Interferometric probes of quantum many-body systems of ultracold atoms

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Collaborators:
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+ Experiments: LMU/MPQ in Bloch's group
TU Vienna in Schmiedmayer's group

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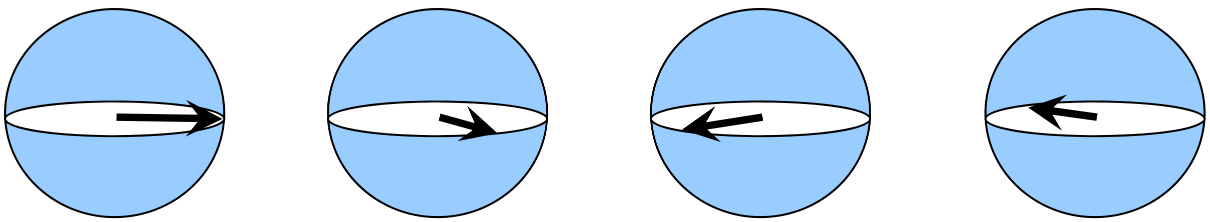
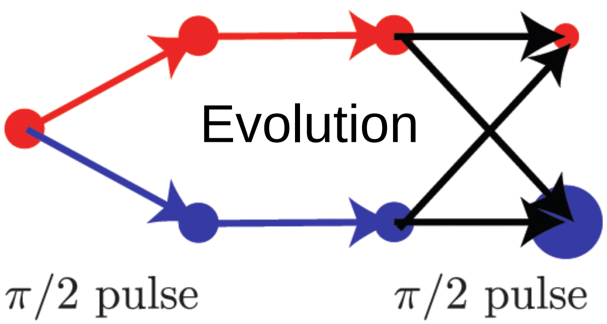
Basic tool of atomic physics/optics: Ramsey interference

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

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



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



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

Outline

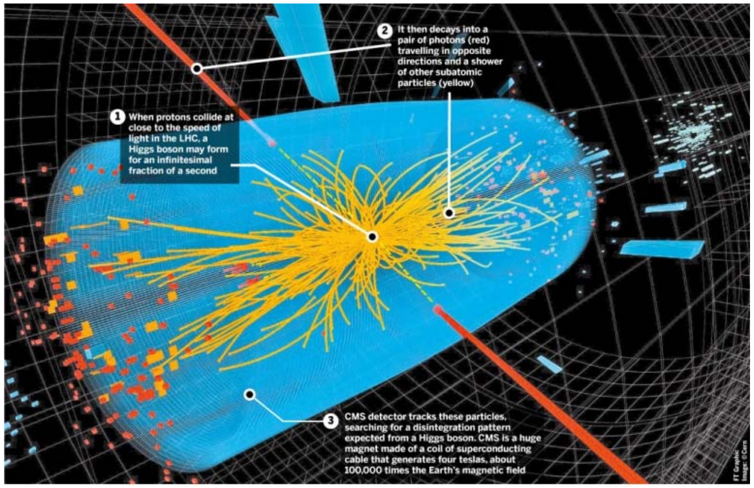
Probing topological properties of Bloch bands with Ramsey/Bloch interference

Exploring prethermalization

Interferometric probe of MBL

Exploring topological states with interferometric probes

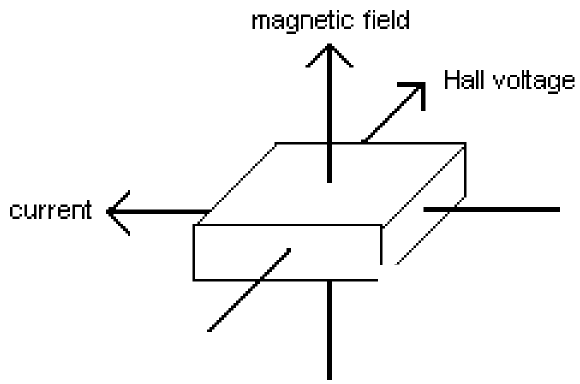
Spontaneous symmetry breaking and order

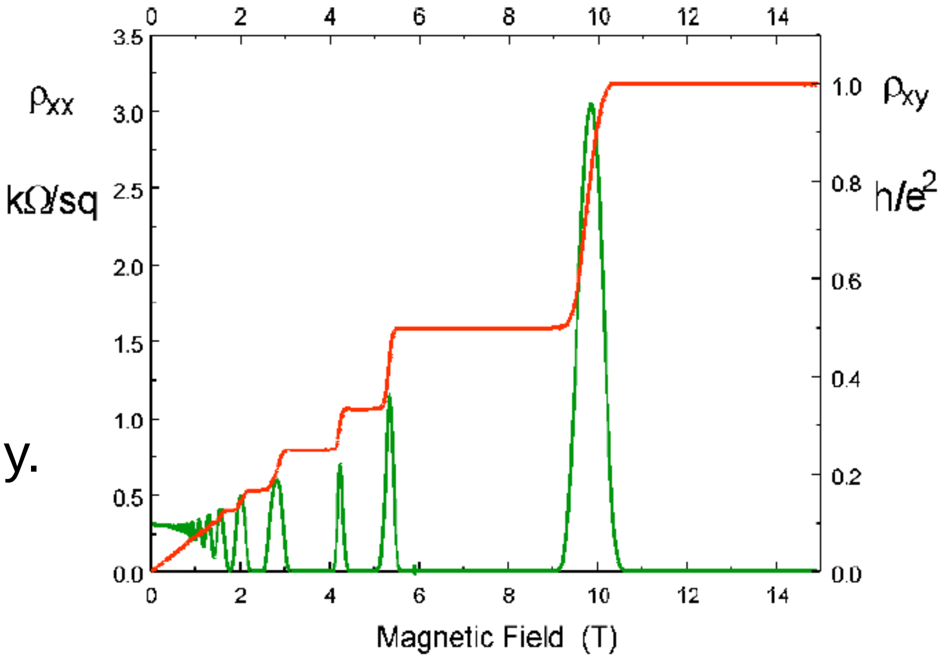


Order beyond symmetry breaking

In 1980 the first ordered phase beyond symmetry breaking was discovered

Integer Quantum Hall Effect: 2D electron gas in strong magnetic field shows plateaus in Hall conductance





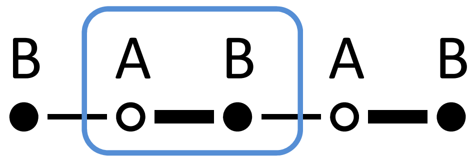
Current along x, measure voltage along y.
On a plateau

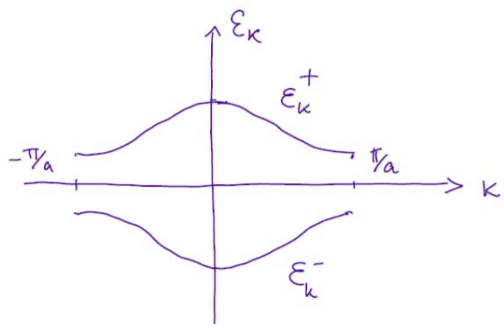
$$\sigma_{xy} = n\frac{e^2}{h}$$

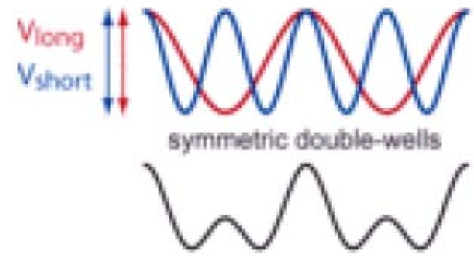
with an accuracy of 10^{-10}

Topological order is the "quantum protectorate" of this precise quantization

SSH Model with bichromatic lattice



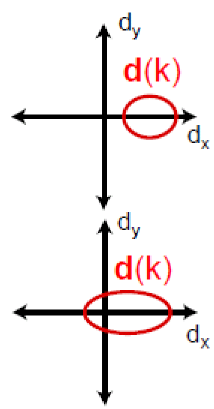




$$H=\sum_i (t+\delta t)c_{Ai}^{\dagger}c_{Bi}+(t-\delta t)c_{Ai+1}^{\dagger}c_{Bi}+h.c.$$

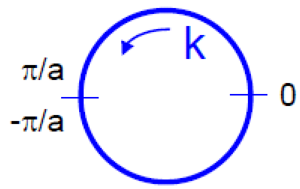
$$H(k)=\mathbf{d}(k)\cdot\vec{\sigma}$$

$$d_x(k)=(t+\delta t)+(t-\delta t)\cos ka$$
$$d_y(k)=(t-\delta t)\sin ka$$
$$d_z(k)=0$$



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.

