Title: Fermi surface symmetric mass generation and its application in nickelate superconductor

Speakers: Dachuan Lu

Series: Quantum Matter

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Abstract: Symmetric mass generation (SMG) is a novel interaction-driven mechanism that generates fermion mass without breaking symmetry, unlike the standard Anderson-Higgs mechanism. SMG can occur in the fermion system without quantum anomalies. In this talk, I will focus on the SMG for the systems with finite fermion density, i.e., the Fermi surface. I will discuss the Fermi surface anomaly and Fermi surface SMG. Lastly, I will talk about its application in the newly found nickelate superconductors, where the superconductivity emerges without a nearby spontaneous symmetry-breaking phase.

Zoom link https://pitp.zoom.us/j/92511977879?pwd=MGgyZ0tsZ0hUZDMvZ2wzc3hJVmprZz09

Fermi surface symmetric mass generation and its application in nickelate superconductor

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University of California San Diego

12.11 Perimeter Institute

References

Formal setup

↓

Applications

- Fermi surface anomaly:
  - **DCL**, Wang, J., & You, Y. Z. (2023). PRB.
- Models of Fermi surface SMG in various dimensions,
  - **DCL**, Zeng, M., Wang, J., & You, Y. Z. (2023). PRB, 107(19), 195133.
- Apply FS SMG to realistic systems – Green's function and $\mathrm{La_3Ni_2O_7}$,
  - **DCL**, Zeng, M., & You, Y. Z. (2023). 108(20), 205117.
  - **DCL**, Li, M., Zeng, Z. Y., Hou, W., Wang, J., Yang, F., & You, PRB, Y. Z. (2023). arXiv:2308.11195.

Yi-Zhuang You
(UCSD)

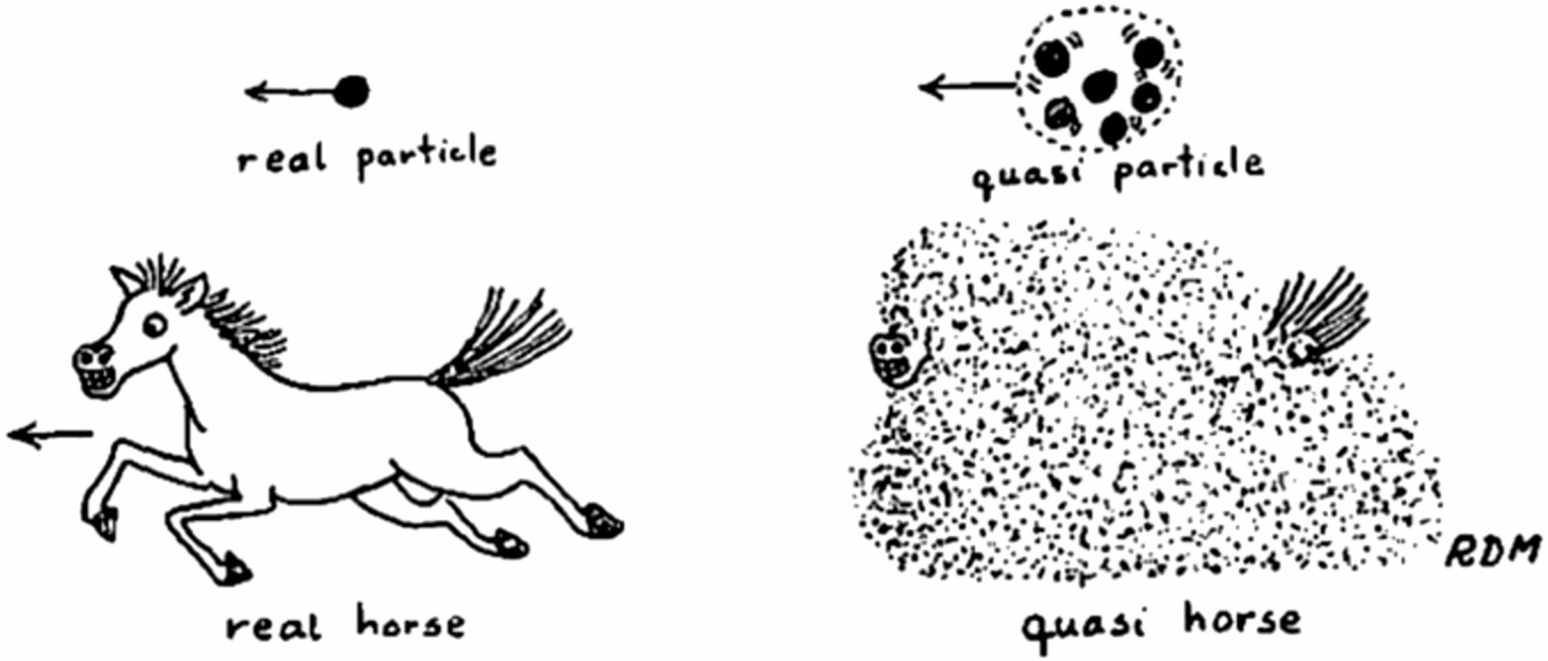
Meng Zeng
(UCSD)

Juven Wang
(Harvard)

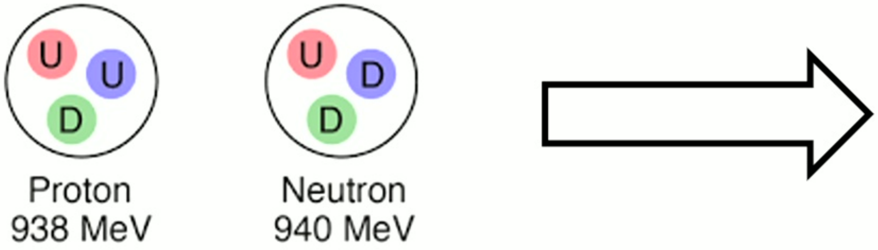
Outline

- Introduction to symmetric mass generation
- Fermi surface anomaly [**DCL**, Wang, You (2023)]
- Fermi surface symmetric mass generation [**DCL**, Zeng, Wang, You (2023)]
- Superconductivity in $\mathrm{La_3Ni_2O_7}$ under pressure
  [**DCL**, Li, Zeng, Hou, Wang, Yang & You (2023)]
- Signatures in Green's function [**DCL**, Zeng, You (2023)]
- Conclusion and future directions

