Multi-RF-Dressed Potentials

Dr. Elliot Bentine, University of Oxford

Multi-RF-Dressed Potentials

- RF-dressed potentials
- Multiple-RF-dressed potentials
  - Explanation
  - The experimental apparatus
  - Technical considerations
  - The MRF double-well and interferometry
- Software toolkit

The Team

- RF-dressed experiment


David Garrick


Abel Beregi


En Chang

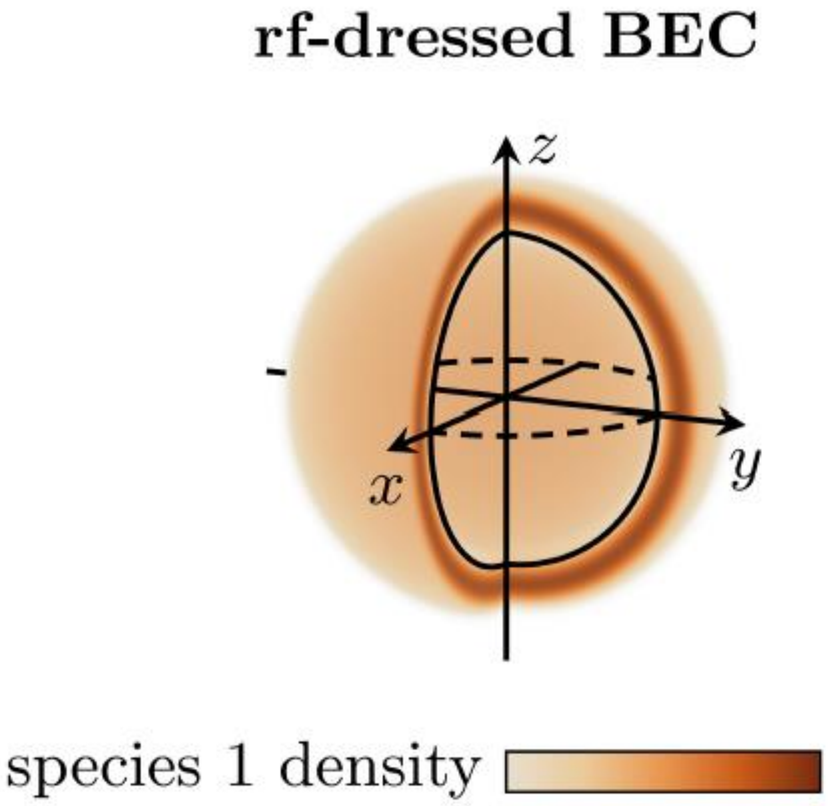

Dr. Shinichi Sunami

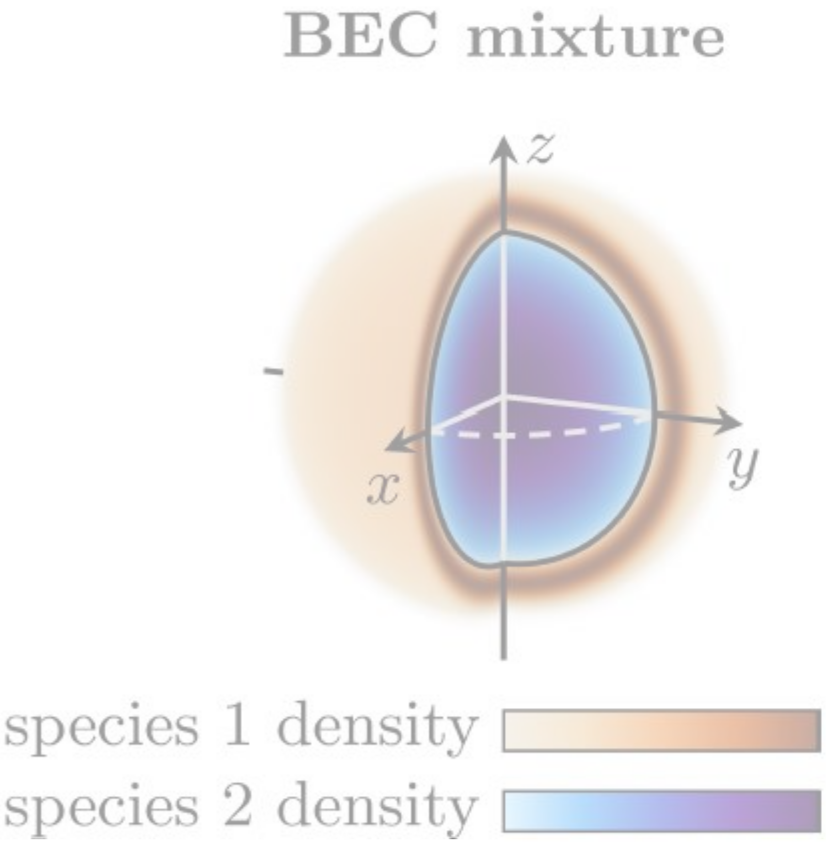

Dr. Elliot Bentine


Prof. Chris Foot

- Previous members:
  - Ben Sheard
  - Ben Sherlock
  - Marcus Gildemeister
  - Edward Owen
  - Tiffany Harte
  - Ben Yuen
  - Kathrin Luksch
  - Adam Barker

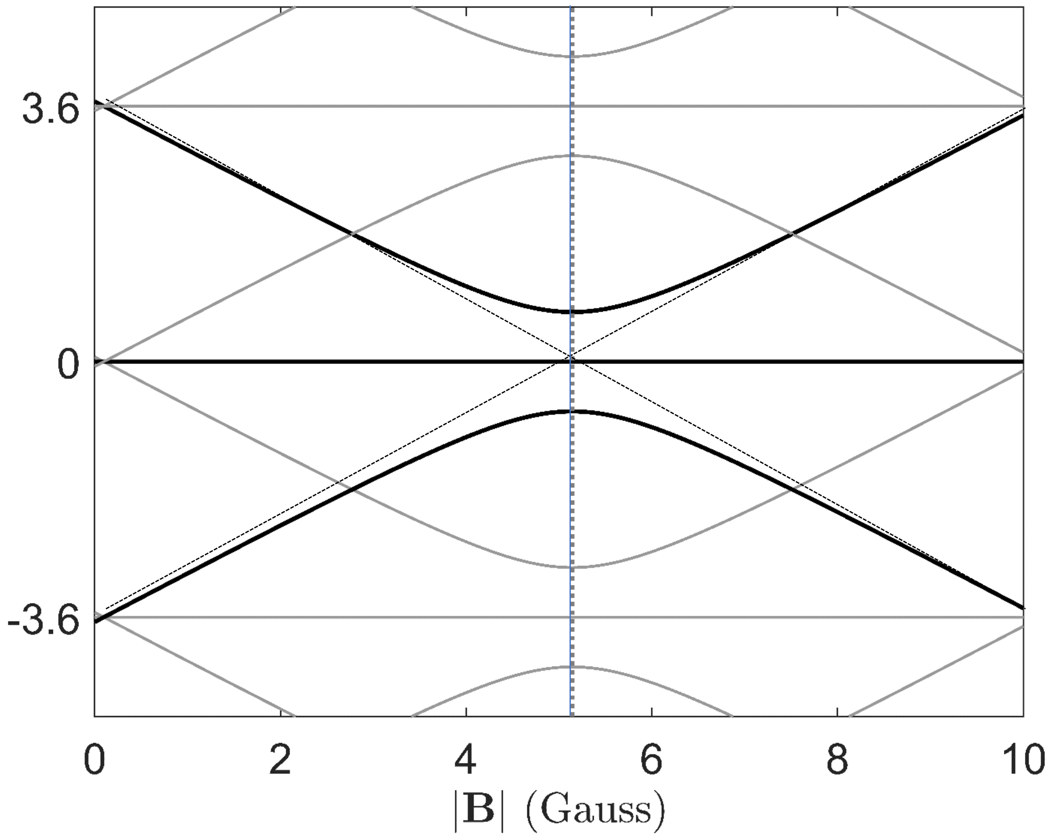
Two types of bubbles:



