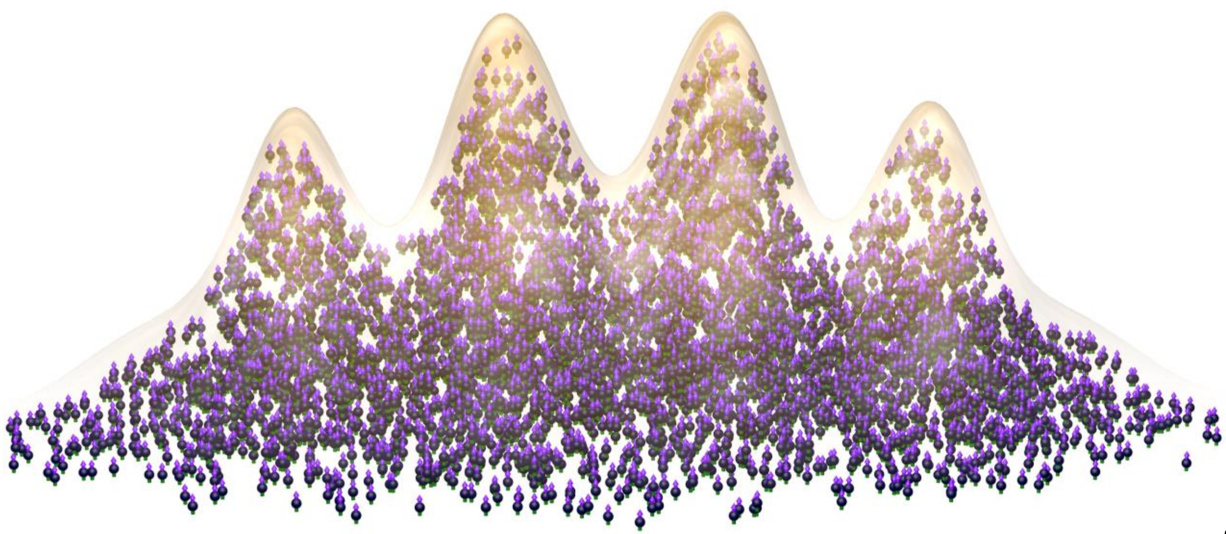
www.erbium.at

Exploring collective phenomena in ultracold Bose-Einstein condensates made of magnetic atoms



Daniel Petter

Dipolar Quantum Gases group

Supervised by Univ.-Prof. Francesca Ferlaino

8. Jan. 2020, MIP Seminar

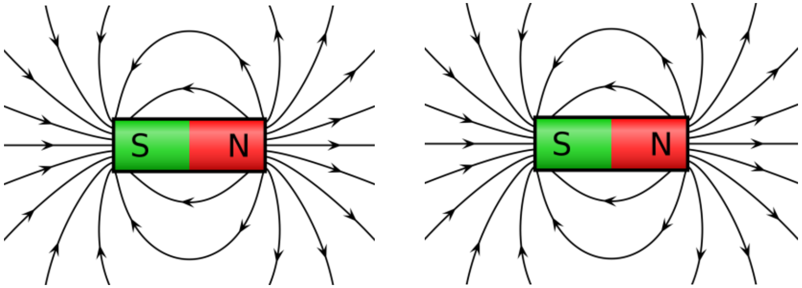
FWF Der Wissenschaftsfonds.

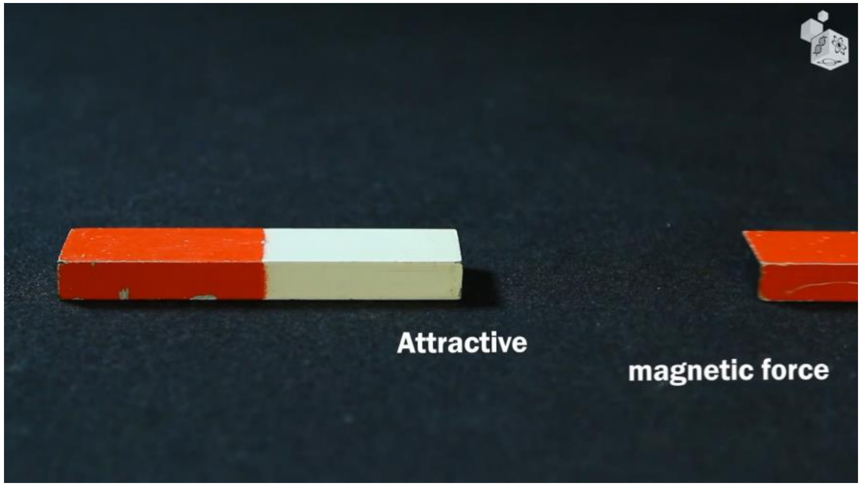
universität innsbruck

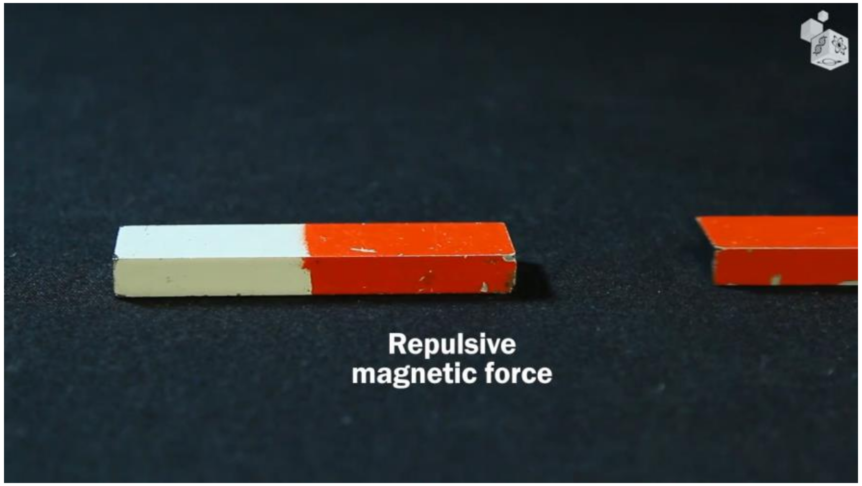
FOR 2247

erc

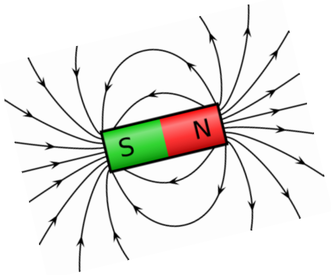
How do two magnets interact?



