ECT* workshop, Trento, June 11th 2019

Meson formation in strongly correlated quantum matter
— A high-energy perspective —

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Bosons Munich: C. Schweizer, M. Berngruber, I. Bloch, M. Aidelsburger

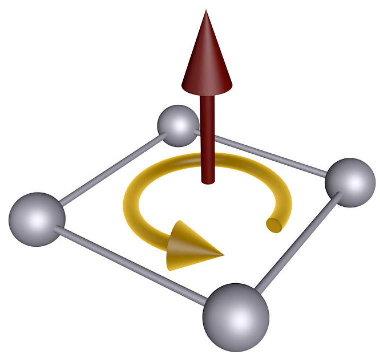
https://sites.google.com//site/quantmanybody/

Motivation

Strongly correlated states of matter

$$\frac{1}{2m}\hat{\Psi}^\dagger \left(i\nabla + \mathcal{A}\right)^2 \hat{\Psi}$$

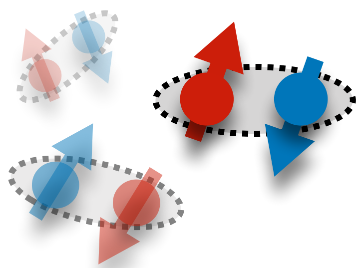
Fractional Quantum Hall effect



$$\frac{1}{4\pi} a_\mu^T K \partial_\nu a_\lambda \epsilon^{\mu\nu\lambda}$$

$$J\ \hat{\mathbf{S}}_i \cdot \hat{\mathbf{S}}_j$$

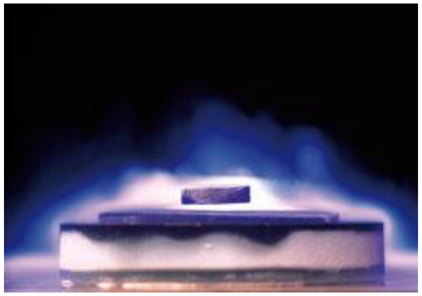
Quantum spin liquids



$$\hat{f}^\dagger_{i,\sigma} \hat{f}^\dagger_{j,\tau} \hat{f}_{i,\tau} \hat{f}_{j,\sigma}$$

$$t \hat{c}^\dagger_{i,\sigma} \hat{c}_{j,\sigma} + U \hat{n}_{i,\uparrow} \hat{n}_{i,\downarrow}$$

High-T_c superconductors



?

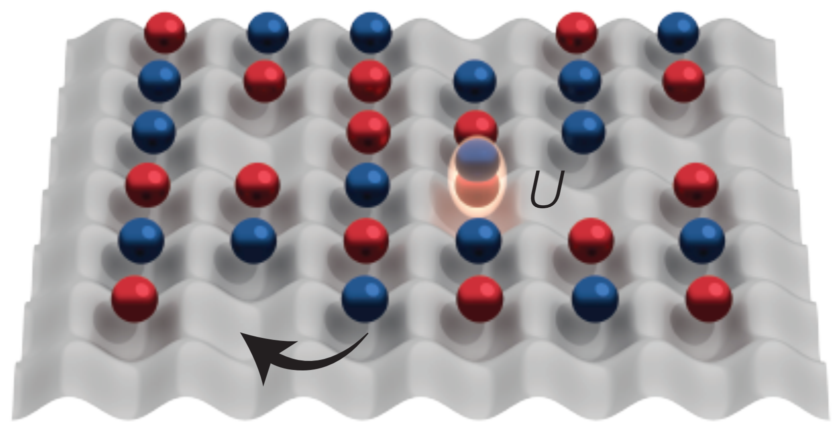
effective gauge theories

The Fermi-Hubbard & *t-J* models

The Fermi-Hubbard model:

$$\hat{\mathcal{H}}_{\mathrm{FH}} = -t \sum_{\langle \mathbf{i},\mathbf{j}\rangle,\sigma} (\hat{c}^\dagger_{\mathbf{i},\sigma}\hat{c}_{\mathbf{j},\sigma} + \mathrm{h.c.}) + U \sum_{\mathbf{j}} \hat{n}_{\mathbf{j},\uparrow}\hat{n}_{\mathbf{j},\downarrow}$$

from: *Chiu et al., arXiv:1810.03584*

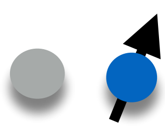


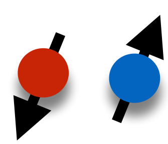
- *Large-U limit: t-J model*

no double-occupancy!

$$t \gg J$$

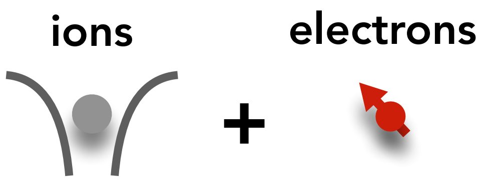
$$\boxed{\hat{\mathcal{H}}_{t-J} = -t\,\hat{\mathcal{P}}\Big[\sum_{\langle \mathbf{i},\mathbf{j}\rangle,\sigma} \hat{c}^\dagger_{\mathbf{i},\sigma}\hat{c}_{\mathbf{j},\sigma} + \mathrm{h.c.}\Big]\hat{\mathcal{P}} + J\sum_{\langle \mathbf{i},\mathbf{j}\rangle}\Big(\hat{\mathbf{S}}_{\mathbf{i}}\cdot\hat{\mathbf{S}}_{\mathbf{j}} - \frac{1}{4}\hat{n}_{\mathbf{i}}\hat{n}_{\mathbf{j}}\Big)}$$





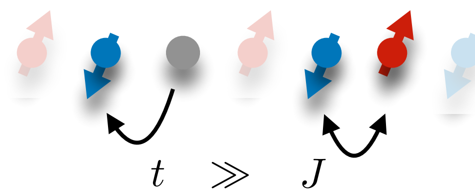
Motivation

Micro-constituents



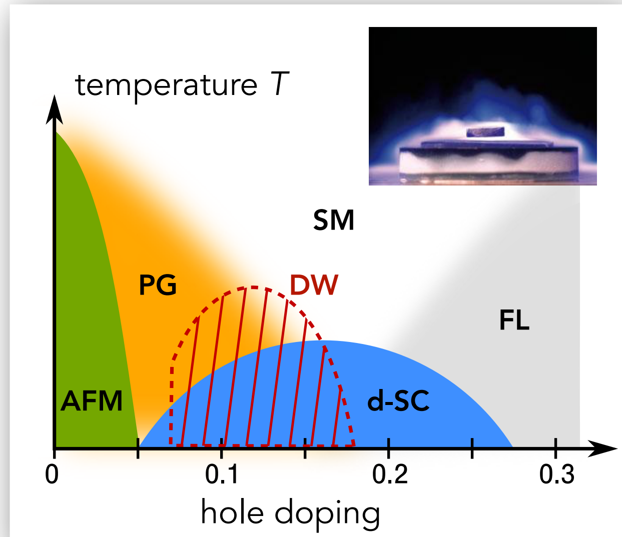
- electronic structure:

Strong interactions:



hopping spin exchange

Physical Phenomena

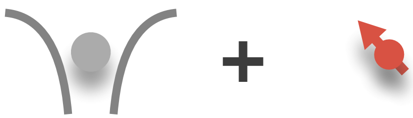


High-temperature superconductors

Motivation

Micro-constituents

ions + electrons

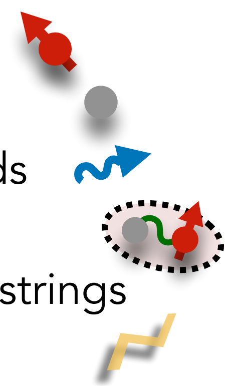


- electronic structure:

introduce

Universal Constituents

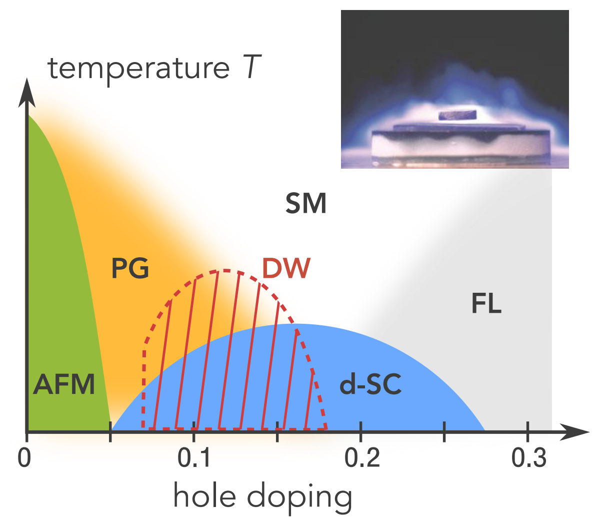
- ✦ spinons
- ✦ chargons
- ✦ gauge fields
- ✦ mesons
- ✦ geometric strings
- ✦ …



Anderson, Science (1987);
Laughlin, PRL (1997);
Senthil, PRB (2001),
FG et al., PRX (2018);

cause

Physical Phenomena



High-temperature
superconductors

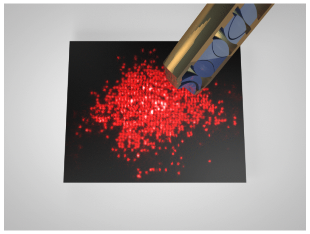
Outline

- *Mesons in correlated quantum matter — meaning & signatures*

- *Spinons & chargons in 1D — Gross / Bloch lab*

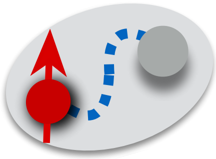
  Hilker et al., Science 357 (2017)

  J. Vijayan*, P. Sompet* et al., arXiv:1905.13638



- *Meson formation in 2D — theory*

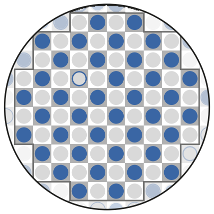
  Grusdt et al., PRX 8 (2018); Grusdt et al., SciPost Phys. 5 (2018); Bohrdt et al., PRB 97 (2018); Grusdt et al., arXiv:1901.01113 (accepted in PRB); Bohrdt et al., in prep.



- *Signatures for meson formation — Greiner lab*

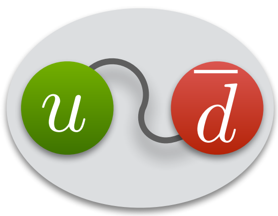
  Chiu et al., arXiv:1810.03584

  Bohrdt et al., arXiv:1811.12425

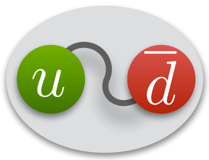


Mesons in strongly correlated quantum matter

— meaning & signatures —



Mesons



Mesons = bound states of confined **partons**

carry **fractionalized** quantum numbers

nucleons: *proton = 3 quarks* $e^* = -e/3, 2e/3$

interacting electrons: $\hat{c}_{\mathbf{j},\sigma} = \hat{h}^\dagger_{\mathbf{j}} \hat{f}_{\mathbf{j},\sigma}$

spin, no charge

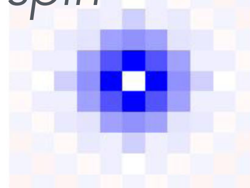
charge, no spin

Mesons

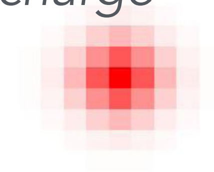
Signatures of meson formation:

- *Internal structure*

spin



charge

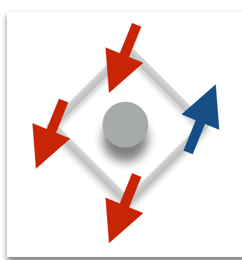


- *Ro-vibrational excitations*

$n^{2s+1}\ell_J$	$u\bar{d}$	$u\bar{s}$
1^1S_0	$\boldsymbol{\pi}$	$\boldsymbol{K}$
1^1P_1	$\boldsymbol{b}_1(1235)$	$\boldsymbol{K}_{1B}$
1^1D_2	$\boldsymbol{\pi}_2(1670)$	$\boldsymbol{K}_2(1770)$
1^3F_4	$\boldsymbol{a}_4(2040)$	$\boldsymbol{K}_4^*(2045)$
2^1S_0	$\boldsymbol{\pi}(1300)$	$\boldsymbol{K}(1460)$

Amsler et al., Phys. Lett. B 667 (2008)

- *Gauss-law*

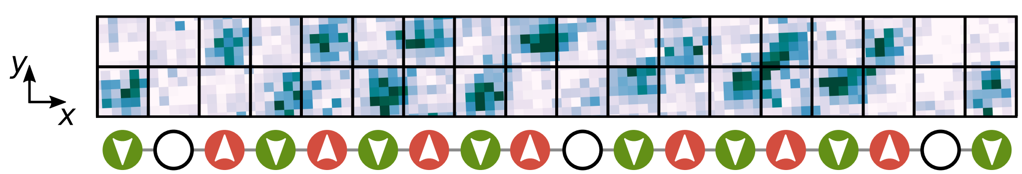


Spinons & chargons in 1D

— partons —

collaboration:
Gross / Bloch group
at MPQ Munich

Hilker et al., Science 357 (2017)

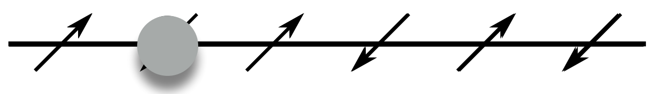


The 1D *t-J* model

Microscopic considerations — 1D

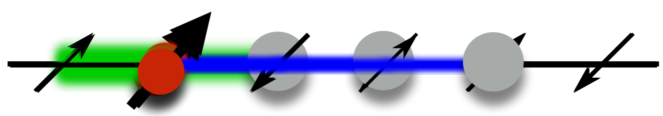
$t \gg J$

- *Impurity physics — single-hole case*



- **Fractional spin** excitation!

$$S = 1/2$$



- Chargon motion **keeps relative spin orientations intact!**

- **Spinon formation** where hole was created!

