Strongly coupled dynamics and their quantum origin

Adrien Florio

Color Meets Flavor Symposium, 15.07.26

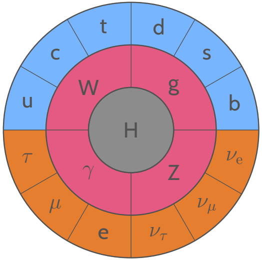
CRC-TR 211
Strong-interaction matter under extreme conditions

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

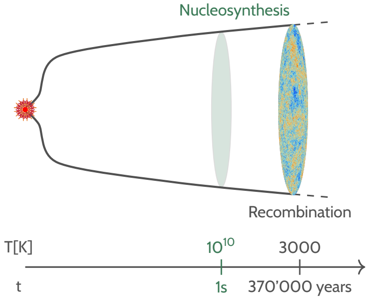
UNIVERSITÄT BIELEFELD
Fakultät für Physik

Standard model of. . .

Particle physics



Cosmology



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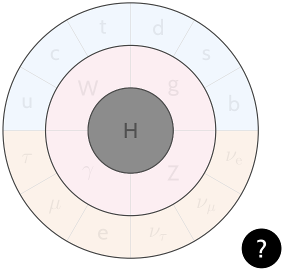

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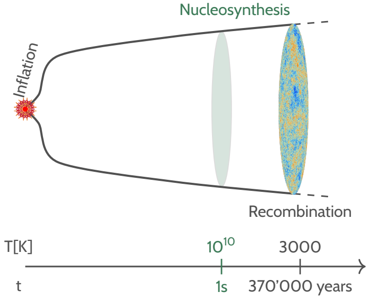

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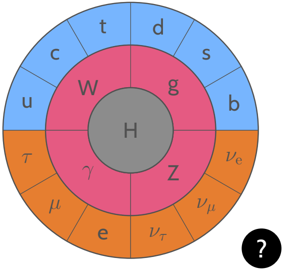

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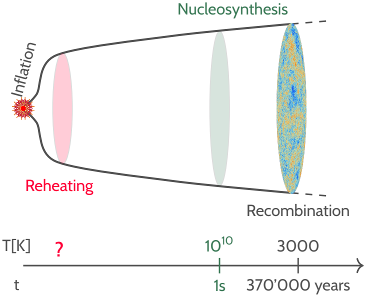

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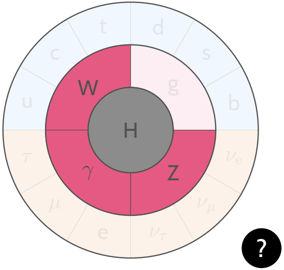

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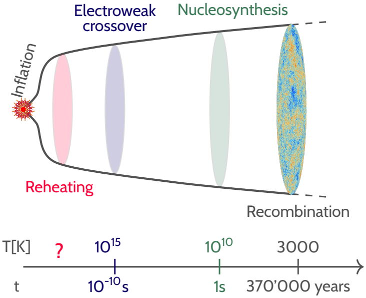

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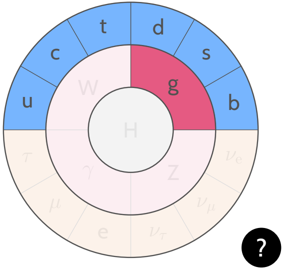

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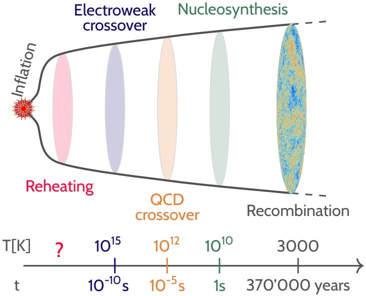

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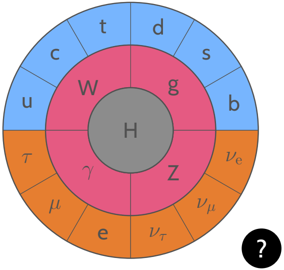

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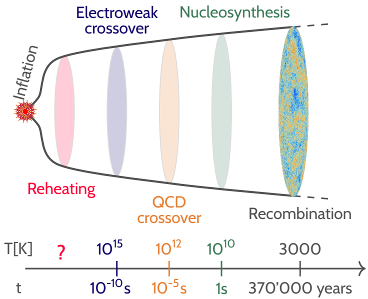

