The Abdus Salam International Centre for Theoretical Physics

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IAEA International Atomic Energy Agency

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Workshop on Quantum Simulations with Ultracold Atoms

16 - 20 July 2012

An optical-lattice-based quantum simulator for relativistic field theories and topological insulators

M. Rizzi
Max Planck Inst. fuer Quantenoptik, Garching, Germany

Trieste, ICTP, July 17th 2012

An optical-lattice-based Quantum Simulator for relativistic field theories and topological insulators

Matteo Rizzi

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Mazza, **MR**, Lewenstein, Cirac, PRA **82** 043629 [1007.2344]

Bermudez, Mazza, **MR**, Goldman, Lewenstein, Martin-Delgado, PRL **105** 190404 [1004.5101]

Mazza, Bermudez, Goldman, **MR**, Martin-Delgado, Lewenstein, NJP **14** 015007 [1105.0932]

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Outline

- quantum simulations & cold gases
- topo-insulators & free-Fermi theories
- exp. setup: superlattice + Raman
- proposal at work: towards 3D-TI
- future directions

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Quantum simulation paradigm

¡HARD!

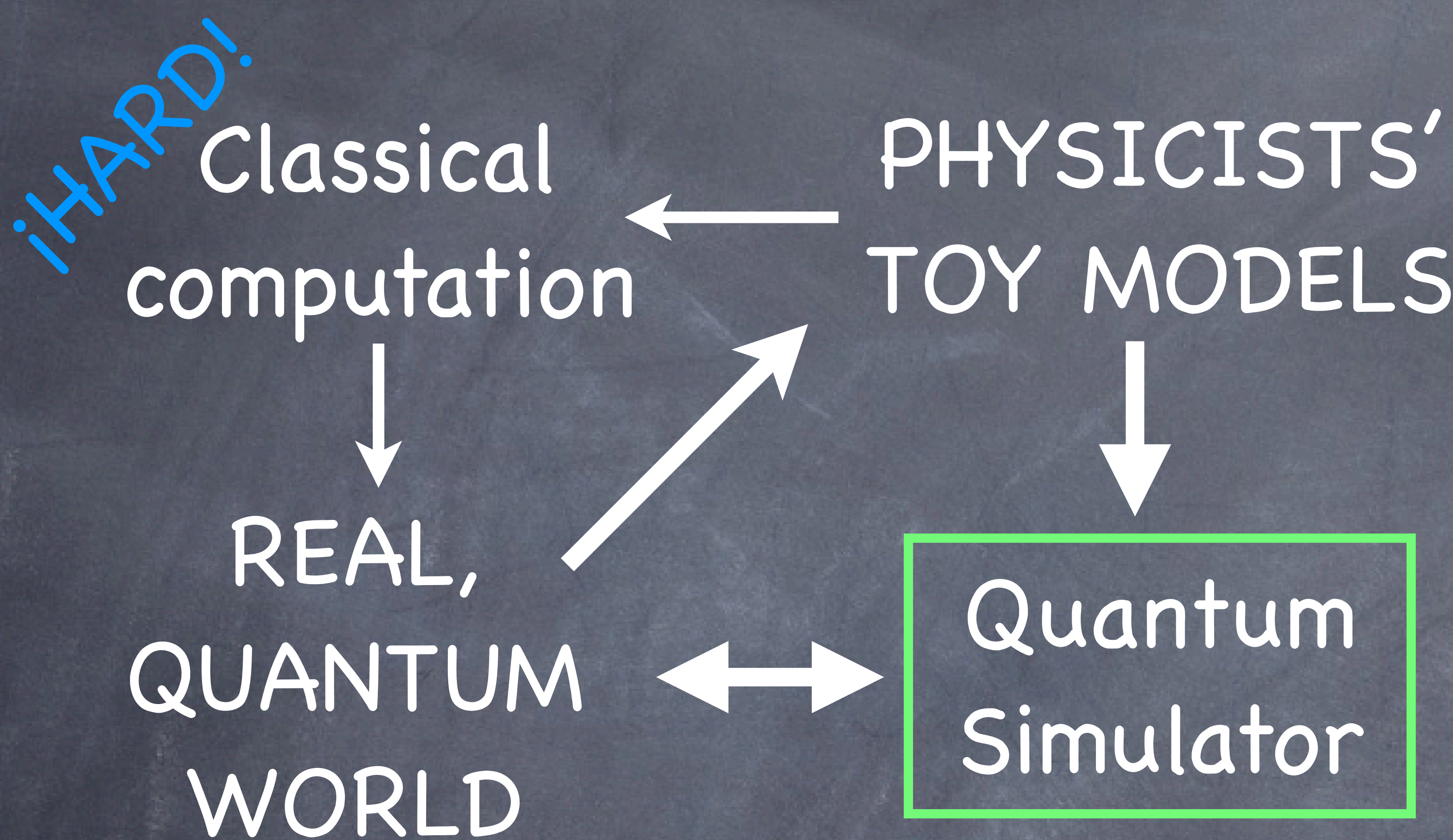
Classical computation

PHYSICISTS' TOY MODELS

REAL, QUANTUM WORLD

R.Feynman, Int. J. Theor. Phys. **21**, 467 (1982) I.Buluta, F.Nori, Science **326**, 108 (2009)

Quantum simulation paradigm



controllable quantum system:

- detailed microscopic knowledge
- high external tunability
- good access for measurements

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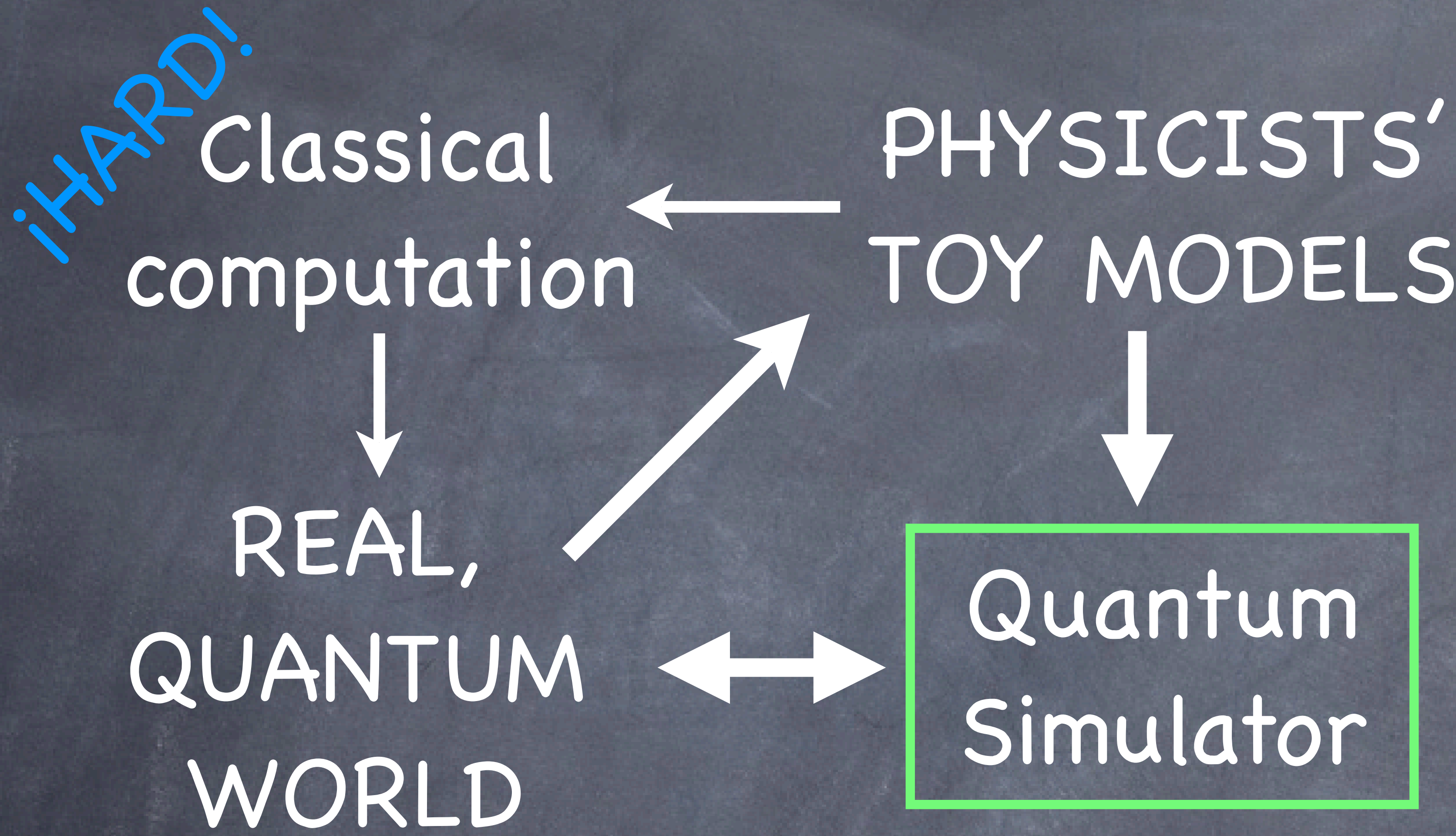

ANALOG

1. map system of interest into the Q-Sim platform (d.o.f., Hamiltonian, observables, ...)
2. let the Q-sim "compute" the quantum solution
3. retrieve the desired informations by measures

PURPOSE BUILT

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"ABSTRACT" INTO LIFE

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Ultracold atoms ~ ideal QS

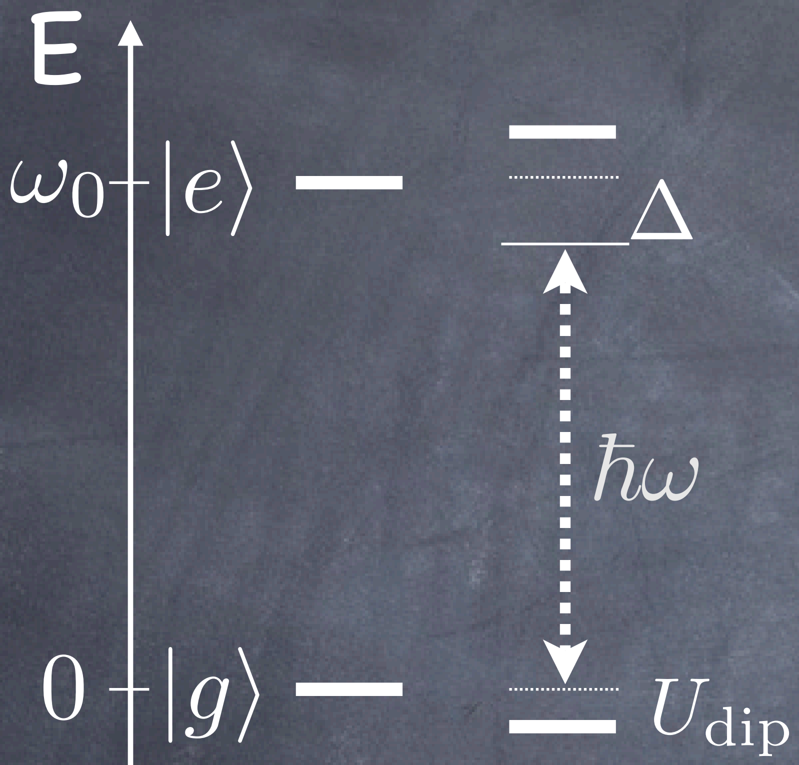
- true quantum systems
  ($T \approx nK$ $\quad$ $S/N \approx k_B$)

- highly controllable
  (dimensionality, geometry, interactions, disorder)

- various imaging techniques
  (mom. dist., correlations, densities, single-site)

- diverse statistics
  (fermions, bosons, mixtures)

