Magnetic monopoles and synthetic spin-orbit coupling in Rydberg macro-dimers

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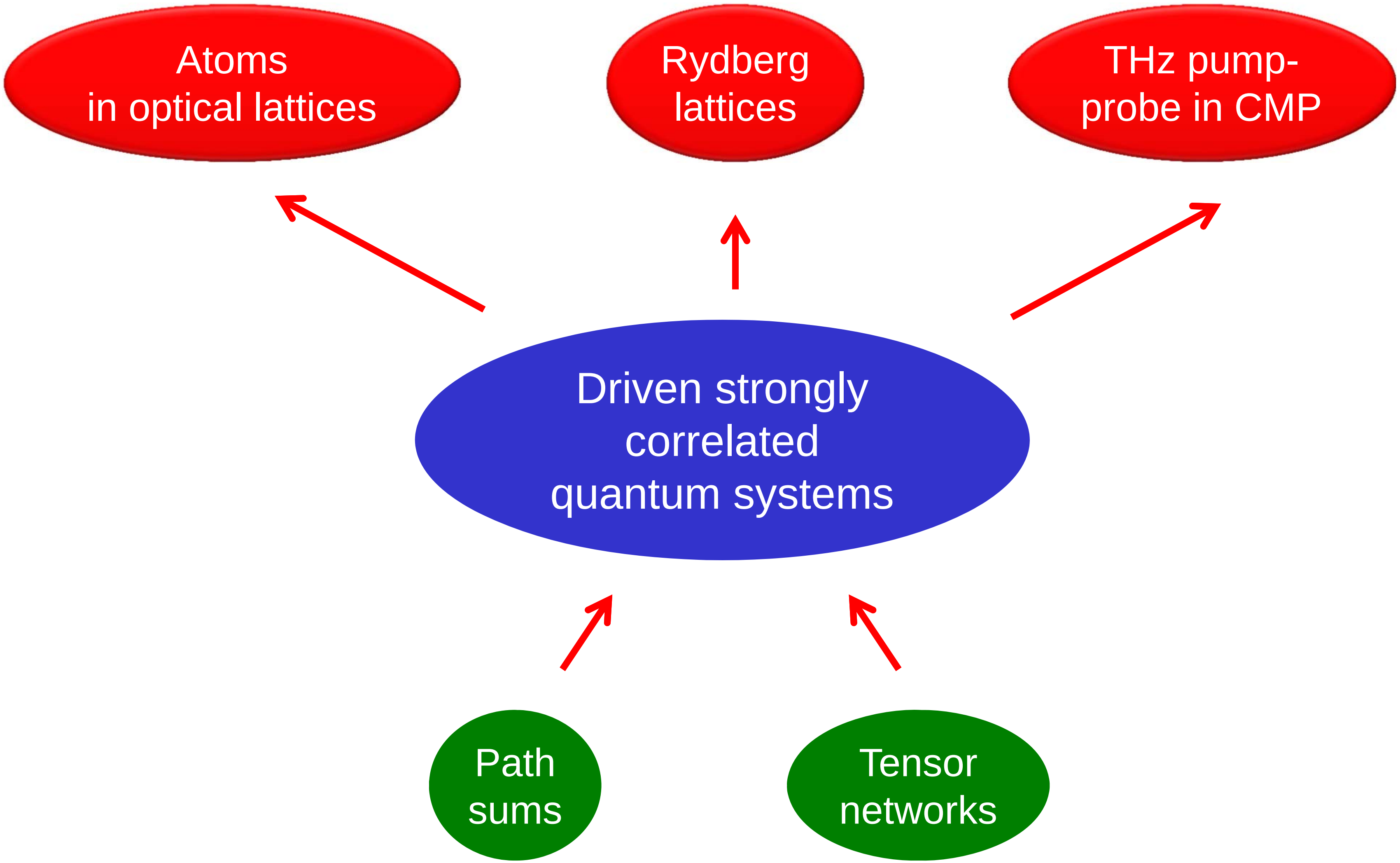
Current research

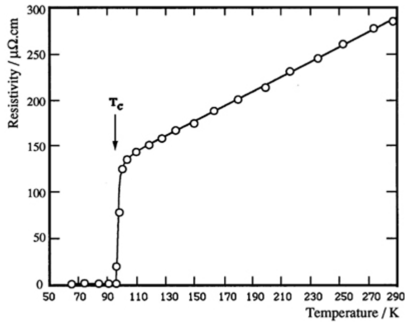


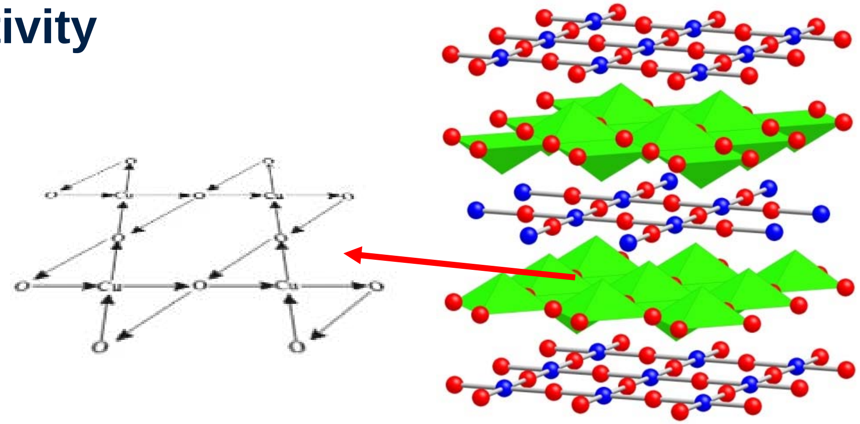
Better understand correlated systems

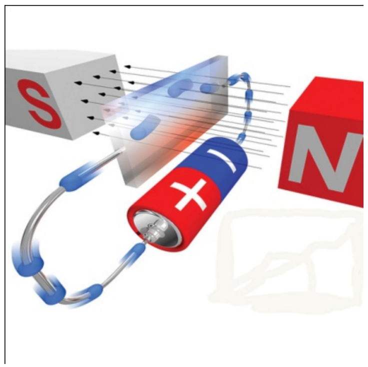
- Understanding quantum properties of electrons in materials:

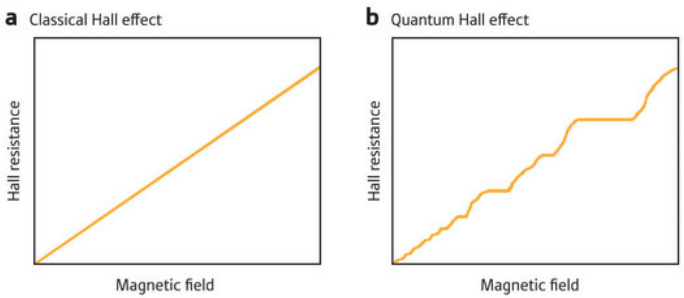
  - **High-temperature superconductivity**

What is the physical mechanism behind it?









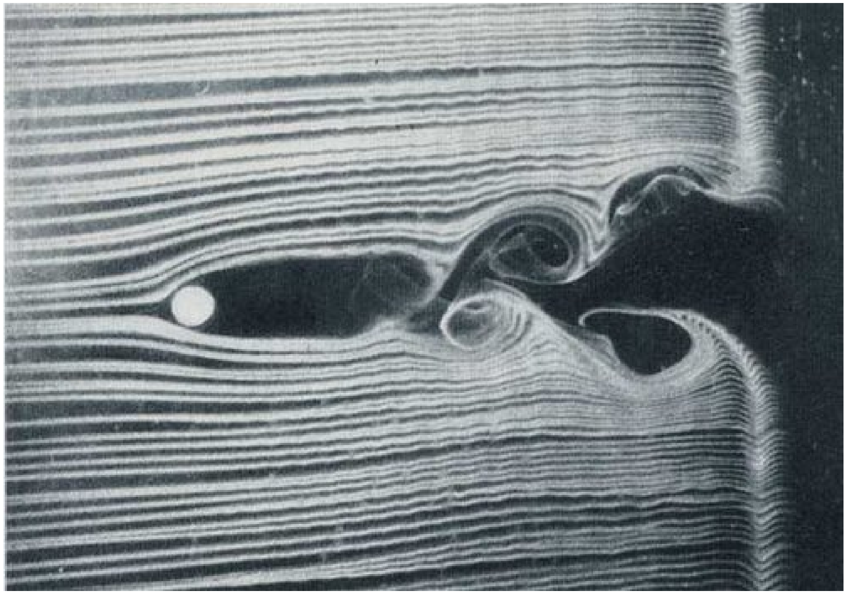
  - **Quantum Hall effect**

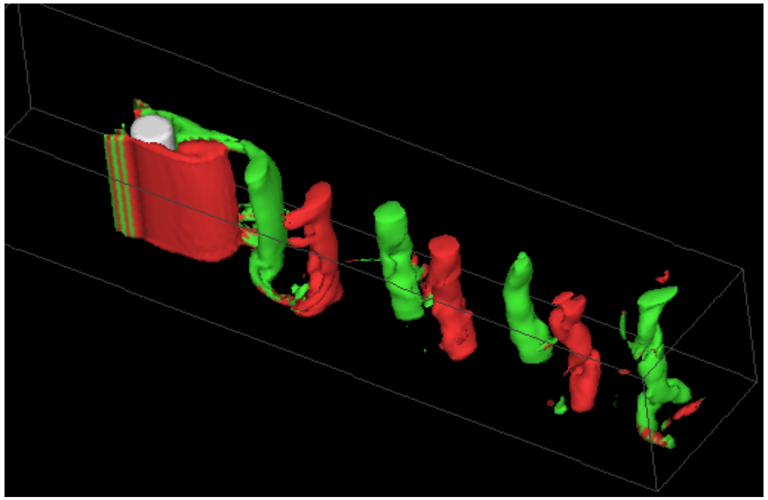
What are the topological properties of fractional QH states?

