

# Quantum Mixtures @ Synthetic Quantum Systems/Heidelberg University

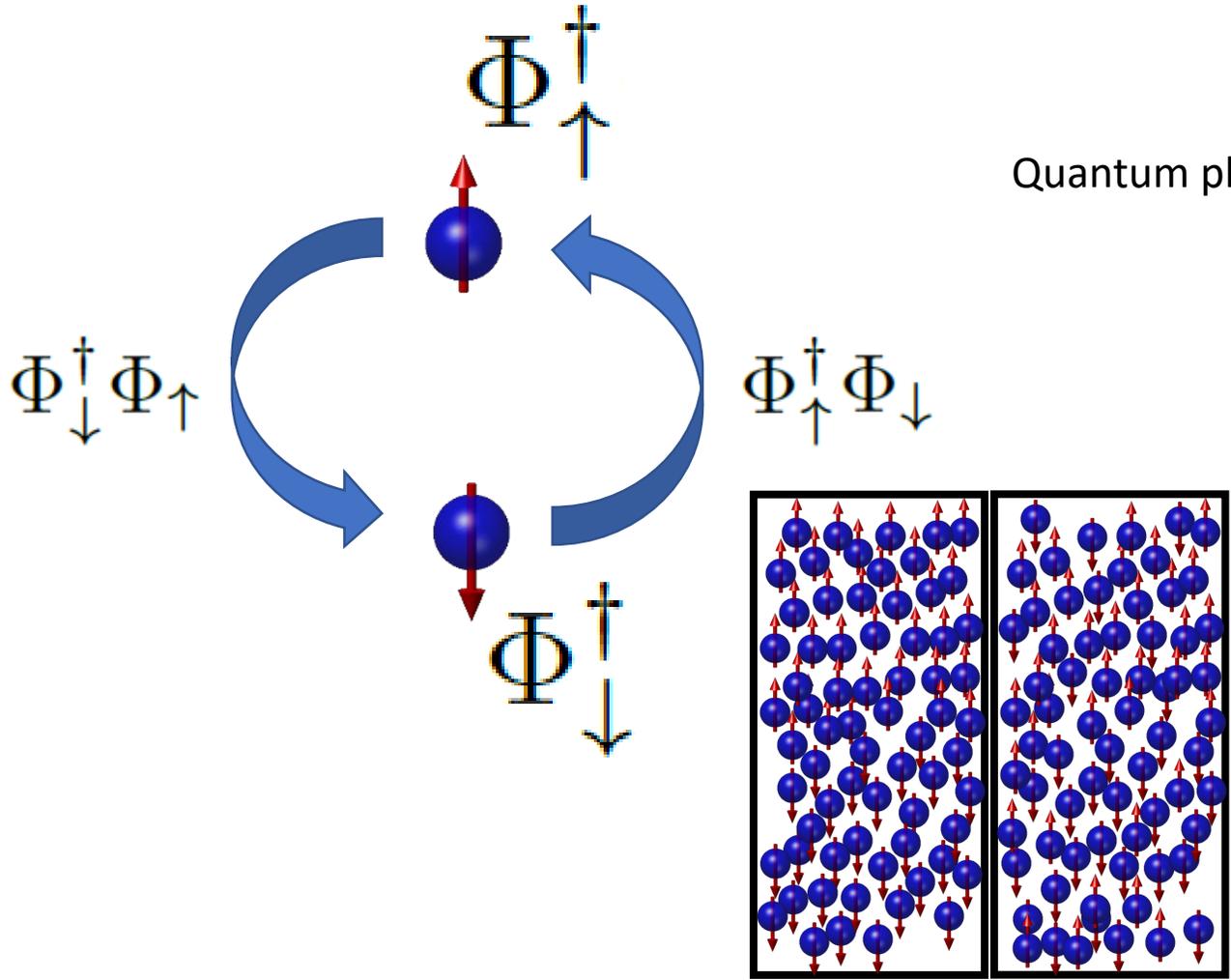
Varena@kip.uni-heidelberg.de



the fax number is: +496221545179

# Coherent Quantum Mixtures

What a new readout allows to access



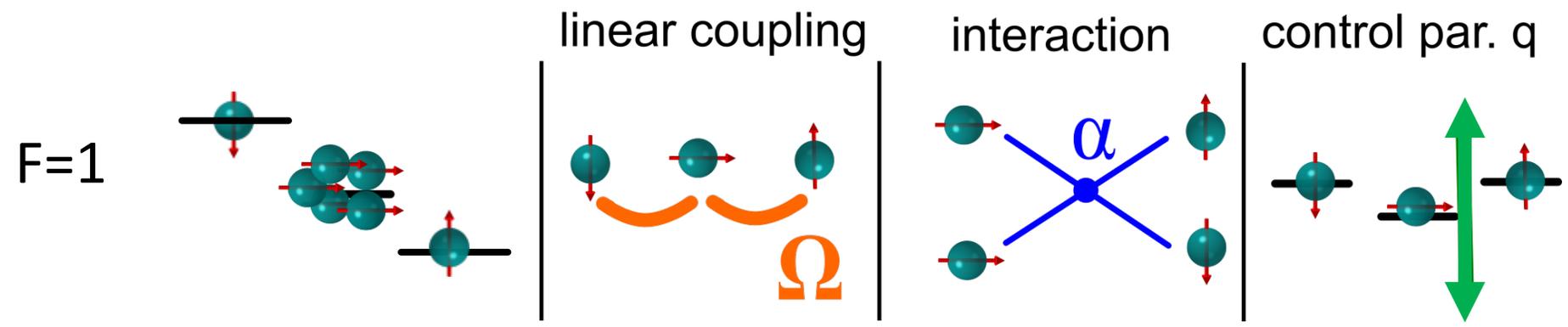
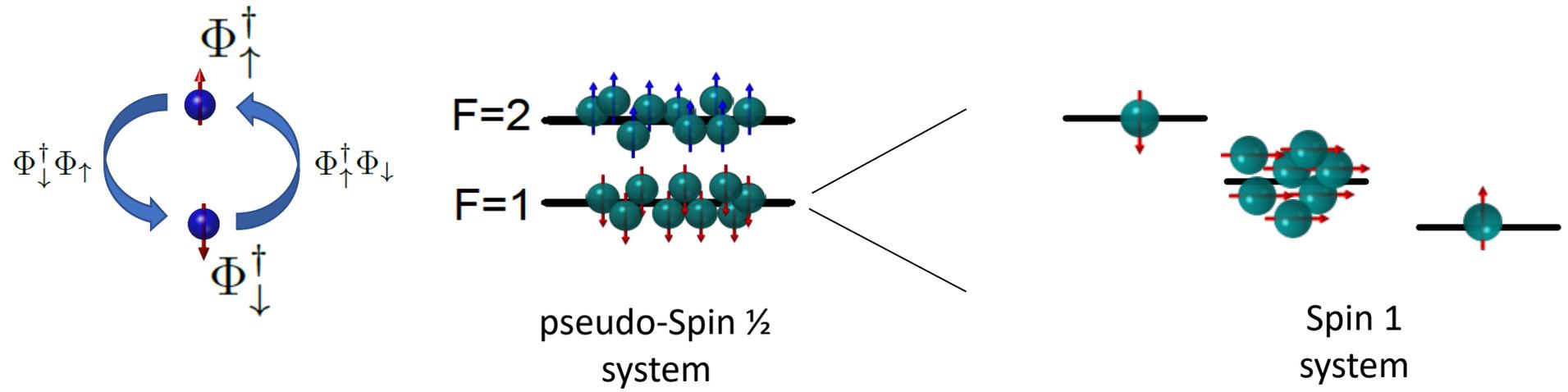
Coherently driven – miscibility of dressed states

Quantum phase transition via coherently coupled immiscible mixtures

Quantum mixtures reveal entanglement generation

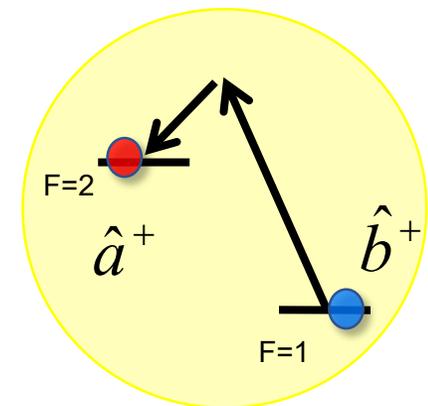
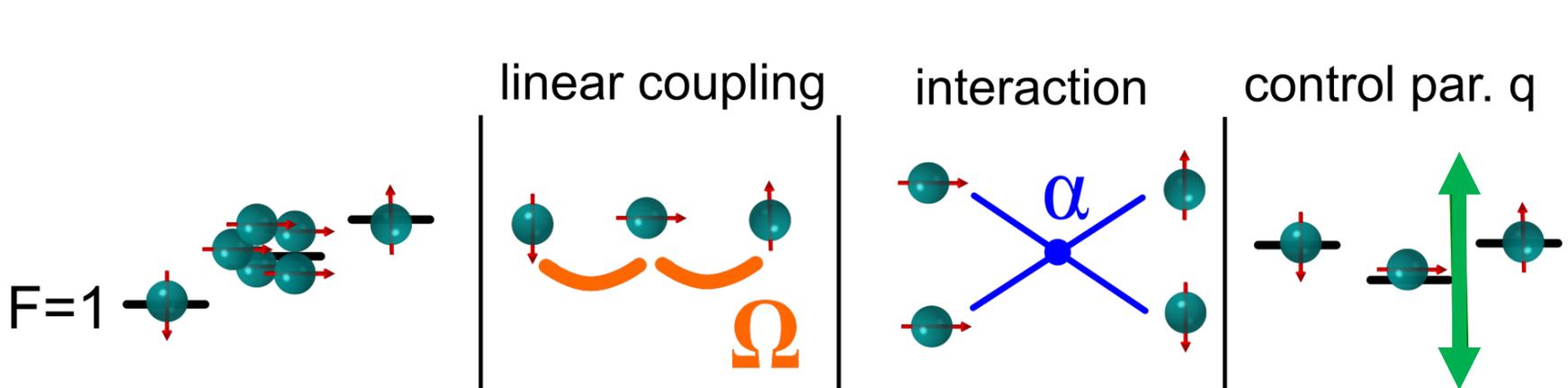
# Coherent Quantum Mixtures – Spinor Condensates

What a new readout allows to access



8 generators – similar  $\hat{H}$

Spin 1 versus Pseudo Spin 1/2



$$\hat{S}_x = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \quad \hat{S}_y = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & -i & 0 \\ i & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \quad \hat{S}_z = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix},$$

$$\hat{H}/h = \hat{Q}_{xz} \frac{\hat{H}}{h} = \hat{Q}_{yz} \frac{q_{\text{eff}}}{2} \hat{Q}_0 + \frac{\tilde{c}_1}{2} \left( \hat{S}_x^2 + \hat{S}_y^2 + \hat{S}_z^2 \right):$$

$$\hat{V}_x = \frac{1}{2} (\hat{Q}_{xx} - \hat{Q}_{yy}) = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}, \quad \hat{V}_y = \hat{Q}_{xy} = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}$$

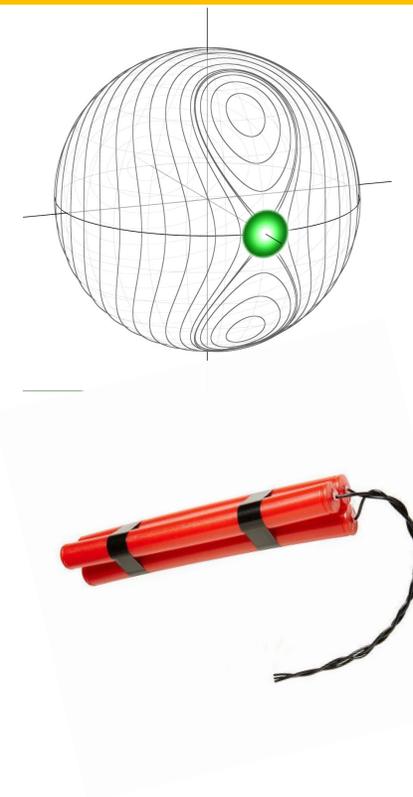
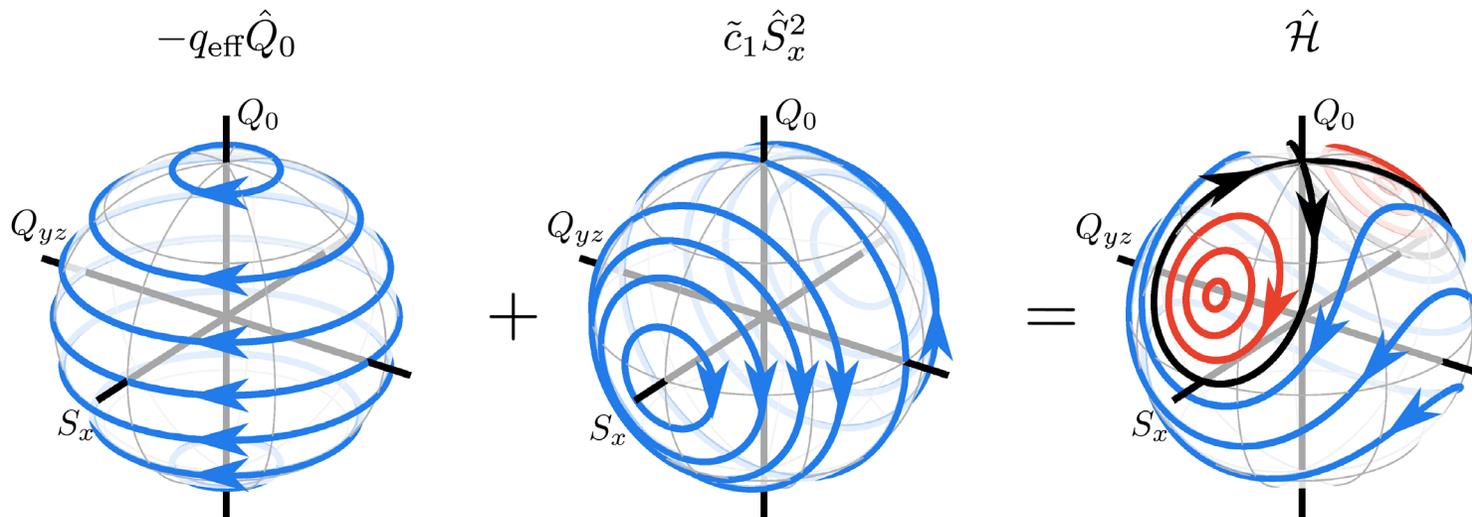
$$H = \chi J_z^2 - \Omega J_x$$

You name it ...

$$\hat{Q}_0 = \begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \quad \hat{S}_x = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \hat{Q}_{yz} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & -i & 0 \\ i & 0 & i \\ 0 & -i & 0 \end{pmatrix}$$

