Rashba SOC (Exp) and quantum feedback (Thy)

I. B. Spielman

Crazy linear dispersion

G. H. Reid, A. Fritsch, D. Genkina, A. Pinera and M. Lu

Rashba SOC and Synthetic dimensions

A. Valdés-Curiel, M. Zhao, J. Tao, Q. Liang

Yang monopole/1D Bose gas:

F. Salces-Carcoba, Y. Yue, E. Altuntas, and C. Billington

Theory of many-body measurement and feedback

H. M. Hurst, S. Guo J. Young with **A. Gorshkov and J. Taylor**

Support

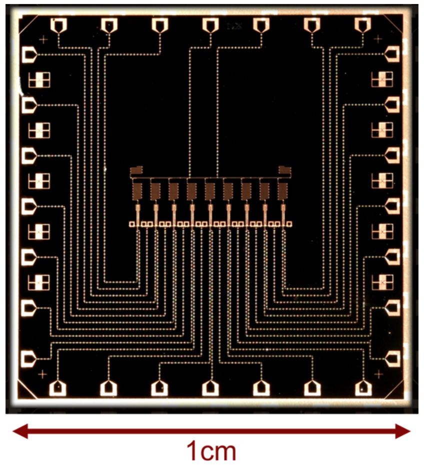
NSF PFC@JQI, AFOSR Quantum Phases MURI, and NIST

Pirate Green beard's tour through uncharted physics

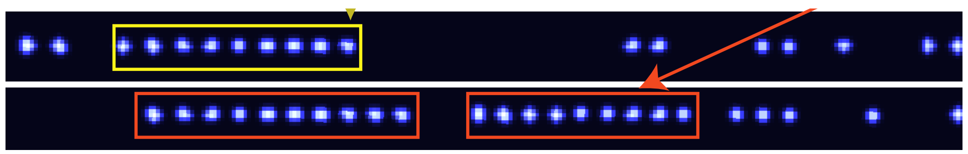
How to engineer complex quantum systems?

Bottom-up engineering

Build the system up from well controlled quantum building blocks, e.g., qbits.



Martinis group / google; Science (2017)



Monroe group; Nature (2017)

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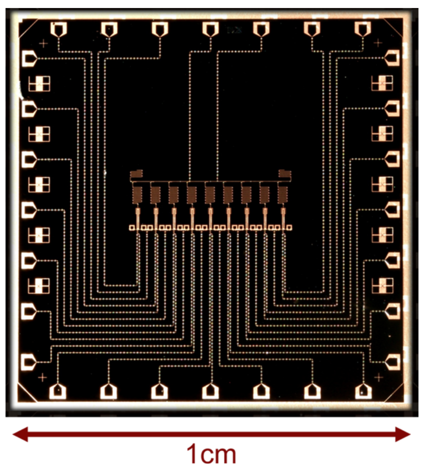
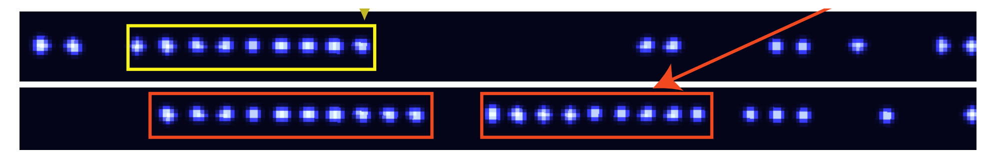


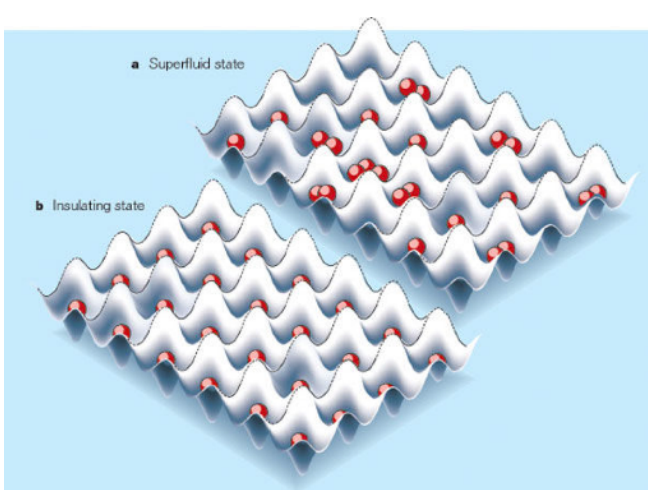
Martinis group / google; Science (2017)



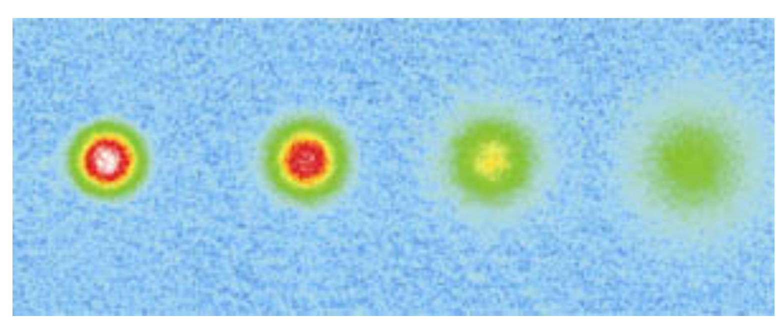
Monroe group; Nature (2017)

Hamiltonian engineering

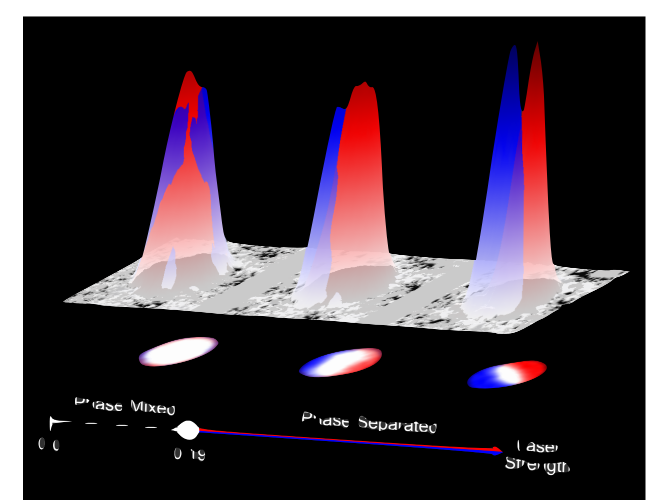
Build the Hamiltonian up with well calibrated control techniques



Bloch group; Nature (2002)



Jin group; Nature (2003)



Lin et al; Nature (2011)

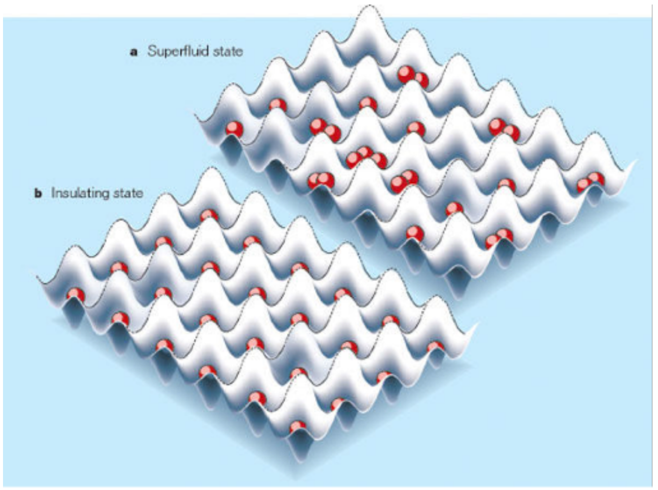
Hamiltonian engineering

Hamiltonian engineering

Optical lattices

e.g., adding potentials

$$H = \frac{\hbar^2 \mathbf{k}^2}{2m} + \frac{V}{2}\cos(2k_r x) + \ldots .$$



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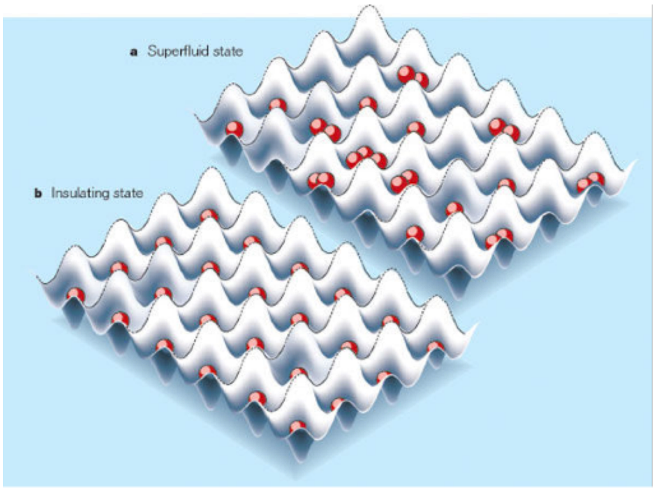
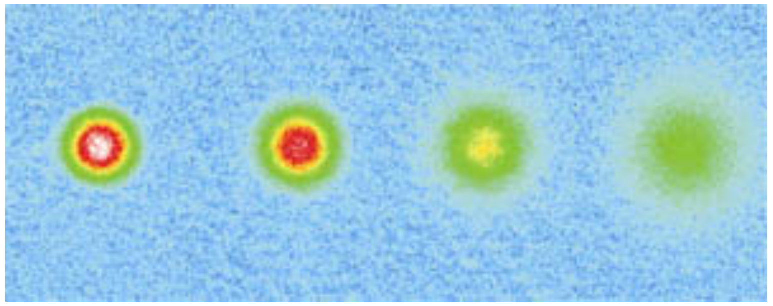


Interaction tuning

e.g., Feshbach resonances

$$H = \ldots. + g_{3\mathrm{D}}\delta(\mathbf{r}_i - \mathbf{r}_j) + \ldots$$



(really a regularized delta function….)

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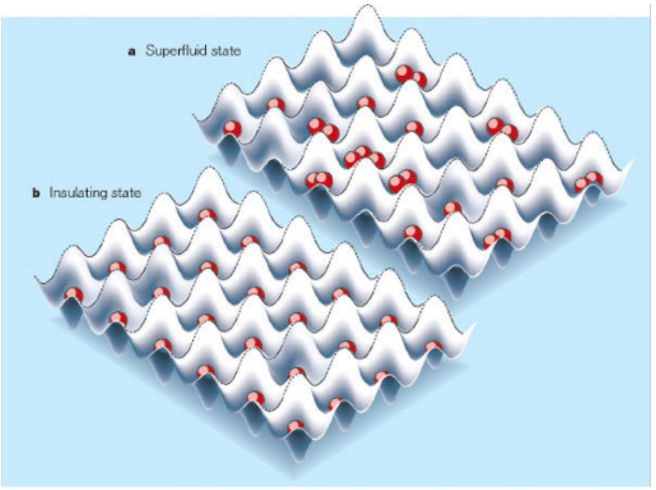

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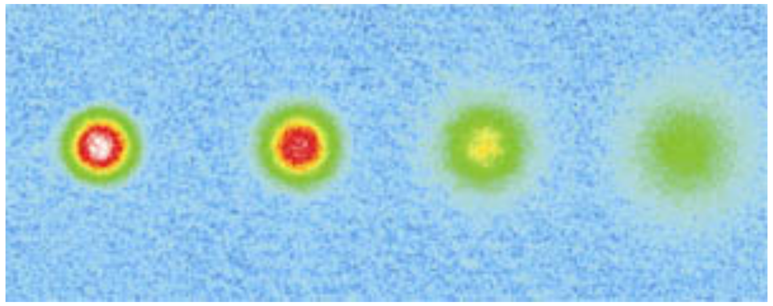
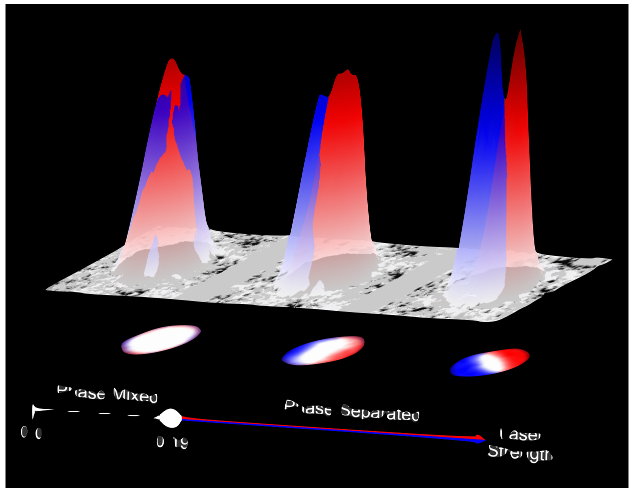


Gauge fields / SOC

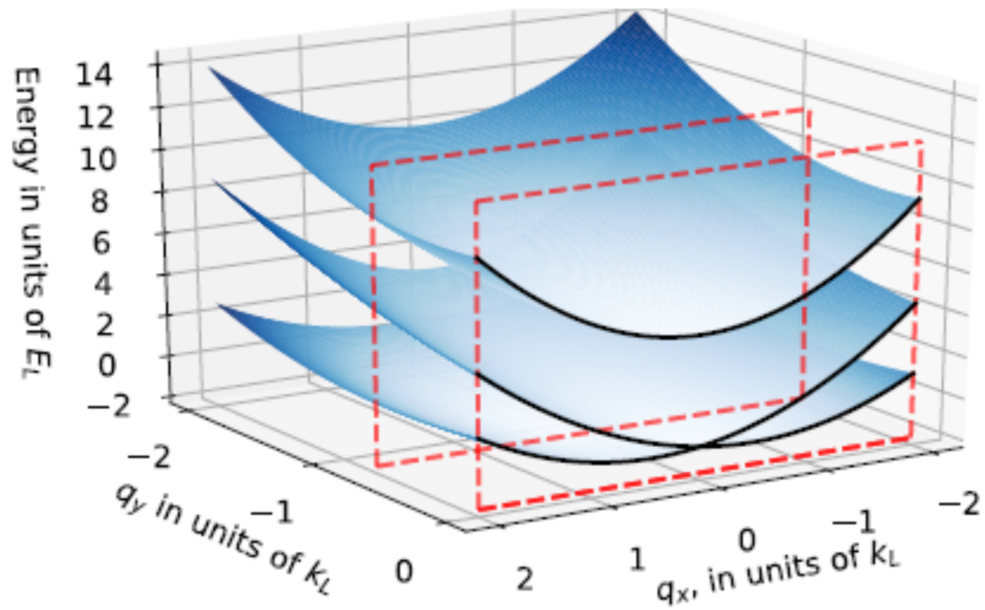
e.g., laser induced motion

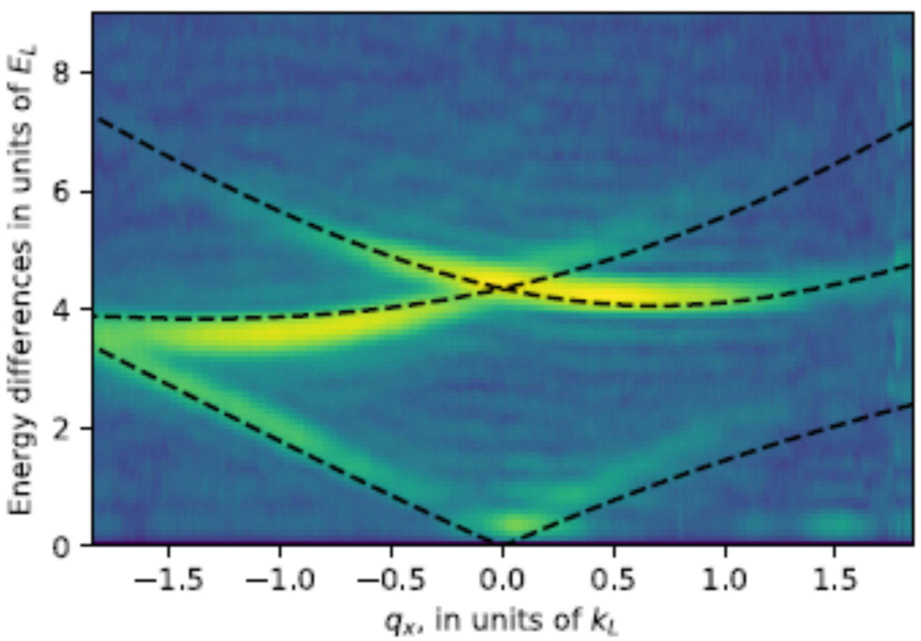
$$H = \frac{\left[\mathbf{k} - \hat{\mathcal{A}}(\mathbf{x})\right]^2}{2m} + \ldots.$$



Outline

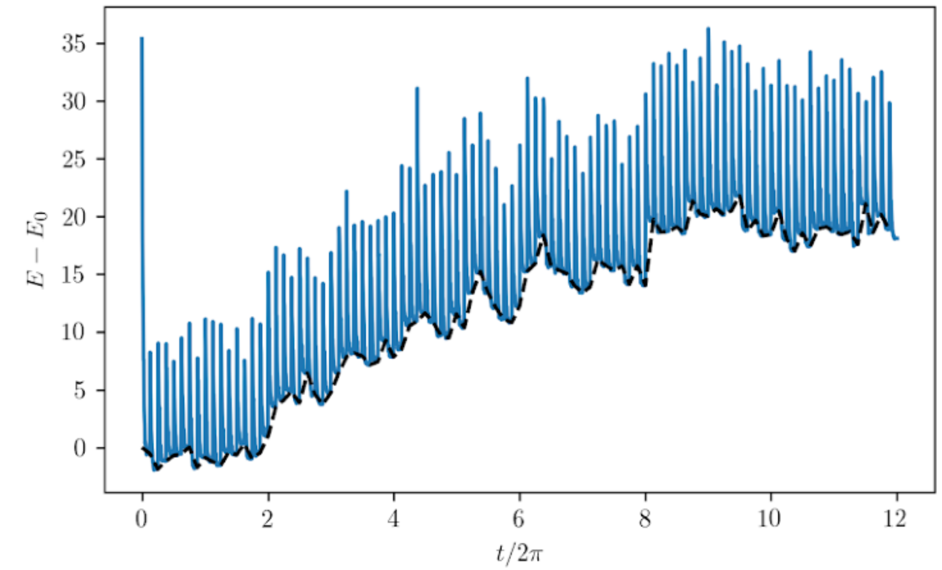
Rashba SOC
(experiment)

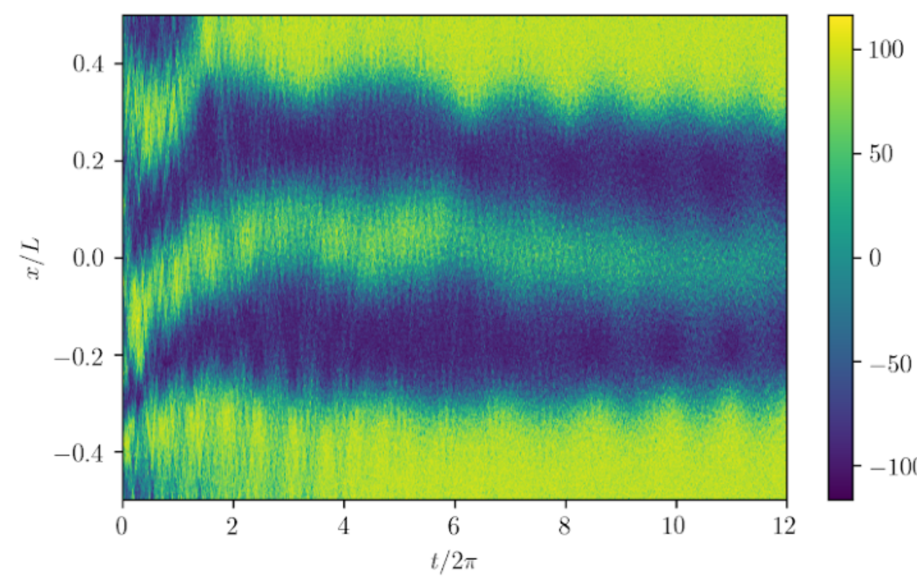




D. L. Campbell, G. Juzeliūnas, and IBS; PRA (2011);
D. L. Campbell and IBS; NJP (2016).
A. Valdés-Curiel *et al. (2019, in preparation)*

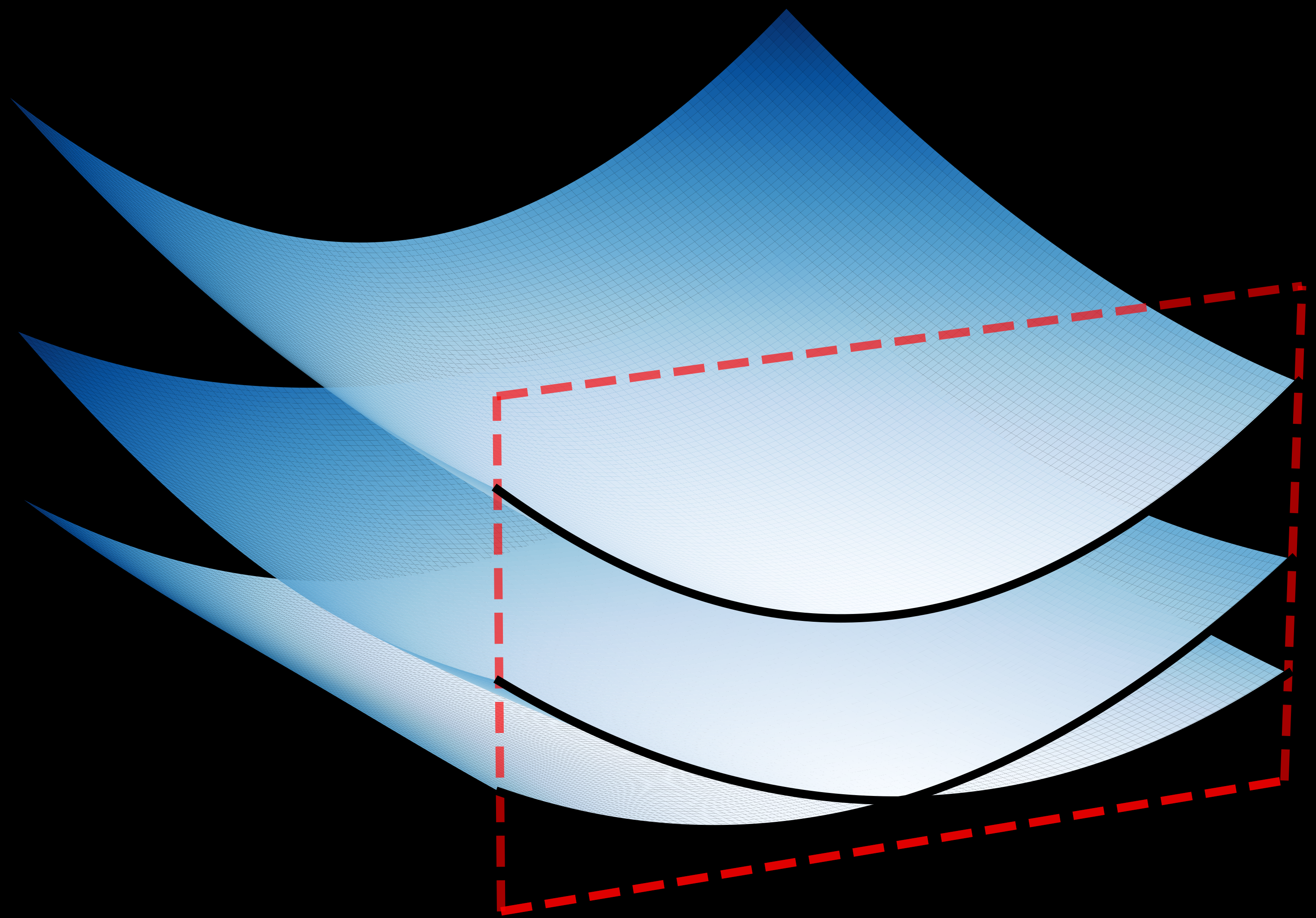
Dynamical steady-state via quantum control
(Theory)





H. M. Hurst and IBS; arxiv.org/abs/1809.08257

Rashba SOC

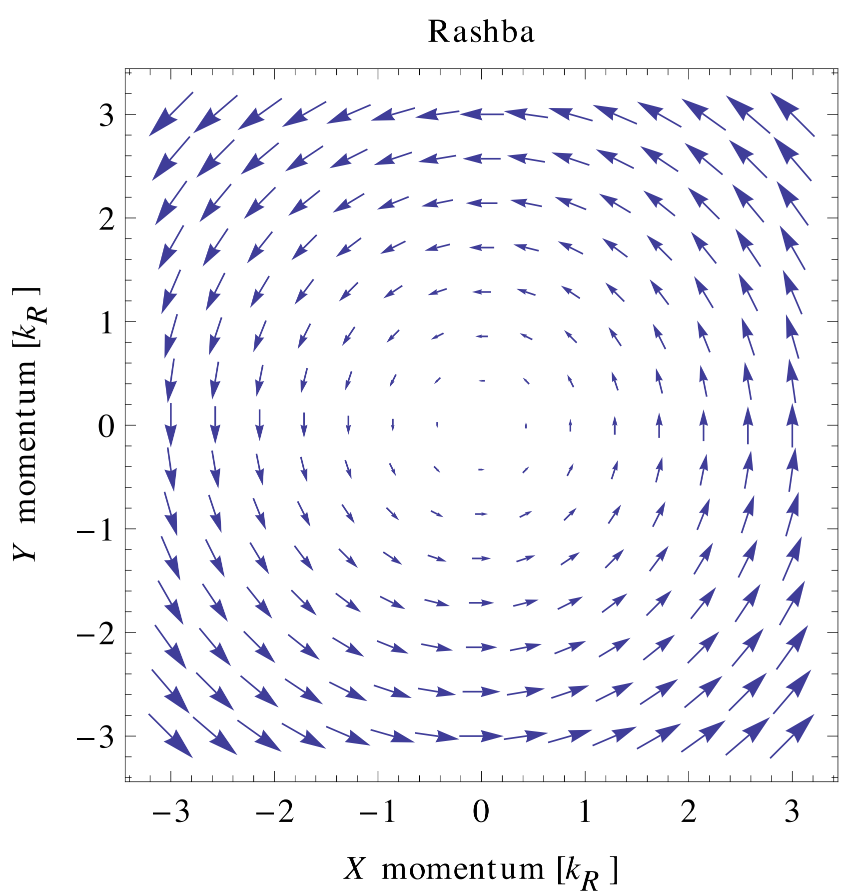


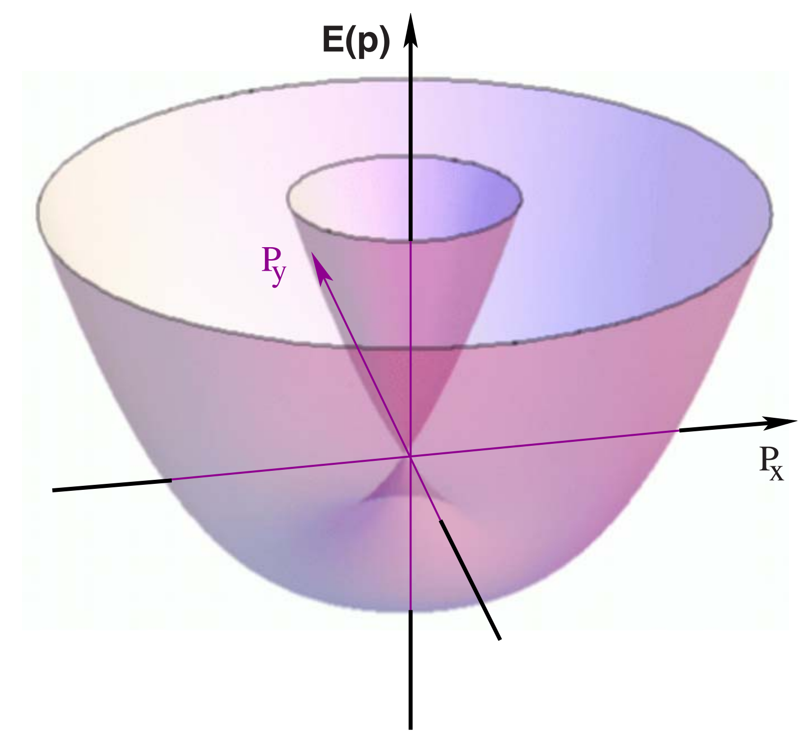
Spin-orbit coupling: Rashba

Spin-orbit coupling

$$H = \frac{\hbar^2 \mathbf{k}^2}{2m}\check{1} + \frac{\delta}{2}\check{\sigma}_z + \alpha\left(k_x\check{\sigma}_y - k_y\check{\sigma}_x\right) + \beta\left(k_x\check{\sigma}_x - k_y\check{\sigma}_y\right).$$

Pure Rashba: $\beta = 0$





Dated reference

T. D. Stanescu and B. Anderson and V. Galitski PRA (2008)

Why Rashba SOC?

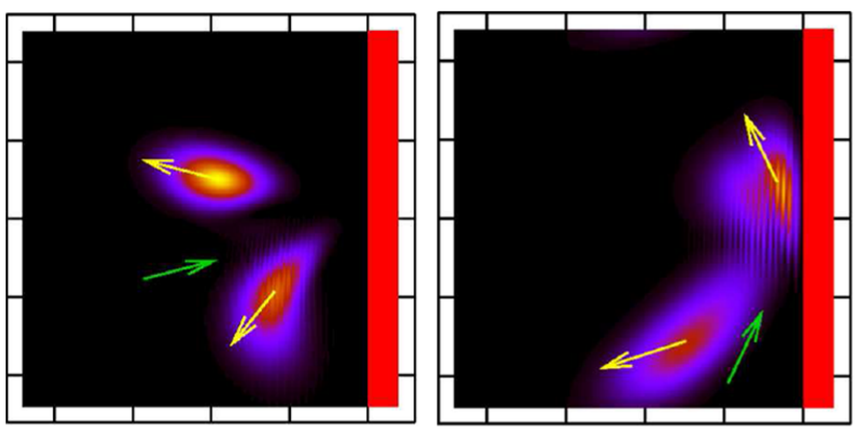
Novel single particle physics

Negative index like reflection for matter waves (phase-matching at **dispersion-boundaries**)
2D Topological insulators (generally with **spin-orbit coupling**)

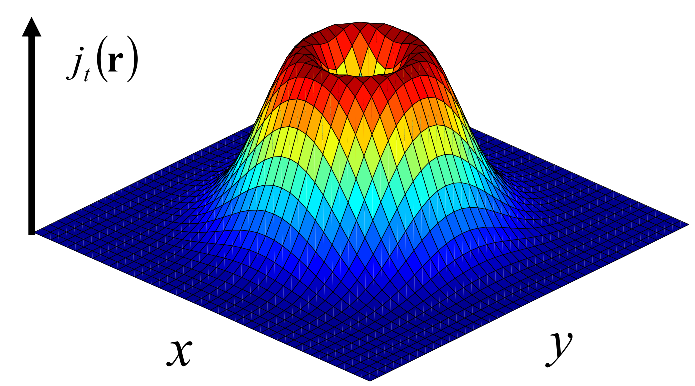
Novel many-body particle physics

Laughlin like physics of bosons (interacting bosons, partially flat 2D ring-dispersion)
Topological superfluids p-wave superconductivity (fermions, spin polarized **p-wave interactions**)

Negative index

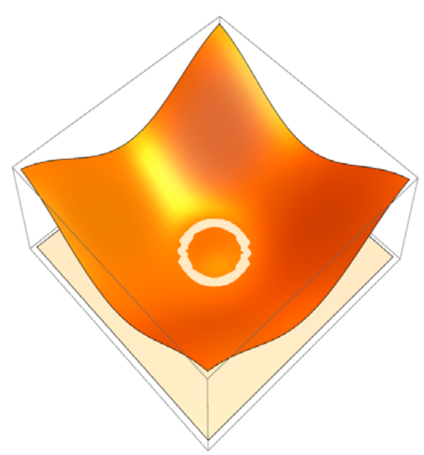


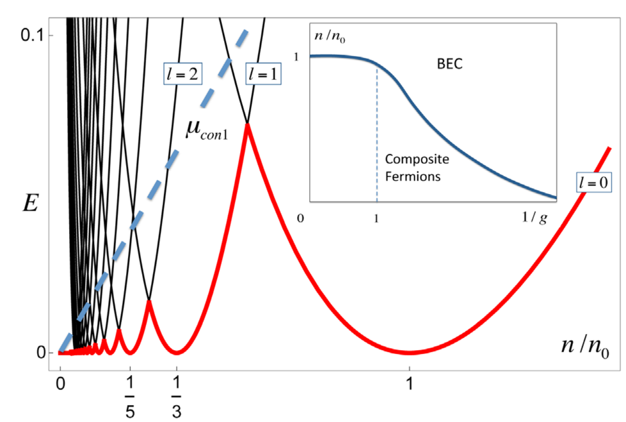
p-wave superconductivity



$$\Omega_{\mathbf{k}} = \frac{1}{2}\frac{\alpha}{(\alpha^2 + k^2)^{3/2}}.$$

FQHE-like physics





References: G. Juzeliūnas, et al; PRL (2008); T. A. Sedrakyan, V. M. Galitski, and A. Kamenev; PRL (2015); C. Zhang, et al; PRL (2008)
More motivation in: V. Galitski and IBS; Nature (2013).

