The Center for Ultracold Atoms at MIT and Harvard

Theoretical work at CUA

NSF Visiting Committee, April 28-29, 2014

CENTER FOR ULTRACOLD ATOMS
Massachusetts Institute of Technology
Harvard University

CUA Theory

Paola Cappellaro quantum control in hybrid systems

Mikhail Lukin many-body systems of ultracold atoms and molecules, hybrid systems

Susanne Yelin Polar molecules, many-body physics of cold atoms and molecules, hybrid systems

Eugene Demler many-body systems of ultracold atoms and molecules

Strength of CUA theory: synergy with experimental work, collaborations between theory and experiment both within and outside of CUA

Examples of CUA theory/experiment collaborations: Cappellaro and Lukin; Yelin and Lukin; Demler, Lukin and Vuletic; Demler and Ketterle; Demler and Zwierlein; Demler, Greiner and Lukin

Experimental collaboration outside of CUA: Bloch's group at MPQ, Schmiedmayer's group at TU Vienna, A. White's group at Univ. of Queensland, Esslinger's group at ETH, Salomon's group at ENS, Imamoglu's group at ETH

Goals of CUA Theory

Identifying new frontiers in cold atoms research

Example:
Interferometric probes of topological states in optical lattices

Zak/Berry phase topological order parameter in 1d
Theory: Harvard, Expt: MPQ/LMU

Measurements of Berry curvature, Chern number
Theory: Harvard, Expt: MPQ/LMU

Extensions to Quantum Spin Hall effect, Z2 order parameter, interacting systems

Developing new theoretical tools, concepts, analytical and numerical methods

Example:
exploring many-body localization

MBL as integrability, real space RG

MBL in systems with long range interactions

Probe of MBL with Ramsey/echo probe

Experiment/theory collaboration and synergy

Examples:

Prethermalization

Higgs resonance in Optical Lattice

Topological quantum walk of photons

BEC polarons

Dynamics of multicomponent Fermi gas

Superradiance and spin squeezing

Identifying new frontiers in cold atoms research

Interferometric probes of topological states in optical lattices

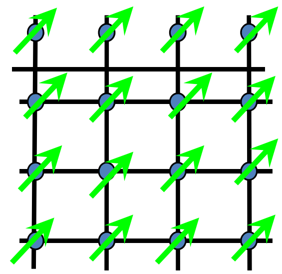
Theory: D. Abanin, T. Kitagawa, E. Demler

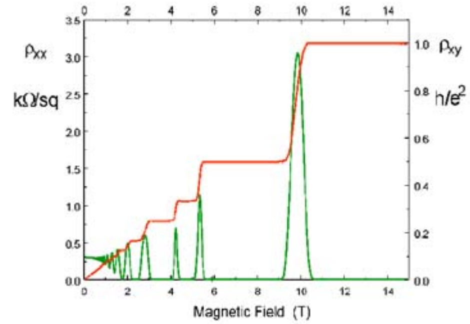
Experiments: M. Atala, M. Aidelsburger, J. Barreiro, I. Bloch (MPQ/LMU)

M. Atala et al., Nature Physics (2013), T. Kitagawa et al., PRL (2013)

Order parameters

Broken symmetries vs topological order



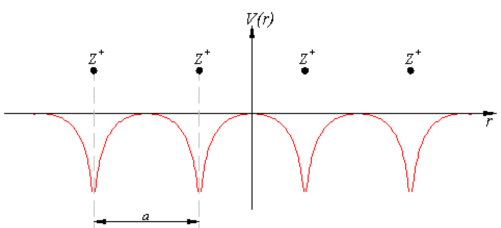


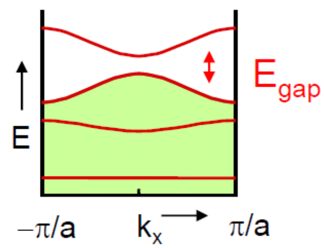
$$\sigma_{xy} = n\frac{e^2}{h}$$

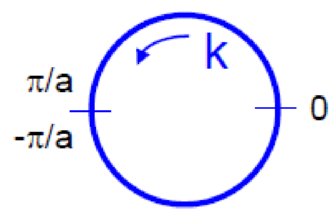
accuracy 10^{-9}

How to measure topological order parameter?

Berry/Zak phase in 1d





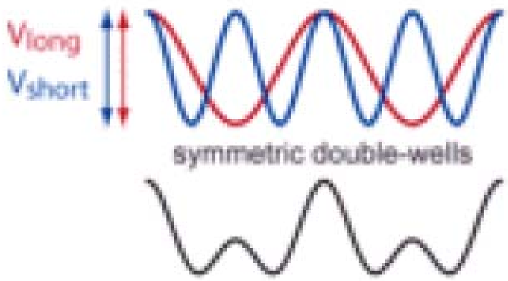


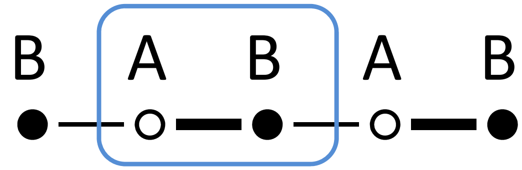
$$\psi(\mathbf{r}) = e^{i\mathbf{k}\cdot\mathbf{r}}u_{\mathbf{k}}(\mathbf{r})$$

$$A(k) = \sum_n \langle\, u_n(k)\,|\,\partial_k\,|\,u_n(k)\,\rangle$$

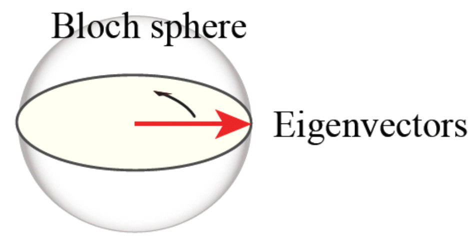
$$P = \frac{e}{\pi}\oint A(k)\,dk$$

SSH Model with bichromatic lattice





$$H = \sum_i (t+\delta t) c^{\dagger}_{Ai} c_{Bi} + (t-\delta t) c^{\dagger}_{Ai+1} c_{Bi} + h.c.$$

