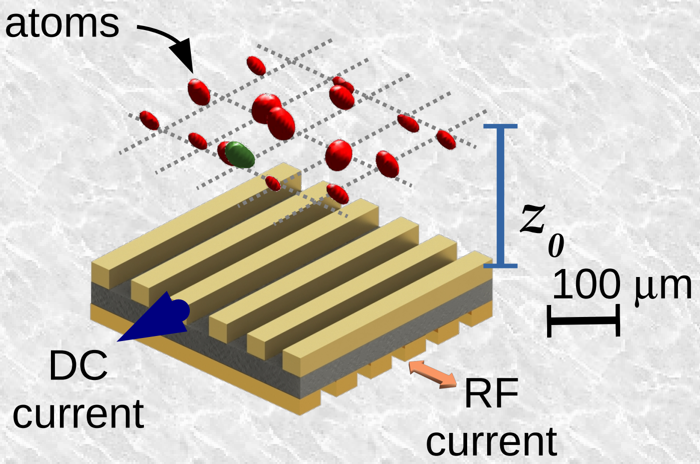
Spatial and internal control of atomic ensembles with harmonic drivings

German A. Sinuco-Leon
Department of Physics and Astronomy
University of Sussex

Atom-chip quantum processor



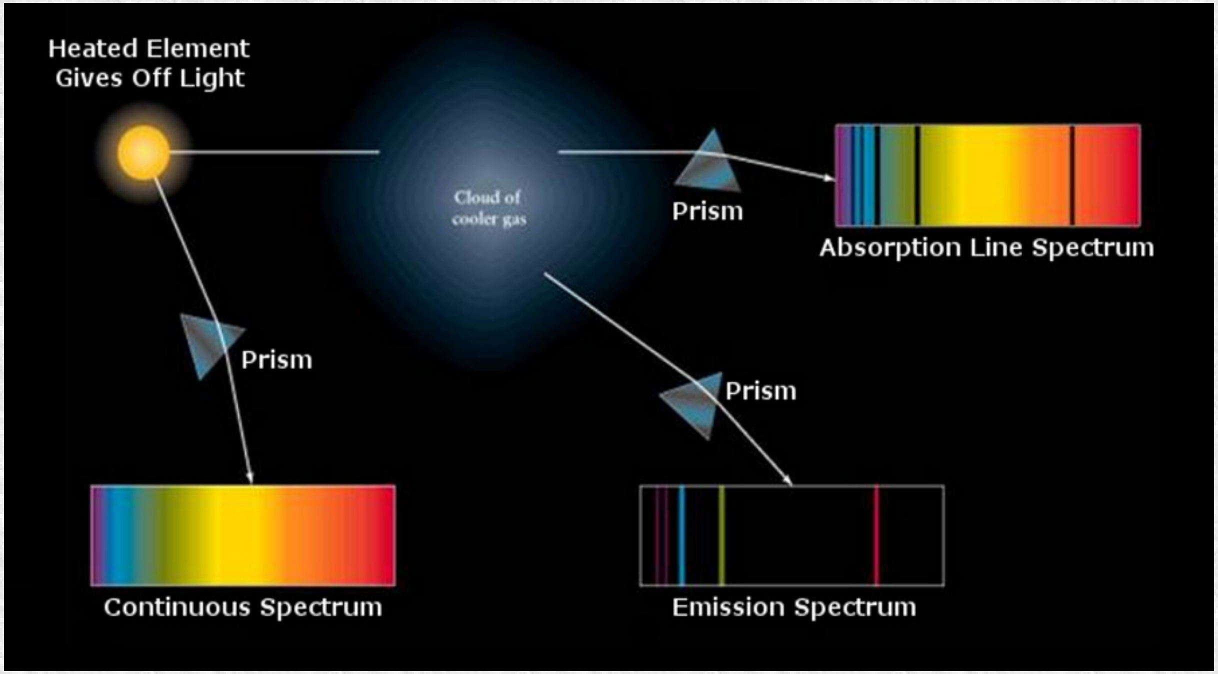
UCL, AMOP seminar, 7th November 2019

Outline

- Some driven quantum systems
- Controlling 87Rb with low-frequency electromagnetic fields
- Time-evolution operator of driven quantum systems
- Outlook

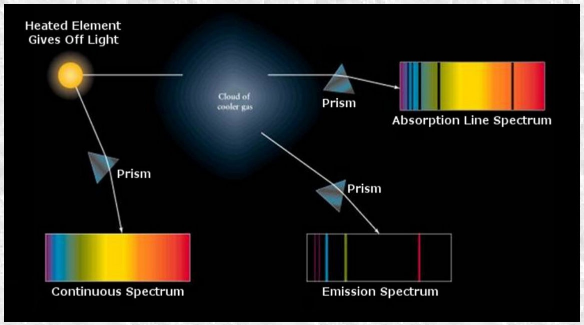
Driving physical systems

If you want to know what it is, just shake it



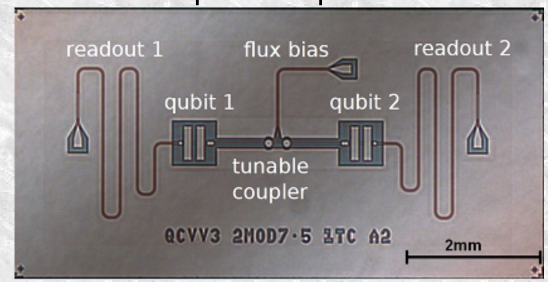
Driving physical systems

Investigate/identify materials



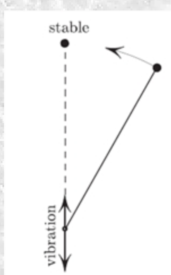
Quantum state control

IBM quantum processor

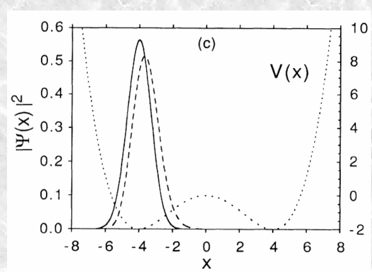


Phys. Rev. Applied 6, 064007 (2016)

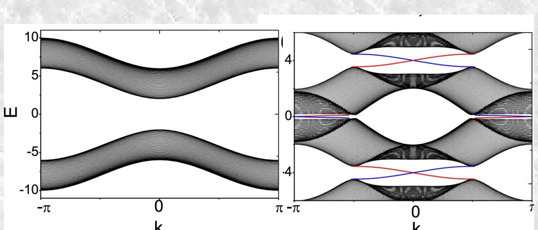
Modify the properties of a system



Kapitza pendulum

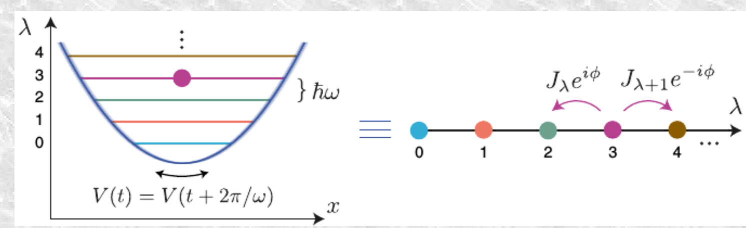


Coherent destruction of tunnelling
Grossmann, *et al.* PRL 1991

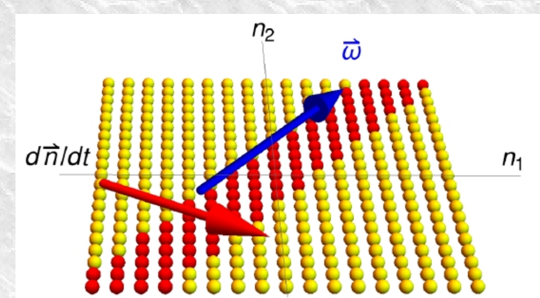


Floquet Engineering

Time-domain quantum simulation



Price, Ozama and Goldman, PRA 95, 023607 (2017)



Martin, Refael and Halperin, PRX 7, 041008 (2017)

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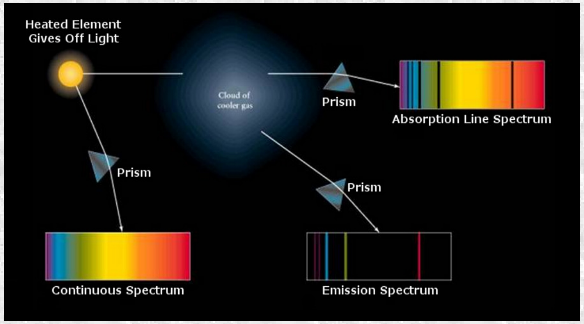

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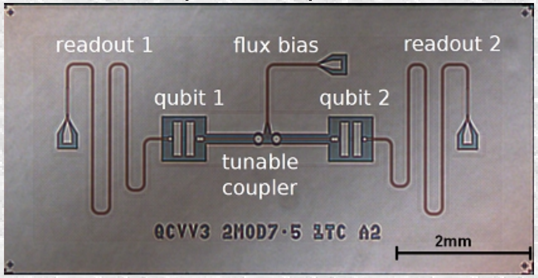