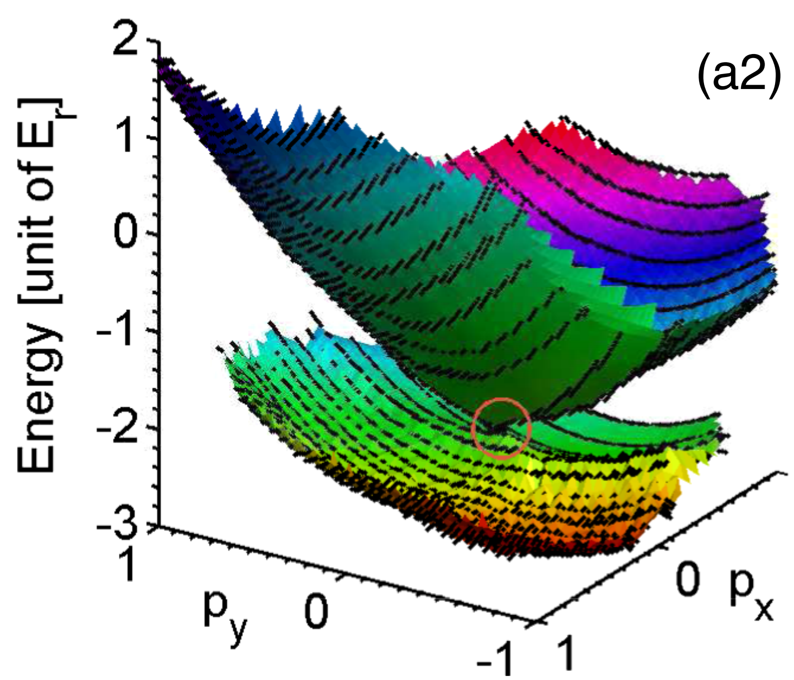
State of the art

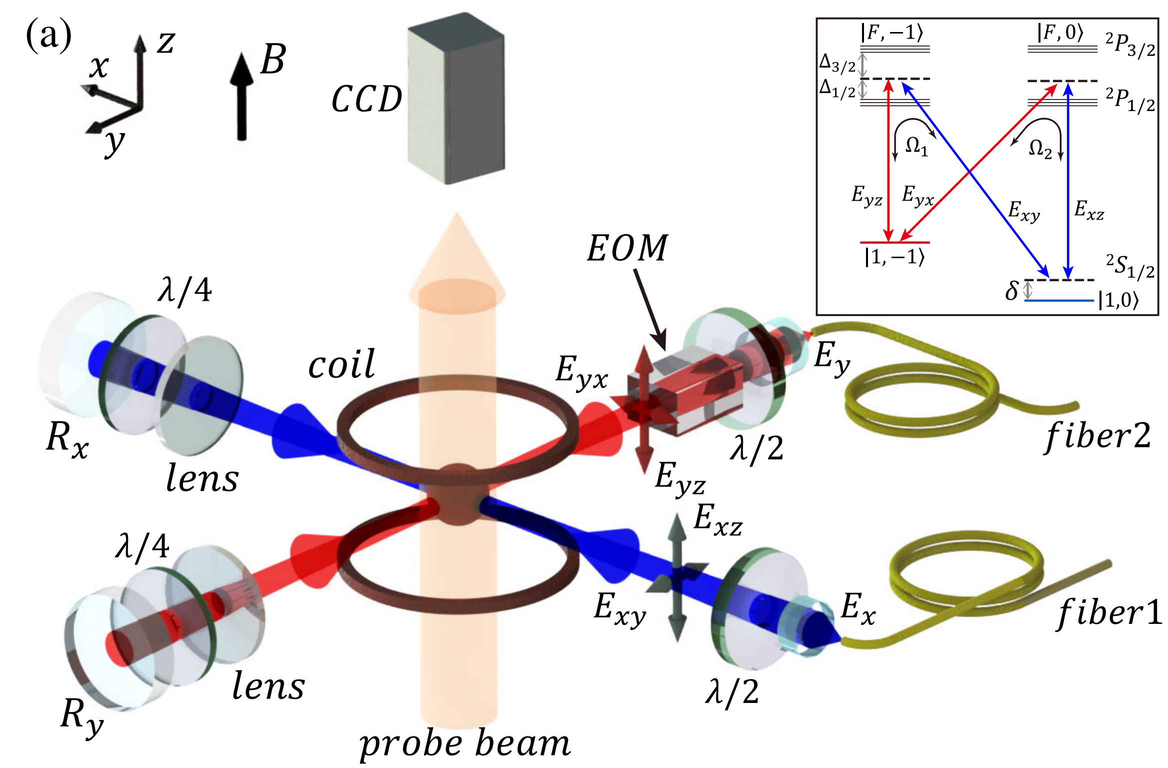
Continuum

Direct implementation of Campbell *et al* in ^{40}K

Lattice

Two-band model with a single Dirac point
("2D SOC" in the vicinity of Dirac point)



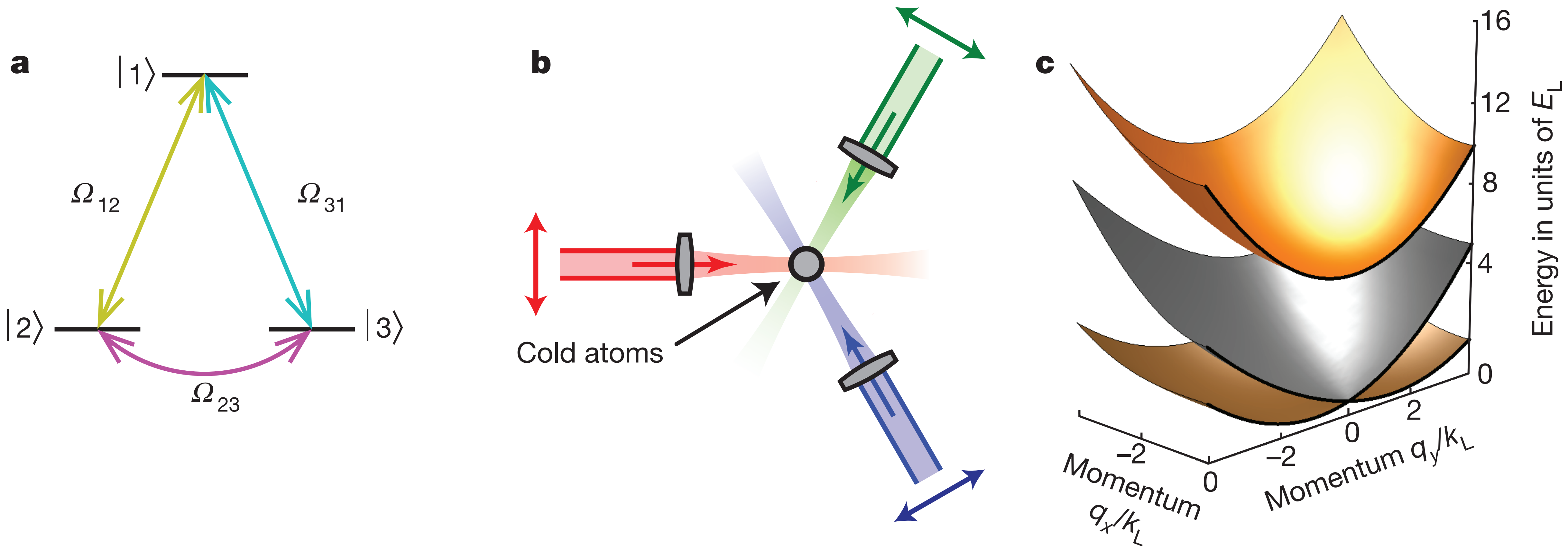


Z. Meng, et al; PRL (2016).

Z. Wu, et al; Science (2016)
W. Sun, et al; PRL (2018)

Basic idea

Raman couple three internal hyperfine states

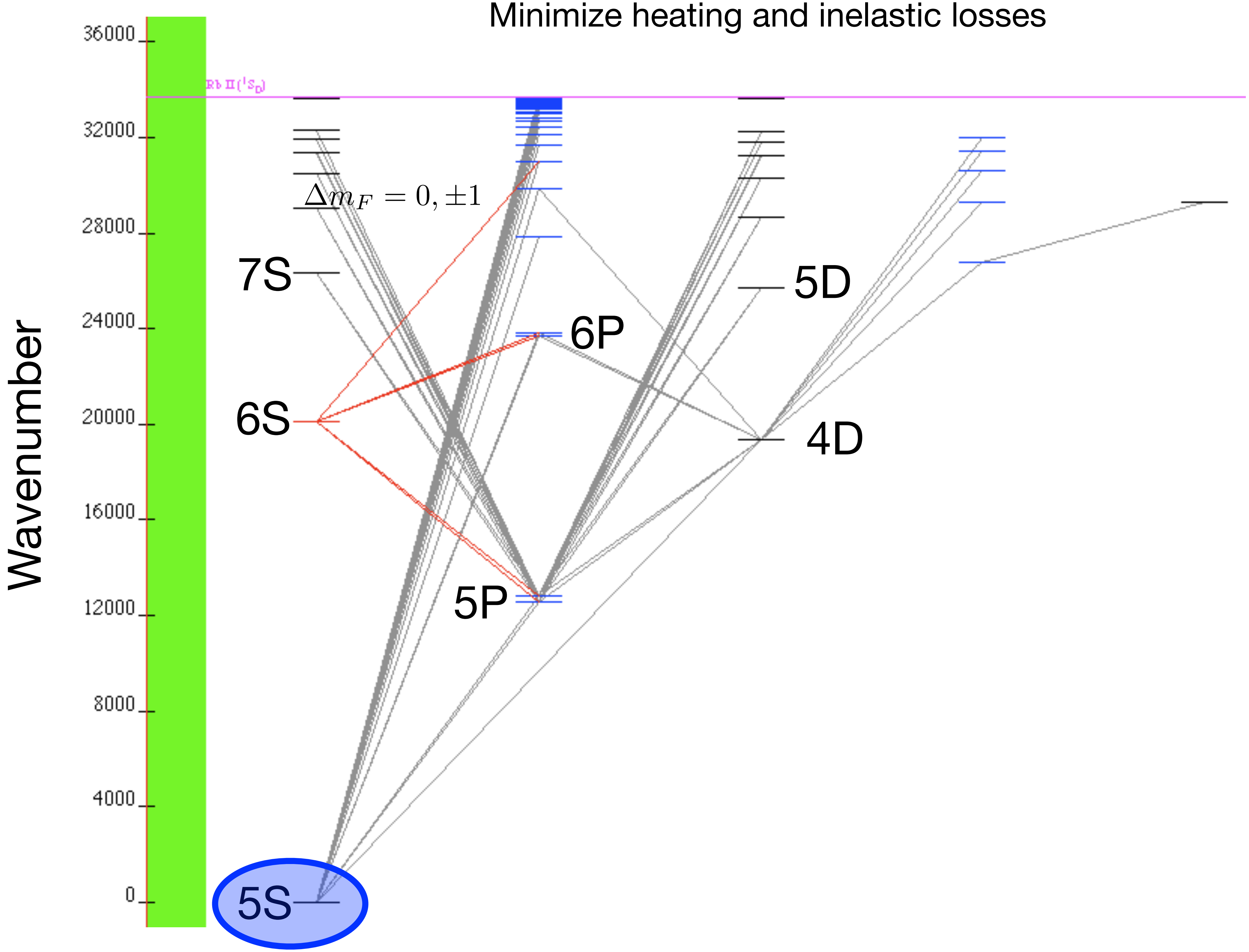


D. L. Campbell, G. Juzeliūnas, and IBS; PRA (2011); V. Galitski, and IBS; Nature (2013)

Goal of present work

Applicability to many body physics

Minimize heating and inelastic losses



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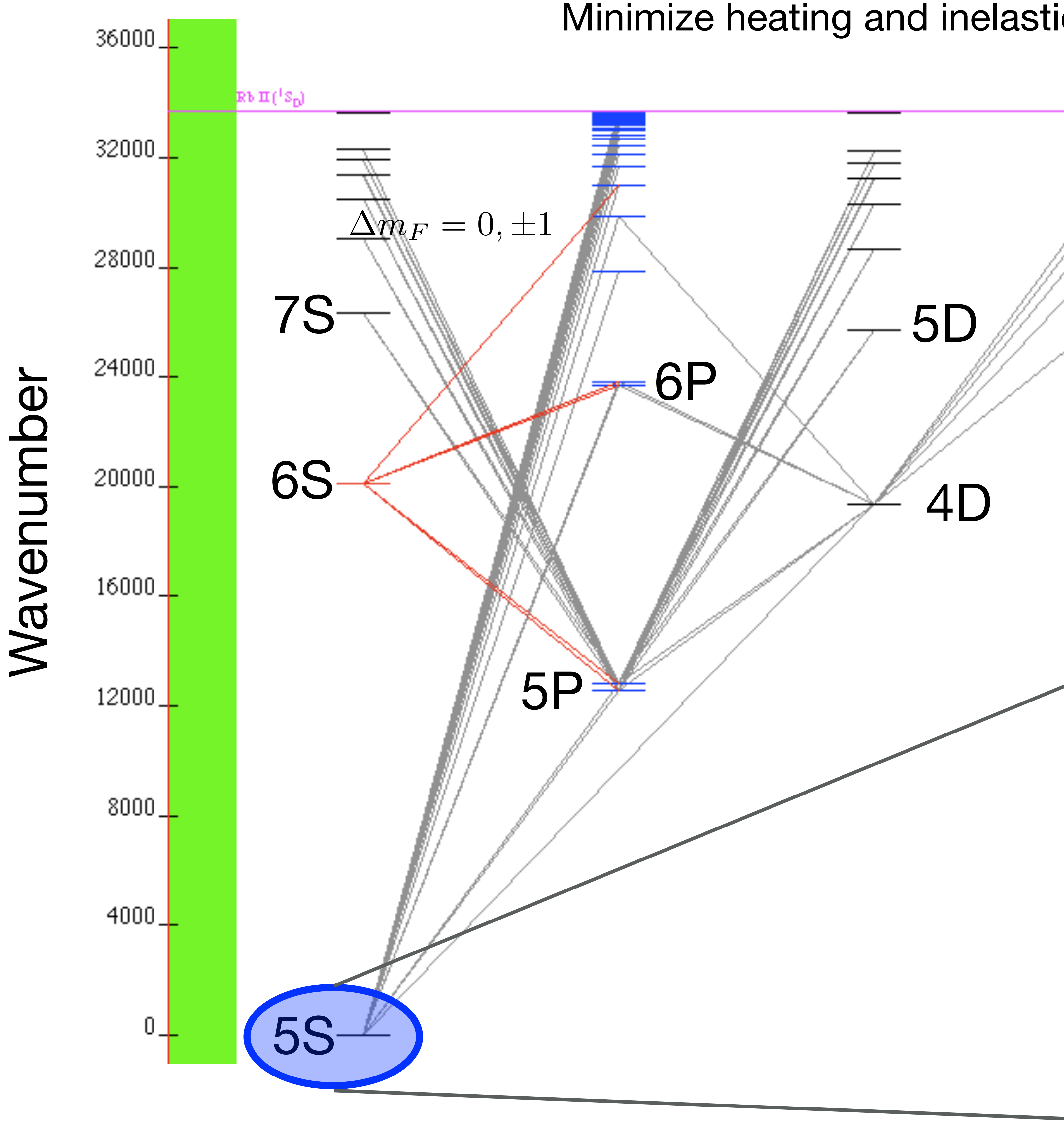
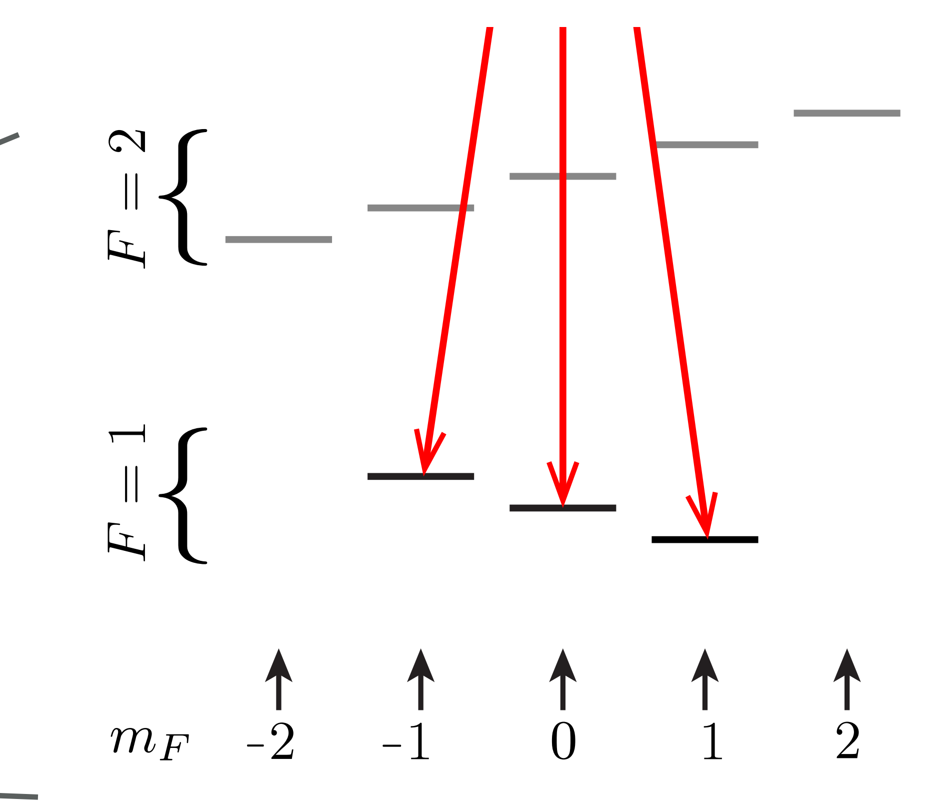


Far-detuned lasers

Limit heating from spontaneous emission



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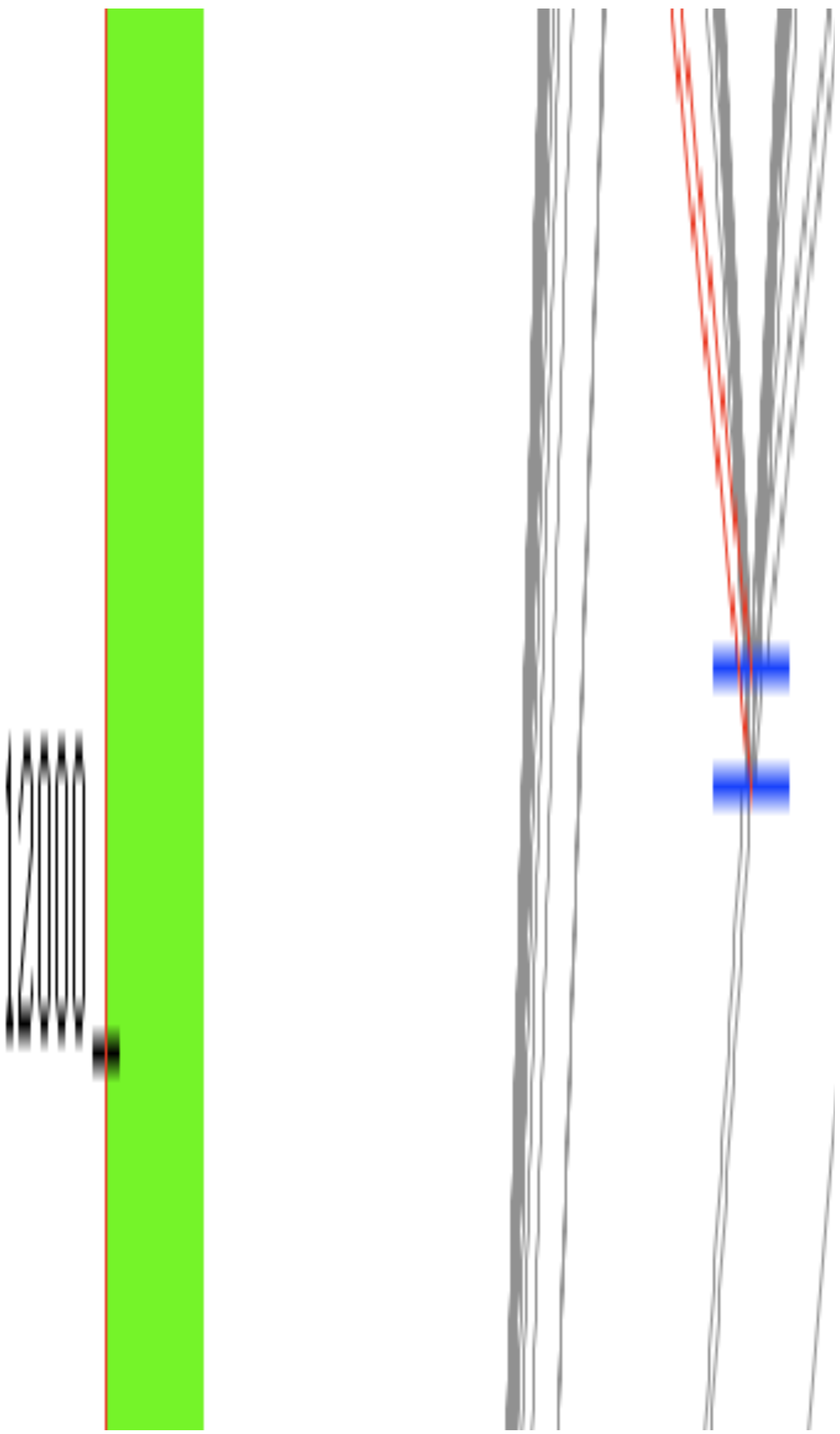

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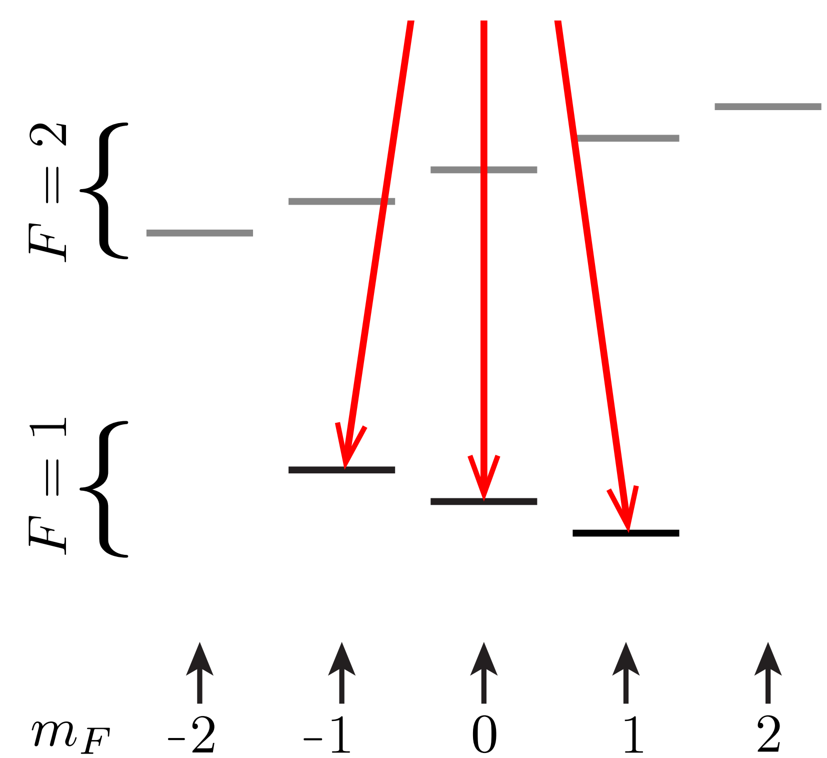

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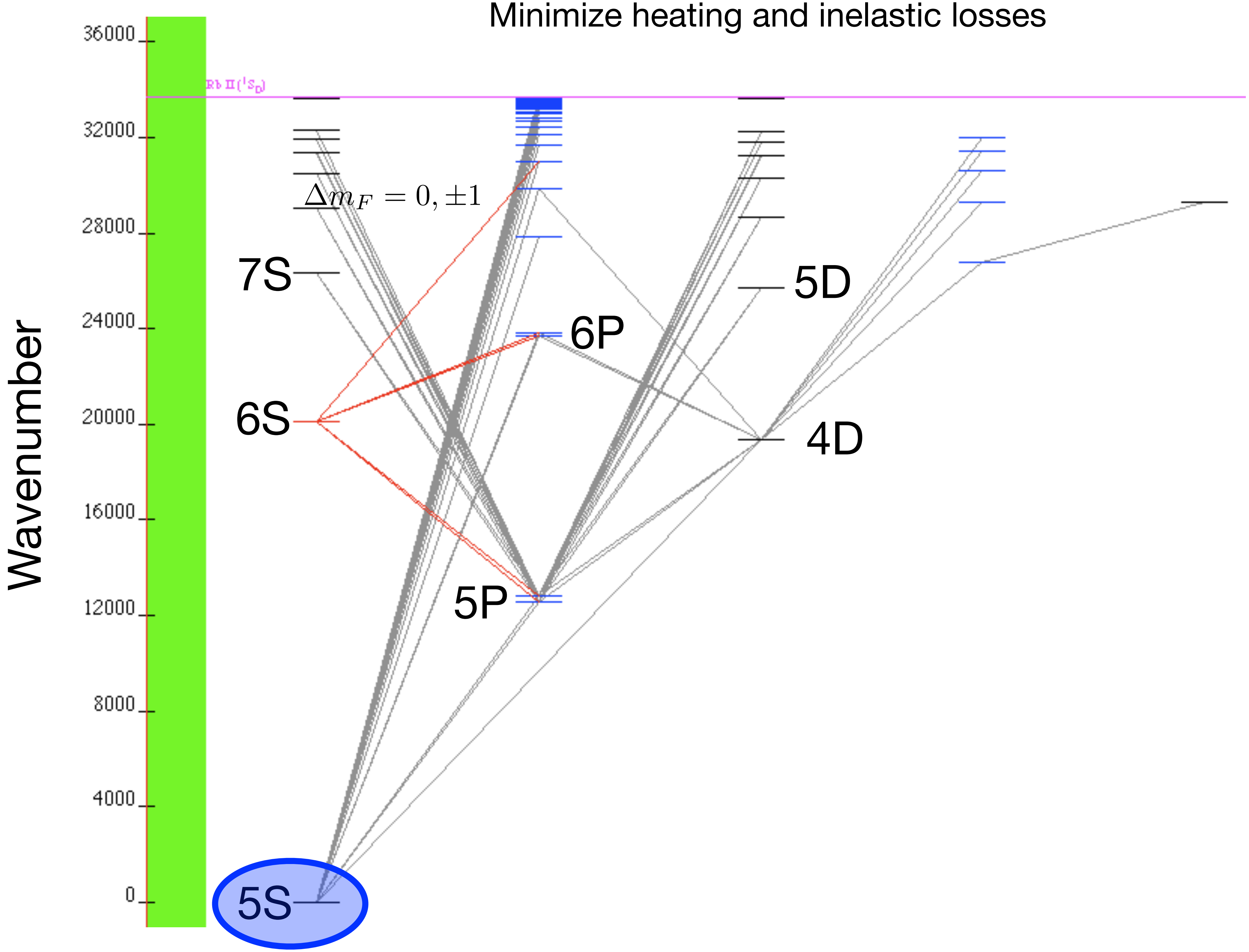

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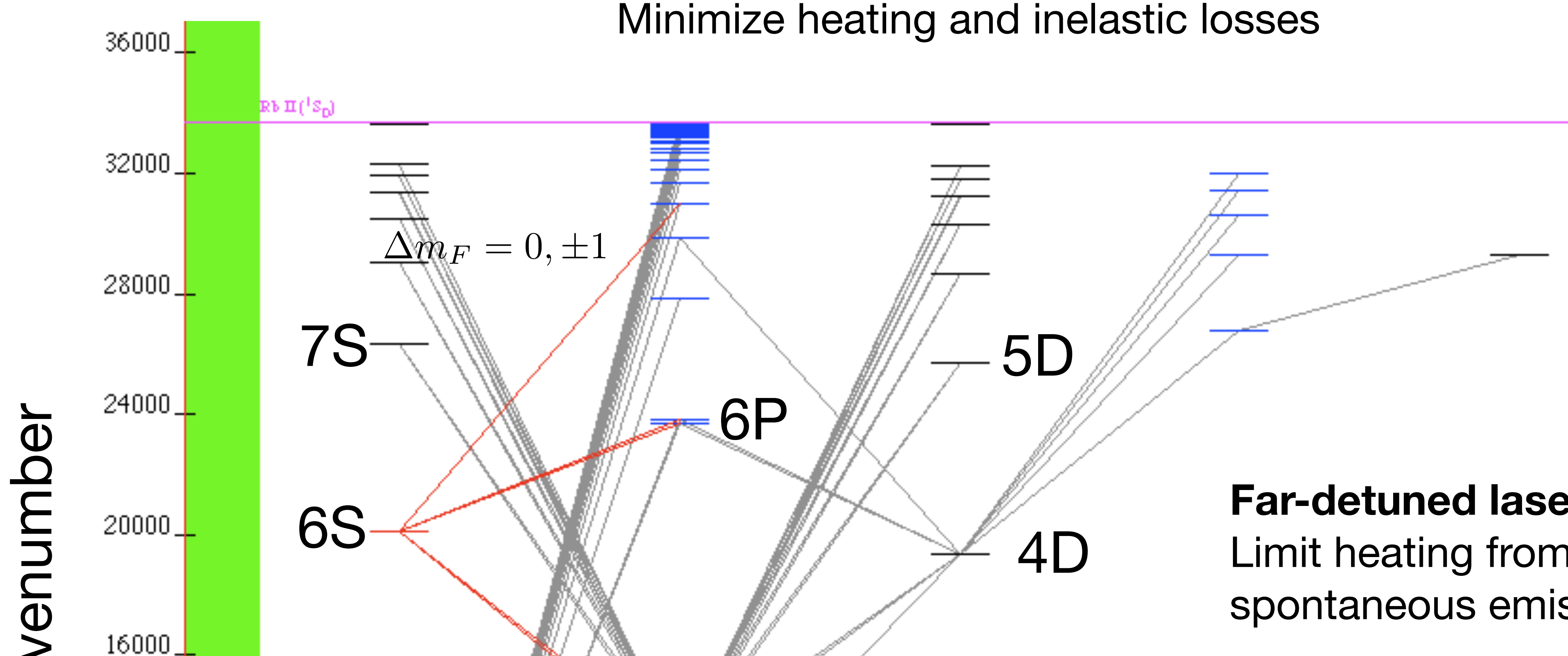

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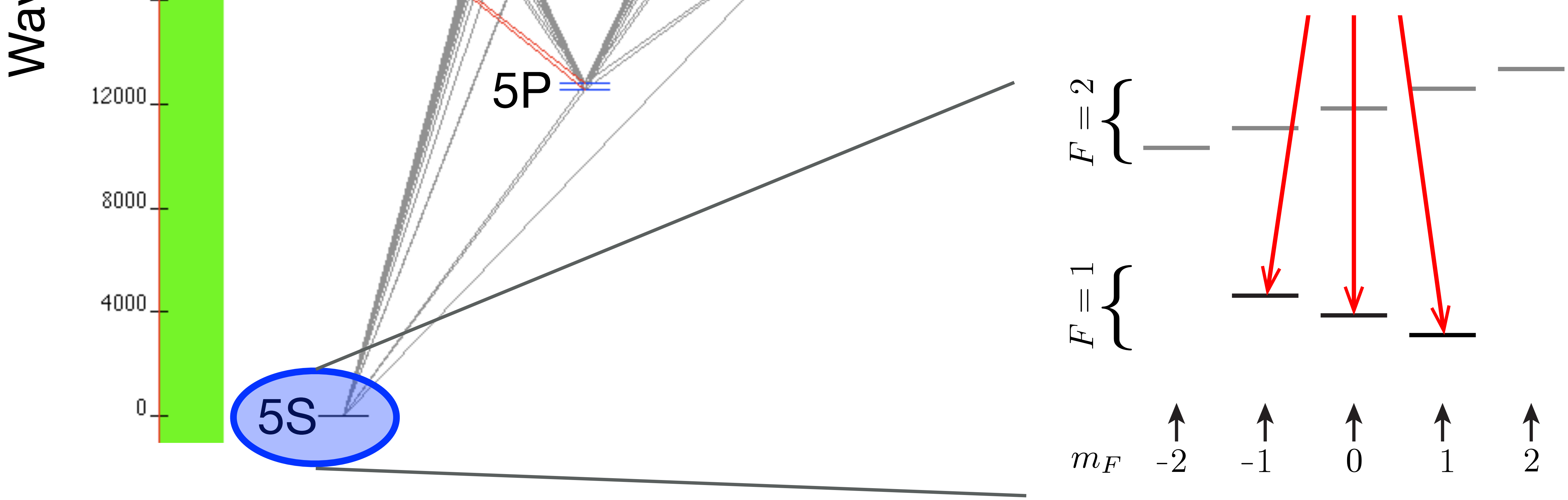

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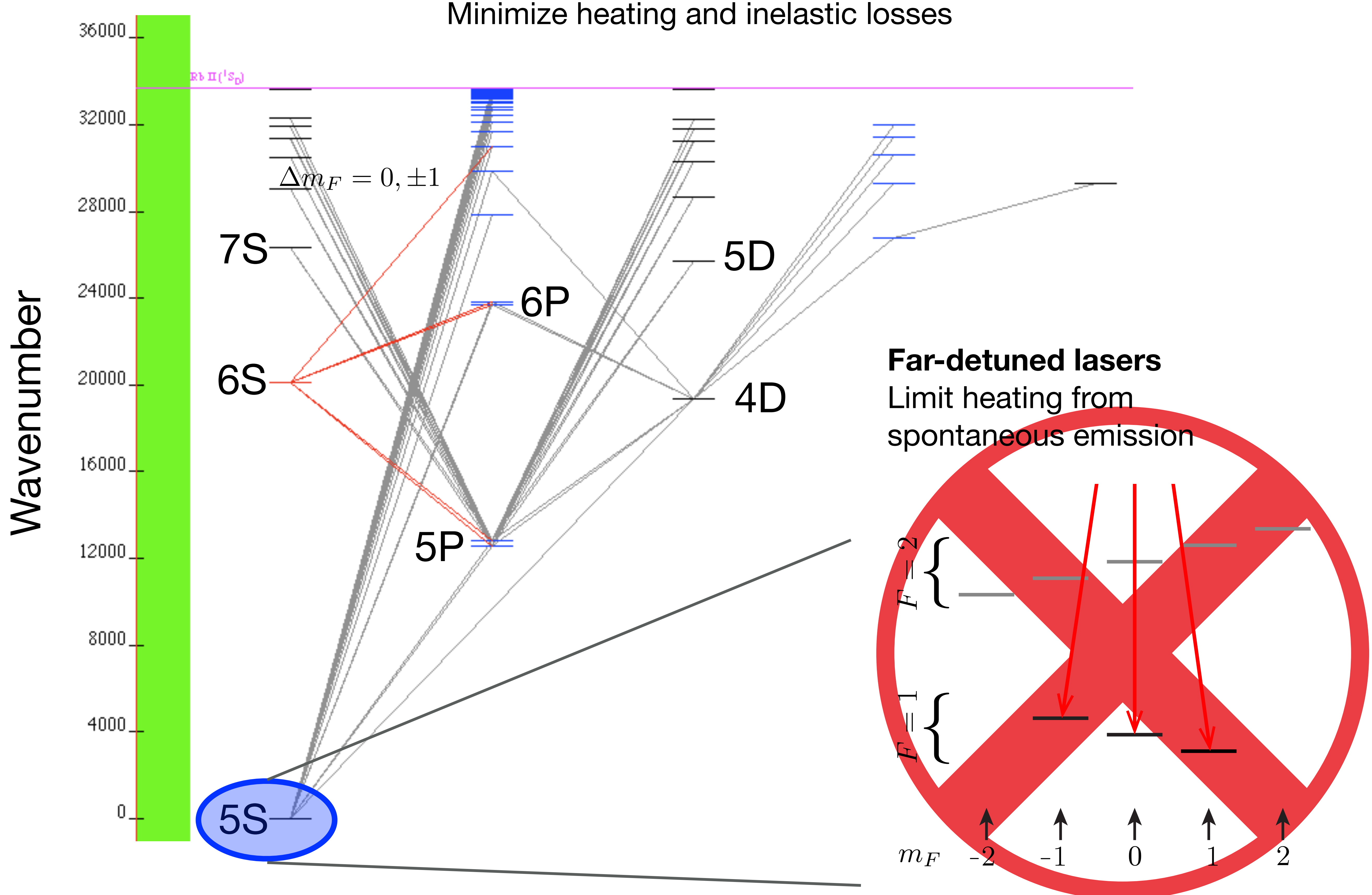

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Goal of present work

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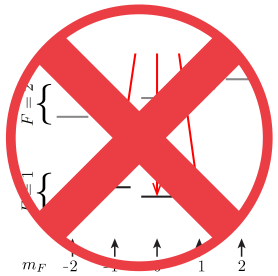
Minimize heating and inelastic losses

Far-detuned lasers

Limit heating from spontaneous emission

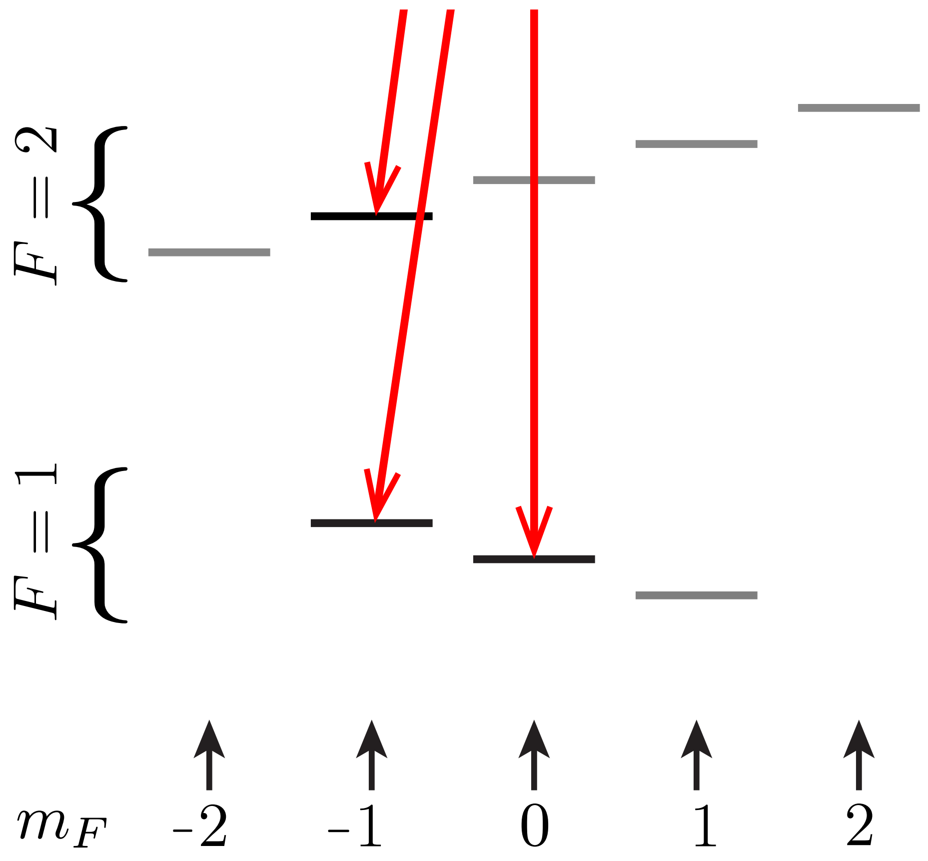
In alkalis this implies $\Delta m_F = 0, \pm 1$