Quantum dynamical systems

	Atoms	Rydberg	CMP	CMP cooled
Time	s – ms	μs – ns	ps – fs	ps – fs
Energy	Hz - kHz	MHz	THz	THz
Temperature	nK	nK	300K	mK
Ratio	$1 - 10$	$10^4 \; - 10^6$	$1 - 10$	10^5
Coherence	s	μs	ps	ns
Driving	μ waves ms	Laser ps	THz fs	THz fs

Classical “simulation”: vortex shedding





The Gross-Pitaevskii equation

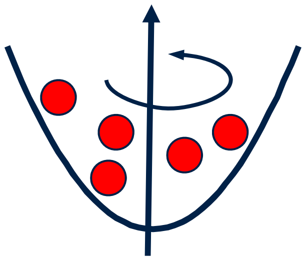
- Describe bosonic atoms in the ultracold quantum regime

$$i\hbar \frac{\mathrm{d}}{\mathrm{d}t} \Psi(x) = \left(\frac{p^2}{2m} + V(x) + g\,|\Psi(x)|^2 \right) \Psi(x)$$

- Extension to multiple atomic components: $\Psi(x) \rightarrow \vec{\Psi}(x)$
- Extension to external gauge fields $\vec{p} \rightarrow \vec{p} - \vec{A}$
- Extension to dipolar interactions $g\,|\Psi(x)|^2 \rightarrow \int dx' \Psi^*(x') V(x', x) \Psi(x')$
- Here we are interested in gauge fields that are generated by symmetry breaking of dipole-dipole interactions between multi-level atoms
- We limit our considerations here to the dynamics of two atoms

Artificial magnetic fields - traps

- Effective magnetic field via rotation

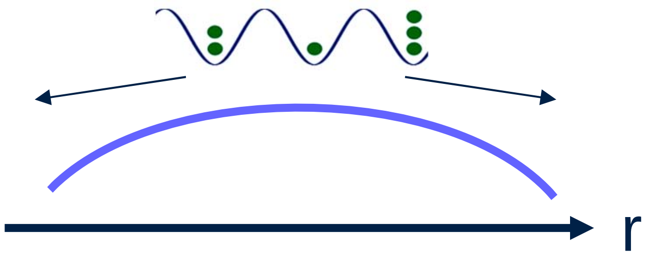


  - ⇨ Theory: N.K. Wilkin *et al.* PRL 1998
  - ⇨ Theory: B. Paredes *et al.* PRL 2001
  - ⇨ Experiment: E. Cornell, JILA
  - ⇨ Experiment: J. Dalibard, ENS
  - ⇨ Experiment: C. Foot, Oxford
  - ⇨ …

- Carefully balance centrifugal terms

- Alternative ways (theory)

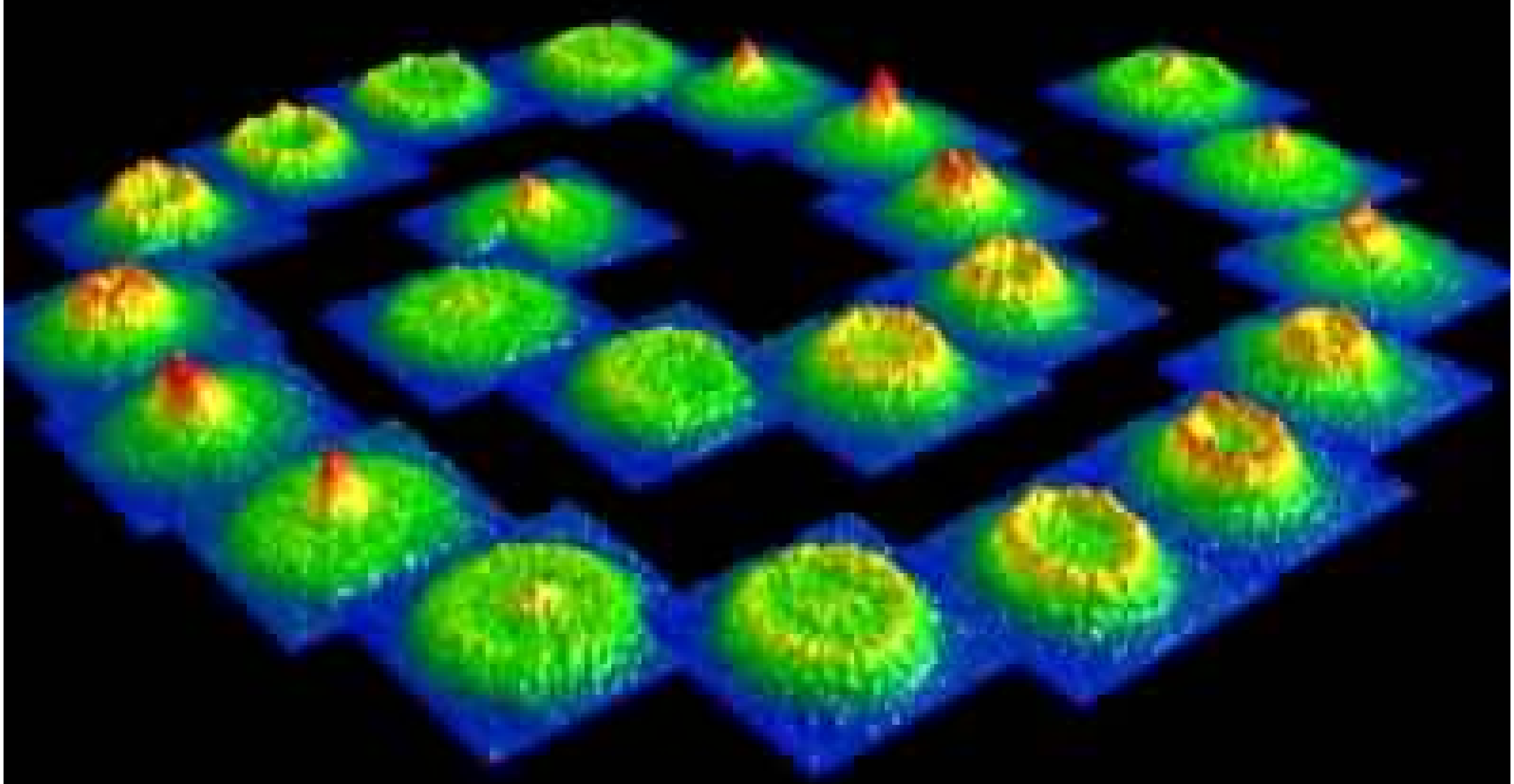
  - ⇨ A.S. Sorensen, E.J. Mueller, …
  - ⇨ G. Juzeliunas, M. *Fleischhauer, ….*
  - ⇨ M. Lewenstein, P. Zoller, ….



- Laser induced magnetic field experiments

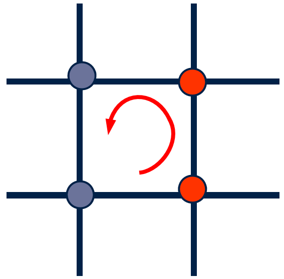
  - ⇨ I. Bloch, Munich
  - ⇨ I.B. Spielmann, Gaithersburgh
  - ⇨ K. Sengstock, Hamburg
  - ⇨ C. Foot, Oxford
  - ⇨ …

V. Bretin *et al.*, PRL. 2004



Artificial magnetic fields - lattices

- Effect of a magnetic field

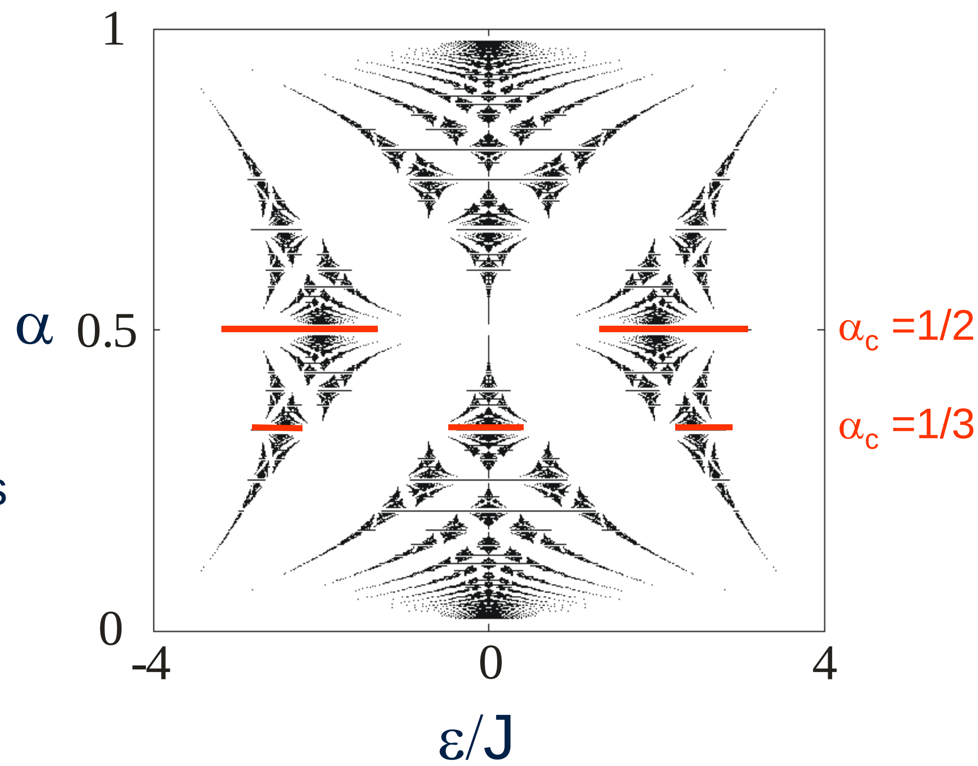


$$e^{\oint \mathbf{A}\cdot d\mathbf{l}} = e^{i2\pi\alpha}$$

➡ The wave function accumulates a phase characterized by α when hopping around an elementary cell

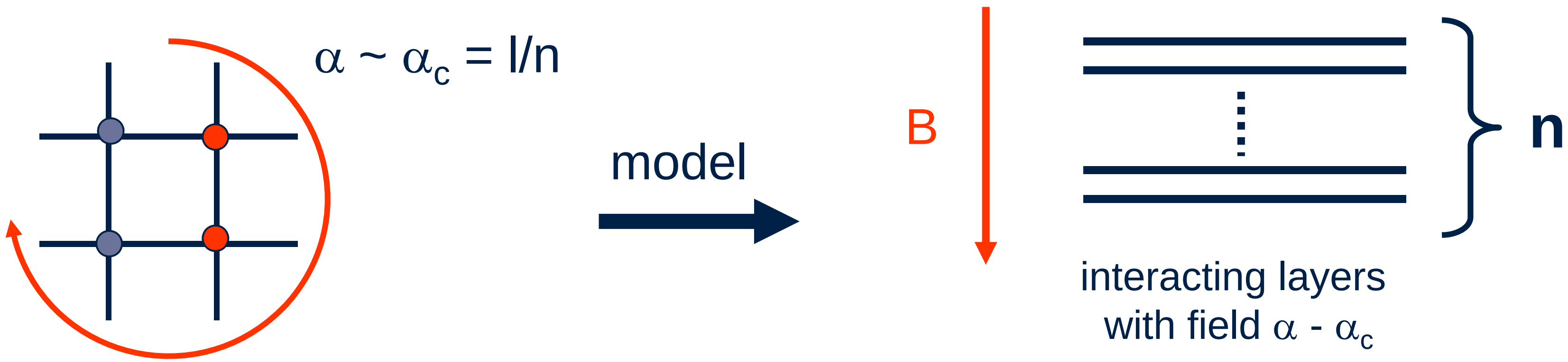
➡ Phase proportional to enclosed magnetic flux