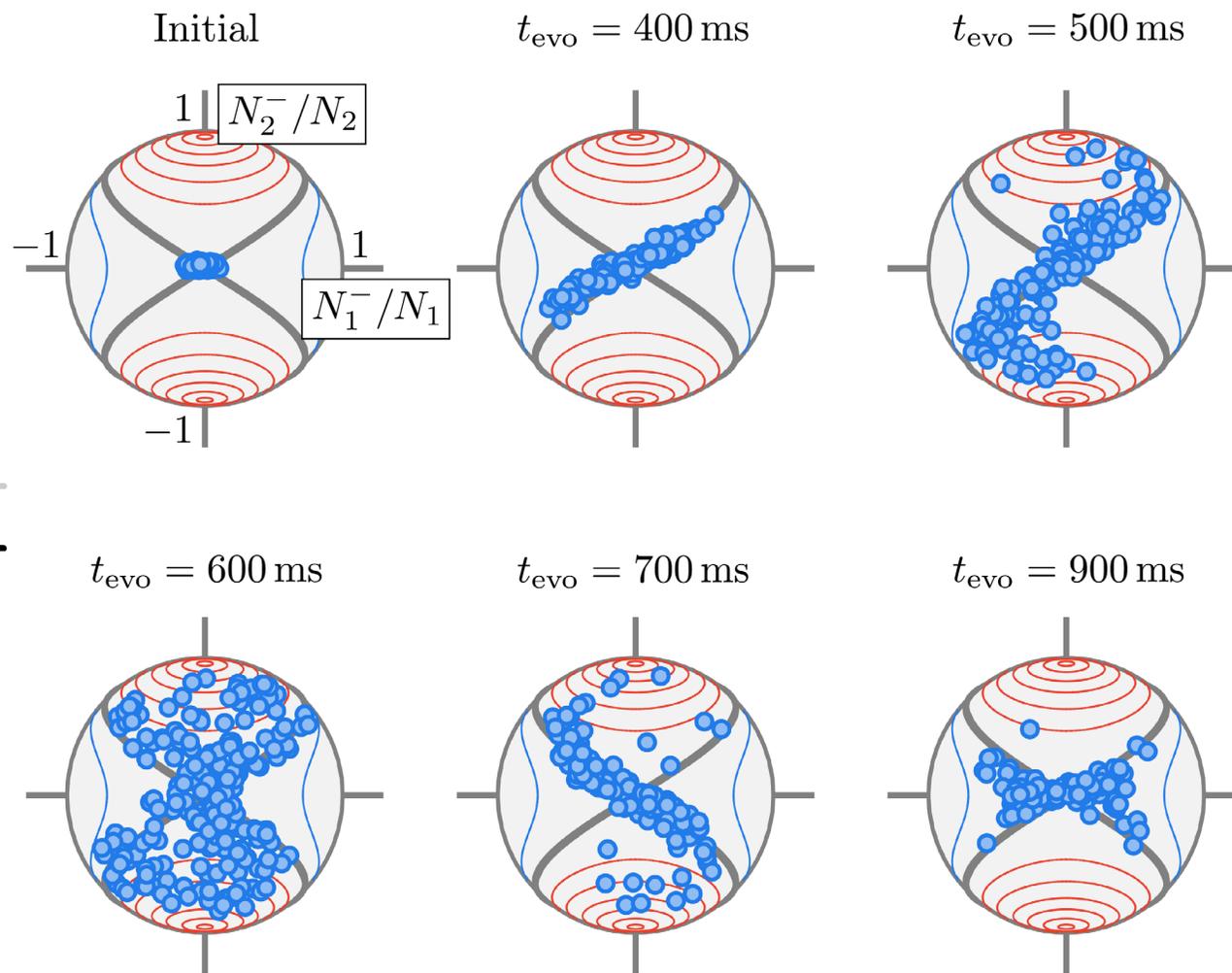
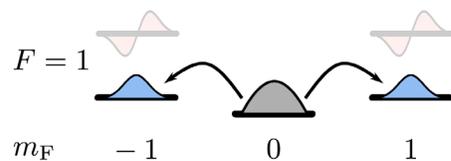
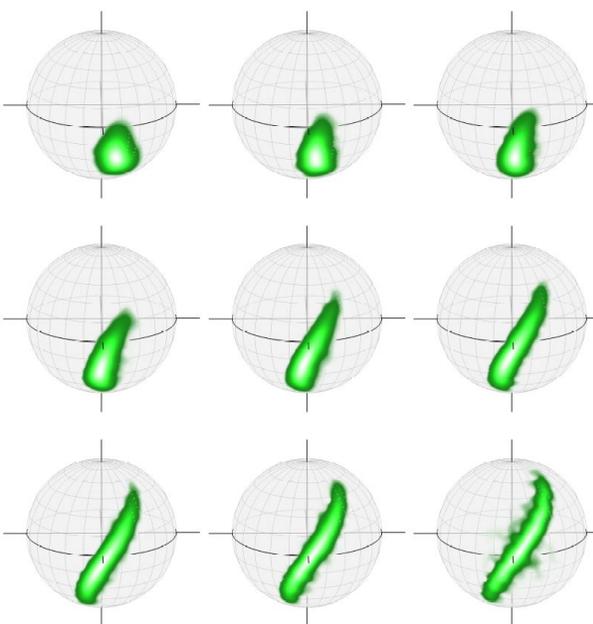
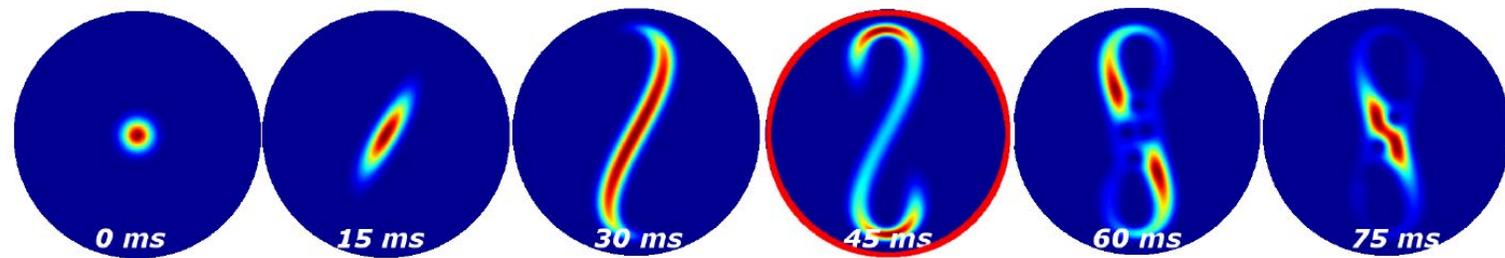
Bifurcation, ...

Spin-nematic subspace



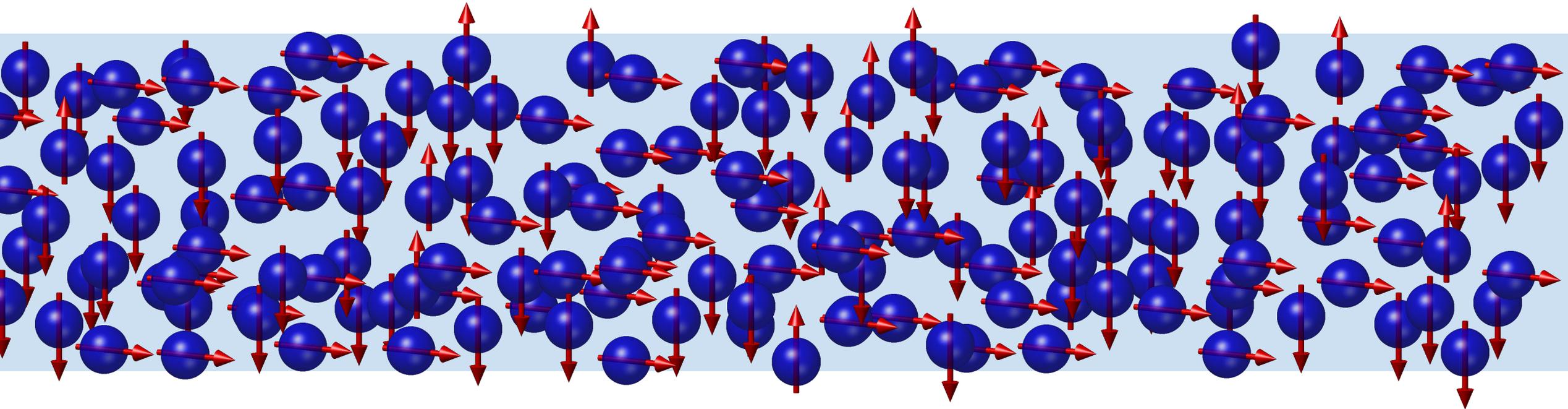
$$E_{\text{MF}} = -h \frac{q_{\text{eff}}}{2} Q_0 + h \frac{\tilde{c}_1}{2} S_x^2.$$

# Observe dynamics



# Quasi-one-dimensional spin-1 bosonic gas

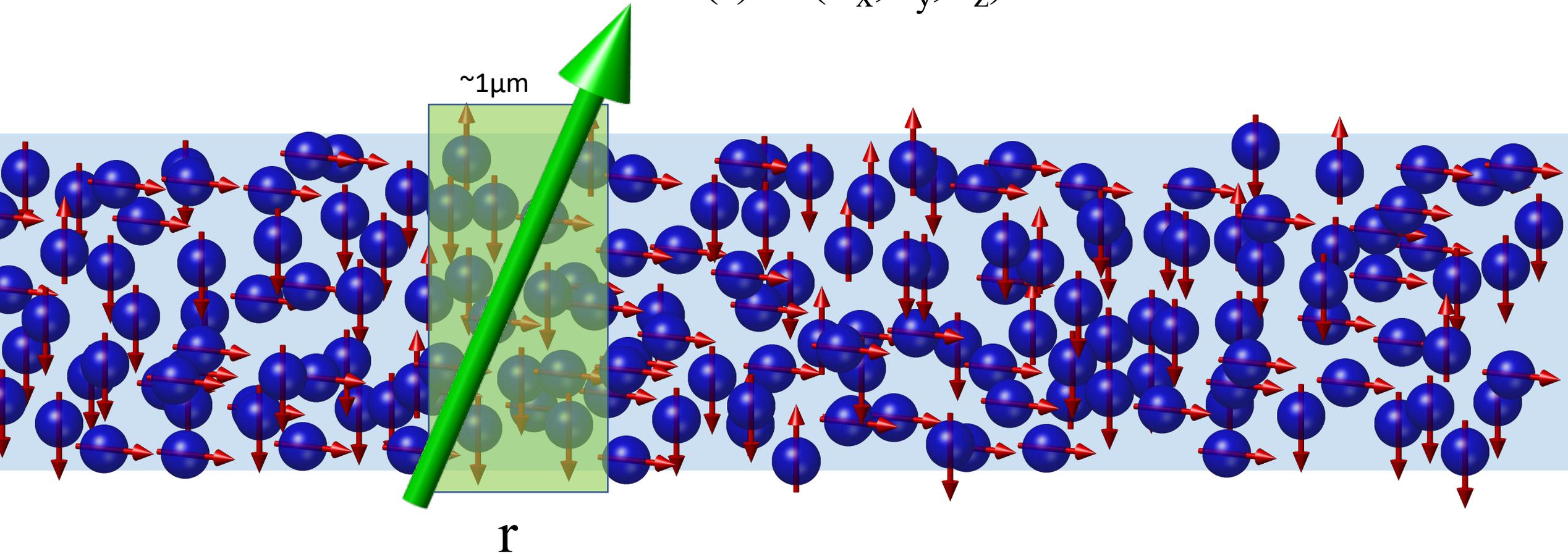
# Quantum Field Settings

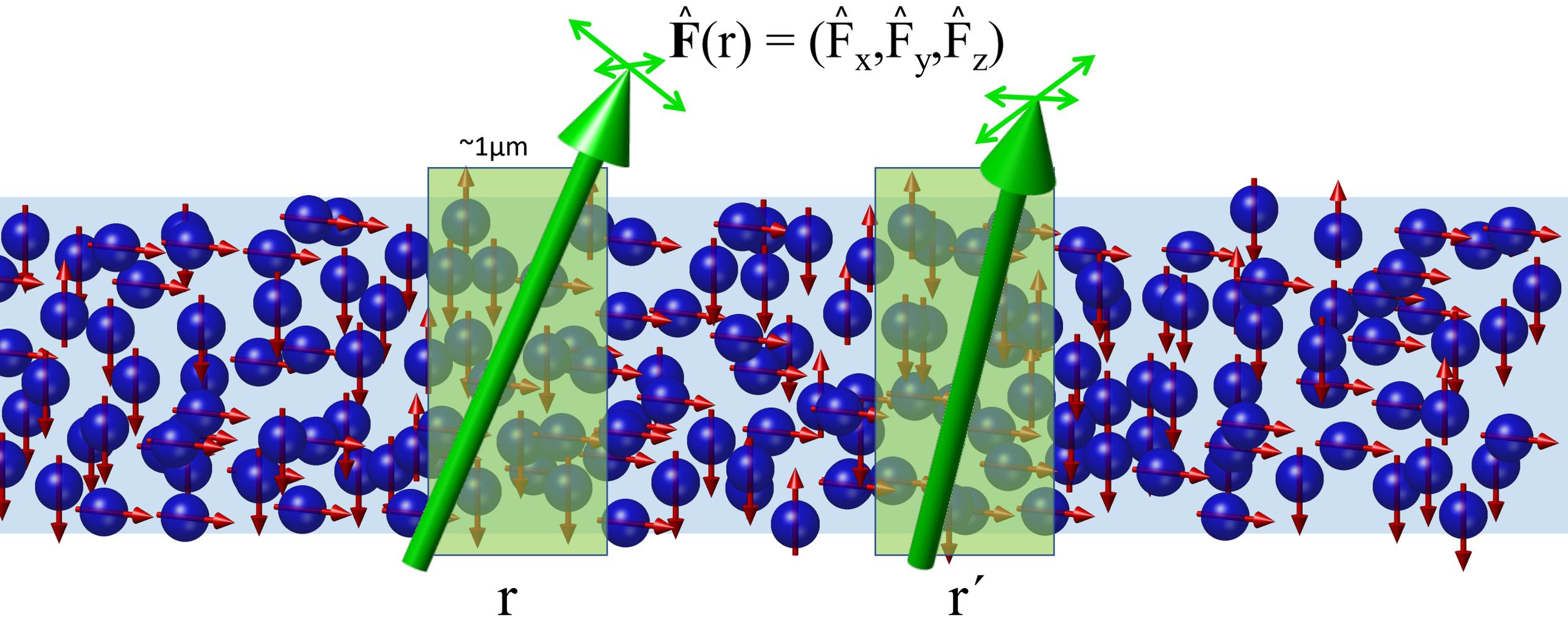


Voxel contains approx. 200 atoms – spin degree is 1d

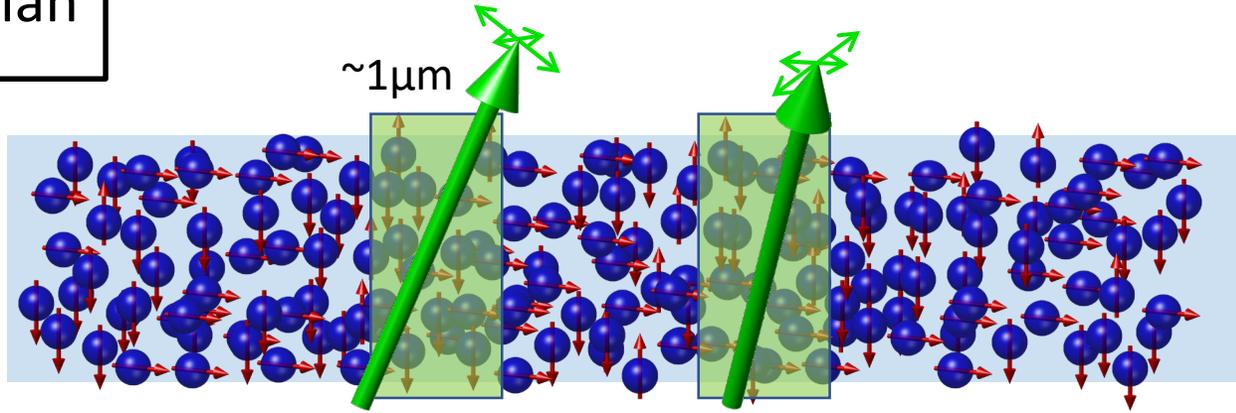
(Quantum) Field Settings

$$\mathbf{F}(\mathbf{r}) = (F_x, F_y, F_z)$$





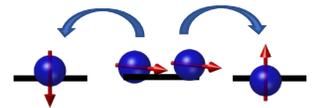
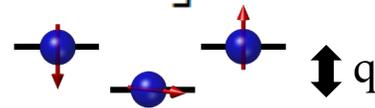
spatial correlation  $\langle \hat{\mathbf{F}}(\mathbf{r})\hat{\mathbf{F}}(\mathbf{r}') \rangle$ ,  $\langle \hat{\mathbf{F}}(\mathbf{r})\hat{\mathbf{F}}(\mathbf{r}')\hat{\mathbf{F}}(\mathbf{r}'') \rangle$ , ...



$$\hat{\psi}_m^{(\dagger)}(\vec{r})$$

$$\hat{\mathcal{H}} = \hat{\mathcal{H}}_0 + \hat{\mathcal{H}}_{\text{int}}$$

$$\hat{\mathcal{H}}_0/h = \int d\vec{r} \hat{\psi}^\dagger \left[ -\frac{\hbar \nabla^2}{4\pi m} + V_{\text{ext}} + qf_z^2 \right] \hat{\psi}$$



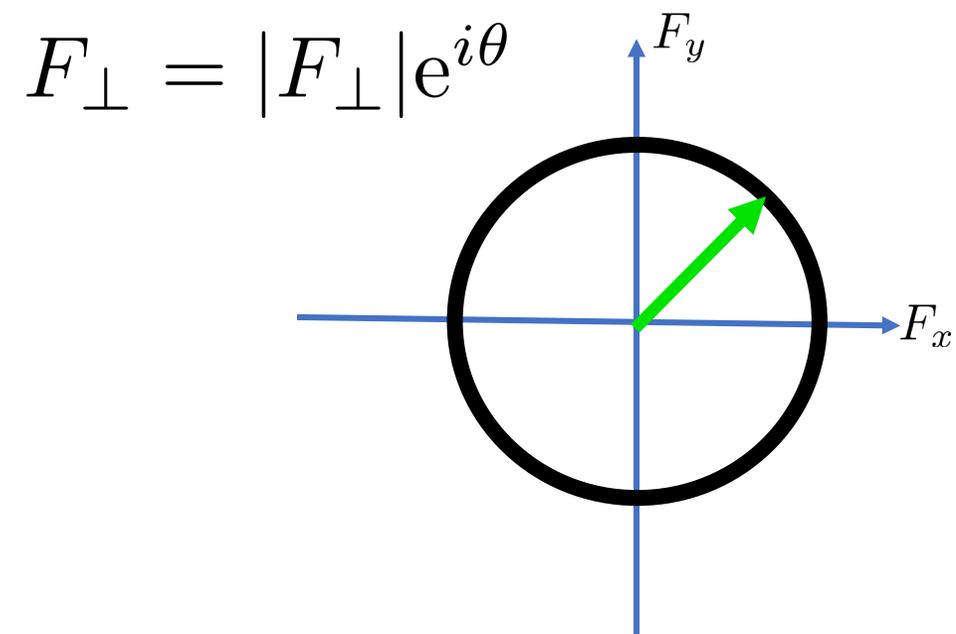
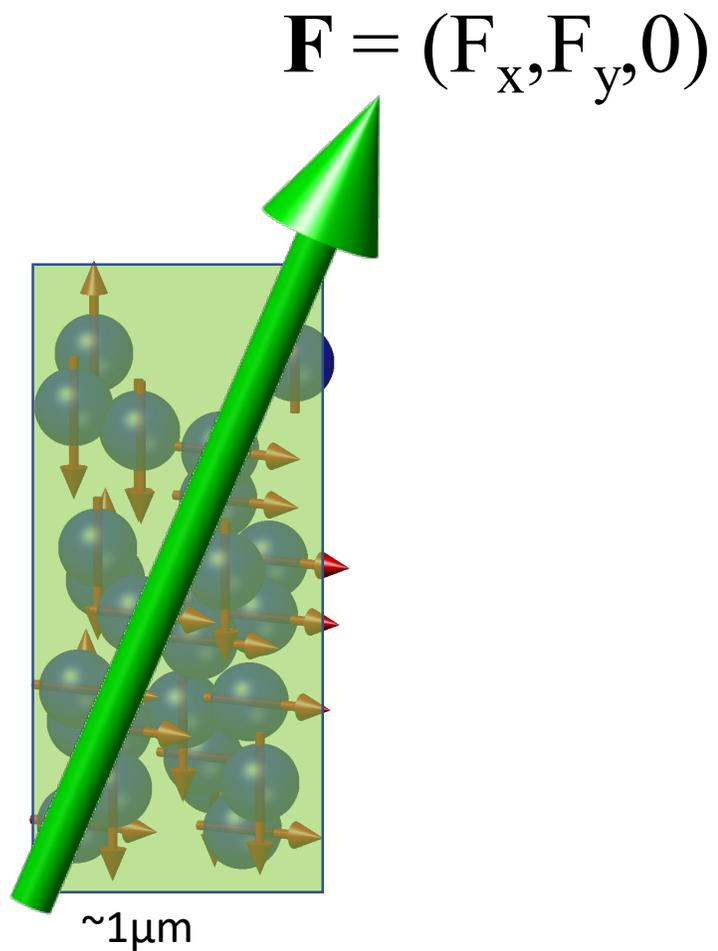
$$\hat{n} = \sum_{i=0,\pm 1} \hat{\psi}_i^\dagger \hat{\psi}_i$$

$$\hat{\vec{F}} = \left( \hat{F}_x, \hat{F}_y, \hat{F}_z \right)$$

$$\hat{F}_x = \frac{1}{\sqrt{2}} \left( \hat{\psi}_{+1}^\dagger \hat{\psi}_0 + \hat{\psi}_{-1}^\dagger \hat{\psi}_0 \right) + \text{h.c.}$$

$$\hat{F}_y = \frac{i}{\sqrt{2}} \left( \hat{\psi}_{+1}^\dagger \hat{\psi}_0 - \hat{\psi}_{-1}^\dagger \hat{\psi}_0 \right) + \text{h.c.}$$

