ANR, FIRST-TF, DIM Nano'K, DIM Sirteq (IFRAF)

Shelving spectroscopy of the Sr intercombination line

Adiabatic spin-dependent momentum transfer in a degenerate Sr Fermi gas

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Phlam – 21 January 2020

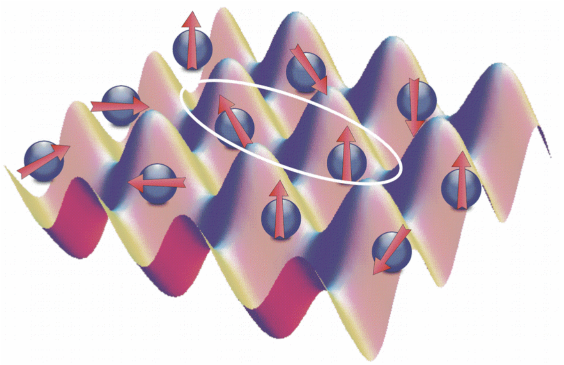
The strontium project at LPL

Implementing quantum magnetism models with ultracold atoms

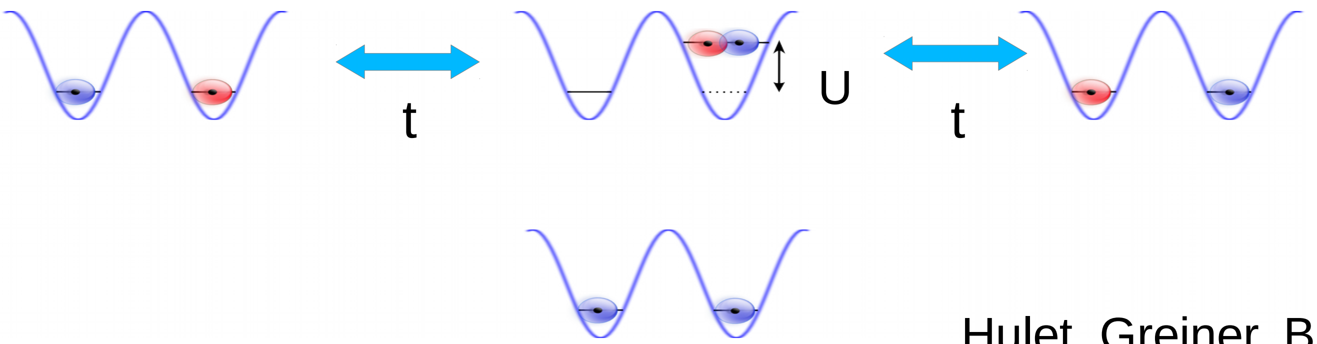
Using ground state atoms, Rydberg state atoms, molecules, ...

Varying the spin-dependence, interaction range, anisotropy...

at LPL : Chromium (long-range anisotropic interactions)
and Strontium (short-range isotropic interactions)



Relevant to both : antiferromagnetic Heisenberg model from super-exchange in the Mott regime



$$H = -\ J \sum_{<i,j>} \vec{S}_i \cdot \vec{S}_j$$

with $J \approx -4t^2/U$

Hulet, Greiner, Bloch, Zwierlein, Kohl, Esslinger, ...

Heisenberg model of magnetism **(effective spin model)**
Tentative model for strongly correlated materials, and
emergent phenomena such as high-Tc superconductivity

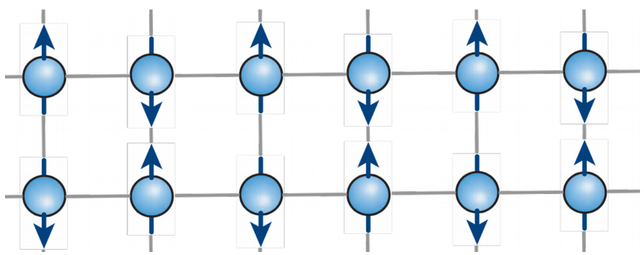
The strontium project at LPL

Fermionic Strontium 87 in optical lattices:
Quantum magnetism beyond spin 1/2 (electron) particles

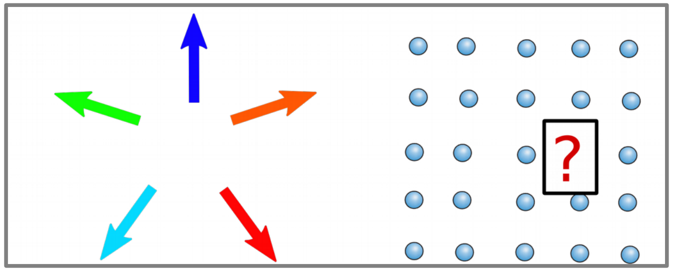
Spin 9/2;   SU(10) symmetry

Exploring magnetism with tunable spin degree of freedom

2 spin states: analogy to spin 1/2 electrons
3 spin states: analogy to quarks with three colours
Up to 10 spin states: ***no equivalent***



2 states: Neel order



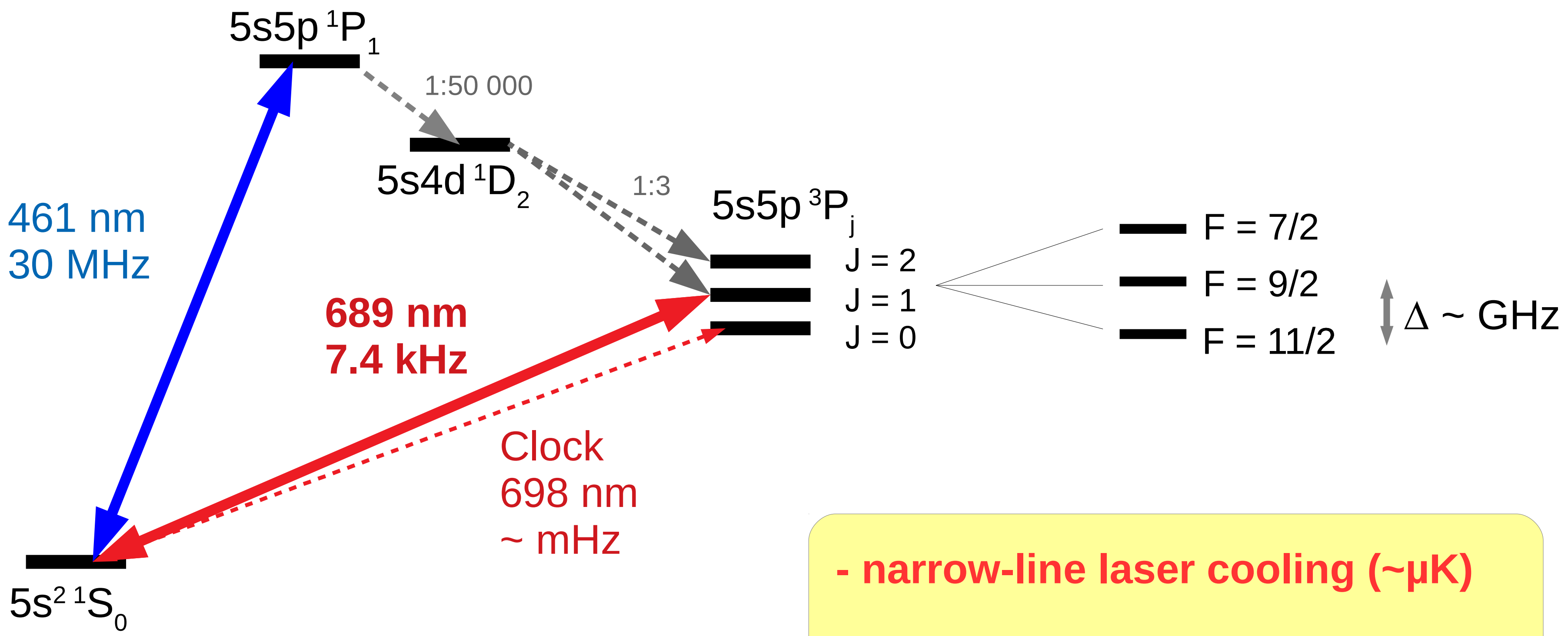
> 5 states : underconstrained magnetism (frustration)

Hermele 2009, PRL **103**, 135301

Narrow atomic transitions:
new control / probe tools
Involving a metrology expertise (clock community)

The strontium project at LPL

Two valence electrons
→ singlet and triplet electronic spin states



^{87}Sr : I = 9/2

- narrow-line laser cooling (~µK)

- hyperfine structure: Δ >> γ
Strong spin-dependent conservative forces

Effective magnetic fields;
site-selective spin control

Outline

1) Shelving spectroscopy of the strontium intercombination line

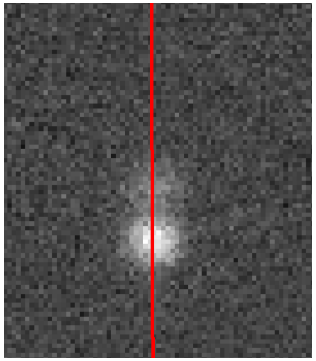
demonstrated on an atomic beam and a hot cell setups

→ applicable to most Sr experiments

ArXiv:1910.11718

2) Birth of the Strontium experiment

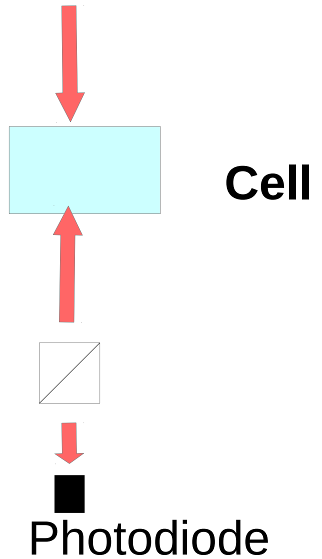
- a degenerate Fermi gas with 10 spin-states
- first experiments of coherent spin manipulation

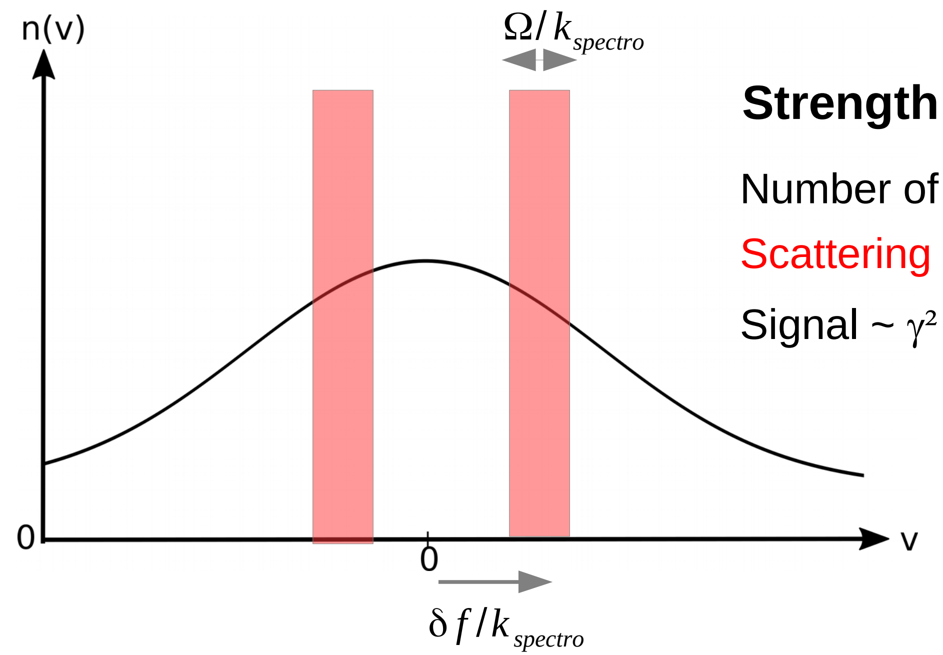


Spin-dependent adiabatic momentum transfer

Shelving spectroscopy of the intercombination line

Saturated absorption spectroscopy
of a narrow line



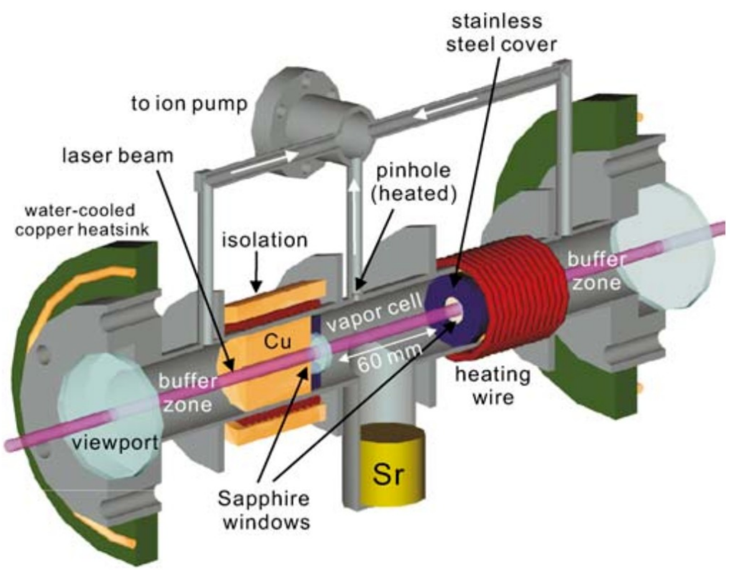


Strength of the signal?

Number of atoms ~ γ or Ω

Scattering rate ~ γ

Signal ~ γ^2



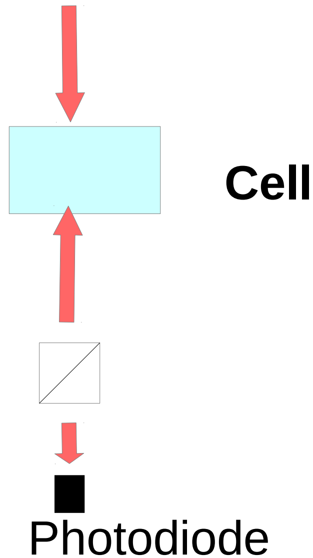
Saturated spectroscopy
on the 7kHz wide Sr line

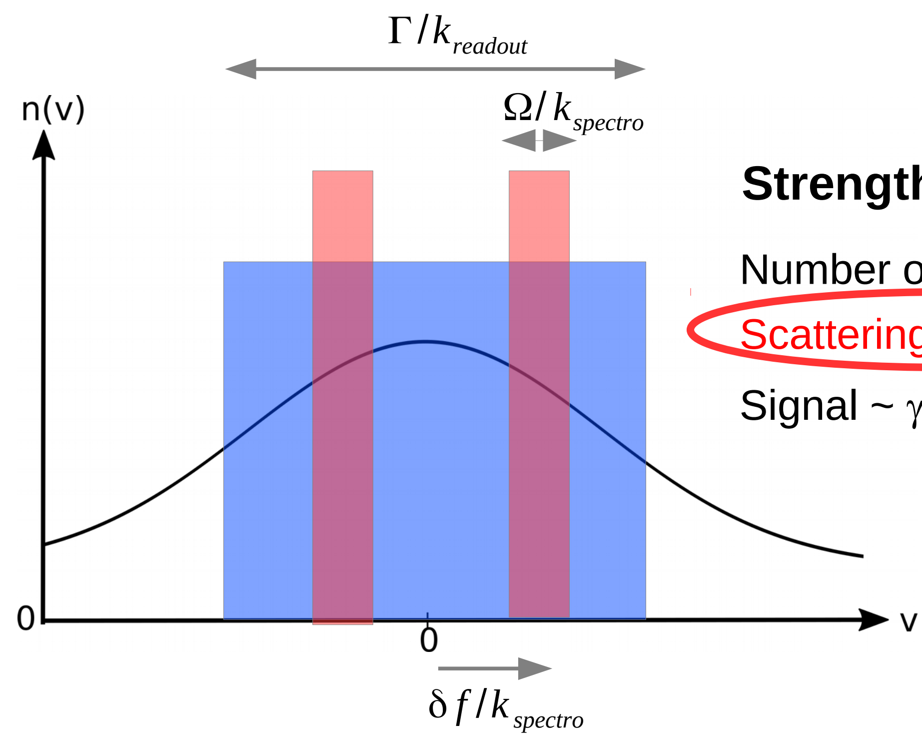
Li 2004, Applied Physics B 78, 315-320: Hot cell

Ferrari 2003, Phys. Rev. Lett. 91, 243002: Atomic beam
10^-11 relative frequency instability after integration

Shelving spectroscopy of the intercombination line

Saturated absorption spectroscopy
of a narrow line





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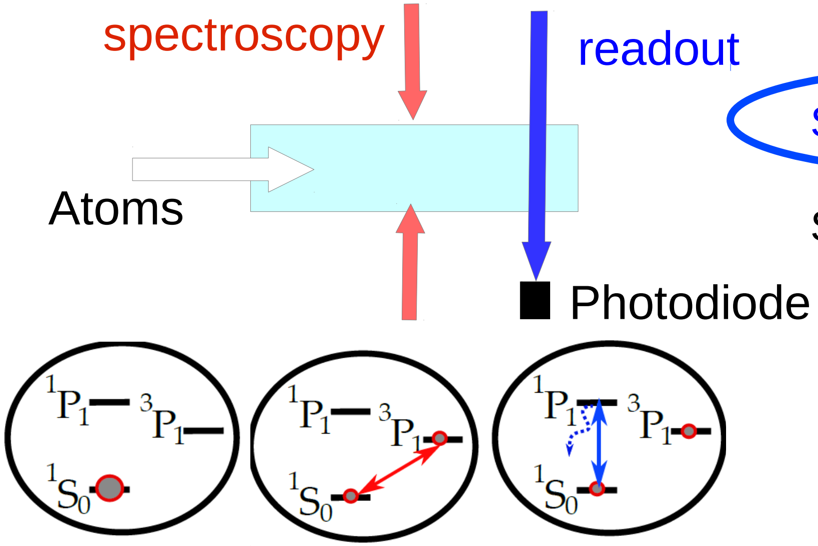
Shelving detection



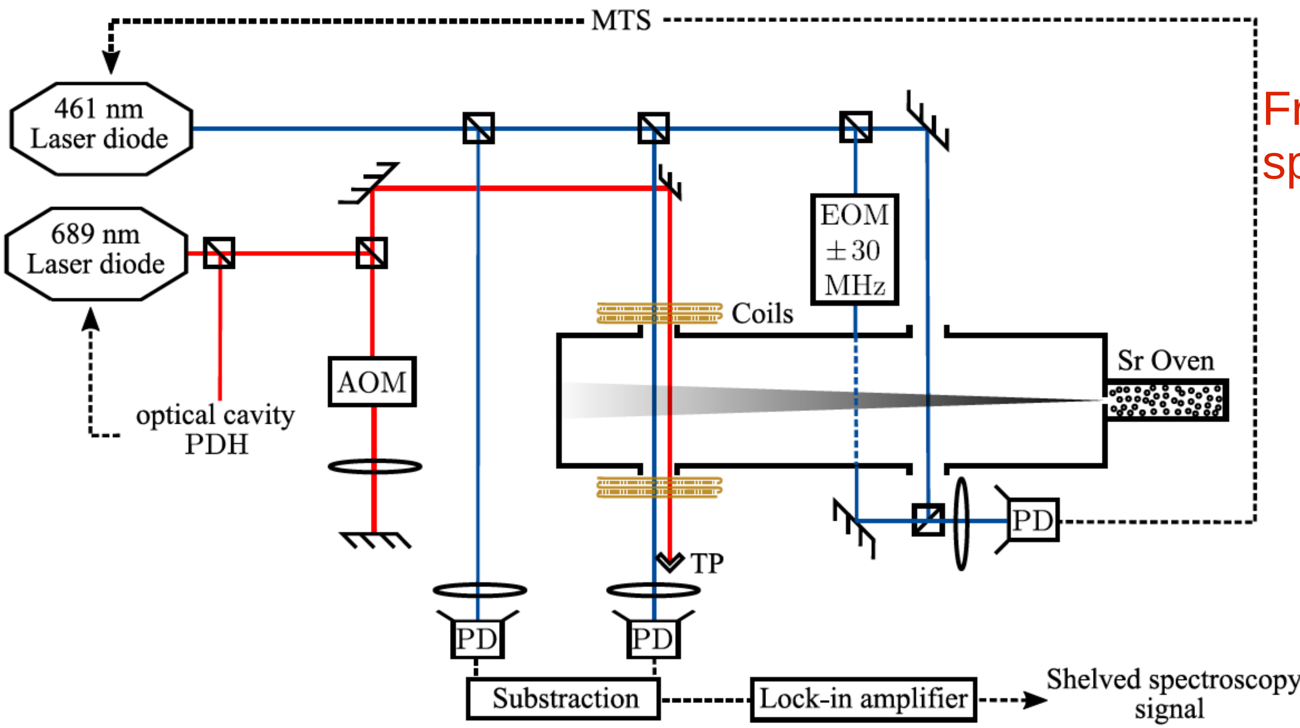
Scattering rate ~ Γ

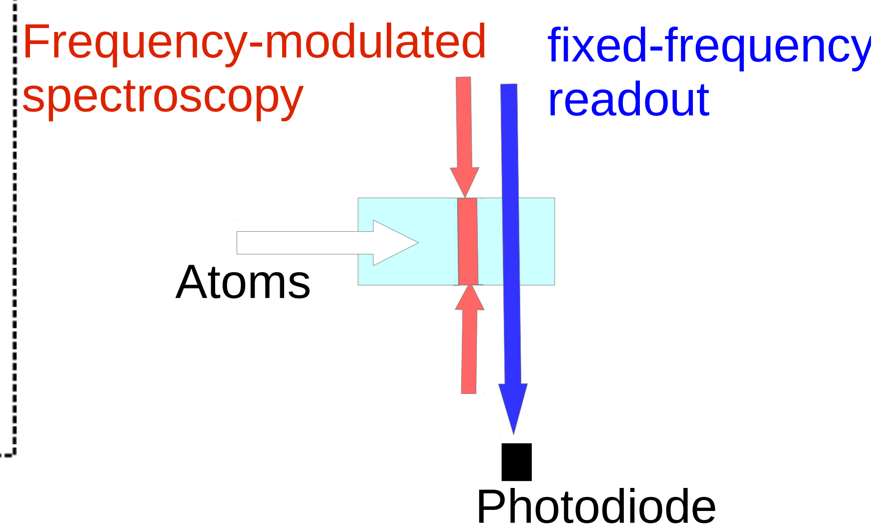
Strontium: Γ/γ = 4000

E.g. thermal Calcium beam clocks:
Kai-Kai 2006, Cinese Phys Lett 23, 3198
Mac Ferran 2009, Appl Phys Lett 95, 031103

