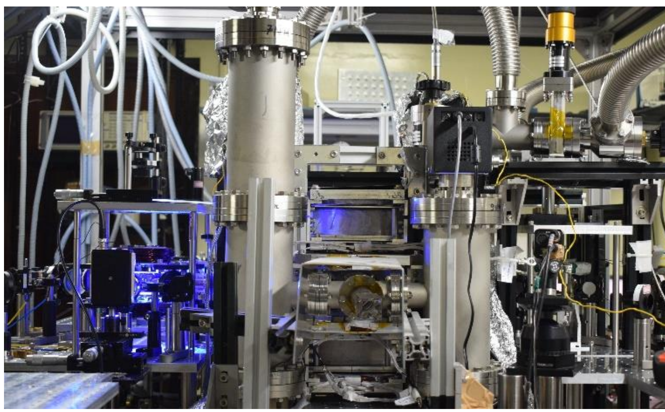
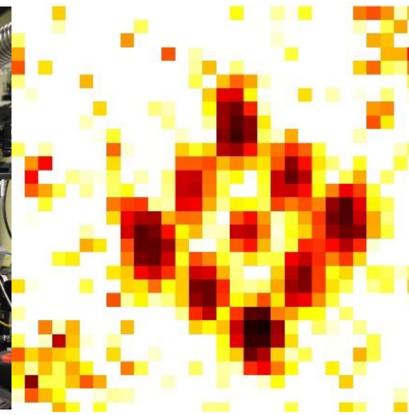
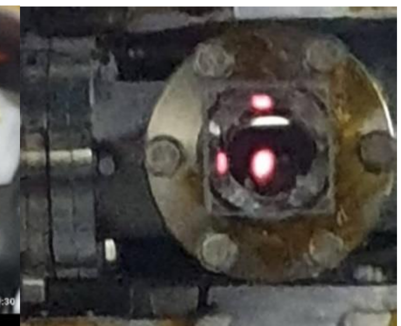
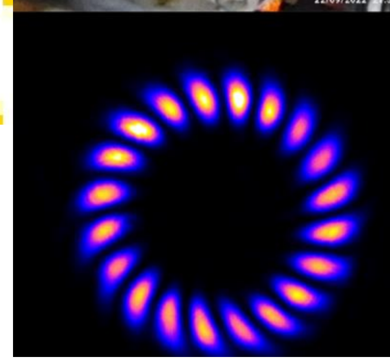
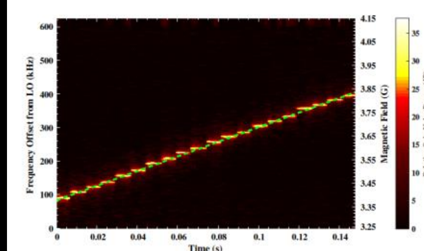
Experiments with cold atom mixtures and applications of driven spin systems

Saptarishi Chaudhuri
Raman Research Institute,
Bangalore

24 January, 2024
ICTS, Bangalore

Research Programs at QuMiX group

- ***Mixtures of cold Sodium and Potassium atoms***
- Spin noise spectroscopy and magnetometry
- Trapped cold atoms in structured optical potential and many body physics
- quantum diffusion and impurity problem

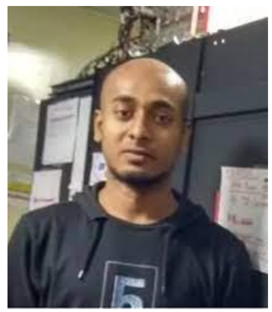
QuMiX Team and Funding Support

Anirban Misra

Sayari Majumder

Gourab Pal

Maheswar Swar
PhD 2022
Post-Doc @ Weizmann, Israel



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Sanjukta Roy

MeitY
Government of India

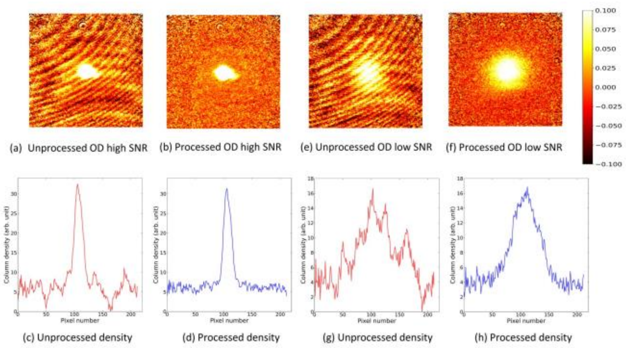
DST@ 1971-2021
विज्ञान एवं प्रौद्योगिकी विभाग
DEPARTMENT OF SCIENCE & TECHNOLOGY

I-HUB QUANTUM TECHNOLOGY FOUNDATION

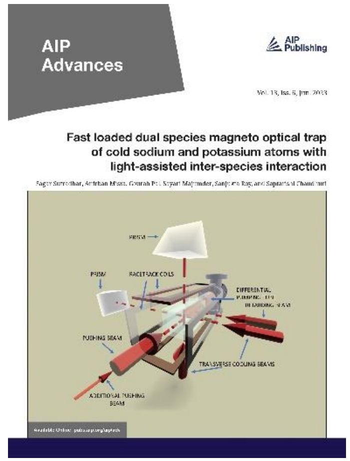
I-HUB Quantum Technology Foundation

RRI

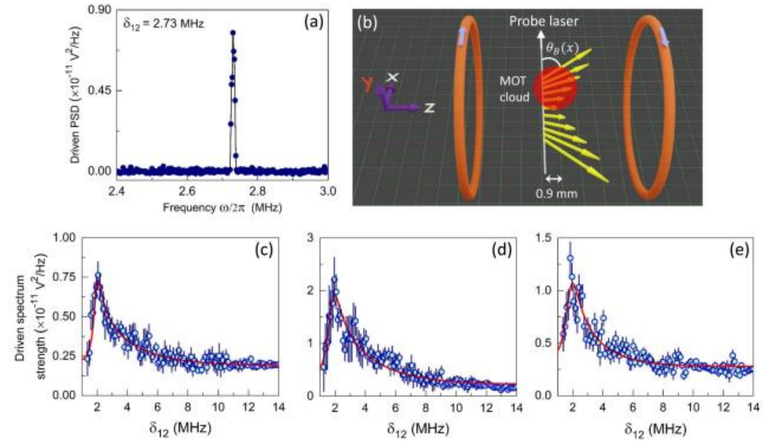
Selected recent publications from Lab relevant to this talk



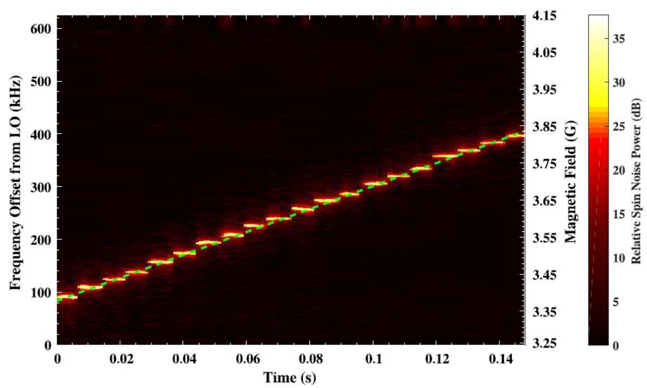
Applied Optics 62 (33), 8786 (2023)



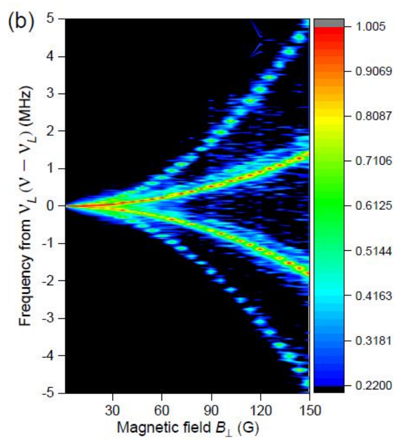
AIP Advances 13, 065317 (2023)

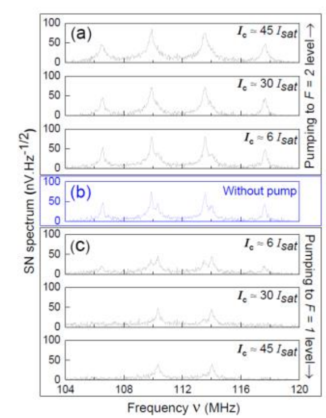


PHYSICAL REVIEW RESEARCH 3, 043171 (2021)



IEEE-TIM, ***70***, pp. 1-8, 2021





Optics Express 26, 24,32168-32183 (2018)

Also: Maheswar Swar, PhD thesis, 2022, Sagar Sutradhar PhD thesis 2023

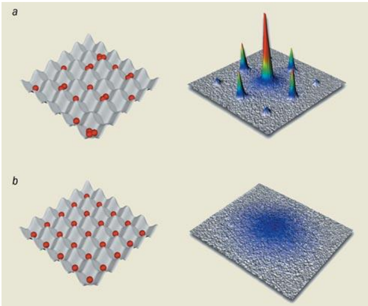
RRI Logo using holographic projection of laser light

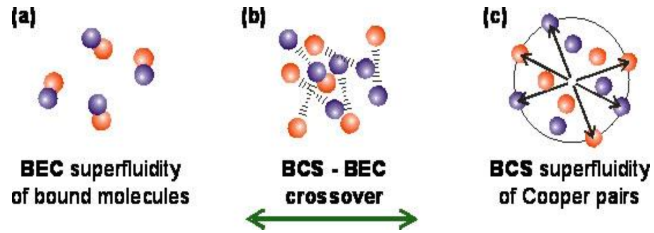
False colour images (intensity heatmap)

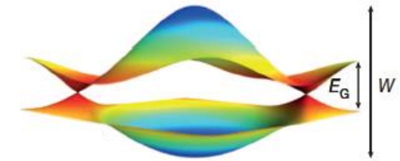
We use the same technique to create structured light and arbitrary optical potential for cold Atoms using MEMS Digital Mirror Devices – more details later in the talk!

Context and motivation

Ultra-Cold Atoms as analog quantum simulators



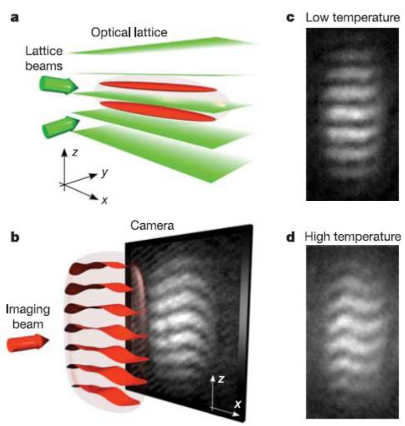




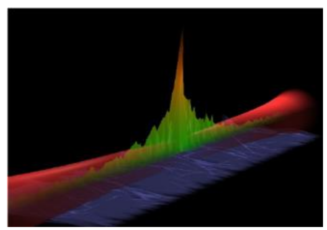
Controlling Dirac points with Fermi gas in Honeycomb lattice ETH Zurich

BEC-BCS crossover (ENS, MIT, JILA, Innsbruck)

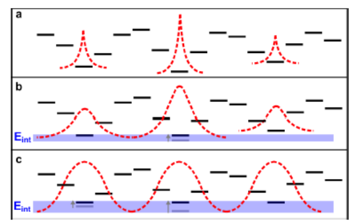
Superfluid-Mott insulator Transition (MPQ Munich, ETH Zurich)



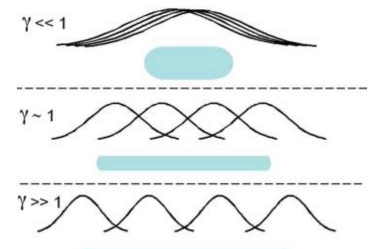
Berezinskii-Kosterlitz-Thouless crossover (ENS, NIST, JILA)



Anderson localization (Florence, Orsay)

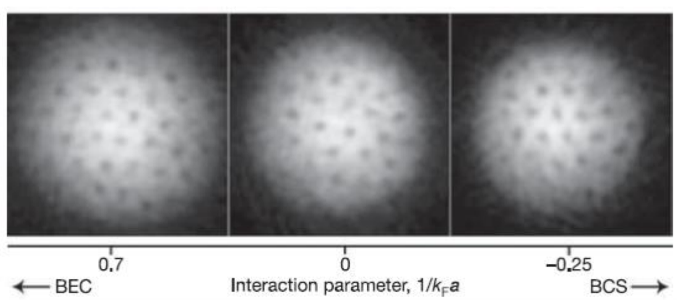


Bose-Glass (Florence)



Tonks-Girardeau gas (Mainz, Penn State)

Time Frame: 2000s - 2015



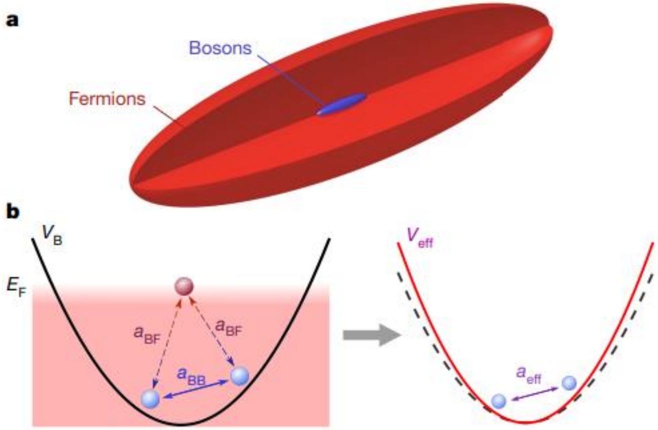
Quantized vortices in Fermion gases (MIT)

Context and motivation

Mixtures of Cold Atoms: mediated and long range interactions

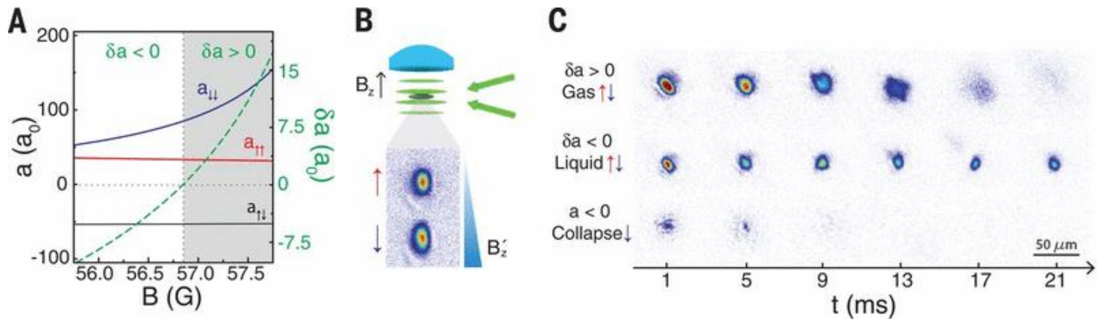
Some examples:

Fermion mediated long-range interactions



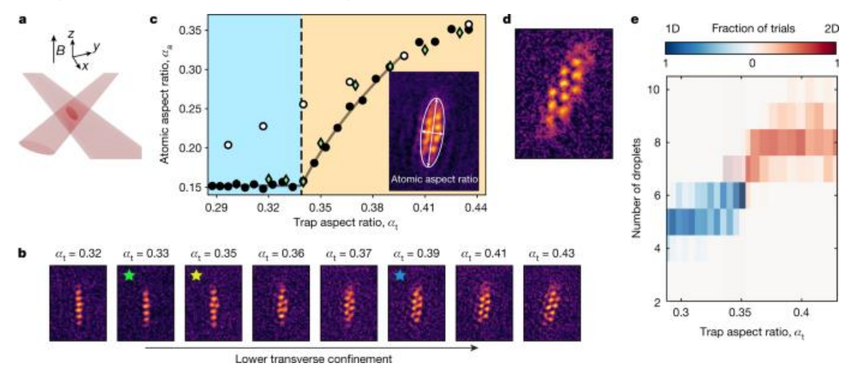
Chicago, Nature, 2019
Also theory predictions (S De & I. B Spielman, App Phys B, 2014)

Quantum droplets in Mixtures of ultra-cold atoms



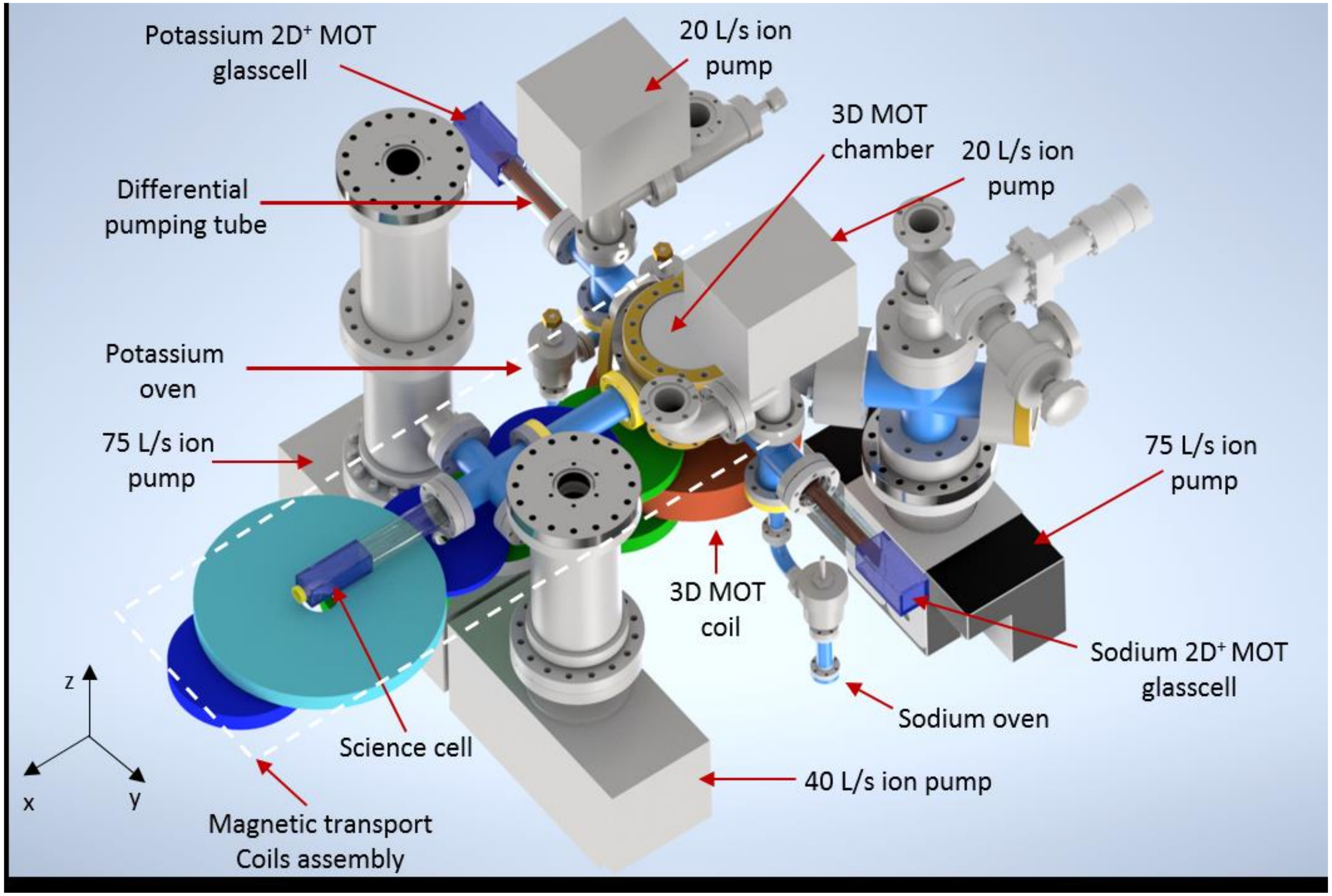
ICFO, Spain, Science 2017

Super-solids in Dipolar Quantum Gas



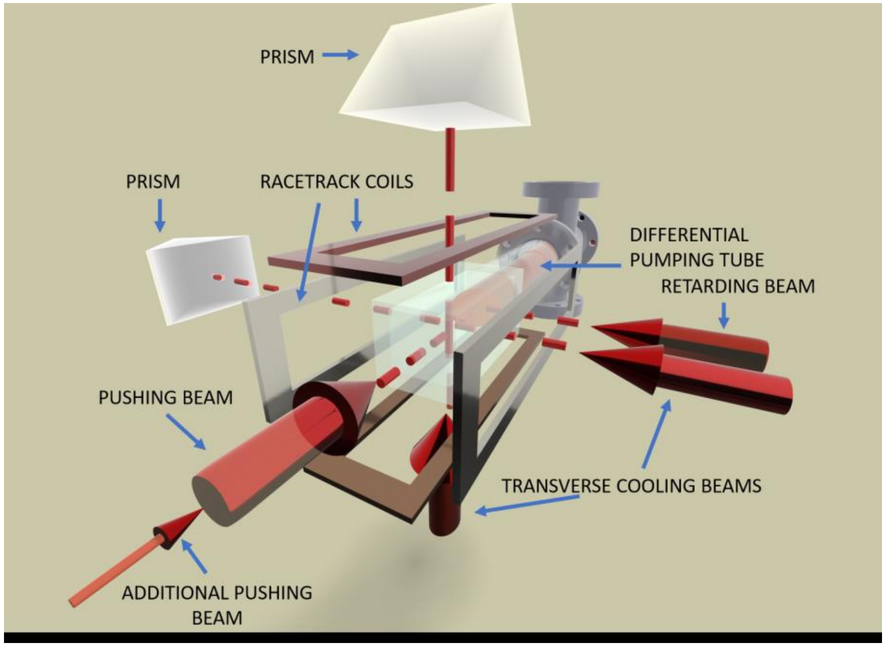
Innsbruck, nature, 2021, also Florence (2022)