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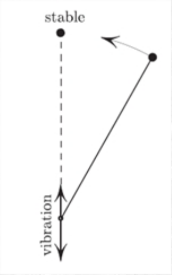

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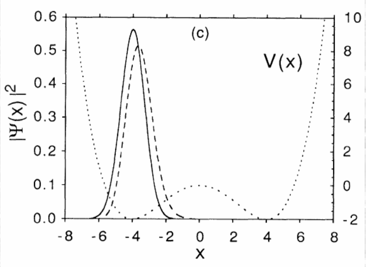

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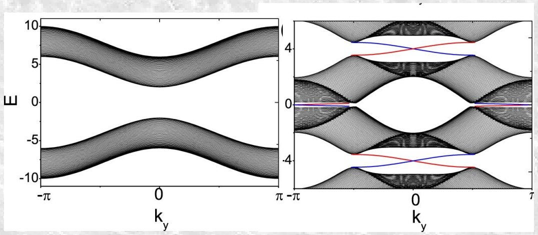

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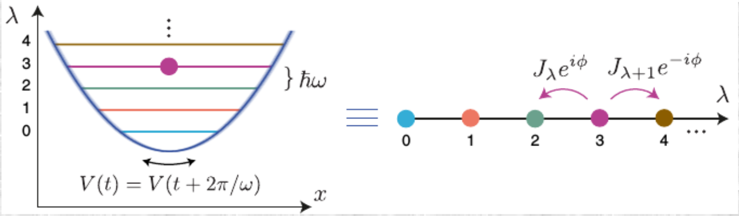

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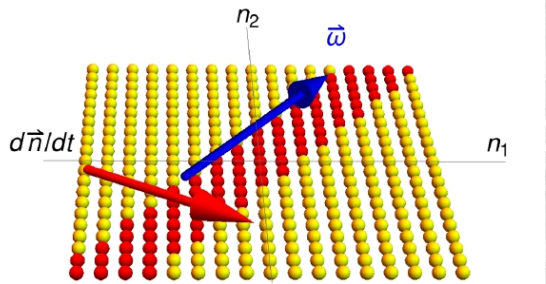
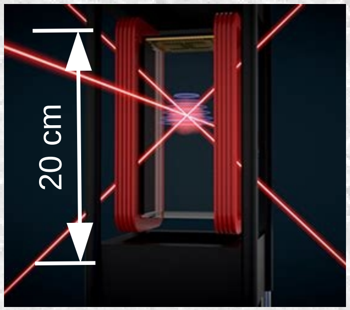
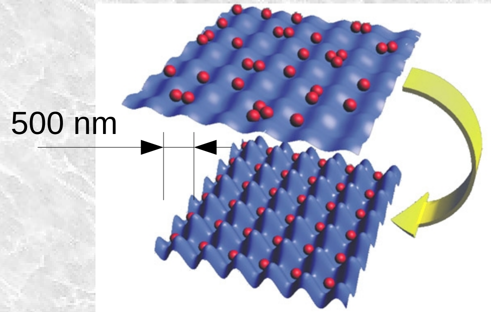
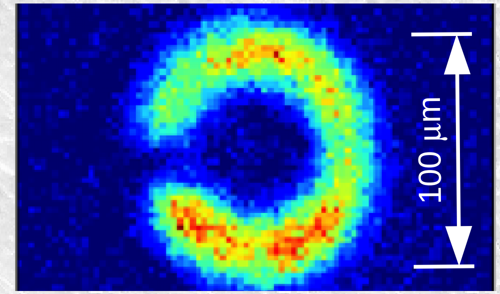


Martin, Refael and Halperin, PRX 7, 041008 (2017)

Controlling atomic ensembles

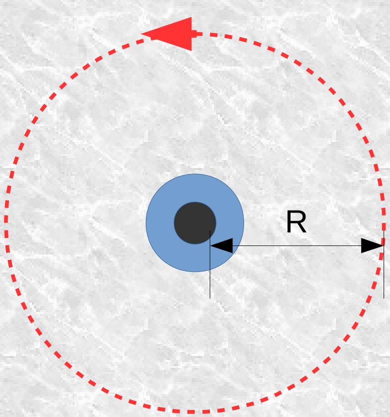




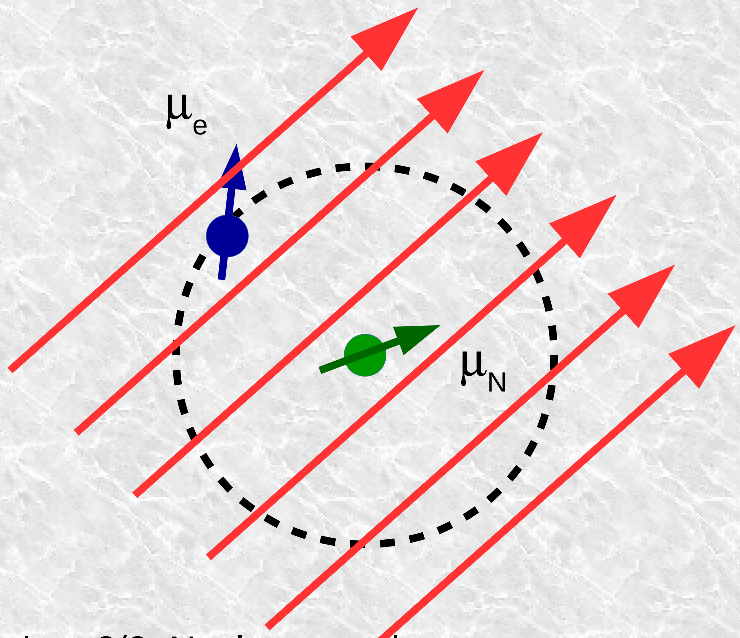


- Laser cooling produce atomic ensembles with temperatures in the range between 1 μk – 1 nK
- At such temperature, the kinetic energy is comparable with the interaction energy with electric and magnetic field produced by near-by sources.
- At T= 1 μK, the magnetic field produced by a current of 1 mA can captures an atom of Rb87 in a circular orbit of radius R = 200 μm

Current = 1 mA
Temperature = 1 μK
Speed = 5 mm/s
Radius = 200 μm

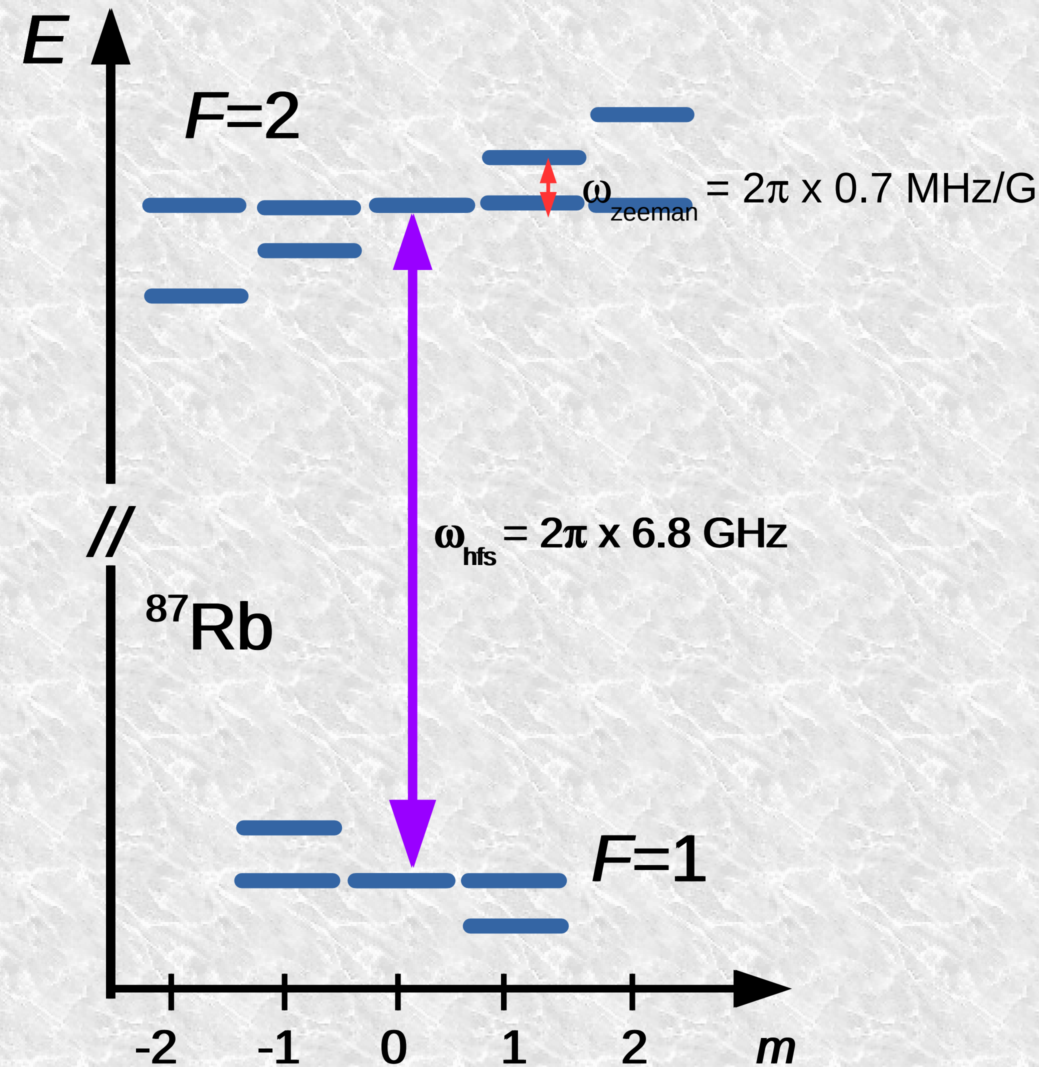


87Rb



I = 3/2 Nuclear angular momentum
S = ½ e^- spin angular momentum
J = 0 e^- orbital angular momentum

