Shelving spectroscopy of the strontium intercombination line

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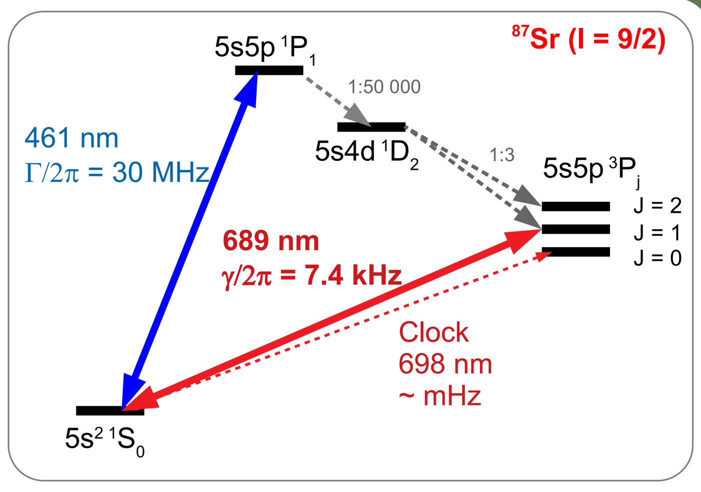
Website: http://www-lpl.univ-paris13.fr/gqm/

Narrow-lines for atomic physics

Optical clocks

Relative instabilities < 10^{-16} at 1s [Ludlow 2015]



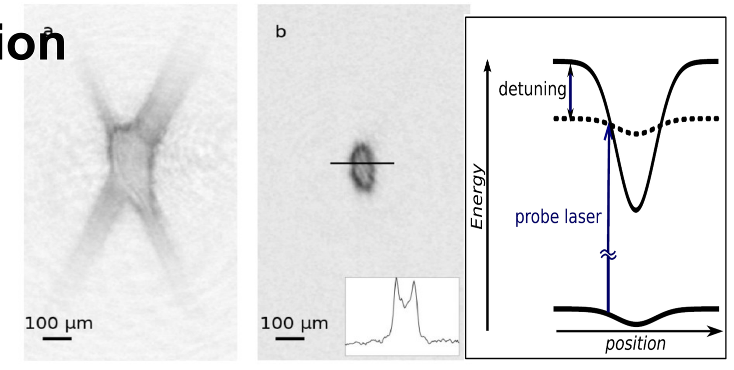
Narrow-line cooling

- Doppler limit $k_B T \approx \hbar \Gamma$
  1 MHz : 50 μK → 1 kHz : 50 nK
- Recoil limit : $k_B T \sim h^2 / 2m\lambda^2 \sim 500$ nK
  [Katori 1999]

Sensitive probes / spin manipulation

Spatial resolution in an inhomogeneous shift : $\delta x \approx \frac{\Gamma}{\nabla \omega}$

Spin sensitivity at low field, $g \mu_B B \gg \hbar \Gamma$



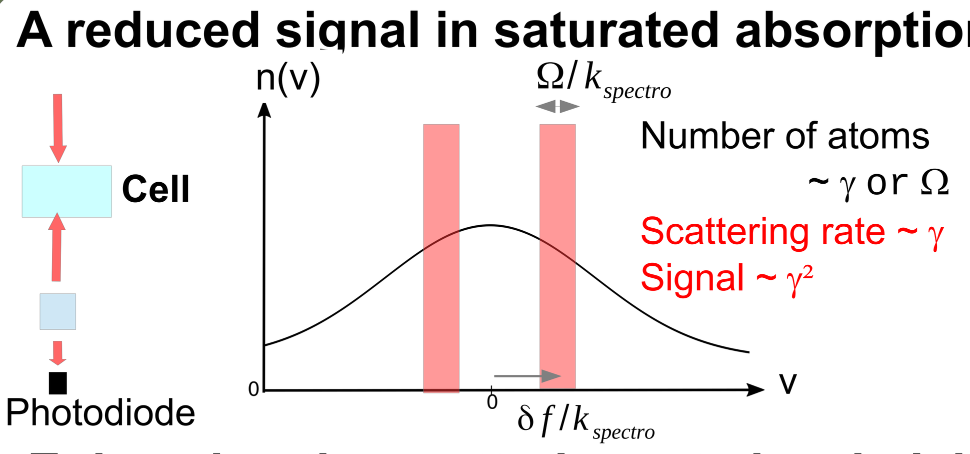
[Brantut 2008]