The Experiment system @ RRI



Reference: *AIP Advances* 13, 065317 (2023)

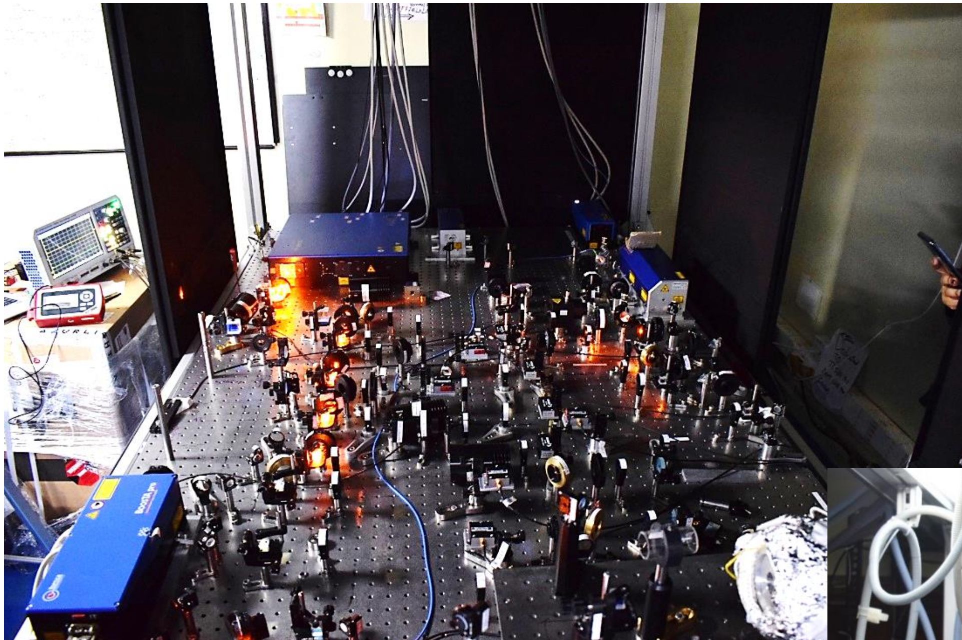
Bright sources of cold atoms



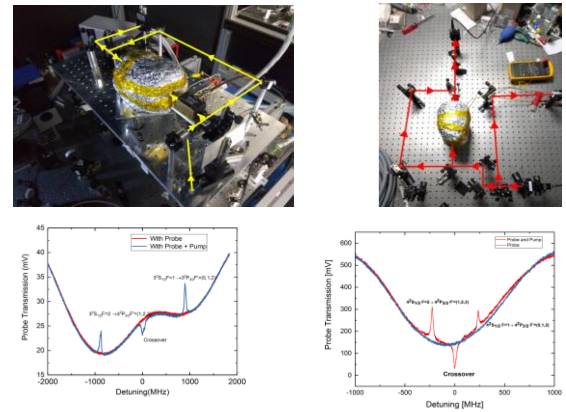
- Fast loading (*~**second***) of cold atoms from two-dimensional magneto-optical traps
- We simultaneously cool and trap: ***10 billion*** Potassium and ***half a billion*** Sodium atoms with trap lifetime ***in minutes***
- These large numbers of trapped atoms helps in good signal-to-noise ratio in subsequent measurements

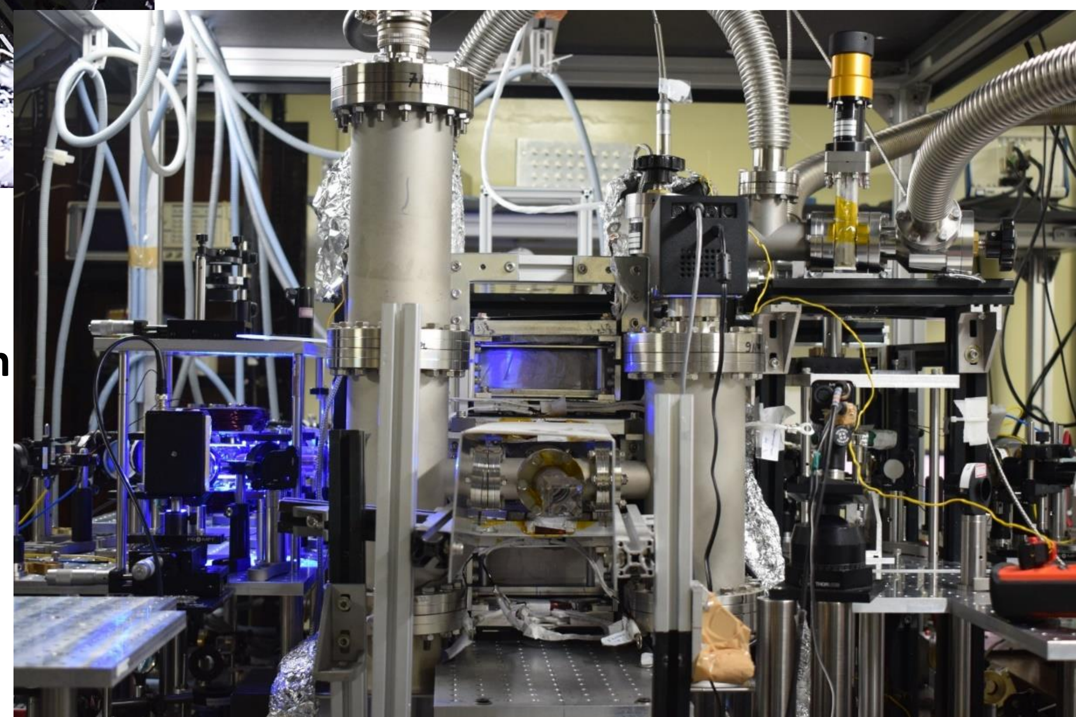
Techniques used: Magneto-Optical trapping, Pure Magnetic trapping, Optical dipole trapping

The Lasers and the Vacuum systems!



SPECTROSCOPY SET-UPS FOR COOLING

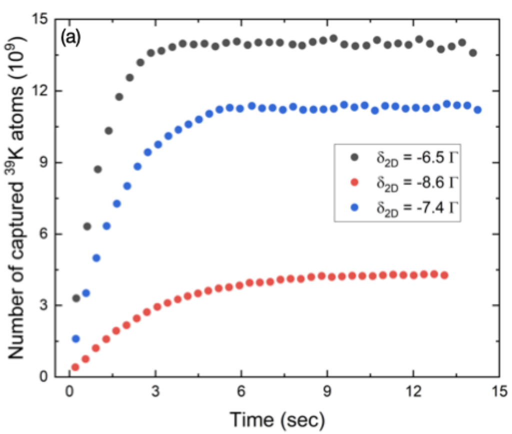


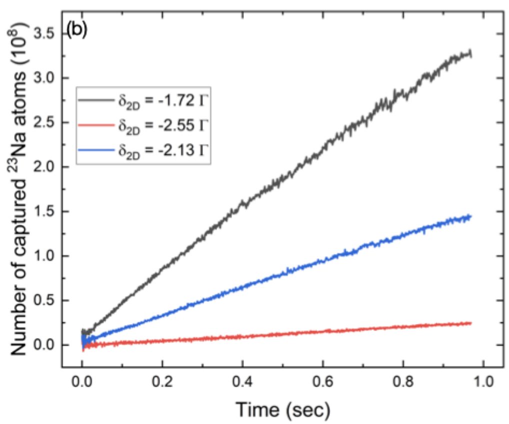


- **Ultra-high vacuum** < 10^{-11} mBar
- Ultra precision **frequency stabilization** of lasers ~ 100 kHz linewidths
- Ultra-stable optical set-up
- High resolution (~ 2.4 µm) imaging

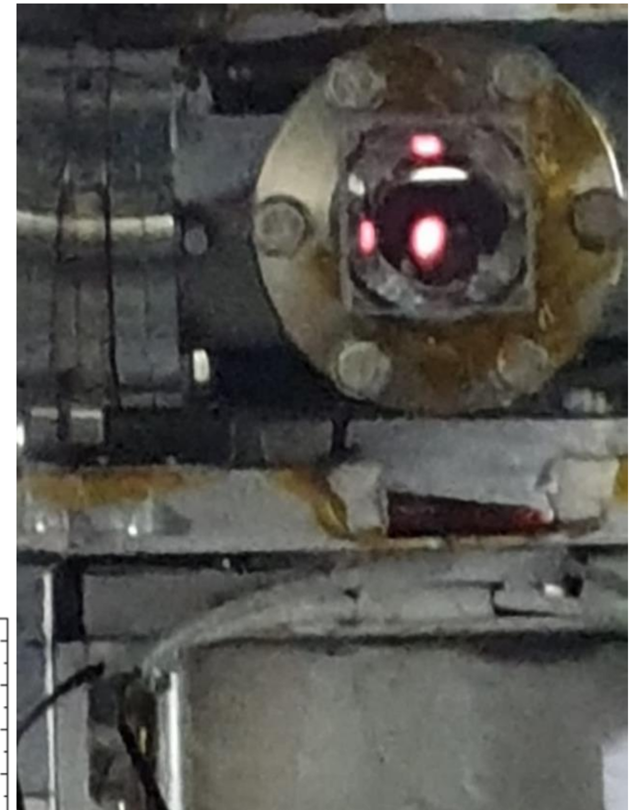
The Sodium and Potassium cold atoms

^{23}Na MOT





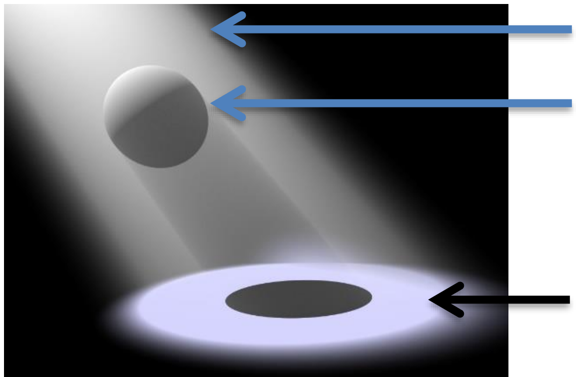
^{39}K MOT



AIP Advances 13, 065317 (2023)

Detection Techniques

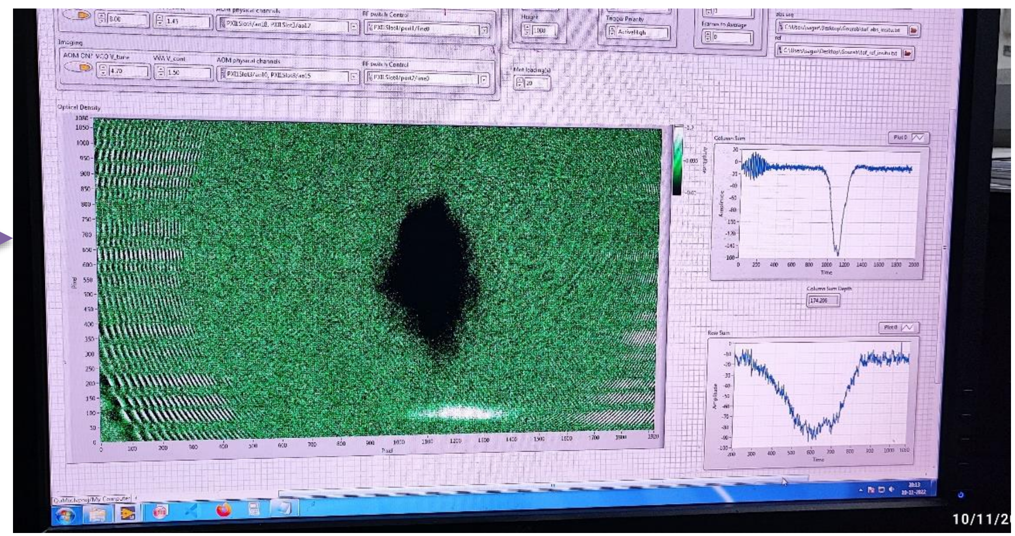
Absorption imaging:



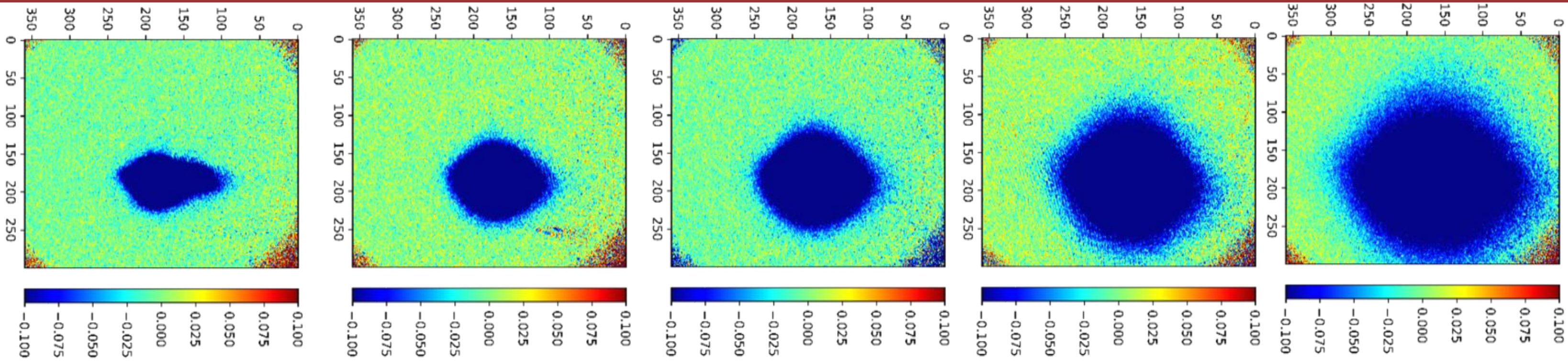
Resonant probe light

Cold atoms

CCD image plane

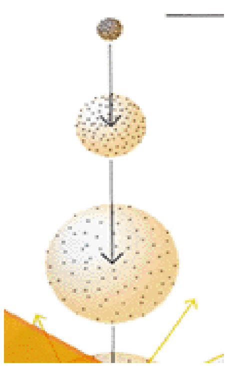


Measuring the temperature and number of atoms



Time in free flight (typically few 10s of msec)

Temperature estimate:



$$T = \frac{m}{k_B}\left(\frac{\sigma_2^{\,2} - \sigma_1^{\,2}}{t_2^{\,2} - t_1^{\,2}}\right)$$

$\sigma_1 \rightarrow$ Size of atomic cloud at time t_1

$\sigma_2 \rightarrow$ Size of atomic cloud at time t_2

No. of Atoms:

$$N = -\frac{A_{pix}}{\sigma_{eg}} \sum_{pix} \ln T_{pix}$$

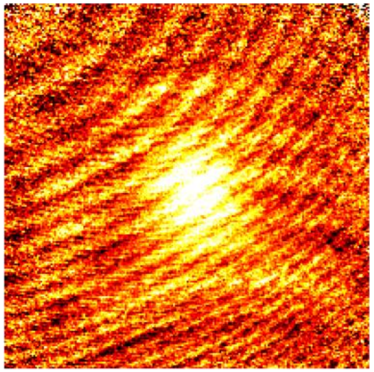
$A_{pix} \rightarrow$ Area of each pixel

$\sigma_{eg} \rightarrow$ Absorption cross-section of the atomic transition

$-\ln T_{pix} \rightarrow$ Optical density at the pixel

Typical measured Temperature of our Sodium cloud ~ 160 μ-Kelvin !

When the signal is not that great!



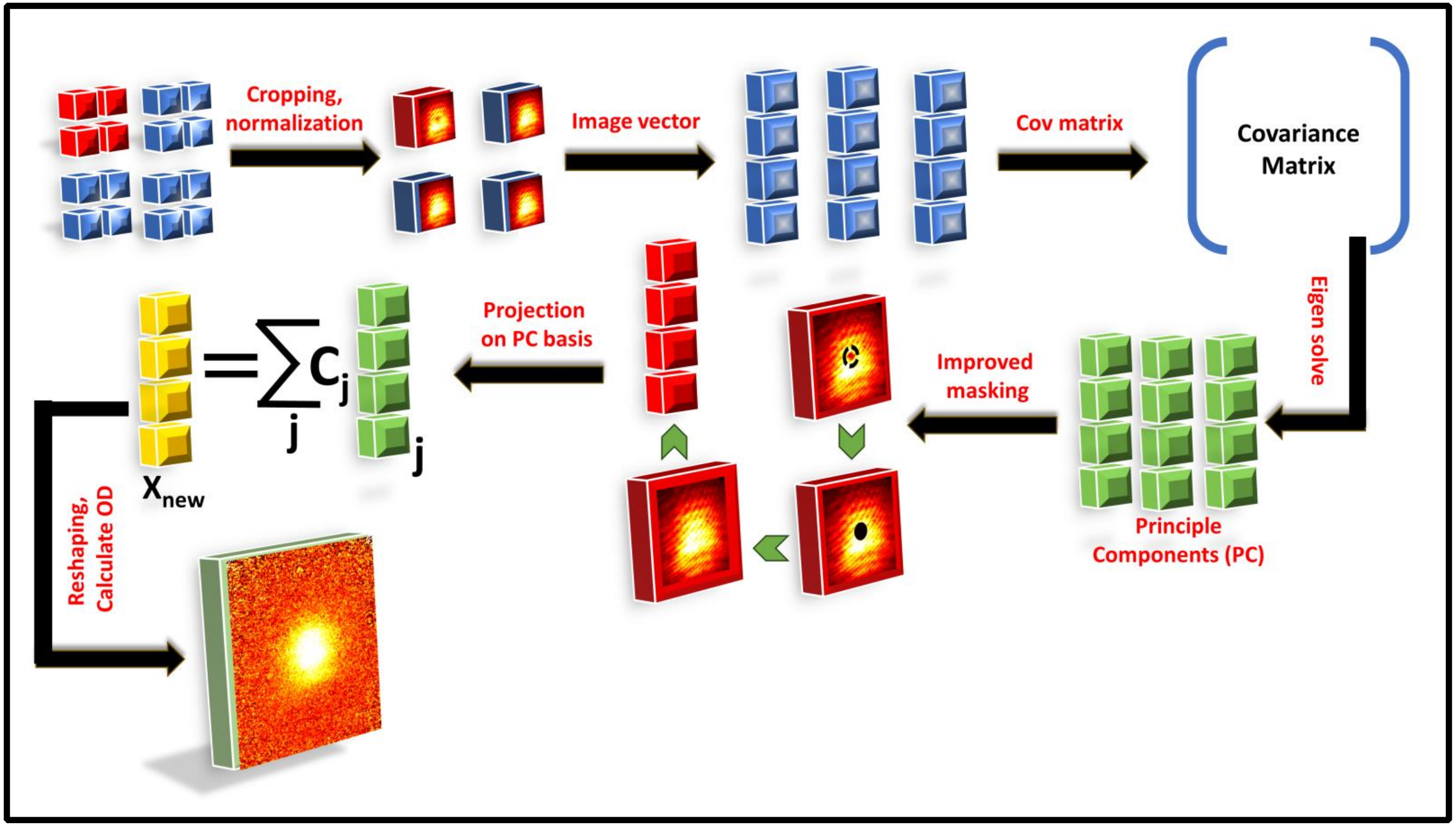
- Long time of flight images
- Low density cloud
- Trying to measure a feeble effect

Low SNR?