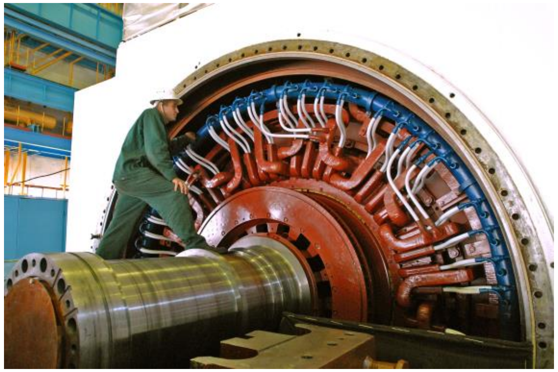




Youtube: Science Bits



Generators of power plants



wikipedia

wikipedia

~mm

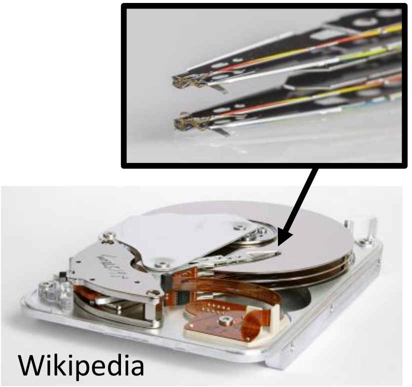
~meter

size of magnet

~100 nm

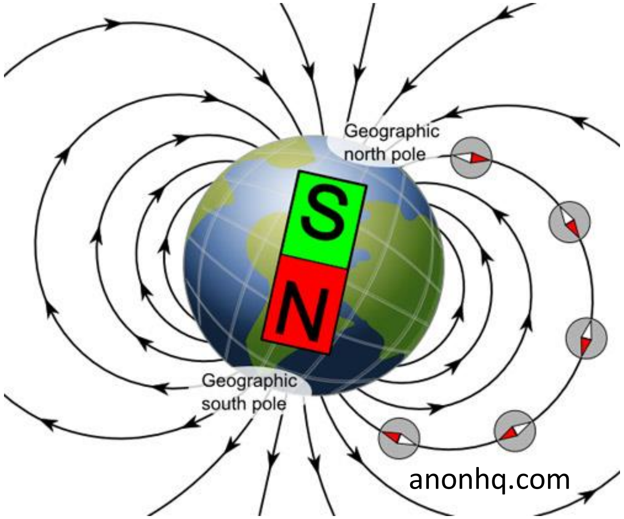
~10 cm

$\sim 10^3$ km

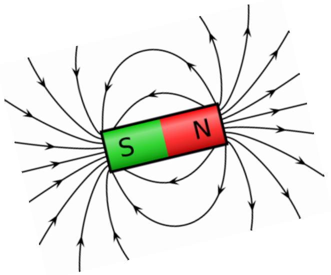


Wikipedia

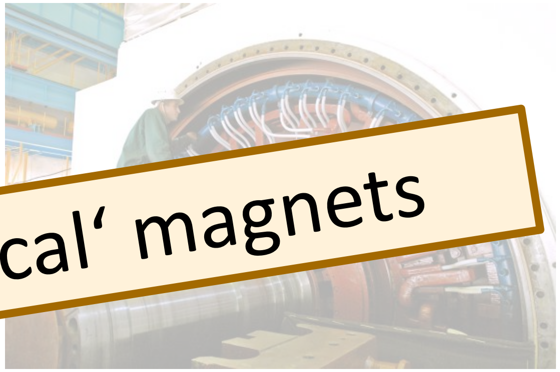
BMW
electrical engine



anonhq.com



Generators of power plants



All ‚classical' magnets

wikipedia

wikipedia

~mm

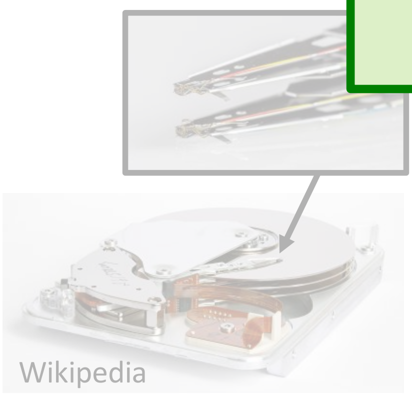
~meter

size of magnet

How do magnetic interactions modify the *quantum* world?

~100 nm

$\sim 10^3$ km



Wikipedia

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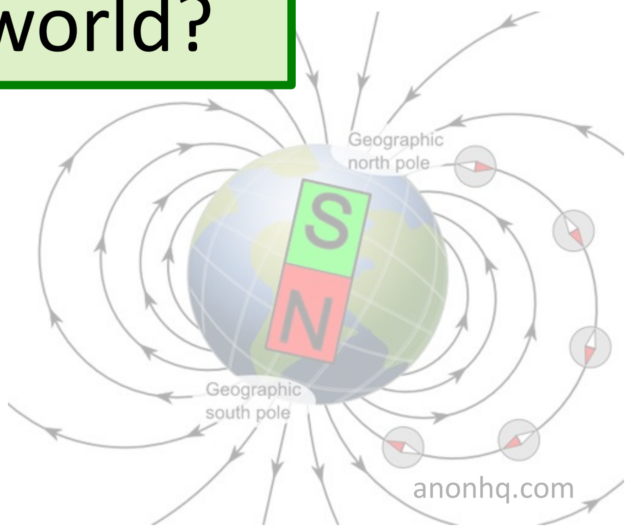
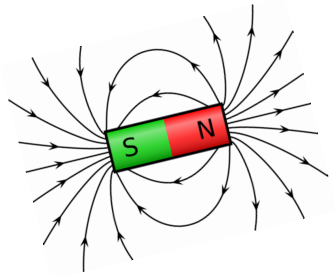
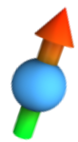


anonhq.com



1) We use the smallest possible magnets (single atoms!)



~0.1 nm

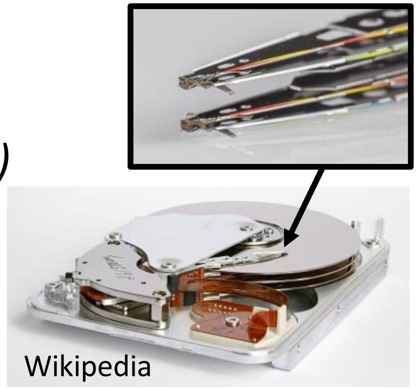
wikipedia

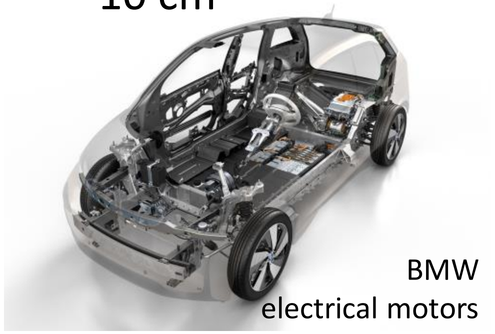
~mm

~100 nm

~10 cm

2) Cool them to ultracold temperatures (~ nanokelvin)
Bose-Einstein-Condensate (BEC)