Photo-association spectroscopy, optical control of interactions

Optical Feshbach resonances : loss rate $K \approx \frac{2\hbar}{m} \frac{\Gamma}{\Delta} a_{opt}$ [Yamazaki 2010]

Frequency referencing on narrow lines

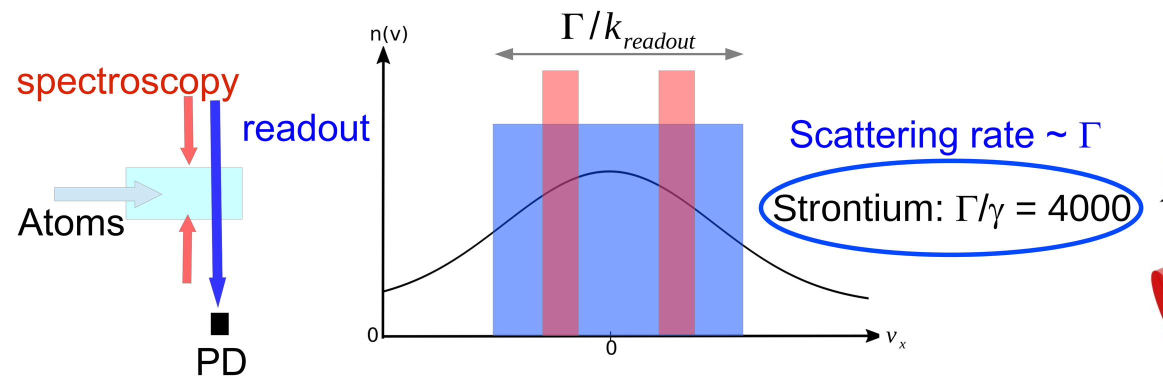
A reduced signal in saturated absorption spectroscopy:

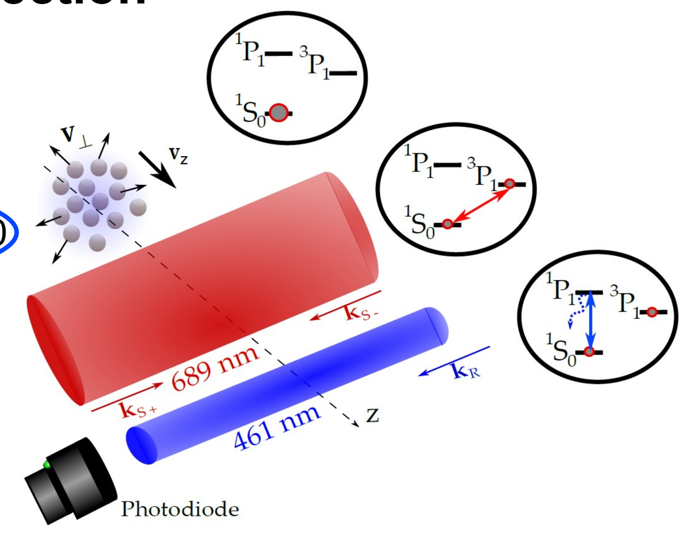


Saturated spectroscopy on the 7kHz-wide Sr intercombination line:

Li 2004: Hot cell
Ferrari 2003: Atomic beam

Enhancing the scattering rate by shelving detection

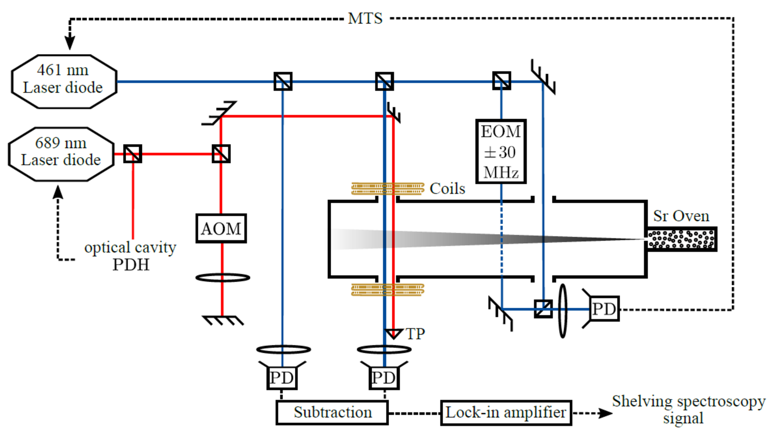




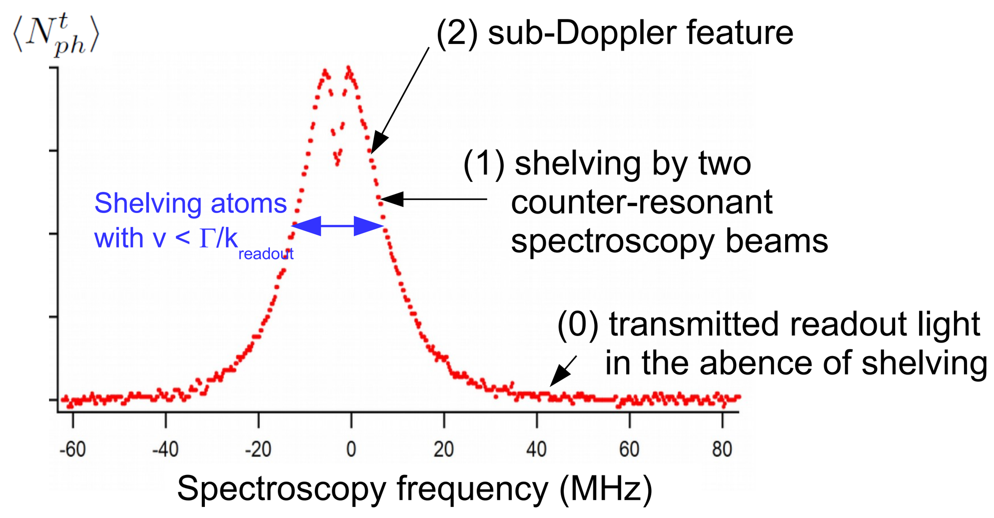
E.g. thermal Calcium beam clocks:
Kai-Kai 2006, Mac Ferran 2009...