Prevent hyperfine-changing collisions

All states in ground hyperfine manifold

(seems to contradict above)



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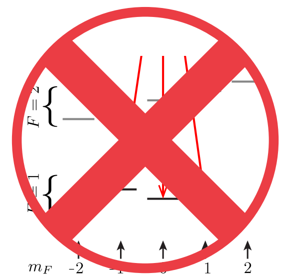

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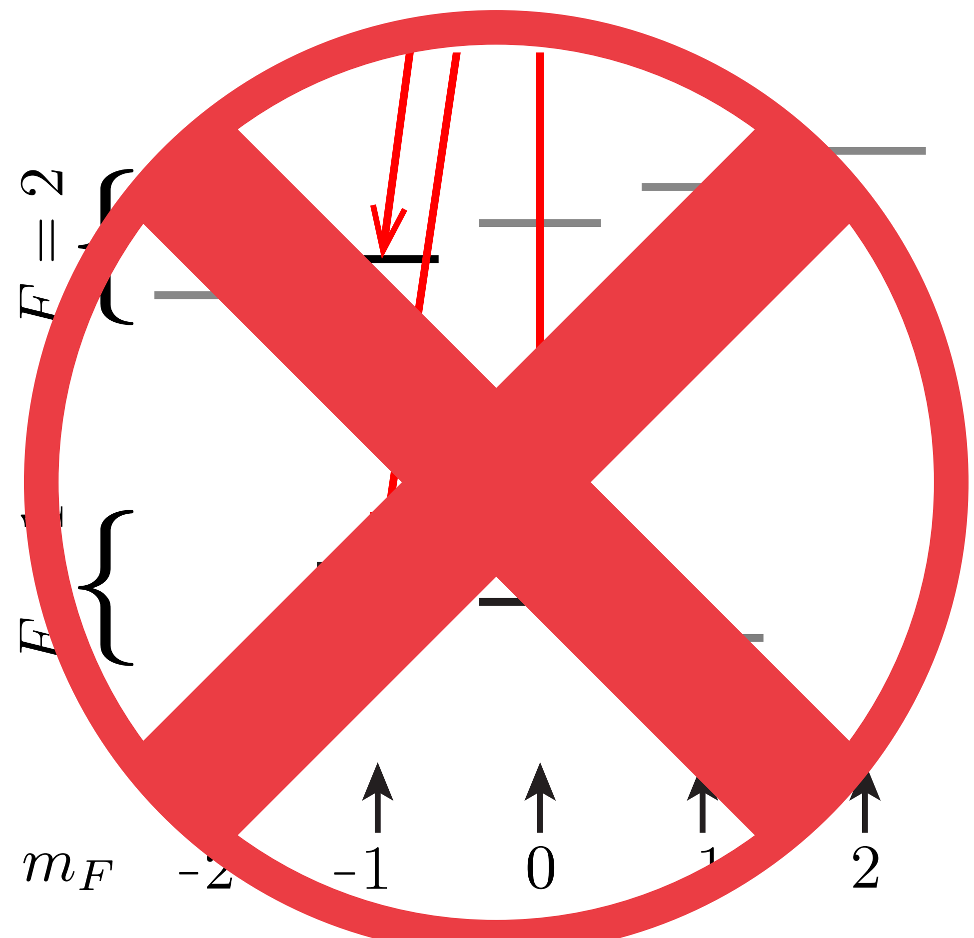

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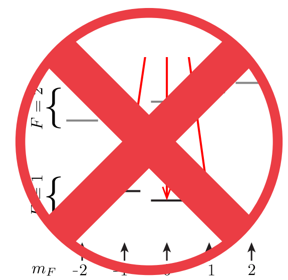

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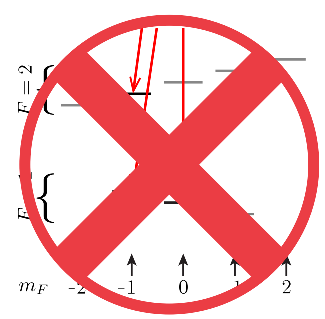
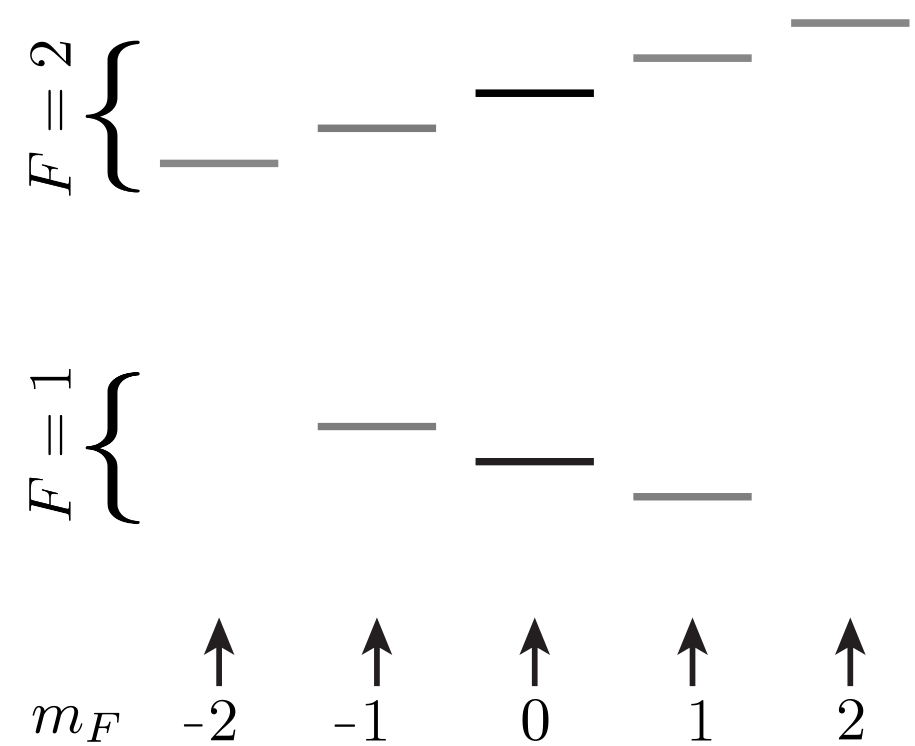


Insensitivity to external environment
magnetic field insensitive
(seems unlikely given states are first order field sensitive)



Proposal: D. L. Campbell and IBS; NJP (2016).

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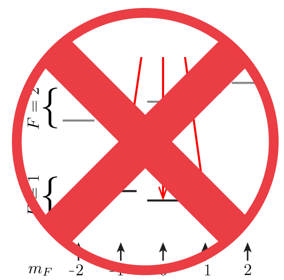

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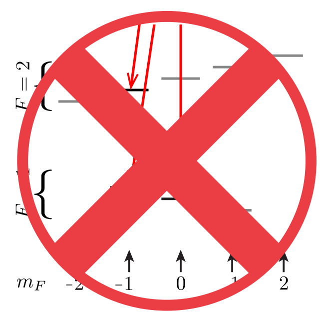

Insensitivity to external environment
magnetic field insensitive
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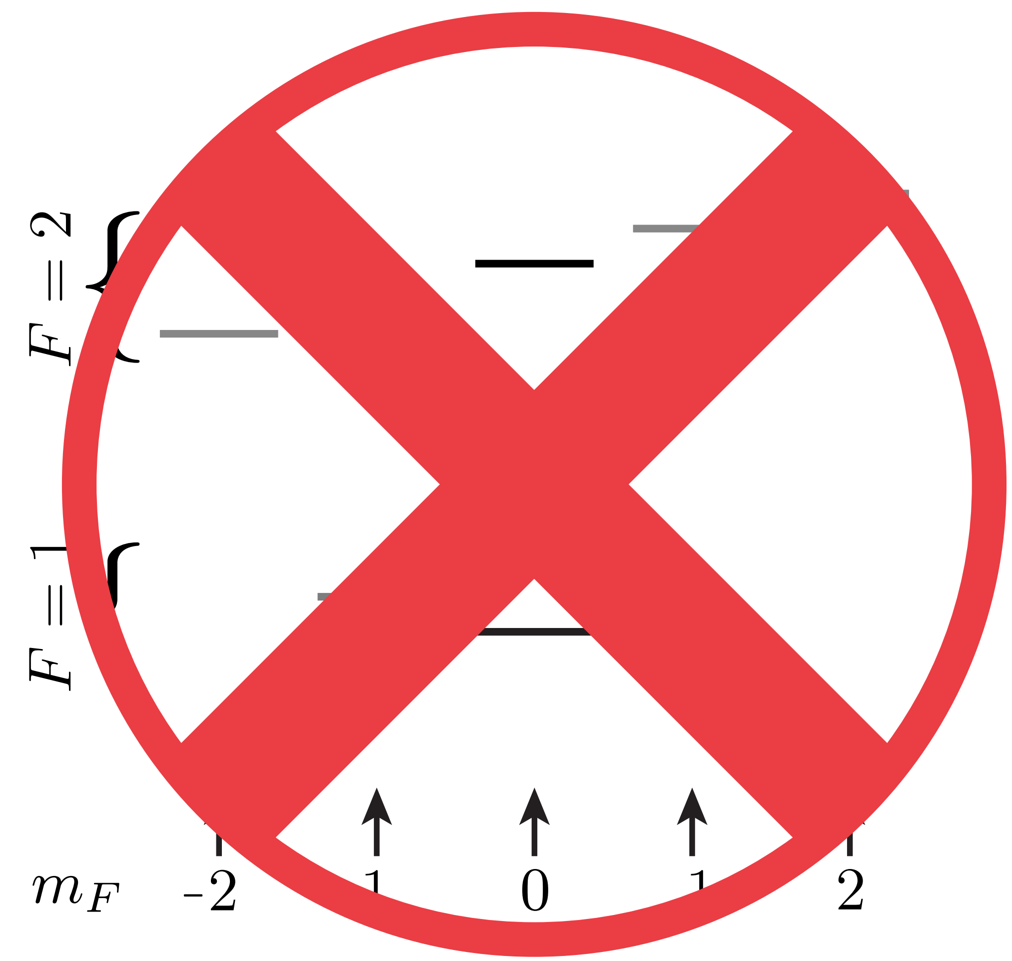
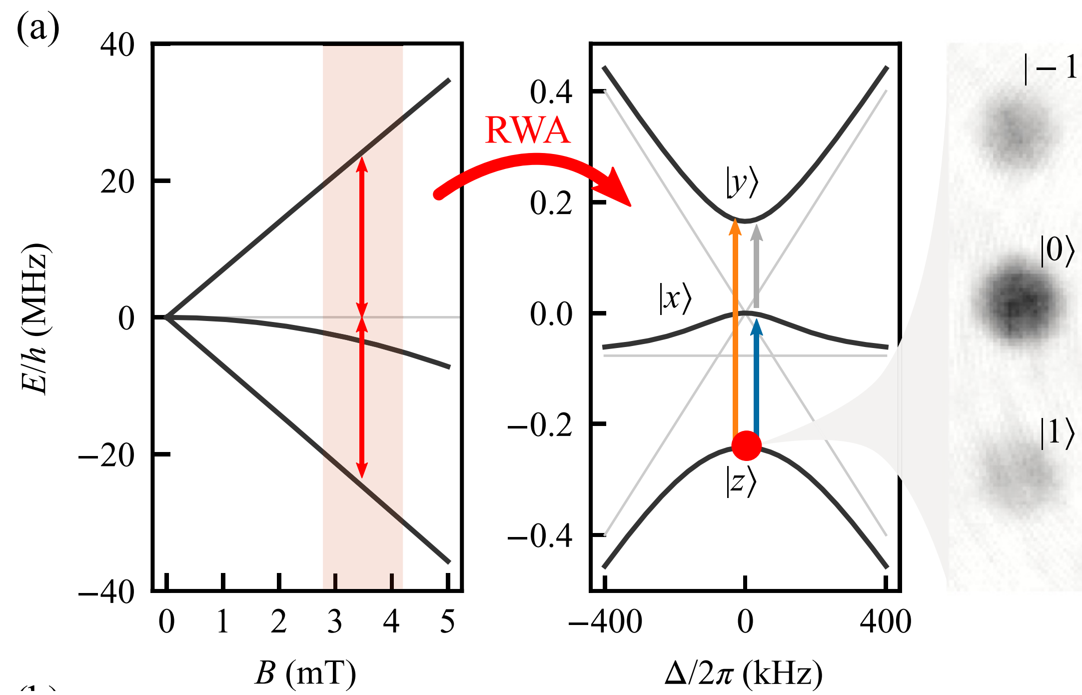


Proposal: D. L. Campbell and IBS; NJP (2016).

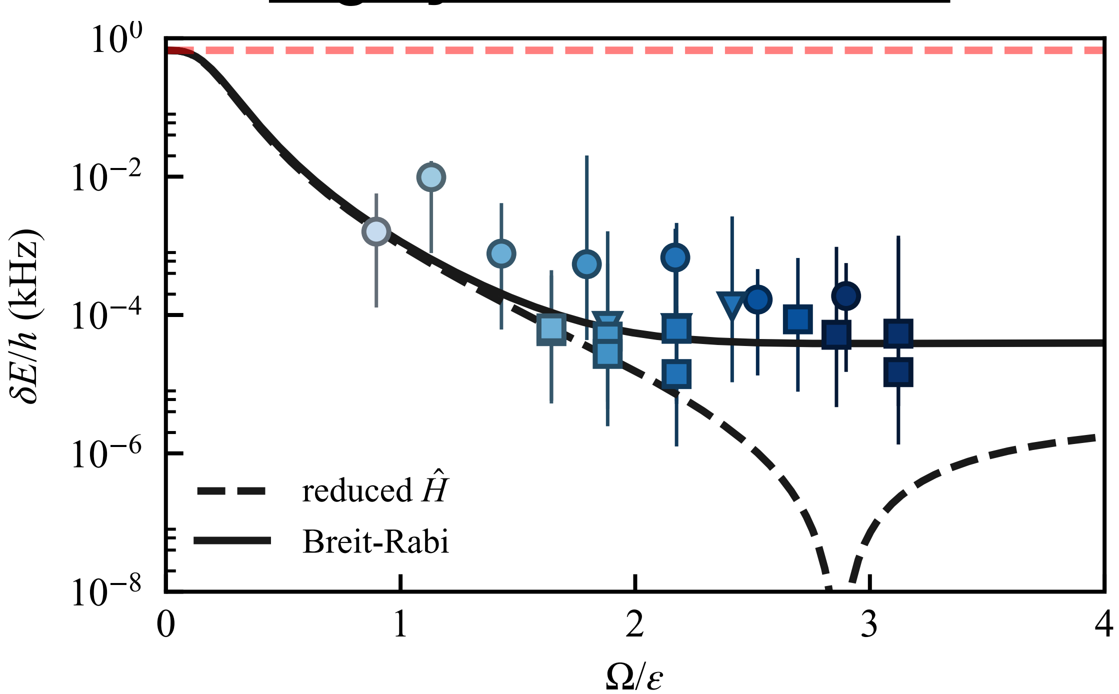
Solution to all problems: CDD

Continuous dynamical decoupling

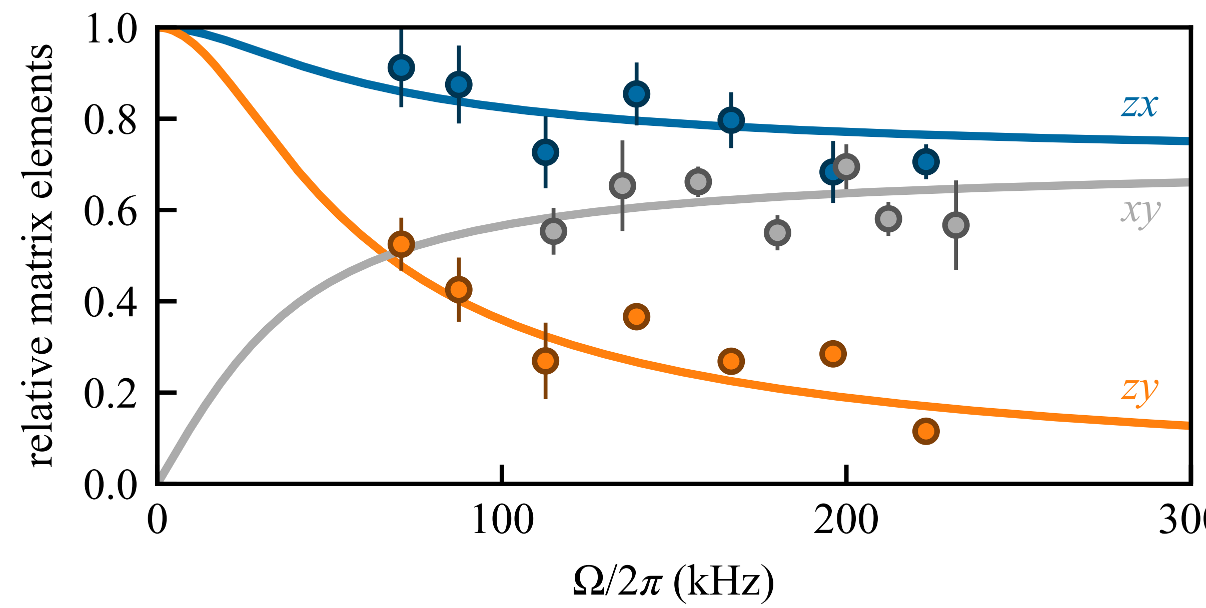
Fancy words for "dressed states"



Highly field insensitive



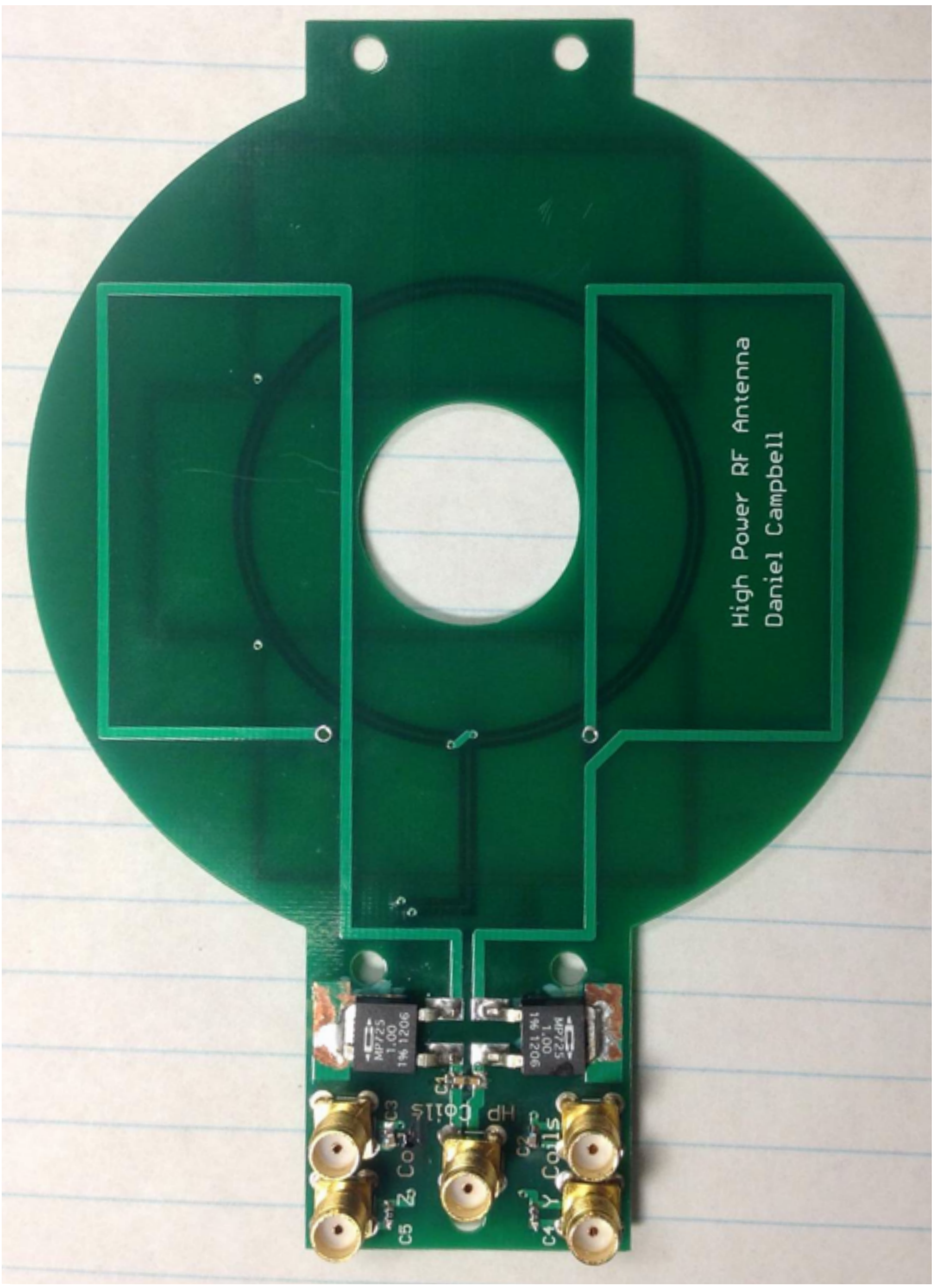
Band curvature



D. Trypogeorgos, A. Valdés-Curiel, N. Lundblad, and IBS; PRA (2018)

Proposal: D. L. Campbell and IBS; NJP (2016). **See also:** N. R. Cooper and J. Dalibard; PRL (2013)

Experimental comment



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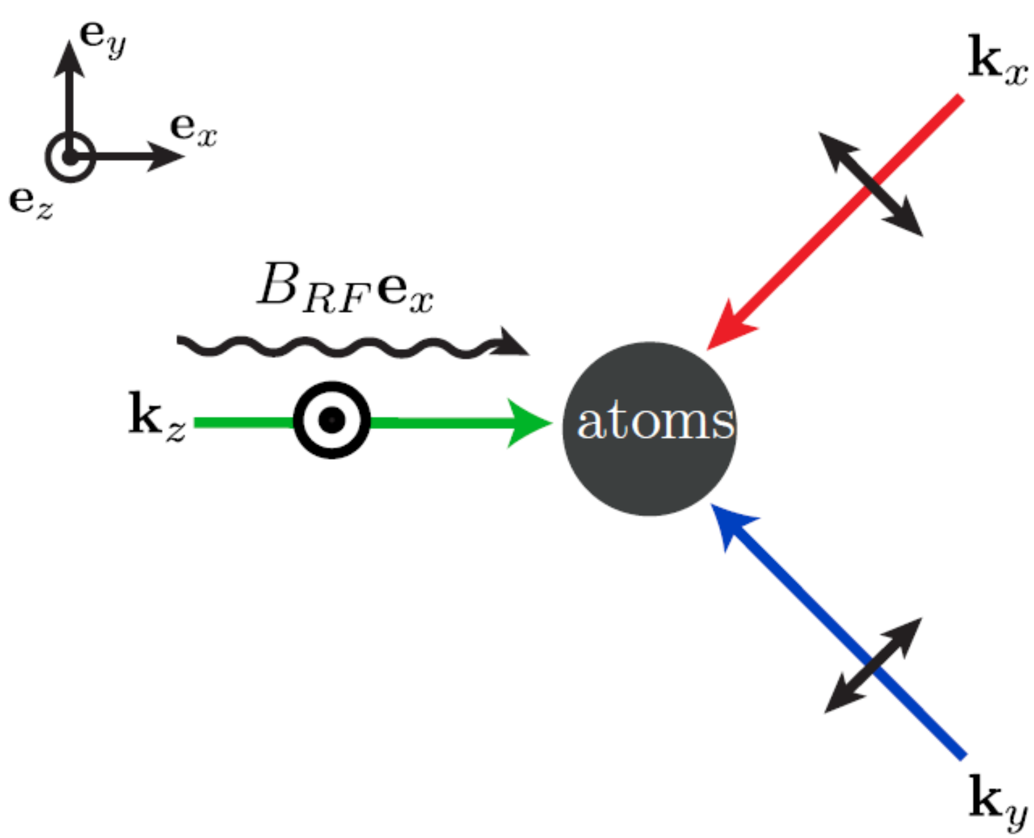
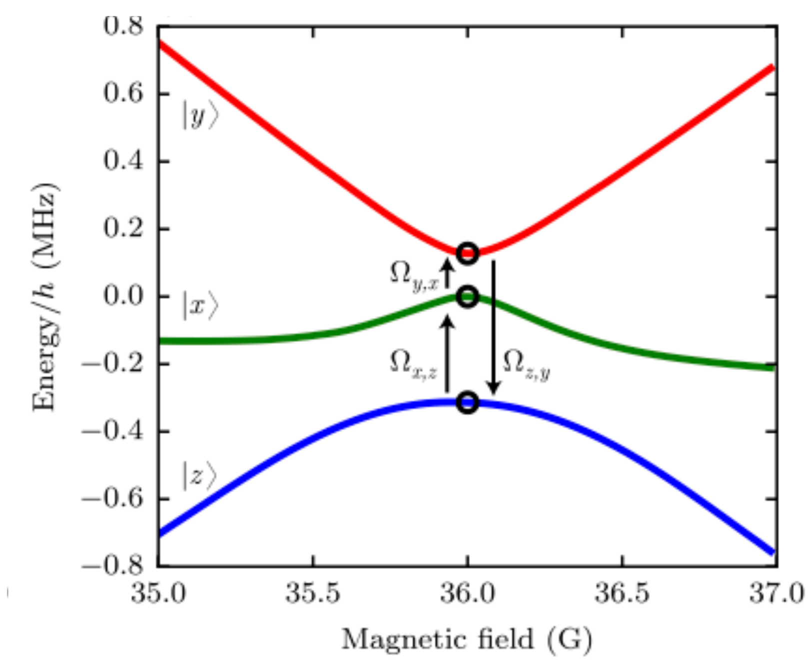
Proposal: D. L. Campbell and IBS; NJP (2016). **See also:** N. R. Cooper and J. Dalibard; PRL (2013)

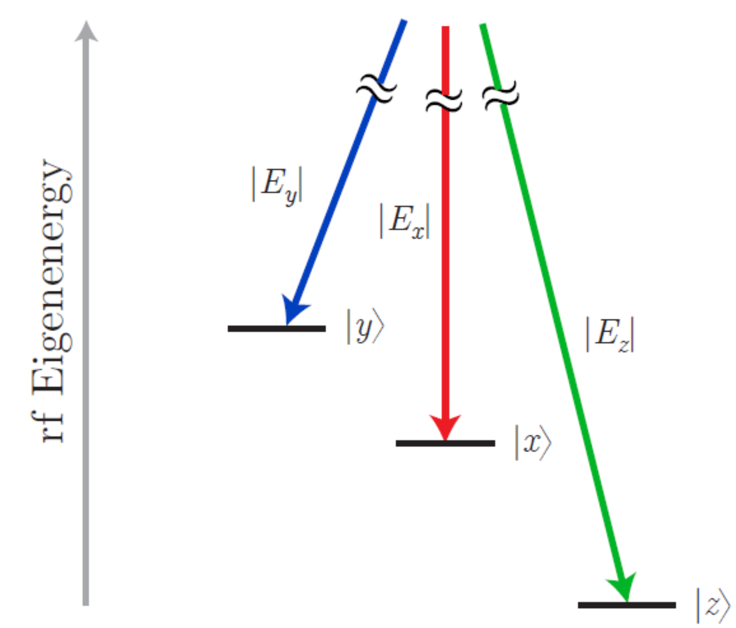
Schematic

Geometry



Level coupling

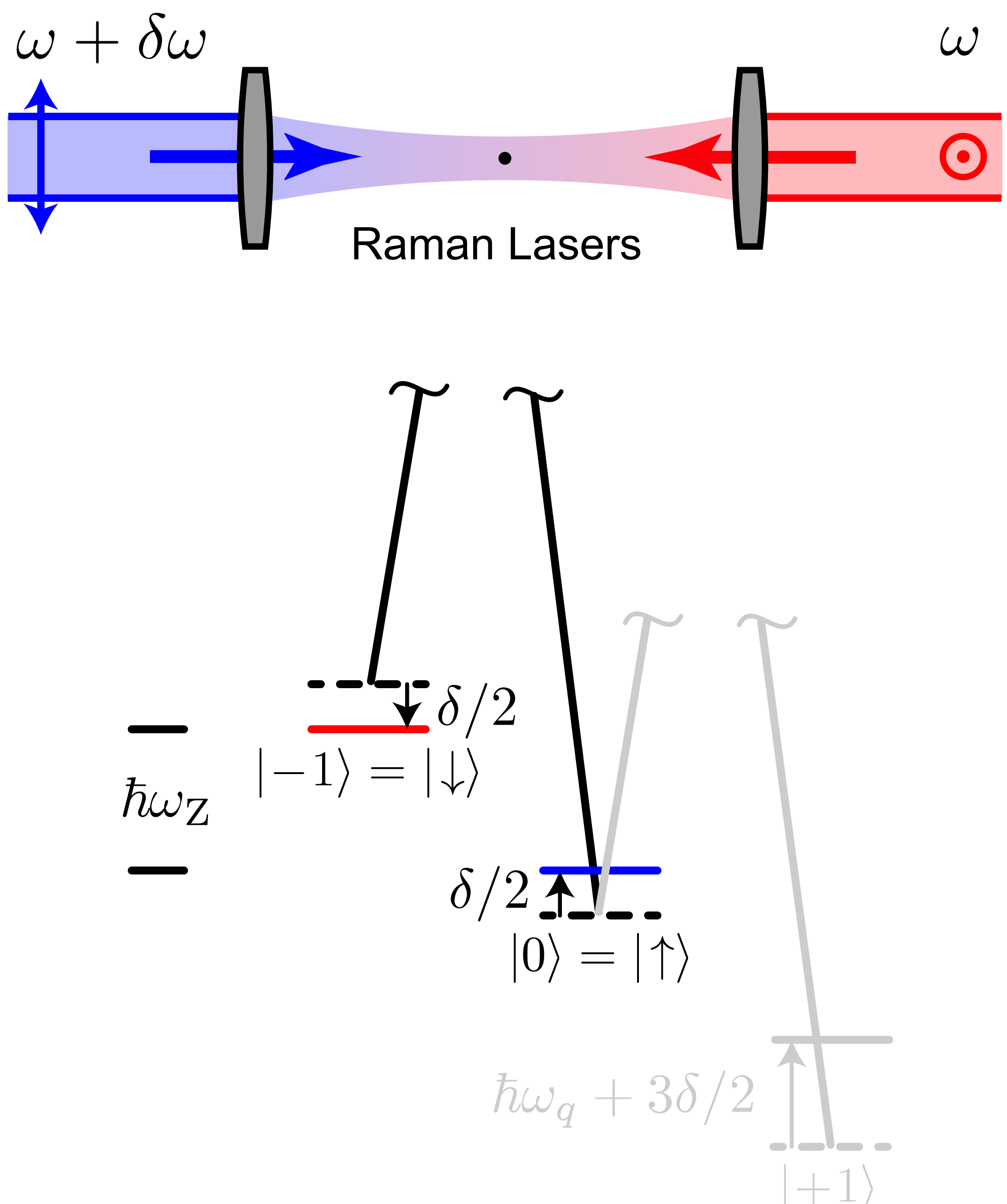




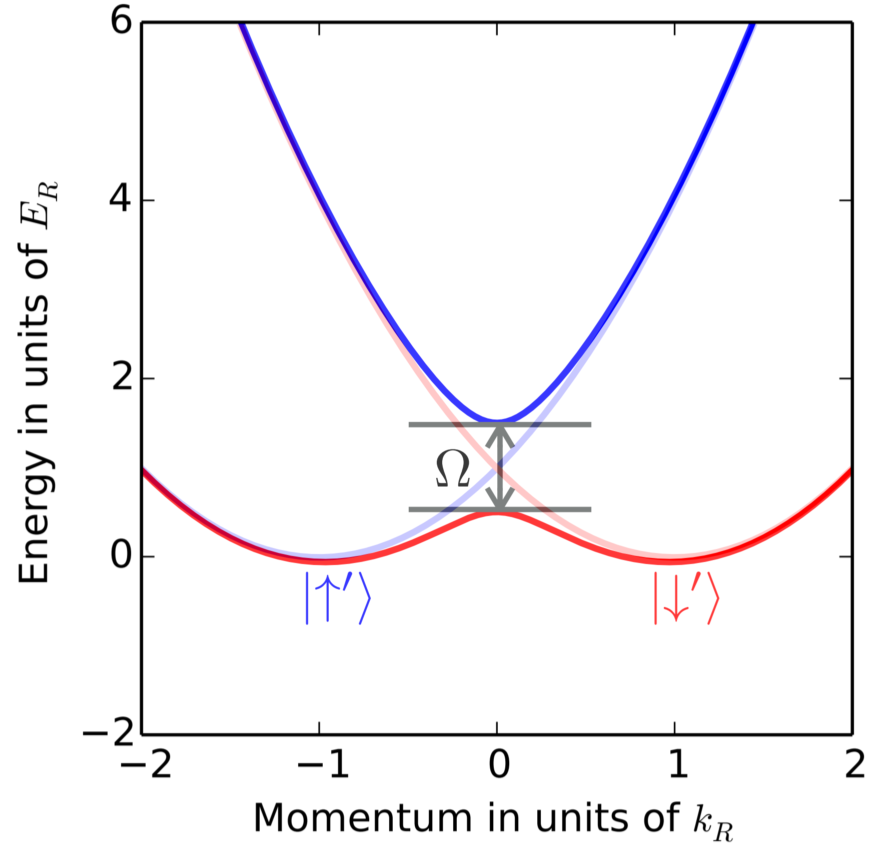
Graphical construction: primer

Two levels

Geometry



Resulting dispersion

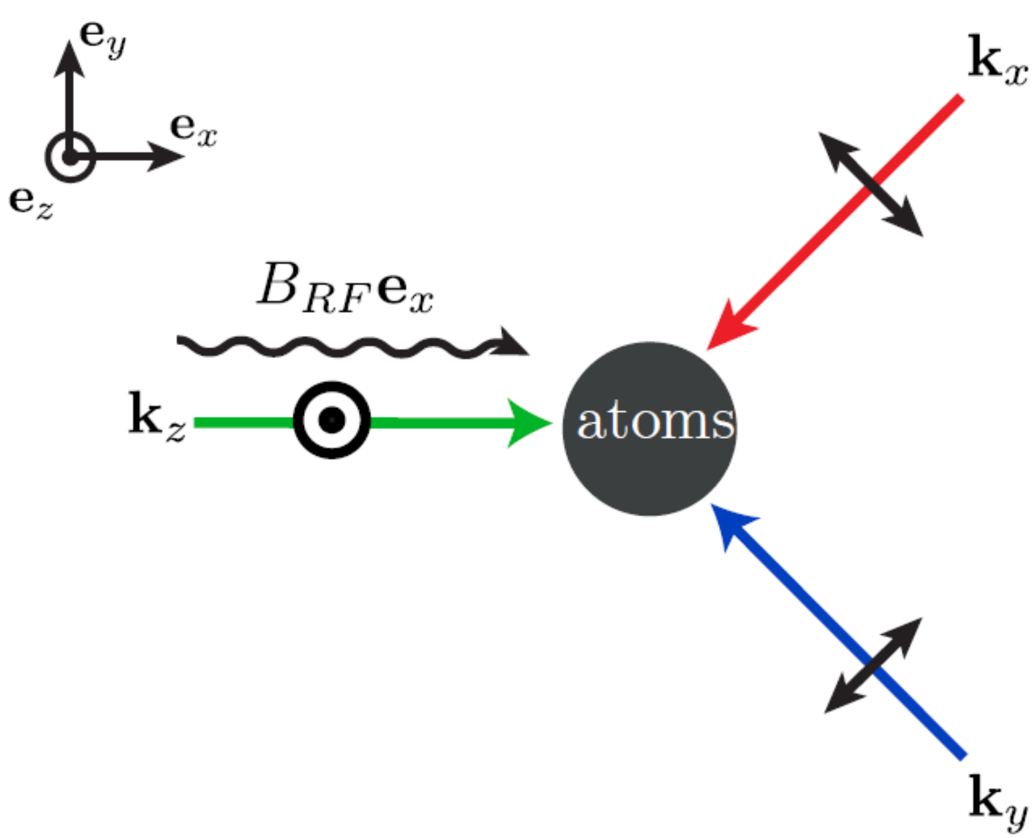


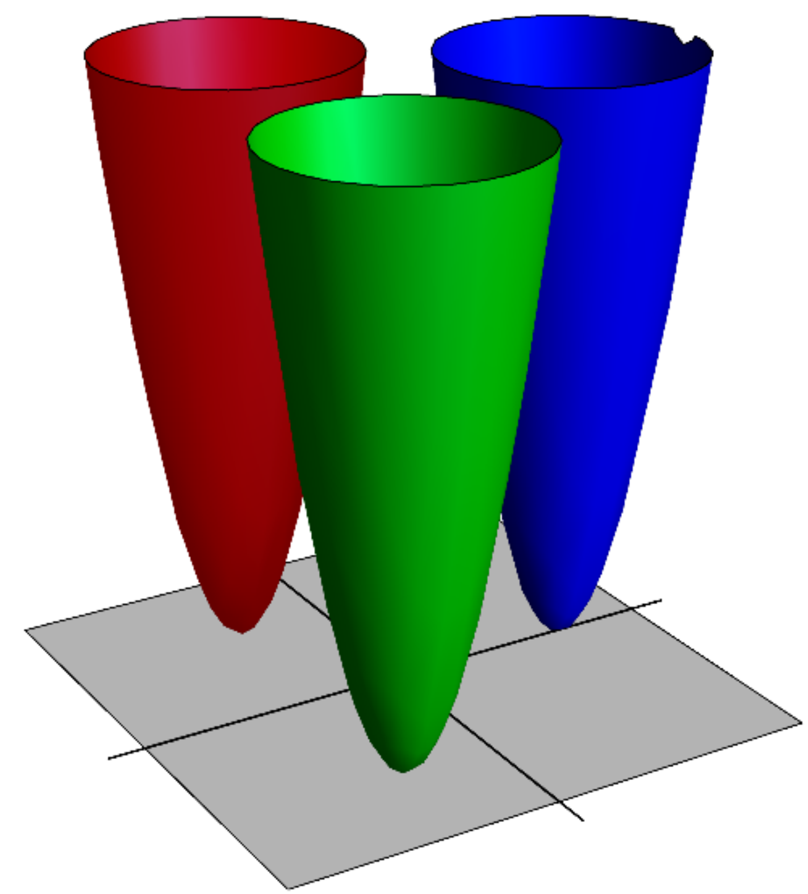
Y.-J. Lin *et al*; Nature (2011)