- Resulting energy spectrum

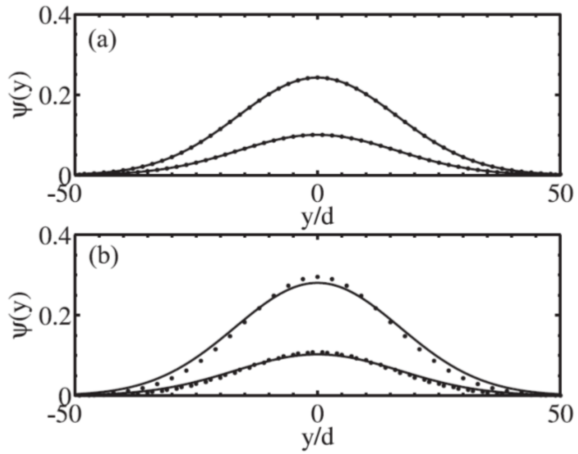


Huge artificial fields: n layers near α=l/n

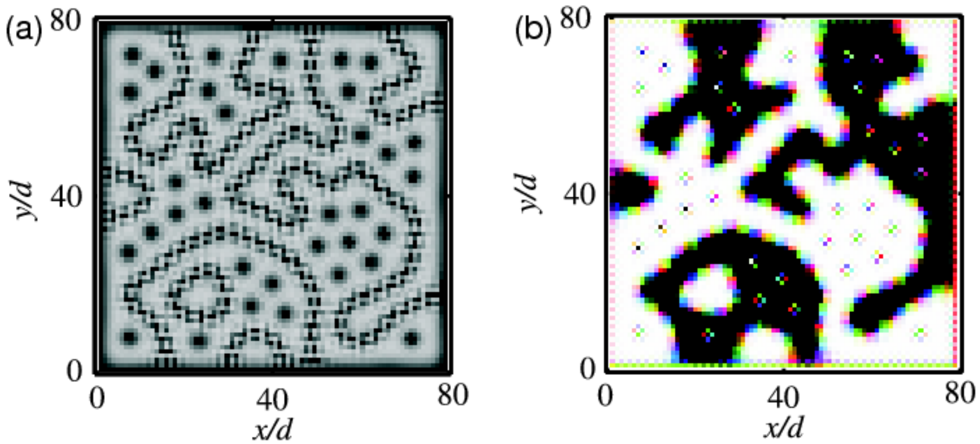
RN Palmer and DJ, PRL 2006



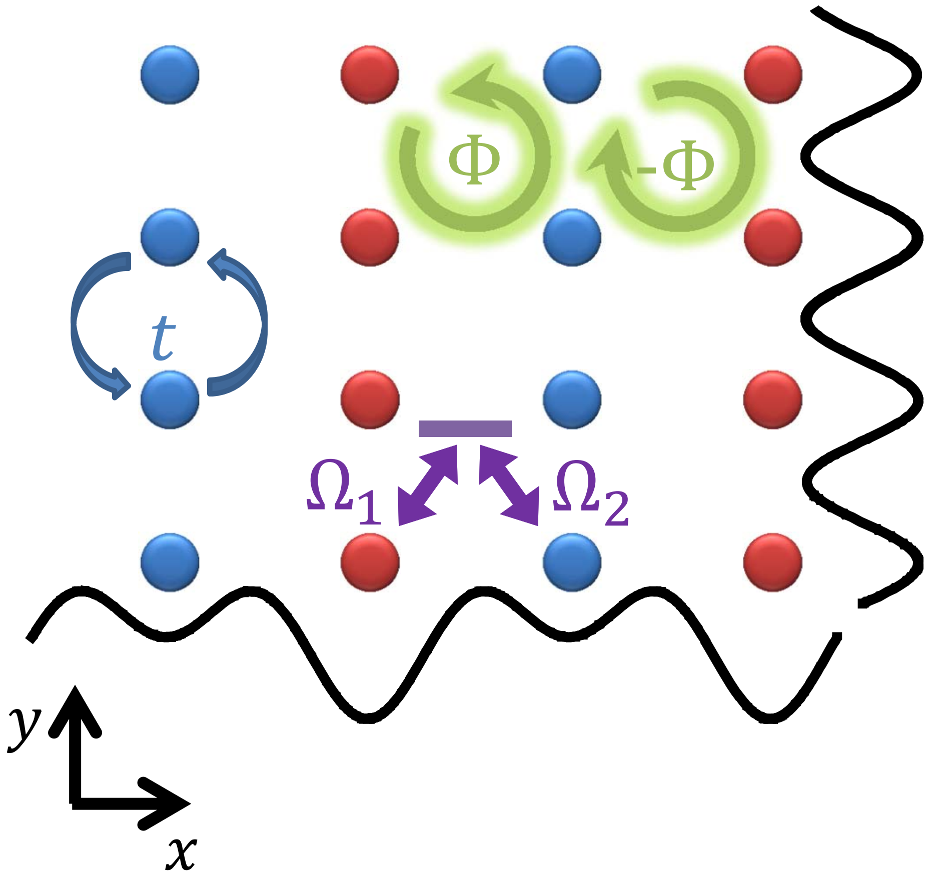
Wave function



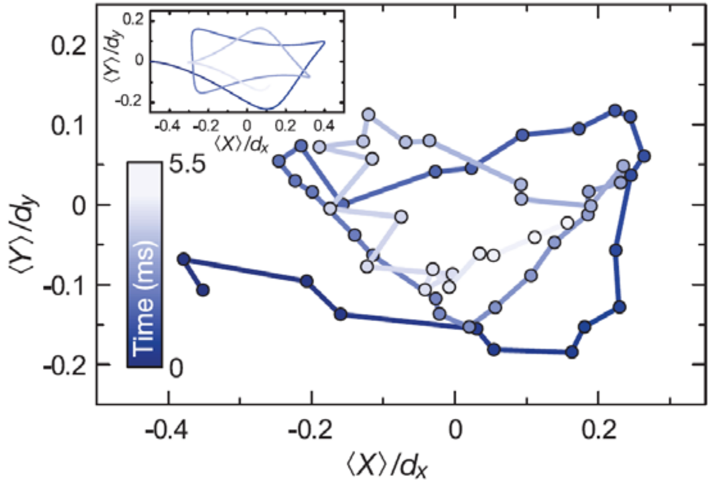
Vortex lattice



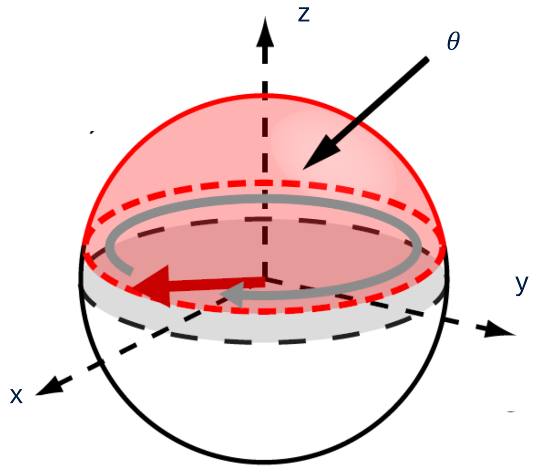
Laser imprinted hopping phases



Proposal: DJ *et al.*, New J. Phys. 2003



M Aidelsburger *et al.*, PRL. 2011

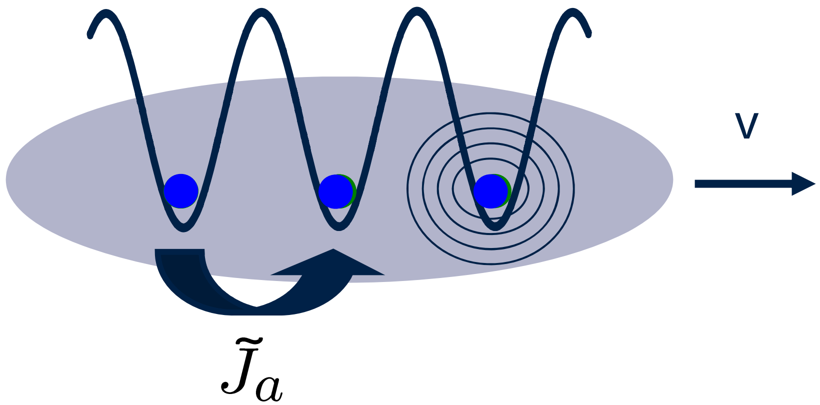


K. Jimenez-Garca *et al.*, PRL. 2012

Lattice moving in a BEC

A. Klein and DJ, EPL 2009

- Optical lattice in a moving BEC at very low temperature



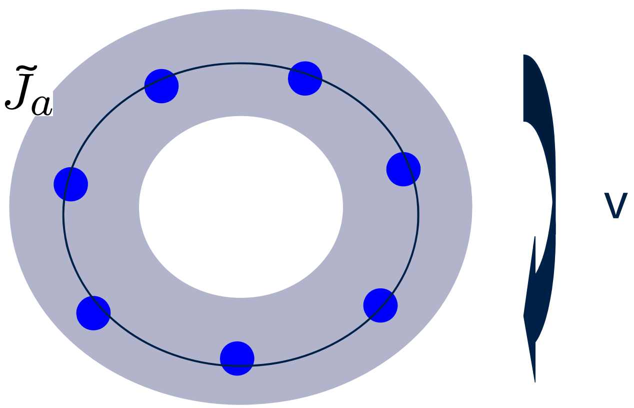
$$q \longrightarrow q - mv$$

$$\tilde{J}_a \longrightarrow \tilde{J}_a \, \mathrm{e}^{\mathrm{i}2\pi\alpha}$$

$$\alpha \propto v$$

⇨ In lowest order for $v \ll c$ this leads to a phase α proportional to v

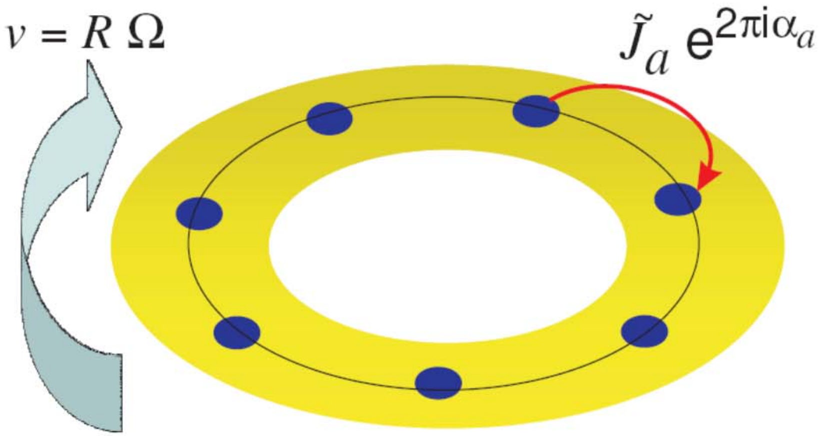
- Rotating optical lattice immersions

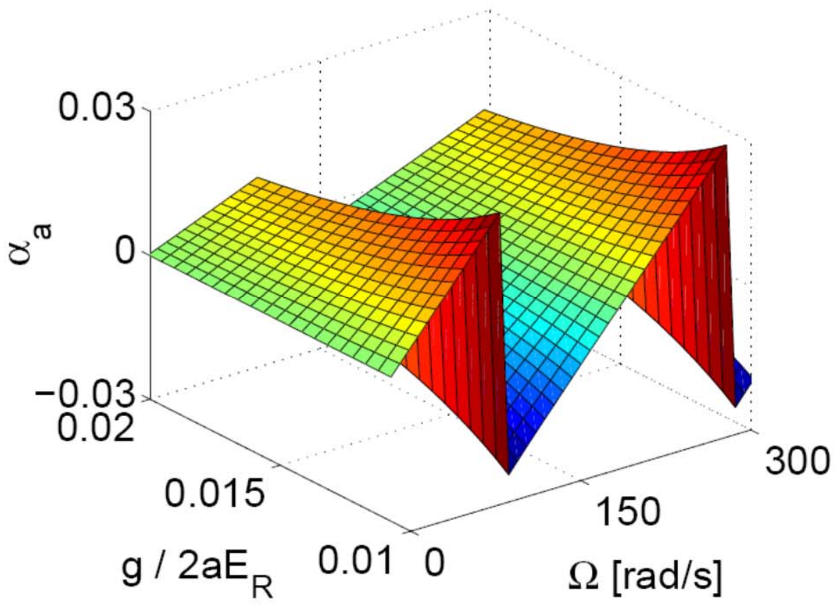


Rotating BEC
Rotating lattice

→ No need to balance centrifugal terms

Lattice on a ring





- In lowest order for $v \ll c$ a phase α proportional to v is induced

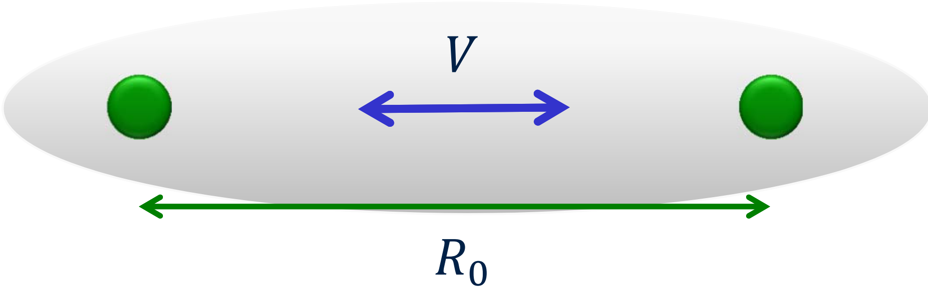