Spin-charge separation:

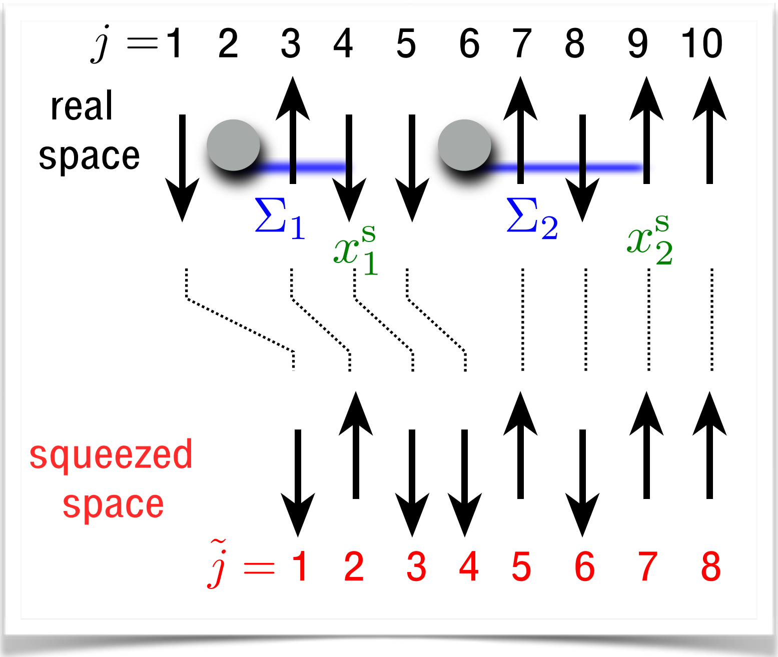
$\boxed{\textit{deconfined spinons and chargons:} \quad t \gg J}$

Ogata & Shiba, PRB 41 (1990)

Squeezed space — 1D

Solution of 1D *t-J* model by re-labeling

- Squeezed space:



- Ground state wavefunction: $t \gg J$

$$\boxed{|\psi\rangle \approx |\psi_{\mathrm{h}}\rangle_{\mathrm{bonds}} \otimes |\psi_{\mathrm{s}}\rangle_{\mathrm{squeezed}}}$$

1D quant. Heisenberg AFM:

$$|\psi_{\mathrm{s}}\rangle_{\mathrm{squeezed}} = |1d \text{ QHAFM}\rangle$$

Kruis et al., PRB 70 (2004)

Ogata & Shiba, PRB 41 (1990)

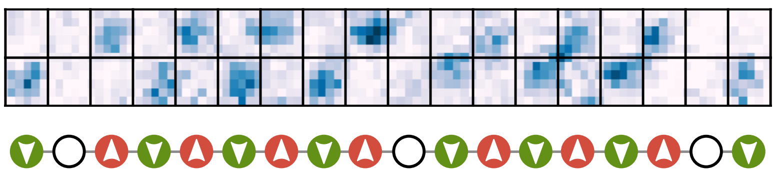
Squeezed space — 1D

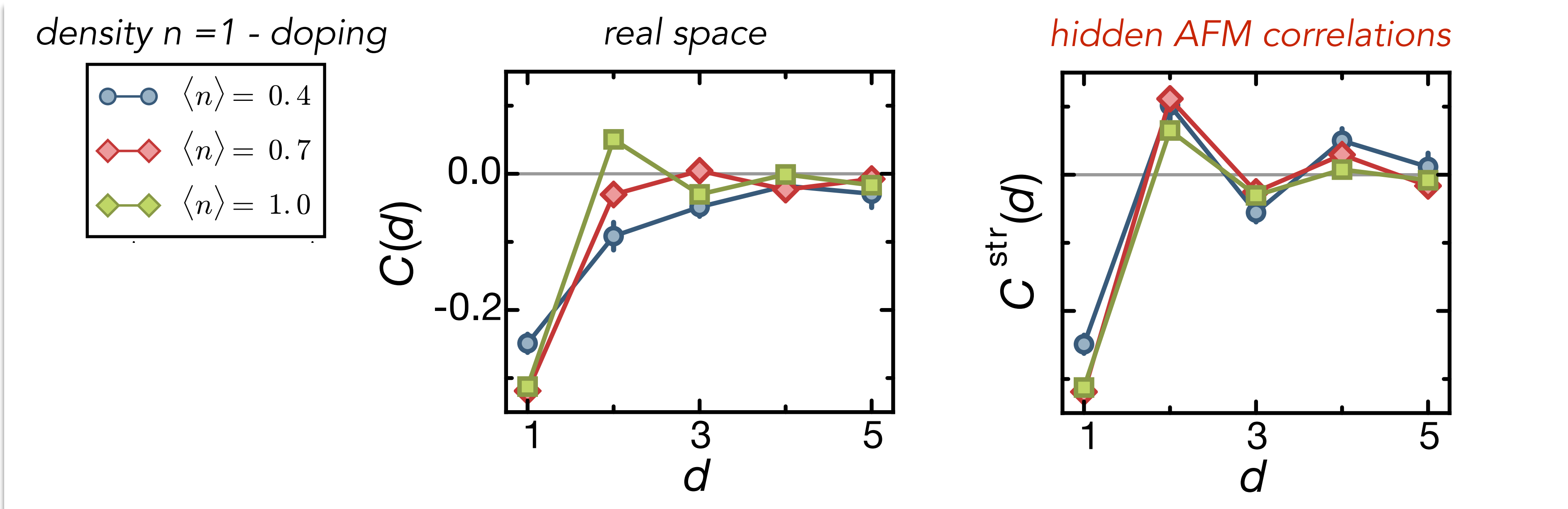
- **Non-local string correlator:** $C \quad (d) = 4 \left\langle \hat{S}^z_{j+d} \qquad \hat{S}^z_j \right\rangle$

factor (-1) for each hole!

Experiment Gross/Bloch group, MPQ

Hilker et al., Science 357 (2017)





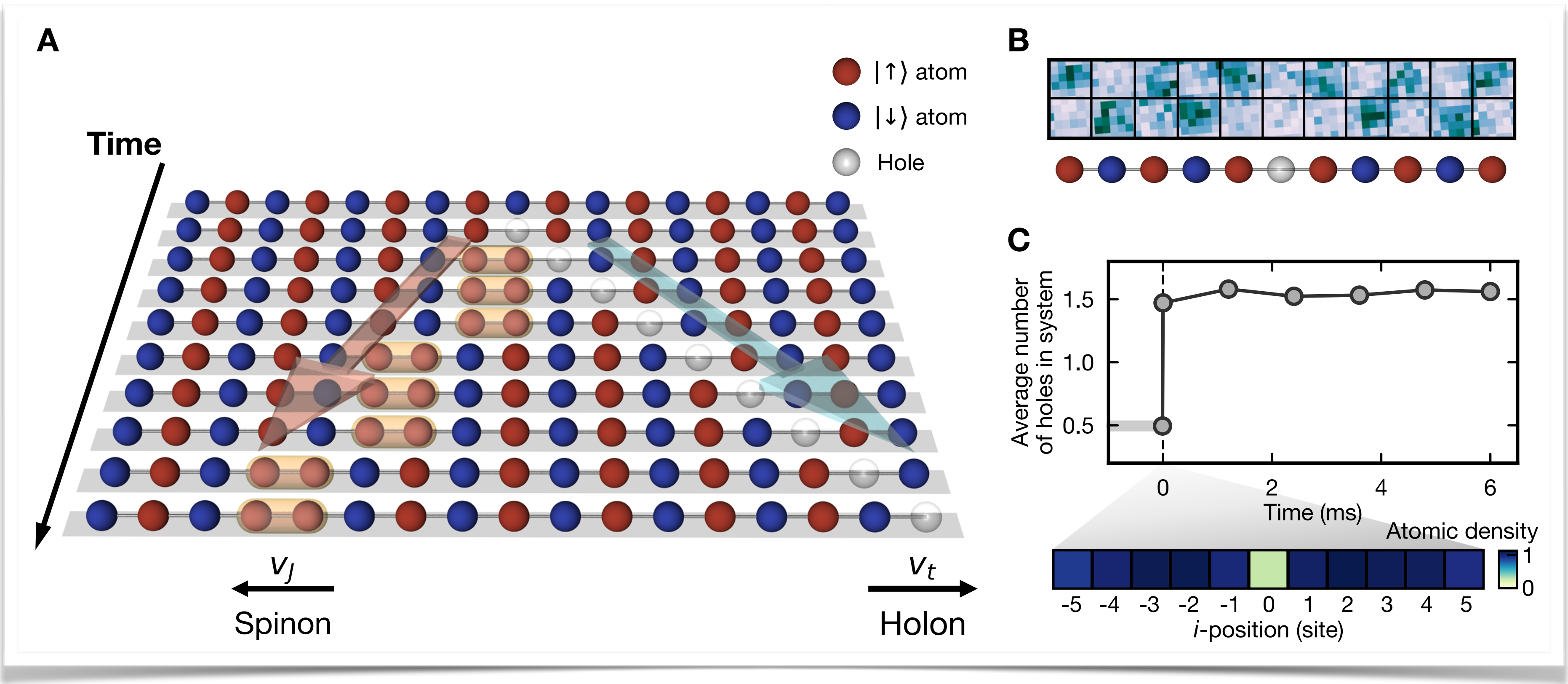
Spin-charge deconfinement

Dynamical probe of parton formation:

Experiment Gross/Bloch group, MPQ

J. Vijayan, P. Sompet* et al., arXiv:1905.13638*

- Release hole in 1D



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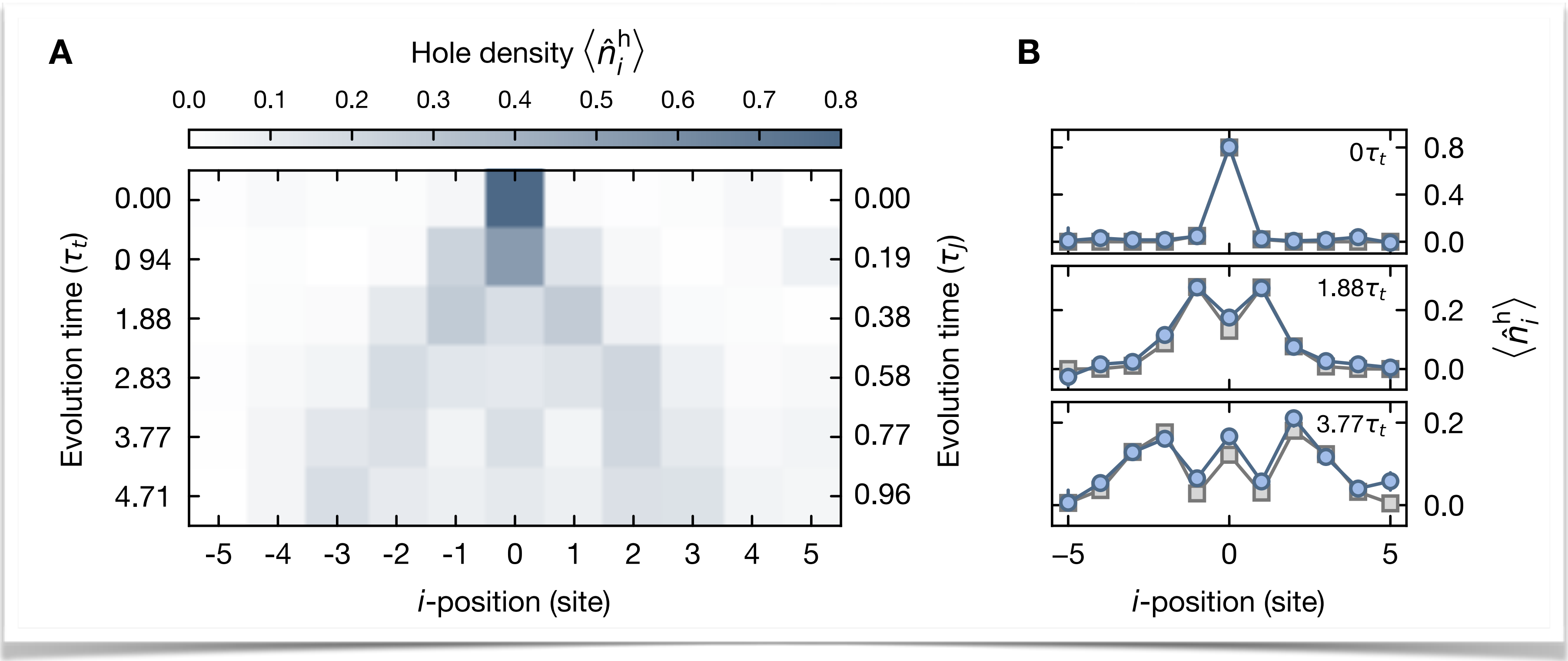