How to measure Berry-Zak phase

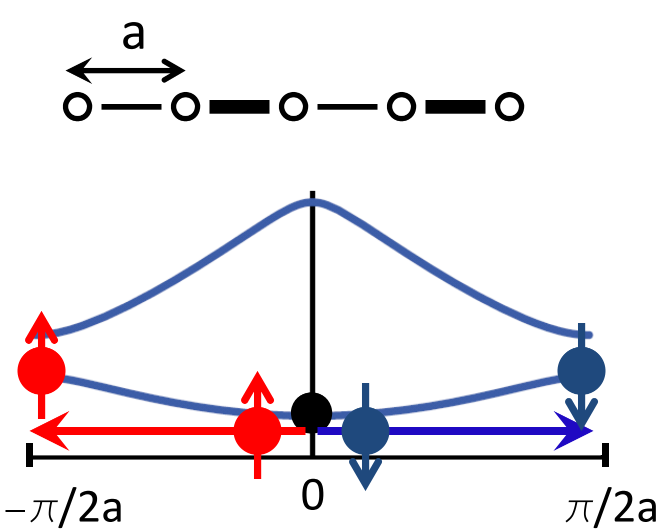


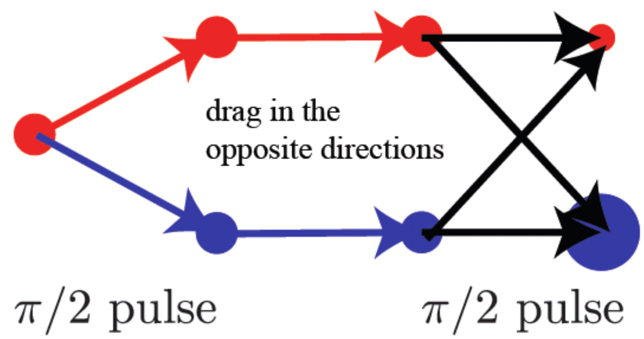
$$A(k) = \frac{1}{i}\langle u_k|\partial_k|u_k\rangle$$

$$P = \oint A(k)\, dk$$

Characterizing SSH model using Zak phase

Two hyperfine spin states experience the same optical potential





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

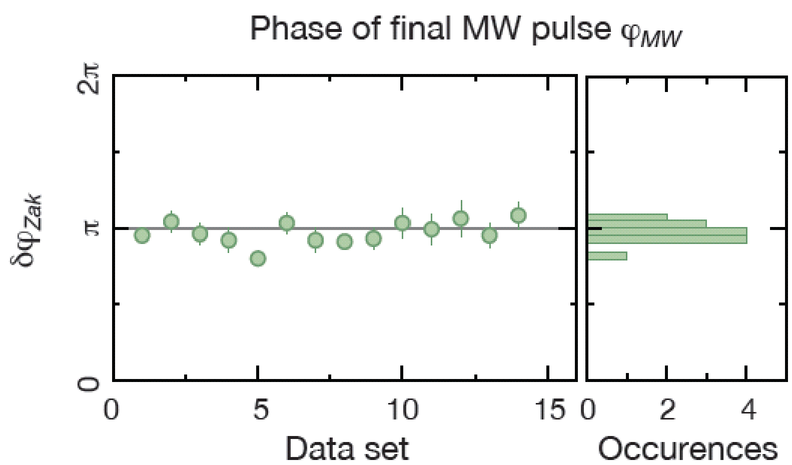
Zak phase is equal to π

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

Zak/Berry phase measurements

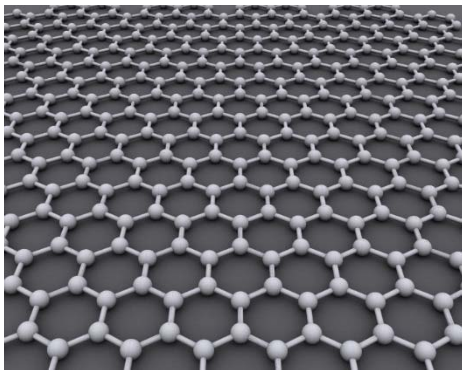
M. Atala et al., Nature Physics (2013)

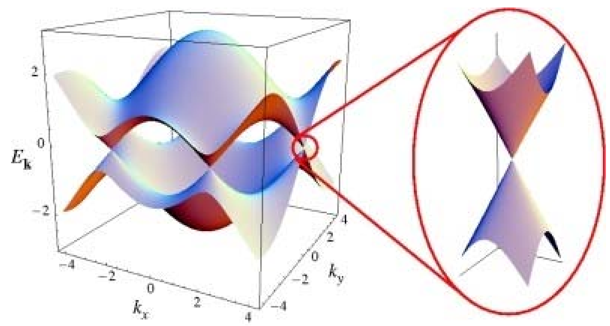
The first direct measurement of topological order parameter either in solid state or condensed matter systems

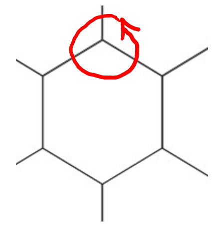


$$\delta\varphi = 0.97(2)\pi$$

Measuring Berry curvature in 2d and Chern number

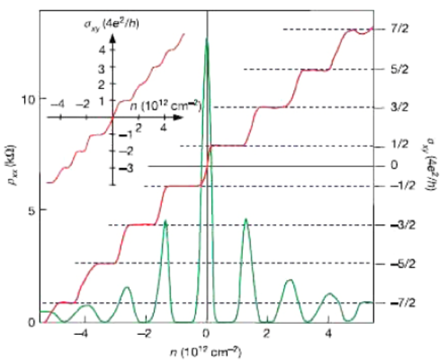






Integral of the Berry phase around the Dirac point

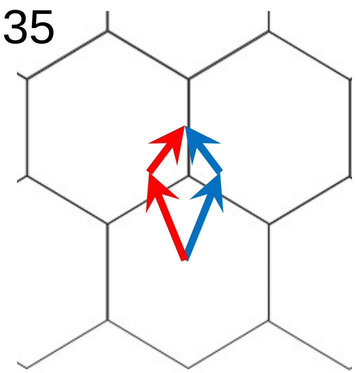
$$\frac{1}{i}\int_C d\vec{k}\,\langle\,\psi_k\,|\,\partial_{\vec{k}}\,|\,\psi_k\,\rangle = \pi$$



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: M. Schleier-Smith, et al., arXiv:1407.5635



Extension to more exotic states:Quantum Spin Hall Effect states and Topological Insulators in 3D. Grusdt et al., PRA (2014)

Demonstration of prethermalization in split 1d condensates

D. Gring et al., Science 337:1318 (2012)
M. Kuhnert et al., Phys. Rev. Lett. 110:090405 (2013)
D. Smith et al., New Journal of Physics 15:075011 (2013)

