UNIVERSITY OF CAMBRIDGE

Imprinting magnetic monopoles onto an atomic gas

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Ways to realize monopoles

Spin ice

Castelnovo *et al*. Nature 2008,
Bramwell, Nature 2009

Topological insulators

Qi *et al*. Science 2009

Anomalous quantum Hall effect

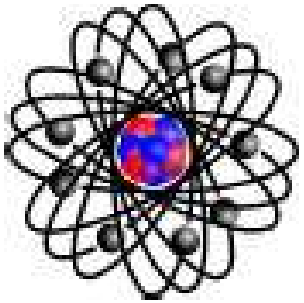
Fang *et al*. Science 2003

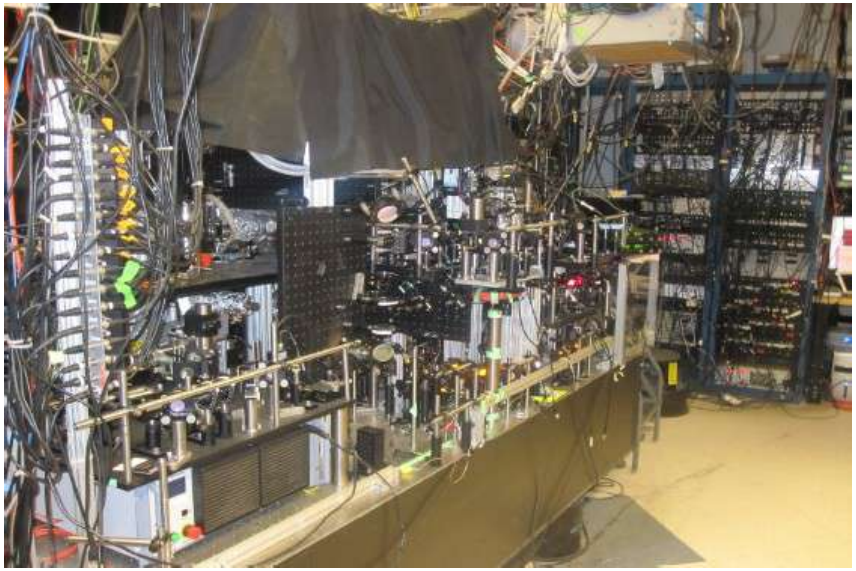
Superfluid ^{3}He

Blaha, PRL 1976

Cold atom gas

Electrons → ^{87}Rb atoms





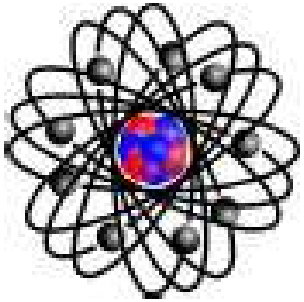
How to imprint a uniform magnetic field

Desired Hamiltonian:

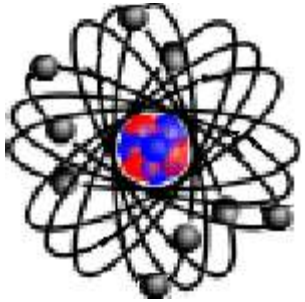
$$\hat{H} = \frac{(\boldsymbol{p} - e\boldsymbol{A})^2}{2\mathrm{m}}$$

$$\boldsymbol{B} = \nabla \times \boldsymbol{A}$$

Laser beam excites transition



$$\kappa = \kappa_0 \mathrm{e}^{\mathrm{i}kx}$$



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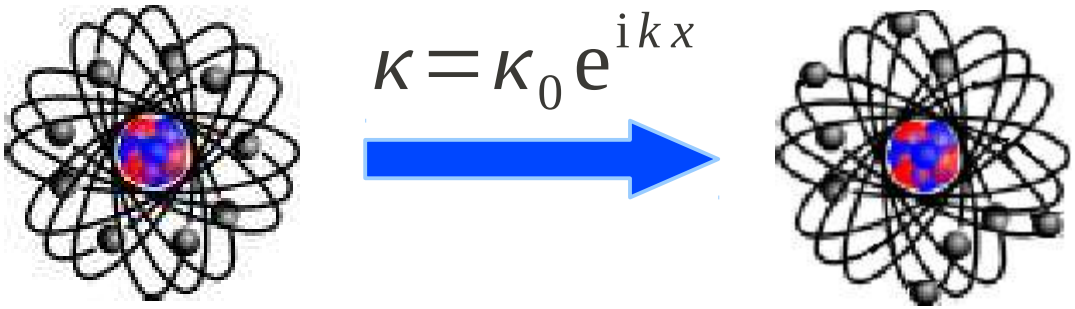
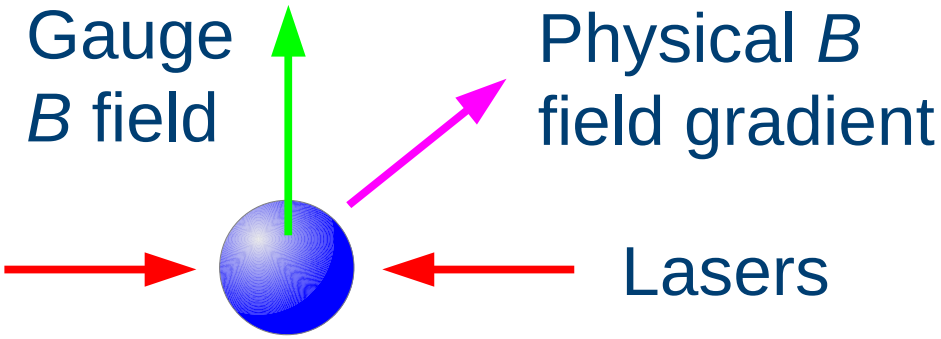