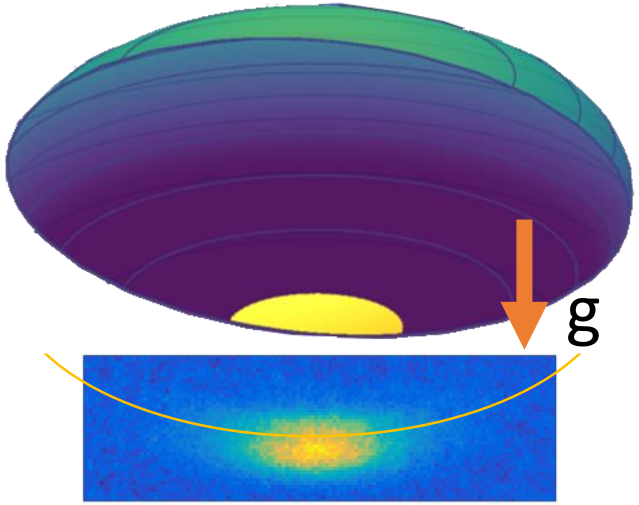


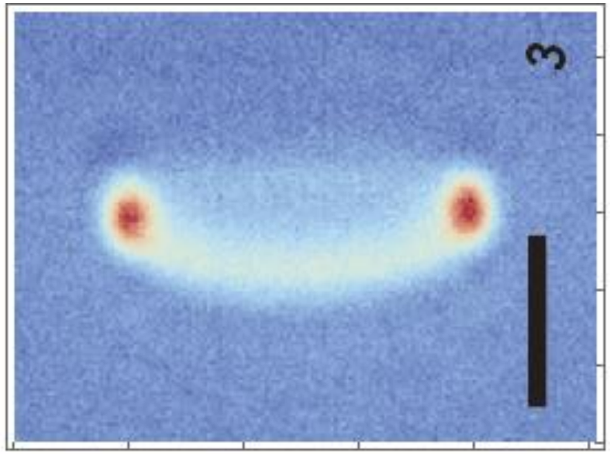
RF dressed potentials

Shown for Rubidium, F=1



$$\tilde{N} = N_{rf} - m_F$$



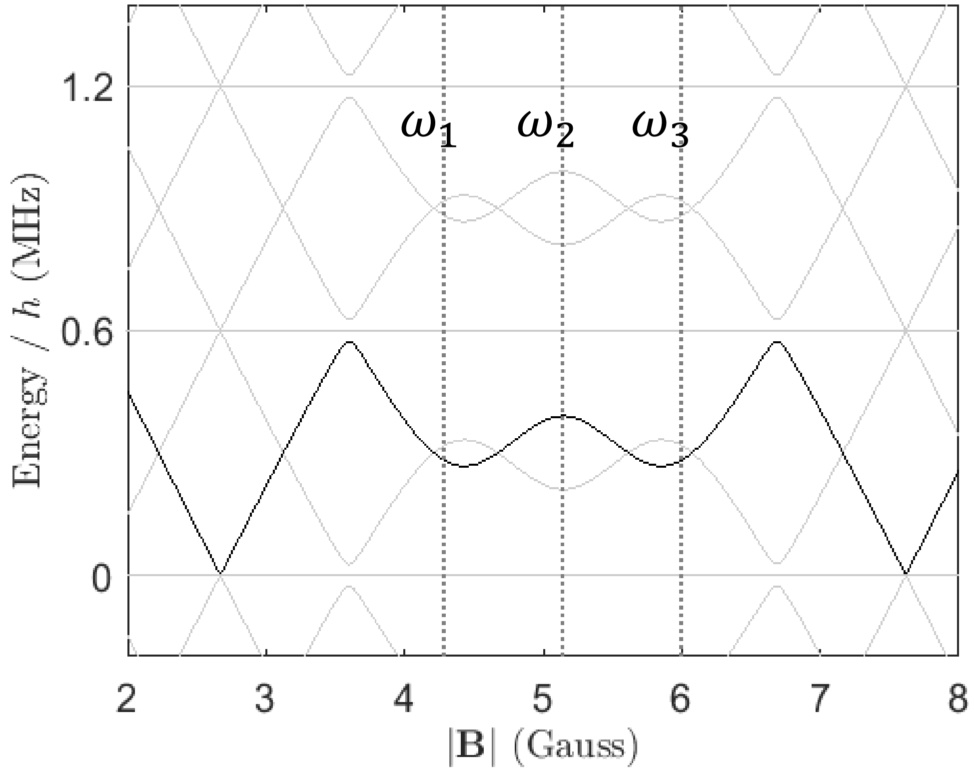


Carollo et al, arXiv:2108.05880

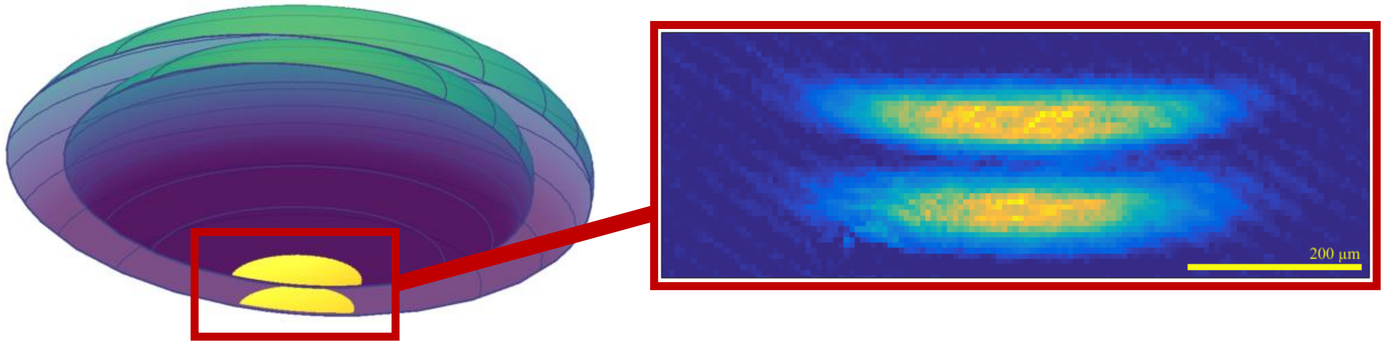
- Bubble parameters:
  - Location of resonance → Bubble size (ω, B')
  - Trap frequency → Bubble thickness (Ω, B')
- Species-selective when Landé g-factors differ (85/87, F=1/F=2)
- Polarisation of the RF field → tip and tilt, swill
- Dynamic control through the RF field

A multiple-RF double shell

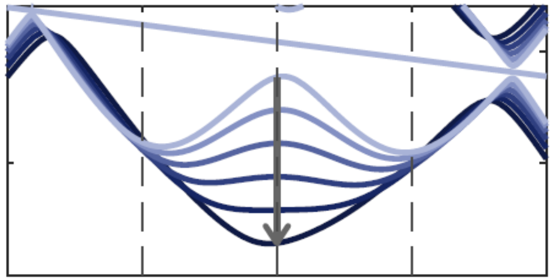
- Three applied frequencies creates three large avoided crossings and a ‘double well’ potential.

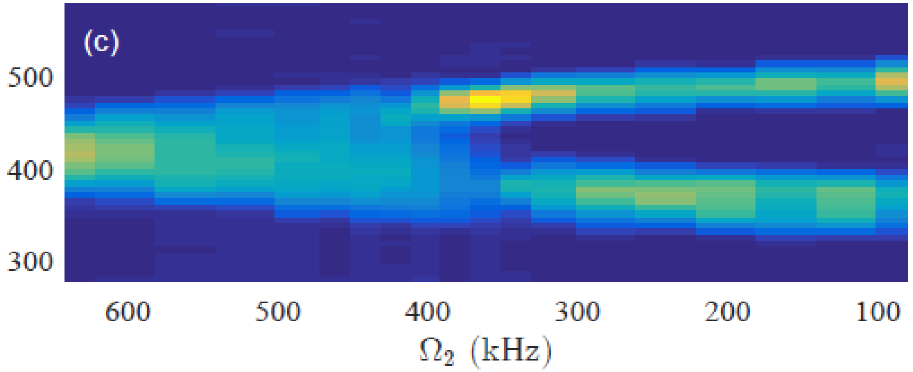


Here: 3.0 MHz, 3.6 MHz, 4.2 MHz ($\Delta\omega = 0.6$ MHz)



- Potential can be sculpted by modifying properties of each frequency component *(below: change amplitude of ‘barrier’ rf)*