New frontier in quantum many-body physics: nonequilibrium dynamics

Long intrinsic time scales

- Interaction energy and bandwidth ~ 1kHz
- System parameters can be changed over this time scale

Decoupling from external environment

- Long coherence times

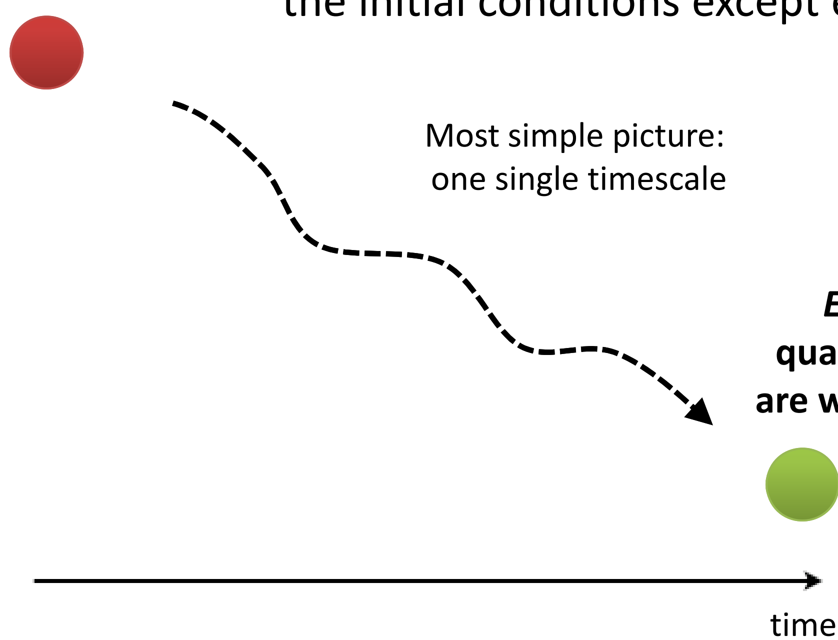
Can achieve highly non equilibrium quantum many-body states

$$H_i \rightarrow H_f \qquad\qquad |\,\Psi(t)\,\rangle = e^{-iH_f t}\,|\,\Psi_i\,\rangle$$

Relaxation to equilibrium in quantum systems

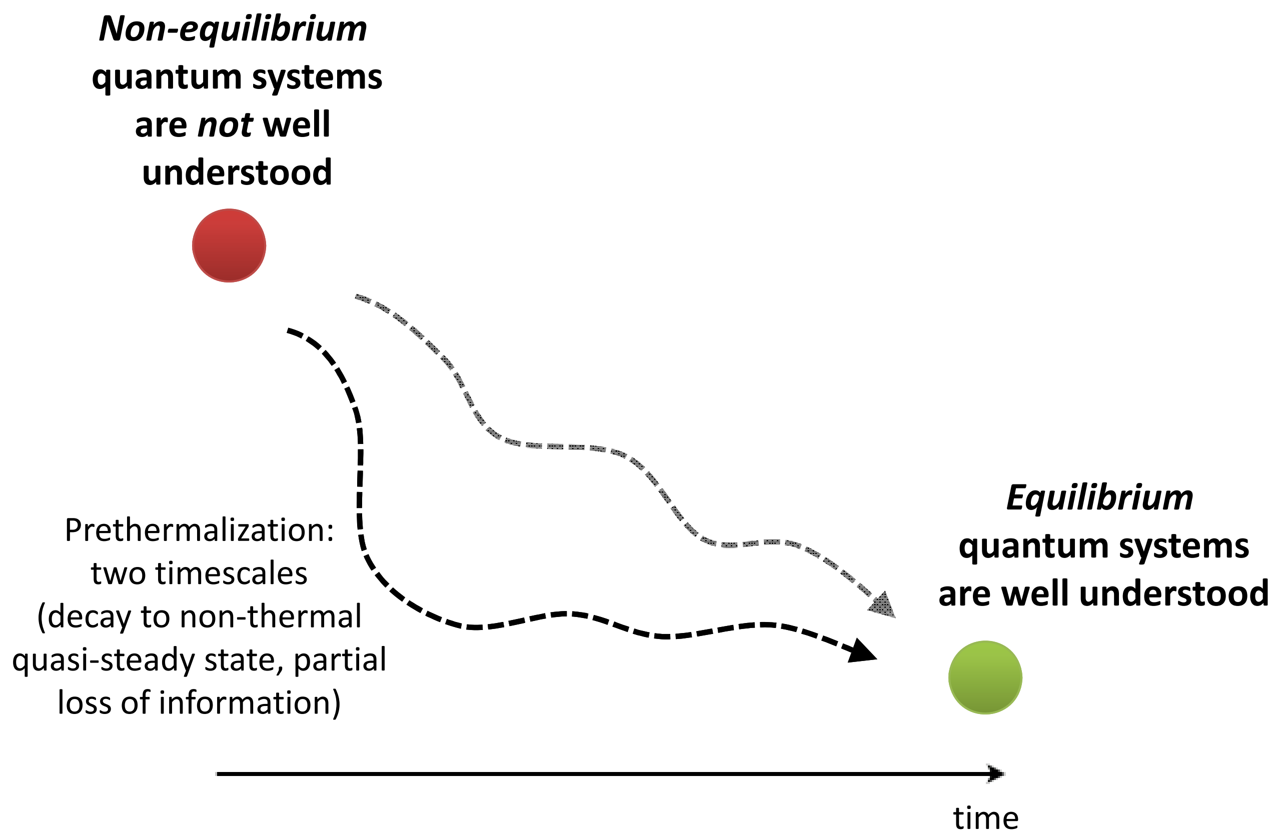
Non-equilibrium **quantum systems are *not* well understood**

Thermalization: an isolated interacting system approaches thermal equilibrium at microscopic timescales. All memory about the initial conditions except energy is lost.

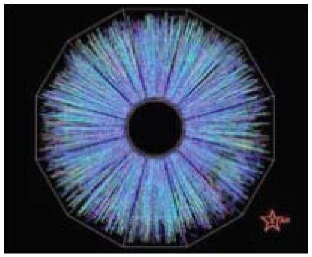


Equilibrium **quantum systems are well understood**

Relaxation to equilibrium in quantum systems



Prethermalization



Heavy ions collisions
QCD

PHYSICAL REVIEW D, VOLUME 60, 105026

Time evolution of correlation functions and thermalization

Gian Franco Bonini* and Christof Wetterich†

VOLUME 93, NUMBER 14 PHYSICAL REVIEW LETTERS week ending 1 OCTOBER 2004

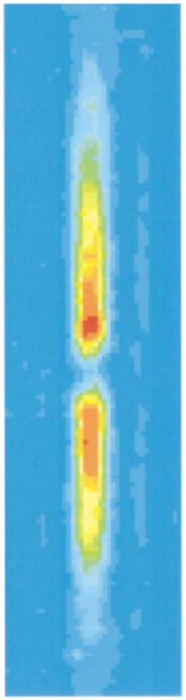
Prethermalization

J. Berges, Sz. Borsányi, and C. Wetterich
Institute for Theoretical Physics, Heidelberg University, Philosophenweg 16, 69120 Heidelberg, Germany
(Received 6 April 2004; published 28 September 2004)

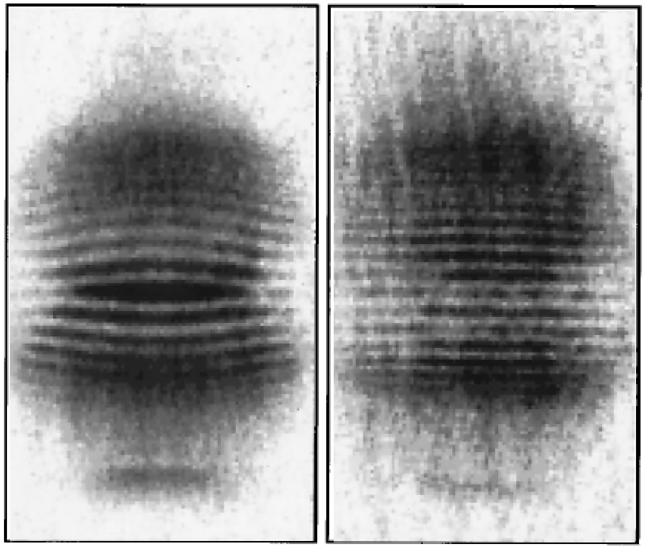
We observe irreversibility and approximate thermalization. At large time the system approaches stationary solution in the vicinity of, but not identical to, thermal equilibrium. The ensemble therefore retains some memory beyond the conserved total energy…This holds for interacting systems and in the large volume limit.