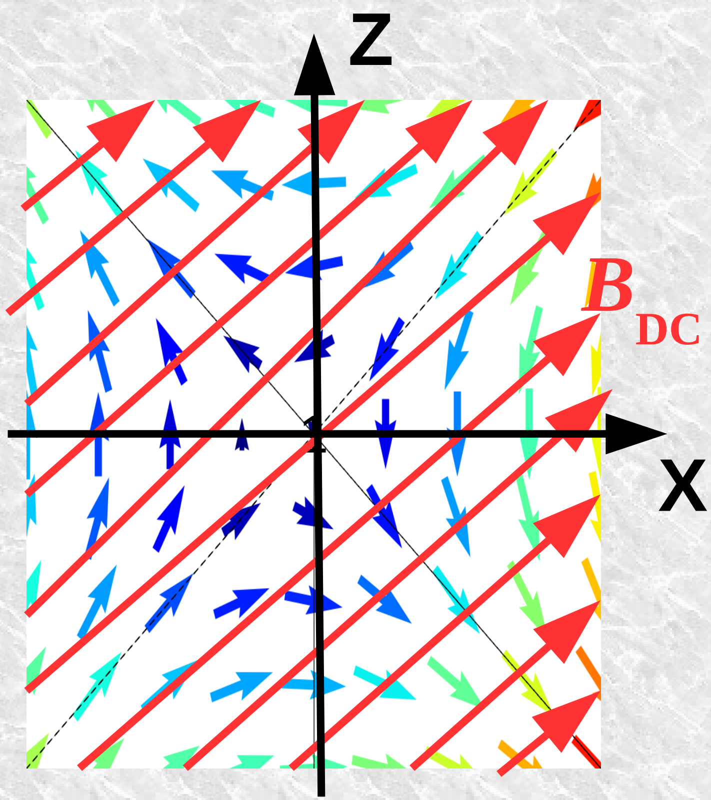
$$H = \frac{\mathbf{P}^2}{2m} + A\,\hat{\mathbf{J}}\cdot\hat{\mathbf{I}} + \mu_B\,\mathbf{B}\cdot\left(g_J\,\hat{\mathbf{J}} + g_I\,\hat{\mathbf{I}}\right)$$



As a result, the electronic ground state manifold can be controlled using a combination of microwave and radiofrequency electromagnetic fields.

Consider an alkali atom slowly moving through a region with inhomogeneous static and a radiofrequency field:

$$H=\frac{\boldsymbol{P}^2}{2m}+\mu_B g_F \boldsymbol{B_{DC}}\cdot\hat{\boldsymbol{F}}+\mu_B g_F \boldsymbol{B_{RF}}\cdot\hat{\boldsymbol{F}}\cos\omega t$$



1. Perform a geometrical rotation to orientate the static field along the z axis.
2. Move to a rotating frame of reference where it is safe to ignore time-dependent terms:

$$U(\boldsymbol{r})=\exp\left(-i\frac{g_F}{|g_F|}\omega t\hat{\boldsymbol{F}}_{\boldsymbol{z}}\right)R_{DC}(\boldsymbol{r})$$

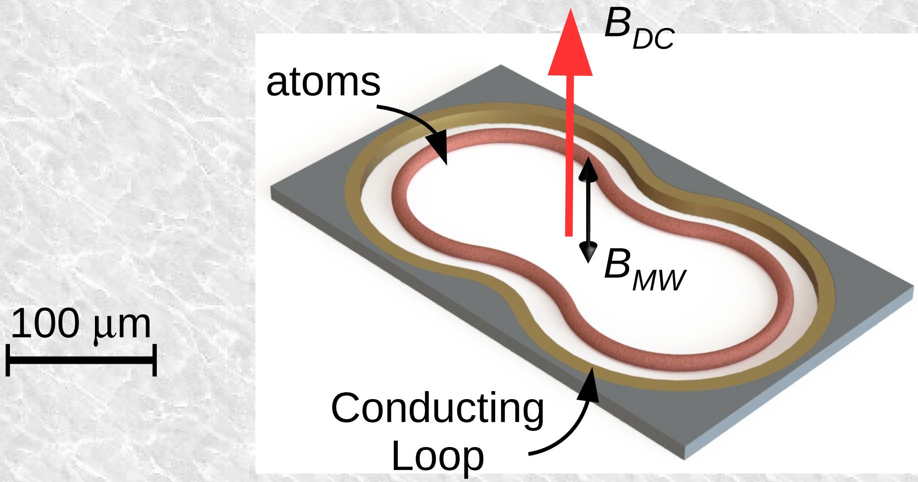
- Rotating wave approximation
- Adiabatic approximation.

$$H\approx\frac{\boldsymbol{P}^2}{2m}+(\mu_B g_F B_{DC}-\hbar\omega)\hat{F}_z+\frac{\mu_B g_F B_{RF}}{2}\hat{F}_x$$

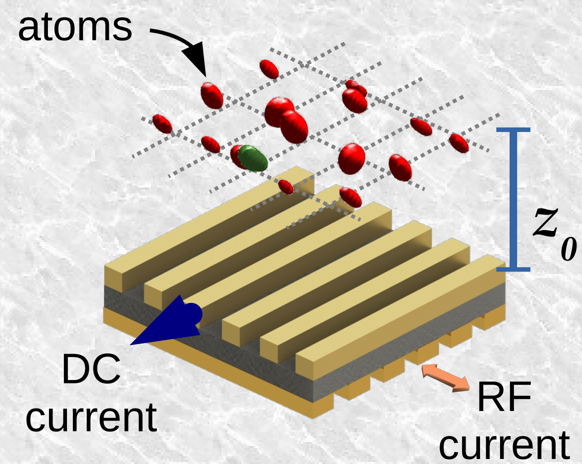
$$H\approx\frac{\boldsymbol{P}^2}{2m}+\sqrt{(\mu_B g_F B_{DC}-\hbar\omega)^2+\left(\frac{\mu_B g_F B_{RF}}{2}\right)^2}\hat{F}_z$$

Controlling 87Rb

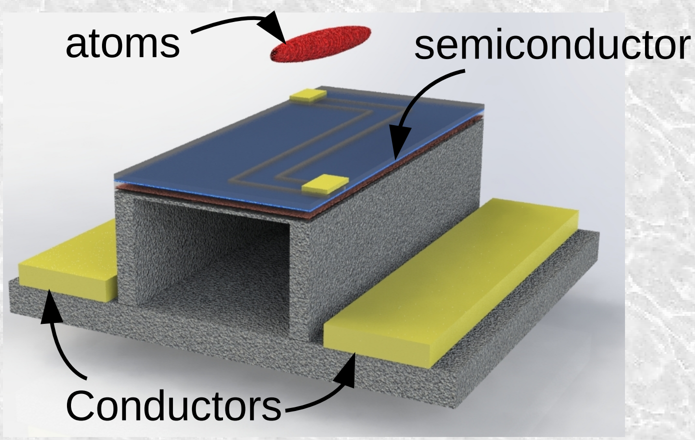
Atom-chip for rotational sensing
Nat. Comm. 2014.



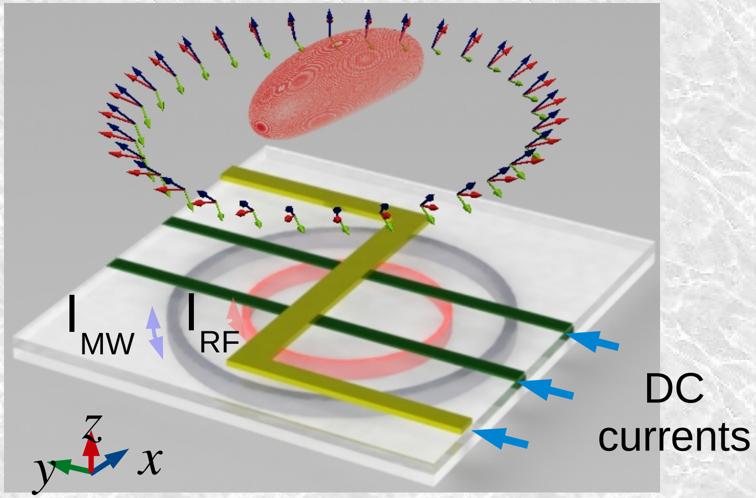
Atom-chip for Quantum Sim. and IP
NJP 2015 and NJP. 2016.