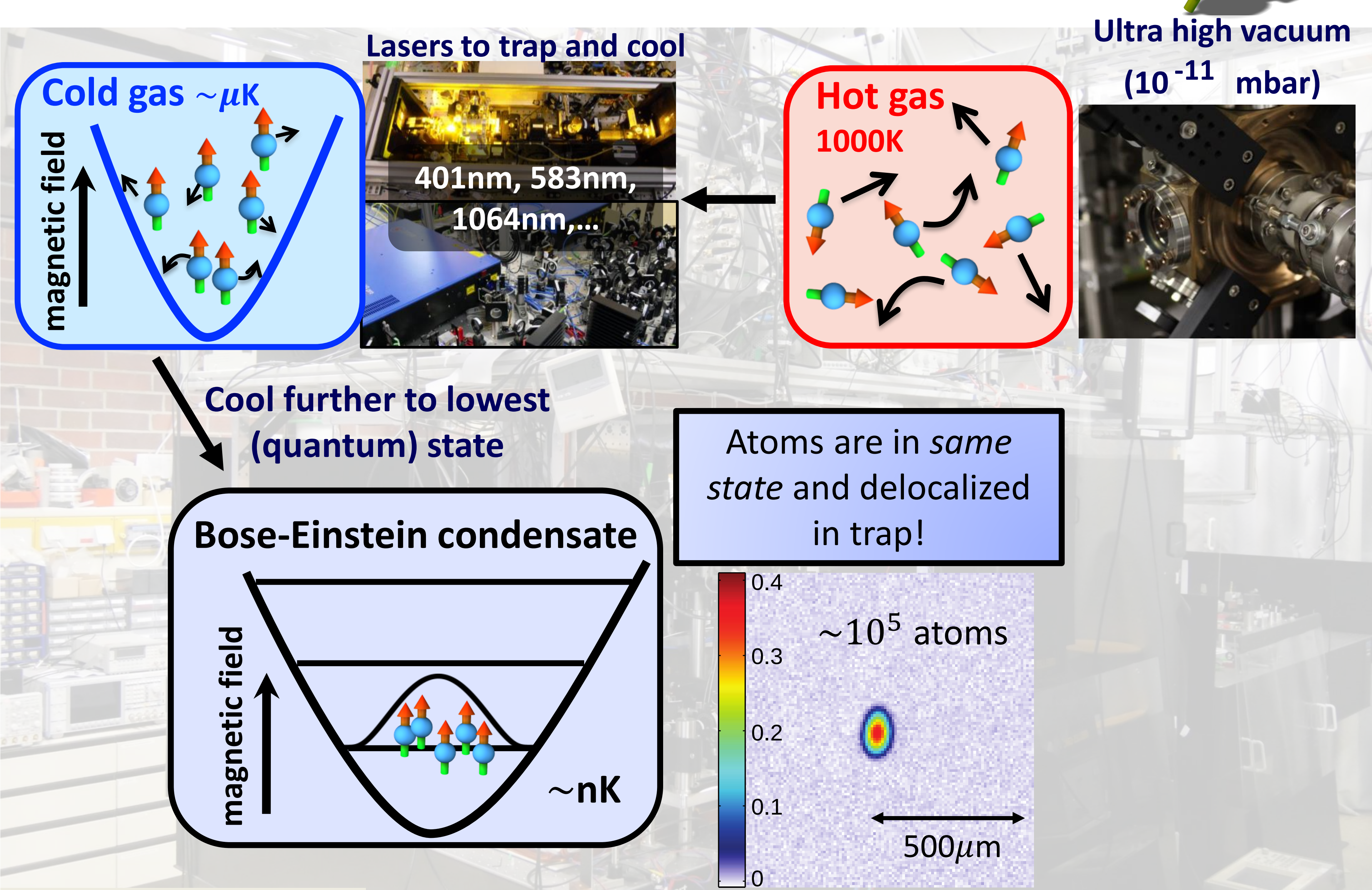
Entering the Quantum World with magnetic Erbium atoms

www.erbium.at

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H hydrogen [1.007; 1.009]																	2 He helium 4.003
3 Li lithium [6.938; 6.997]	4 Be beryllium 9.012											5 B boron [10.80; 10.83]	6 C carbon [12.00; 12.02]	7 N nitrogen [14.00; 14.01]	8 O oxygen [15.99; 16.00]	9 F fluorine 19.00	10 Ne neon 20.18
11 Na sodium 22.99	12 Mg magnesium 24.31											13 Al aluminium 26.98	14 Si silicon [28.08; 28.09]	15 P phosphorus 30.97	16 S sulfur [32.05; 32.08]	17 Cl chlorine [35.44; 35.46]	18 Ar argon 39.95
19 K potassium 39.10	20 Ca calcium 40.08	21 Sc scandium 44.96	22 Ti titanium 47.87	23 V vanadium 50.94	24 Cr chromium 52.00	25 Mn manganese 54.94	26 Fe iron 55.85	27 Co cobalt 58.93	28 Ni nickel 58.69	29 Cu copper 63.55	30 Zn zinc 65.38(2)	31 Ga gallium 69.72	32 Ge germanium 72.63	33 As arsenic 74.92	34 Se selenium 78.96(3)	35 Br bromine 79.90	36 Kr krypton 83.80
37 Rb rubidium 85.47	38 Sr strontium 87.62	39 Y yttrium 88.91	40 Zr zirconium 91.22	41 Nb niobium 92.91	42 Mo molybdenum 95.96(2)	43 Tc technetium	44 Ru ruthenium 101.1	45 Rh rhodium 102.9	46 Pd palladium 106.4	47 Ag silver 107.9	48 Cd cadmium 112.4	49 In indium 114.8	50 Sn tin 118.7	51 Sb antimony 121.8	52 Te tellurium 127.6	53 I iodine 126.9	54 Xe xenon 131.3
55 Cs caesium 132.9	56 Ba barium 137.3	57-71 lanthanoids	72 Hf hafnium 178.5	73 Ta tantalum 180.9	74 W tungsten 183.8	75 Re rhenium 186.2	76 Os osmium 190.2	77 Ir iridium 192.2	78 Pt platinum 195.1	79 Au gold 197.0	80 Hg mercury 200.6	81 Tl thallium [204.3; 204.4]	82 Pb lead 207.2	83 Bi bismuth 209.0	84 Po polonium	85 At astatine	86 Rn radon
87 Fr francium	88 Ra radium	89-103 actinoids	104 Rf rutherfordium	105 Db dubnium	106 Sg seaborgium	107 Bh bohrium	108 Hs hassium	109 Mt meitnerium	110 Ds darmstadtium	111 Rg roentgenium	112 Cn copernicium		114 Fl flerovium		116 Lv livermorium		
		57 La lanthanum 138.9	58 Ce cerium 140.1	59 Pr praseodymium 140.9	60 Nd neodymium 144.2	61 Pm promethium	62 Sm samarium 150.4	63 Eu europium 152.0	64 Gd gadolinium 157.3	65 Tb terbium 158.9	dysprosium 162.5	Ho holmium 164.9	68 Er erbium 167.3	69 Tm thulium 168.9	70 Yb ytterbium 173.1	71 Lu lutetium 175.0	
		89 Ac actinium	90 Th thorium 232.0	91 Pa protactinium 231.0	92 U uranium 238.0	93 Np neptunium	94 Pu plutonium	95 Am americium	96 Cm curium	97 Bk berkelium	98 Cf californium	99 Es einsteinium	100 Fm fermium	101 Md mendelevium	102 No nobelium	103 Lr lawrencium	

erbium

Entering the Quantum World with magnetic Erbium atoms



Courtesy of Simon Baier

THE FAMILY OF BOSE-EINSTEIN-CONDENSATES

www.erbium.at

= Bose-Einstein condensed

1 μ_B (H)

~0 μ_B (group 2)

6 μ_B (Cr)

~0 μ_B (He)

10 μ_B (Dy)

2012 (Er)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
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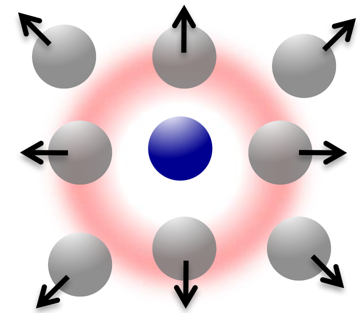
magnetic moment: 7 μ_B

Two Interactions between the atoms in the BEC

Tunable with magnetic field strength

contact **interaction**
isotropic and short ranged
(can be tuned repulsive or attractive)



Can be **tuned relatively to each** other in experiment

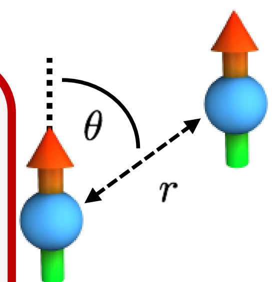
Fixed
strength in upcoming measurements

Dipole-Dipole Interaction (DDI)

$$V_{\mathrm{dd}} = \frac{\mu_0 \mu^2}{4\pi} \frac{1 - 3\cos^2\theta}{r^3}$$

anisotropic

long range



$\mu = 7\ \mu_B$

50 TIMES **STRONGER** MAGNETS
THAN ALKALI ATOMS

EXPLORE NEW PHYSICS

Publications within this (upcoming) thesis:

- *Quantum-Fluctuation-Driven Crossover from a Dilute Bose-Einstein Condensate to a Macrodroplet in a Dipolar Quantum Fluid*
  L. Chomaz, S. Baier, D. P., M. J. Mark, F. Wächtler, L. Santos, F. Ferlaino, PRX **6**, 041039 (2016)

- *Observation of roton mode population in a dipolar quantum gas*
  L. Chomaz, R. v. Bijnen, D. P., G. Faraoni, S. Baier, J. H. Becher, M. J. Mark, F. Waechtler, L. Santos, F. Ferlaino, Nat. Phys. **14**, 442 (2018)

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- *Probing the Roton Excitation Spectrum of a stable dipolar Bose gas,*
  D. P., G. Natale, R. M. W. van Bijnen, A. Patscheider, M. J. Mark, L. Chomaz, F. Ferlaino, PRL **122,** 183401 (2019)

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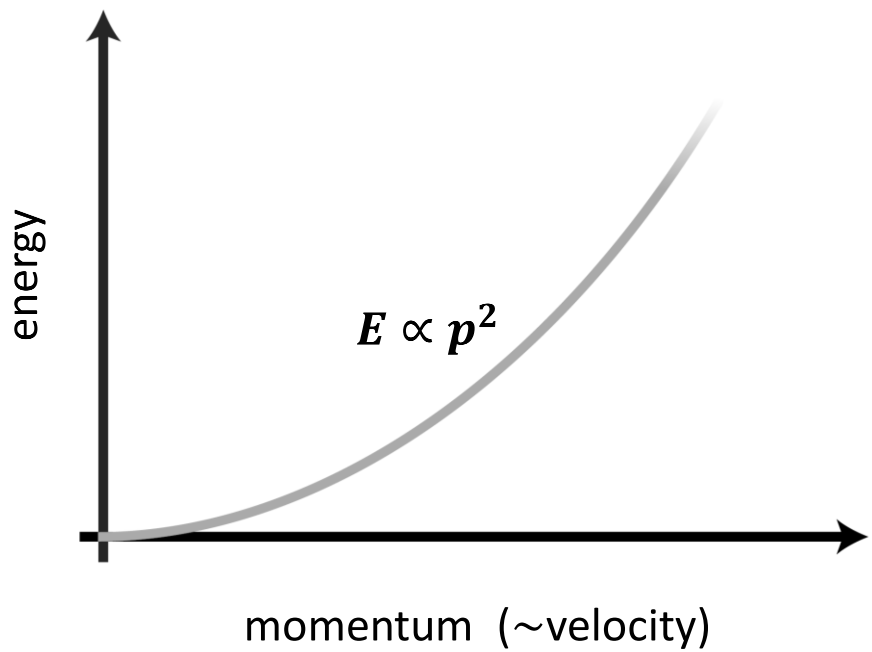
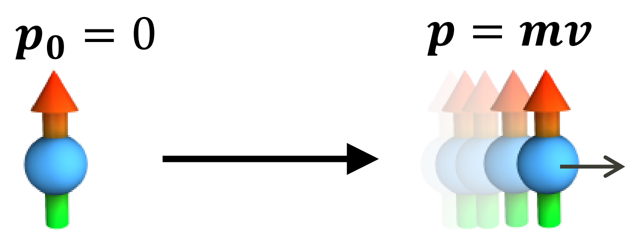
What is an excitation spectrum (dispersion relation)?

Describes the energy $\boldsymbol{E}$ that is needed to excite a physical system at a certain momentum $\boldsymbol{p}$ (or velocity $\boldsymbol{v}$)



A simple example to get started:
a single atom (no BEC)

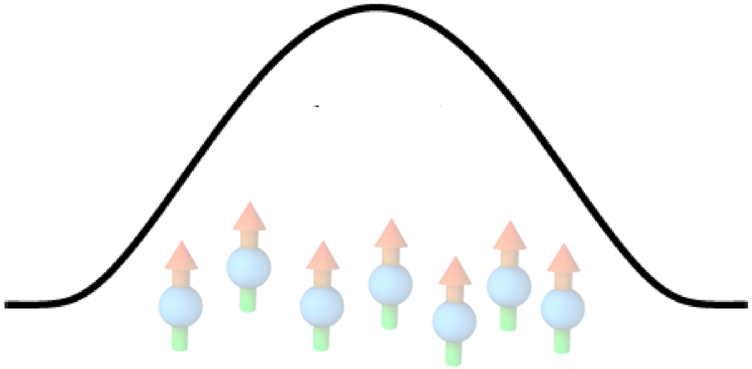


$$E = \frac{1}{2} m v^2 = \frac{p^2}{2m}$$

$\boldsymbol{m}$ ... mass of atom

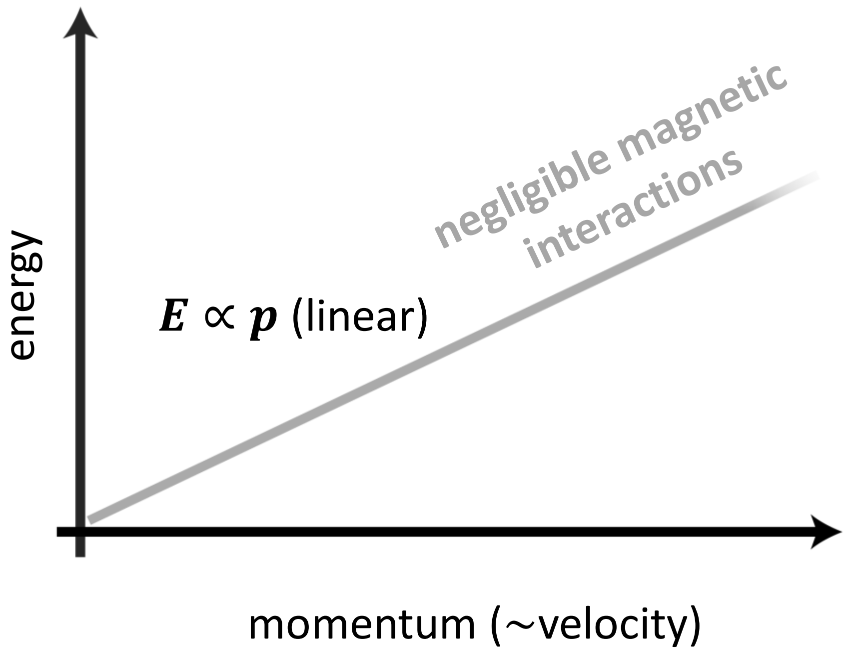
Excitation spectrum of a Bose-Einstein condensate

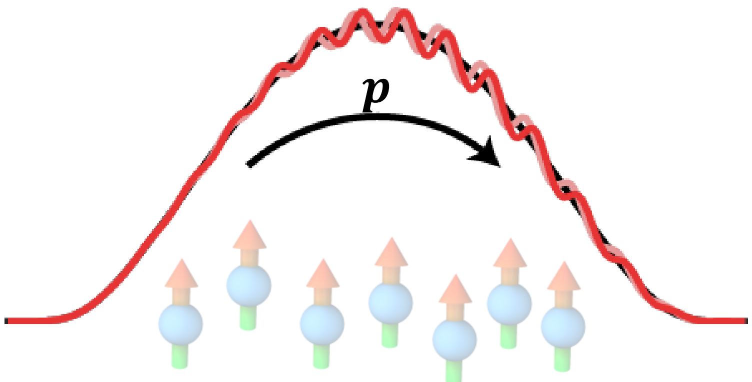
At low momentum, atoms respond ***collectively*** (due to delocalisation + interactions)