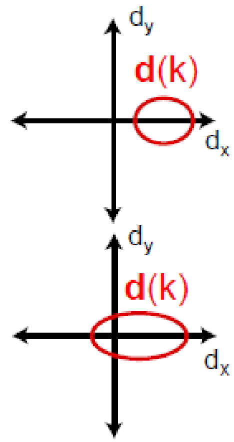


$$H(k) = \mathbf{d}(k) \cdot \vec{\sigma}$$

$$d_x(k) = (t+\delta t) + (t-\delta t)\cos ka$$

$$d_y(k) = (t-\delta t)\sin ka$$

$$d_z(k) = 0$$



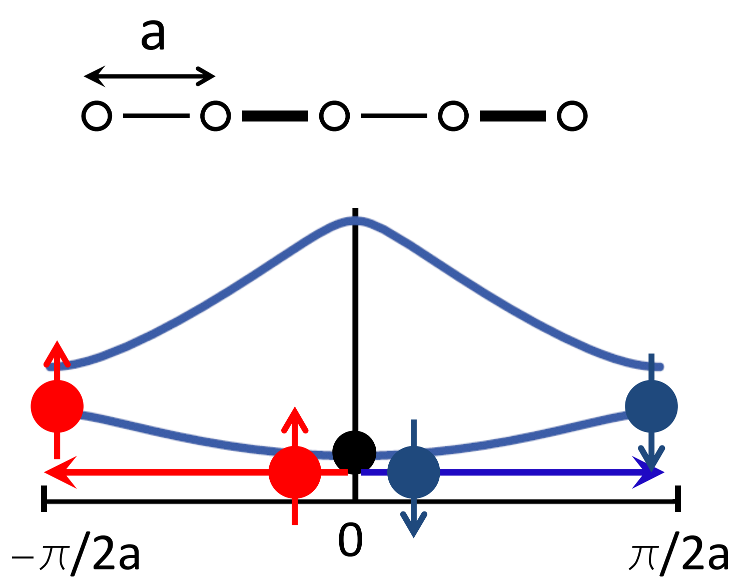
$\delta t>0$: Berry phase 0

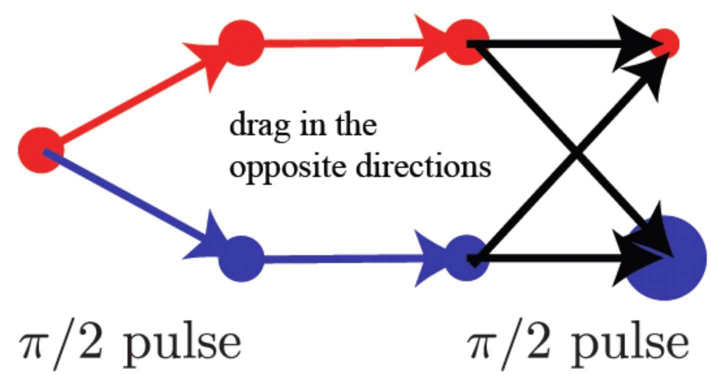
$\delta t<0$: Berry phase π

When $d_z(k)=0$, states with $\delta t>0$ and $\delta t<0$ are topologically distinct.
We can not deform two paths into each other without closing the gap.

Characterizing SSH model using Zak phase

Two hyperfine spin states experience the same optical potential





$$\varphi_{\text{tot}} = \varphi_{\text{Zak}} + \varphi_{\text{dyn}} + \varphi_{\text{Zeeman}}$$

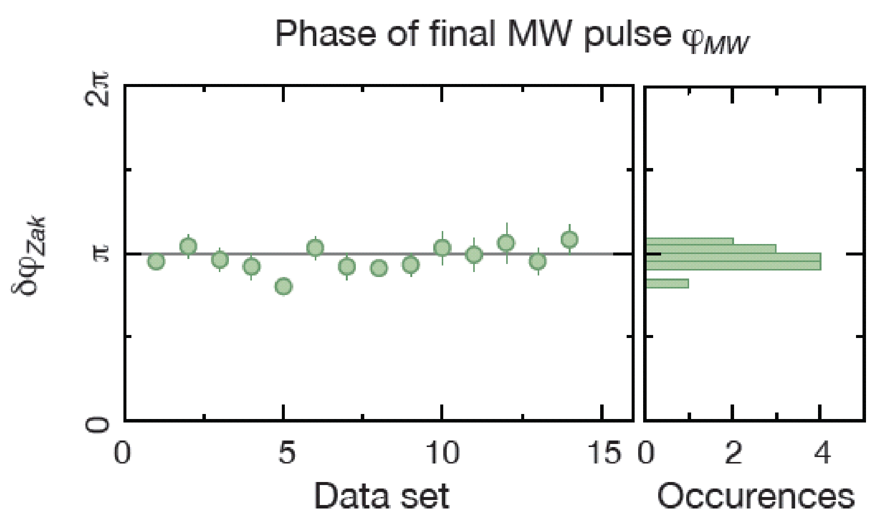
Zak phase is equal to π

$$\frac{1}{i}\int_{-\pi}^{\pi} dk \, \langle \psi_k \,|\, \partial_k \,|\, \psi_k \rangle = \pi$$