Emergence in condensed matter

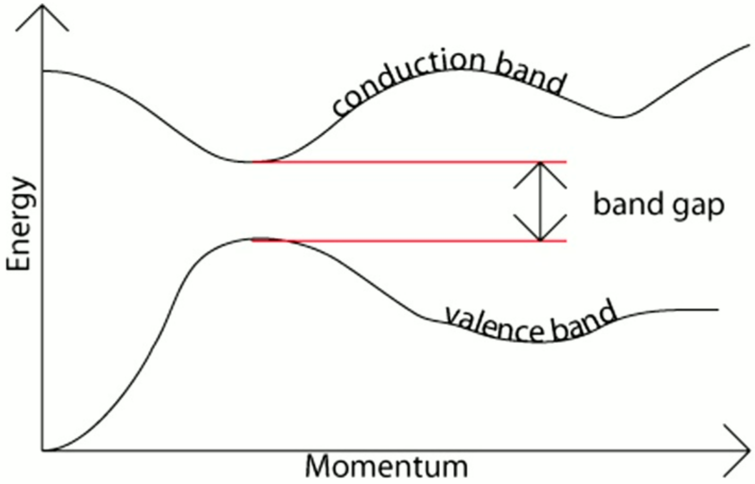


Mass is emergent in condensed matter



$$E = mc^2$$

Mass in our universe

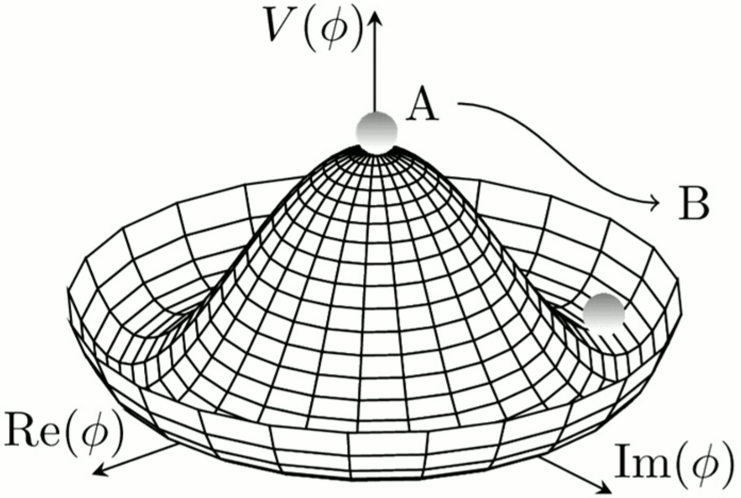


Mass is emergent in material

$m = \Delta$ band gap

How to generate mass – Anderson-Higgs

- Anderson-Higgs mechanism – spontaneously symmetry breaking



$$\phi\bar{\psi}\psi \subset \mathcal{L}$$

$$\langle\phi\rangle \neq 0$$

$$m \sim \langle\phi\rangle$$

Anderson Higgs mechanism

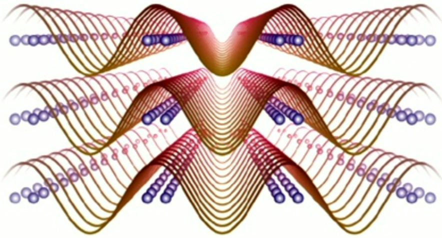
- Spontaneously symmetry breaking

Break spin $SO(3)$

$\Delta \sim 30meV$

Break charge $U(1)$

$\Delta \sim 1{\sim}10meV$



Break translation

$\Delta \sim 1{\sim}10meV$

Symmetric mass generation

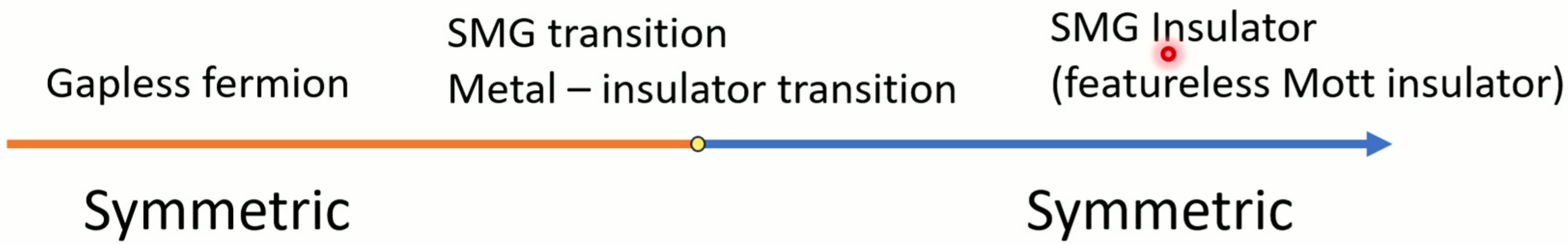
- Generating mass without breaking symmetry

1. New correlated phase and phase transition
2. Pseudo gap phase in strongly correlated materials
3. Simulating Standard model on lattice
4. ……

Symmetric mass generation

- Generating mass without breaking symmetry

1. New correlated phase and beyond Landau phase transition



Gapless fermion

SMG transition
Metal – insulator transition

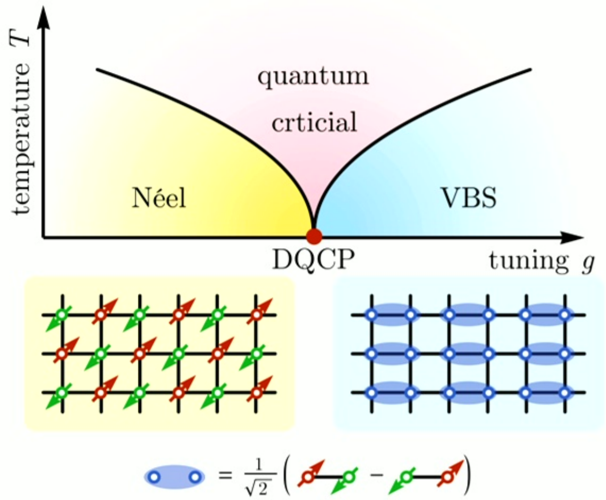
SMG Insulator
(featureless Mott insulator)

Symmetric

Symmetric

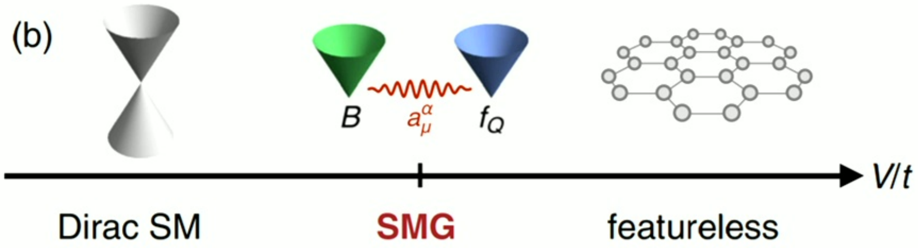
Symmetric mass generation

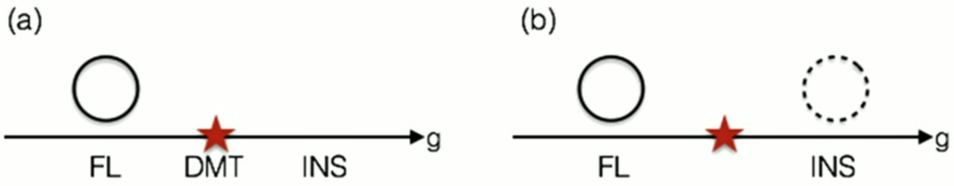
- Beyond Landau paradigm



Deconfined quantum critical point

[Senthil, Vishwanath, Balents, Sachdev (2004)]
[Wang, Nahum, Metlitski, Xu, Senthil (2017)]





SMG transition

[You, He, Xu, Vishwanath (2018)]
[Zou, Chowdhury (2020)]

Beyond Landau transition

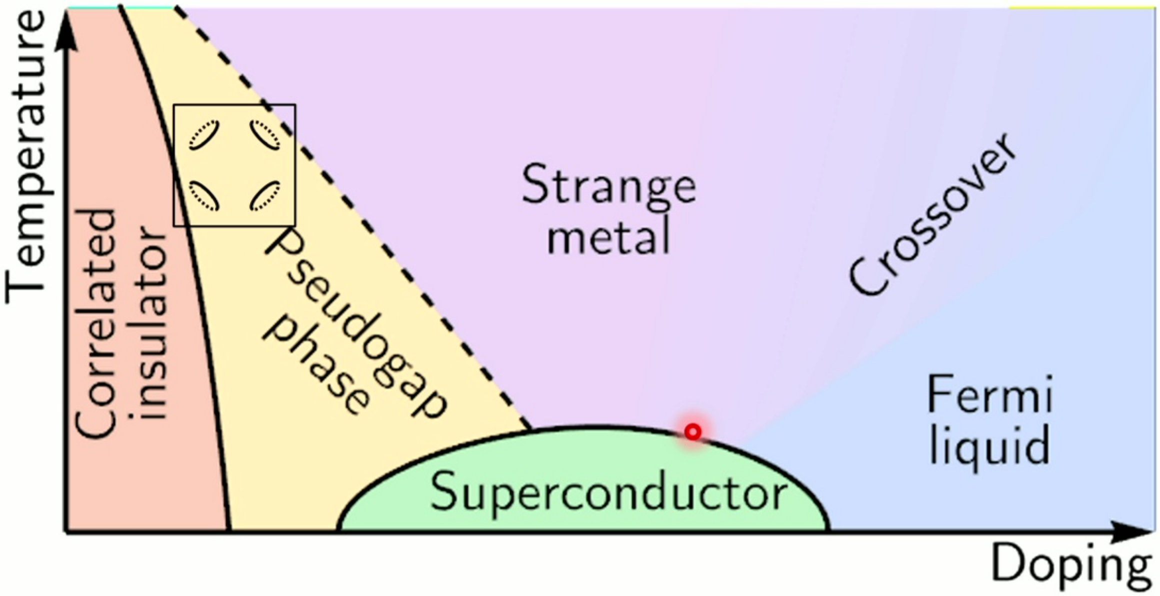
Deconfined quantum criticality	**SMG transition**
SSB1 to SSB2	Symmetric to Symmetric
Mixed anomaly	Anomaly free
Emergent gauge field	Emergent gauge field
U(1) gauge theory + matter	Nonabelian gauge theory + matter (?)
Self-duality and duality web	Duality web for $U(1) \times U(1)$ (?)
Multicritical point and pseudocriticality*	Need further numerical study (?)
Monopole carries charge	Need further analysis (?)