Two independent setups

1) Directed thermal beam



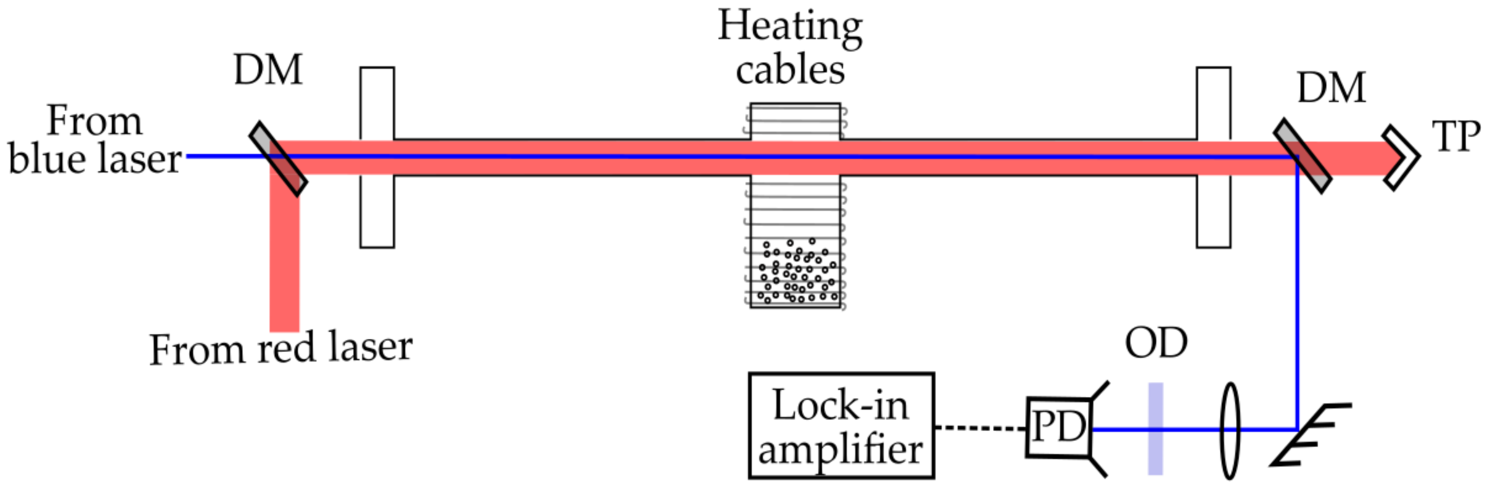


Well defined atomic beam direction
Separated interrogation and readout: compatible with Ramsey schemes

Two independent setups

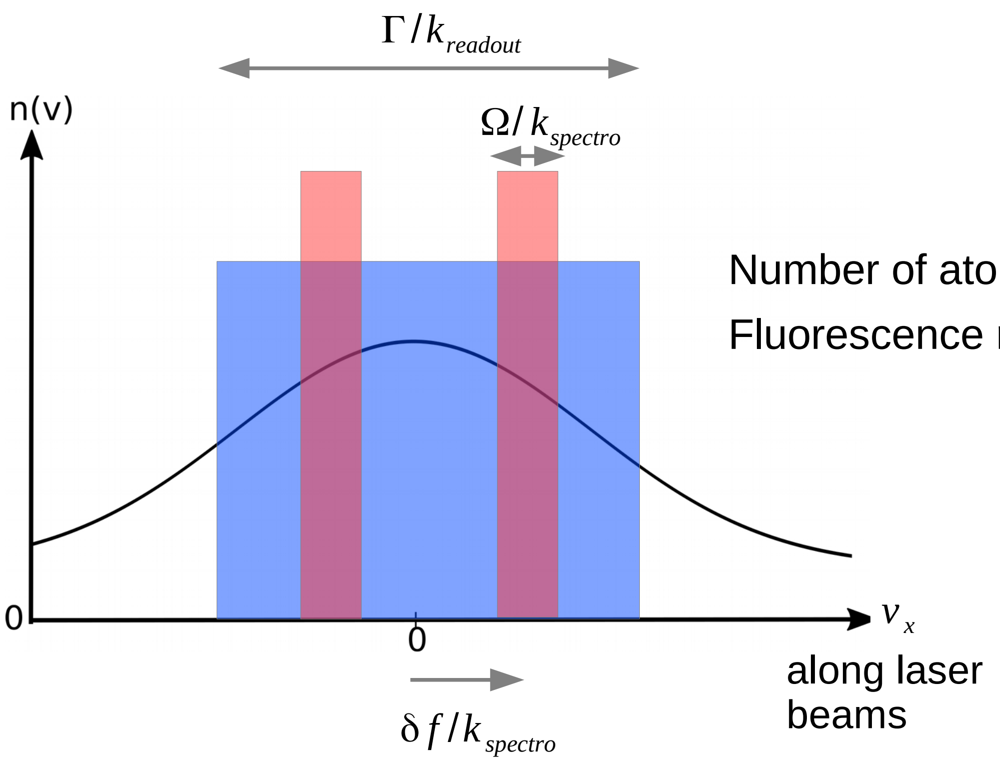
2) Hot vapour cell

Completely independent setup: lasers, detection electronics...



Isotropic velocity distribution
Locally overlapped interrogation and readout

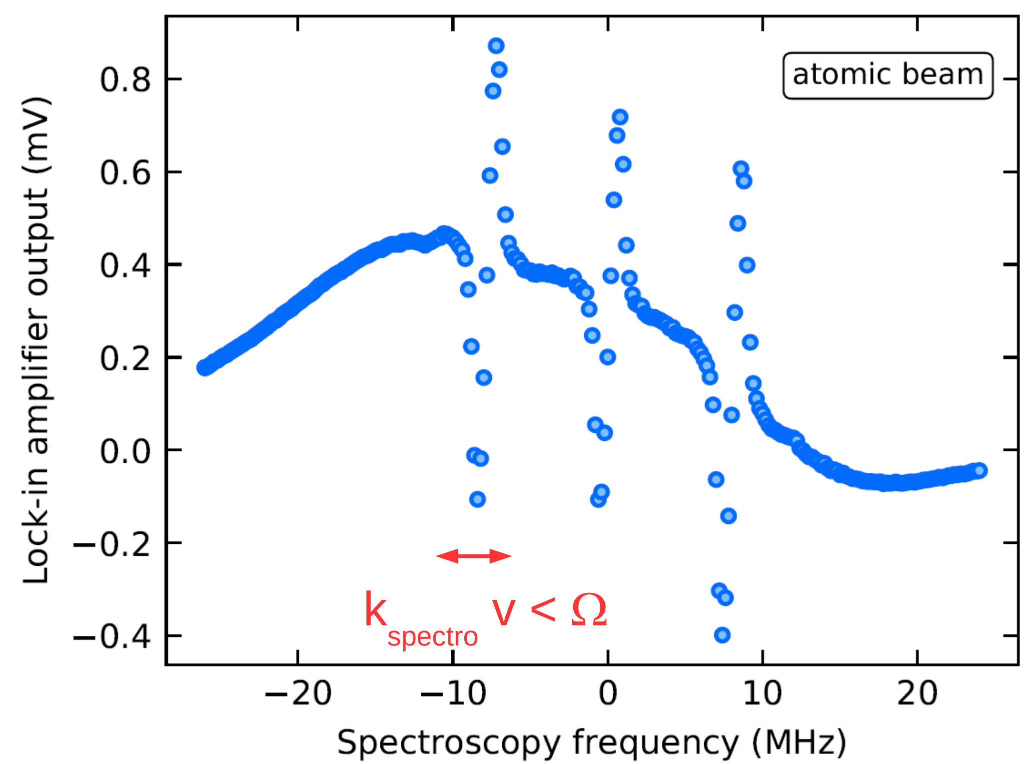
Doppler spectrum overview



Number of atoms ~ γ or Ω

Fluorescence rate ~ Γ

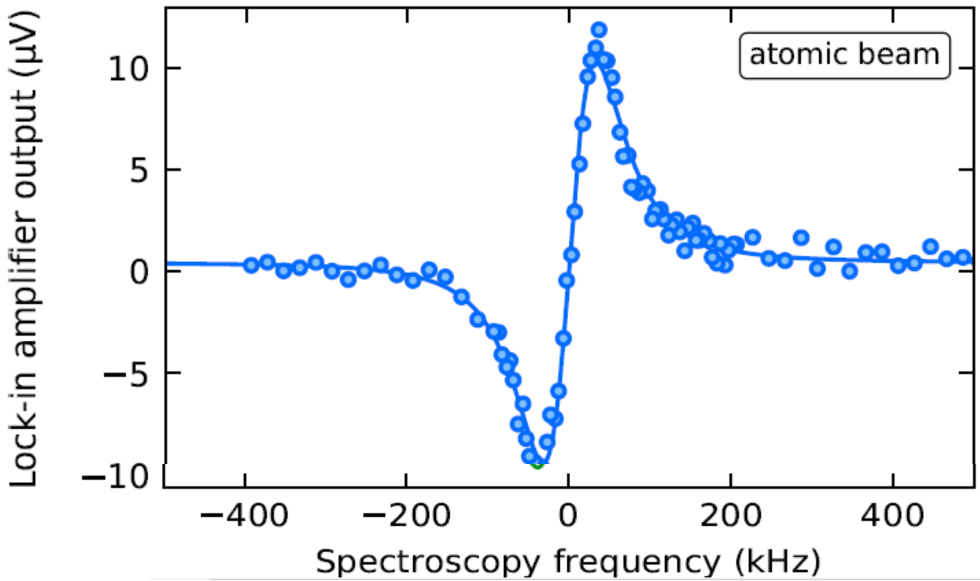
Doppler spectroscopy of atoms with $k_{readout}$ v < Γ



Optimal modulation amplitude (next slide):
the Doppler spectrum becomes negligible

Three lines: σ+, σ-, and cross-over (π)
g μ B / h = 7 MHz

SubDoppler line – atomic beam



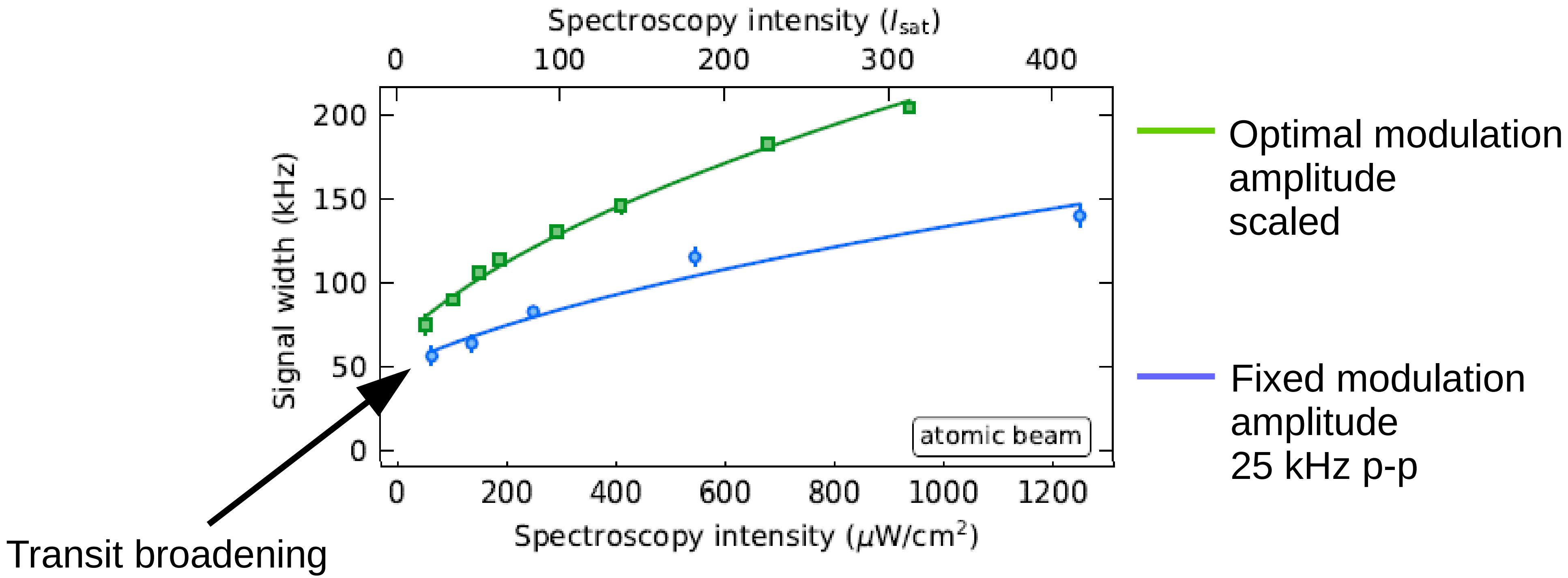
Lorentzian FWHM : 110 kHz

Contributions:

I = 83 Isat → Ω = 50 kHz
power broadening FWHM ~ 70 kHz

Modulation amplitude (p-p) 66 kHz

Transit broadening, FWHM : ~ 50 kHz



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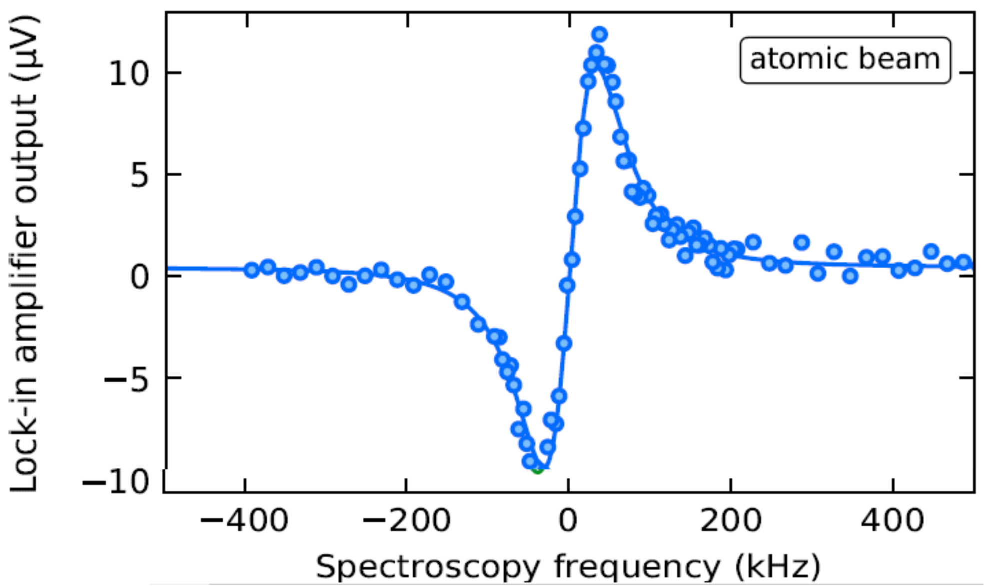

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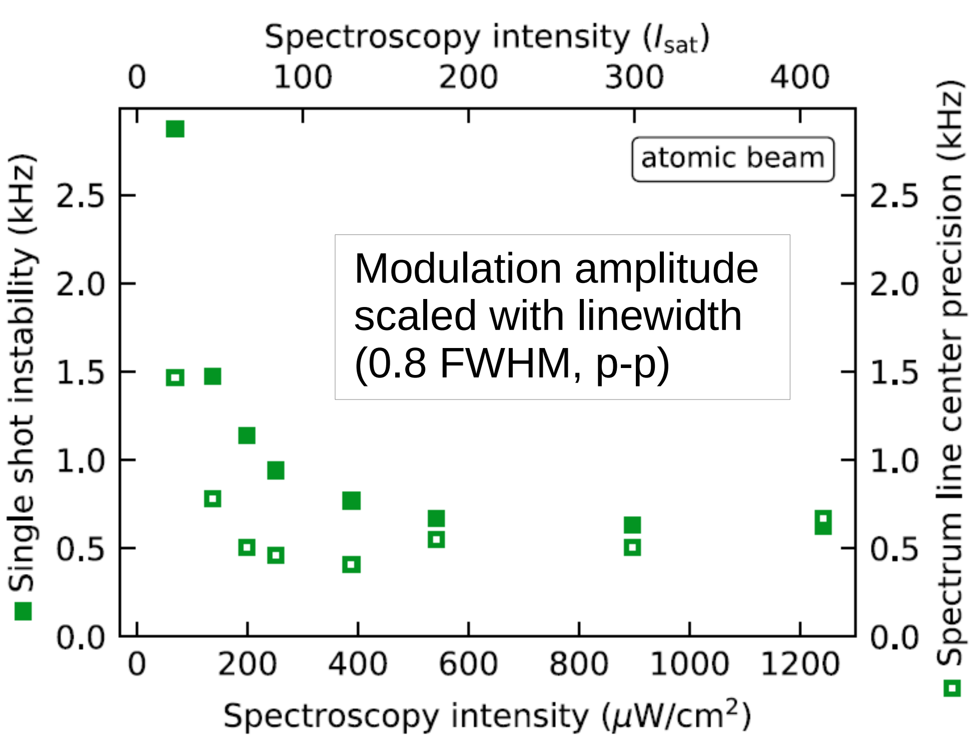
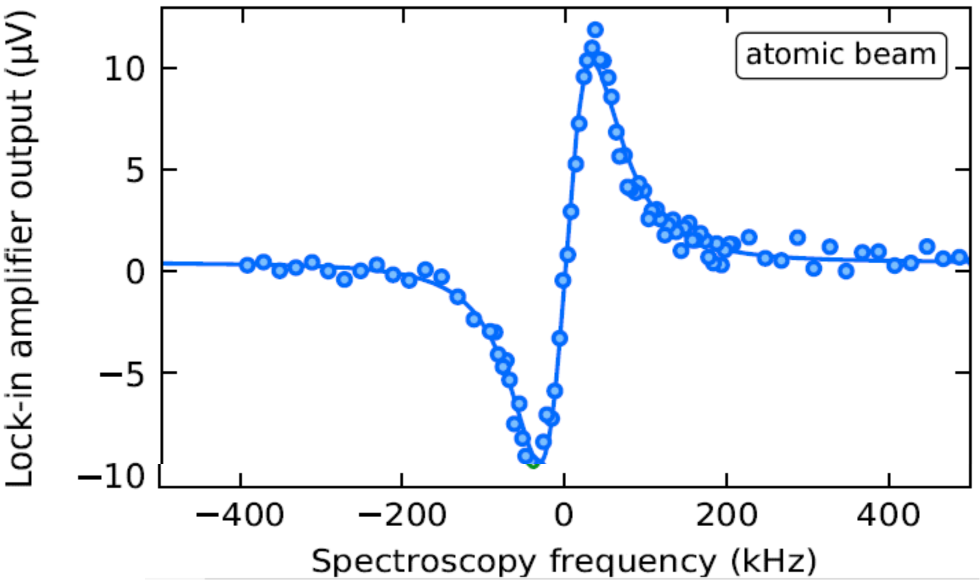


Frequency instability:
Lowest when power-broadening dominates over transit broadening

High intensities: baseline drifts and
lineshape distortion

Optimal at 100 Isat;
Fit precision statistically consistent with the short-term instability and the sampling

Performances – atomic beam



Lock-in amplifier integration time 1s

Frequency instability at 1s (1-shot) : 1,2 kHz
Relative freq instability at 1s: 2 10^-12

Fit uncertainty 450 Hz
(statistically consistent with the sampling)

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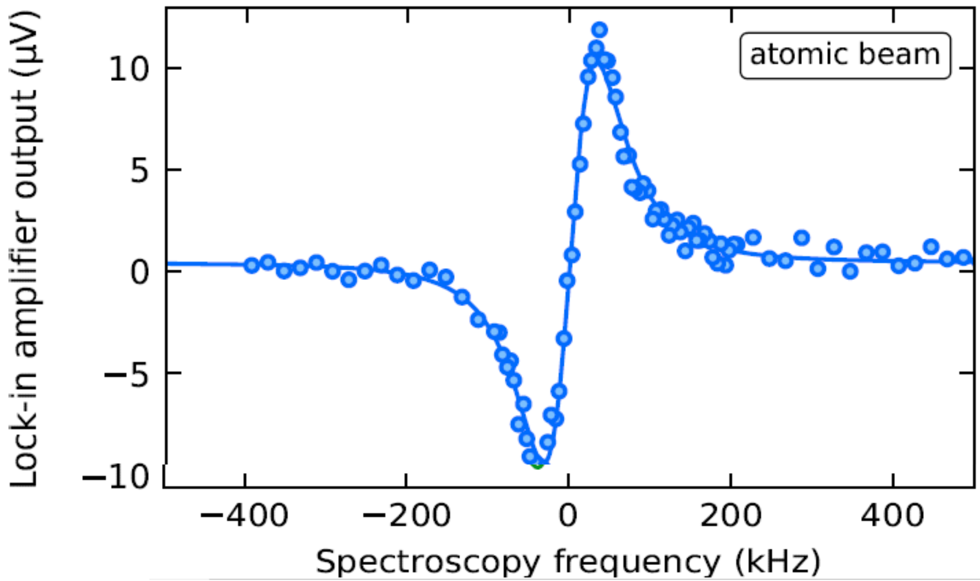

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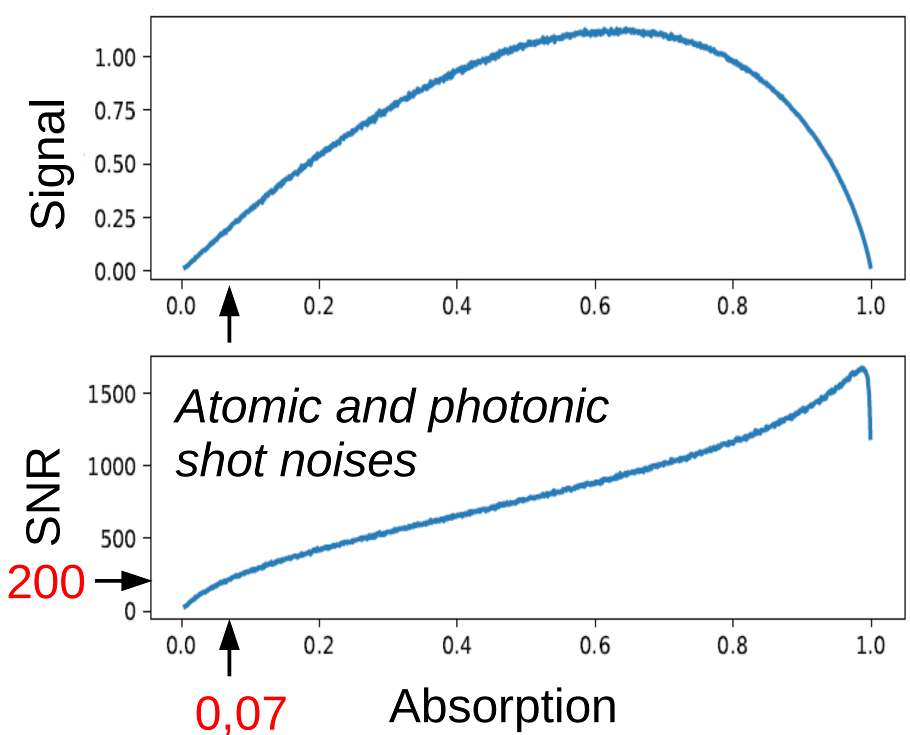
Technically limited performances;
what could be the fundamental limit?