The interference pattens in the highly coherent and monochromatic probe plays spoilsport

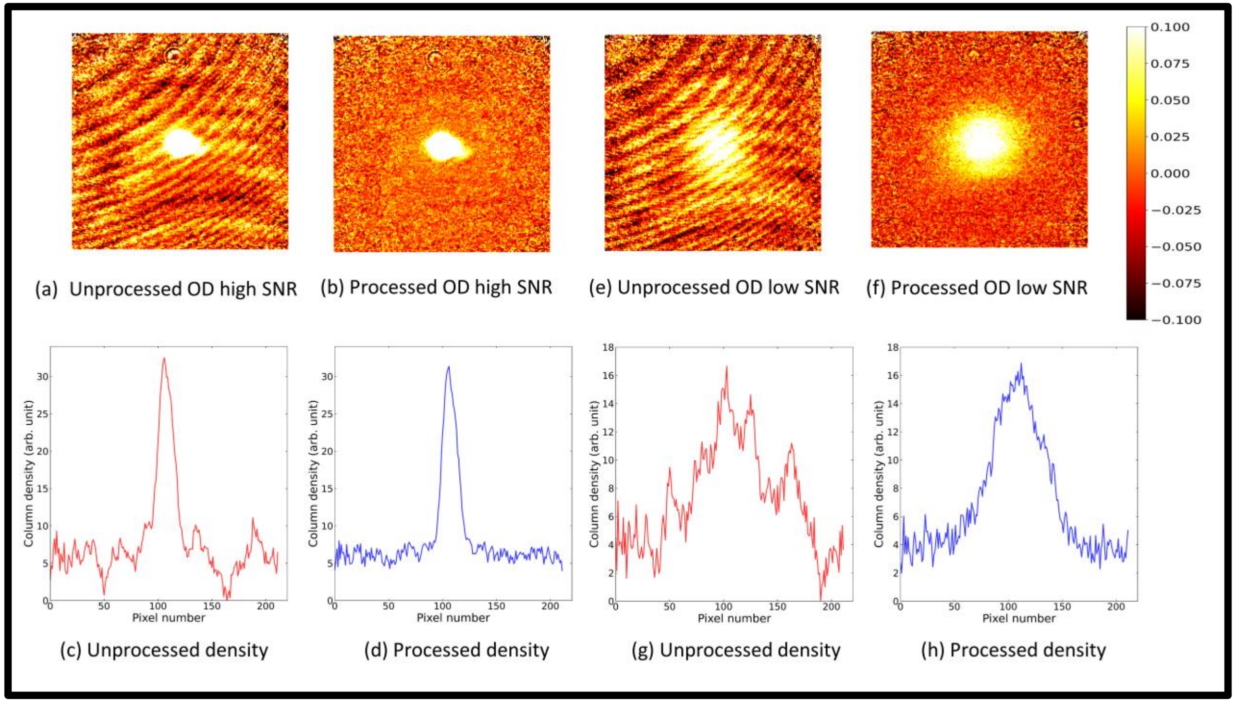
We developed a AI based technique to improve the image qualities

Algorithm flowchart



Gourab Pal, Saptarishi Chaudhuri, Applied Optics, Vol. 62 No. 32 (2023)

De-noising results



(a) Unprocessed OD high SNR (b) Processed OD high SNR (e) Unprocessed OD low SNR (f) Processed OD low SNR

(c) Unprocessed density (d) Processed density (g) Unprocessed density (h) Processed density

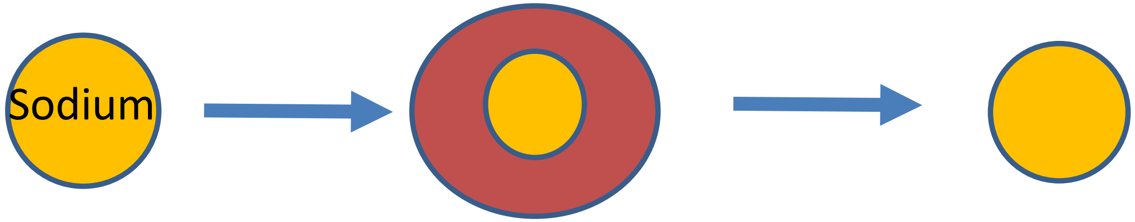
Need?

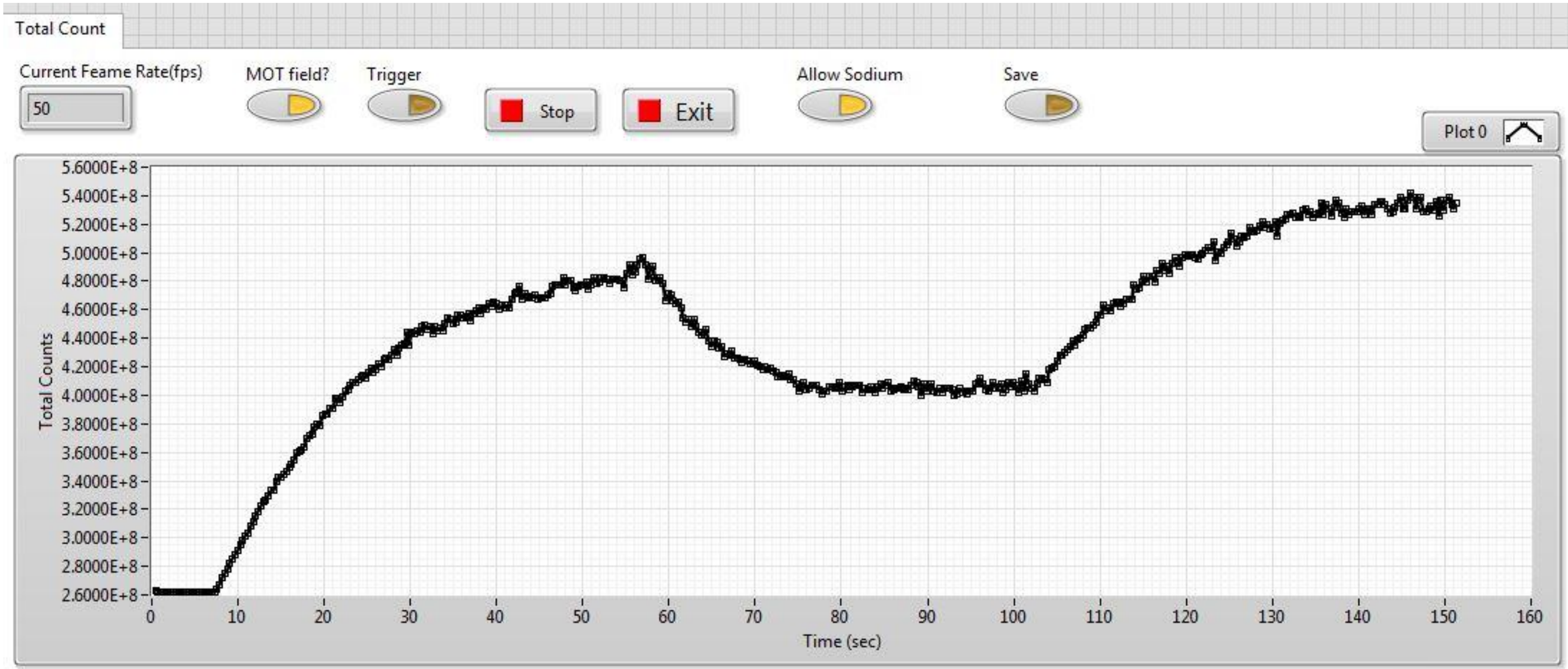
- ✓ **Enhancing SNR**
- ✓ **Better estimation of parameters**
- ✓ **More reliable experimental outcomes**

Gourab Pal, Saptarishi Chaudhuri, Applied Optics, Vol. 62 No. 32 (2023)

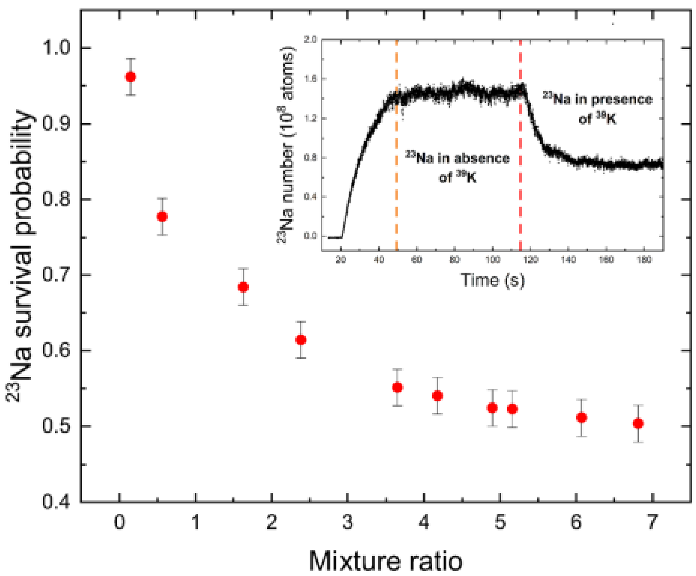
Interspecies interactions between cold atoms

Sodium in Potassium bath

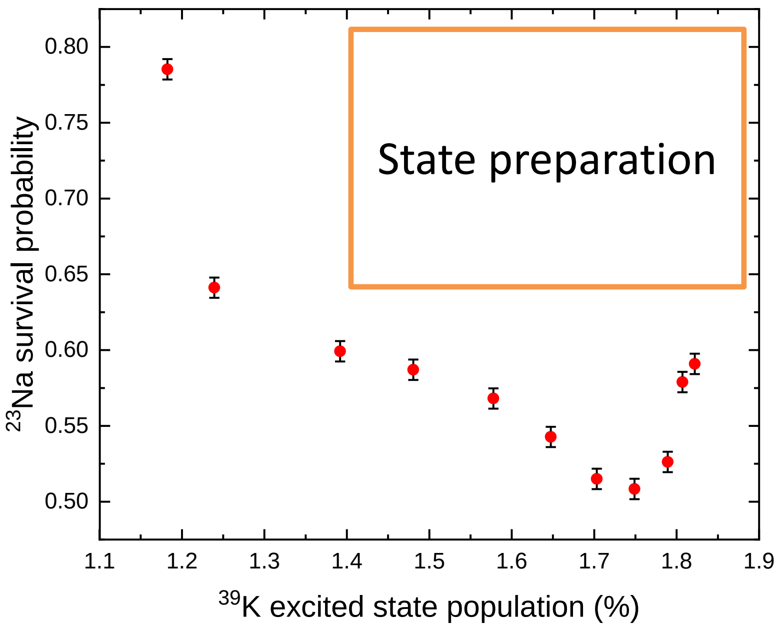




Effect of Impurity fractions



Effect of off-resonant dipolar interactions

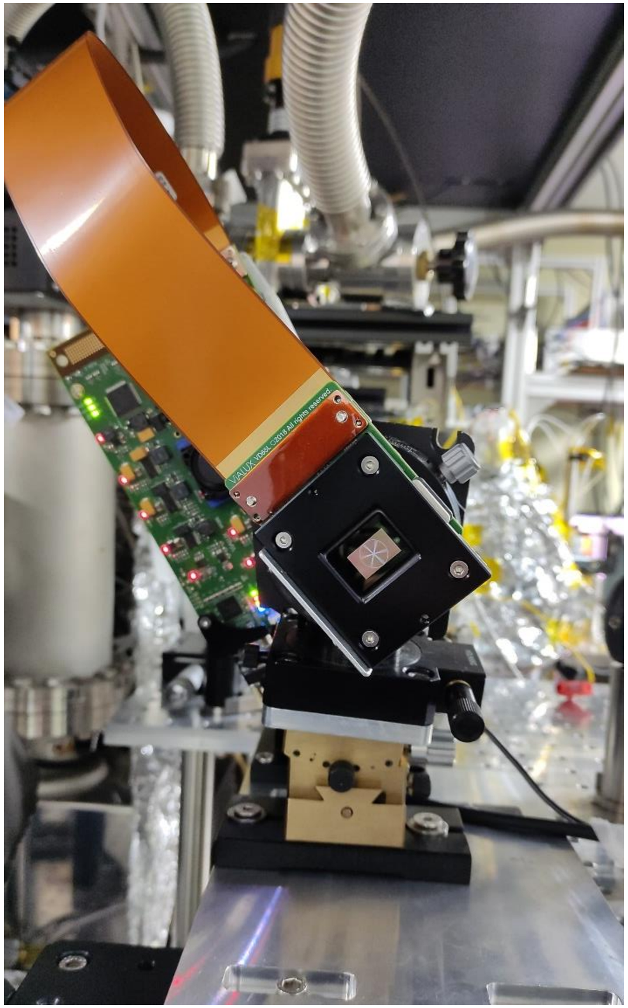


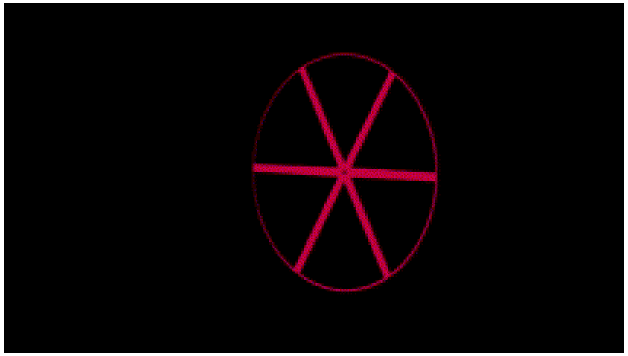
These results allows for detailed understanding of the interspecies cold collision cross section and a better understanding of two-body potential: We measure these parameters experimentally and develop related theoretical understanding!

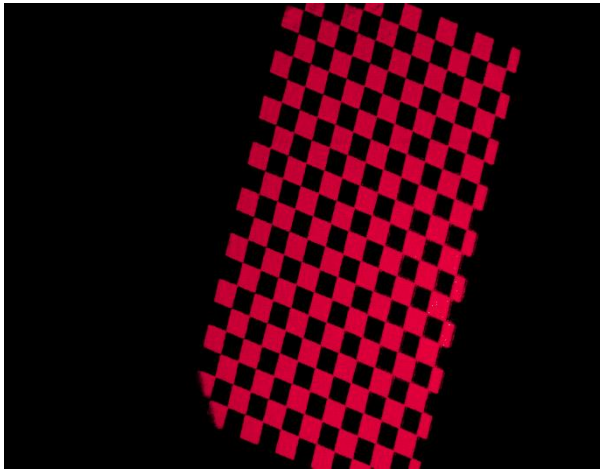
- ***Shaped traps for cold atoms***

- ***Orbital Angular momentum of light → Interaction with cold atoms***

Holographic trapping potential using MEMS



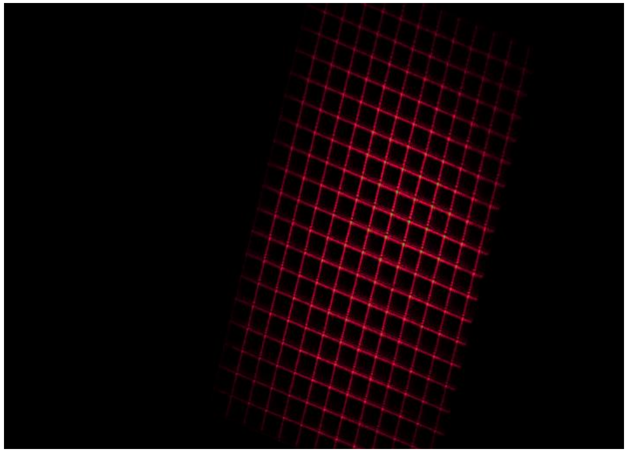




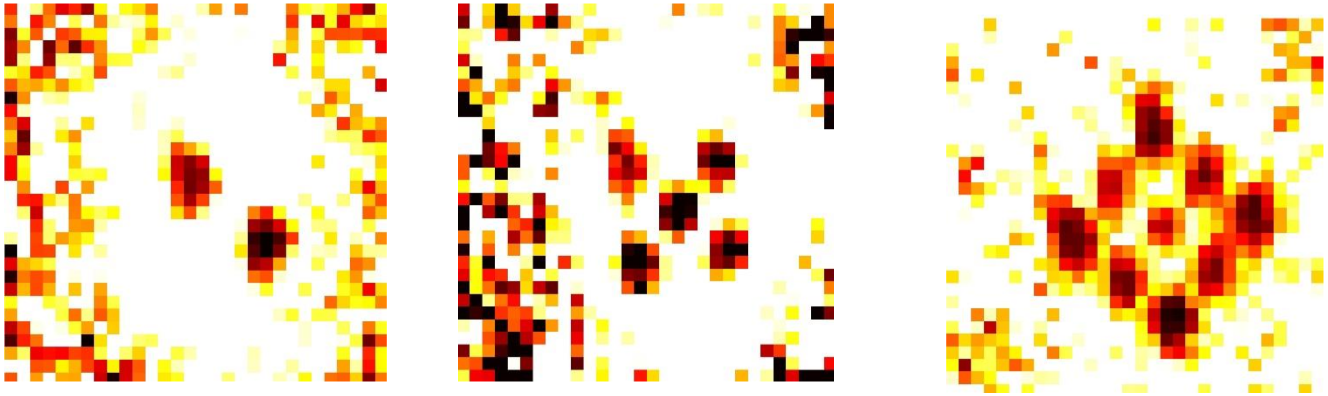
Arbitrary optical potential
For cold atoms created by
MEMS based devices

Tremendous possibilities
To simulate condensed
matter physics with cold
atoms

New direction for quantum
architecture using cold
atoms



Holographic trapping potential using MEMS

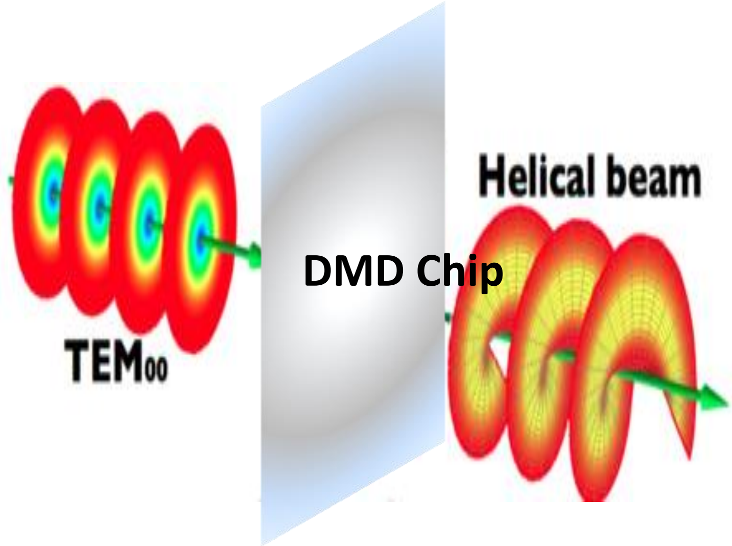


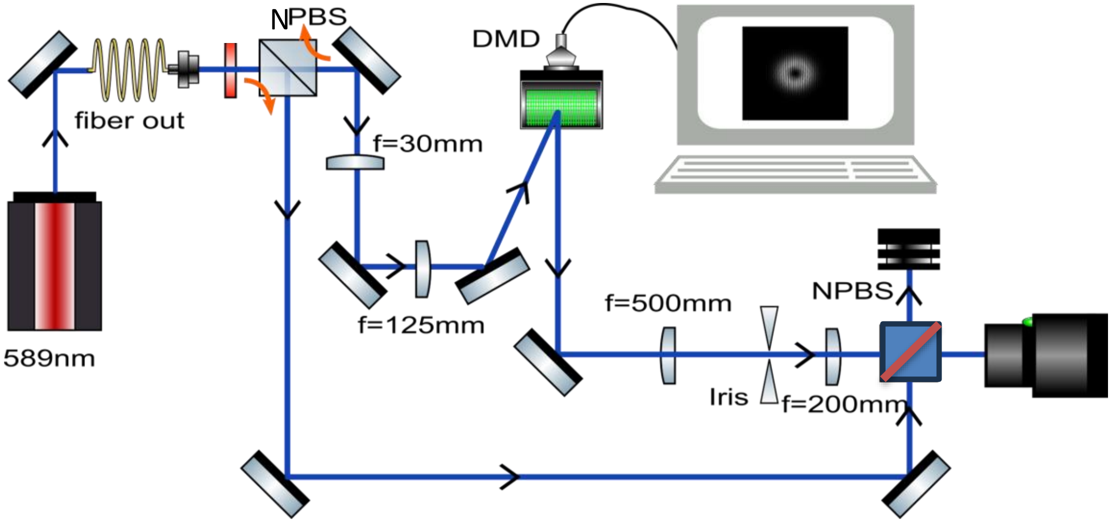
Black region: Atoms

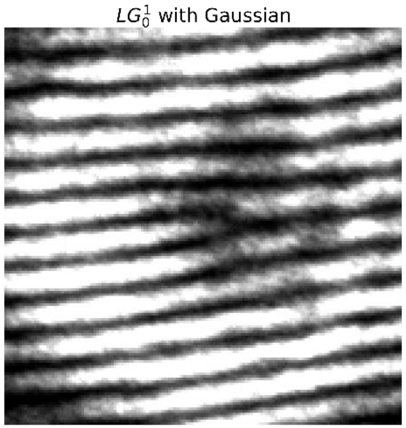
Atoms “ordered in space” by light

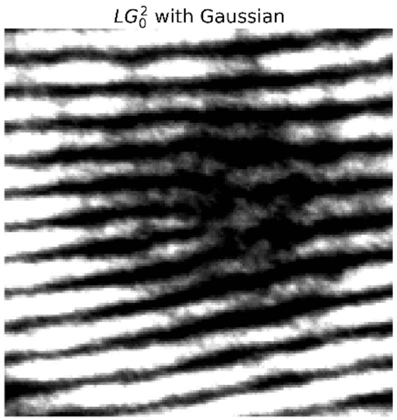
Outlook: 1)atoms trapped in an array as scalable quantum systems
→ large N quantum processors
2) Creating “true” random potentials → quantum scattering in random media
3) Foundational questions in Quantum mechanics using “flat” potentials
4)Schrodinger picture in “external potential” which is “tailored”
5) We are presently working on creating Orbital Angular Momentum (OAM) states of light interacting with cold atoms