Cold gases: optical potentials



Γ dipole moment e-g

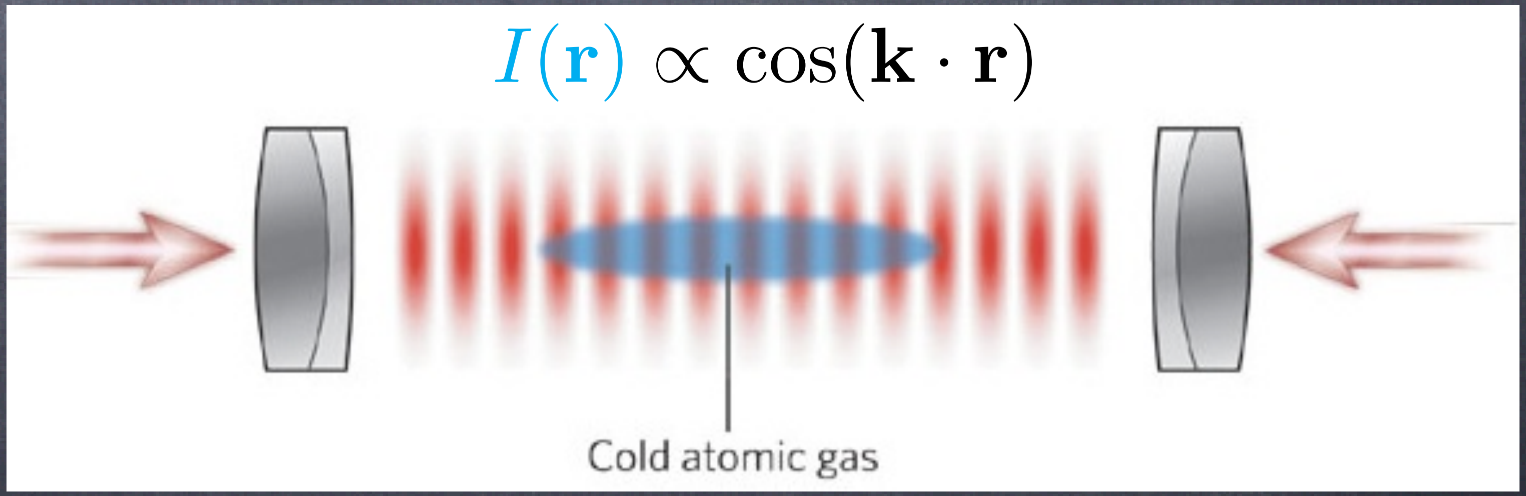
$$U_{\rm dip}(\mathbf{r}) \propto \frac{\Gamma}{\Delta} I(\mathbf{r})$$ ac Stark shift

$$\hbar\Gamma_{\rm sc} \propto \frac{\Gamma^2}{\Delta^2} I(\mathbf{r})$$ photon scattering

Grimm et al., Adv. At., Mol., Opt. Phys. 42, 95 (2000).

Trapping possibilities:

- spatial dependent $I(\mathbf{r})$
- spin dependent Δ
- speckle potentials

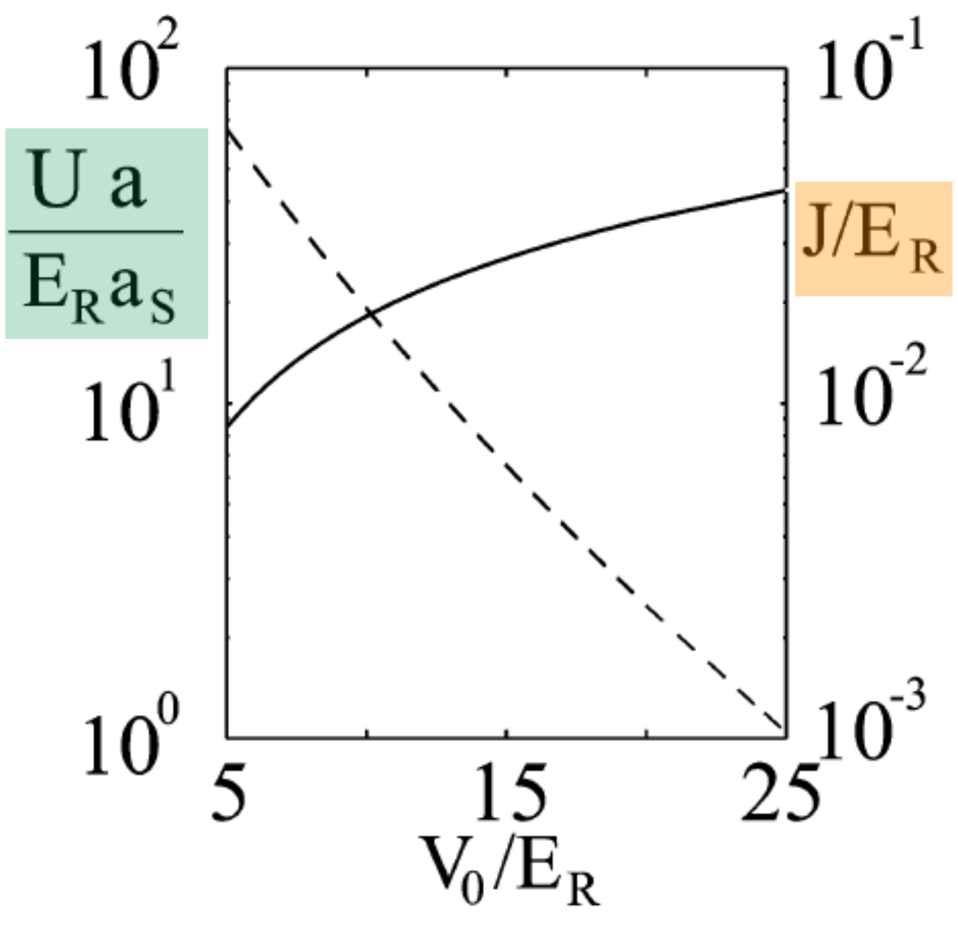


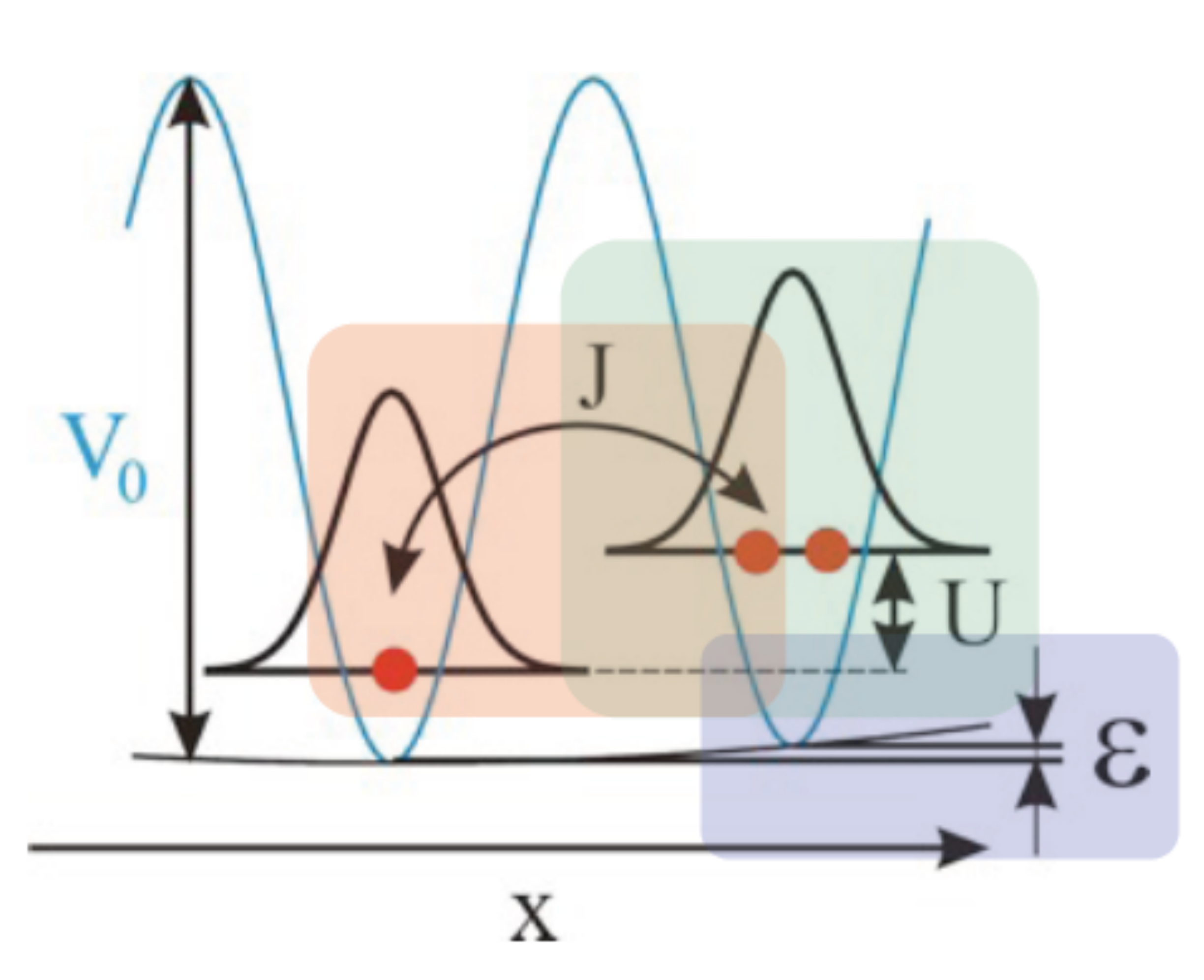
Cold gases: mapping to Hubbard

Tight-binding model out of localized (single particle) Wannier functions

$$H = -J \sum_{<i,j>} b_i^\dagger b_j + \sum_i \epsilon_i \hat{n}_i + \frac{1}{2} U \sum_i \hat{n}_i(\hat{n}_i - 1)$$

Jaksch et al. PRL **81** 3108 (1998)