SNR (thus also instability) a factor 10 behind
atomic shot noise limitation : 2 10^-13 at 1s

Spectrum at only 7% readout absorption
Very strong improvement achievable by reaching
to **high densities : 3 10^-14 at 1s**

Very similar to Ca-beam clocks,
e.g. McFerran 2009: 7 10^-14 at 1s

Theoretical estimates



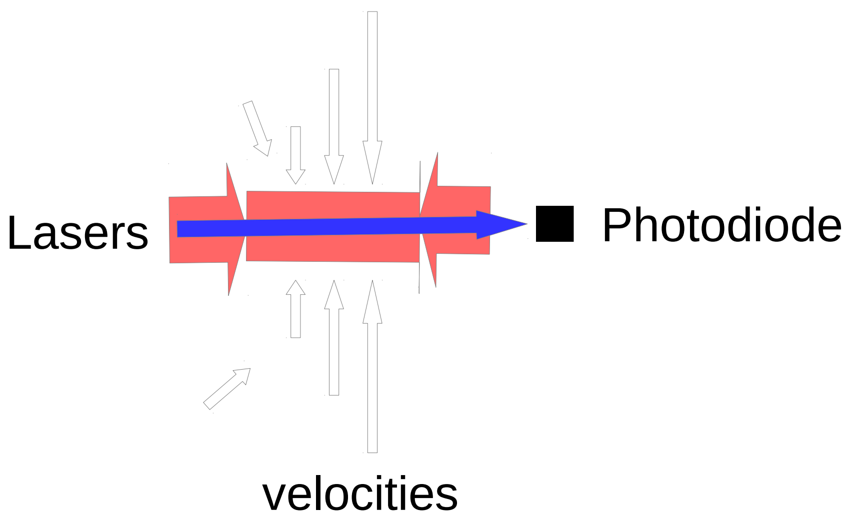
Applicability to a hot cell

Lineshape robustness:

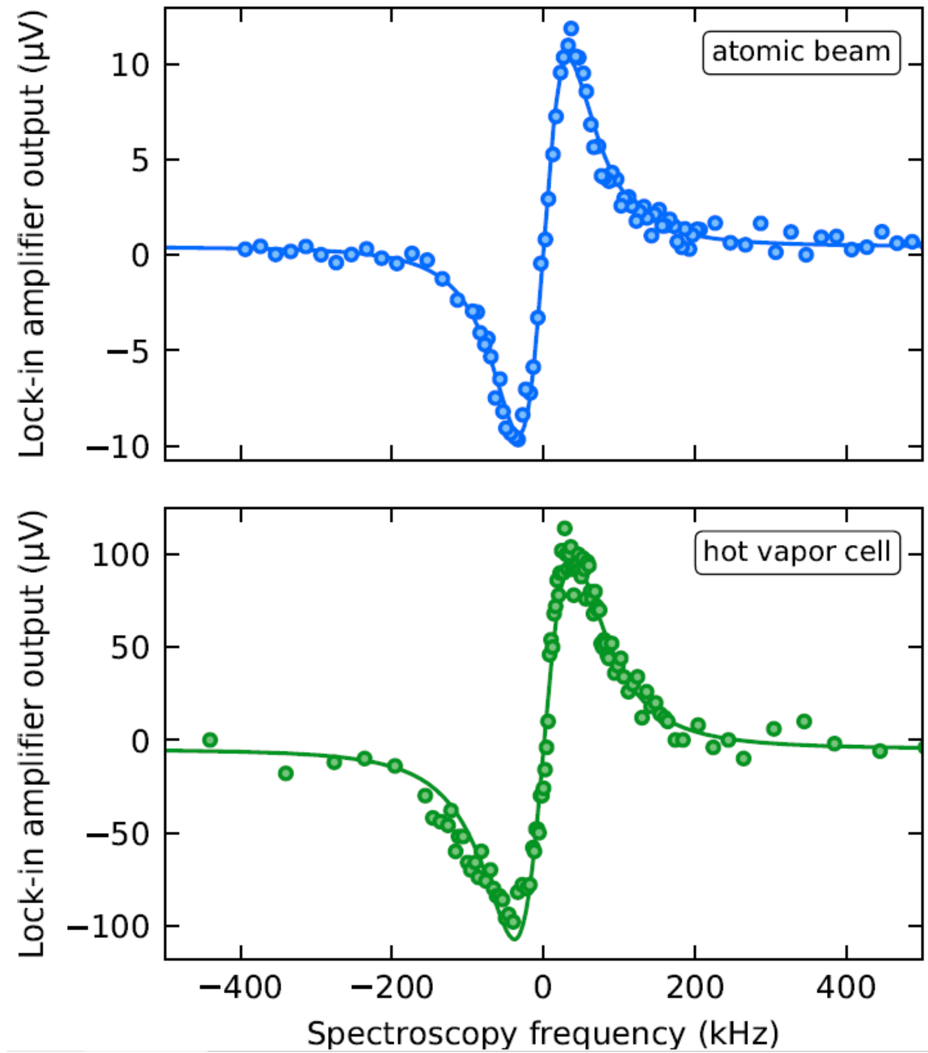
Typical transit time 8 µs << 1/γ = 21 µs:
coherent evolution.

The shape still remains close to Lorentzian, due to **velocity averaging**

→ **strong stability of the lineshape with I**



Reproduction of the same spectrum, at same I/Isat.



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Compactness and **source lifetime**:

- No signal degradation nor shift vs pressure up to 10^-3 mbar of Argon: **no need for pump**

- Absorption 80% despite 100K lower temperature

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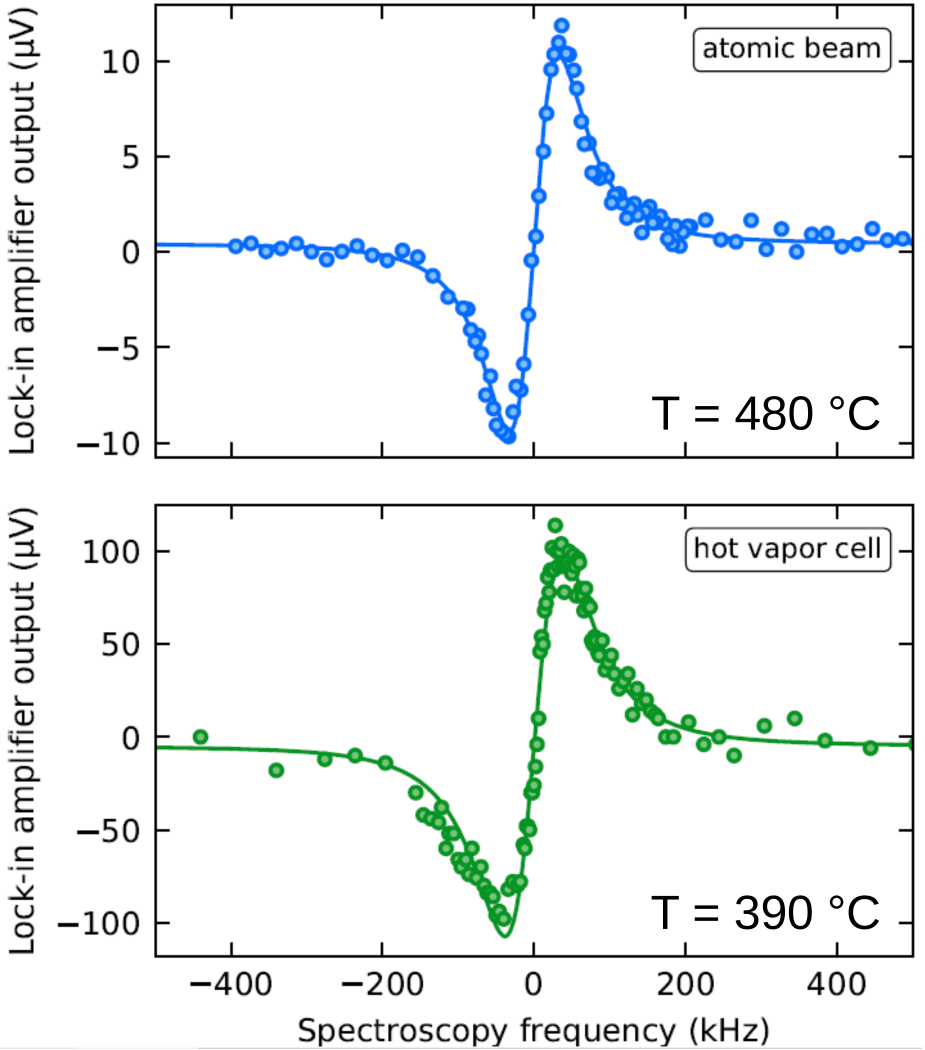

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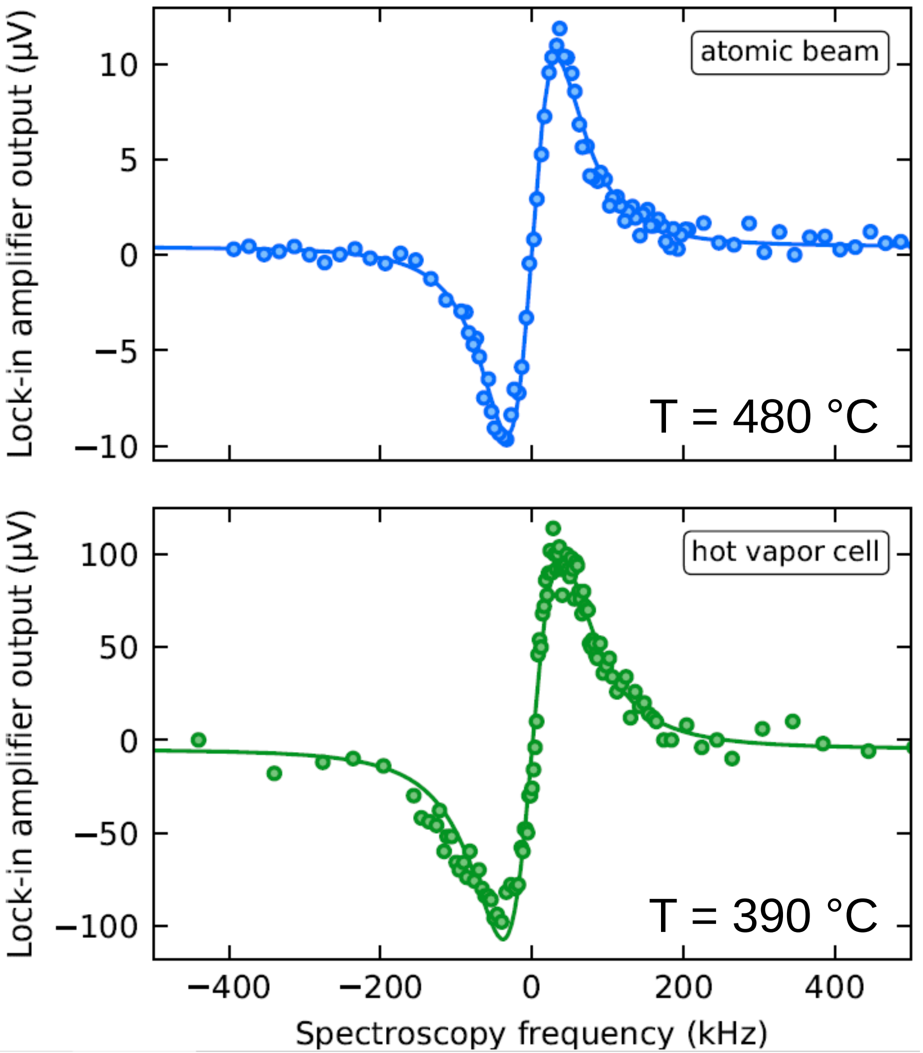
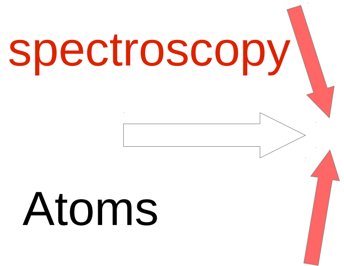
Robust against first order Doppler shift

Reproduction of the same spectrum, at same I/Isat.





$$\vec{k}_1 \cdot \vec{v} = \vec{k}_2 \cdot \vec{v} \neq 0$$

Beam : 50 µrad → 10 kHz shift (and similar broadening)
Cell: symmetric velocity distribution → only broadening

Concluding remarks

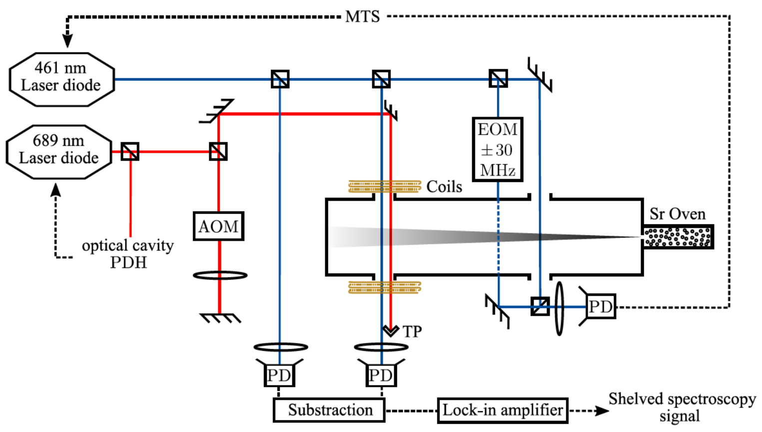
A robust solution, demonstrated on two fully independent setups:

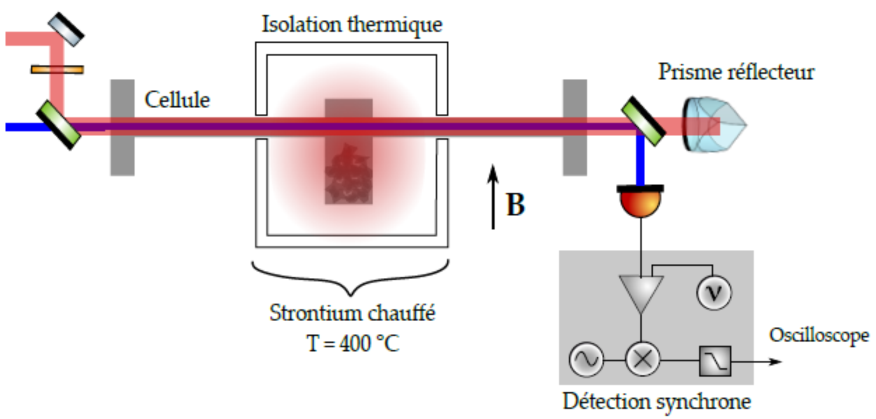
Atomic beam with separated interrogation zone,

and

Hot cell with overlapping beams

ArXiv:1910.11718





Shelving detection easily applicable to all strontium experiments

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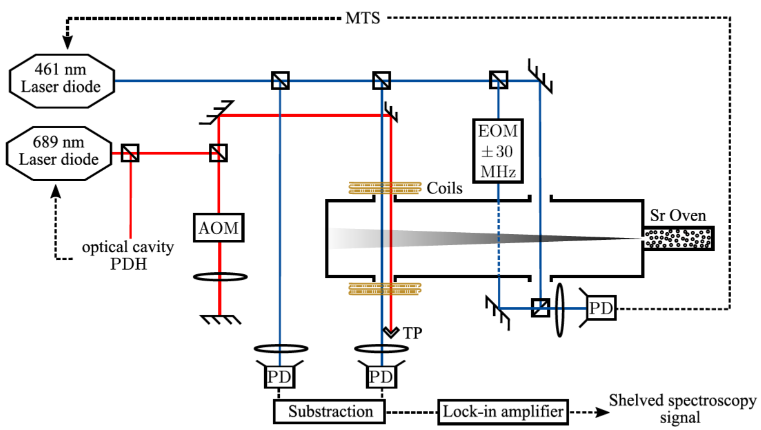
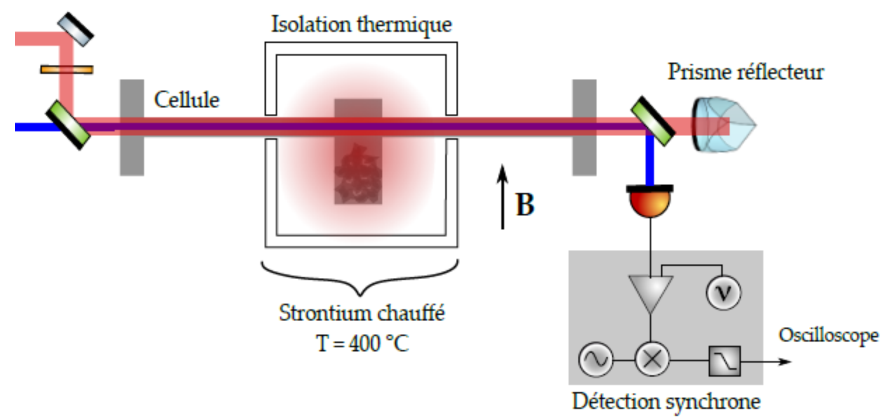




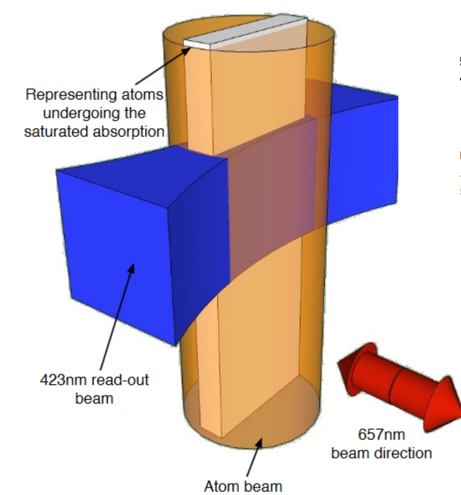
Shelving detection easily applicable to all strontium experiments

A reference of metrological interest?

- short-term instability: achieved 2 10^-12 at 1s (beam setup)
  achievable 3 10^-14 at 1s with same setup

→ perspectives similar to Ca-beam clocks, as low-cost clock

[Kürzig group project: a transportable Sr Ramsey clock]



Many ideas of Ca-beam clocks should be identically applicable
(Mc Ferran2009, Shang 2017)

Outline

1) Shelving spectroscopy of the strontium intercombination line
demonstrated on an atomic beam and a hot cell setups
→ applicable to most Sr experiments

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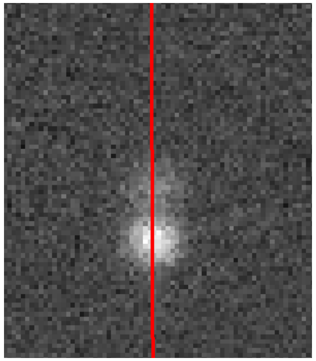
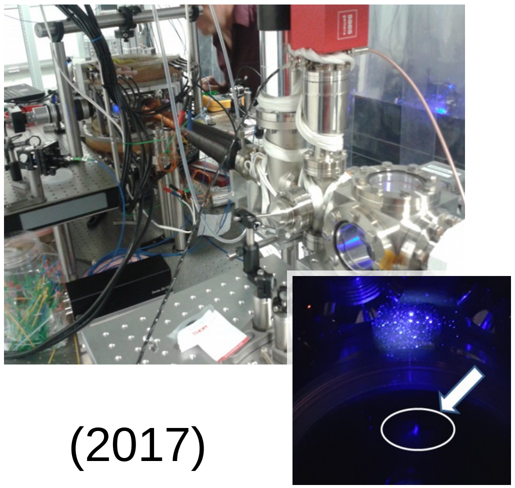
2) Birth of the Strontium experiment
- a degenerate Fermi gas with 10 spin-states
- first experiments of coherent spin manipulation

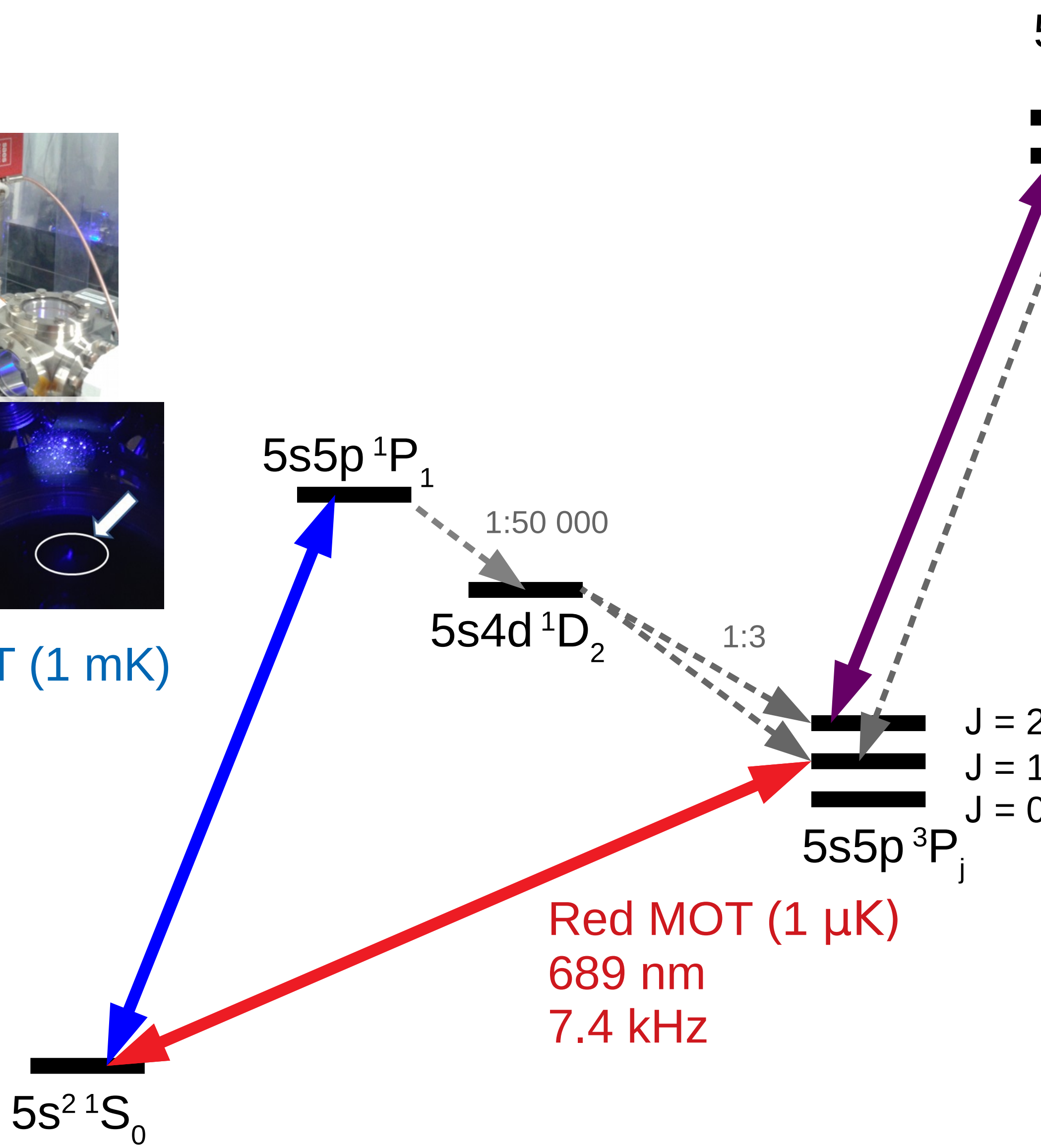


Spin-dependent adiabatic momentum transfer

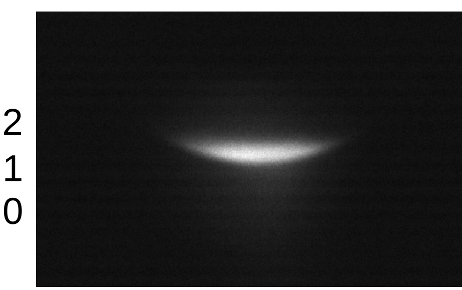
Birth of the strontium experiment



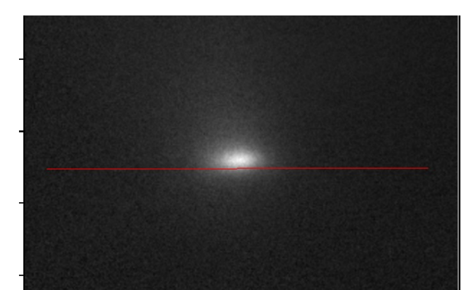
(2017)



