Title: Theoretical advances from simulating strongly correlated quantum matter and doped antiferromagnets

Speakers: Fabian Grusdt

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Subject: Quantum Information

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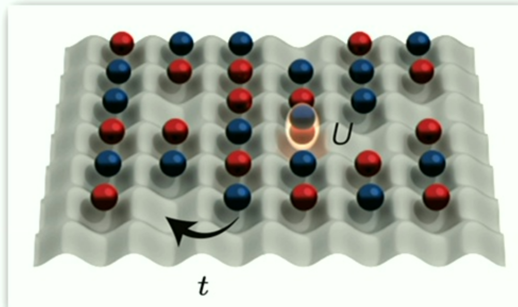
Theoretical advances from simulating strongly correlated quantum matter and doped antiferromagnets



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LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN MCQST FOR 2414 DFG-Research Unit QUANTERA ERA-NET Cofund in Quantum Technologies Dynamite erc European Research Council

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www.quantummanybody.de

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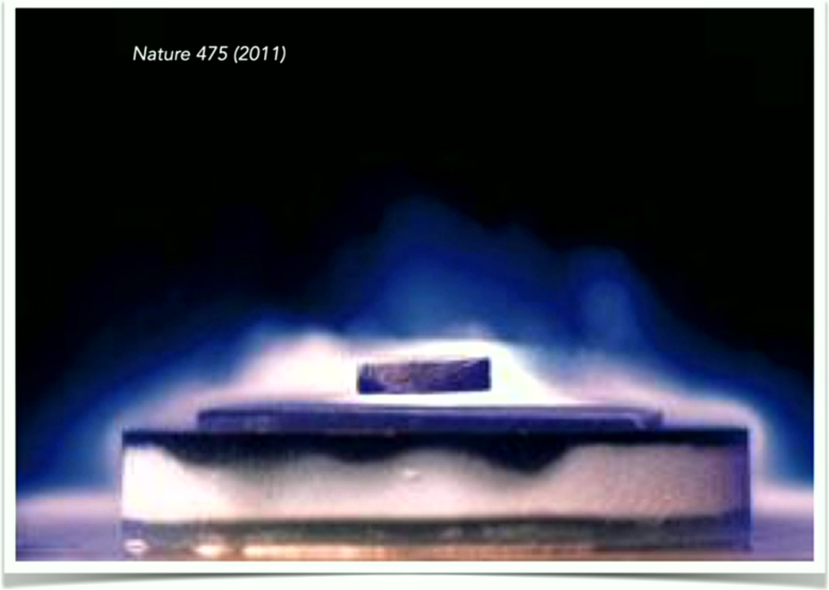
Motivation

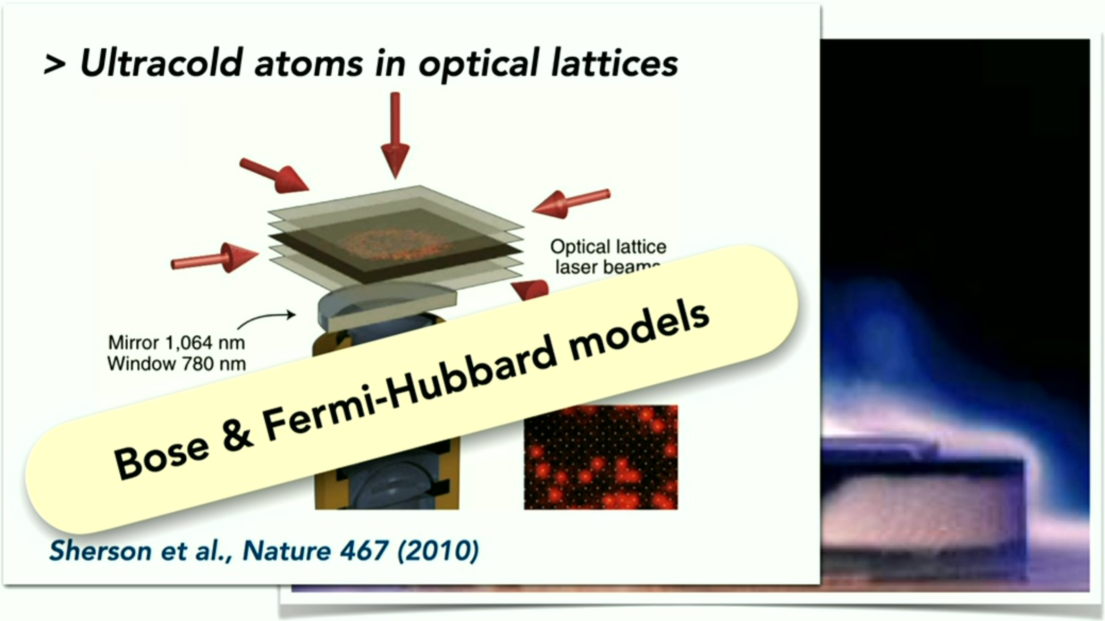
Quantum simulation of Quantum Matter



High-Tc superconductivity

Motivation

Quantum simulation of Quantum Matter



High-Tc superconductivity

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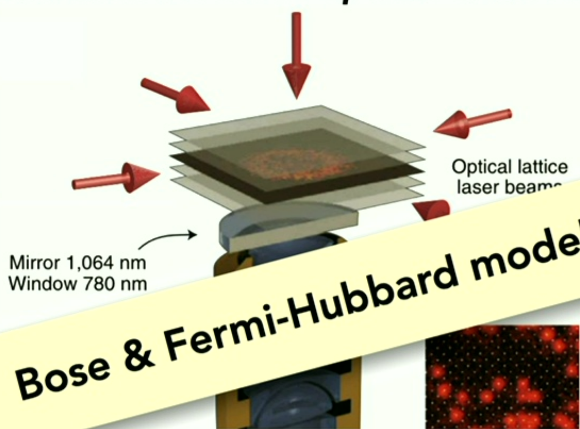
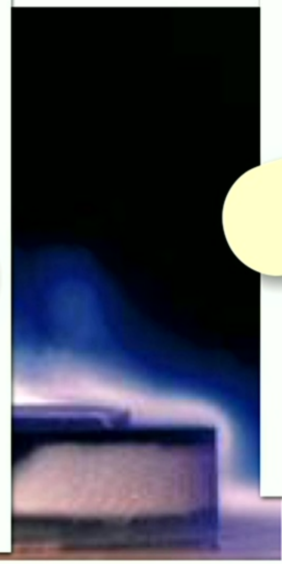
Motivation

Quantum simulation of Quantum Matter

> *Ultracold atoms in optical lattices*





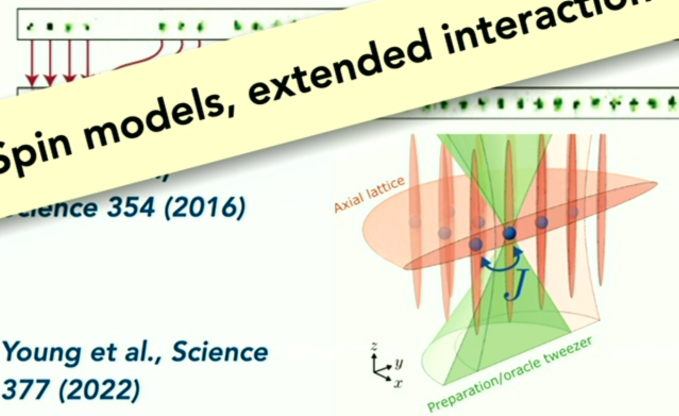
Bose & Fermi-Hubbard models

Sherson et al., Nature 467 (2010)

> *Rydberg tweezer arrays*

Spin models, extended interactions

cience 354 (2016)

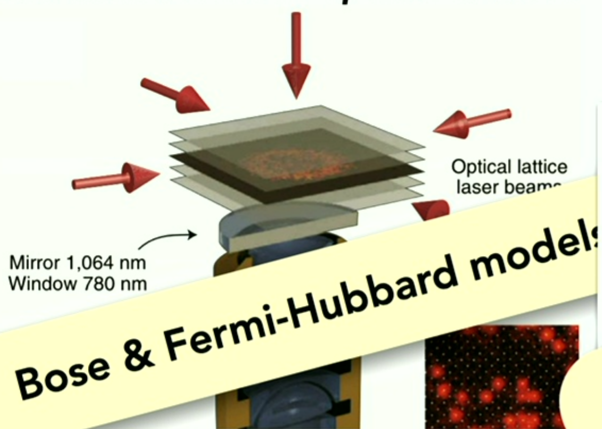


Young et al., Science 377 (2022)

Motivation

Quantum simulation of Quantum Matter

> Ultracold atoms in optical lattices



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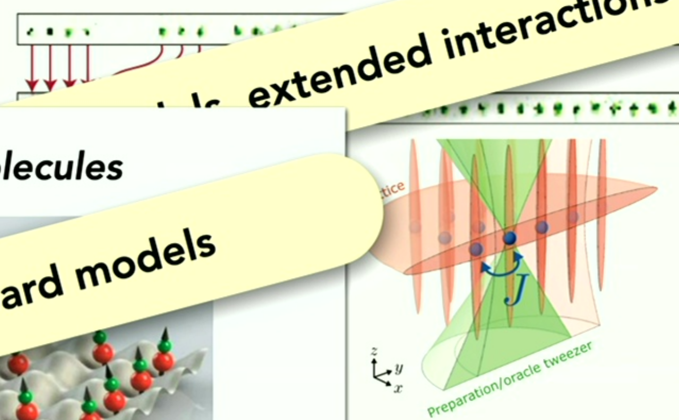
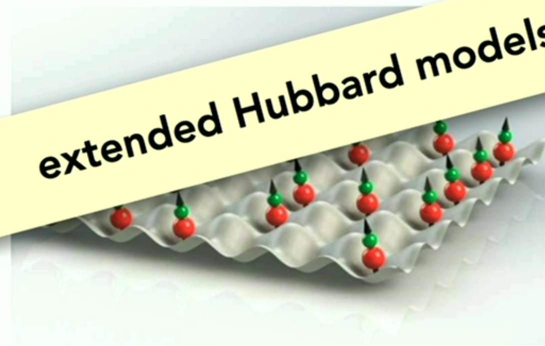


extended interactions

> Dipolar atoms & molecules



extended Hubbard models

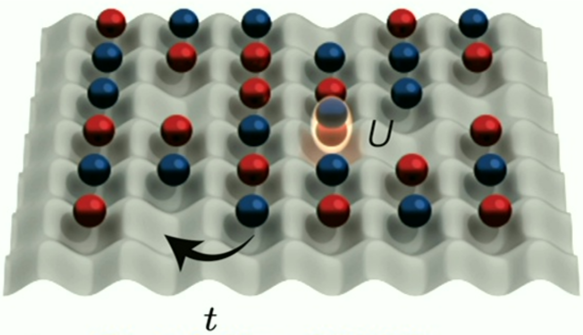
Christakis et al., Nature 614 (2023)

Doped quantum magnets

The Fermi-Hubbard and *t-J* Models

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

repulsive *U>0* — *strong pairing?!?*

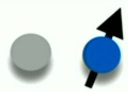


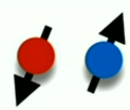
from: Chiu et al., Science 365 (2019)

* **Large $U \gg t$: no double-occupancy**

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

+ NNN hopping term O(J)





Doped quantum magnets

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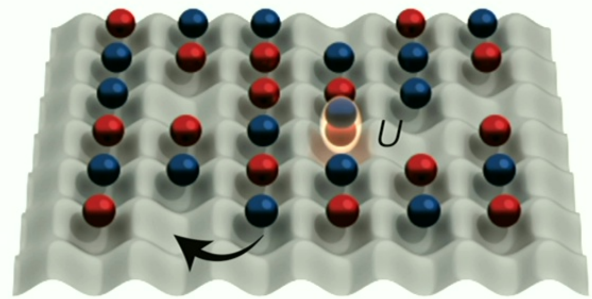

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* ***Large*** $U \gg t$***: no double-occupancy*** $t \gg J$

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

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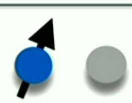

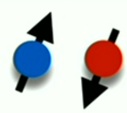

fermionic charge model

bosonic spin model

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Doped quantum magnets

The Fermi-Hubbard and *t-J* Models

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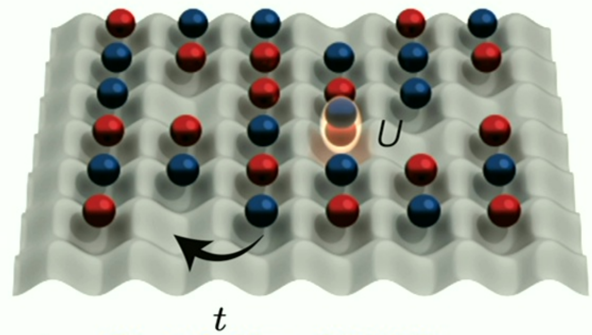