Shelving detection in all settings : atomic beams and hot vapor cell

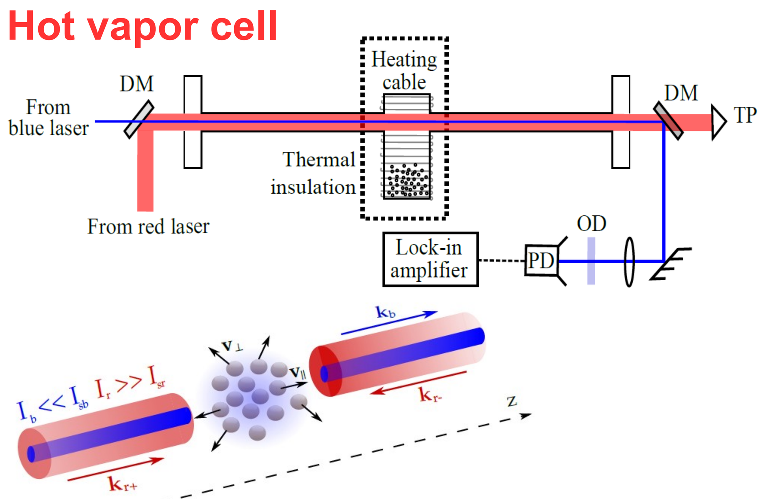
Atomic beam



Well defined atomic beam direction
Separated interrogation and readout

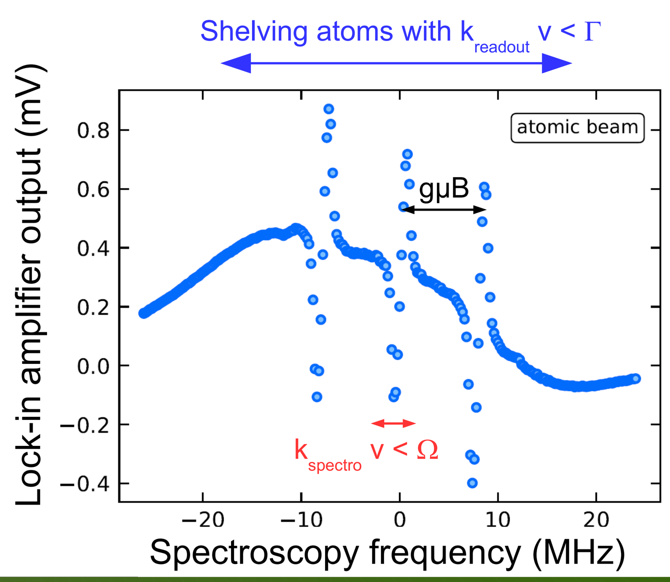


Hot vapor cell

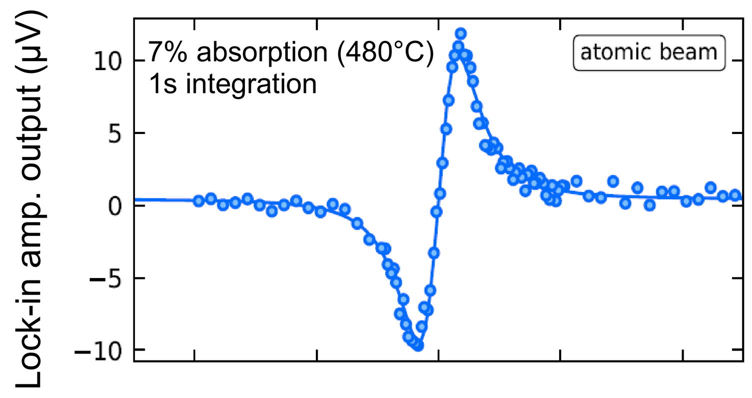


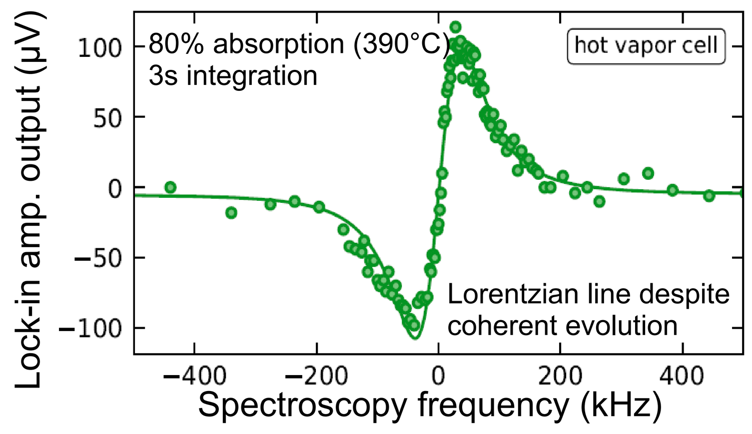
Isotropic velocity distribution
Locally overlapped interrogation and readout

Lock-in amplifier demodulation:



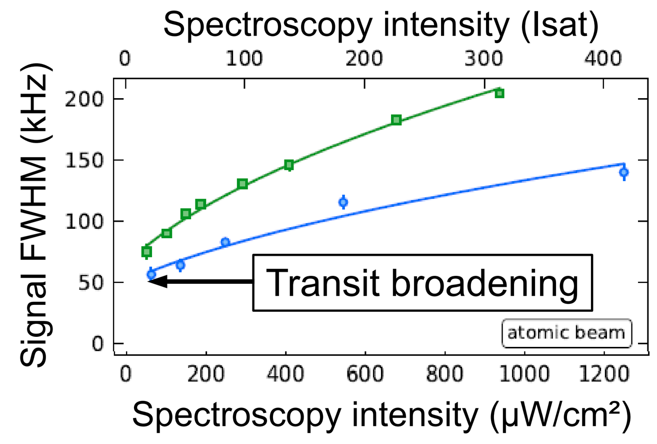
Three lines: σ+, σ-, and cross-over (π)