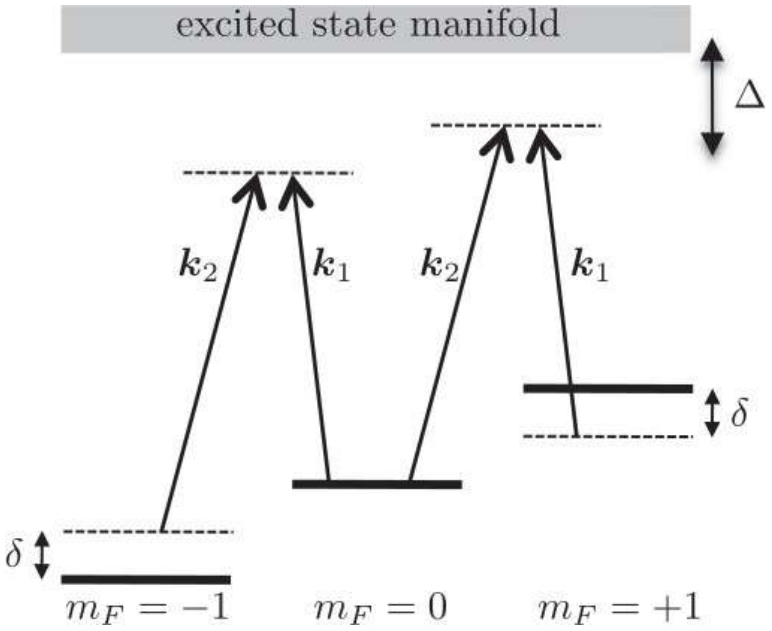
How to imprint a uniform magnetic field

$$\hat{U} = \frac{\hbar}{2}\begin{pmatrix} -2\delta' y & \kappa_0 e^{ikx} & 0 \\ \kappa_0 e^{-ikx} & 0 & \kappa_0 e^{ikx} \\ 0 & \kappa_0 e^{-ikx} & 2\delta' y \end{pmatrix}$$

$$\chi = e^{ikx}\cos^2\frac{\theta}{2}|-1\rangle - \frac{\sin\theta}{\sqrt{2}}|0\rangle + e^{-ikx}\sin^2\frac{\theta}{2}|1\rangle$$

$$\tan\theta = \frac{\kappa_0}{\sqrt{2}\delta'}$$

$$\boldsymbol{A} = \langle\chi|\nabla\chi\rangle = \frac{\delta' y}{\kappa_0}\hat{e}_x$$

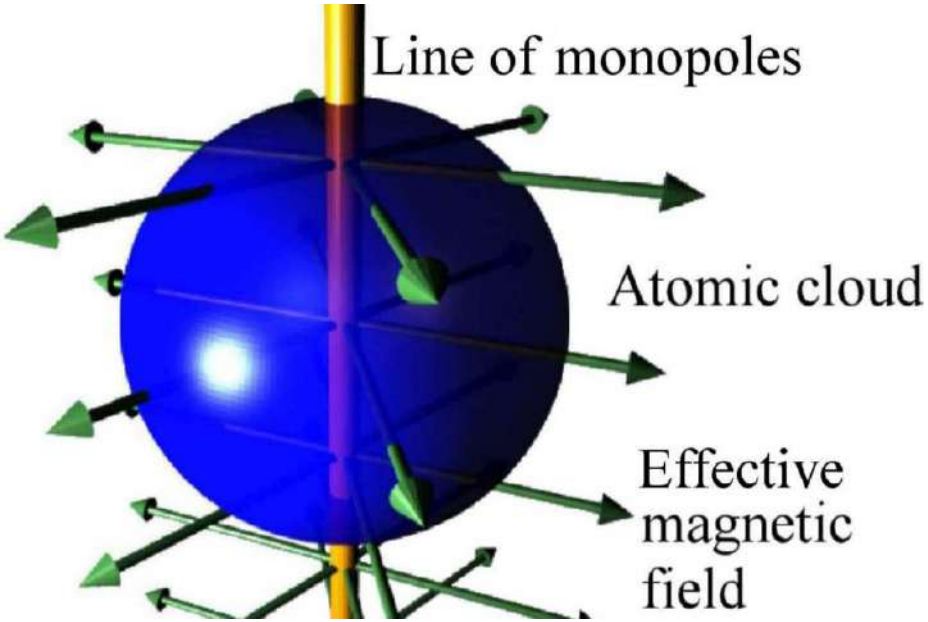


Spielman PRA (2009)