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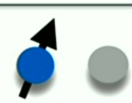
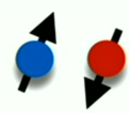
~~+ NNN hopping term O(J)~~

neglected in *t-J*





fermionic charge model

bosonic spin model

Doped quantum magnets

Annals of Physic

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Annals

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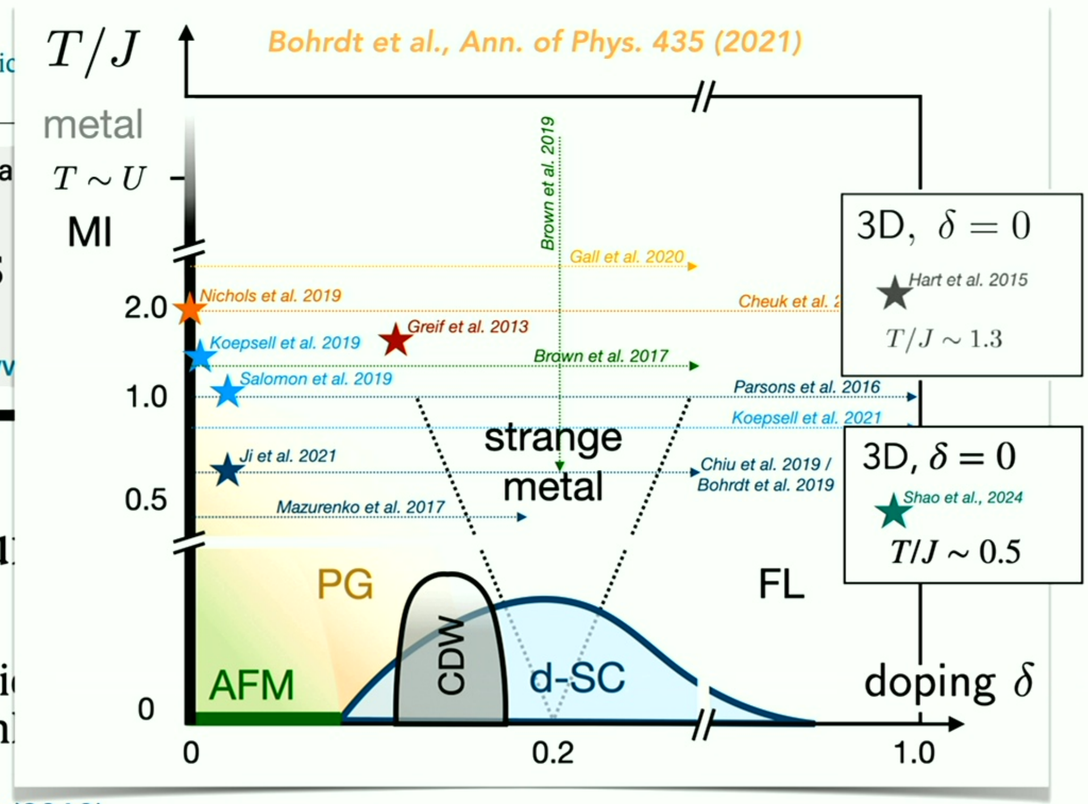
Exploration of doped quantu
ultracold atoms

Annabelle Bohrdt [a,b,c,d], Lukas Homei
Christian Reinmoser [f,b], Eugene Deml

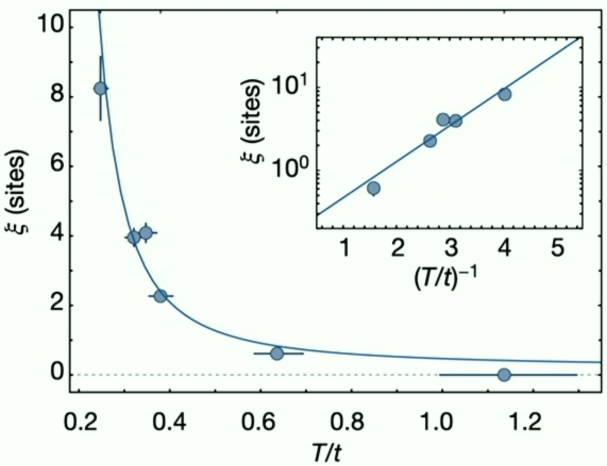


Earlier reviews: ***Esslinger, Ann. Rev. Cond. Mat. 1 (2010)***
Tarruell & Sanchez-Palencia, Compt. Rend. Phys. 19 (2018)

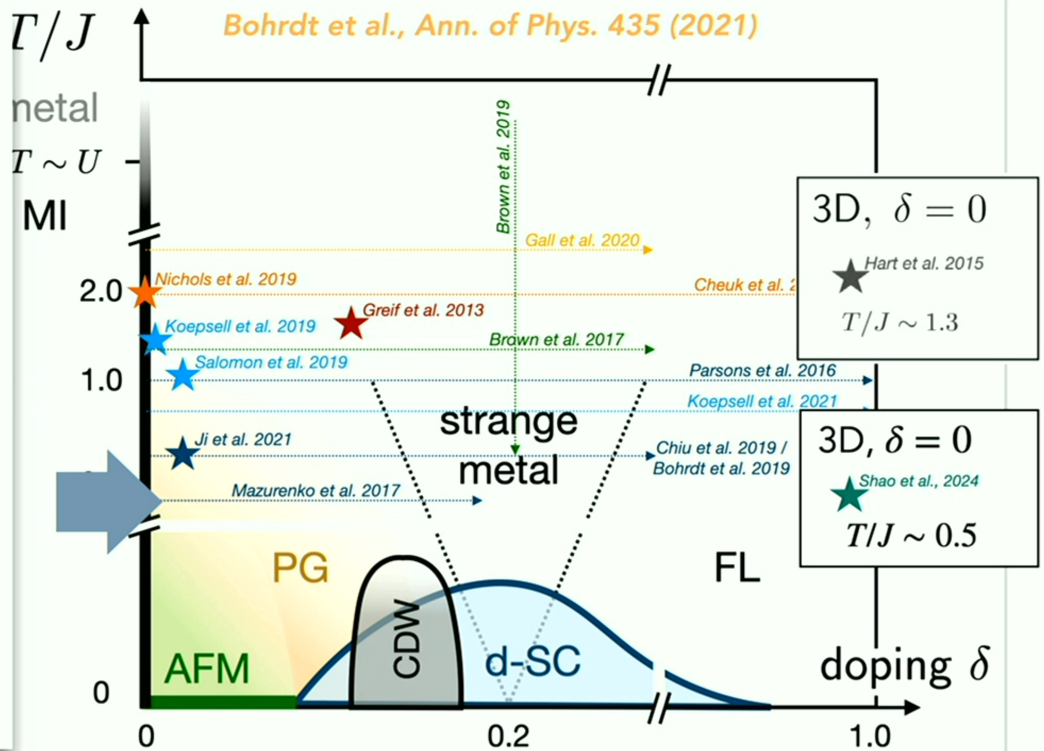
Doped quantum magnets

Antiferromagnet in 2D

Mazurenko et al., Nature 545 (2017) — Greiner lab



✱ *Bulk antiferromagnet (AFM)*



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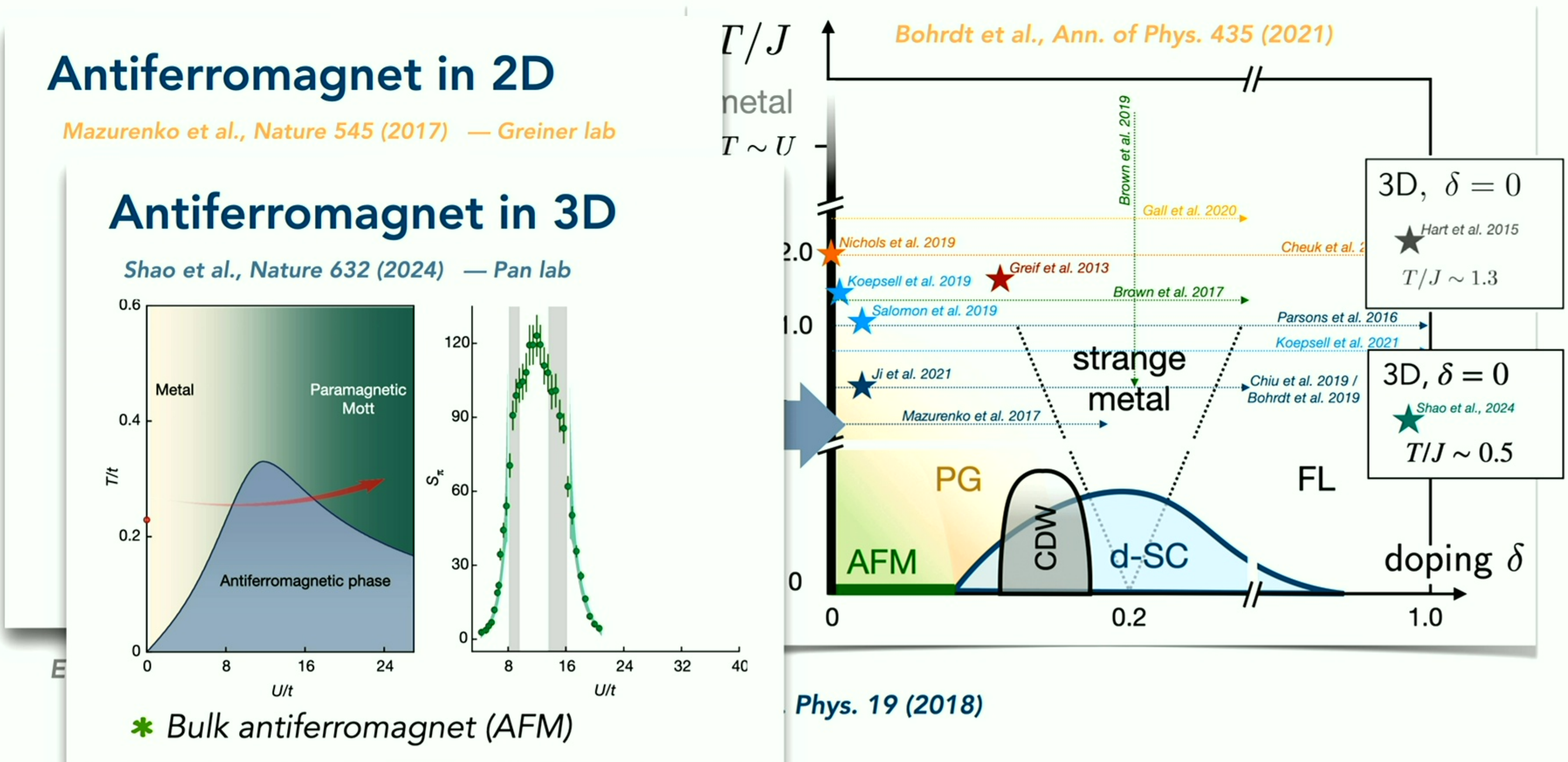

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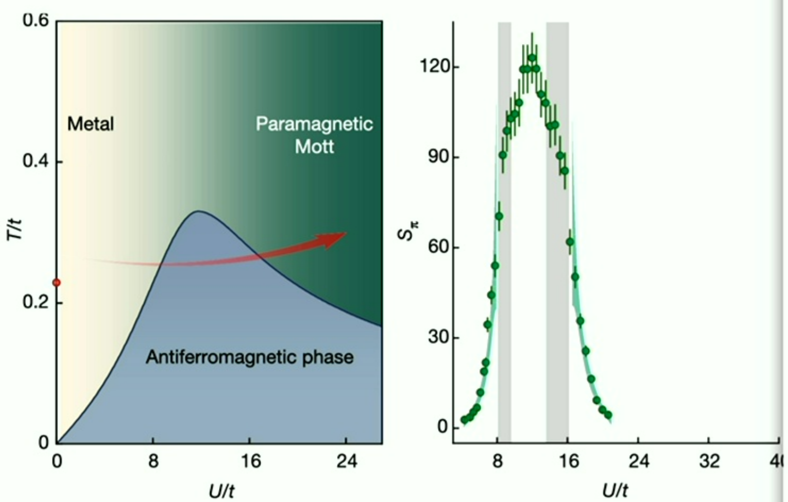
Doped quantum magnets

Antiferromagnet in 2D

Mazurenko et al., Nature 545 (2017) — Greiner lab

Antiferromagnet in 3D

Shao et al., Nature 632 (2024) — Pan lab



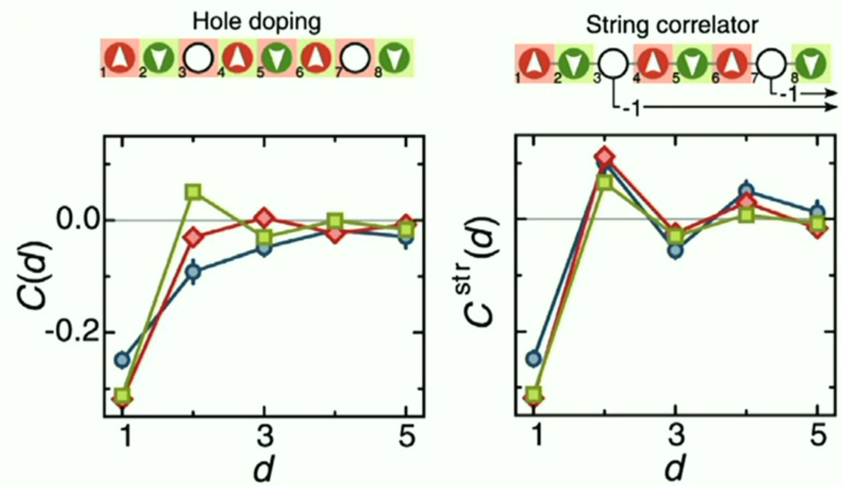
✱ *Bulk antiferromagnet (AFM)*

T/J

Bohrdt et al., Ann. of Phys. 435 (2021)

Hidden AFM correlations in 1D

Hilker et al., Science 357 (2017) — Bloch lab



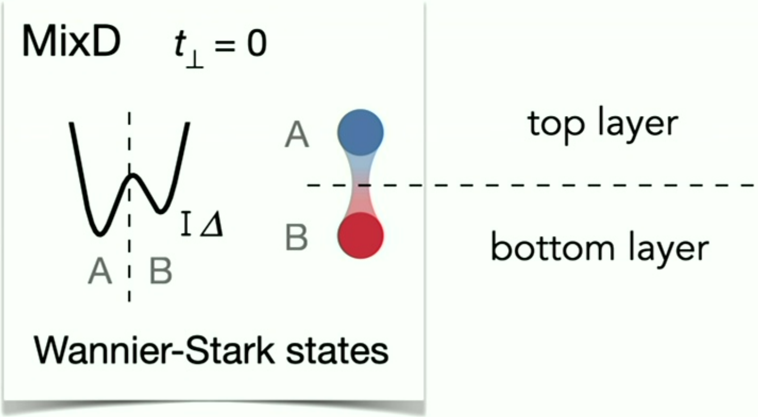
✱ *Signatures of spin-charge separation!*