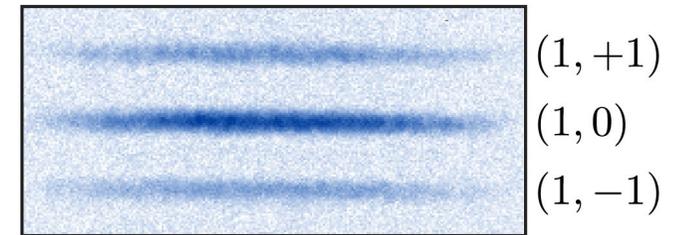
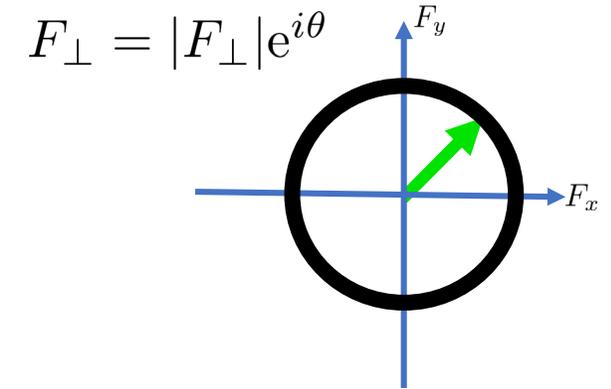
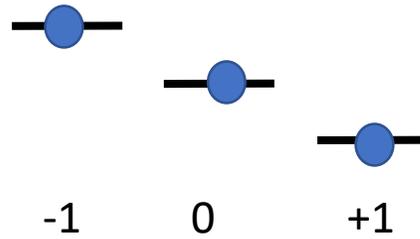
$$\hat{F}_z = \hat{\psi}_{+1}^\dagger \hat{\psi}_{+1} - \hat{\psi}_{-1}^\dagger \hat{\psi}_{-1},$$



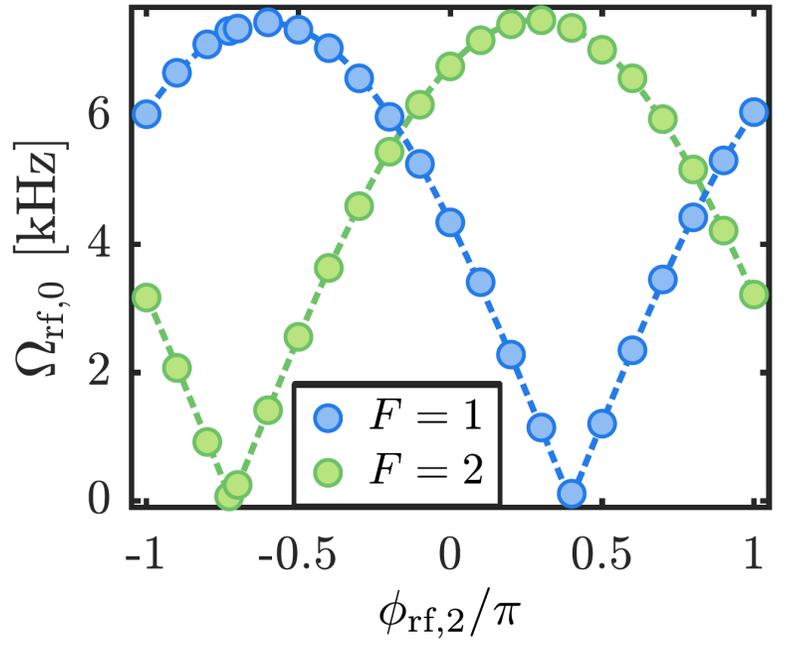
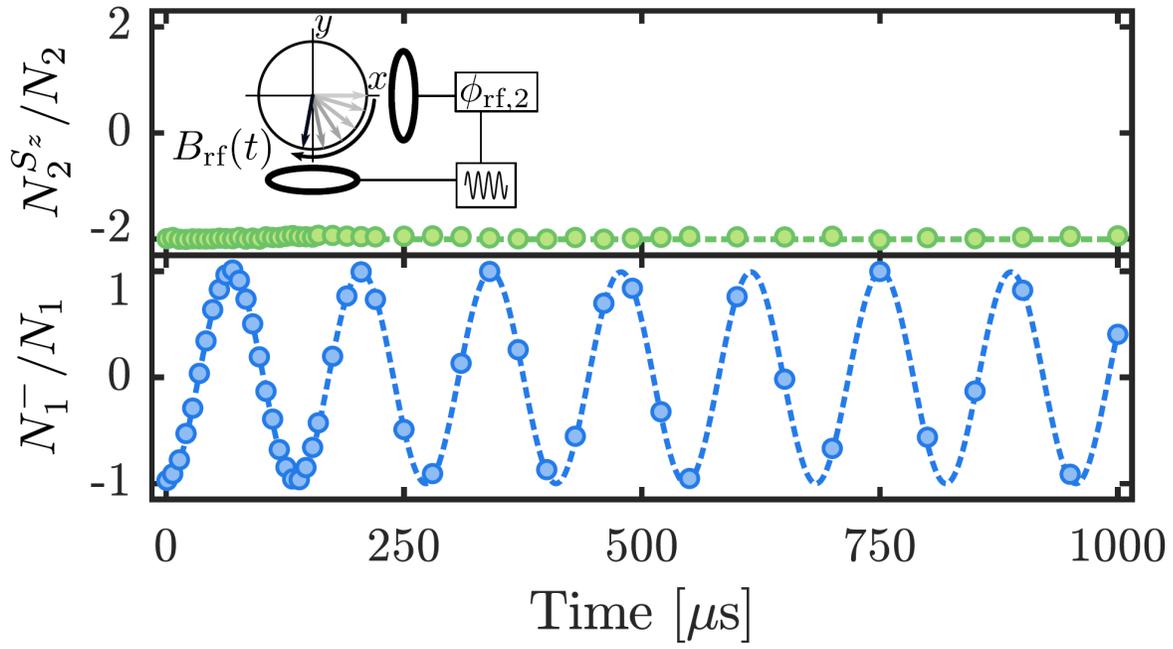
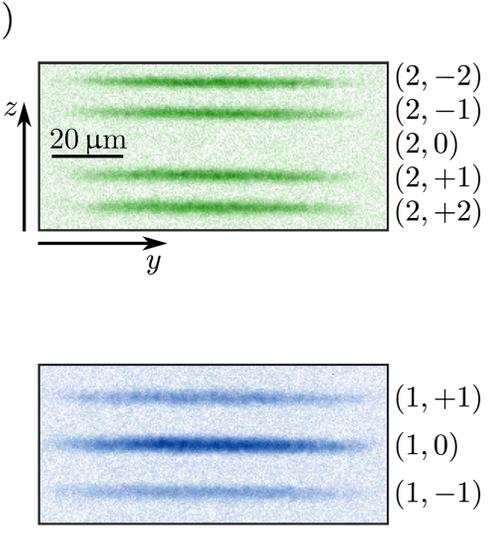
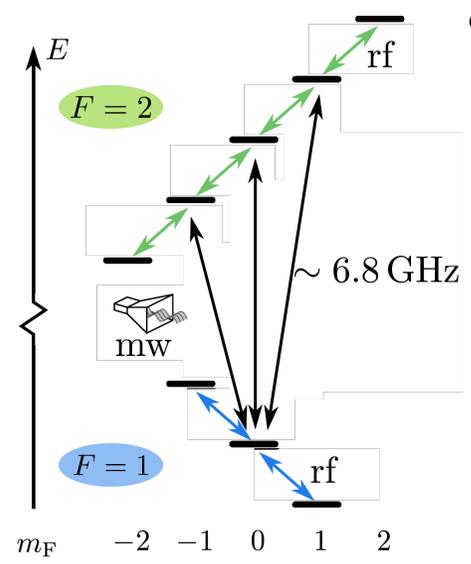
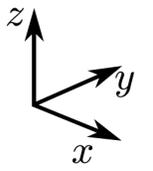
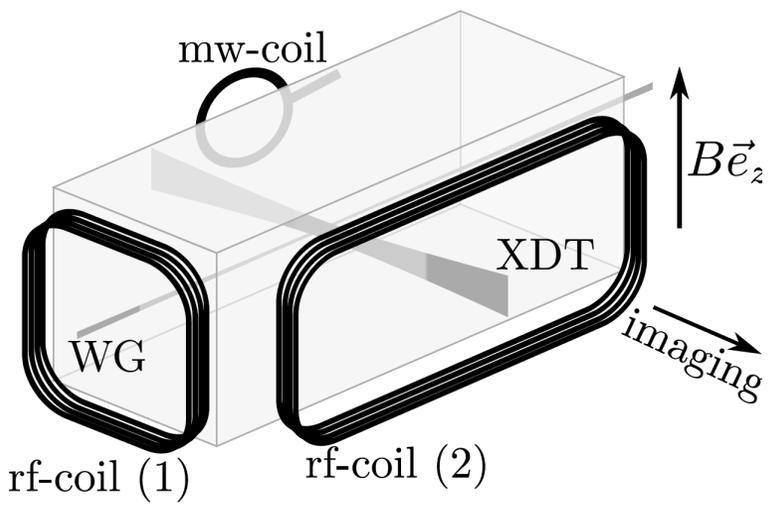
No information about the spin direction

$F=1$

$m_F$



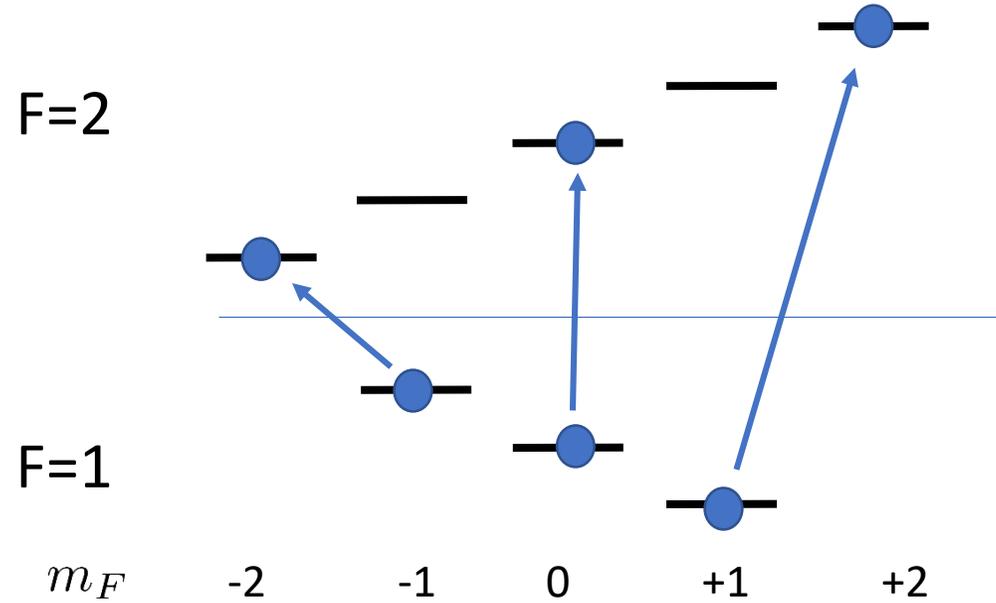
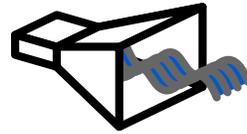
# Experimental details



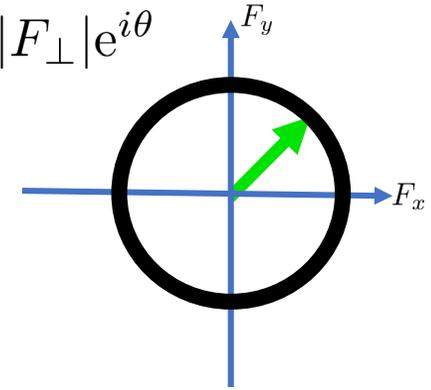
# readout after expanding Hilbert space

Kunkel et al. Phys. Rev. Lett. 123, 063603 (2019)

Microwave



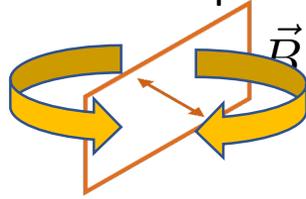
$$F_{\perp} = |F_{\perp}| e^{i\theta}$$



# readout after expanding Hilbert space

Kunkel et al. Phys. Rev. Lett. 123, 063603 (2019)