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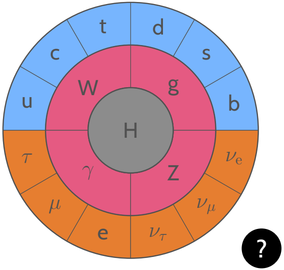

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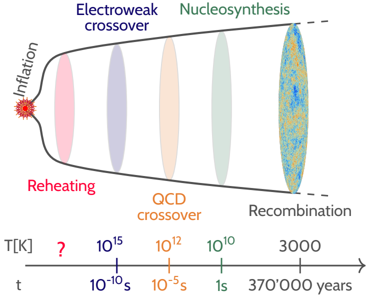


Out-of-equilibrium dynamics is key

Classical dynamics

Quantum dynamics

Quantum information

Classical dynamics

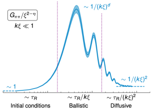
Quantum dynamics

Quantum information

- Critical dynamics of QCD
  [**AF**, Grossi, Mazeliauksas, Teaney, Soloviev, PRL 25]

QCD @ T_c
$\sim$
$O(4)$ ferromagnet

dynamics $\longrightarrow$



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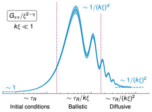


Chiral/axial dynamics

Chiral/axial dynamics

- Chiral/axial charge leads to anomalous transport

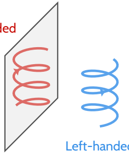
- Anomalous transport changes IR dynamics

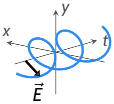
  $\updownarrow$

  Chiral hydro

- Axion-like dynamics and interaction with non-Abelian topology

Helixes

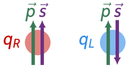




Circularly polarized light

$$h_B \propto \overrightarrow{A} \cdot \overrightarrow{B}$$

Massless fermions



$$h_F \propto \frac{\vec{p} \cdot \vec{s}}{|\vec{p}\,|} = \quad +1 \quad -1$$

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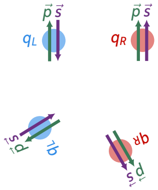

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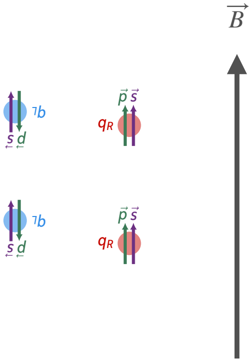

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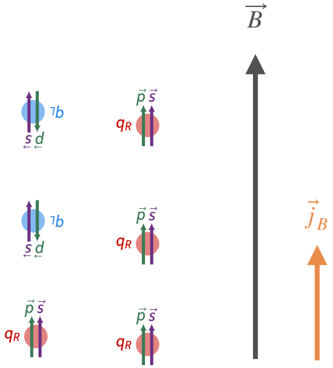

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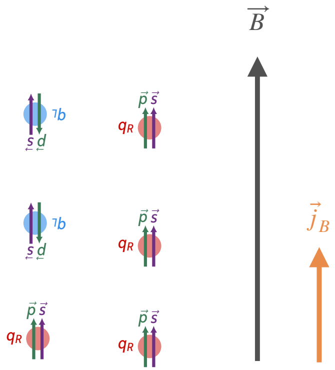

Anomalous transport: $\vec{j}_B \propto \sigma_5 \vec{B}$ not $\vec{j}_B \propto \sigma \vec{E}$

"Chiral magnetic effect"

Chiral/axial dynamics

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$\updownarrow$

Chiral hydro

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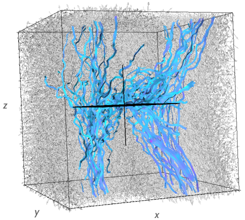
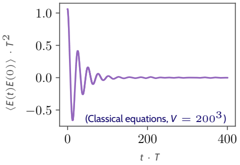
Generate large scale magnetic fields



First observation from microscopic simulations (3D classical dynamics)
[Figueroa, **AF**, Shaposhnikov, JHEP 19]



Consistent hydrodynamics based on magnetic flux conservation

Electric response and first principle extraction of resistivity
[Das, **AF**, Iqbal, Poovutikul, SciPost Phys. 24]

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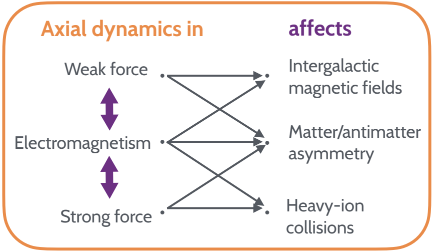

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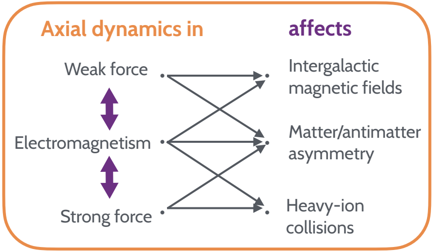

Combined non-linear Abelian and non-Abelian dynamics?