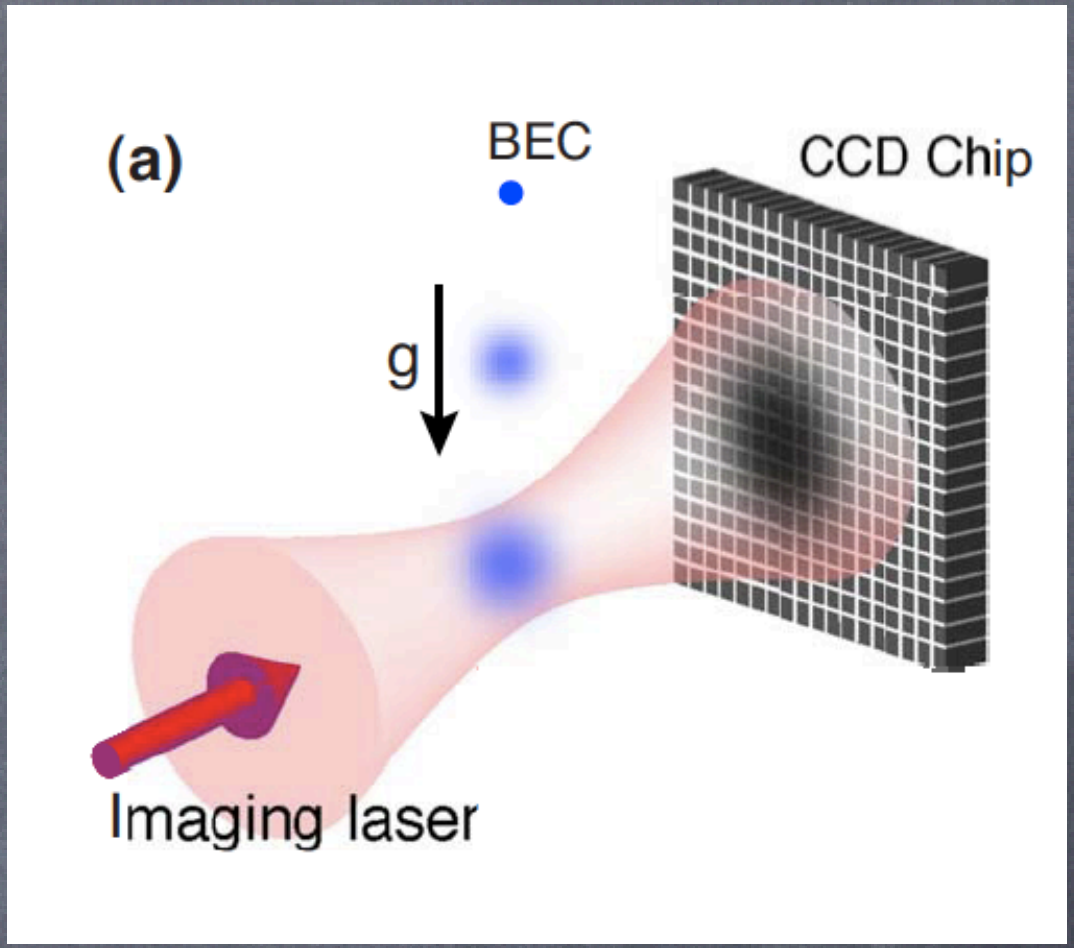


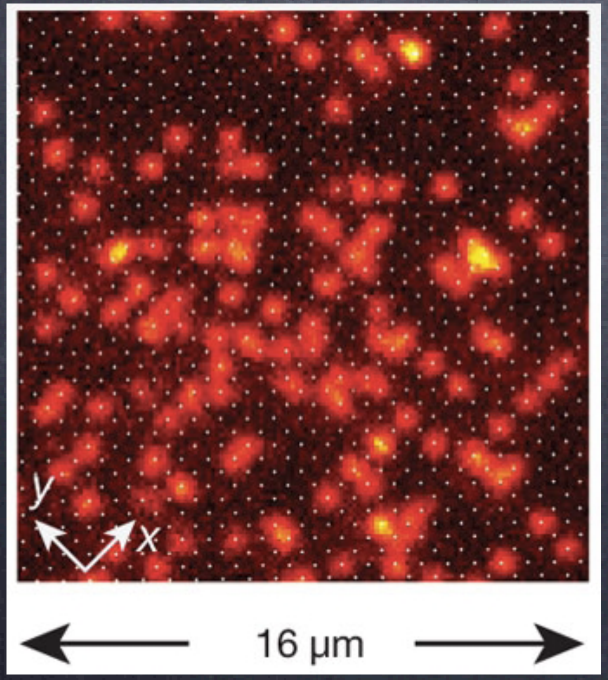


Cold gases: detection

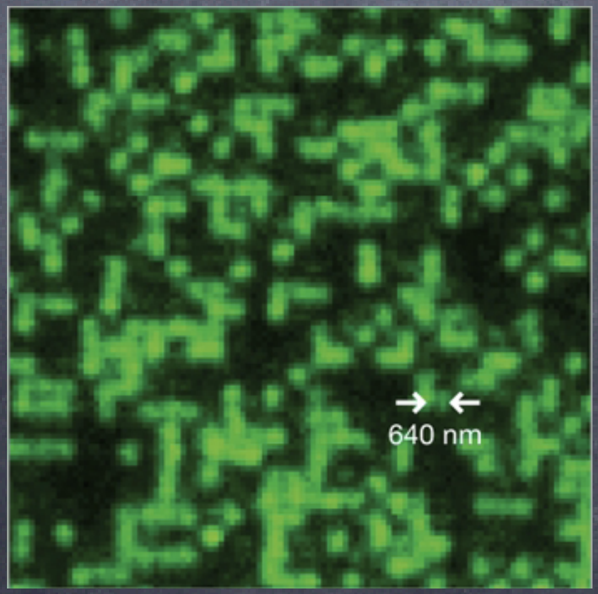
time-of-flight (TOF) imaging

$$\langle \hat{n}(\mathbf{x}) \rangle_{\mathrm{TOF}} \simeq \langle \hat{n}\left(\mathbf{k} = \frac{\mathbf{mx}}{\hbar \mathbf{t}}\right) \rangle_{\mathrm{trap}}$$





Bloch group @ MPQ



Greiner group @ Harvard

Single-site imaging/manipulation

(some) CA-QS in recent years

- Mott-Superfluid transition
- exotic SFs in imbalanced fermions
- antiferromagnetic spin-chains
- itinerant ferromagnetism
- Anderson localization
- equation of state (fermions/bosons)
- ...

Cold gases: synthetic gauge potentials

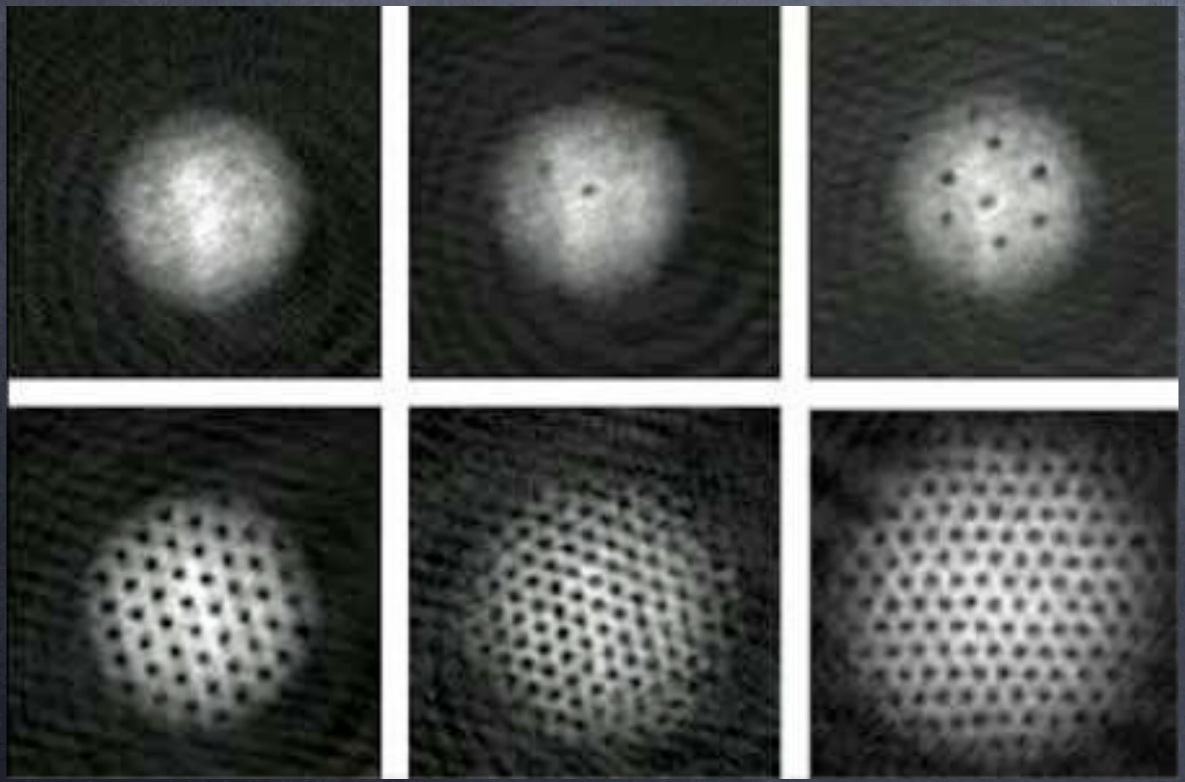
ultracold atoms are neutral !
real magnetic fields affect only spin d.o.f.

↓

how to access rich "orbital" physics
of electrons in magn. fields !? $\mathbf{p} \to (\mathbf{p} - e\mathbf{A})^2$

↙

rotation of harmonic traps



A. Fetter, Rev.Mod.Phys. **81** 647 ('09)

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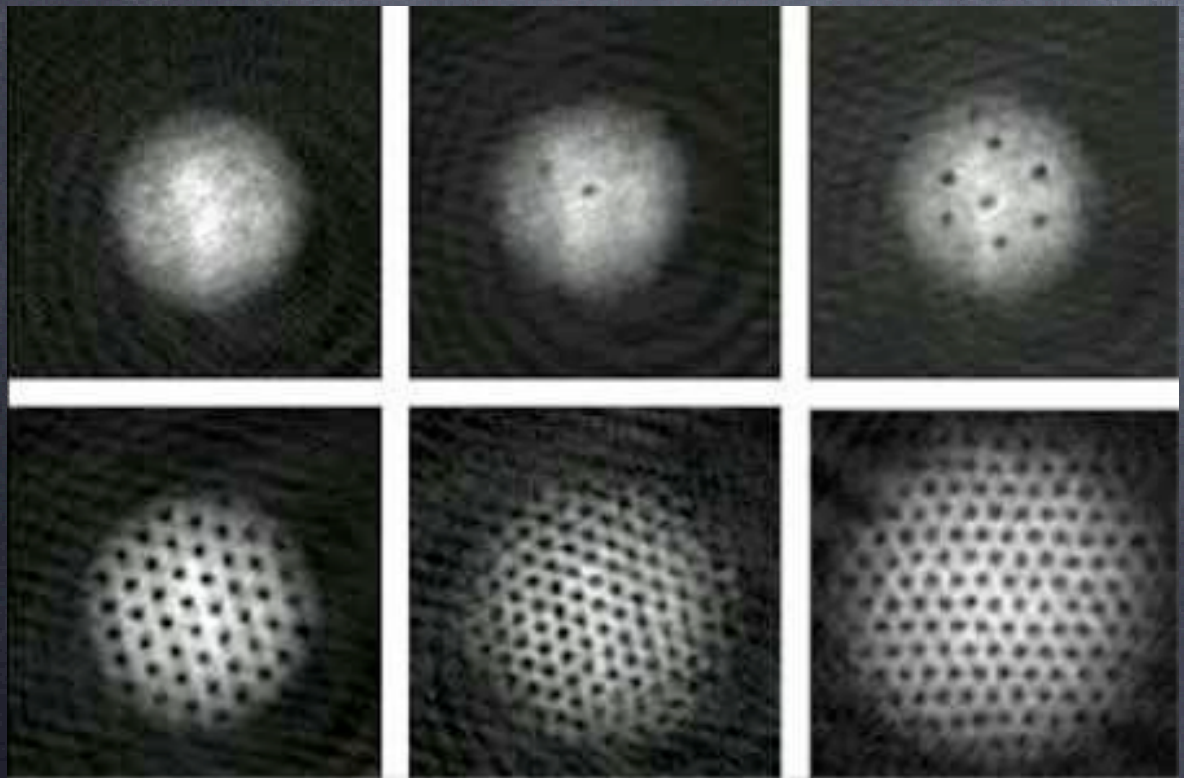

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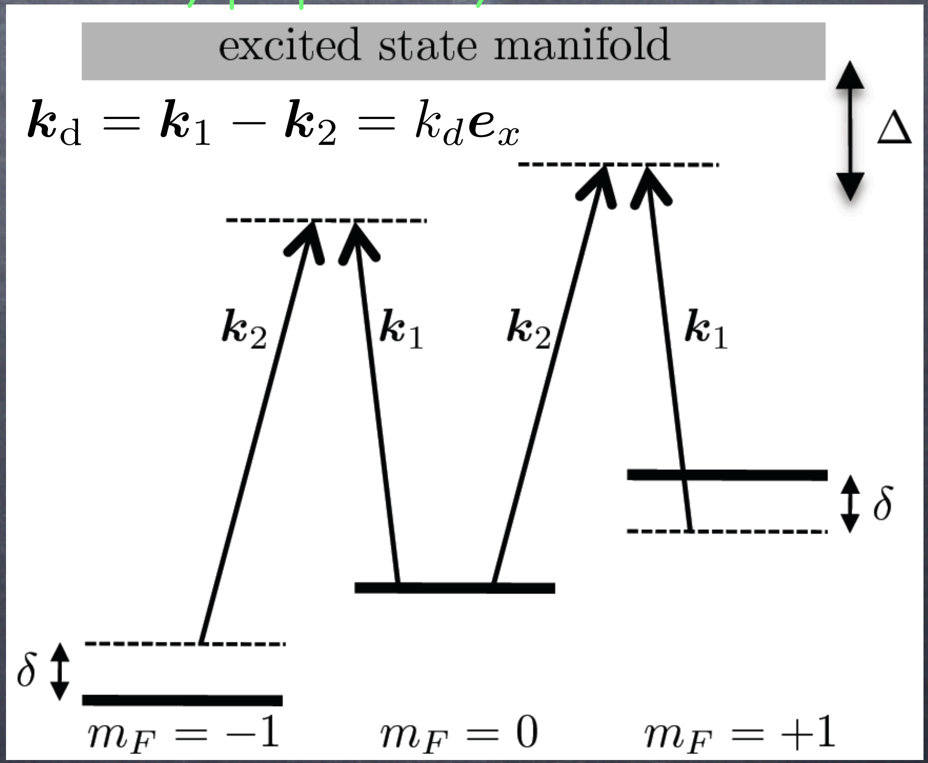
laser-assisted methods

early proposals by Juzeliunas et al.