Radio-frequency



$$\Delta\phi = \pi/2$$

rotation around  
**y-Axis**

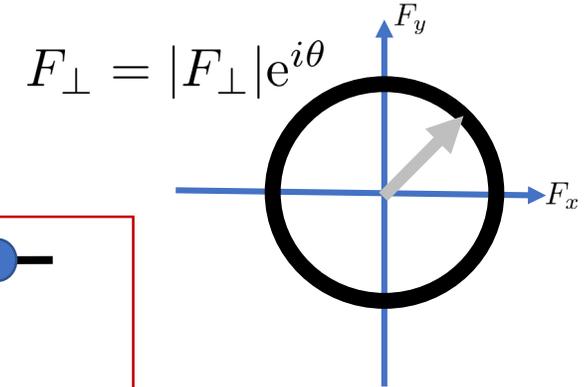
$$F=2$$

rotation around  
**x-Axis**

$$F=1$$

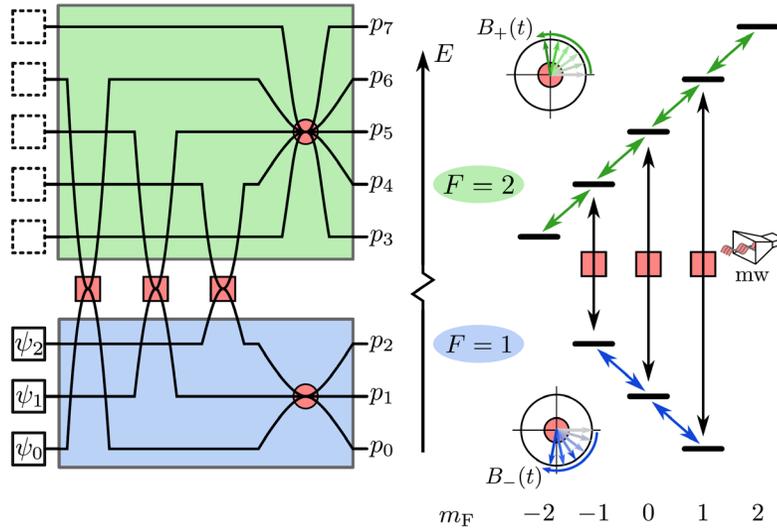
$m_F$

-2   -1   0   +1   +2

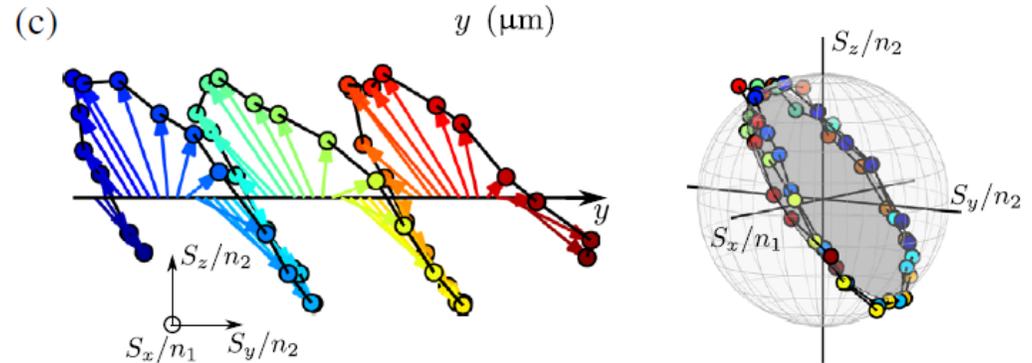
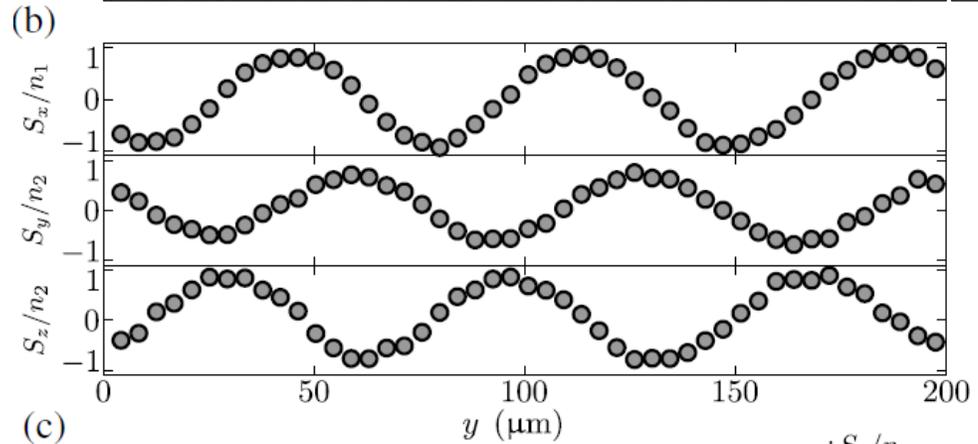
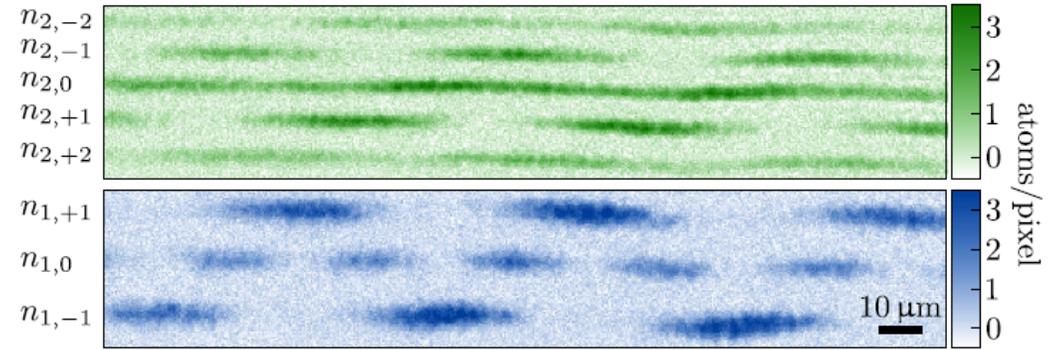


# Implementation of POVMs

Kunkel et al. Phys. Rev. Lett. 123, 063603 (2019)



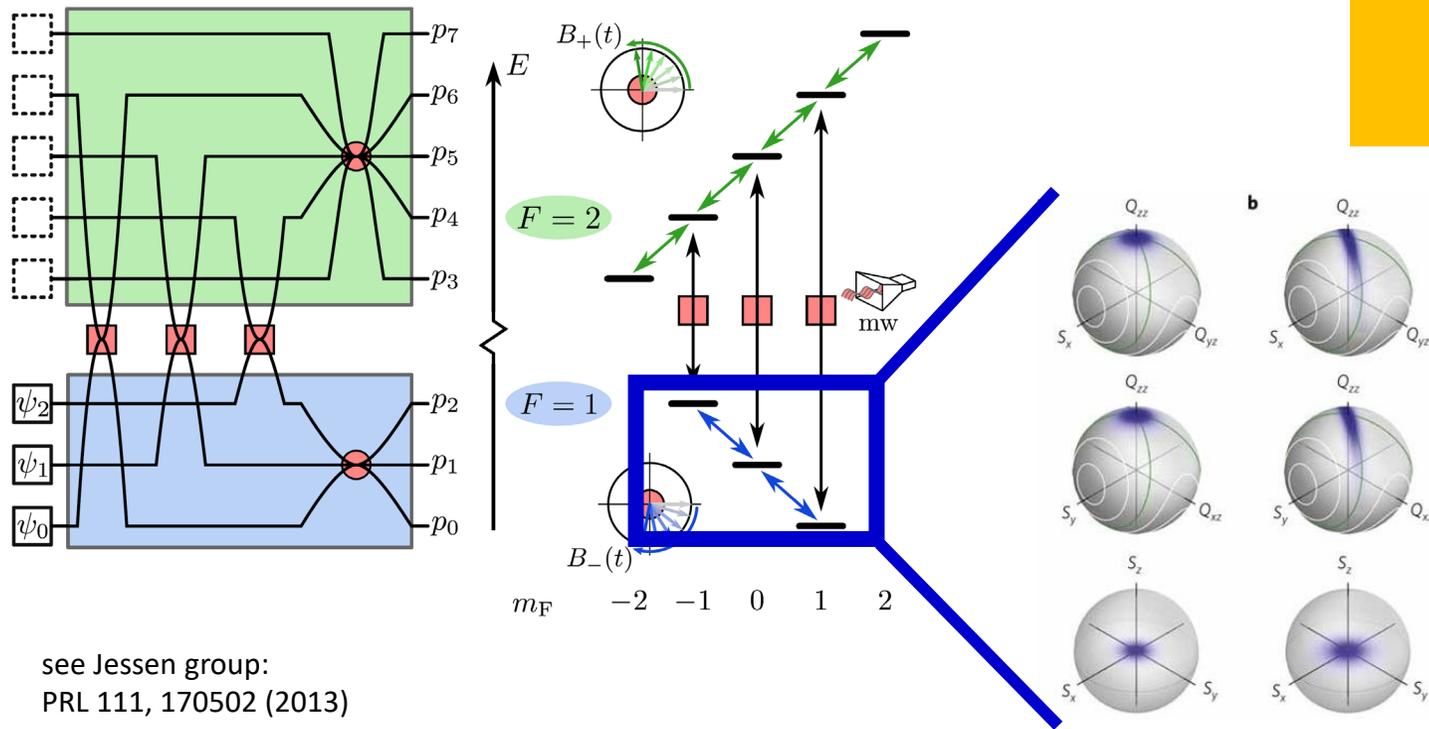
see Jessen group:  
PRL 111, 170502 (2013)



# Implementation of POVMs

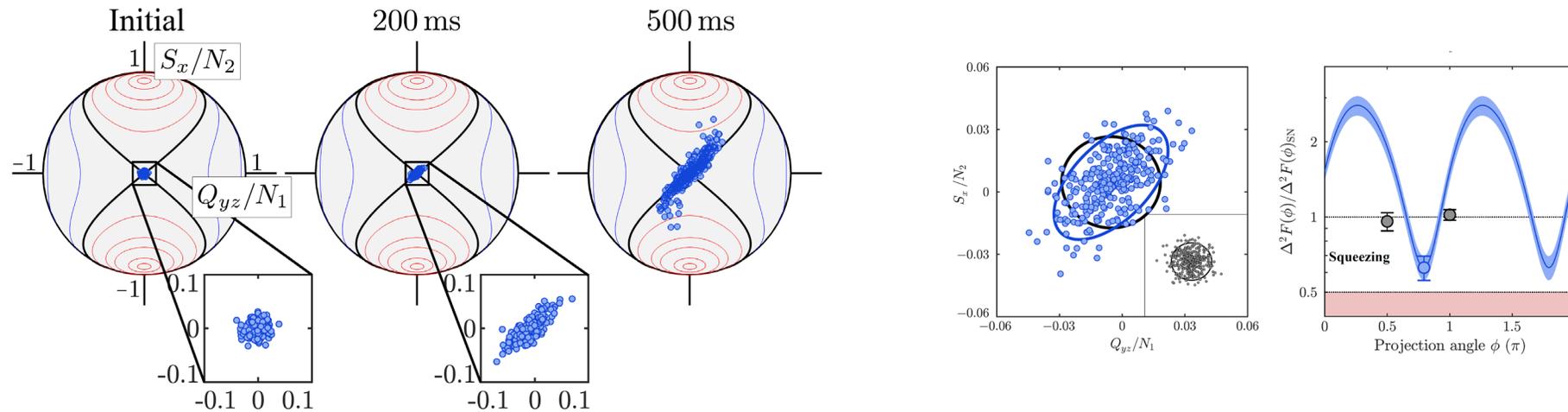
readout beyond the standard quantum limit

Kunkel et al. Phys. Rev. Lett. 123, 063603 (2019)



Spin-nematic squeezed  
Mike Chapman group  
Nature Physics **8**, 305–308 (2012)

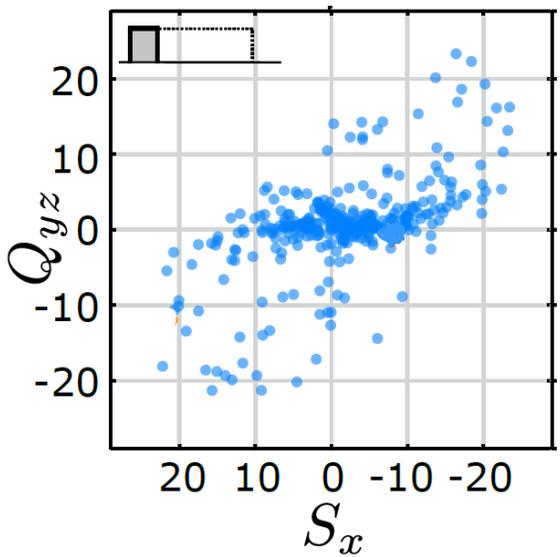
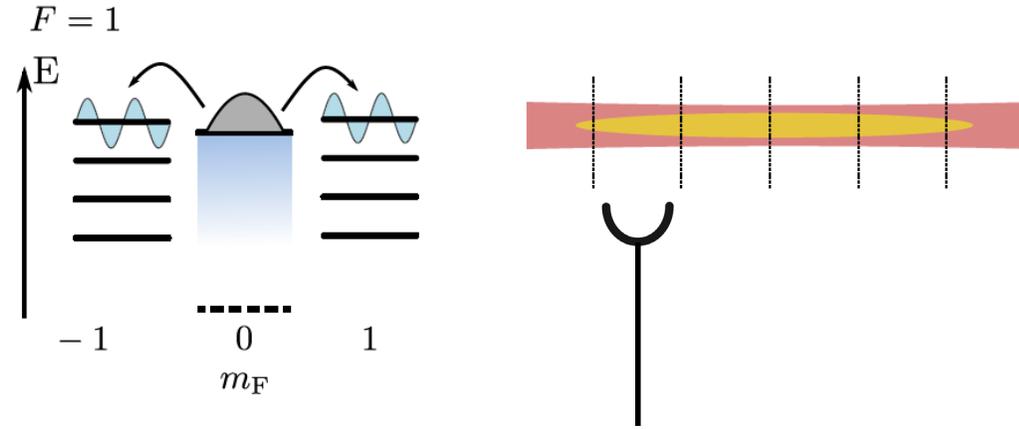
see Jessen group:  
PRL 111, 170502 (2013)



# How half an atom can spoil the party

## global and local detection at the quantum limit

Kunkel et al. Phys. Rev. Lett. 128, 02304023 (2022)

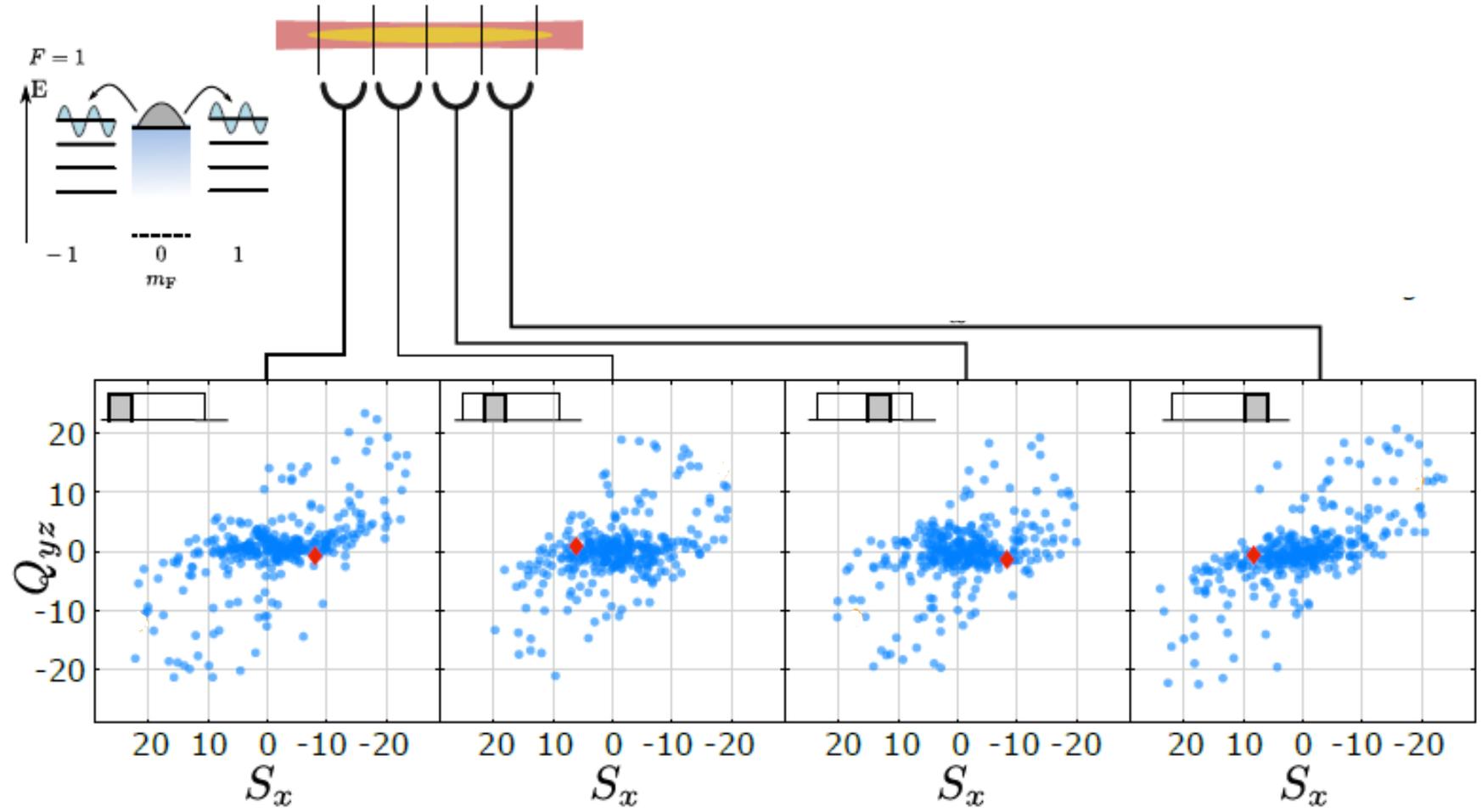


Readout was for 6 months detecting „0.4 atoms“ to many  $10^{-5}$  off- resonant excitation of  $\mu\text{w}$ - pulse