Zak/Berry phase measurements

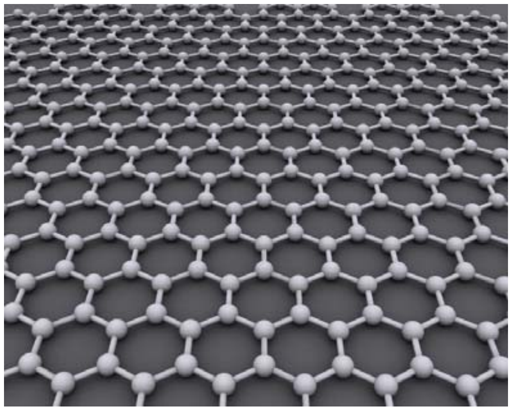
M. Atala et al., Nature Physics (2013)

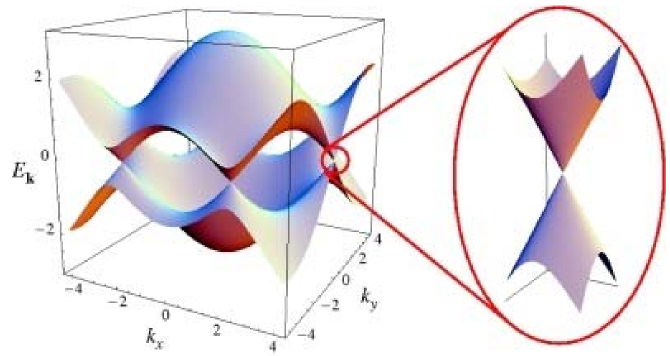
The first direct measurement of topological order parameter either in solid state or condensed matter systems

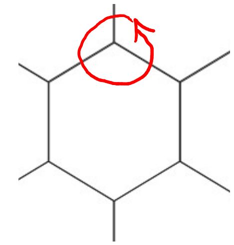


$$\delta\varphi = 0.97(2)\pi$$

Measuring Berry curvature in 2d and Chern number

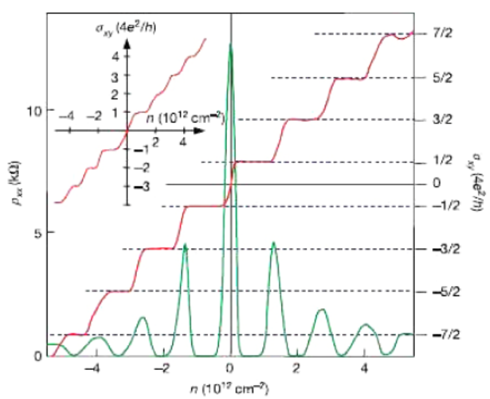






Integral of the Berry phase around the Dirac point

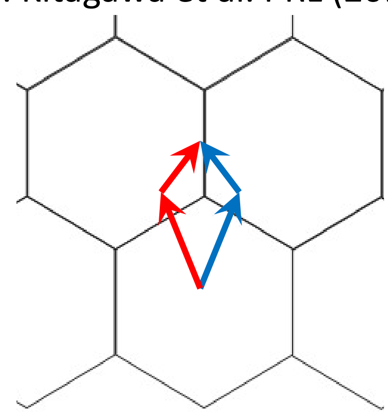
$$\frac{1}{i}\int_C d\vec{k}\,\langle\,\psi_k\,|\,\partial_{\vec{k}}\,|\,\psi_k\,\rangle\;=\;\pi$$



Manifestation of Berry phase of Dirac points in grapheme: IQHE plateaus are shifted by 1/2

Interferometric probe of Berry curvature and Chern number in 2d systems

Theory: Kitagawa et al. PRL (2013), Expt. MPQ



Extension to more exotic states:Quantum Spin Hall Effect states and Topological Insulators in 3D. Grusdt et al., arXiv:1402.2434

Developing new theoretical tools, concepts, analytical and numerical methods

Exploring many-body localization

Conceptual understanding of MBL states as integrabilty

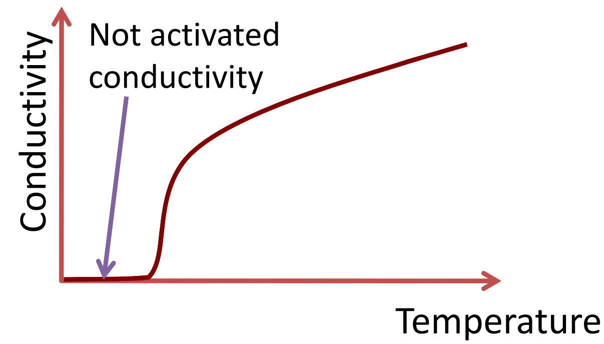
Role of long range interactions

How to probe MBL phases in experiments

Many-body localization (MBL)

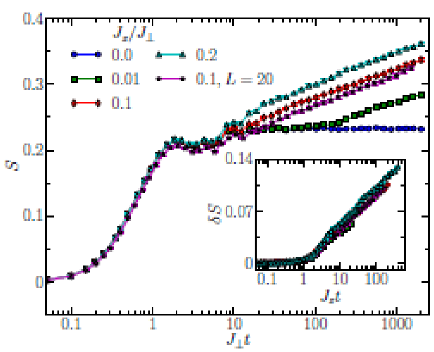
– Anderson
– Basko, Aleiner, Altshuler
– Huse, Oganesyan, Pal
– Aleiner, Altshuler, Shlyapnikov
– …