Prethermalization in ultracold atoms, theory: Eckstein et al. (2009); Moeckel et al. (2010), L. Mathey et al. (2010), R. Barnett et al.(2010)

Interference of independent condensates



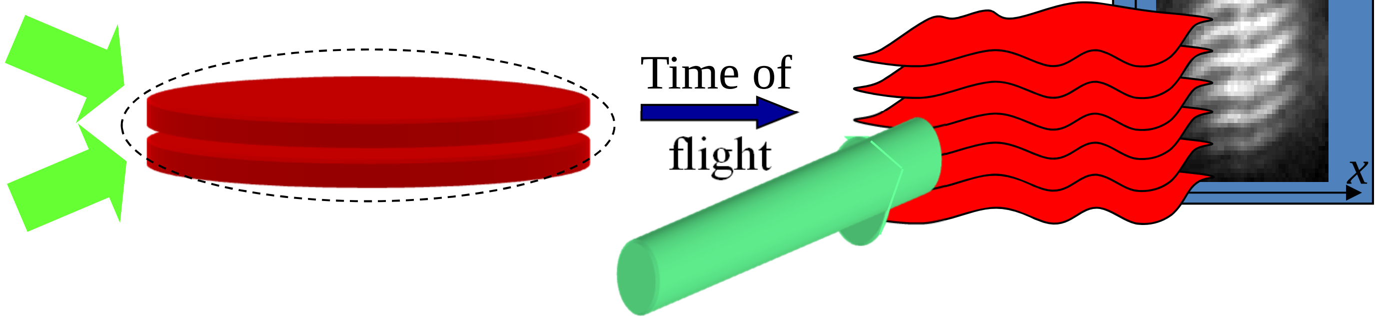
Experiments: Andrews et al., Science 275:637 (1997)



Theory: Javanainen, Yoo, PRL 76:161 (1996)
Cirac, Zoller, et al. PRA 54:R3714 (1996)
Castin, Dalibard, PRA 55:4330 (1997)
and many more

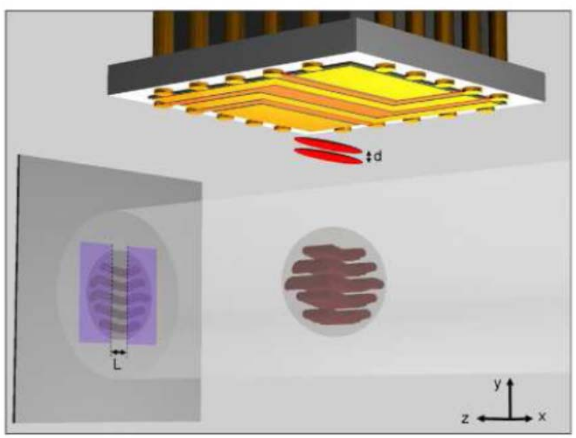
Experiments with 2D Bose gas

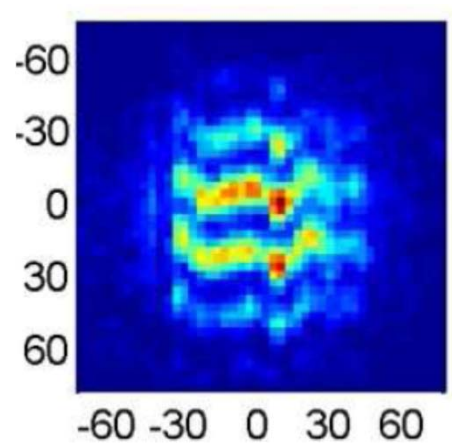
Hadzibabic, Krüger, Dalibard, et al., Nature 2006



Experiments with 1D Bose gas

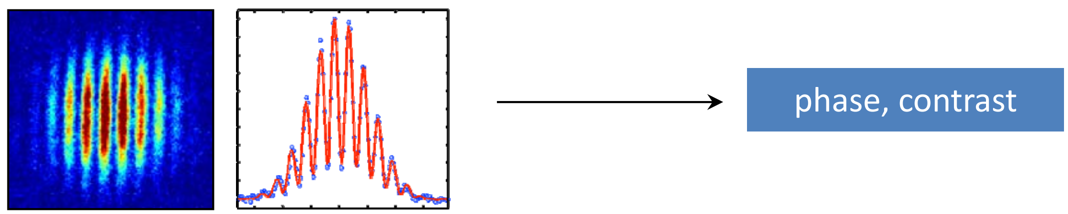
Hofferberth, Lesanovsky, et al., Nat. Physics 2008