Hybrid atom-chip technology
JMO 2018.

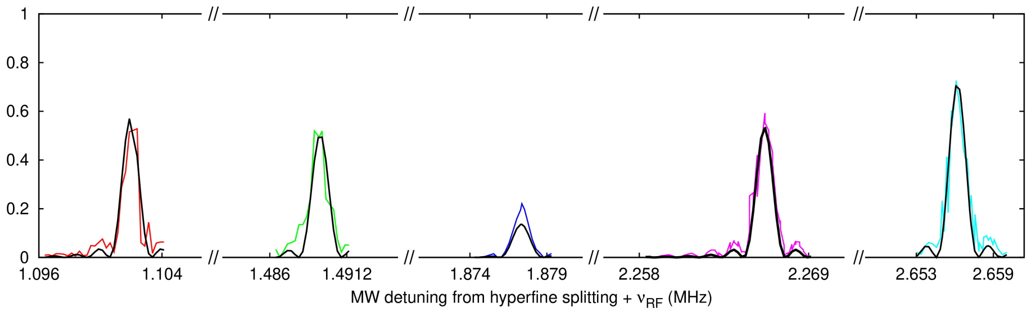


RF + MW dressing
In prep., 2019.



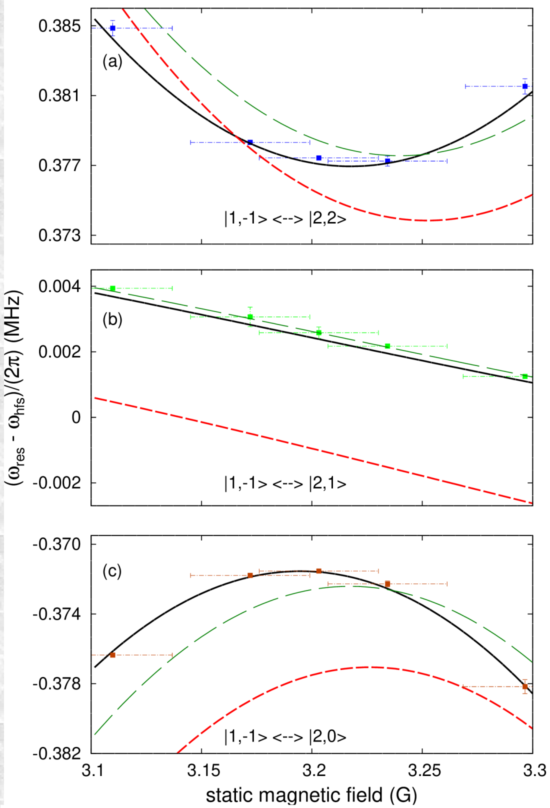
Controlling 87Rb

Microwave spectroscopy of radio-frequency dressed 87Rb



Sinuco, G. *et al.* ArXiv 1904.12073

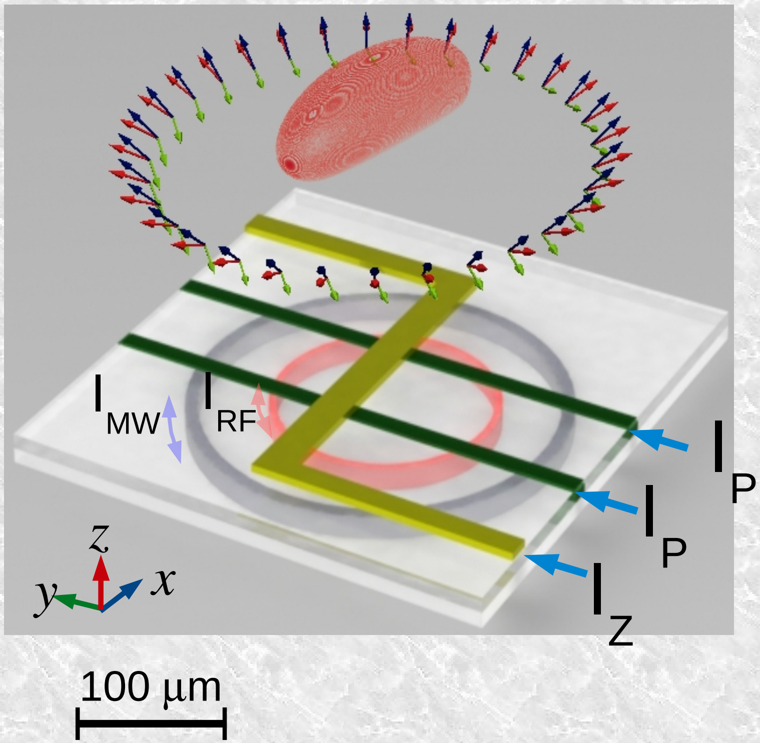
Protection of microwave q*d*its with radio-frequency dressing



Sinuco, G. *et al.* (2019)
In preparation

With B. Garraway (Sussex), W. von Klitzing (Crete) and T. Fernolhz (Nottingham)

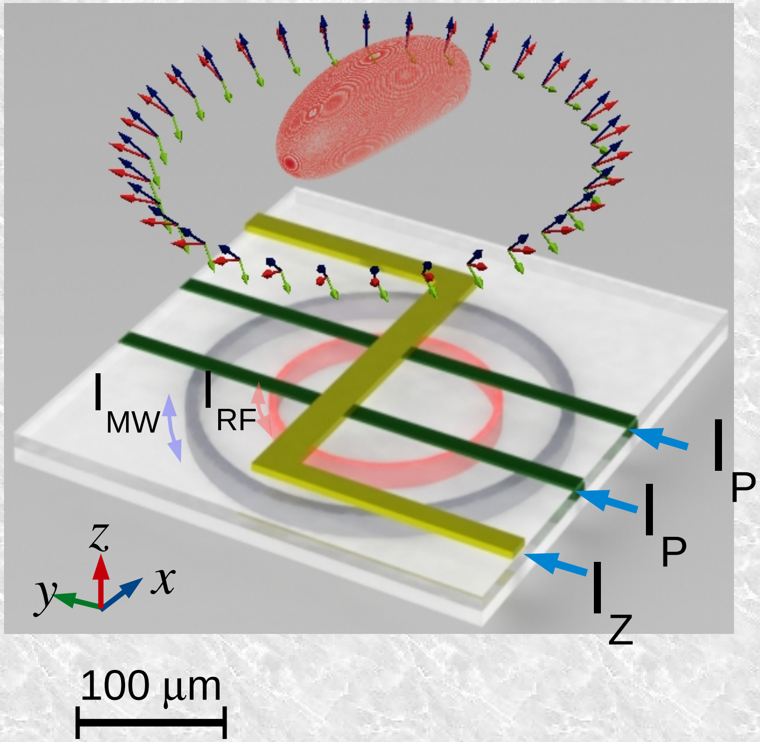
Controlling 87Rb



To do:

- ✓ Experimental bounds of the parameter space
- ✓ Define the problem and geometry
- ✓ Electromagnetic simulator
- ✓ Calculate the effective energy potential landscape
- ✓ Estimate non-adiabatic effects
- ✓ Evaluate near surface effects:
  - Johnson-noise
  - Casimir-Polder attraction

Controlling 87Rb



- Beyond Rotating wave approximation
- Polychromatic driving: RF + MW

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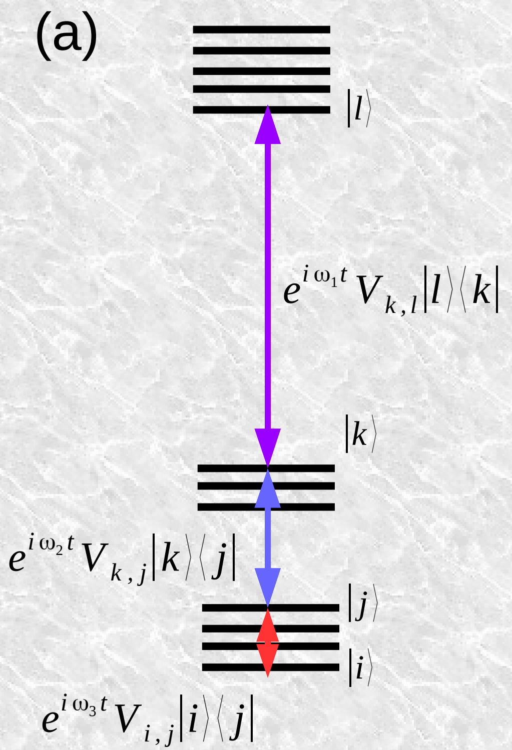
$$H \approx \frac{\boldsymbol{P}^2}{2m} + \sqrt{(\mu_B g_F B_{DC} - \hbar\omega)^2 + \left(\frac{\mu_B g_F B_{RF}}{2}\right)^2}\,\hat{F}_z$$

Driven Quantum Systems

Generic energy level structure of a quantum system. The arrows represent harmonic couplings of different frequencies.