Physical picture

Geometry

Resulting uncoupled dispersion

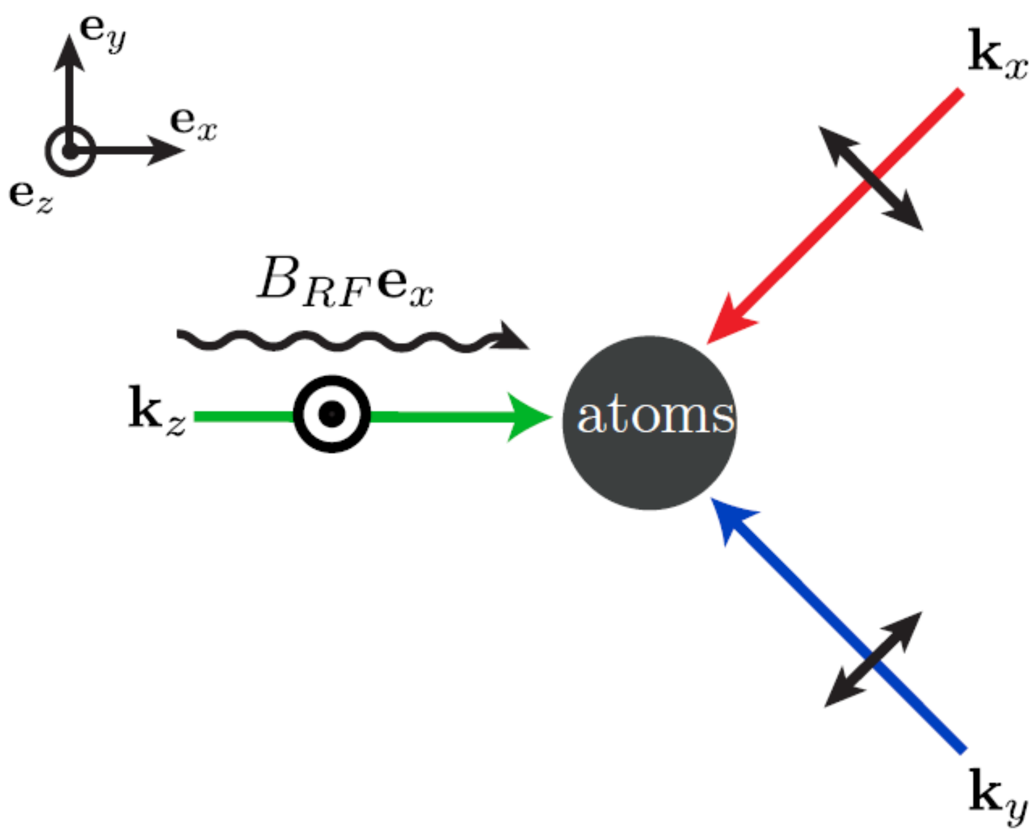




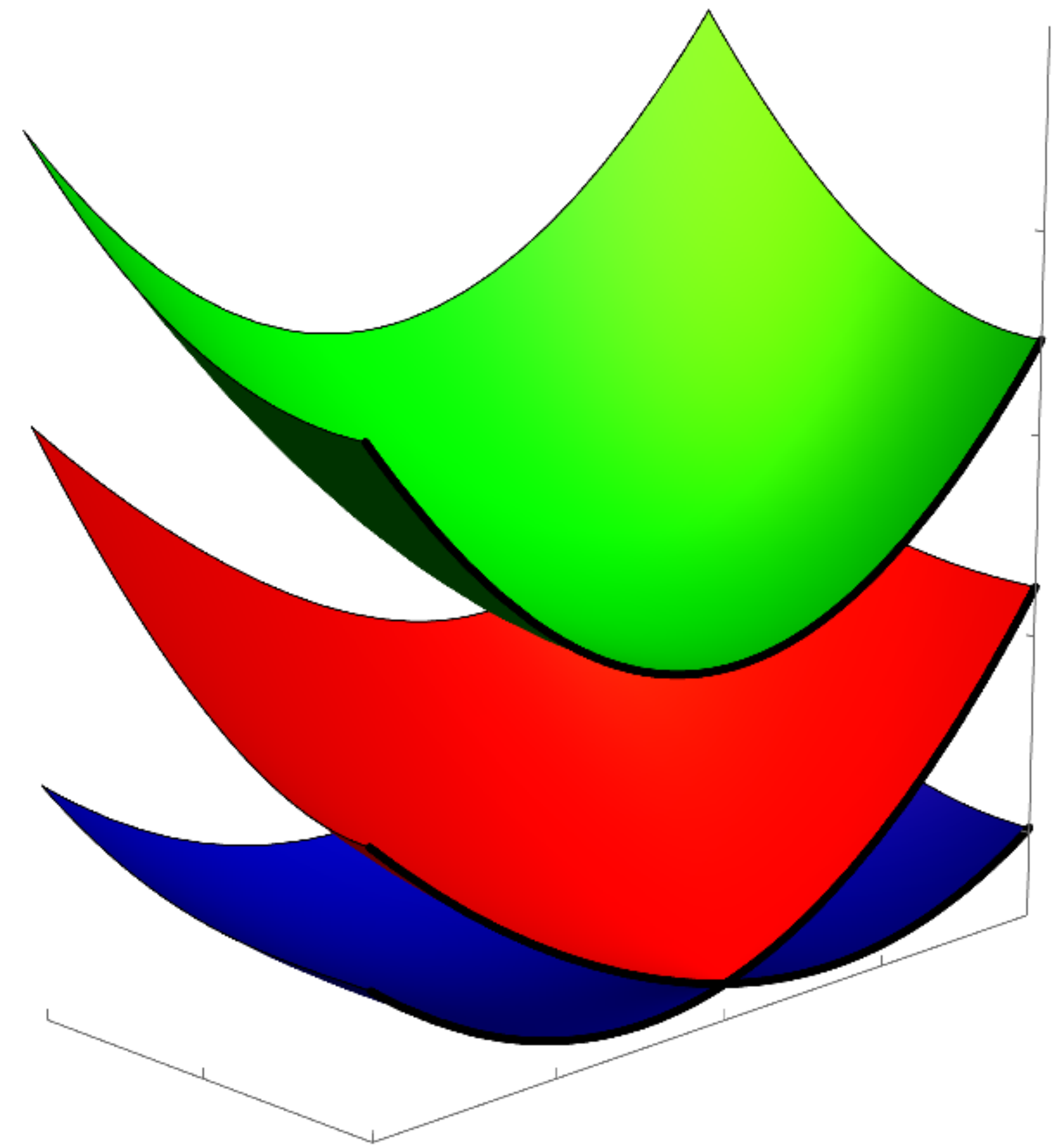
D. L. Campbell, G. Juzeliūnas, and IBS; PRA (2011)

Physical picture

Geometry



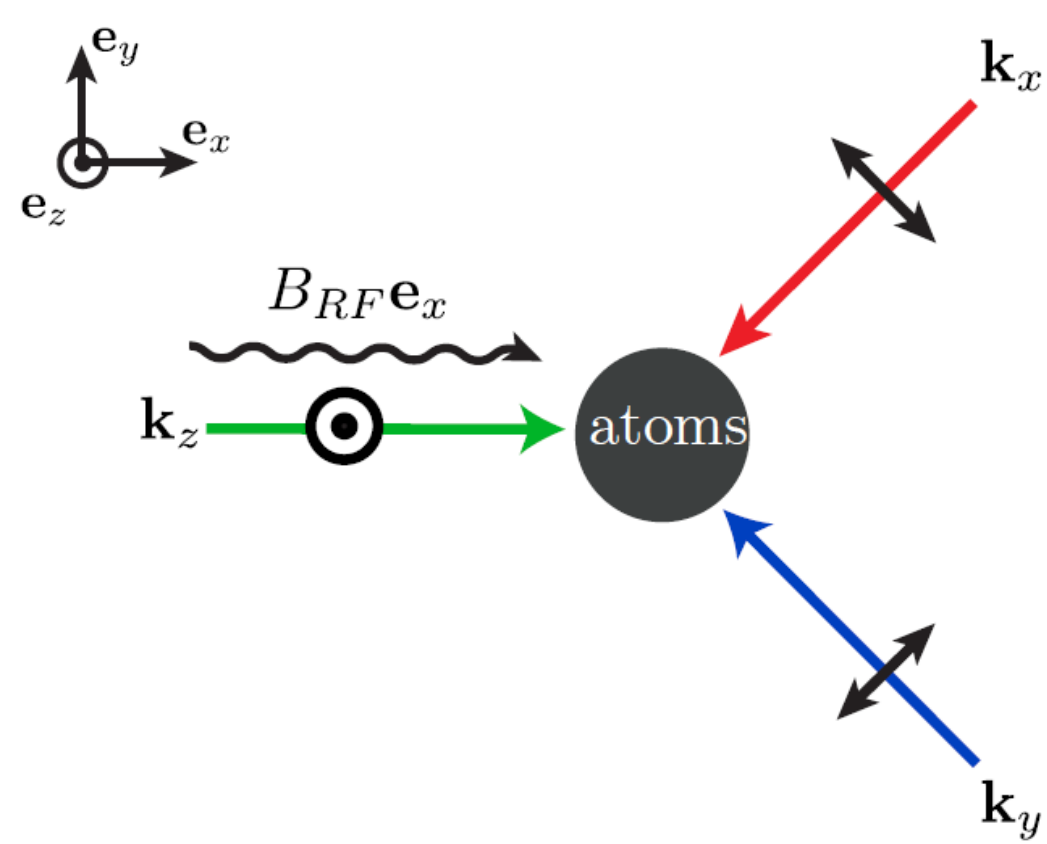
Resulting dispersion



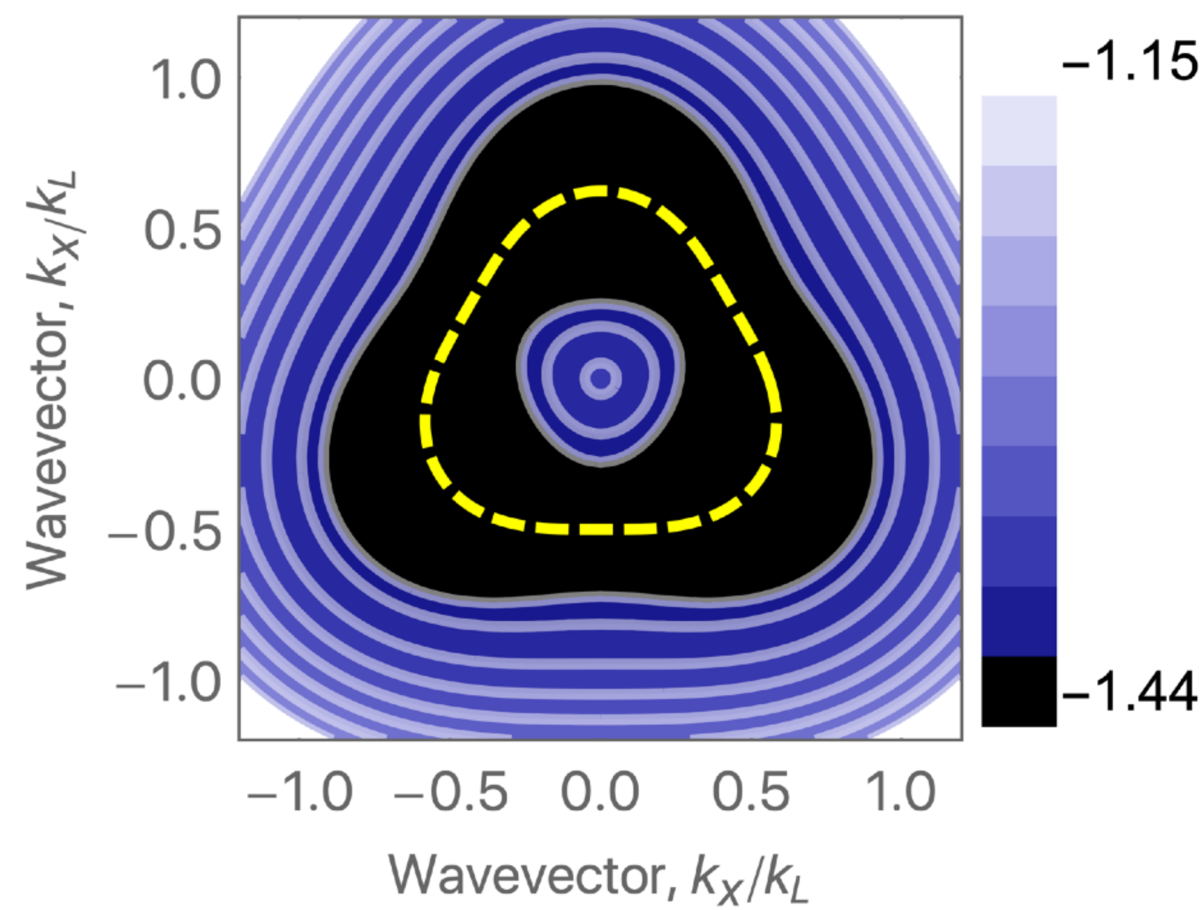
D. L. Campbell, G. Juzeliūnas, and IBS; PRA (2011)

Physical picture

Geometry



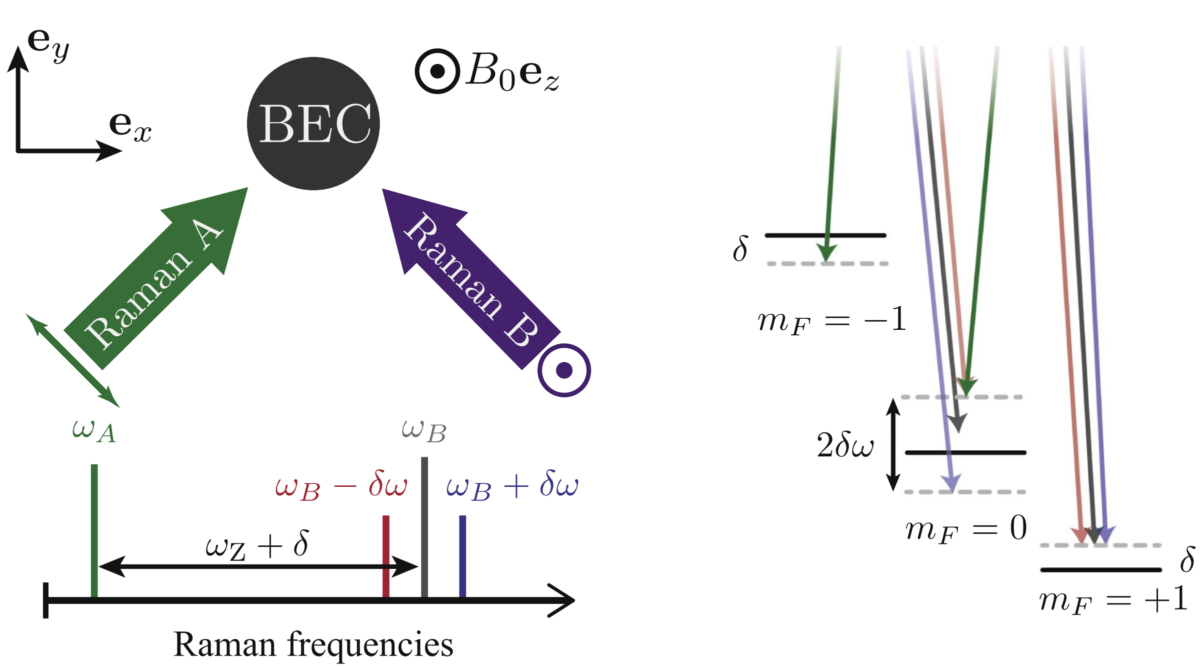
Resulting dispersion



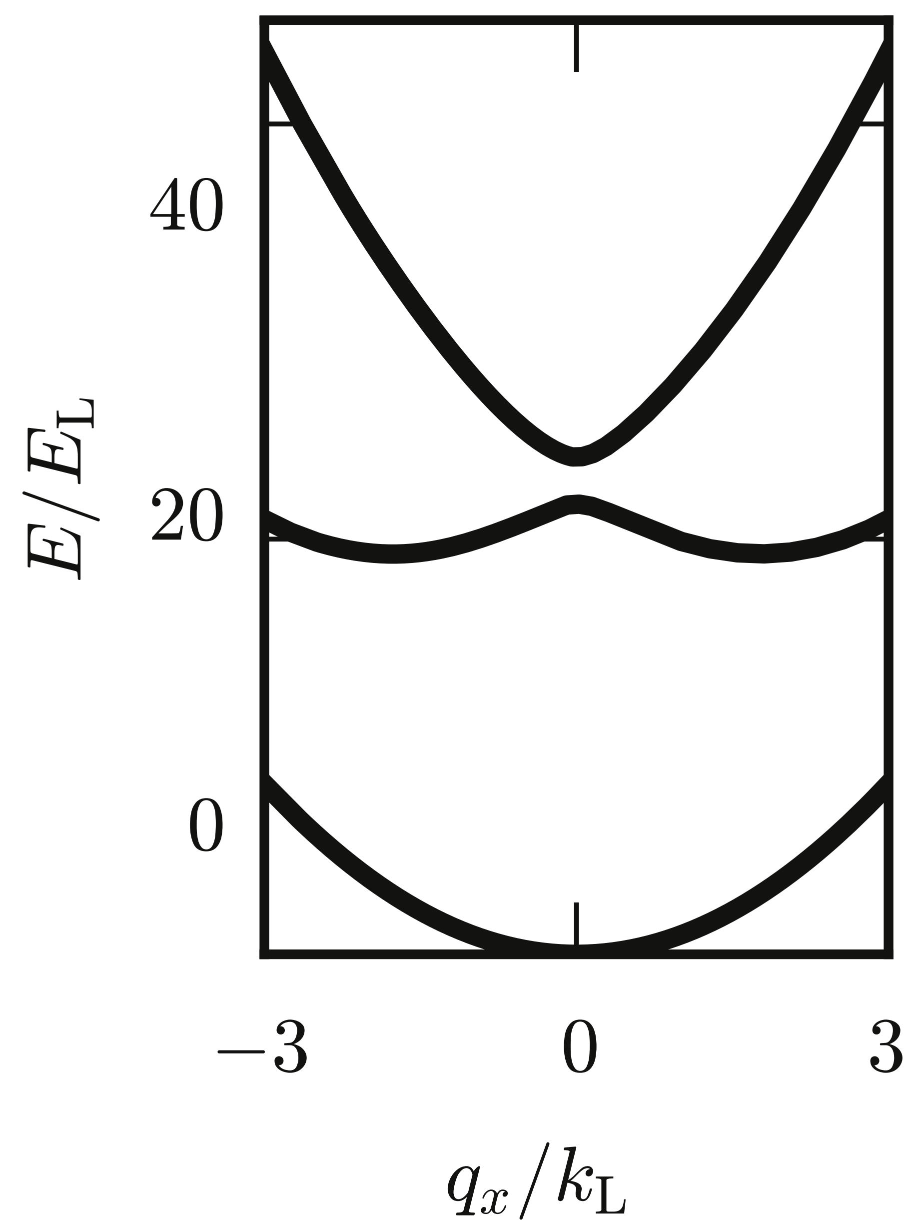
D. L. Campbell, G. Juzeliūnas, and IBS; PRA (2011)

Fourier transform spectroscopy (aside)

Setup



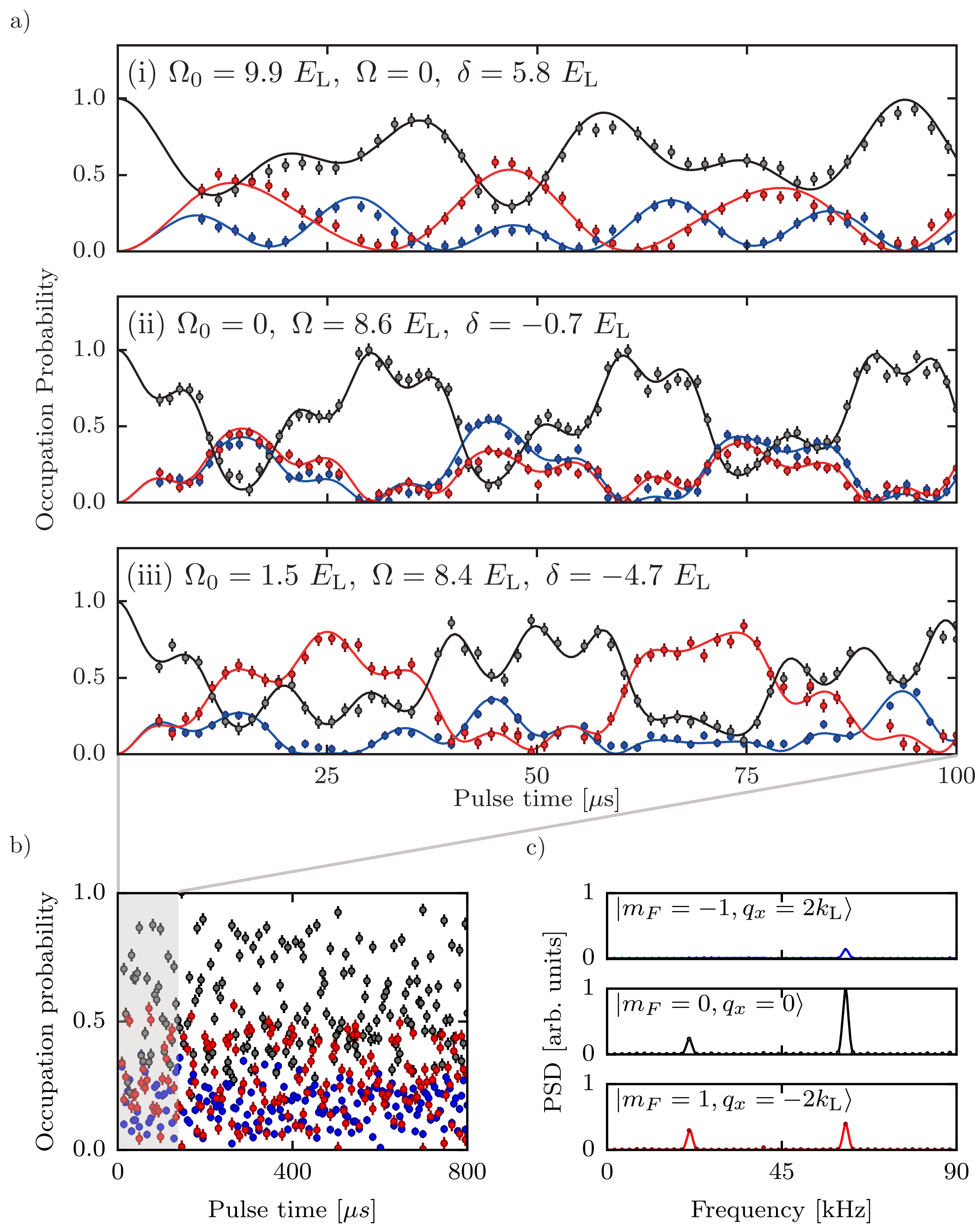
Dispersion relation



A. Valdés-Curiel et al; NJP (2018)

Fourier transform spectroscopy (aside)

Time traces



Frequencies?

Measurement basis

Evolution basis

$$|\psi_0\rangle \rightarrow |\psi_0(t)\rangle = \sum_j \langle j|\psi_0\rangle\, e^{-i\omega_j t}\, |j\rangle$$

Then detect probability in $\{|\psi_k\rangle\}_k$

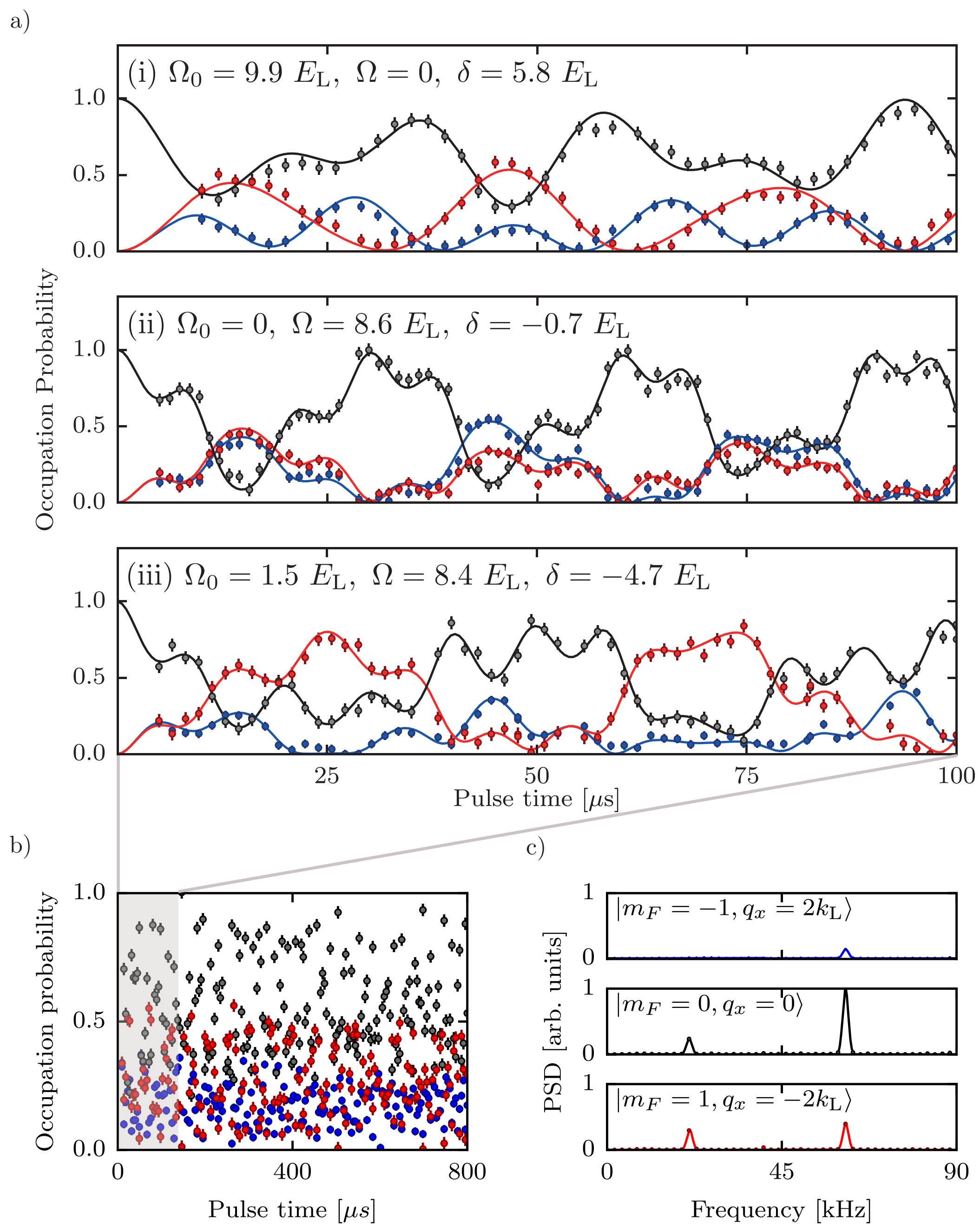
$$P_k(t) = |\langle\psi_k|\psi(t)\rangle|^2$$
$$= 1 + 2\sum_{j,j'} |\, \langle\psi_k|j\rangle\, \langle j|\psi_0\rangle\, \langle\psi_0|j'\rangle\, \langle j'|\psi_k\rangle\, |\cos[(\omega_j - \omega_{j'})t]$$

all frequency differences

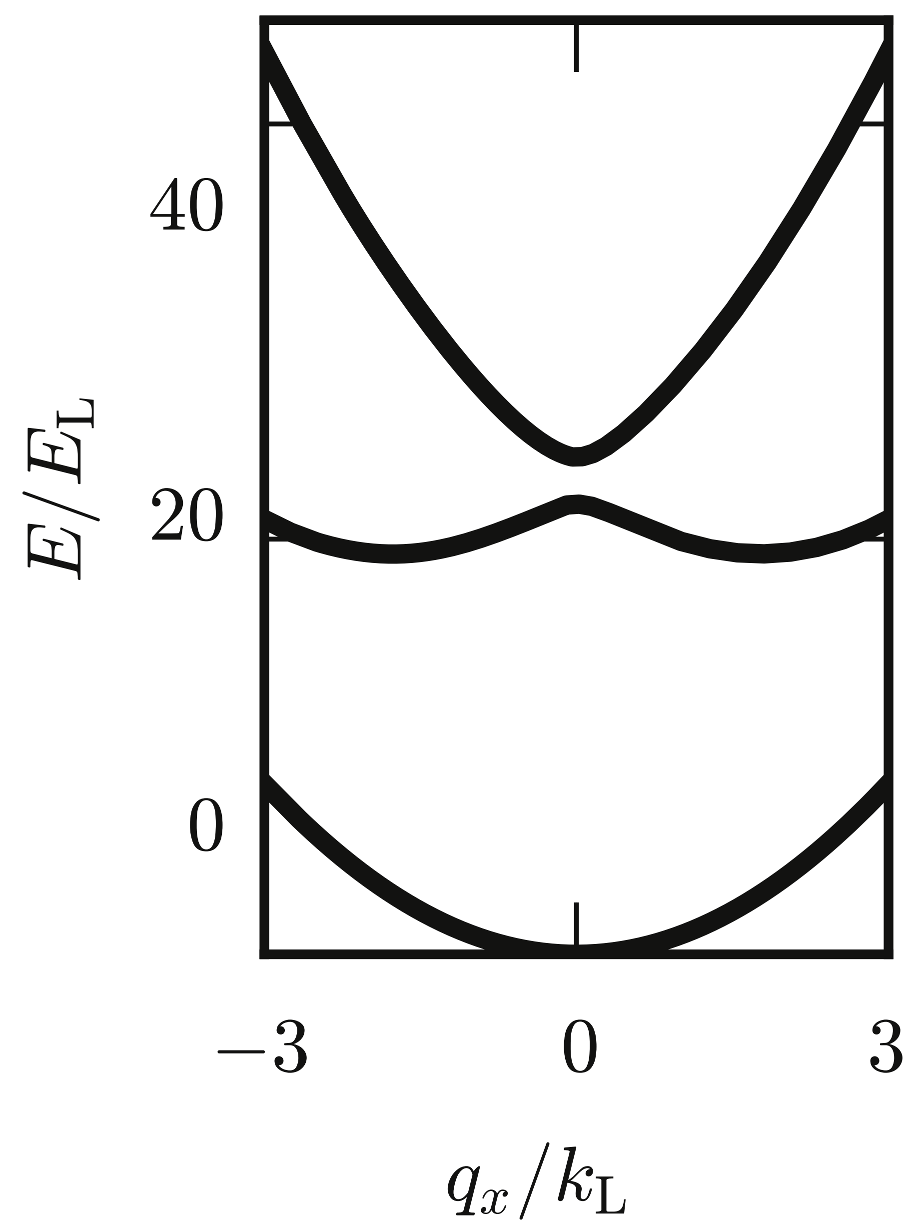
A. Valdés-Curiel et al; NJP (2018)

Fourier transform spectroscopy (aside)