Synthetic uniform magnetic field

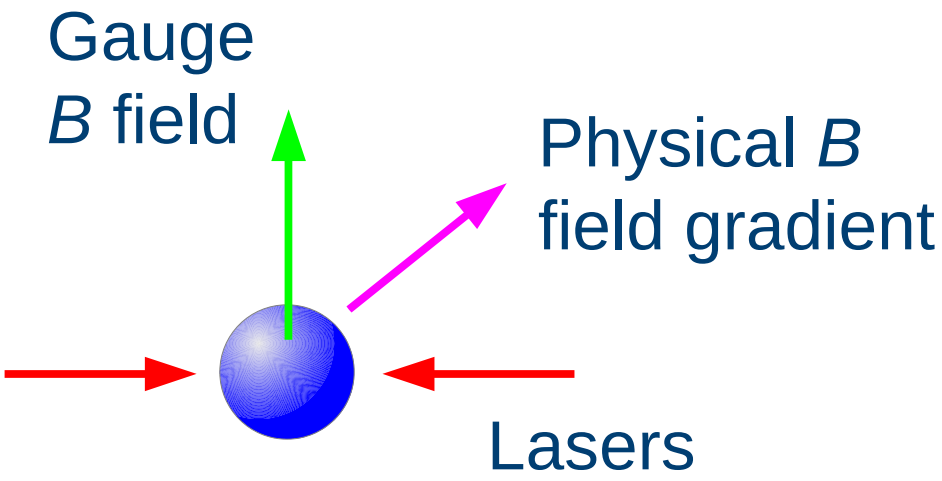
Lin *et al*. Nature 2009

A line of magnetic monopoles

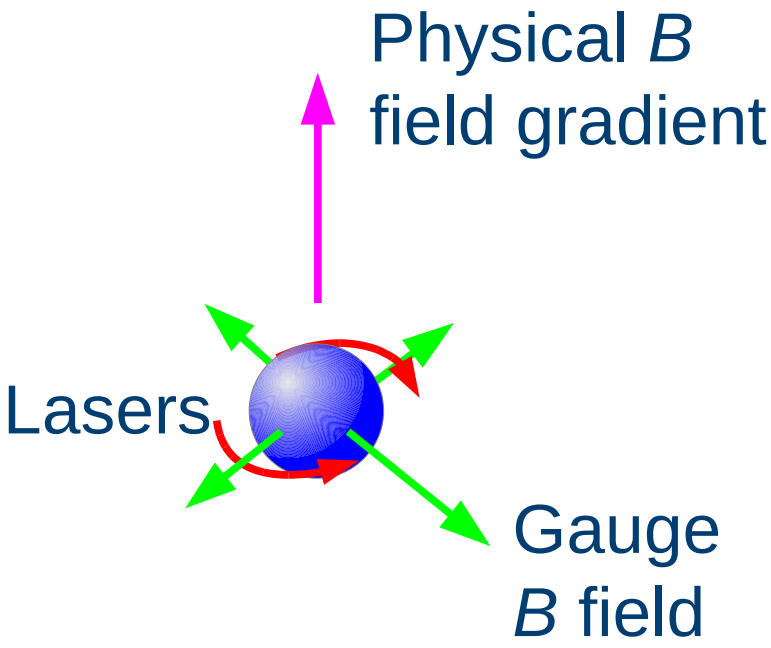


A line of magnetic monopoles

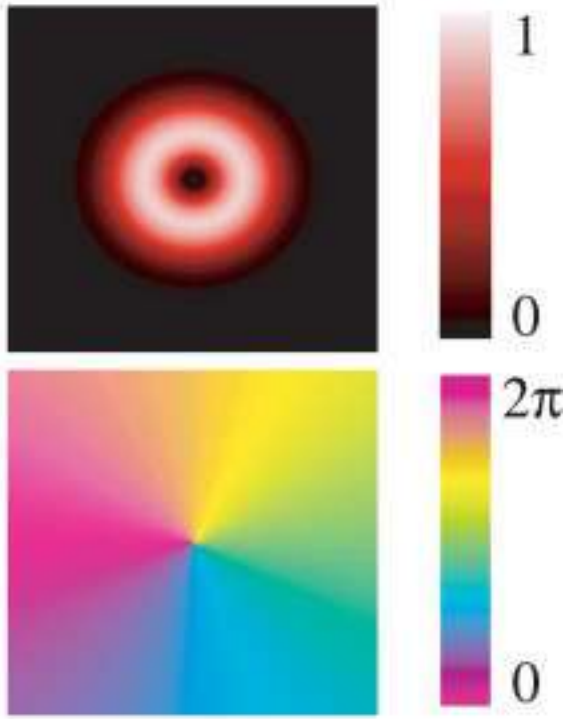
Uniform *B* field



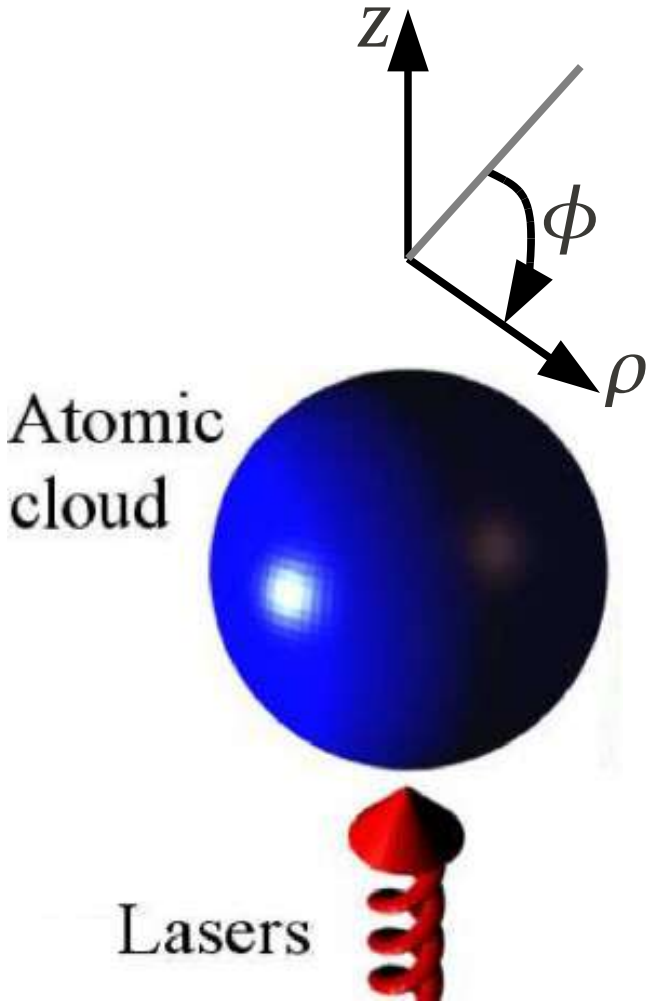
Monopolar *B* field



How to imprint the magnetic monopoles



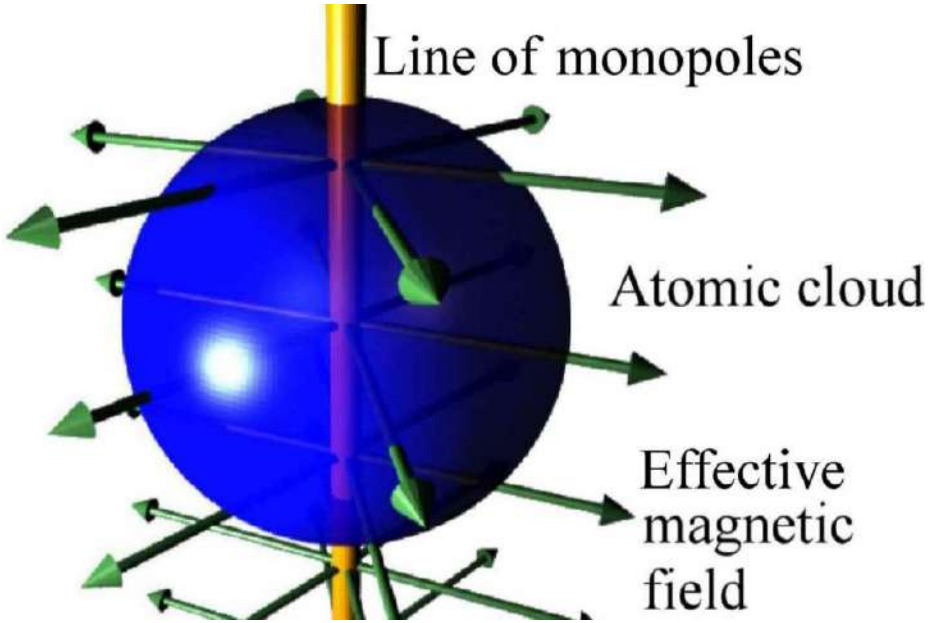
$$\kappa = \kappa_0 \rho \, e^{i\phi - \rho^2}$$