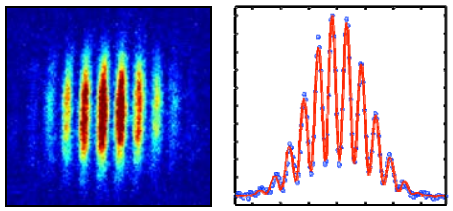
FDF of phase and contrast

- Matter-wave interferometry



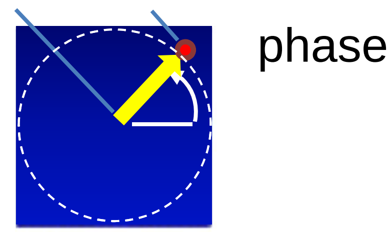
FDF of phase and contrast

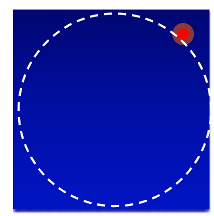
- Matter-wave interferometry



phase, contrast

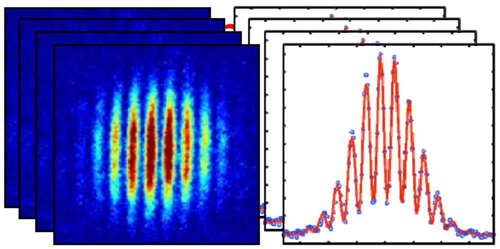
- Plot as circular statistics





FDF of phase and contrast

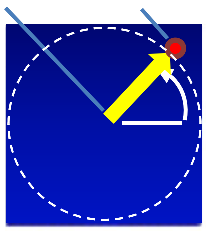
- Matter-wave interferometry: repeat



phase, contrast

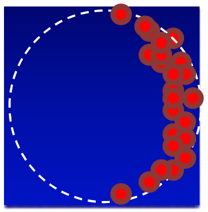
i>100

- *contrast$_i$*



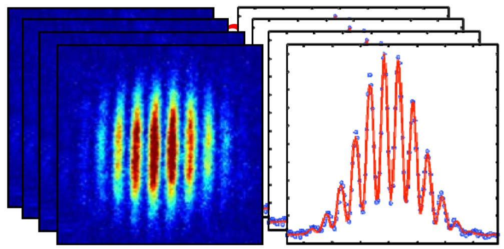
phase

accumulate statistics



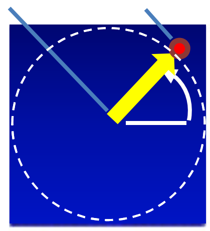
FDF of phase and contrast

- Matter-wave interferometry: repeat



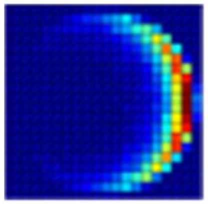
→ phase, contrast i>100

- *contrast$_i$*



phase$_i$ →

accumulate statistics

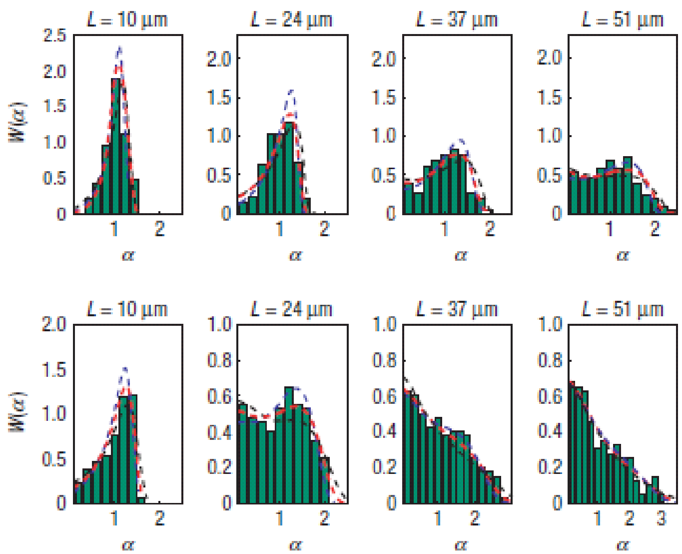


This is the full distribution function of phase & contrast

Distribution function of interference fringe contrast

Hofferberth et al., Nature Physics 4:489 (2008)

Normalized fringe contrast



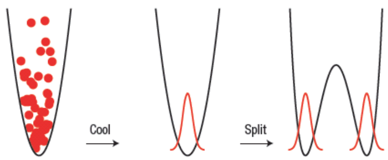
Quantum fluctuations dominate:
asymetric Gumbel distribution
(low temp. T or short length L)

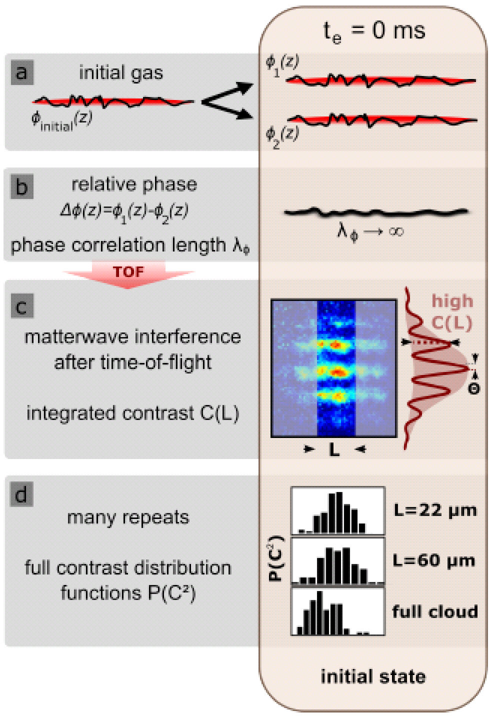
Thermal fluctuations dominate:
broad Poissonian distribution
(high temp. T or long length L)

Intermediate regime:
double peak structure

Comparison of theory and experiments: no free parameters

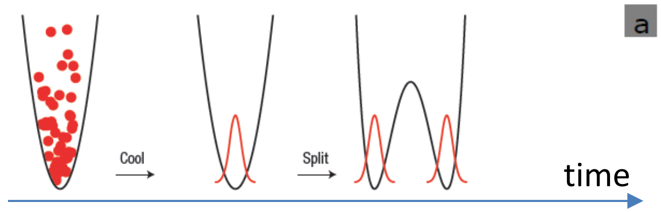
Measurements of dynamics of split condensate

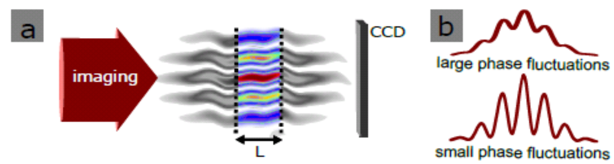


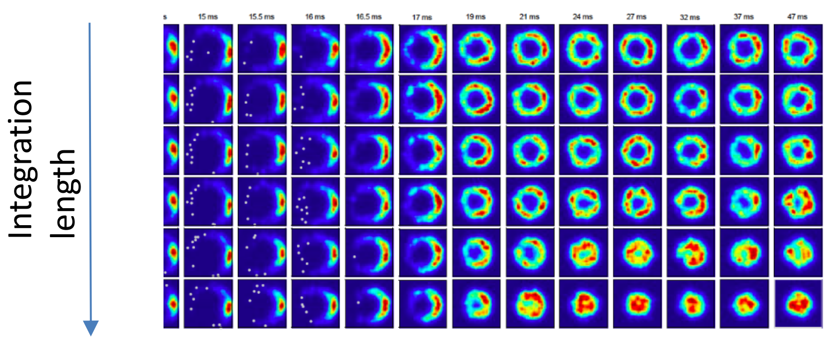


Experimental demonstration of prethermalization

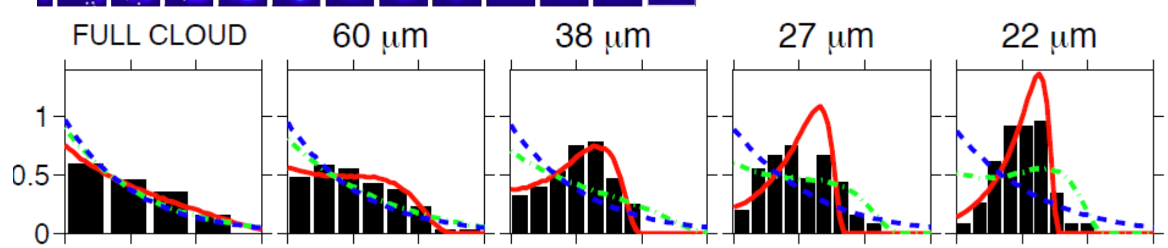
Probing thermolization using local resolution and complete characterization of quantum noise. M. Gring et al., Science (2012)







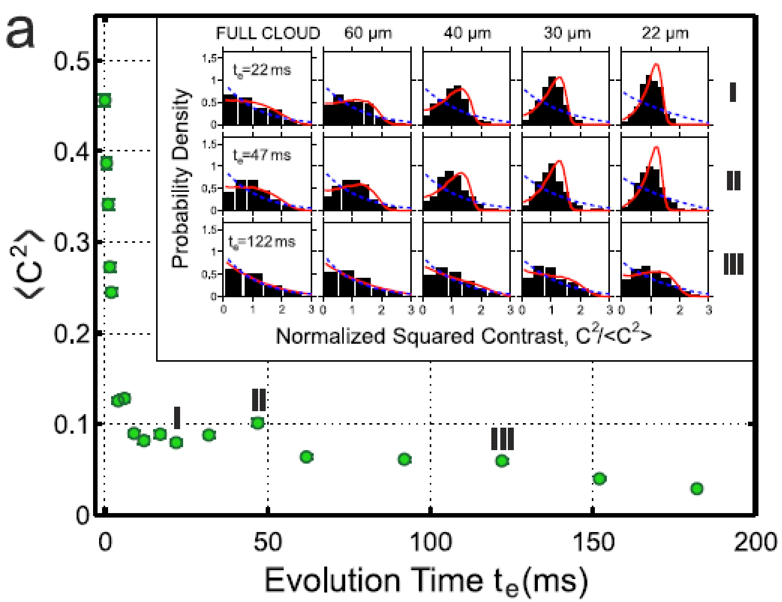
Initial T=120 nK (blue line).
After 27.5 ms identical to thermal system at T= 15 nK
At all lengthscales
In all correlation functions