Excitation spectrum of a Bose-Einstein condensate

At low momentum, atoms respond ***collectively*** (due to delocalisation + interactions)

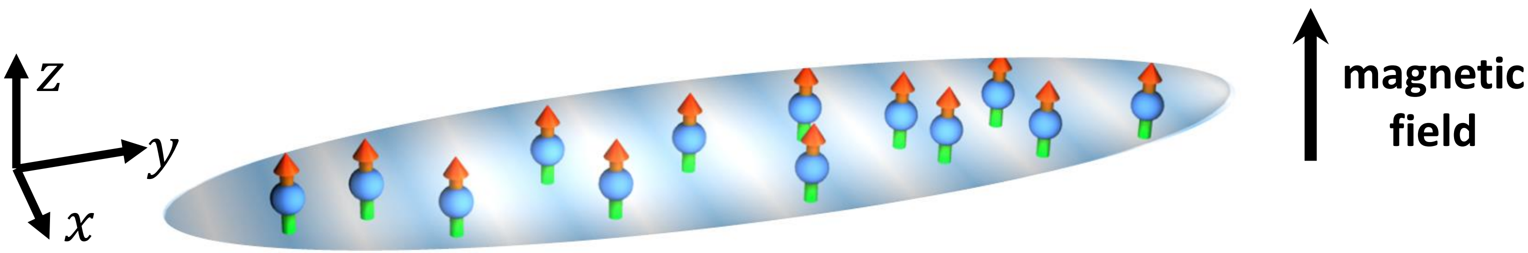


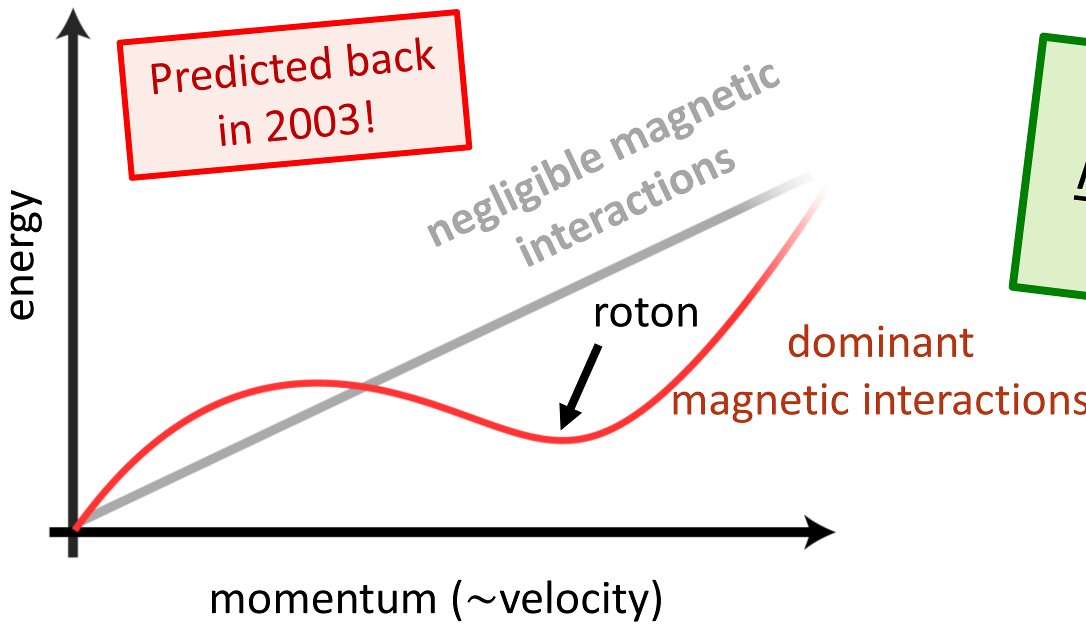


Collective excitations travel as ***plane waves*** through BEC (similar to phonons in solids, or waves in water)

Excitation spectrum of a *magnetic* Bose-Einstein condensate

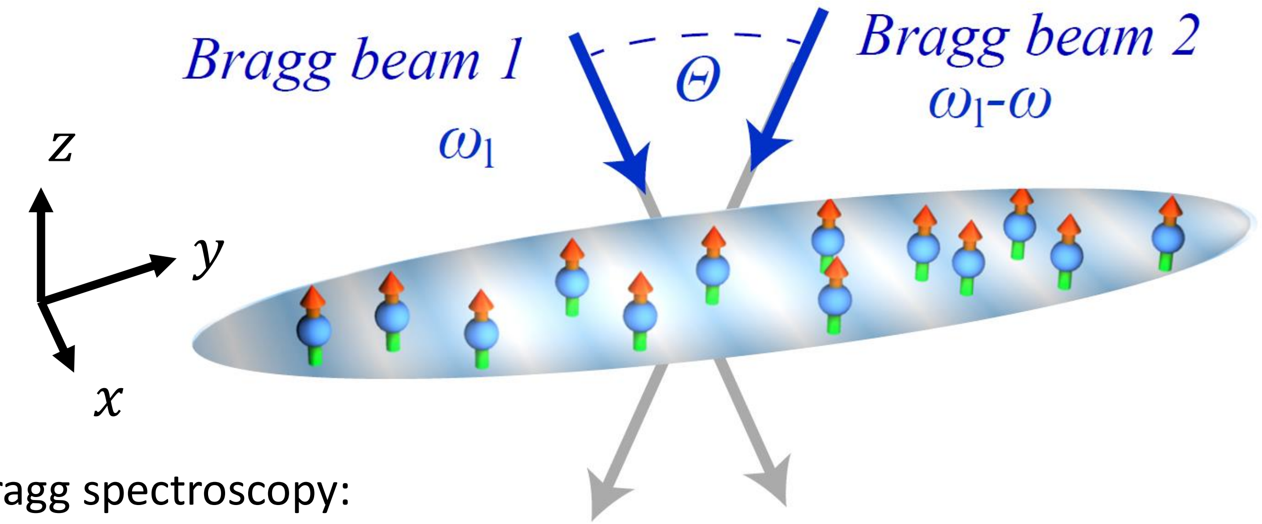
At low momentum, atoms respond ***collectively*** (due to delocalisation + interactions)





How to probe roton minimum in excitation spectrum?