Subsystems are different to global system

global and local detection  
at the quantum limit

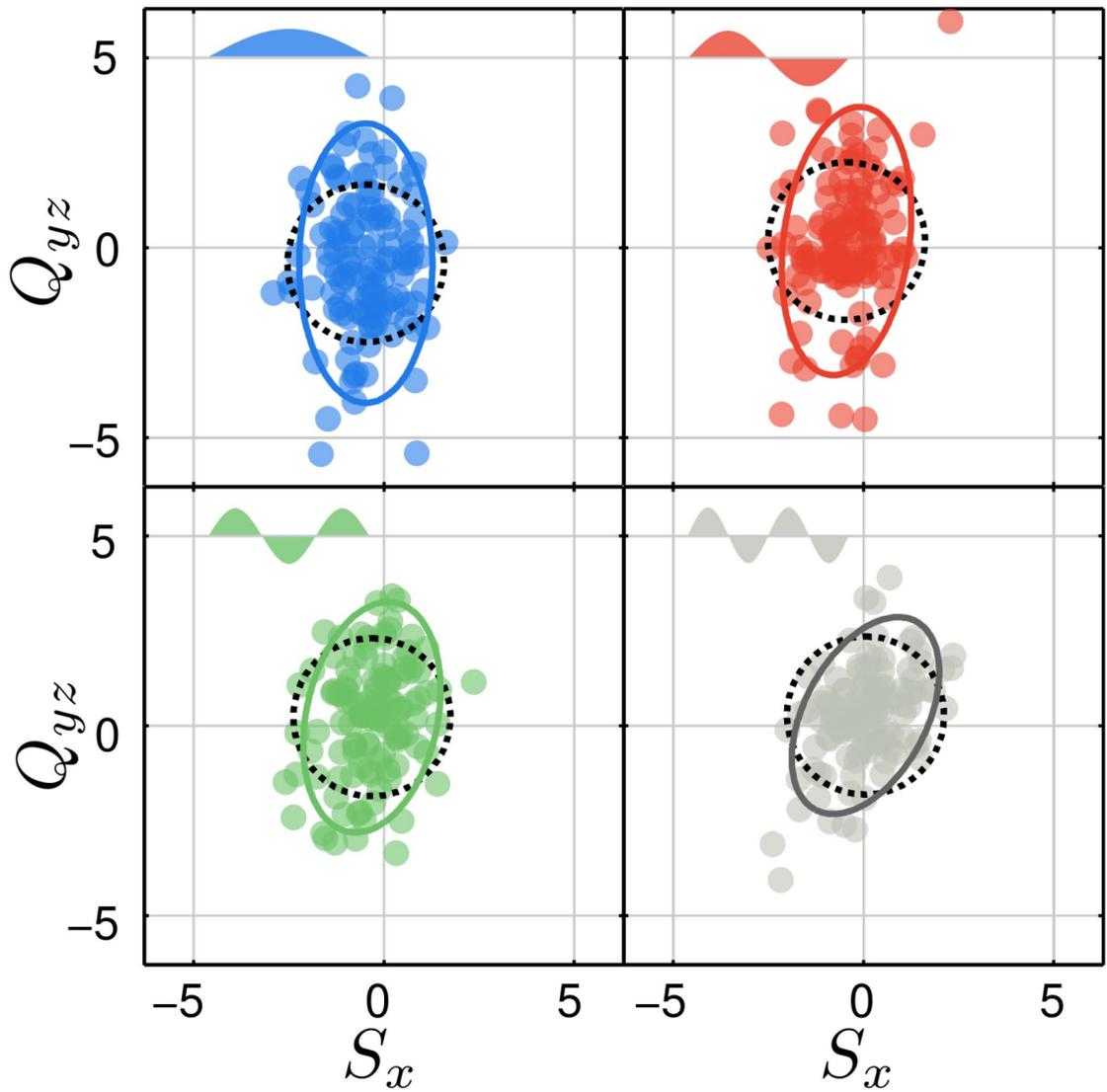
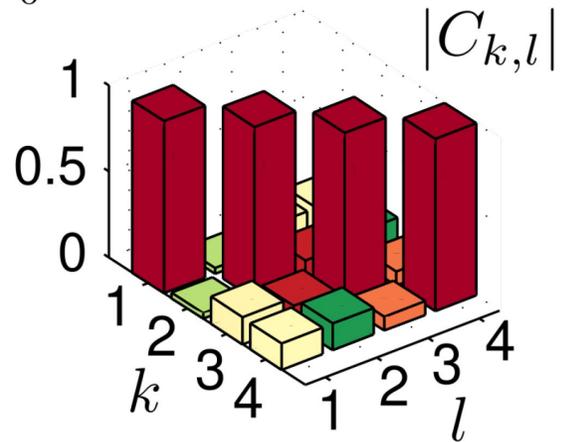
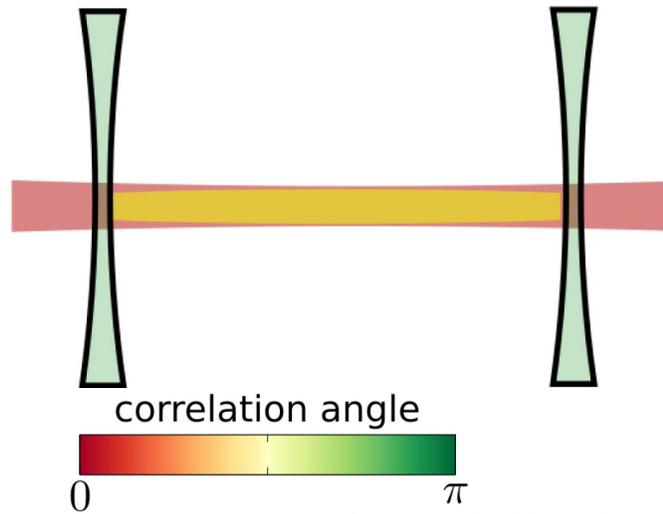
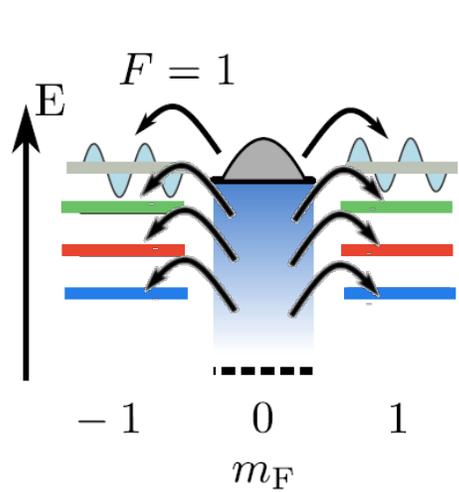
Kunkel et al. Phys. Rev. Lett. 128, 020402 (2022)



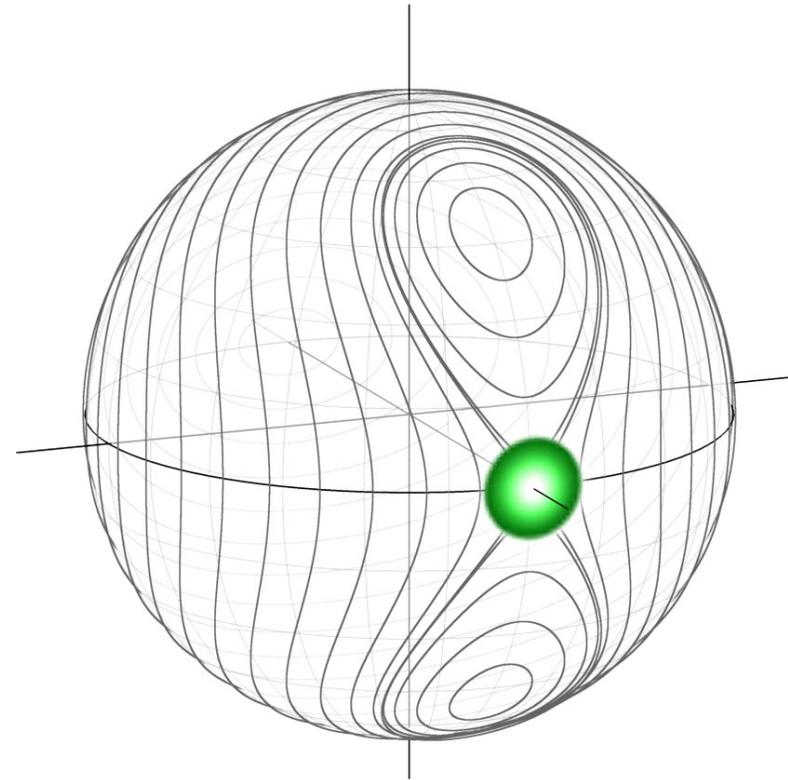
# Prepare spatially entangled state

# spatially entanglement structures

Kunkel et al. Phys. Rev. Lett. 128, 020402 (2022)

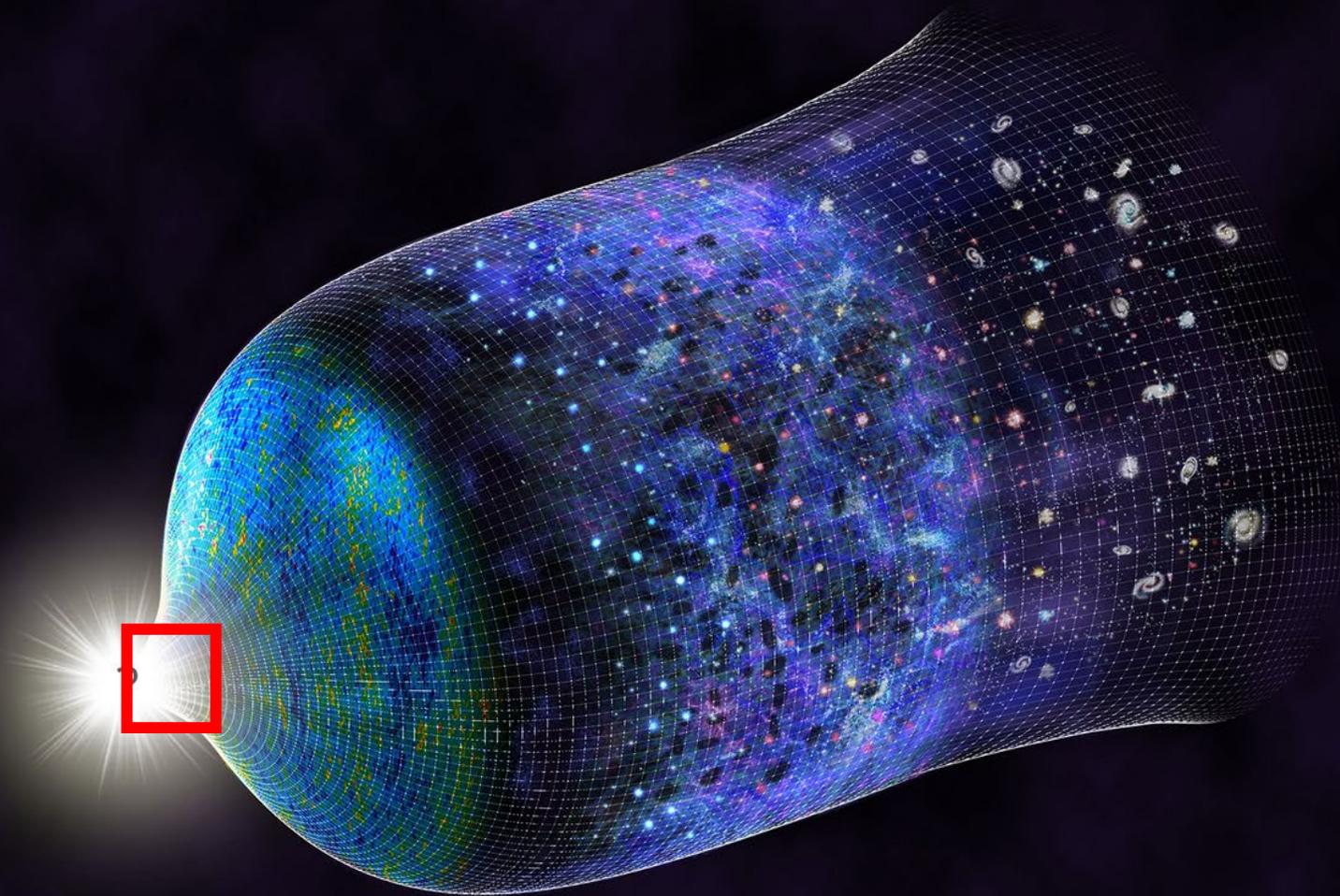


What is the biggest explosion ?

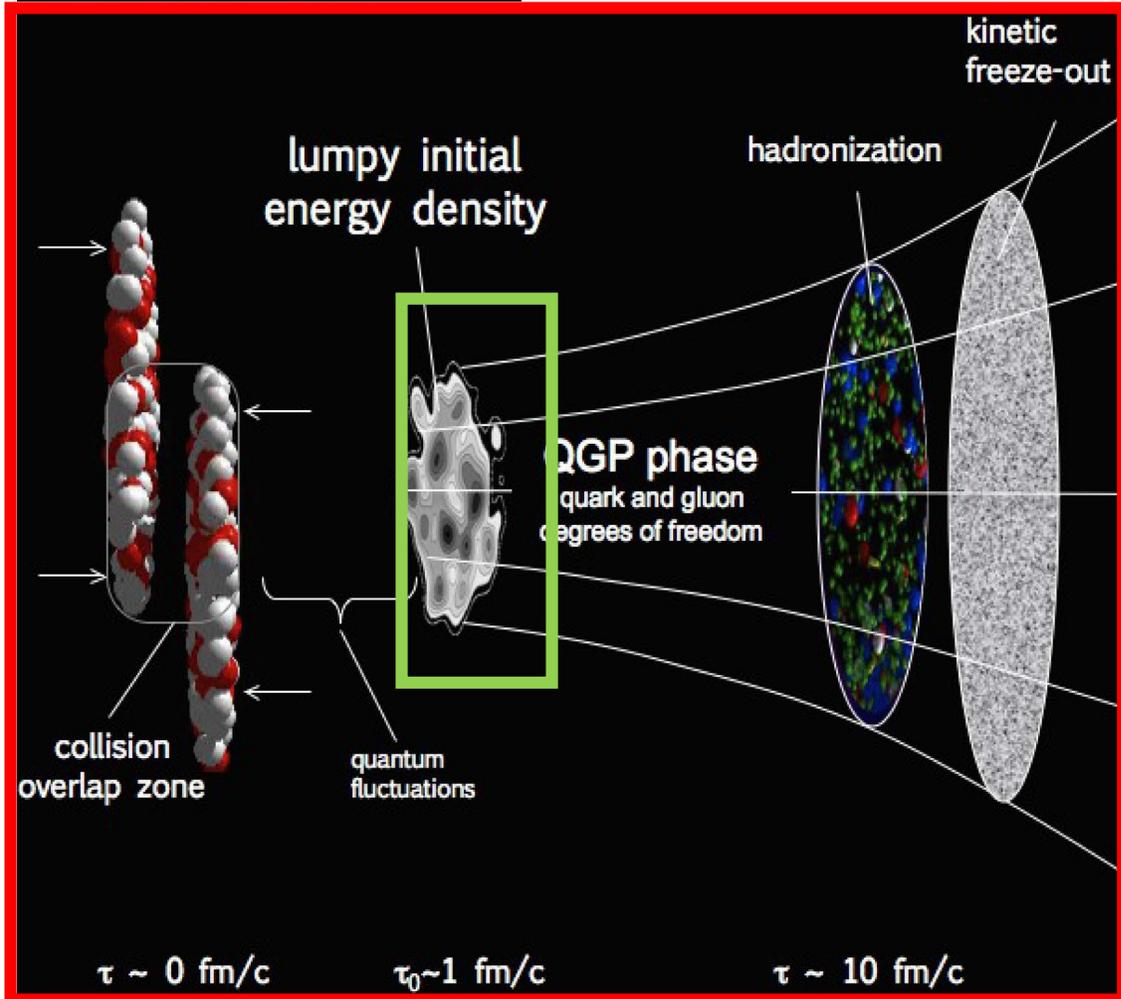
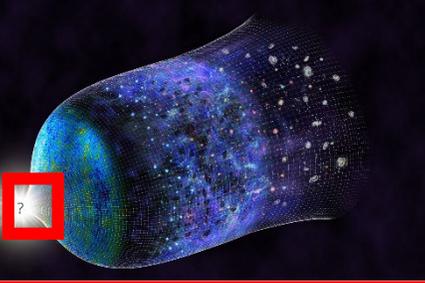


TNT squeezing

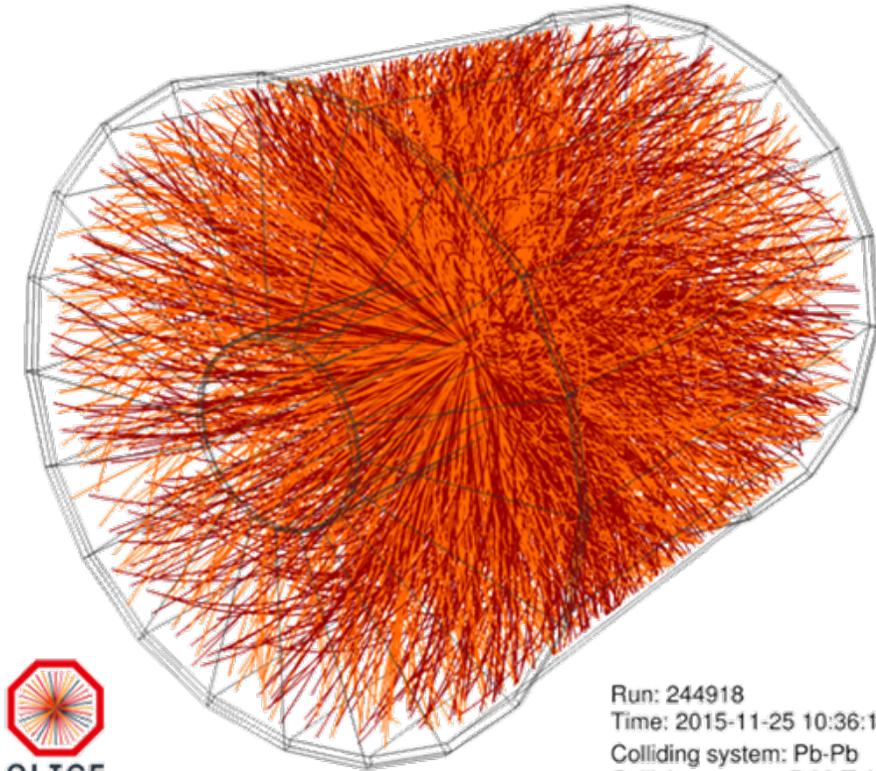
# Spinor Condensates as Quantum Field Simulator – Universal Dynamics



