Exploring exotic states with Ramsey interferometry

Eugene Demler (Harvard)

Collaborators:
S. Gopalakrishnan, M. Knap, M. Lukin, T. Kitagawa (Harvard)
D. Abanin (Perimeter Inst.),
M. Atala, M. Aidelsburger, J. Barreiro, I. Bloch (MPQ/LMU)
A. Kantian, T. Giamarchi (Univ. Geneva)
A. Imambekov, A. Shashi (Rice)
Y. Nishida (Tokyo Inst. Of Technology)

-MIT

$$ NSF, AFOSR MURI, DARPA OLE,
MURI ATOMTRONICS, MURI QUISM

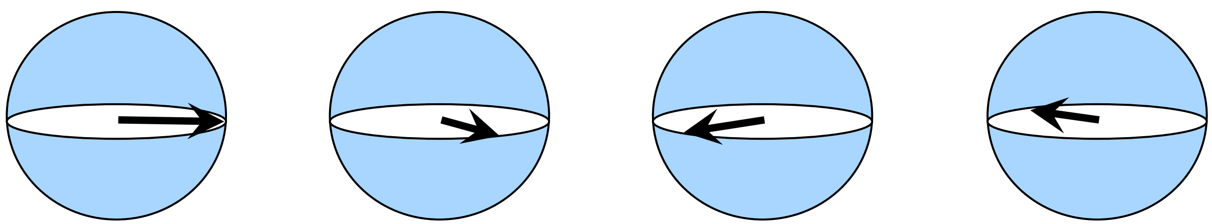
Ramsey interference

p/2 pulse

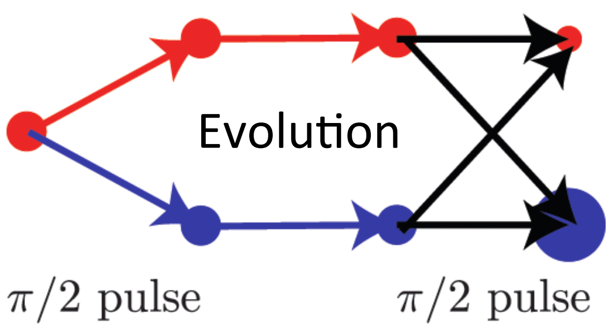
$$|\downarrow\rangle \rightarrow \frac{1}{\sqrt{2}}|\downarrow\rangle + \frac{1}{\sqrt{2}}|\uparrow\rangle$$

Evolution

$$|\Psi(t)\rangle = \frac{1}{\sqrt{2}}e^{-i\mathcal{H}_{\downarrow}t}|\downarrow\rangle + \frac{1}{\sqrt{2}}e^{-i\mathcal{H}_{\downarrow}t}|\uparrow\rangle$$



p/2 pulse + measurement of S_z gives relative phase accumulated by the two spin components



Used for atomic clocks, gravitometers, accelerometers, magnetic field measurements

Outline

Exploring exotic states with Ramsey interferometry

Exploring orthogonality catastrophe with cold atoms
M. Knap et al., PRX (2012)

Measuring Berry/Zak phase in optical lattices
M. Atala et al., arXIv:1212.0572, T. Kitagawa et al., PRL (2013)

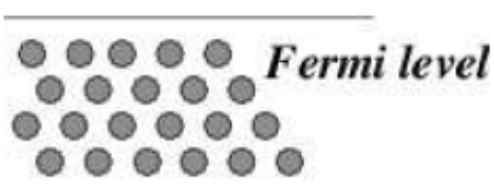
Measuring dynamical spin correlation functions
M. Knap, et al., arXiv:1307.0006

Probing many-body localization
M. Knap, S. Gopalakrishnan, et al.

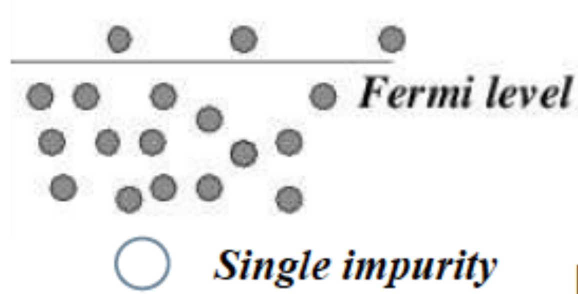
Exploring orthogonality catastrophe with ultracold atoms

M. Knap, A. Shashi, Y. Nishida, A. Imambekov, D. Abanin, ED, PRX (2012)

Anderson orthogonality catastrophe



$|FS>$



$|FS'>$

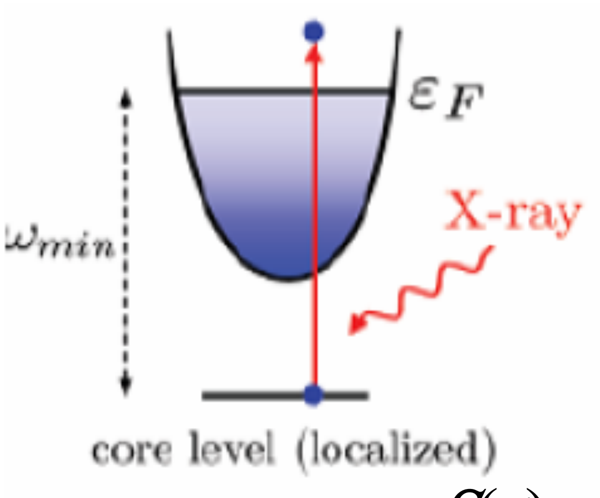
-Overlap $S = \langle FS | FS' \rangle$

- $S \to 0$ as system size $L \to \infty$, "orthogonality catastrophe"

-Infinitely many low-energy electron-hole pairs produced

Fundamental property of the Fermi gas

Orthogonality catastrophe in X-ray absorption spectra

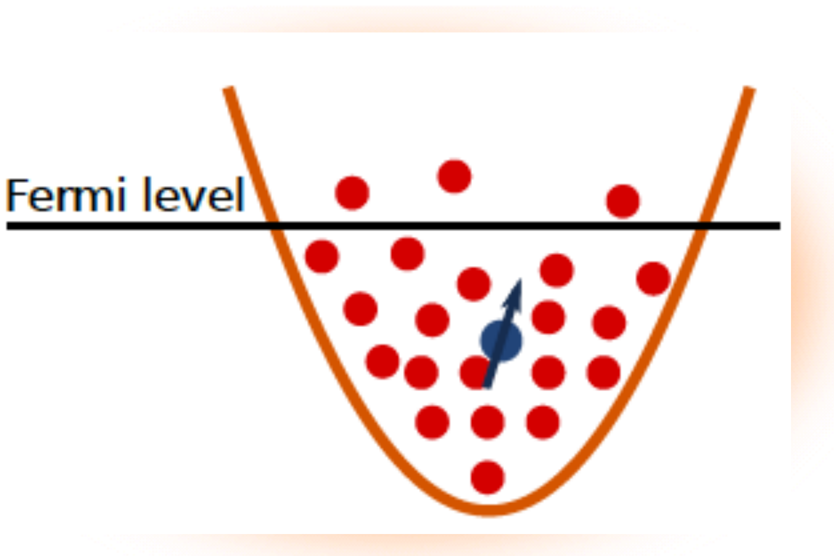


Without impurity   *With impurity*

-Relevant overlap: $S(t) = \left\langle FS \right| e^{iH_0 t} e^{-iH_f t} \left| FS \right\rangle \propto t^{-\delta^2/\pi^2}$

δ -- scattering phase shift at Fermi energy, $\tan\delta = -k_F a$

Orthogonality catastrophe with cold atoms: Setup



-Fermi gas+single impurity

-Two pseudospin states of impurity, $|\uparrow\rangle$ and $|\downarrow\rangle$

- $|\uparrow\rangle$ -state scatters fermions
  $|\downarrow\rangle$ -state does not

-Scattering length a

-Fermion Hamiltonian for pseudospin $|\uparrow\rangle, |\downarrow\rangle$ -- H_0, H_f

Earlier theoretical work on Kondo and FES with relation to cold atoms:
Zwerger, Lamacraft, Kamenev, Gangardt, Giamarchi, Kollath,...