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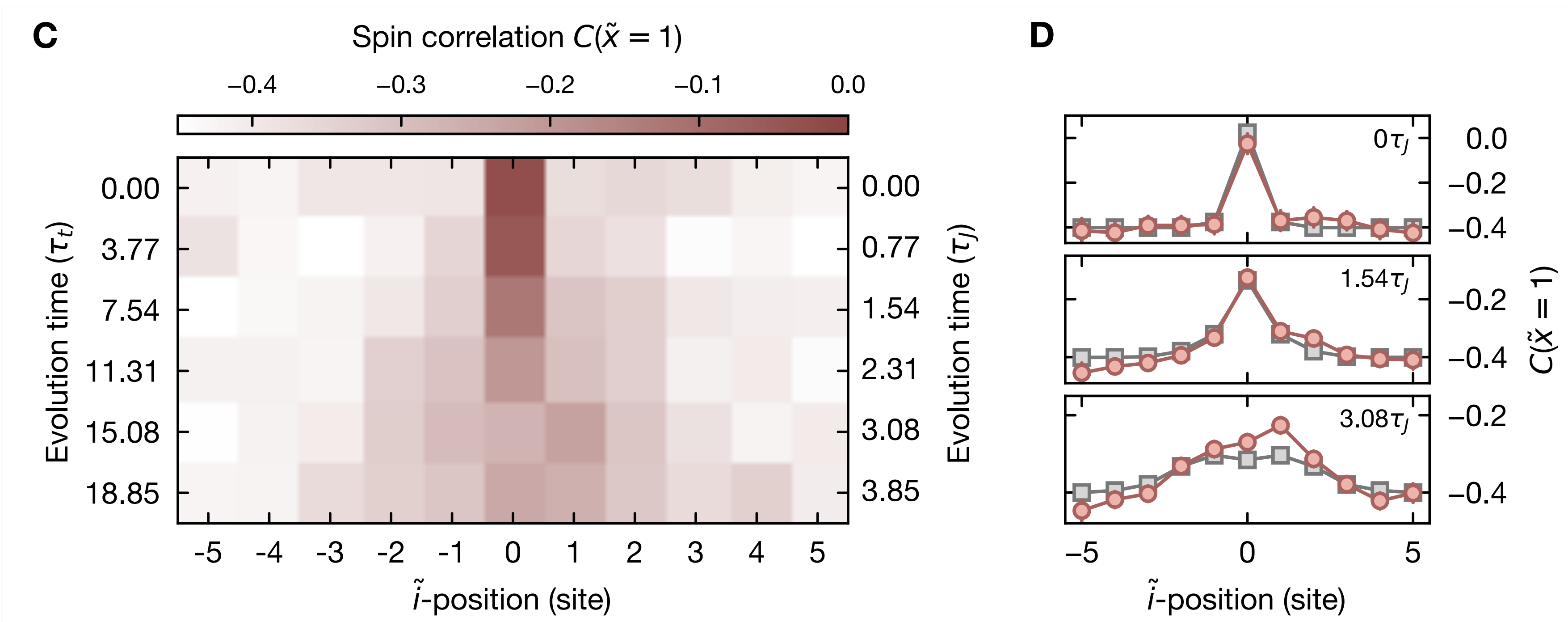

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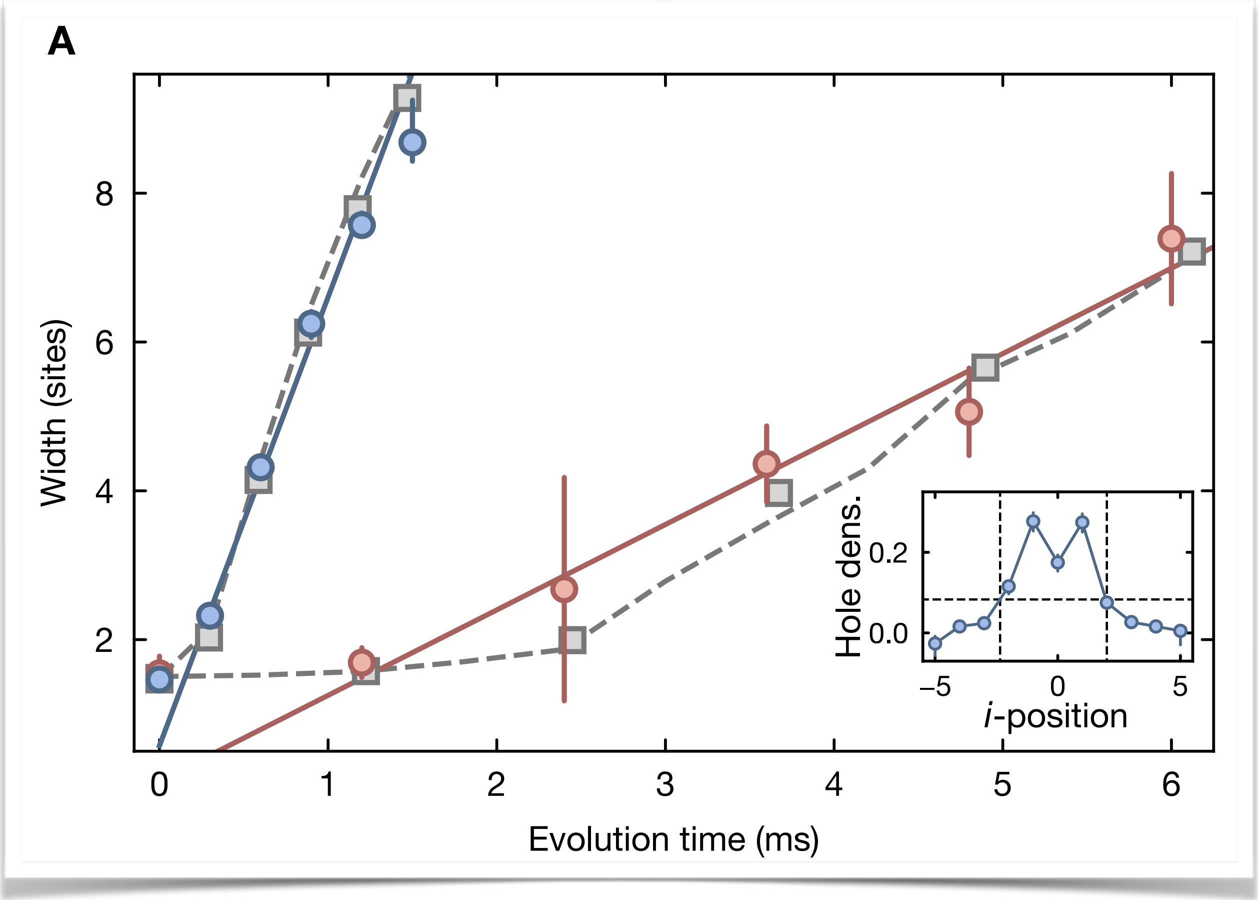
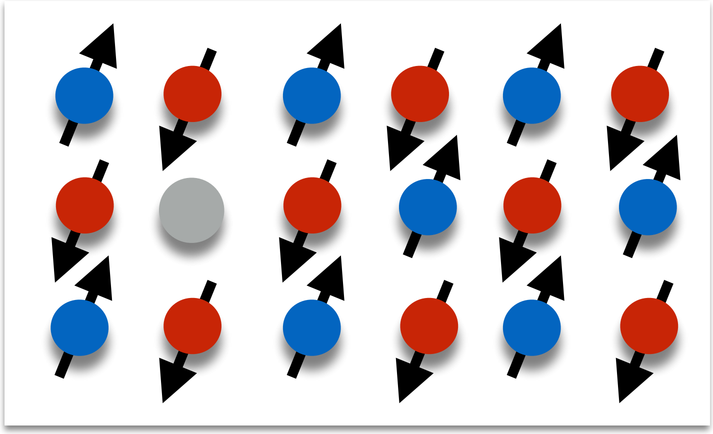


Meson formation in 2D

— geometric strings —

Theory collaboration:
Annabelle Bohrdt, Michael Knap,
Zheng Zhu, and Eugene Demler

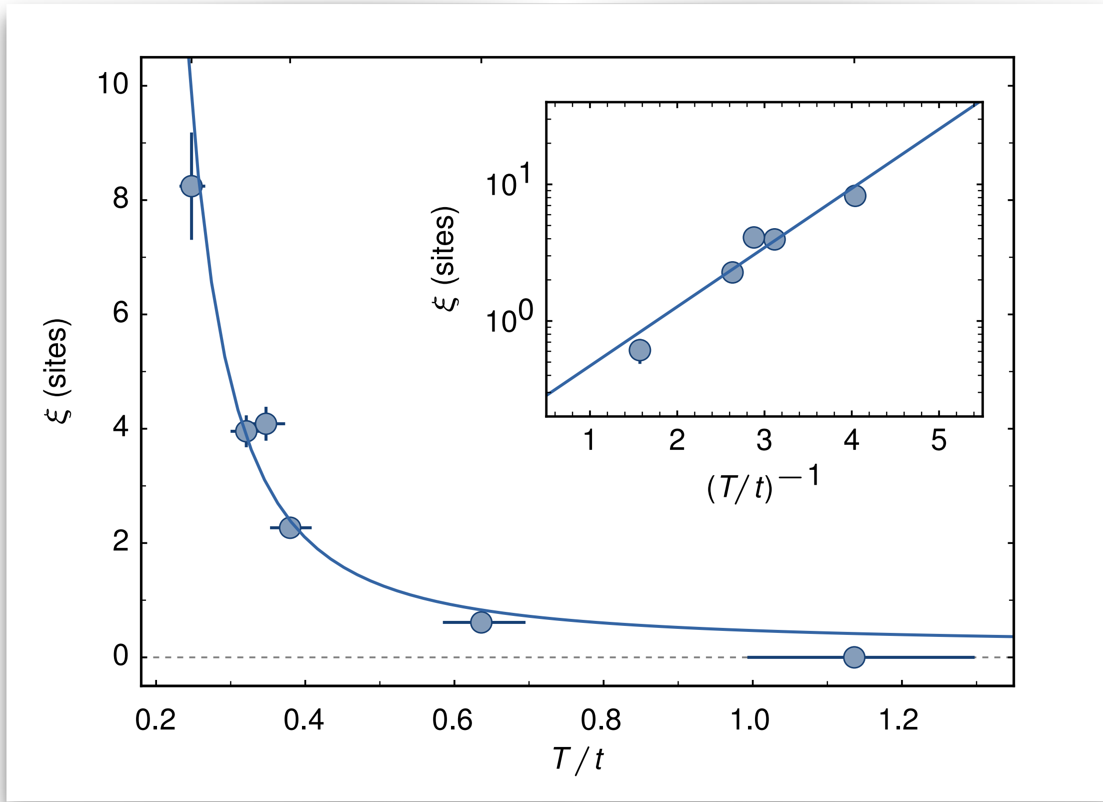


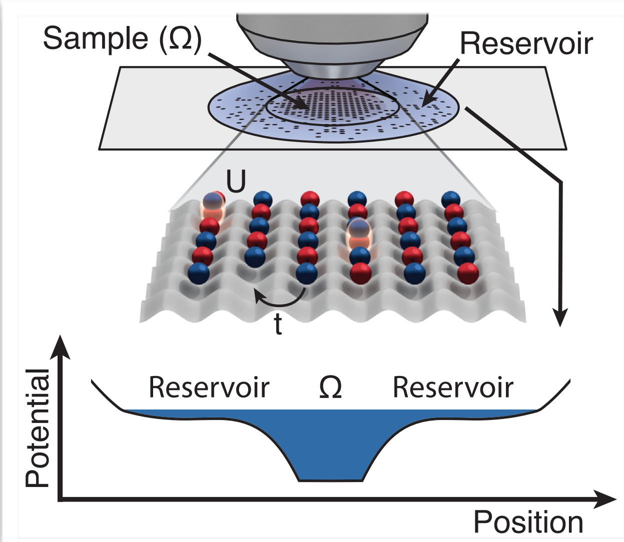
Long-range AFM in 2D

- **Long-range anti-ferromagnet in 2D:**

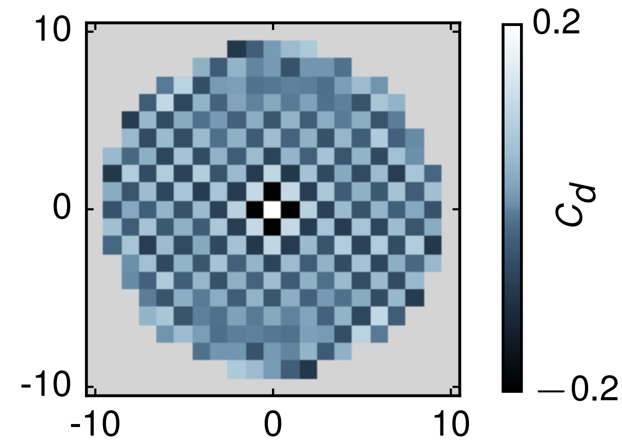
Experiment Greiner group, Harvard

Mazurenko et al., Nature 545 (2017)