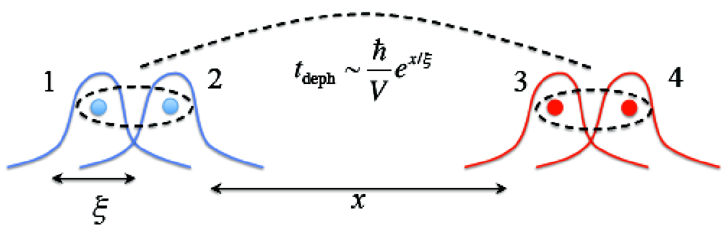
- localization in the presence of interactions
- system does not act as its own bath (discrete local spectrum)



- MBL states vs. Anderson localized states

→ interactions create non-local correlations (growth of entanglement)





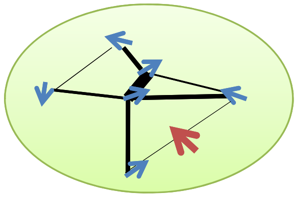
Bardarson et al., PRL (2012)
Vosk, Altman, PRL (2013)
Abanin, et al. PRL (2013)

Systems with interactions and disorder

Central spin problem in q-dots

NV centers in diamond

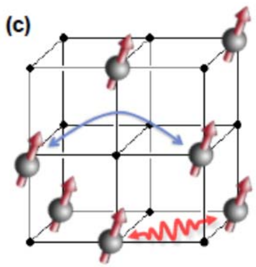
- Marcus et al. (2004)
- Lukin et al. (2006)
- Jelezko et a. (2007)
- Awschalom et al. (2007)



Nuclear spin interactions mediated by electron spin

Polar molecules in optical lattices

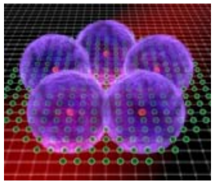
- Ye et al. (2013)



Angular momentum as spin degree of freedom

Rydberg atoms

- Ryabtsev et al. (2010)
- Bloch et al. (2012)
- Lukin, Vuletic et al. (2013)



Strong interactions due to large electric dipole moment

New common feature: long range interactions

Hierarchical structure of excited many-body states in disordered systems: MBL and integrability

Pekker, Refael, Altman, Demler, Oganesyan, PRX (2014)

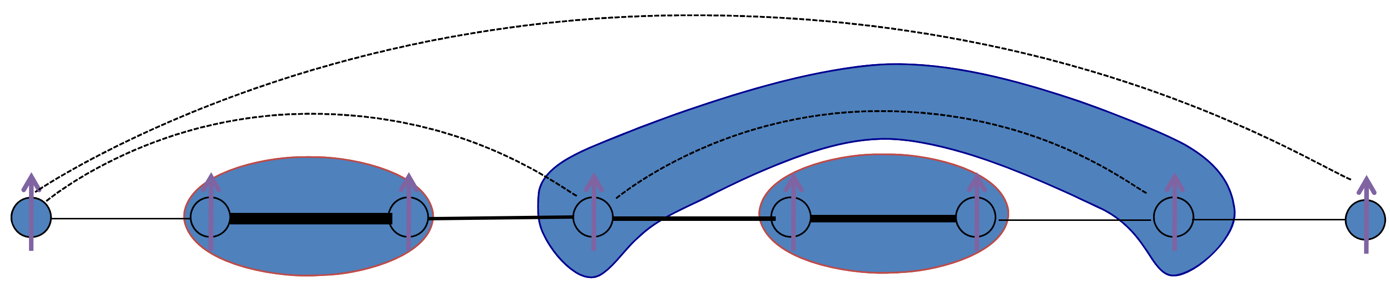
Conjecture

MBL states have hierarchical structure described by power law distributions of couplings and gaps. They are essentially integrable

Implications of the conjecture

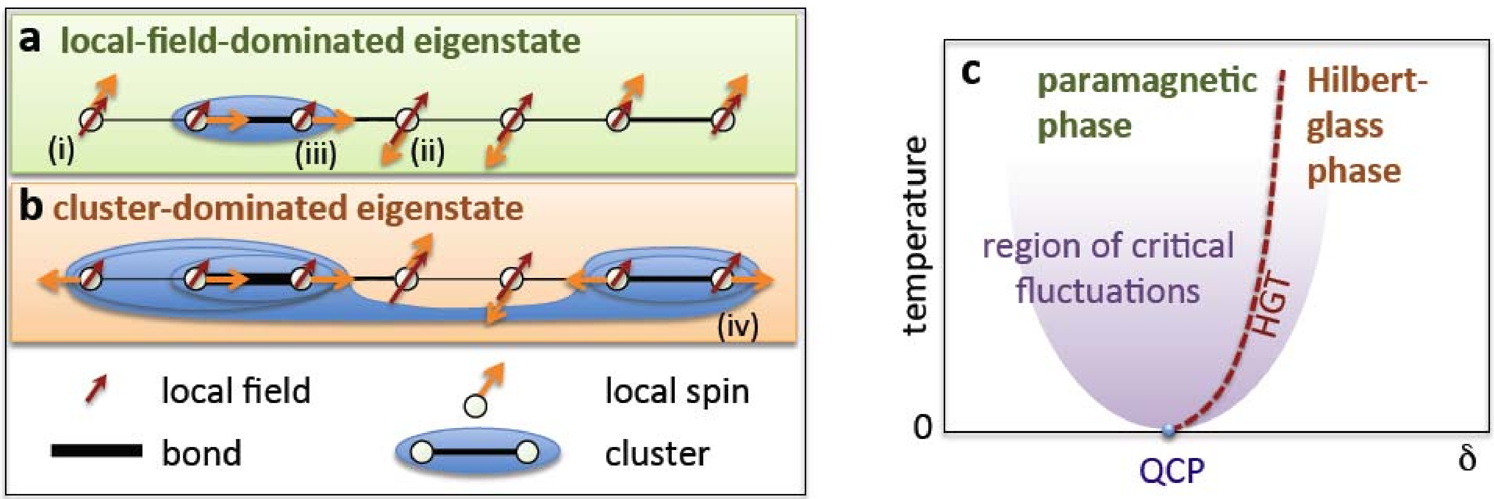
Strongly coupled spins precess fast around each other.