Lin, Spielman, et al. Nature 462, 628 ('09)

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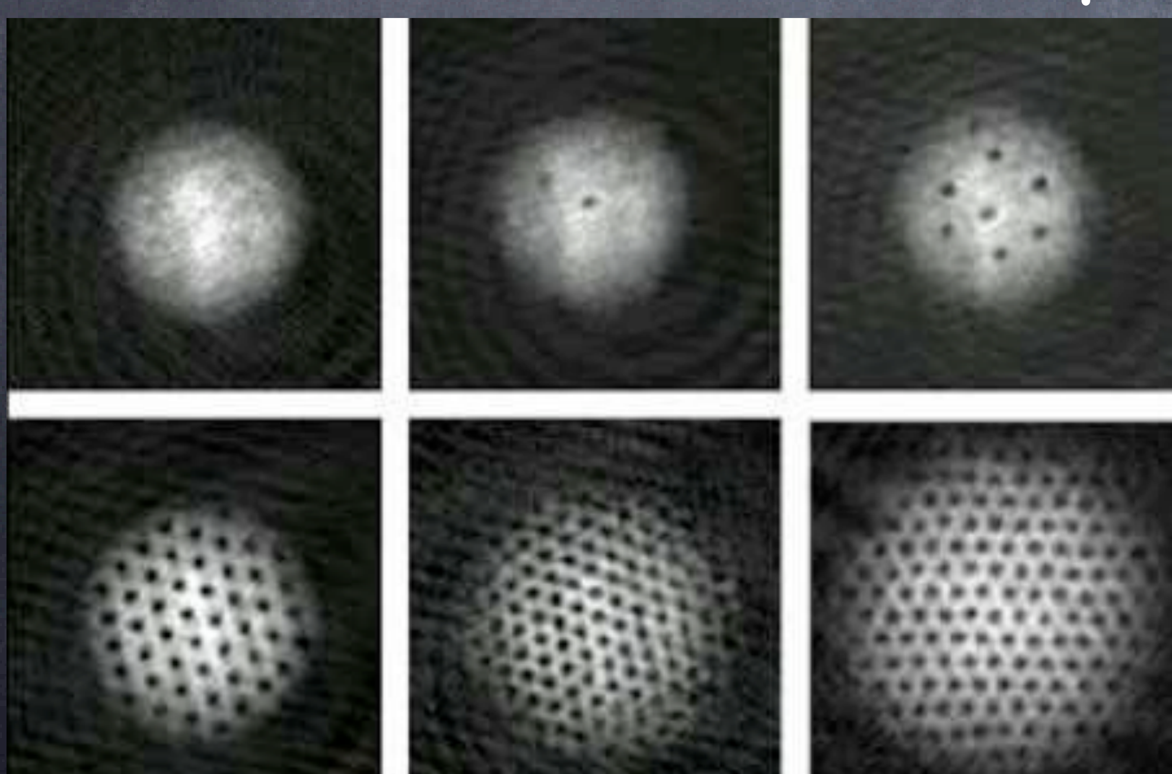

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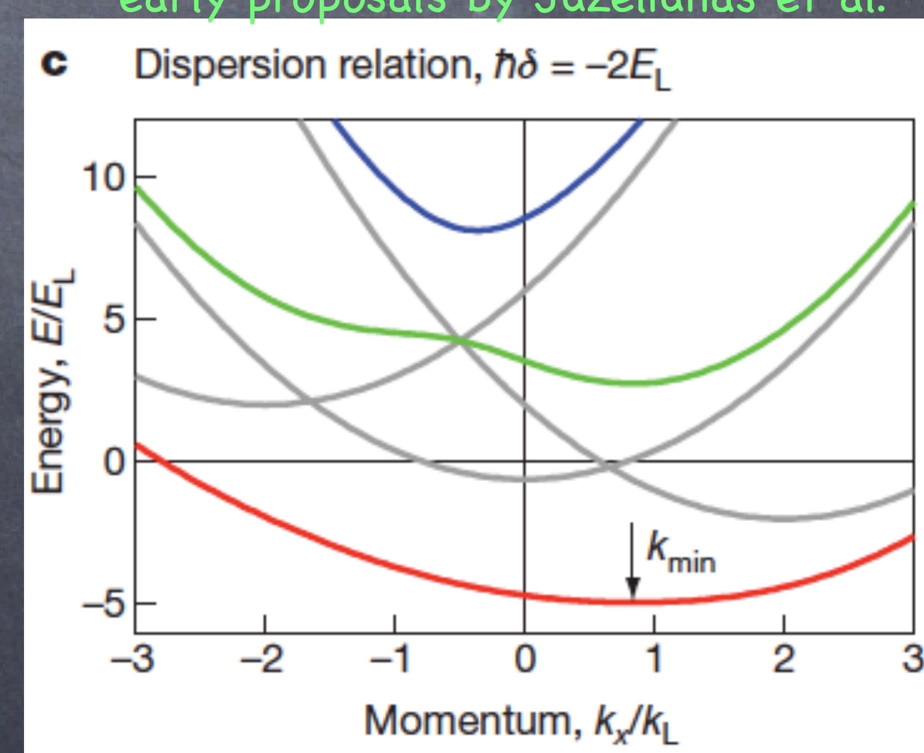

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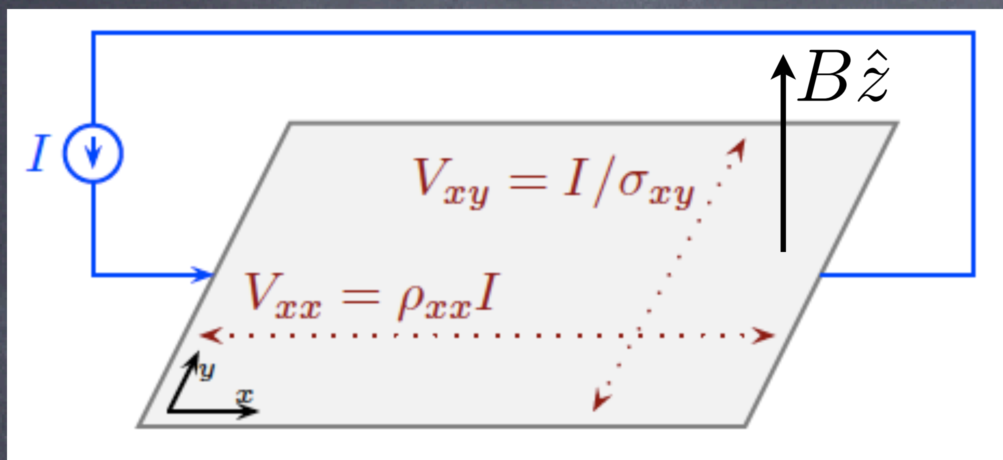
Quantum Hall physics

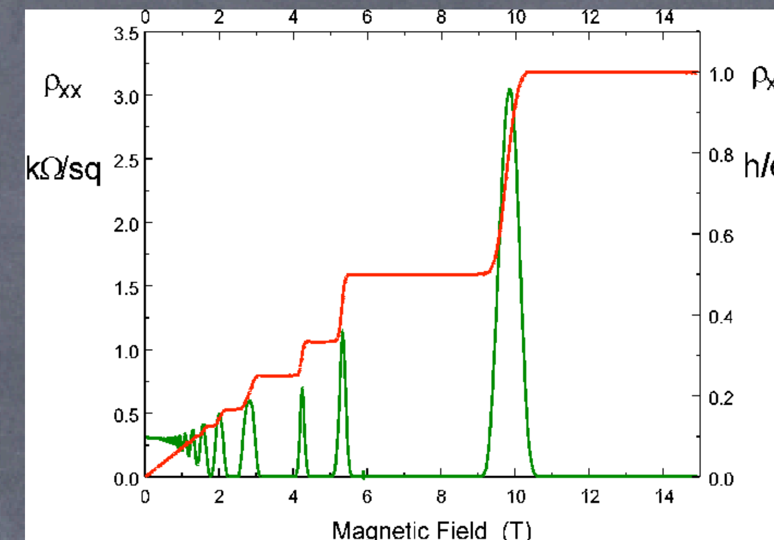
- 2D electron gas @ low T & intense B



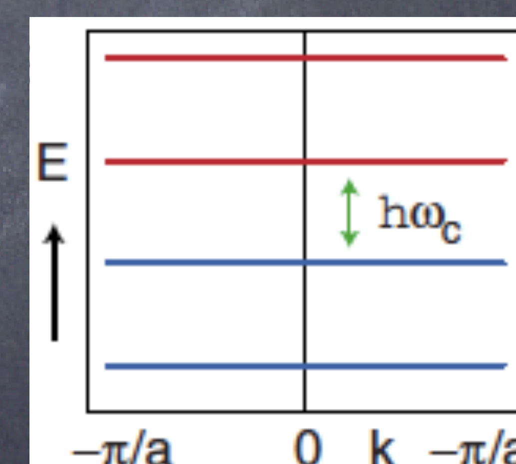
$$\sigma_{\mathrm{xy}} = \nu \frac{e^2}{h}$$

$$\nu = \frac{n_e \phi_0}{B}$$

$$\boxed{\nu = \frac{p}{q}}$$



- precise & robust quantization of transport properties
- spectrum: (flat) Landau levels with gaps



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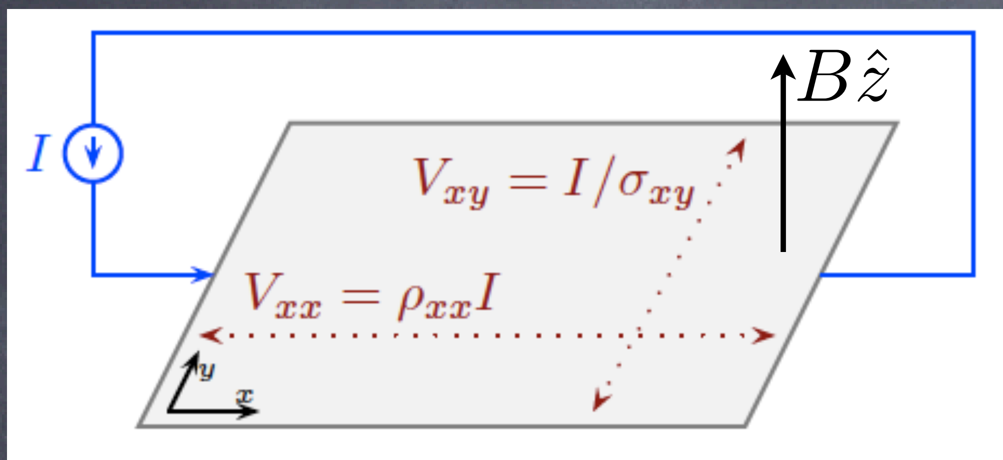

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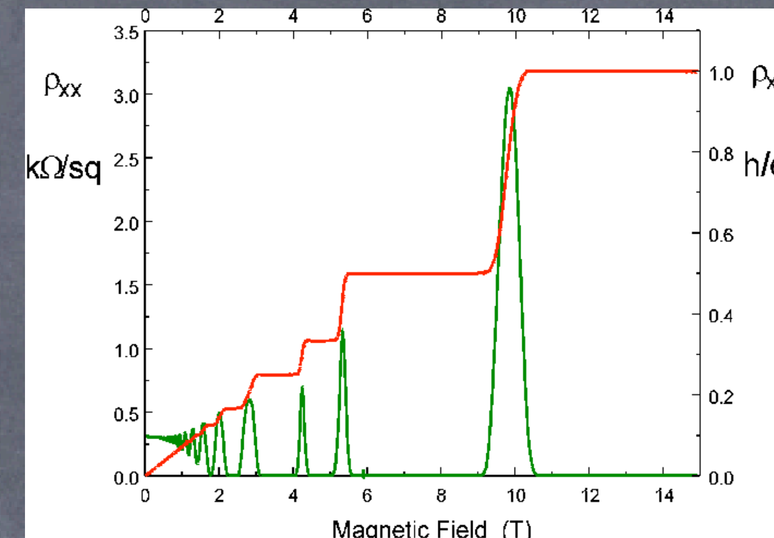
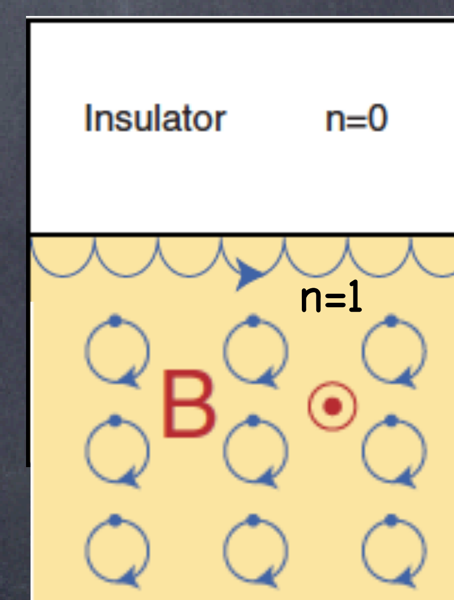