88Sr (May 2018)



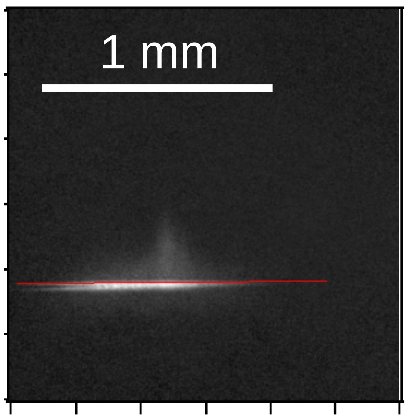
87Sr

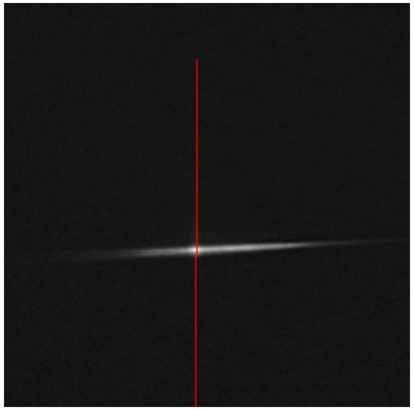


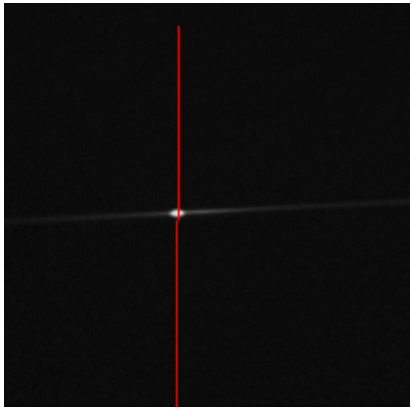
Cold and dense: in principle ideal for loading an optical trap

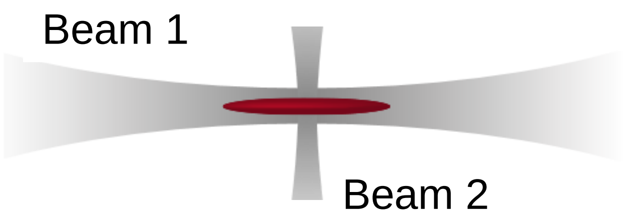
Birth of the strontium experiment

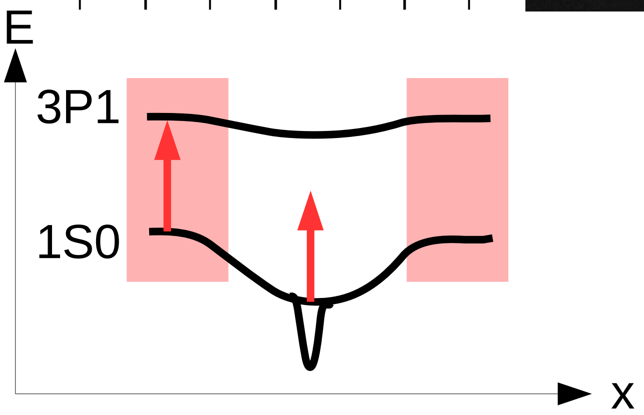
Laser cooling in light shifts from the dipole trap O(100 kHz)
3 µK

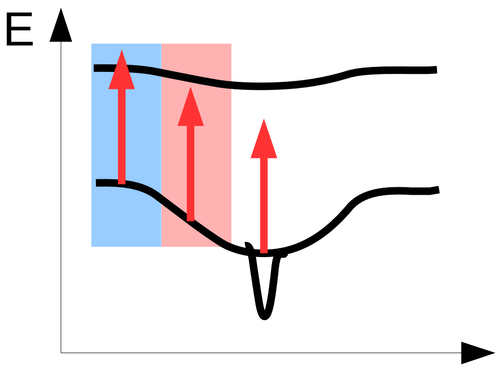










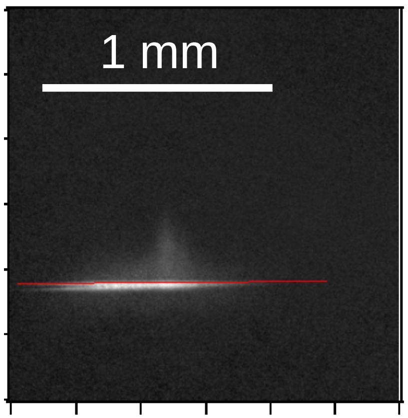


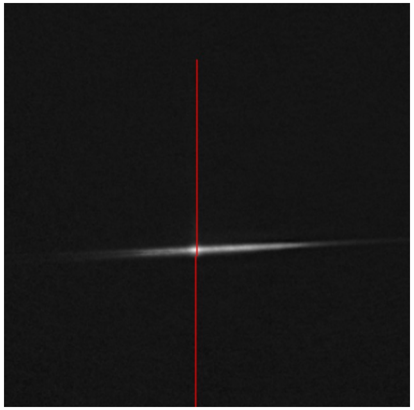
Loading stage sensitive to frequency drifts by O(10 kHz): stable referencing essential

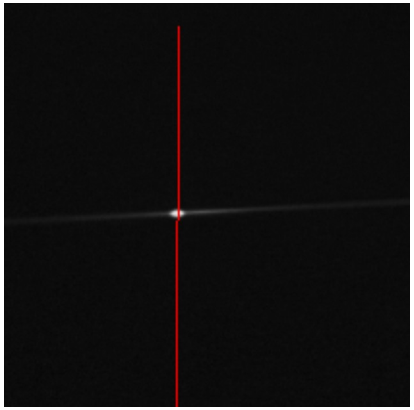
Birth of the strontium experiment

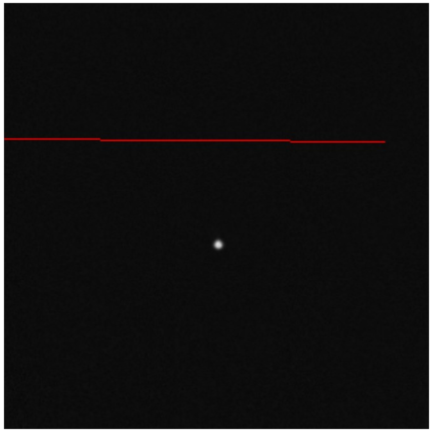
Laser cooling in light shifts from the dipole trap O(100 kHz)
2 μK

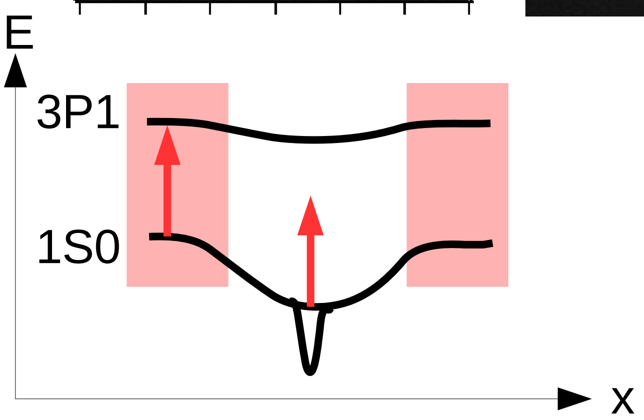
Evaporation

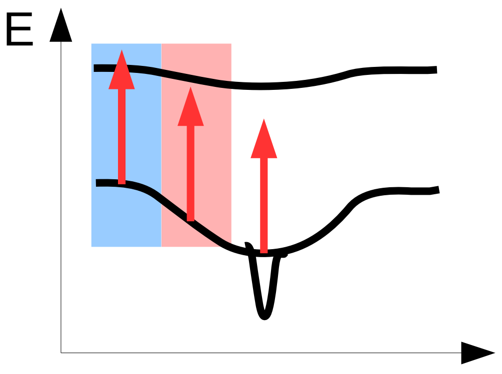


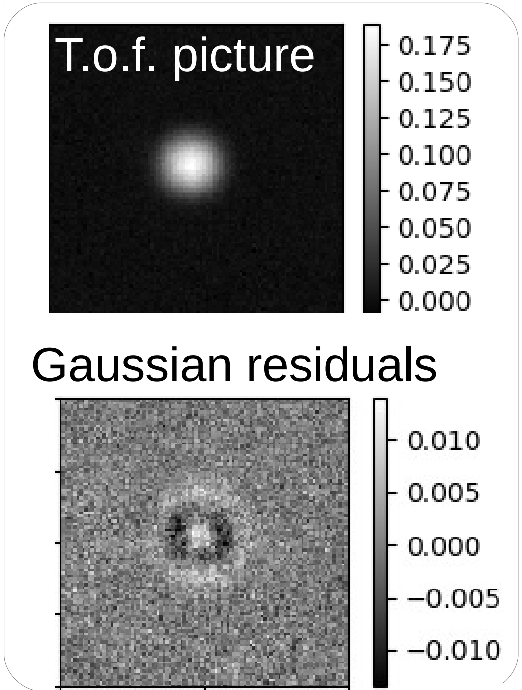












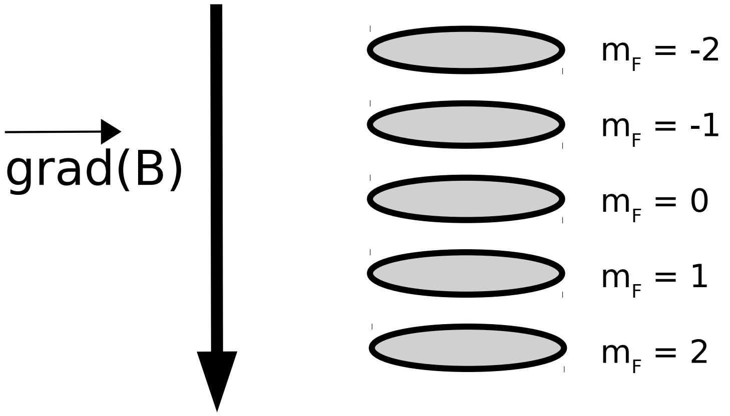
Loading stage sensitive to frequency drifts by O(10 kHz): stable referencing essential

Since spring 2019 : Fermi gas with 10 spin states, down to T/Tf ~ 0,2

Spin state measurement

- Stern-Gerlach separation,

  + broad line imaging ?



Alkali atoms

Impossible because of very small (purely nuclear) magnetic dipole moment.

How to spatially separate the spin states,
before imaging on the broad line?

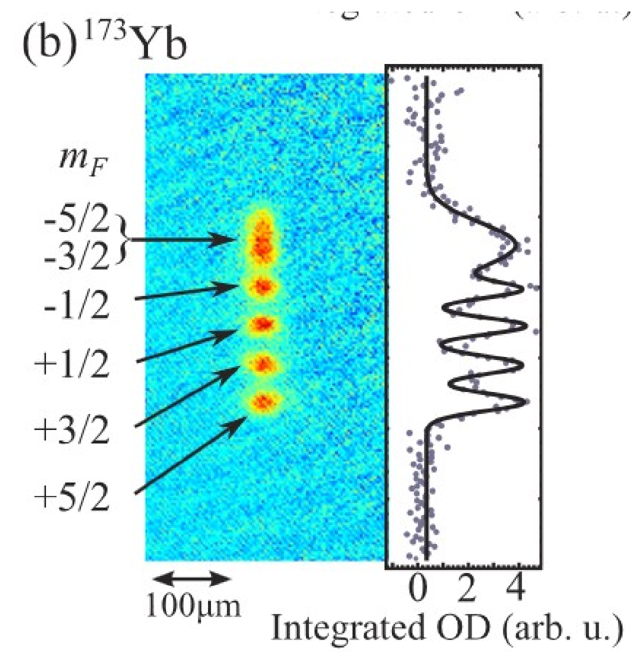
Spin state measurement

Established technique in this spirit:
Optical Stern-Gerlach separation

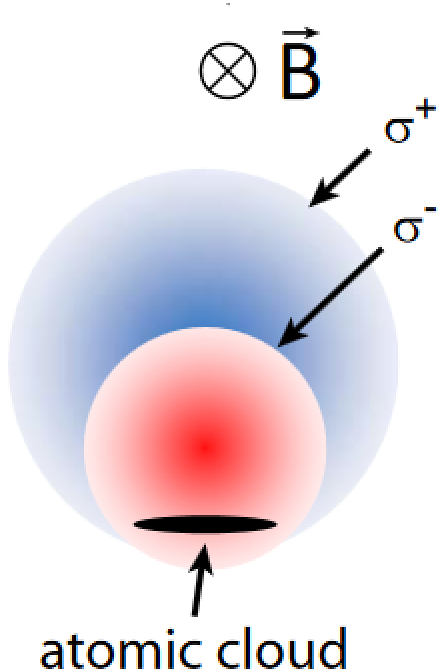
large gradients of spin-dependent light shifts applied for ~ 1ms