Neel state



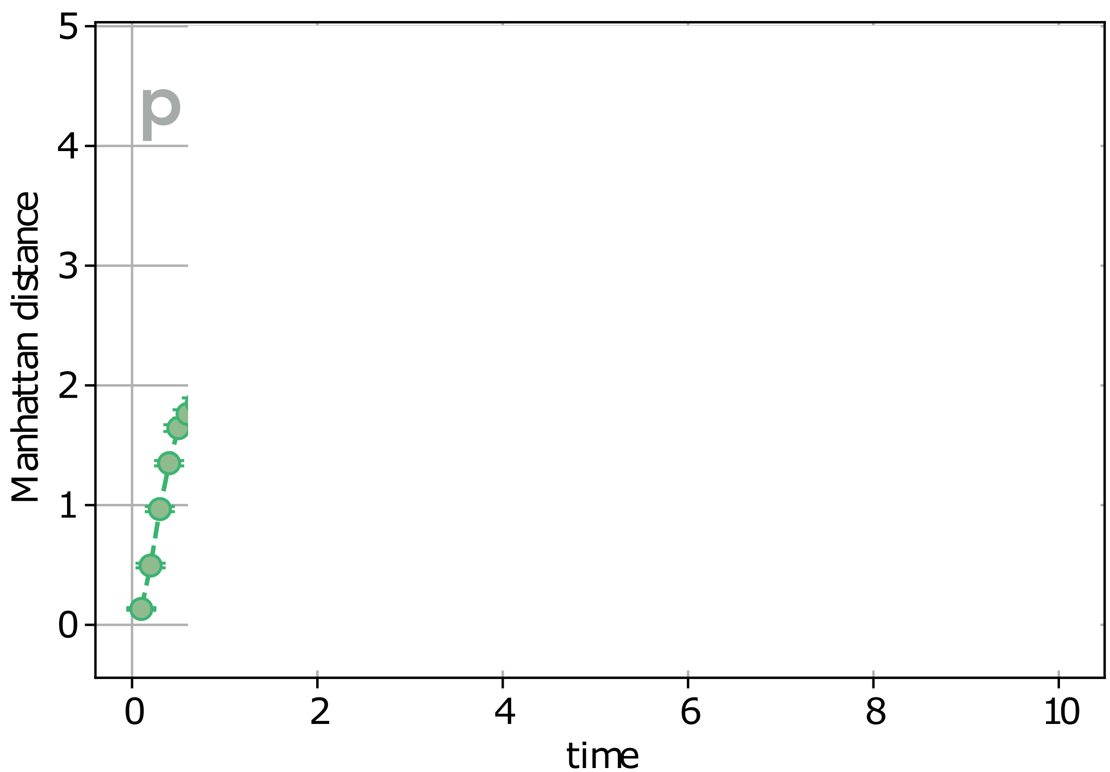
Confinement?

Dynamical probe of parton formation:

MPS simulations: A. Bohrdt

M. Zaletel et al., PRB 91 (2015)

A. Bohrdt, FG, M. Knap, in prep.



- Release hole in 2D

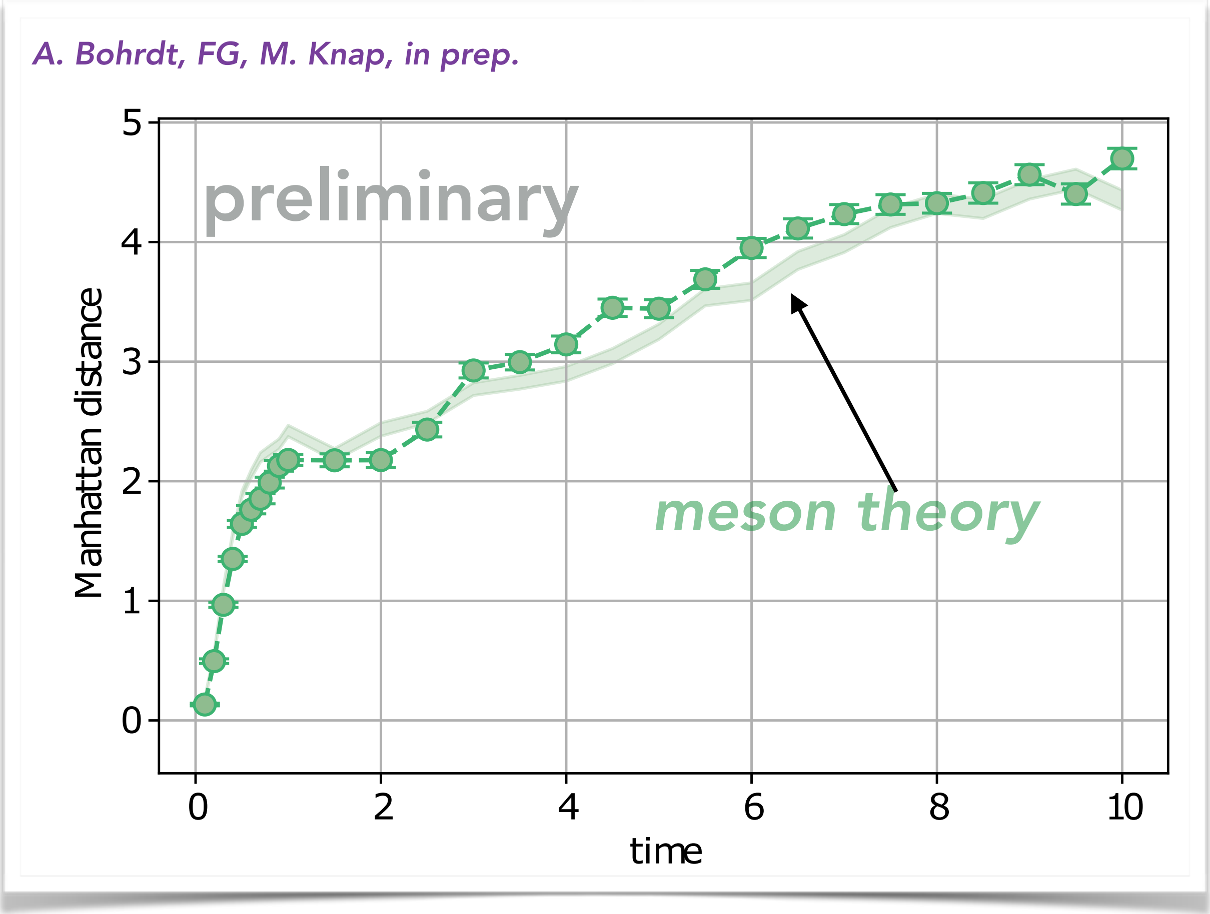
- fast ballistic expansion
- cross-over
- slow ballistic expansion

Confinement?

Dynamical probe of parton formation:

MPS simulations: Annabelle Bohrdt

M. Zaletel et al., PRB 91 (2015)

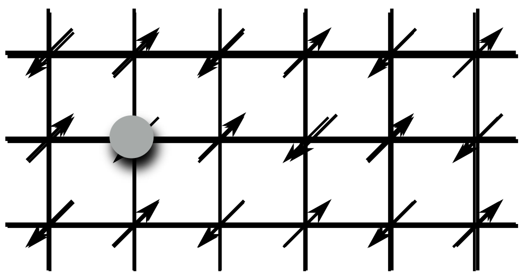


- Release hole in 2D

  - fast ballistic expansion
  - cross-over
  - slow ballistic expansion

Parton picture

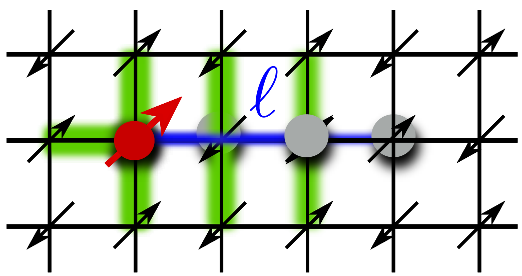
Parton-picture of magnetic polarons:



* **Fractional spin** excitation!

$$S = 1/2$$

* Chargon motion quickly **distorts 2D Neel state!**

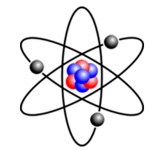


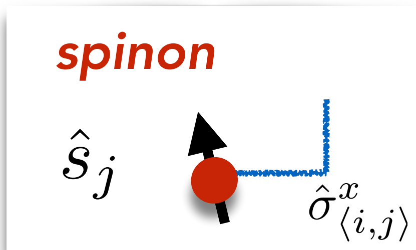
* Chargon is **bound to the fractional spin (spinon)** at end of string!

$$E \propto J \times \ell$$

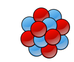
competition: $t \longleftrightarrow \ell \times J$ *> emergent length scale!*

Parton-picture of magnetic polarons:



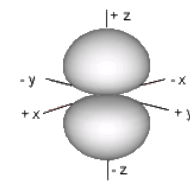


* effective mass: $m_{\rm s} \simeq 1/J$
* hopping within one sub-lattice



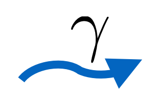
* effective mass: $m_{\rm h} \simeq 1/t \ll m_{\rm s}$

Born-Oppenheimer:
strong-coupling expansion!



* number not conserved!

- weak polaronic dressing!
- Decay of excited states!



Beran et al., Nuc.Phys.B (1996)   *Grusdt et al., PRX 8 (2018)*

Parton picture

Dynamical probe of parton formation:

MPS simulations: Annabelle Bohrdt

M. Zaletel et al., PRB 91 (2015)

- Release hole in 2D

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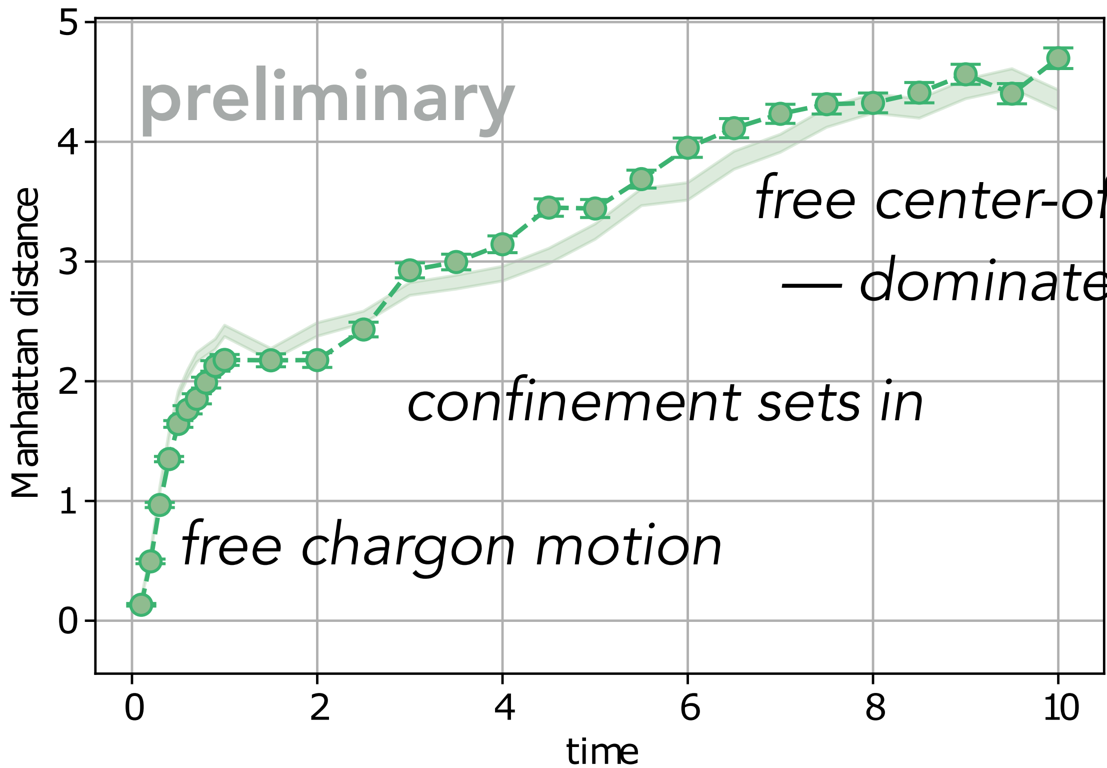
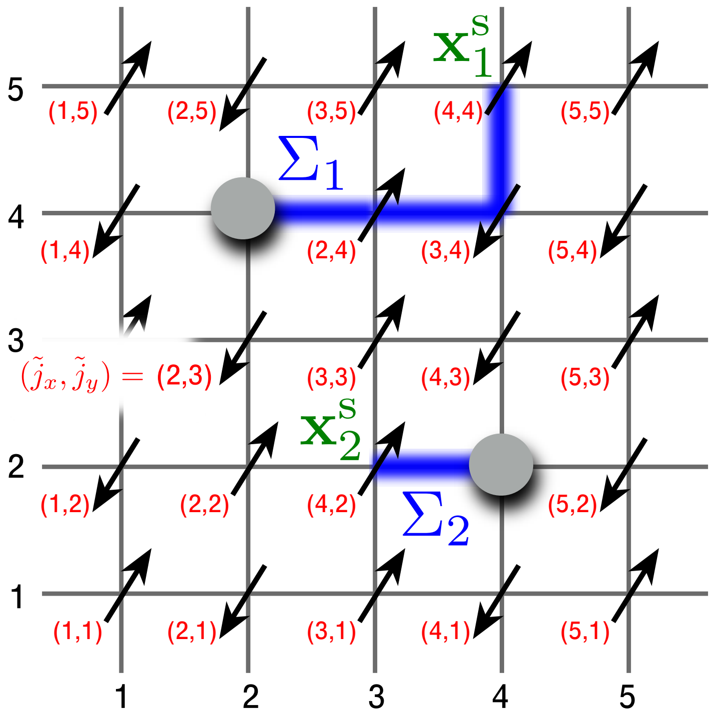


Squeezed space — 2D

Solution of 2D *t-J* model by re-labeling

- Squeezed space:



- Ground state wavefunction:

$$\boxed{|\psi\rangle \approx |\psi_{\mathrm{h}}(\Sigma)\rangle \otimes |\psi_{\mathrm{sp}}\rangle \otimes |\psi_0\rangle_{\mathrm{sqz}}}$$

string wavefunction

spinon wavefunction

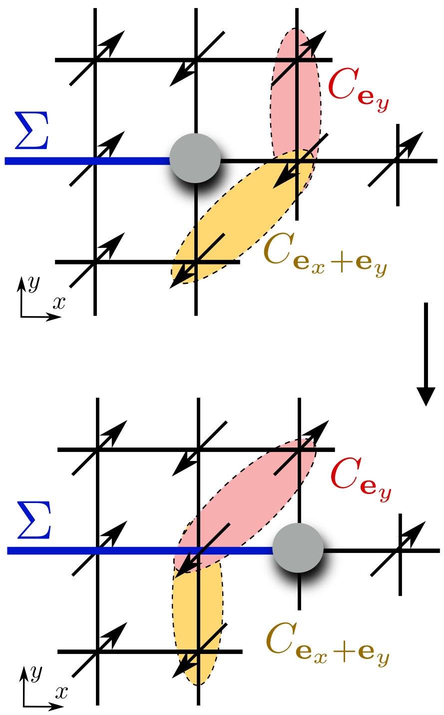
spin background 2D QHAF

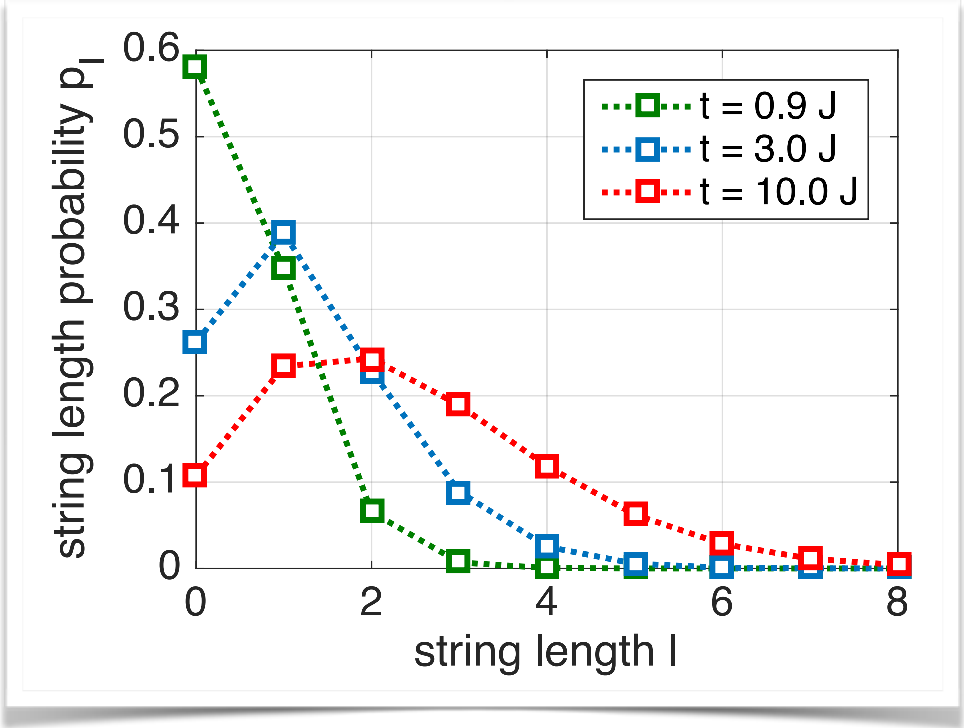
Grusdt et al., PRX 8 (2018) *Grusdt et al., arXiv:1901.01113*

Squeezed space — 2D

Focus on charge fluctuations (fastest)

- Frozen spin approximation (FSA): consider only chargon motion
- Chargon motion assumed to create memory of its trajectory





Grusdt et al., PRX 8 (2018) Grusdt et al., arXiv:1901.01113 (accepted in PRB)

Internal structure of mesons

— rotational excitations —

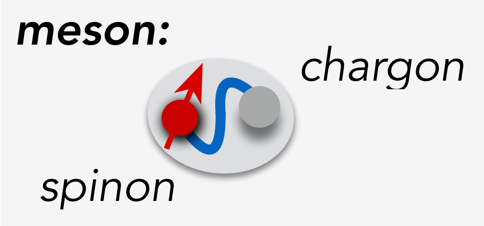
Rotational excitations

Born-Oppenheimer Ansatz

$$\boxed{|\psi\rangle \approx |\psi_{\rm h}(\Sigma)\rangle \otimes |\psi_{\rm sp}\rangle \otimes |\psi_0\rangle_{\rm sqz}}$$

string wavefunction
— charge fluctuations

localized spinon

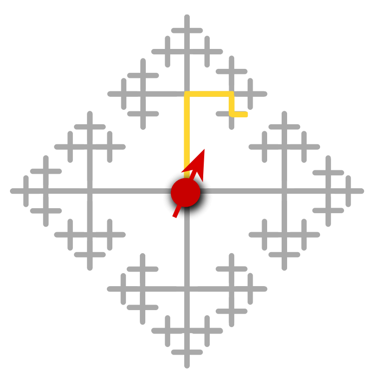


- *Bethe lattice model*

  $\sim t \gg J$

  radial potential

  $V_{\rm pot} \propto J \times \ell_\Sigma$



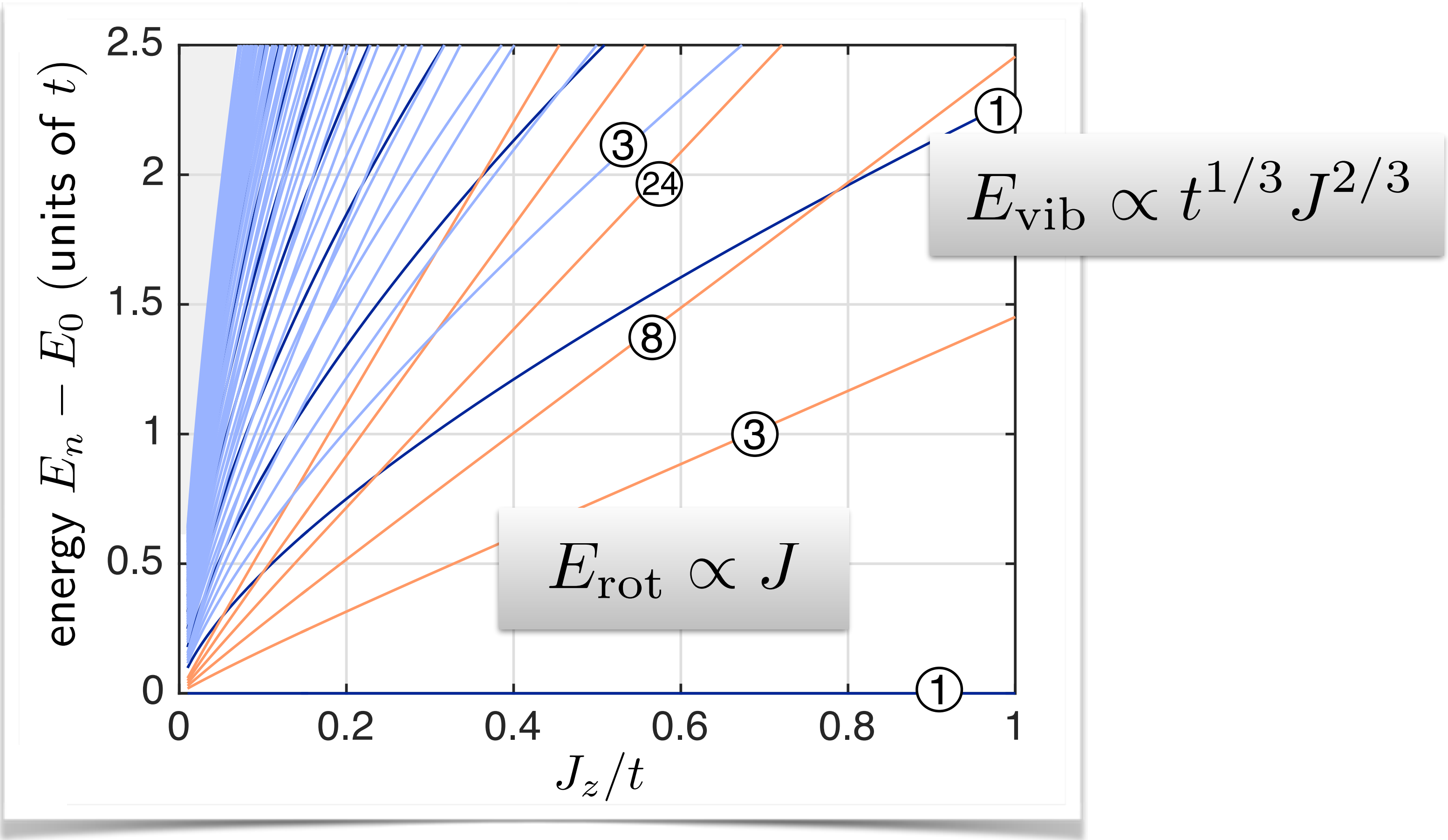
* C4 symmetry on central node
* C3 symmetry per other node
* rotational quantum numbers:

  $m_4, m_3^{(1)}, m_3^{(2)}, m_3^{(3)}, \ldots$

Rotational excitations

Simplified Bethe-lattice model

Grusdt et al., PRX 8 (2018)

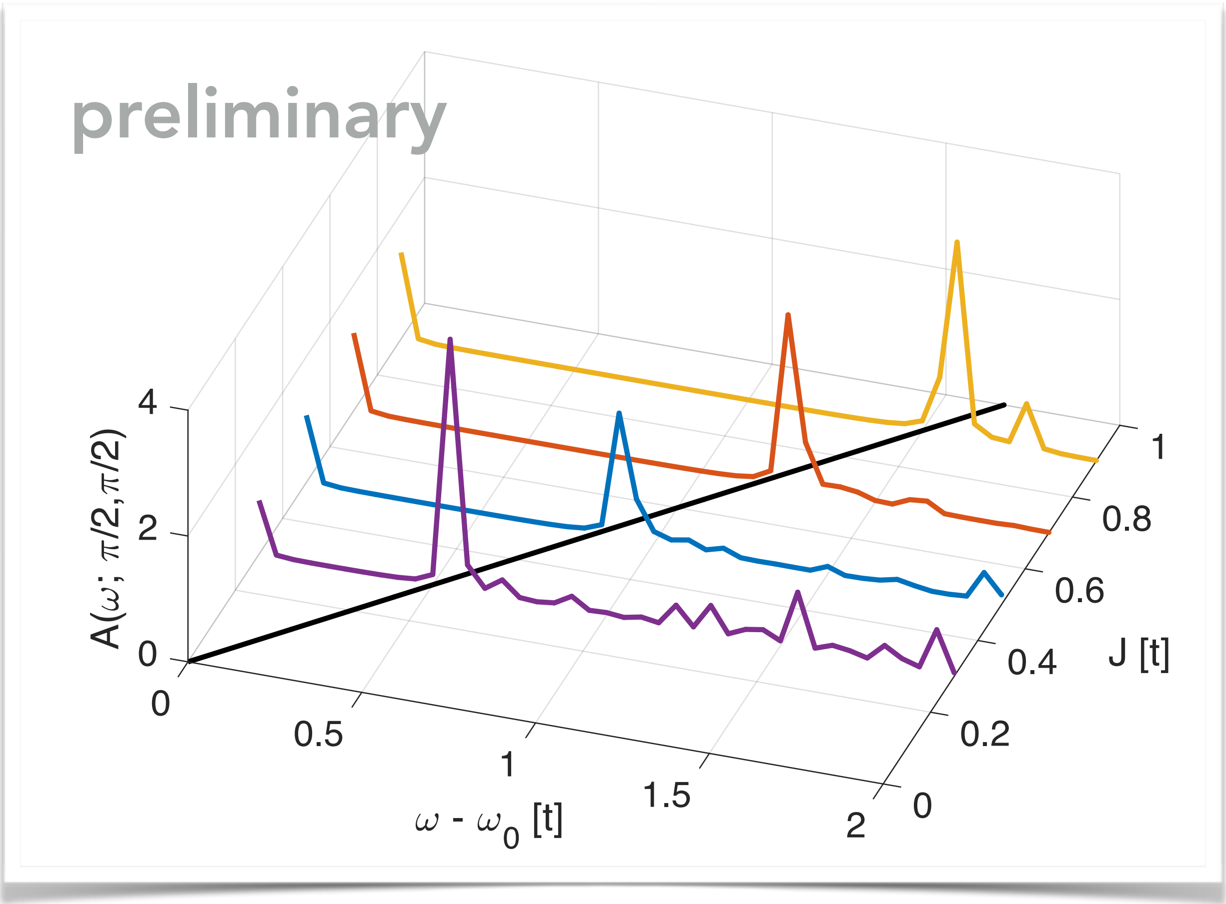


n — *radial excitations* $m_{3,4}$ — *rotational excitations*

Rotational excitations

- Rotational spectroscopy: *t-J* model

Bohrdt et al., in prep.