- precise & robust quantization of transport properties
- spectrum: (flat) Landau levels with gaps
- q=1 -> Integer QHE: single particle physics

↓

- related to a topological invariant (TKNN)
- presence of zero-energy edge modes



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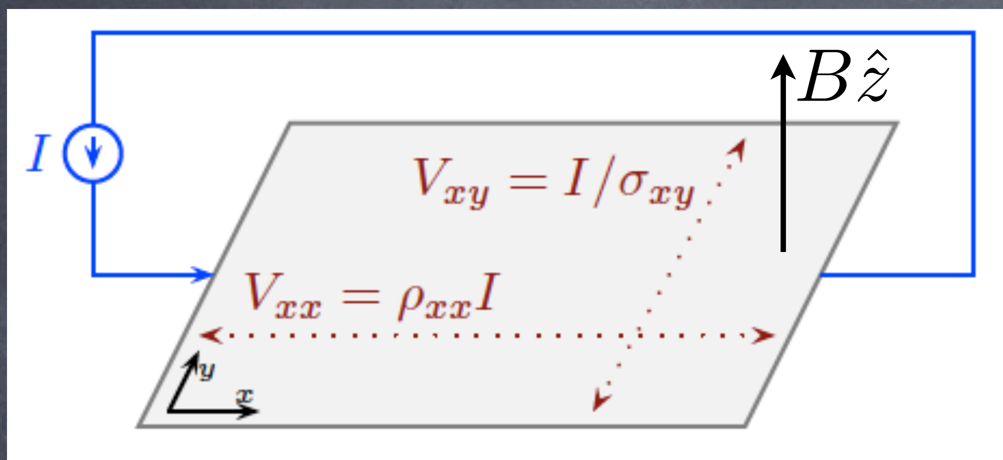

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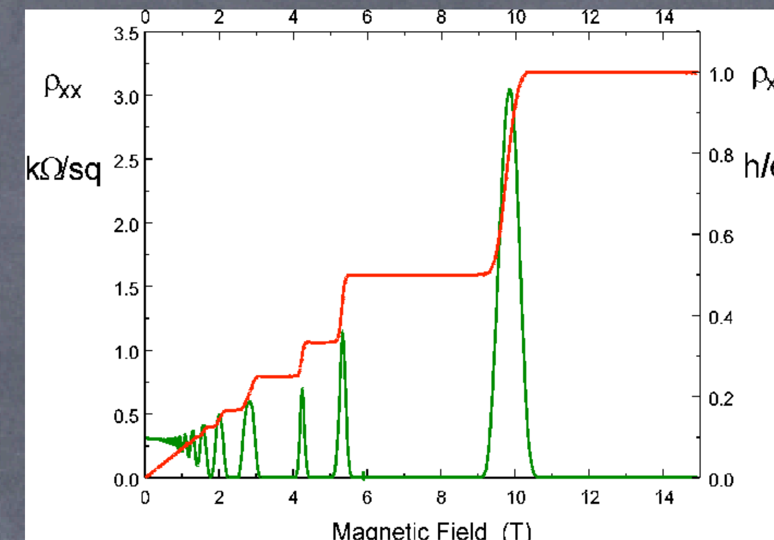

- precise & robust quantization of transport properties
- spectrum: (flat) Landau levels with gaps

- q≠1 -> Fractional QHE: many-body physics

$\Downarrow$

- interactions generate strong correlations
- non-perturbative, e.g. Laughlin $\nu = 1/3 \,:\, \Psi = \prod_{j<l} (z_j - z_l)^3$

Topological insulators

IQHE is a paradigmatic example of:

- gapped bulk systems showing "exotic" properties

  --> transport (or response to EM probes)

- bulk characterized by a topological invariant

  --> integral on the toroidal Brillouin zone (TKNN)

- gapless edge states carry informations on the bulk

  --> holographic principle

M. Hasan, and C.L. Kane, Rev. Mod. Phys. **82** 3045 ('10)

Topological insulators

Full characterization via free-Fermi Hamiltonians with symmetries:

- T = time-reversal
- C = particle-hole
- S = CT = chiral

Class	Name	T	C	S	$d=1$	$d=2$	$d=3$
A	Unitary	0	0	0		$\boxed{\mathbb{Z}\ \text{[IQHE]}}$	
AIII	Chiral unitary	0	0	1	$\mathbb{Z}$		$\mathbb{Z}$
AI	Orthogonal	$+1$	0	0			
BDI	Chiral Orthogonal	$+1$	$+1$	1	$\mathbb{Z}$ [1D polyac.]		
AII	Symplectic	-1	0	0		$\mathbb{Z}_2$ [QSHE]	$\boxed{\mathbb{Z}_2\ \text{[3DTI]}}$
CII	Chiral Symplectic	-1	-1	1	$2\mathbb{Z}$		$\mathbb{Z}_2$

A. Altland, and M. R. Zirnbauer, Phys. Rev. B **55**, 1142 ('97)
M. Hasan, and C.L. Kane, Rev. Mod. Phys. **82** 3045 ('10)

Target Hamiltonian

Quantum simulator for non-interacting Fermions:

$$H_{\rm sys} = \sum_{\mathbf{r}} \sum_{\tau\tau'} \left[\sum_{\boldsymbol{\nu}} t_\nu c^\dagger_{\mathbf{r}+\boldsymbol{\nu}\tau'} [U_{\boldsymbol{\nu}}]_{\tau'\tau} c_{\mathbf{r}\tau} + \Omega c^\dagger_{\mathbf{r}\tau'} [\Lambda]_{\tau'\tau} c_{\mathbf{r}\tau} + \text{H.c.} \right]$$

with control over all parameters D, Ω, Λ, t, U

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with control over all parameters <u>D, Ω, Λ, t, U</u>

IDEA! cold gases in an optical lattice setup that is:

- bichromatic
- spin-independent
- Raman assisted

Not many-body but rich

$$H_{\text{sys}}(\{t_\nu, U_{\mathbf{r}\boldsymbol{\nu}}, \Lambda, \Omega\}) \;\rightarrow\; H_{\text{eff}} \approx H_{\text{rel}}, H_{\text{top}}$$

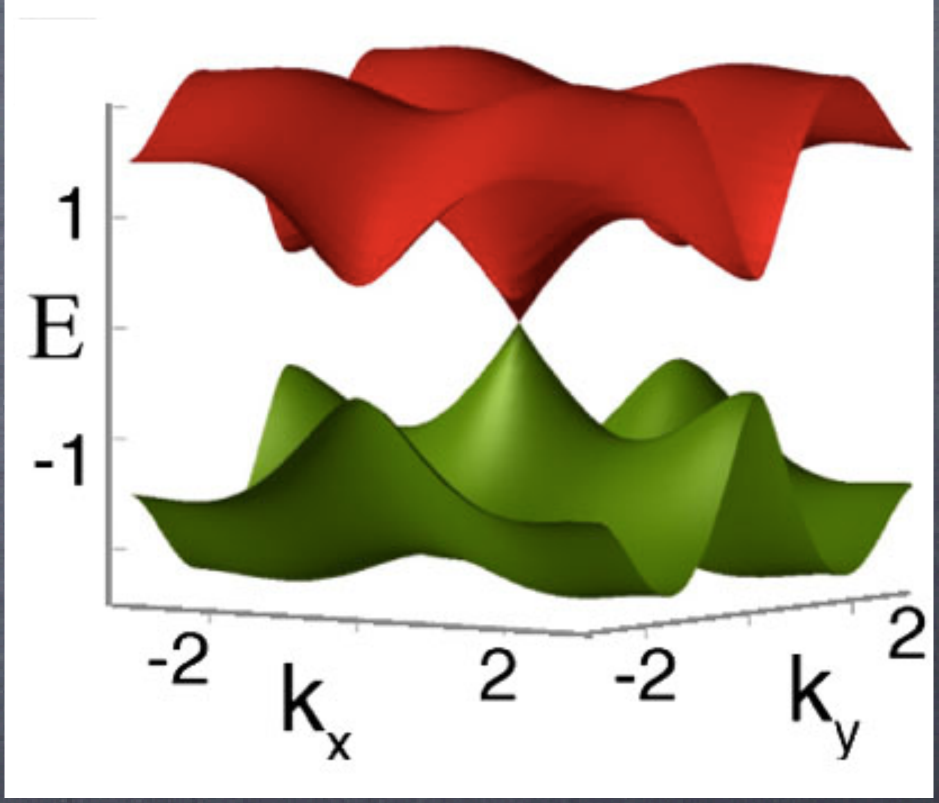
H_{rel} emerging relativistic fermions
with/-out mass in D=1,2,3
-> as graphene BUT richer <-

↓

tailorable to get isolated
boundary massless fermions

↓

Topological Insulators ! H_{top}



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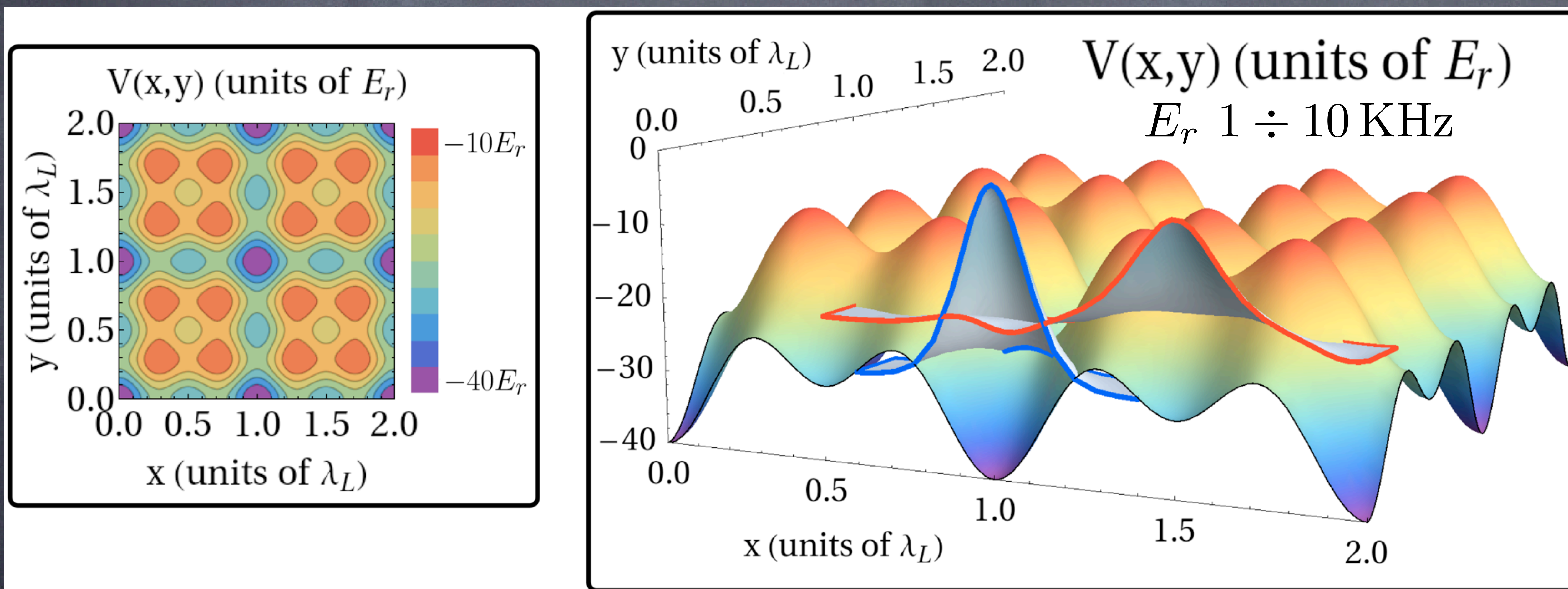
Sketch of the proposal

$$V(\mathbf{x}) = -V_0 \sum_{j\in\{1,2,3\}} \left[\cos^2(qx_j) + \xi \cos^2(2qx_j)\right]$$

