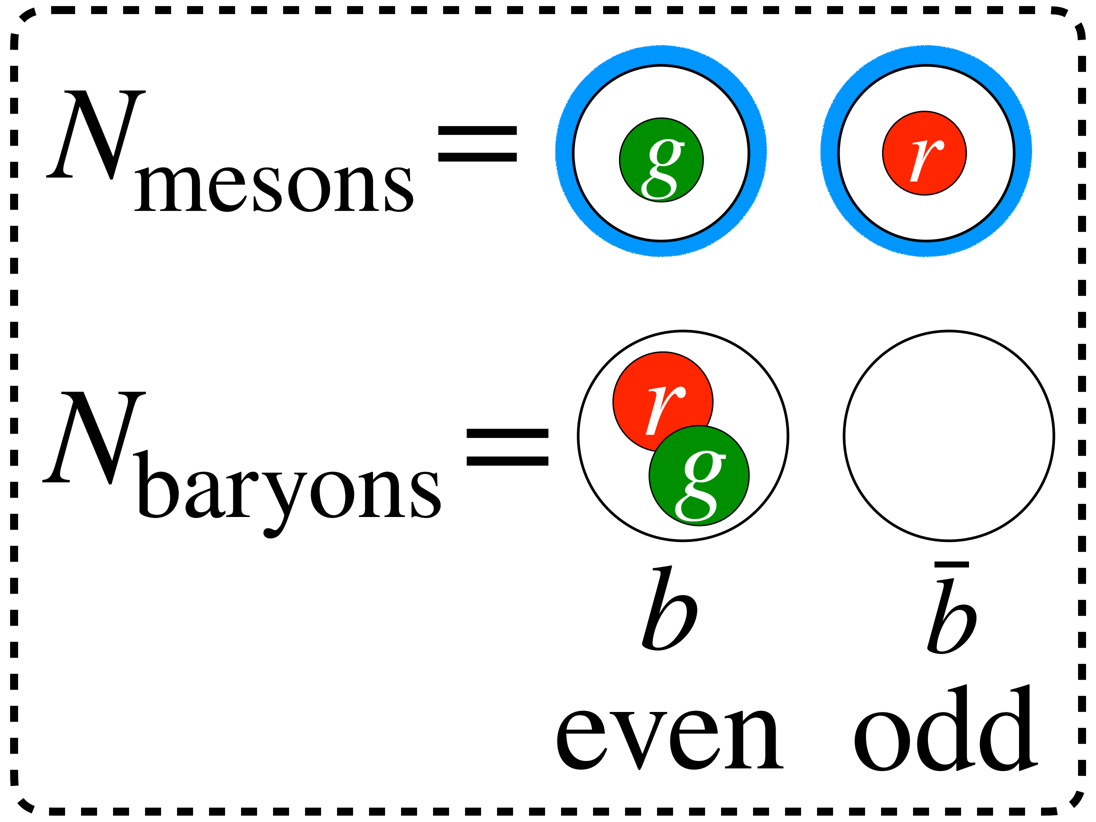
Lee et al., Phys. Rev. D 108, 094518 (2023)

REAL-TIME DYNAMICS OF ENTROPY

ENTROPY GROWS FAST WITH TEMPERATURE!

MATTER DENSITY IMBALANCE





How do different environments change the final composition of matter density?