Time traces



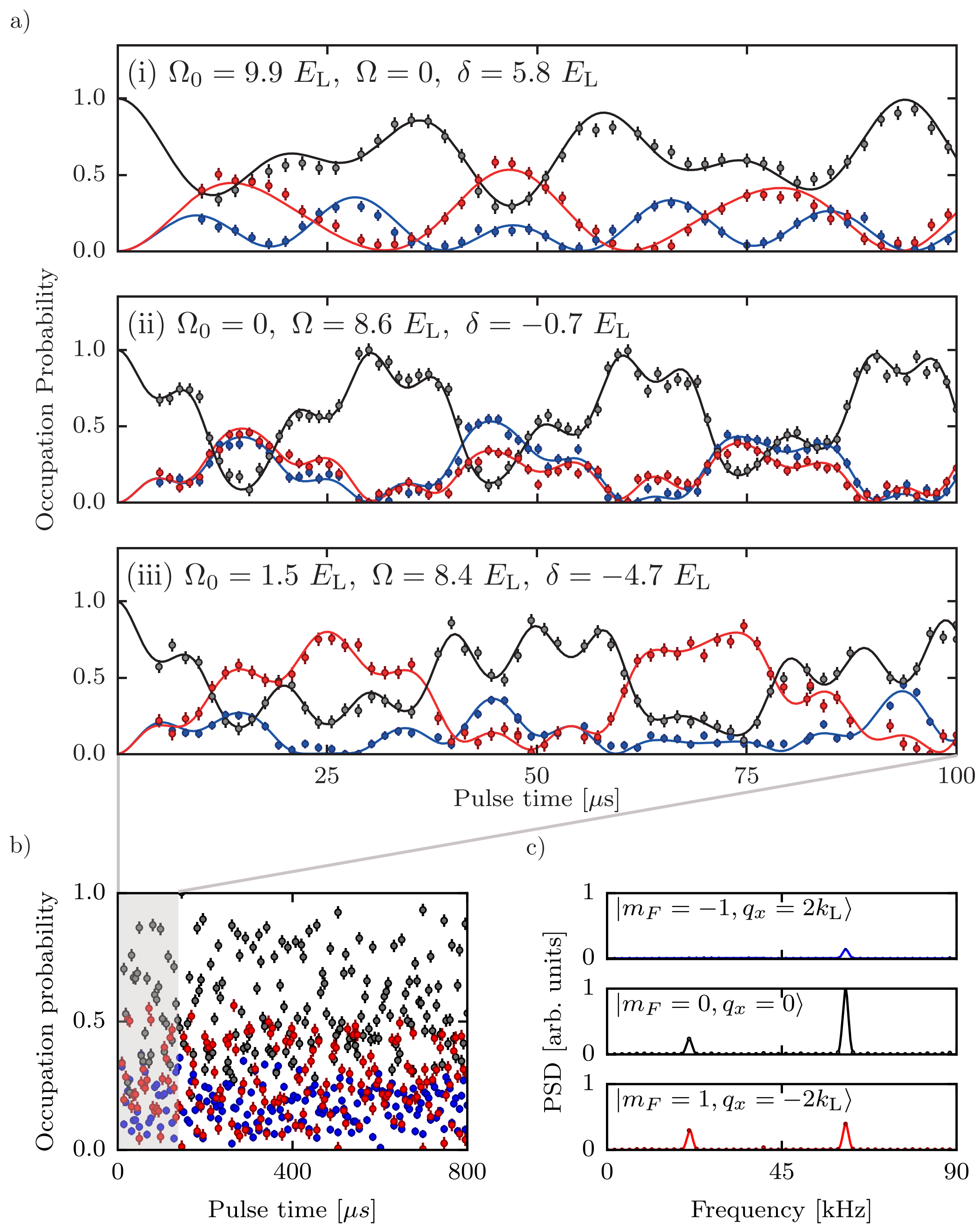
Dispersion relation



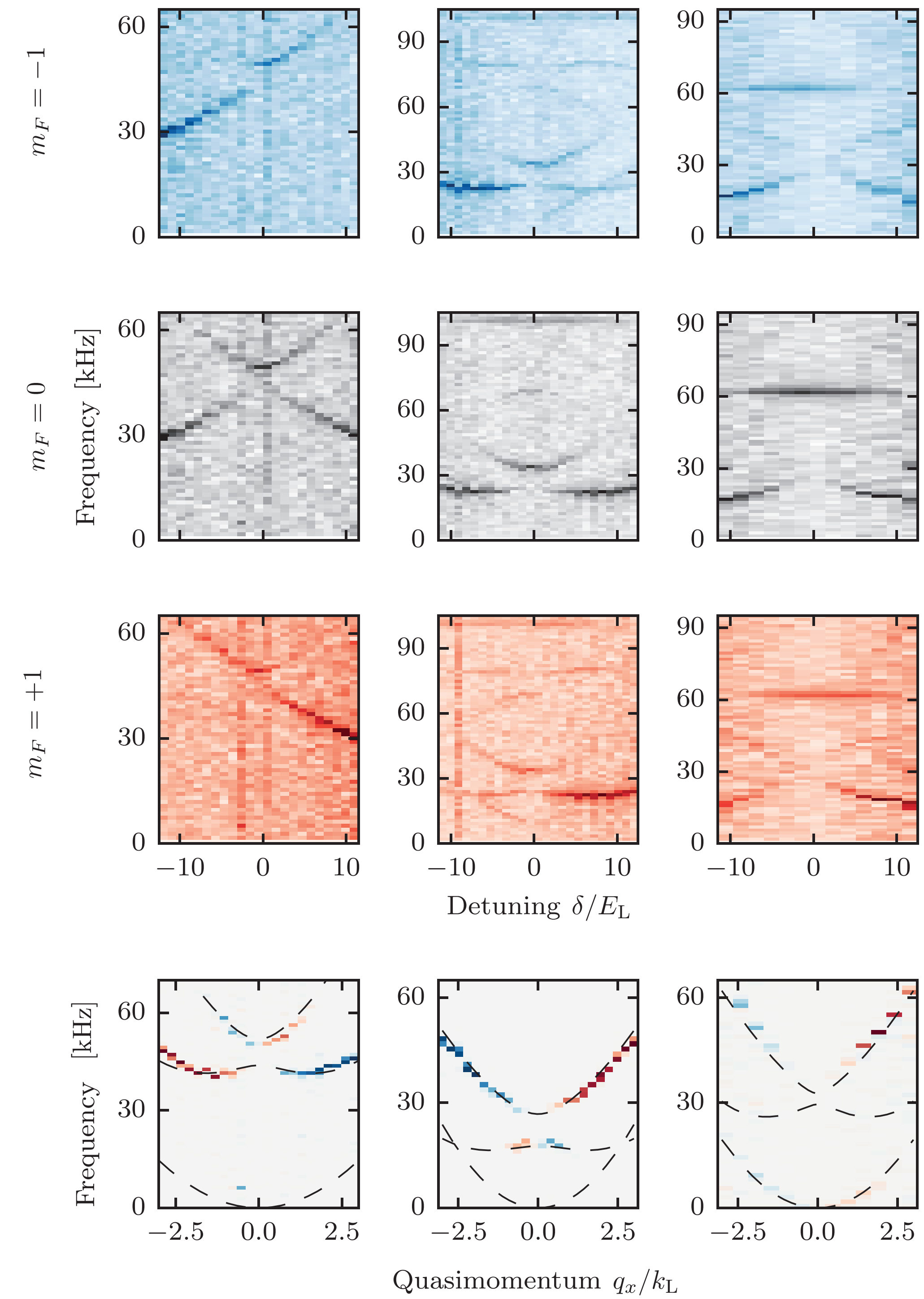
A. Valdés-Curiel et al; NJP (2018)

Fourier transform spectroscopy

Time traces



Dispersion relations

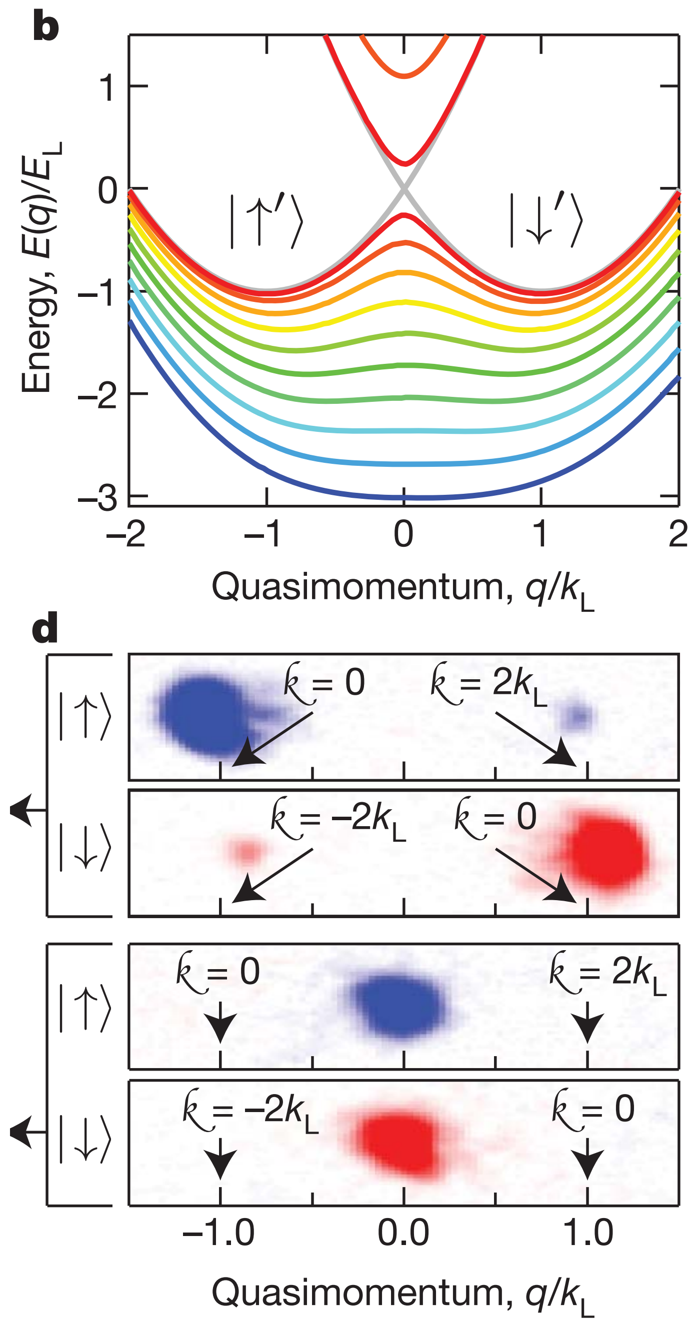


A. Valdés-Curiel et al; NJP (2018)

What data looks like

Reminder of 1D SOC

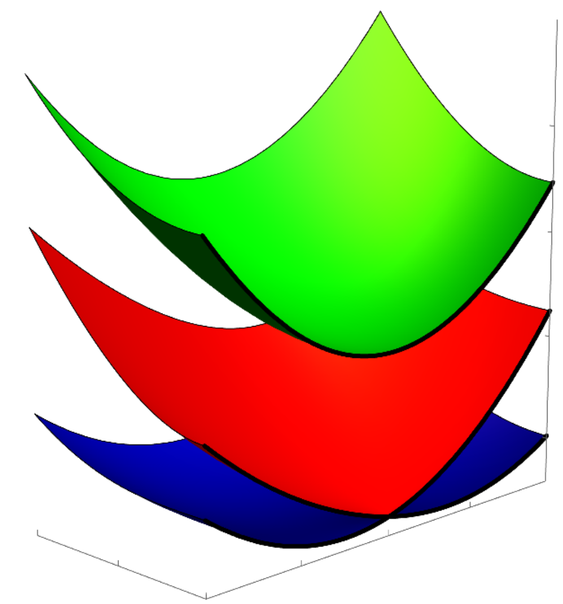
Spin-momentum locking

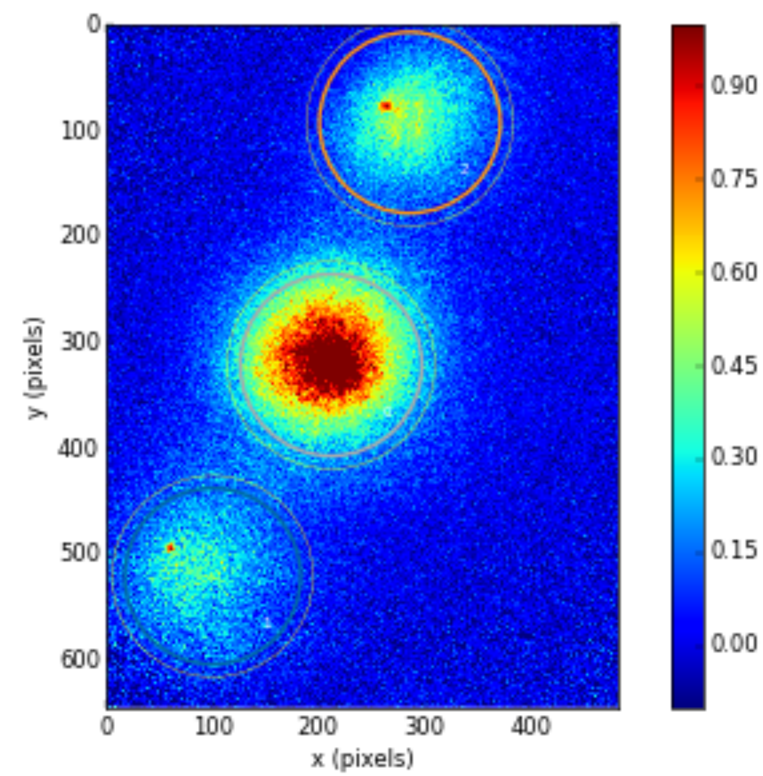


Lin *et al*; Nature (2011)