$$\alpha_a = \frac{1}{2\pi}\frac{\kappa^2 n_0}{L}\sum_{q\neq q_0}\frac{\varepsilon_q^0}{E_q^B}\frac{1}{(\hbar\omega_q)^2}\,\mathrm{e}^{-q^2\sigma^2/2}\sin(qa)$$

Parameters: BEC: ^{87}Rb with linear density of 5£10^{6}m^{-1}, circumference L=12μm

Lattice: 30 lattice sites with ^{23}Na atoms and coupling $\kappa/2aE_R$=0.035

How can we use atom-atom interactions to study gauge fields?

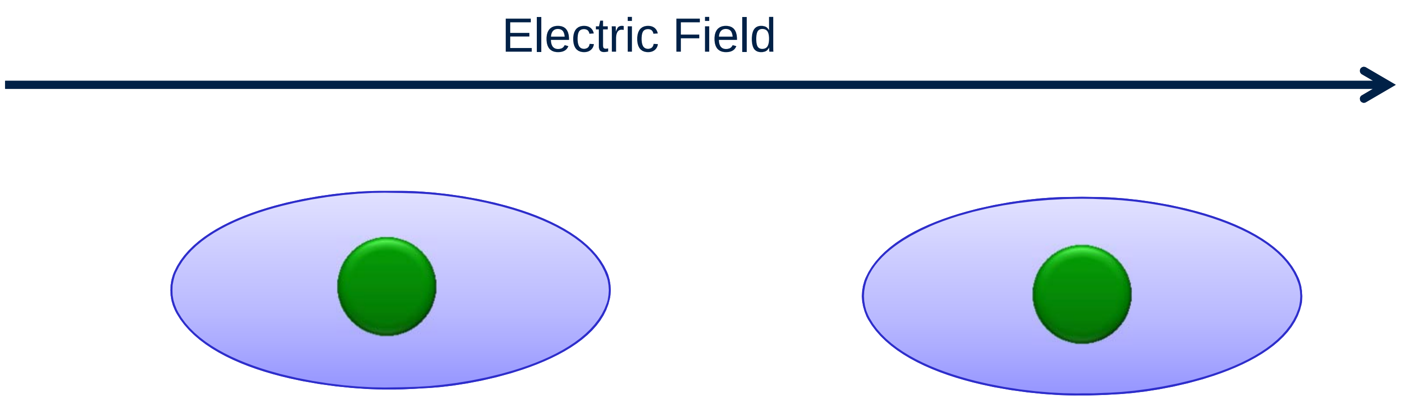
Interaction induced gauge fields - history



- Inconsistency in the Born-Oppenheimer approximation
  - ➡ G. Herzberg and H.C. Longuet-Higgins, Discuss. Faraday Soc. **35**, 77 (1963)
- Berry phases
- Magnetic Monopoles
- Abelian Gauge Fields
- Non-abelian Gauge Fields
  - ➡ J. Moody, A. Shapere and F. Wilczek, PRL **56**, 893 (1986)

Dipole-dipole interactions

- Excite atoms to high lying states with large electron orbit



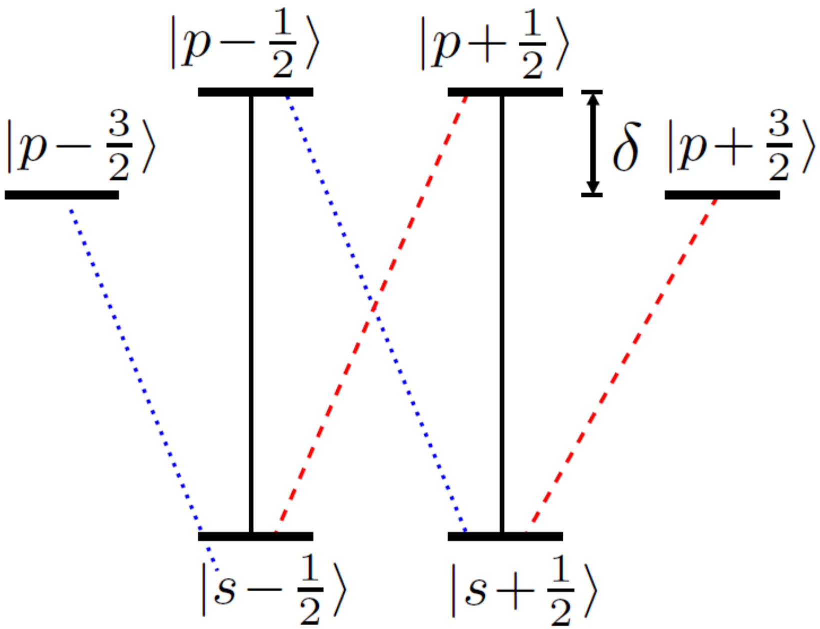
- Apply electric field to induce large dipoles
- Dipole-dipole interaction potential (atomic units)

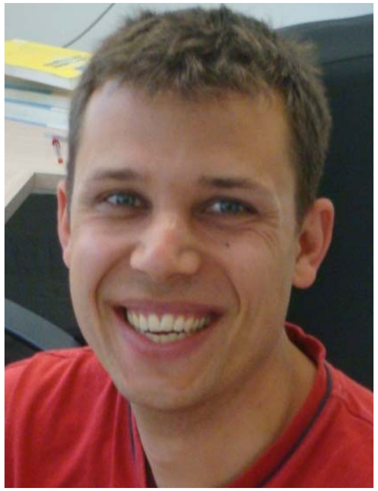
$$\hat{V}_{\mathrm{dd}} = \frac{1}{R^3}[\hat{\boldsymbol{d}}^{(1)} \cdot \hat{\boldsymbol{d}}^{(2)} - 3(\hat{\boldsymbol{d}}^{(1)} \cdot \vec{\boldsymbol{R}})(\hat{\boldsymbol{d}}^{(2)} \cdot \vec{\boldsymbol{R}})]$$