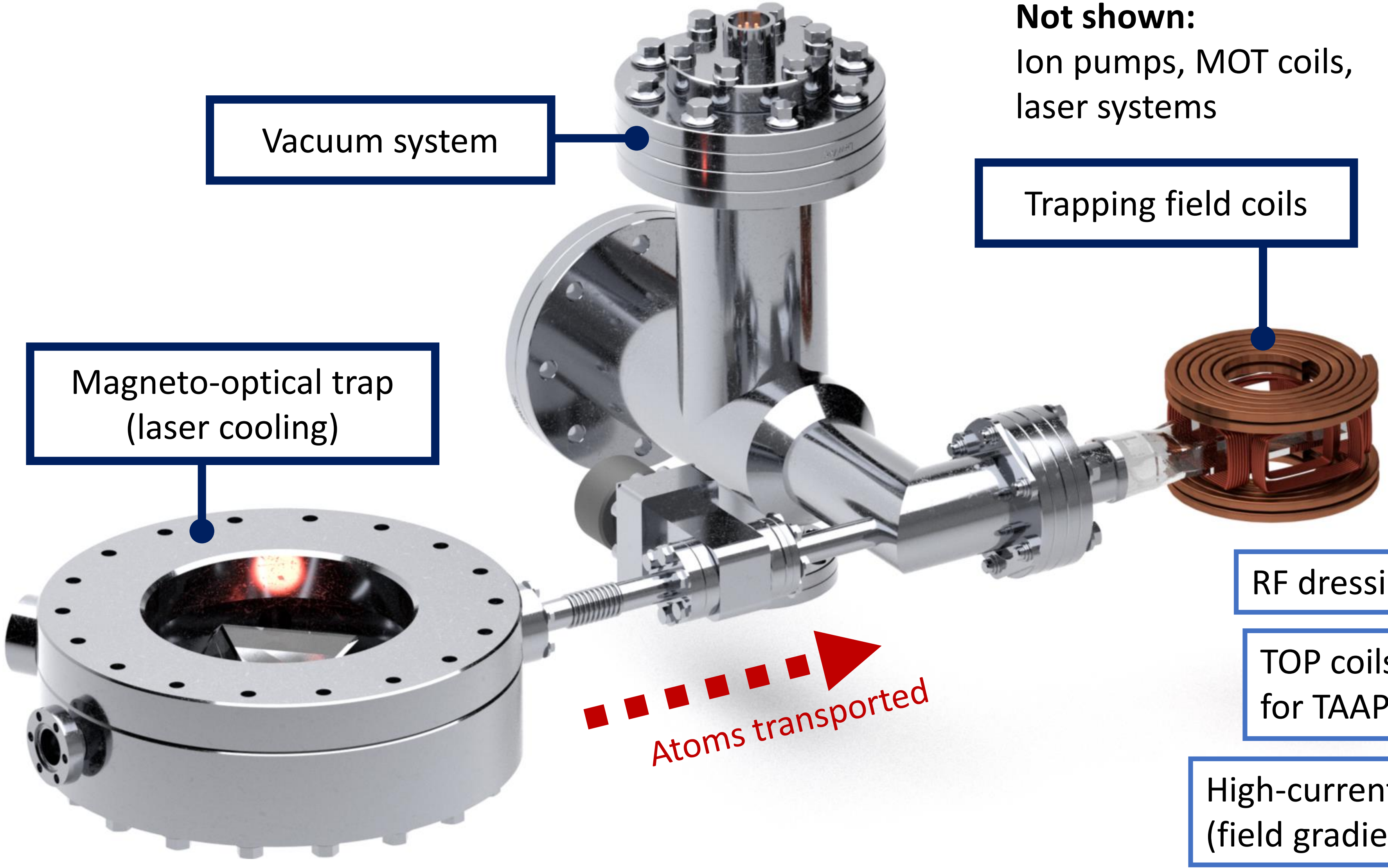




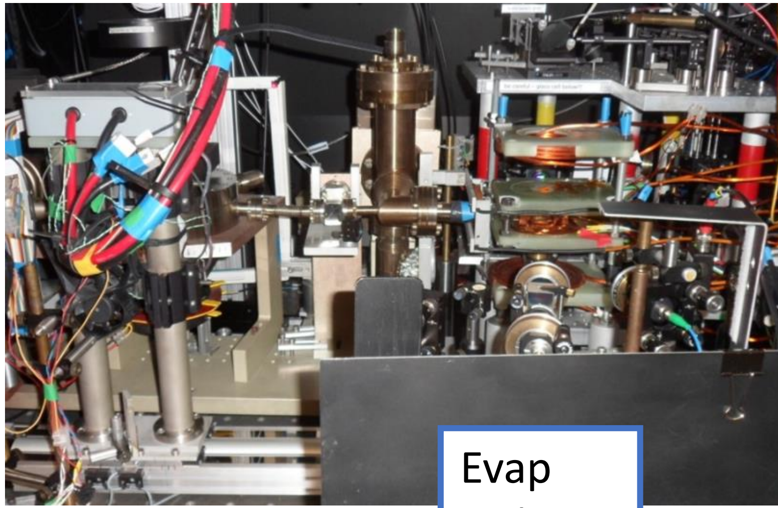
Harte et al, 2018 *arXiv:1706.01491*

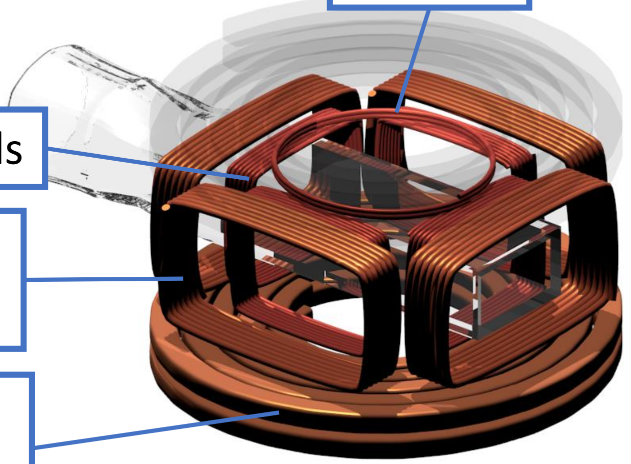
The RF-dressed apparatus

Not shown:
Ion pumps, MOT coils, laser systems



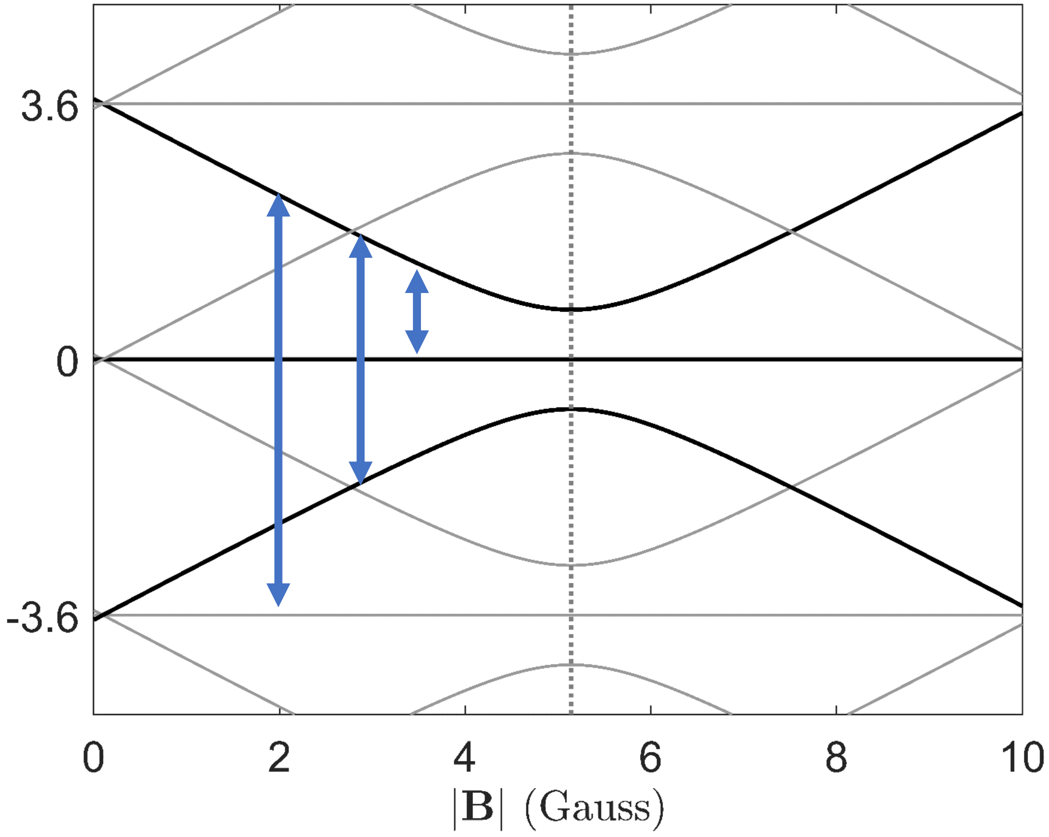
Much messier in reality!





RF spectroscopy in the SRF potential

- A second weak RF field can be used to perform evap Easwaran et al, 2010 arXiv:1002.2620
- **RF spectroscopy:** Apply a second weak probe rf and measure atom loss.



Many possible transitions, even for single dressing RF!

Luksch et al, NJP 2019

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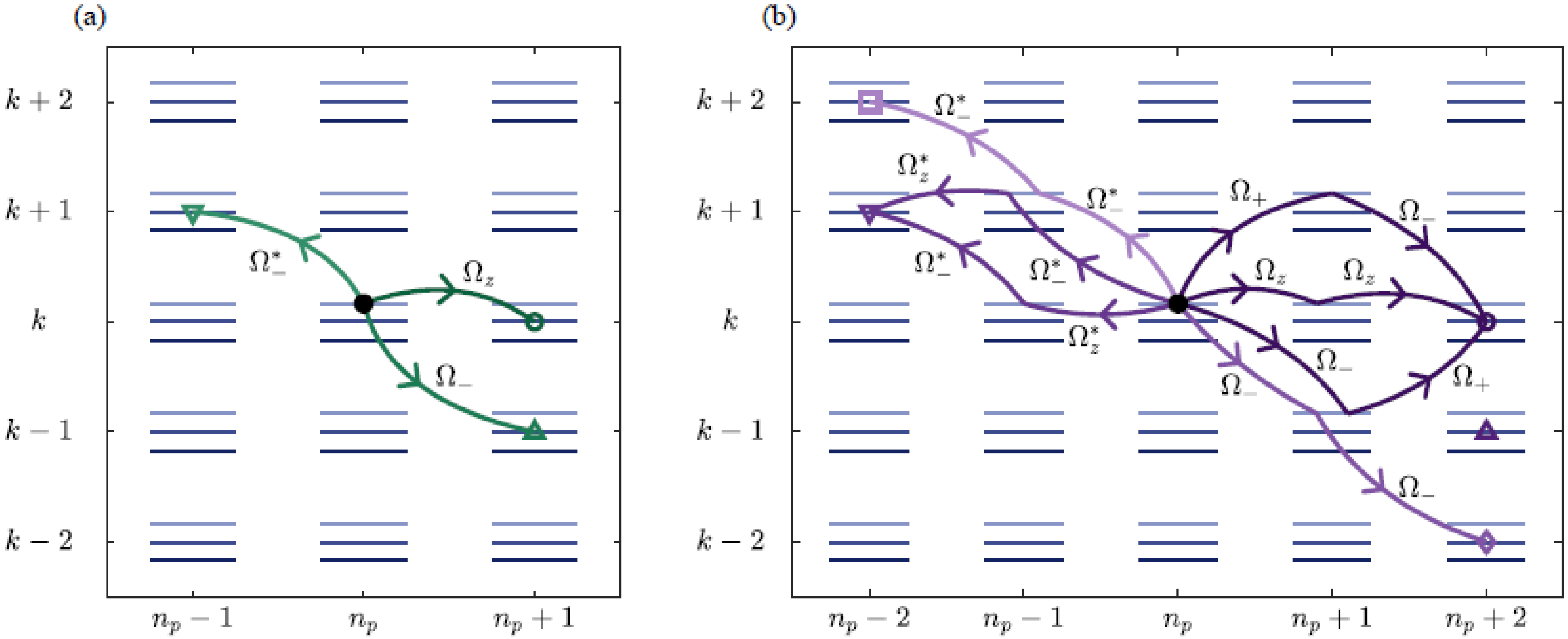