# Little Bang(s) at CERN



0.000 000 000 000 000 000 000 000 1 sec



# Little Bang(s) at CERN



Jürgen Berges



Thomas Gasenzer

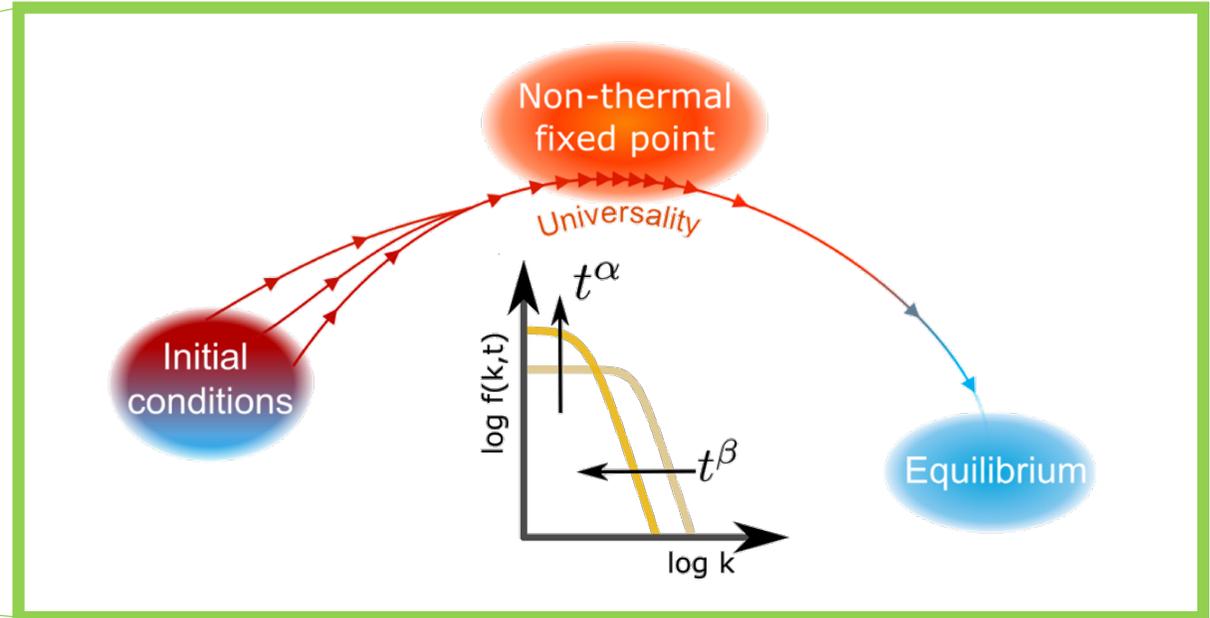
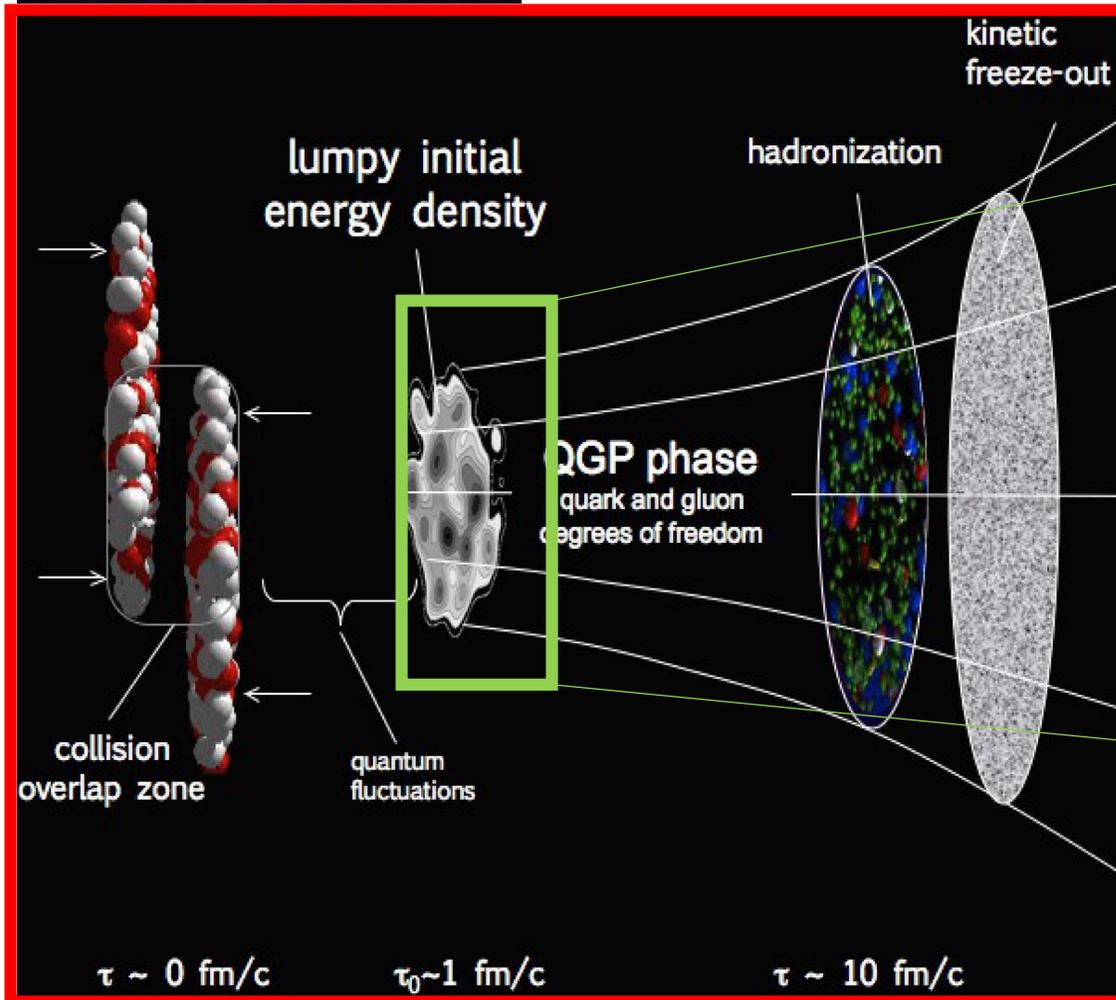
Non-thermal fixed point

J. Berges, A. Rothkopf, J. Schmidt, PRL 101 (2008)

J. Berges, G. Hofmeister, NPB 813 (2009)

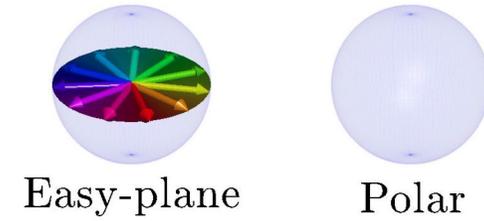
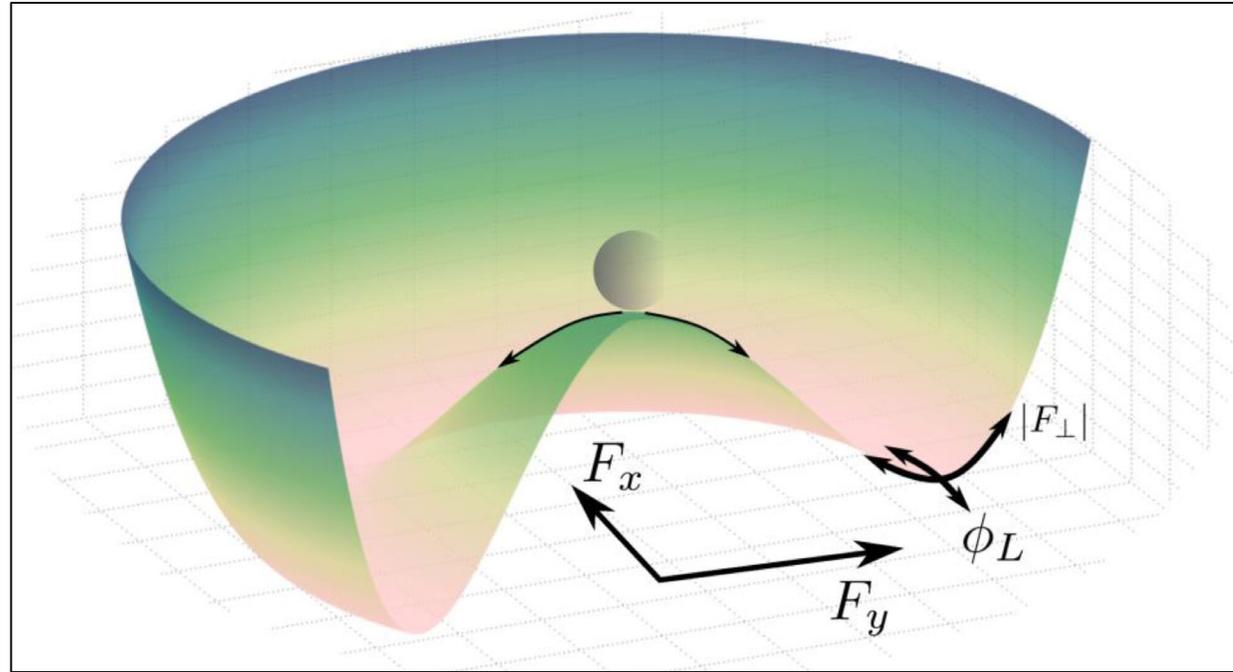
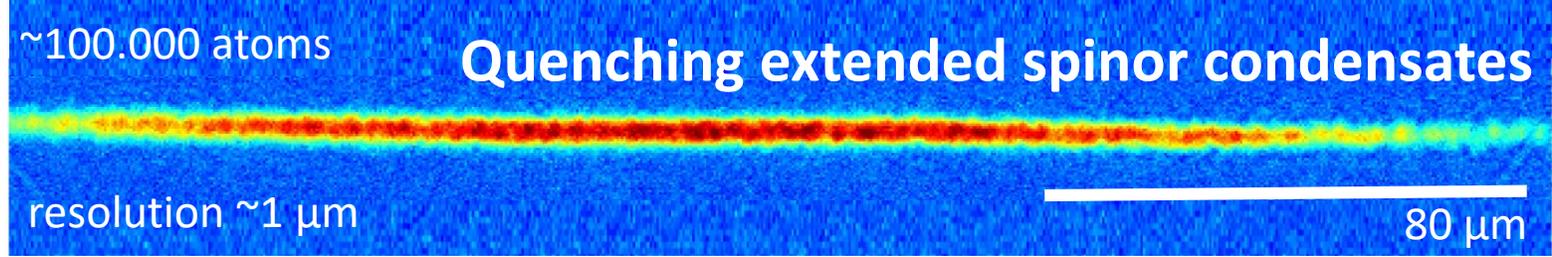
C. Scheppach, J. Berges, T. Gasenzer, PRA 81 (2010)

...

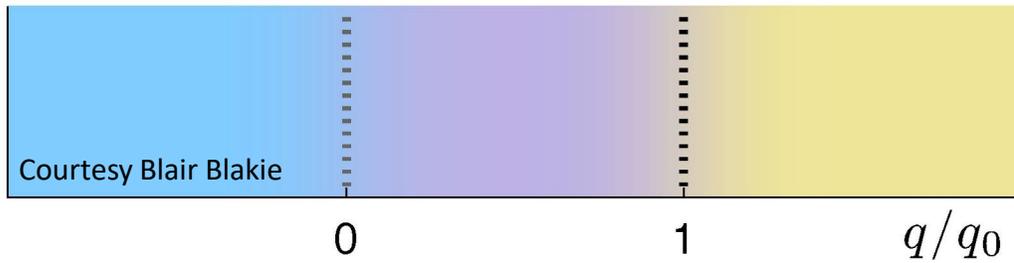


0.000 000 000 000 000 000 000 000 1 sec

# Quantum Bang(s)

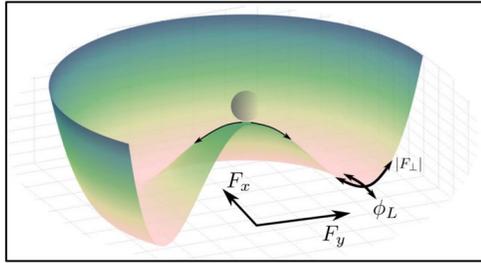


$F=1$

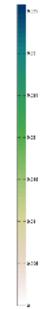


# Watching the build-up of transverse spin

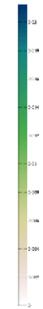
dynamics



0.2s



0.4s



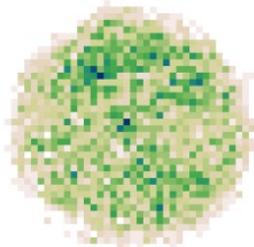
0.6s



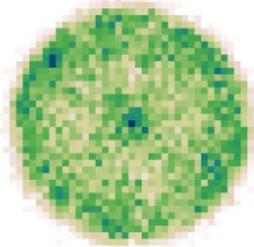
0.8s



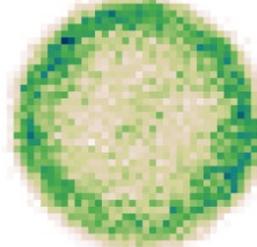
1s



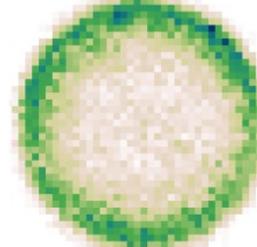
10s



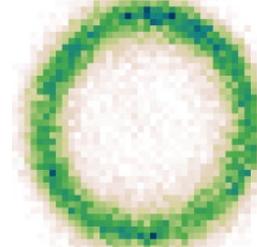
14s



20s

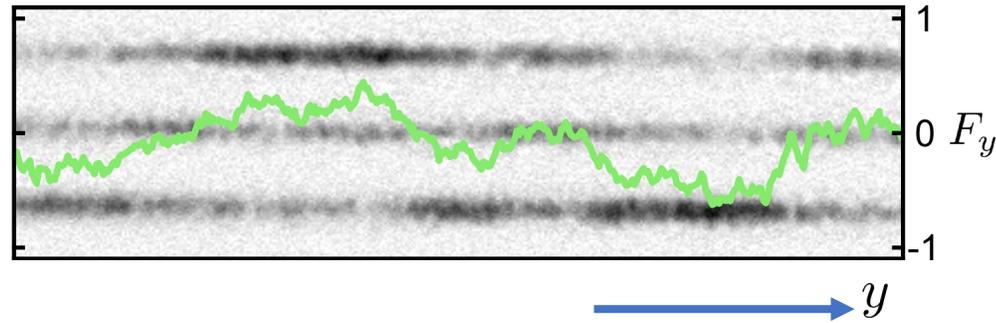


42s



# Spatial information in Fourier space

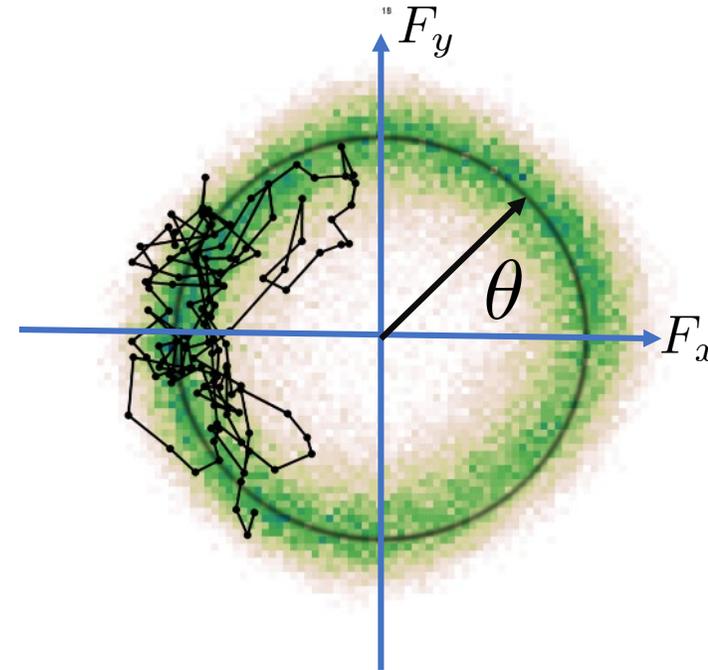
dynamics



Correlation functions  $\langle \theta(y)\theta(y') \rangle$

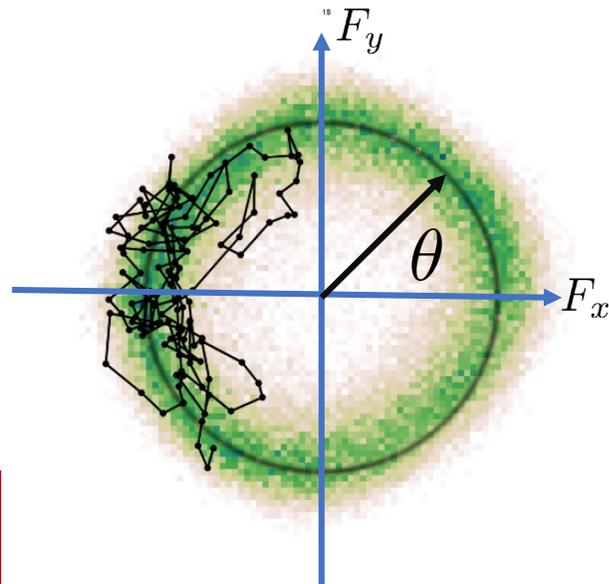
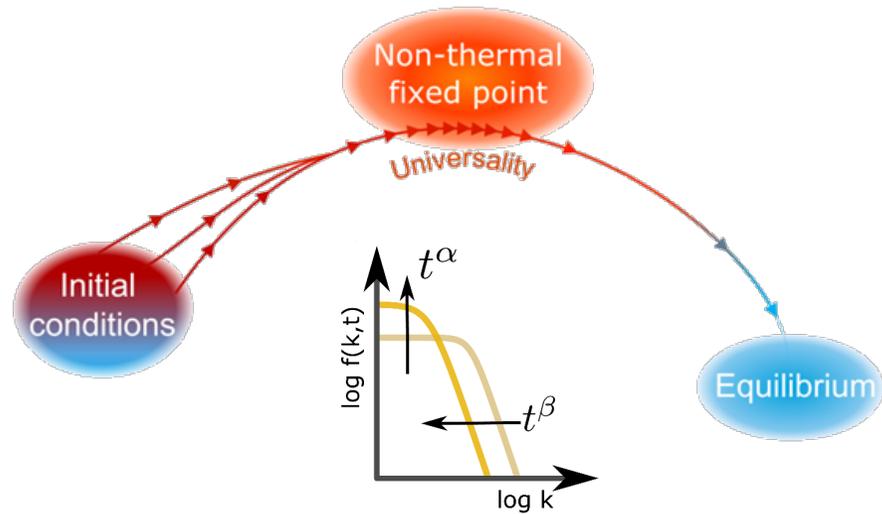
Structure factor