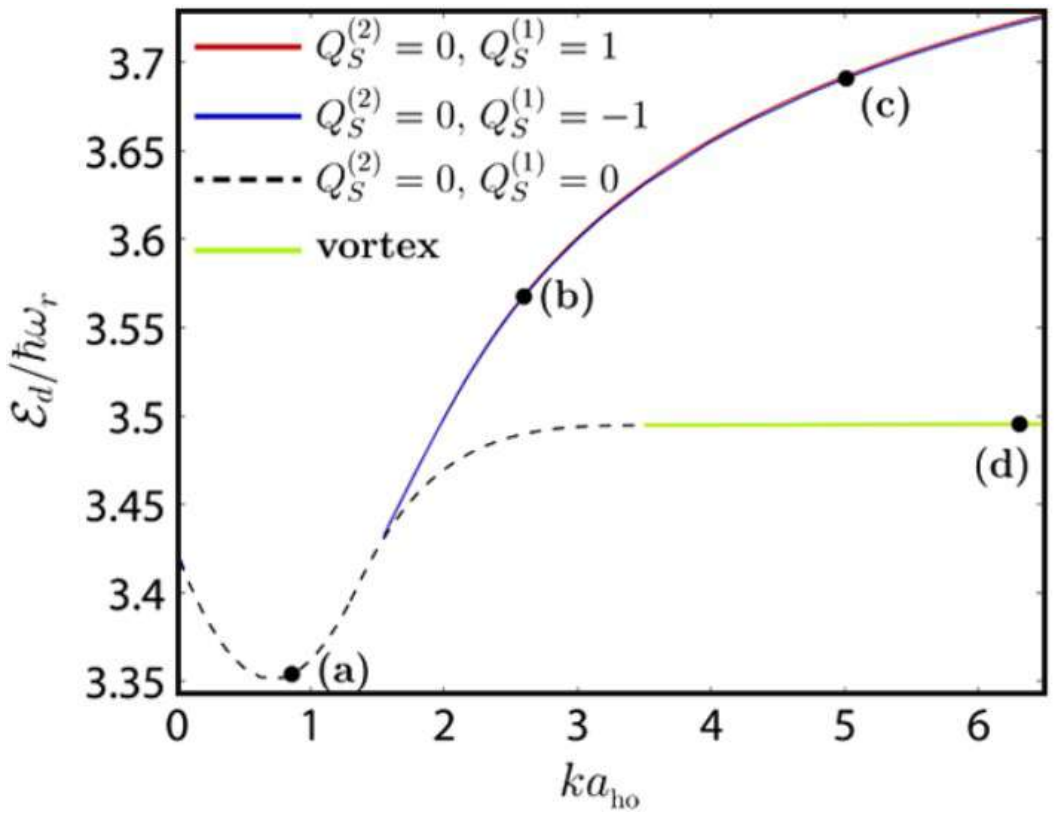
How to imprint the magnetic monopoles

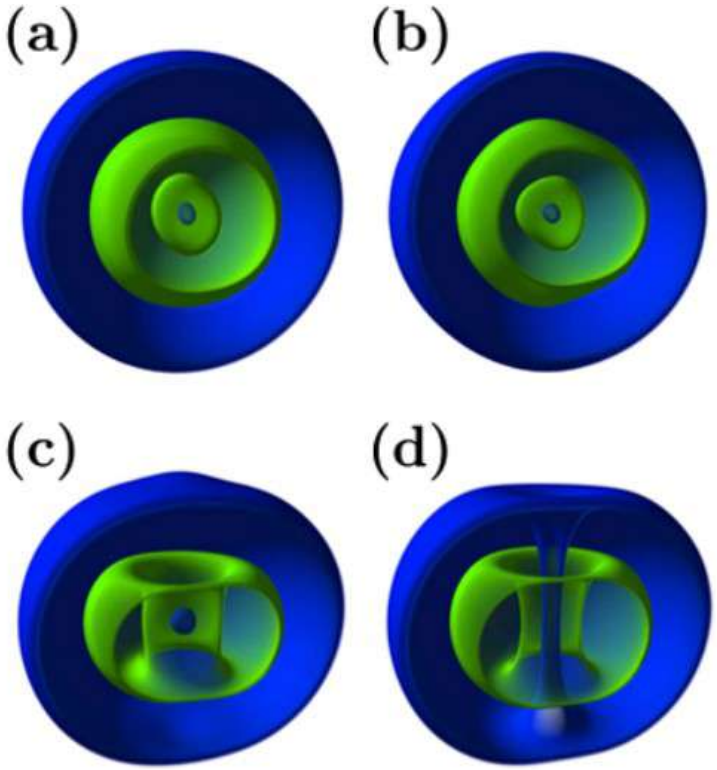
$$\hat{U} = \frac{\hbar}{2}\begin{pmatrix} -2\delta' z & \kappa_0 \rho\, \mathrm{e}^{\mathrm{i}\phi - \rho^2} & 0 \\ \kappa_0 \rho\, \mathrm{e}^{-\mathrm{i}\phi - \rho^2} & 0 & \kappa_0 \rho\, \mathrm{e}^{\mathrm{i}\phi - \rho^2} \\ 0 & \kappa_0 \rho\, \mathrm{e}^{-\mathrm{i}\phi - \rho^2} & 2\delta' z \end{pmatrix}$$

$$\begin{pmatrix} B_\rho \\ B_\phi \\ B_z \end{pmatrix} \approx \frac{\sqrt{2}\hbar\delta'}{\kappa_0 \rho}\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$$