Internal structure of mesons

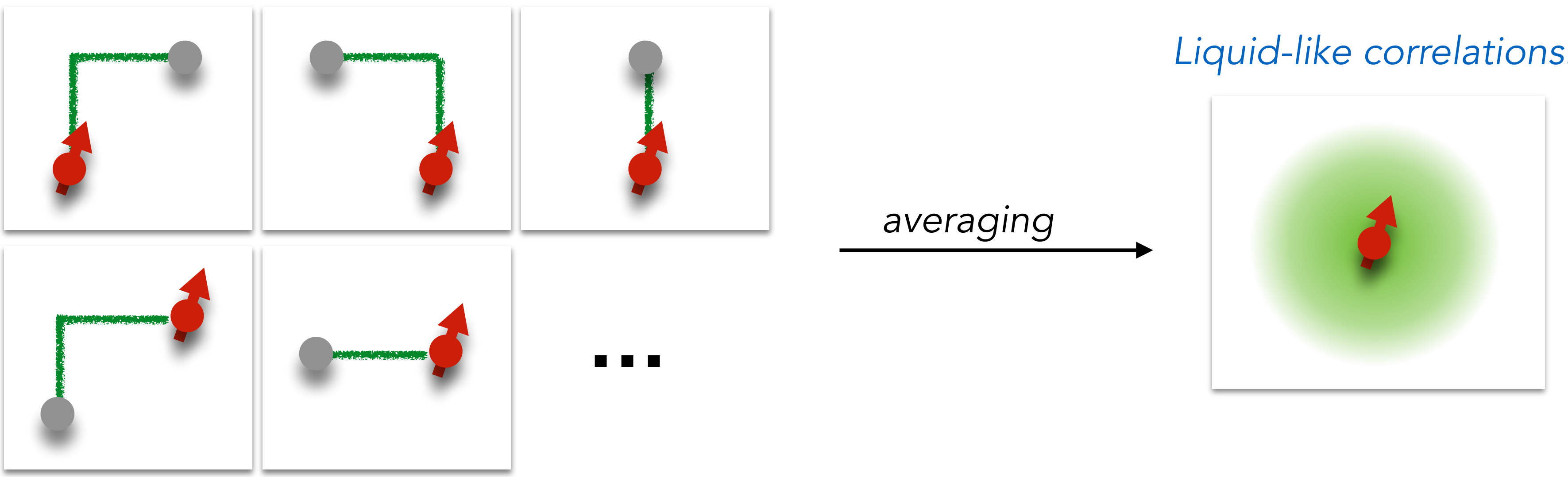
— geometric strings —

Detecting geometric strings

Direct signatures of geometric strings?

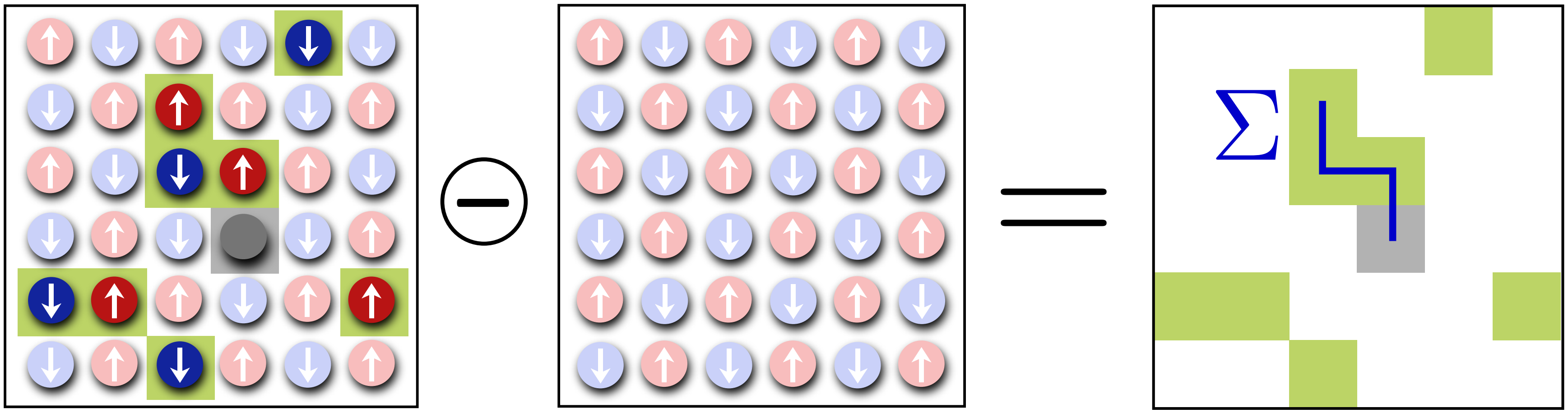
* Short-range *hidden order* — *washed out by averaging!*

$\Rightarrow$ Analyze individual snapshots!



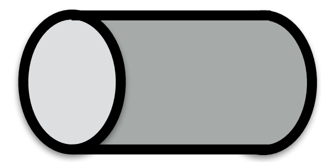
Detecting geometric strings

- Internal structure of mesons: pattern analysis

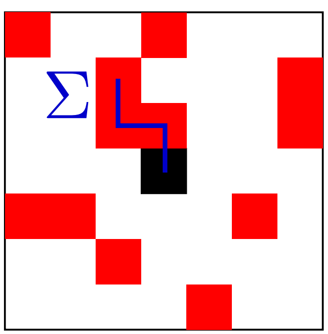


Single hole in the *t-J* model

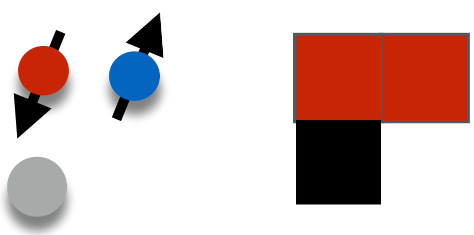
- DMRG simulations (A. Bohrdt) with one hole on a 6x8 cylinder,
  — sampling in Fock basis using Metropolis Monte-Carlo

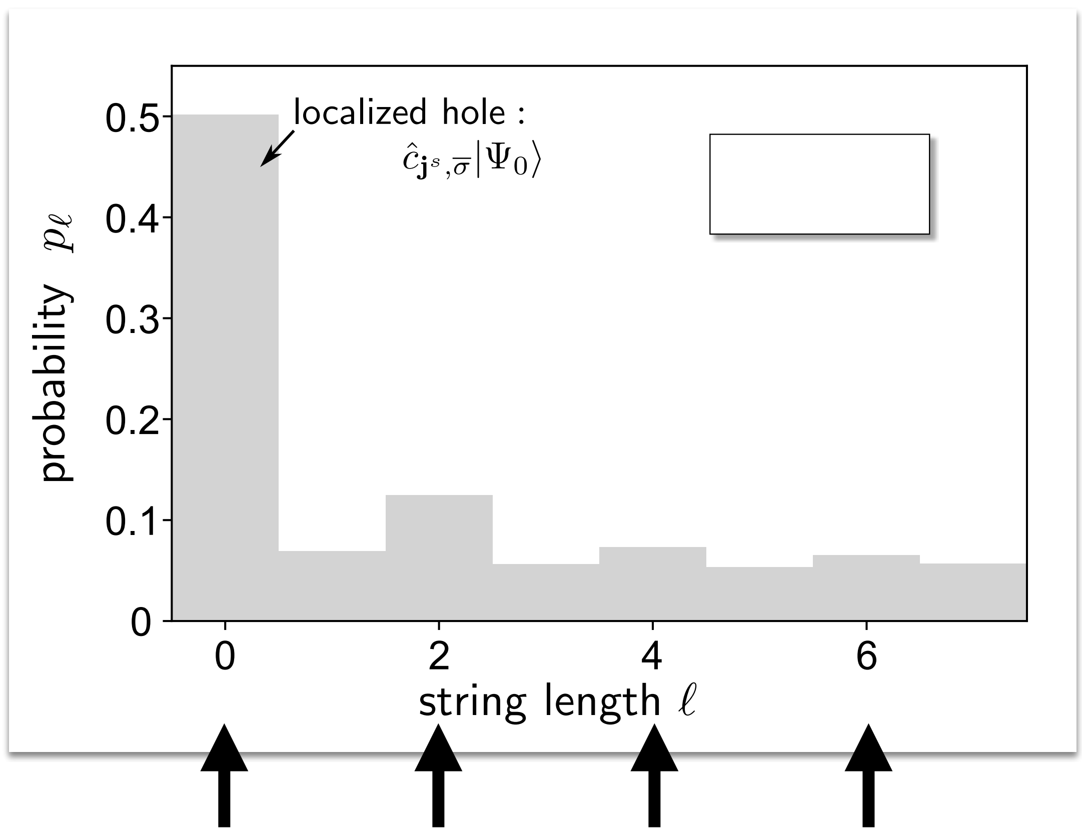


- deviations from perfect checkerboard pattern



=> string length





Grusdt et al., arXiv:1901.01113 (accepted in PRB)

Detecting geometric strings

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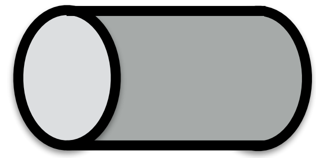
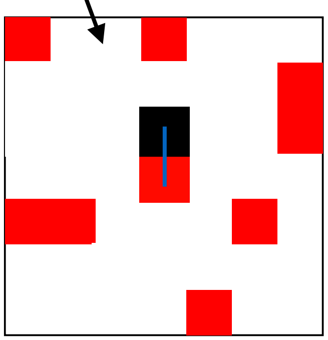
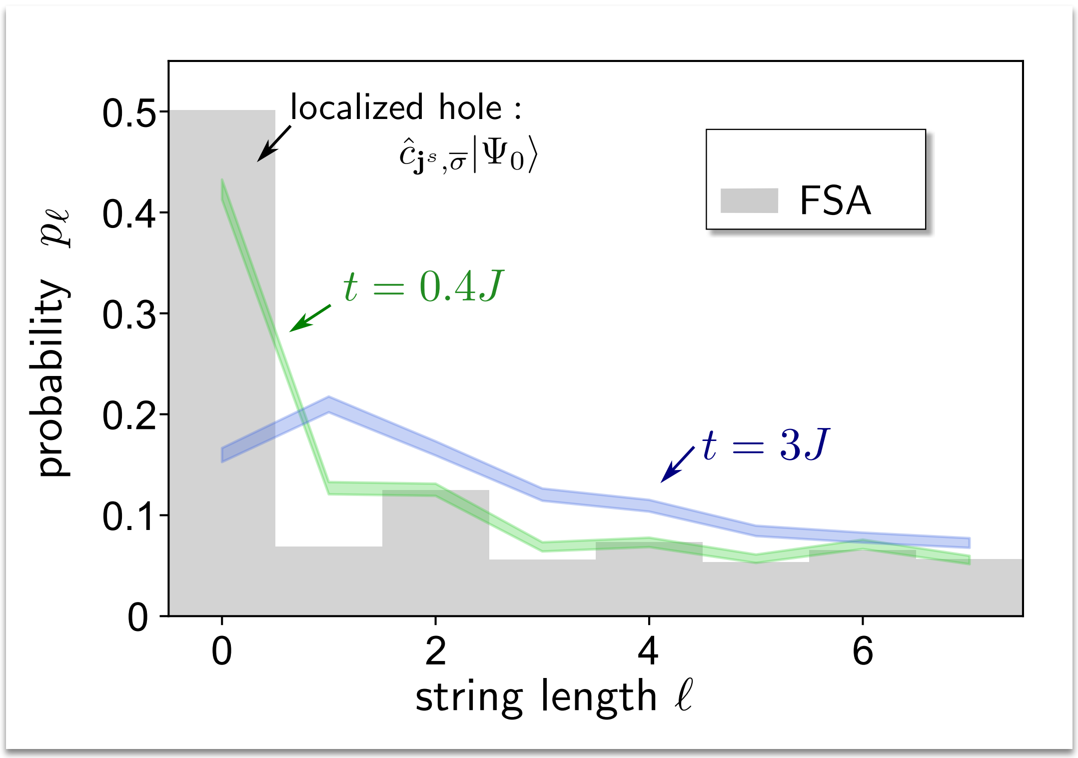


- frozen spin approximation (FSA)

localized hole



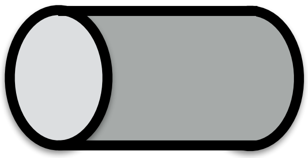


Grusdt et al., arXiv:1901.01113 (accepted in PRB)

Detecting geometric strings

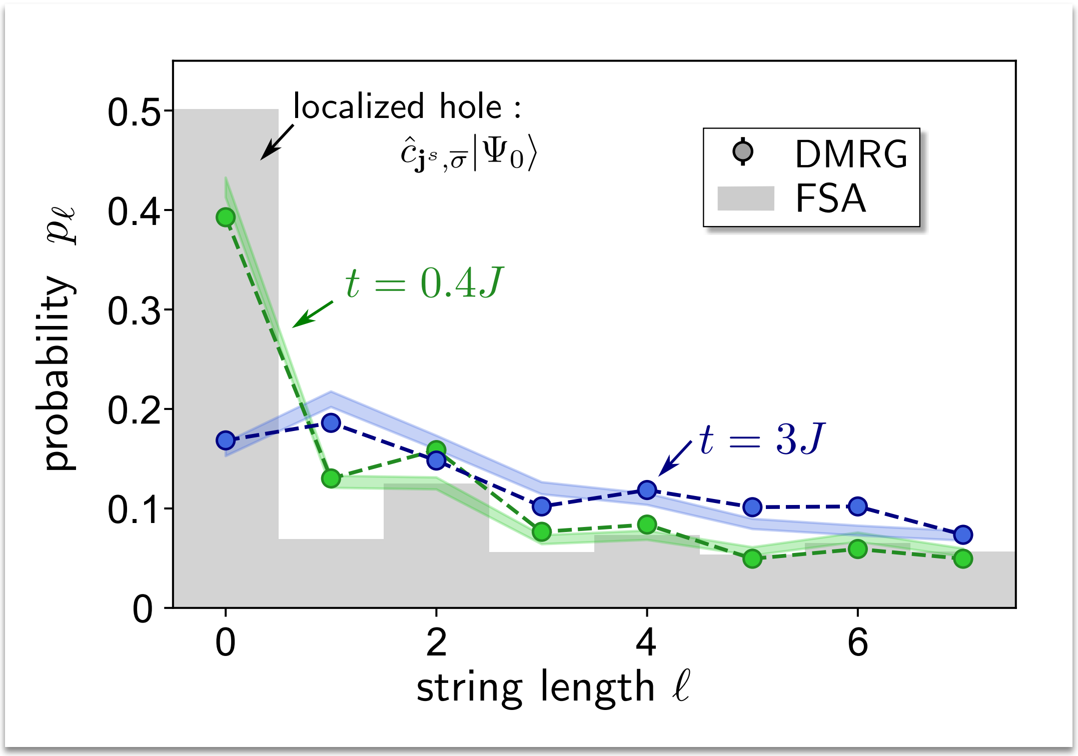
Single hole in the *t-J* model

- DMRG simulations (A. Bohrdt) with one hole on a 8x8 cylinder,
  — sampling in Fock basis using Metropolis Monte-Carlo



- full DMRG simulation:

- short-range hidden string order!