* [**DCL**, Xu, You (2021)], [Ma, Wang (2020)]

Symmetric mass generation

- Generating mass without breaking symmetry

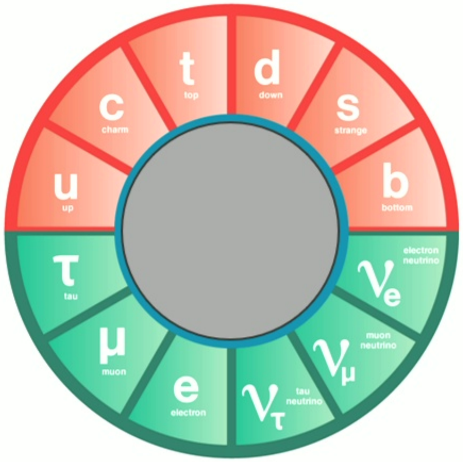
2. Pseudo gap phase in strongly correlated materials

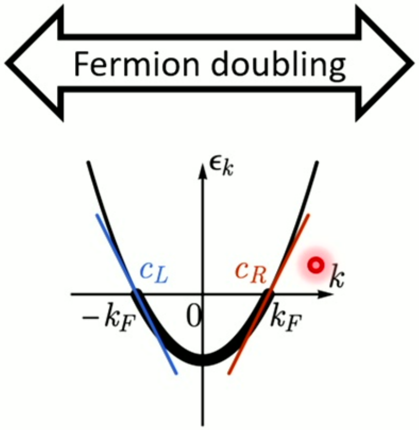


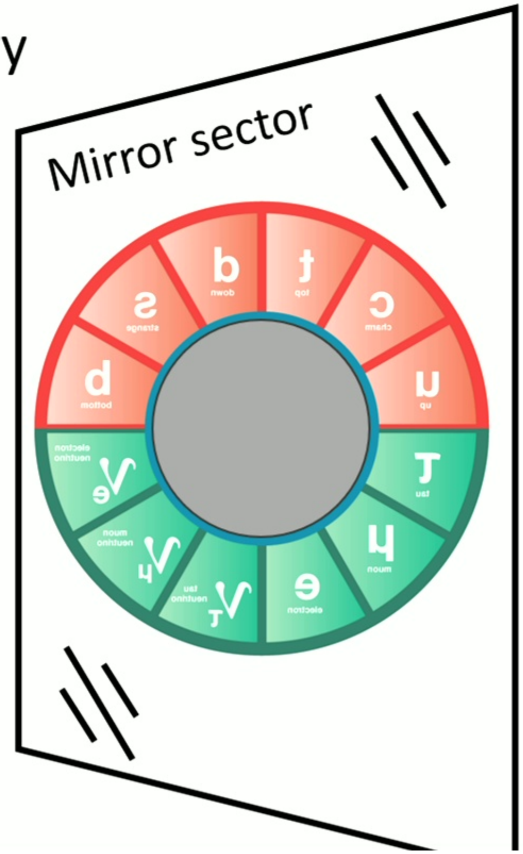
Symmetric mass generation

- Generating mass without breaking symmetry

3. Simulating Standard model on lattice:




Fermion doubling



[E Eichten, J Preskill (1986)]

Symmetric mass generation – 0+1d example

Complex fermions on a 0+1d quantum dot with particle-hole symmetry,

$$P:\ c_a \to c_a^\dagger, i \to -i, \ a \text{ is the layer index}$$

This symmetry forbids any fermion bilinears, even if there are several copies,

$$P: c_a^\dagger c_b + c_b^\dagger c_a \to c_a c_b^\dagger + c_b c_a^\dagger = -(c_a^\dagger c_b + h.c.)$$
$$P: c_a c_b + c_b^\dagger c_a^\dagger \to c_a^\dagger c_b^\dagger + c_b c_a = -(c_a c_b + h.c.)$$

But

$$H_{\text{int}} = c_1 c_2 c_3 c_4 + h.c.$$

is symmetric and will gap out 4 copies of such system.

Symmetric mass generation – 0+1d example

- Interaction reduced classification of SPTs
  - 1+1d Majorana chain has dangling Majorana zero mode at the boundary protected by $\mathbb{Z}_2$ symmetry $i \to -i, \chi_{2i-1} \to -\chi_{2i-1}$.
  - $N > 1$ copies of the Majorana chains still have the anomalous boundary modes, if only adding fermion bilinears at the boundary.
  - The boundary modes can be symmetrically gapped out if 8 copies of Majorana chains by specially designed 4-fermion interaction term.

[Fidkowski, Kitaev (2010)]

‘t Hooft anomaly

- ‘t Hooft anomaly of a global symmetry is the obstruction to
  - Gauging the symmetry
  - Or a symmetric gapped phase with a unique ground state
- SMG requires the **vanishing ‘t Hooft anomaly** (also gravitational anomaly and other anomalies) to have the symmetric gapped phase.

* Anomaly for noninvertible symmetry only forbids symmetric gapped phase with unique ground state

* [Choi, Rayhaun, Sanghavi, Shao (2023)]

Symmetric mass generation

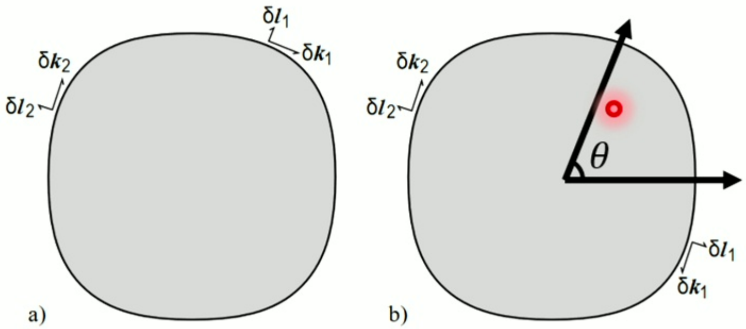
Protecting symmetry	**Anomaly free**	**Examples**
Ordinary global symmetry	Group cohomology/cobordism	3-4-5-0 chiral fermion
Loop group symmetry	Fermi surface anomaly	Bilayer square latt
Noninvertible symmetry	Admits fibre functor *	Ising^2 CFT
Subsystem symmetry	Group cohomology/cobordism	…
Higher form symmetry	Group cohomology/cobordism	…
…	…	…

Interaction needs to be carefully designed to gap out the gapless degrees of freedom.

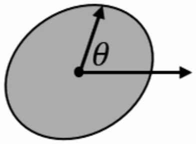
* [R Thorngren, Y Wang 2019], [Y Choi, DCL, Z Sun 2023]

Fermi liquid – loop group symmetry

- Fermi liquid with generic Fermi surface is stable against interactions.



Fermi liquid – loop group symmetry



Hamiltonian for the Fermi liquid:

$$H_{FL} = \sum_{\theta} \epsilon_\theta n_\theta + \sum_{\theta,\theta'} f_{\theta,\theta'} n_\theta n_{\theta'}$$

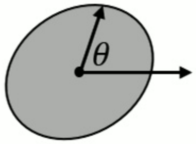
Where $n_\theta = \psi_\theta^\dagger \psi_\theta$. It has an emergent $LU(1)$ symmetry,

$$LU(1): \psi_\theta \to e^{i\phi(\theta)} \psi_\theta$$

$\phi(\theta)$ is a continuous function and has the equivalent relation $\phi(\theta) \sim \phi(\theta) + 2\pi$.

[Else, Thorngren, Senthil (2021)], [Wang, Hickey, Ying, Burkov (2021)]

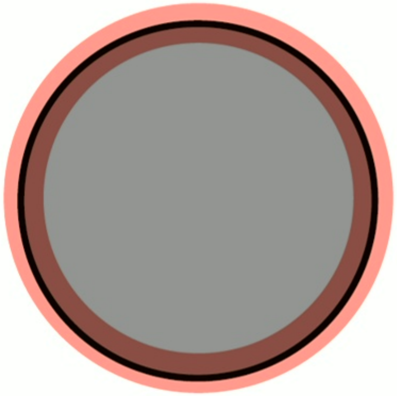
Fermi liquid – loop group symmetry



Subgroups of $LU(1)$: $\psi_\theta \to e^{i\phi(\theta)}\psi_\theta$

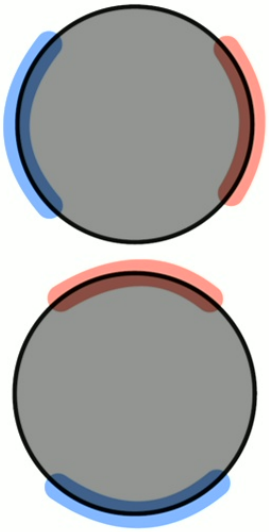
Total U(1)

$\phi(\theta) = \phi_0$

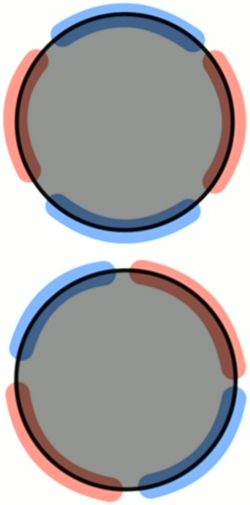


Translation

$\phi(\theta) = \boldsymbol{a} \cdot \boldsymbol{k}_F(\theta)$



d-wave like



Higher order

……

Fermi surface anomaly

- The necessary condition for SMG is **anomaly free**. For $LU(1)$:

$$\sum_i \underset{\substack{\uparrow \\ \text{charge}}}{q_i}\,\underset{\substack{\uparrow \\ \text{filling fraction}}}{\nu_i} = 0 \bmod 1$$

Mixed anomaly between charge and translation symmetry.