2D SOC with three states

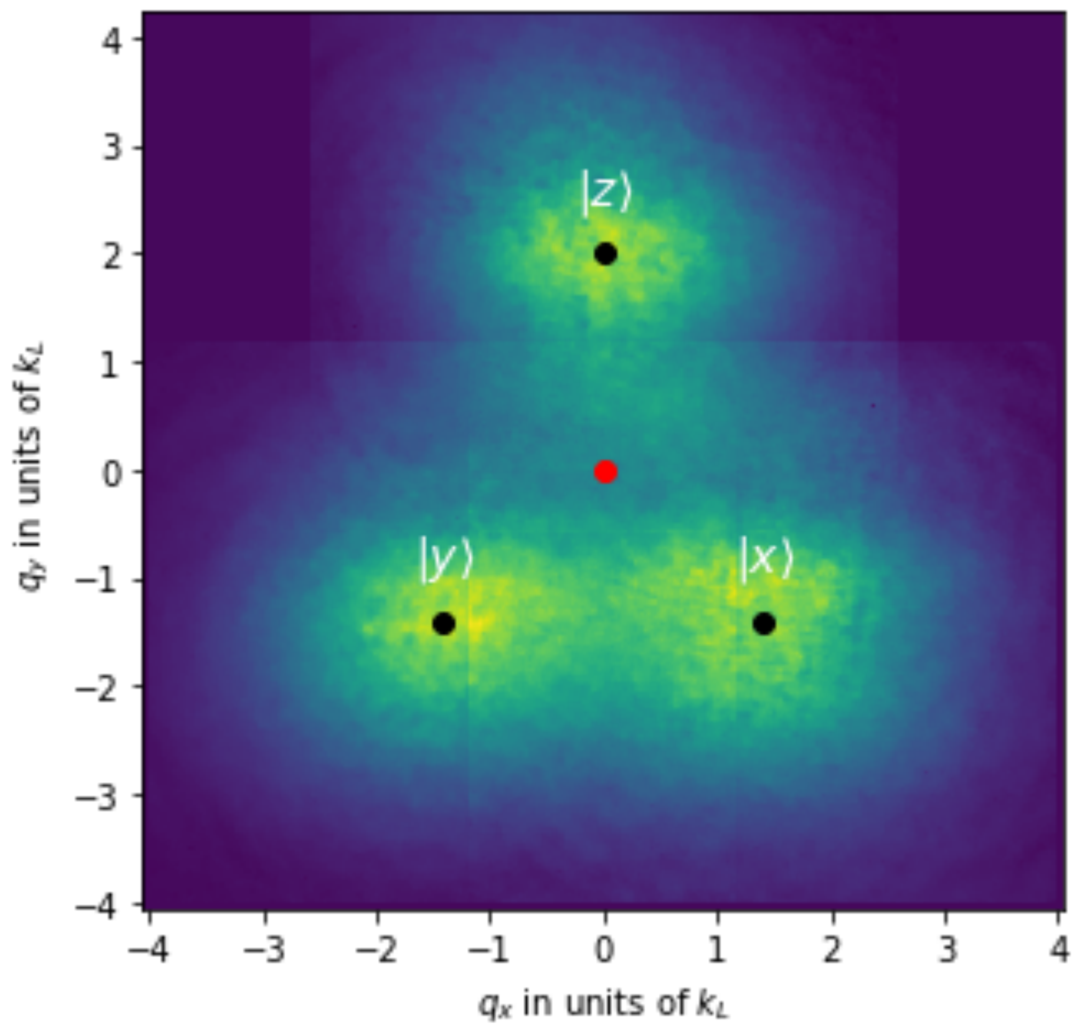
Same idea





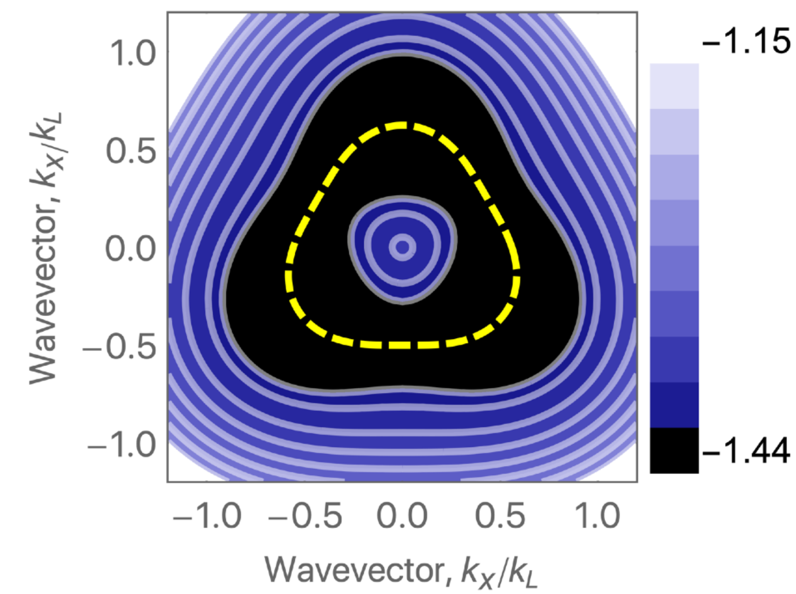
Fourier transform spectroscopy

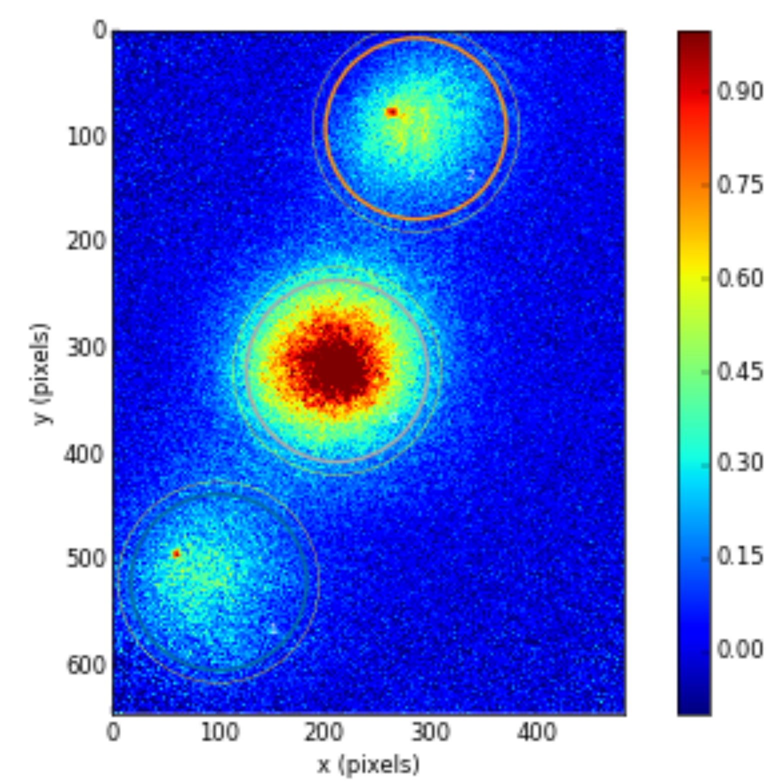
<u>Initial state</u>



<u>2D SOC with three states</u>

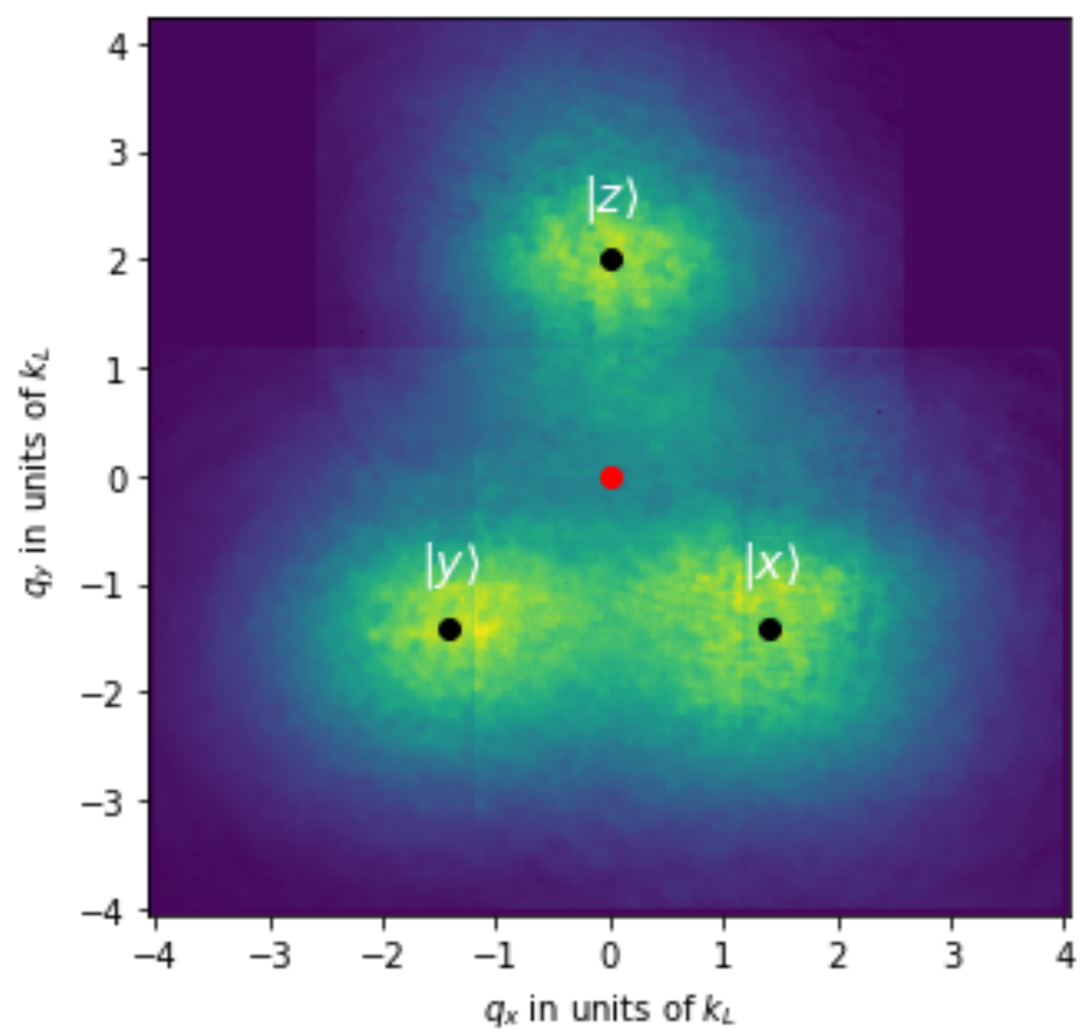
Same idea



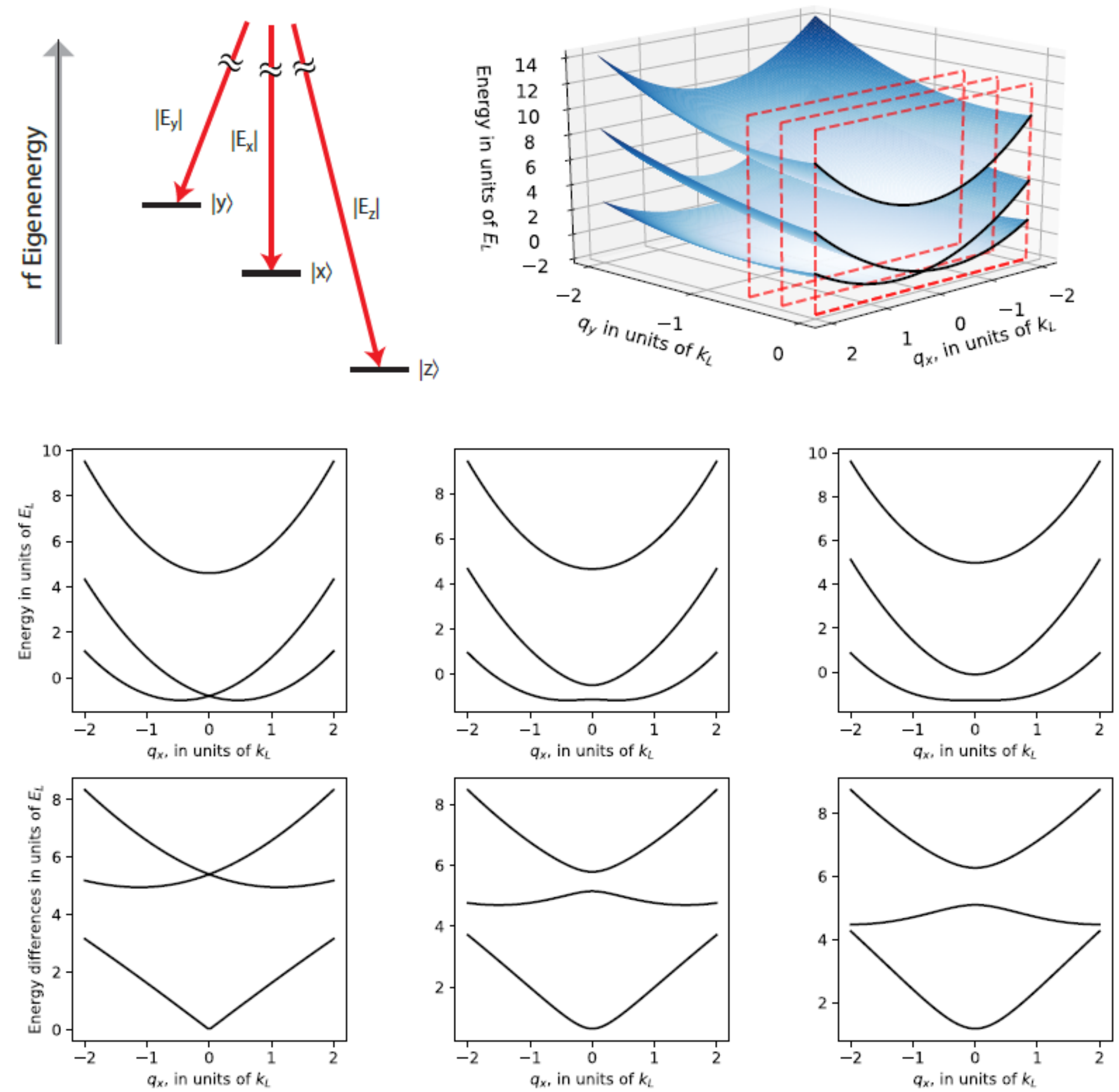


Fourier transform spectroscopy

Initial state

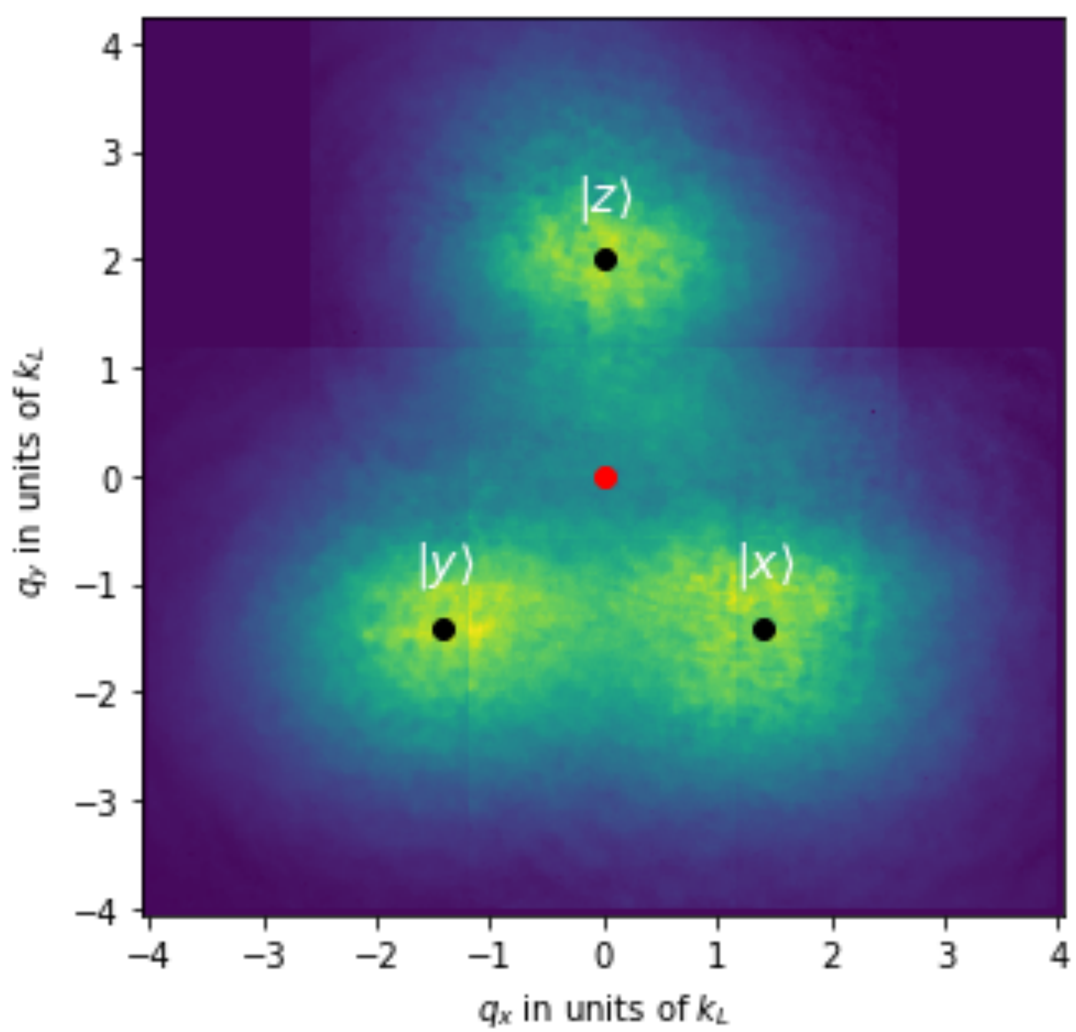


Target energies

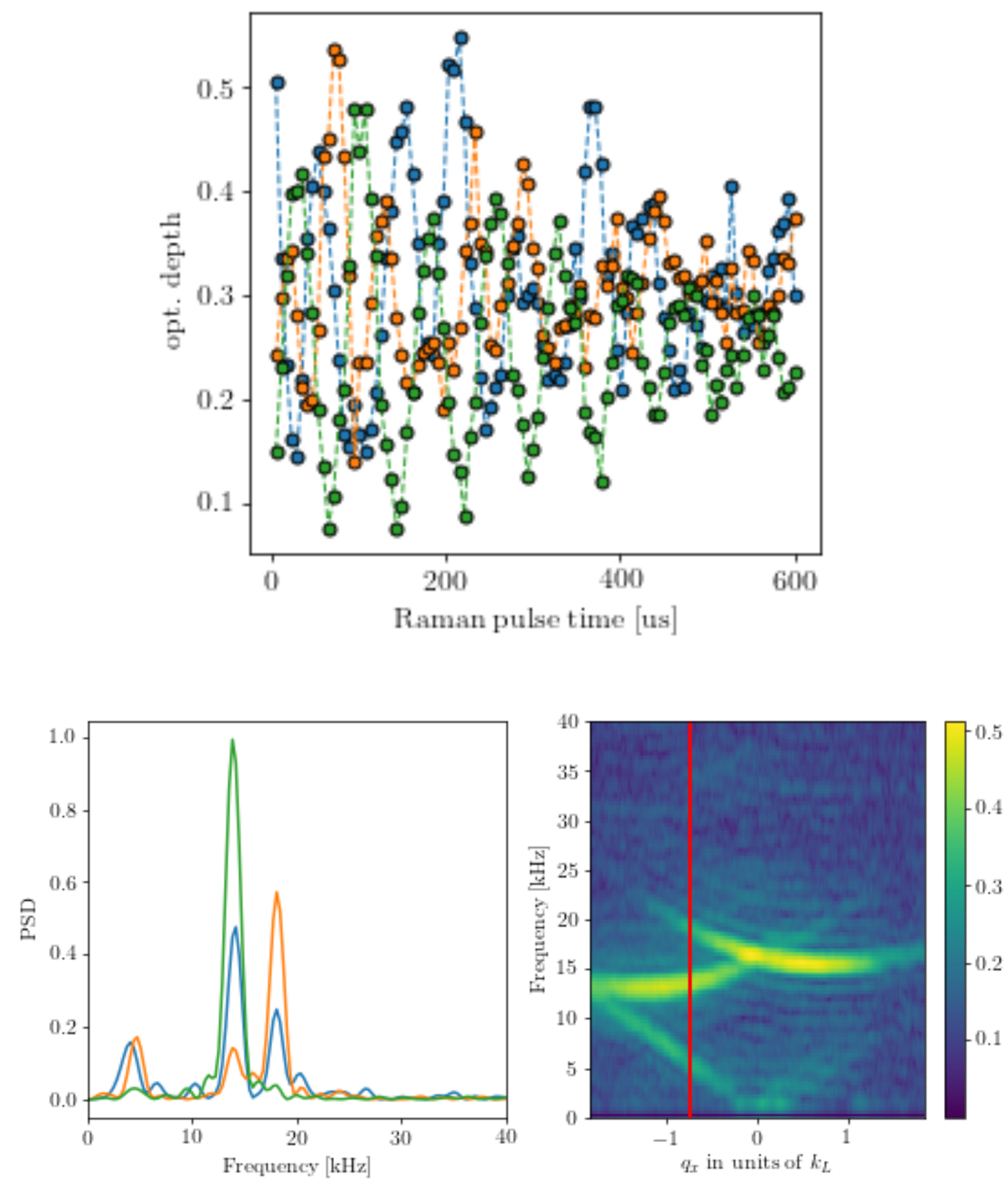


Fourier transform spectroscopy

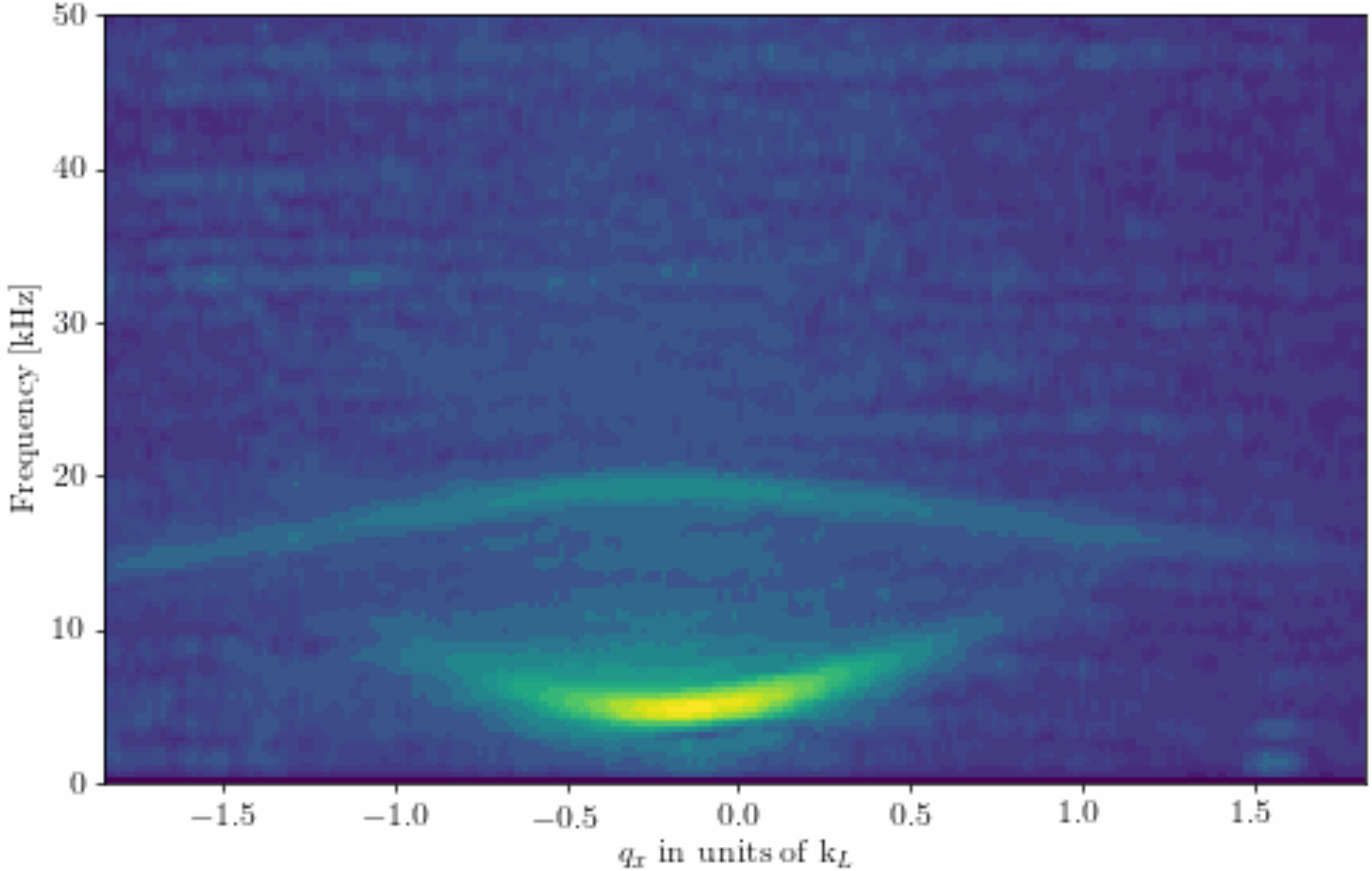
Initial state



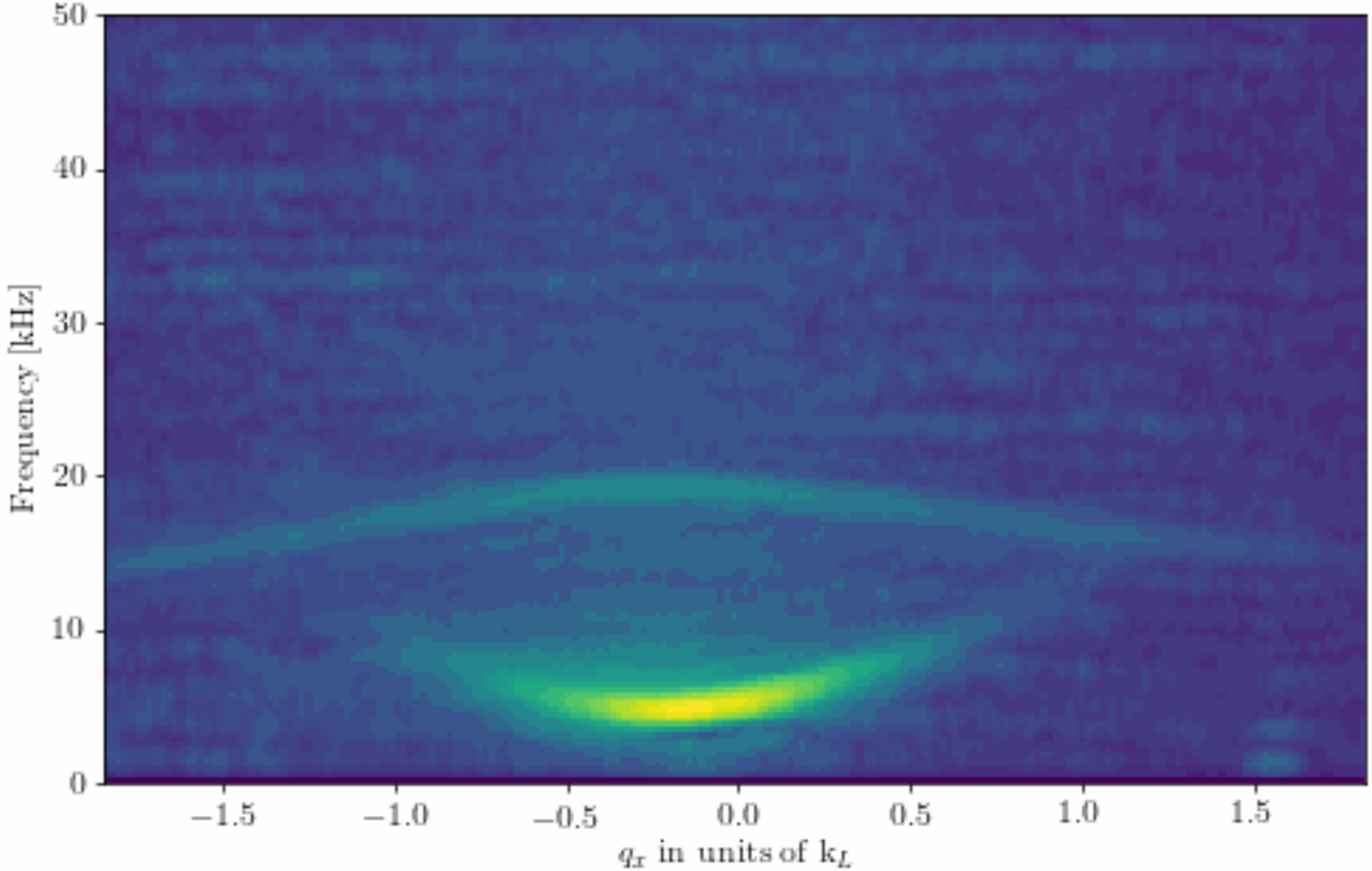
Observations



Fourier transform spectroscopy



Fourier transform spectroscopy

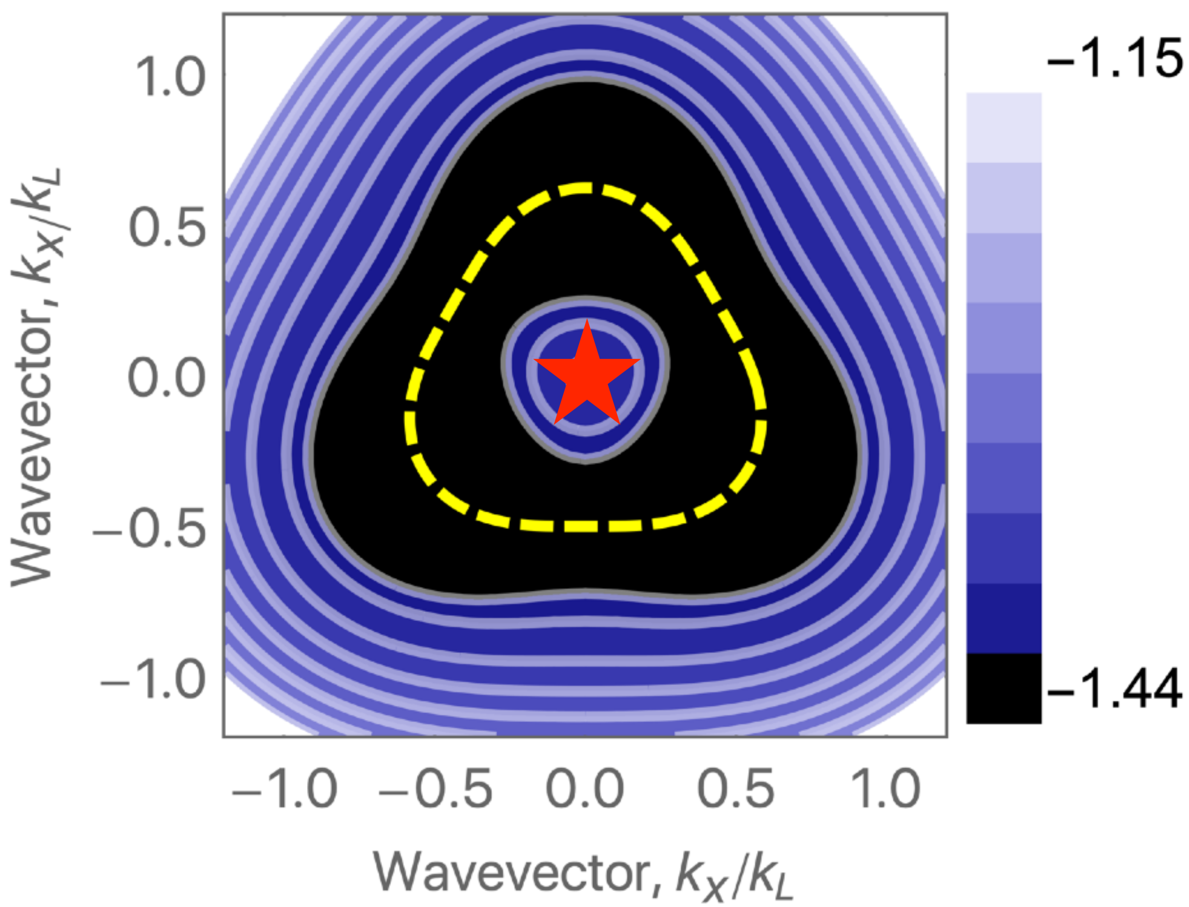


“Band” topology

Dispersion

Single Dirac point + non-periodic potential

“Chern index” = 1/2



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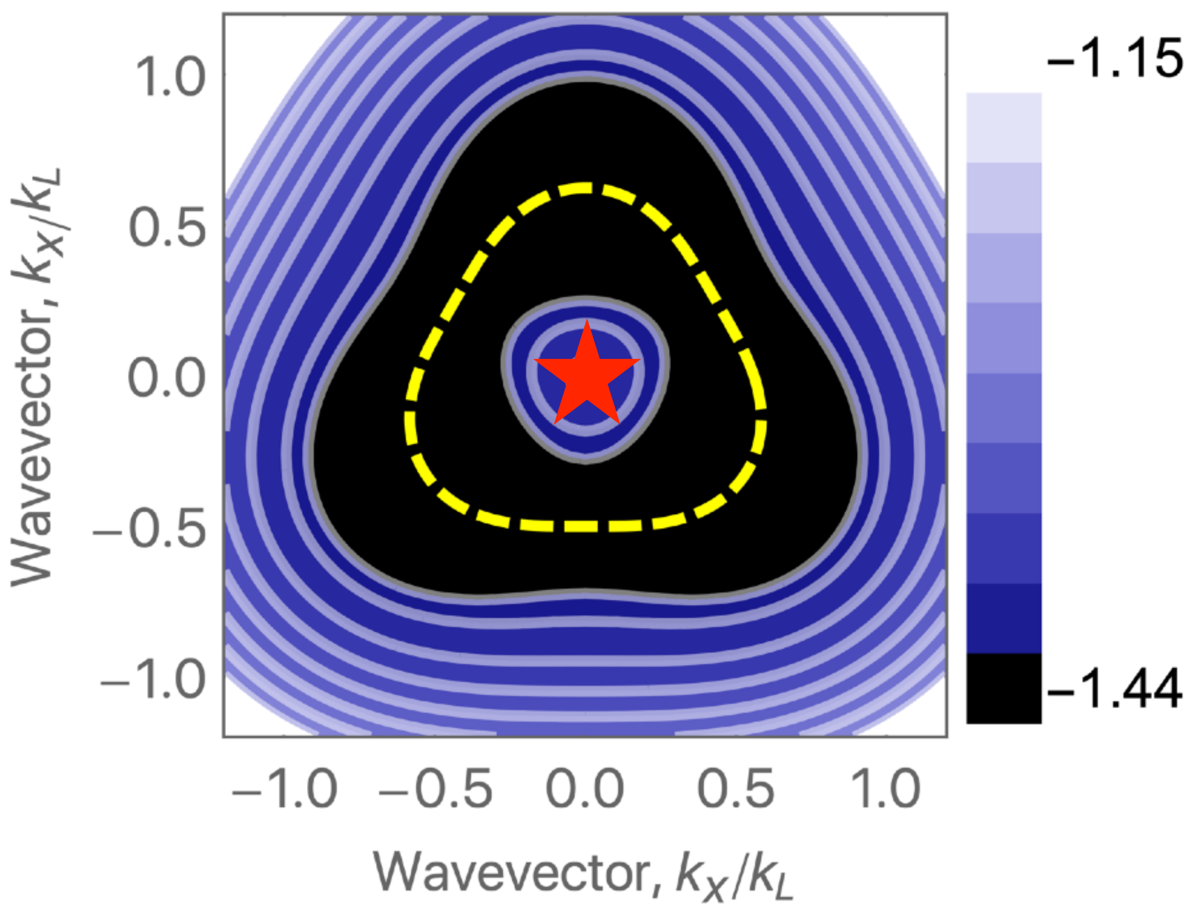
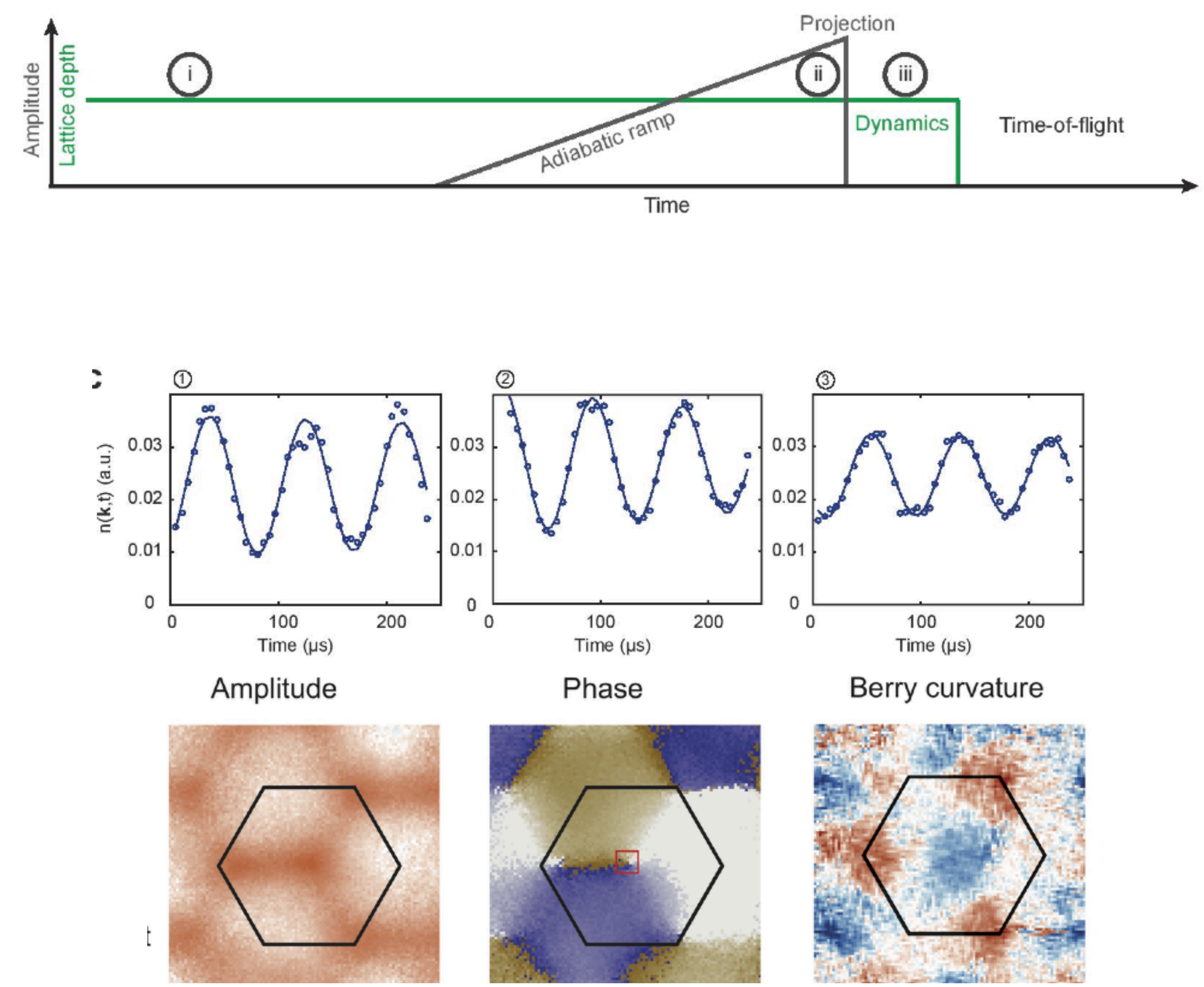


Measurement inspiration

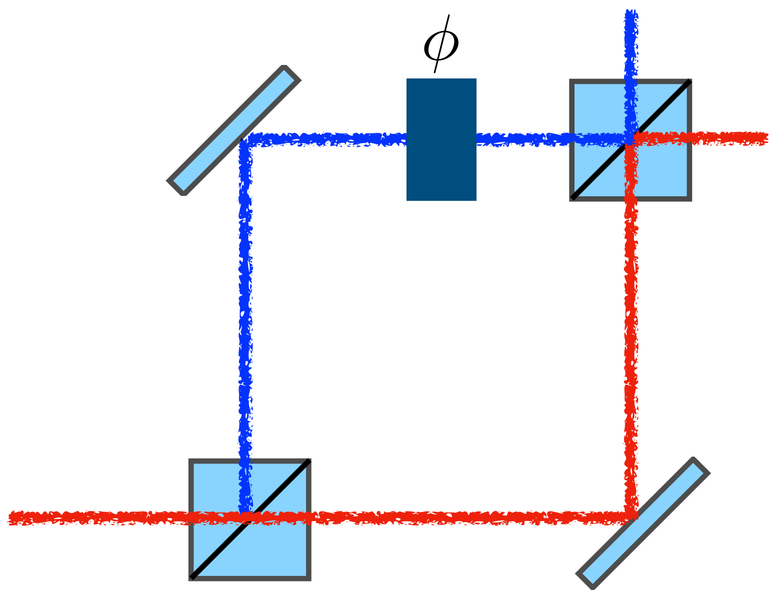


P. Hauke, M. Lewenstein, and A. Eckardt; PRL (2014)
N. Fläschner, et al; Science (2016)

Measuring phases

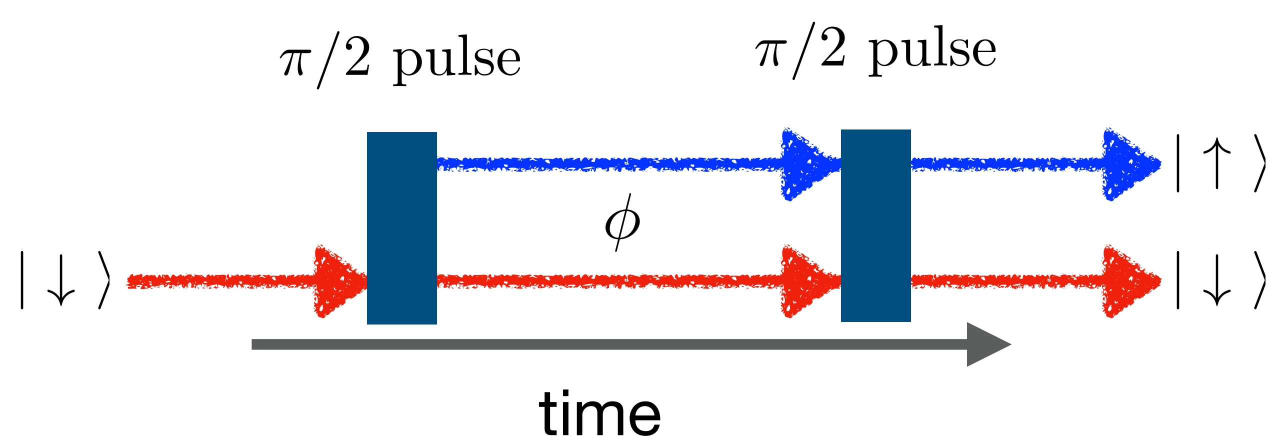
Measuring phases in optics

Interferometer



Measuring phases with atoms

Ramsey Interferometer



Here we change "phi" to learn about the phases imparted by the first pulse

Measuring phases

$$A_j = i \sum_n \psi_n^*(k)\, \partial_{k_j} \psi_n(k) \qquad (6)$$

↑ real valued

now if we express $\psi_n(k) = |\psi_n(k)|\, e^{i\phi_n(k)}$

$$A_j = \underbrace{i \sum_n |\psi_n(k)|^2 \left(i \partial_{k_j} \phi_n(k)\right)}_{\text{real}} + \underbrace{i \sum_n |\psi_n(k)|\, \partial_{k_j} |\psi_n(k)|}_{\text{imaginary}} \to 0$$

$$\boxed{A_j = -\sum_n |\psi_n(k)|^2\, \partial_{k_j} \phi_n(k)} \quad \text{thus:} \qquad (7)$$

$$\boxed{\Omega_{ij} = -\sum_n |\psi_n(k)|^2 \left[\partial_{k_i}\partial_{k_j} - \partial_{k_j}\partial_{k_i}\right] \phi_n(k)} \qquad (8)$$

this is <u>Really Important</u>: A_j and Ω_{ij} are the weighted averages of gradients of the phases in each component of $\psi_n(k)\,|k,n\rangle$ separately.

Measuring phases

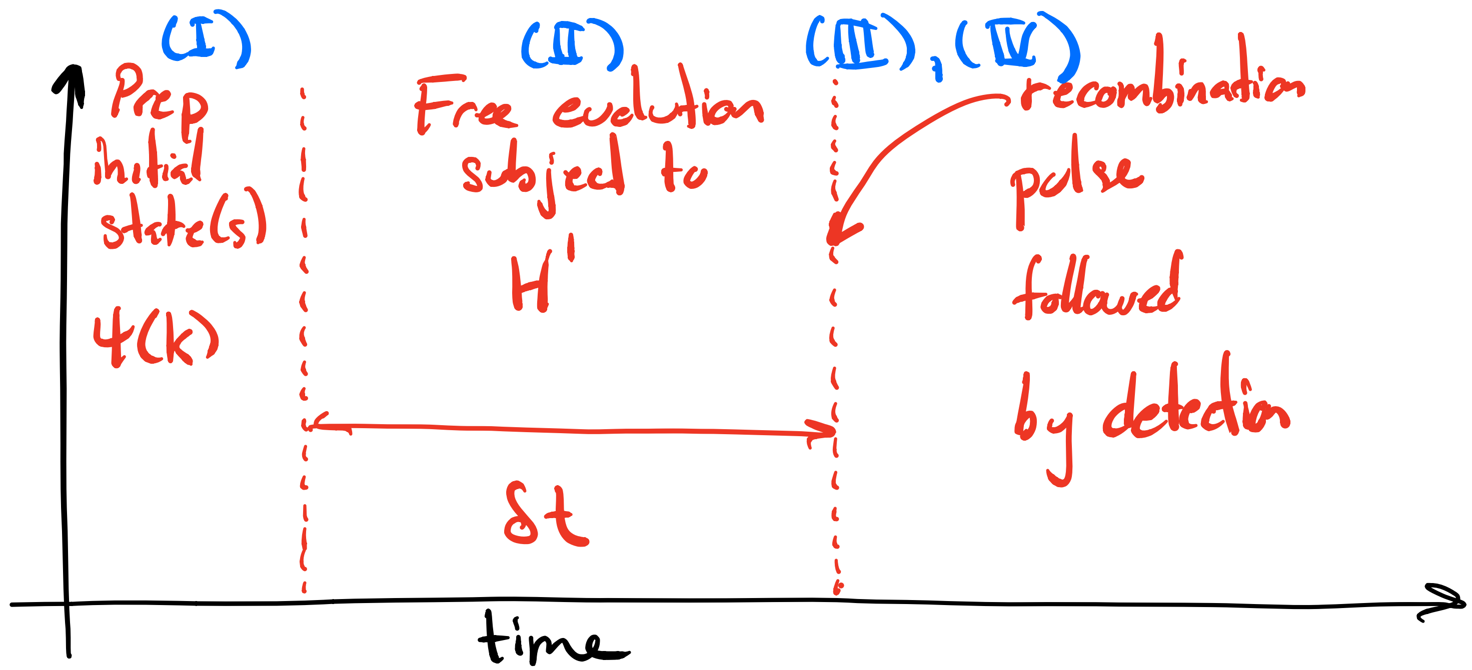


Fig. 1

$$P_m^{n,n'}(k) = |\psi_n(k)\psi_{n'}(k)|\, U_{m,n} U_{n',m} \exp(i\delta E_{n,n'}\delta t - i\delta\phi_{n,n'}) + c.c.$$

can contribute a k-independent phase.

known

$$= |\psi_n(k)\psi_{n'}(k) U_{m,n} U_{n',m}|\, 2\cos(\delta E_{n,n'}(k)\delta t - \delta\phi_{n,n'}(k) + \phi^U_{n,m}) \quad (13)$$

fits to time evolution gives all phase differences

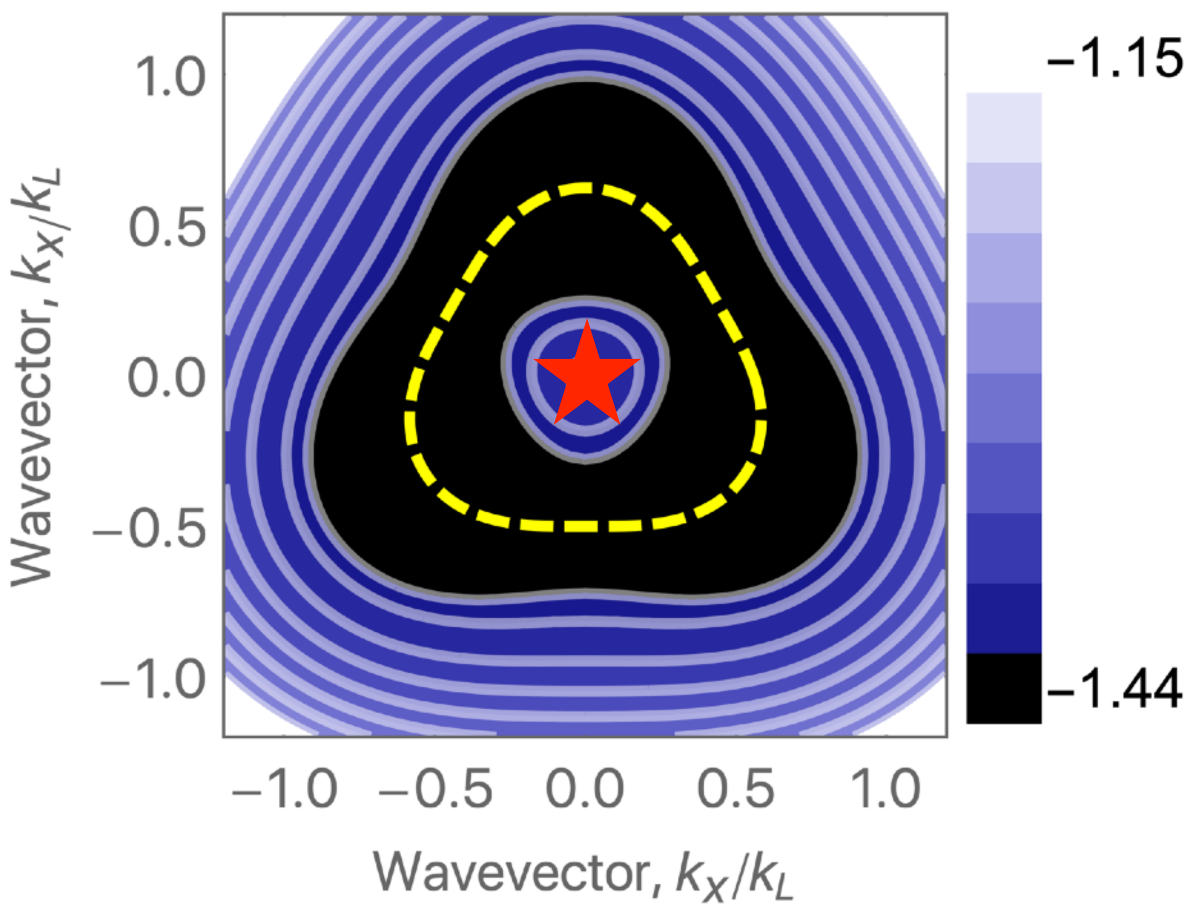
$N_{tot}(N_{tot}-1)/2$ equations

"Band" topology

Dispersion

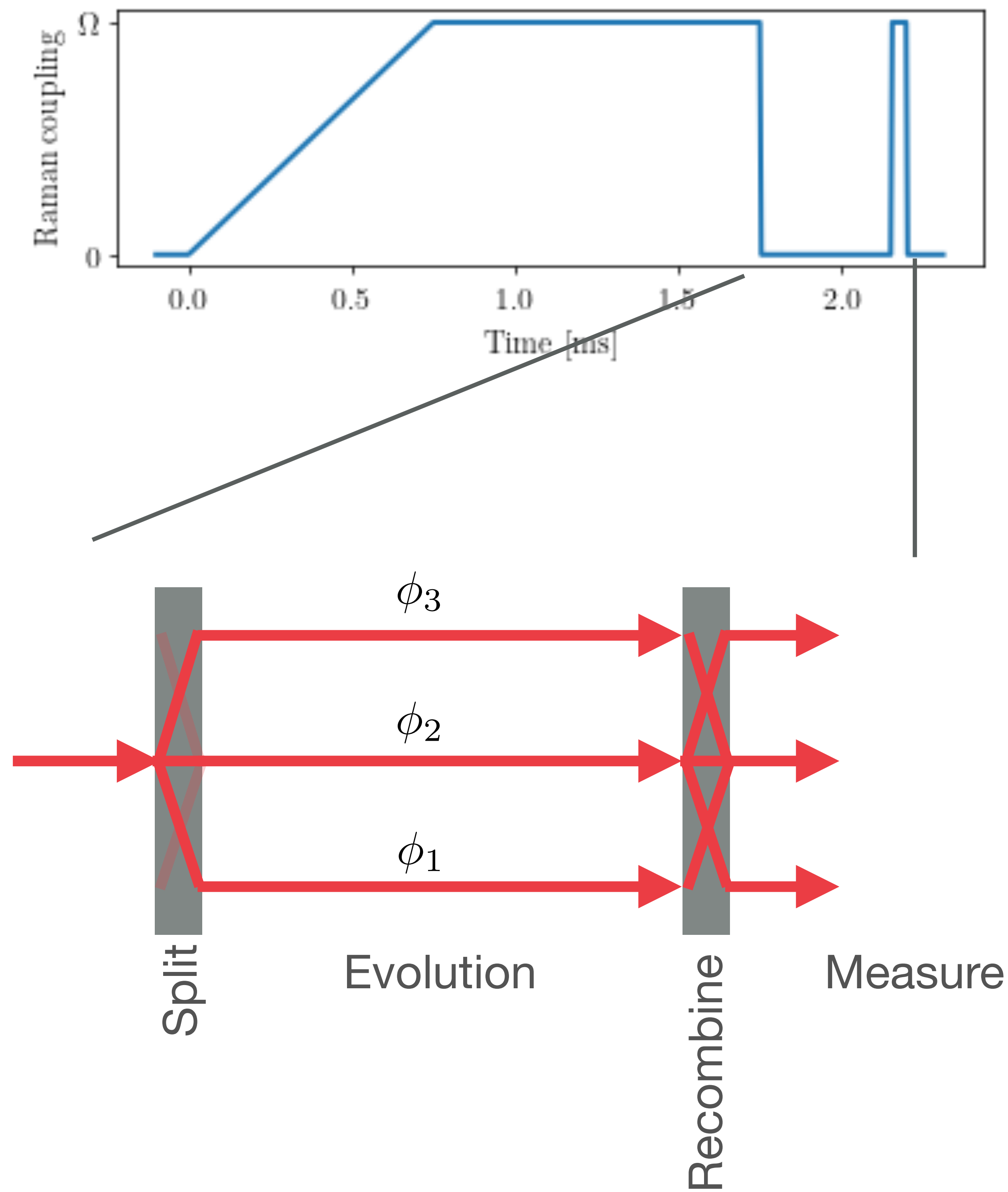
Single Dirac point + non-periodic potential

"Chern index" = 1/2



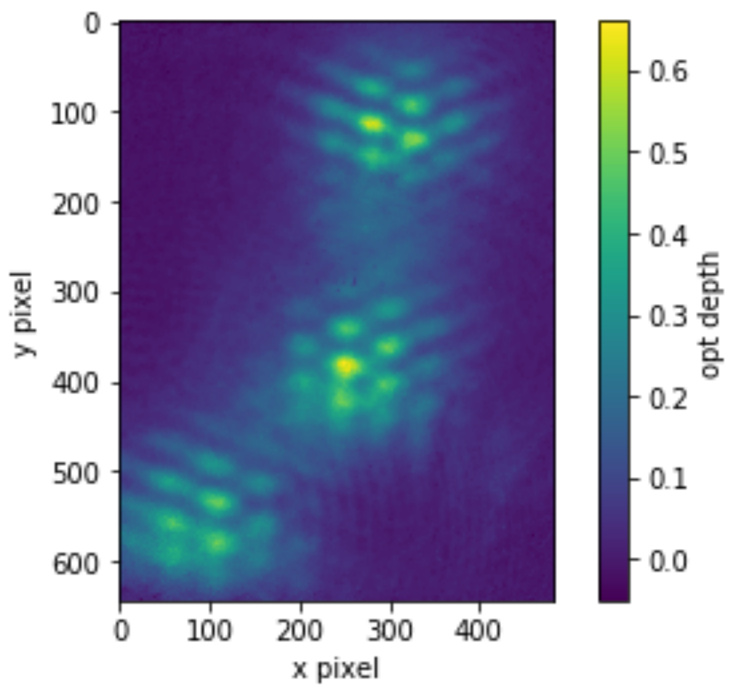
Our version

Three arm Ramsey interferometer

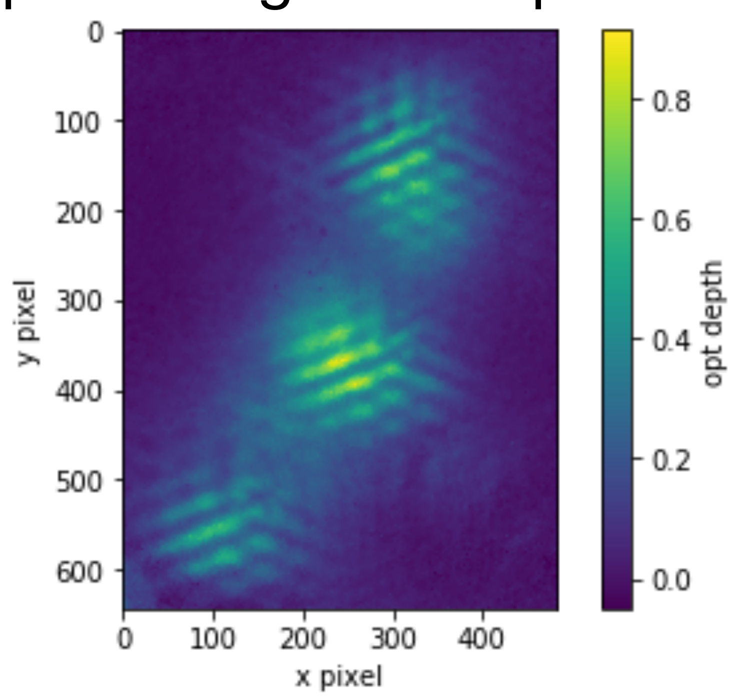


“Band” topology

Typical image: no Dirac point



Typical image: Dirac point



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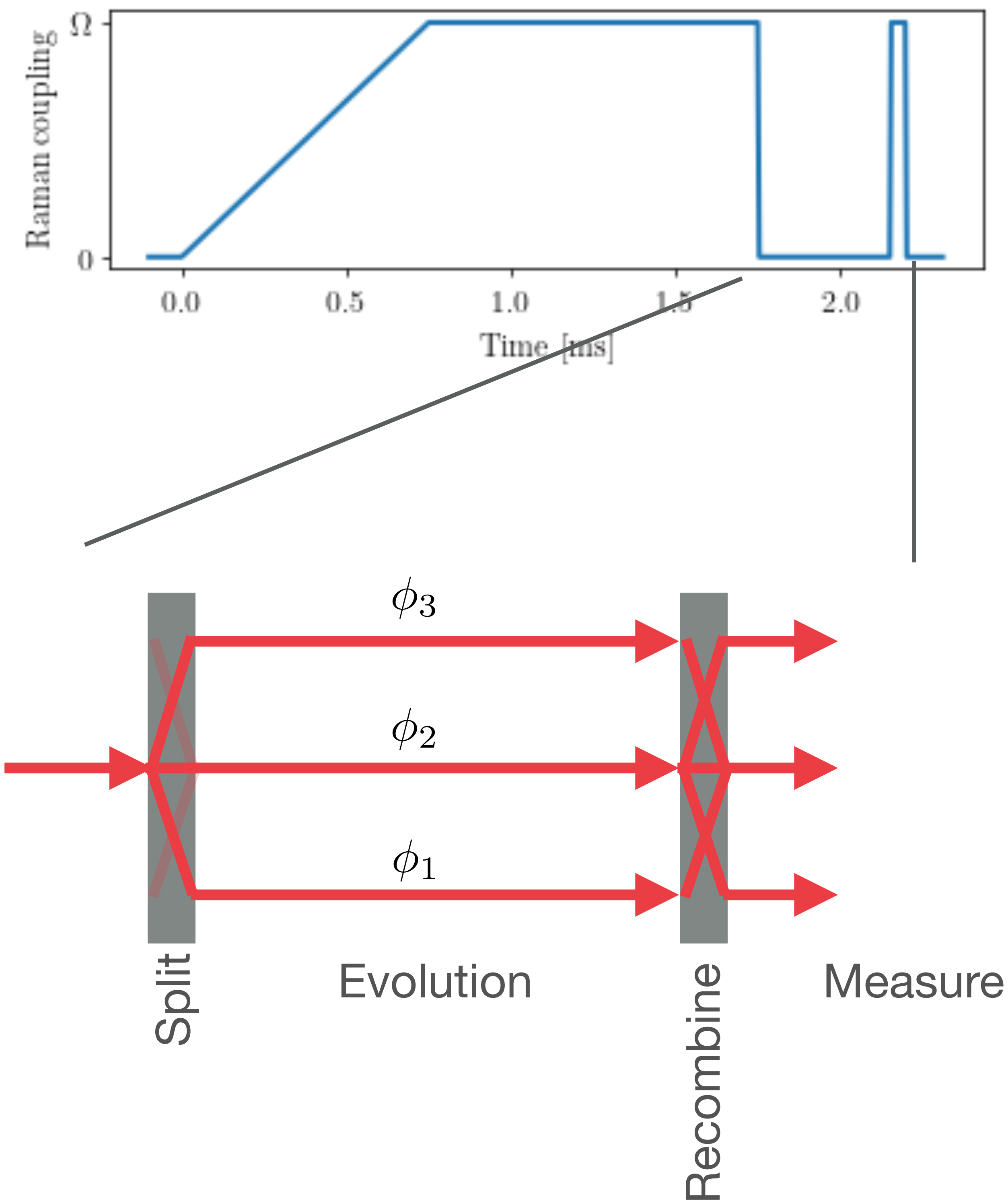
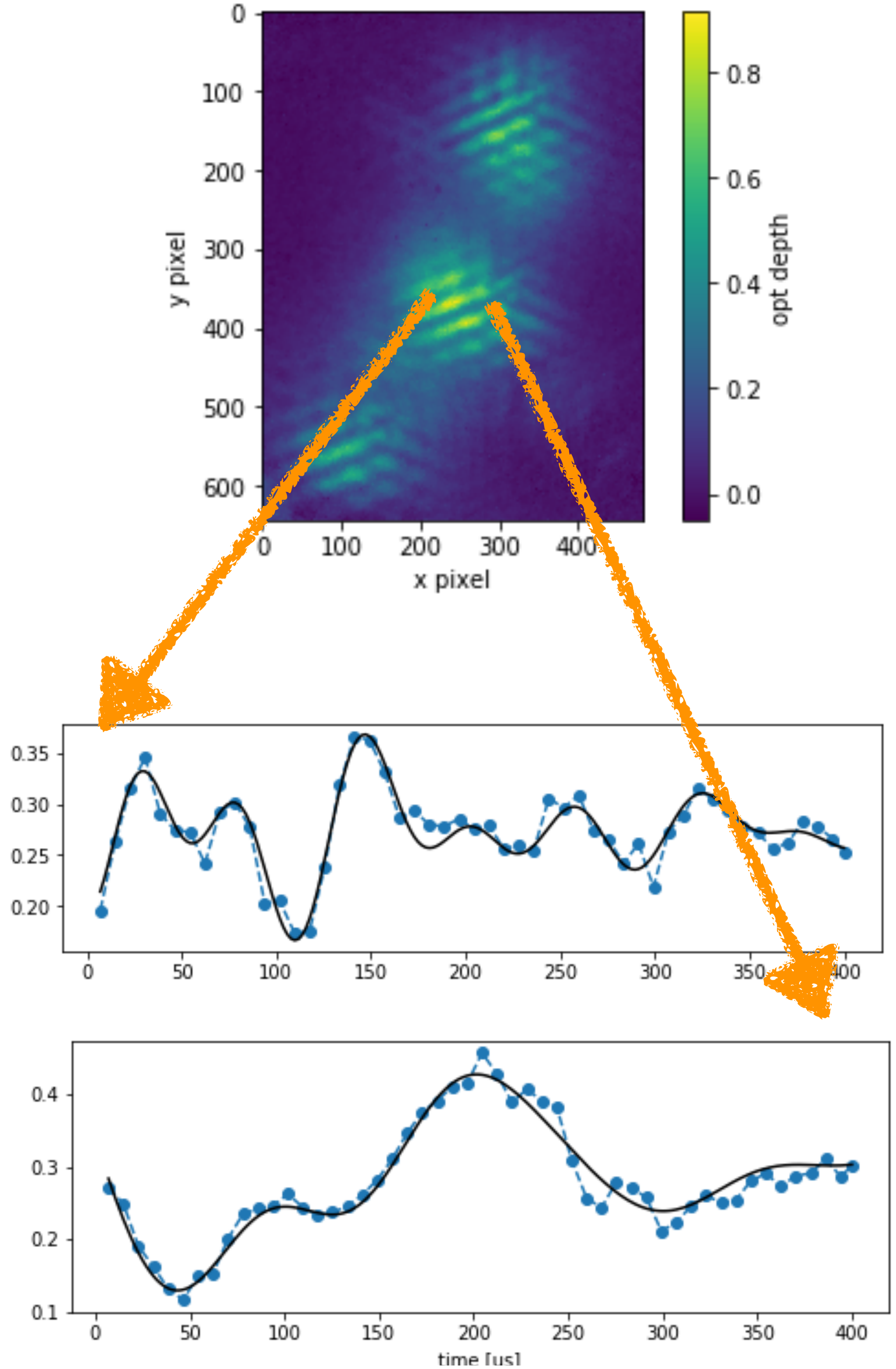
Three arm Ramsey interferometer