Luksch et al, NJP 2019

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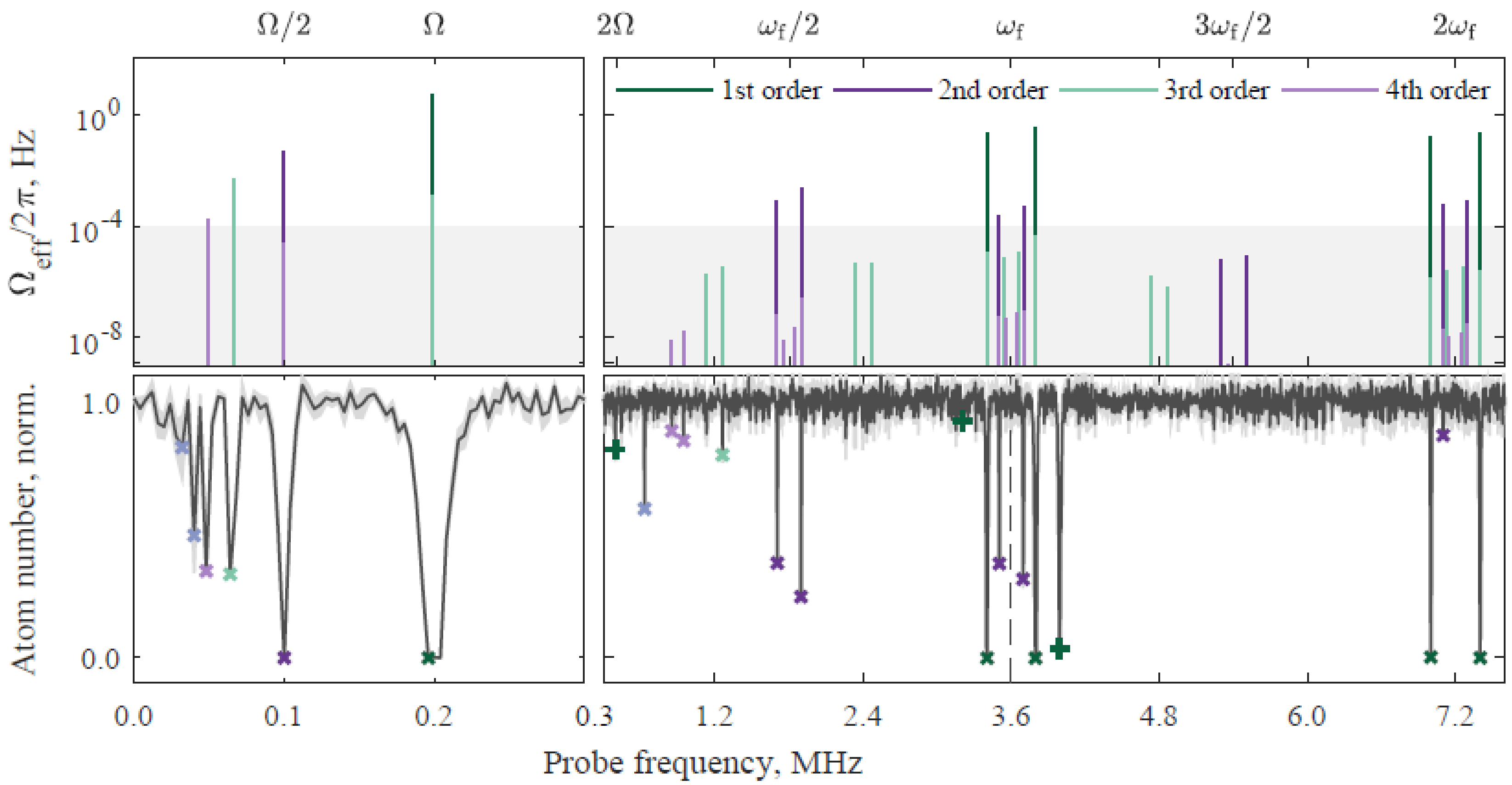
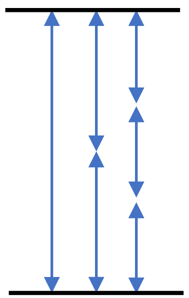
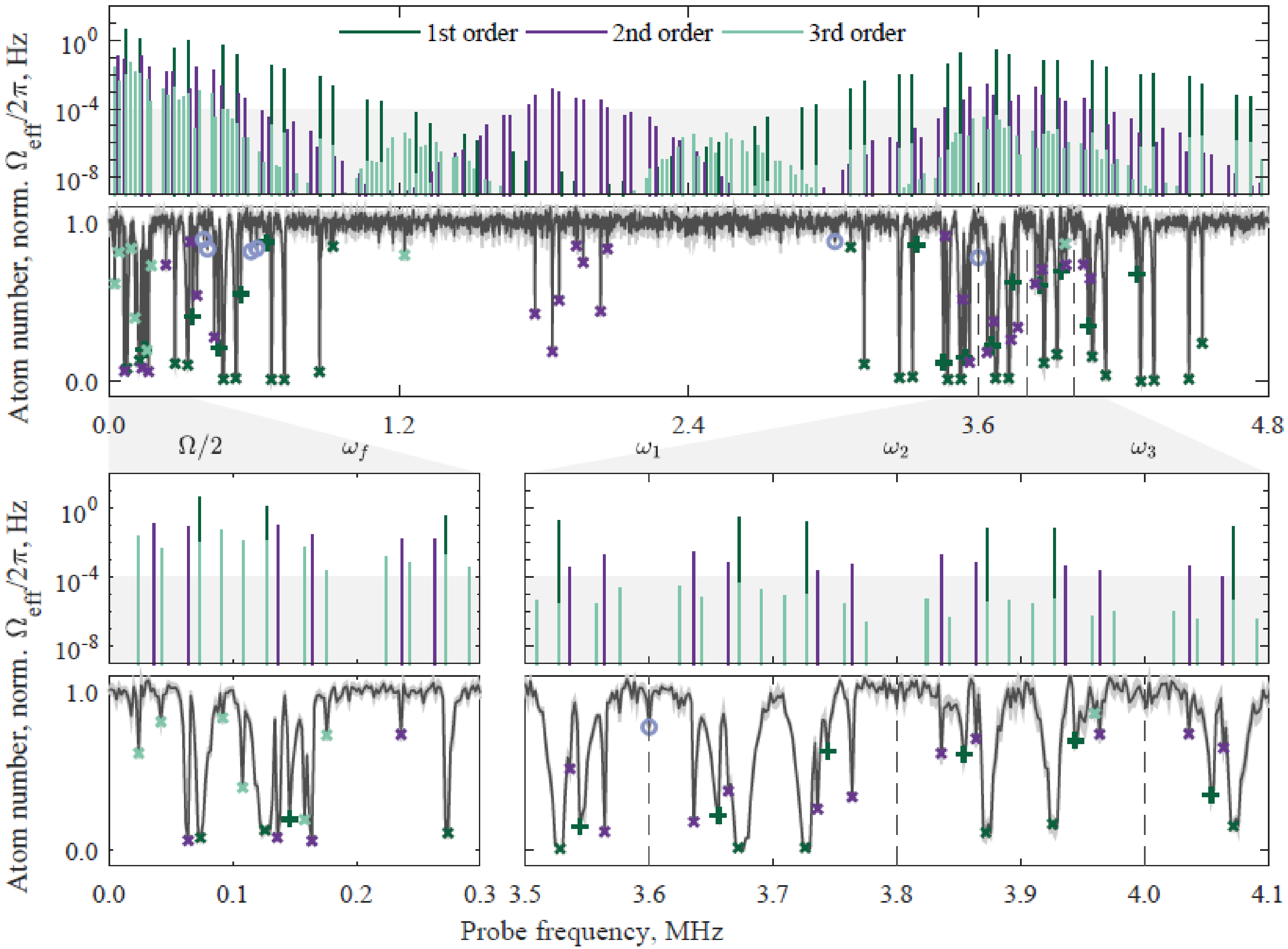


Single RF, circ polarised

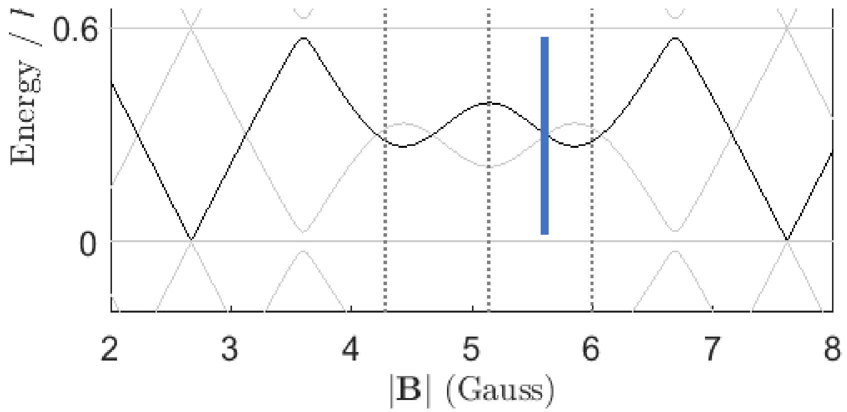


Luksch et al, NJP 2019

RF spectroscopy in the MRF potential



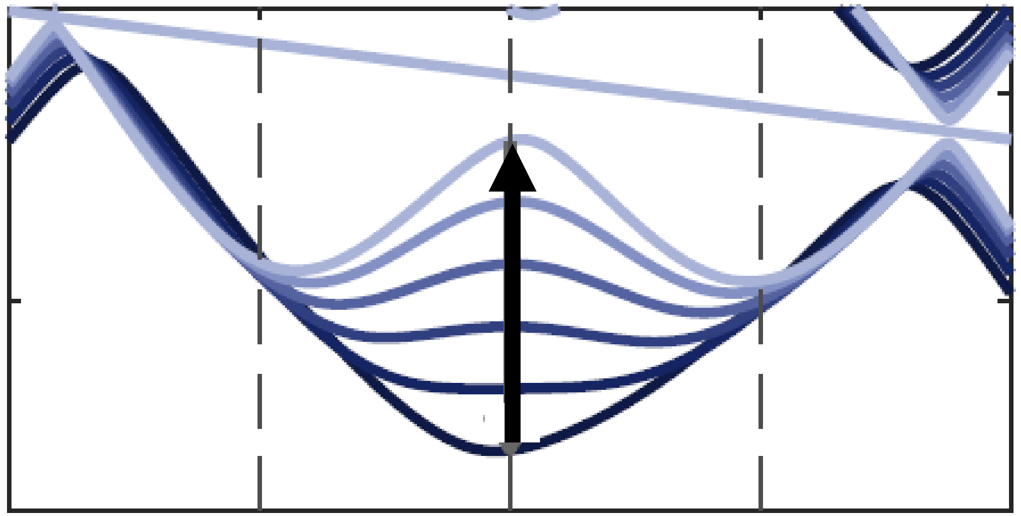
- Great number of transitions allowed for MRF dressing.
- Requires extremely clean RF spectrum to prevent atom loss.