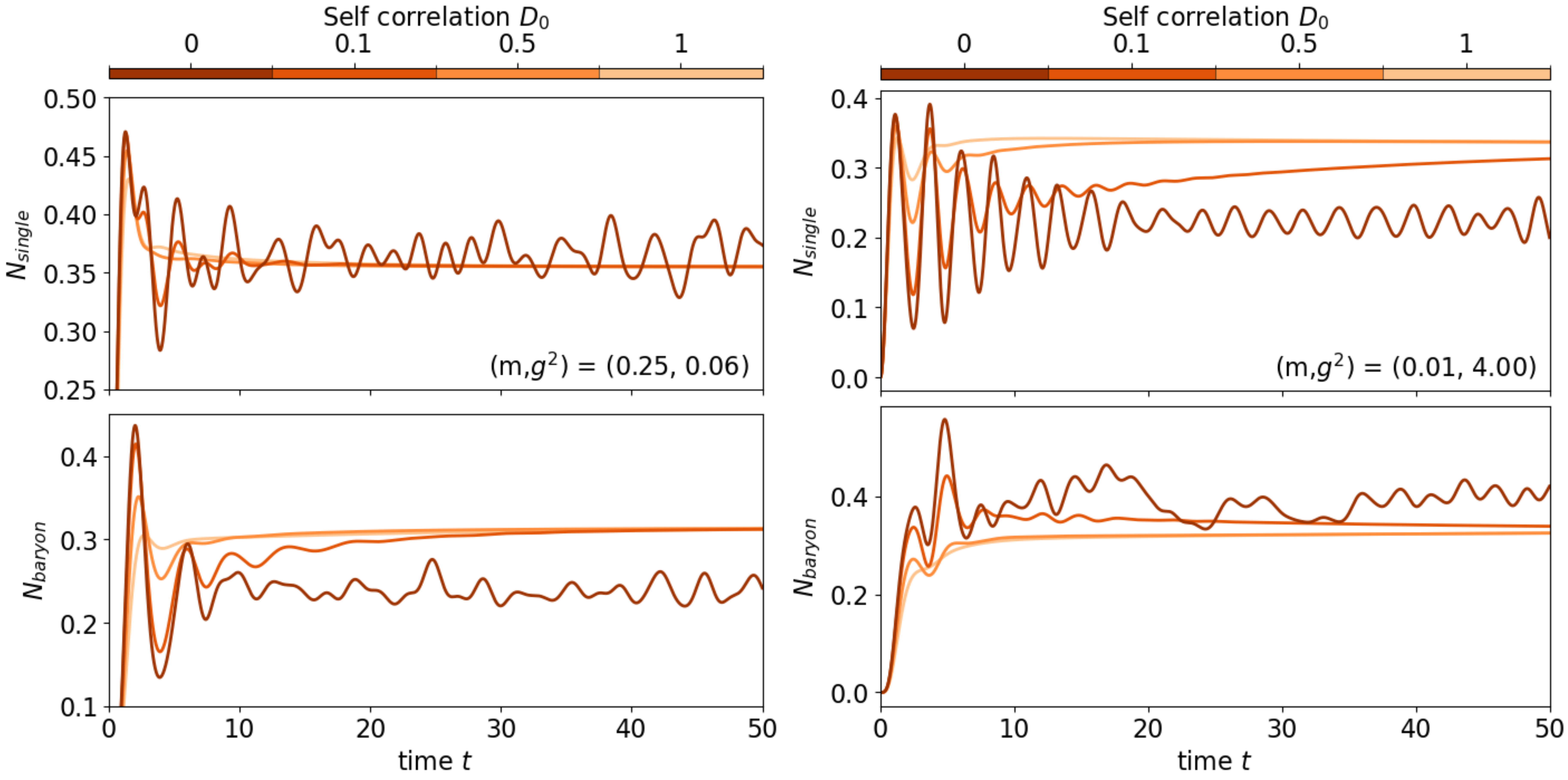
MATTER PROPORTION $\mathscr{MP} = \dfrac{N_{\text{mesons}}}{N_{\text{baryons}}}$

$$\mathscr{MPD} = \underset{\substack{\downarrow \\ \langle \mathcal{O} \rangle \,=\, \mathrm{Tr}(\mathcal{O}\rho_{ss})}}{\mathscr{MP}_{\text{open}}} - \underset{\substack{\downarrow \\ \mathrm{Tr}(\mathcal{O}\rho_{Gibbs})}}{\mathscr{MP}_{\text{closed}}}$$

$$\mathscr{MPD} \begin{array}{l} = 0 \Rightarrow \text{No change} \\ > 0 \Rightarrow \text{Environment induces mesons} \\ < 0 \Rightarrow \text{Environment induces baryons} \end{array}$$