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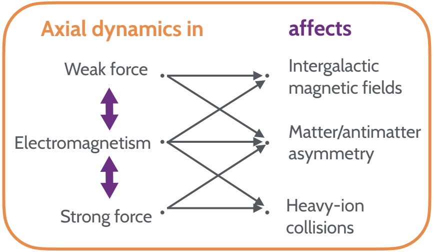

Combined non-linear Abelian and non-Abelian dynamics?

Effective coupling: $h_F \cdot \mathrm{Tr}\left(\vec{E} \cdot \vec{B}\right)$

Chiral imbalances $\longleftrightarrow$ **Axion-like particles**

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$\updownarrow$

Chiral hydro

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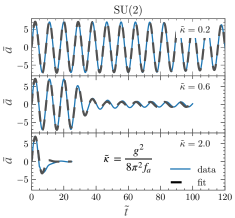
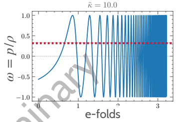


First fully dynamical non-Abelian axion dynamics

[Berghaus, **AF**, Laine, Sattler, JHEP 26]

SU(2) axion preheating dynamics

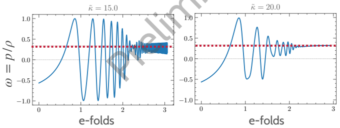
[Berghaus, **AF**, Laine, Sattler, wip]



$\omega = 1/3$

$\wr$

radiation



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https://github.com/cosmolattice/cosmolattice

CosmoLattice

New early universe simulations standard

REPORT ON PROGRESS

Present and future of CosmoLattice

Daniel G Figueroa[1,3], Adrien Florio[2,3] and Francisco Torrenti[1,3]

~100 papers using it

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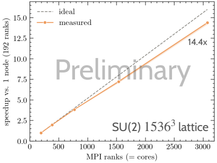
Coming this month!



Strong scaling speed-up

[AF, Sattler, 2607.????]

https://github.com/cosmolattice/templat

TempLat

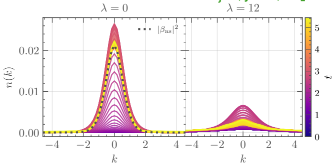
High performance generalist lattice field theory framework

Classical dynamics

Quantum dynamics

Quantum information

- Particle creation in expanding metric: 1+1D $\lambda\phi^4$ [Budd, **AF**, Frenklakh, Mukherjee, JHEP, 26]



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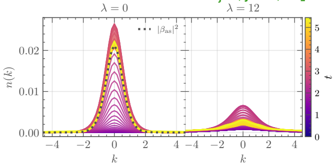


Thermalization

Thermalization

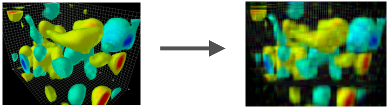
- One dimensional model can be (mostly) solved with tensor networks

- First principle simulations of the *quantum dynamics* of string breaking

- Effective thermalization from unitary time evolution through entanglement

Matrix Product State: physically motivated, systematically improvable compression for quantum states

Singular value decomposition (SVD)



Schwinger model: electro~~magnetism~~ in 1+1 dimensions

Electric field — Vector potential

$$H = \int \mathrm{d}x \left[\frac{1}{2} E^2 + \bar{\psi} \left(-i\gamma^1 \partial_1 + g A^1 \gamma_1 + m \right) \psi \right]$$

Fermion

Confines! $\partial_x E = \delta(x) \leftrightarrow E(x) = \Theta(x)$

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$$En. \sim m + m + E\ell_1$$

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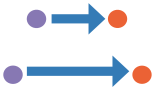

$$En. \sim m + m + E\ell_1$$

$$En. \sim m + m + E\ell_2$$

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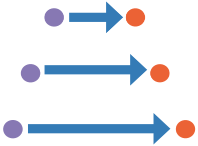

$$En. \sim m + m + E\ell_1$$

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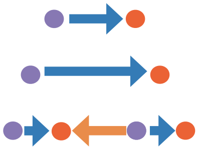

$En. \sim m + m + E\ell_1$

$En. \sim m + m + E\ell_2$

$En. \sim \cancel{m + m + E\ell_3}$

$\downarrow$

$m + m + m + m$

Screen field by creating particles!