Ramsey fringes – new manifestation of OC

-Utilize control over spin

-Access coherent coupled dynamics of spin and Fermi gas

-Ramsey interferometry

1) p/2 pulse $|\downarrow\rangle|FS\rangle \rightarrow \frac{1}{\sqrt{2}}|\downarrow\rangle|FS\rangle + \frac{1}{\sqrt{2}}|\uparrow\rangle|FS\rangle$

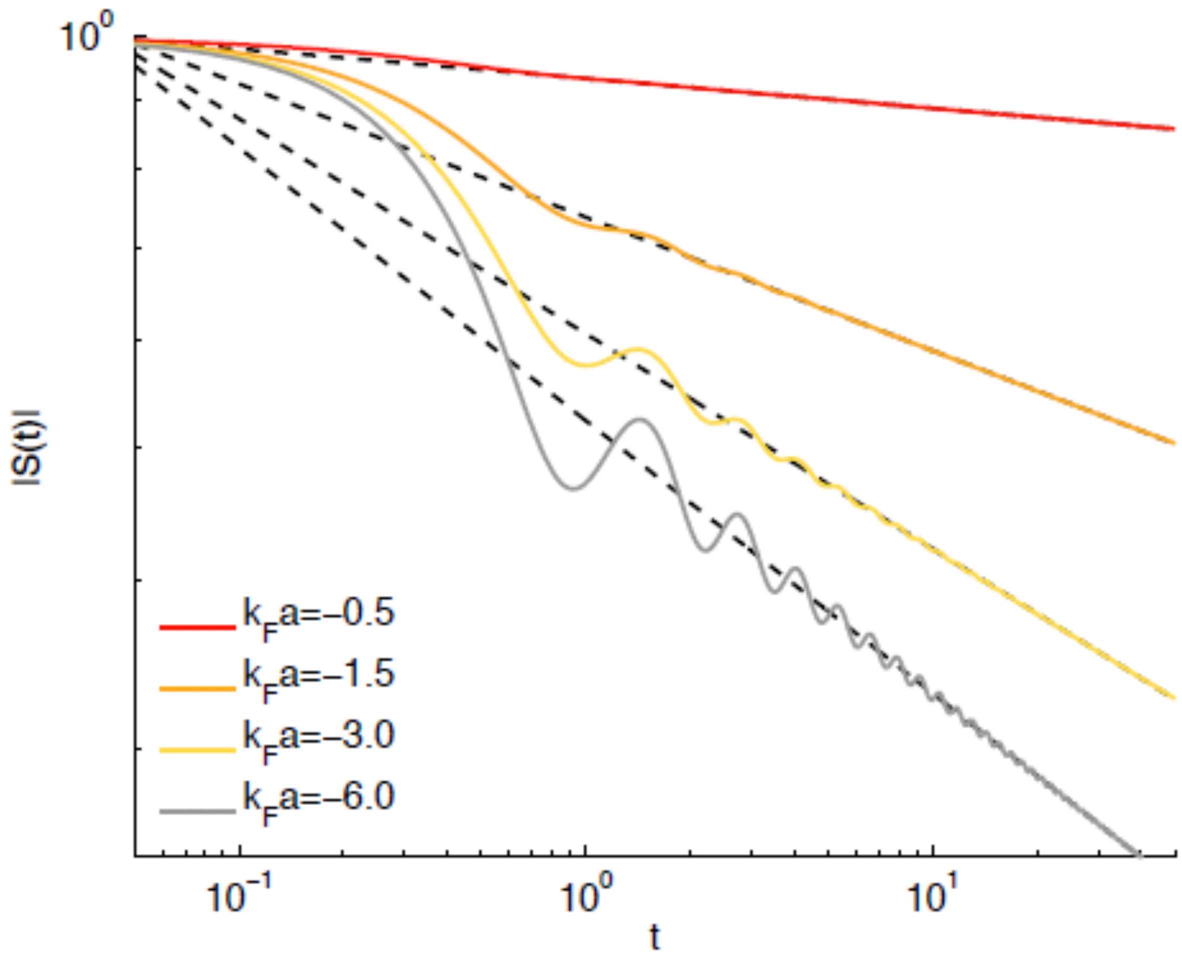
2) Evolution $\frac{1}{\sqrt{2}}|\downarrow\rangle e^{-iH_0 t}|FS\rangle + \frac{1}{\sqrt{2}}|\uparrow\rangle e^{-iH_f t}|FS\rangle$

3) Use p/2 pulse to measure $< S_x >= \mathrm{Re}[S(t)]$

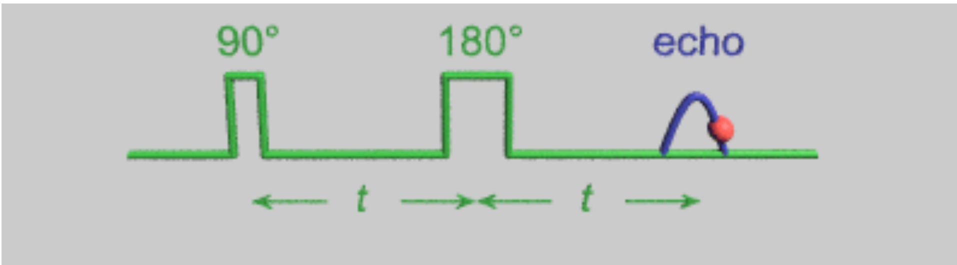
$$S(t) = \left\langle FS \right| e^{iH_0 t} e^{-iH_f t} \left| FS \right\rangle$$

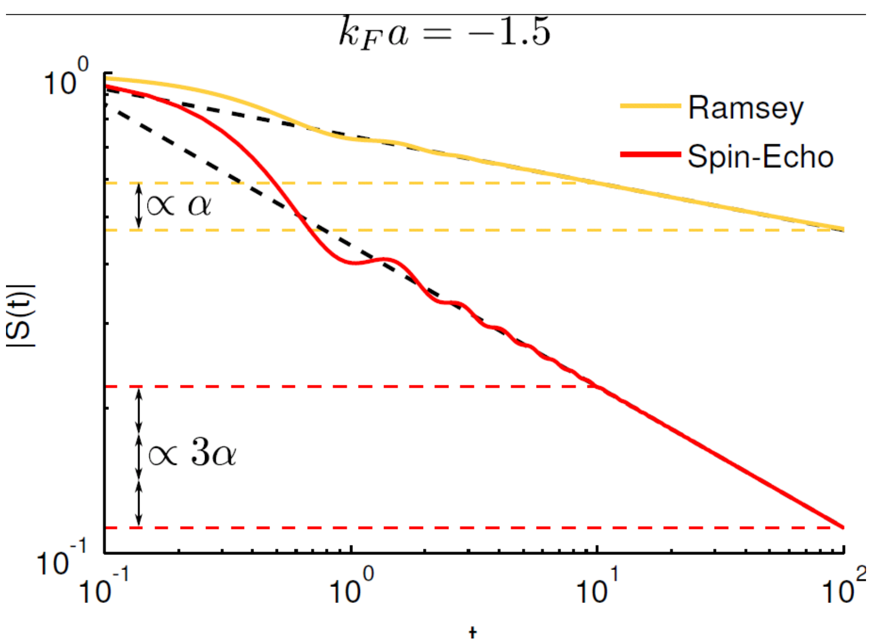
Direct measurement of OC in the time domain