S. Folling, et al., Nature 448, 1029 (2007).



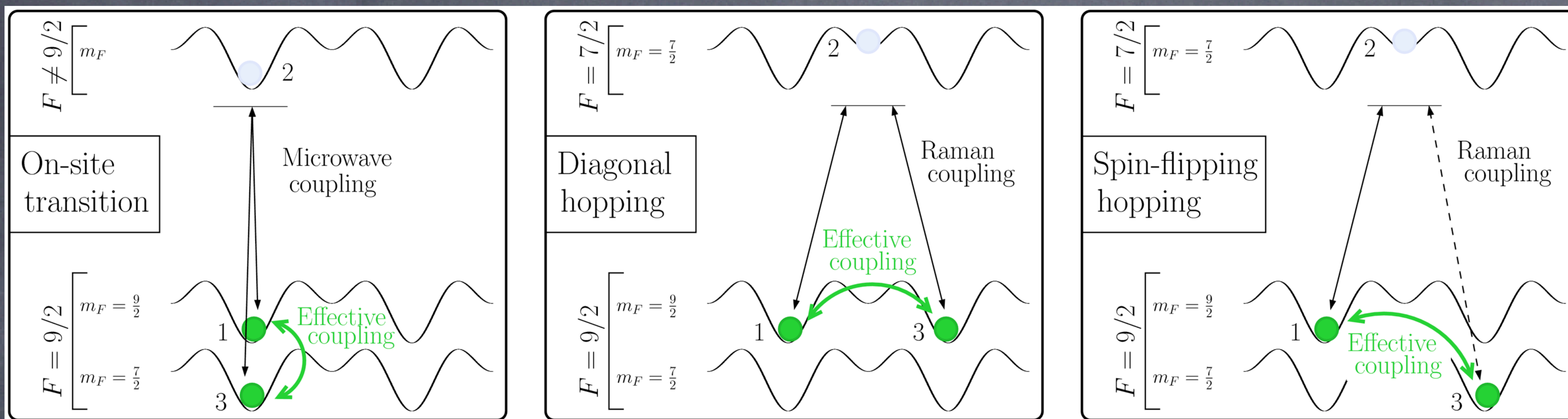
lowest band <--> simulation sites

higher band(s) <--> auxiliary buses

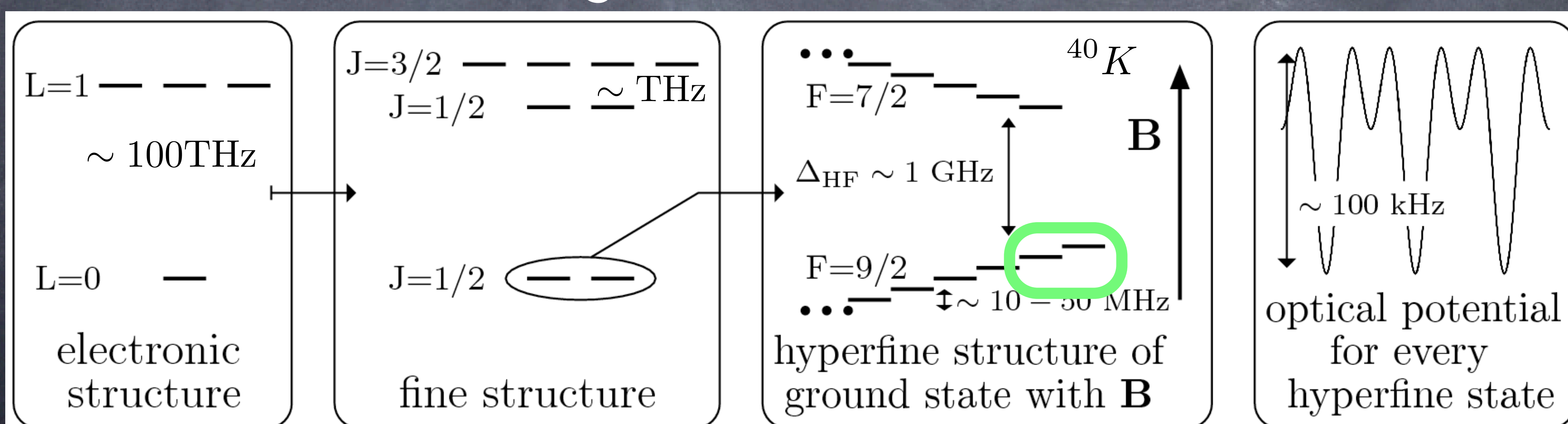
hyp.fine state <--> spin d.o.f.

Sketch of the proposal

adiabatic elimination of different Raman couplings



hierarchy of energy scales to address transitions



inspired by Ruostekoski PRL 103 080406 (02) // Jaksch-Zoller NJP 5 56 (03) // Gerbier-Dalibard NJP 12 033007 (10)

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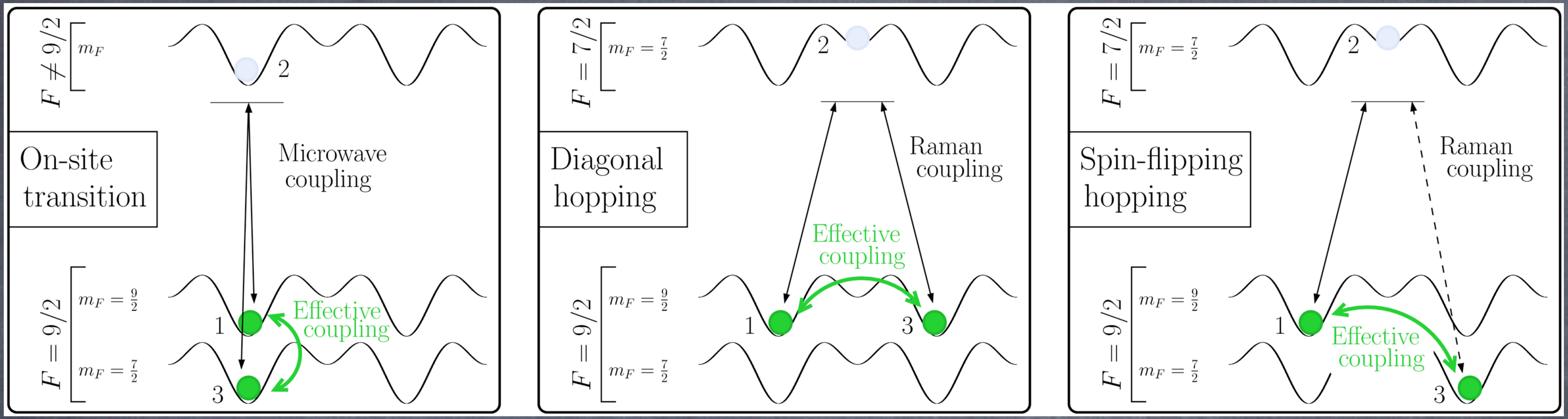

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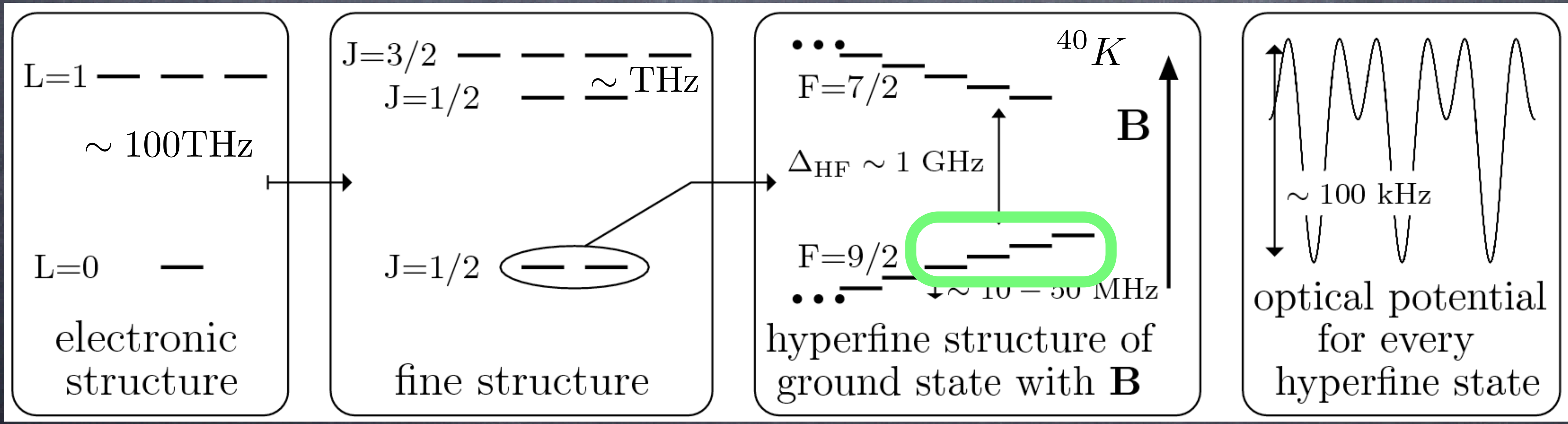

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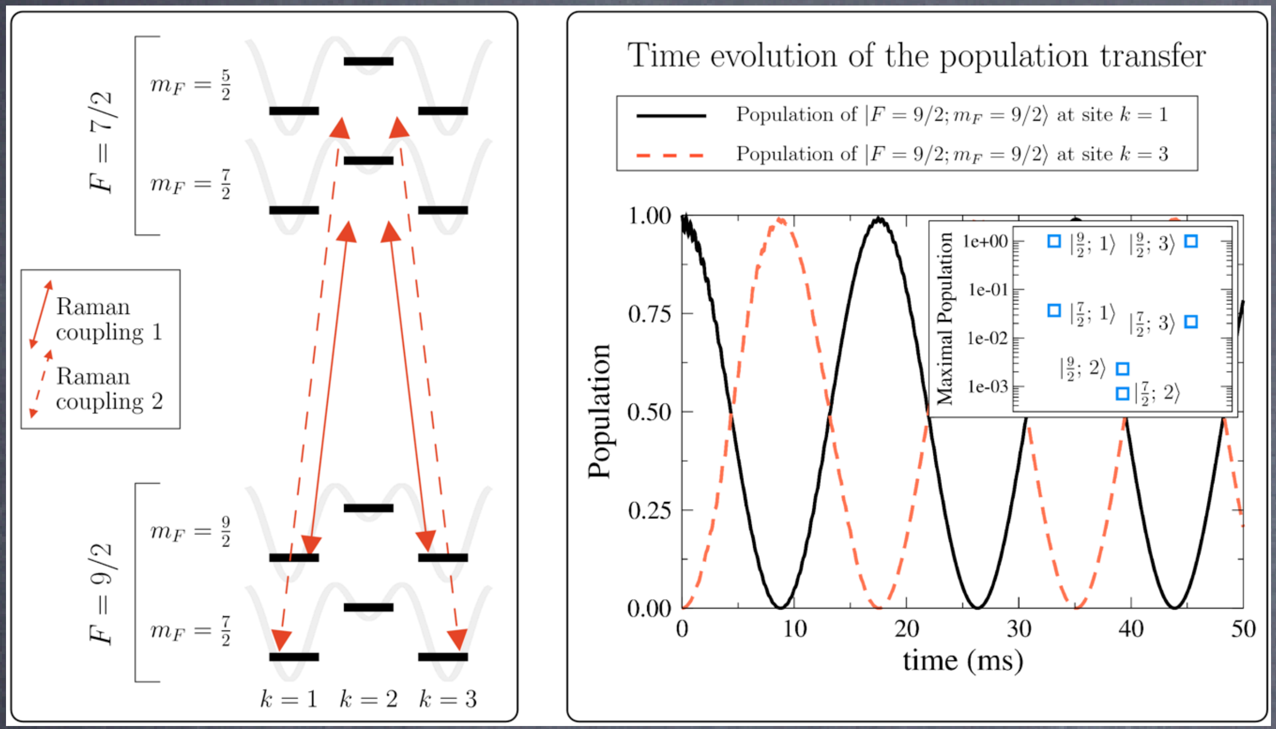
Numerical Validation