They mediate coupling between outer spins



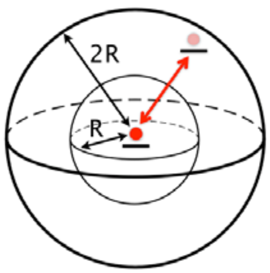
Phase diagram of JJ' model

$$H = \sum_i h_i \sigma_i^z + J_i \sigma_i^x \sigma_{i+1}^x + J'_i \sigma_i^z \sigma_{i+1}^z$$



Localization with Long-Range Hops/Interactions

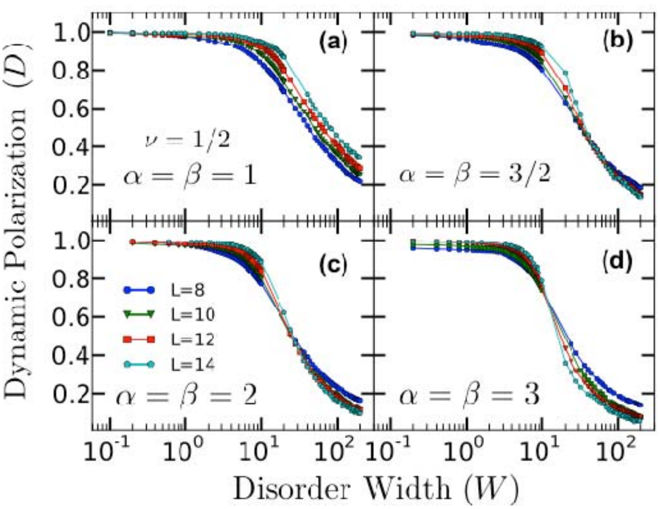
$$H = \sum_i \mu_i n_i + \sum_{ij} \frac{t_{ij}}{R_{ij}^{\alpha}} a_i^{\dagger} a_j$$

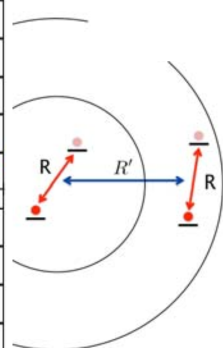


d-dimension, α- exponent of hopping

For d ≥ α, there is no localization   P. W. Anderson, Phys. Rev. (1958)

$$H = \sum_i \mu_i n_i + \sum_{ij} \frac{t_{ij}}{R_{ij}^{\alpha}} a_i^{\dagger} a_j + \sum_{ij} \frac{V_{ij}}{R_{ij}^{\beta}} n_i n_j$$





With interactions localization disappears for 2d ≥ α

N. Yao, C. Laumann, S. Gopalakrishnan, M. Knap et al. arXiv:1311.7151

Consequencies

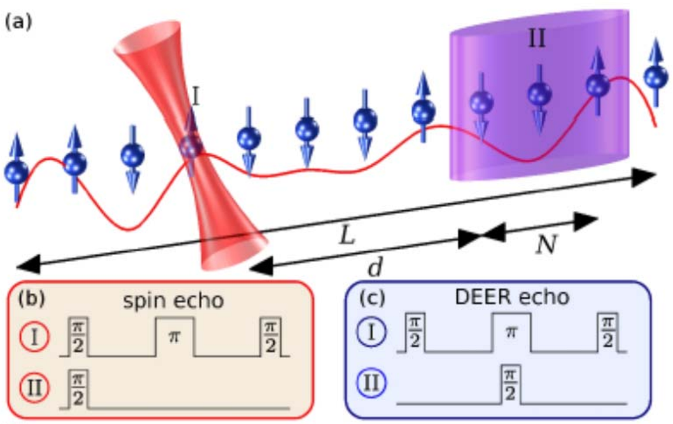
1) Dipoles in 2D are delocalized
2) Experimental – tunable power-laws

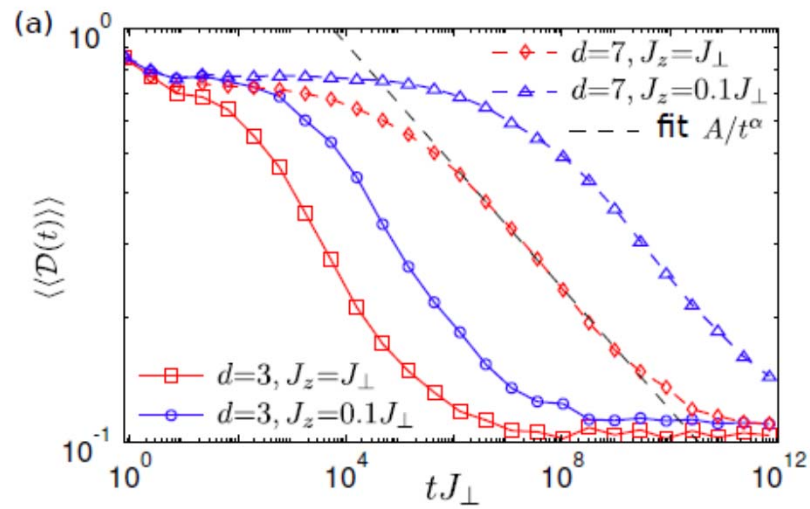
Double Electron-Electron Resonance as a smoking gun probe of MBL