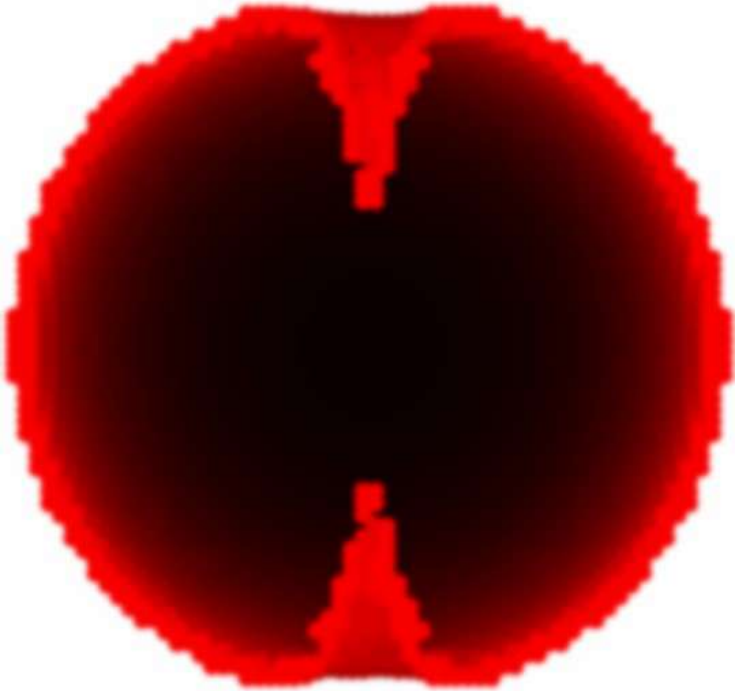
Single magnetic monopole





Pietilä & Möttönen PRL (2009)

4 monopoles embedded



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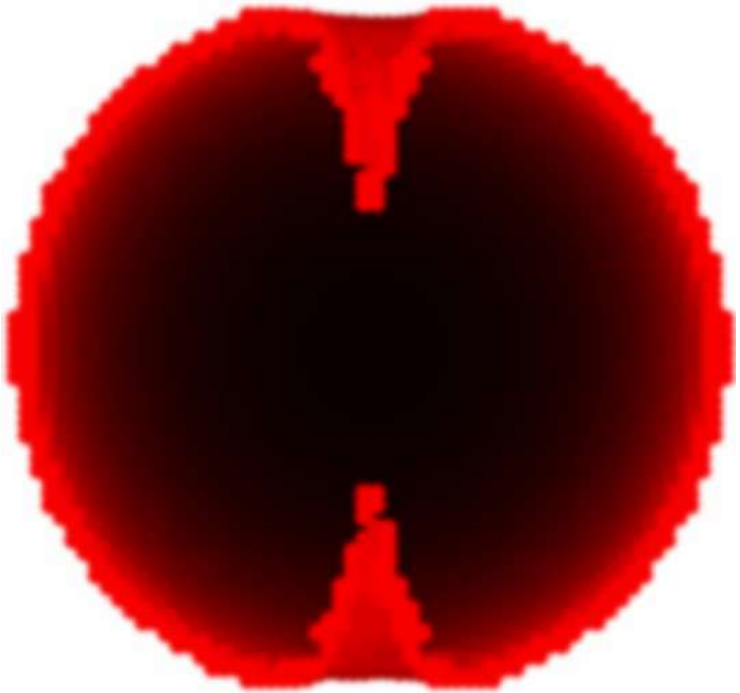
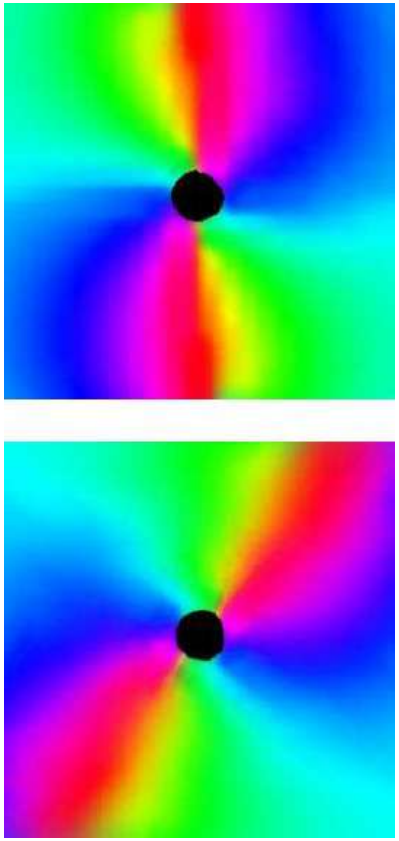
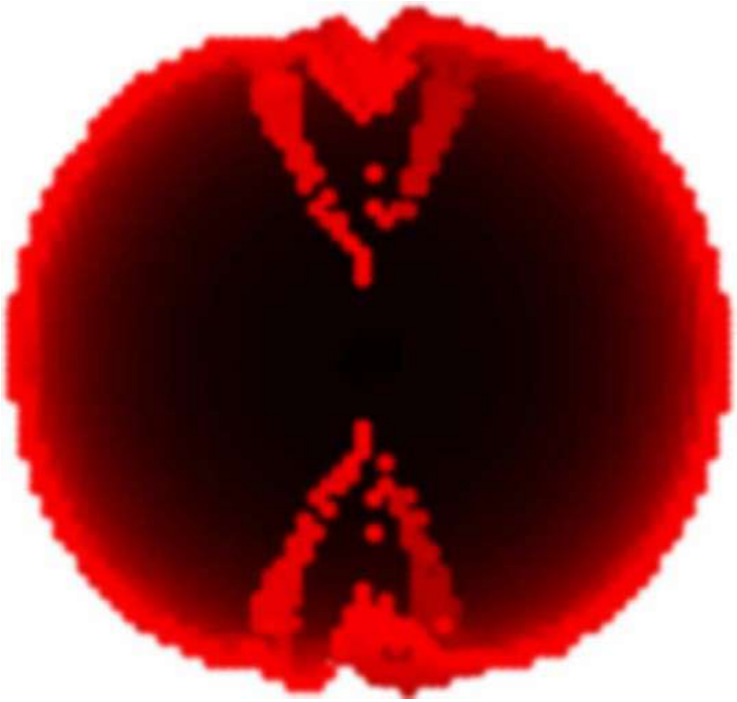
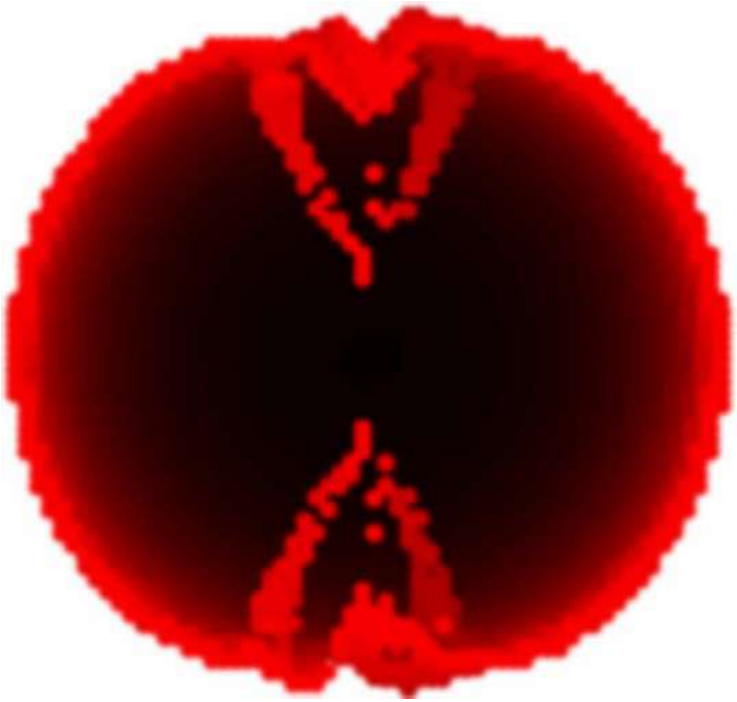