Heavy-fermions & Kondo physics

The Anderson & Kondo models

- Cold atoms: *Bohrdt et al., Ann. of Phys. 435 (2021)*

$$\hat{\mathcal{H}} = -t_{AB} \sum_{\sigma} (\hat{a}^\dagger_\sigma \hat{b}_\sigma + \text{h.c.}) + \sum_{\mu=a,b} U_\mu \hat{n}_{\mu\uparrow} \hat{n}_{\mu\downarrow} + \Delta \sum_{\sigma} \hat{n}_{b\sigma}$$



- ***Large*** $|\Delta \pm U_{A,B}| \gg t_{AB}$***: Kondo coupling*** *Trotzky et al., Science 319 (2008)*

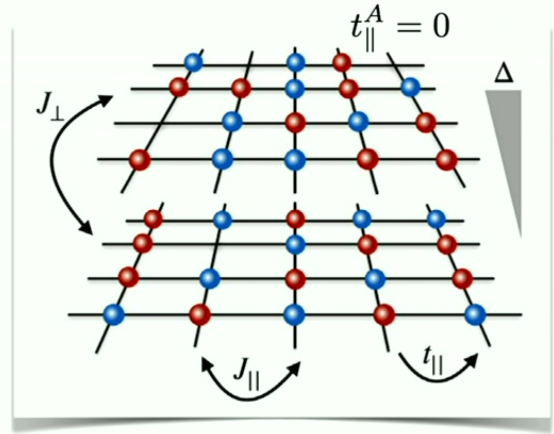
$$\hat{\mathcal{H}}_{\text{K}} = J_\perp \, \hat{\mathbf{S}}_A \cdot \hat{\mathbf{S}}_B$$

$$J_\perp = \frac{2t_{AB}^2}{U_A - \Delta} + \frac{2t_{AB}^2}{U_B + \Delta}, \quad t_\perp = 0$$

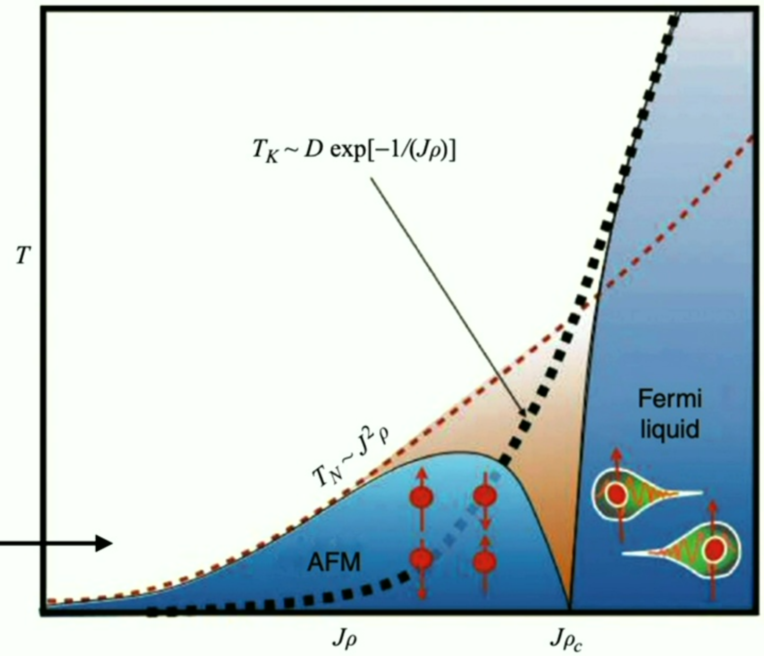
Heavy-fermions & Kondo physics

The Doniach phase diagram: Kondo lattice

Coleman, "Introduction to Many-Body physics"



RKKY interactions dominate



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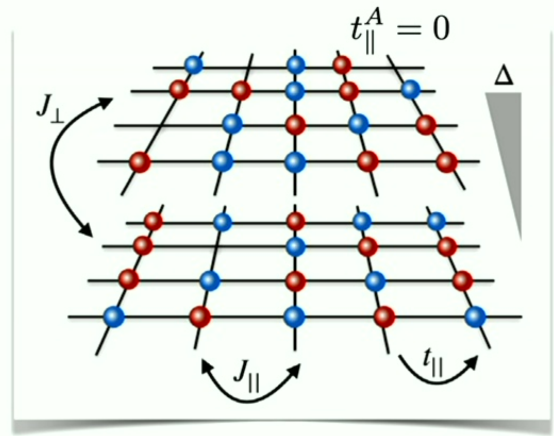

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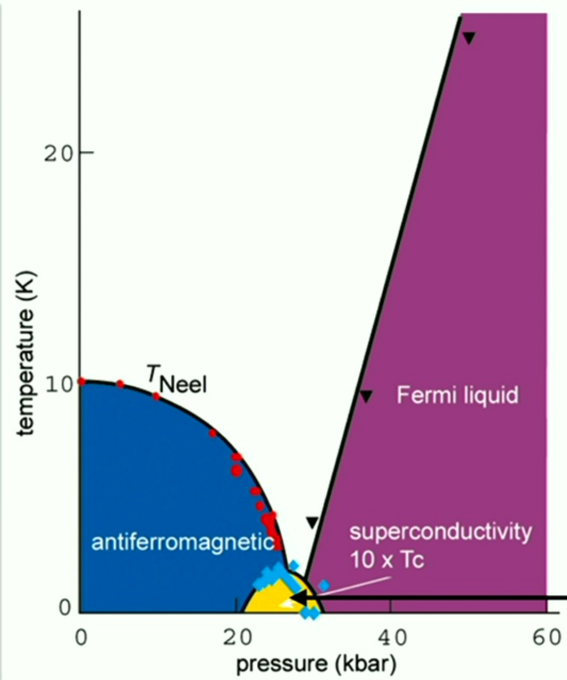


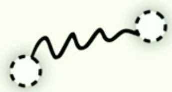
Kondo interactions dominate

Heavy-fermion superconductor

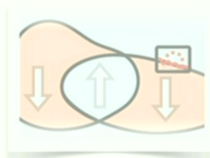
https://physicsworld.com/a/ferromagnetic-superconductors/


Cuprate land
Quantum
simulation
mixD land?!
Kondo land

Outline

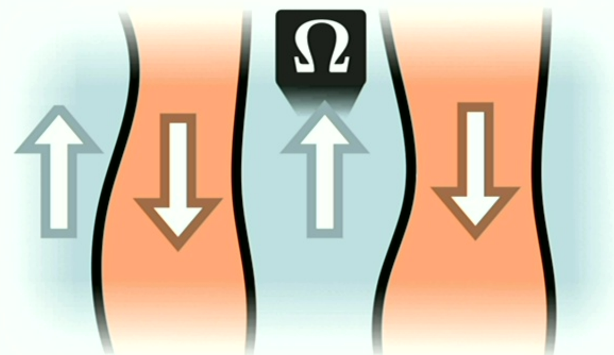


New models: Stripe formation and strong pairing



New scenario: Hidden symmetry breaking & AFM order

Stripes



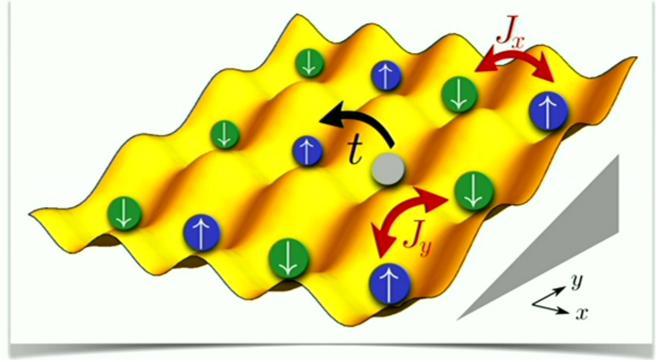
The mixD *t-J* model

Mixed-dimensional systems:

- **Suppressed** charge motion along *y*!
- **Tunable super-exchange** interactions along *y*!

$$J_x = \frac{4t^2}{U}, \qquad J_y = \frac{2t^2}{U+\Delta} + \frac{2t^2}{U-\Delta}$$

see also: Dimitrova et al., PRL 124 (2020)
Trotzky et al., Science 319 (2008)



Grusdt et al., SciPost Phys. 5 (2018)

- Effective mixD *t-J* Hamiltonian:

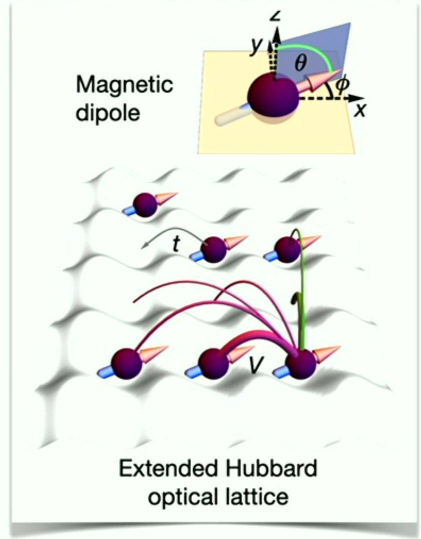
$$\hat{\mathcal{H}} = \sum_{\langle i,j \rangle_x} \left[-t \sum_{\sigma} \hat{\mathcal{P}}_{\text{GW}} \left(\hat{c}^{\dagger}_{i,\sigma} \hat{c}_{j,\sigma} + \text{h.c.} \right) \hat{\mathcal{P}}_{\text{GW}} + J_x \left(\hat{\boldsymbol{S}}_i \cdot \hat{\boldsymbol{S}}_j - \frac{\hat{n}_i \hat{n}_j}{4} \right) \right] + J_y \sum_{\langle i,j \rangle_y} \left(\hat{\boldsymbol{S}}_i \cdot \hat{\boldsymbol{S}}_j - \frac{\hat{n}_i \hat{n}_j}{4} \right)$$

The mixD *t-Jz* model

Mixed-dimensional toy model:

Kebric et al., in prep.

Su et al., Nature 622 (2023)



$$\hat{\mathcal{H}} = -t \sum_{\sigma,\langle \boldsymbol{i},\boldsymbol{j}\rangle_x} \hat{\mathcal{P}}\big(\hat{c}^\dagger_{\boldsymbol{i},\sigma}\hat{c}_{\boldsymbol{j},\sigma} + \text{h.c.}\big)\hat{\mathcal{P}} + \sum_{\langle \boldsymbol{i},\boldsymbol{j}\rangle} J_z \hat{S}^z_{\boldsymbol{i}}\hat{S}^z_{\boldsymbol{j}}$$

1D 2D

1:1 mapping to Z2 LGT with dynamical charges

$$\hat{\mathcal{H}} = -t \sum_{\langle \boldsymbol{i},\boldsymbol{j}\rangle_x} \Big(\hat{h}^\dagger_{\boldsymbol{i}}\,\hat{\tau}^z_{\langle \boldsymbol{i},\boldsymbol{j}\rangle_x}\hat{h}_{\boldsymbol{j}} + \text{h.c.}\Big) + \frac{J_z}{2}\sum_{\boldsymbol{j}} \hat{n}^h_{\boldsymbol{j}} - \frac{J_z}{4}\sum_{\langle \boldsymbol{i},\boldsymbol{j}\rangle_x} \hat{n}^h_{\boldsymbol{i}}\hat{n}^h_{\boldsymbol{j}} - \frac{J_z}{8}\sum_{\langle \boldsymbol{i},\boldsymbol{j}\rangle_y} (1-\hat{n}^h_{\boldsymbol{i}})(1-\hat{n}^h_{\boldsymbol{j}})$$
$$\times \Big[\hat{\tau}^x_{\langle \boldsymbol{i}-\boldsymbol{e}_x,\boldsymbol{i}\rangle_x}\hat{\tau}^x_{\langle \boldsymbol{j}-\boldsymbol{e}_x,\boldsymbol{j}\rangle_x} + \hat{\tau}^x_{\langle \boldsymbol{i},\boldsymbol{i}+\boldsymbol{e}_x\rangle_x}\hat{\tau}^x_{\langle \boldsymbol{j},\boldsymbol{j}+\boldsymbol{e}_x\rangle_x}\Big]$$

Grusdt & Pollet, PRL 125 (2020)

> confinement?!