Ramsey fringes as a probe of OC
First principle calculations



Spin echo: probing non-trivial dynamics of the Fermi gas





-Unlike the usual situation (spin-echo decays slower than Ramsey)

-Cancels magnetic field fluctuations

-Universal

-Generalize to n pi-pulses to study even more complex response functions

Probing band topology with Ramsey/Bloch interference

M. Atala et al., arXIv:1212.0572

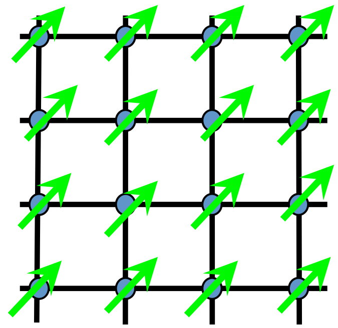
T. Kitagawa et al., PRL (2013)

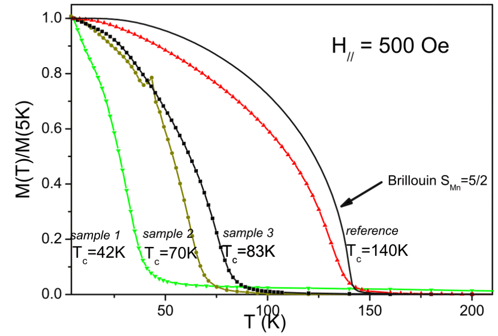
Theory: D. Abanin, T. Kitagawa, E. Demler

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

Order parameters

Magnetization - order parameter in ferromagnets



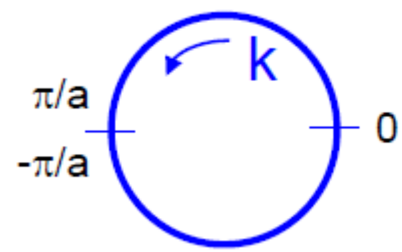


How to measure topological order parameter?

Berry/Zak phase in 1d

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

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

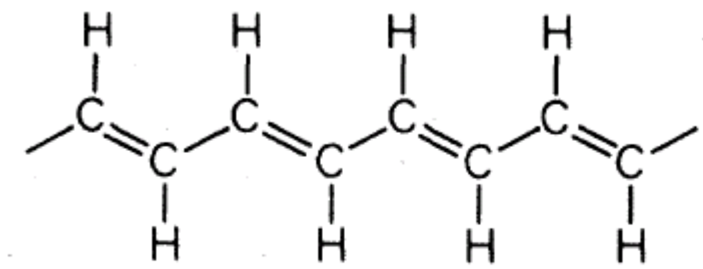


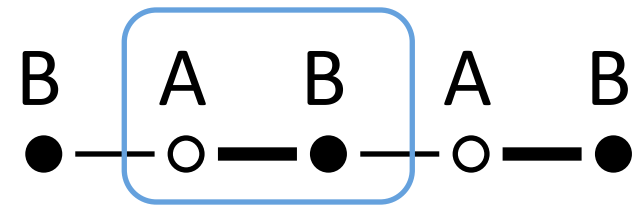
Related to polarization in 1d systems

$$P = \frac{\text{dipole moment}}{\text{length}}$$

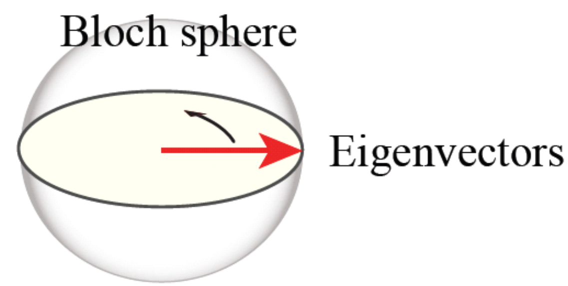
Vanderbilt, King-Smith
PRB 1993

Su-Schrieffer-Heeger Model





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

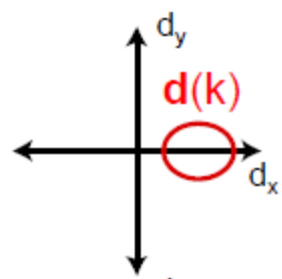


$$H(k)=\mathbf{d}(k)\cdot\vec{\sigma}$$

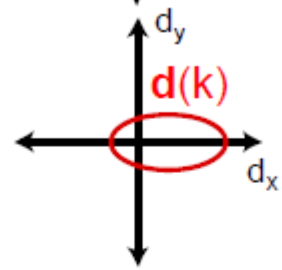
$$d_x(k)=(t+\delta t)+(t-\delta t)\cos ka$$