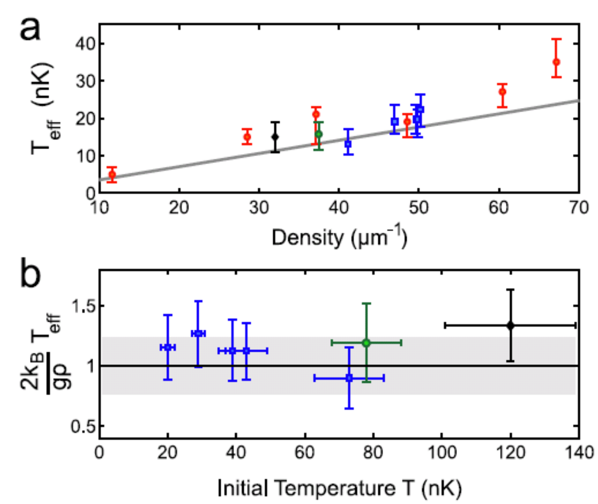


Prethermalization

Theory: T. Kitagawa, A. Imambekov, et al., PRL(2010), NJP (2011)
Expt: M. Gring et al., Science 2012

$$k_B T_{\text{eff}} = g\rho/2$$



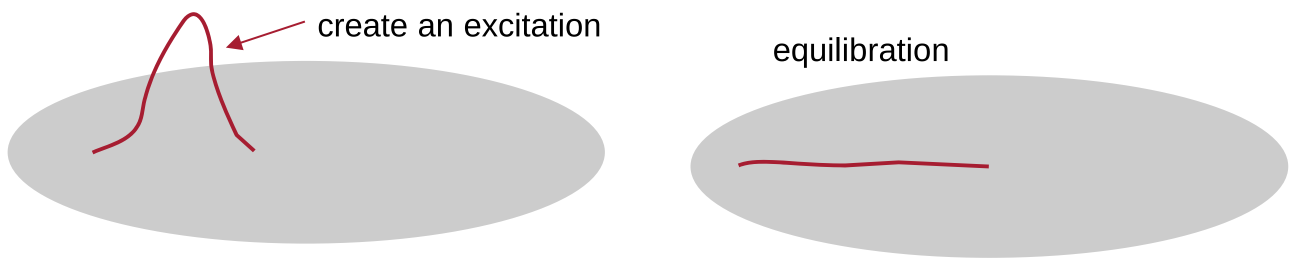


Interferometric probe of many-body localization

M. Knap, T. Giamarchi, et al., PRL (2013)
M. Knap, M. Serbyn, et al., PRL (2014)

Many-Body Localization

Ergodicity: equivalence of temporal and ensemble averaging
Equilibration is exchange of particles, energy, ...
Thermalization means system acts as it's own bath



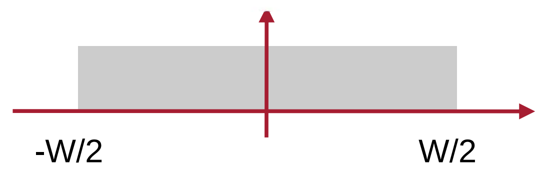
Many-Body Localized states: phases of interacting many-body systems, which do not exhibit ergodicity

Single-particle localization

Non-interacting particles in quenched disorder

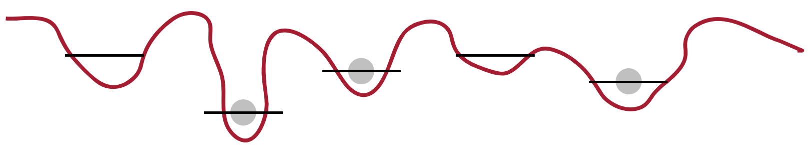
$$\mathcal{H} = -t \sum_{\langle ij \rangle} b_i^\dagger b_j + \sum_i V_i n_i$$

$$V_i \in [-\mathrm{W}/2, \mathrm{W}/2]$$



hopping cannot overcome disorder

P. W. Anderson, Phys. Rev. (1958)



← **zero conductivity**

(critical strength of disorder depends on dimension)

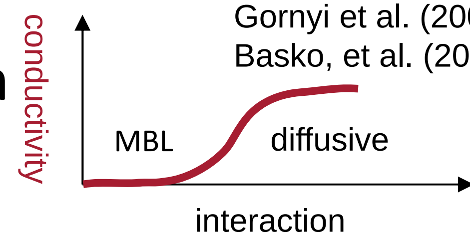
wave-functions are exponentially localized

$$\psi(r) \sim e^{-r/\xi}$$ ← localization length

Many-body localization (MBL)

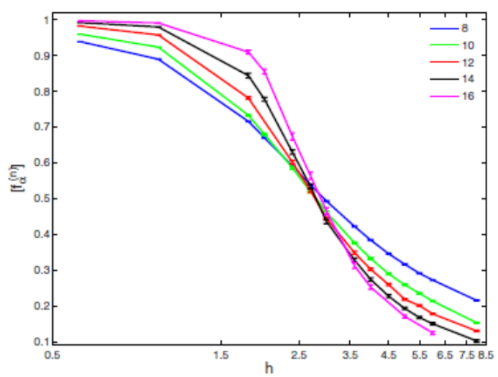
add interactions V: system can still be localized

system does not act as its own bath (discrete local spectrum)
→ fails to thermalize



Gornyi et al. (2005)
Basko, et al. (2006)

Many-body localization in spin systems in 1d



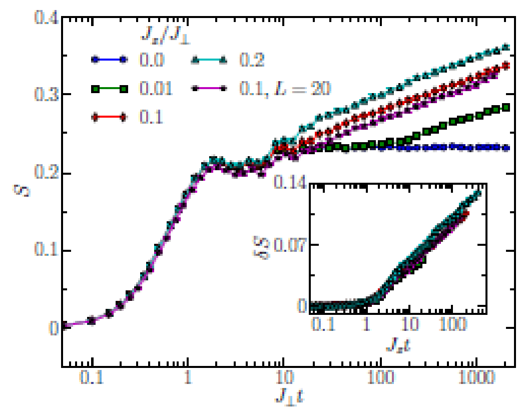
A. Pal, D. Huse (2006)

$$H = \sum_{i=1}^{L} [h_i \hat{S}_i^z + J \hat{\vec{S}}_i \cdot \hat{\vec{S}}_{i+1}]$$

The fraction of the initial spin polarization that is dynamic

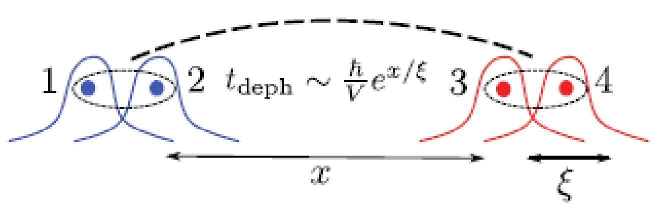
Entanglment growth in quenches with random spin XXZ model

Bardarson, Pollman, Moore, PRL 2012



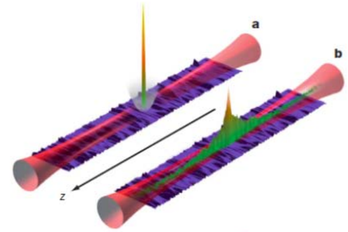
Exponentially small interaction induced corrections to energies