Power law decay of DEER signal with time

arXiv:1403.0693

M. Serbyn, M. Knap, S. Gopalakrishnan, Z. Papić, N. Y. Yao, C. R. Laumann, D. A. Abanin, M. D. Lukin, E. A. Demler

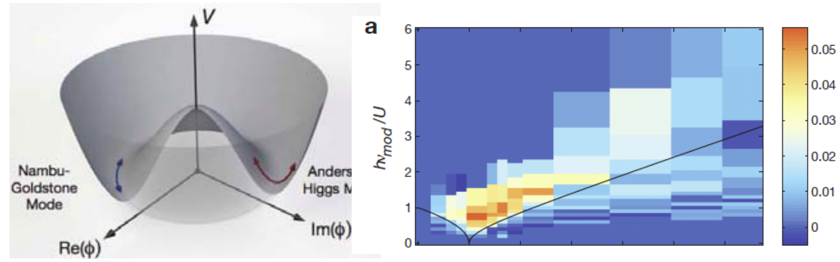




thermal and ensemble averaging

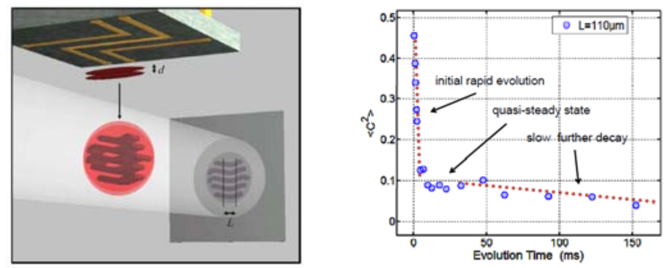
Theory/Experiment interactions and collaborations

Observation of Higgs mode in superfluid phase of ultracold atoms in 2d



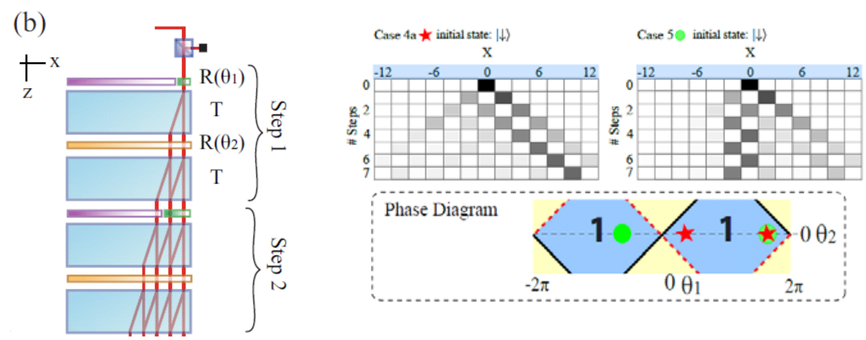
M. Enders et al., Nature 487:454 (2012)

Demonstration of prethermalization in split 1d condensates



D. Gring et al., Science 337:1318 (2012)

Demonstration of edge states in topological quantum walk of photons including Floquet insulator

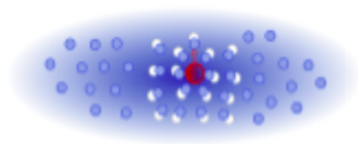


T. Kitagawa et al., Nature Communications 3:882 (2012)

Polarons in BEC

motivated by experiments in Zwierlein's group

Experiment/theory collaboration and synergy

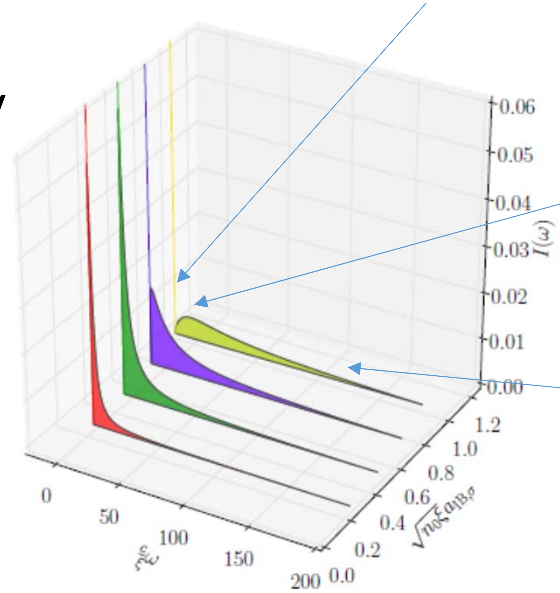


A. Shashi et al., arXiv:1401.0952

+ F. Grusdt, Y. Shchadilova, A. Shashi, R. Schmidt, et al., unpublished

related to Frolich polarons in solid state systems, electrons in magnetic systems