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

$$d_z(k)=0$$



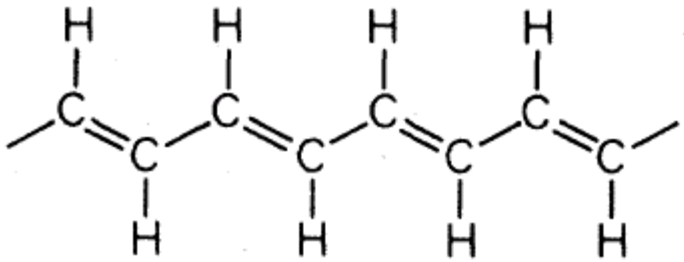
$\delta t>0$: Berry phase 0



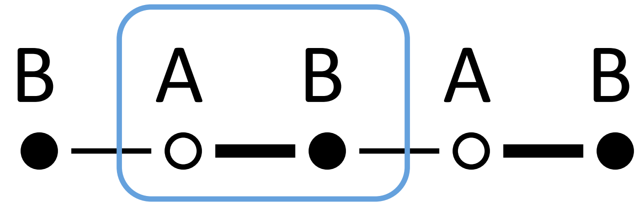
$\delta t<0$: Berry phase π

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

SSH model in bichromatic lattices

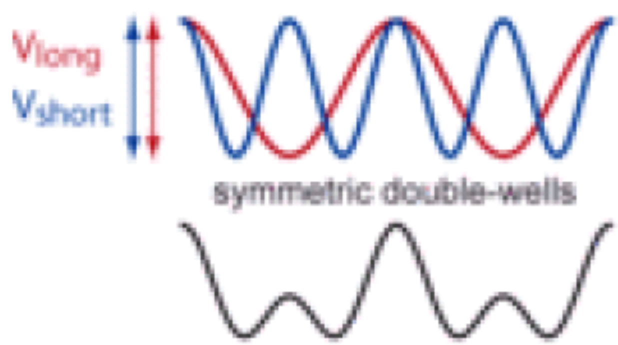


Su, Schrieffer, Heeger, 1979



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

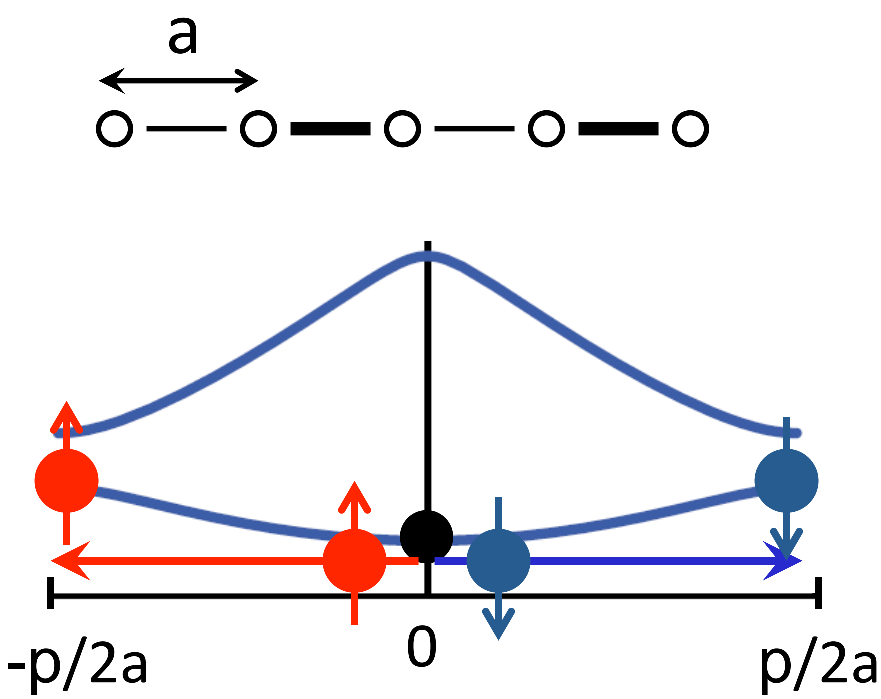
Analogous to bichromatic optical lattice potential

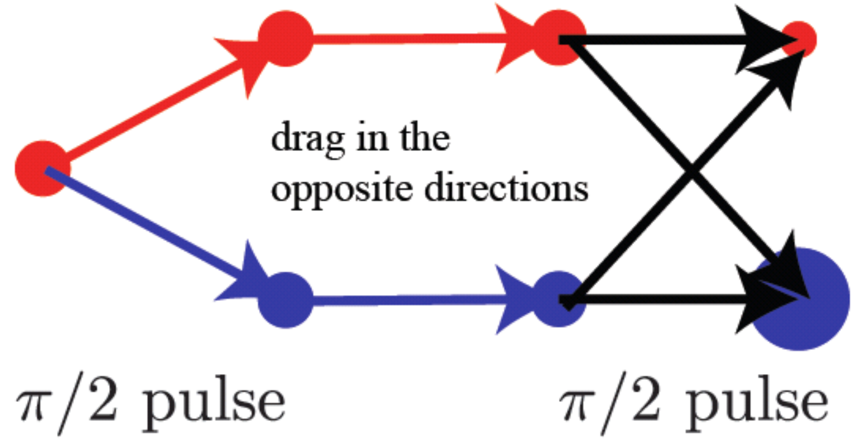


I. Bloch et al.,
LMU/MPQ

Characterizing SSH model using Zak phase

Two hyperfine spin states experience the same optical potential





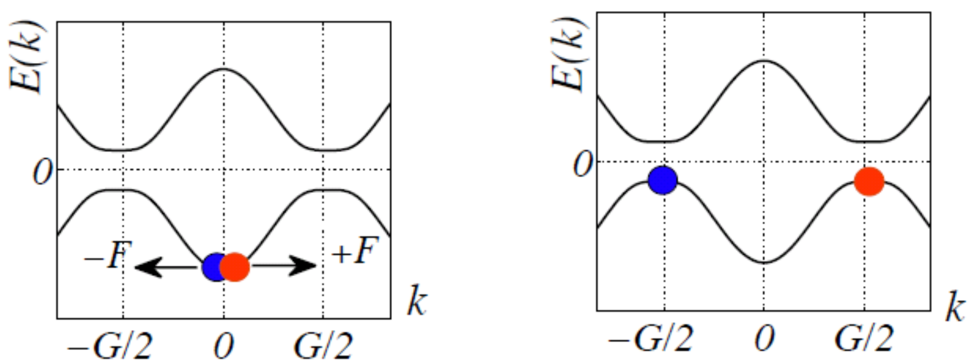
$$\varphi_{\text{tot}} = \varphi_{\text{Zak}} + \varphi_{\text{dyn}} + \varphi_{\text{Zeeman}}$$

Zak phase is equal to p

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

Problem: experimentally difficult to control Zeeman phase shift

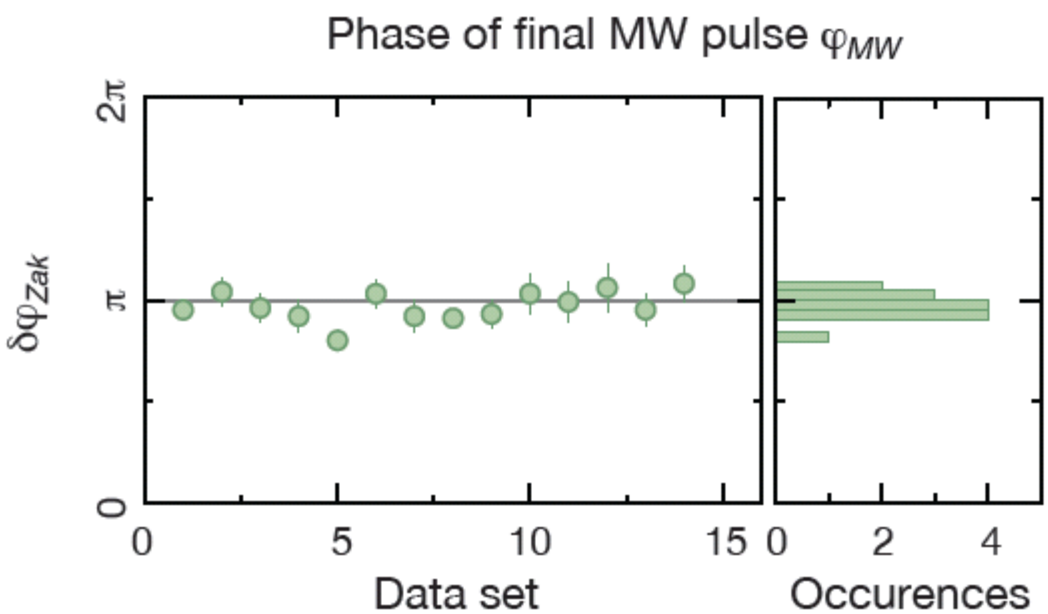
Spin echo protocol for measuring Zak phase



Dynamic phases due to dispersion and magnetic field fluctuations cancel. Interference measures the difference of Zak phases of the two bands in two dimerizations.