Vosk, Altman, PRl 2013
Serbin, Papic, Abanin, PRL 2013



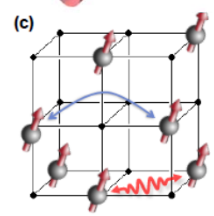
Systems with interactions and disorder

Ultracold atoms
- Aspect et al. (2008)
- Roati et al. (2008)
- DeMarco et al. (2011)



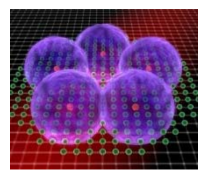
Disorder created by laser speckle

Ultracold atoms and
Polar molecules in optical lattices
- Ye et al. (2013)



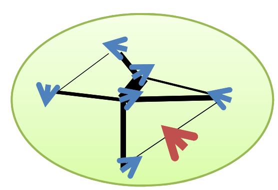
Angular momentum as spin degree of freedom

Rydberg atoms
- Pfau et al. (2008)
- Ryabtsev et al. (2010)
- Bloch et al. (2012)



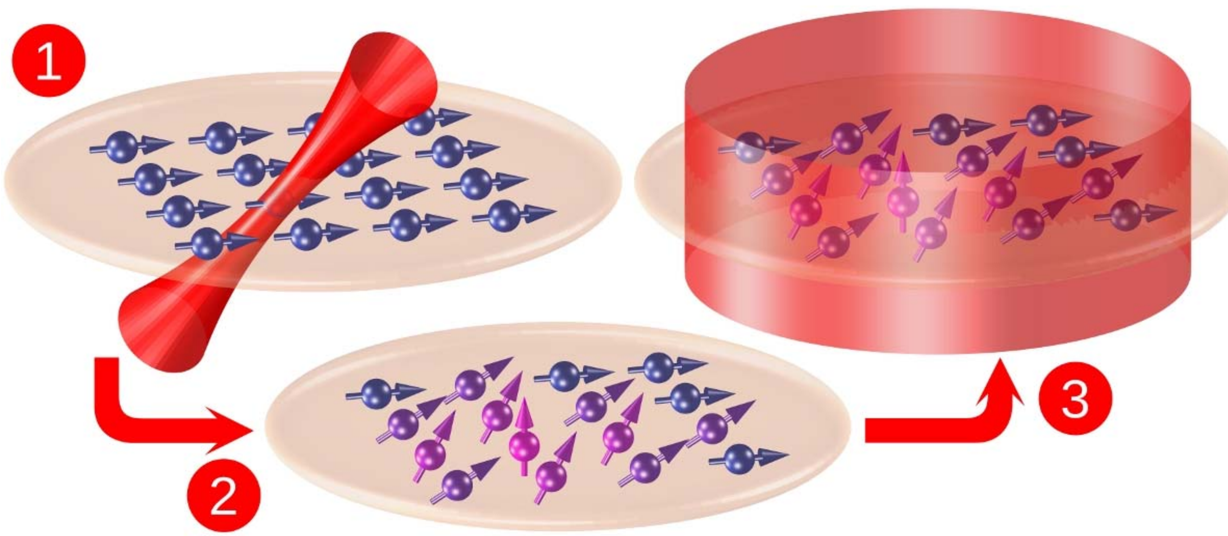
Strong interactions due to
large electric dipole moment

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

Many-body spin Ramsey protocol



Measures the usual retarded spin correlation function

$$\frac{\theta(t)}{Z}\sum_{n} e^{-\beta E_n}\,\langle\, n \,|\, S_i^x(0)\, S_i^x(t) \,-\, S_i^x(0)\, S_i^x(t) \,|\, n \,\rangle$$

Spin correlation function as quantum quench

$$\langle n \,|\, S_i^x(t)\, S_i^x(0) \,|\, n \rangle \;=\; \langle n \,|\, e^{i\mathcal{H}t}\, S_i^x(0)\, e^{-i\mathcal{H}t}\, S_i^x(0) \,|\, n \rangle$$

$$= \langle n \,|\, e^{i\mathcal{H}t}\, e^{-i\tilde{\mathcal{H}}_i t} \,|\, n \rangle$$

$\tilde{\mathcal{H}}_i$ differs from $\mathcal{H}$ by

$$S_i^y \to -S_i^y$$
$$S_i^z \to -S_i^z$$

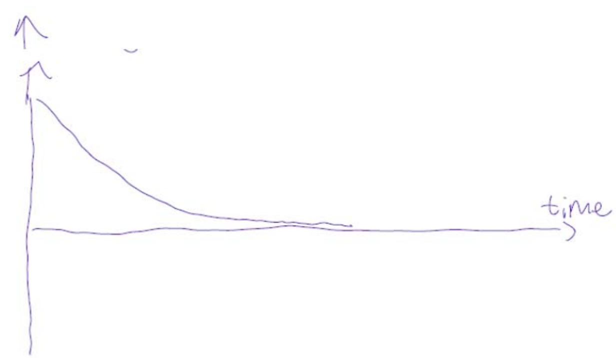
Spin correlation function as quantum quench

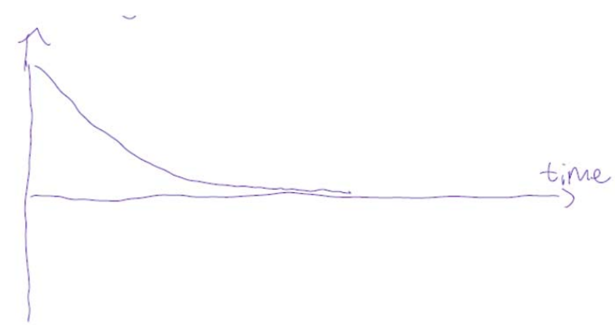
$$\langle n | e^{i\mathcal{H}t} e^{-i\tilde{\mathcal{H}}_i t} | n \rangle$$

In a localized phase, local quench affects only a few excitations. For each eigenstate expect non-decaying oscillations

After averaging over thermal ensemble (and/or disorder realizization) find decay

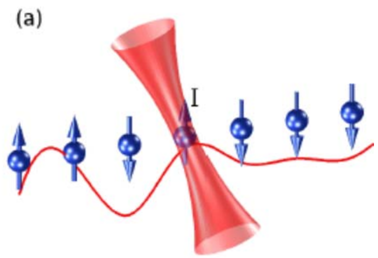
In a delocalized phase (diffusive regime), local quench affects all excitations. Expect decay akin orthogonality catastrophe

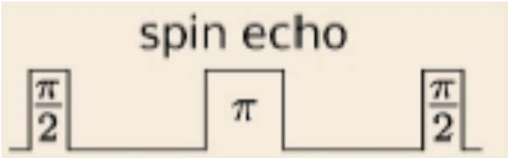




Ramsey + spin echo

M. Knap, S. Gopalakrishnan, M. Serbyn, et al.

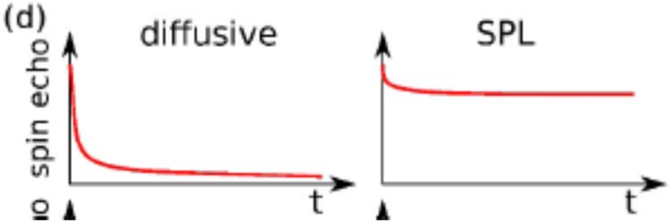




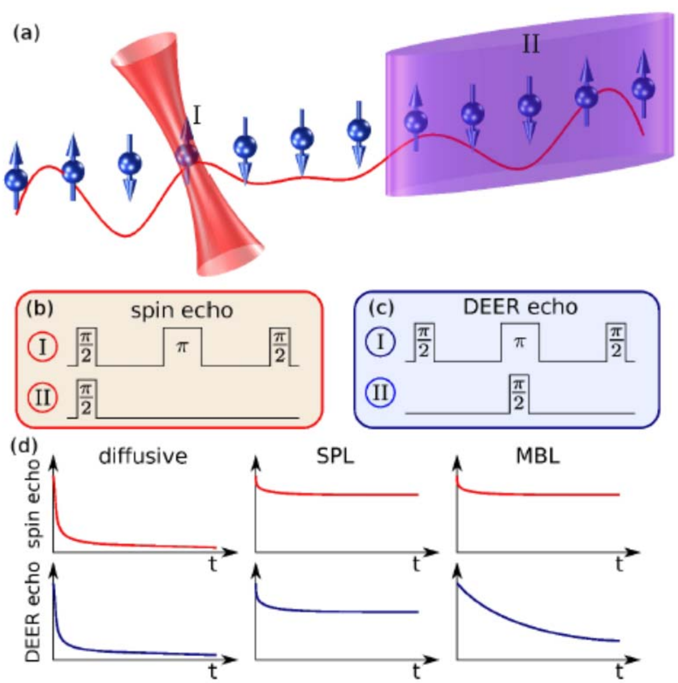
"Cartoon" model of the localized phase $\mathcal{H}_{\rm SPL} = \sum_i h_i^z S_i^z$