Goal: study its quantum dynamics

Thermalization

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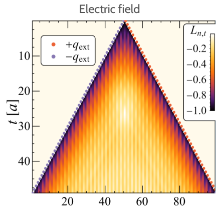
$$\min H \to |\psi_0\rangle$$

quench

$$|\psi(t)\rangle = e^{i\int \mathrm{d}t H(t)}|\psi_0\rangle$$



[**AF**, Frenklakh, et al., PRL 23] [**AF**, Frenklakh, et al., PRD 24]
Dept. of Energy highlight [**AF**, Frenklakh, et al., PRD 25]

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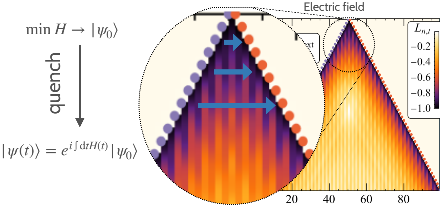

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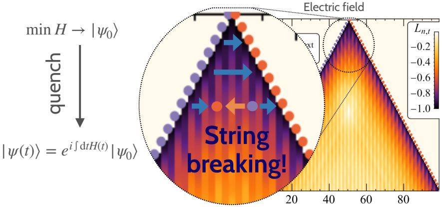

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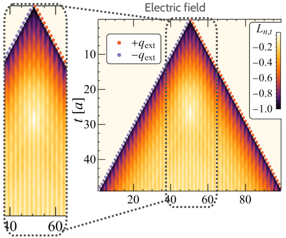
Effective T_{eff} ?



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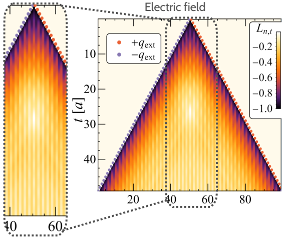

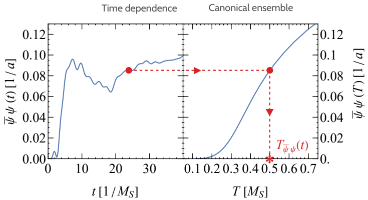

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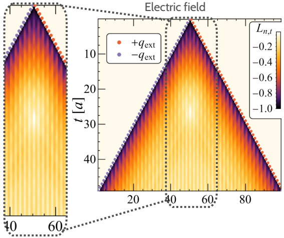

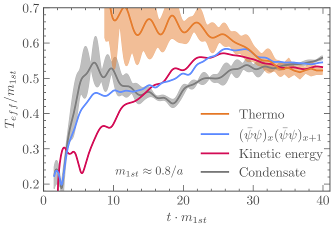

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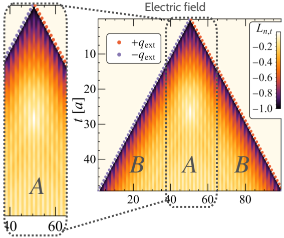
$$T = \frac{p+\epsilon}{s} \rightarrow \frac{p+\epsilon}{s_{EE}}$$

$$s_{EE} = -\,\mathrm{Tr}\left(\rho_A \log(\rho_A)\right)$$

$$\rho_A = \mathrm{Tr}_B\left(|\psi\rangle\langle\psi|\right)$$



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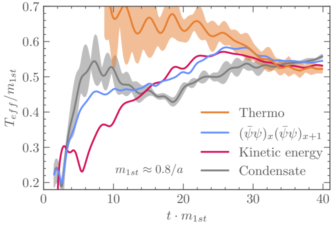

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1+1 dimensional models

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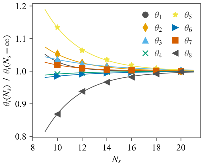
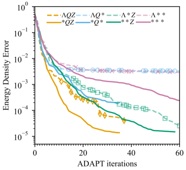
Quantum simulations and algorithms development

SC2-ADAPT-VQE: Co-designed ground state preparation for Schwinger model



Smooth infinite volume limit

[Gustafson, Sherbert, **AF**, et al., PRA 25]