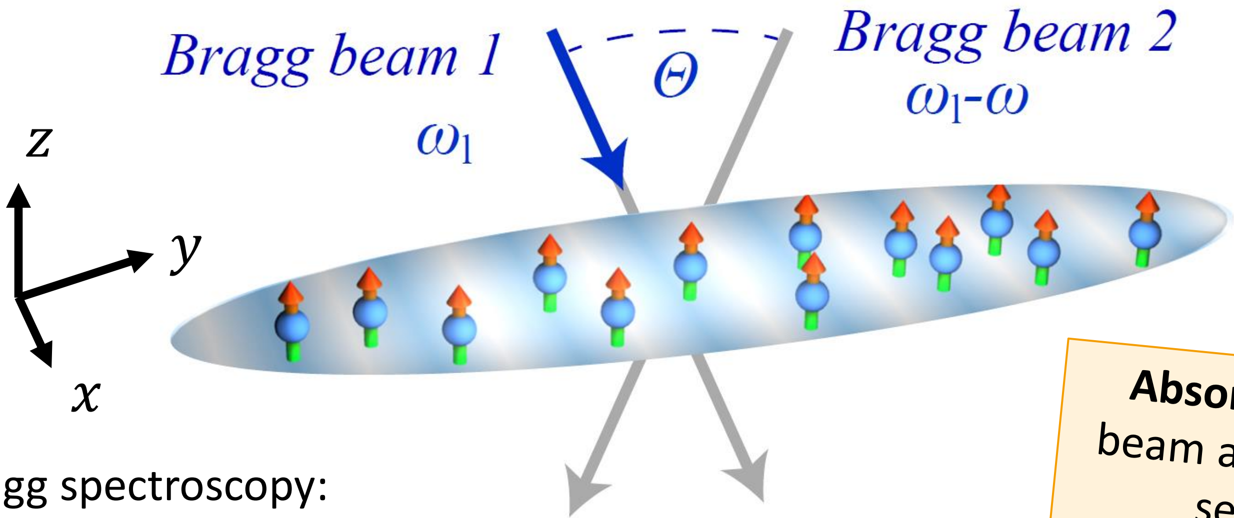
Excitation spectrum of a *magnetic* Bose-Einstein condensate



Bragg spectroscopy:

- Two laser beams cross under angle θ at atomic cloud
- Frequency difference ω
- Excitation via *two–photon process*

Excitation spectrum of a *magnetic* Bose-Einstein condensate



Absorption from first beam and **emission** into second beam

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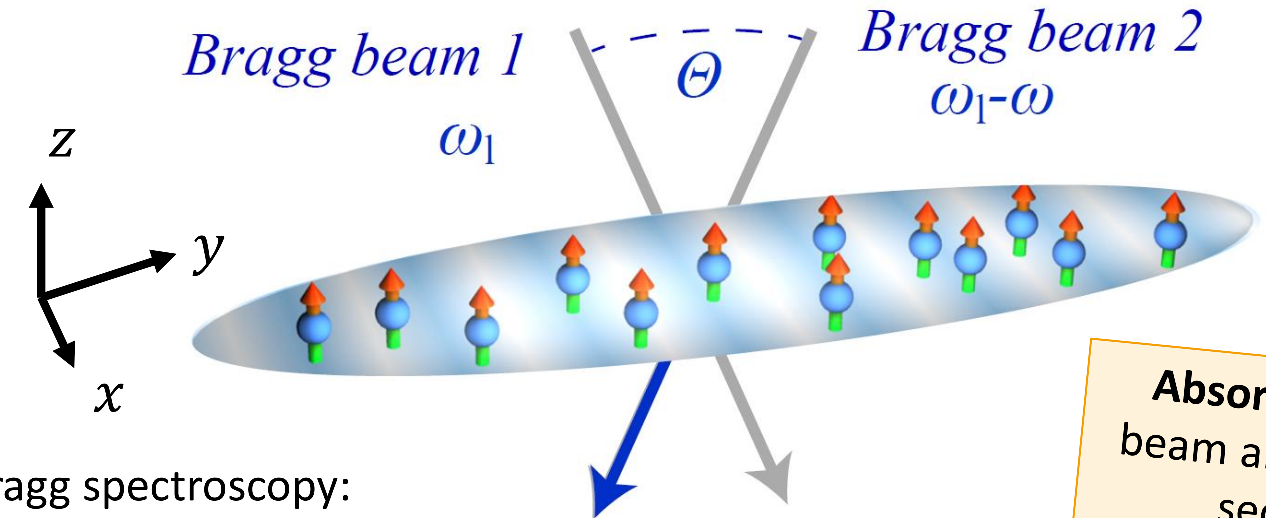
Excitation spectrum of a *magnetic* Bose-Einstein condensate



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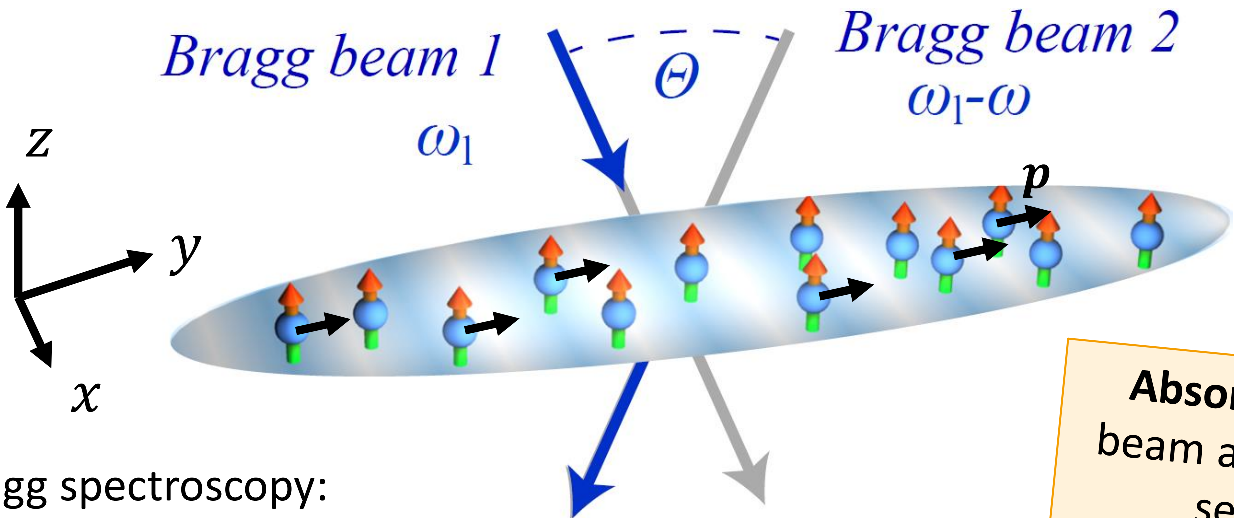


Bragg spectroscopy:

- Two laser beams cross under angle θ at atomic cloud
- Frequency difference ω
- Excitation via *two–photon process*
- Momentum transfer $\boldsymbol{p}$ happpens only when energy ($\hbar\omega$) matches excitation spectrum

Absorption from first beam and **emission** into second beam

EXPLORING NEW PHYSICS (AND UPGRADE THE EXPERIMENT)

Implement a Bragg spectroscopy setup:

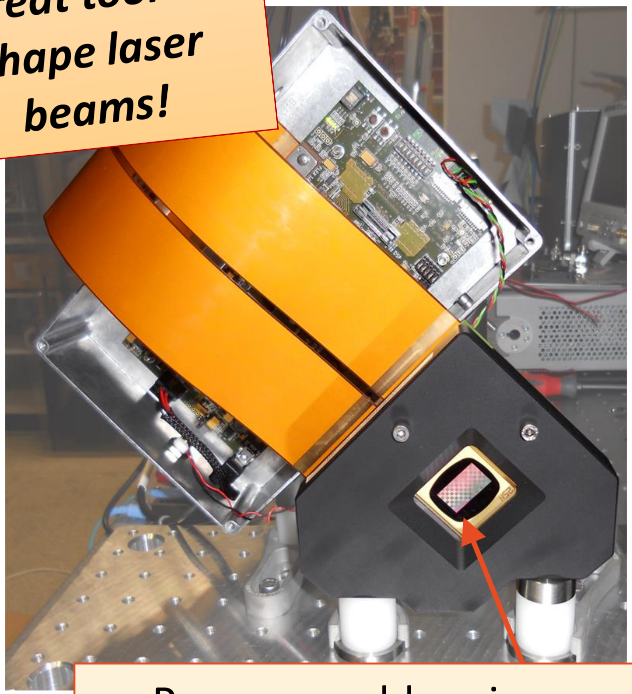
Main requirement:

Easy tunability over relevant momentum and energy range

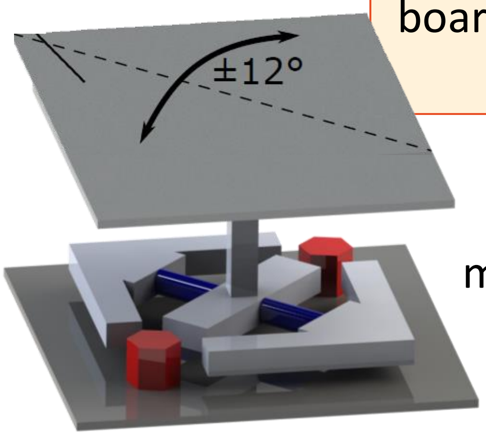
Technical implementation with *digital micromirror device:*

- Use holographic gratings to create *two Bragg beams* from *one incoming laser beam*
- Allows to change momentum $\boldsymbol{p}$ and frequency ω independently via computer programm

Great tool to shape laser beams!