Orbital Angular Momentum of light



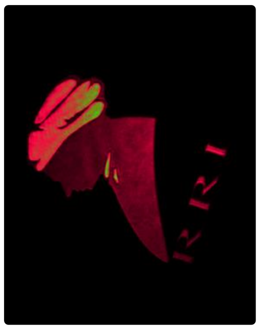


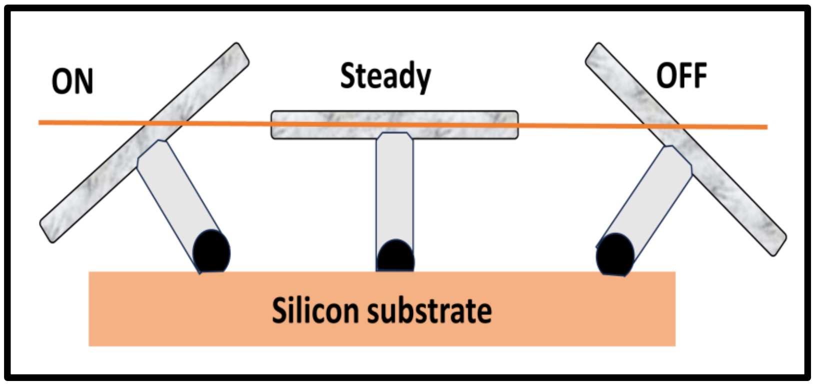




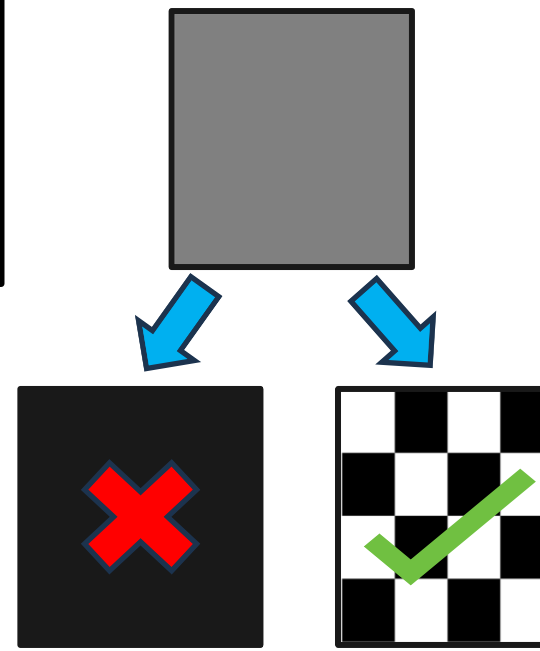
- Creation of laser light with topological charge
- Fast switching (~100 micro-sec) between topological charge in light
- Aim: interaction between OAM of light with trapped cold atoms and BECs

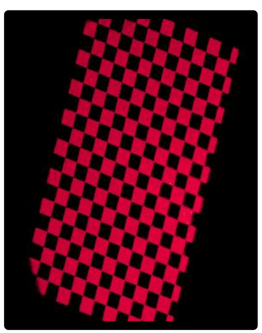
Fast control of OAM light: DMD

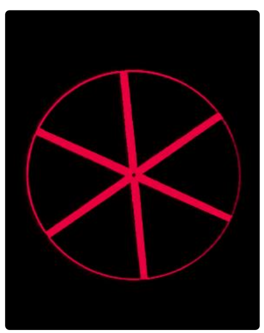


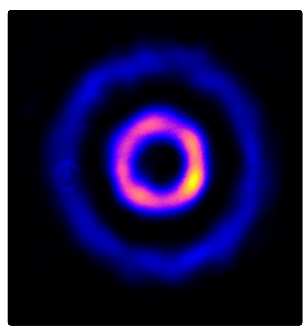


Floyd-Steinberg error-diffusion algorithm

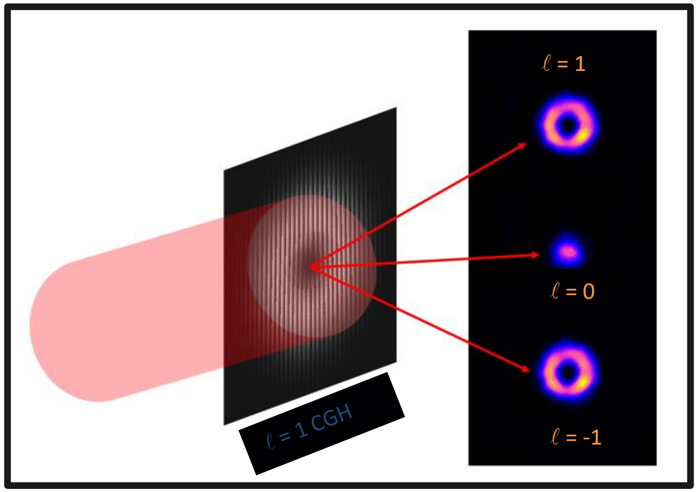






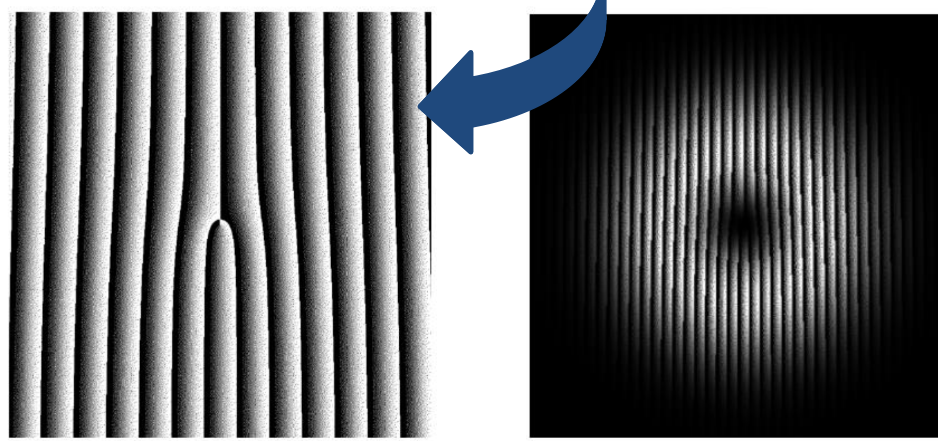


verification of topological charges



$$LG_p^l = \sqrt{\frac{2p!}{\pi(p+|l|)!}}\frac{1}{w(z)}\left(\frac{\sqrt{2}r}{w(z)}\right)^{|l|}\exp\left(-\frac{r^2}{w^2(z)}\right)$$
$$L_p^{|l|}\left(\frac{2r^2}{w^2(z)}\right)\exp\left(-ik\frac{r^2}{2R(z)}\right)\exp(-il\phi)$$
$$\exp\left(i(2p+|l|+1)\arctan\left(\frac{z}{z_R}\right)\right)$$

Gaussian + Laguerre Gaussian
Mathematically generated interference pattern

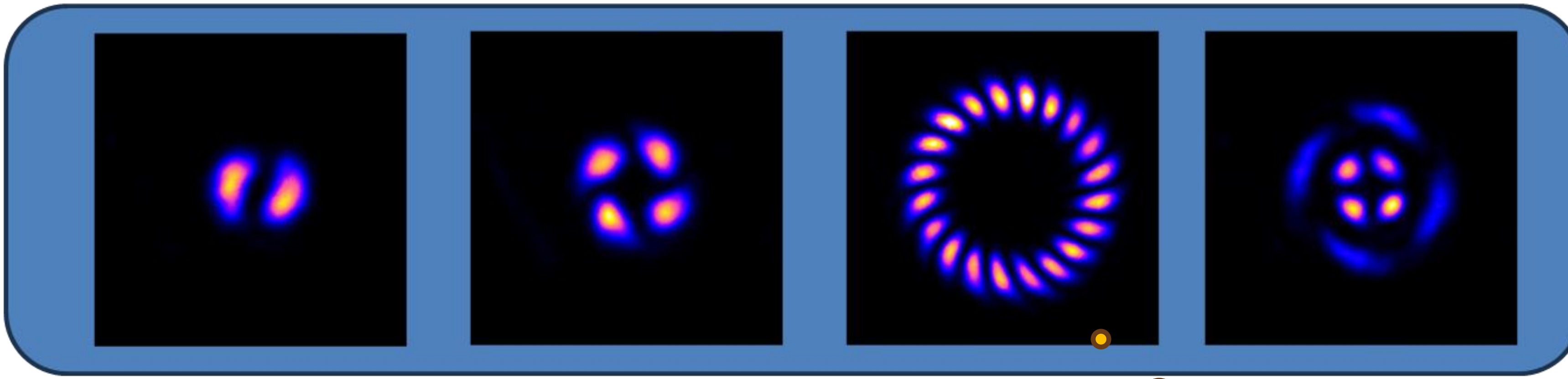


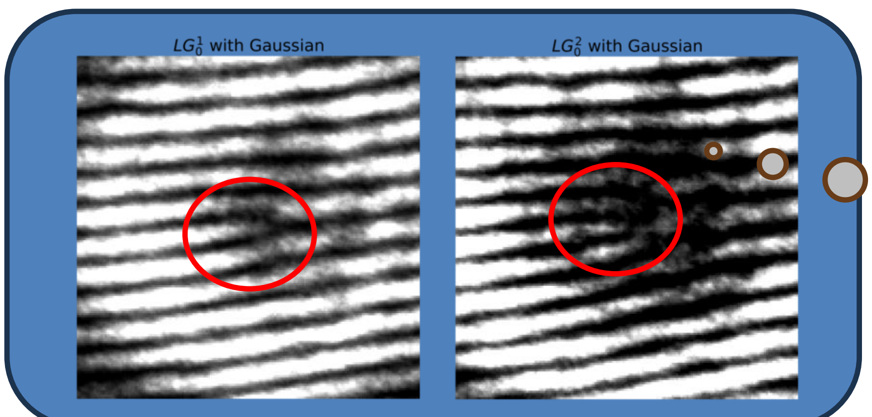
(a) ℓ=1 dislocation (zoomed view)

(b) CGH with ℓ = 1, k = 0.8

verification of topological charges

1. Interfere ℓ = n beam with its conjugate (ℓ = -n) and obtain a petal interference pattern and count the number of petals
2. Interfere the LG beam carrying topological charge with gaussian beam and count the number of forks in the interference pattern

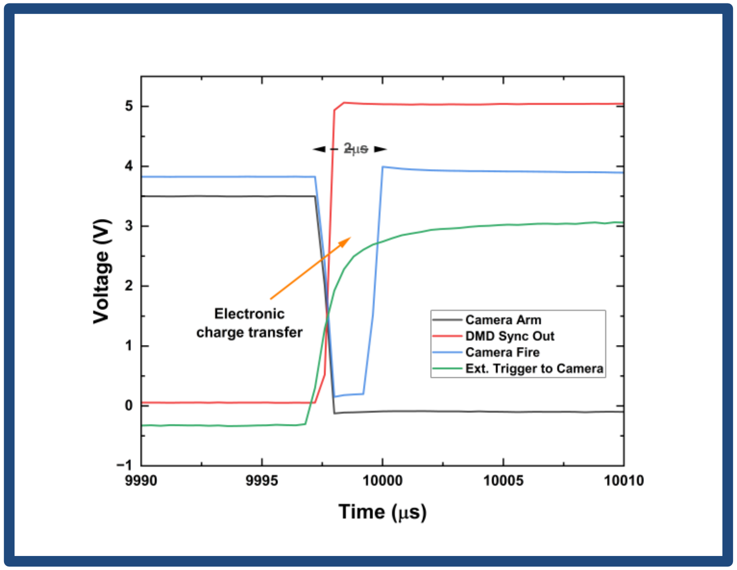


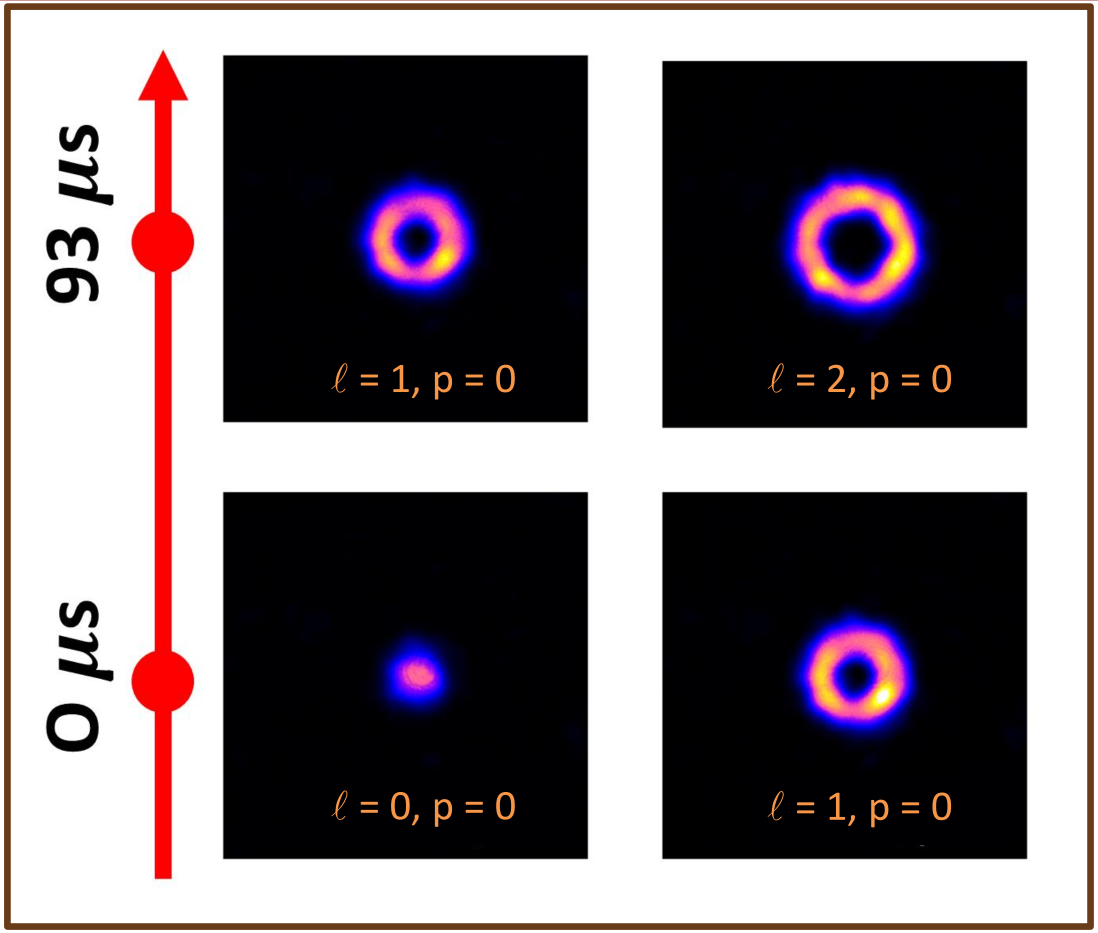


Count the fork

Count the petals

Time-resolved generation





- Creation of laser light with topological charge
- Fast switching (~100 micro-sec)
- between topological charge in light
- Aim: interaction between OAM of light with trapped cold atoms and BECs
- Magnetometry with high spatial and temporal resolutions

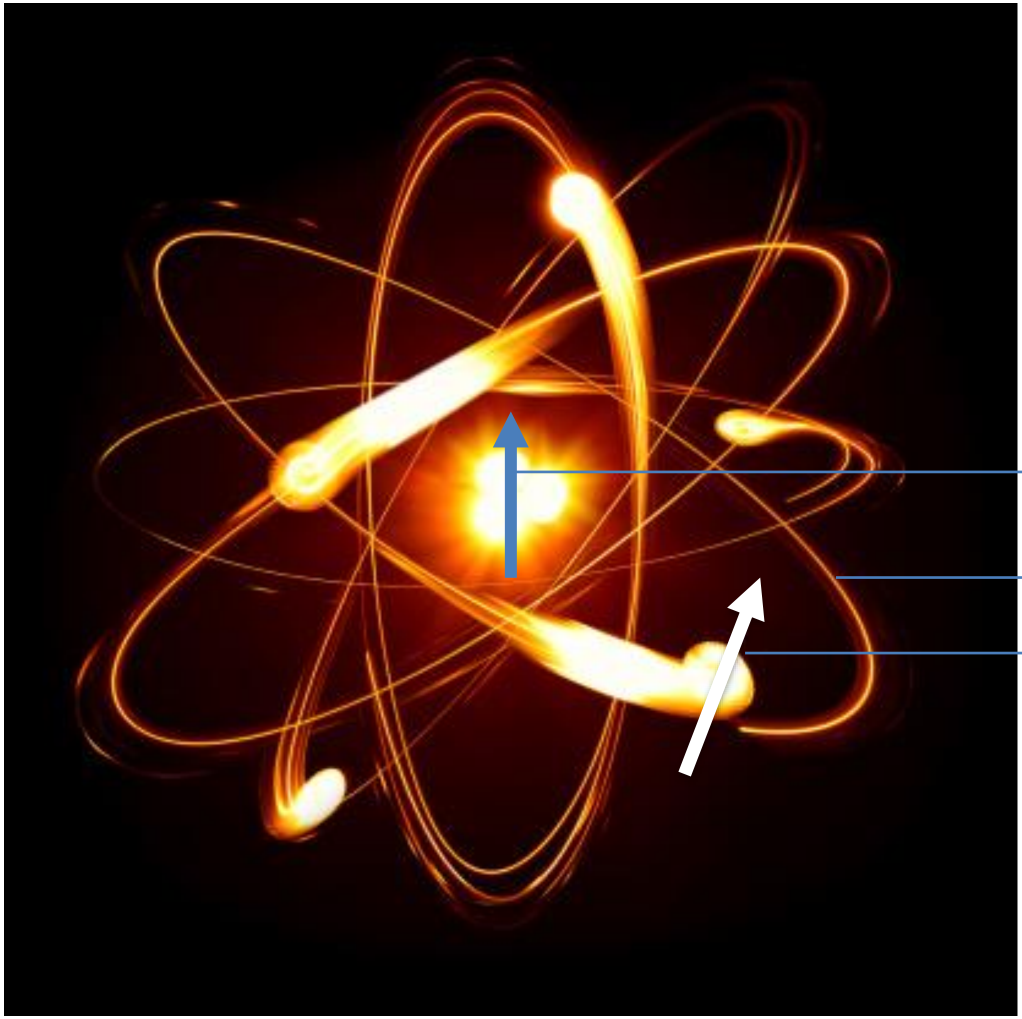
Manuscript under preparation

Part - II

Spin fluctuations measurements in cold and thermal atoms

Applications in Magnetometry

What is “Spin” in atoms



Nuclear spin → **I**

Orbital angular momentum, **L**

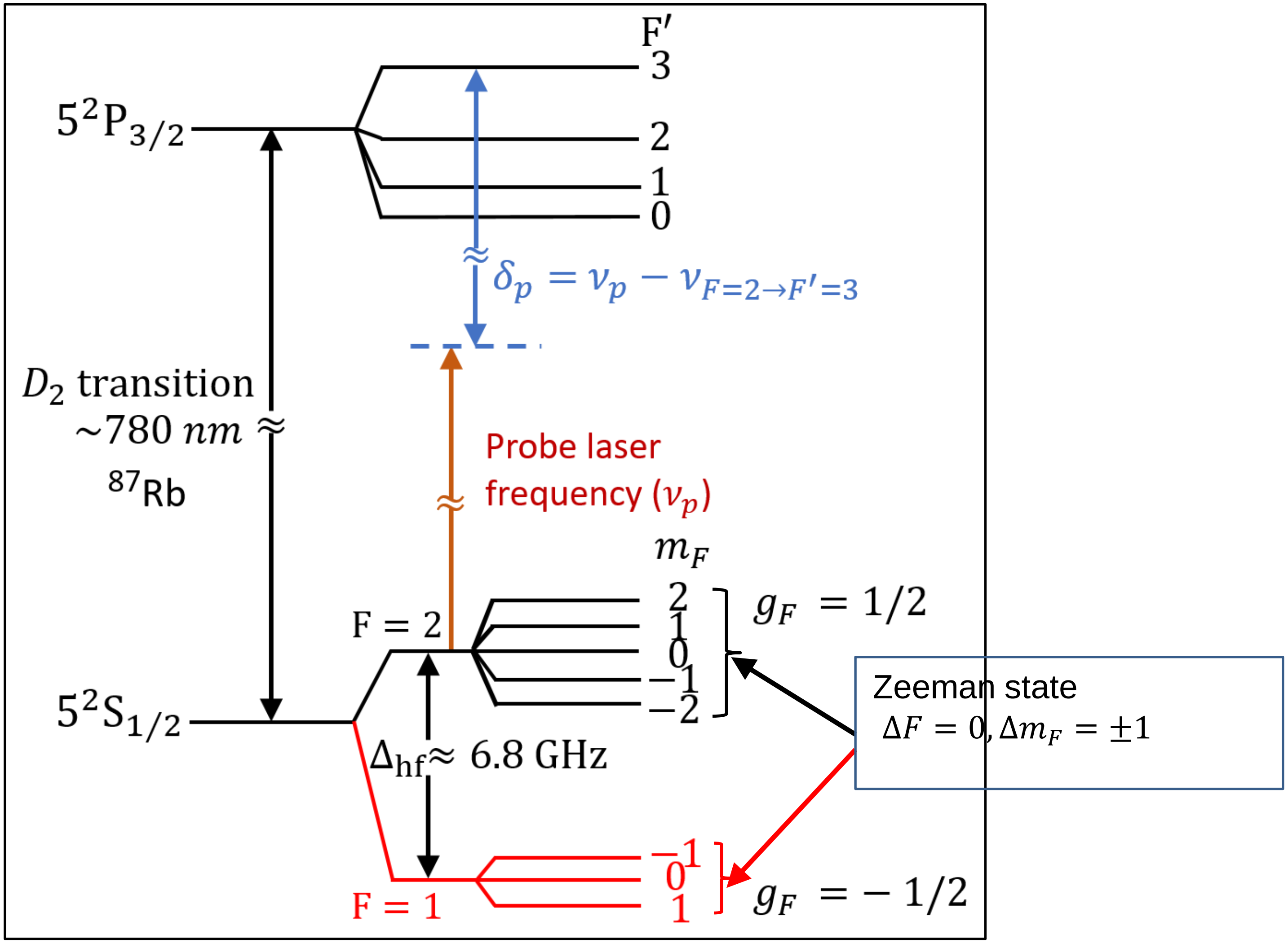
Electron spin →**S**

Electron angular Momentum, **J = L + S**
(Fine structure)