The mixD *t-Jz* model

Mapping to Z2 gauge theory:

Phase: 0 or π | tunneling | electric terms

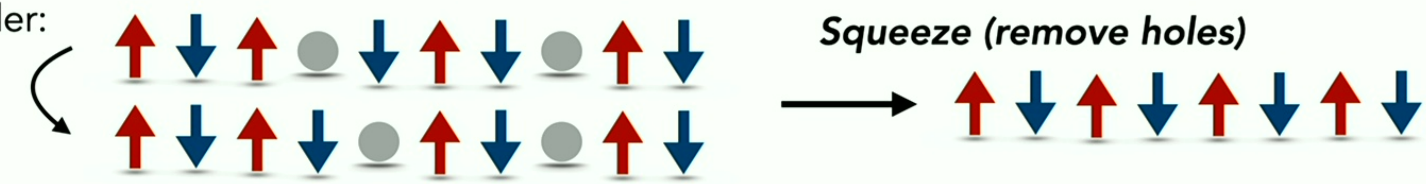
$\mathbb{Z}_2$ minimal coupling $\quad -\hat{h}^\dagger_{\mathbf{i}} \hat{\tau}^z_{\langle \mathbf{i},\mathbf{j}\rangle} \hat{h}_{\mathbf{j}} + \text{h.c.} \quad -\frac{J_z}{4} \hat{\tau}^x_{\langle \mathbf{i},\mathbf{j}\rangle} \hat{\tau}^x_{\langle \mathbf{i}+\mathbf{e}_y,\mathbf{j}+\mathbf{e}_y\rangle}$

- **Key ingredient: Squeezed space construction**

  Kruis et al., PRB 70 (2004)

  - The 1D t-J_z model: $$\hat{\mathcal{H}} = -t \sum_{\sigma,\langle \boldsymbol{i},\boldsymbol{j}\rangle_x} \hat{\mathcal{P}}\left(\hat{c}^\dagger_{\boldsymbol{i},\sigma} \hat{c}_{\boldsymbol{j},\sigma} + \text{h.c.}\right)\hat{\mathcal{P}} + \sum_{\langle \boldsymbol{i},\boldsymbol{j}\rangle} J_z \hat{S}^z_{\boldsymbol{i}} \hat{S}^z_{\boldsymbol{j}}$$

  - Hidden AFM order:



Related experiments: Hilker et al., Science 357 (2017)

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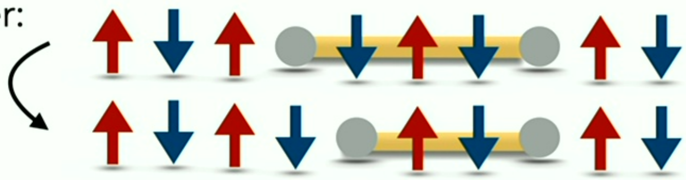
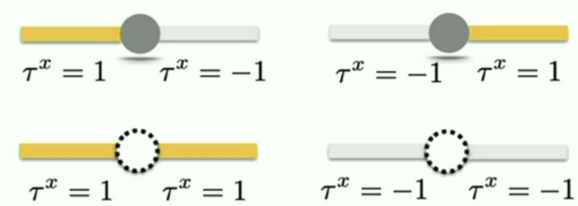


Z2 Gauss law (constraint): $\hat{G}_{\mathbf{j}}|\psi\rangle = |\psi\rangle, \quad \forall \mathbf{j}$

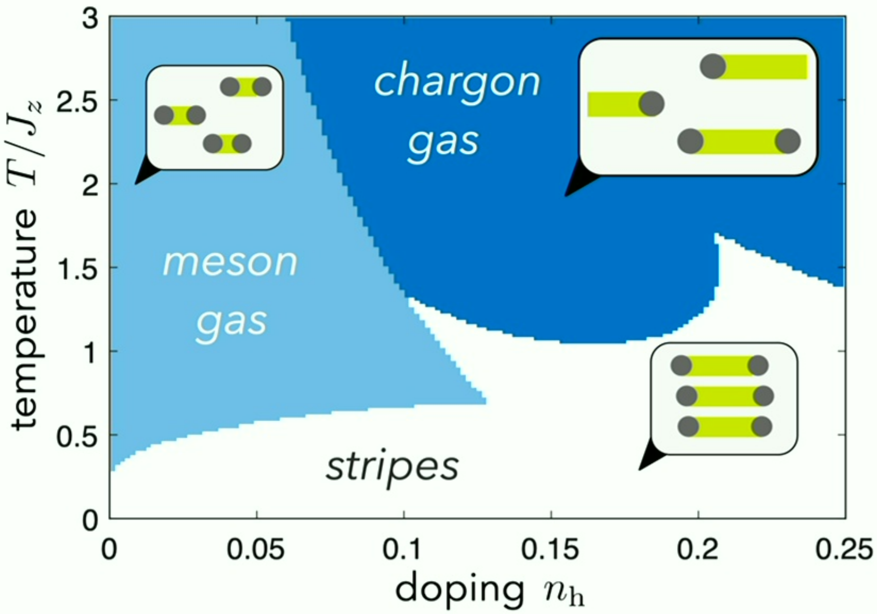


Related experiments: Hilker et al., Science 357 (2017)

The mixD *t-Jz* model

Exotic phases — hidden AFM order & meson gas:

Mean-field description



Grusdt & Pollet, PRL 125 (2020)

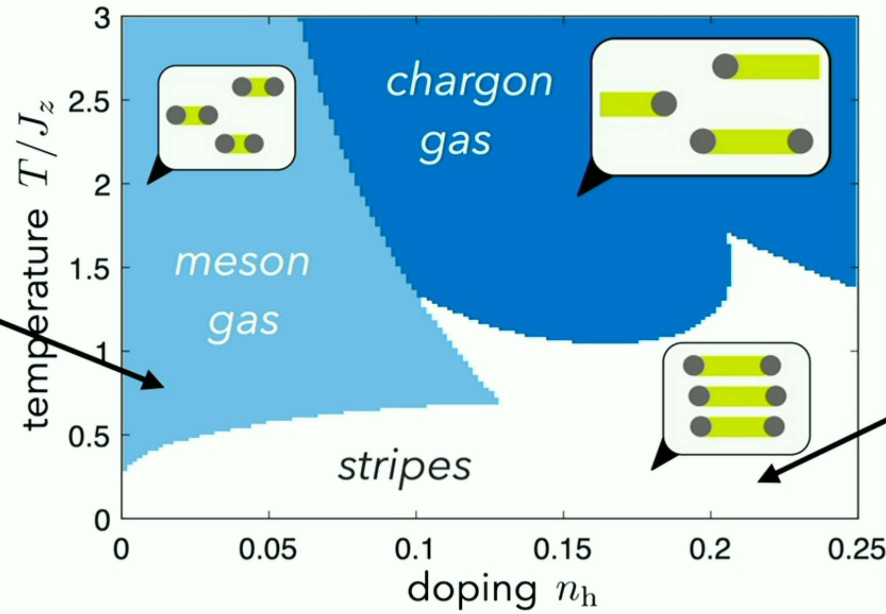
The mixD *t-Jz* model

Exotic phases — hidden AFM order & meson gas:

Mean-field description

Confined chargons

- AFM order



Stripes

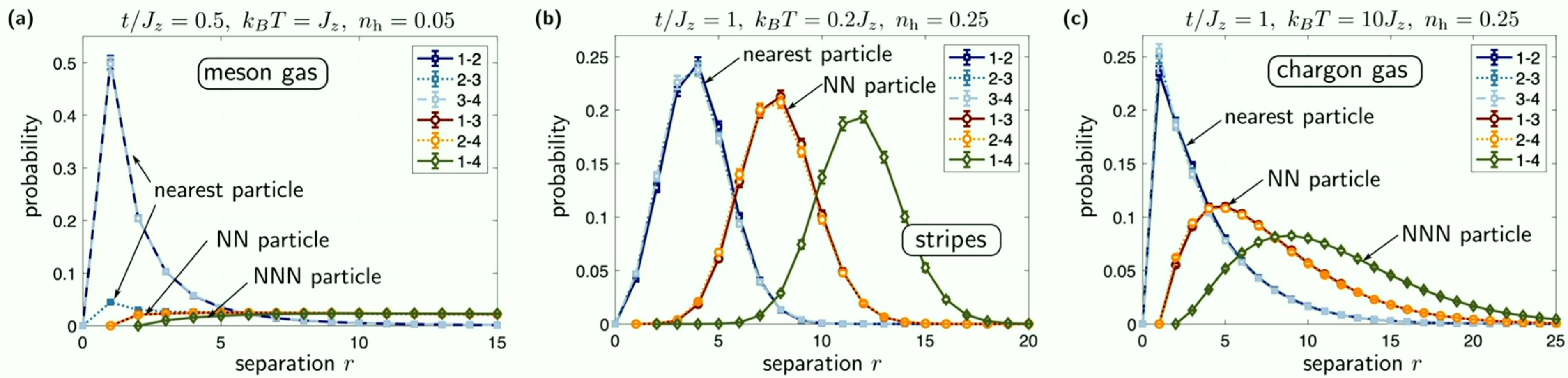
- incommensurate AFM order along x
- long-range AFM along y

Grusdt & Pollet, PRL 125 (2020)

The mixD *t-Jz* model

Exotic phases — hidden AFM order & meson gas:

Particle-distance histograms — from QMC simulations (Lode Pollet)



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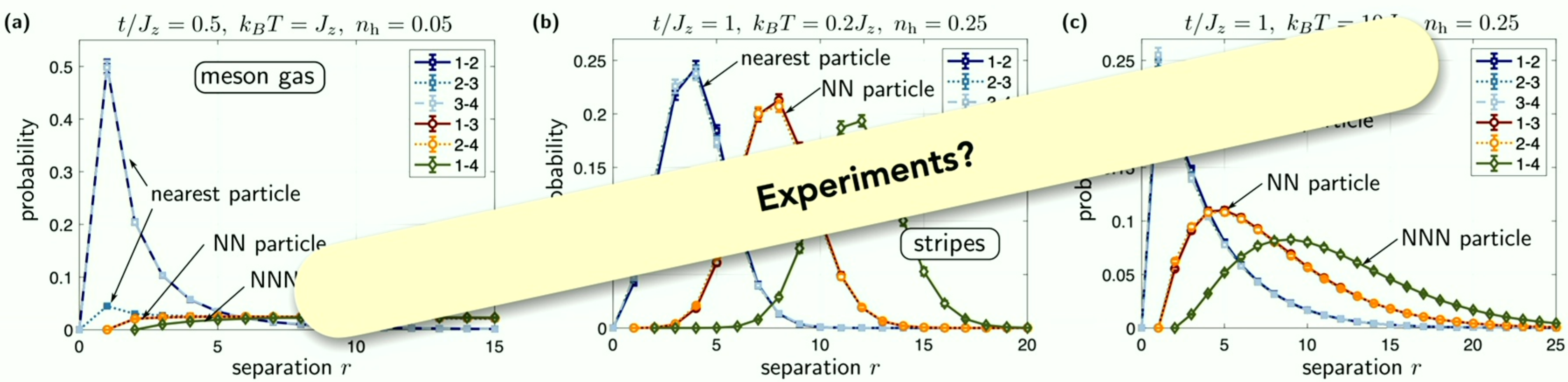
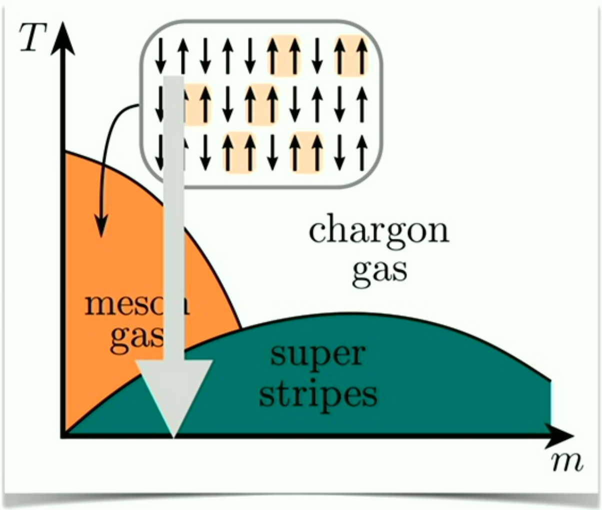


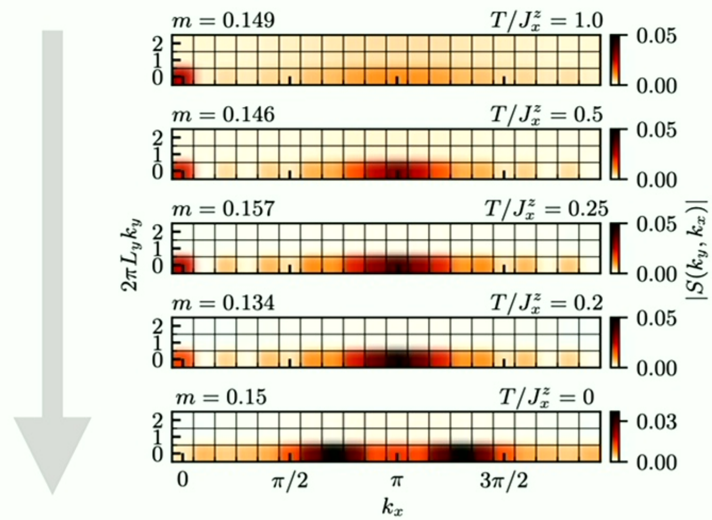
Grusdt & Pollet, PRL 125 (2020)