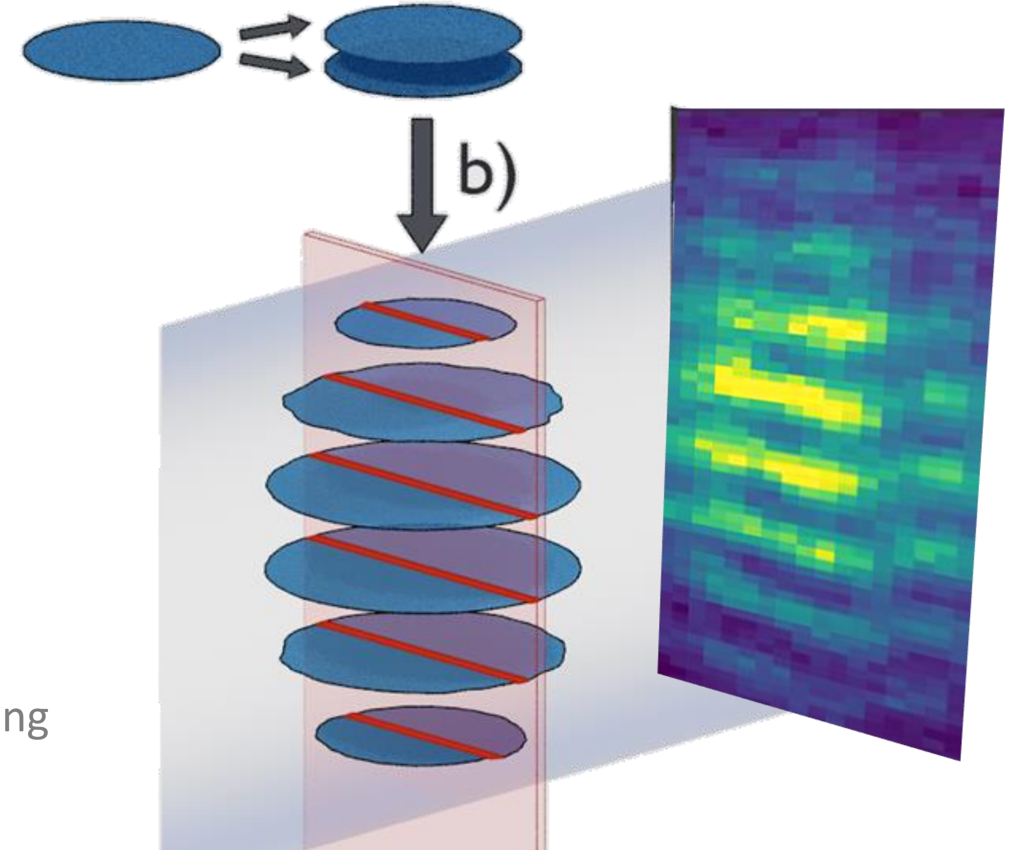


Luksch et al, NJP 2019

Matter-wave interference in the MRF potential

- Start with a condensed 2D cloud; lift barrier to split.
- Drop clouds; expand and overlap during freefall, producing fringes.

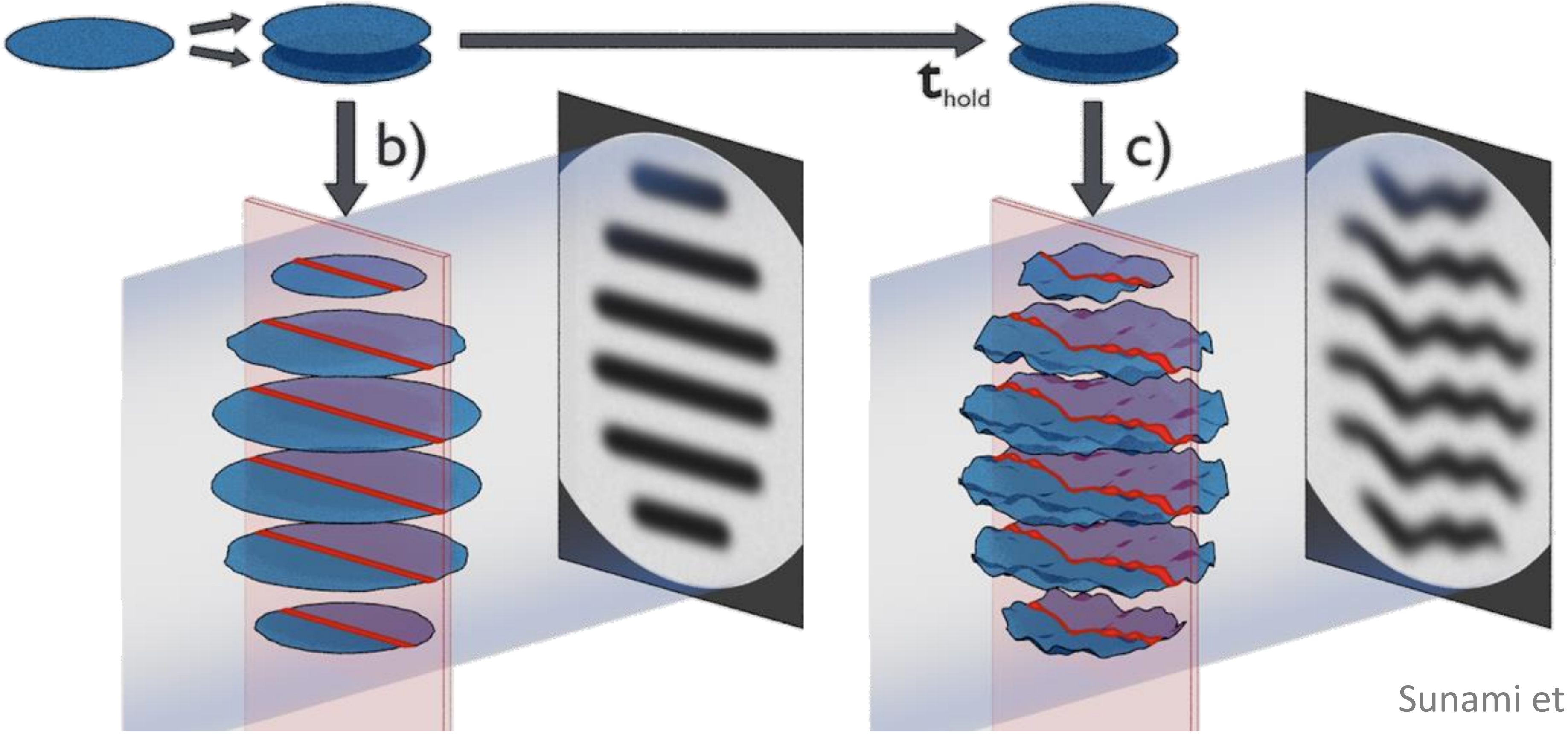




(Requires high field gradient and low Rabi frequencies of the dressing RF to get 2D confinement – as in Romain's talk! $\omega_z \sim 1\ \mathrm{kHz}$

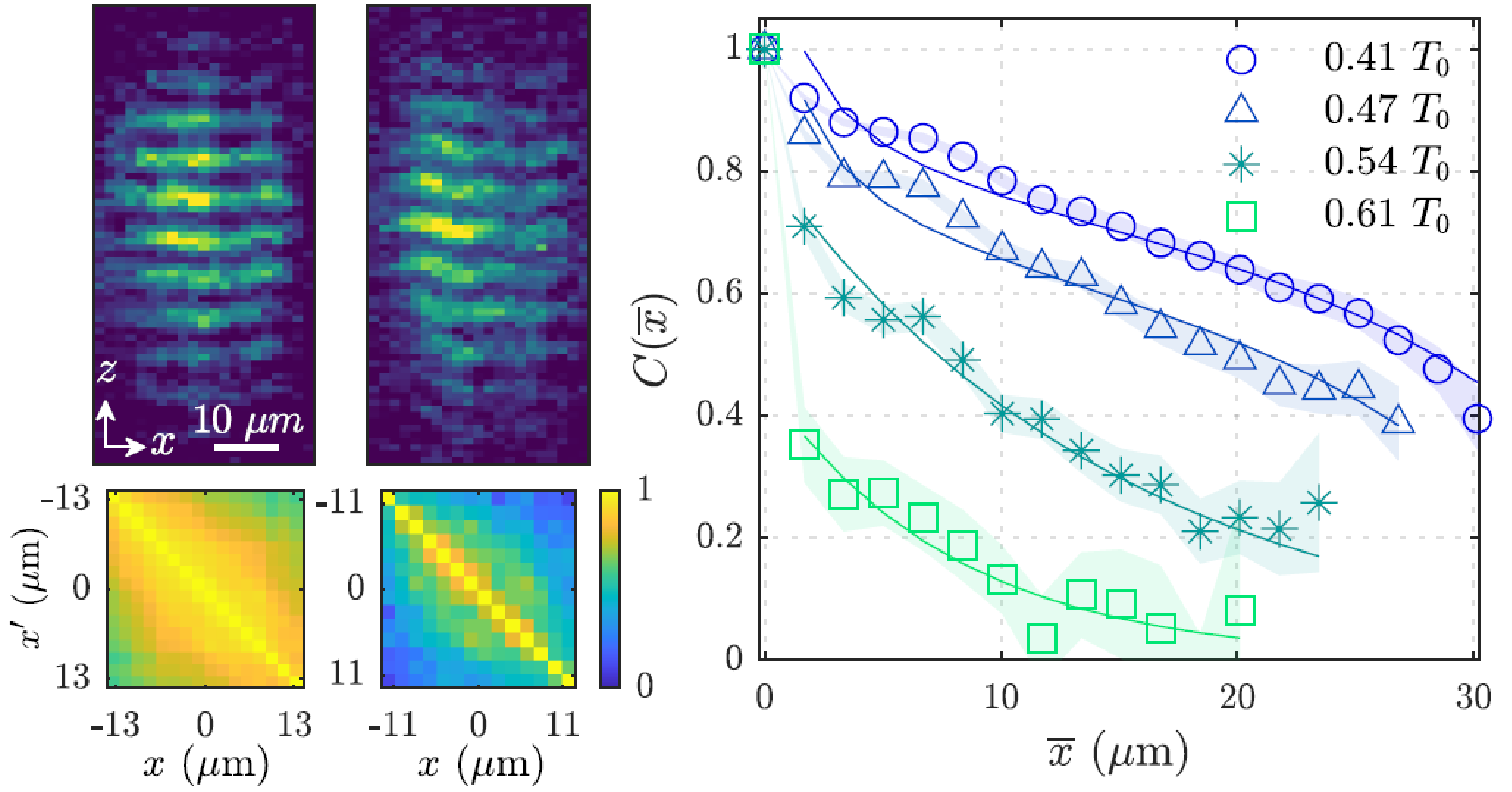
Matter-wave interference in the MRF potential

- Splitting the 2D cloud produces two daughter clouds of lower density.
- The daughter clouds **may** be quenched through the Berezinskii-Kosterlitz-Thouless transition
- Fringes provide a way to measure phase fluctuations in the 2D system.