* This can be generalized to other flavor groups.

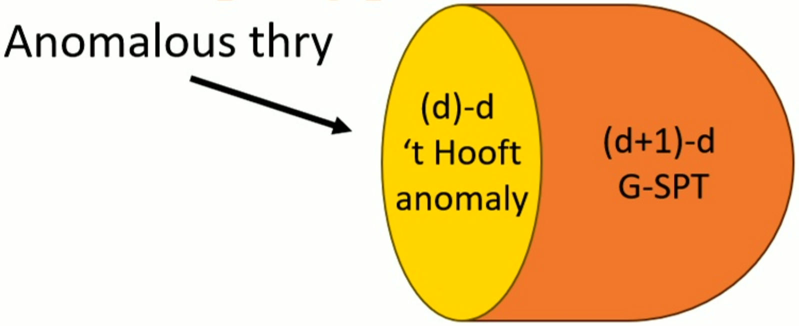
* [DCL, Wang, You (2023)]

Fermi surface anomaly

Anomalous Mott insulator

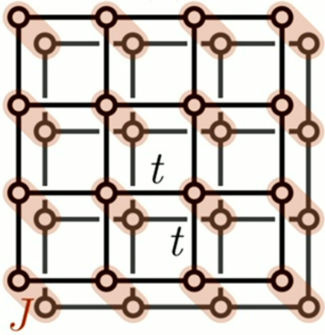
- Symmetry breaking (AFM, VBS)
- Topological order (QSL)
- Gapless spin excitations (DQCP)

Cuprate, herbertsmithite, $SrCu_2(BO_3)_2$ …



Anomaly free SMG insulator

- Unique symmetric ground state.



$La_3Ni_2O_7$ under pressure

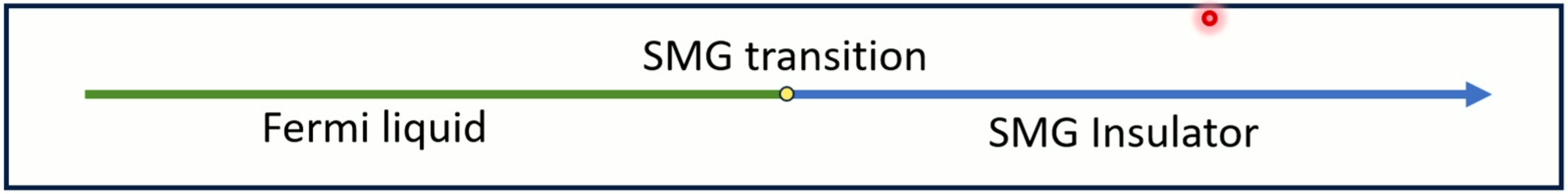
$$H = t\sum_{\langle ij\rangle,l} c_{il}^{\dagger} c_{jl} + h.c. - \mu \sum_{il} c_{il}^{\dagger} c_{il} \\ + J\sum_i S_{i1}\cdot S_{i2}$$

Fermi surface symmetric mass generation

- Phase diagram:


???
Fermi liquid
SMG Insulator
(featureless Mott insulator)

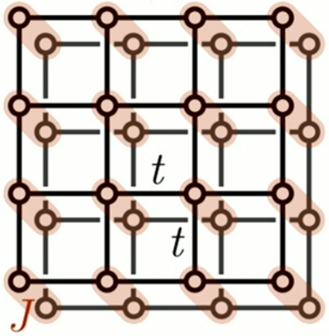
- Possible scenarios:


SMG transition
Fermi liquid
SMG Insulator

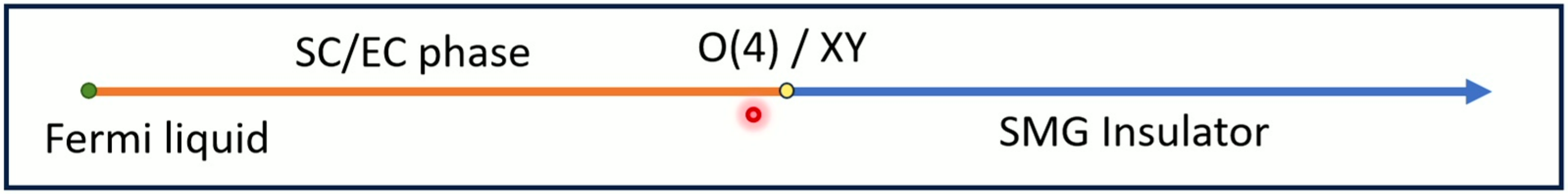

SSB phase
SMG transition
Fermi liquid
SMG Insulator

Fermi surface symmetric mass generation

- Current model fits in scenario 2:
- SSB phase is exciton condensation or superconductivity
- Undergo transition to disorder the SSB order



$$H = t\sum_{\langle ij\rangle,l} c_{il}^{\dagger} c_{jl} + h.c. + J\sum_{i} S_{i1}\cdot S_{i2}$$



Fermi surface anomaly

- The necessary condition for SMG is **anomaly free**. For $LU(1)$:

$$\sum_i \underbrace{q_i}_{\text{charge}} \underbrace{\nu_i}_{\text{filling fraction}} = 0 \bmod 1$$

Mixed anomaly between charge and translation symmetry.

* This can be generalized to other flavor groups.

* [DCL, Wang, You (2023)]

Nickelate superconductor $La_3Ni_2O_7$

Article

Signatures of superconductivity near 80 K in a nickelate under high pressure

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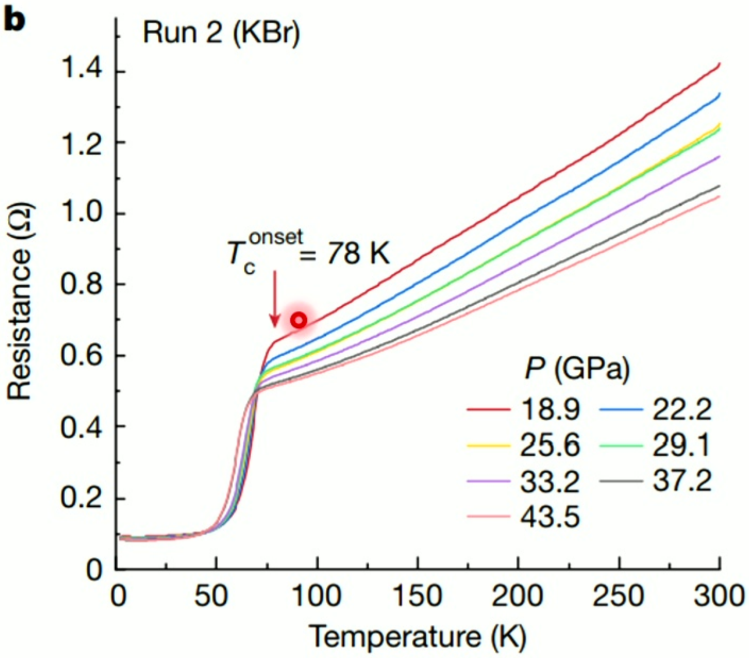
Hualei Sun[1,7], Mengwu Huo[1,7], Xunwu Hu[1], Jingyuan Li[1], Zengjia Liu[1], Yifeng Han[2], Lingyun Tang[3], Zhongquan Mao[3], Pengtao Yang[4], Bosen Wang[4], Jinguang Cheng[4], Dao-Xin Yao[1], Guang-Ming Zhang[5,6] ✉ & Meng Wang[1] ✉

Although high-transition-temperature (high-T_c) superconductivity in cuprates has been known for more than three decades, the underlying mechanism remains unknown[1–4]. Cuprates are the only unconventional superconductors that exhibit bulk superconductivity with T_c above the liquid-nitrogen boiling temperature of 77 K. Here we observe that high-pressure resistance and mutual inductive magnetic susceptibility measurements showed signatures of superconductivity in single crystals of $La_3Ni_2O_7$ with maximum T_c of 80 K at pressures between 14.0 GPa and 43.5 GPa. The superconducting phase under high pressure has an orthorhombic structure of *Fmmm* space group with the $3d_{x^2-y^2}$ and $3d_{z^2}$ orbitals of Ni cations strongly mixing with oxygen $2p$ orbitals. Our density functional theory calculations indicate that the superconductivity emerges coincidently with the metallization of the σ-bonding bands under the Fermi level, consisting of the $3d_{z^2}$ orbitals with the apical oxygen ions connecting the Ni–O bilayers. Thus, our discoveries provide not only important clues for the high-T_c superconductivity in this Ruddlesden–Popper double-layered perovskite nickelates but also a previously unknown family of compounds to investigate the high-T_c superconductivity mechanism.