Programmable mirror board with 1920x1080 tiny mirrors



mirror

Implement a Bragg spectroscopy setup:

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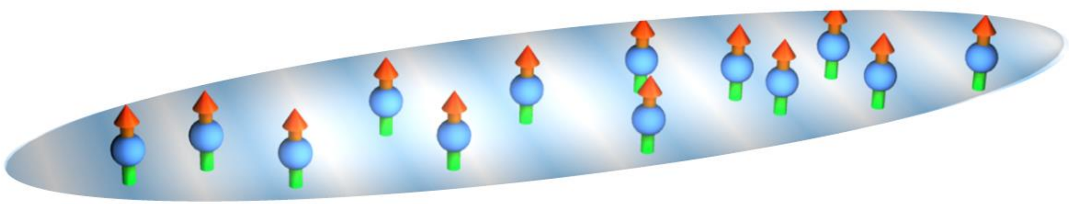
- Allows to change momentum $\boldsymbol{p}$ and frequency ω independently via computer programm

- Reguirements: Additional Laser setup, Programming, offline calibration, implementation into experiment

Excitation spectrum of a *magnetic* Bose-Einstein condensate

Measurement sequence:

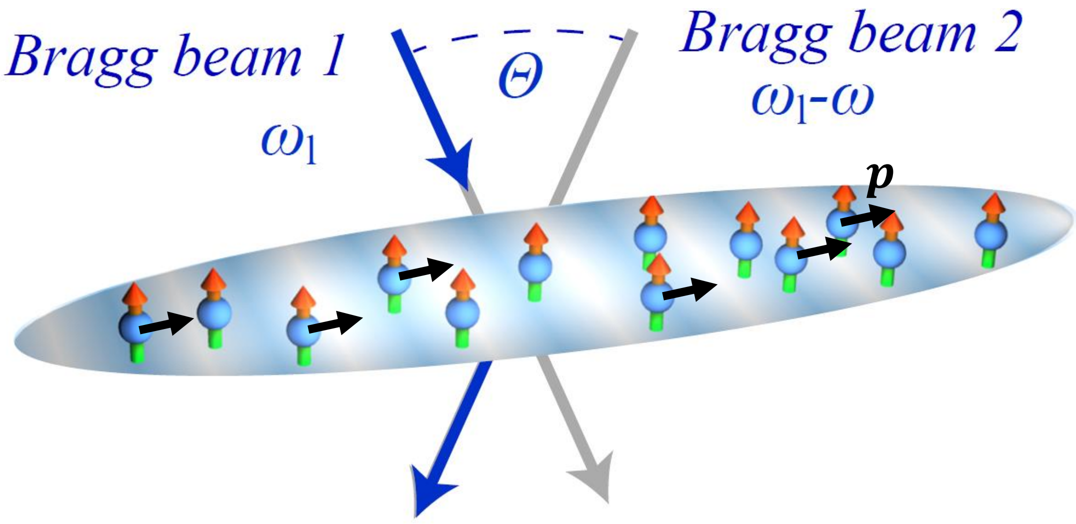
- Prepare cloud



Excitation spectrum of a *magnetic* Bose-Einstein condensate

Measurement sequence:

- Prepare cloud
- Apply a short Bragg pulse with fixed momentum
- Let atoms expand in free space (switch off trap)
- Take a picture



Excitation spectrum of a *magnetic* Bose-Einstein condensate

Measurement sequence:

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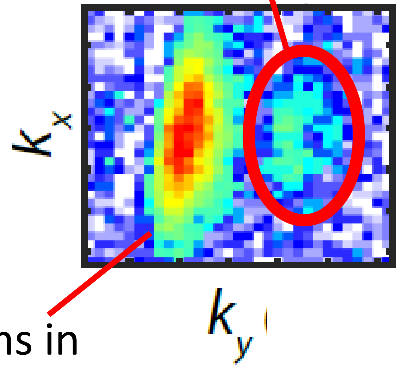
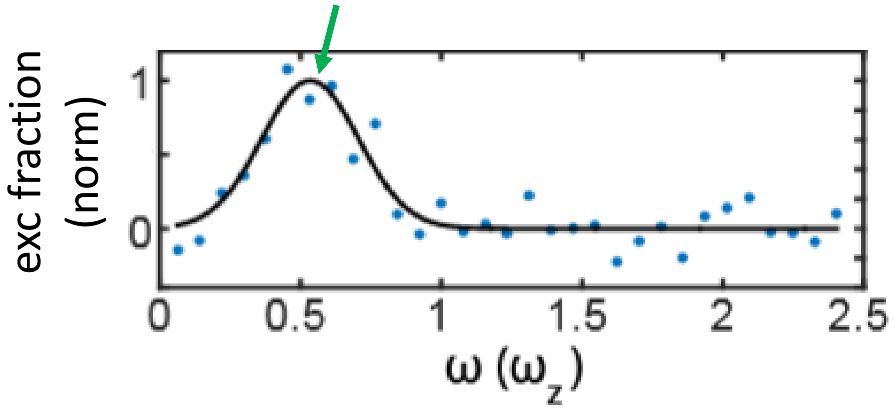
On resonance: excited atoms F_{ex}



atoms in BEC

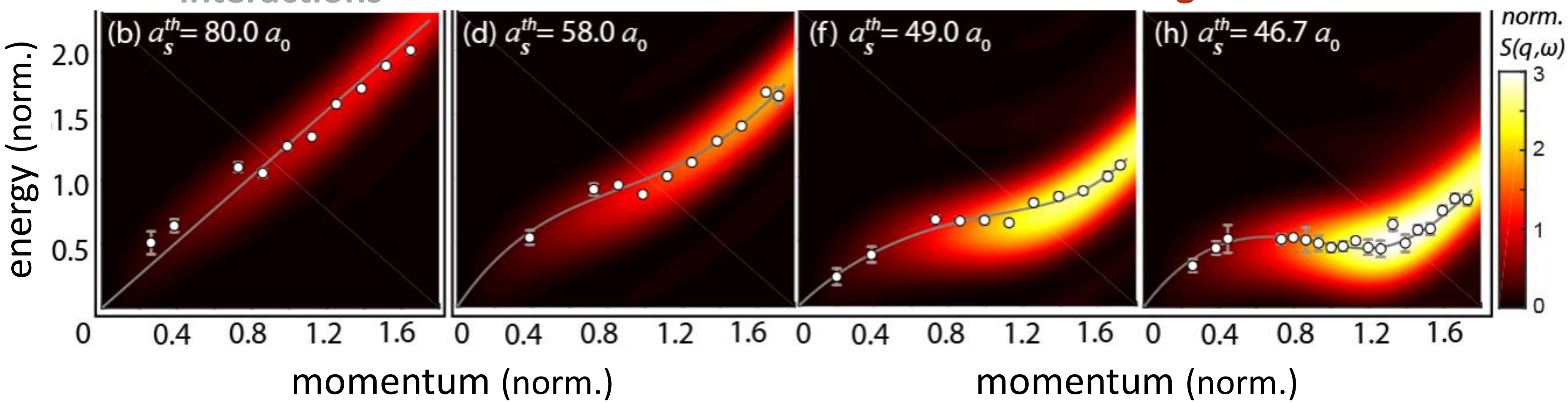
Vary energy $\hbar\omega$ and fit resonance position