Runge-Kutta evolution of the full link model

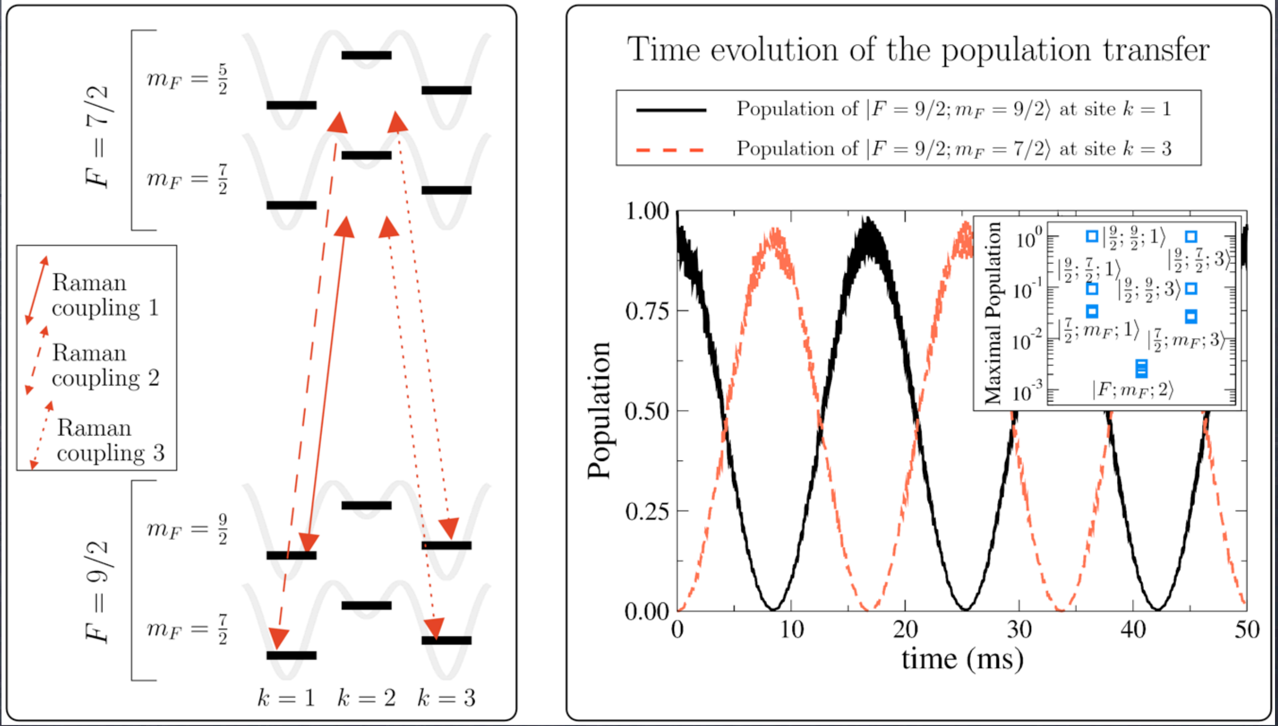


DIAGONAL

- eff. hopping ~ 100Hz
- "fidelity" > 97%
- Zeeman helps tuning different elements

OFF-DIAGONAL

- "fidelity" > 88%
- additional staggering to avoid on-site flips

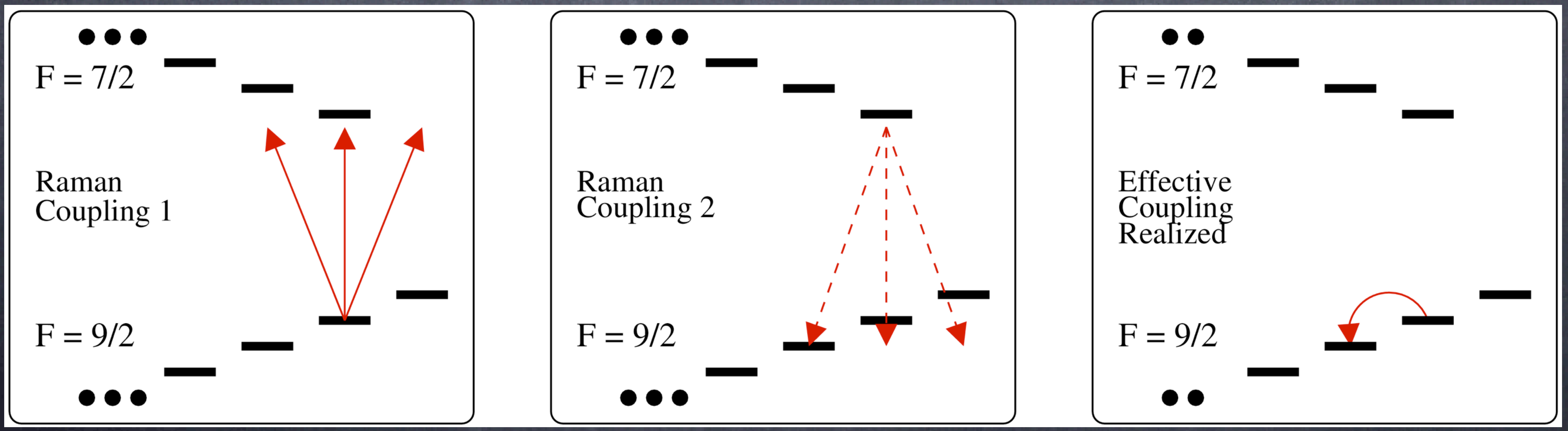


A proposal for all dimensions

- need of momentum transfer
  --> directionality selection rule !
  (laser aligned to x/y/z rules over x/y/z only)

$$\boxed{|S_{1,2}| \neq 0 \quad \text{iff} \quad |(\mathbf{p}_1 - \mathbf{p}_2) \cdot \boldsymbol{\nu}| \neq 0}$$

- polarization selection rule is reliable in 1D only, but hierarchy of energies helps in 2- & 3-D



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Relativistic field theory

our superlattice+Raman setup gives control on

$$H_{\rm sys} = \sum_{\mathbf{r}} \sum_{\tau\tau'} \left[\sum_{\boldsymbol{\nu}} t_\nu c^\dagger_{\mathbf{r}+\boldsymbol{\nu}\tau'} [U_{\boldsymbol{\nu}}]_{\tau'\tau} c_{\mathbf{r}\tau} + \Omega c^\dagger_{\mathbf{r}\tau'} [\Lambda]_{\tau'\tau} c_{\mathbf{r}\tau} + \text{H.c.} \right]$$

to simulate Dirac equation

$$\boxed{H_{\rm DI} = c\boldsymbol{\alpha}\cdot\mathbf{p} + mc^2\beta \qquad \begin{array}{l} \{\alpha_\nu, \alpha_\mu\} = 2\delta^{\nu\mu} \\ \{\alpha_\nu, \beta\} = 0 \end{array}}$$

via low-energy effective description

$$H_{\rm sys}(\{t_\nu, U_{\mathbf{r}\boldsymbol{\nu}}, \Lambda, \Omega\}) \;\to\; H_{\rm eff} \approx H_{\rm rel} = \int \mathrm{d}\mathbf{r}\; \Psi(\mathbf{r})^\dagger H_{\rm DI} \Psi(\mathbf{r})$$

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D	α_x	α_y	α_z	β	Γ
1	σ_x			σ_z	$\mathbf{i}\sigma_x$
2	σ_x	σ_y		σ_z	$\mathbf{i}\sigma_y$
3	$\sigma_z \otimes \sigma_x$	$\sigma_z \otimes \sigma_y$	$\sigma_z \otimes \sigma_z$	$\sigma_x \otimes \mathbb{I}_2$	$-\mathbf{i}\alpha_x\alpha_y\alpha_z$

number of hyperfine states needed for the simulation

$$\dim \Psi(\mathbf{r}) = N_D = \begin{cases} 2 & D = 1, 2 \\ 4 & D = 3 \end{cases}$$

Shaping dispersion relations

- step 1: naive massless Dirac fermions

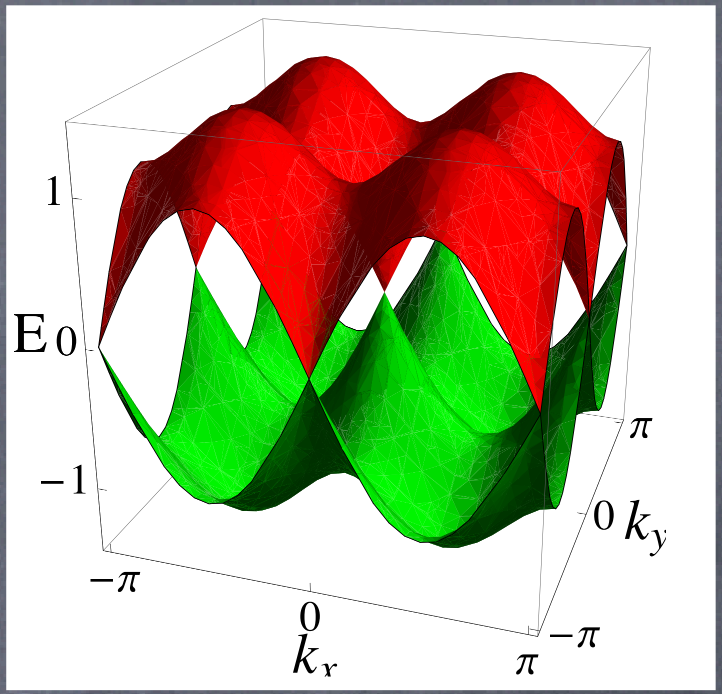
$$\boxed{U_\nu = \mathbf{i}\alpha_\nu}$$
$$\Lambda = 0$$

$$\longrightarrow H = \sum_{\mathbf{k}\in\mathrm{BZ}} \Psi^\dagger_{\mathbf{k}} \left(\sum_\nu 2t_\nu \sin k_\nu \alpha_\nu \right) \Psi_{\mathbf{k}} \longrightarrow$$

$$\downarrow$$

$$\boxed{c = 2t}$$
$$\mathbf{p_d} = \mathbf{k} - \mathbf{K_d}$$

$$H_{\mathrm{eff}} = \sum_{\mathbf{d}} \sum_{\mathbf{p_d}} \Psi^\dagger(\mathbf{p_d}) \left[c\alpha^{\mathbf{d}} \cdot \mathbf{p_d} \right] \Psi(\mathbf{p_d})$$



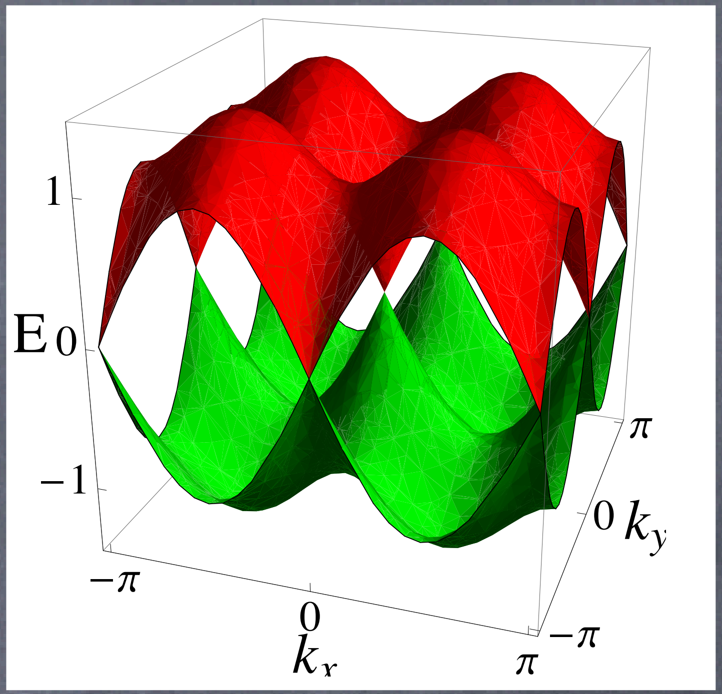
Shaping dispersion relations

- step 1: naive massless Dirac fermions

$\boxed{U_\nu = \mathrm{i}\alpha_\nu}$ $\Lambda = 0$ $\longrightarrow$ $H = \sum_{\mathbf{k}\in BZ} \Psi^\dagger_{\mathbf{k}} \left(\sum_\nu 2t_\nu \sin k_\nu \alpha_\nu \right) \Psi_{\mathbf{k}}$ $\longrightarrow$

$\downarrow$

$\boxed{c = 2t}$ $\mathbf{p_d} = \mathbf{k} - \mathbf{K_d}$ $H_{\text{eff}} = \sum_{\mathbf{d}} \sum_{\mathbf{p_d}} \Psi^\dagger(\mathbf{p_d}) \left[c\alpha^{\mathbf{d}} \cdot \mathbf{p_d} \right] \Psi(\mathbf{p_d})$