RF spectroscopy



Quasiparticle peak

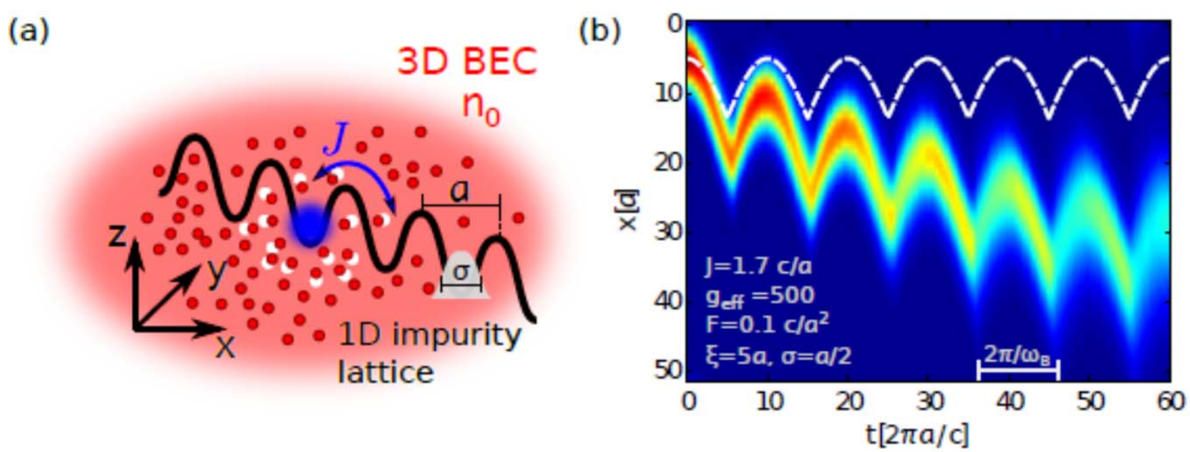
Universal (dimension dependent) low frequency spectrum: signature of many-body orthogonality catastrophe

Universal (dimension dependent) high frequency tail: related to two particle physics

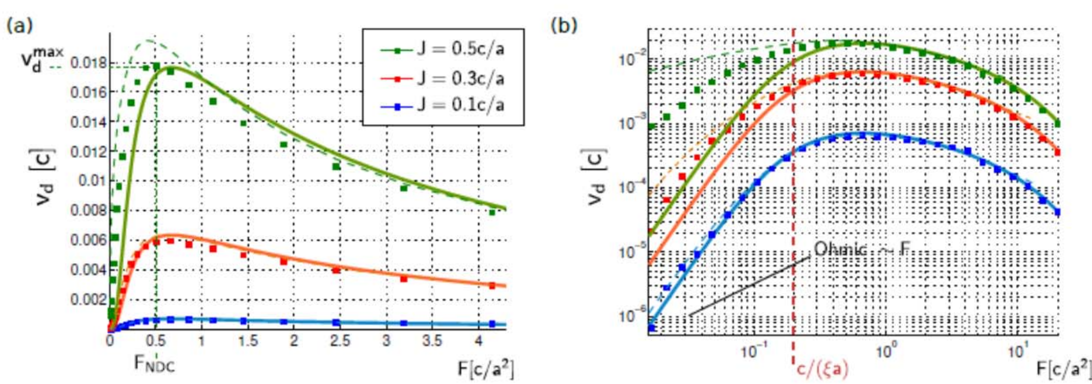
Bloch oscillations of BEC polarons in optical lattices

motivated by experiments in Greiner's group

+ F. Grusdt, A. Shashi, et al., unpublished



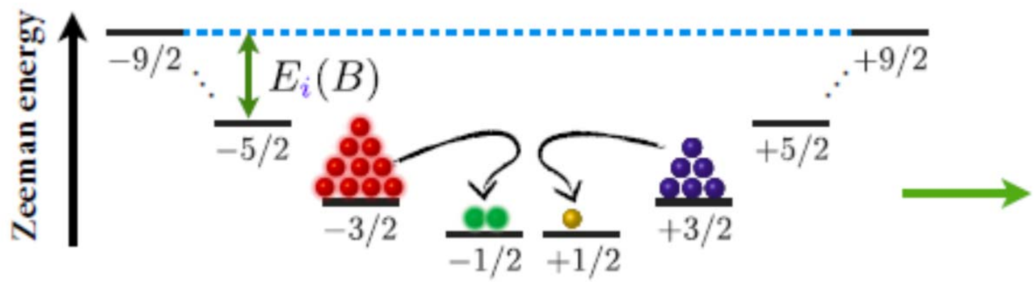
Drift beyond Esaki-Tsu model: nonlinear drift velocity for small force