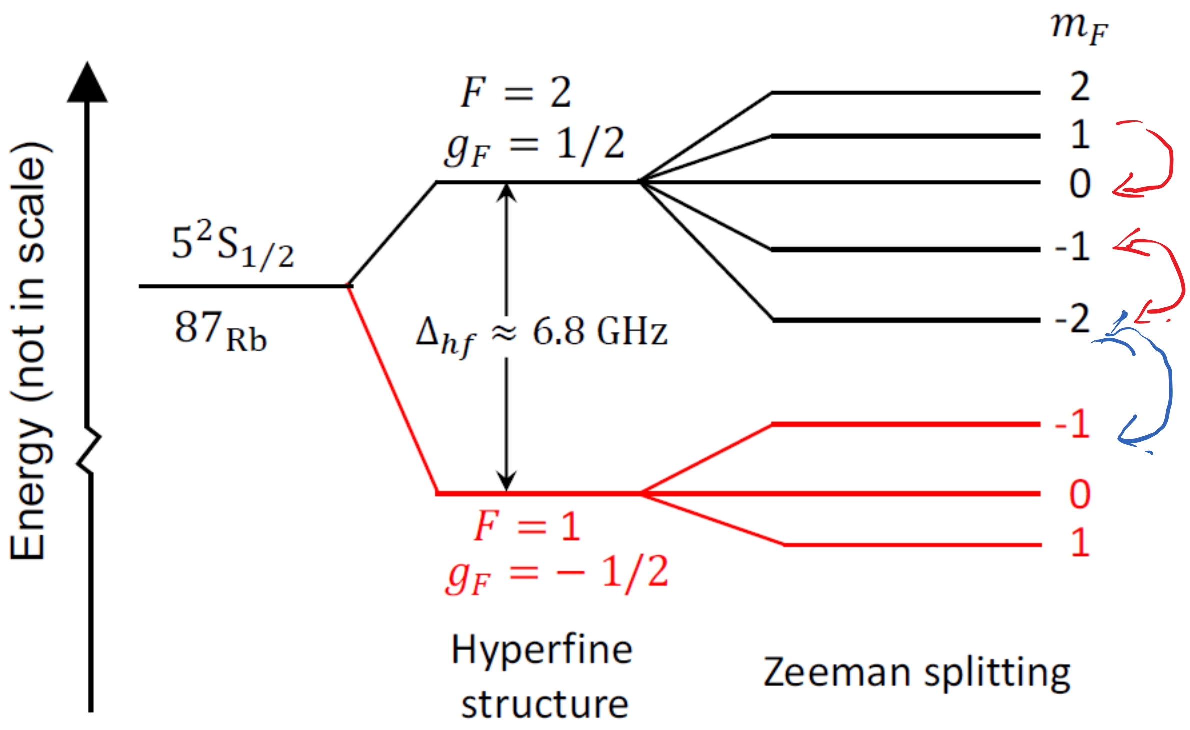
Total angular momentum, **F = I + J**
(Hyperfine structure)

What is “Spin” in atoms

Example : Rubidium atoms (our test bed for some of the experiments)



What is atomic Spin fluctuations

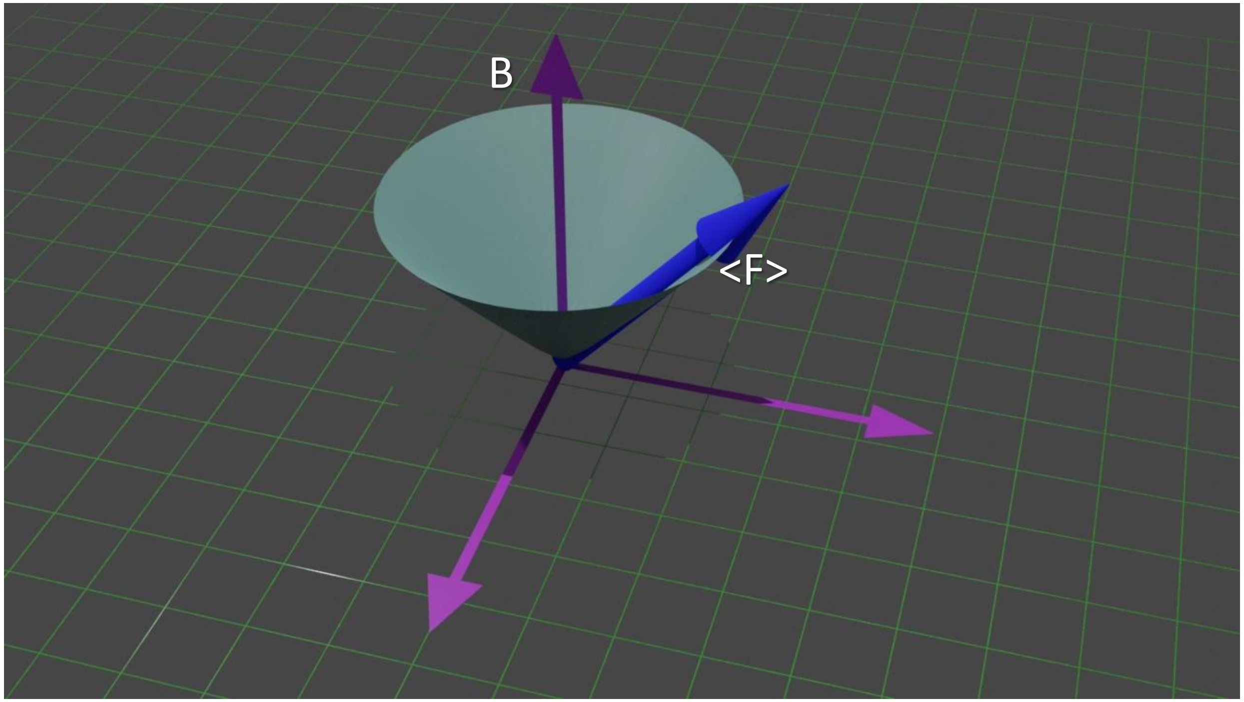


Population fluctuation between Zeeman levels

Reasons – 1) Thermal bath coupling, 2) Quantum fluctuations, 3) spin exchange collisions ….

How to measure atomic Spin fluctuations

Larmor precession of atomic spins in external magnetic field



B : External magnetic field (Quantization axis)
<F>: atomic spin projection vector

(Detour) Experimental technique: Faraday rotation and its fluctuations

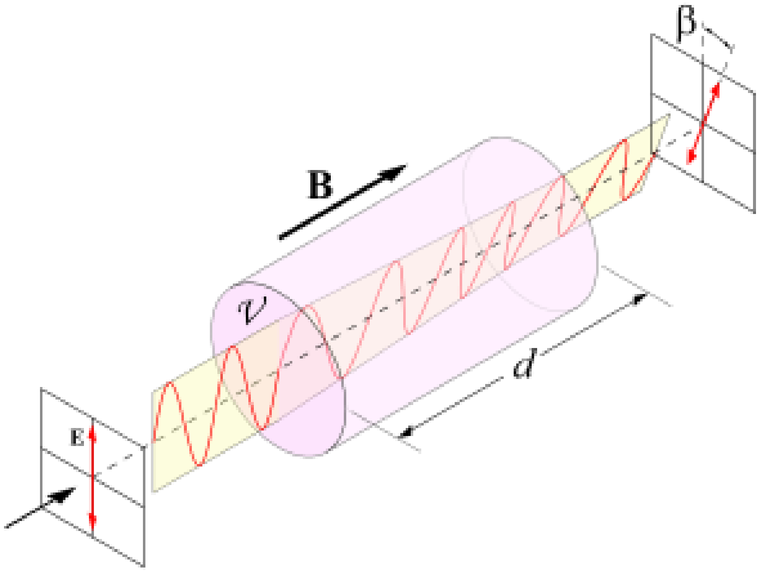
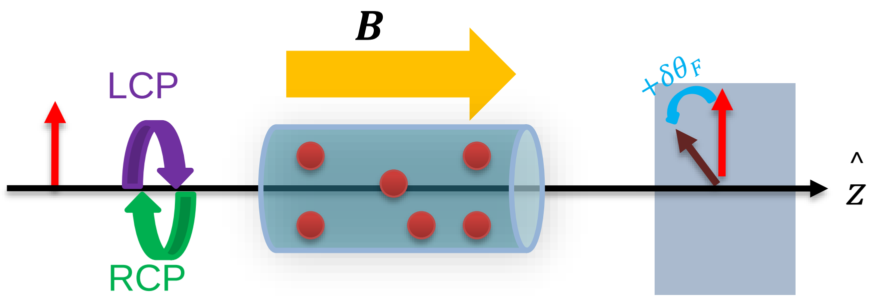


Image source: Wikipedia

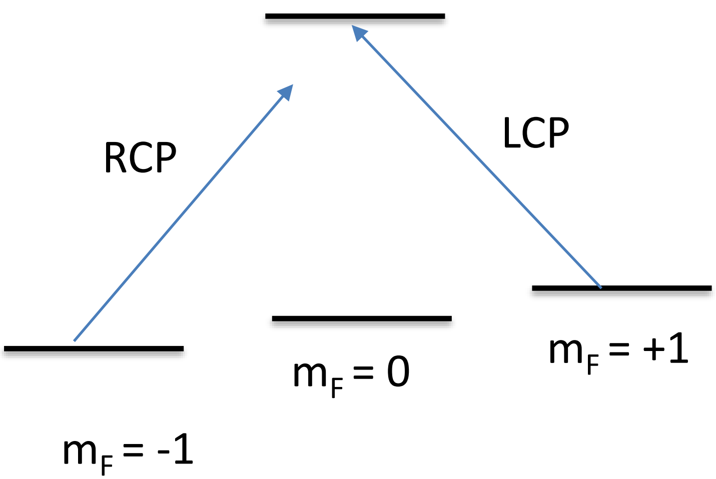
(Detour) Experimental technique: Faraday rotation and its fluctuations

An atomic physicist's explanation



LCP, RCP = Left / right circularly Polarized light

can be mapped to σ+ / σ- states Of light with correct quantization axis identification



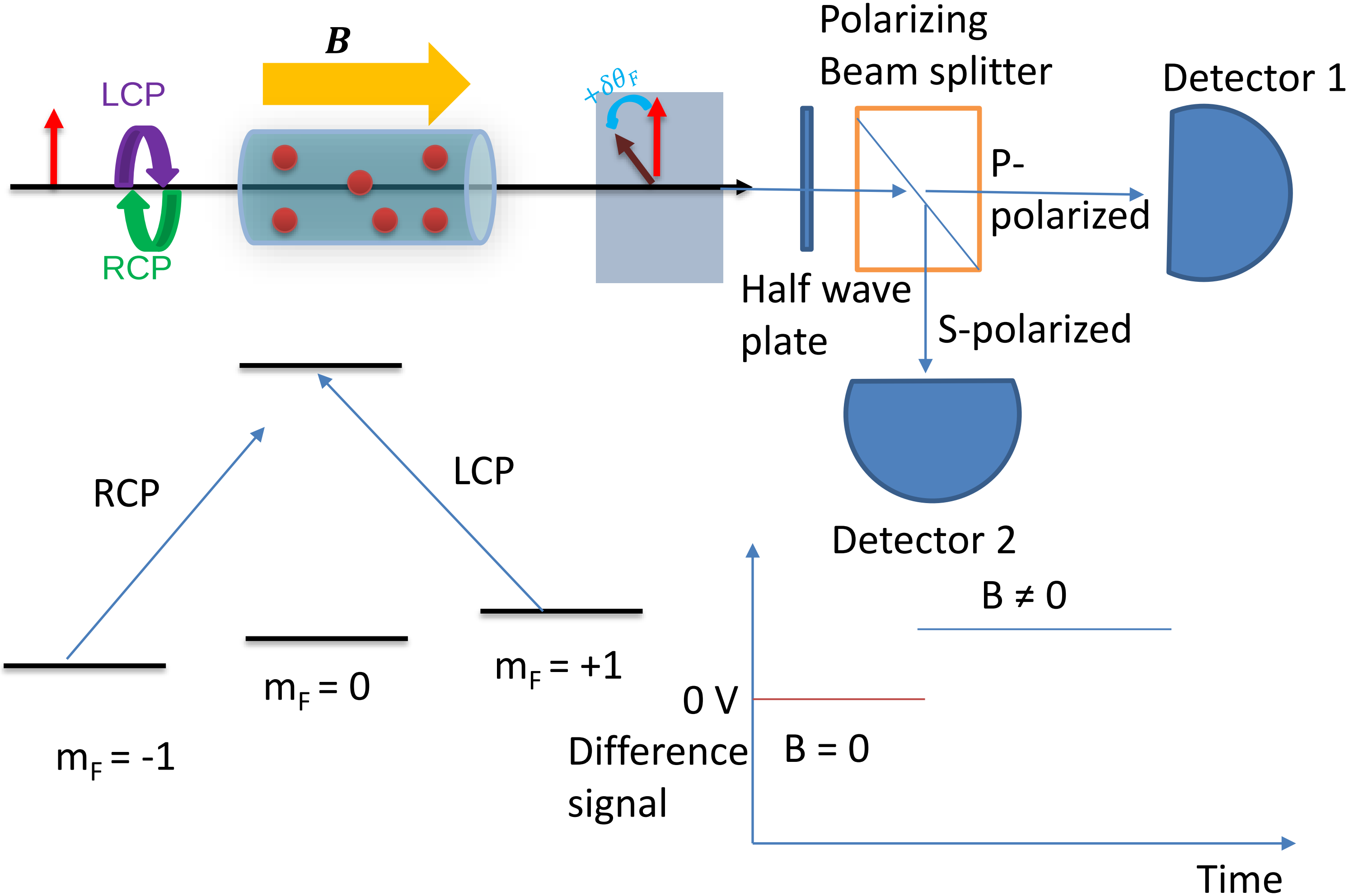
1) Depending on frequency of the laser w.r.t atomic transition →

2) different phase shift of LCP / RCP light →

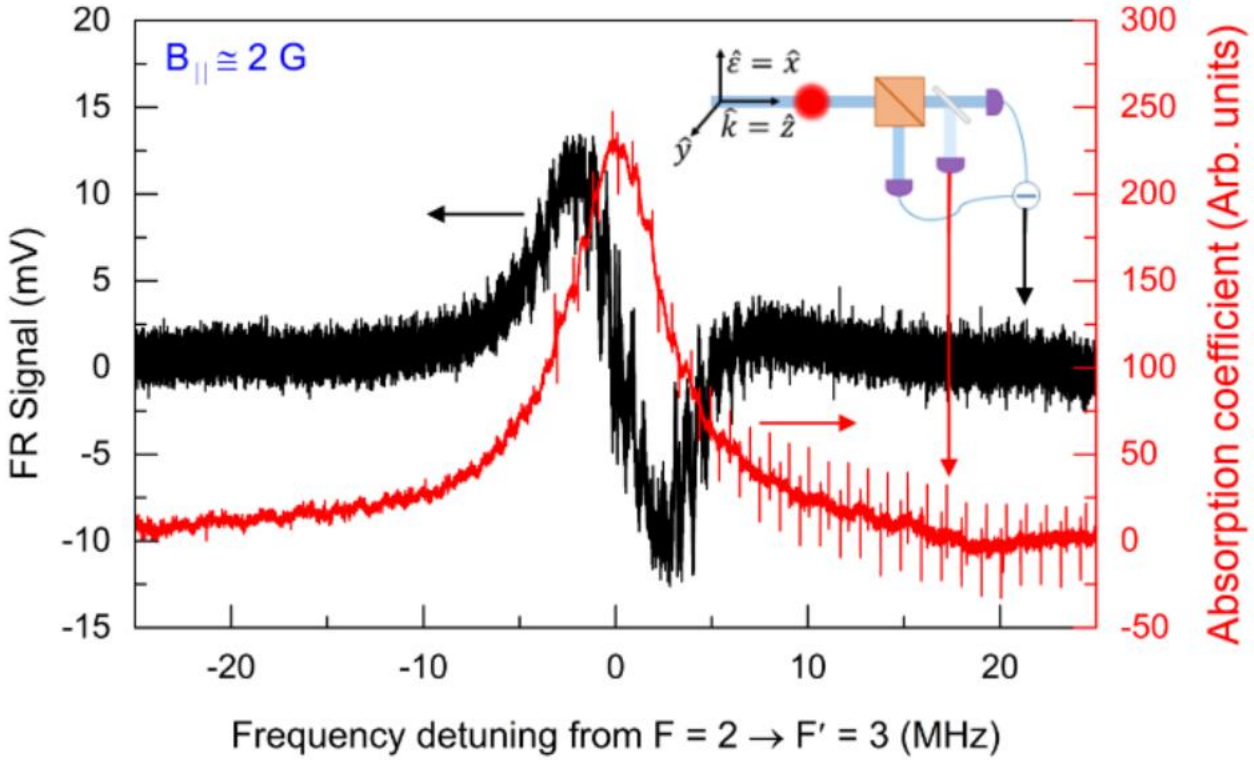
3) resultant outcoupled light polarization vector rotates by a angle w.r.t input polarization

(Detour) Experimental technique: Faraday rotation and its fluctuations

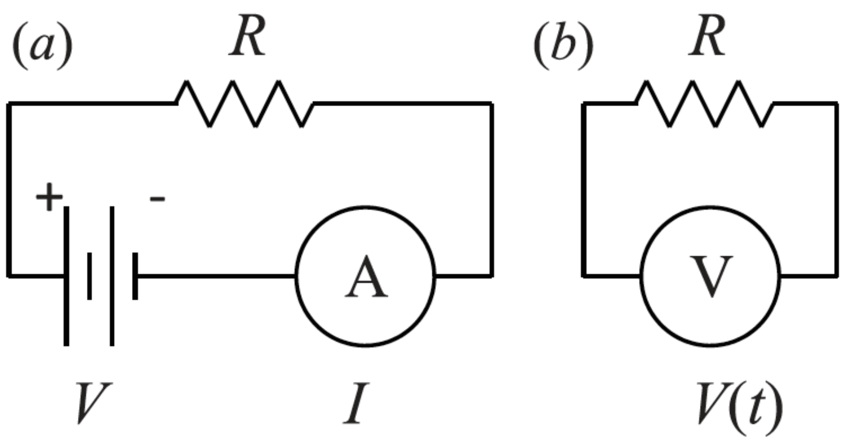
An atomic physicist's explanation



Faraday rotation from cold atoms



Johnson-Nyquist noise (1928):



$$R = \frac{V}{I}$$

Voltage variance per hertz of bandwidth:

$$\langle V^2 \rangle = 4k_B T R$$

(Fluctuation-dissipation theorem)