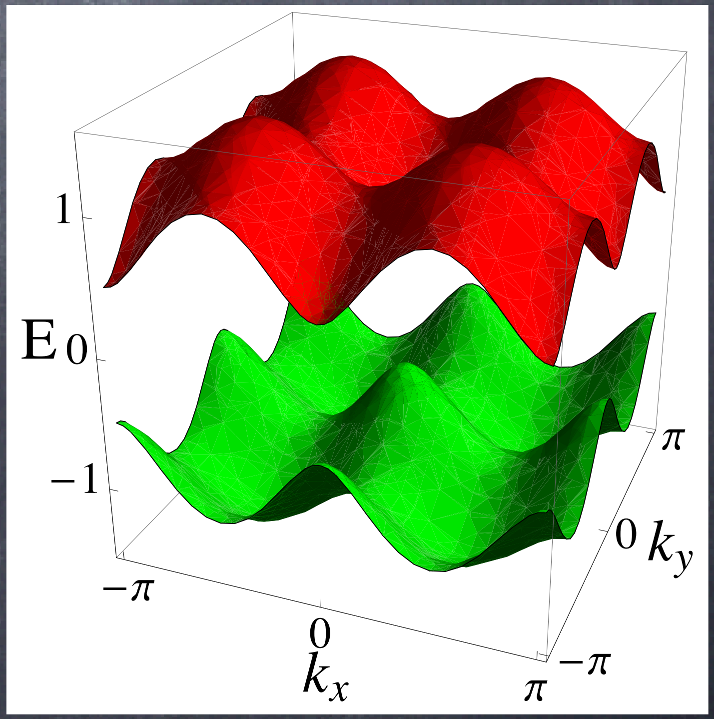


- step 2: naive massive Dirac fermions

$\boxed{\Lambda = \beta}$ $\longrightarrow$ extra $\sum_{\mathbf{k}\in BZ} \Psi^\dagger_{\mathbf{k}} \Omega \beta \Psi_{\mathbf{k}}$ $\longrightarrow$

$\downarrow$

$\boxed{mc^2 = \Omega}$ $H_{\text{eff}} = \dots \left[c\alpha^{\mathbf{d}} \cdot \mathbf{p_d} + mc^2 \beta \right] \dots$



Shaping dispersion relations

- naive Dirac fermions suffer "doubling"
  due to chiral (D=1,3)/time reversal (D=2) symmetry Γ
  (Nielsen-Ninomiya theorem)

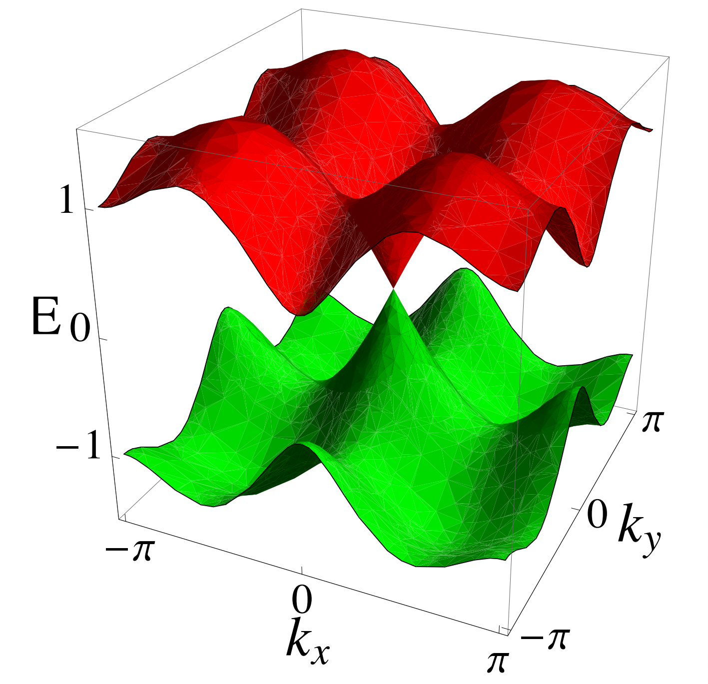
$$\downarrow$$

- step 3: Wilson fermions avoid "doubling"

$$\boxed{\tilde{U}_{\boldsymbol{\nu}} = -\beta} \qquad \tilde{H} = \sum_{\mathbf{k}\in \mathrm{BZ}} \Psi^\dagger_{\mathbf{k}} \left(\sum_\nu -2\tilde{t}_\nu \cos k_\nu \beta \right) \Psi_{\mathbf{k}}$$

$$\downarrow$$

$$m_\nu c^2 = 2\tilde{t}_\nu \qquad \boxed{m_{\mathbf{K_d}} = m - \sum_\nu (-1)^{d_\nu} m_\nu}$$



- step 3b: Kaplan fermions $m_{\mathbf{K_0}} < 0$ & boundary theories

A fractional capacitor for 3D TI

- 4 components gas
- chirality $\gamma_5 = \sigma_z \otimes \mathbb{I}$
- on-site $\Lambda = \beta = \sigma_x \otimes \mathbb{I}$
- hopping $U_\nu = \alpha_\nu = \sigma_z \otimes \sigma_\nu$
  $\tilde{U}_\nu = -\beta$

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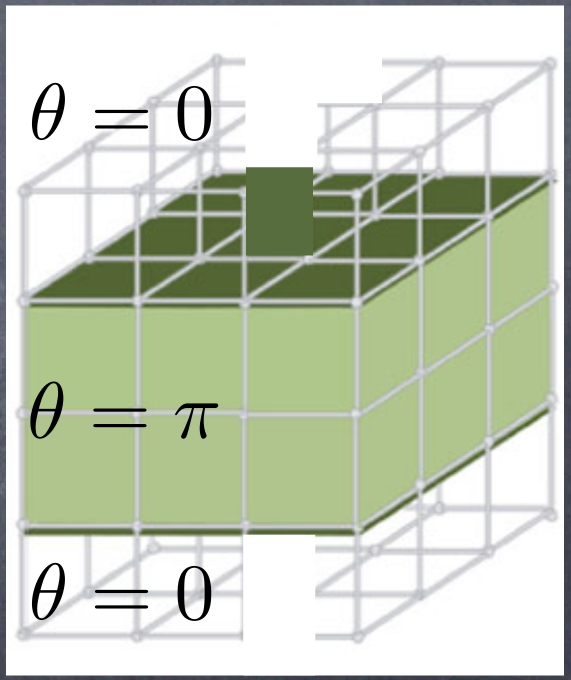
- create finite regions with negative mass by focusing on-site corrections Λ
  - complex mass gives axions...



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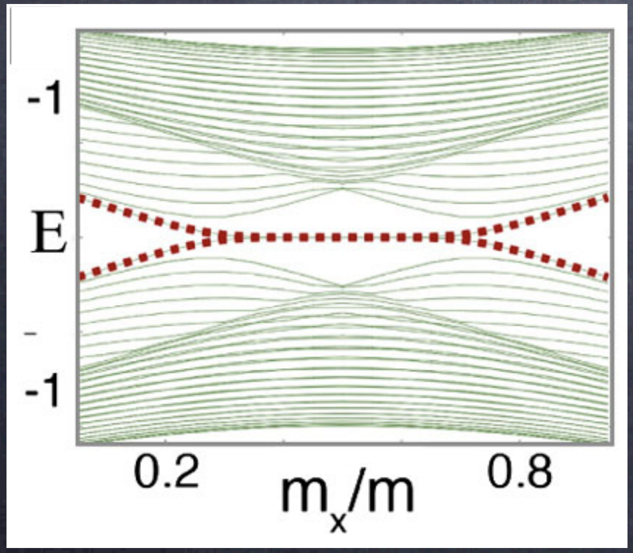

- zero-energy edge states for a wide parameter window

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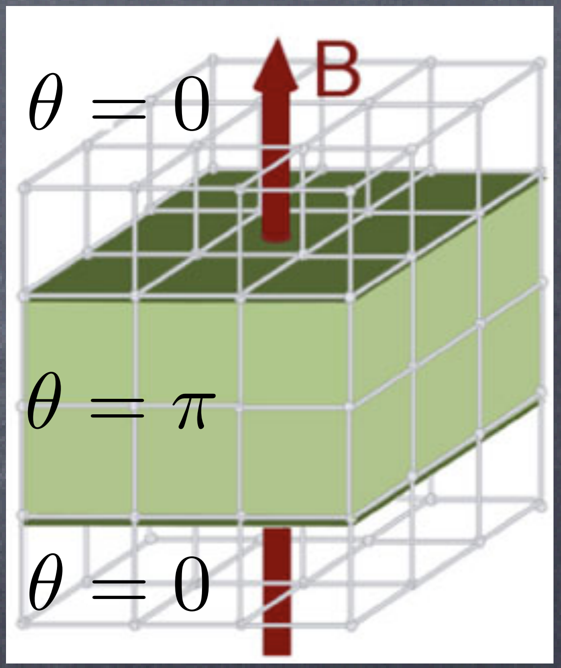
A fractional capacitor for 3D TI

- peculiar response to artificial magnetic field (engineerable in cold gases)

Magneto-Electric effect $\nabla \cdot \mathbf{E} = 4\pi\rho - (e^2/\pi c)\nabla\theta \cdot \mathbf{B}$



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A fractional capacitor for 3D TI

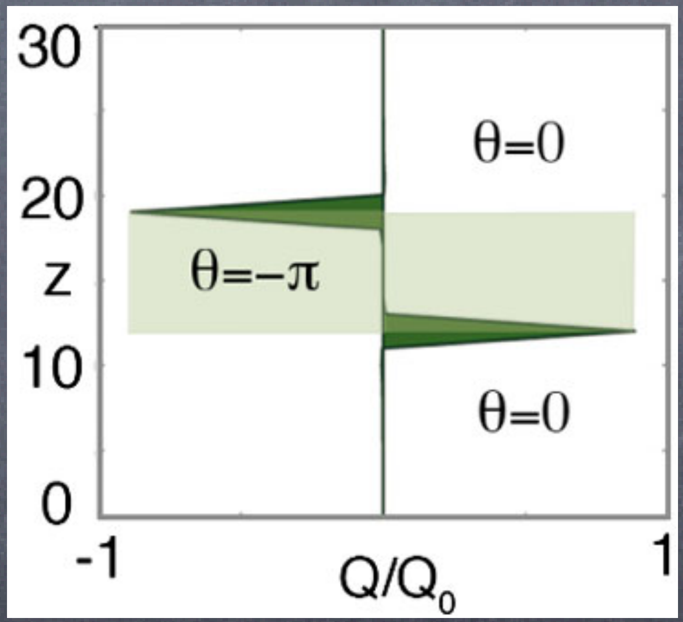
- peculiar response to artificial magnetic field (engineerable in cold gases)

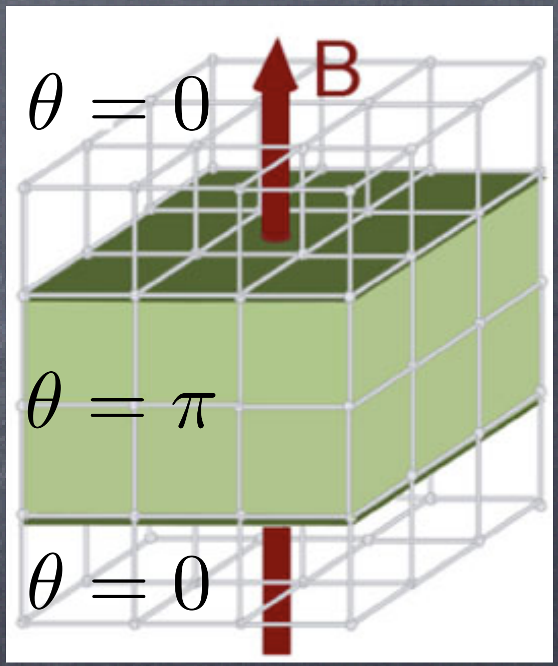
Magneto-Electric effect $\nabla \cdot \mathbf{E} = 4\pi\rho - (e^2/\pi c)\nabla\theta \cdot \mathbf{B}$

- Fractional charge:

$$Q = e/2\,[\delta(z - z_1) - \delta(z - z_2)]$$

detectable by in-situ imaging of cold gases !





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PRL **105** 190404 [1004.5101]

Outline

- quantum simulations & cold gases
- topo-insulators & free-Fermi theories
- exp. setup: superlattice + Raman
- proposal at work: towards 3D-TI
- future directions

Future directions

- beyond single-particle physics for TI's:
  - is the Q-simulator robust?
  - how does the periodic table change?
  - are there other invariants?
- topologically non-trivial flat-bands
  - geometry of the lattice to shape flat-bands
  - interactions/dissipations lead to FTI's as FQHE !?
  - dipolar terms (long-range) add something?
- topological superconductors & anyons
  - alkali-earth paired with condensates

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Outline

- quantum simulations & cold gases
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Mazza, **MR**, Lewenstein, Cirac, PRA **82** 043629 [1007.2344]

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