Expect phase p

Zak/Berry phase measurements



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

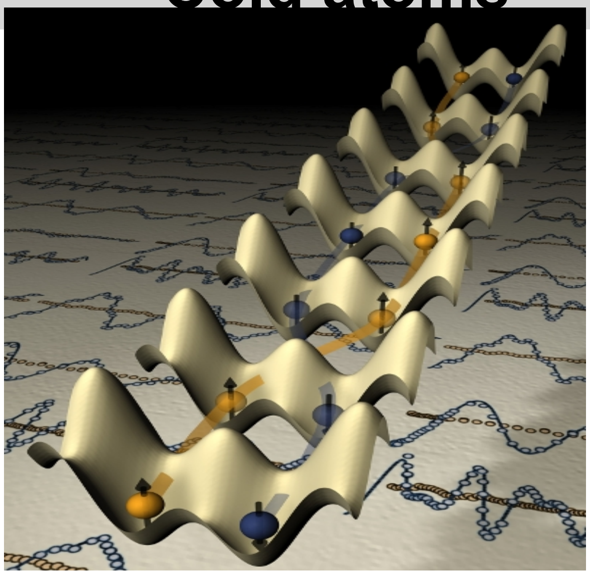
Exploring dynamical response functions in spin models using many-body Ramsey interference

M. Knap, A. Kantian, T. Giamarchi, I. Bloch, M. Lukin, E. Demler

arXiv:1307.0006

Probing spin dynamics in synthetic matter

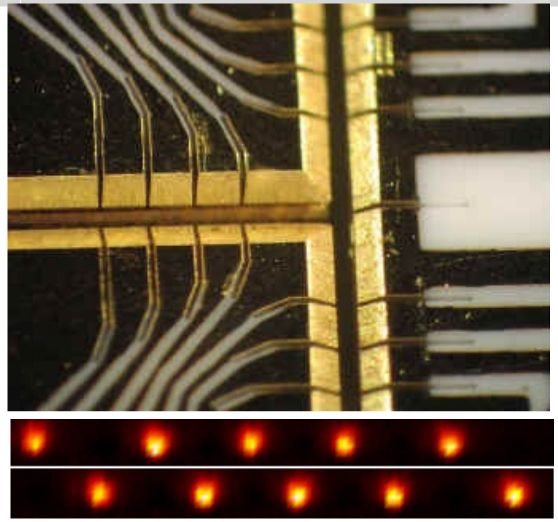
Cold atoms



MPQ group

- **Heisenberg model** of XXZ type
- super-exchange
- e.g. ^{87}Rb mixtures of $|1,-1\rangle$ and $|2,-2\rangle$

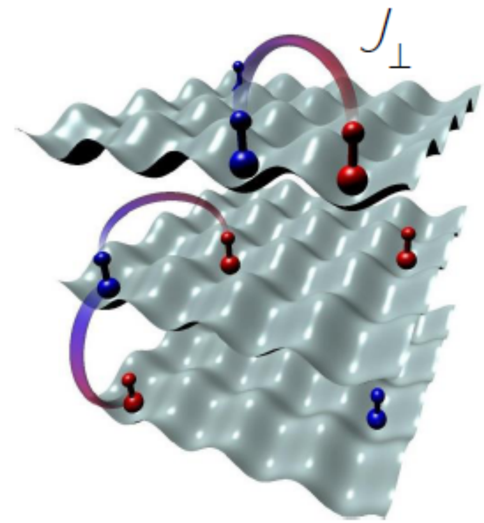
Trapped ions



JQI group

- **LR transverse field Ising model**
- interactions mediated by phonons
- e.g. ^{171}Yb

Dipolar interac

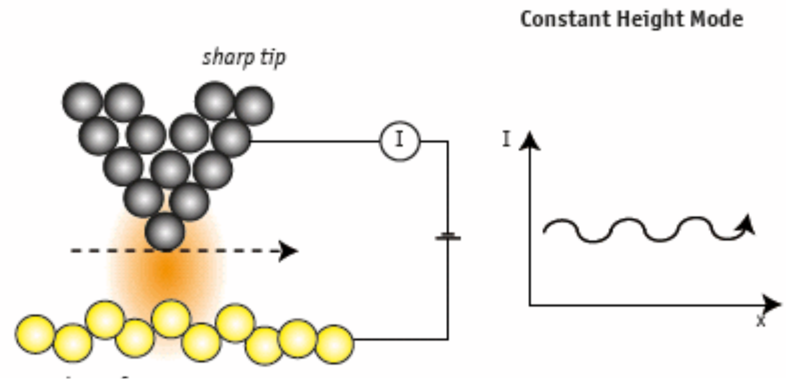


JILA group

- **LR XX model**
- Molecules, e.g. K
- Atoms w/ large m moments, e.g. Cr

Dynamic probes of many-body systems

- condensed matter
  → common framework to understand diverse probes
  - neutron/X-ray scattering
  - optical response
  - STM
  - ...



- retarded Green's functions:

$$G_{\mathrm{ret}}^{AB,\mp}(t) := -\frac{i\theta(t)}{Z}\sum_n e^{-\beta E_n}\langle n|B(t)A(0) \mp A(0)B(t)|n\rangle$$

- information about excitation spectra and quantum phase transition (e.g. scaling)

Dynamic probes of many-body systems

- Synthetic many-body systems (atoms, molecules, ions):

→ typically dynamics explored through quench experiments

$$\langle \Psi_0 | U_Q^\dagger \, e^{i\mathcal{H}t} \, \mathcal{O} \, e^{-i\mathcal{H}t} \, U_Q | \Psi_0 \rangle$$

Quench

Evolution

Measurement

- no direct information about excitations

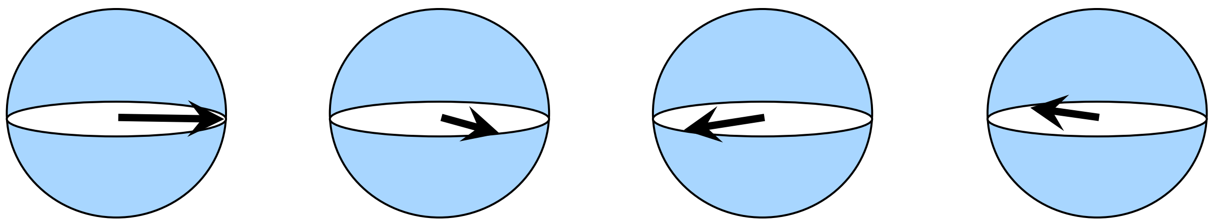
→ exceptions: RF-spectroscopy

Proposal: use many-body Ramsey interferometry to measure dynamic spin-correlation functions

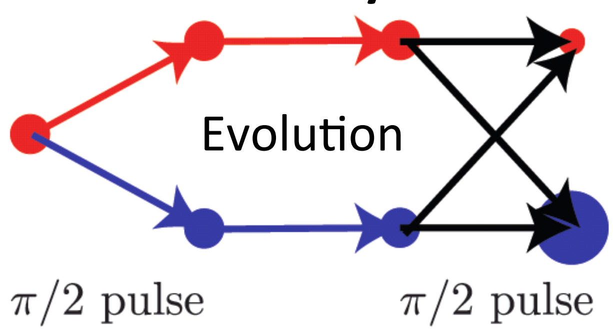
Ramsey interference

p/2 pulse $$|\downarrow\rangle \rightarrow \frac{1}{\sqrt{2}}|\downarrow\rangle + \frac{1}{\sqrt{2}}|\uparrow\rangle$$

Evolution $$|\Psi(t)\rangle = \frac{1}{\sqrt{2}} e^{-i\mathcal{H}_\downarrow t}|\downarrow\rangle + \frac{1}{\sqrt{2}} e^{-i\mathcal{H}_\downarrow t}|\uparrow\rangle$$