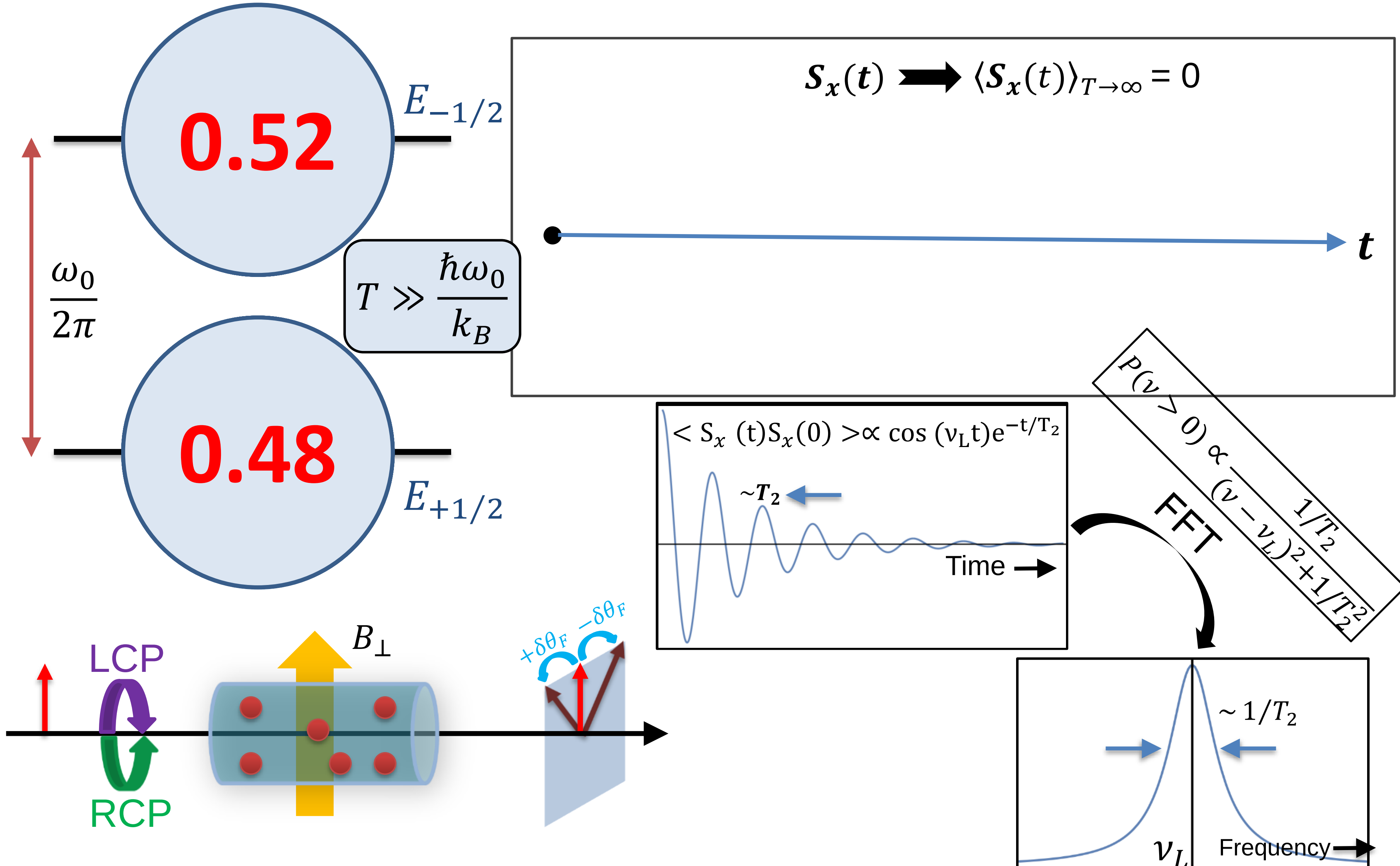
T: Temperature

R: Resistance

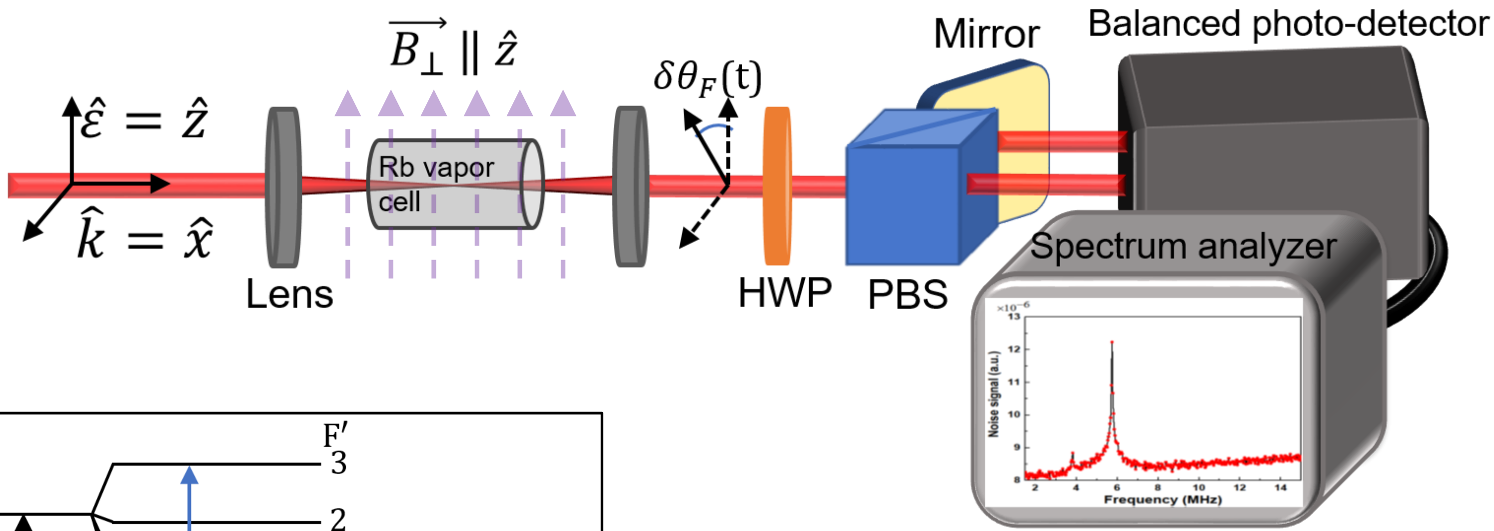
k_B: Boltzmann constant

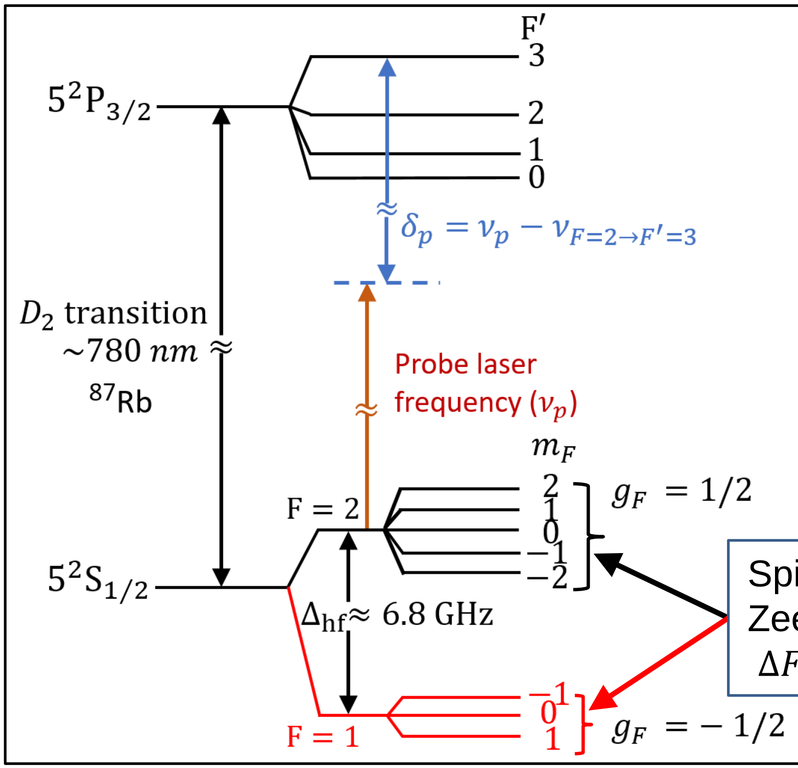
Spin Noise and correlation spectroscopy

spin noise spectroscopy (SNS)



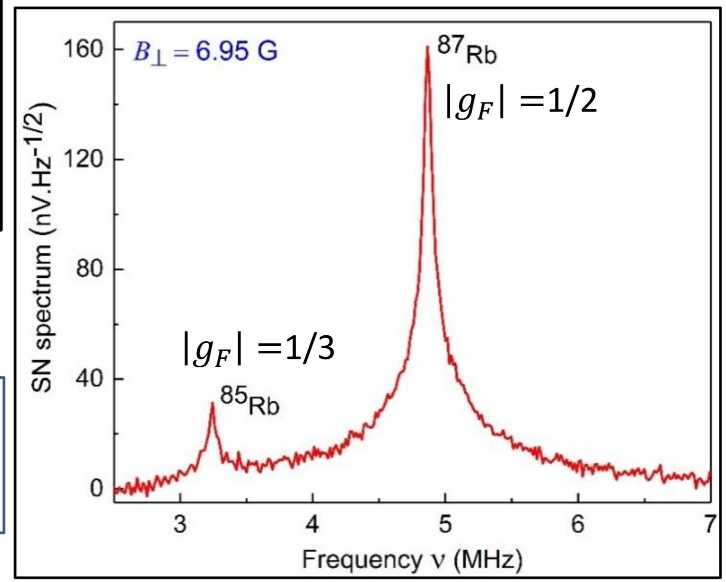
Intrinsic spin noise (SN) spectrum



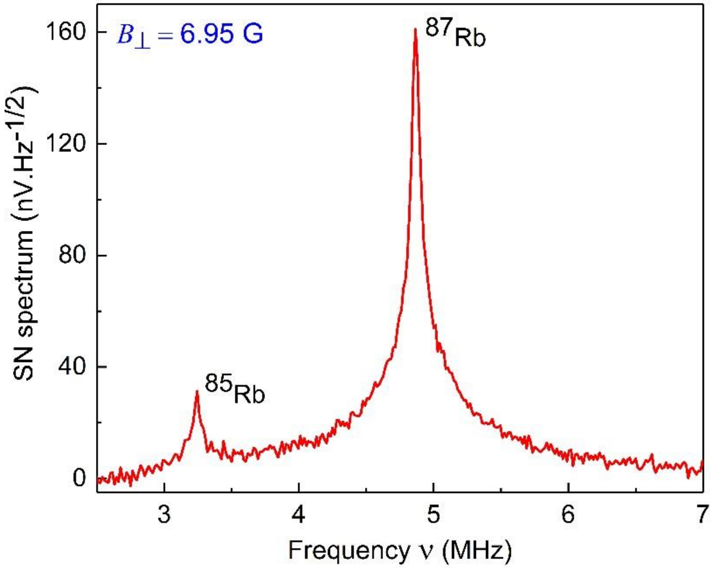


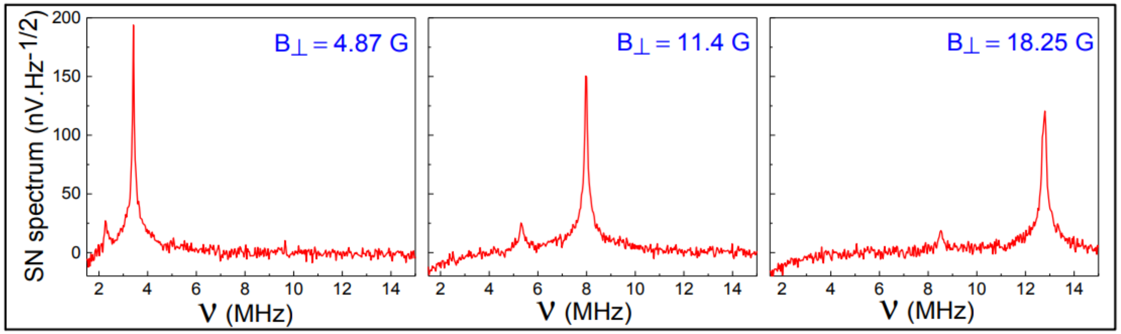
$$\Sigma = \int_0^\infty d\nu\, P(\nu) \propto \frac{I_p^2}{\delta_p^2}\left(\frac{n_0 l}{A}\right)$$

Spin fluctuations between Zeeman state
$\Delta F = 0, \Delta m_F = \pm 1$

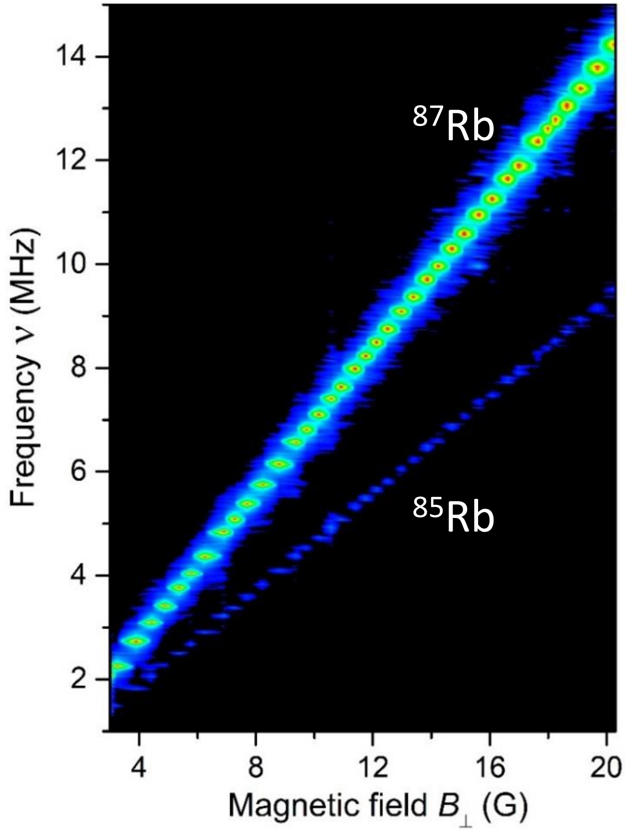


Linear Zeeman regime (Low field measurements)





$$|g_F| = \frac{h\nu_L}{\mu_B B_\perp}$$



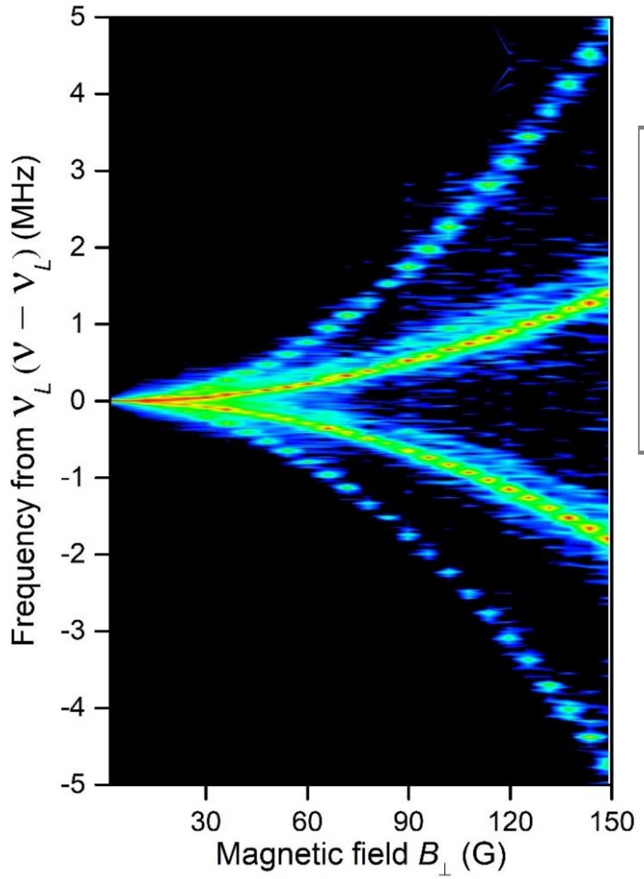
Parameters	Extracted value
$\lvert g_F \rvert$ (^{87}Rb)	0.500 (1)
$\lvert g_F \rvert$ (^{85}Rb)	0.333 (1)
Spin coherence rate	$\sim 3 \times 10^5\ s^{-1}$
$n_{^{87}Rb} : n_{^{85}Rb}$ (T = 100°C)	$\approx 11 : 1$

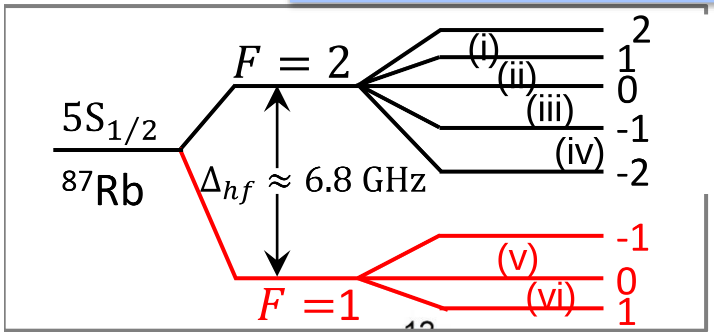
Opt. Express 26, 32168 (2018).

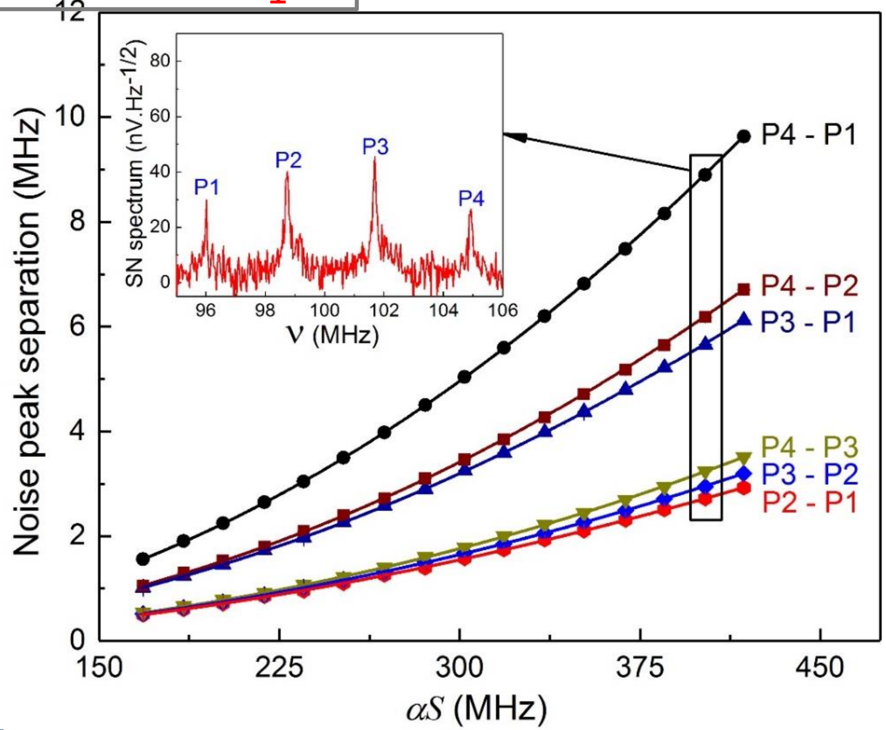
non-linear Zeeman regime (High field!)

$$E_{F=I\pm\frac{1}{2},m_F} = -\frac{h\Delta_{\mathrm{hf}}}{2(2I+1)} + g_I\mu_B B_\perp m_F \pm \frac{h\Delta_{\mathrm{hf}}}{2}\sqrt{1+\frac{4m_F}{2I+1}x+x^2}$$

$$x = \frac{(g_J - g_I)\mu_B B_\perp}{h\Delta_{\mathrm{hf}}}$$



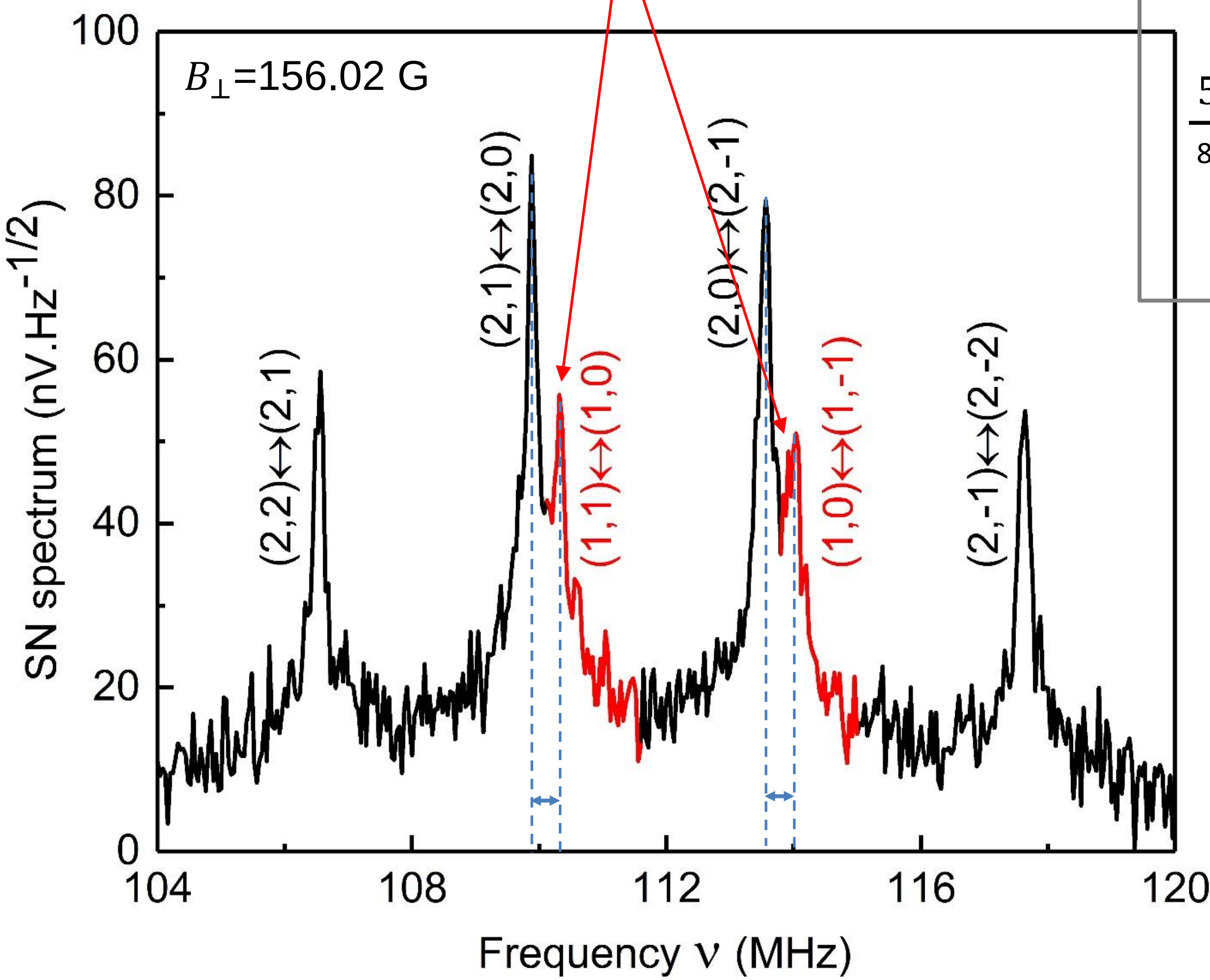


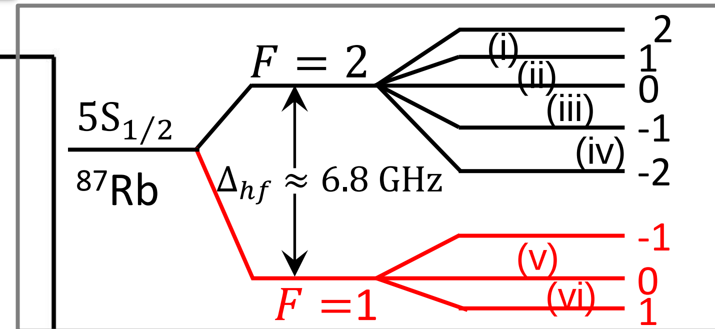


Opt. Express 26, 32168 (2018).