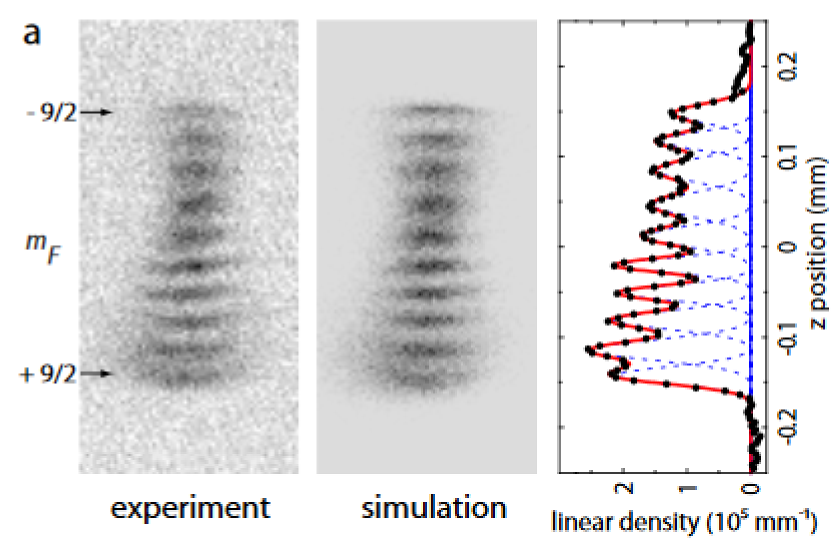
Requires specific lasers and beamshapes

We present an alternative scheme that simply relies on the narrow-line MOT beams



Yb: Taie 2010, Phys. Rev. Lett. 105, 190401

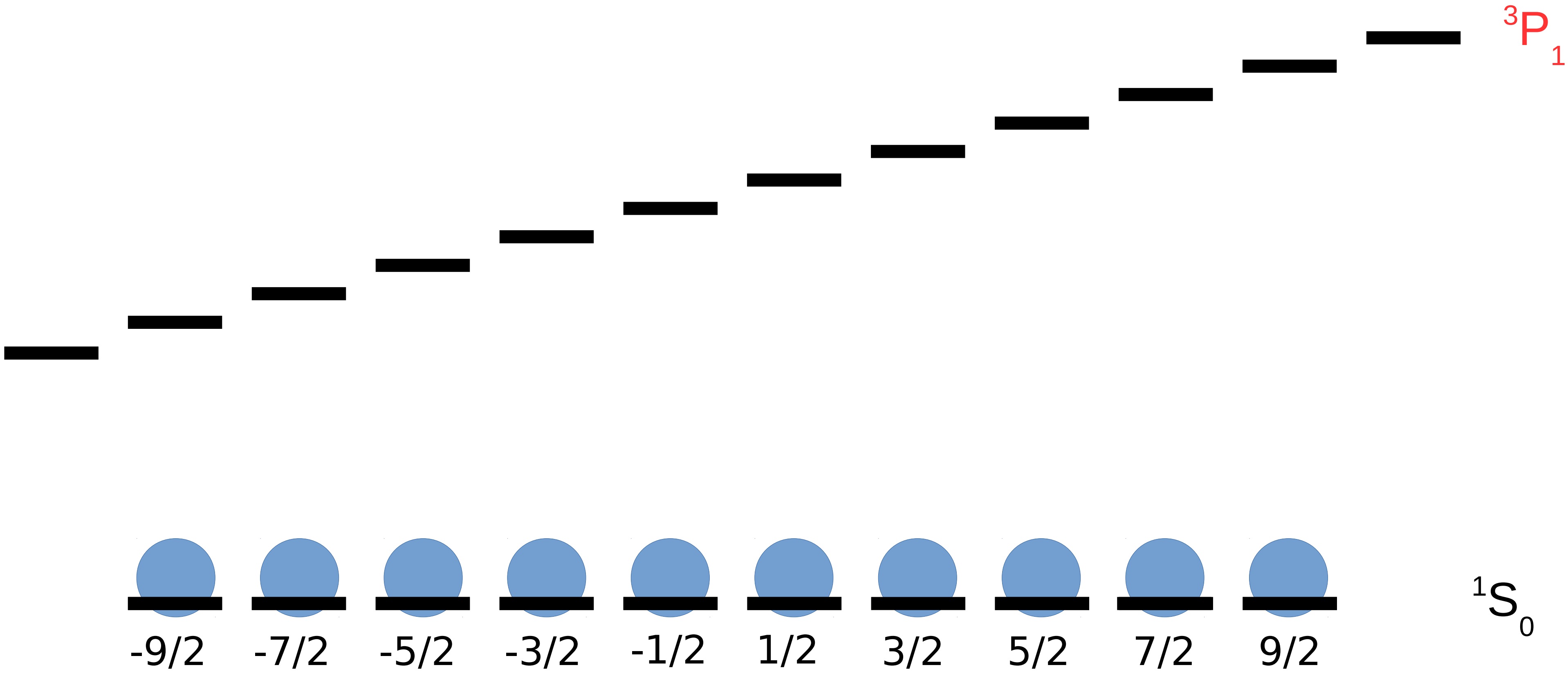




Sr: Stellmer 2011, Phys. Rev. A 84, 043611

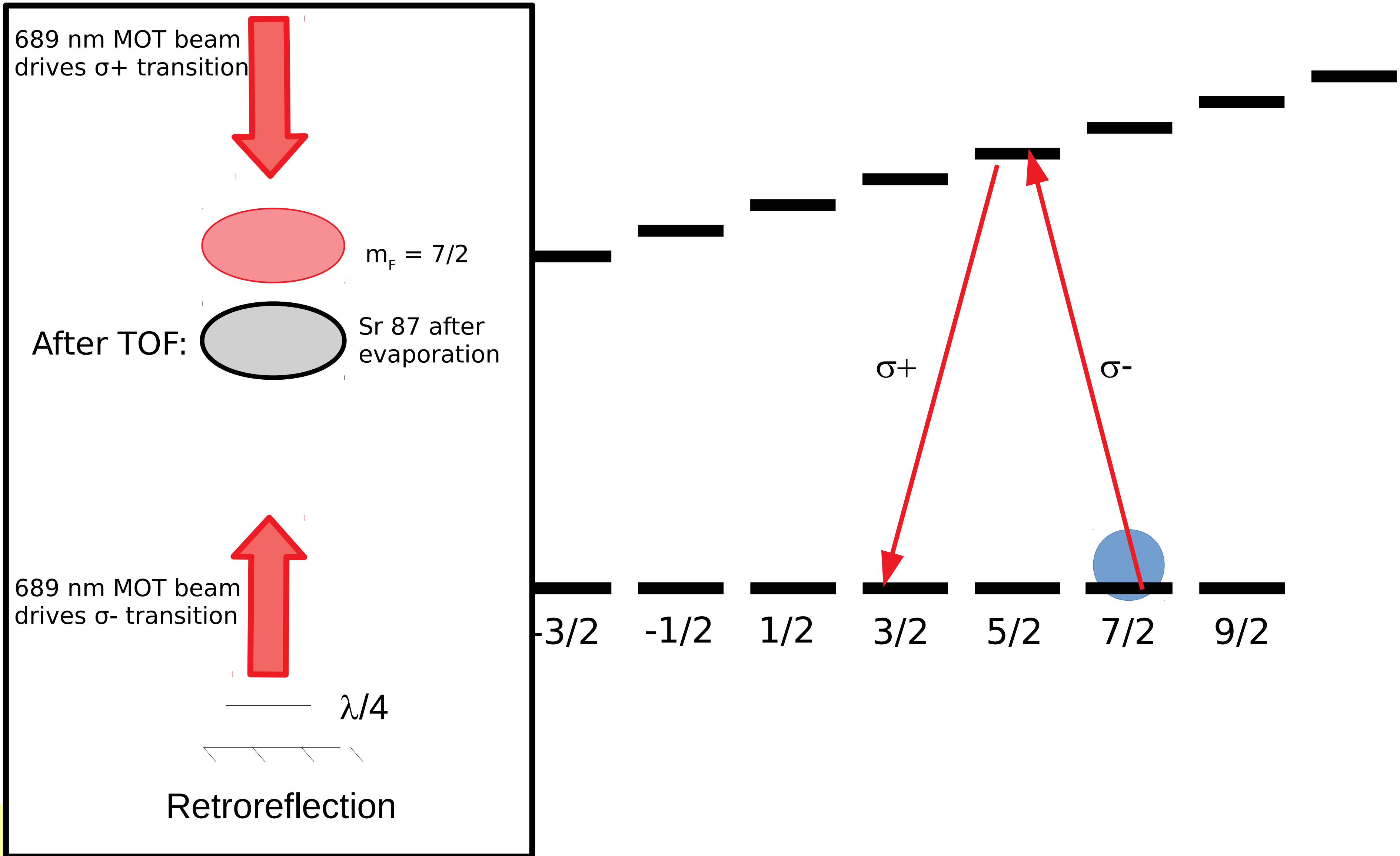
Spin state measurement

Spin-dependent momentum transfer



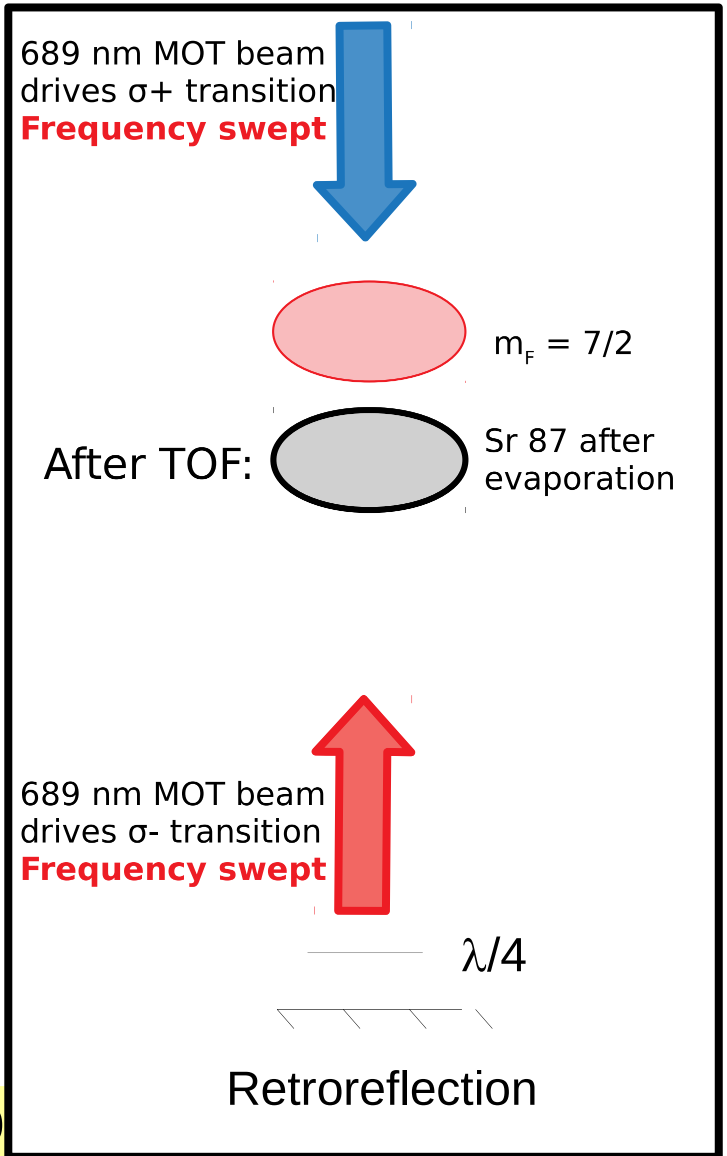
Spin state measurement

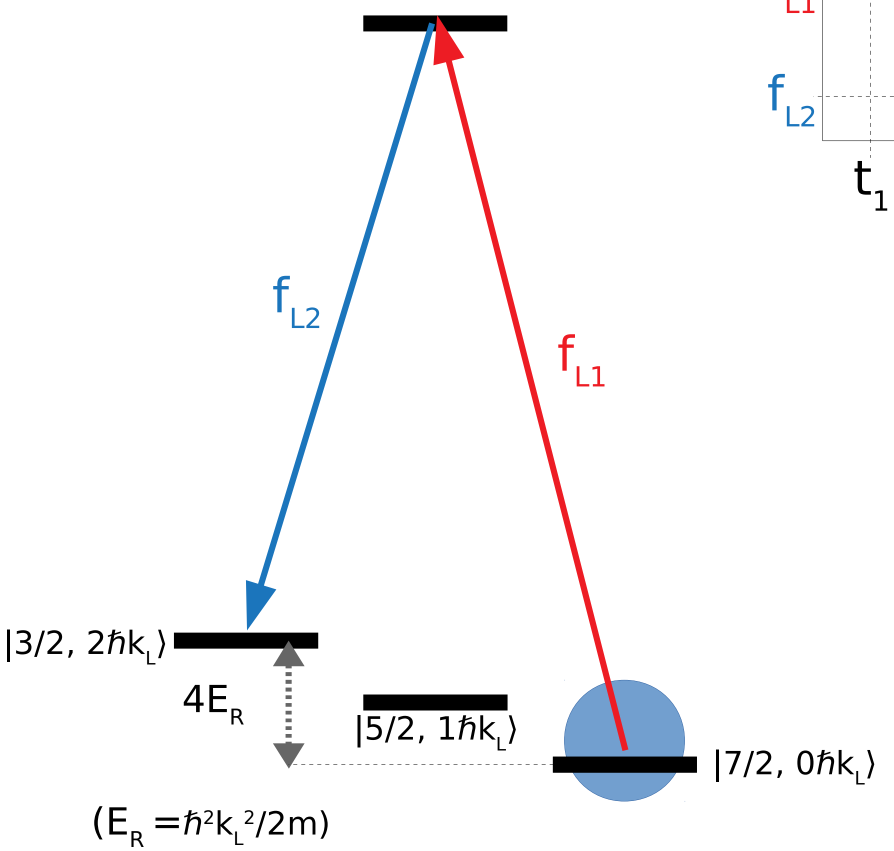
Spin-dependent momentum transfer

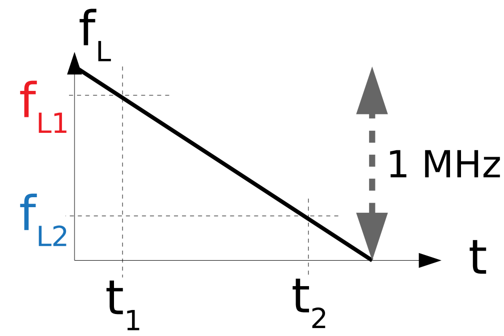


Spin state measurement

Spin-dependent momentum transfer

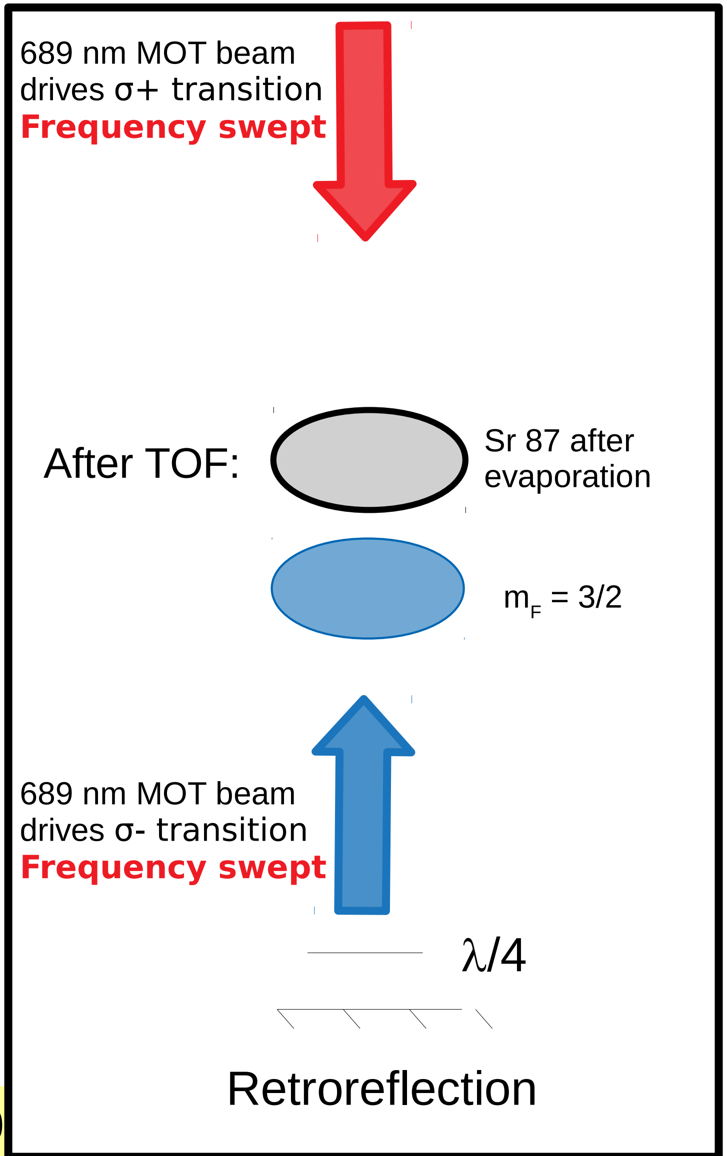


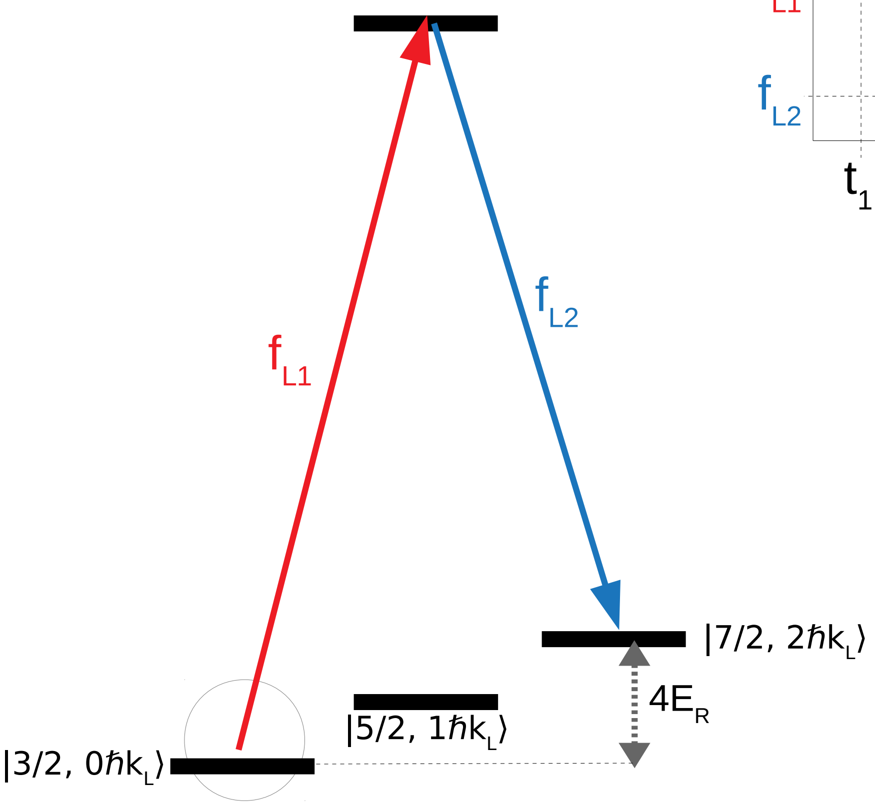


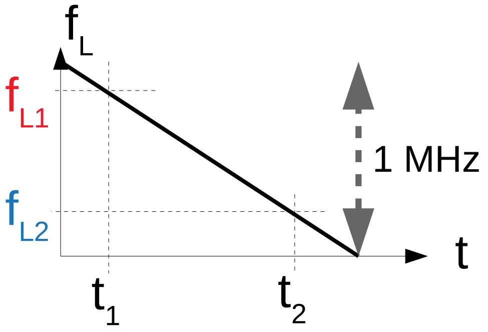


Spin state measurement

Spin-dependent momentum transfer

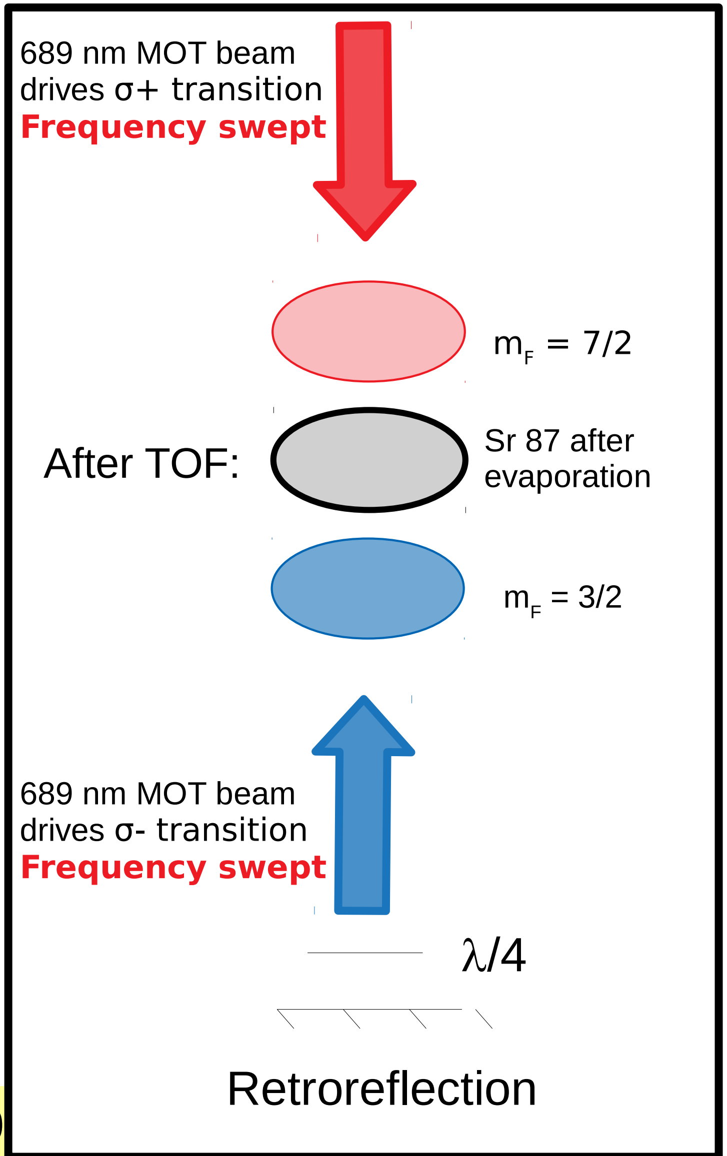


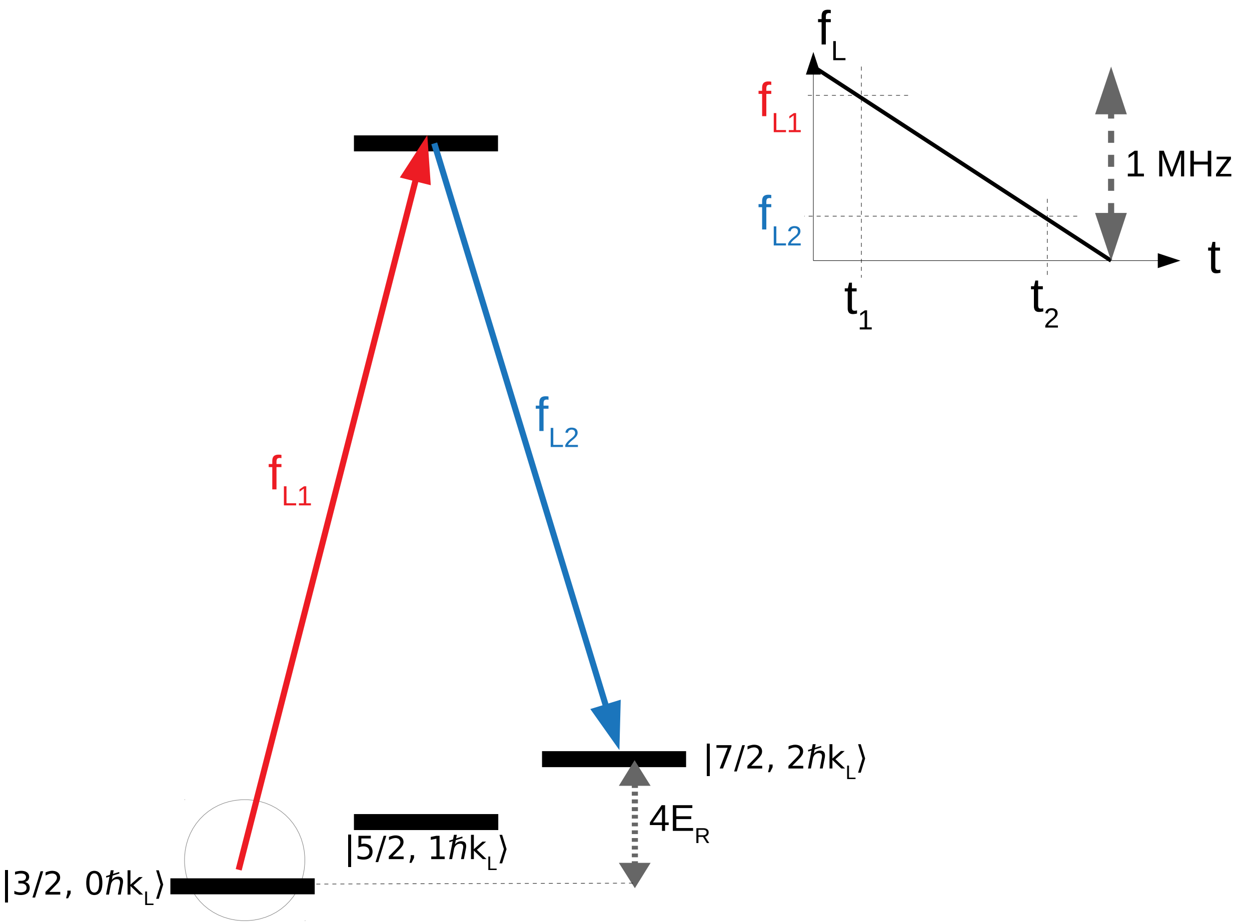