The mixD XXZ model

Experiment Er lab — Greiner group: *Kebric et al., in prep.*



DMRG simulations



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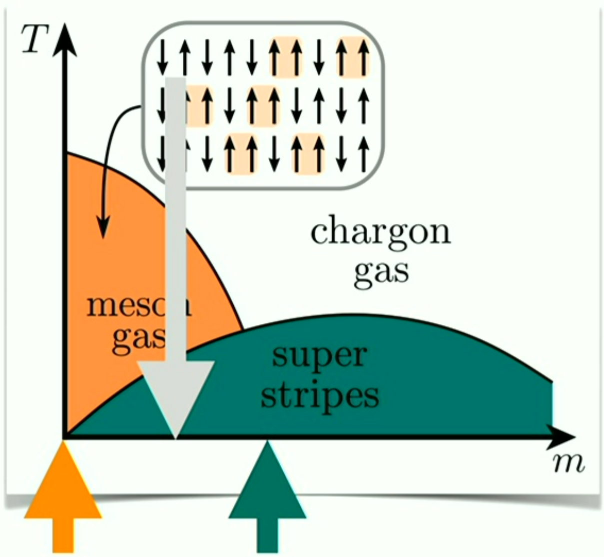
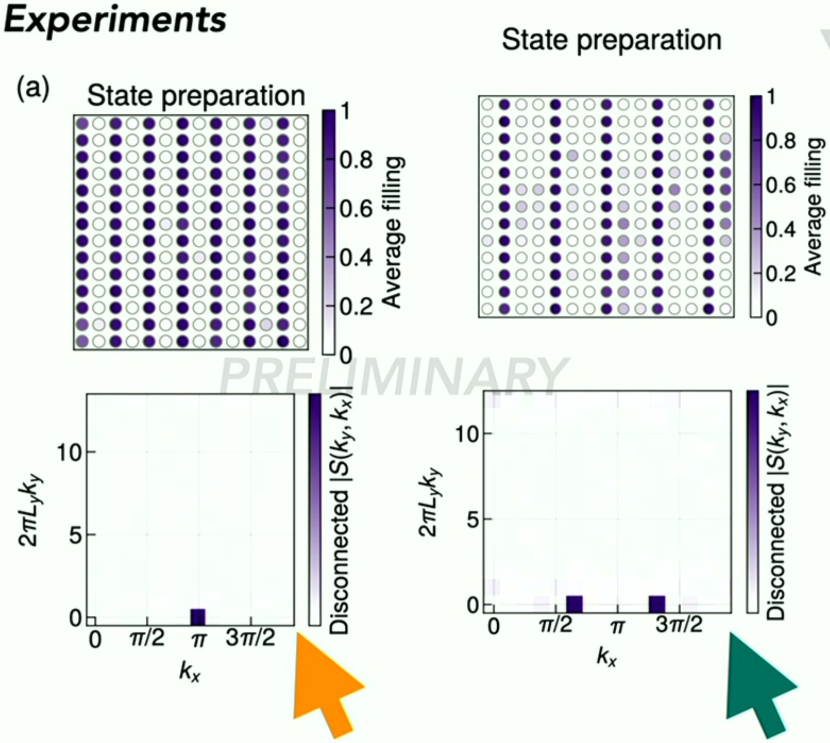
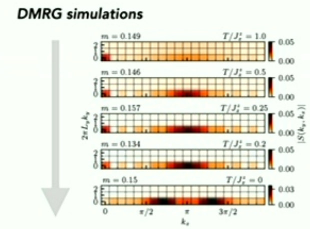


Experiments





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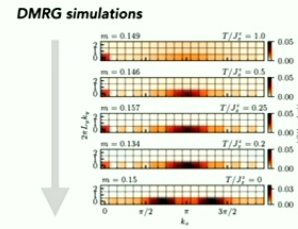
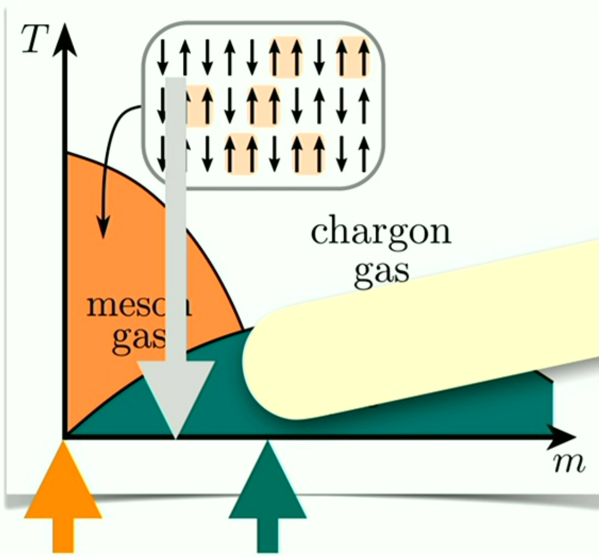
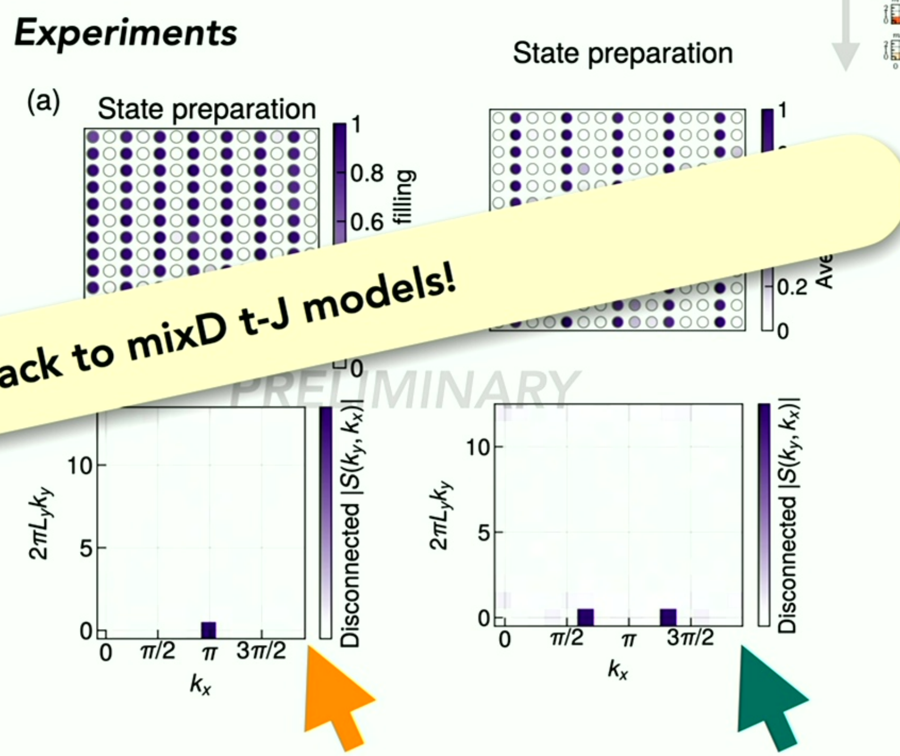


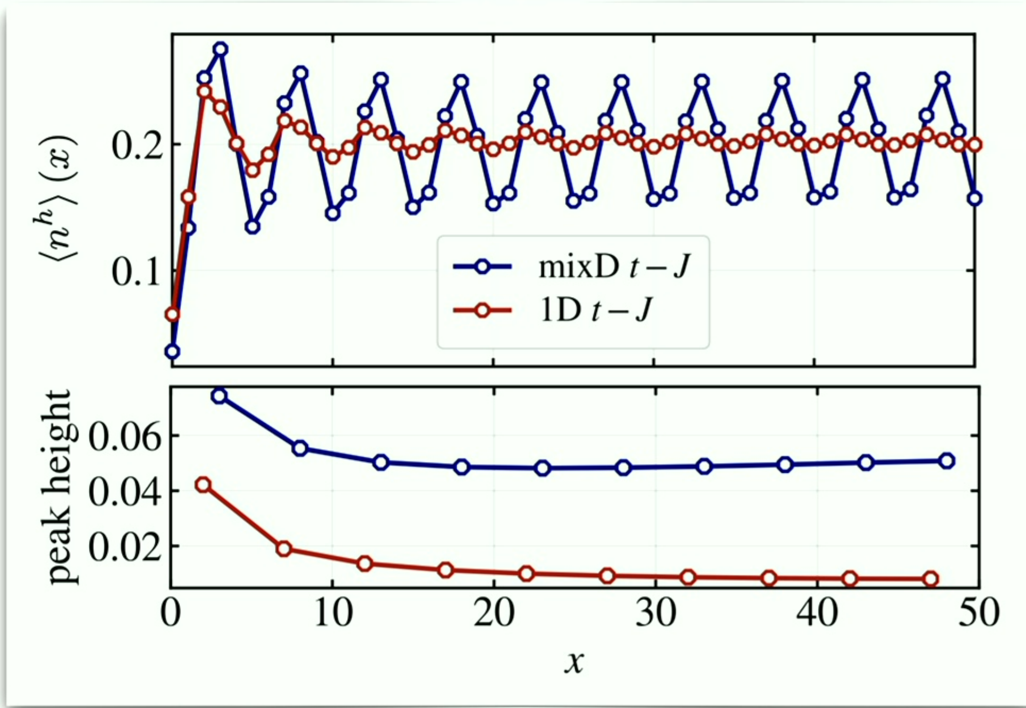




The mixD *t-J* model

Stripe formation in mixed dimensions:

Schlömer et al., PRR 5, L022027 (2023)



- Ground state:

  1D: Friedel oscillations

  mixD: long-range CDW

The mixD *t-J* model

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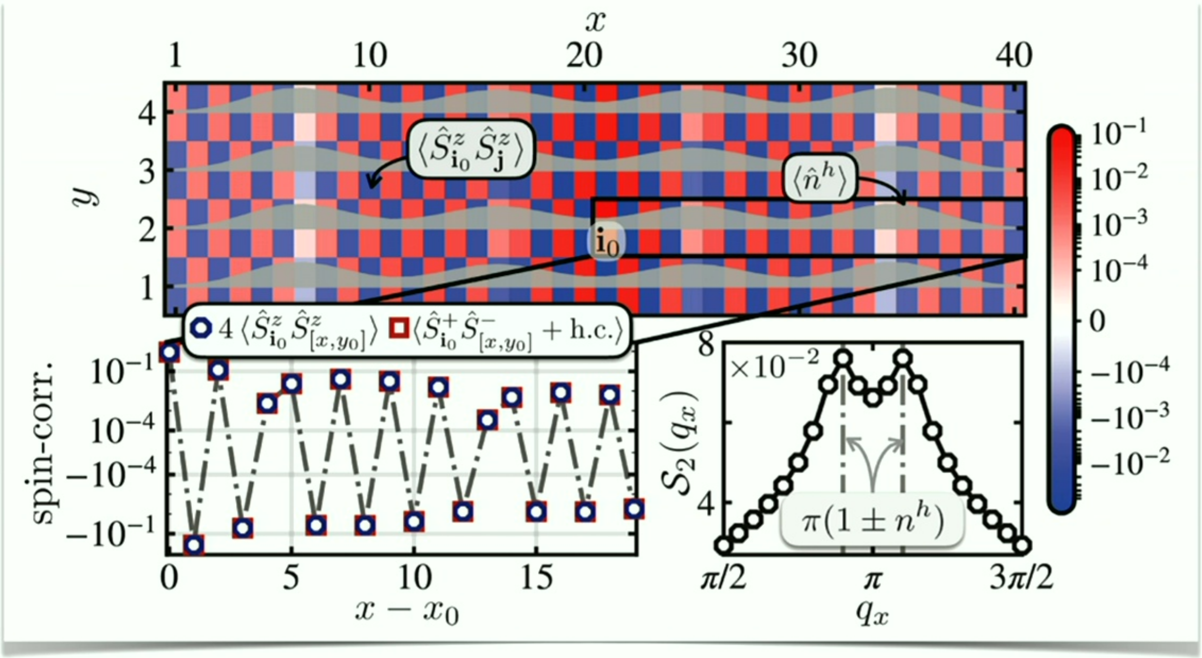
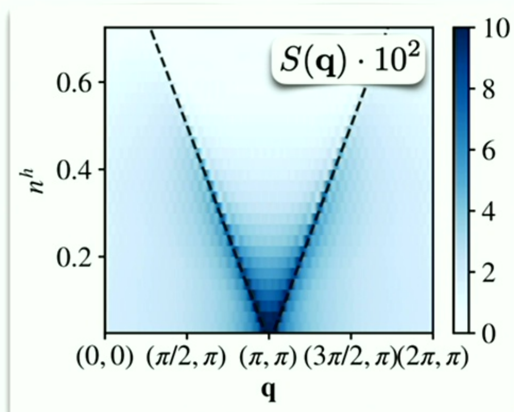
Schlömer et al., PRR 5, L022027 (2023)



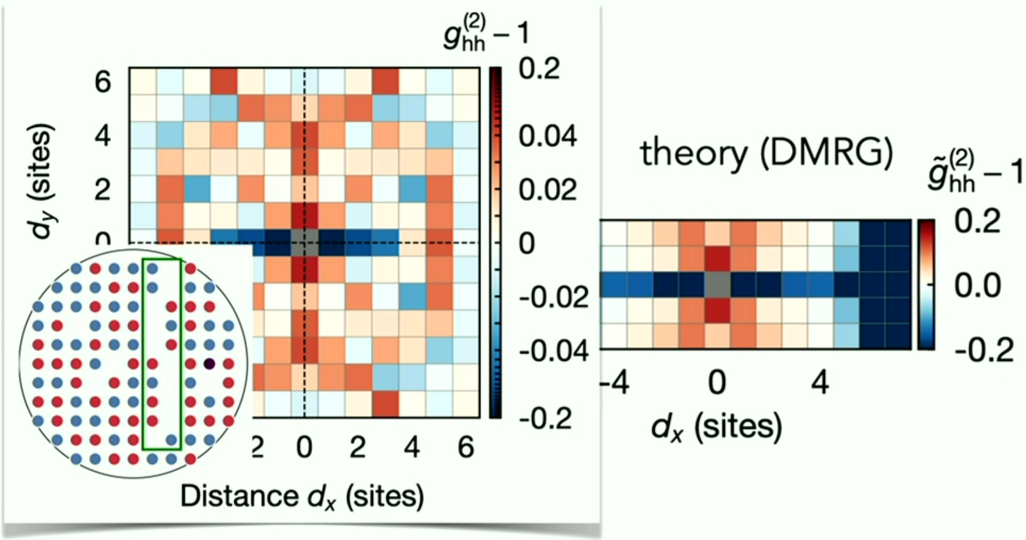
- Ground state:
  - 1D: Friedel oscillations
  - mixD: long-range CDW
- Incommensurate magnetism (mixD):

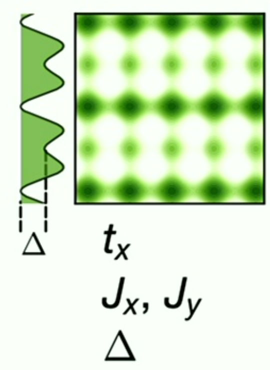


The mixD *t-J* model

Stripe formation in mixed dimensions:

Bourgund et al., arXiv:2312.14156 — Bloch lab





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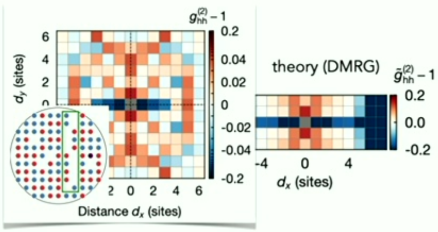
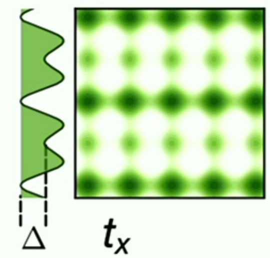
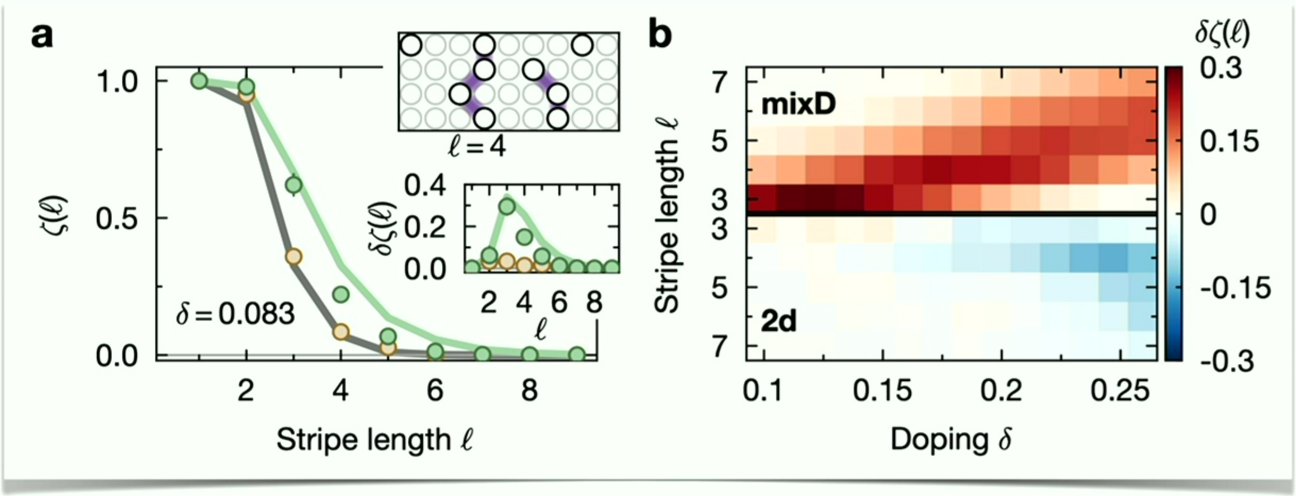


MixD



t_x
J_x, J_y
Δ



The mixD t-J model

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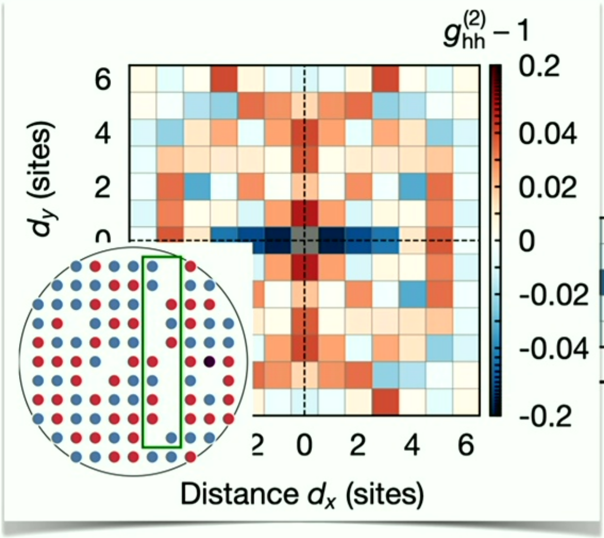
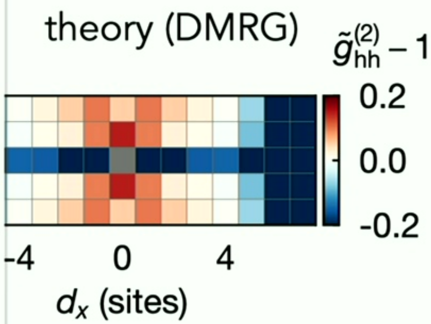
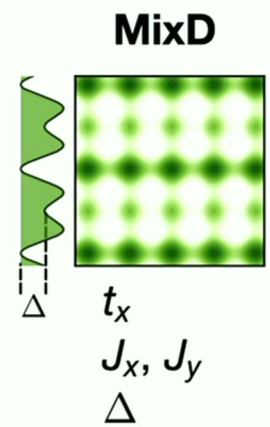
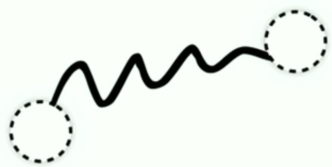




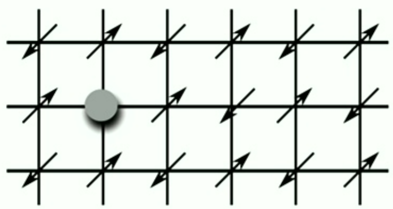


Pairing



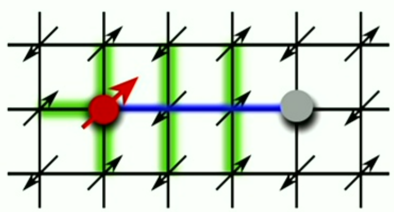
The parton picture

Linear confinement force in doped antiferromagnets:



* **Fractional spin** excitation!

$$S = 1/2$$



* Movement of the hole distorts the Neel state — **spin is carried by distortion!**

* Hole is **bound to the fractional spin (spinon)** at end of string (2D)!

$$E \propto \ell$$

Bulaevskii et al., JETP 27 (1968), Trugman, PRB 37 (1988)
Manousakis, PRB 75 (2007, Kane et al., PRB 39 (1989)
Grusdt et al., PRX 8 (2018)
Grusdt et al., PRB 99 (2019)
Bohrdt et al., PRB 102 (2020)
Bohrdt et al., PRL 127 (2021)

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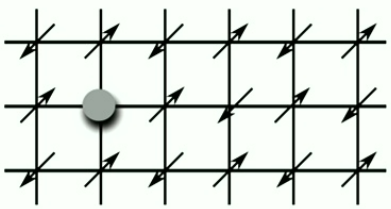

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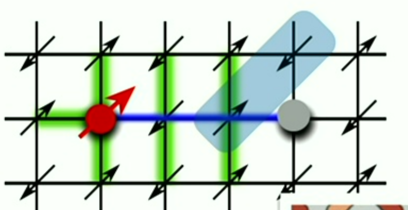
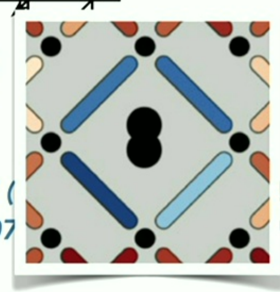


Koepsell et al., Nature 572 (2019)
— Bloch lab



Bulaevskii et al., JETP 27 (… *B 37 (1988)*
Manousakis, PRB 75 (2007 … *(1989)*

Grusdt et al., PRX 8 (2018)
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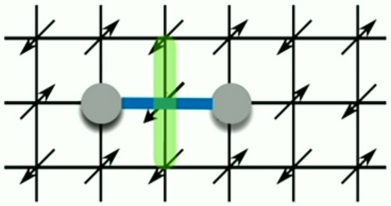
Bohrdt et al., PRB 102 (2020)
Bohrdt et al., PRL 127 (2021)

The parton picture

Pairing from sharing one string:

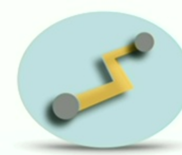


* **Two** hole excitations

* Hole motion generates **string**

* One hole is **bound to another hole** at end of string (2D)

$$E \propto \ell$$

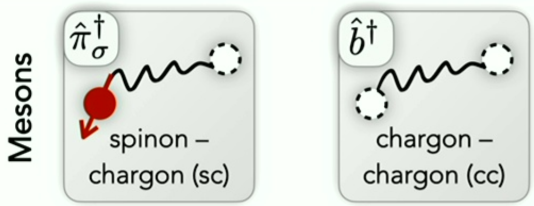


Shraiman & Siggia, PRL 60 (1988)
Bohrdt et al., arXiv:2210.02322v2
Bohrdt et al., Nat. Phys. 18 (2022)
Grusdt et al., SciPost Phys. 14, 090 (2023)

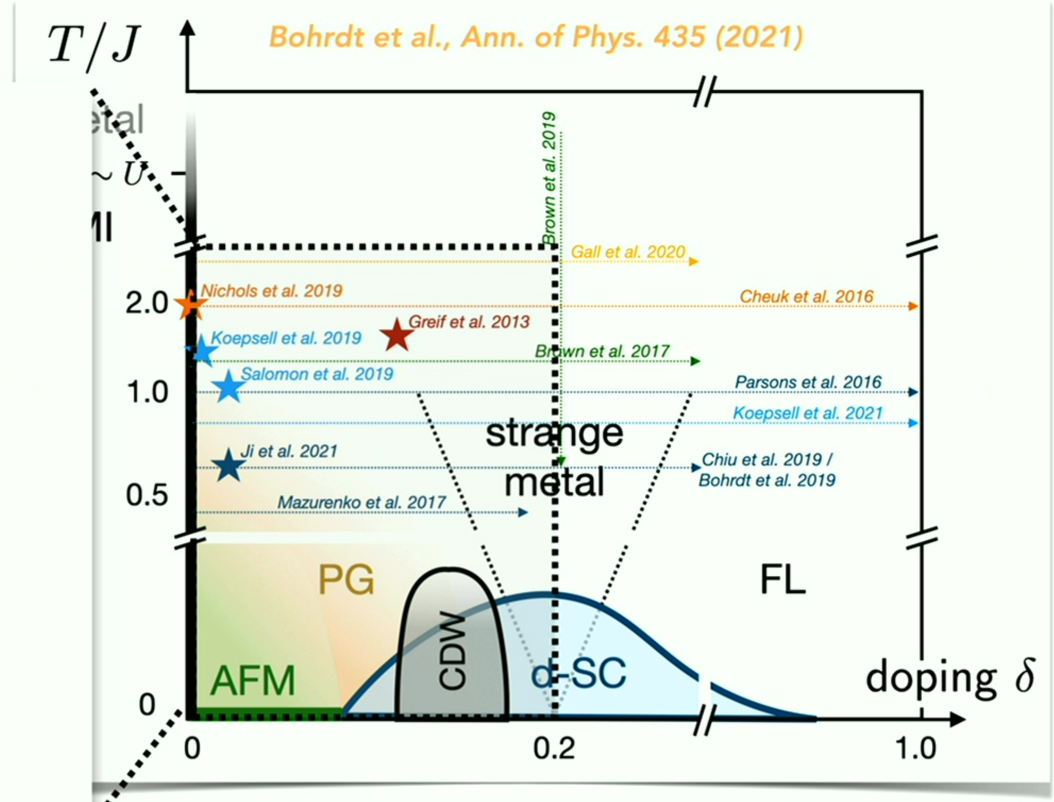
The parton picture

Low doping meson picture

Béran et al., Nuc. Phys. B 473 (1996)
Bohrdt et al., PRB 102 (2020)
Homeier et al., arXiv:2312.02982



* *Charge carriers with rich internal structure!*



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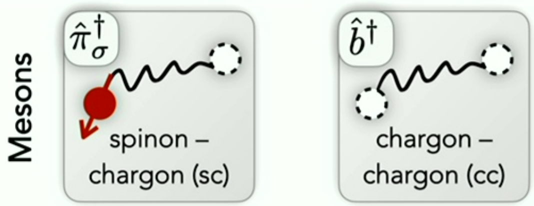
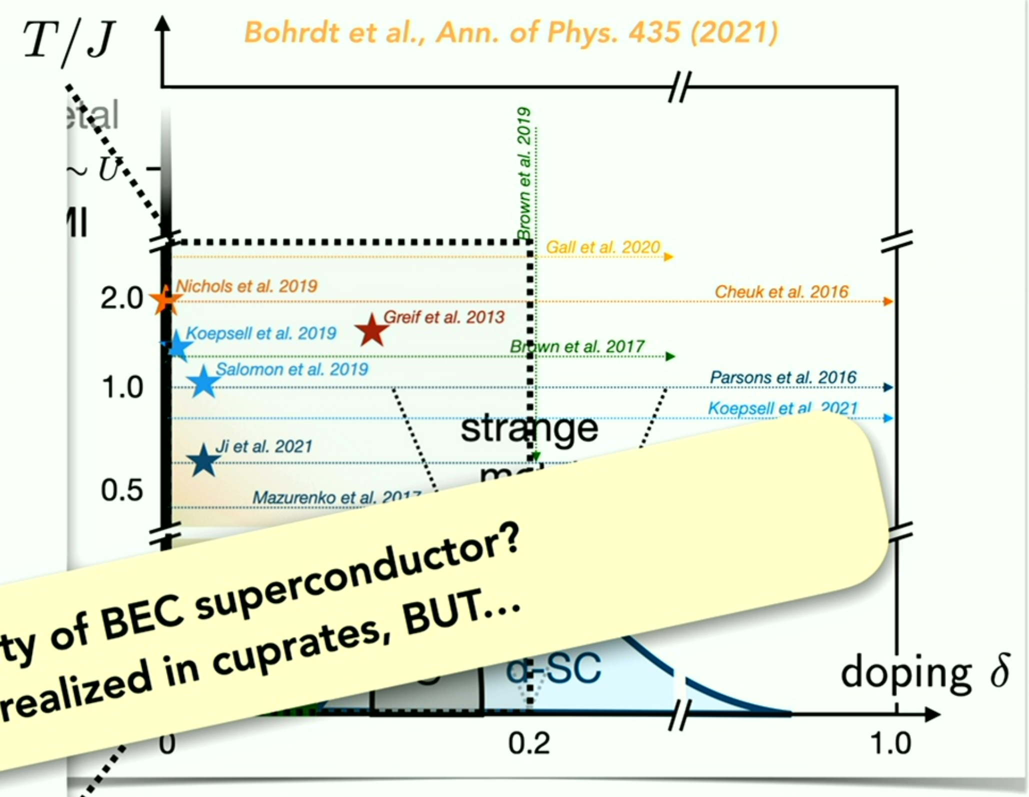