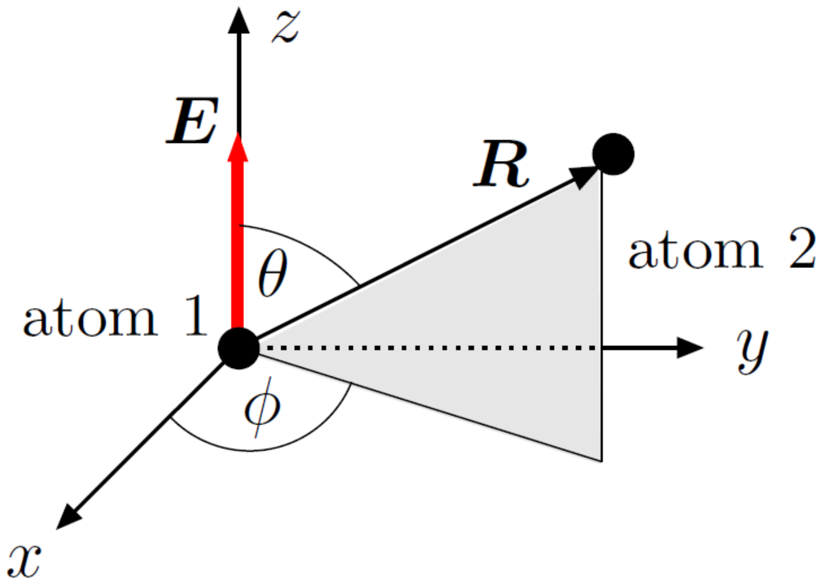
- Large molecules bound by this interaction can be formed for large n

Rydberg macro-dimers

M. Kiffner et al., PRA 2012



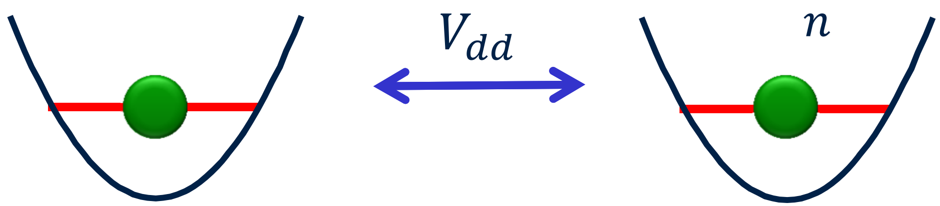




Investigate the interactions between one atom in the s-manifold and the other in the p-manifold.

Dipolar bound molecules

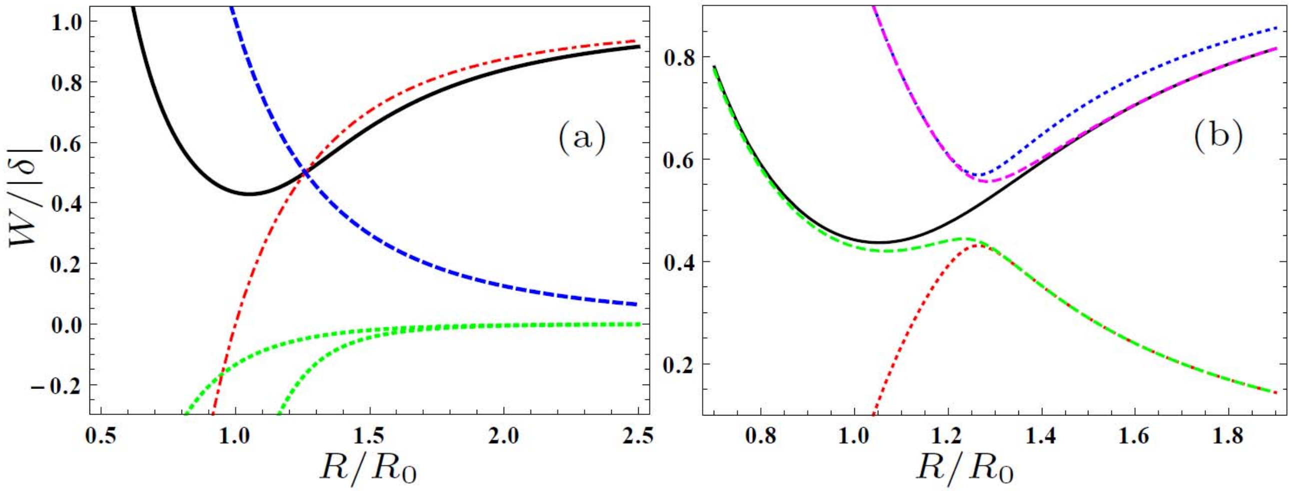
M. Kiffner et al., PRA 2012



- Dipole-dipole interaction potential

$$\hat{V}_{\rm dd} = \frac{1}{R^3}[\hat{\boldsymbol{d}}^{(1)} \cdot \hat{\boldsymbol{d}}^{(2)} - 3(\hat{\boldsymbol{d}}^{(1)} \cdot \vec{\boldsymbol{R}})(\hat{\boldsymbol{d}}^{(2)} \cdot \vec{\boldsymbol{R}})]$$

- Large molecules bound by this interaction can be formed for large n

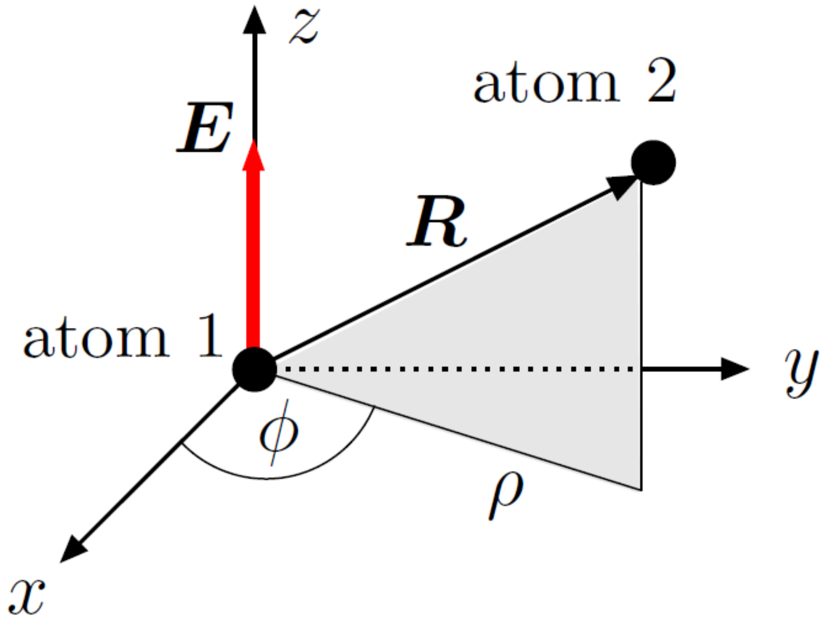


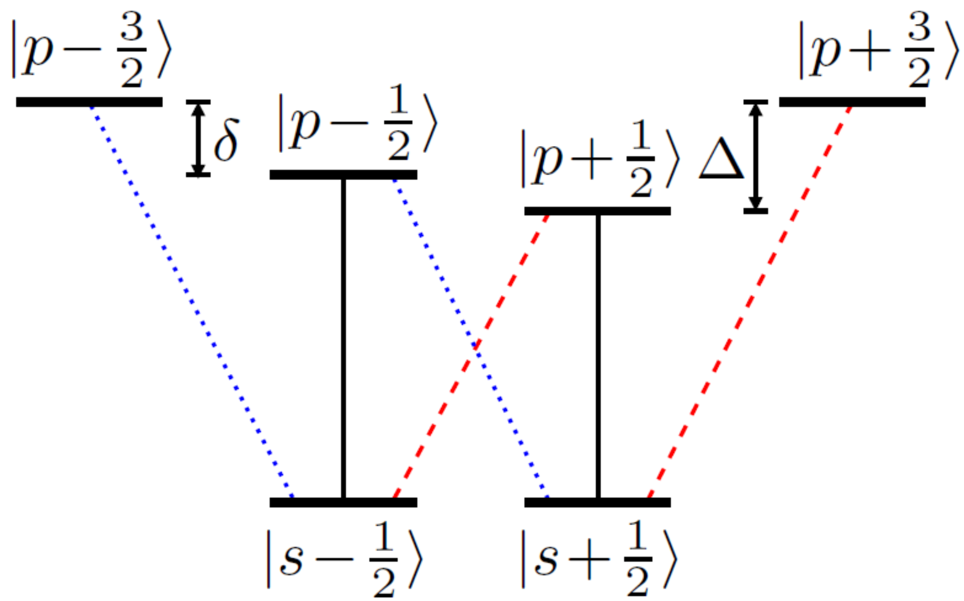
$$R_0 = \left(\frac{n^4}{3|\delta|}\right)^{\frac{1}{3}}$$

(atomic units)

Gauge fields in giant Rydberg molecules

M. Kiffner, W. Li, and DJ, submitted 2013





- We consider $s-p$ manifold of highly excited Rydberg state n
- Break symmetry by inducing Stark shifts δ and Δ

$$|\Psi\rangle = \sum_{i=1}^{N} \int \mathrm{d}^3 R\, \alpha_i(\boldsymbol{R})|\psi_i(\boldsymbol{R})\rangle \otimes |\boldsymbol{R}\rangle \qquad i\hbar\partial_t \boldsymbol{\alpha} = \left[\frac{1}{2\mu}(\boldsymbol{p}\mathbb{1} - \boldsymbol{A})^2 + V\right]\boldsymbol{\alpha}$$

Consider the low energy physics

- We project onto the q lowest lying internal states

$$i\hbar\partial_t\tilde{\boldsymbol{\alpha}} = \left[\frac{1}{2\mu}(\boldsymbol{p}\mathbb{1} - \tilde{\boldsymbol{A}})^2 + \tilde{V} + \Phi\right]\tilde{\boldsymbol{\alpha}}$$

$$\Phi_{kl} = \frac{1}{2\mu}\sum_{p=q+1}^{N} \boldsymbol{A}_{kp}\cdot\boldsymbol{A}_{pl}$$

$$V_{kl} = \delta_{kl}\epsilon_k(\boldsymbol{R})$$

$$\boldsymbol{A}_{kl} = i\hbar\langle\psi_k(\boldsymbol{R})|\nabla|\psi_l(\boldsymbol{R})\rangle$$

- Transformation rules

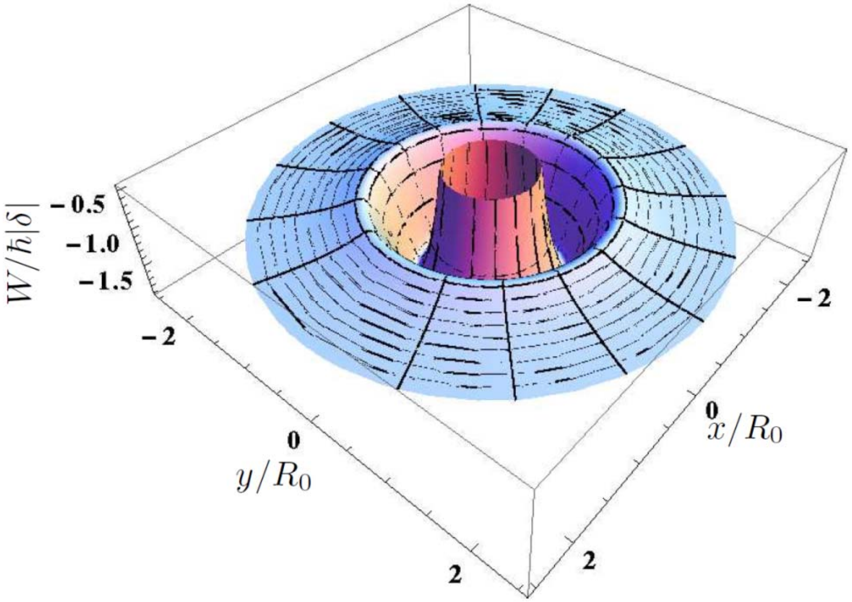
$$\tilde{\boldsymbol{\alpha}} \to U(\boldsymbol{R})\tilde{\boldsymbol{\alpha}}$$