Spin state measurement

Spin-dependent momentum transfer

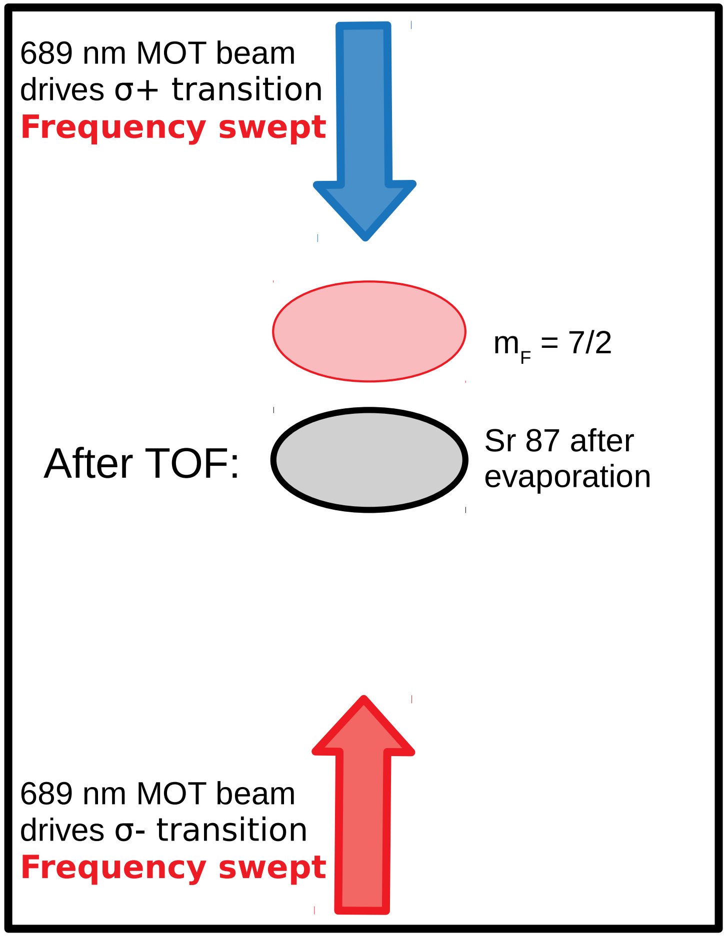


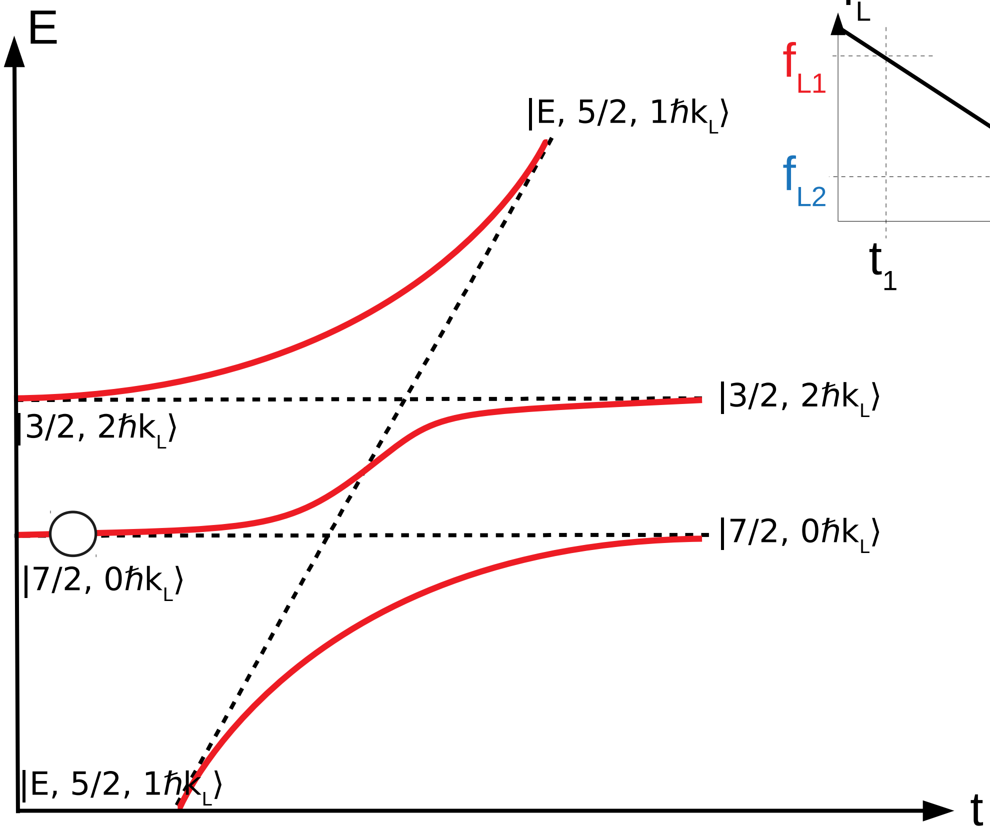


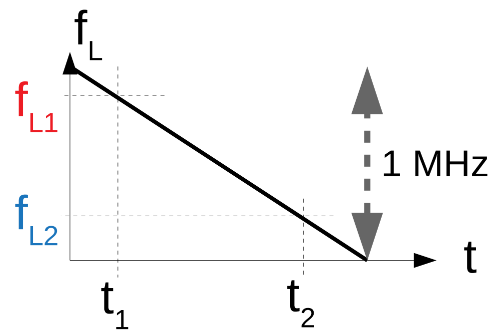
Two spin states separated in one run

Spin state measurement

Adiabatic spin-dependent momentum transfer

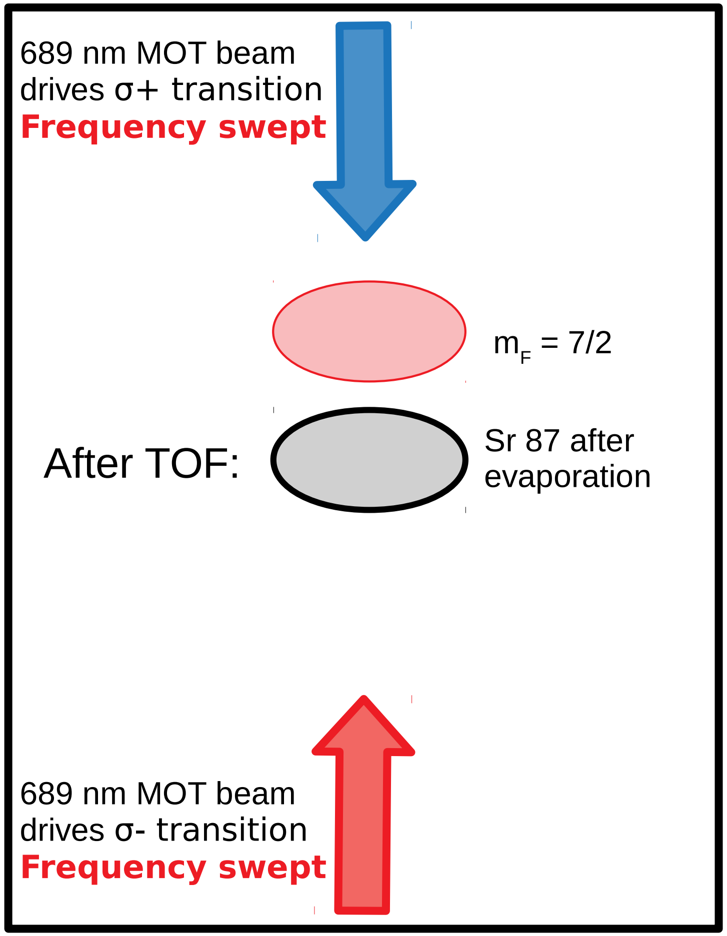


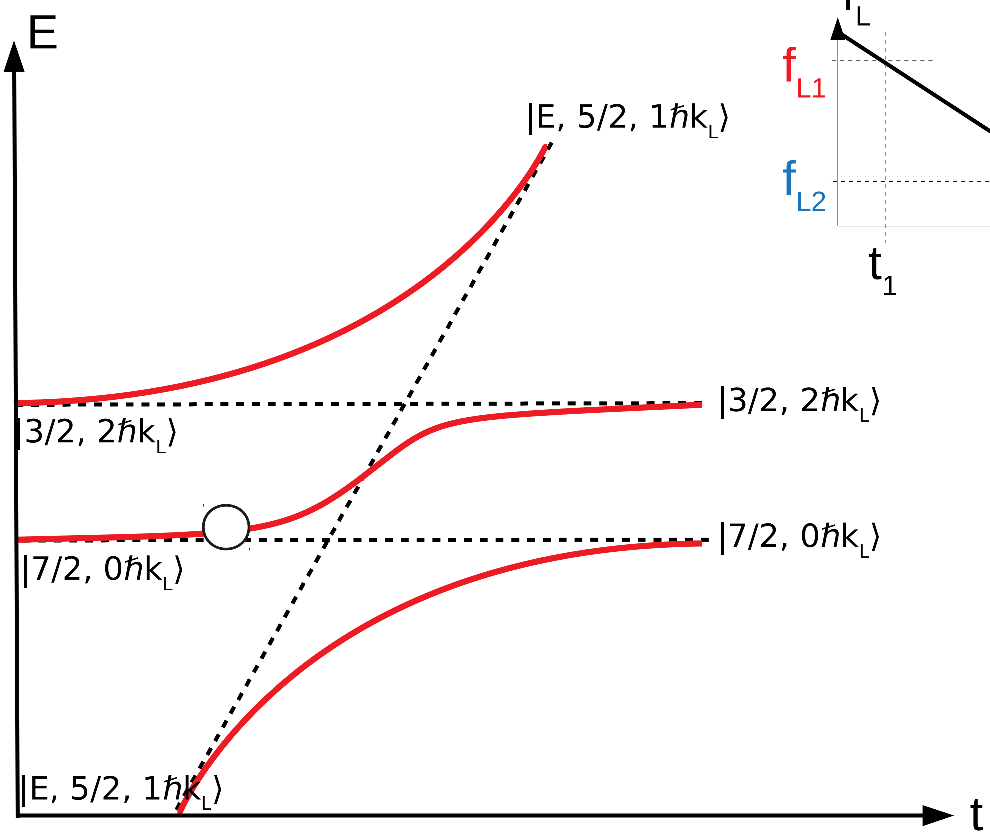


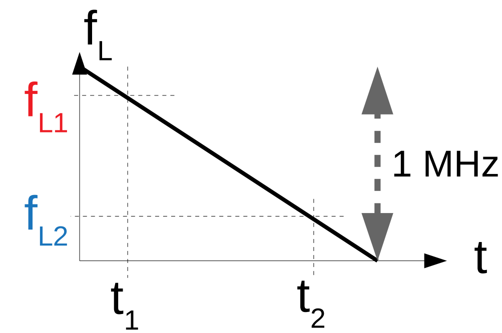


Spin state measurement

Adiabatic spin-dependent momentum transfer

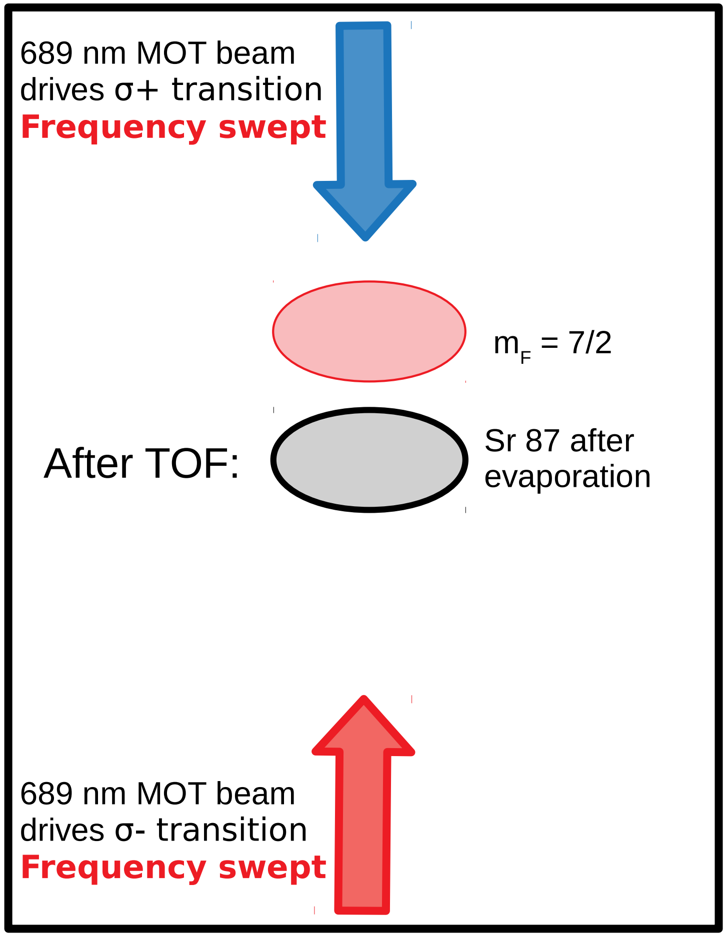


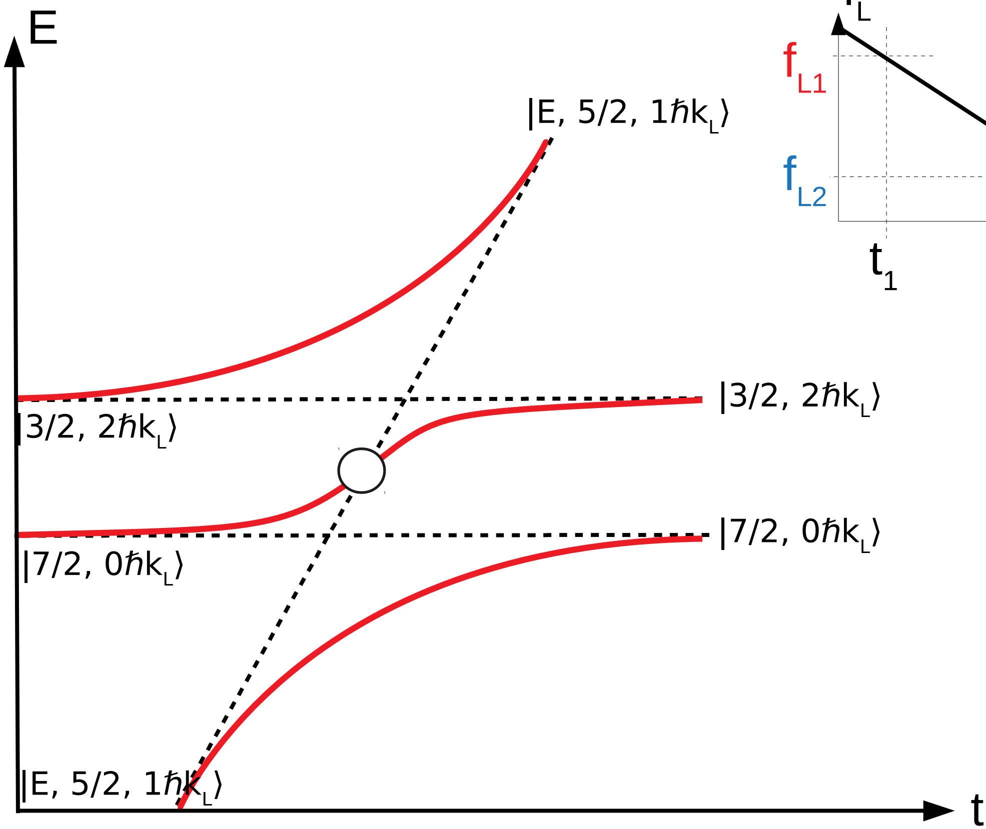


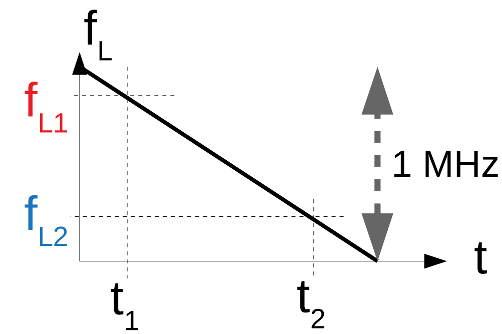


Spin state measurement

Adiabatic spin-dependent momentum transfer

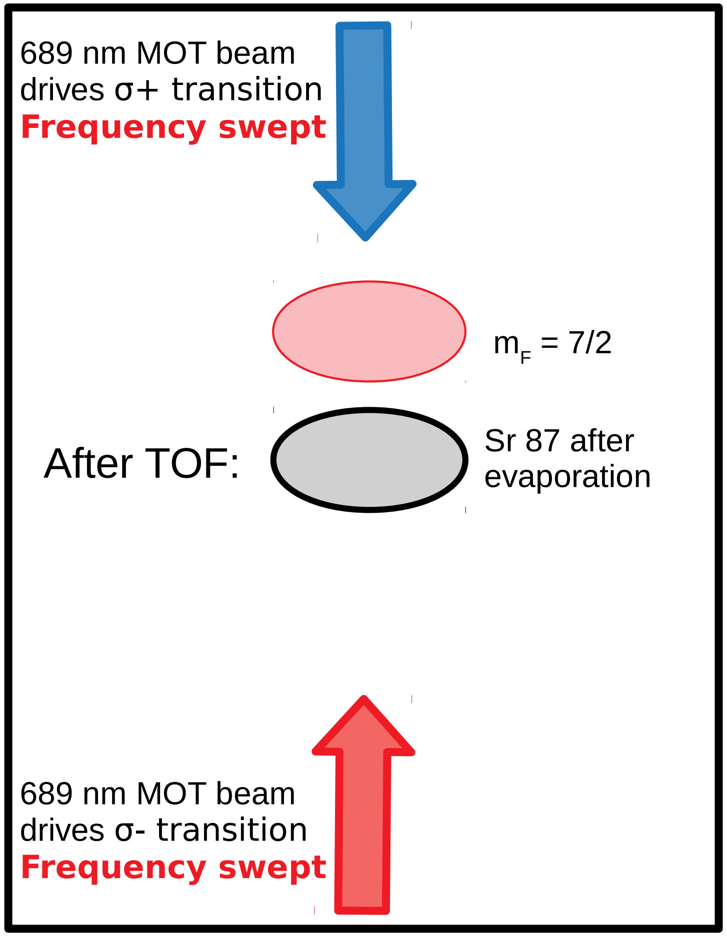


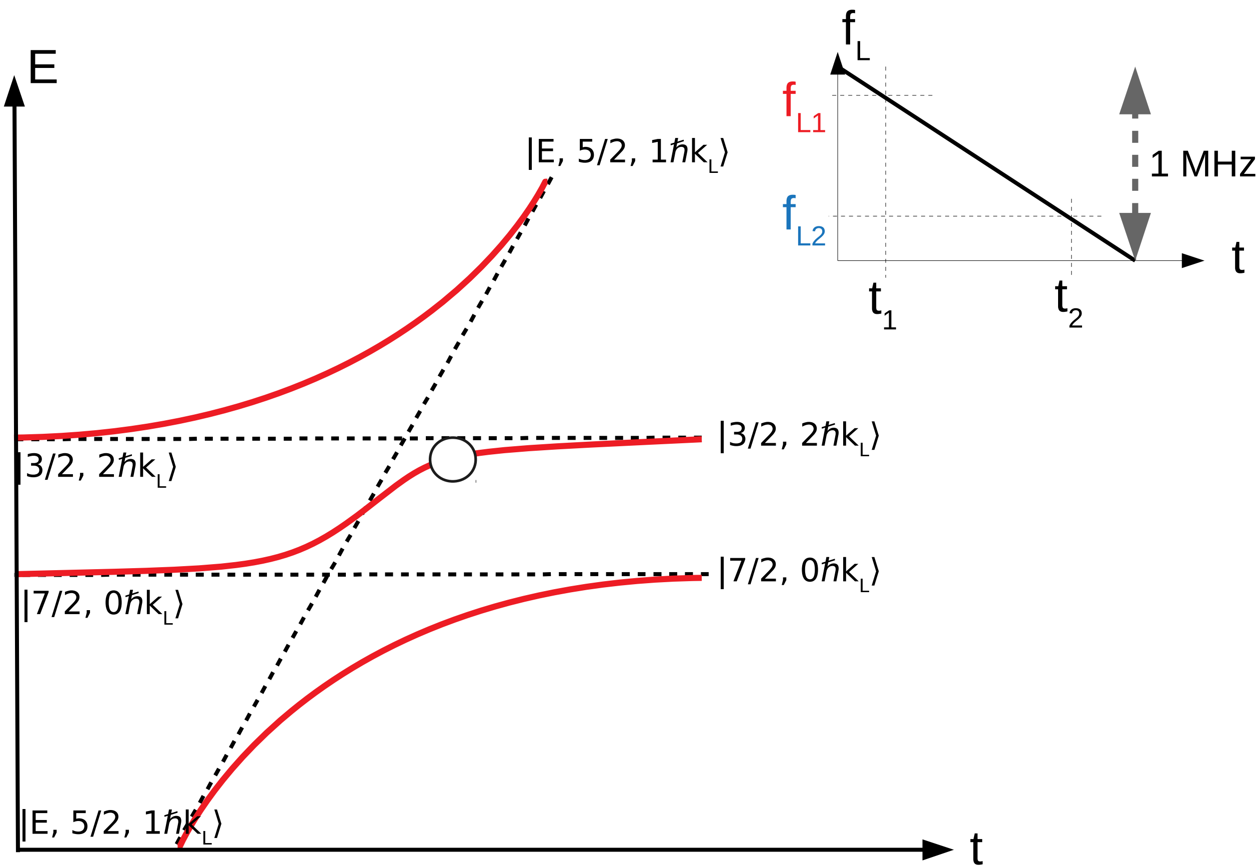




Spin state measurement

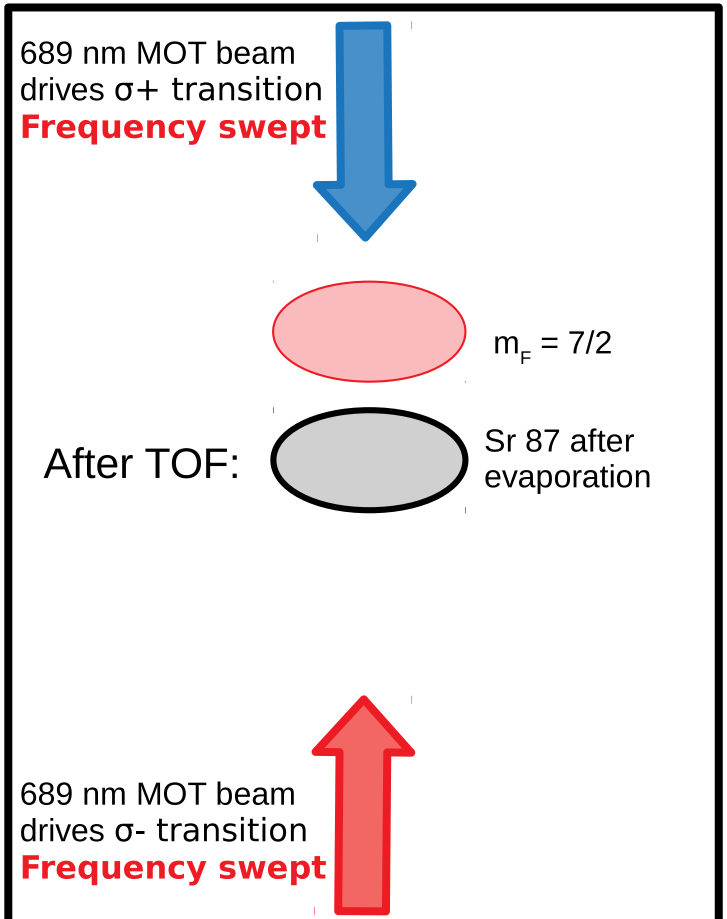
Adiabatic spin-dependent momentum transfer