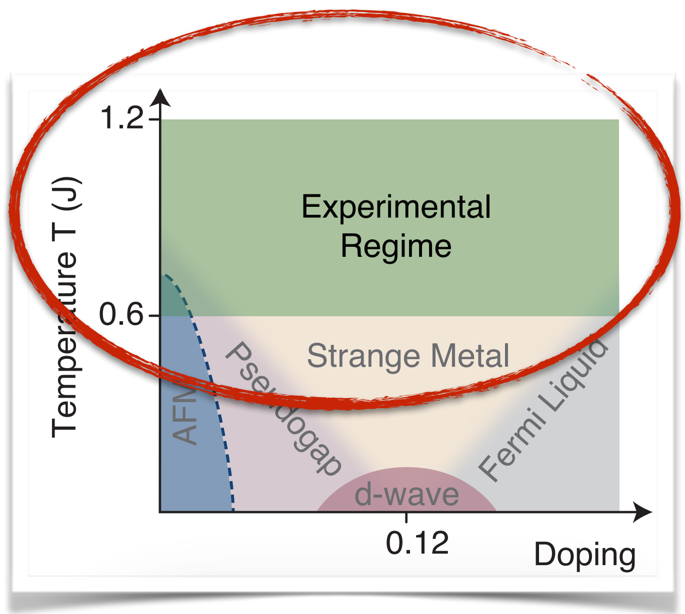


Grusdt et al., arXiv:1901.01113 (accepted in PRB)

Signatures for meson formation

— experimental results —

collaboration:
Greiner group
at Harvard

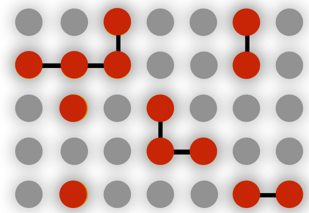


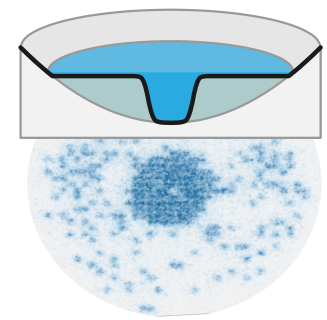
Chiu et al., arXiv:1810.03584

Detecting string patterns

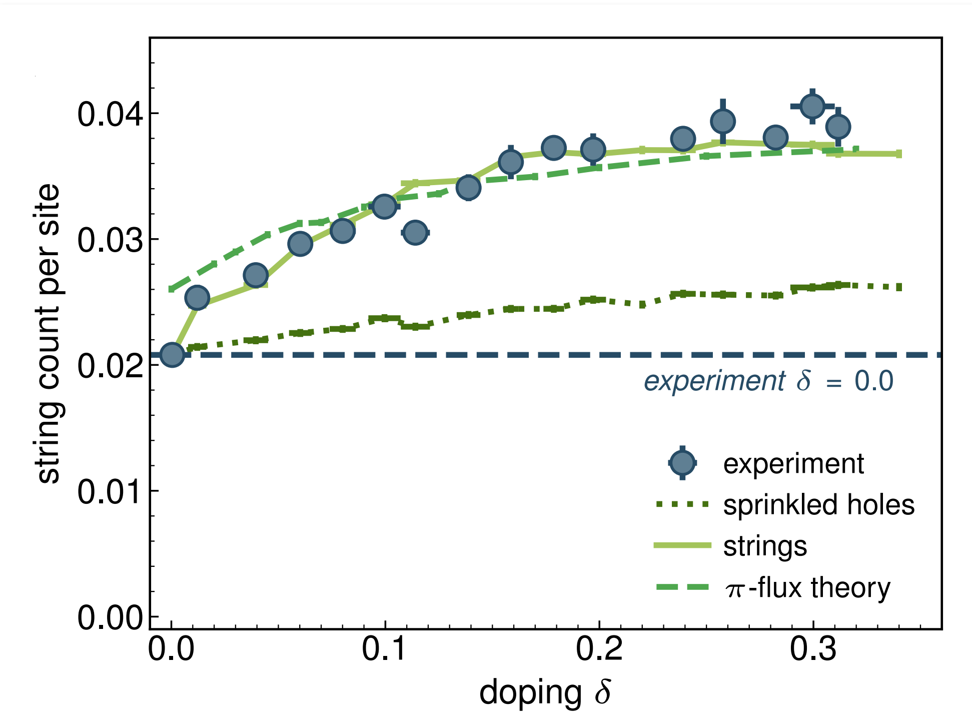
Disappearance of the AFM by doping — *hidden correlations?*

Experiment Greiner lab, Harvard

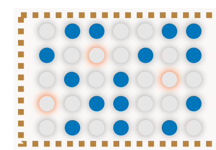




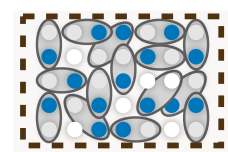
* String patterns:



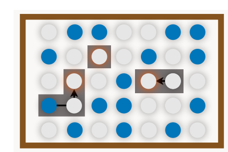
sprinkling



π-flux theory
(1 fit parameter)



geometric string theory
*(**no** fit parameter)*

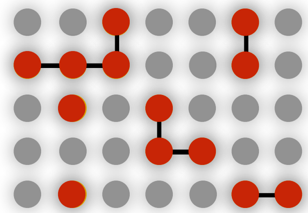


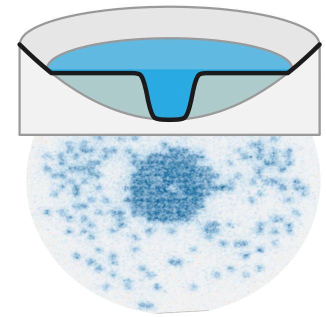
Chiu et al., arXiv:1810.03584

Detecting string patterns

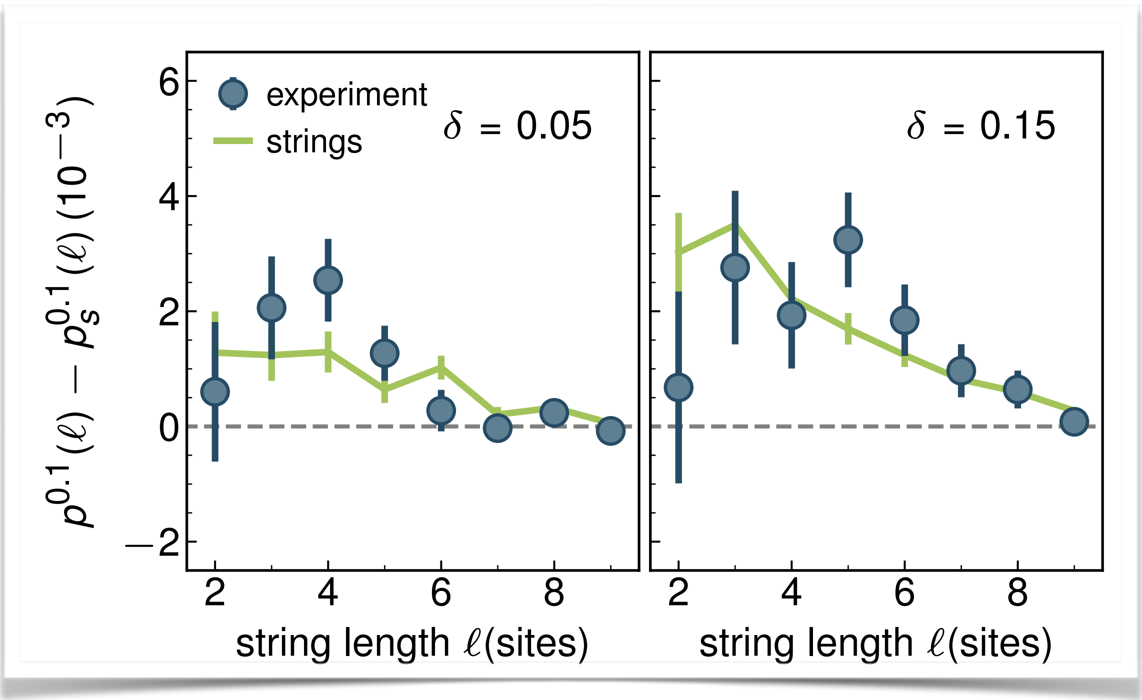
Disappearance of the AFM by doping — *hidden correlations?*

Experiment Greiner lab, Harvard

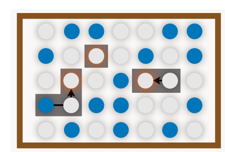




- String patterns:



geometric string theory
*(**no** fit parameter)*

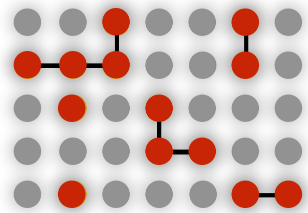


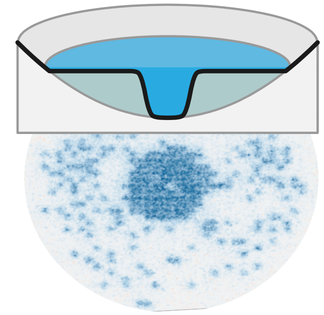
Chiu et al., arXiv:1810.03584

Detecting string patterns

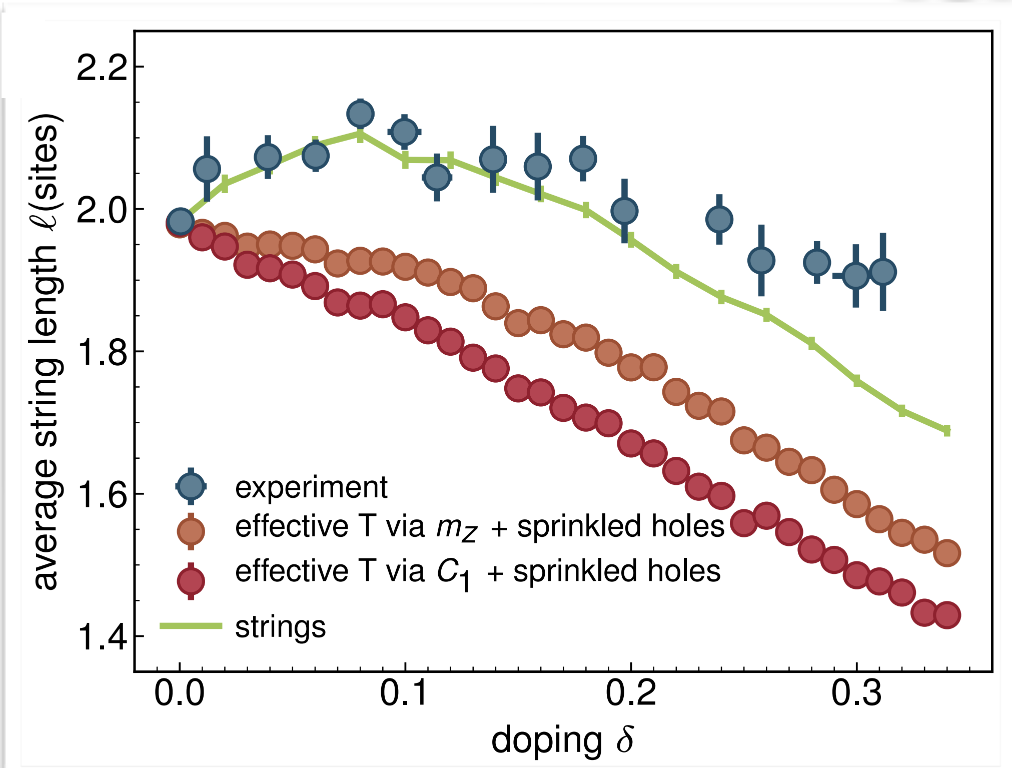
Disappearance of the AFM by doping
— hidden correlations?