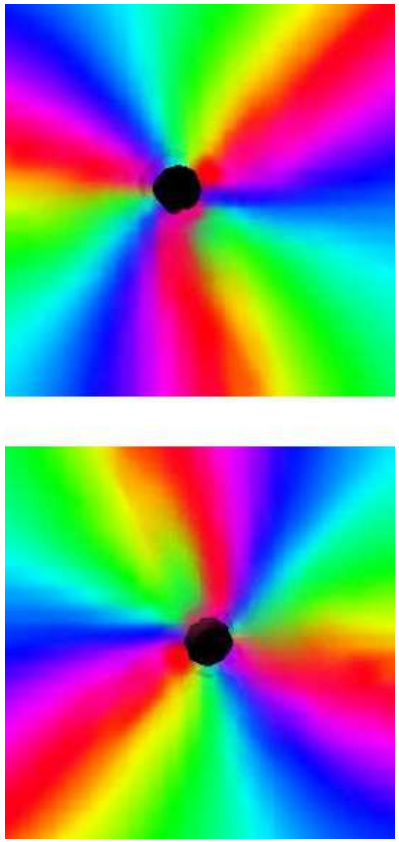


12 monopoles embedded

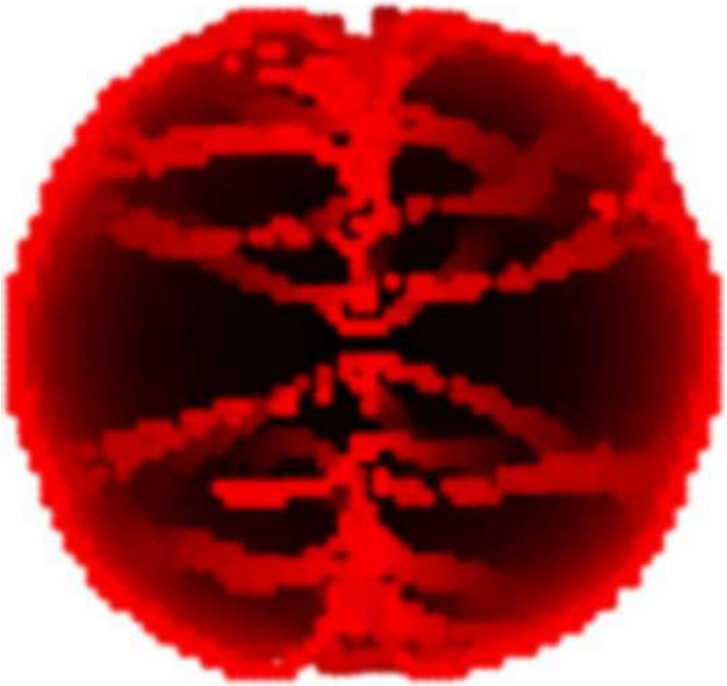


12 monopoles embedded





55 monopoles embedded



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