MATTER DENSITY IMBALANCE

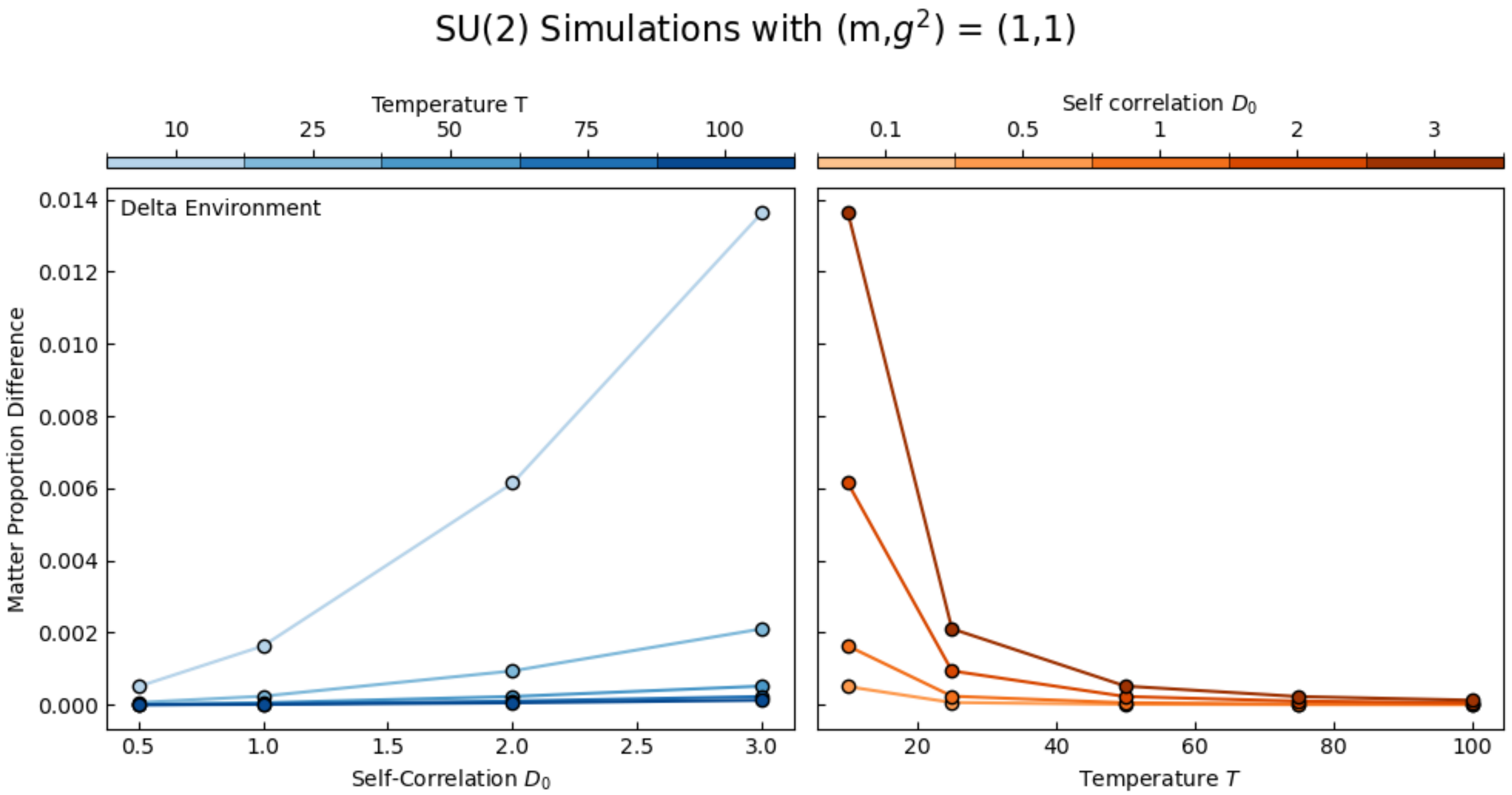
Delta Correlator

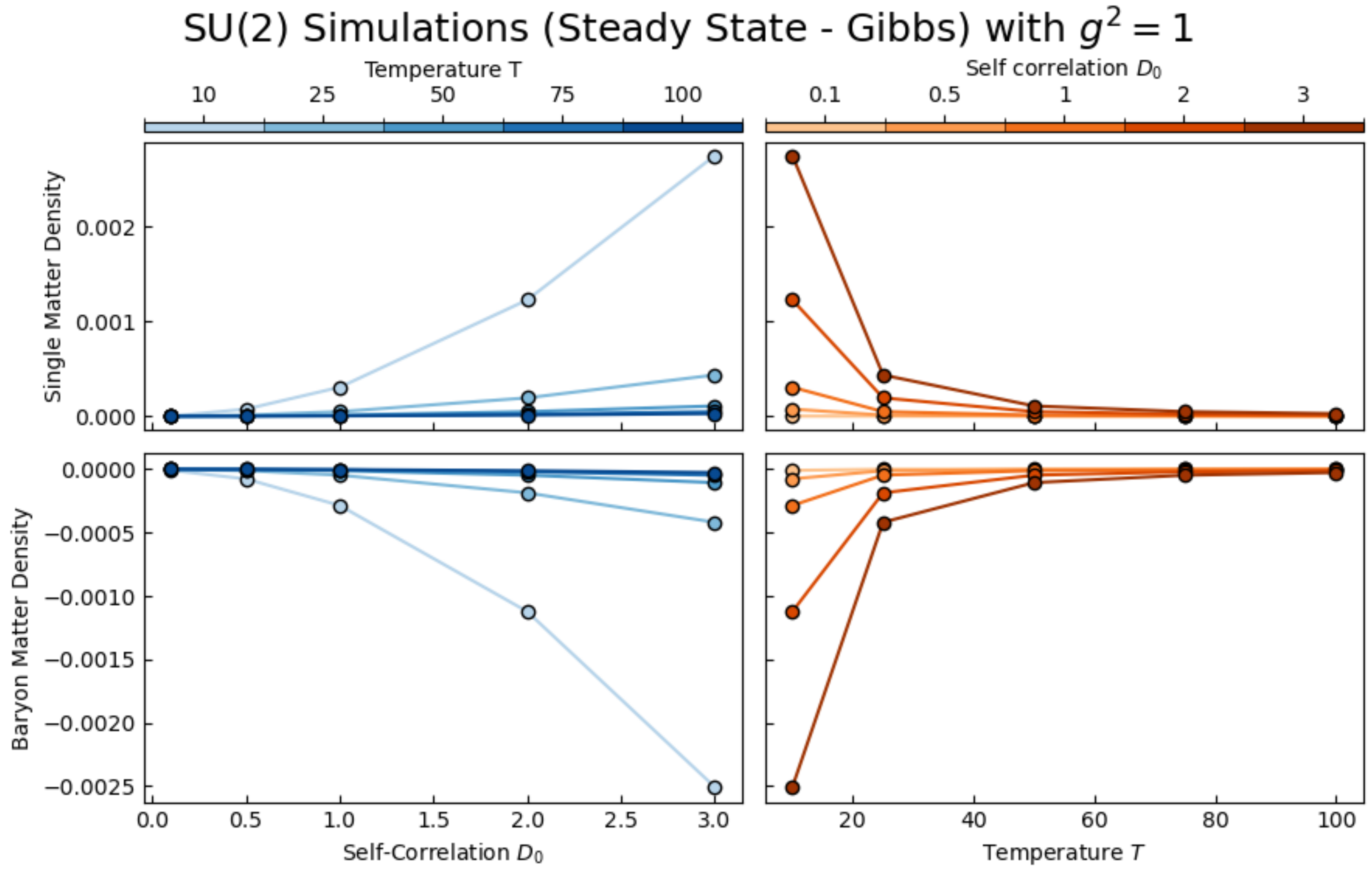


Results changes with Hamiltonian parameters

$$m, g^2$$

MATTER COMPOSITION ANALYSIS





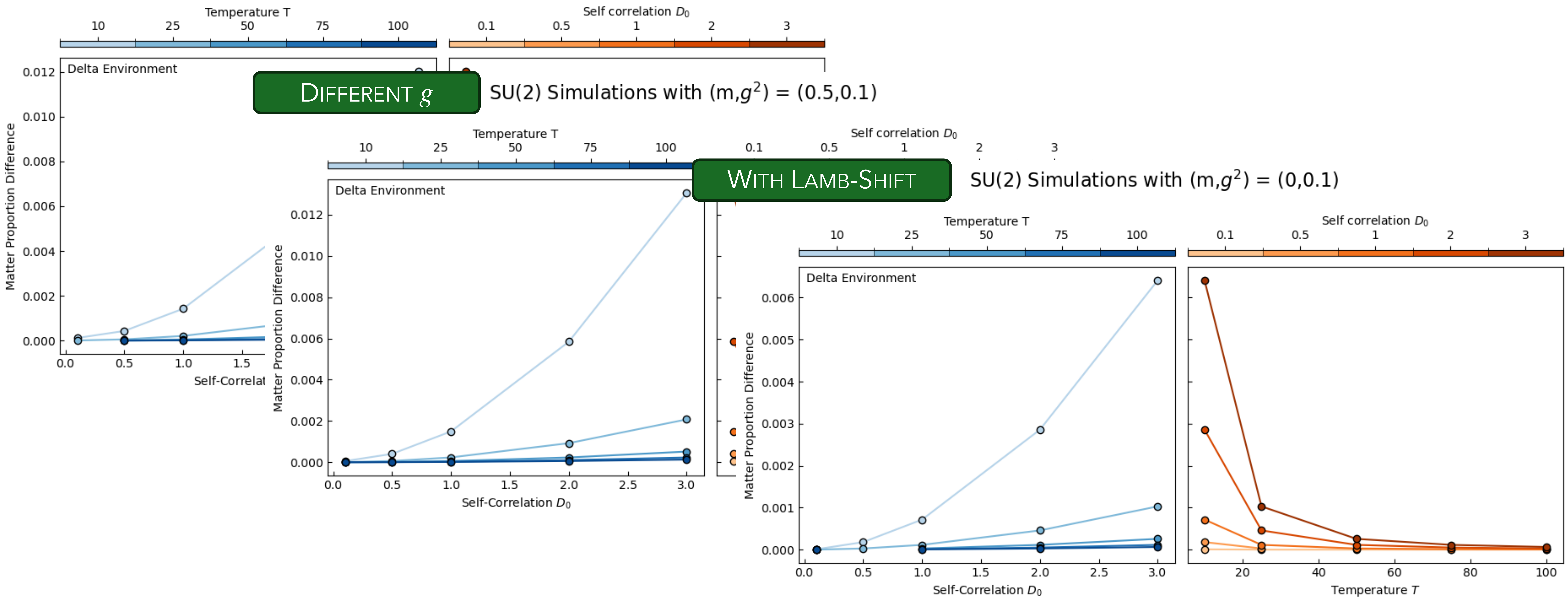
CAN WE FIND A REGION WITH MPD $<$ 0?