Sunami et al (2021), arXiv:2108.08840

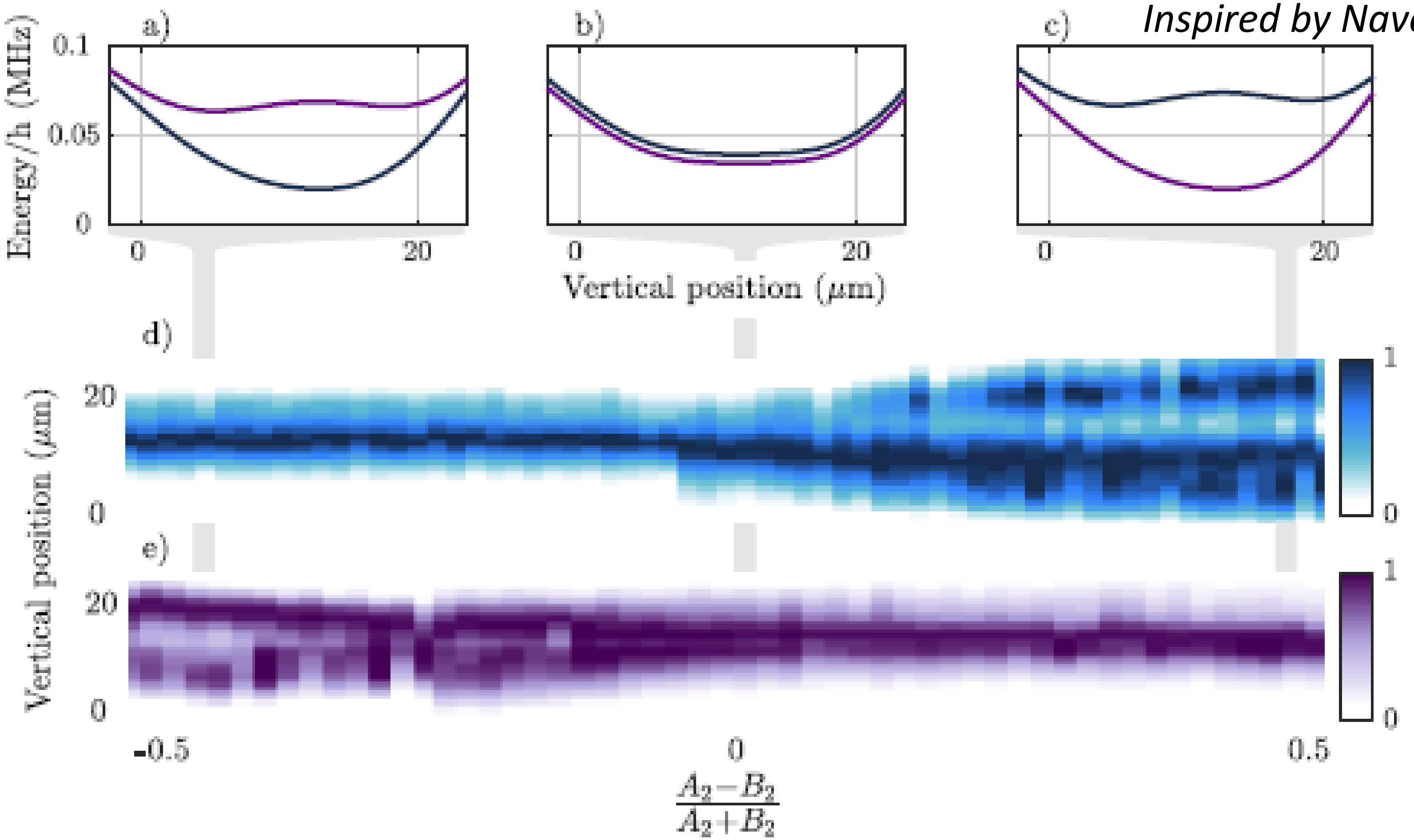
Matter-wave interference in the MRF potential



Sunami et al (2021), arXiv:2108.08840

Species-selective double well

Inspired by Navez 2016 arXiv:1604.01212



F=1

F=2

$$\mathbf{B}_{\mathrm{RF}} = \sum_{i=1}^{N} B_i \Big(\cos(\omega_i t)\,\hat{\mathbf{e}}_x - \sin(\omega_i t)\,\hat{\mathbf{e}}_y \Big) + A_i \Big(\cos(\omega_i t)\,\hat{\mathbf{e}}_x + \sin(\omega_i t)\,\hat{\mathbf{e}}_y \Big)$$

Barker et al, 2020 arXiv:2003.05925

Software

AtomECS

Software suite for simulating cold atom experiments.

arXiv | Cornell University

Condensed Matter > Quantum Gases

arXiv:2105.06447 (cond-mat)

[Submitted on 13 May 2021]

AtomECS: Simulate laser cooling and magneto-optical traps

X. Chen, M. Zeuner, U. Schneider, C. J. Foot, T. L. Harte, E. Bentine

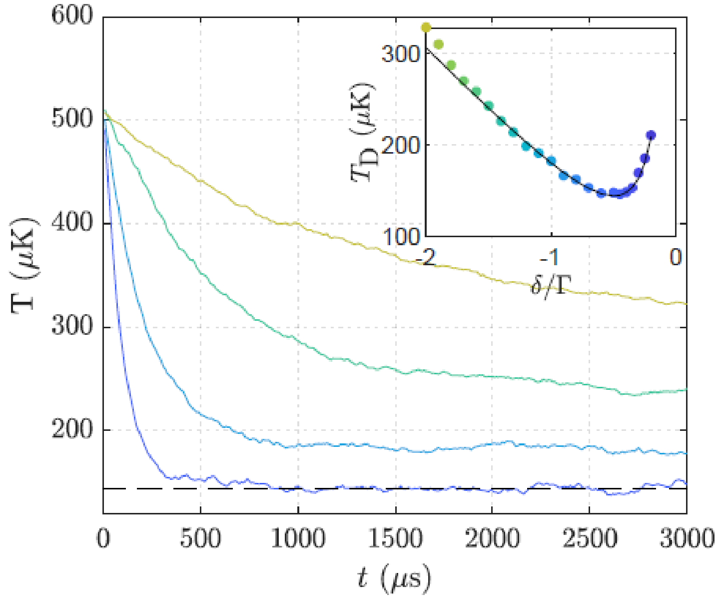
- Started as MOT simulation code but now has many features.

- **Scattering forces** on atoms in near-resonant optical fields.
  - Multi-beam rate equation approach.
  - Respects Doppler limit, to some extent recoil limit.
  - More detail given in paper.
- **Magnetic** and **dipole-force** traps.
- **S-wave collisions** between particles.

- Written in rust using the Entity-Component-System (ECS) pattern.
- **Data-oriented** architecture gives great parallel performance.
- **Unit tests**, **integration tests** and **continuous integration**
  - Automated testing of each module in the program, and all modules together. Currently >50 different tests.
  - Make changes without fear of breaking functionality!

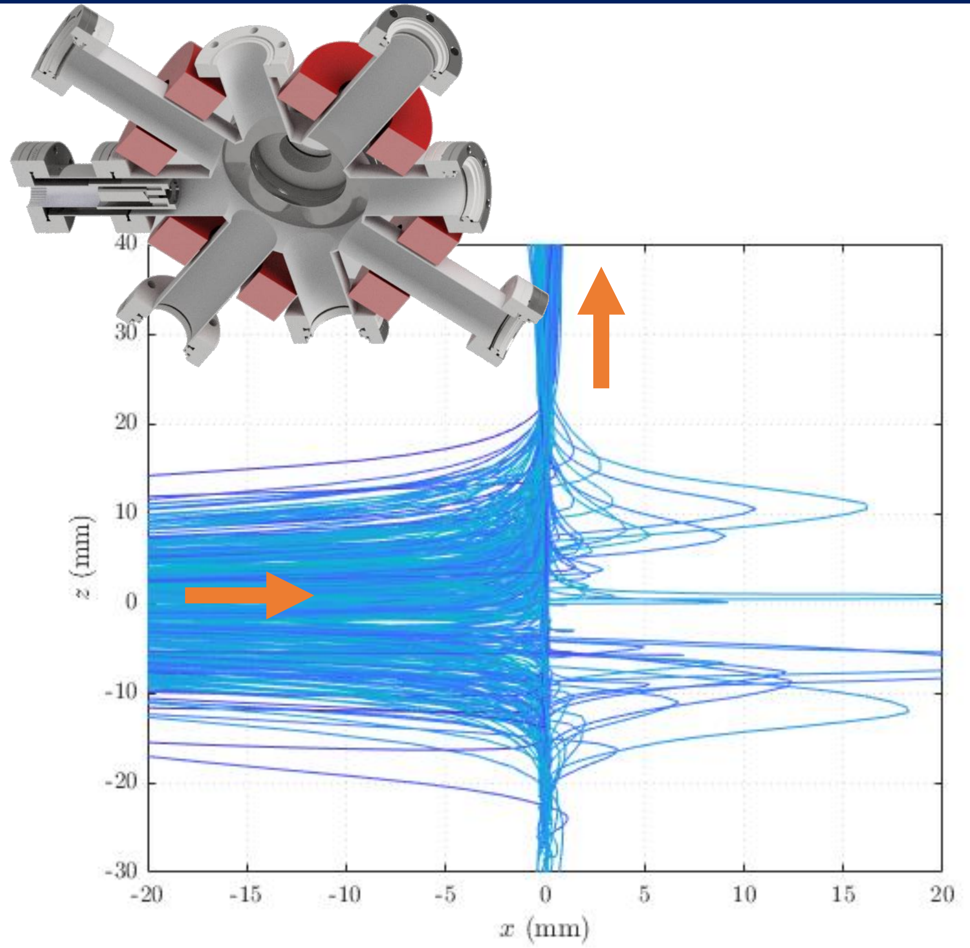
https://github.com/TeamAtomECS/AtomECS

Developers now also include:
Cambridge: *Xintong Su, Kimberly Tkalcec, Brian Bostwick*
Oxford: *Abigail Coughlan, David Garrick*



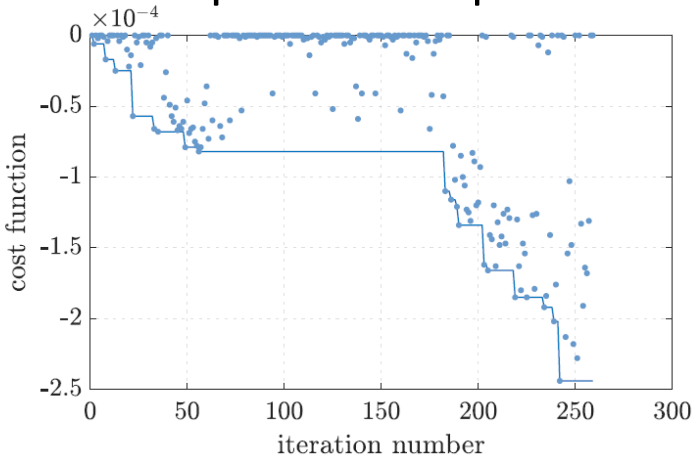
Above: Simulations of Doppler limit in AtomECS for a 3D MOT. **Inset:** Good agreement between theoretical limit over a range of beam detunings.