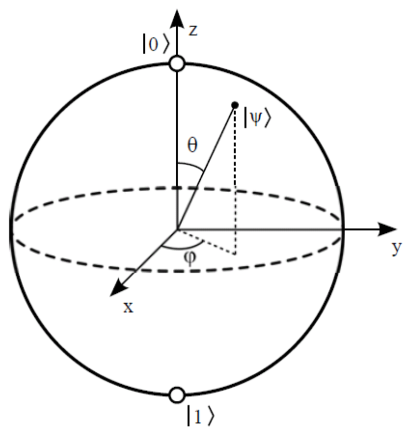


p/2 pulse + measurement ot S_z gives relative phase accumulated by the two spin components



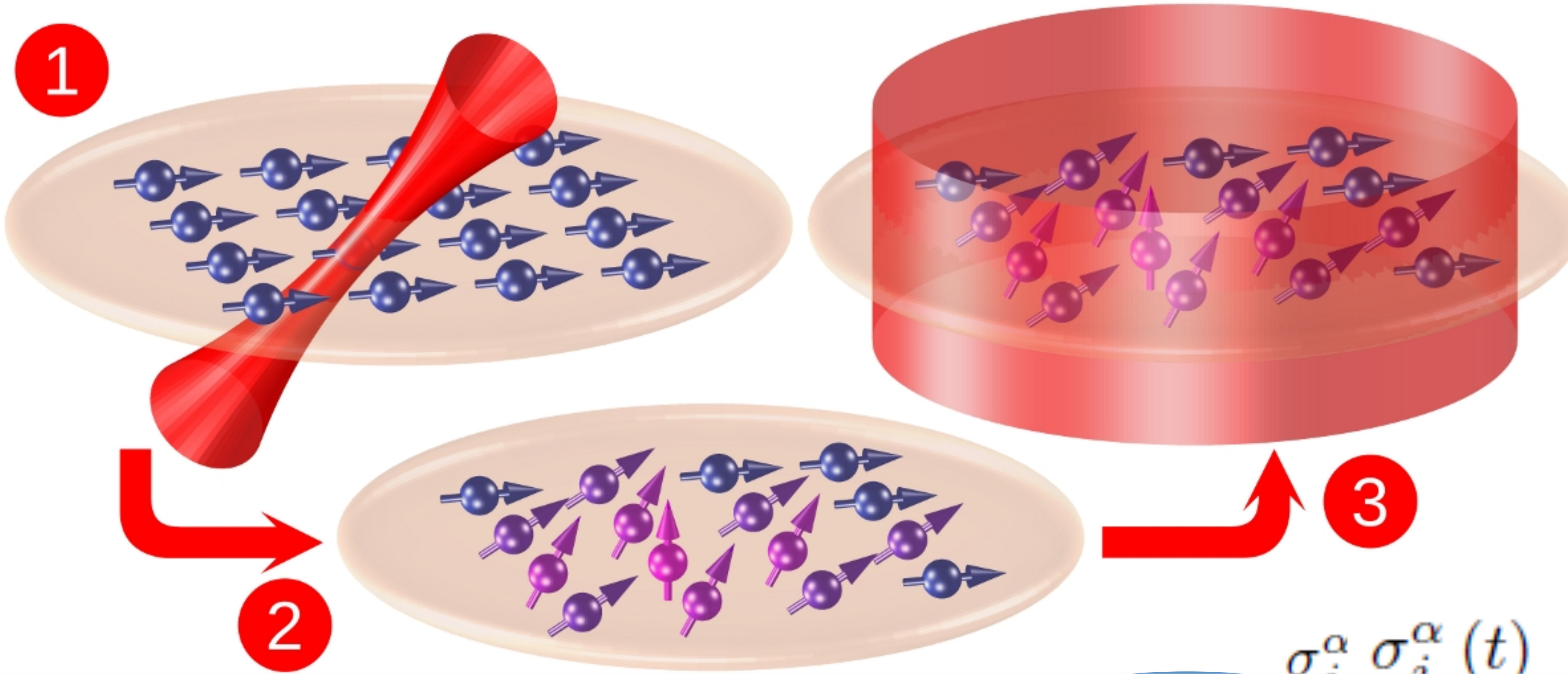
Spin rotations

$$R_j(\theta, \phi) = \hat{1} \cos\frac{\theta}{2} + i(\sigma_j^x \cos\phi - \sigma_j^y \sin\phi) \sin\frac{\theta}{2}$$



p/2 pulse: $R_j(\frac{\pi}{2}, \phi) = \frac{1}{\sqrt{2}}(1 + e^{i\phi}\sigma_j^+ + e^{-i\phi}\sigma_j^-)$

Many-body spin Ramsey protocol



Many-body spin Ramsey protocol

$$M_{ij}(\phi_1,\phi_2,t) = \sum_n \frac{e^{-\beta E_n}}{Z} \langle n | R_i^\dagger(\phi_1) e^{i\hat{H}t} R^\dagger(\phi_2) \sigma_j^z R(\phi_2) e^{-i\hat{H}t} R_i(\phi_1) | n \rangle$$

$$\begin{aligned} M_{ij}(\phi_1,\phi_2,t) = \frac{1}{2}\big(& \cos\phi_1 \sin\phi_2 G_{ij}^{xx,-} + \cos\phi_1 \cos\phi_2 G_{ij}^{xy,-} \\ & - \sin\phi_1 \sin\phi_2 G_{ij}^{yx,-} - \sin\phi_1 \cos\phi_2 G_{ij}^{yy,-}\big) \\ & + \text{terms with odd number of } \sigma^{x,y} \text{ operators} \, , \end{aligned}$$

- for many relevant cases terms with odd number of spin-x/spin-y operators vanish
- additional degree of freedom:

$\rightarrow$ phases of the laser field

Heisenberg model

$$\hat{H}_{\text{Heis}} = \sum_{i<j} J_{ij}^{\perp}(\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y) + J_{ij}^z \sigma_i^z \sigma_j^z$$

- global symmetry $\sigma^x \to -\sigma^x \quad \sigma^y \to -\sigma^y \quad \sigma^z \to \sigma^z$
- U(1) symmetry around z axis

$$\begin{aligned} M_{ij}(\phi_1, \phi_2, t) = \frac{1}{4}\{ & \sin(\phi_1+\phi_2)(G_{ij}^{xx,-} - G_{ij}^{yy,-}) \\ & - \sin(\phi_1-\phi_2)(G_{ij}^{xx,-} + G_{ij}^{yy,-}) \\ & + \cos(\phi_1+\phi_2)(G_{ij}^{xy,-} + G_{ij}^{yx,-}) \\ & + \cos(\phi_1-\phi_2)(G_{ij}^{xy,-} - G_{ij}^{yx,-})\} \, . \end{aligned}$$

Spin echo for Heisenberg model

- Problem of shot to shot fluctuations of magnetic field: p/2 pulse makes a superposition of states with different Sz

p/2 pulse: $$R_j(\frac{\pi}{2}, \phi) = \frac{1}{\sqrt{2}}(1 + e^{i\phi}\sigma_j^+ + e^{-i\phi}\sigma_j^-)$$

- Need to implement spin echo.