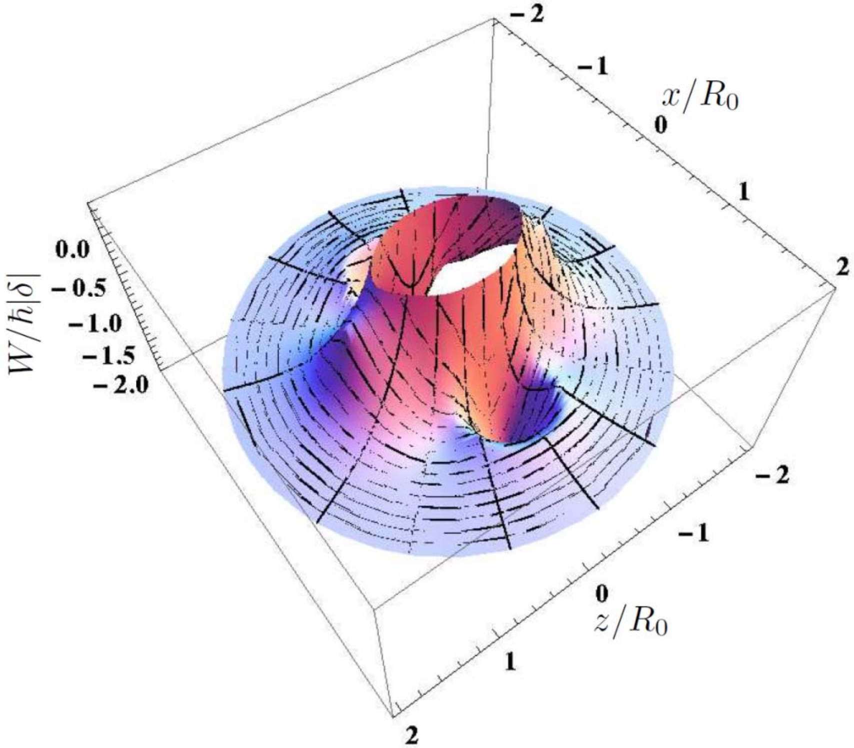
$$\tilde{\boldsymbol{A}} \to U(\boldsymbol{R})\tilde{\boldsymbol{A}}U^\dagger(\boldsymbol{R}) - i\hbar[\nabla U(\boldsymbol{R})]U^\dagger(\boldsymbol{R})$$

$$\Phi \to U(\boldsymbol{R})\Phi U^\dagger(\boldsymbol{R}).$$

- Therefore $\tilde{A}$ and Φ are gauge fields

Potential for q=1





- The potential is shown for $\Delta = -3\,|\delta|$
- The depth of the potential increases with decreasing ratio $\frac{\Delta}{\delta}$
- The potential is azimuthally symmetric
- The radial trapping frequency is given by $\omega_{\mathrm{vib}} = 2\sqrt{\frac{|\delta|}{R_0^2 \mu}}$

Artificial magnetic field

- Lorentz Force

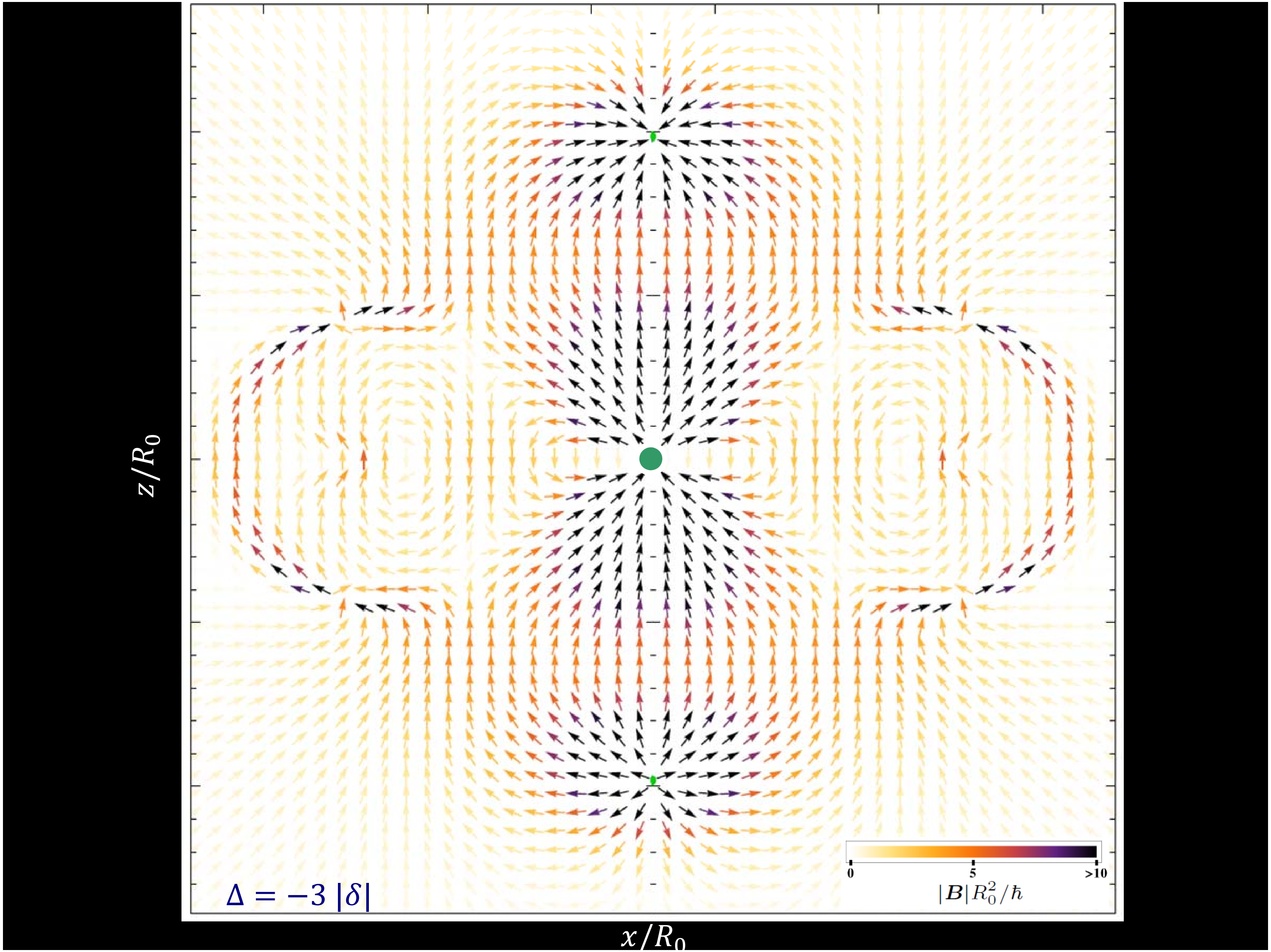
$$\mu\partial_t^2\boldsymbol{R} = -\nabla V + \frac{1}{2\mu}\left\{[(\boldsymbol{p}-\boldsymbol{A})\times\boldsymbol{B}] - [\boldsymbol{B}\times(\boldsymbol{p}-\boldsymbol{A})]\right\}$$

- We cannot determine charge and field individually from this setup

- Magnetic field derives from vector potential

$$B^{(i)} = \frac{1}{2}\varepsilon_{ikl}F^{(kl)},$$

$$F^{(kl)} = \partial_k A^{(l)} - \partial_l A^{(k)} - \frac{\imath}{\hbar}\left[A^{(k)}, A^{(l)}\right]$$