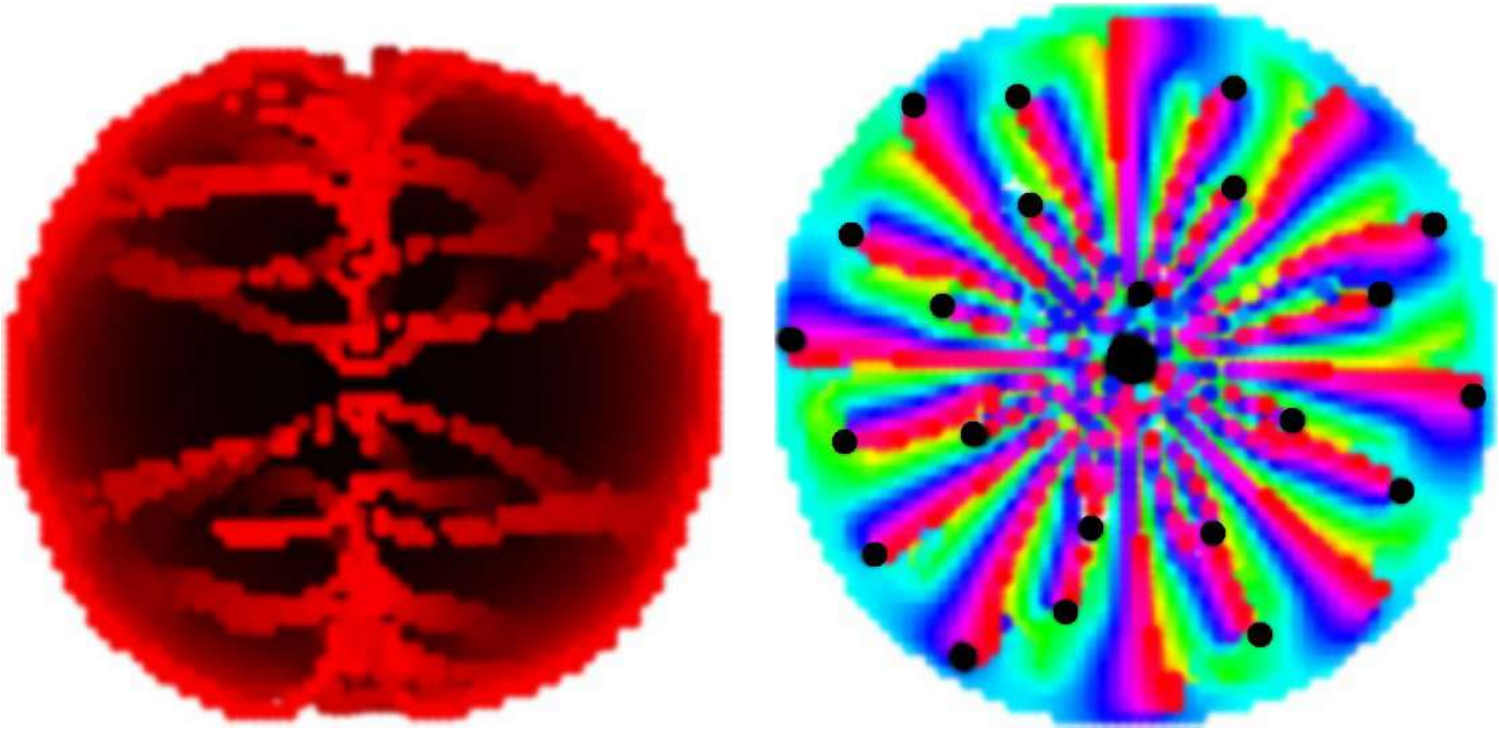
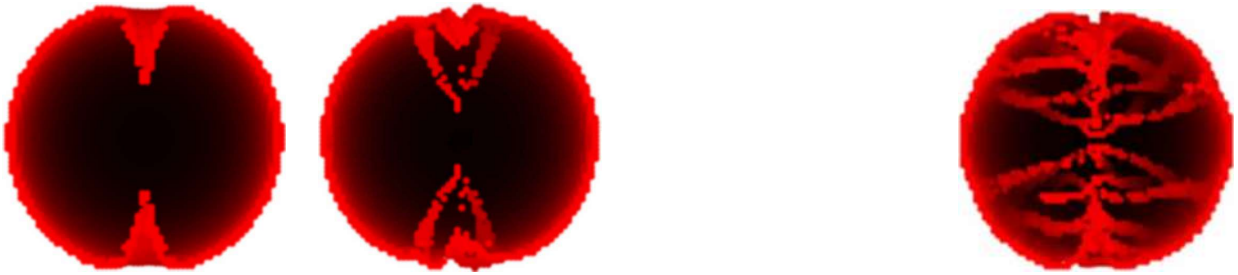
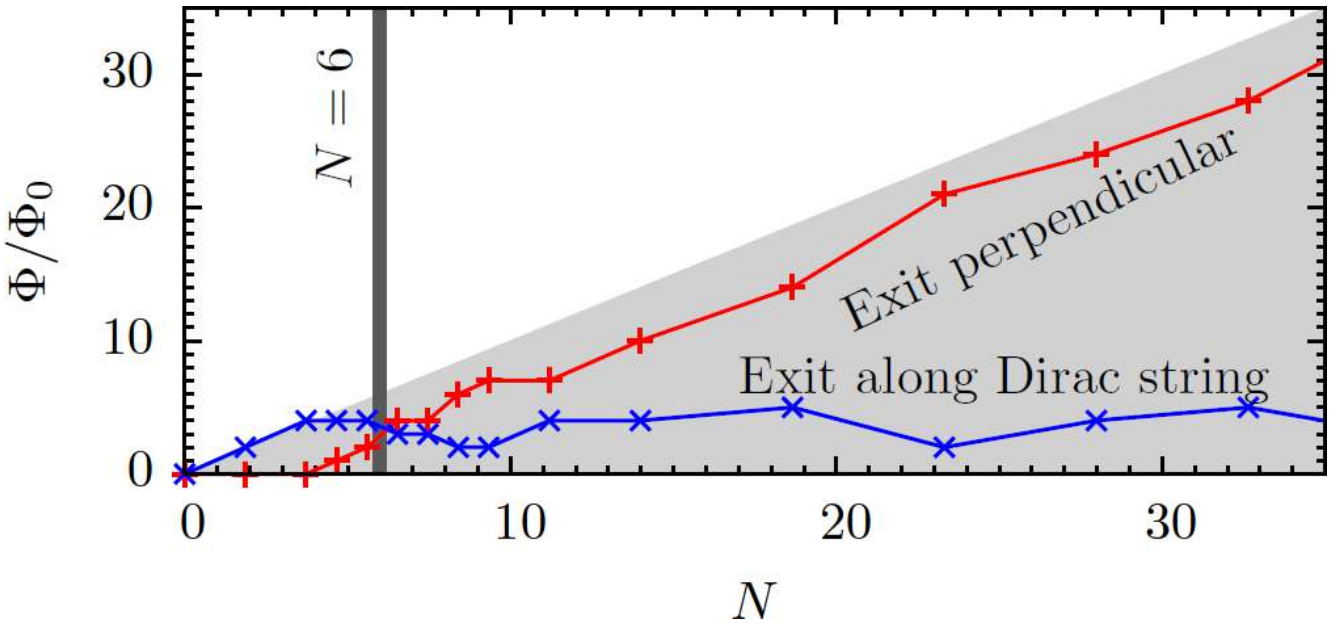
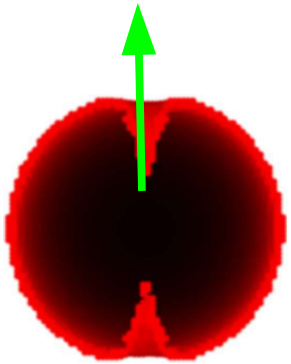