Driven Quantum Systems

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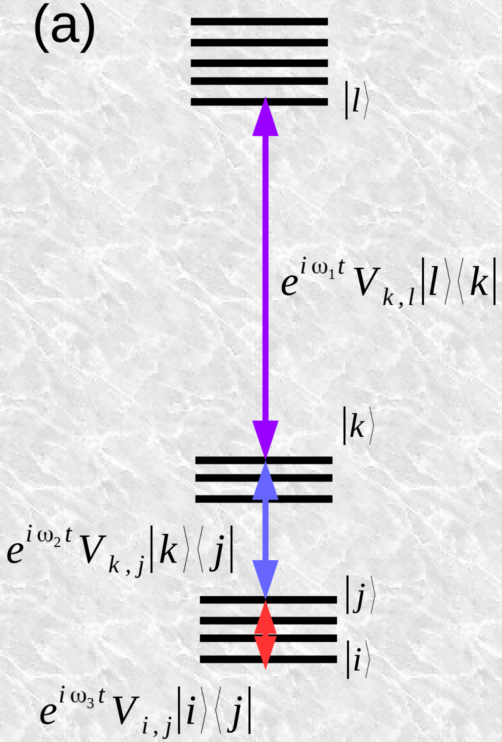

We consider the Hamiltonian of a quantum system driven by several harmonic fields:

$$H = \sum_i E_i |i\rangle\langle i| + \sum_l \sum_n \sum_{i,j} V_{ij} e^{n\omega_l t} |i\rangle\langle j| + h.c.$$

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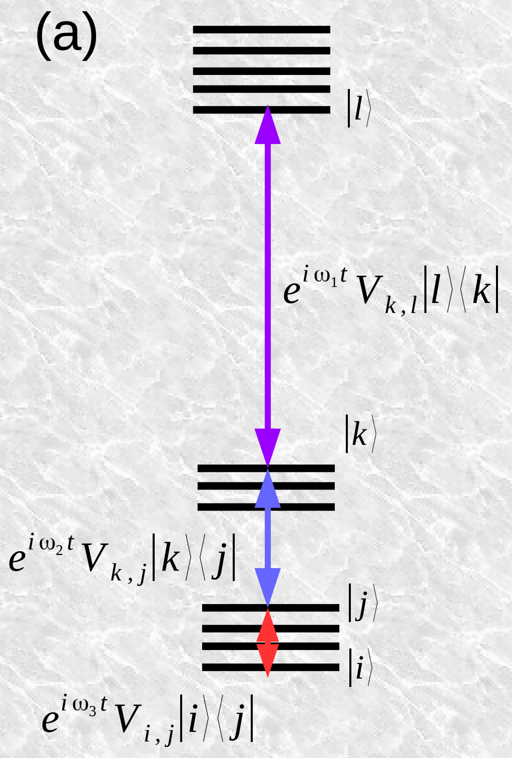

We consider the Hamiltonian of a quantum system driven by several harmonic fields:

$$H = \sum_{\vec{n}} \hat{H}_{\vec{n}} e^{i\vec{n}\cdot\vec{\omega}t}$$

To find the time-evolution operator, we build a unitary transformation that takes the Hamiltonian to a time-independent and diagonal form, i.e.:

Driven Quantum Systems

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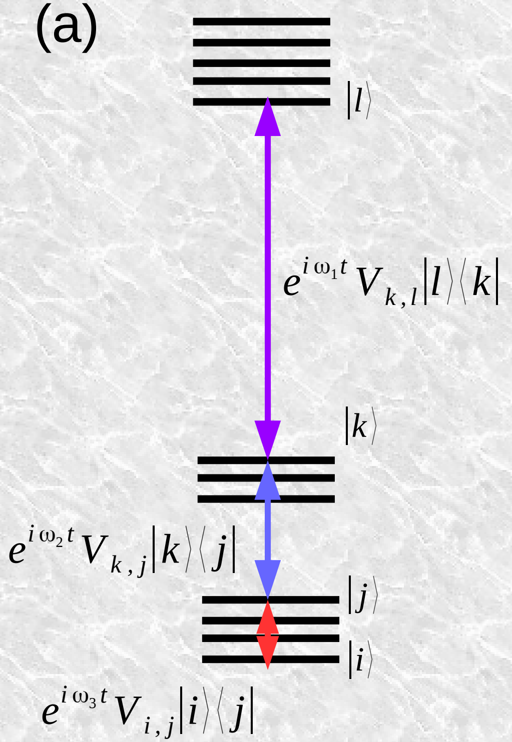

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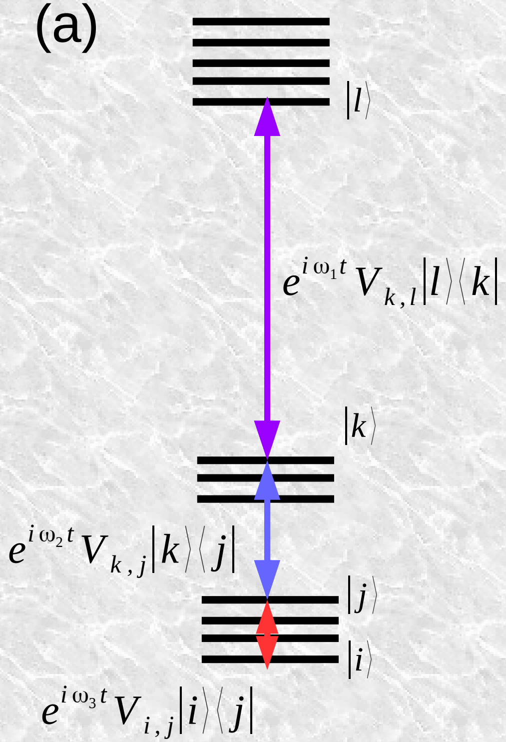

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As a function of position, these values are the State-dependent potential energy landscape

Driven Quantum Systems

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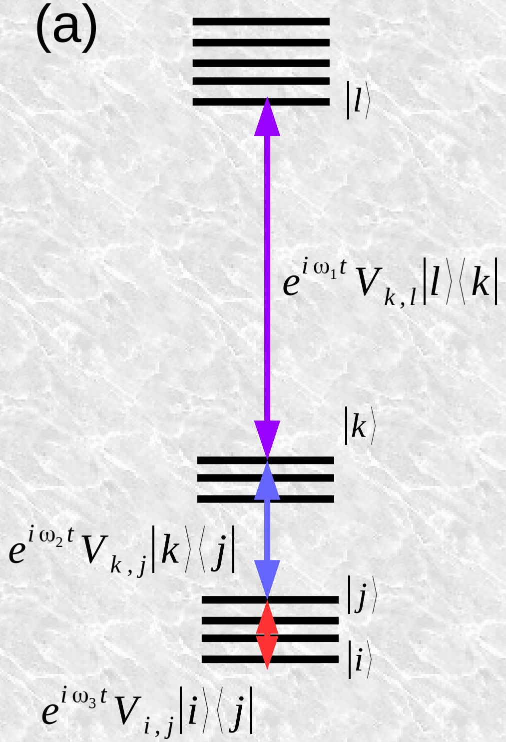

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The harmonic dependence of the driving let us find this unitary transformation using the Fourier decomposition:

$$\hat{U}_F(t) = \sum_{i\lambda} e^{i\vec{n}\cdot\vec{\omega} t} u_{i\lambda}^{\vec{n}} |i\rangle\langle\lambda|$$

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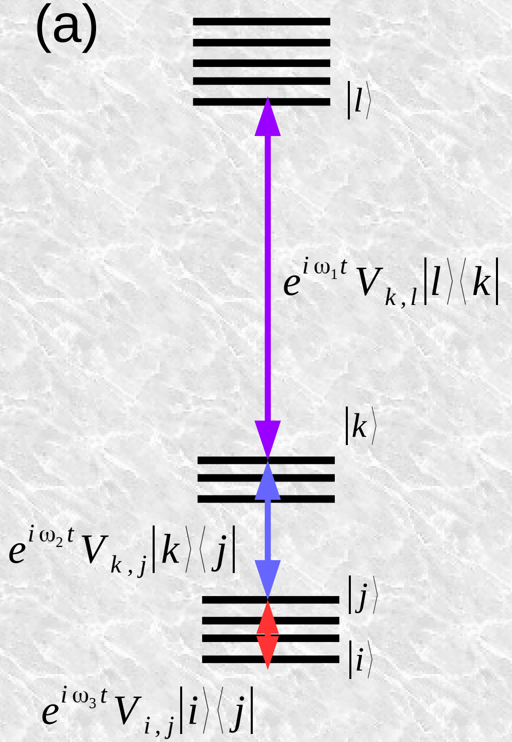


We consider the Hamiltonian of a quantum system driven by several harmonic fields:

$$H = \sum_{\vec{n}} \hat{H}_{\vec{n}} e^{i\vec{n}\cdot\vec{\omega}t}$$

This procedure defines the micromotion operator:

$$\hat{U}_F(t) = \sum_{i\lambda} e^{i\vec{n}\cdot\vec{\omega}t} u^{\vec{n}}_{i\lambda} |i\rangle\langle\lambda|$$

and the basis of dressed states:

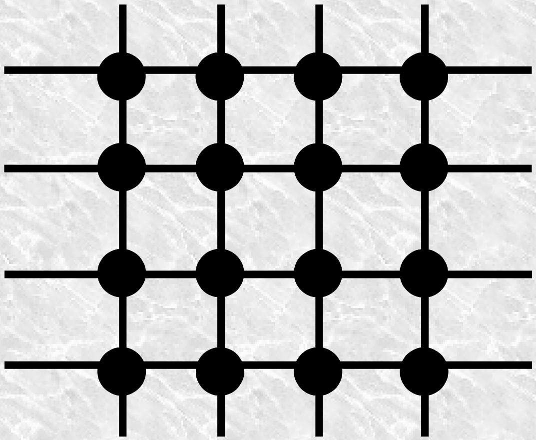
$$\{\lambda, |\lambda\rangle\}$$

As a time-dependent superposition of bare states

$$U(t',t) = U_F(t') e^{i\hat{\bar{H}}(t'-t)} U_F^{\dagger}(t)$$

U(t',t) – Floquet band engineering

Shining light on conventional insulators produces a system whose effective energy bands have a non-trivial topology. (Linder, Nat. Phys. **7**, 490 (2011))



$$H = \sum_m \hat{H}_m e^{im\omega t}$$

$$U(t',t) = U_F(t') e^{i\hat{\hat{H}}(t'-t)} U_F^\dagger(t)$$

$$\hat{\hat{H}} = H_0 + \sum_m \frac{1}{m\hbar\omega}[\hat{H}_m, \hat{H}_m^\dagger] + \ldots$$

$$H(t) = \sum_{n,m} J_x(t) a_{n,m}^\dagger a_{n+1,m} + h.c$$

$$+ J_y(t) \exp(i\alpha n) a_{n,m}^\dagger a_{n,m+1} + h.c.$$

Anisimovas, *et al.*, ArXiv: 1504.03583

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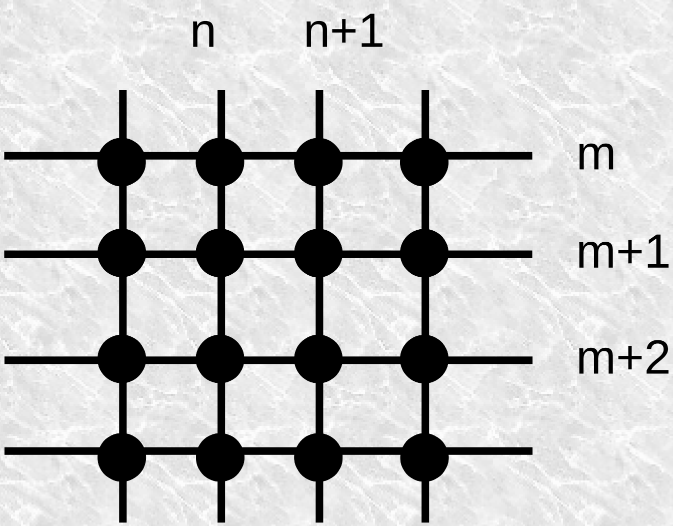
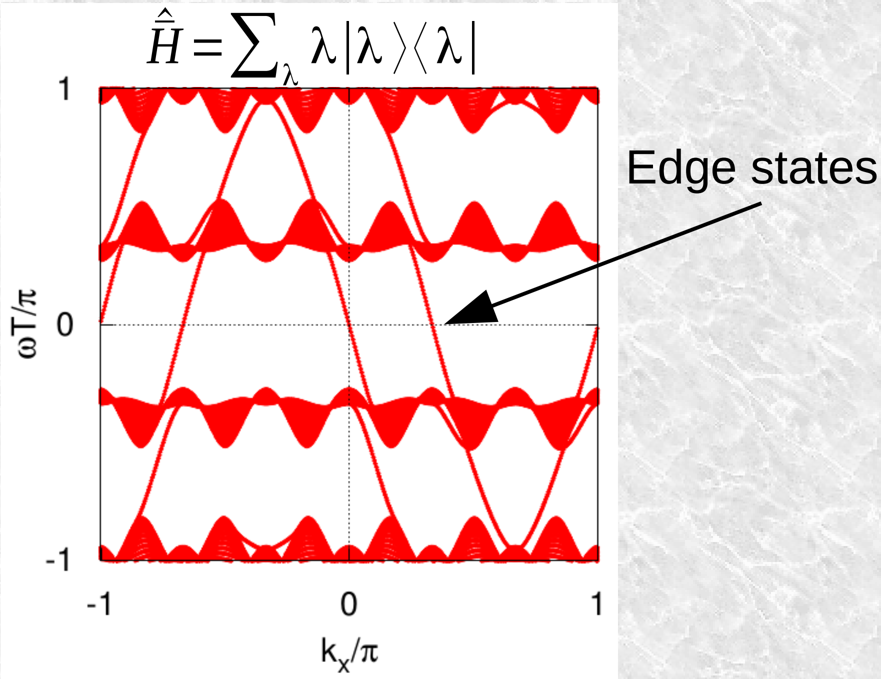




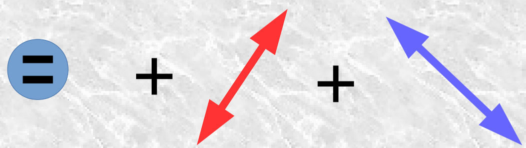
$$H(t) = \sum_{n,m} J_x(t)\, a^{\dagger}_{n,m} a_{n+1,m} + h.c$$

$$+ J_y(t) \exp(i\alpha n)\, a^{\dagger}_{n,m} a_{n,m+1} + h.c.$$

- The time-evolution operator determines the bulk-edge correspondence.
  Roy and Harper, arxiv 1603.06944 (2016)

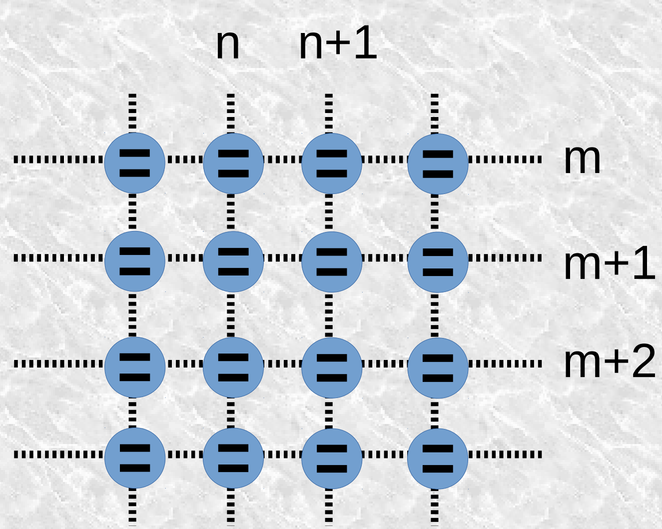
- The micromotion operator determines the time-scale of heating effects (arxiv 1508.0579)

U(t',t) – Time-domain quantum simulations of lattice models



$$H(t) = mS_z + v_1 \sin(\omega_1 t + \varphi_1) S_x - b_1 \cos(\omega_1 t + \varphi_1) S_z$$
$$+ v_2 \sin(\omega_2 t + \varphi_2) S_y - b_2 \cos(\omega_2 t + \varphi_2) S_z$$

$$H = mS_z + \vec{n} \cdot \vec{\omega} + \left(v_1 e^{i\varphi_1} S_x - b_1 e^{i\varphi_1} S_z\right)\delta_{n,n+1} - \left(v_1 e^{-i\varphi_1} S_x + b_1 e^{-i\varphi_1} S_z\right)\delta_{n,n-1}$$
$$+ \left(v_2 e^{i\varphi_2} S_y - b_2 e^{i\varphi_2} S_z\right)\delta_{m,m+1} - \left(v_2 e^{-i\varphi_2} S_x + b_1 e^{-i\varphi_2} S_z\right)\delta_{m,m-1}$$