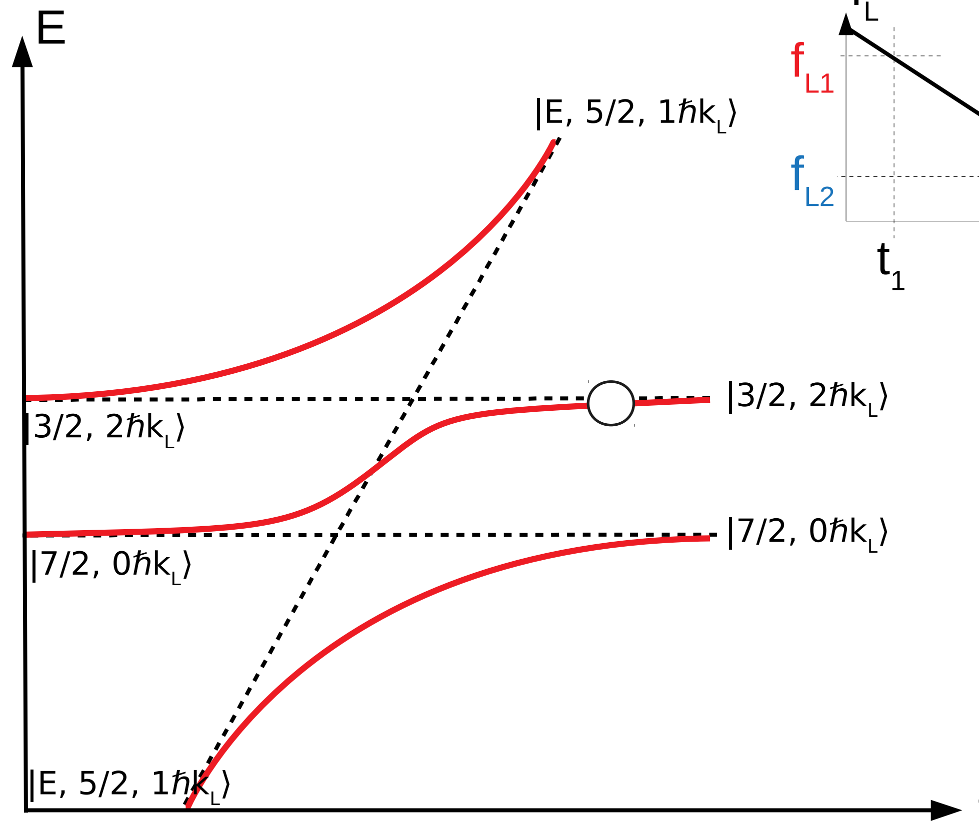


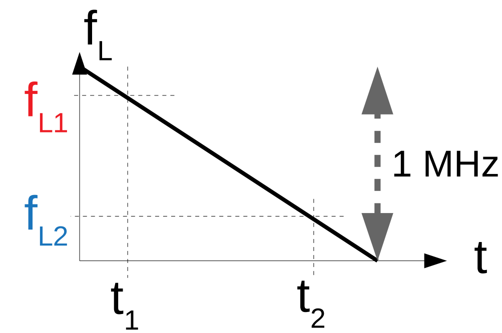


Spin state measurement

Adiabatic spin-dependent momentum transfer

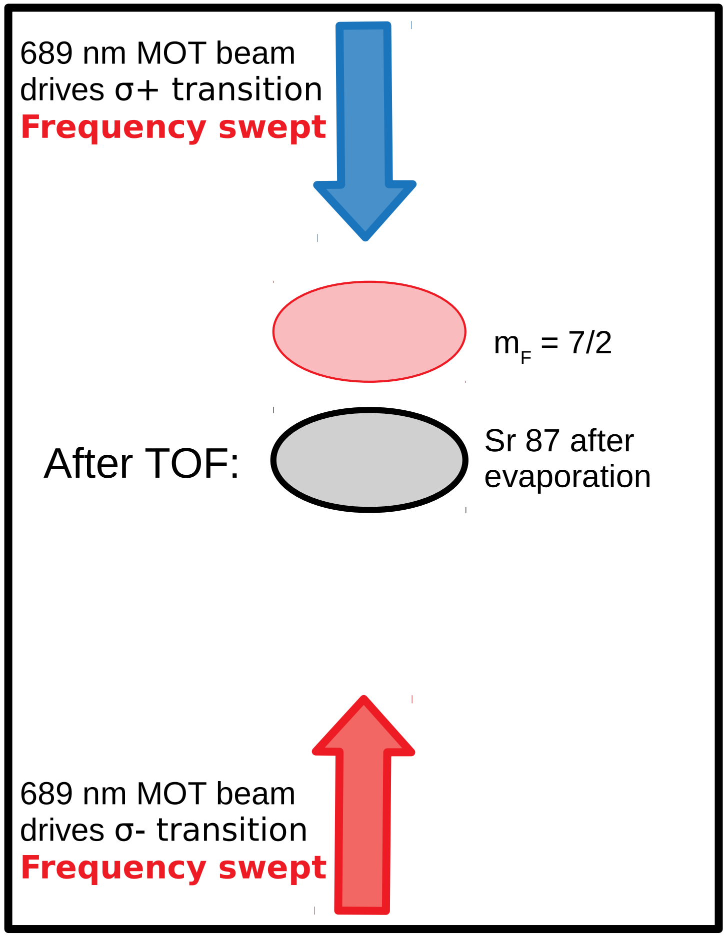


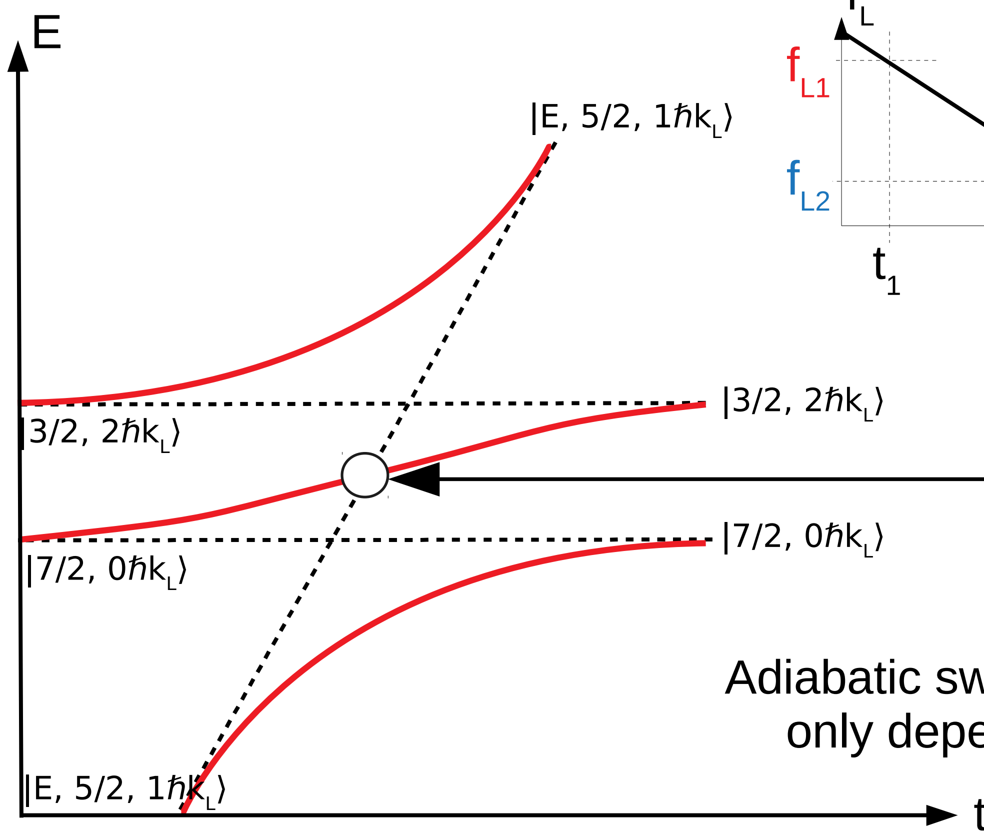




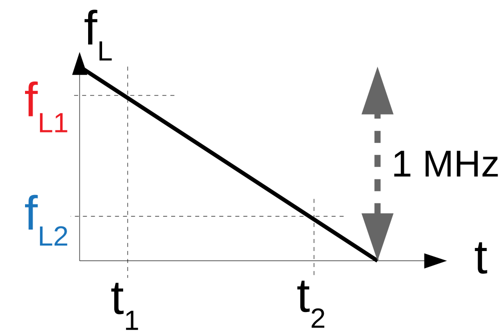
Spin state measurement

Adiabatic spin-dependent momentum transfer





$$p(E)=\frac{4Er^2}{2\Omega^2}$$

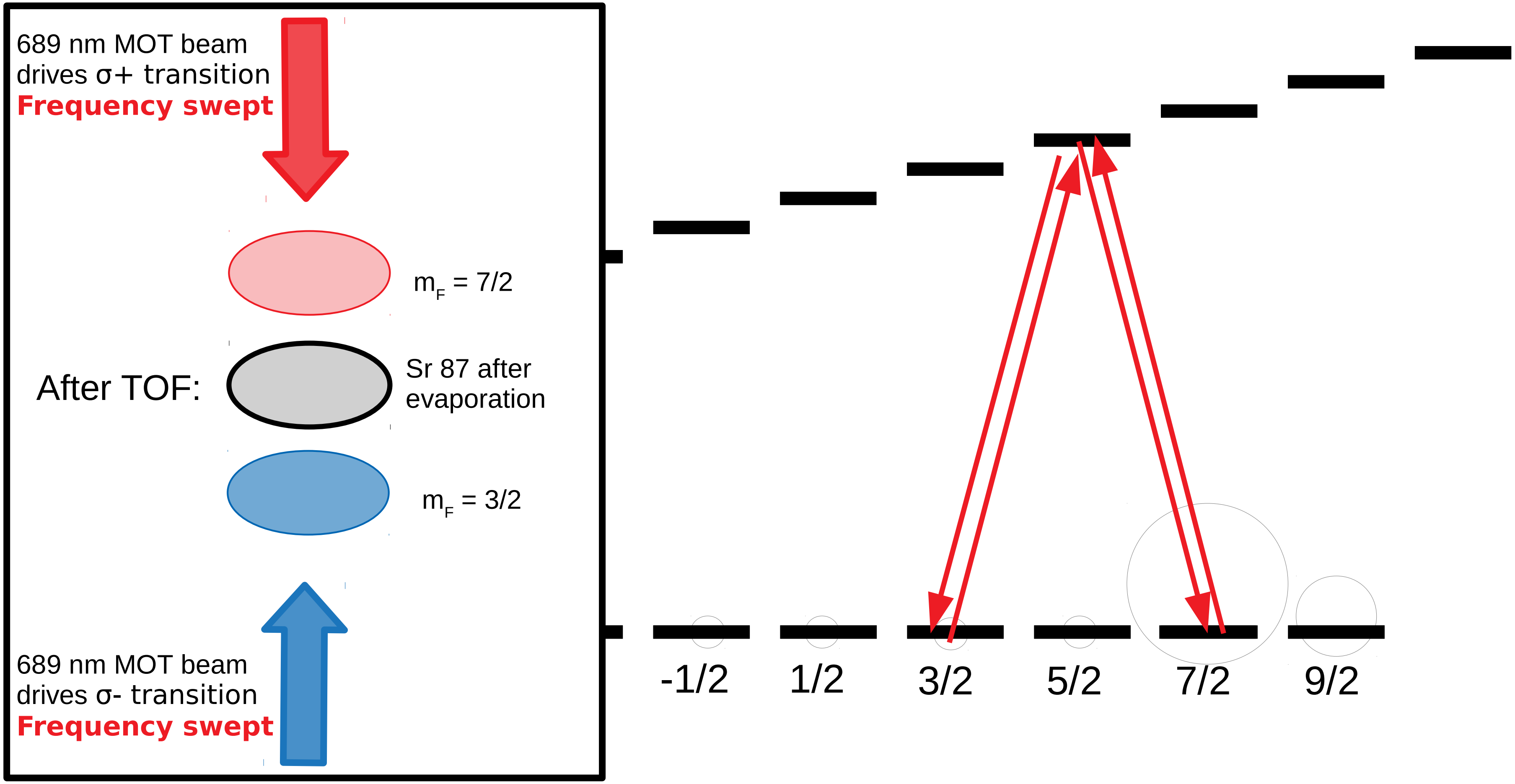


Adiabatic sweep duration only depends on Er

"Grey" adiabatic state:
spontaneous emission strongly suppressed
through the atomic resonance

reminiscent of STIRAP

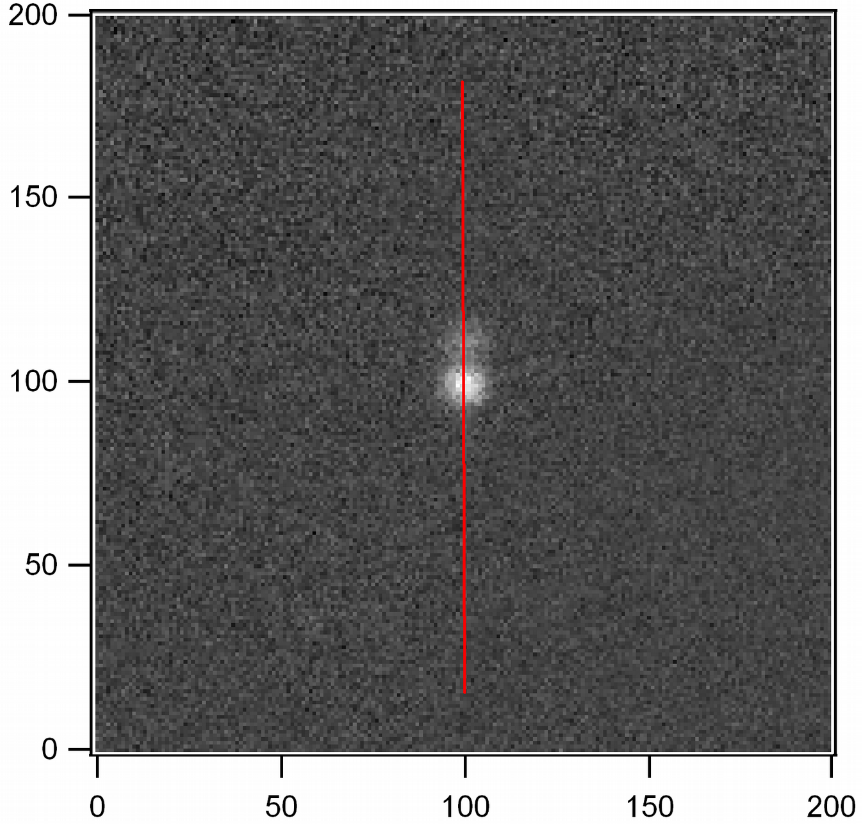
Full population measurements

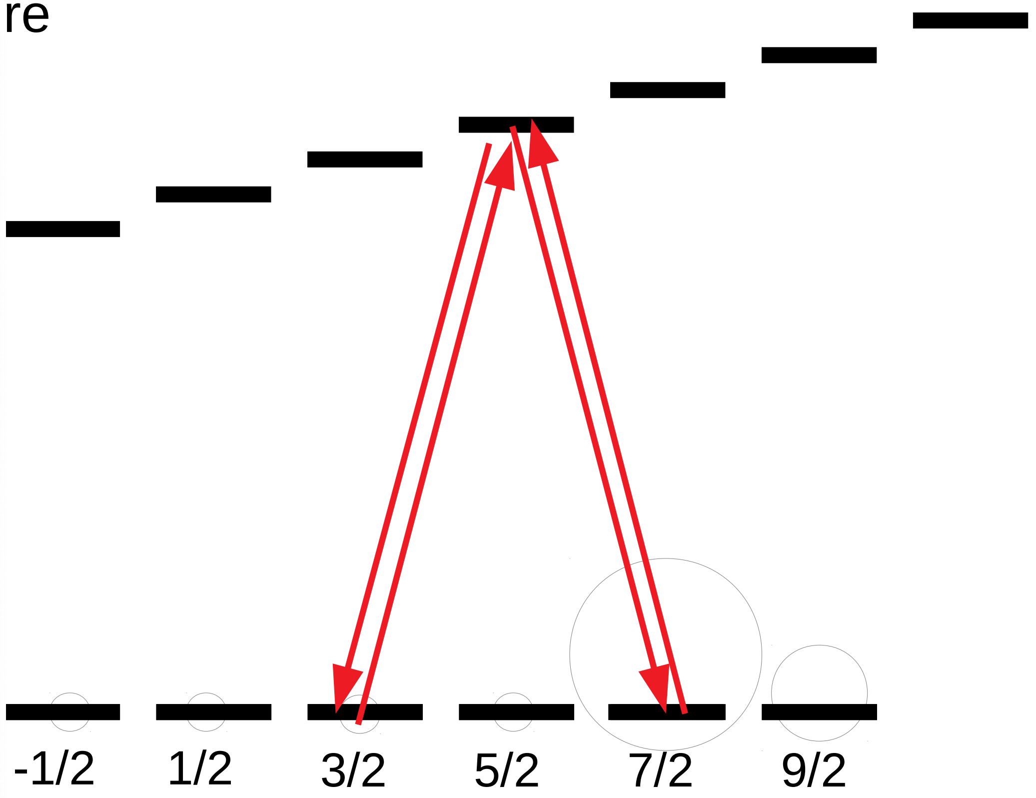


Two spin state populations measured in one run

Full population measurements

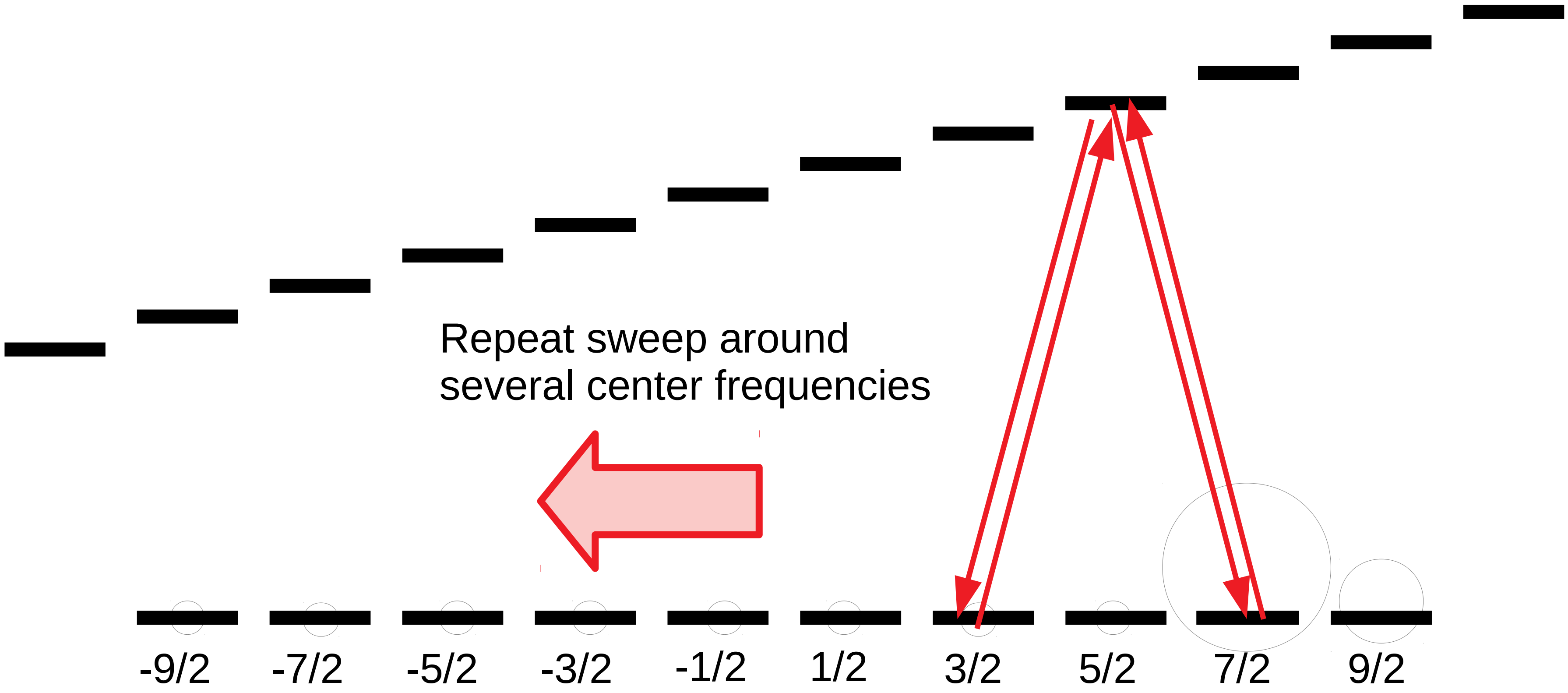
Sample from optical pumping procedure





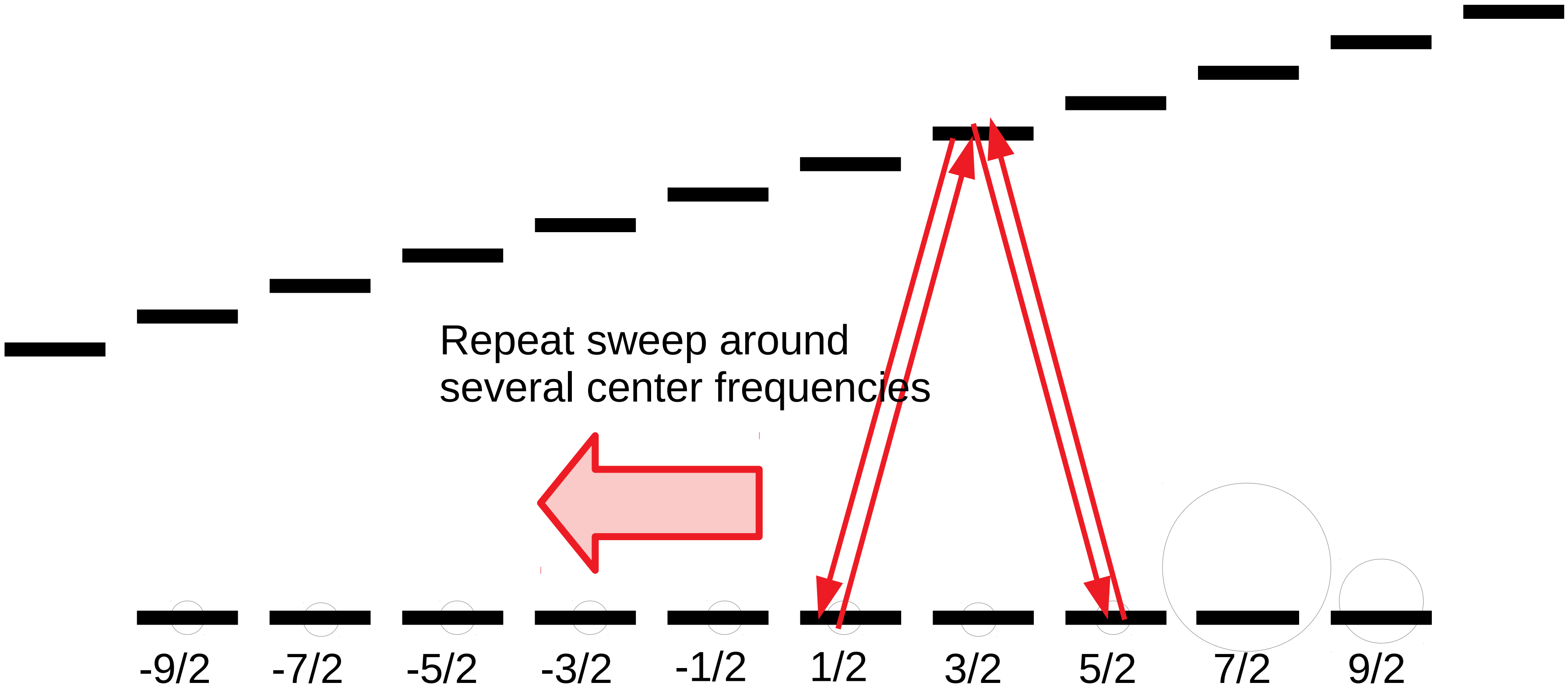
Two spin state populations measured in one run

Full population measurements



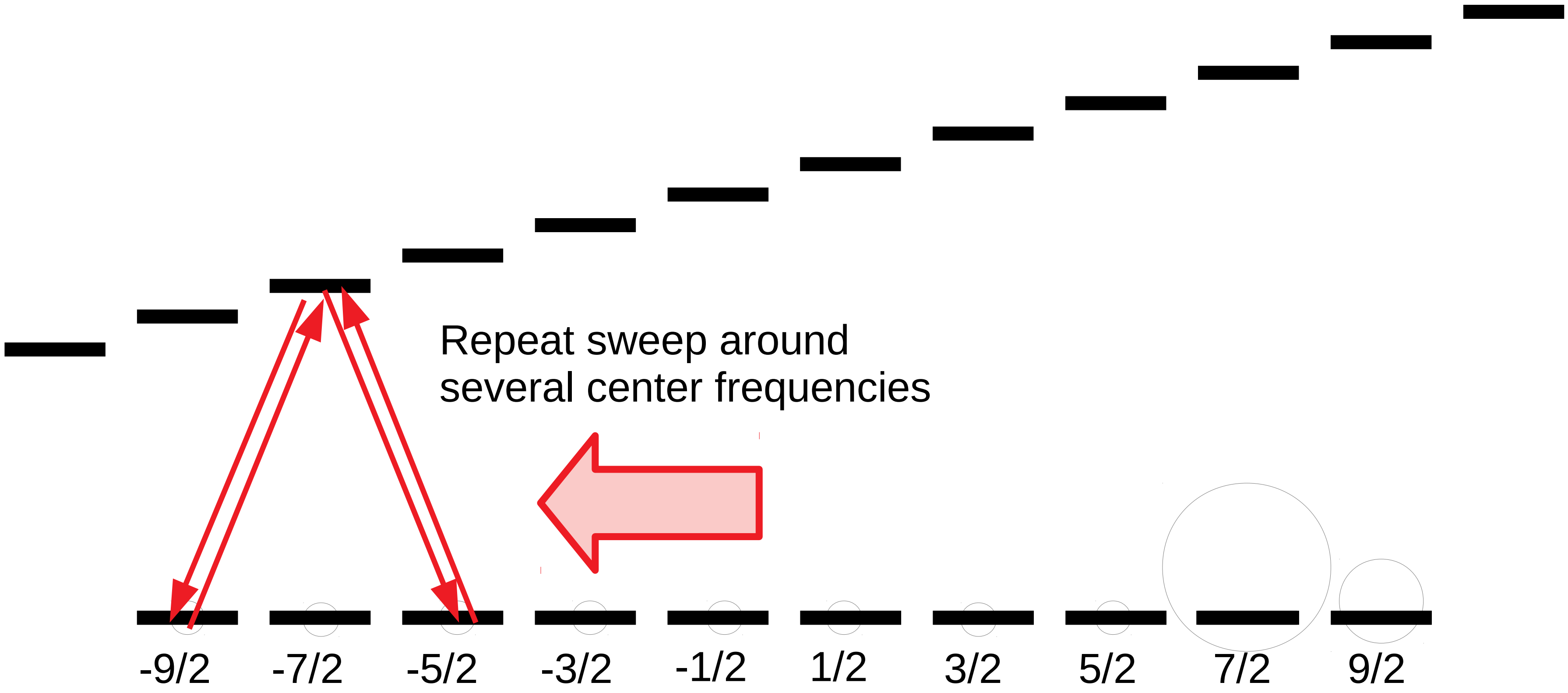
Spin state measurement

Full population measurements

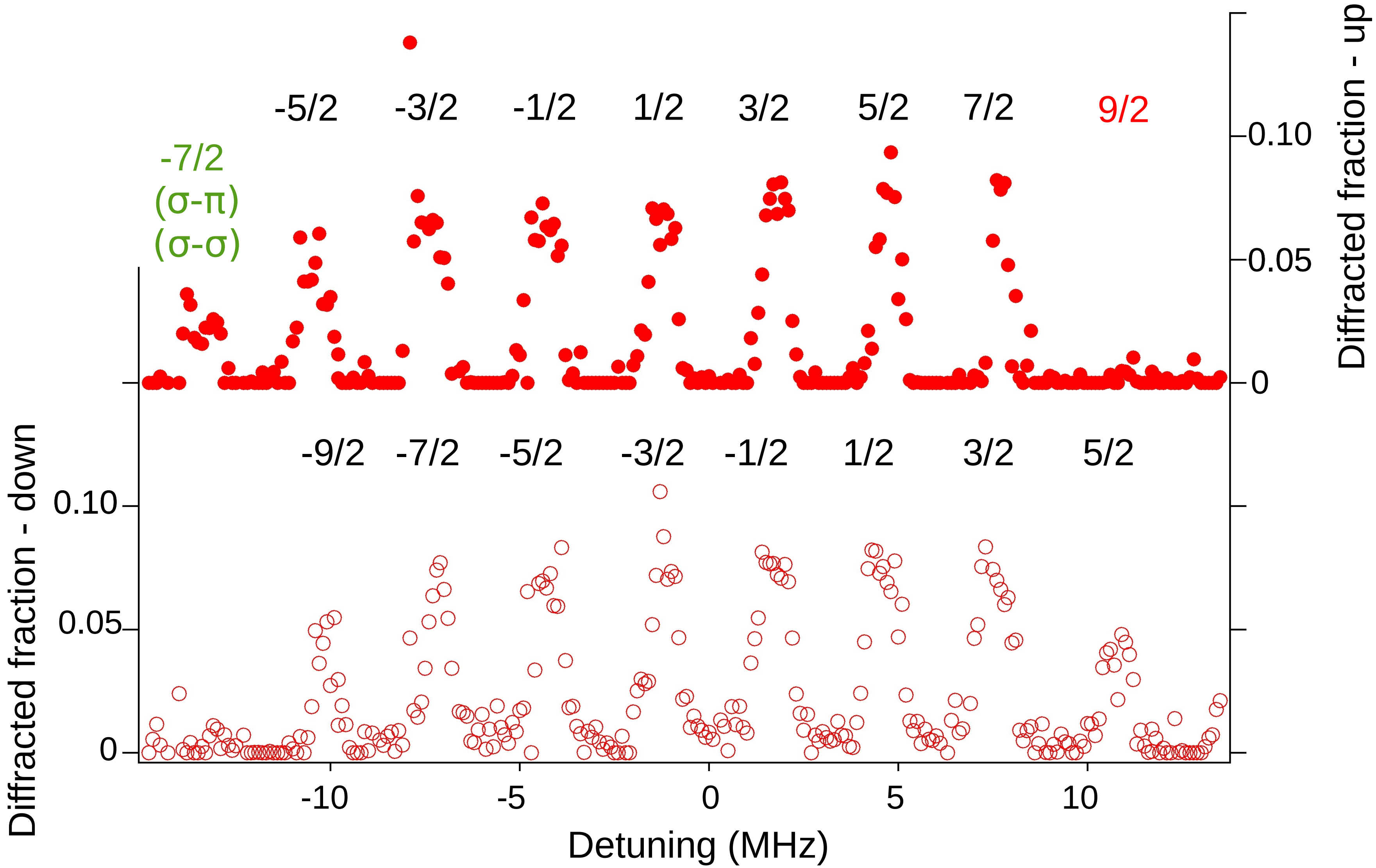


Spin state measurement

Full population measurements



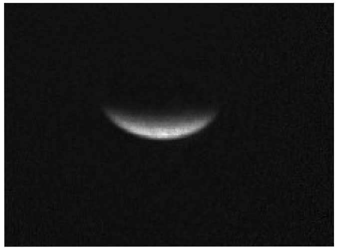
Spin state measurement



Average diffraction efficiency ~70%
Mostly limited by laser intensity (4 mW/cm²) / small Clebsh Gordan coefficients