z/R_0
x/R_0
$\Delta = -3\ |\delta|$
0
5
>10
$|\boldsymbol{B}| R_0^2/\hbar$

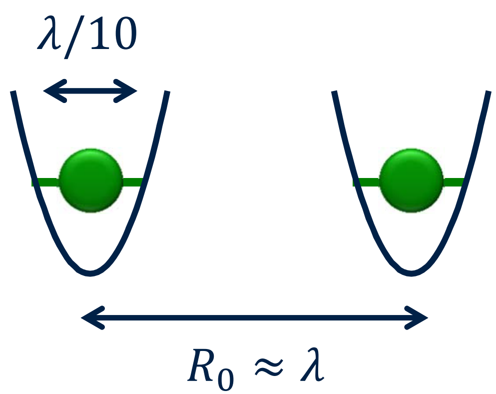
Artificial magnetic field

- The monopoles have an adjustable separation of the order of microns

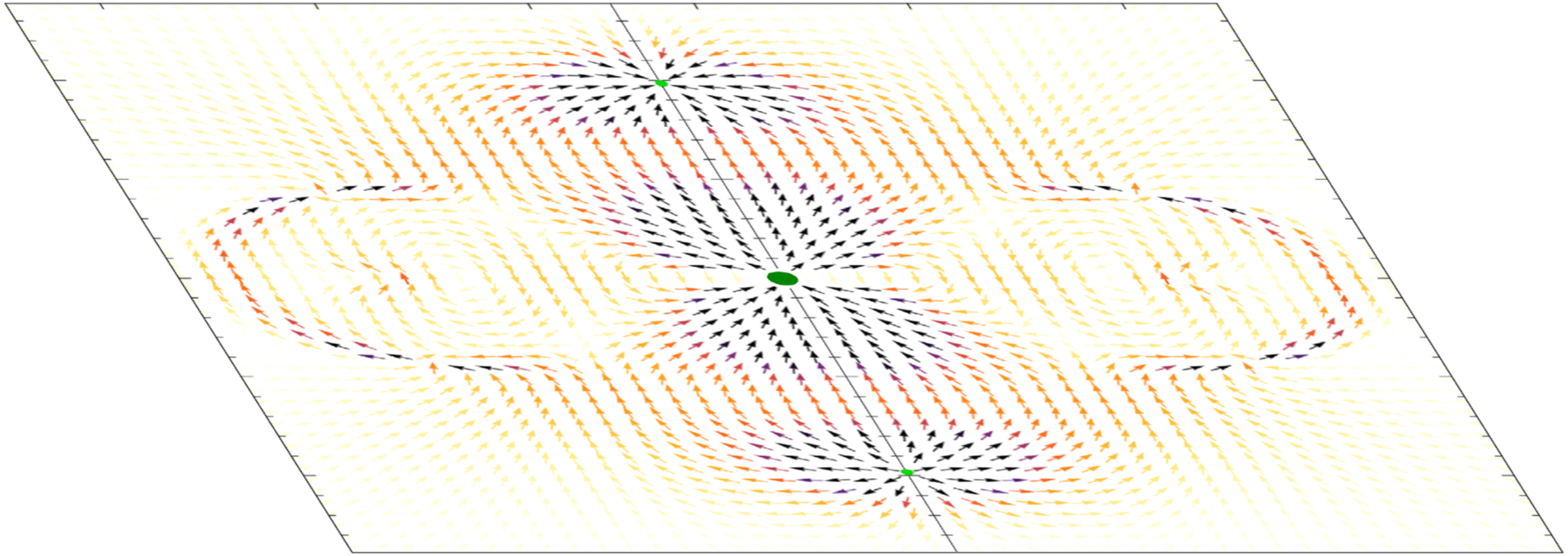
- They have Chern numbers of

$$C_{\pm} = \frac{1}{2\pi} \int \boldsymbol{B} \cdot \mathrm{d}\boldsymbol{S} = \pm 1$$

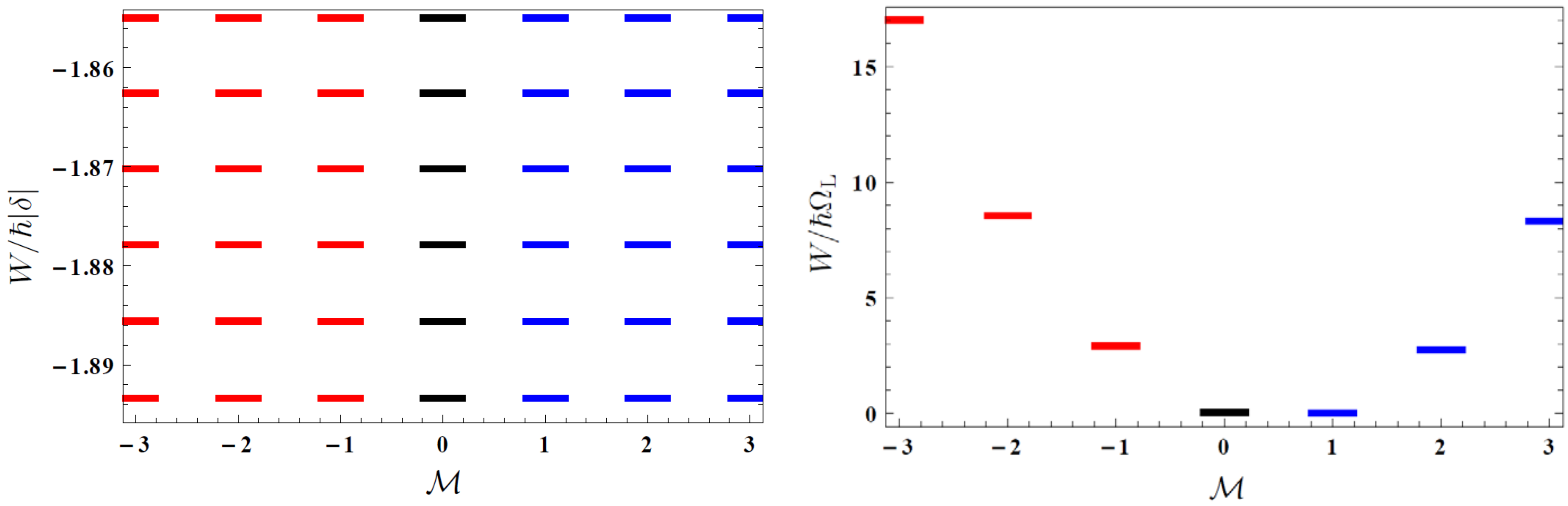
- The magnetic field diverges near the monopoles leading to strong deflection in a scattering experiment, e.g. starting from an optical lattice