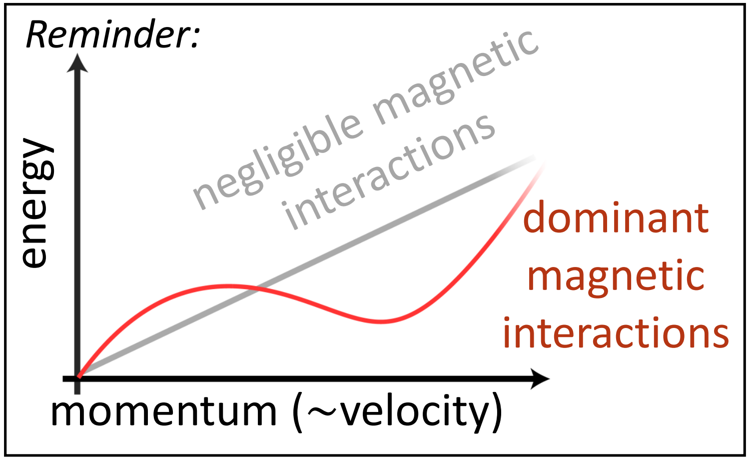


Excitation spectrum of a *magnetic* Bose-Einstein condensate

Repeat for different momenta and compare to theory

negligible magnetic interactions ⟷ **dominant magnetic interactions**

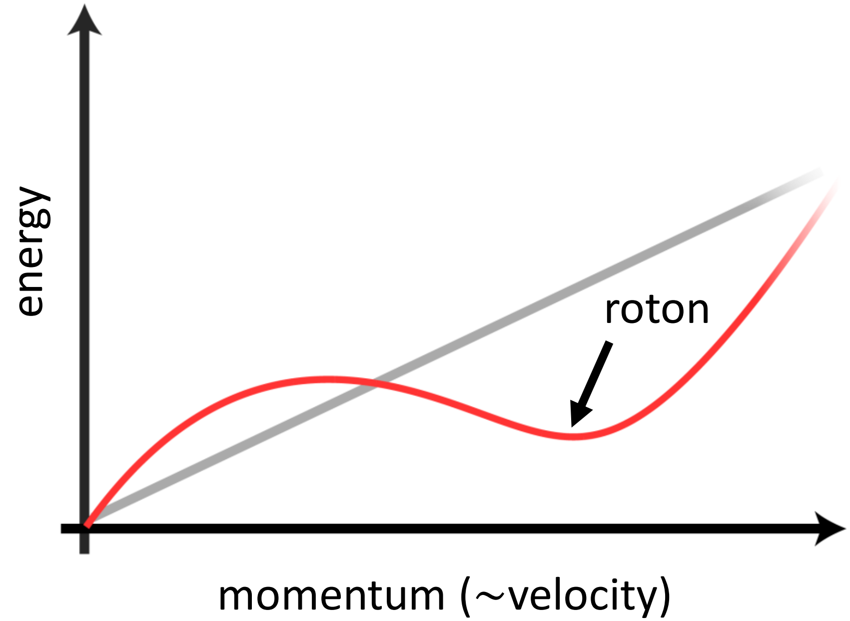




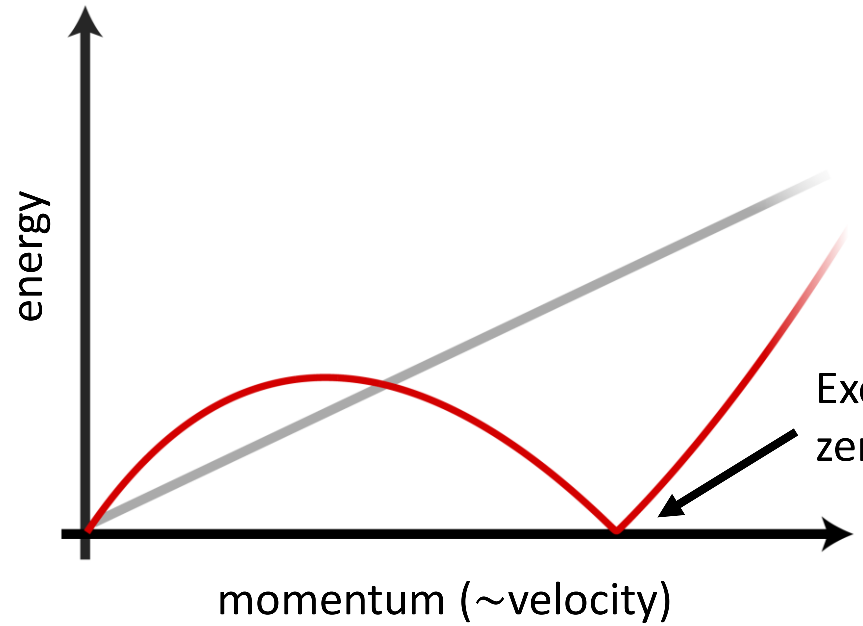
D. P., G. Natale, R. M. W. van Bijnen, A. Patscheider, M. J. Mark, L. Chomaz, F. Ferlaino, PRL **122,** 183401 (2019)

Outlook– Most recent results

What happens when the energy of the roton minimum is tuned to zero?

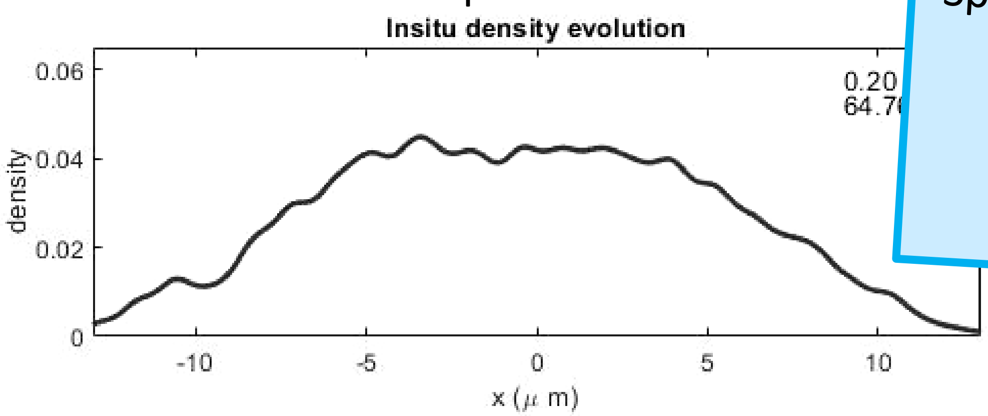


What happens when the energy of the roton minimum is tuned to zero?



Phase transition!

Simulation of full experiment:



Spontaneous *‚crystalline‘* structure in gas!
New quantum phase of matter oberserved
see PRX **9**, 021012 (2019)
and two other exp. groups

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Thank you!