"Band" topology

Typical image: Dirac point



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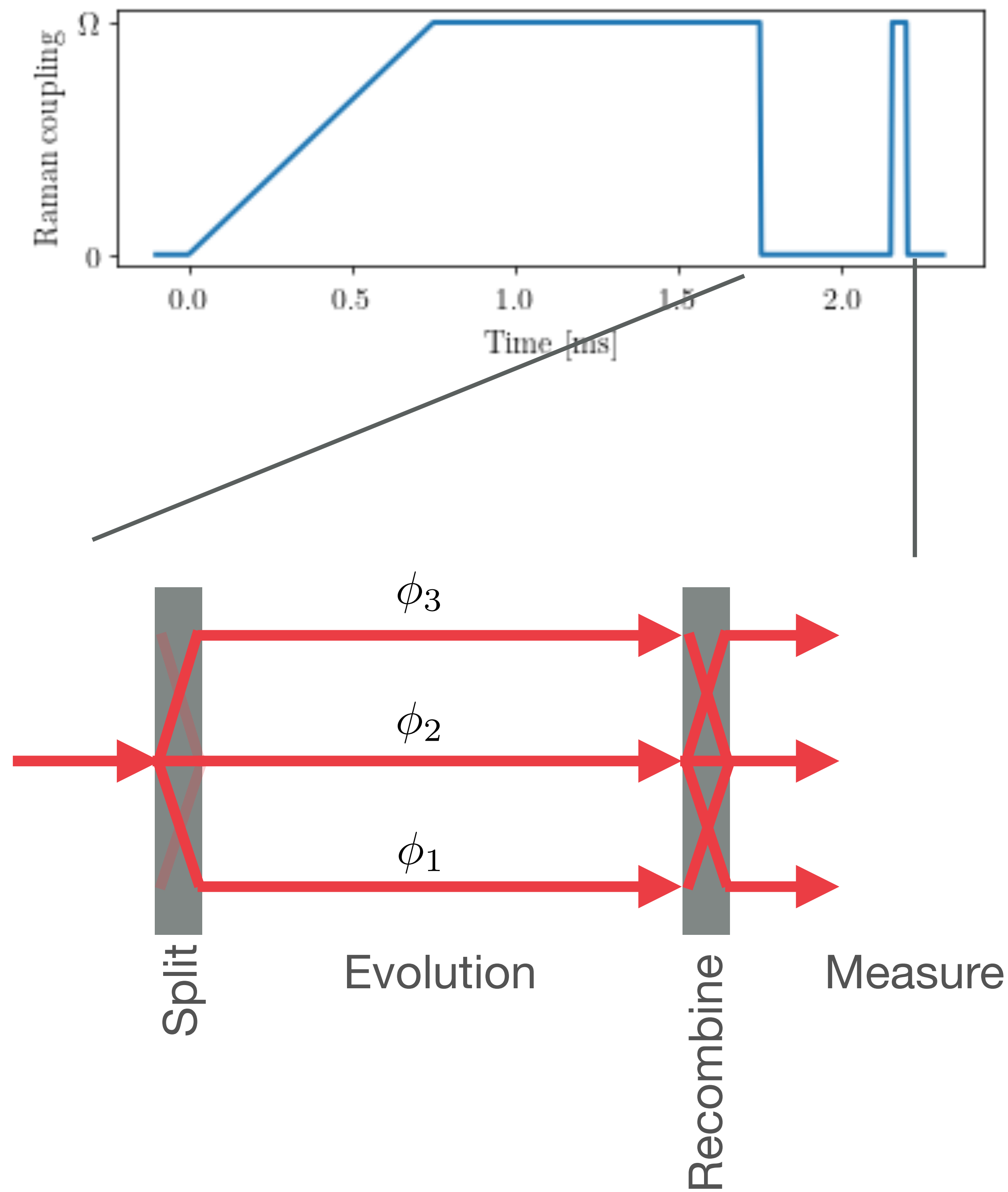

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Single Dirac point + non-periodic potential
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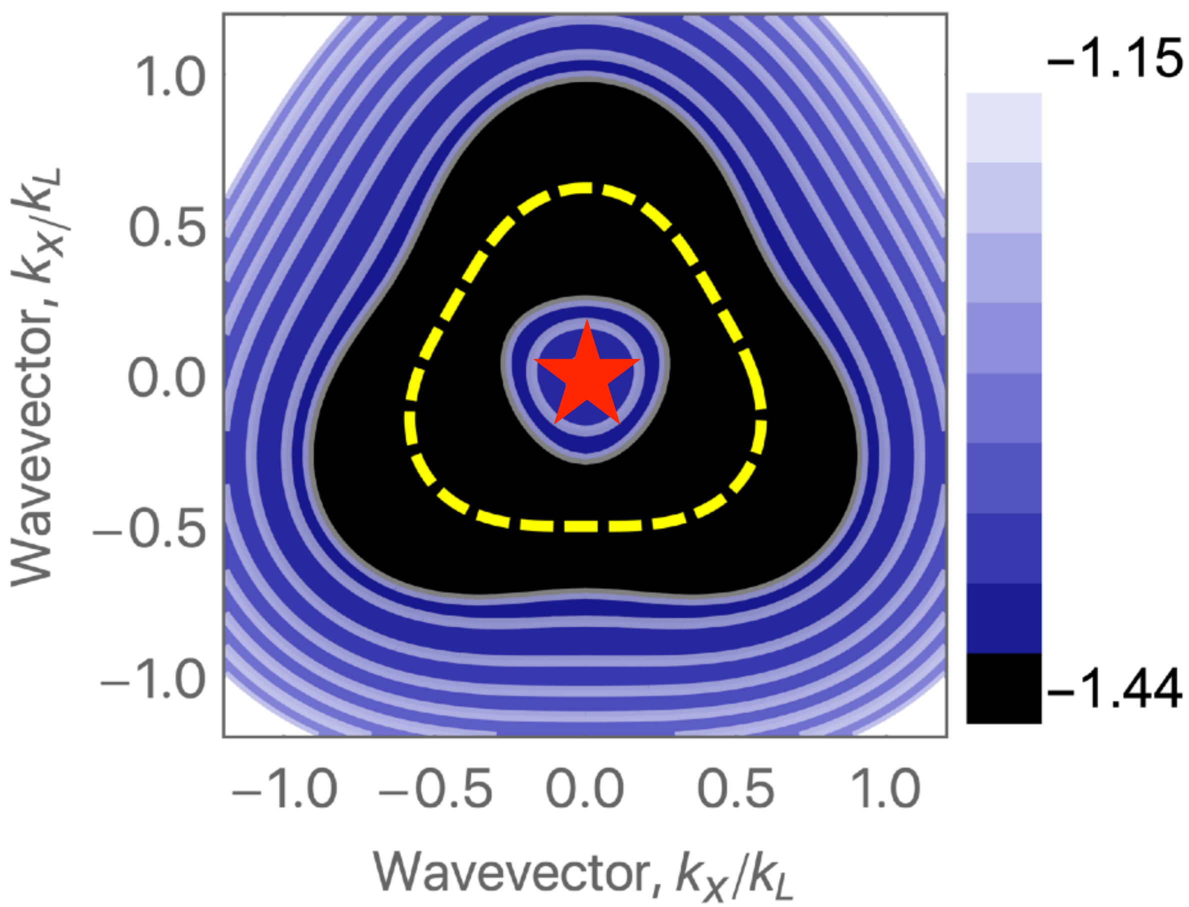
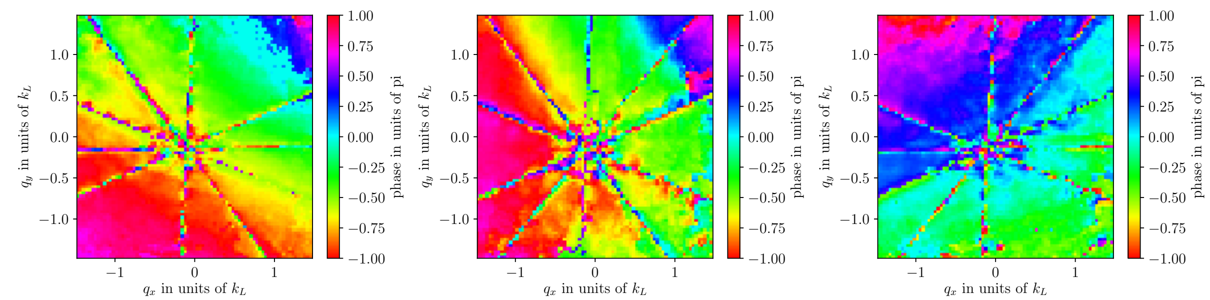


Result

Preliminary

Phase map

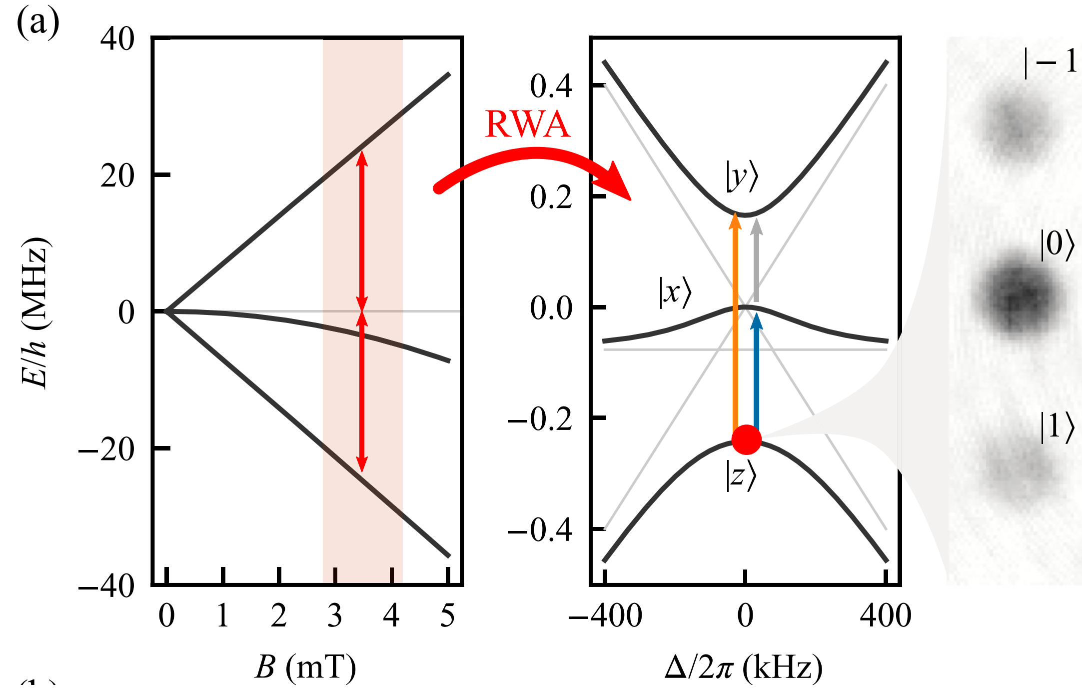


A. Valdés-Curiel et al; (2019, in preparation)

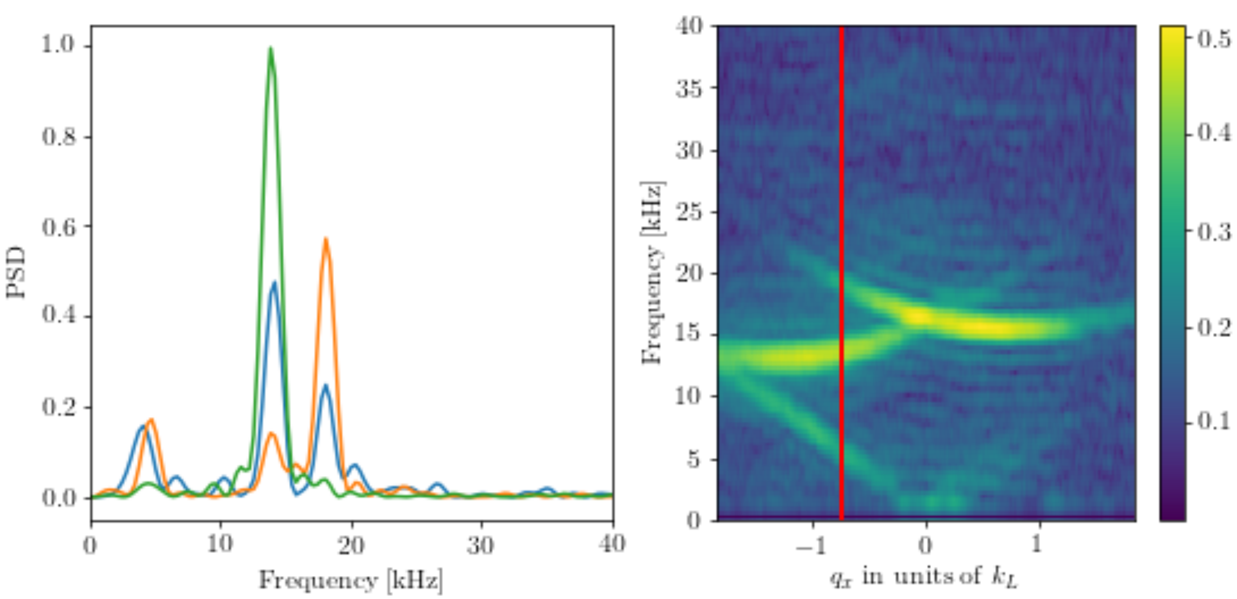
CDD

Continuous dynamical decoupling

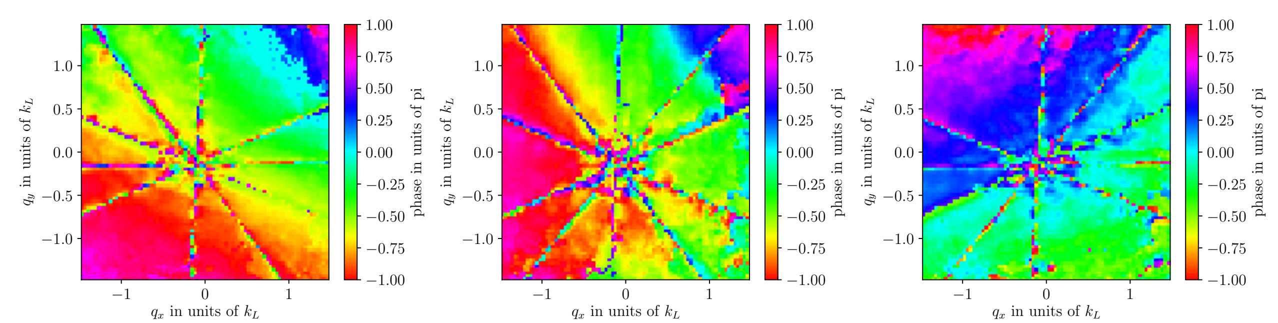
Fancy words for “dressed states”



Energies



Phases



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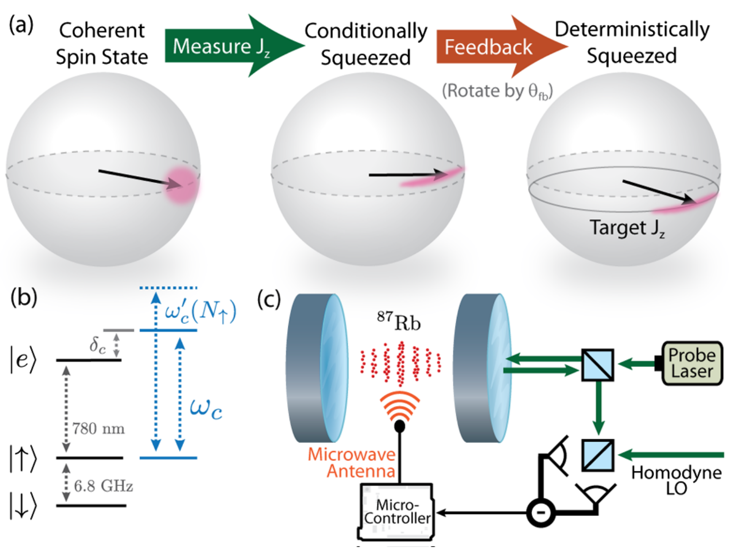
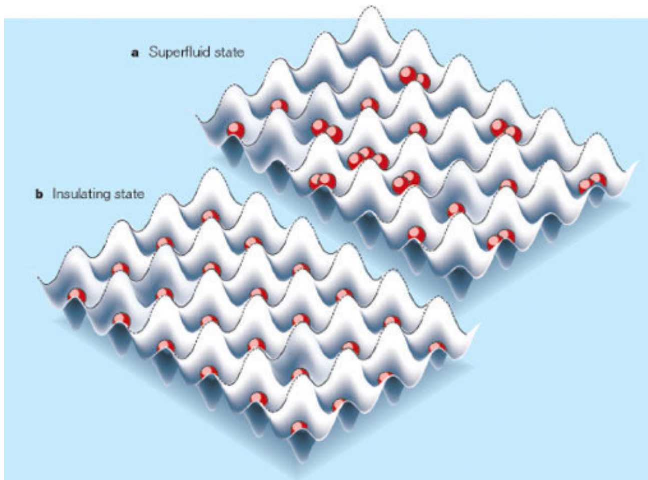
Beyond Hamiltonian Engineering



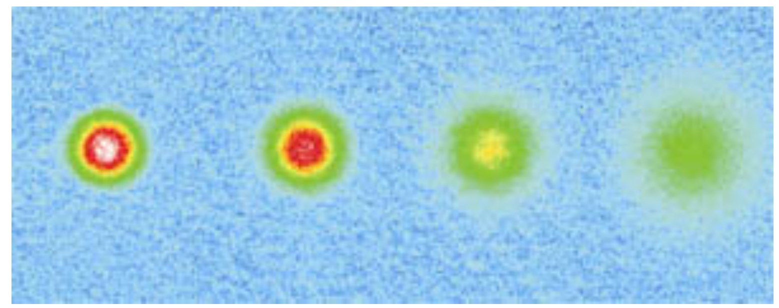
Beyond Hamiltonian Engineering

Hamiltonian engineering

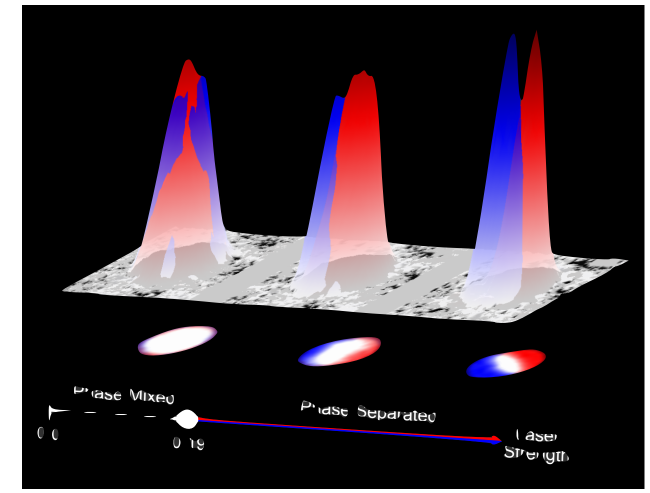
Build the Hamiltonian up with well calibrated control techniques



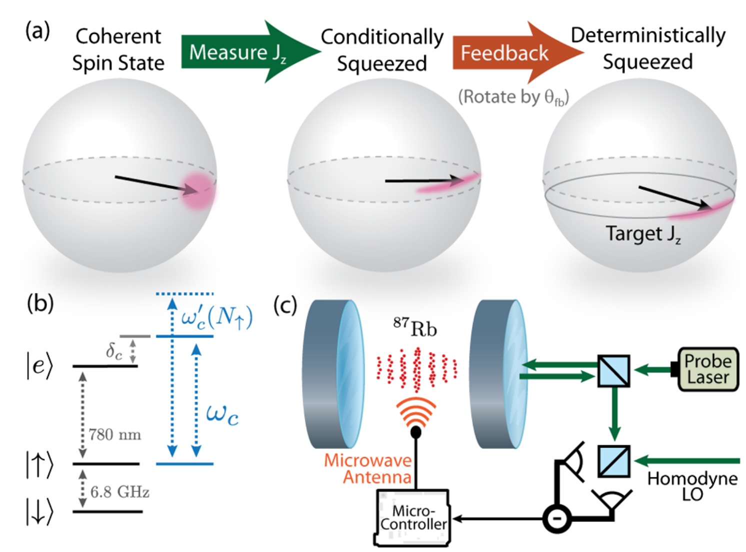
Bloch group; Nature (2002)



Jin group; Nature (2003)



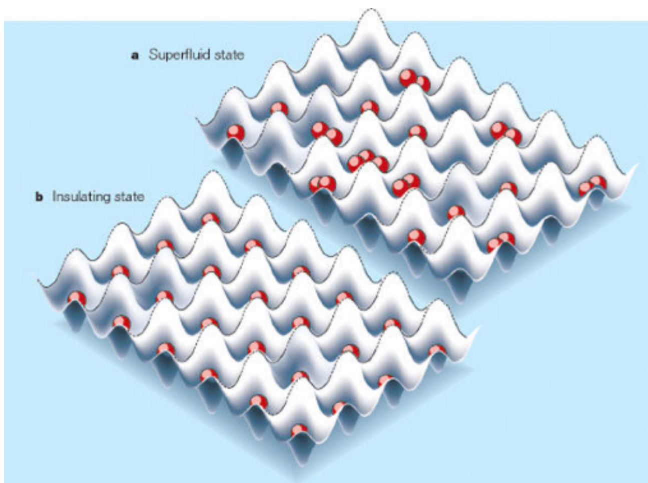
Lin et al; Nature (2011)



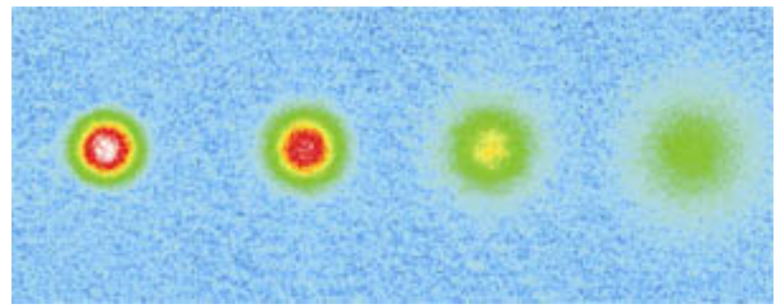
Beyond Hamiltonian Engineering

Hamiltonian engineering

Build the Hamiltonian up with well calibrated control techniques



Bloch group; Nature (2002)



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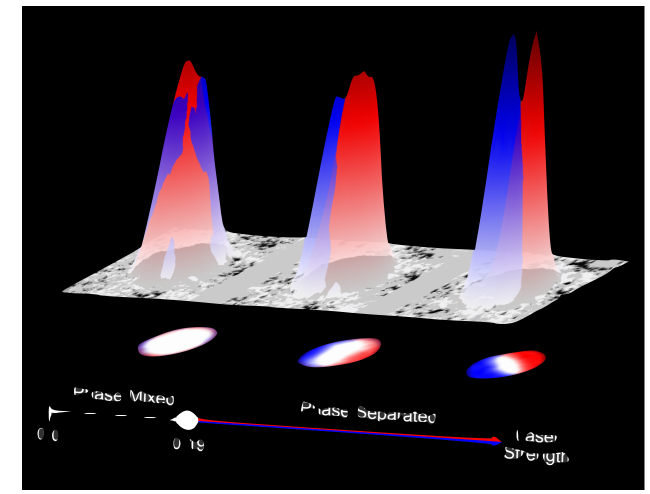
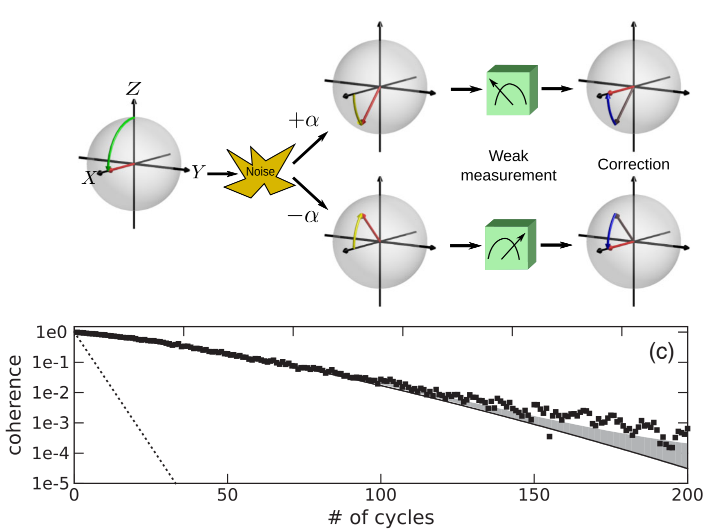


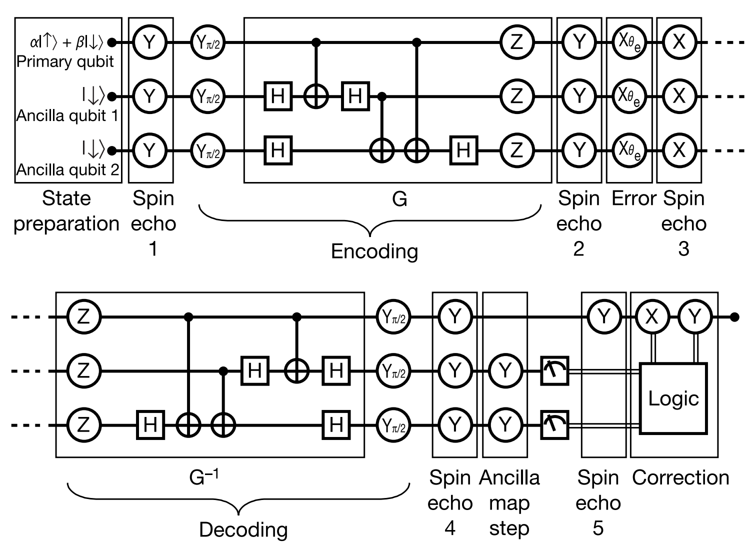
Lin et al; Nature (2011)

Open system engineering

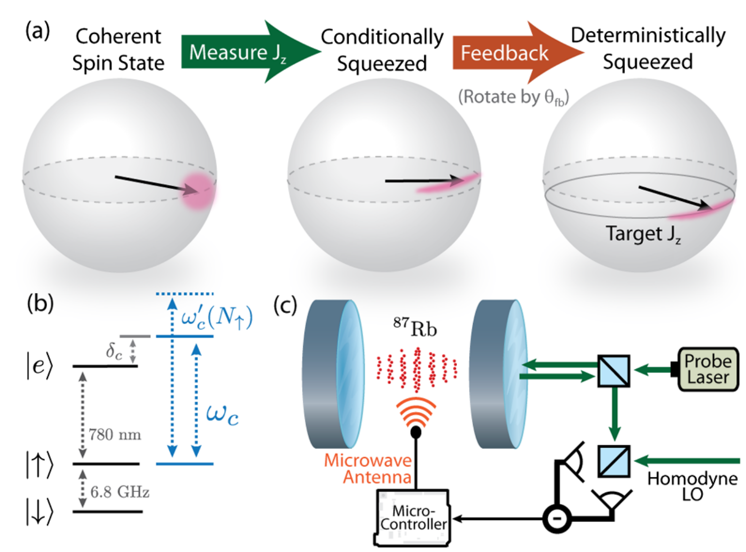
Control system state / dynamics by incorporating the reservoir



E. Vanderbruggen et al PRL (2013)



J. Chiaverini, et al; Nature (2004)



K. C. Cox, et al; PRL (2016)

Please let me know of missing relevant references in the following

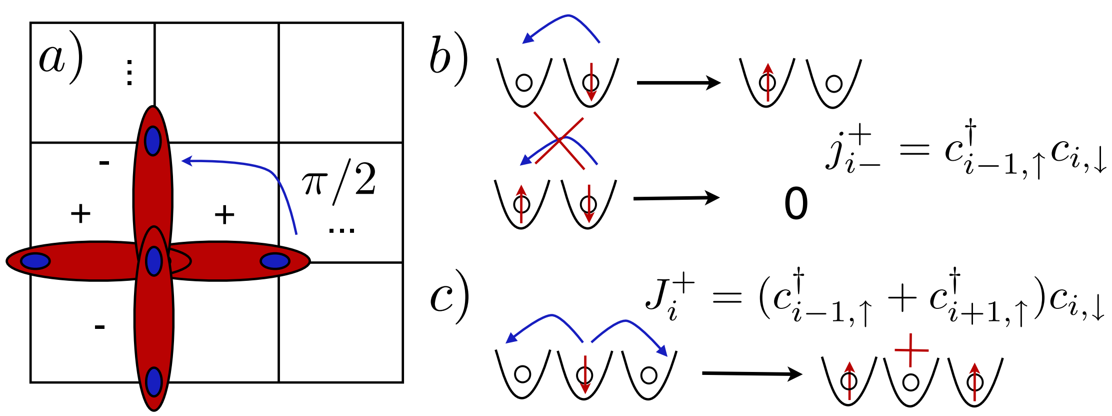
(particularly if it is yours!)