Deflection near monopole



Larmor frequency

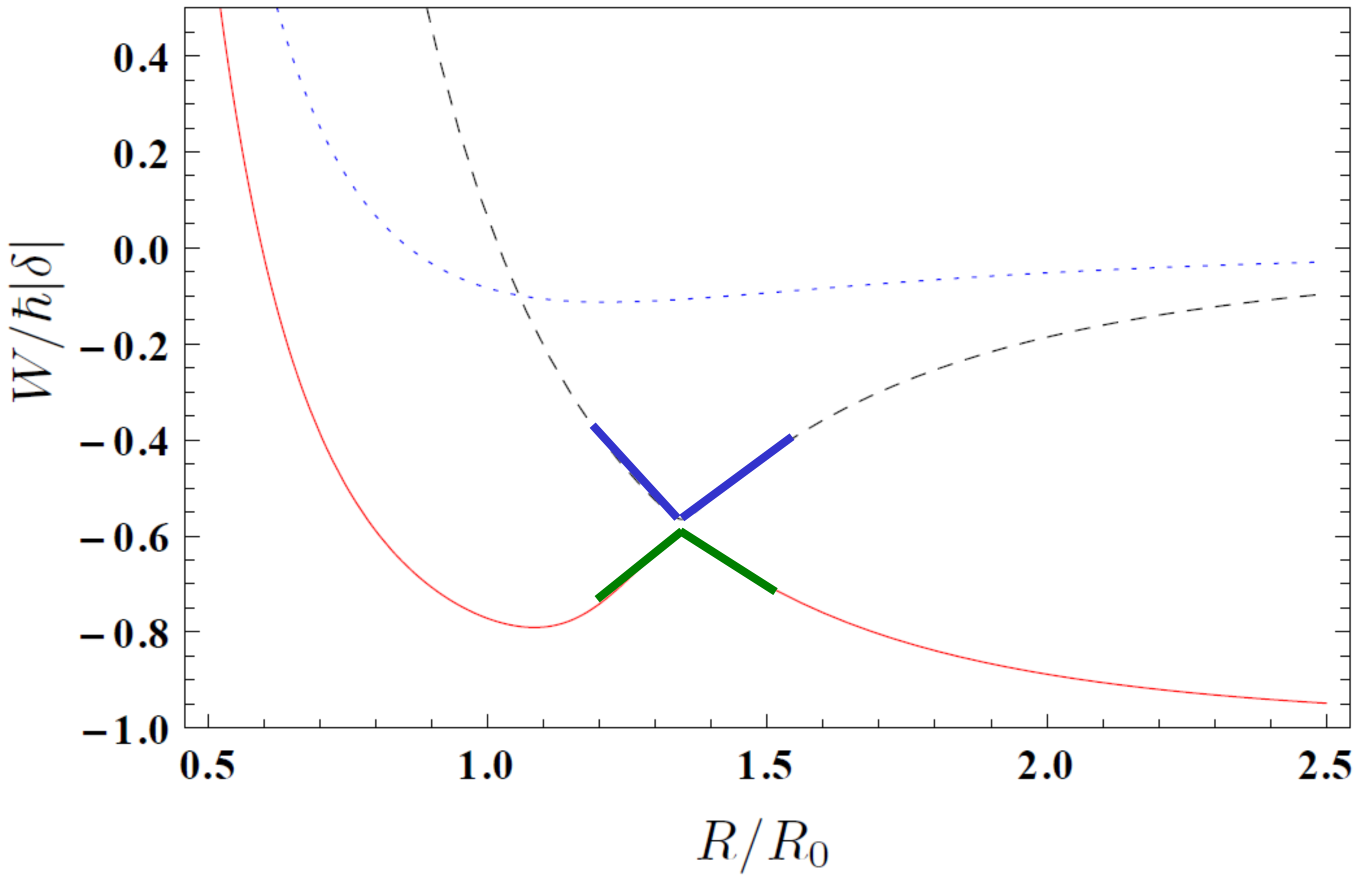


- Larmor precession

$$\omega_{\rm L} = \frac{\hbar}{2\mu R_0^2}\tilde{B} = \Omega_{\rm L}\tilde{B}$$

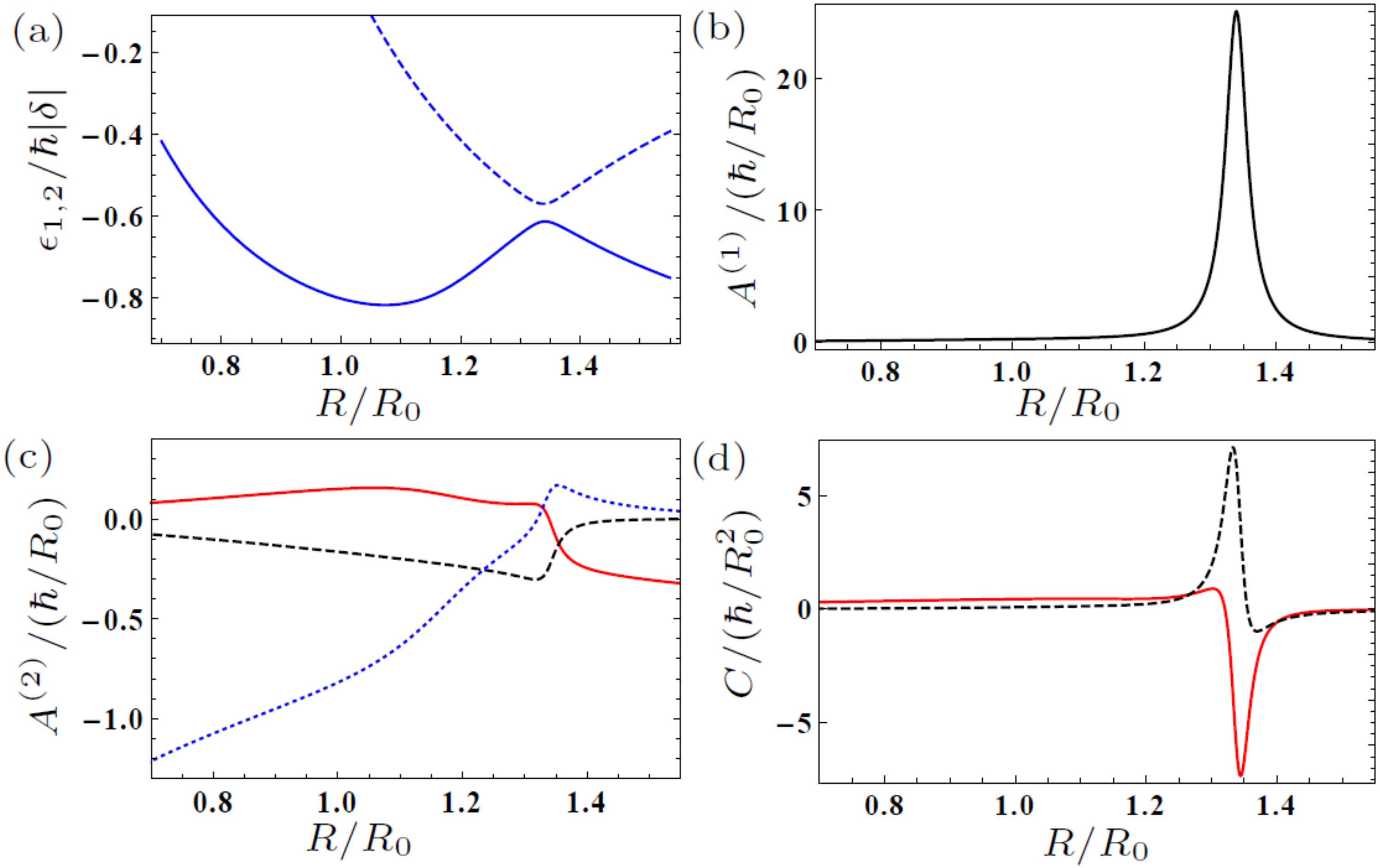
- This is only of order Hz for heavy atoms (e.g. Rb) but can be in the kHz region for light atoms (e.g. Li, but experimentally not easy) and smaller R_0

Non-Abelian gauge field for q=2



- Detuning $\Delta = -1.15|\delta|$
- We consider physics near avoided crossing where $\boldsymbol{A}_{12} \cdot \boldsymbol{p}$ is the dominant coupling

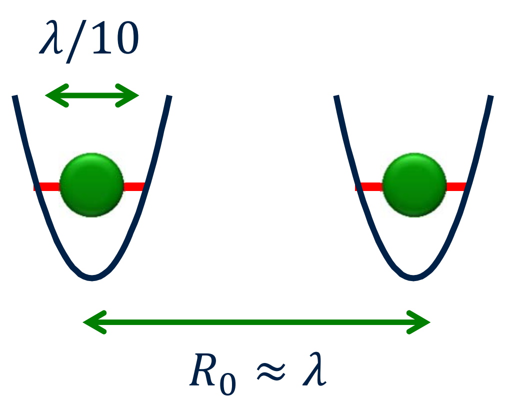
Non-Abelian character

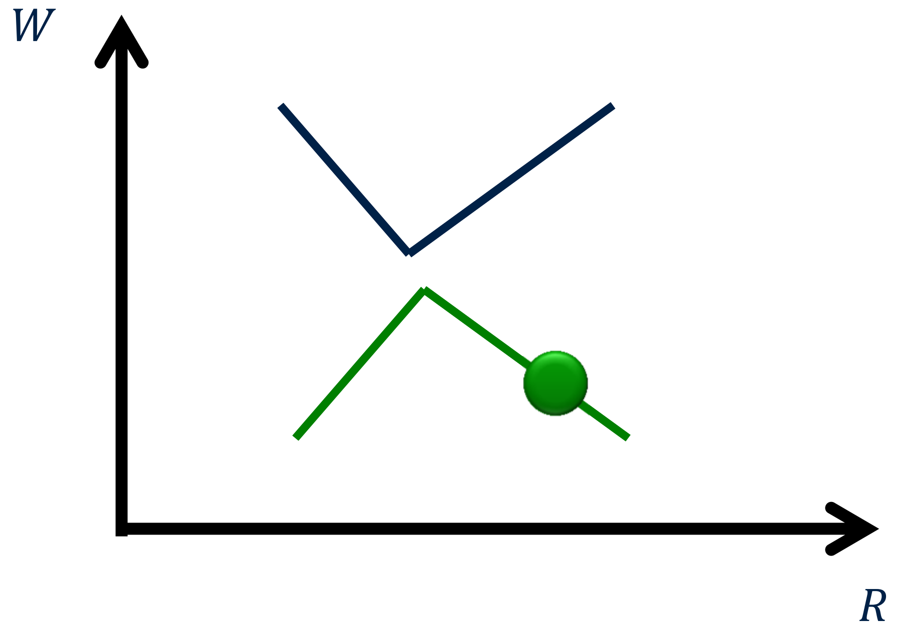


- Commutator of vector potential $\tilde{A}$ components (which are 2x2 matrices here)

$$C = \frac{i}{\hbar}\left[A^{(1)}, A^{(2)}\right]$$

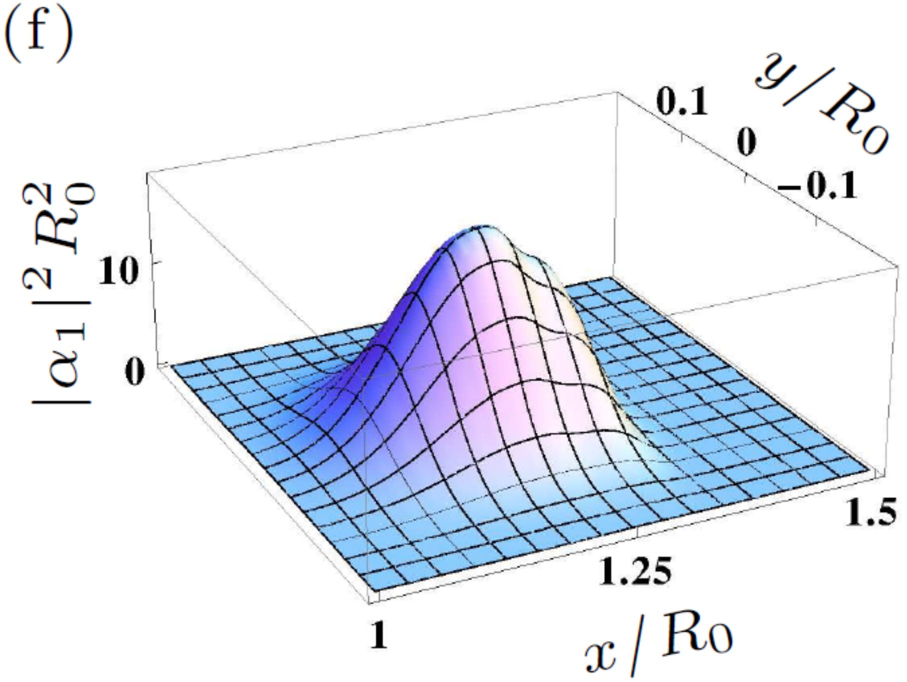
Start from optical lattice atoms





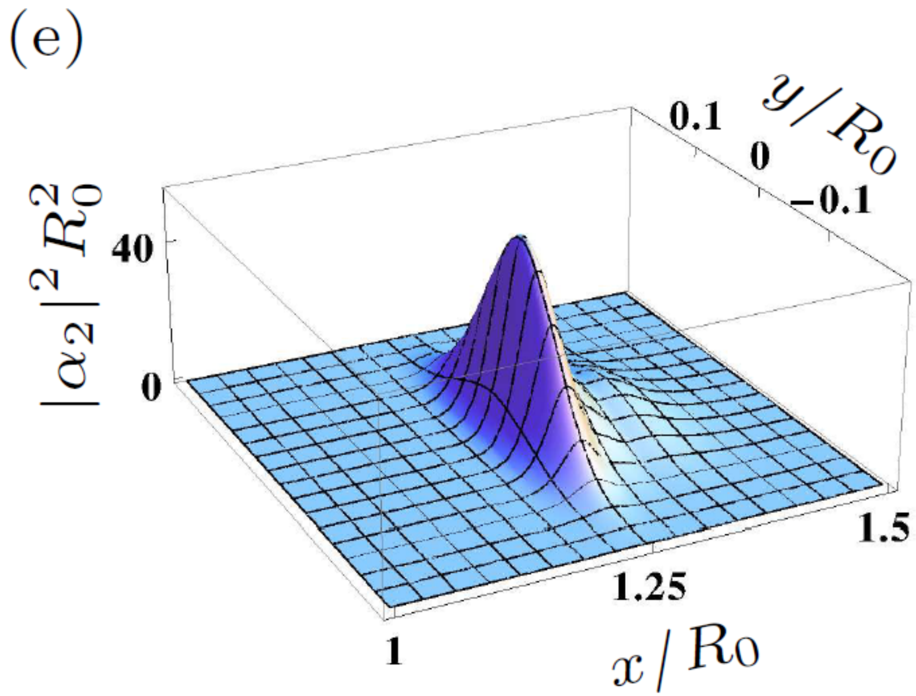
- Dynamically change the detuning on time scales of $\approx 1/\delta$
- This dynamically changes R_0 and hence mimics dynamics in the potential
- Create the atoms in different internal states starting from the optical lattice to study non-Abelian character

Internal state occupations after beam splitter



Occupation in different internal states will depend on velocity for adiabatic dynamics

Particle experiences different potentials depending on internal state. Wave packet will thus separate in space



Summary and Conclusion

- The cold atom toolbox
  - ➡ Versatile and controllable new tool interaction induced gauge potentials
  - ➡ Use optical fields to probe the dynamics push atoms optically
  - ➡ Extensions to multiple atoms and lattice models
  - ➡ Controlled entangling operations between Rydberg atoms
- Special Thanks to our experimental collaborators: T. Gallagher, W. Li

Sarah Al-Assam
"TNS Library"

Stephen Clark
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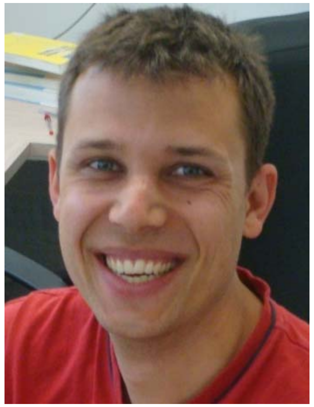

Martin Kiffner
"Rydberg"

Tomi Johnson
"Transport"

Thank you!