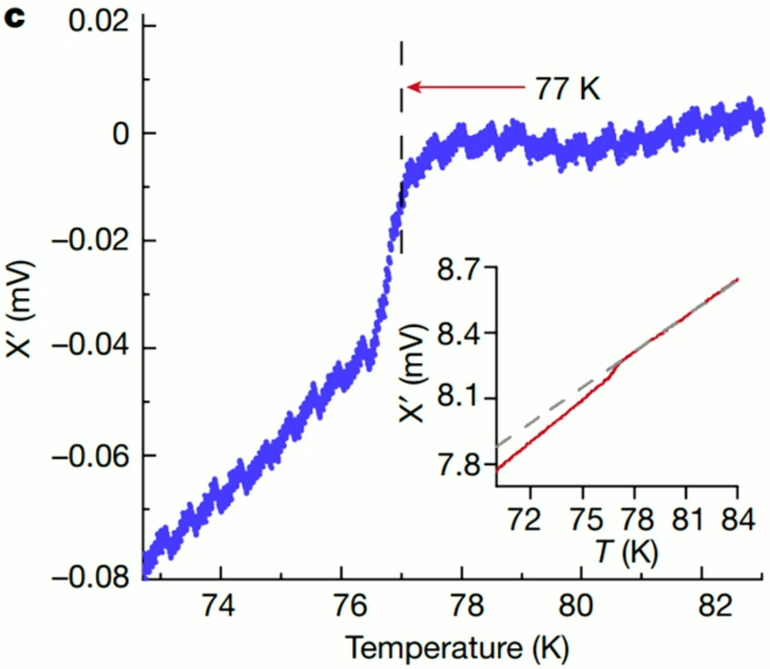
Meng Wang
(SYSU, China)

[H. Sun, et.al. Nature 621, 493-498 (2023)]

Nickelate superconductor $La_3Ni_2O_7$

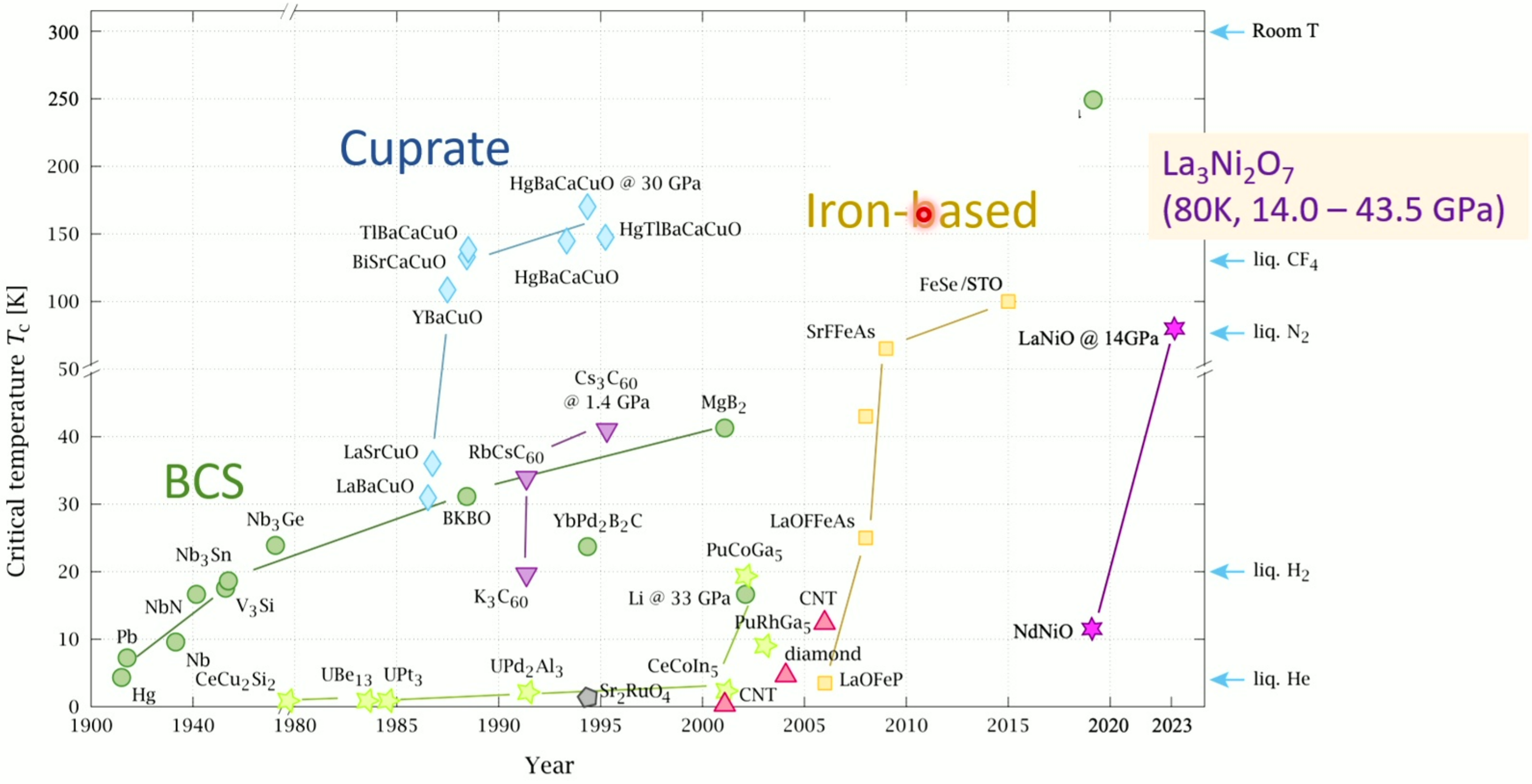


[H. Sun, et.al. Nature 621, 493-498 (2023)]



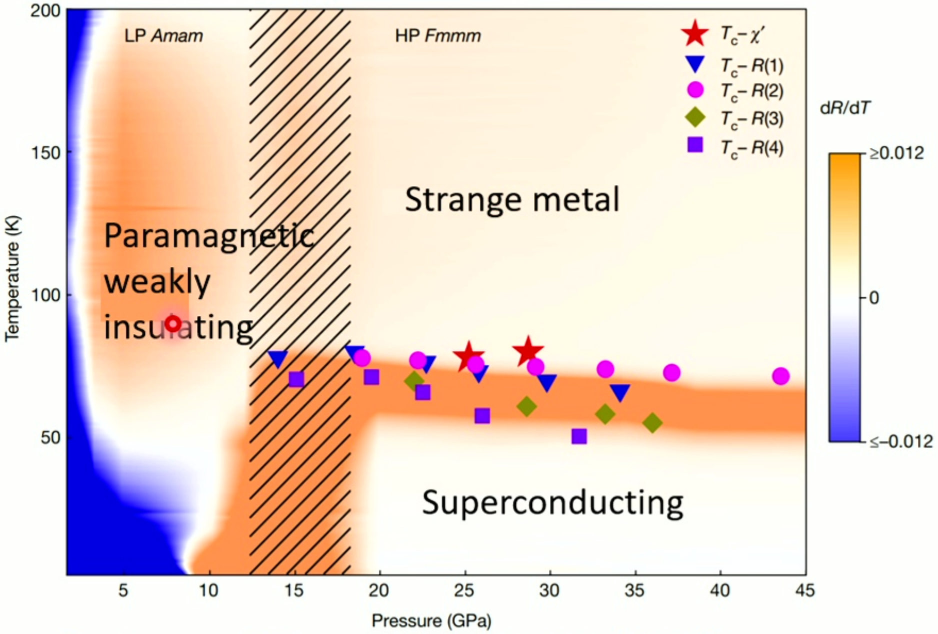
a prominent diamagnetic response at 25.2 GPa with a current frequency of 393 Hz and a magnitude of 50 mA