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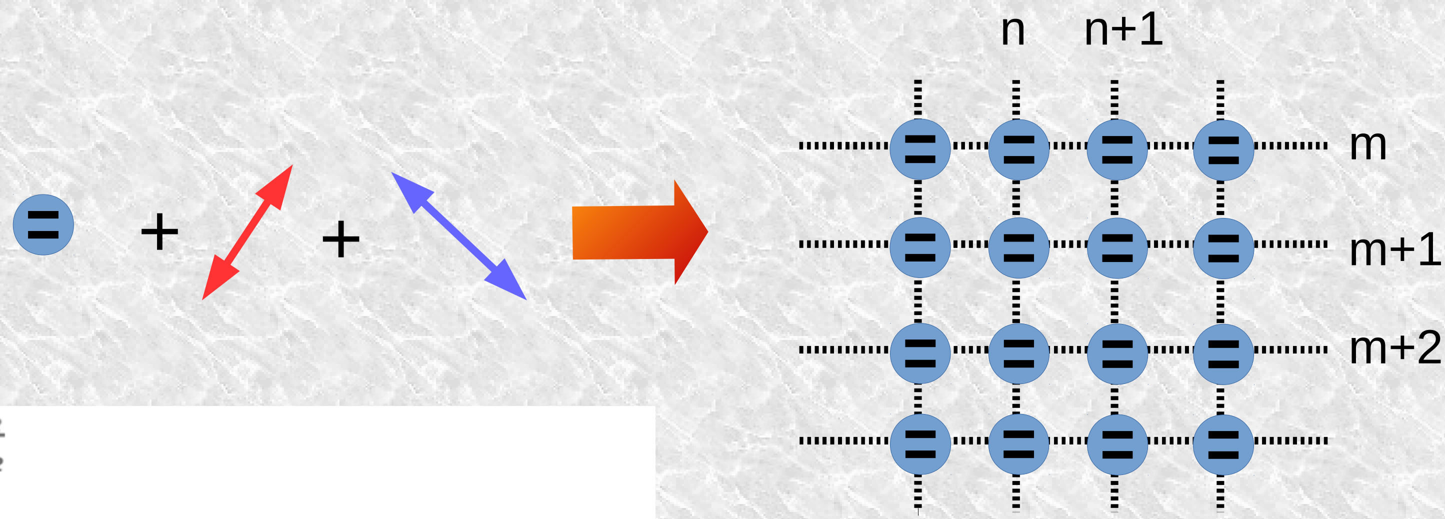

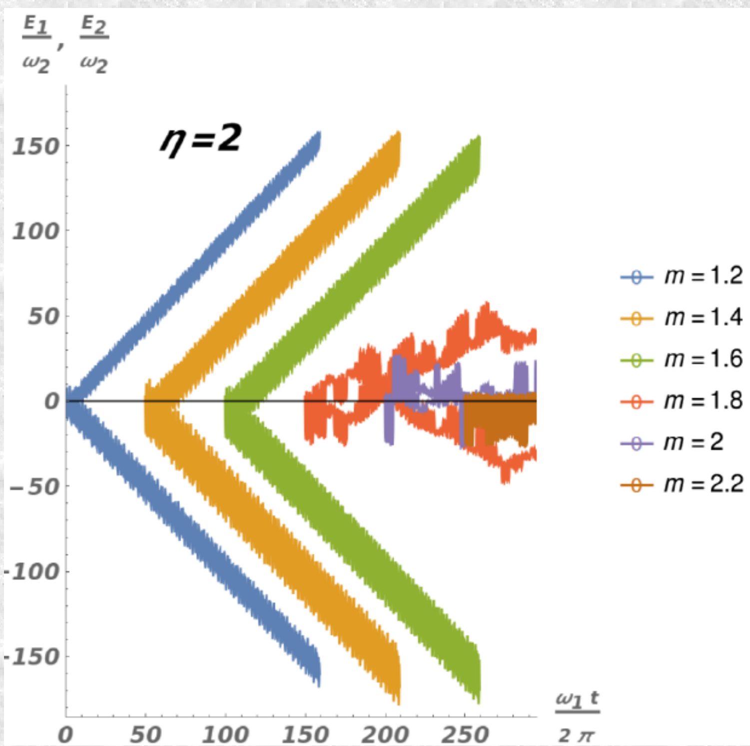

Martin, Refael and Halperin,
PRX 7, 041008 (2017)

Energy absorption from drives 1 and 2, as functions of time for different *m's.* Strong and red-detuned driving.

Time-evolution operator

many-body lattice models

micromotion operator

"The essence of our theory is that by using the latter interpretation … problems involving Hamiltonians periodic in time may be solved by methods applicable to time-independent Hamiltonians"
Jon Shirley, Phys. Rev. **138**, B979 (1969).

$$H=\sum_{\vec{n}}\hat{H}_{\vec{n}}e^{i\vec{n}\cdot\vec{\omega}t}$$

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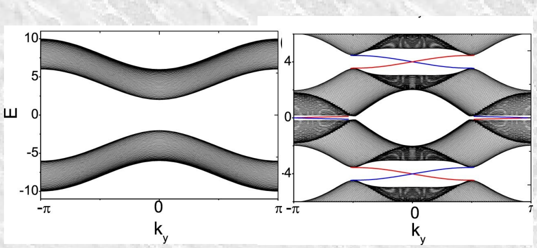
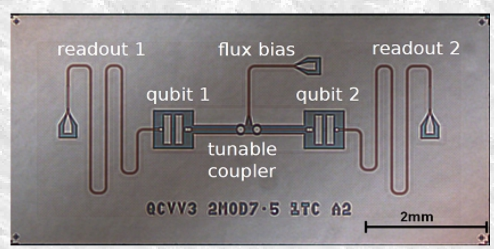
Interplay between geometry, disorder, driving an interactions.



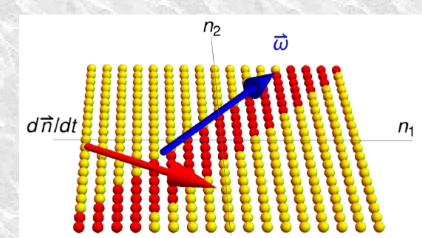
Dynamical Engineering

Quantum control



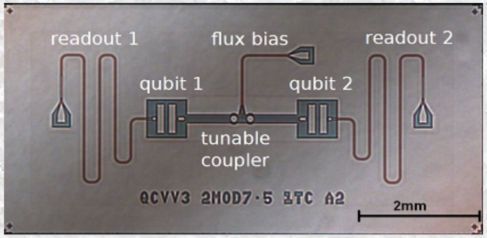
- Robust
- Fast

High-dimensional time-domain quantum simulations

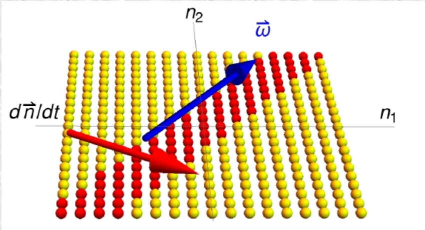


Outlook

Quantum control



Time-domain quantum simulations



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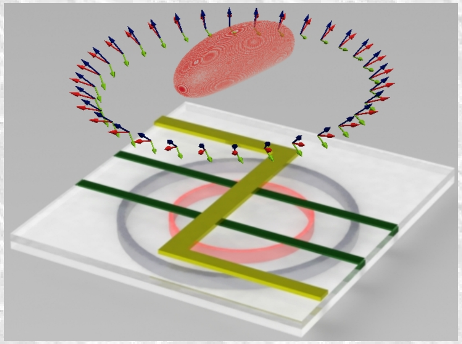
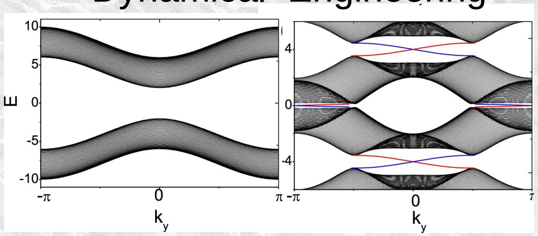
Atomic Quantum technology



Dynamical Engineering



Renormalisation of the Floquet Hamiltonian

$$\hat{\bar{H}} = \hat{U}_F^{\dagger} \hat{H} \hat{U}_F - i\hbar \hat{U}_F^{\dagger} \partial_t \hat{U}_F = \sum_{\lambda} \lambda |\lambda\rangle\langle\lambda|$$

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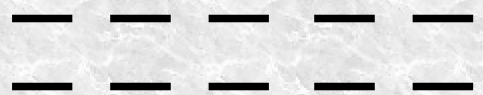
1D biased tight binding model

...



...

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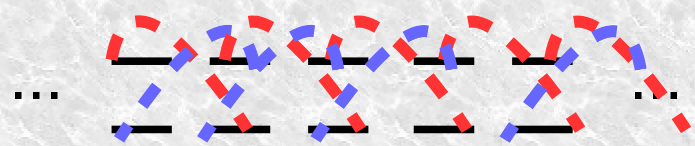

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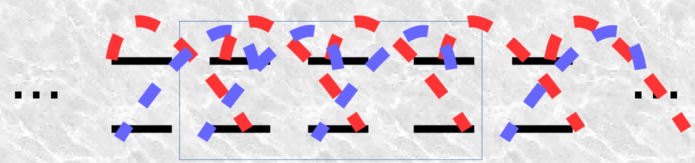

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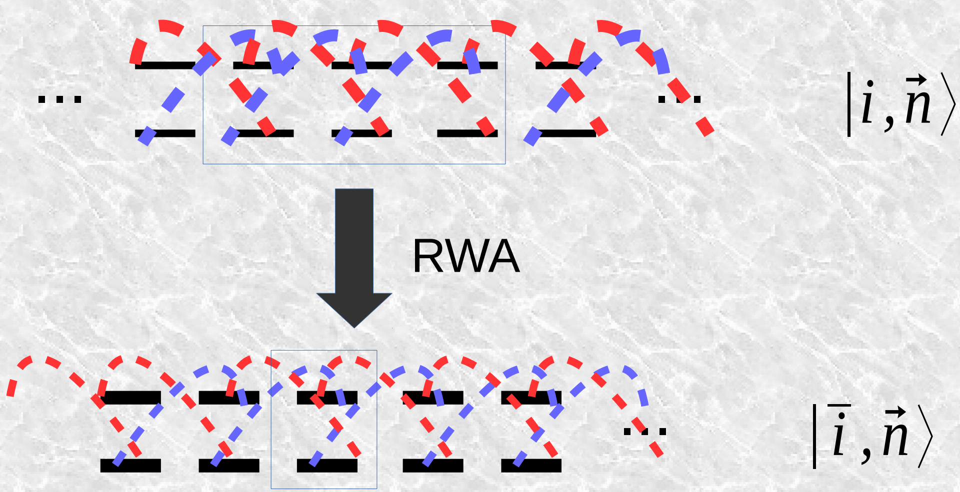