Thank you for your attention

Birth of the strontium 87 experiment at LPL



Spin 9/2 Fermi gases at T/Tf ~ 0.2

Adiabatic spin-dependent momentum transfer

A free-space version of our ambitions inside the optical lattice:
coherent, position-dependent manipulations of the spin degree of freedom (S.O.C)

I. Manai, P. Bataille, A. Litvinov, J. Huckans, F. Wiotte, A. Kaladjian, O. Gorceix,
E. Maréchal, M. Robert-de-Saint-Vincent, B. Laburthe-Tolra

Shelving spectroscopy of the Sr intercombination line ArXiv:1910.11718

Simple scheme applicable to most Sr spectroscopy setups (cell and beam),
for a large signal enhancement

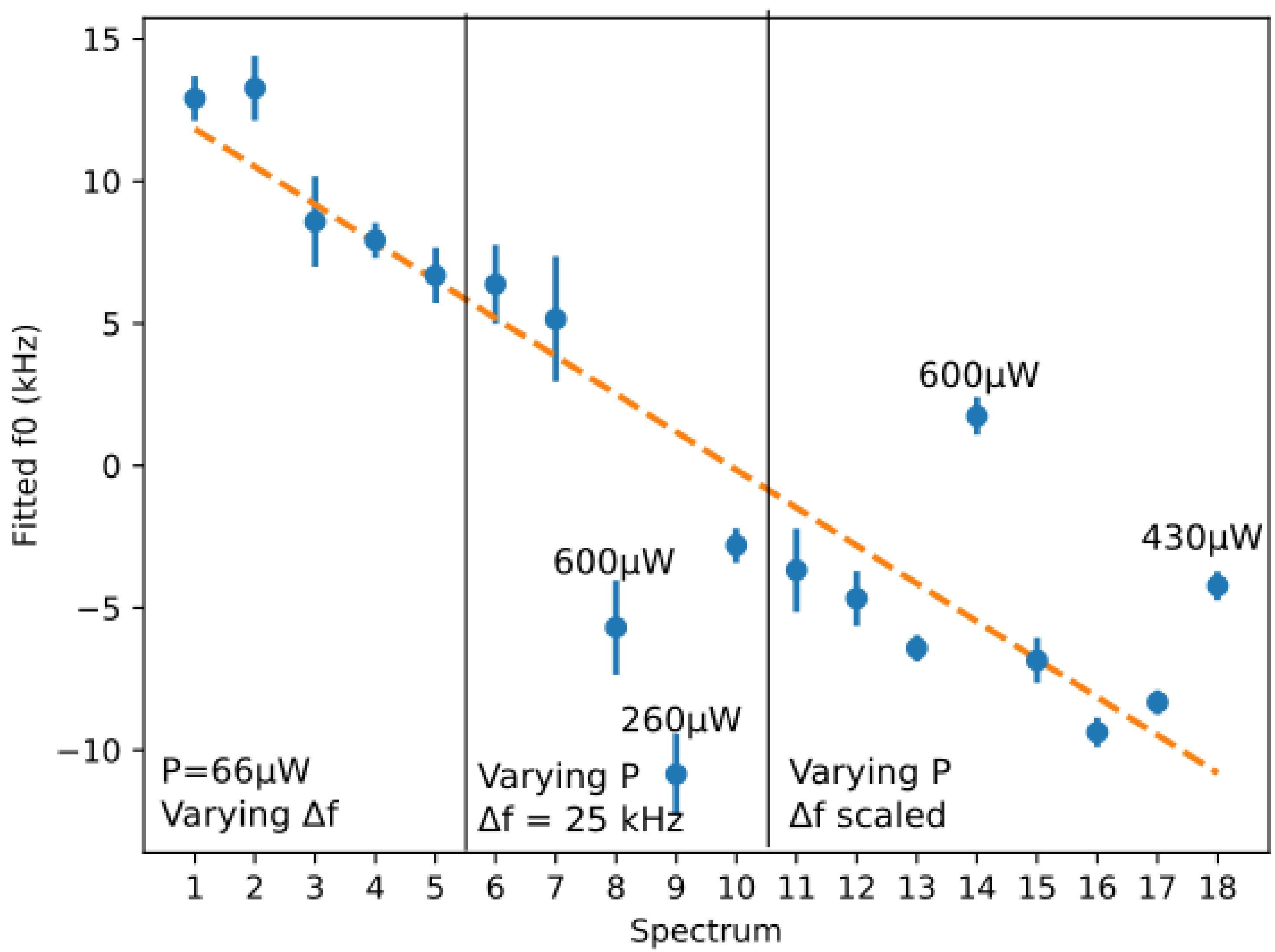
Demonstrated relative instability 2 10^-12 at 1s; expected limitations to a few 10^-14 at 1s,
Offers perspectives for low-complexity frequency references

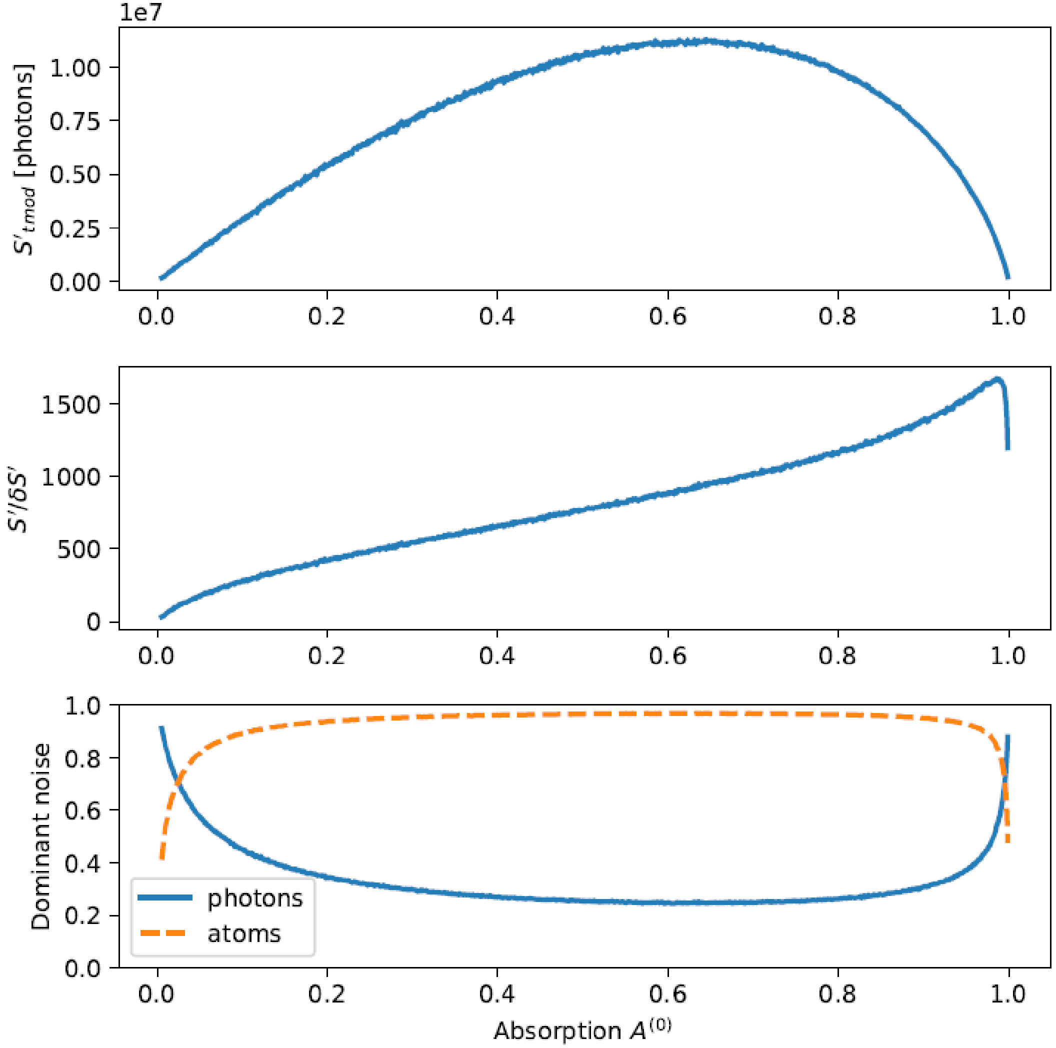
Manai, Duval, Bataille, Wiotte, Laburthe-Tolra, Maréchal, Robert-de-Saint-Vincent
Laboratoire de Physique des Lasers

A. Molineri, C. Briosne-Fréjaville, R. Journet, F. Nogrette, M. Cheneau
Laboratoire Charles Fabry

ANR, FIRST-TF, DIM Nano'K, DIM Sirteq (IFRAF)

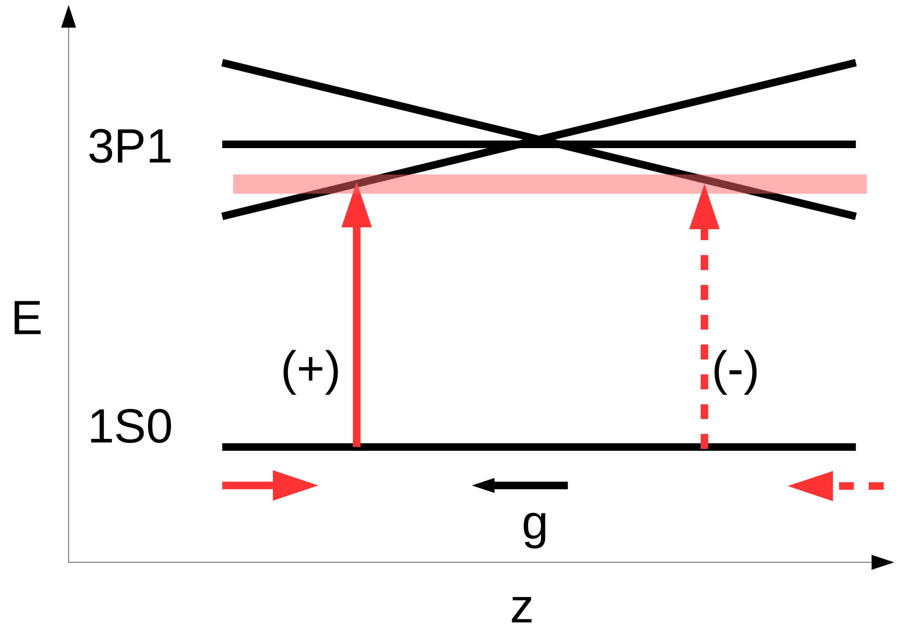
Reproducibility




1e7
S'_{tmod} [photons]
1.00
0.75
0.50
0.25
0.00
0.0
0.2
0.4
0.6
0.8
1.0
$S'/\delta S'$
1500
1000
500
0
Dominant noise
photons
atoms
Absorption $A^{(0)}$

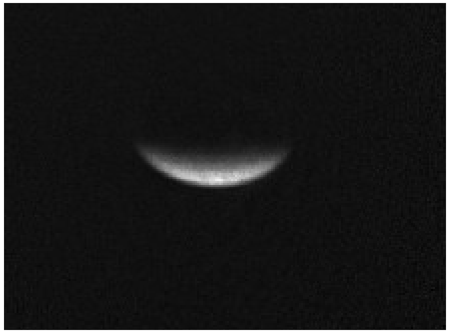
Narrow-line cooling of 88 Sr

Illustrations of specificities in narrow-line MOTs

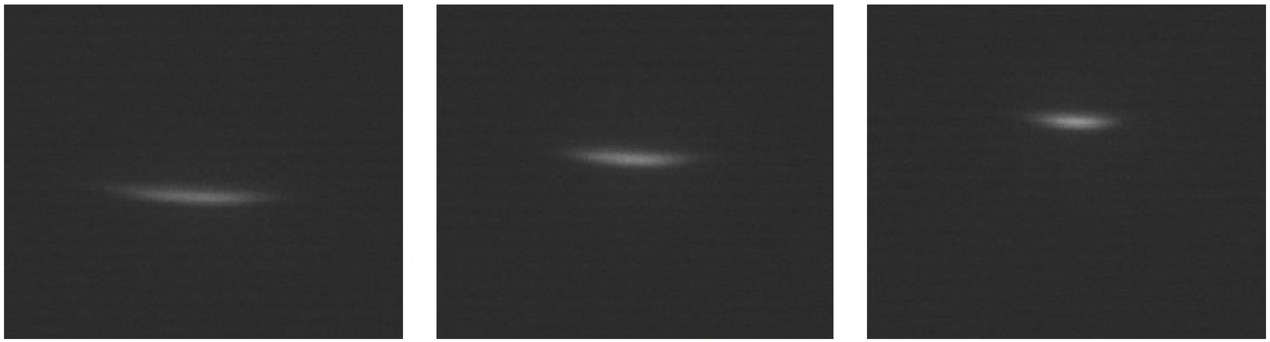


Laser cooling
on a resonant shell

→ capture stage
requires
artificial line
broadening

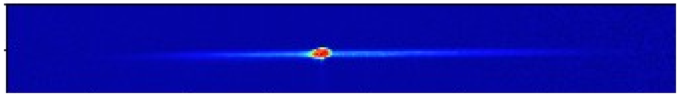


Tool: strong MOT compression by a frequency ramp



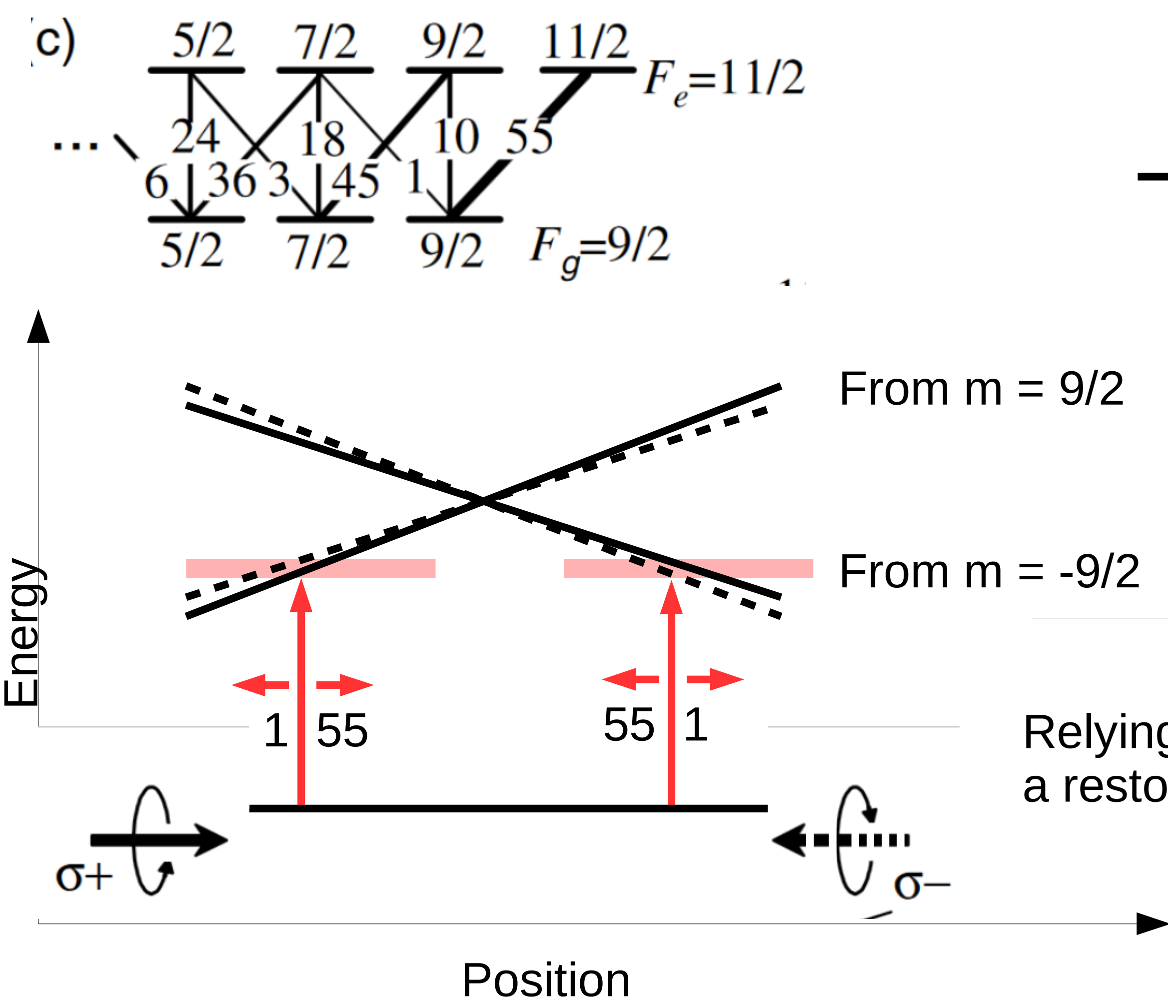
$F = 99\,\mathrm{MHz}$ $F = 99.2\,\mathrm{MHz}$ $F = 99.4\,\mathrm{MHz}$

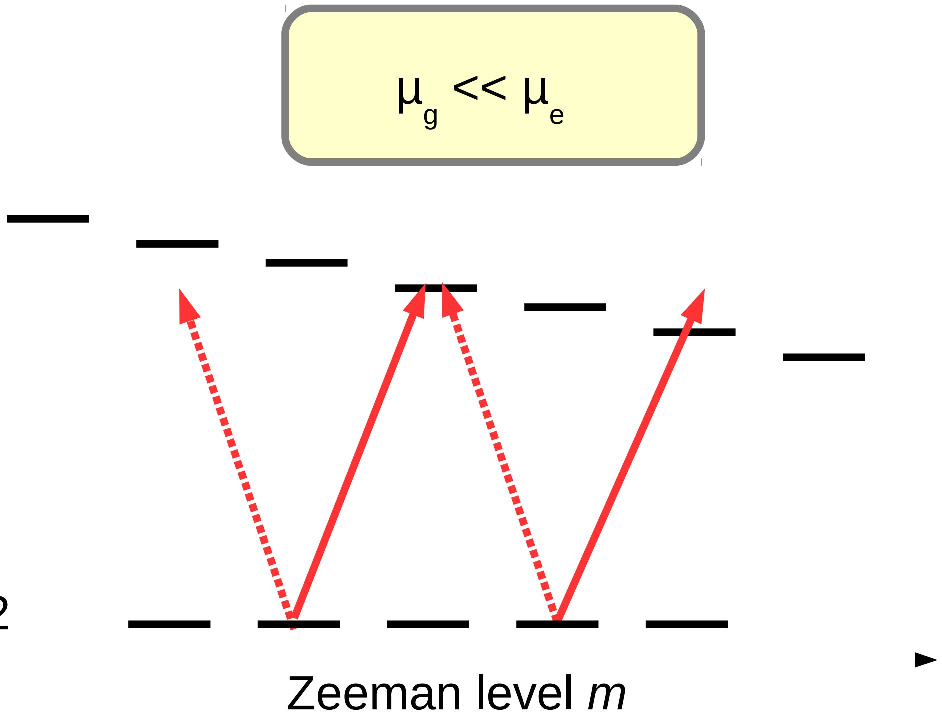
July 2018: 88 Sr in a dipole trap



Narrow-line cooling of 87 Sr

Mukayami et al, PRL 90, 113002 (2003): complications from the hyperfine structure





Relying on polarisation-dependent detunings,
a restoring force for *m* could be ejecting for another

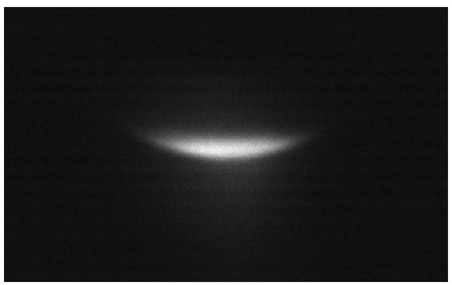
- restoring force from Clebsh Gordan
- Only one side of the trap...

Enable spin state randomisation
Laser cooling on a second transition
with much lower Lande factor

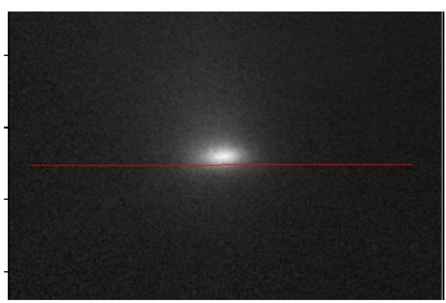
Birth of the strontium experiment

- narrow-line laser cooling (~μK)

^{88}Sr (May 2018)



^{87}Sr



Temperature

Doppler limit : $k_B T \sim \frac{\hbar \Gamma}{2} \sim k_B \times 350\, nK$

Recoil limit: $k_B T \sim \frac{h^2}{2 m \lambda^2} \sim k_B \times 460\, nK$

Density / Phase space density

Reduced radiation trapping

$$n_0 = \frac{\kappa}{\Gamma s_0 \sigma \hbar k_L} = \frac{4}{3\pi} \frac{|\delta|}{\Gamma} \frac{\gamma_J b'}{\Gamma} k_L^2.$$

Katori et al (1999) :
free space MOT, 10^{12} / cm^3
10^{-2} phase space density

In principle ideal for loading a 3D optical trap
Ido et al (2000), Stellmer et al (2013) :

Laser cooling in dipole traps to PSD's of up to 1