Nickelate superconductor $La_3Ni_2O_7$

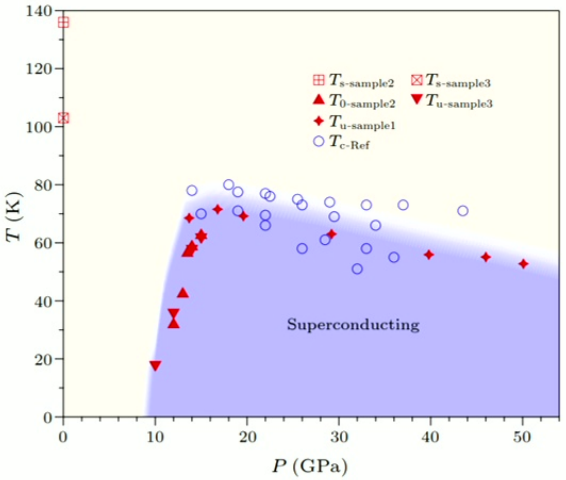


$La_3Ni_2O_7$
(80K, 14.0 – 43.5 GPa)

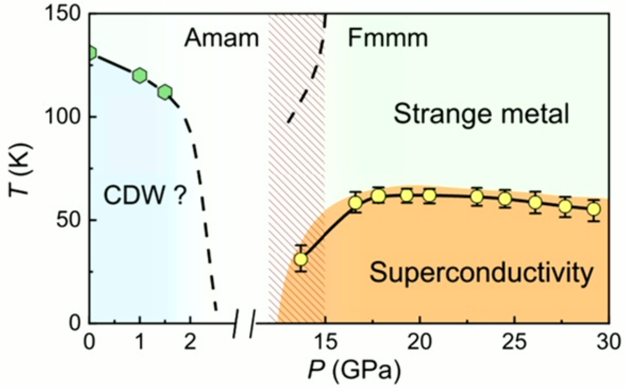
Phase diagram of $La_3Ni_2O_7$



[H. Sun, et.al. Nature 621, 493-498 (2023)]



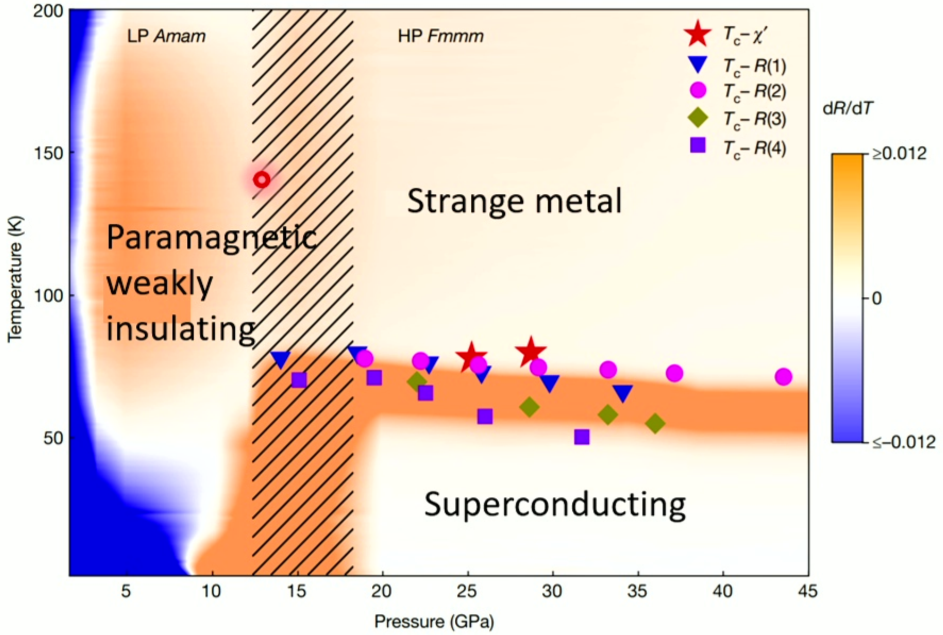
[J. Hou et al CPL 40 117302 (2023)]



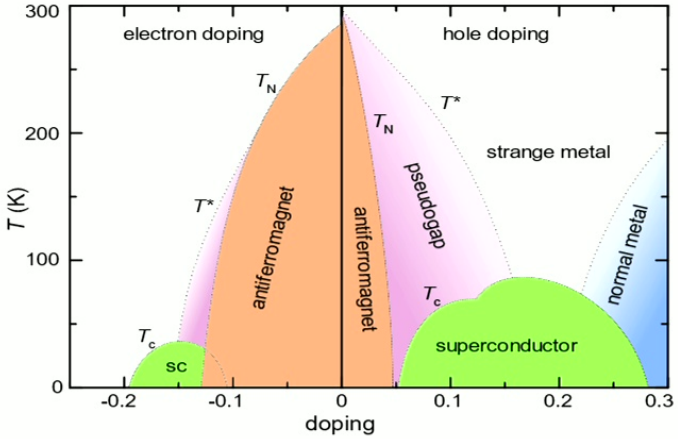
[Y. Zhang et.al. arXiv:2307.14819]

Phase diagrams among different materials

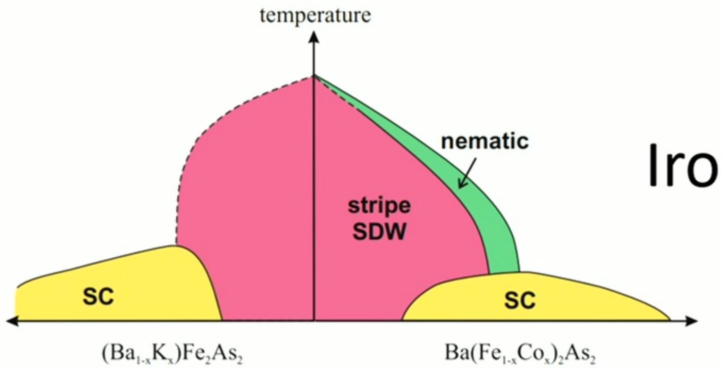
$La_3Ni_2O_7$



[H. Sun, et.al. Nature 621, 493-498 (2023)]