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

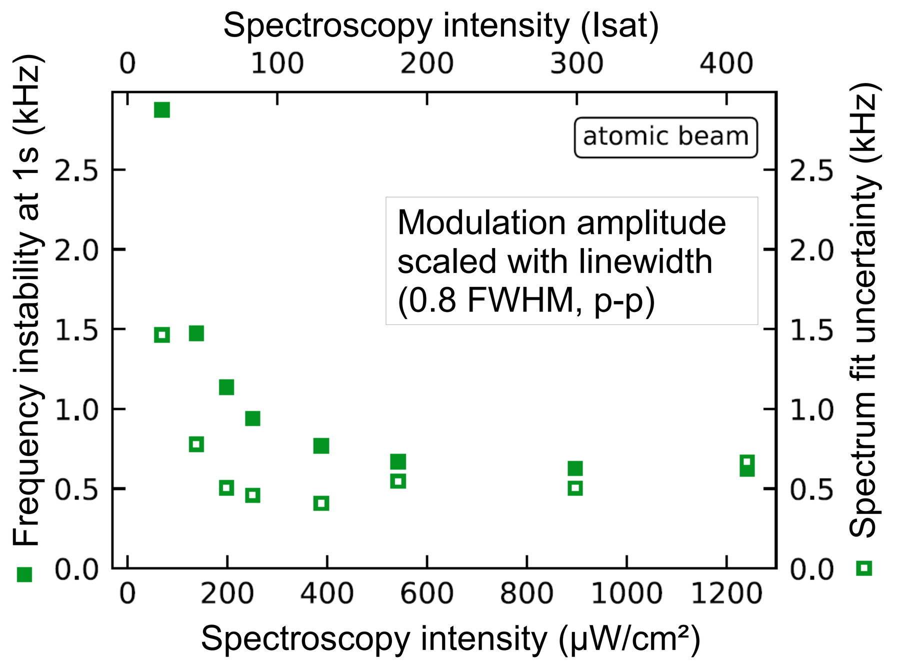


Robust scheme, applicable to all existing Sr cells (hot vapors and beams)

Atomic beams: Ramsey schemes applicable
(and improvements, e.g. Mc Ferran 2009, Shang 2017)
Vapor cells: High absorption at low temperature (source lifetime)
Pressure robustness (see perf.) → no pump
Vanishing first-order Doppler bias

Performances

Measurement instability

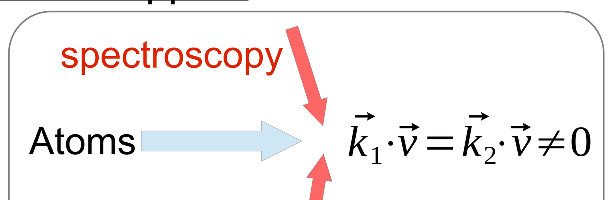


Short-term instability optimal when power-broadening dominates over transit broadening

Atomic beam with 7% readout beam absorption:
$2\ 10^{-12}$ relative instability at 1s
fit uncertainty 450 Hz *consistent with sampling*

Measurement biases

1st-order Doppler: retroreflection ~ 50 μrad



Beam: up to 10 kHz shift, 15 kHz broadening
Cell: symmetric broadening

2nd-order Doppler: 260 Hz
Recoil doublet : +/- 4.8 kHz
AC-stark shift: 0.2 Hz

Pressure: signal loss at 10^{-3} mbar of Ar
no shift or broadening detected
Expected: 30 kHz broadening [Crane 1994]

→ Hot cell: - no need for a pump
- viewport protection by bufffer gas

Fundamental noise limitations

Statistics of the transmitted readout light

$$\langle N^t_{ph} \rangle = \langle T \rangle \langle N^i_{ph} \rangle$$
$$\mathrm{Var}(N^t_{ph}) = \langle T \rangle \langle N^i_{ph} \rangle + \mathrm{Var}(T) \langle N^i_{ph} \rangle^2$$

Photon shot noise — Effect of atom shot noise on the transmission

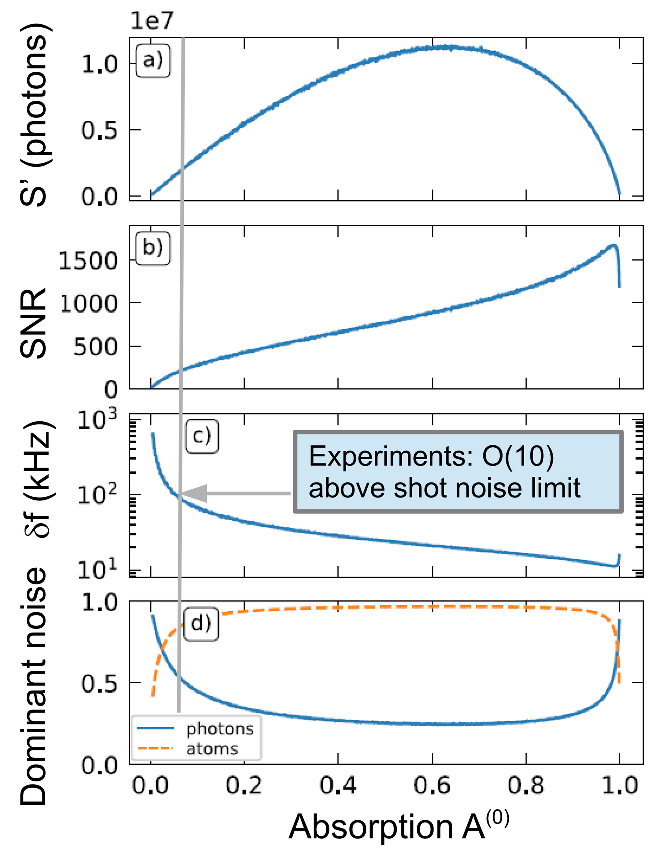
Advantage of shelving detection: relative photon shot noise can be low