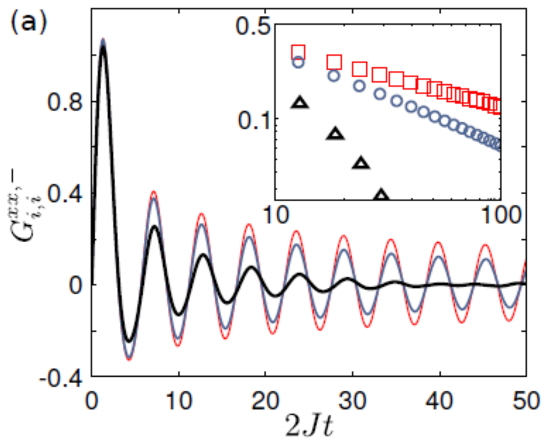
  Add p pulse at t/2

$$R_\pi = \prod_j i(\sigma_j^x \cos\phi_\pi - \sigma_j^y \sin\phi_\pi)$$

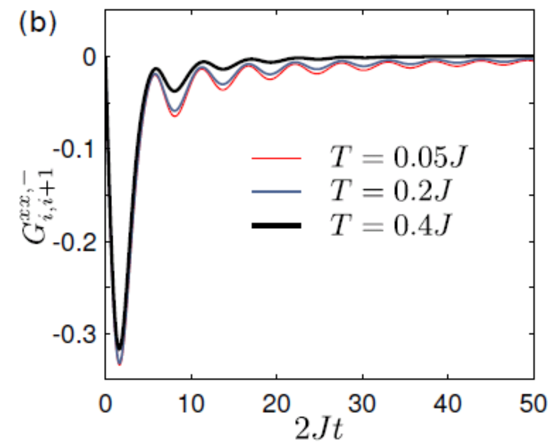
- Heisenberg is invariant under this transformation
- Zeeman term is cancelled

Antiferromagnetic Heisenberg model

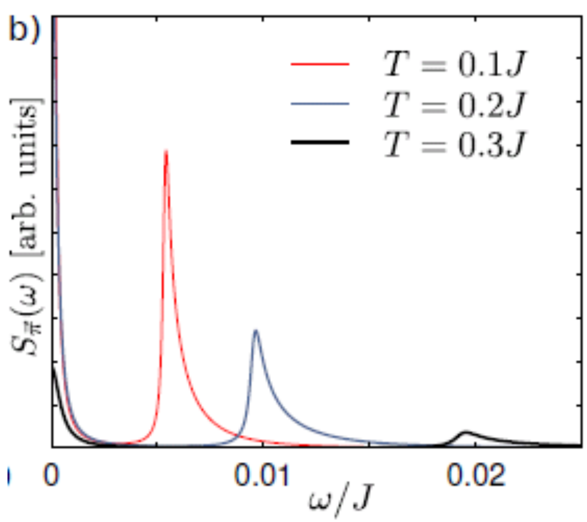
On-site correlations



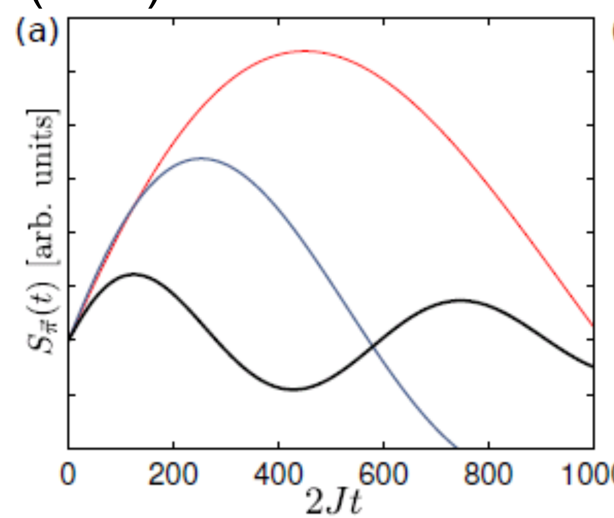
Nearest neighbor correlations



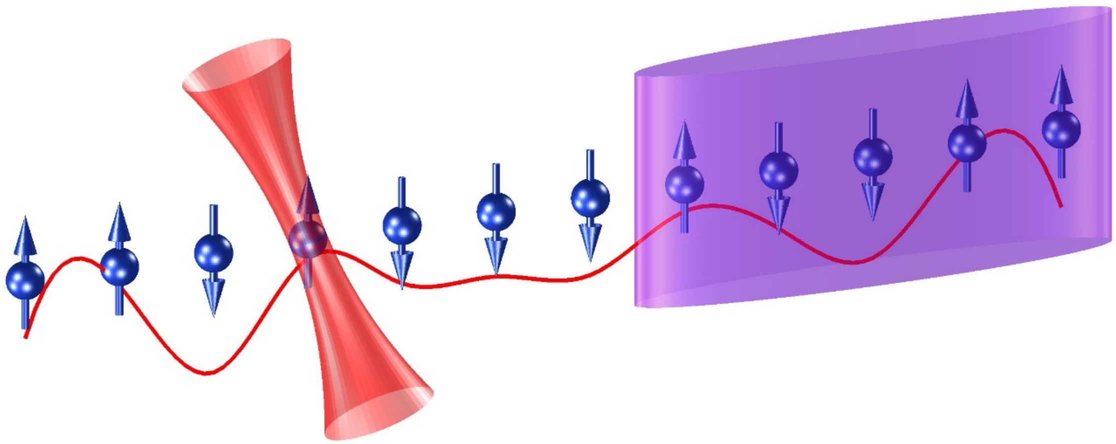
Momentum (p,p) correlations (frequency)



Momentum (p,p) correlations (time)



Interferometric probe of many-body localization



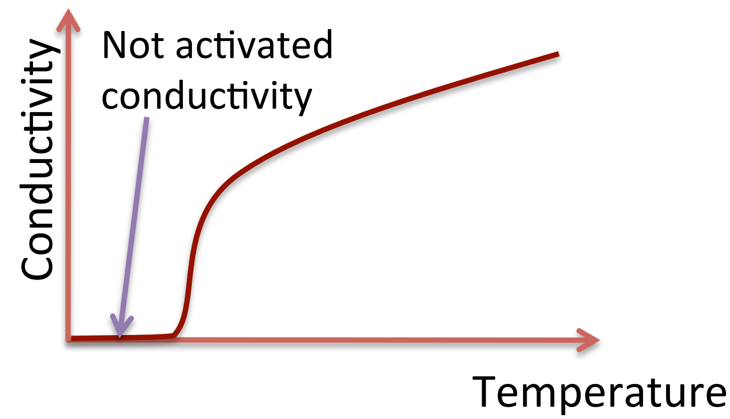
M. Serbyn, M. Knap, S. Gopalakrishnan, Z. Papic, M. Lukin, D. Abanin, E. Demler

Many-body localization (MBL)

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

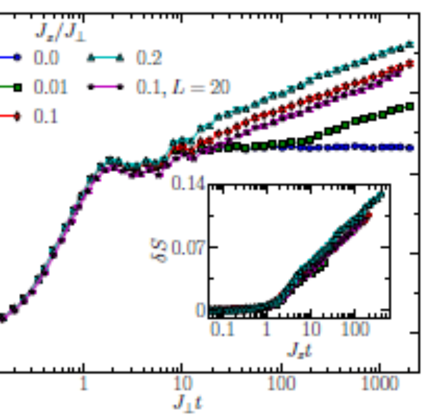
- localization in the presence of interactions

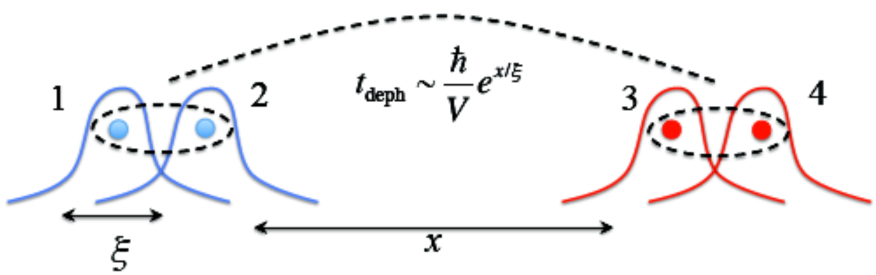
- system does not act as its own bath (discrete local spectrum)