Symmetry restricted pools of operators

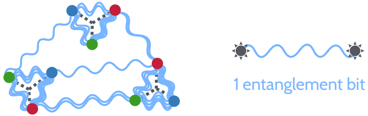
[Shirali, Sherbert, Chen, **AF**, et al., 2510.03083]

Classical dynamics

Quantum dynamics

Quantum information

- Multipartite entanglement and confinement [AF, PRD 24]



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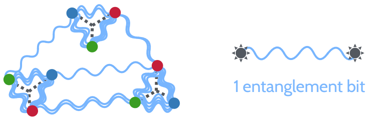
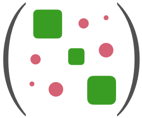


Entanglement asymmetry

Entanglement asymmetry

- Quantum correlations in a state probe symmetry phases
- Potential to be more sensitive to phase transition than local order parameters
- Outlook: compute it in higher dimensions

Symmetric Asymmetric

$\rho =$ 

$$[\rho, \hat{Q}] \begin{cases} = 0 \\ \neq 0 \end{cases}$$

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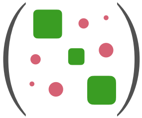
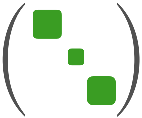
$\rho =$  $[\rho, \hat{Q}] \begin{cases} = 0 \\ \neq 0 \end{cases}$

Idea: measure how much ●

$\rho_{sym} =$  $\propto \sum_q \mathbb{P}_q \rho \mathbb{P}_q$

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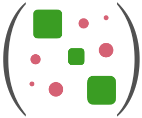
$\rho =$  $[\rho, \hat{Q}] \begin{cases} = 0 \\ \neq 0 \end{cases}$

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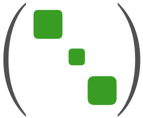
$\rho_{sym} =$  $\propto \sum_q \mathbb{P}_q \rho \mathbb{P}_q$

Entanglement asymmetry:

$$\Delta S = S_\rho - S_{\rho_{sym}}$$

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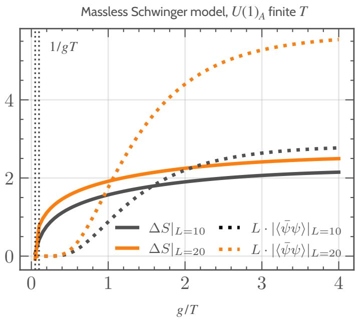

[**AF**, Murciano, PRD 26]

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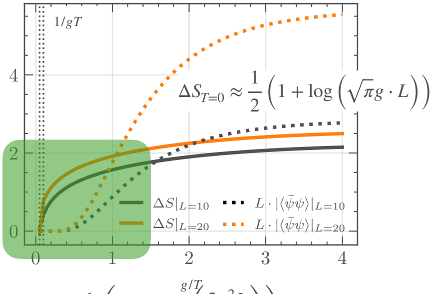
Massless Schwinger model, $U(1)_A$ finite T



$$\Delta S \approx \frac{1}{2}\left(-1 + \log\left(\frac{2g^2 L}{T}\right)\right)$$

$1/(gL) < g/T \ll gL$

Parametric enhancement over local order parameter!

[**AF**, Murciano, PRD 26]

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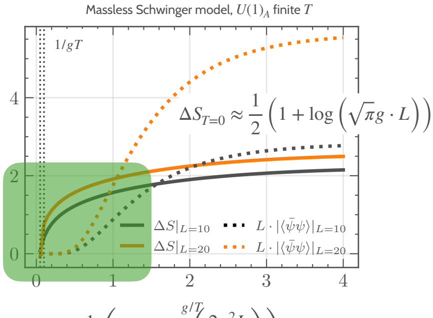

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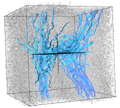
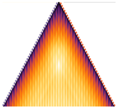
Take-home

Full non-linear non-Abelian axion dynamics

Classical dynamics



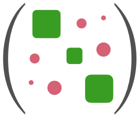


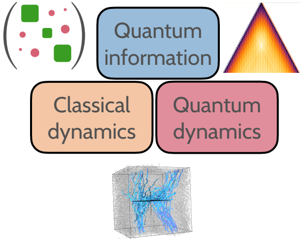
Quantum dynamics

Thermalization from first principles

Entanglement asymmetry as an efficient order parameter

Quantum information





V. Krishnan F. Brökemeier

F. Sattler M. Memon

Perfect time to further explore strongly coupled dynamics and their quantum origin

Thank you!