Experiment Greiner lab, Harvard

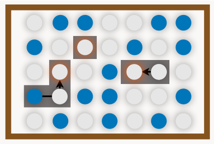




* Average string length:



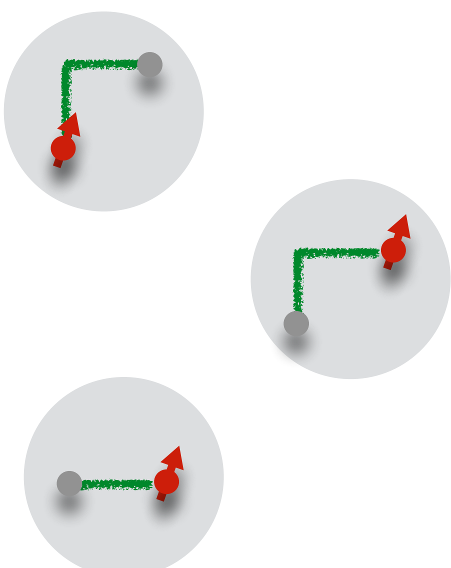
geometric string theory
(__no__ fit parameter)

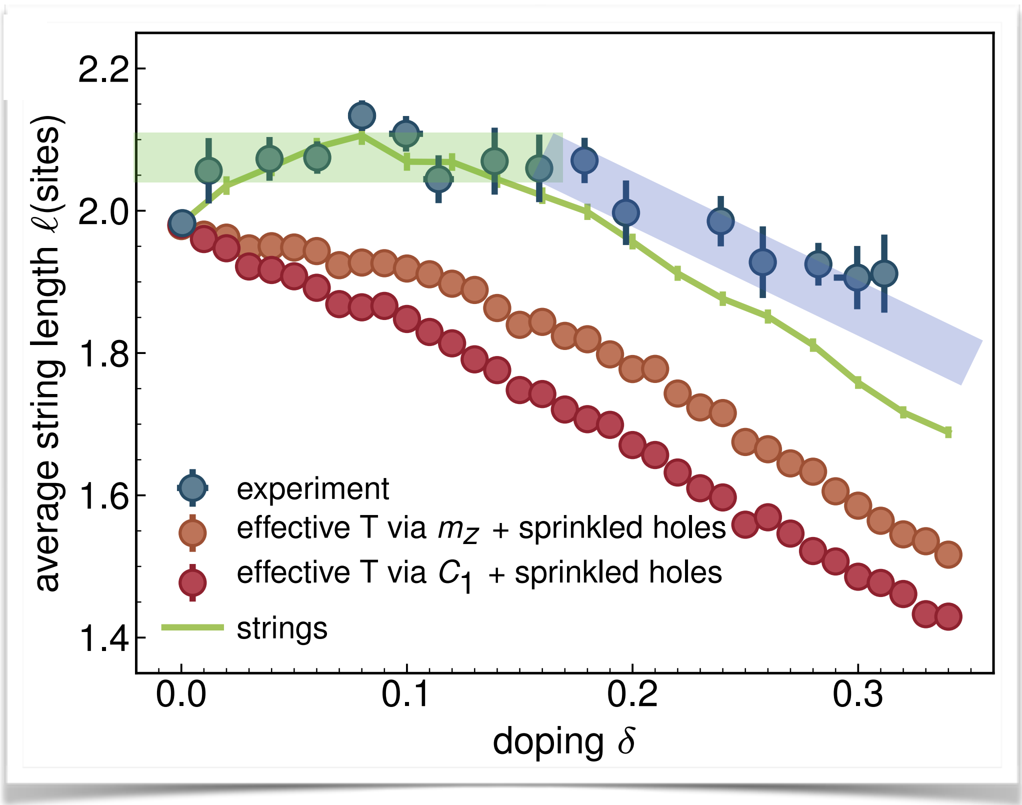


Chiu et al., arXiv:1810.03584

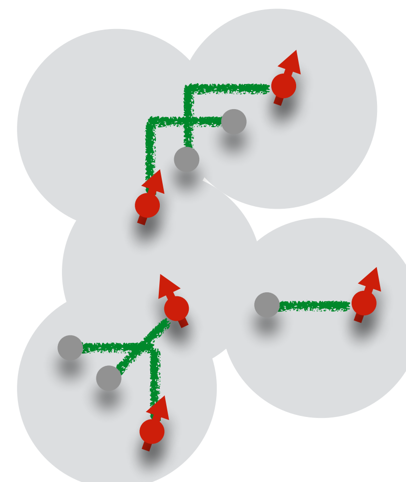
Disappearance of the AFM by doping
— hidden correlations?

independent holes with strings attached





overlapping strings



Chiu et al., arXiv:1810.03584

Outlook

Deconfinement of partons: description by Z2 LGT

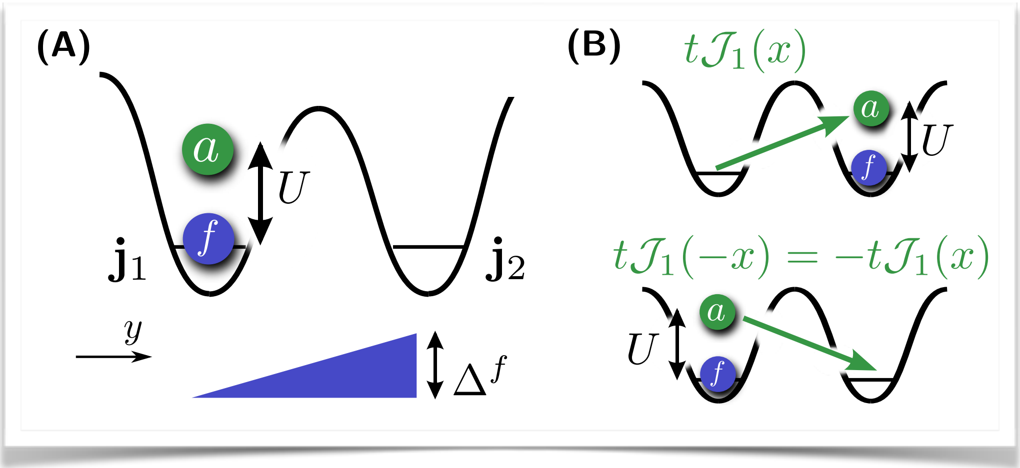
Senthil & Fisher, PRB 62 (2000)

$\mathbb{Z}_2$ minimal coupling $$-t_y^a \lambda^y \; \hat{\tau}^z_{\langle \mathbf{j}_2, \mathbf{j}_1 \rangle} \; \hat{a}^\dagger_{\mathbf{j}_2} \hat{a}_{\mathbf{j}_1} + \text{h.c.}$$

- Can be implemented in ultracold atom systems!

  Barbiero et al., arXiv:1810.02777

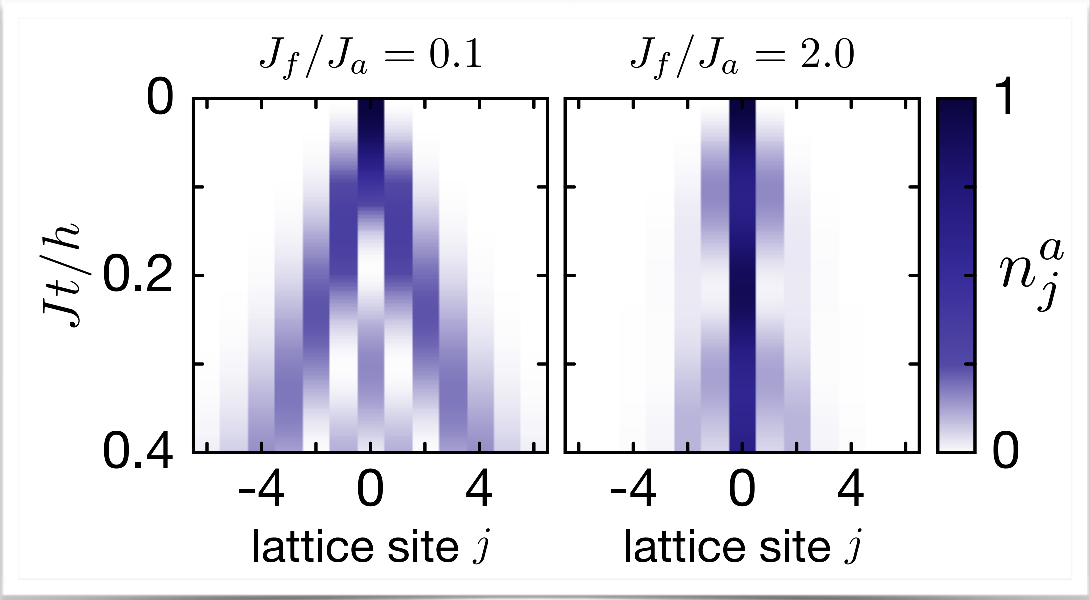
  Schweizer et al., arXiv:1901.07103



Outlook

Parton dynamics

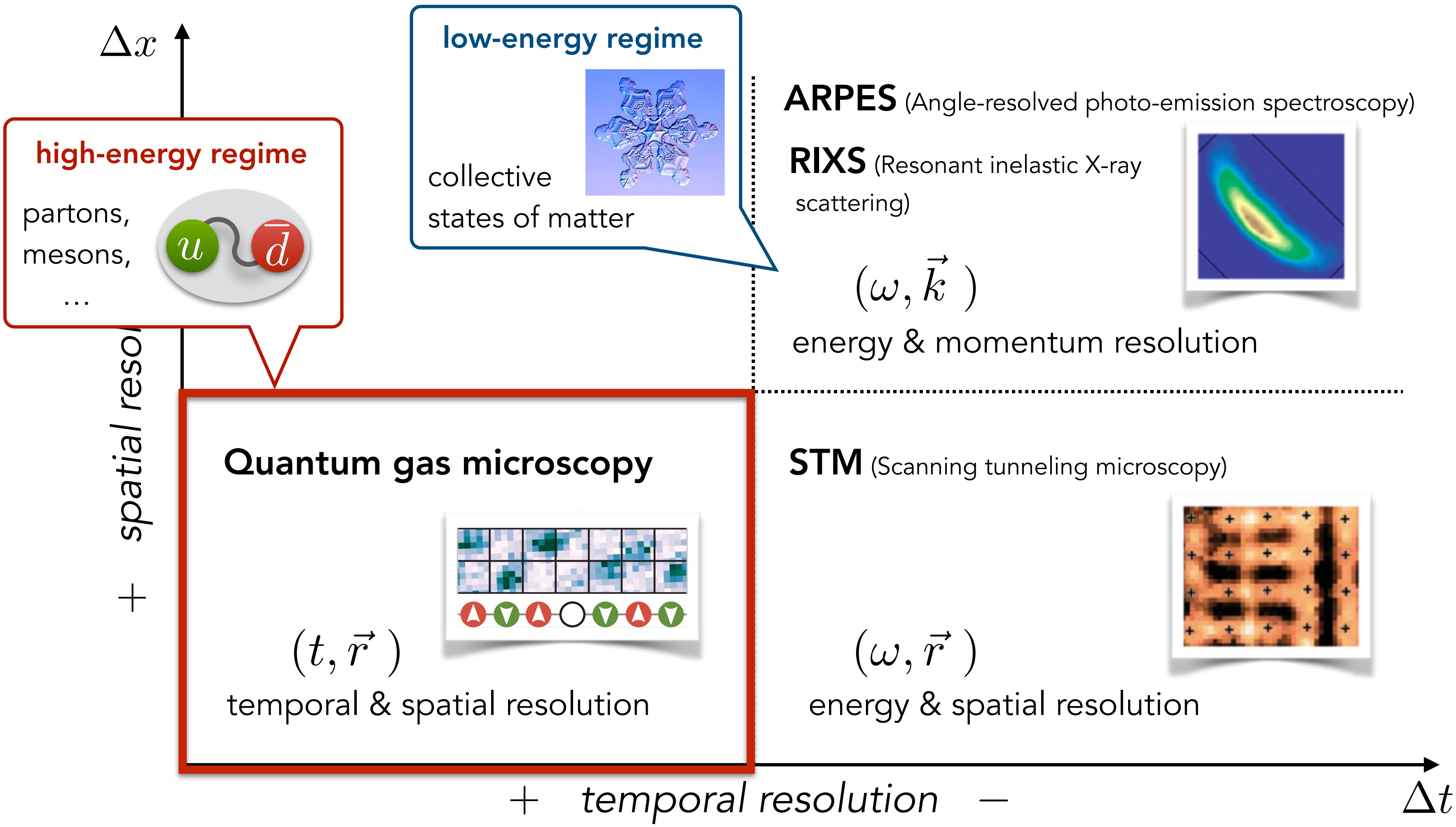
- Real-space probes of confinement



Schweizer et al., arXiv:1901.07103

Quantum gas microscopy

Summary



... thanks for your attention!

Gordon and Betty MOORE FOUNDATION

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(Munich)

Eugene Demler
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Immanuel Bloch
(Munich)

Markus Greiner
(Harvard)

Christian Gross
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Daniel Greif
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Ultracold magnetism

Eugene Demler
Markus Greiner
Immanuel Bloch
Daniel Greif
Christian Gross
Annabelle Bohrdt
Christie Chiu
Geoffrey Ji
Muqing Xu
Timon Hilker
Joannis Koepsell
Guillaume Salomon
Jayadev Vijayan
Pimonpan Sompet
Sarah Hirte
Michael Knap
Zheng Zhu
Tao Shi
Lode Pollet
Ahmed Omran
Marton Kanasz-Nagy

Z2 lattice gauge theory

C. Schweizer, L. Barbiero, M. Berngruber, I. Bloch, M. Aidelsburger, Eugene Demler, Nathan Goldman

PHYSICS

https://sites.google.com//site/quantmanybody/