- MBL states vs. Anderson localized states

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





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

A simple model

- a caricature of the MBL

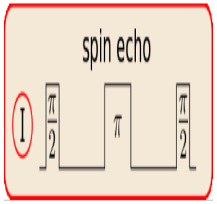
$$\hat{H}_\tau = \sum_i h_i \tau_i^z + \sum_{ij} \mathcal{J}_{ij} \tau_i^z \tau_j^z$$

  no spin diffusion, always many-body localized
  Note: spin dynamics is nontrivial for general model (eg. XXZ)

- Ramsey
  - system is prepared in an eigenstate $|\uparrow\downarrow\downarrow\uparrow\downarrow\ldots\rangle$
  - Initialize spin I in superposition: $|+\rangle_\mathrm{I} = (|\uparrow\rangle_\mathrm{I} + |\downarrow\rangle_\mathrm{I})/\sqrt{2}$
  - precession of spin: $h_\mathrm{eff}(\mathrm{I}) = h_\mathrm{I} + \sum_j \mathcal{J}_{\mathrm{I}j} \tau_j^z$
  - thermal average → dephasing: signal would decay

Spin-echo

- Spin-echo can distinguish dephasing from diffusion

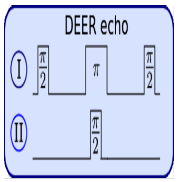


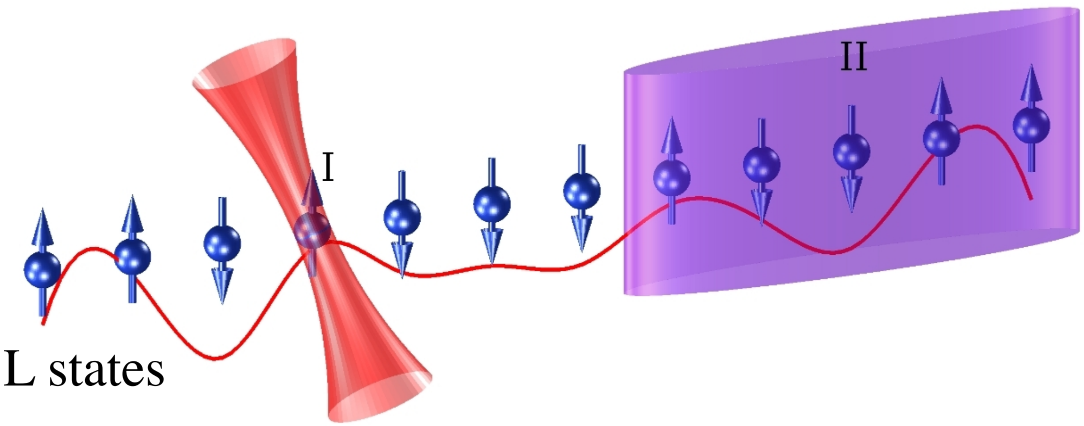
→ forward and backward precession with opposite sign
→ perfect revival for the simple model
→ survives disorder average

- BUT: Spin-echo cannot probe the slow growth of entanglement

DEER protocol

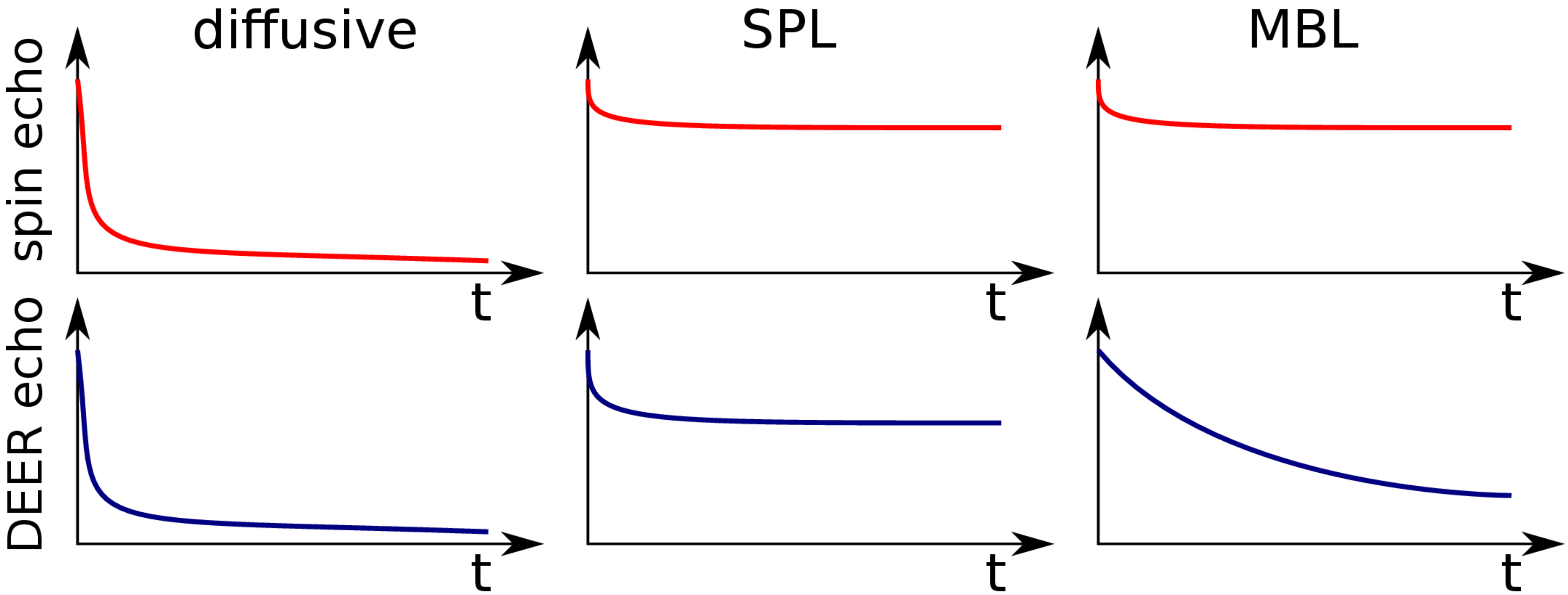
- Solution: DEER protocol





- distinguishes SPL from MBL states
- probes dephasing due to interactions (entanglement)

Distinguishing different phases

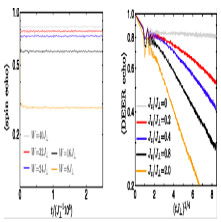


XXZ Heisenberg chain

- Hamiltonian

$$\hat{H} = 2J_\perp \sum_{\langle ij \rangle} (\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_j^+ \hat{\sigma}_i^-) + J_z \sum_{\langle ij \rangle} \hat{\sigma}_i^z \hat{\sigma}_j^z + \sum_i h_i \hat{\sigma}_i^z$$

- results



Summary

Exploring exotic states with Ramsey interferometry

Exploring orthogonality catastrophe with cold atoms
M. Knap et al., PRX (2012)

Measuring Berry/Zak phase in optical lattices
M. Atala et al., arXIv:1212.0572, T. Kitagawa et al., PRL (2013)

Measuring dynamical spin correlation functions
M. Knap, et al., arXiv:1307.0006

Probing many-body localization
M. Knap, S. Gopalakrishnan, et al.