Some applications (g_I measurements)

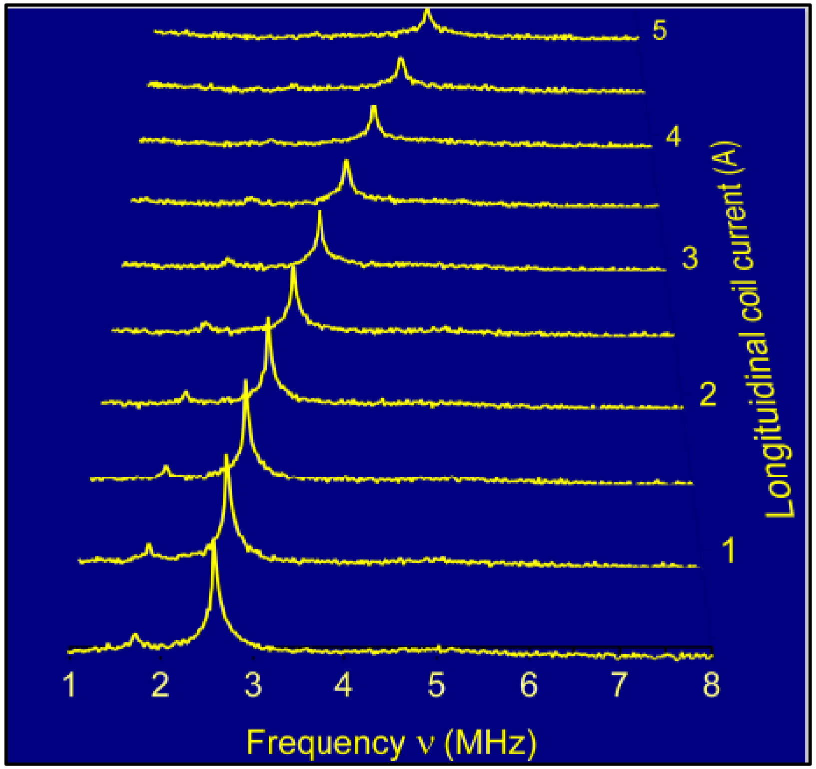
$$E_{F = I \pm \frac{1}{2}, m_F} = -\frac{h\Delta_{\mathrm{hf}}}{2(2I+1)} + g_I \mu_B B_\perp m_F \pm \frac{h\Delta_{\mathrm{hf}}}{2}\sqrt{1 + \frac{4m_F}{2I+1}x + x^2}$$



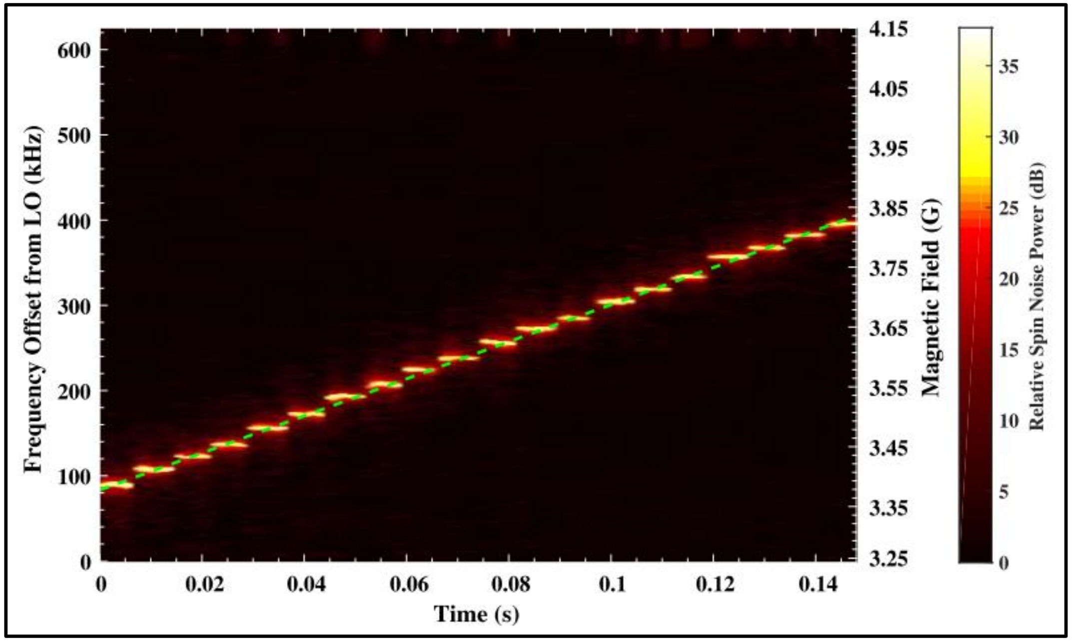


$$g_I = -0.00100627(2558)$$

Vector and time resolved magnetometry



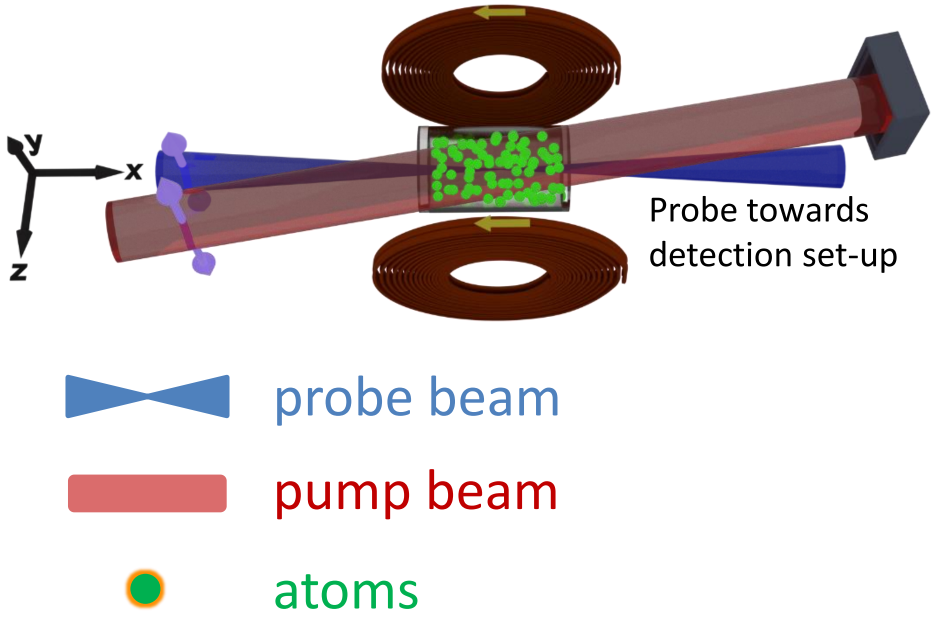
Local magnetic field direction changes spin noise spectrum both as a shift and line-shape change.

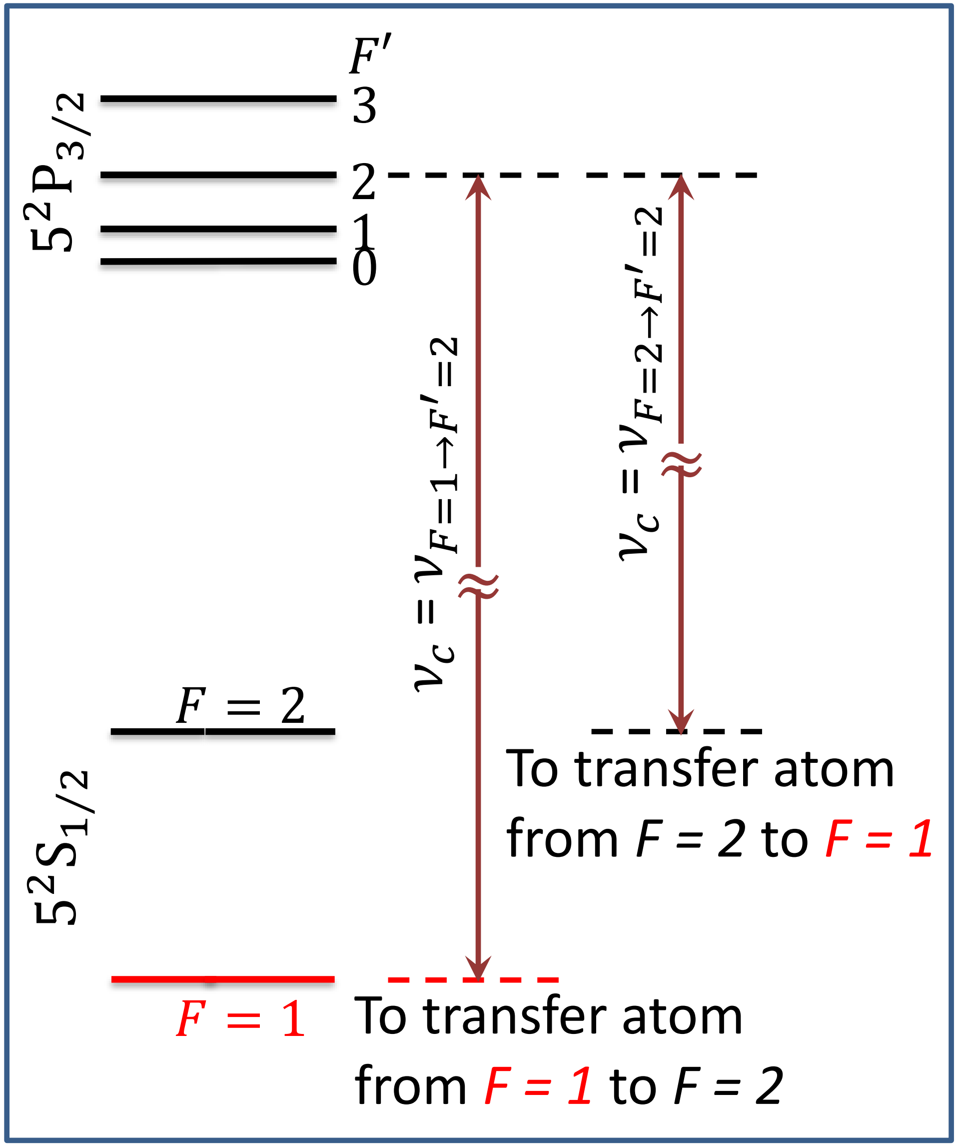


Our fast FPGA based detectors can resolve spin noise signal at *m-sec* time scale --- may be useful For *sensing* biological processes non-invasively

Ref: IEEE TIM, 2021

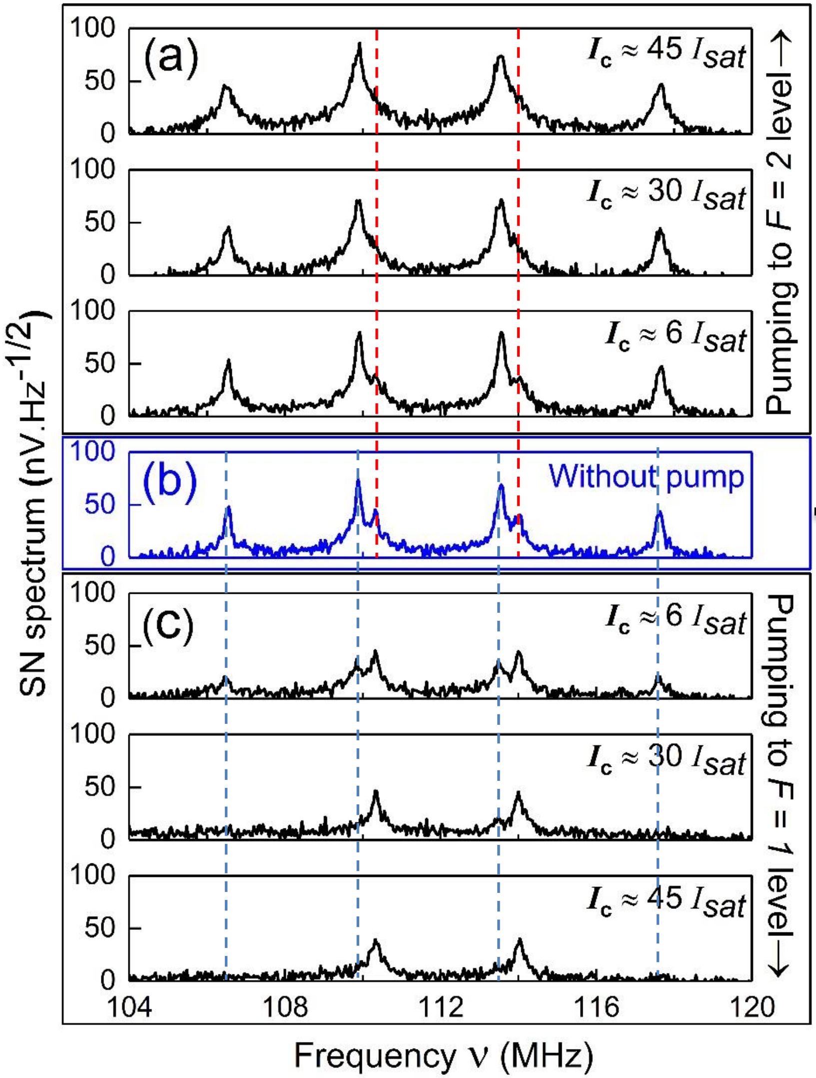
Spin coherence in optically pumped atomic systems

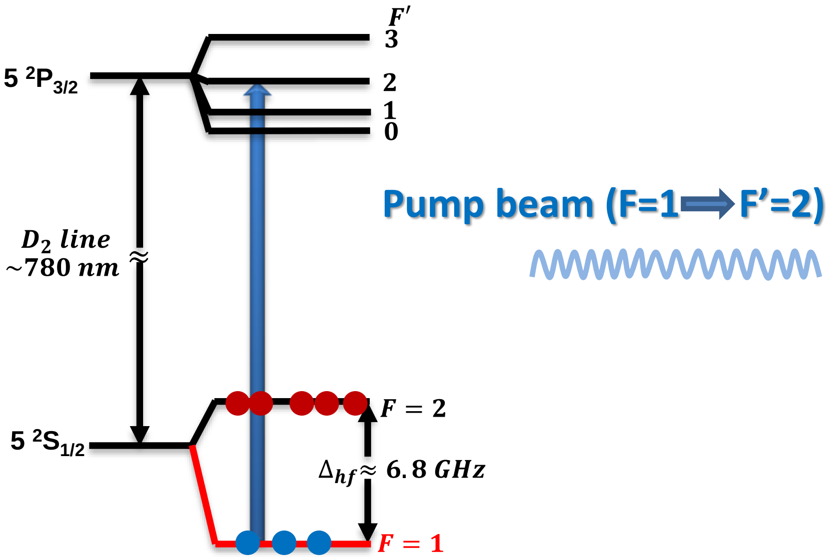


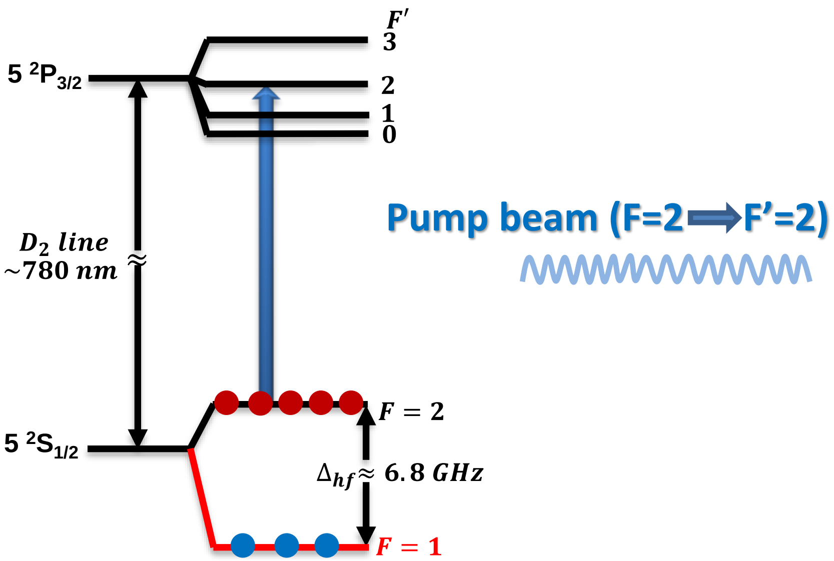


optically pumped atomic systems

During experiment, $\delta_p = -10.6$ GHz

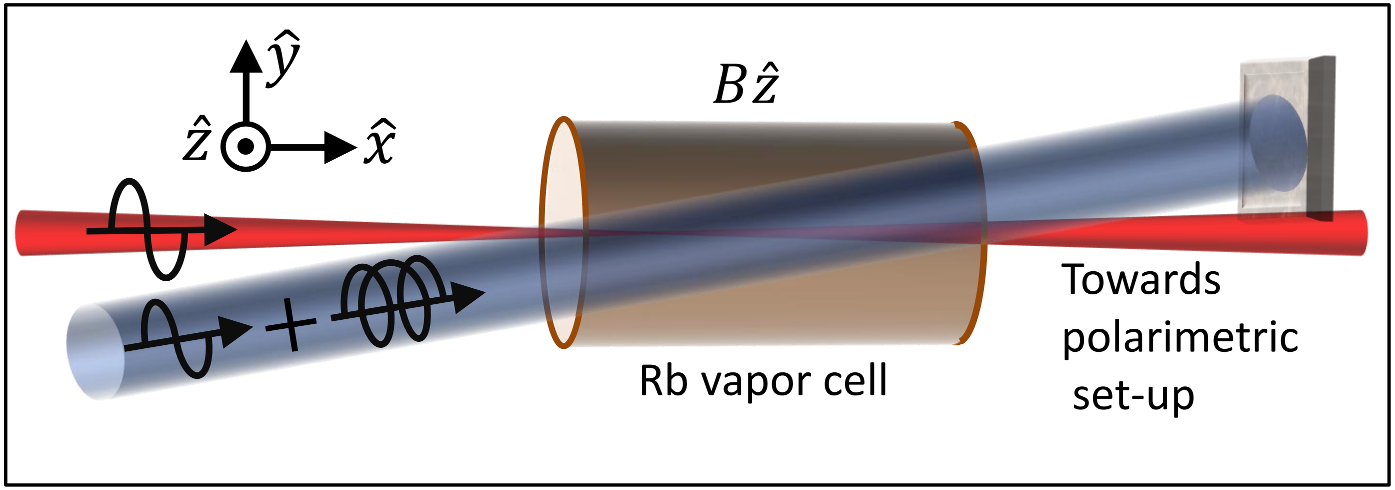


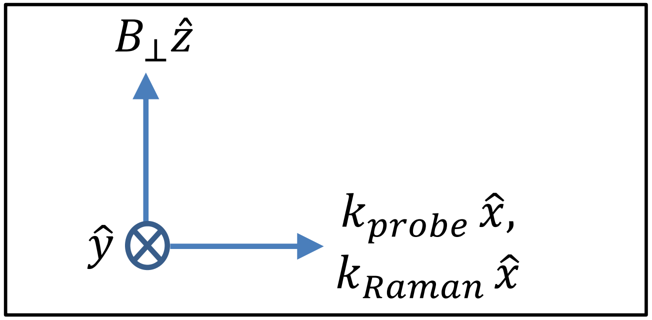




Opt. Express 26, 32168 (2018).