✱ *Charge carriers ... structure!*



Possibility of BEC superconductor?
— not realized in cuprates, BUT…

Background

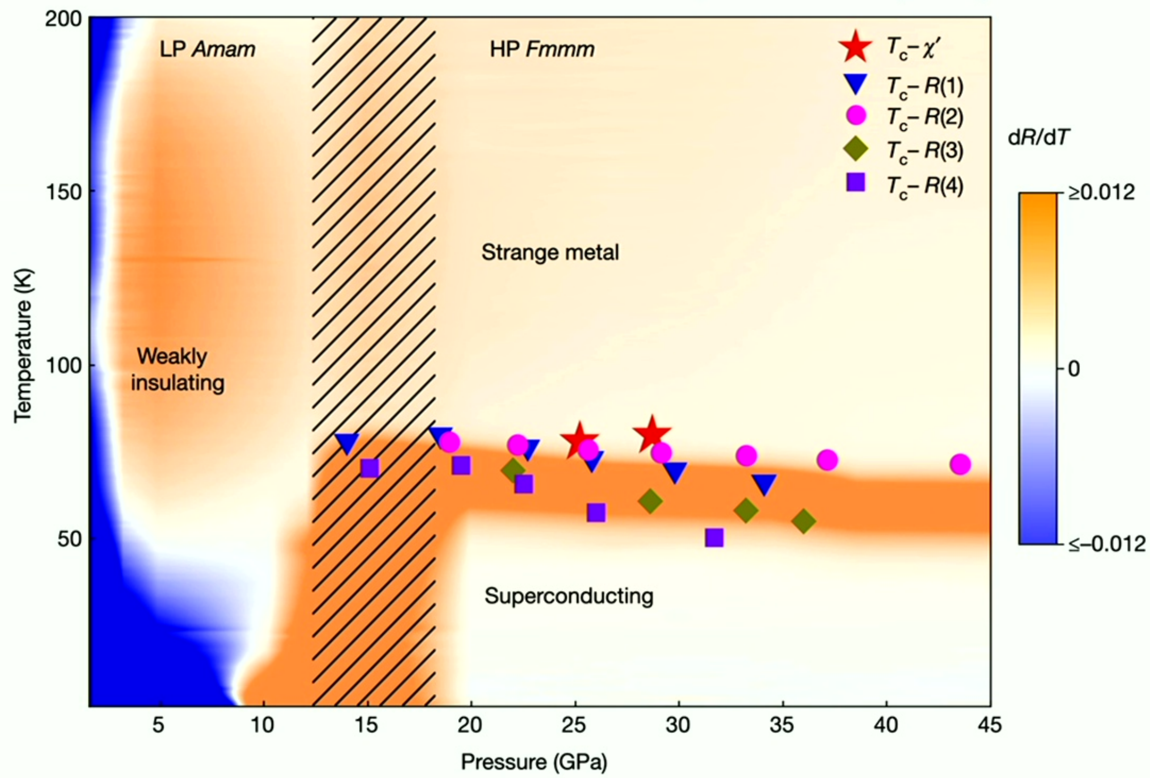
A new high-Tc superconductor: LNO

- *High-Tc superconductors:* $T_c \gtrsim 30K$

- *2023:* $La_3Ni_2O_7$ *— LNO @> 20 GPa*

  $T_c \approx 80K$

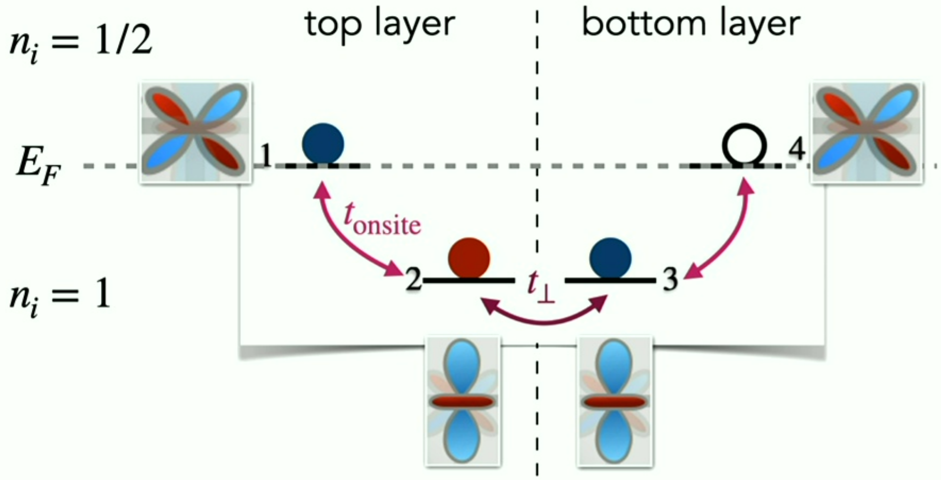
Sun et al., Nature 621 (2023)



The mixD bilayer *t-J* model

From 4-band model to mixD:

- Solids — *LNO:* *Sun et al., Nature 621 (2023)*



$$\hat{\mathcal{H}}_{\text{BL}} = -t_\parallel \sum_{\langle \mathbf{i},\mathbf{j} \rangle, \sigma, \alpha} \hat{\mathcal{P}} (\hat{c}^\dagger_{\mathbf{i},\sigma,\alpha} \hat{c}_{\mathbf{j},\sigma,\alpha} + \text{h.c.}) \hat{\mathcal{P}} + J_\parallel \sum_{\langle \mathbf{i},\mathbf{j} \rangle, \alpha} \left(\hat{\mathbf{S}}_{\mathbf{i},\alpha} \cdot \hat{\mathbf{S}}_{\mathbf{j},\alpha} - \frac{\hat{n}_{\mathbf{i},\alpha} \hat{n}_{\mathbf{j},\alpha}}{4} \right)$$

Lu et al., arXiv:2307.14965v2; *Oh & Zhang, PRB 108 (2023)*

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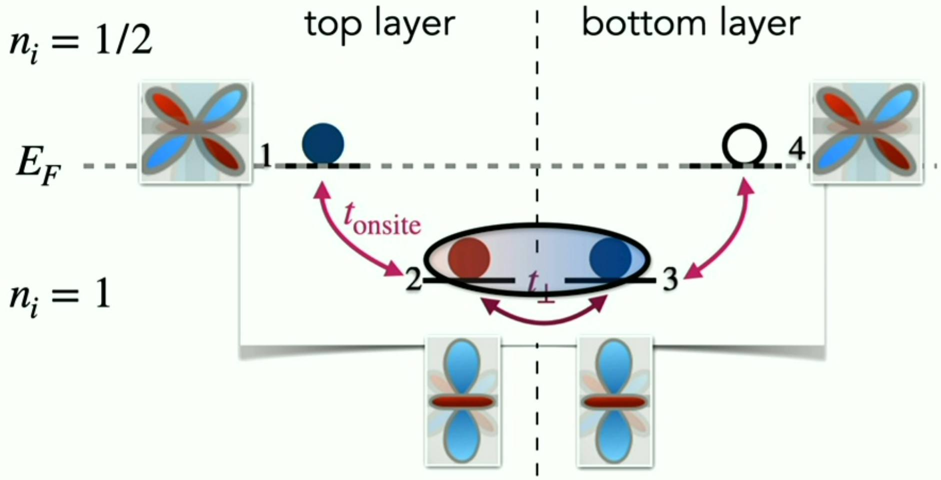

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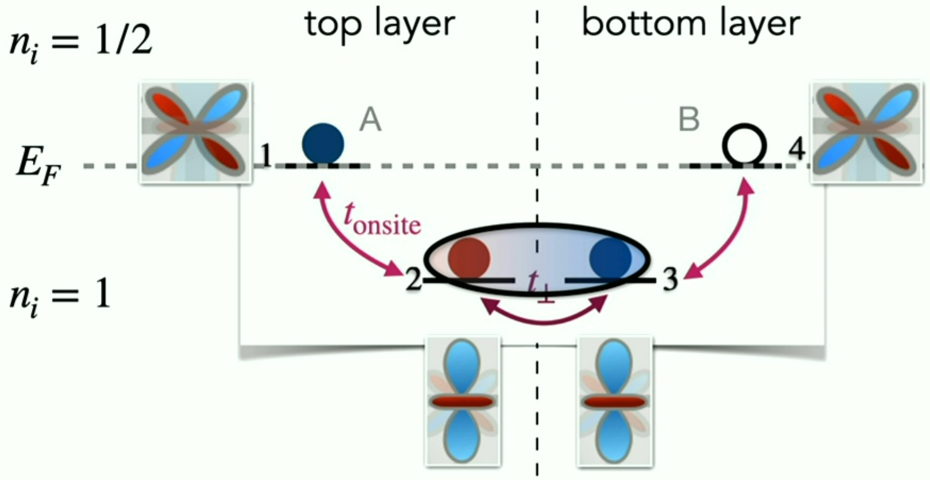
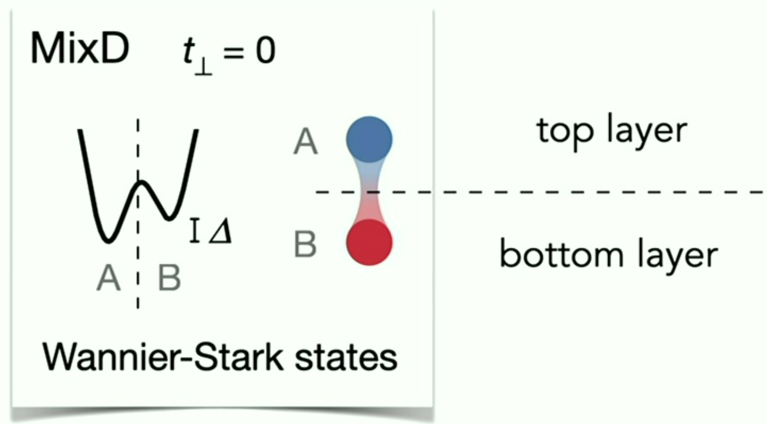


* Cold atoms: *Bohrdt et al., Ann. of Phys. 435 (2021)*



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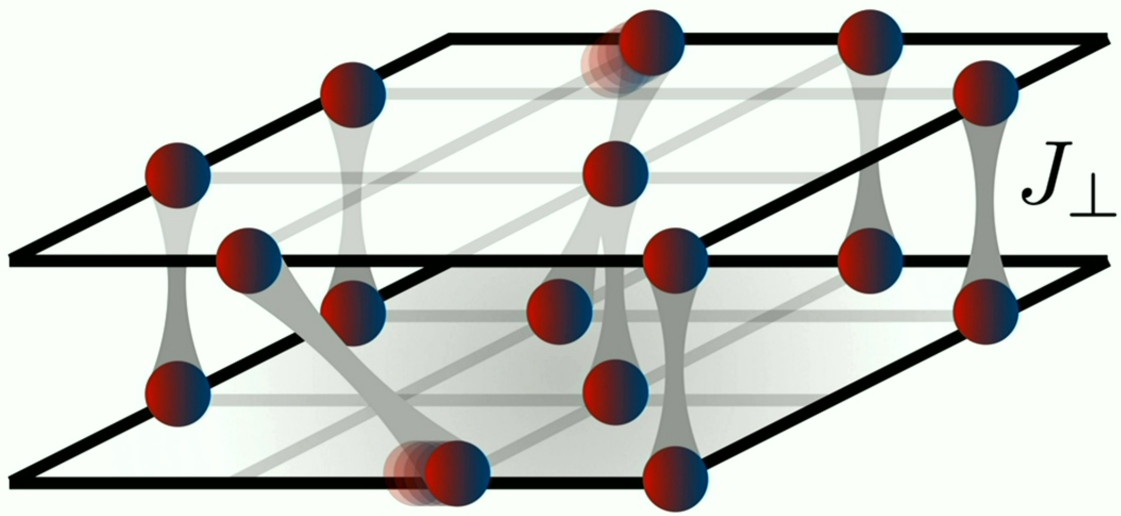

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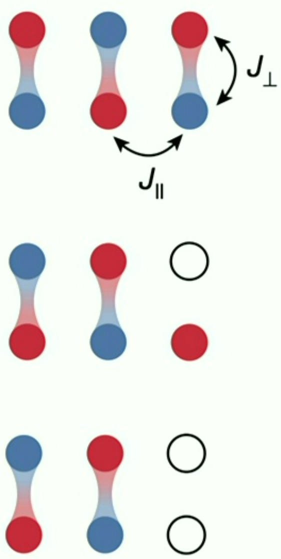
Basic physics & a few surprises

- Strong pairing from super-exchange
  Bohrdt et al., Ann. of Phys. 435 (2021)



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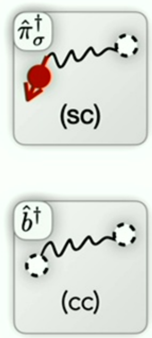
$\Delta E = +J_\perp$