AtomECS: Example simulations

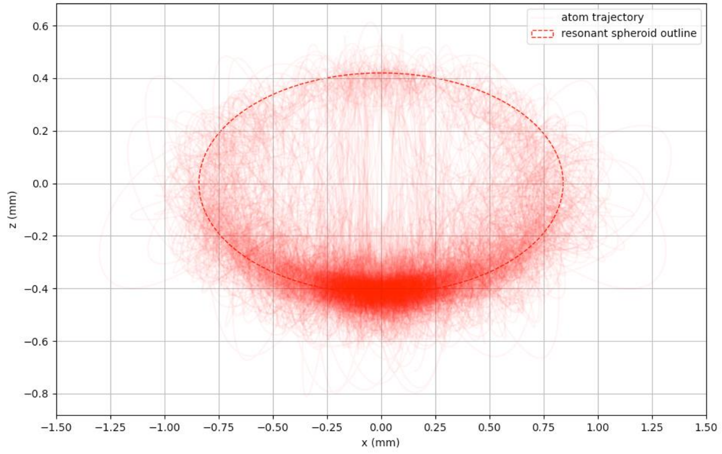


Simulating a 2D MOT source
Atoms come from an oven on the left, captured by MOT beams; laser-cooled flux ejected to next chamber.

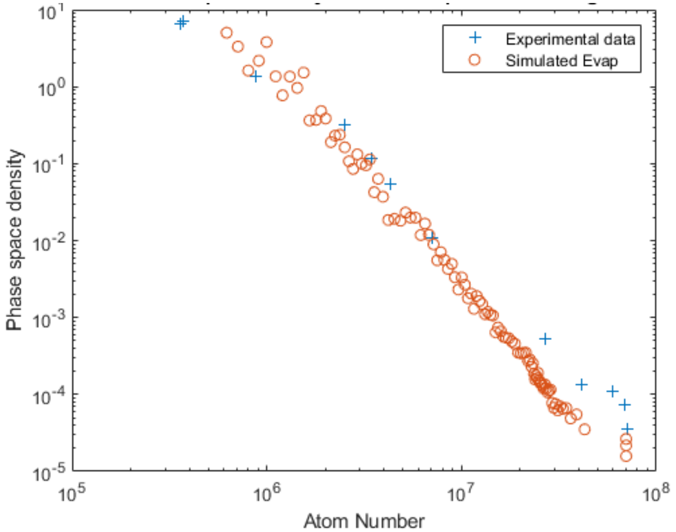
Optimisation of experiments



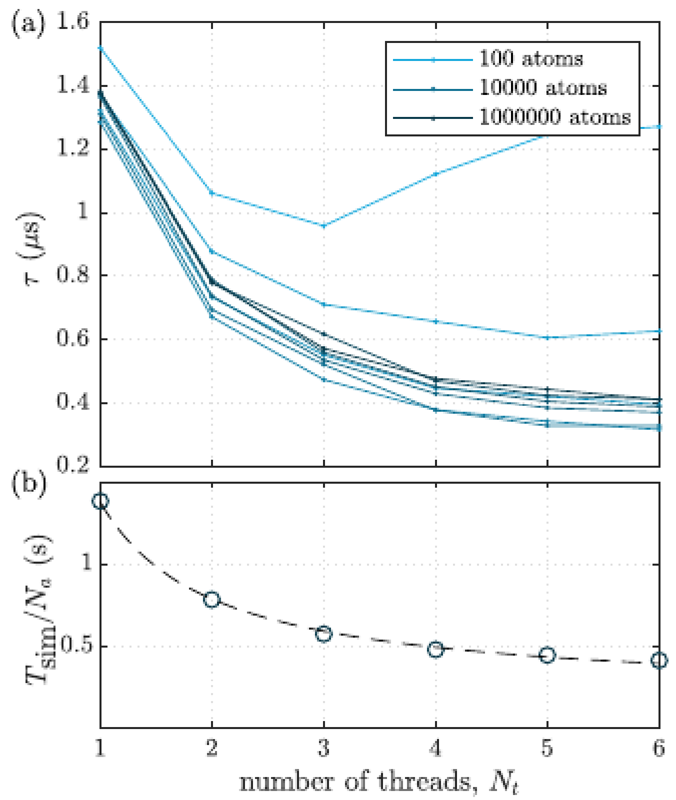
Atoms trapped in an RF-dressed potential
(Josh Greensmith)



Collisions/Evaporative cooling

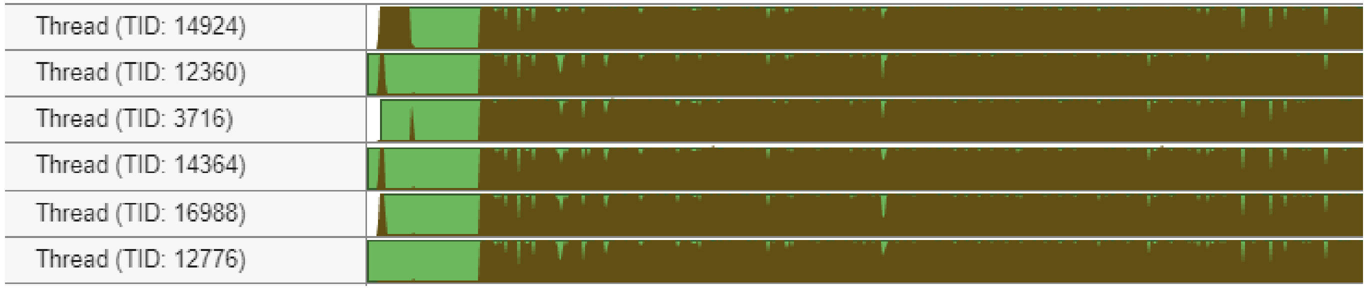


AtomECS: performance



- (a) shows the wall time per step per atom for a MOT simulation.
  - For >1000 atoms the parallel execution becomes effective.
- (b) shows fit to Amdahl's law for 10^6 atoms. Gives ~85% of program parallelised.
- Benchmarks:
  - *AION 2D MOT, capture from an oven:* 10^6 atoms initially ejected, 15ms of motion, 200 atoms captured. 4s to simulate.
  - *Evap,magnetic trap*: $5x10^3$ pseudo-particles simulated, s-wave collisions, 2s of motion. Takes 2.5s to simulate.

Right: Load balancing of AtomECS over multiple CPU cores



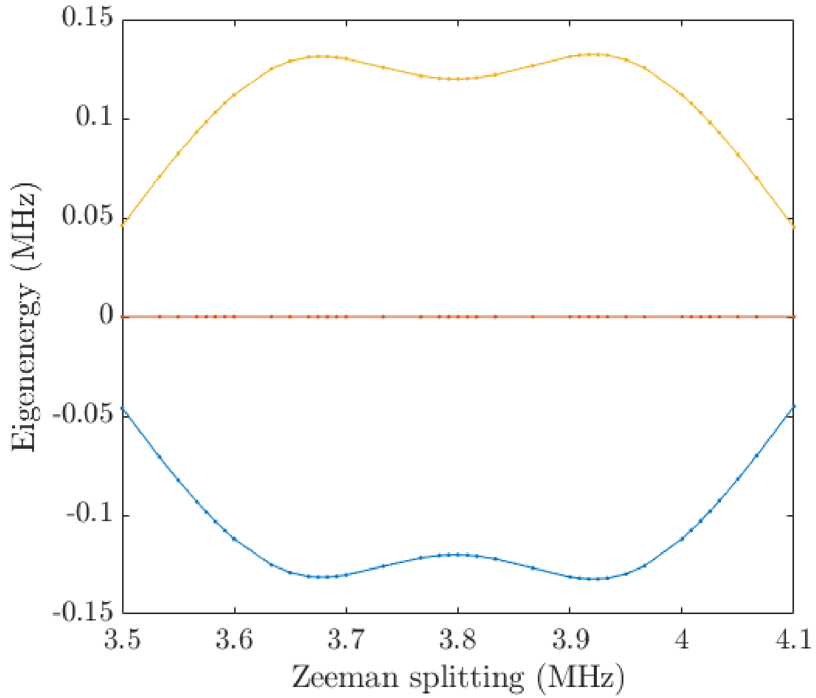
Calculator for RF-dressed Adiabatic Potentials

- Makes it easy to calculate RF-dressed potentials.
- Calculates dressed eigenenergies by integrating TDSE and then applying Floquet theory (a time analog of Bloch's theorem).
- Works for multiple frequencies, arbitrary polarisation, multiple species

```
RF  = [ 3.6 3.8 4.0 ]; % MHz
amp = [ 0.16 0.2 0.16 ] / 0.7; % Gauss

ap = AP.Calculator()
        .LinearPolarised(RF, amp)
        .OfSpecies('species', 87, 'F', 1);
ap.PY = pi/2; ap.BY = ap.BX * 0.2;

sampler = AP.Sampler.LineSampler(ap);
sampler.StartB = linspace(3.5, 4.1, 10); %starting fields
sampler.Sample();
```



https://github.com/ElliotB256/CRFAP

Thanks for listening!