Spin echo $h_i^z \to -h_i^z$

$$|\Psi_{zi}(t)\rangle = e^{i\mathcal{H}_{zi}\frac{t}{2}}\, e^{-i\mathcal{H}_{zi}\frac{t}{2}}\, |\Psi_{zi}(0)\rangle$$

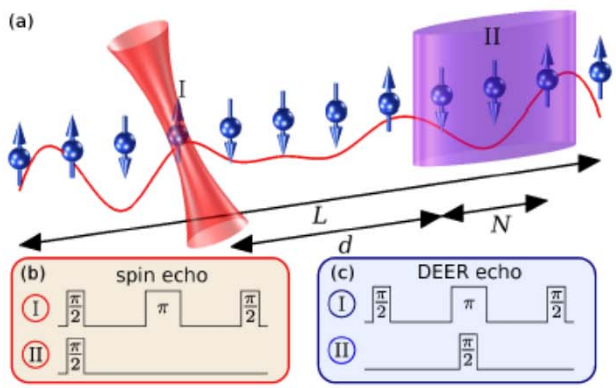


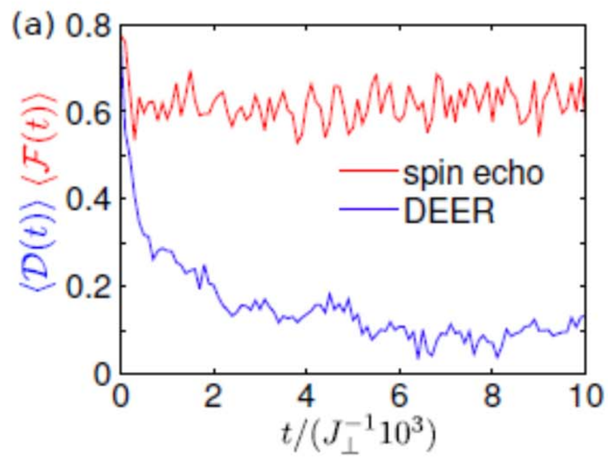
Double Electron-Electron Resonance
Ramsey sequence



Double Electron-Electron Resonance
Ramsey sequence

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

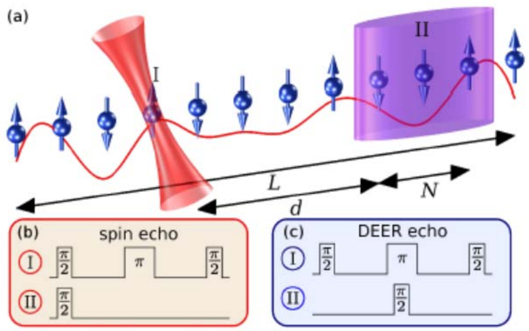


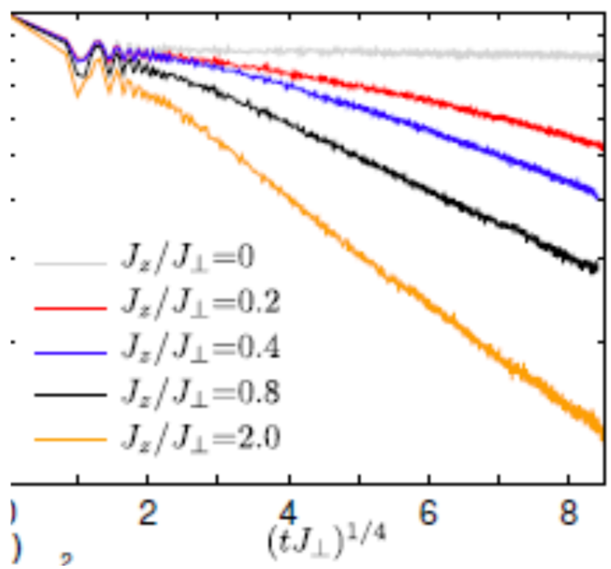


single realization
thermal averaging over 50 eigenstates

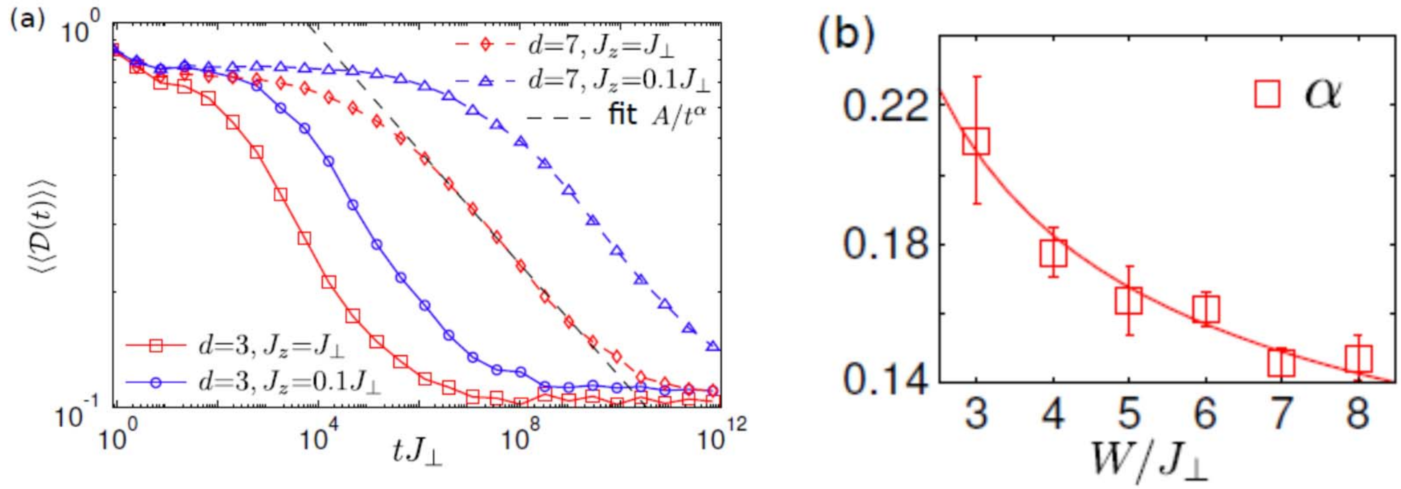
Double Electron-Electron Resonance
Ramsey sequence

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





Double Electron-Electron Resonance
Ramsey sequence



Summary

Inerferometric techniques are a powerful new tool
for studying quantum many-body systems in and out
of equilibrium

Topological properties of Bloch bands
can be studied with Ramsey/Bloch interference

Interference fringe contrast can be used
to characterize transient prethermalized states
in split 1d condensates

Many Body Localization can be explored
with interferometric Double-Electron-Electron
Resonance method