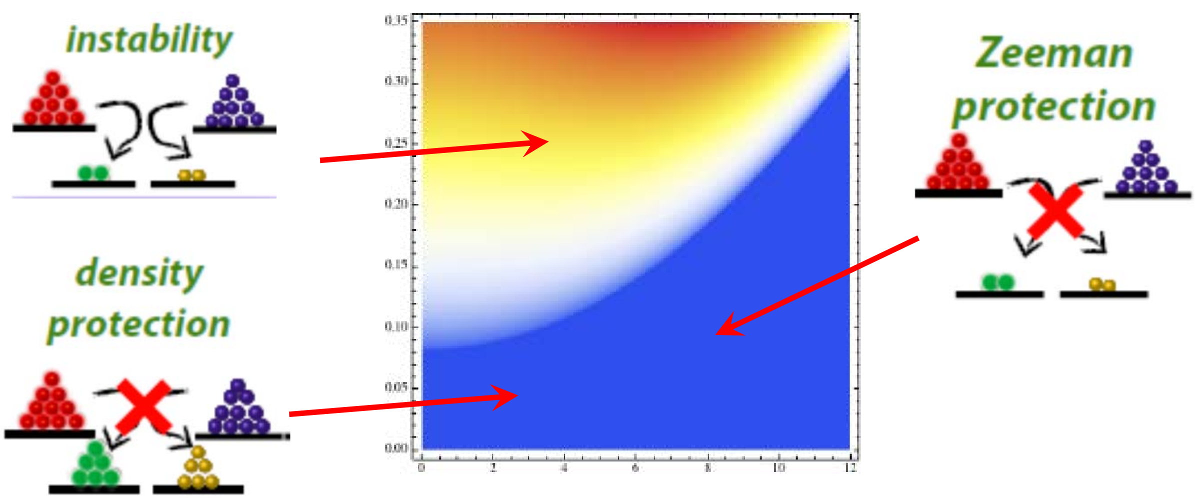


Dynamics of multicomponent Fermi gases

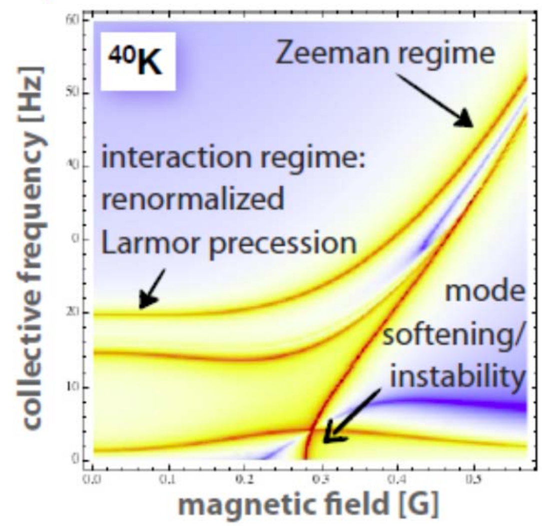
motivated by CUA experiments, also Krauser et al., Science (2014), Scazza et al. arXiv (2014)

R. Schmidt, M. Knap, A. Shashi, et al., unpublished





collective modes in presence of small coherences



motivated by experiments in Vuletic's and Lukin's labs

Superradiance and Entanglement

Does (Dicke) superradiance need/create entanglement?

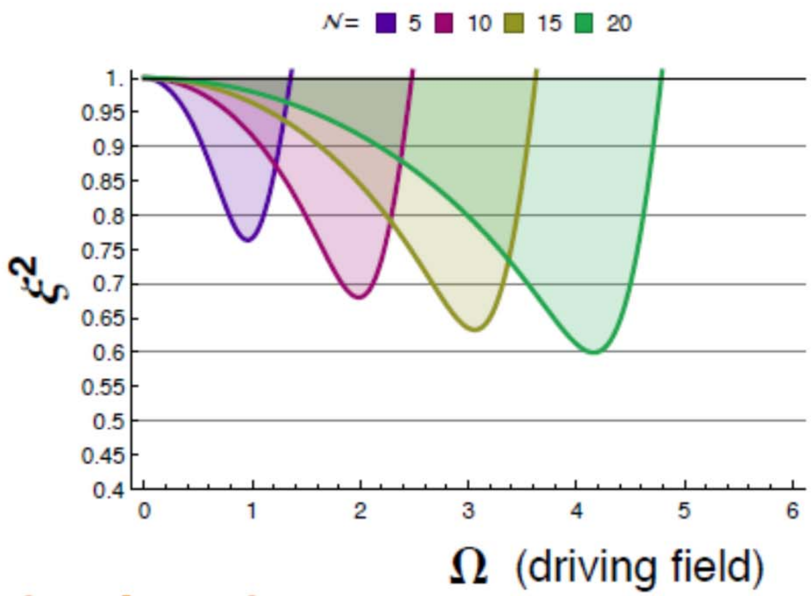
Why do we ask:

- Many-partite entanglement is a hot topic and as of yet unsolved theoretical question
- Superradiance is based on fully symmetric ("Dicke") states, (nearly) each of which is entangled
- What type of nonlinearity do cooperative effects/superradiance supply?

Wolfe, Yelin,Phys. Rev. Lett. 112, 140402 (2014)

Superradiant Spin Squeezing

- Superradiance alone and driving the 2-level transition alone do not create entanglement - but both together do
- Is entanglement useful? (I.e., could it improve measurements?)
- Yes - the system is (strongly) spin-squeezed!



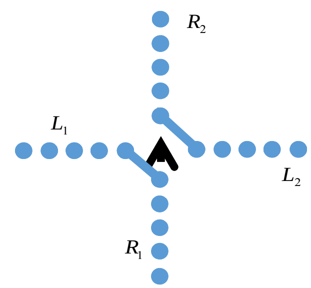
Conclusion: For systems with high optical density extremely simple spin squeezing scheme!

$$\xi^2 \equiv \frac{\text{optimal variance}}{\text{unsqueezed optimal variance}}$$

(squeezing parameter: $\xi^2 < 1 \Rightarrow$ system is squeezed)

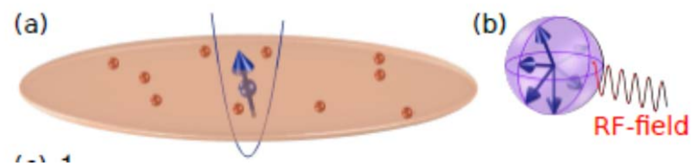
Future directions

Measuring and utilizing entanglement entropy

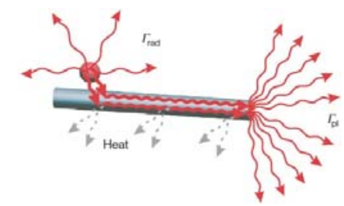


quantum switch for measuring entanglement entropy from Abanin, Demler, PRL (2012)

Driven/open/nonequilibrium quantum many-body systems (cold atoms/optics/CM interface)

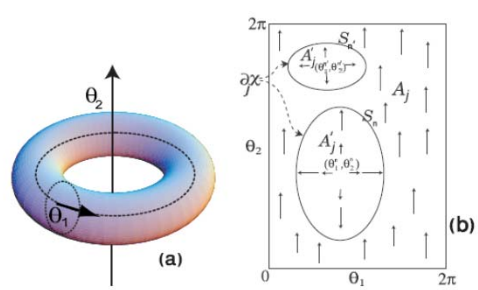


Rabi oscillations of mobile impurity



QD + optical fiber

Interferometry of many-body states



Chern number for a fractional QH state from Hafezi et al. EPL (2008)