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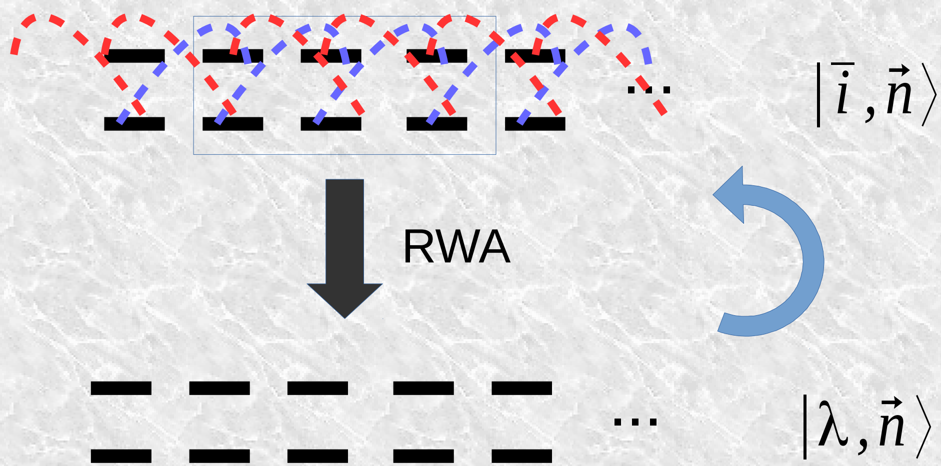

Variational parametrization of the micromotion operator

$$\hat{\bar{H}} = \hat{U}_F^\dagger \hat{H} \hat{U}_F - i\hbar \hat{U}_F^\dagger \partial_t \hat{U}_F = \sum_\lambda \lambda |\lambda\rangle\langle\lambda|$$

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G. Torlai and R. G. Melko, PRL. **120**, 240503 (2018)

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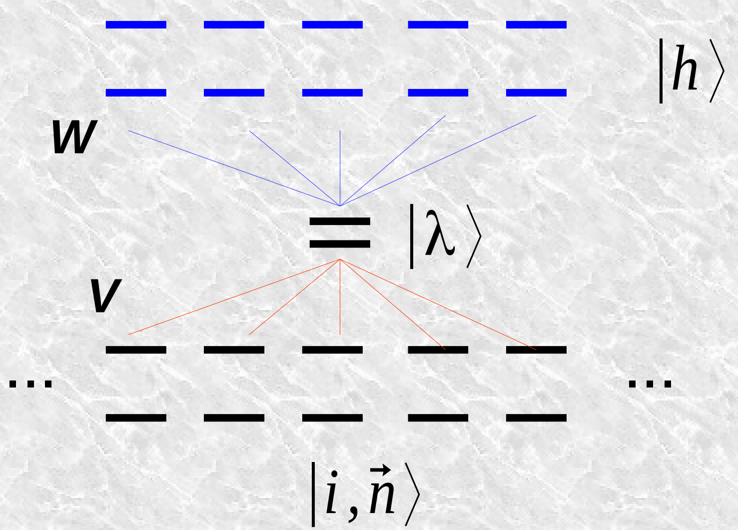

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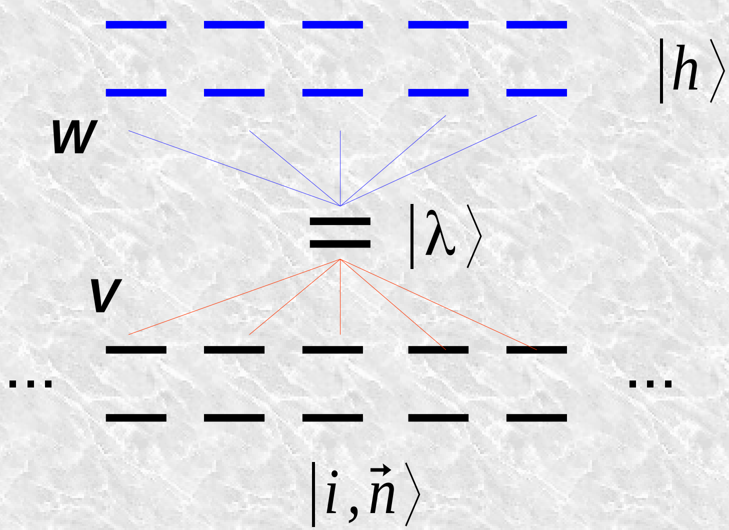


$$\rho_{i\lambda}^{\vec{n}}=\sum_{\{h\}}\exp\left(a\lambda+\vec{b}\cdot\vec{\sigma}+\vec{c}\cdot\vec{h}+\lambda W_{\lambda,h}\cdot\vec{h}+\lambda V_{\lambda,\sigma}\cdot\vec{h}\right)$$

$$\lambda=-1,1\quad \vec{\sigma}=(i,\vec{n})\quad \vec{h}=\{-1,1\}^N$$

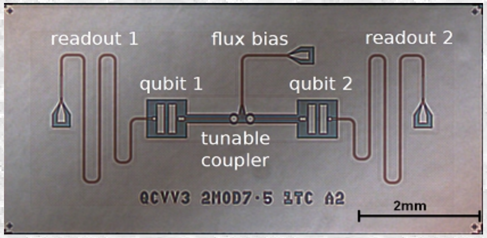
Minimise the distance between the transformed Hamiltonian

$$\hat{\hat{H}}=\hat{U}_F^{\dagger}\hat{H}\,\hat{U}_F-i\hbar\,\hat{U}_F^{\dagger}\partial_t\hat{U}_F$$

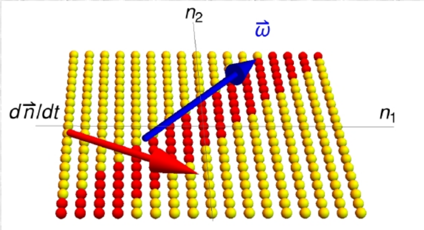
and a diagonal time-independent matrix.

Outlook

Quantum control



Time-domain quantum simulations



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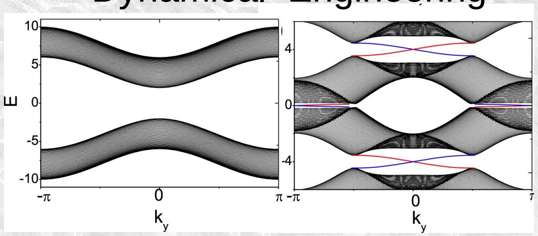
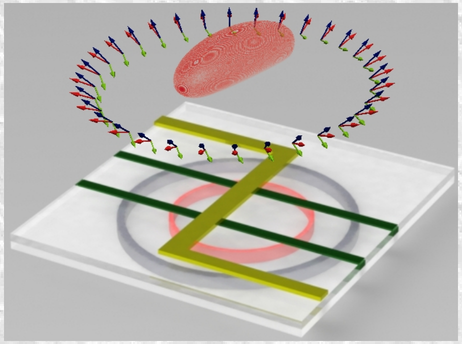
Dynamical Engineering



Atomic Quantum technology



U(t',t) with ML

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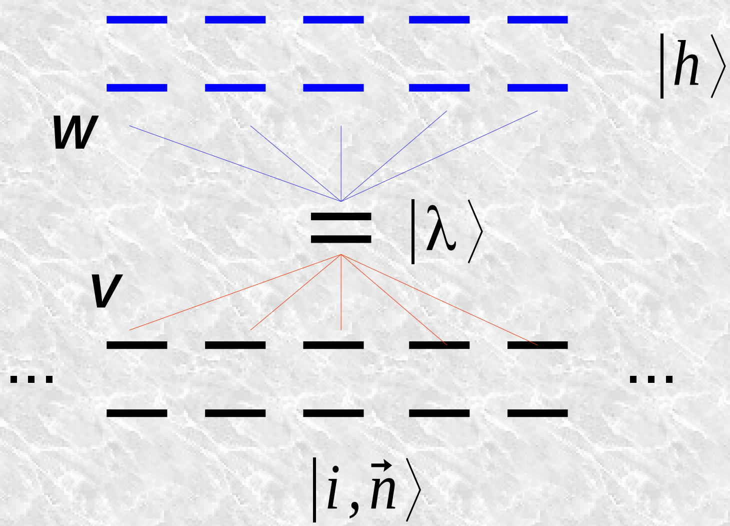

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