MATTER COMPOSITION ANALYSIS

FINITE DENSITY SU(2) Simulations with (m,g^2) = (1,1)

DIFFERENT g SU(2) Simulations with (m,g^2) = (0.5,0.1)

WITH LAMB-SHIFT SU(2) Simulations with (m,g^2) = (0,0.1)



SUMMARY:

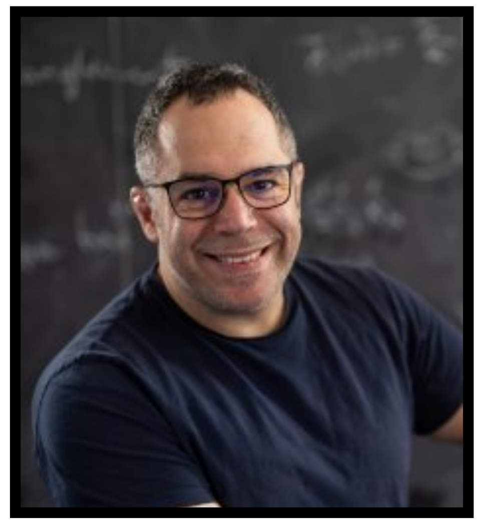
- HAMILTONIAN LATTICE GAUGE THEORIES
- OPEN QUANTUM SYSTEMS THEORY
- TENSOR NETWORK SIMULATIONS
- THERMALIZATION TIME
- ENTROPY & LOCAL OBSERVABLES

THANKS!

Mainz Institute for Theoretical Physics


E. PARRA


S. KUHN


JAD HALIMEH


G. MAGNIFICO

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