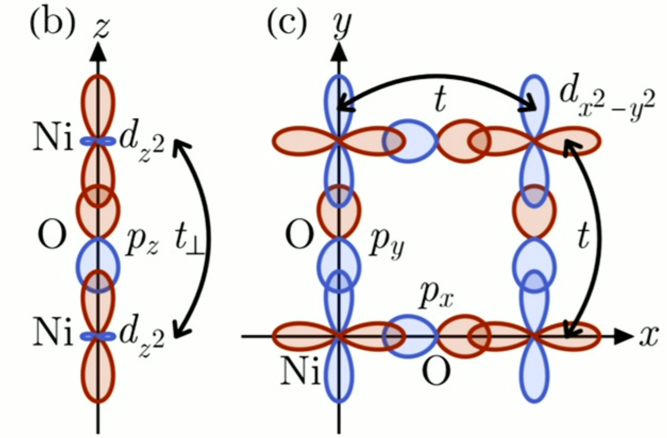


Cuprate

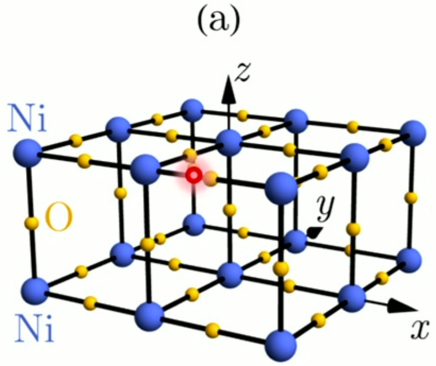


Iron-based

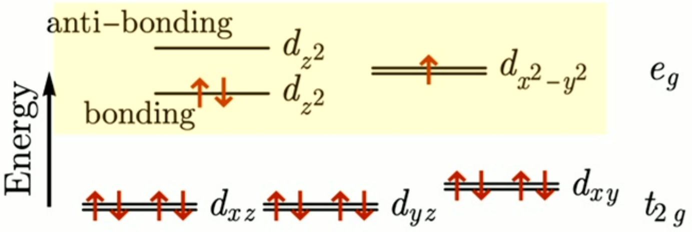
Electronic structure

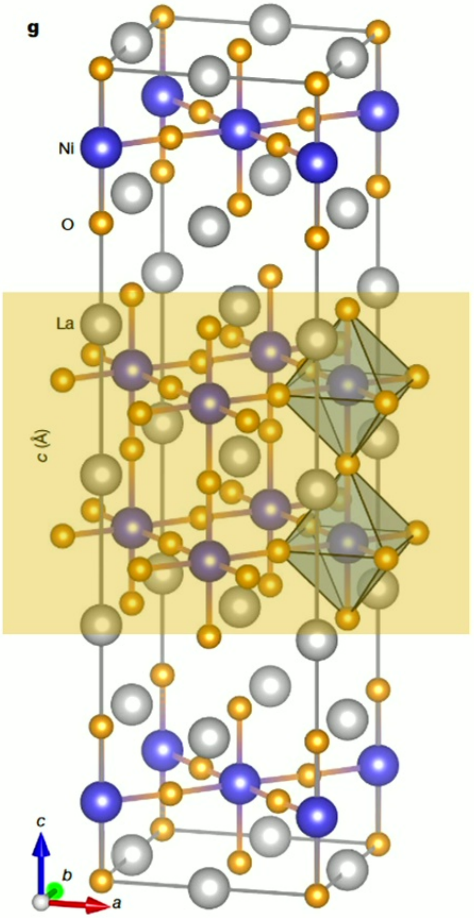


Inter-layer Intra-layer

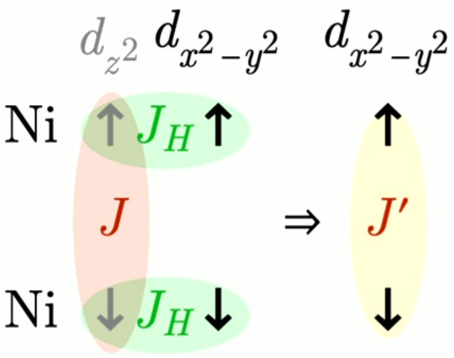


($Ni^{2.5+} \rightarrow 3d^{7.5}$) ×2 layers

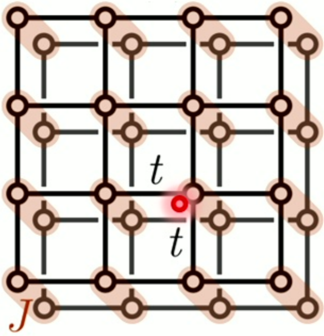




Minimal model



d_{z^2} forms spin singlet across the two layers



$$H = t\sum_{\langle ij\rangle,l} c_{il}^{\dagger}c_{jl} + h.c. - \mu\sum_{il} c_{il}^{\dagger}c_{il}$$

$$+J\sum_{i} S_{i1}\cdot S_{i2}$$

The interlayer J coupling will drive the system to a unique symmetric ground state.

$$|0\rangle = \bigotimes_i \left(c_{i1\uparrow}^{\dagger}c_{i2\downarrow}^{\dagger} - c_{i1\downarrow}^{\dagger}c_{i2\uparrow}^{\dagger}\right)|\mathrm{vac}\rangle$$

[DCL, et al, arXiv:2308.11195]

BCS-BEC crossover

$$H = t\sum_{\langle ij\rangle,l} c_{il}^{\dagger}c_{jl} + h.c. - \mu\sum_{il} c_{il}^{\dagger}c_{il} + J\sum_{i} S_{i1}\cdot S_{i2}$$

Weak coupling limit, $J/t < 1$

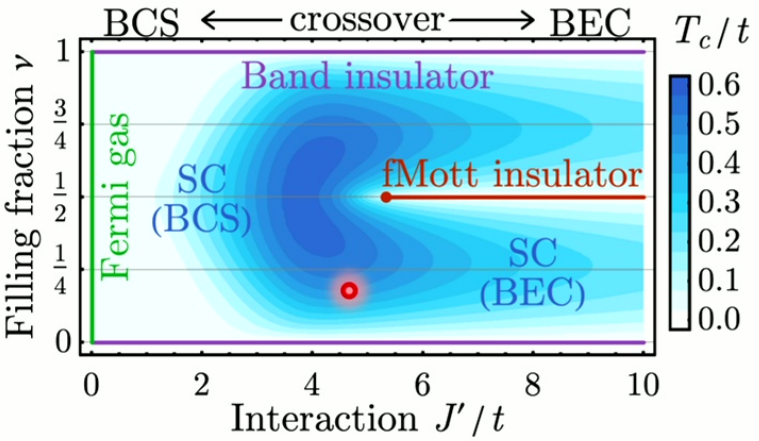
- BCS theory

$$\frac{1}{J} = \int \frac{d^2\boldsymbol{k}}{(2\pi)^2}\frac{1}{2\xi_{\boldsymbol{k}}}\tanh\frac{\xi_{\boldsymbol{k}}}{2T_c}$$

Strong coupling limit, $J/t \gg 1$

- Bose-Einstein condensate (BEC)

$$T_c = \frac{8\pi t^2}{3J}|\Delta|^2$$

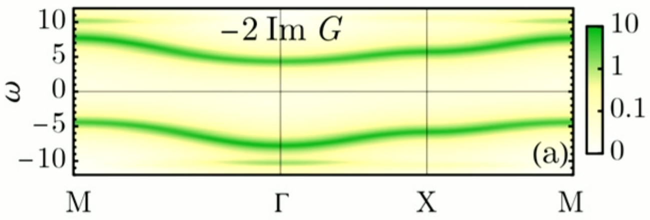


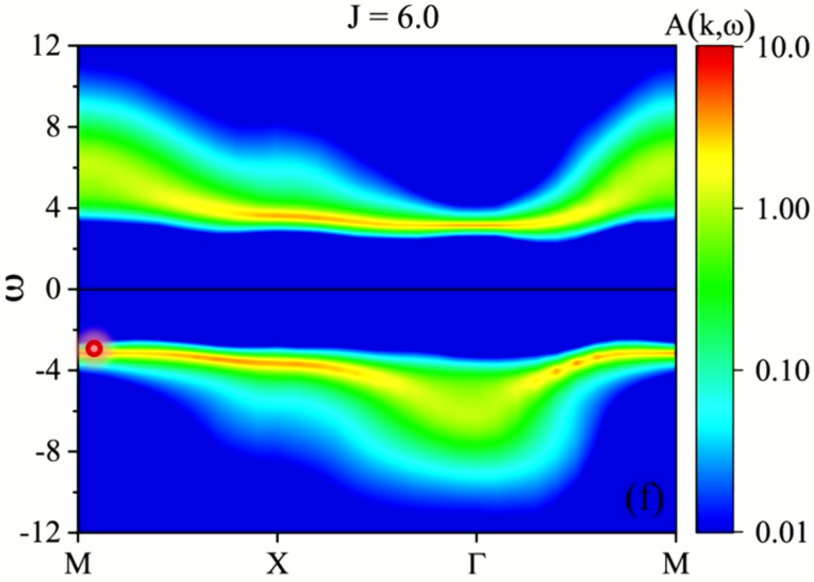
[DCL, et al, arXiv:2308.11195]

Signature of Featureless Mott Insulator

- Cluster perturbation theory and quantum Monte Carlo study of spectral function:

J=8t

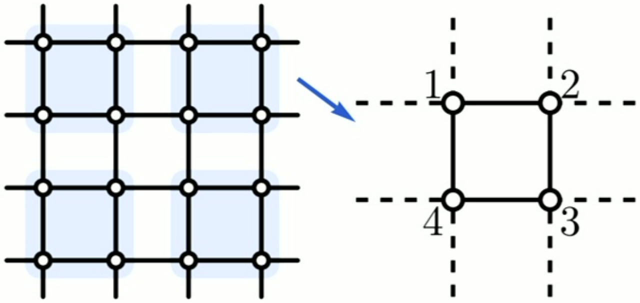




[DCL, et al, arXiv:2307.12223]

[WX Chang, S Guo, YZ You, ZX Li. arXiv:2311.09970]

Cluster perturbation theory



- Calculate the Green's function in a cluster

$$G_{ij}(\omega) = \sum_{m>0} \frac{\langle 0|c_i|m\rangle\langle m|c_j^\dagger|0\rangle}{\omega - (E_m - E_0)} + \frac{\langle m|c_i|0\rangle\langle 0|c_j^\dagger|m\rangle}{\omega + (E_m - E_0)}$$

- Add hopping as perturbation

$$G(\omega, \boldsymbol{k})_{ij} = \left(\frac{G_0(\omega)}{1 - T(\boldsymbol{k})G_0(\omega)}\right)_{ij}$$