- RF-dressed experiment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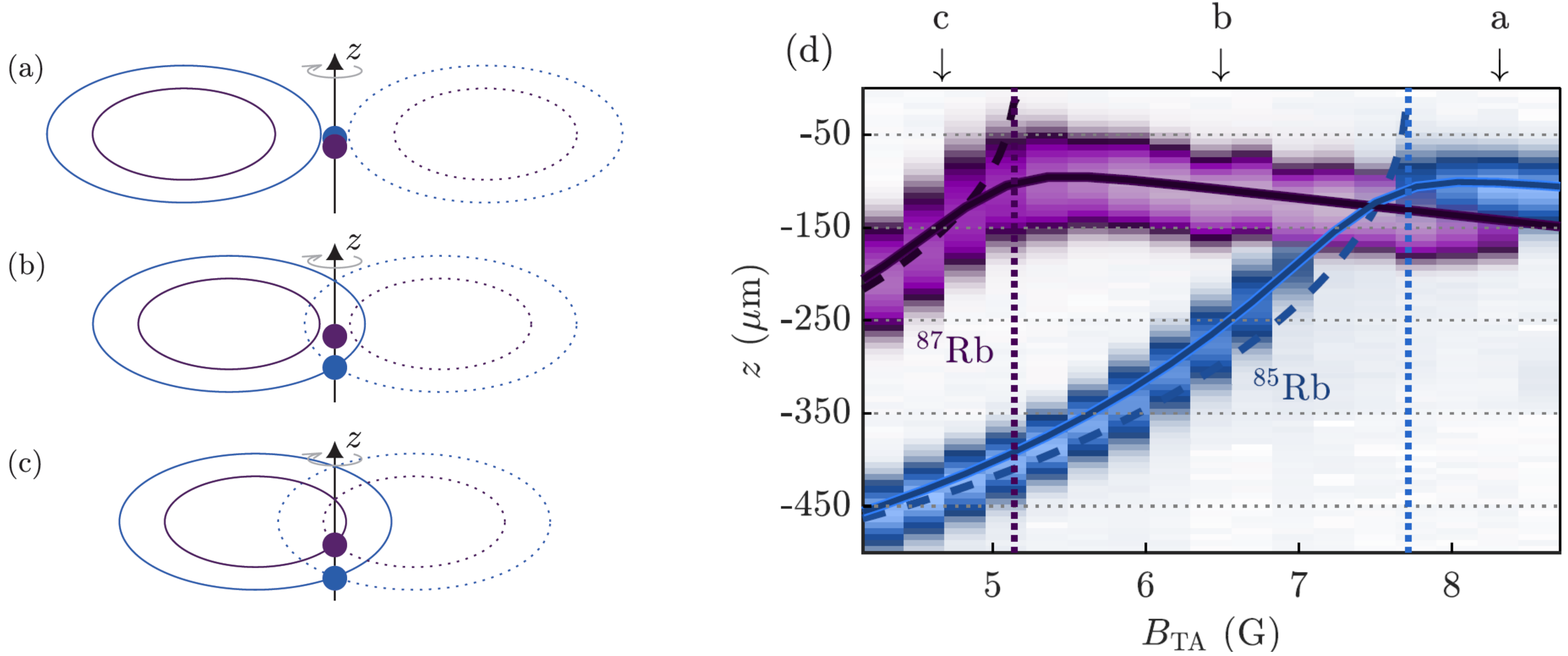
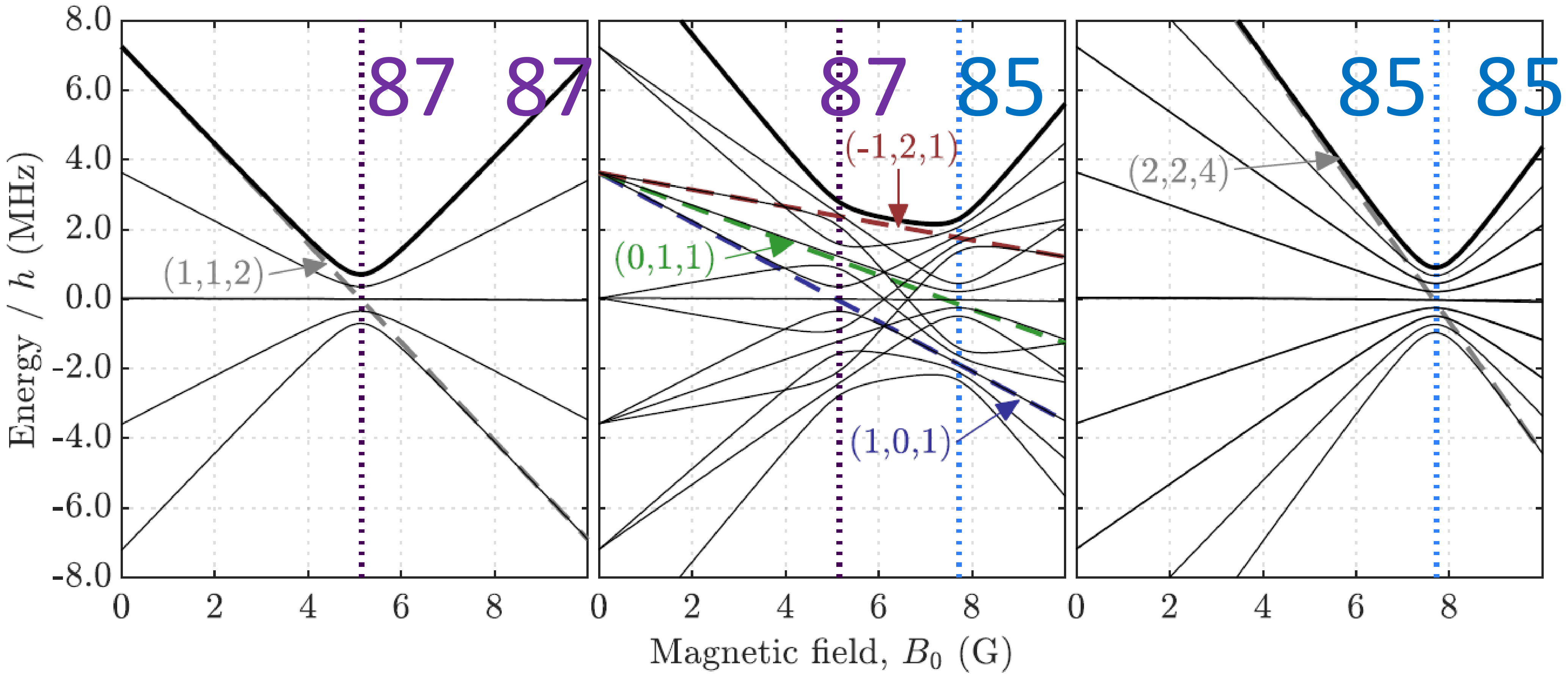
Species-selective trapping (Rb 85-87)

- Species-selective trapping possible when the Landé g-factors differ.



RF dressed collisions

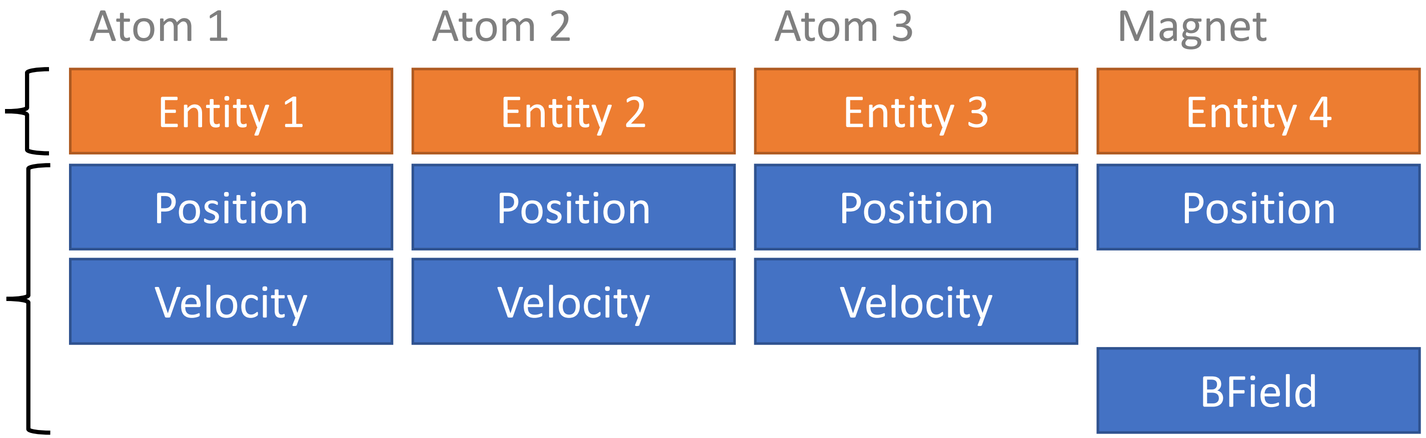


Entity-Component-System (ECS) pattern

The ECS bit of AtomECS

Each *thing* is an **entity.**

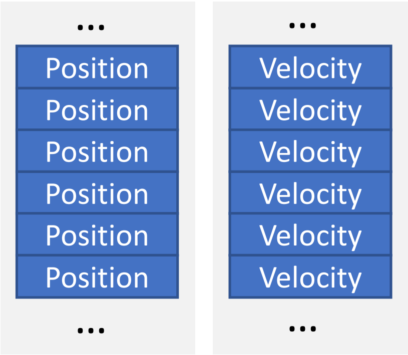
Components describe the entities.



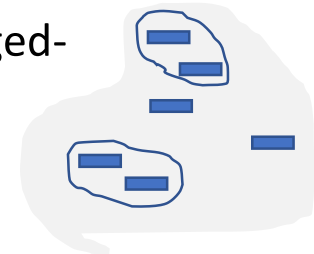
Systems implement program functionality by operating on collections of entities and components

Advantages of the ECS Pattern

1. Produces a **flat, contiguous** program memory structure – *really* fast for getting memory into processor.



Versus 'heap' in managed-memory applications



2. Easy **parallelisation**! Systems are explicit about the components they read and write, and so solving dependency is easy.

UpdatePositionSystem

Write Access: Position

Read Access: Velocity

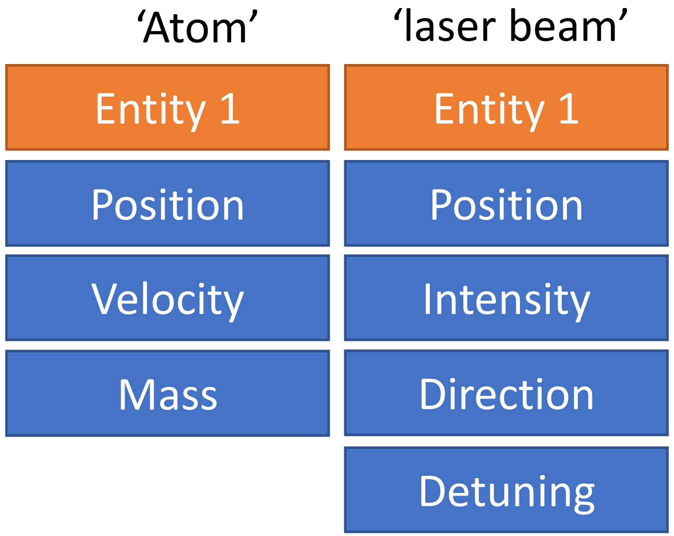
CalculateDopplerShiftSystem

Write Access: DopplerShift

Read Access: Velocity

→ *Trivial to run simultaneously!*

3. **Behaviour by composition** avoids the *behaviour by inheritance* antipattern. Flexible program structure.



4. Small systems implement very specific features – **easy to test**!