$$f_{\theta}(k) = \text{FT} \langle \theta(y)\theta(y') \rangle$$

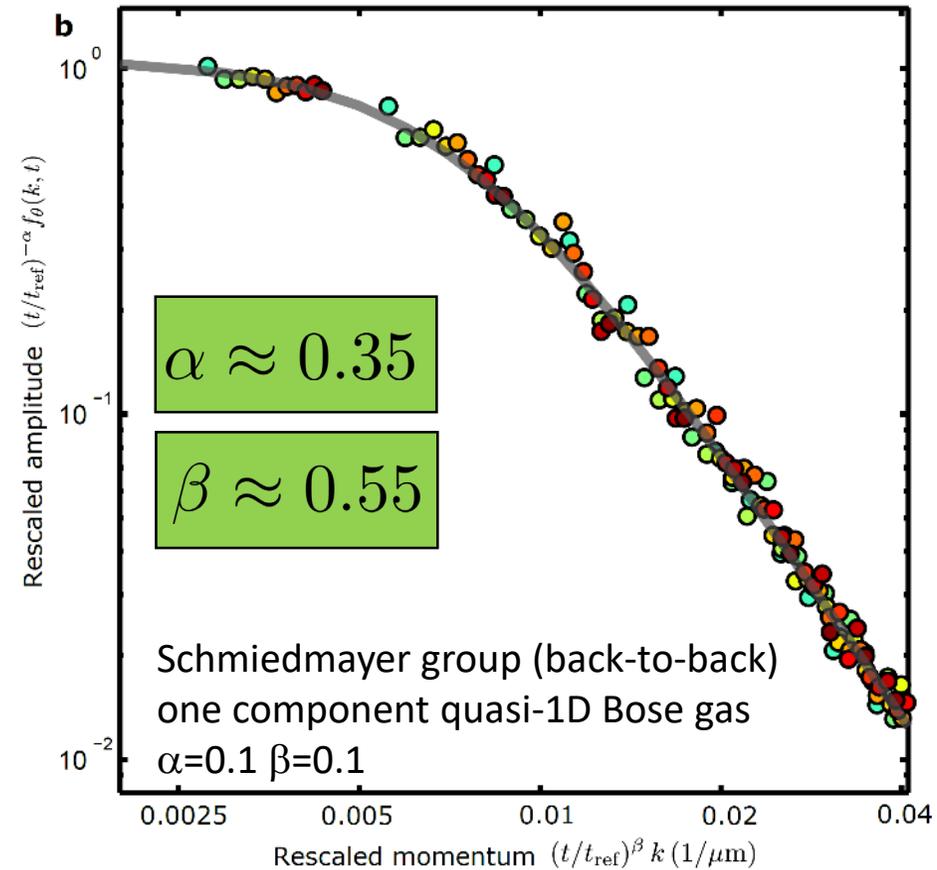


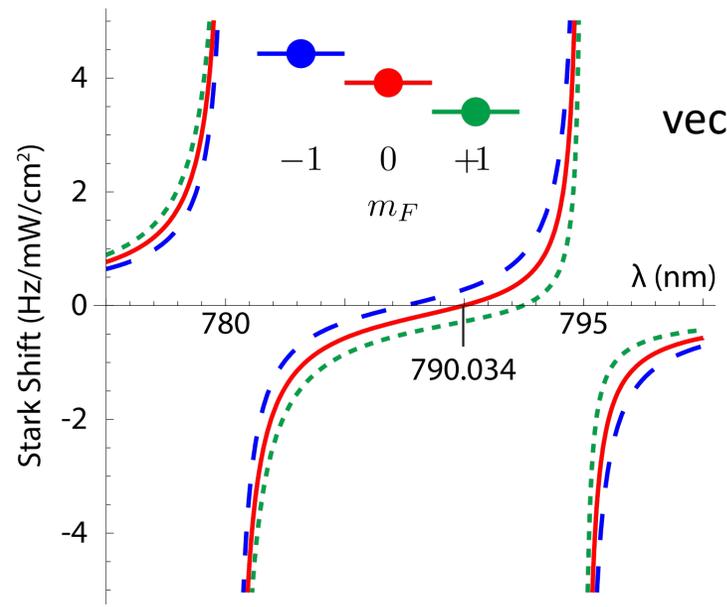
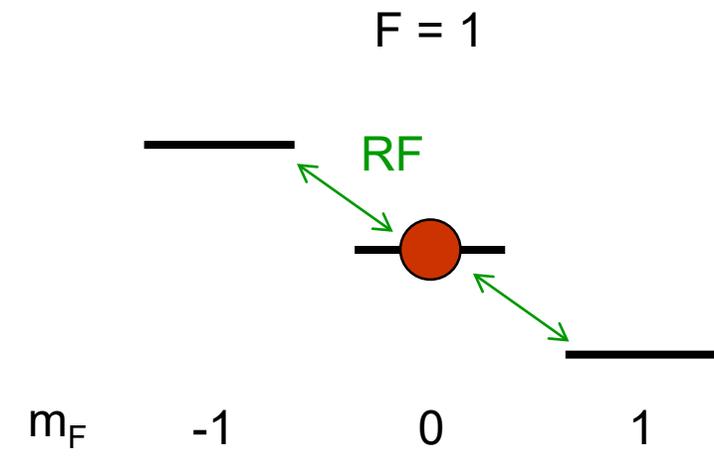
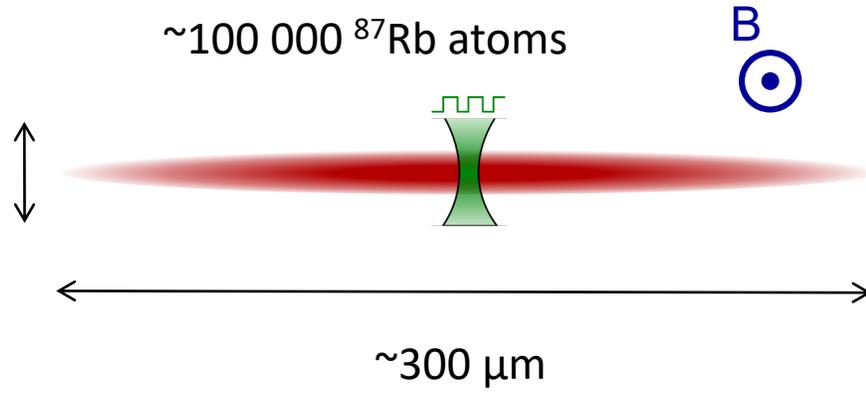
,close to'  $O(N)$  expectations

Nature **568**, 217 (2018)



Time (s) 4 5 6 7 8 9



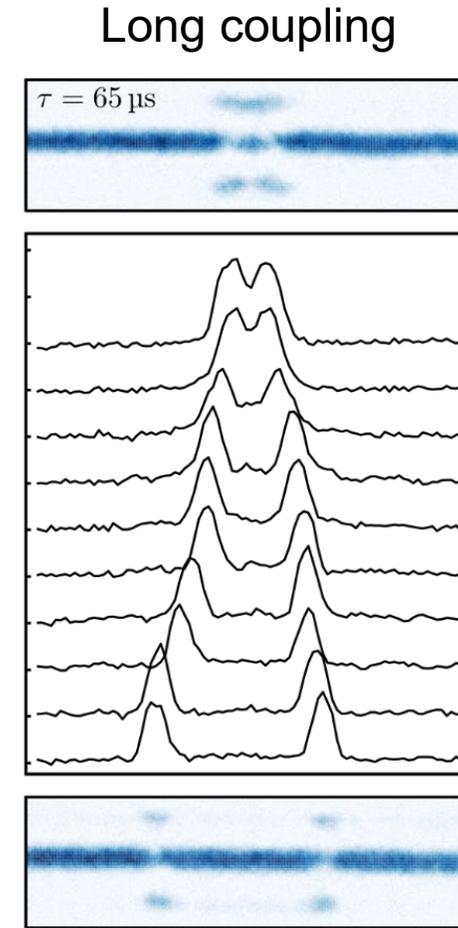
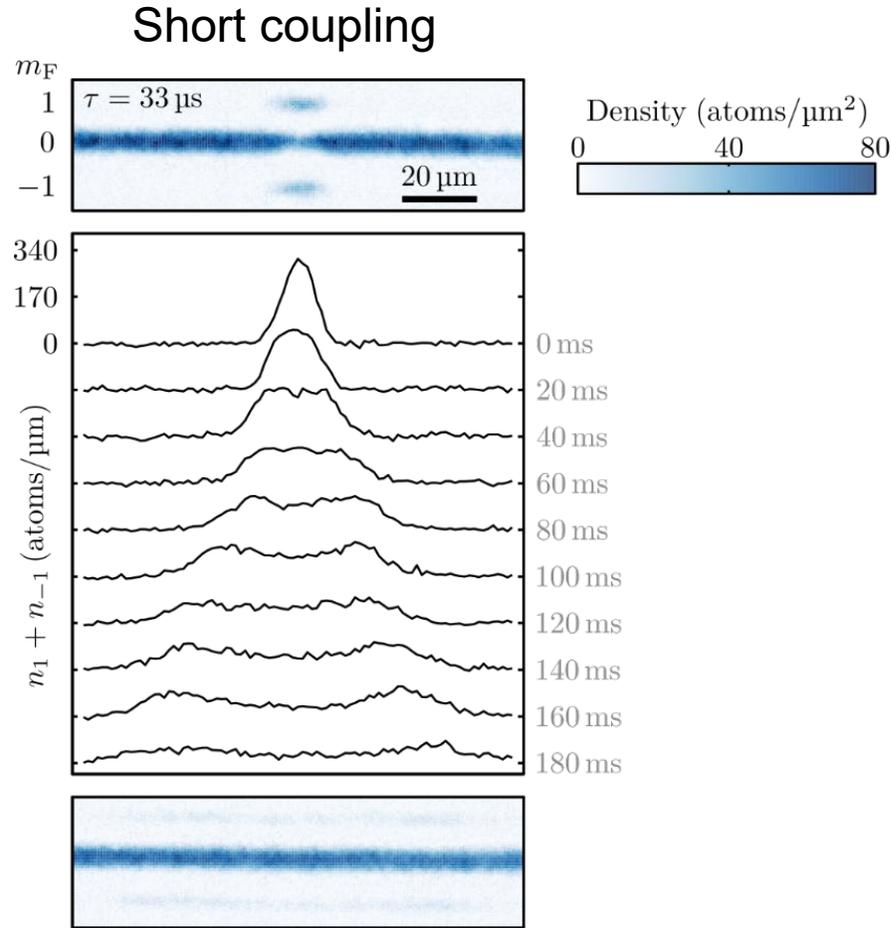


vector Stark shift  $\rightarrow$  local effective magnetic field

Graph: G. E. Marti, D. M. Stamper-Kurn; arXiv:1511.01575

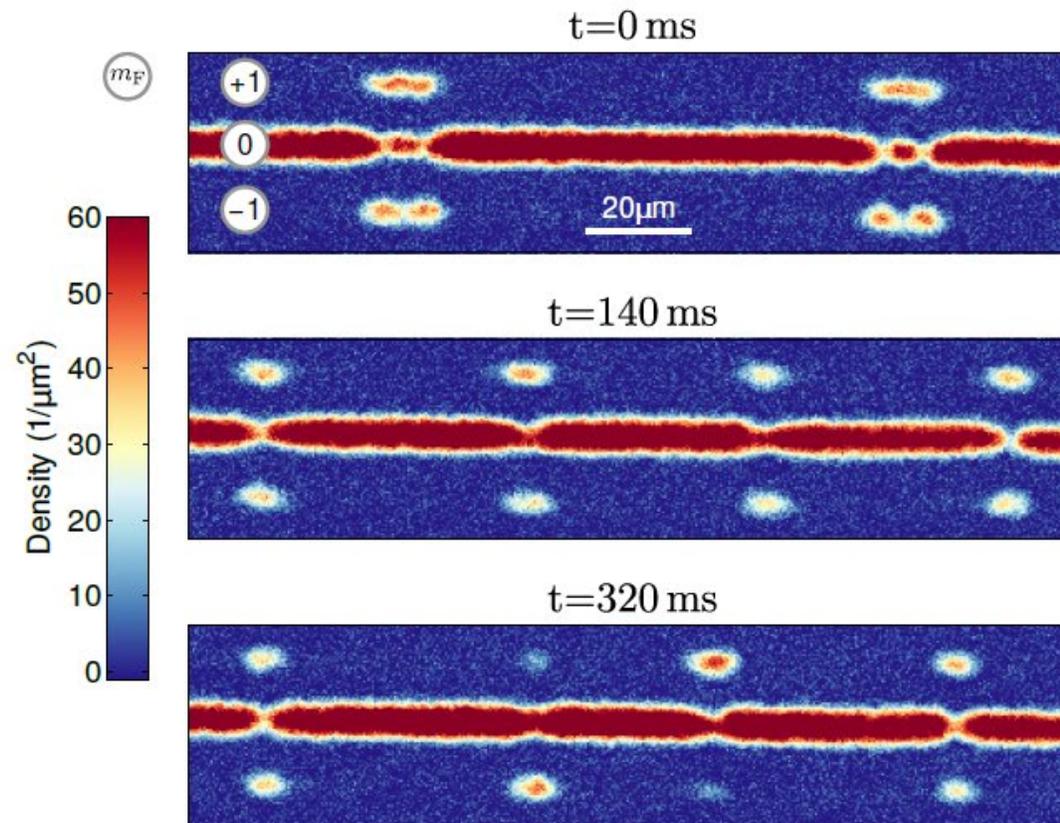
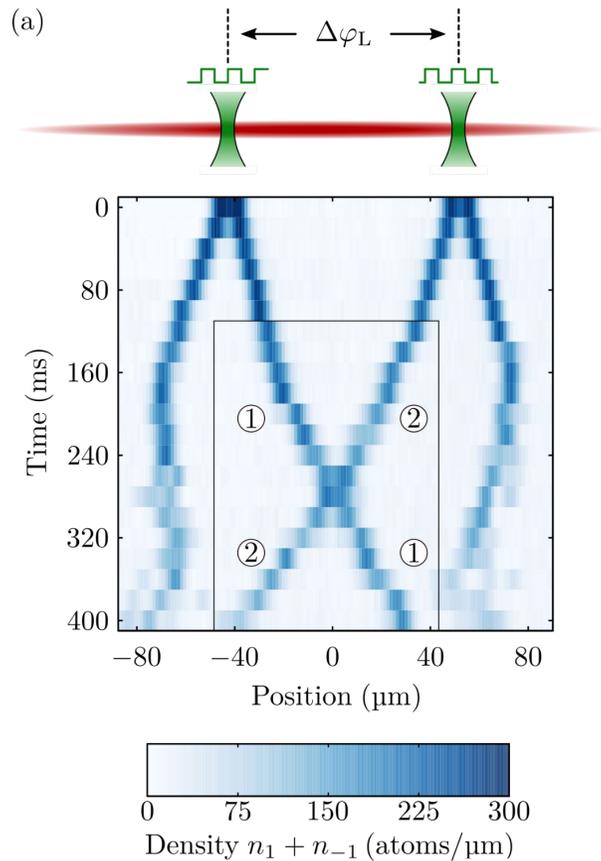
Local linear response

localized time dependent magnetic field



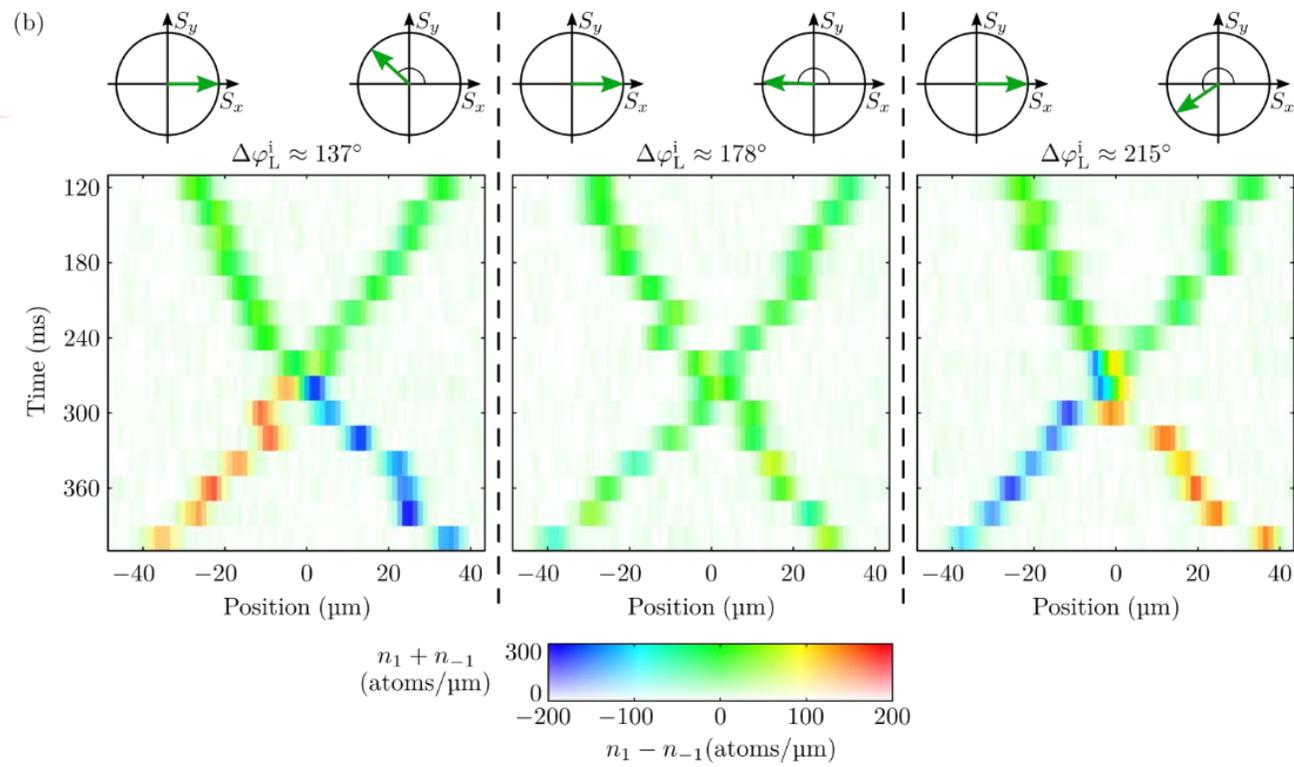
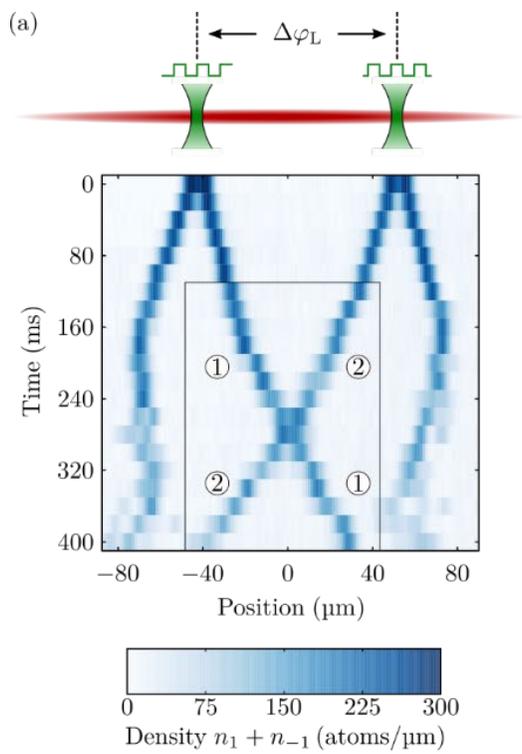
Beyond linear response

preparation of solitons ?