Phase behavior

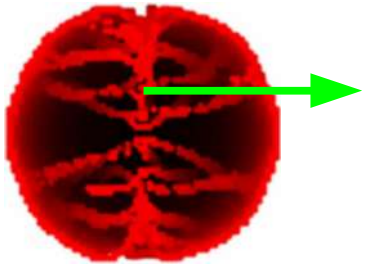




Energetics of flux escape



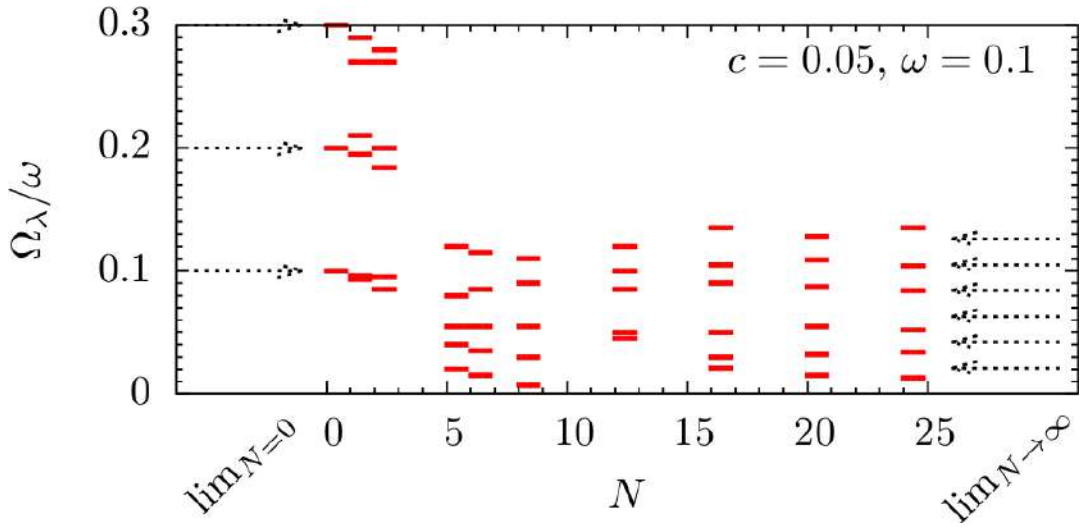
$$E = \frac{C}{6} N^2 L$$



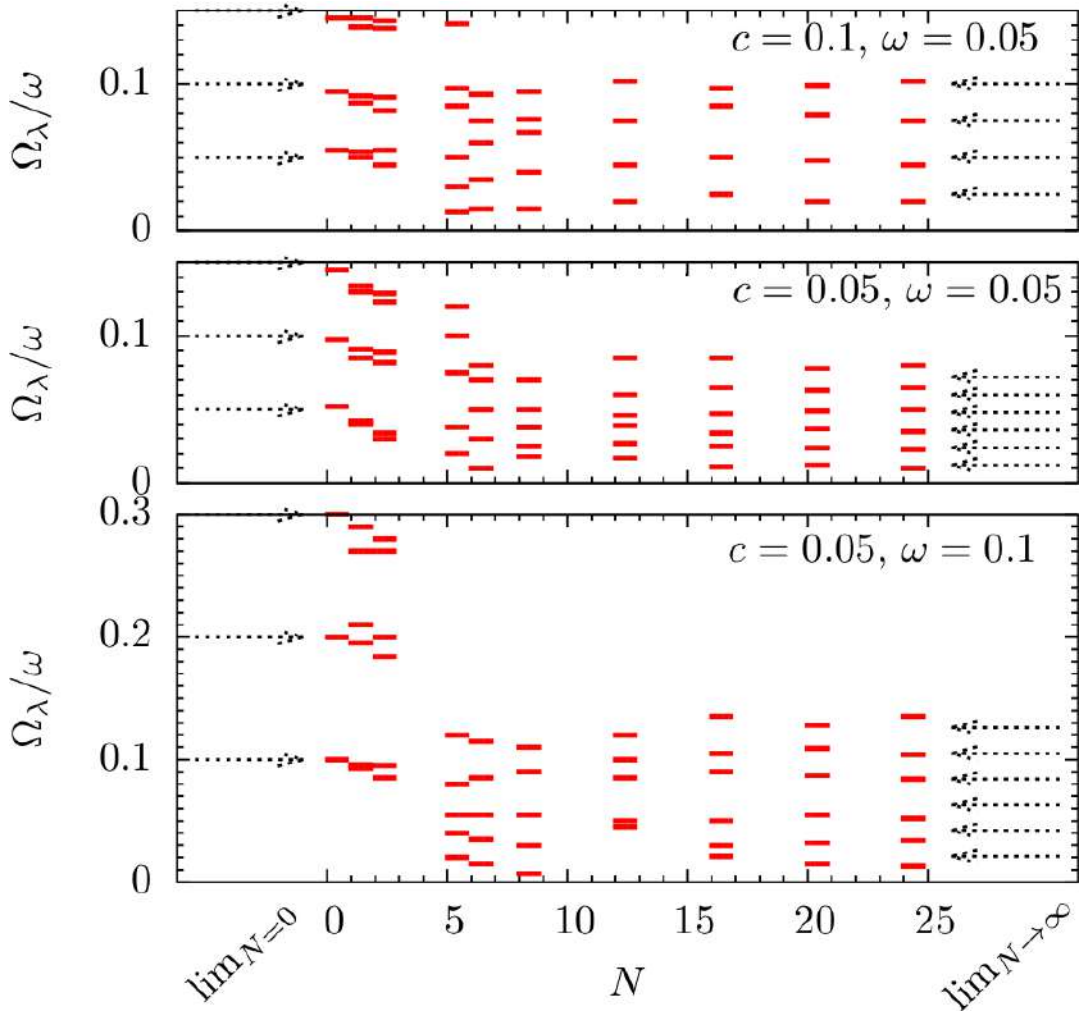
$$E = C N L$$

Crossover at $N = 6$

Collective modes



Collective modes



Summary

Proposed an experimental prescription to embed a line of magnetic monopoles onto an atomic gas

The atomic gas undergoes a transition when 6 monopoles are trapped