Spectroscopy instability

$$S' = G\left(P\tau \frac{\lambda_R}{hc}(1 - A^{(2)})\right) - G\left(P\tau \frac{\lambda_R}{hc}(1 - A^{(1)})\right)$$
$$= G\left(N^{t,(2)}_{ph} - N^{t,(1)}_{ph}\right).$$

$$\mathrm{SNR} = \sqrt{\frac{t_{\mathrm{integr}}}{2\,t_{\mathrm{sample}}}} \cdot \sqrt{\frac{\left(\langle N^{t,(1)}_{ph} \rangle - \langle N^{t,(2)}_{ph} \rangle\right)^2}{\mathrm{Var}(N^{t,(1)}_{ph}) + \mathrm{Var}(N^{t,(2)}_{ph})}}$$

$$\delta f = \frac{\gamma(I)}{2\pi} \frac{3\sqrt{3}}{32} \frac{1}{\mathrm{SNR}}$$



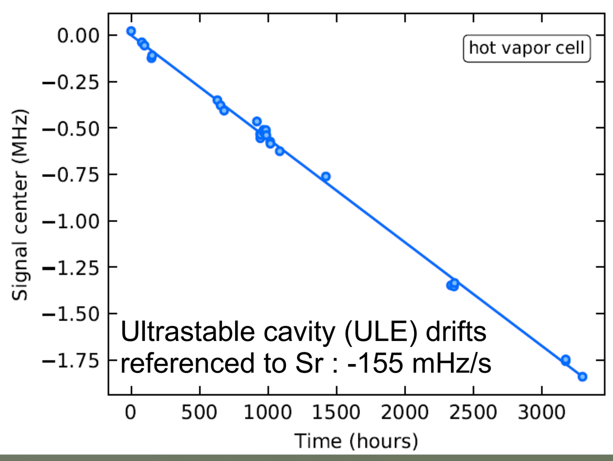
Strong improvement achievable:
at high densities, 3 10^{-14} at 1s
Very similar to Ca-beam clocks, e.g. McFerran 2009: 7 10^{-14} at 1s

Outlooks

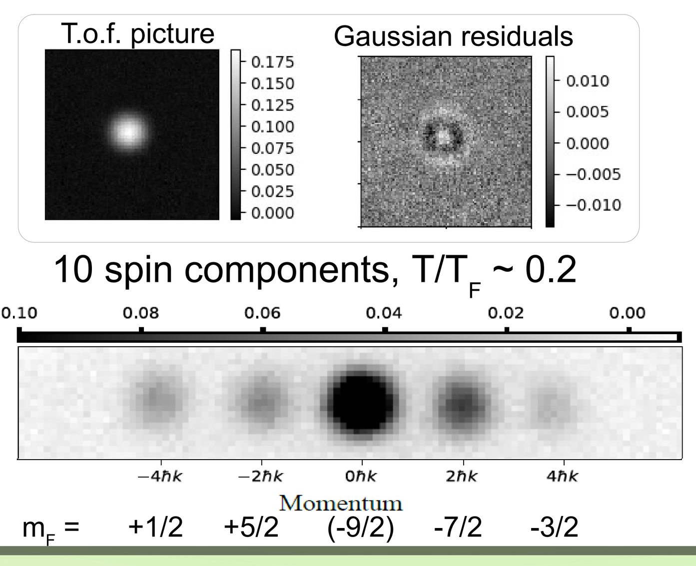
Shelving spectroscopy

Robustness and ease of implementation:
applicable to all kinds of cell
Expected performance limitations ~ 10^{-14}:
a future as low-complexity clock?

Experiments outlook:
characterization of the **long-term stability**
(*requires a second absolute reference*)



Other progresses: *- SU(10)-symmetric Fermi sea of ^{87}Sr*
- Adiabatic spin-dependent momentum transfer
(Bataille 2020)



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