$N_h = 1$

$\Delta E = 0$

$N_h = 2$

$$E_b = J_\perp$$



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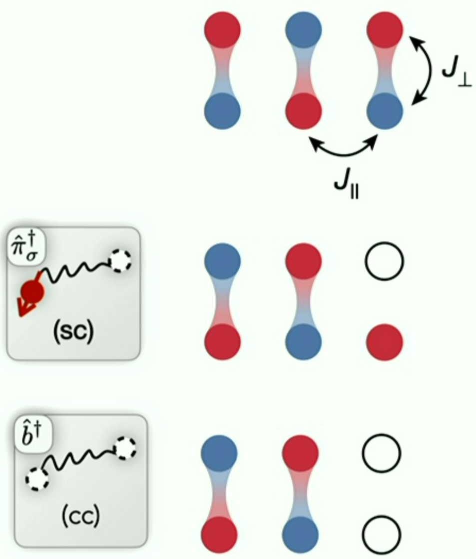

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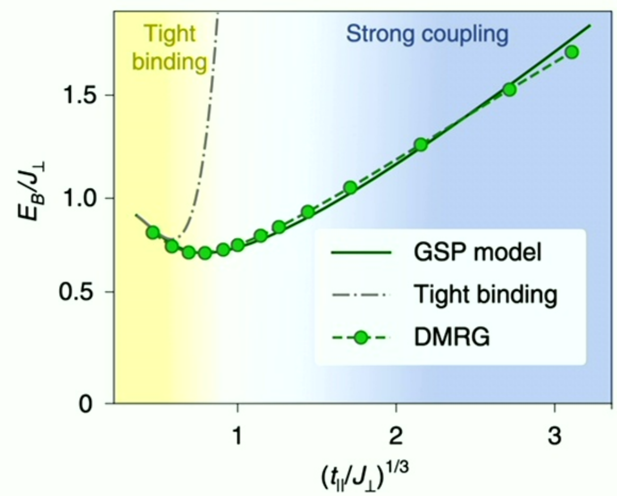
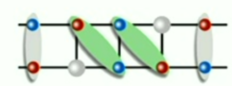
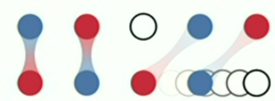
Surprise #1: Binding energy $E_b > J_\perp$

Bohrdt et al., Nat. Phys. 18 (2022)



ladder





$E_b \simeq J_\perp^{2/3} t_\parallel^{1/3}$

The mixD bilayer *t-J* model

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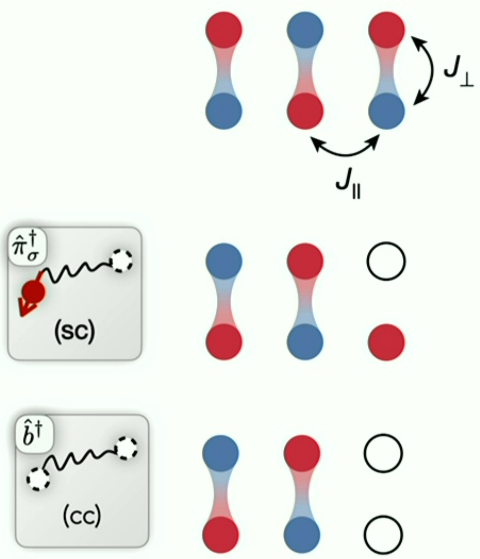

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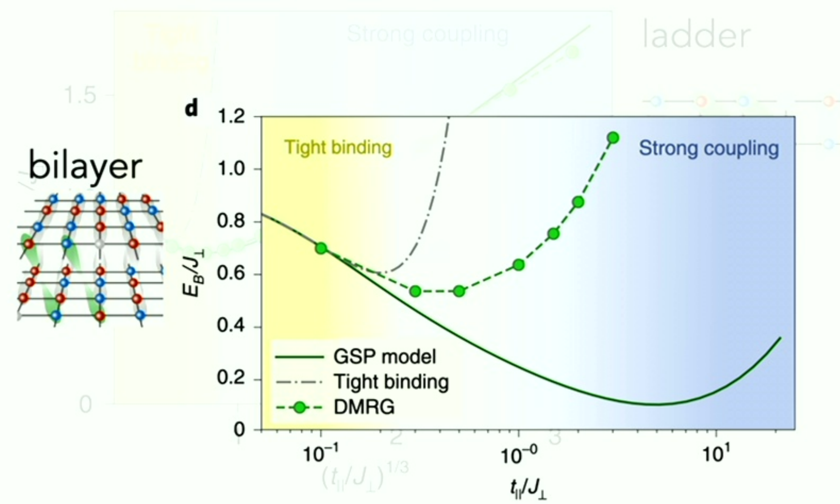

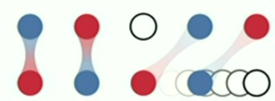

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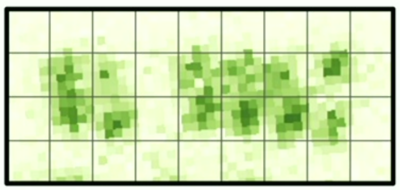
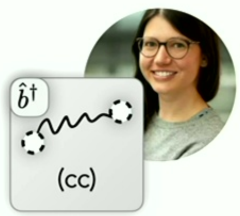
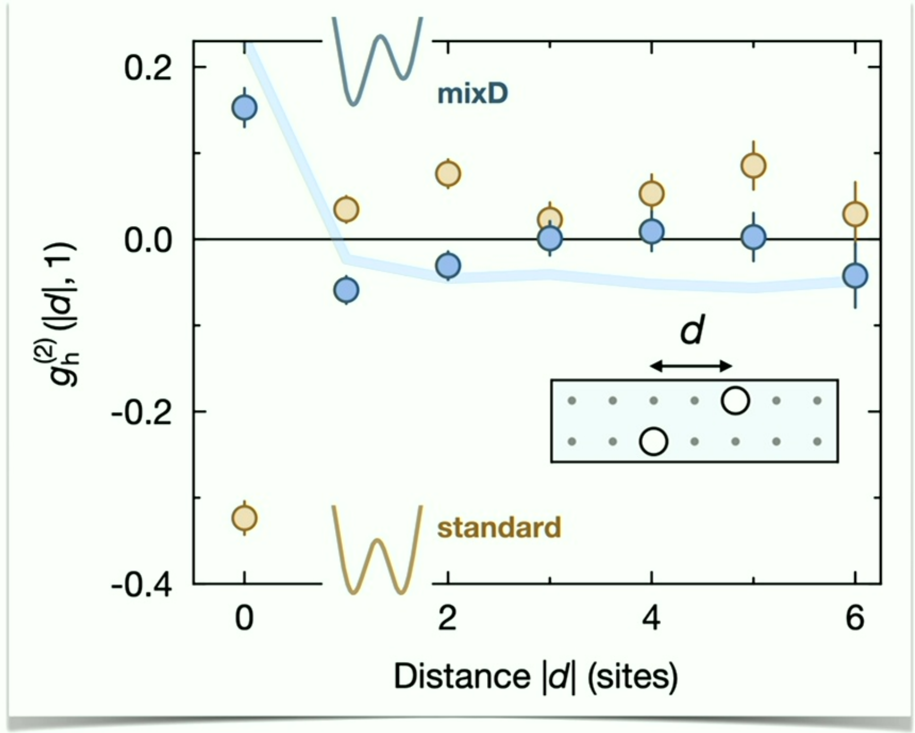
Experimental observation of hole pairing

- MixD AFM ladder — Bloch group (LMU/MPQ)





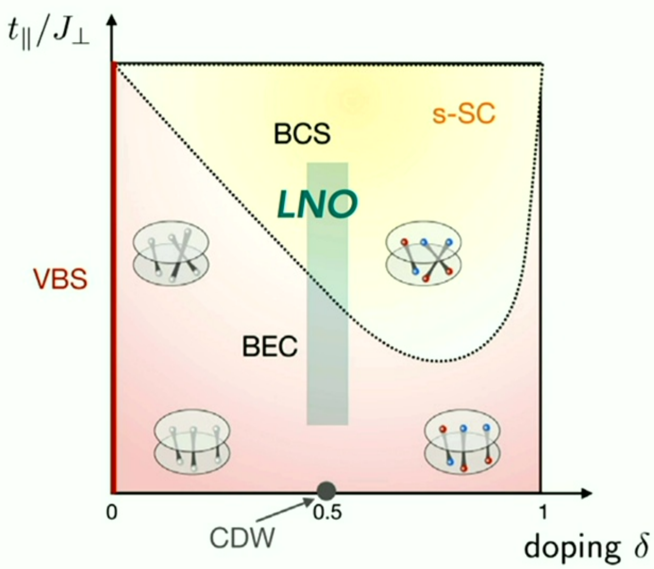
Hirthe et al., Nature 613 (2023)



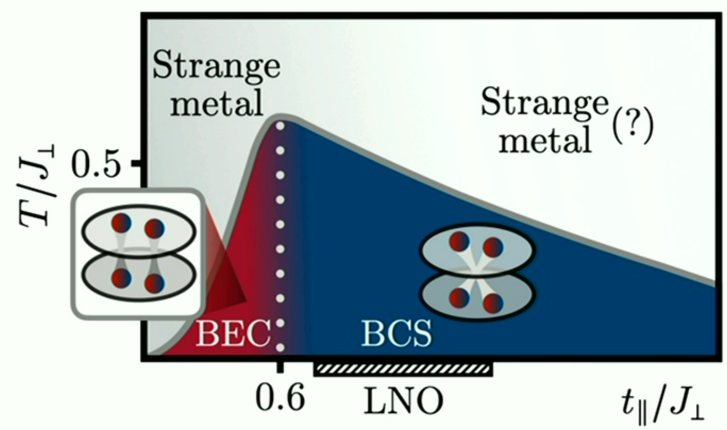
The mixD bilayer *t-J* model

Basic physics & a few surprises

- BEC-BCS crossover upon doping
  Bohrdt et al., Ann. of Phys. 435 (2021)
  Lange et al., PRB 109 (2024)
  Yang, Oh & Zhang, arXiv:2309.15095



Surprise #2: Large critical Tc
Schlömer et al., arXiv:2311.03349

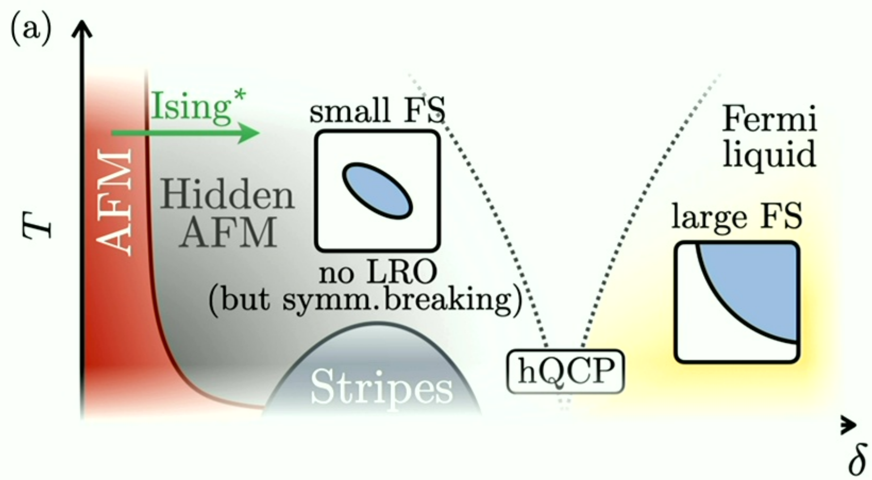


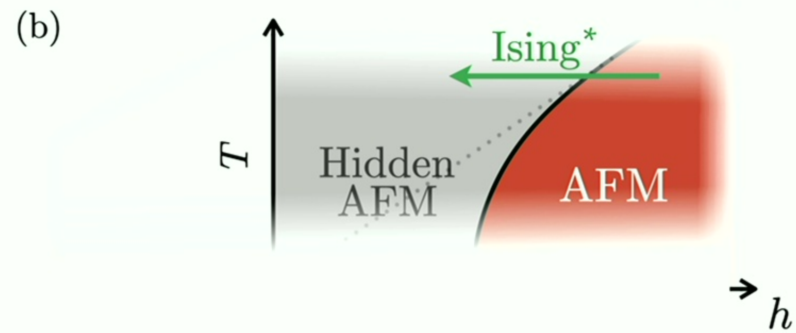
$T_c \simeq 0.5 J_\perp$ — achievable in cold atoms!

Pseudogap from fluctuating stripes

Melting stripes: Hidden AFM order

Schlömer et al., in prep.





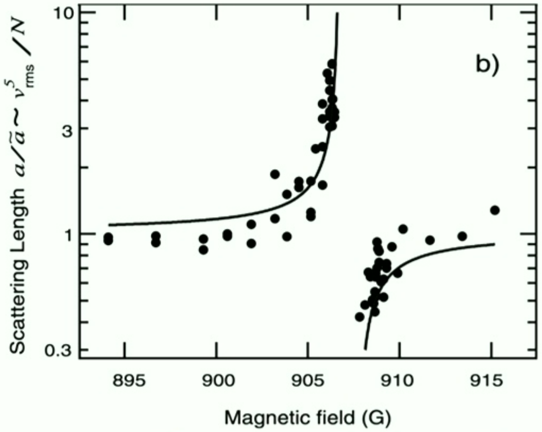
T=0 physics: check arXiv...!


Cuprate land
Quantum
simulation
mixD land?!
Kondo land

Motivation

Controlling interactions via Feshbach resonances

Ultracold atoms



Review: ***C. Chin, Rev. Mod. Phys. 82 (2010)***

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Pit Ber
(LMU M

Schlömer

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