Overarching question

<u>What types of matter are possible in dynamical steady state?</u>

<u>Structured reservoir</u>

Optical pumping



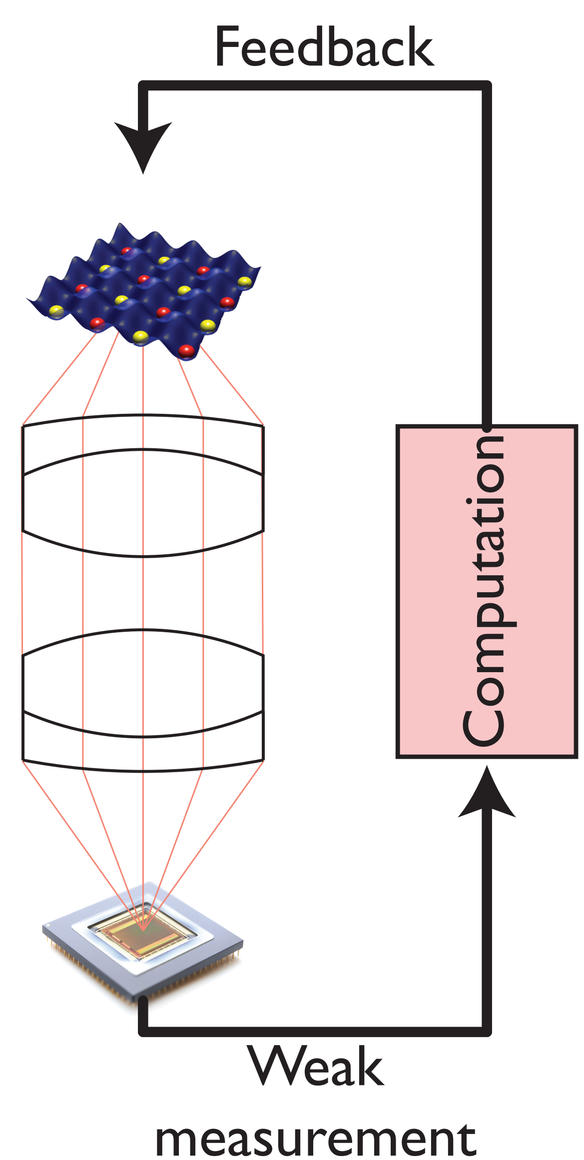
Design quantum jump operators to drive into many-body state of interest

This example is *d*-wave pairing

S. Diehl, et al; PRL (2010)

<u>Simple reservoir</u>

Move complexity to classical control problem



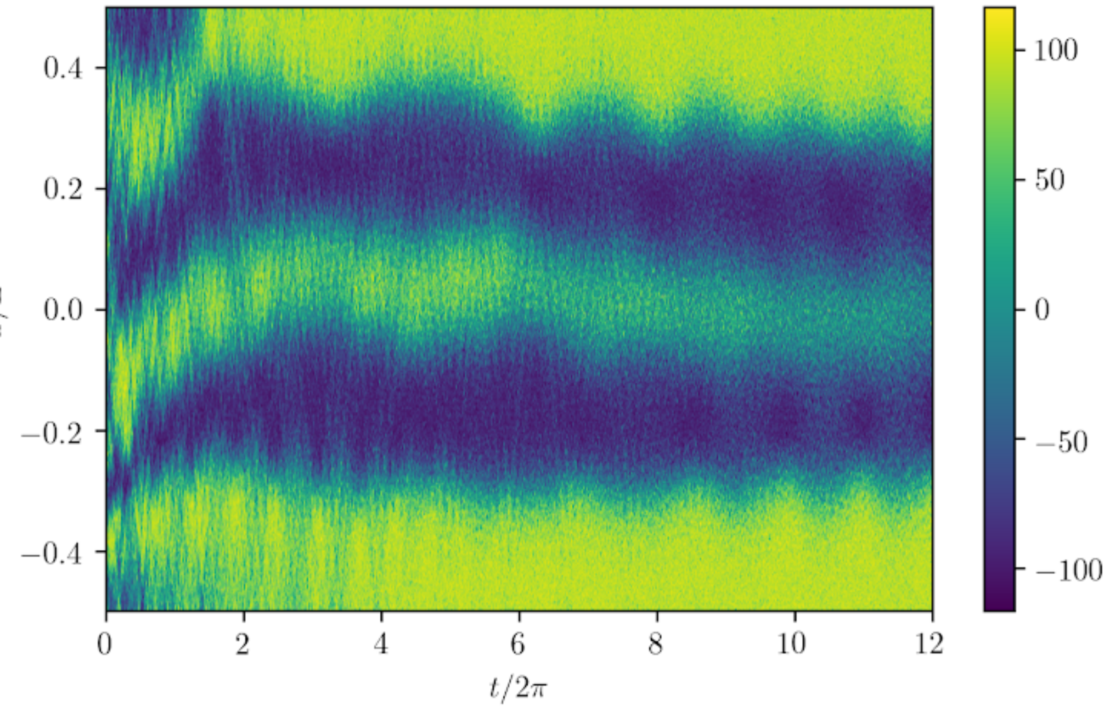
H. M. Hurst and IBS (2019, under review)

Theory program

Altered mean field systems

Large systems

Physical insights

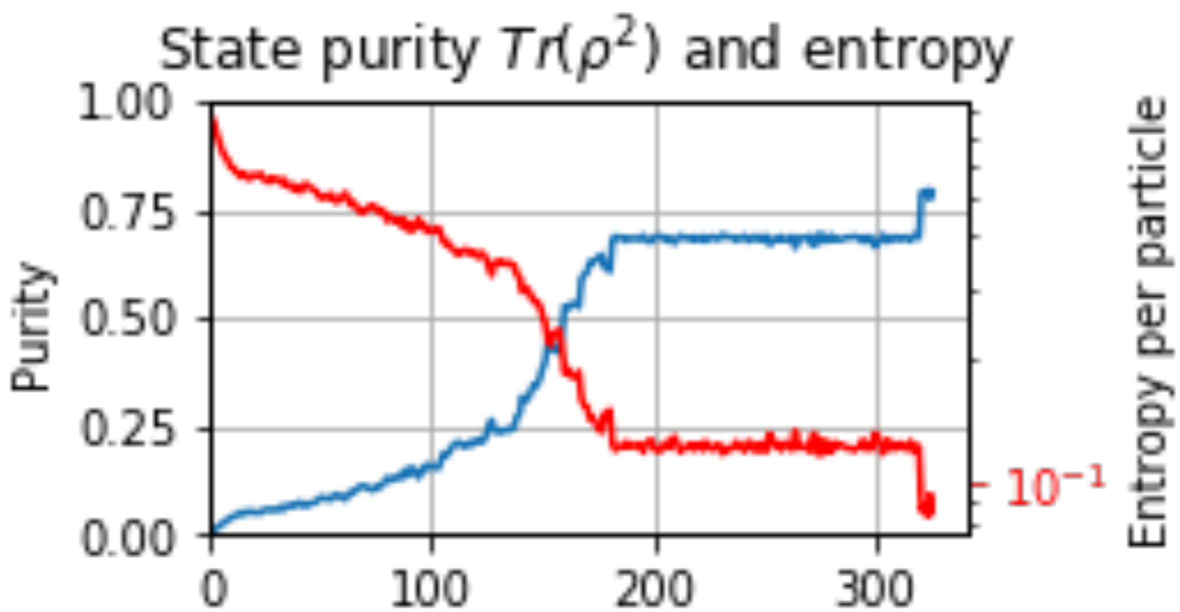


Postdoc: H. M. Hurst

Exact numerics

Small lattice systems

(With Gorshkov group)



Student: J. Young

QI / field theory viewpoint

Analytic methods

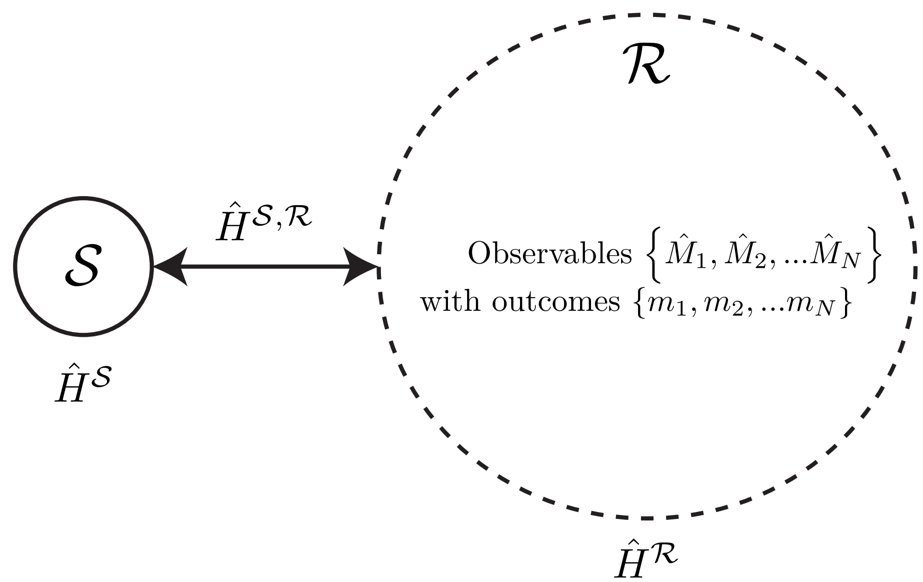
(With Taylor group)

Just starting

Measurement model

Stochastic Schrodinger equation

Usefully provides system dynamics *and* measurement record



Key point: a full projective measurement of *R* puts system in a conditional pure state

$$\left|\Psi'_{|\mathbf{m}}\right\rangle \approx |\mathbf{m}\rangle \otimes \left|s_{|\mathbf{m}}\right\rangle$$

Describe as Kraus operator

$$\left|s_{|\mathbf{m}}\right\rangle = \hat{K}(\mathbf{m})\left|s_0\right\rangle$$

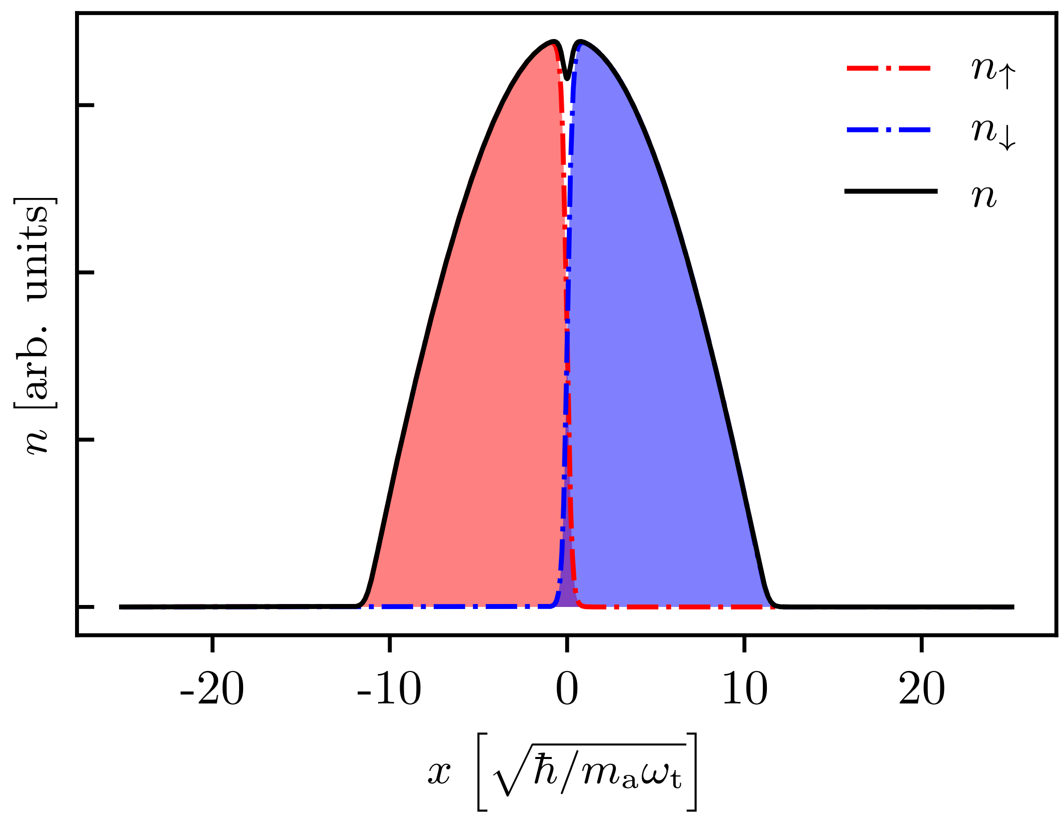
For dispersive measurement of a coherent state (for MFT)

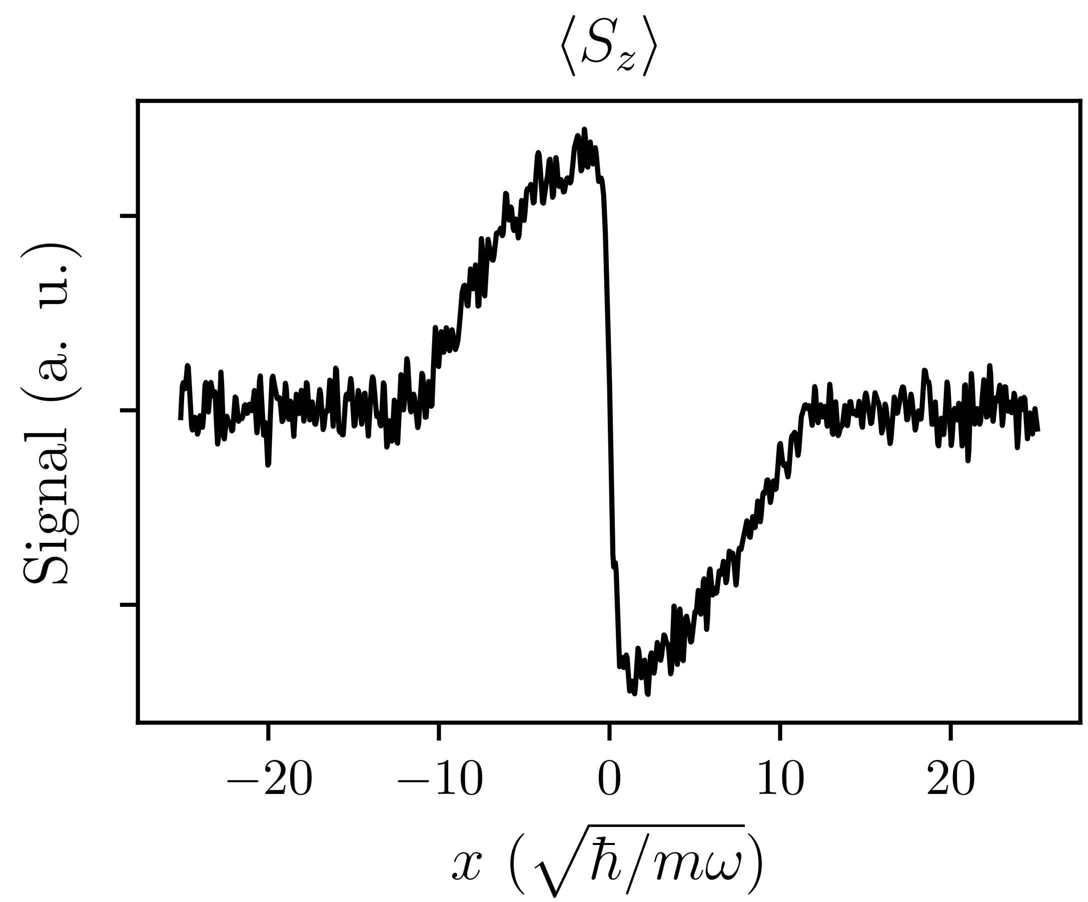
$$\psi_{|m}(x) = \left(1 + \varphi m(x) - \frac{\varphi^2}{4}\right)\psi(x) \qquad \text{with} \qquad M_j = \langle \hat{n}_j \rangle + \frac{m_j}{\varphi}$$

Lecture Notes on Continuous quantum Measurement; I. H. Deutsch (2015)

Example: Add spin degree of freedom

Measure magnetization in addition to density





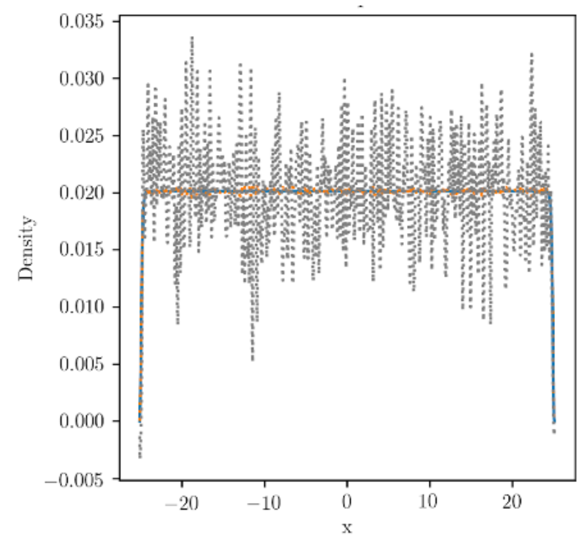
$$\hat{H} = \hat{H}_0 + \frac{g_0}{2}\left(\hat{n}_\uparrow + \hat{n}_\downarrow\right)^2 + \frac{g_2}{2}\left(\hat{n}_\uparrow - \hat{n}_\downarrow\right)^2$$

H. M. Hurst et al (2019, under review)

Cooling + feedback

State following weak measurement of density

Most simple case of density measurement

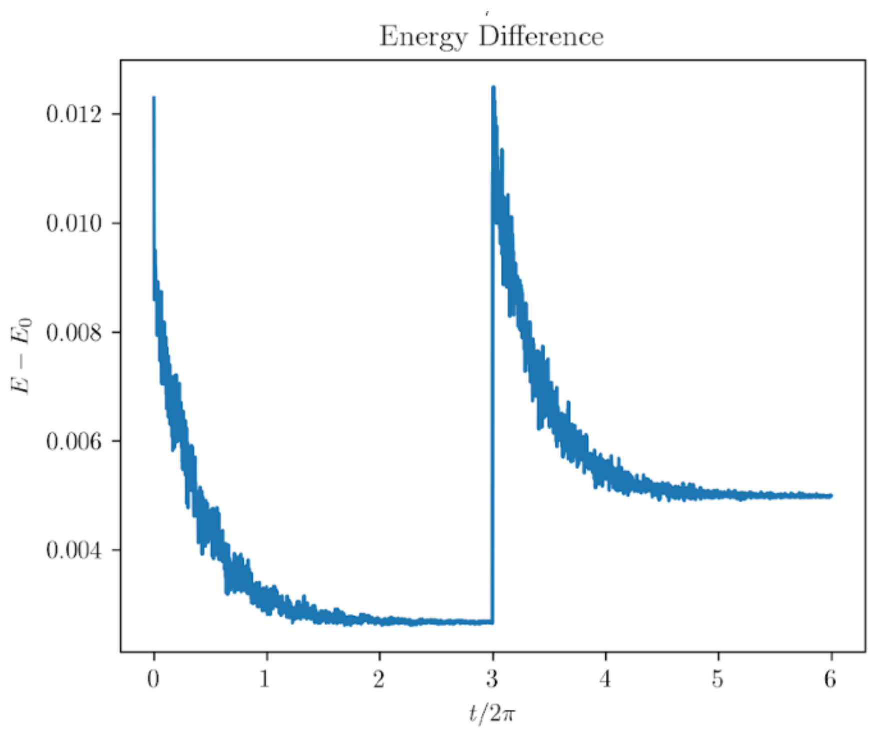


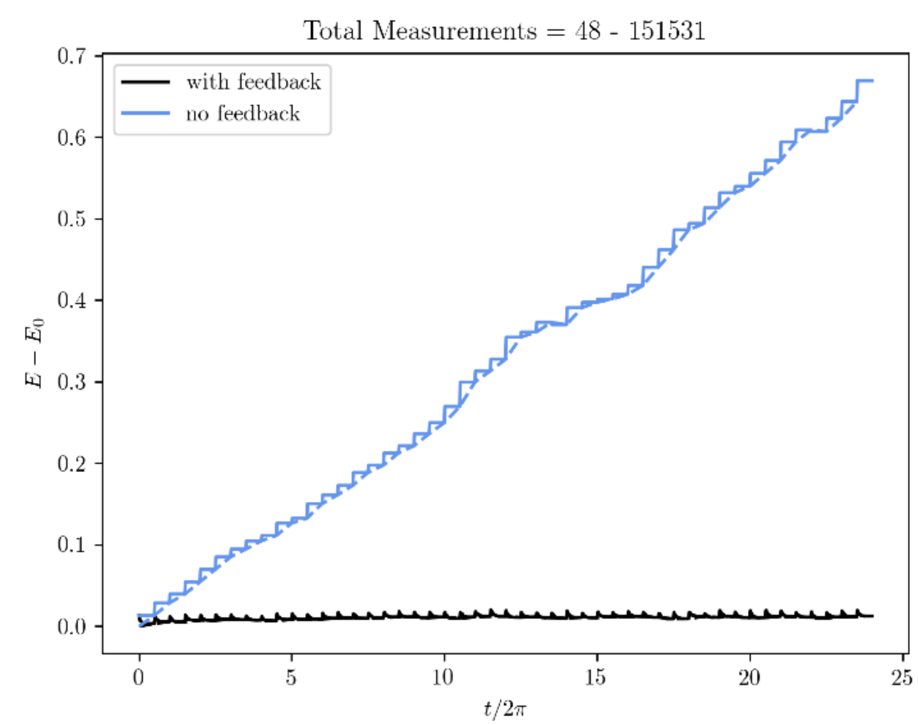
Estimator of density from measurement

Actual density following measurement

Feedback

Apply potential best matched to current estimate of density and adiabatically remove





For state preparation near MFT: A. C. J. Wade, J. F. Sherson, and K. Mölmer; PRL (2015)

Cooling + feedback

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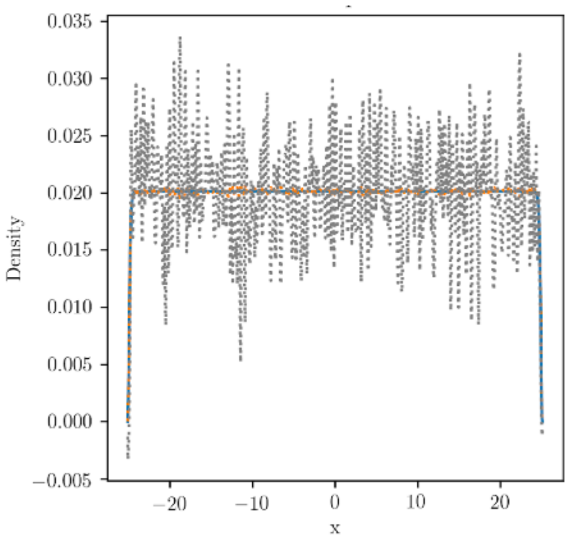

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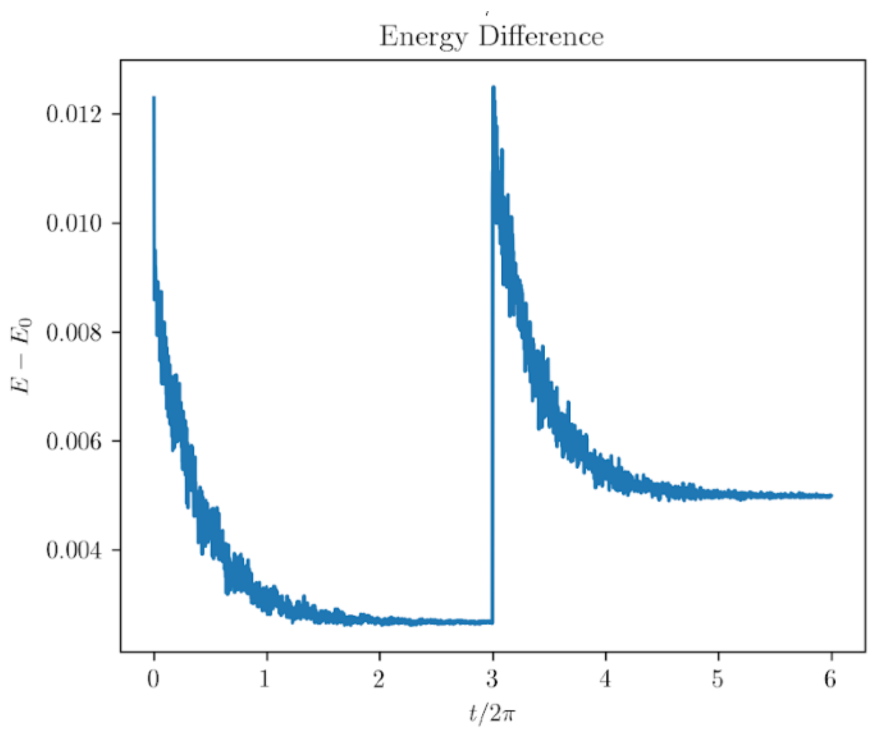
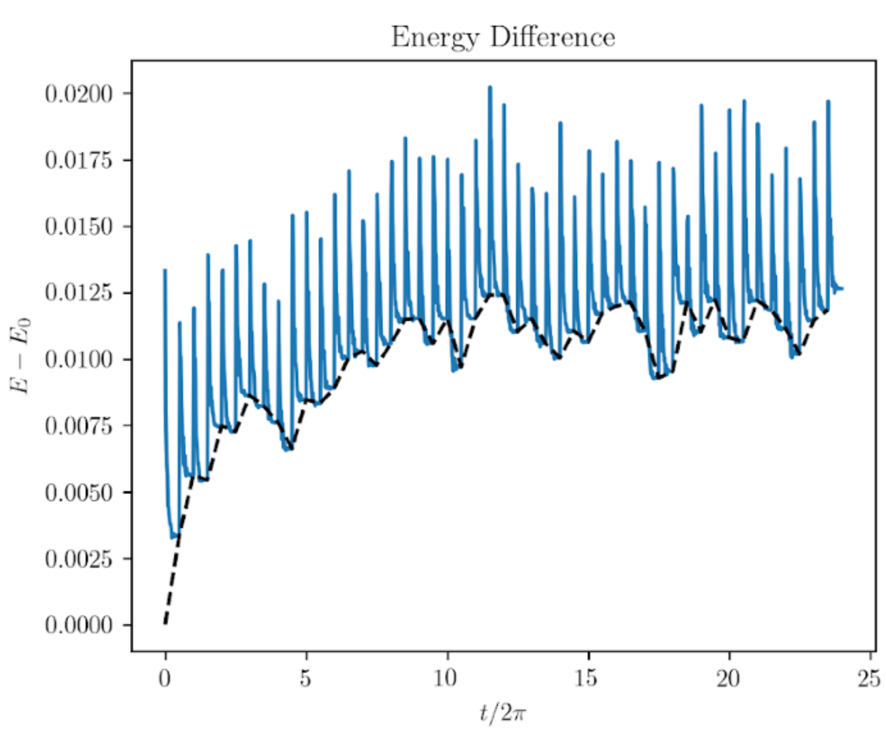




For state preparation near MFT: A. C. J. Wade, J. F. Sherson, and K. Mölmer; PRL (2015)

Effective Hamiltonian limit

Parametric terms in Hamiltonian

$$\hat{H} = \hat{H}_0 + f[M(x)]\hat{\psi}^\dagger(x)\hat{\psi}(x)$$

e.g. effective local interactions

Local potential from density estimator

$$\hat{H} = \hat{H}_0 + \boxed{gM(x)\hat{\psi}^\dagger(x)\hat{\psi}(x)}$$
$$= \hat{H}_0 + \boxed{g\langle\psi^\dagger(x)\hat{\psi}(x)\rangle\hat{\psi}^\dagger(x)\hat{\psi}(x)} + \boxed{\frac{g}{\varphi}m(x)\psi^\dagger(x)\hat{\psi}(x)}$$

Almost four-field interaction term

Added noise term

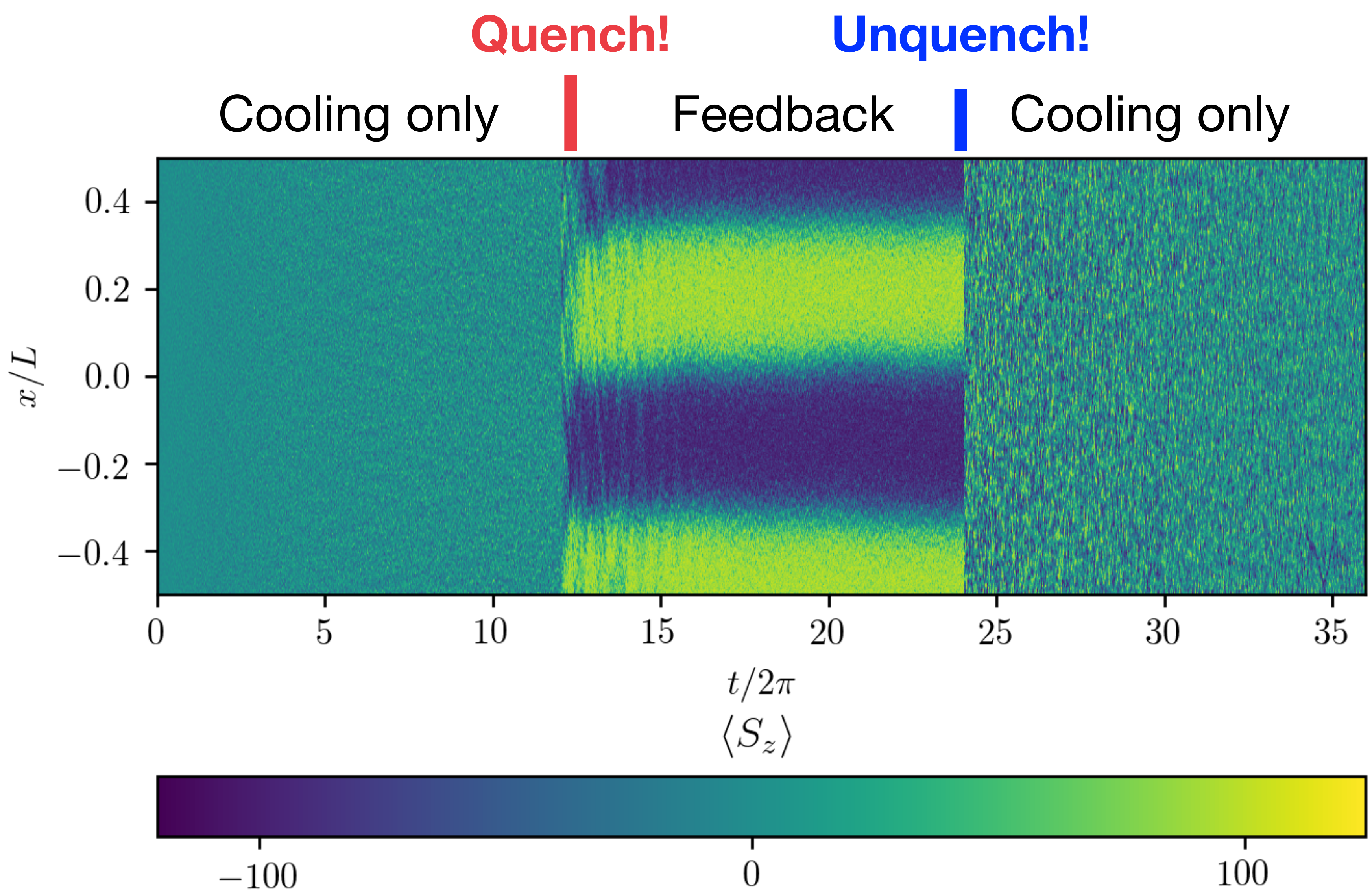
Even simulate “fire-wall” models of gravity

D. Carney, P. C. E. Stamp, and J. M. Taylor; Classical and Quantum Gravity (2019)

Example

<u>Phase transitions in magnetic systems</u>

Quench from easy plane to easy axis ferromagnet



$$\hat{H} = \hat{H}_0 + \frac{g_0}{2}\left(\hat{n}_\uparrow + \hat{n}_\downarrow\right)^2 + \frac{g_2}{2}\left(\hat{n}_\uparrow - \hat{n}_\downarrow\right)^2$$

$$\to \hat{H} + g\left\langle \hat{n}_\uparrow - \hat{n}_\downarrow \right\rangle^2 \left(\hat{n}_\uparrow - \hat{n}_\downarrow\right) + \frac{g}{\varphi} m(x) \left(\hat{n}_\uparrow - \hat{n}_\downarrow\right)$$

H. M. Hurst et al (2019, in preparation)

Open questions / directions

Reality motivated questions

Information lost to environment

Not all light is collected
Feedback cannot cool all modes that were excited by measurement

Detectors are imperfect
Feedback signal will add noise

Together
What will practical lifetimes be?

Finite bandwidth

Feedback delayed
Needed for cooling, but unwanted for control

Conceptual questions

Properties of quasi-equilibrium

Do non-thermal dynamical steady-states exist?

Can states outside of usual CMP rules exist?
e.g., order in 1D

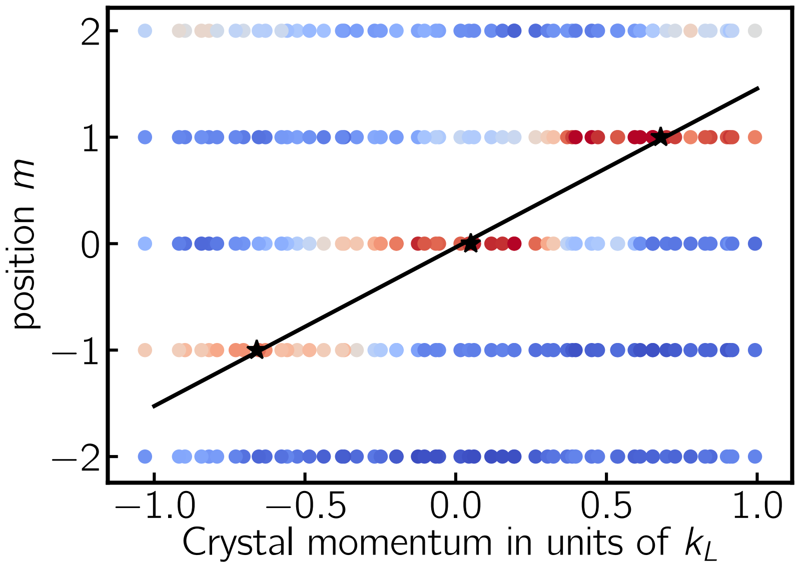
Effective field theory description

When can feedback behave as new interactions?
Long-range quasi-interactions…

‘Continuous Quantum Measurements and Path Integrals' M. B. Mensky (1993)

Other recent experiments

Chern number from Diophantine relation

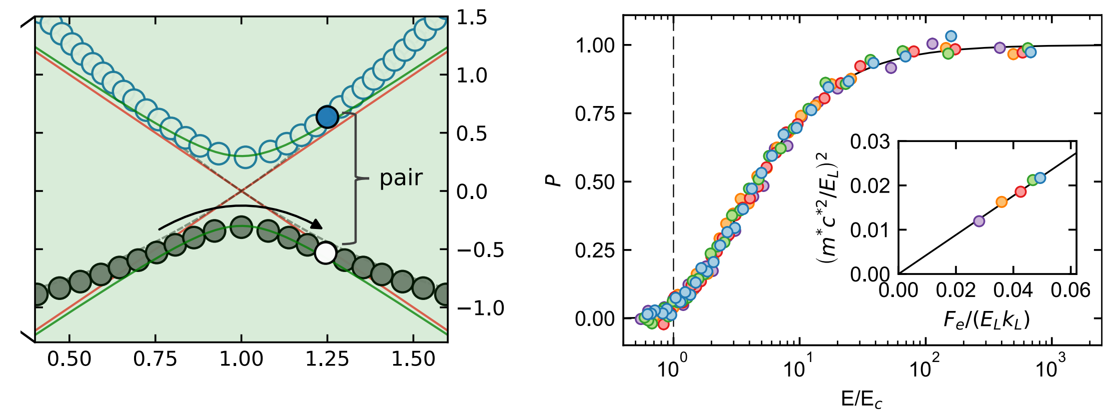


D. Genkina, et al. (2019, accepted)

Pair production

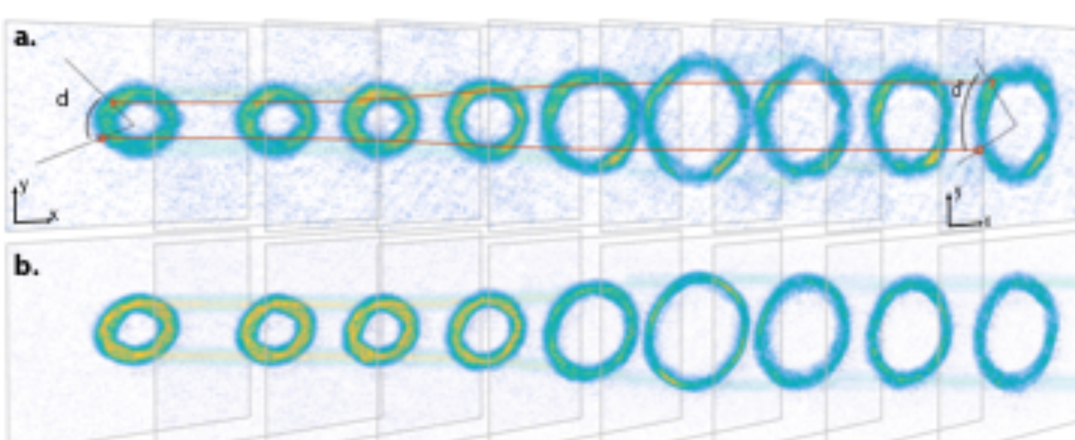
Amusingly equivalent to L.-Z. tunneling

$$q_e E_C = \frac{m^2 c^3}{\hbar}$$



A. Pinero et al; (2019, in preparation)

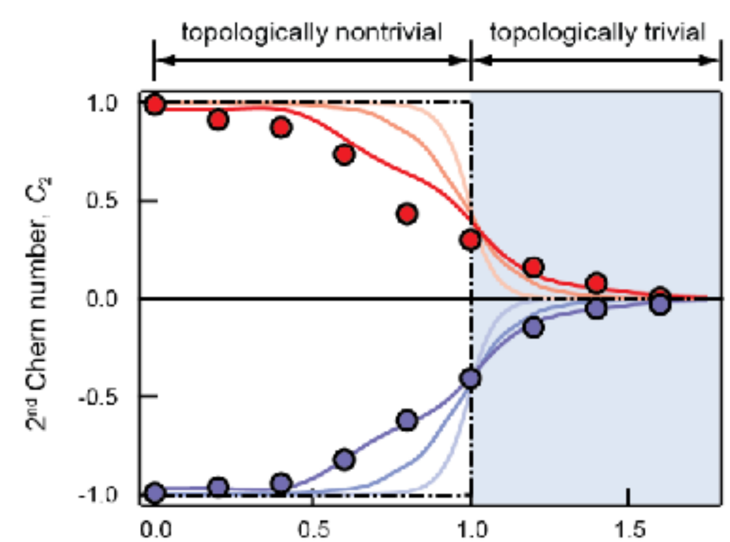
Expanding universe



S. Eckel, et al. PRX (2018)
[with T. Jacobson and G. K. Campbell @ JQI]

Topological transition / Yang monopole

Non-Abelian systems: second Chern number



S. Sugawa, et al. Science (2018)