Collisions confirm vector-soliton

preparation of 4 and more solitons

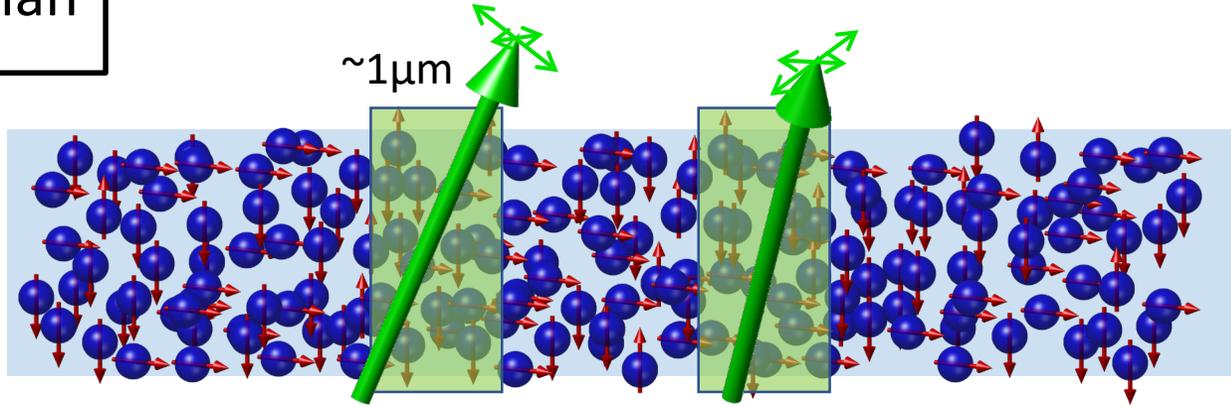


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Confirm analytical prediction

spin dependent collisions

# The Hamiltonian



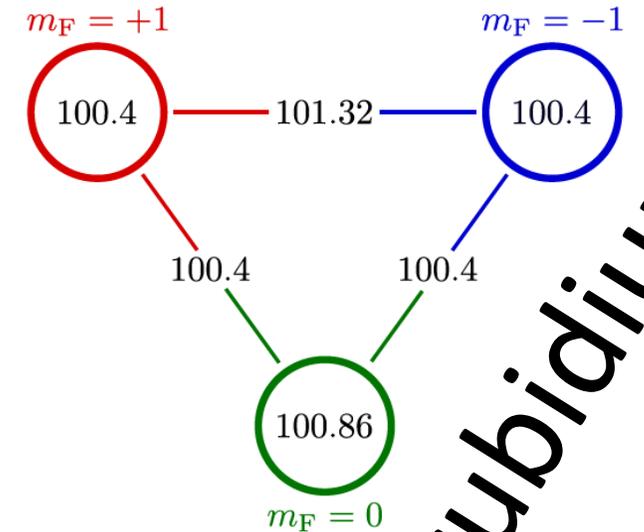
# Quantum Field Settings

$$\hat{\psi}_m^{(\dagger)}(\vec{r})$$

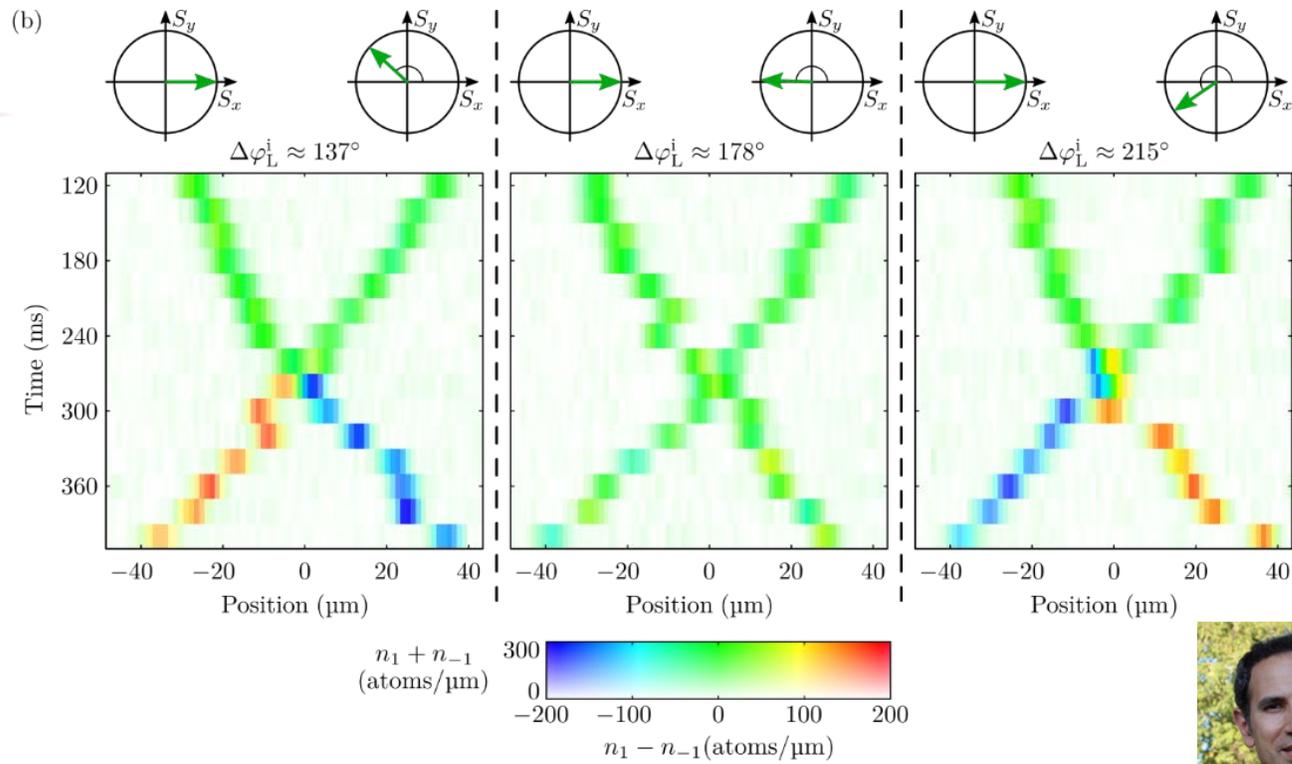
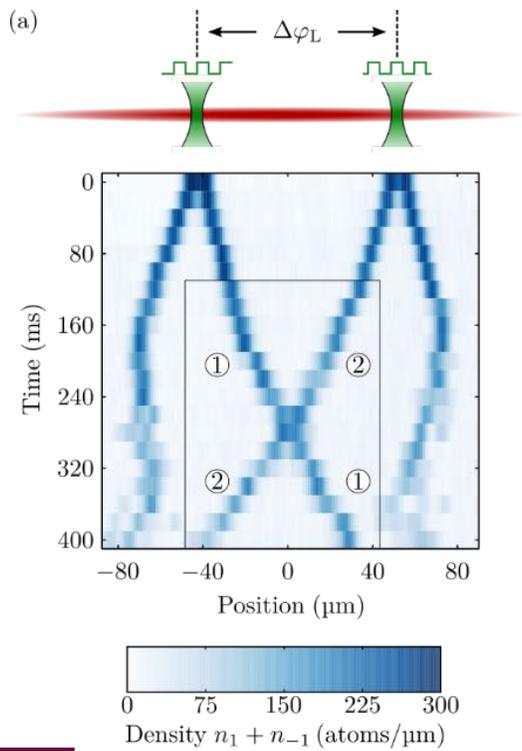
$$\hat{\psi}_j(x) = \psi_j(x) + \delta\hat{\psi}_j(x)$$

$$i\hbar\partial_t\psi_j = \left( -\frac{\hbar^2\nabla^2}{2m} + V_{\text{ext}} + \sum_k g_{jk} |\psi_k|^2 \right) \psi_j$$

$g_{jk}=g$  Manakov Model



rubidium



Panos Kevrekidis

$$\hat{\mathbf{p}}_2 = \chi \left[ \mathbf{p}_2 - \frac{A}{1+A} (\mathbf{p}_1^\dagger \mathbf{p}_2) \mathbf{p}_1 \right]$$

$$\chi^2 = \left[ 1 + \frac{C}{(1+A)(1+A^*)} |\mathbf{p}_1^\dagger \mathbf{p}_2|^2 \right]^{-1}$$

$$\frac{1}{1+A} = \frac{z_1(z_1^* - z_2)(q_0^2 - z_1^* z_2)}{z_1^*(z_1 - z_2)(q_0^2 - z_1 z_2)},$$

$$\frac{A}{1+A} = \frac{z_2(z_1 - z_1^*)(q_0^2 - |z_1|^2)}{z_1^*(z_1 - z_2)(q_0^2 - z_1 z_2)}, \quad \frac{B}{1+A^*} = \frac{z_1^*(z_2^* - z_2)(q_0^2 - |z_2|^2)}{z_2(z_1^* - z_2^*)(q_0^2 - z_1^* z_2^*)},$$

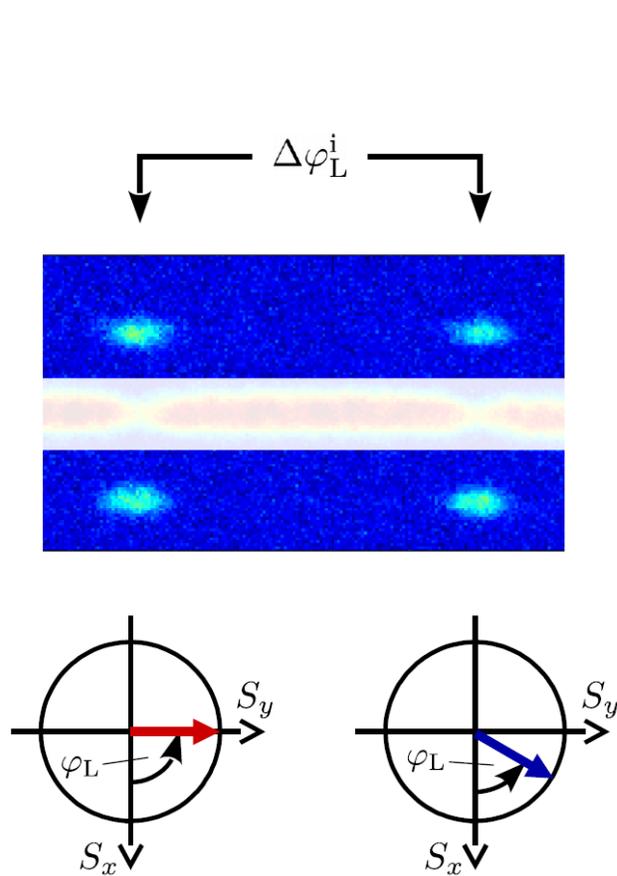
$$\frac{C}{(1+A)(1+A^*)} = \frac{(z_1^* - z_1)(z_2 - z_2^*)(q_0^2 - |z_1|^2)(q_0^2 - |z_2|^2)}{|z_1 - z_2|^2 |q_0^2 - z_1 z_2|^2}.$$

Collisions of 3 component **repulsive** Manakov model  
 = collisions of 2 component **attractive** Manakov model

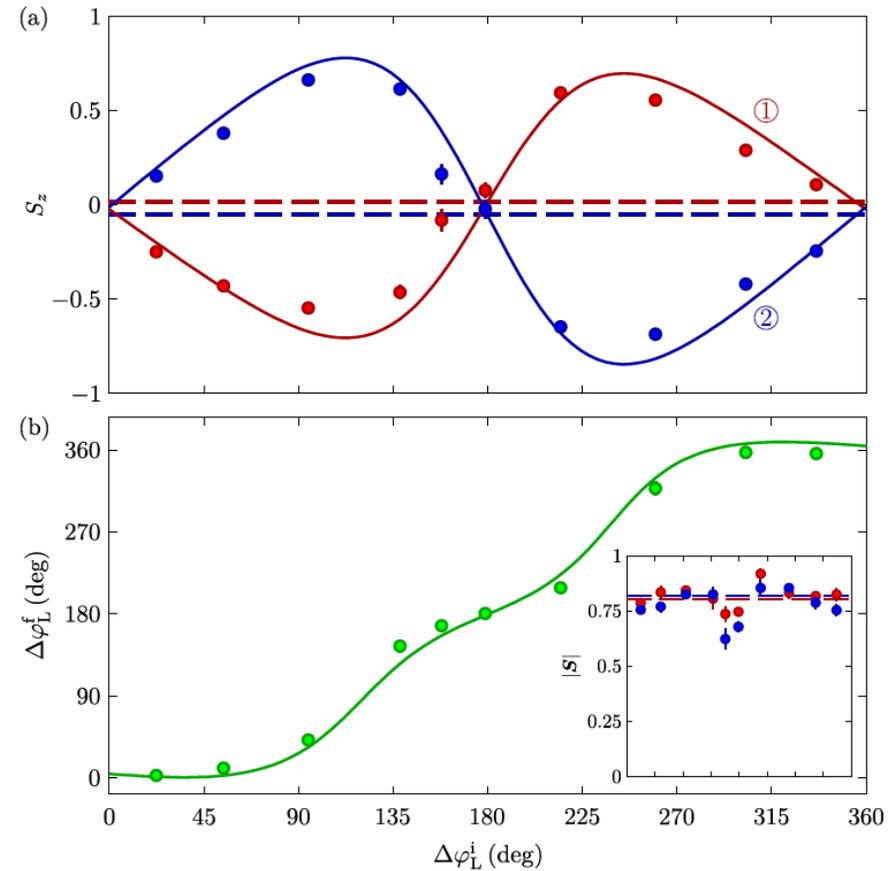
Analytical prediction: B. Prinari et al., J. Math. Phys. 56, 071505 (2015)

Confirm analytical prediction

spin dependent collisions



### vector soliton

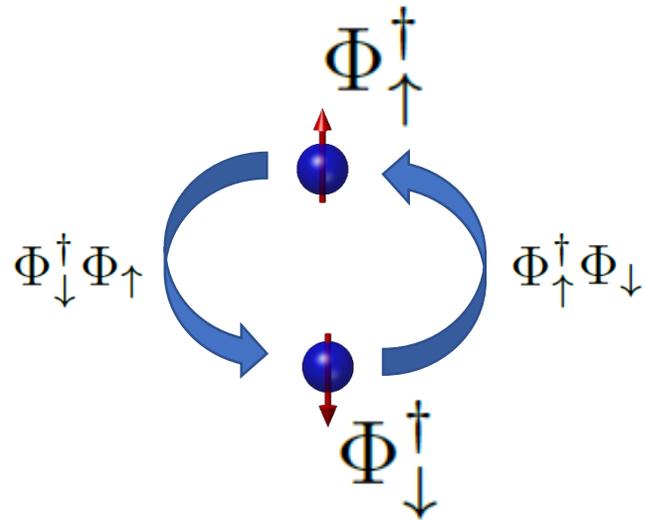


Experiments with 2 component gases: Washington, Atlanta, Paris, Trento, ...

Confirm analytical prediction

spin dependent collisions  
 Phys. Rev. Lett. 125, 170401 (2020)

# Coherent Quantum Mixtures ... with so many facets

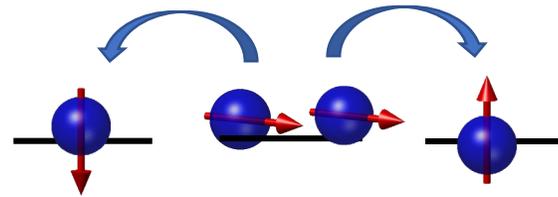


Coherently driven – miscibility of dressed states

Quantum phase transition via coherently coupled immiscible mixtures

Quantum mixtures reveal entanglement generation

Spinor condensates close to  $O(N)$  model



If you want to join the team, let me know.

Positions are available any time.

Literature: PhD theses @ [www.synqs.org](http://www.synqs.org)



Eike  
Nicklas



Wolfgang  
Muessel



Helmut  
Strobel



Philipp  
Kunkel



Maximilian  
Prüfer



Stefan  
Lannig