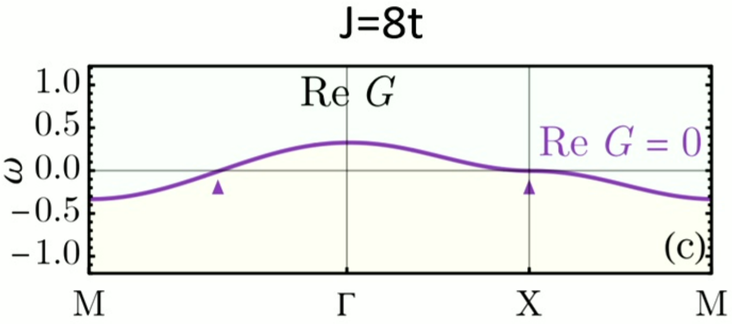
- Reconstruct the Green's function in momentum space

$$G(\omega, \boldsymbol{k}) = \frac{1}{L}\sum_{i,j} e^{-i\boldsymbol{k}\cdot(\boldsymbol{r}_i - \boldsymbol{r}_j)}\, G(\omega, \boldsymbol{k})$$

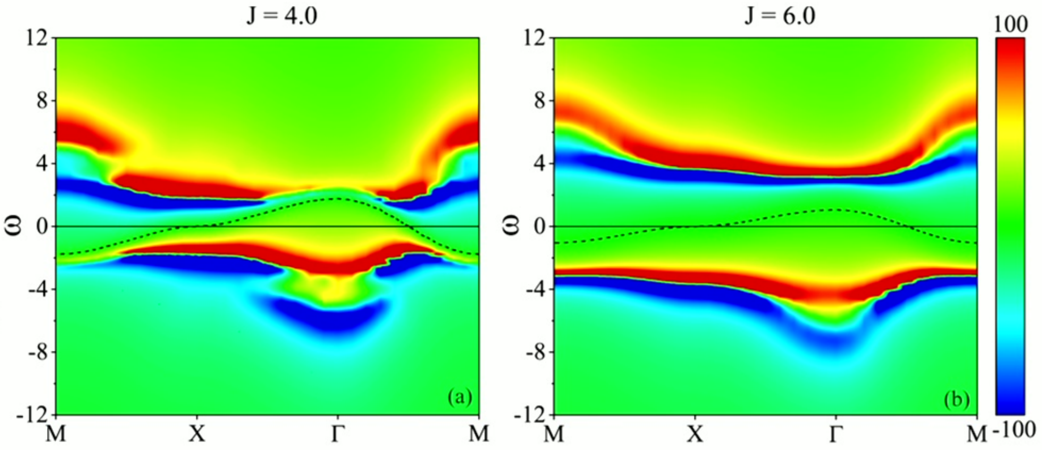
Signature of Featureless Mott Insulator

- Reconstruct the electron Green's function by the Kramers-Kronig relation

$$G(k,\omega) = \frac{1}{2\pi}\int \mathrm{d}\omega' \, \frac{A(k,\omega')}{\omega - \omega'}$$



[DCL, et al, arXiv:arXiv:2307.12223]



[WX Chang, S Guo, YZ You, ZX Li. arXiv:2311.09970]

Green's function zero

- Fermi liquid → Symmetric mass generation

$$\frac{1}{\omega-\epsilon_k} \to \frac{\omega+\alpha(J)\epsilon_k}{(\omega-\epsilon_k/2)^2-J^2}$$

Intuitive understanding: From SSB Green's function

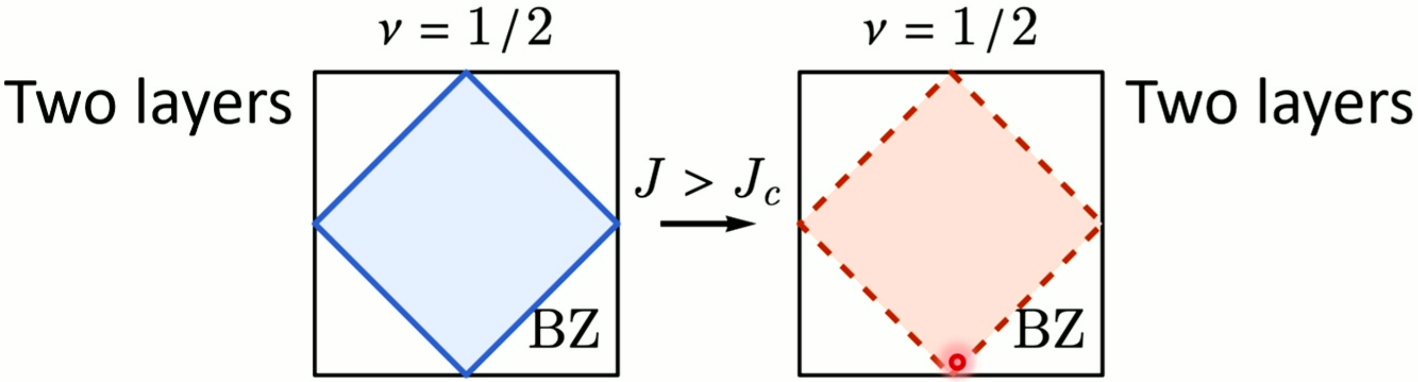
$$\frac{1}{\omega-\epsilon_k\sigma^z+\Delta\sigma^x} \to \frac{-\omega+\epsilon_k\sigma^z \cancel{+\Delta\sigma^x}}{-\omega^2+\epsilon_k^2+\Delta^2}$$

"Averaging over SSB order"

Signature of Featureless Mott Insulator

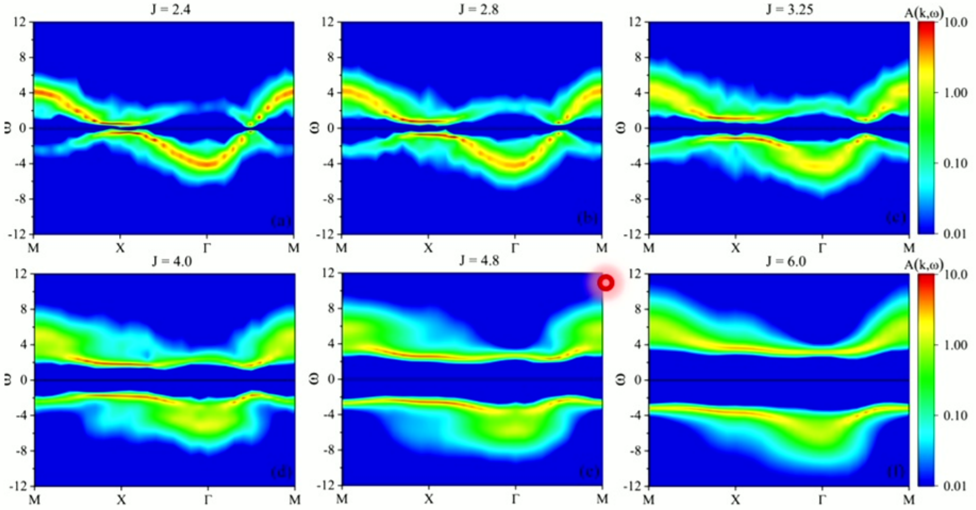
- **Luttinger's theorem**: the Fermi volume fraction in the Brillouin zone = the filling fraction (density) of electrons.

- Featureless Mott insulators are gapped and symmetric: pole Fermi surface must be replaced by zero Fermi surface.



Fermi surface SMG transition at Half-filling

- Quantum Monte Carlo: Transition is O(4) Wilson Fisher, $J_c = 3.24$
- Call for more systematic RG analysis



[Chang, Guo, You, Li (2023)]

Summary

- Fermi surface SMG and its condition
- Theoretical understanding of $\mathrm{La_3Ni_2O_7}$ being an 80K superconductor under pressure beyond 14GPa
  - Pairing mechanism: electron interaction-driven, BEC, doping SMG insulator (Mott insulator without symmetry breaking, fractionalization …)
  - Pairing order: interlayer, spin-singlet, s-wave
  - Features:
    - T_c decreases with pressure
    - Absence of nearby SSB phases
  - Spectral features: strong band renormalization + Green’s function zeros for d_{z^2} orbital.

Future directions

- SMG transition
  - Critical theory
  - Duality, monopole scaling, renormalization group analysis
- Generalized symmetry mass generation
  - Involving self-duality → noninvertible symmetry
  - Higher form symmetry
  - Subsystem symmetry
- Application to other realistic systems
  - Heavy fermion system
  - Pseudo-gap physics

Thank you for your attention! Questions?