coherently driven atomic systems

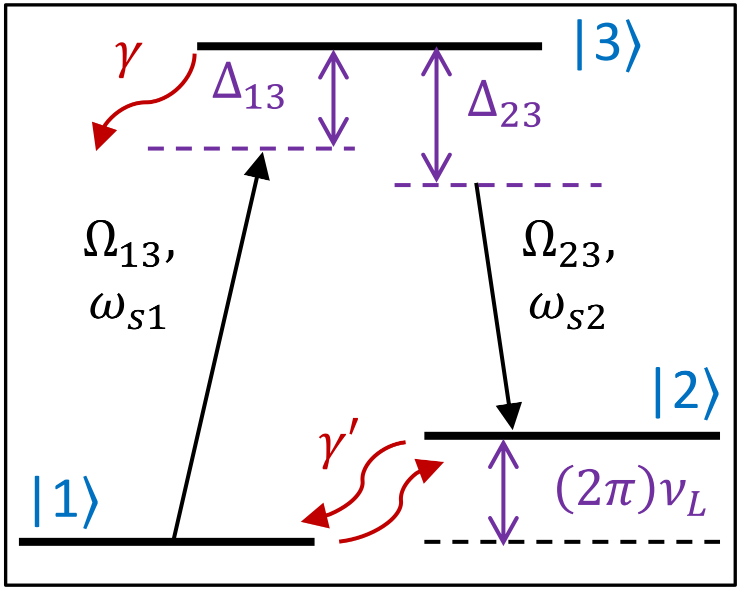


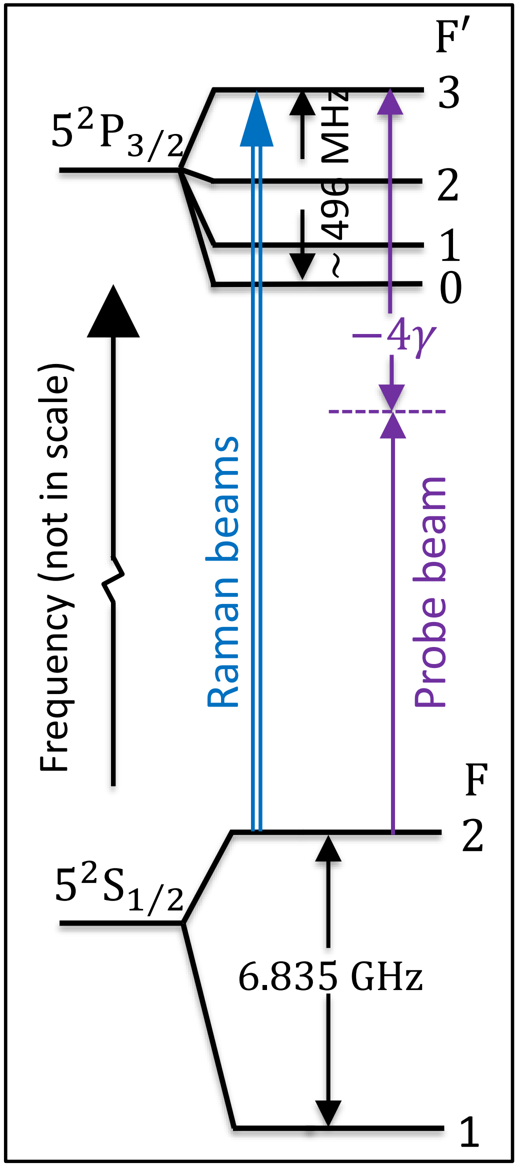


$|1\rangle \equiv |F = 2, m_F = -1\rangle$

$|2\rangle \equiv |F = 2, m_F = 0\rangle$

$|3\rangle \equiv |F' = 3, m_{F'} = 0\rangle$





Phys. Rev. Res. (2021).

Million fold signal enhancement: Thanks to Prof. C. V. Raman!

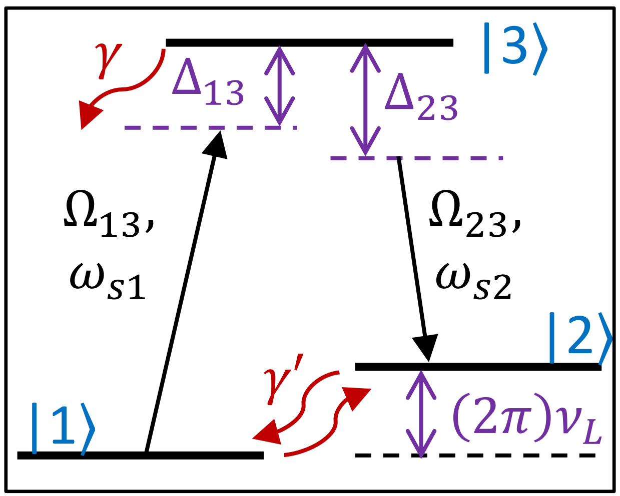
$$\frac{\mathcal{H}}{\hbar} = (\Delta_{23} - \Delta_{13})\mu^\dagger\mu - \Delta_{13}\sigma^\dagger\sigma - \Omega_{13}(\sigma + \sigma^\dagger) - \Omega_{23}(\mu + \mu^\dagger),$$

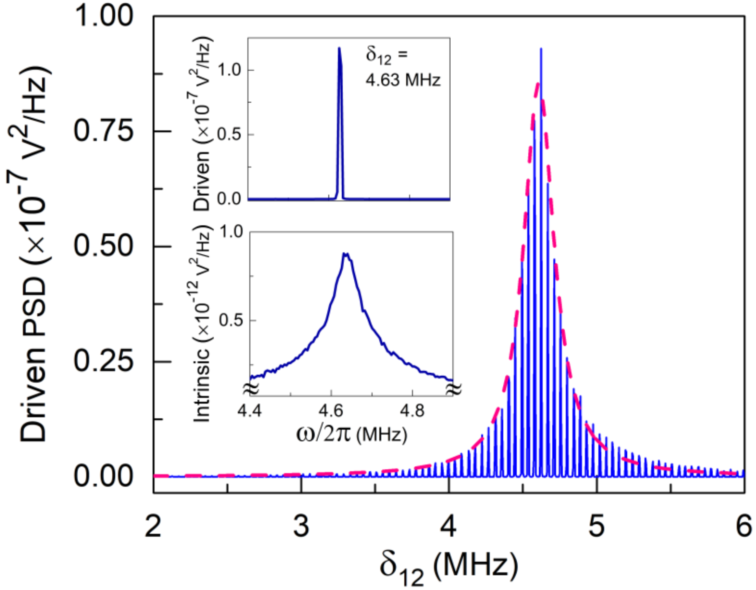
$$\sigma^\dagger = |1\rangle\langle 3|,\ \mu^\dagger = |2\rangle\langle 3|,\ \nu^\dagger = |1\rangle\langle 2|$$

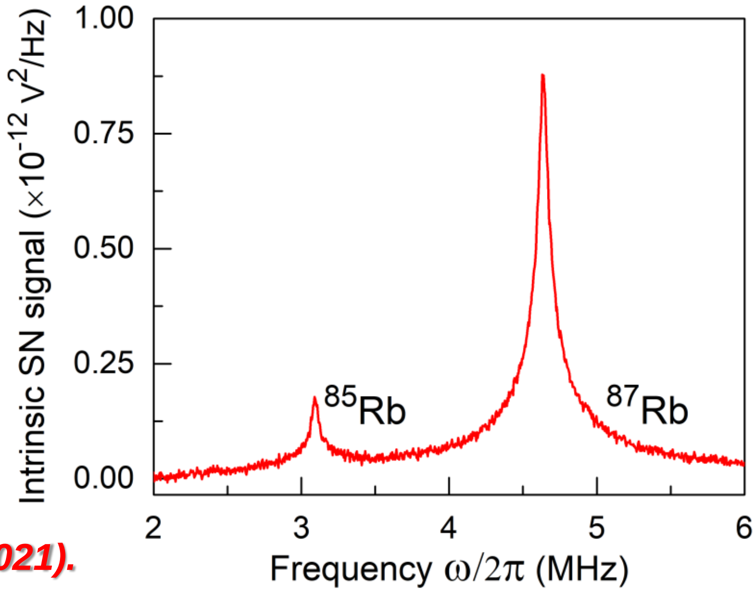
$$P(\omega) = \delta(\omega + \omega_{s2} - \omega_{s1})|\rho_{21}|^2$$

$$\omega = \omega_{s1} - \omega_{s2} =: 2\pi\delta_{12}$$

$$2\pi\delta_{12} = 2\pi\nu_L - (\Delta_{23} - \Delta_{13})$$

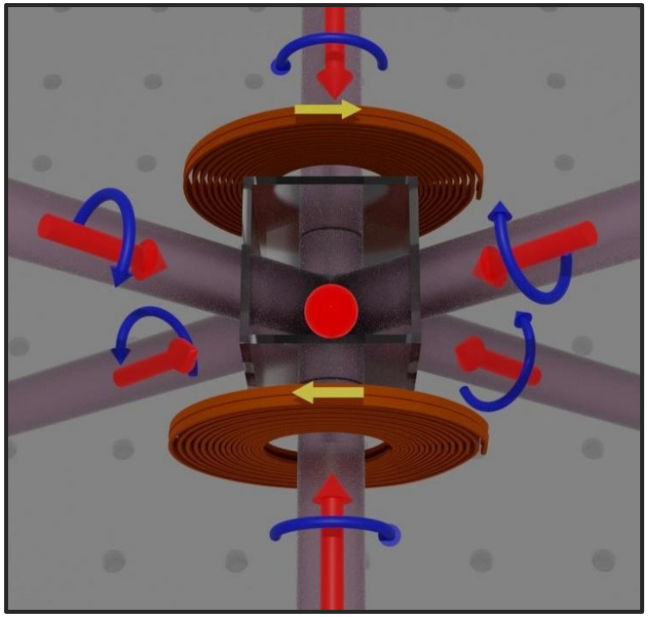


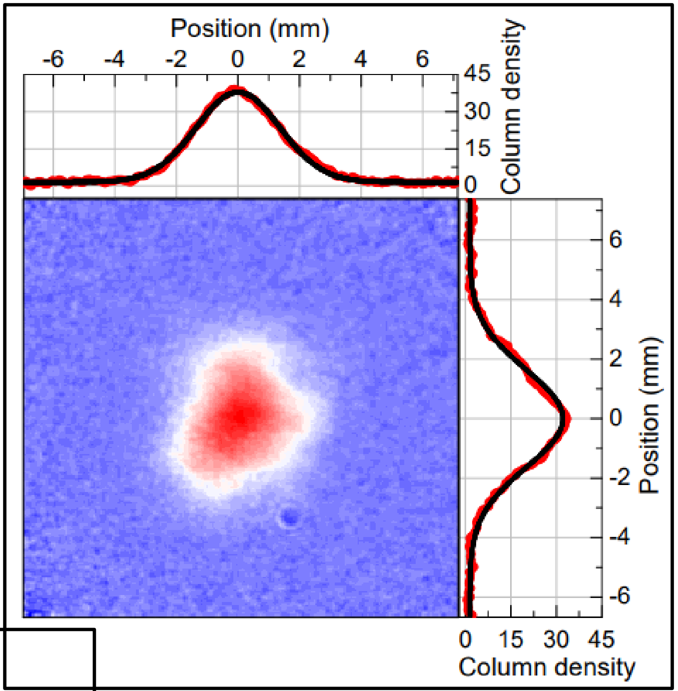


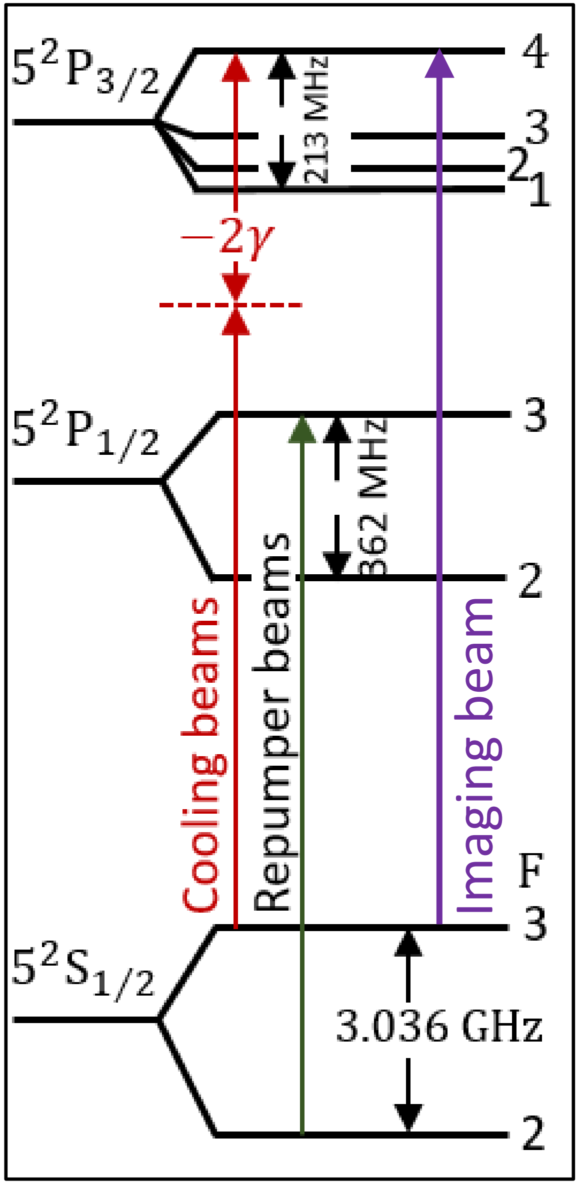


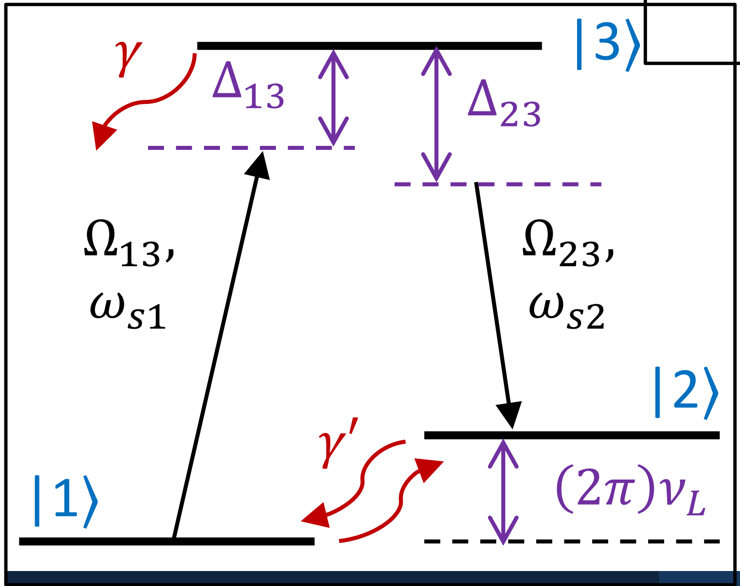
Phys. Rev. Res. (2021).

First ever direct spin fluctuation detection in cold atoms



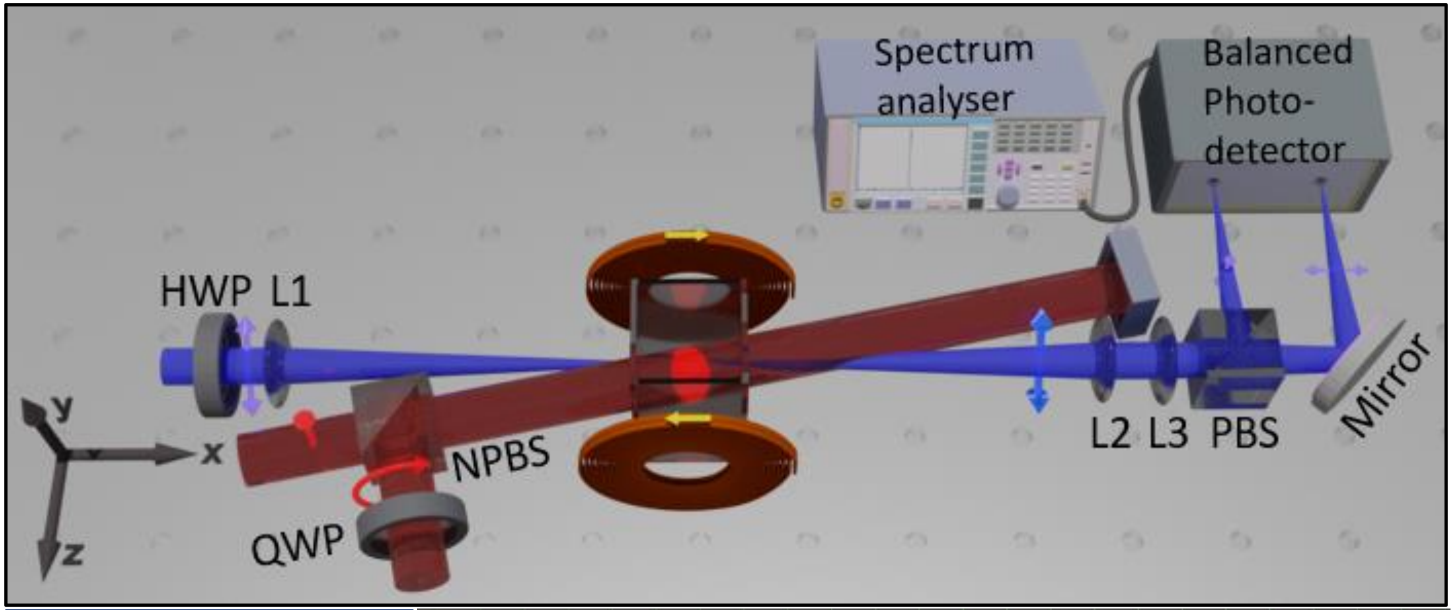


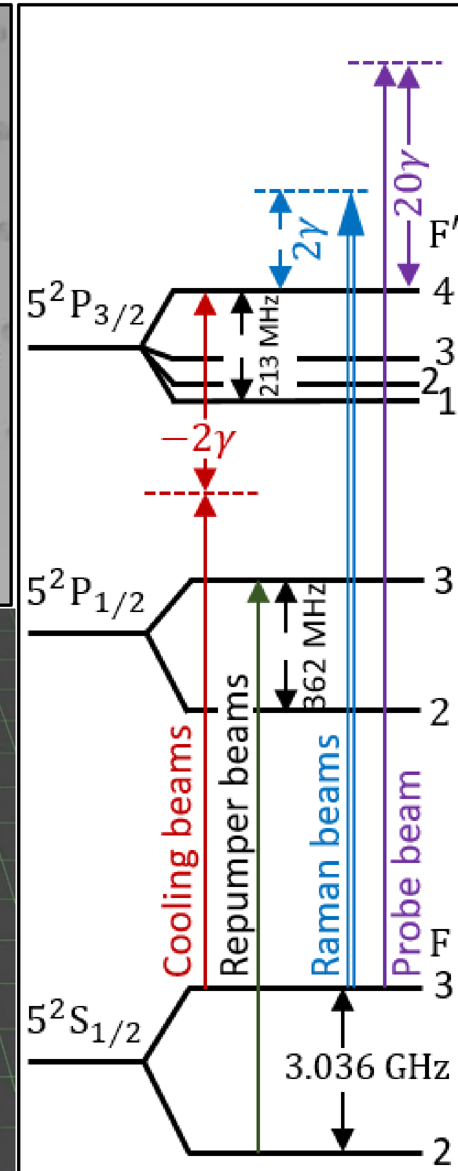




Phys. Rev. Res. (2021).

Spin coherence in Magneto Optically Trapped atoms

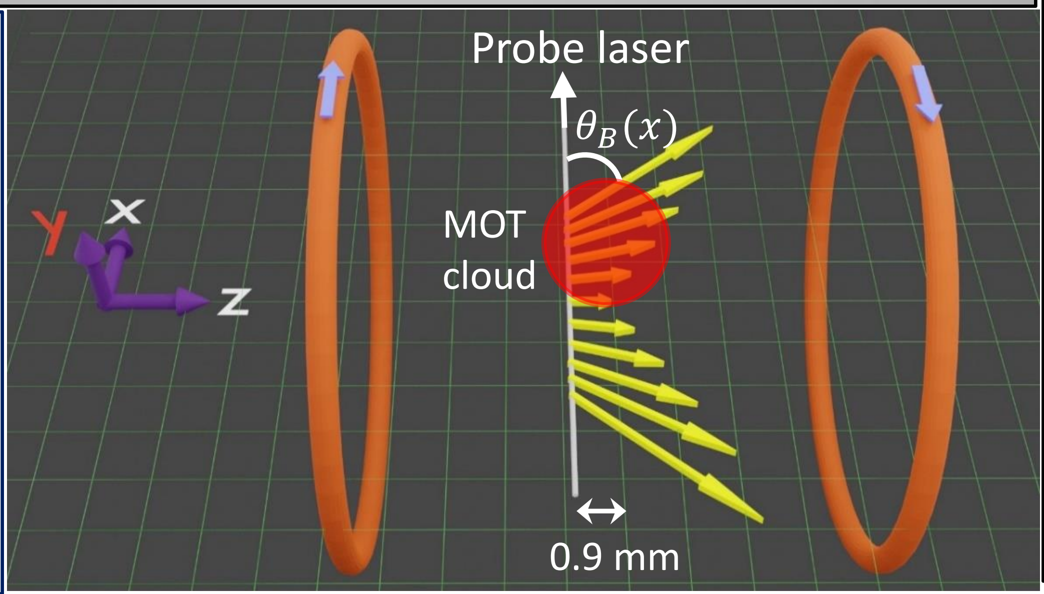




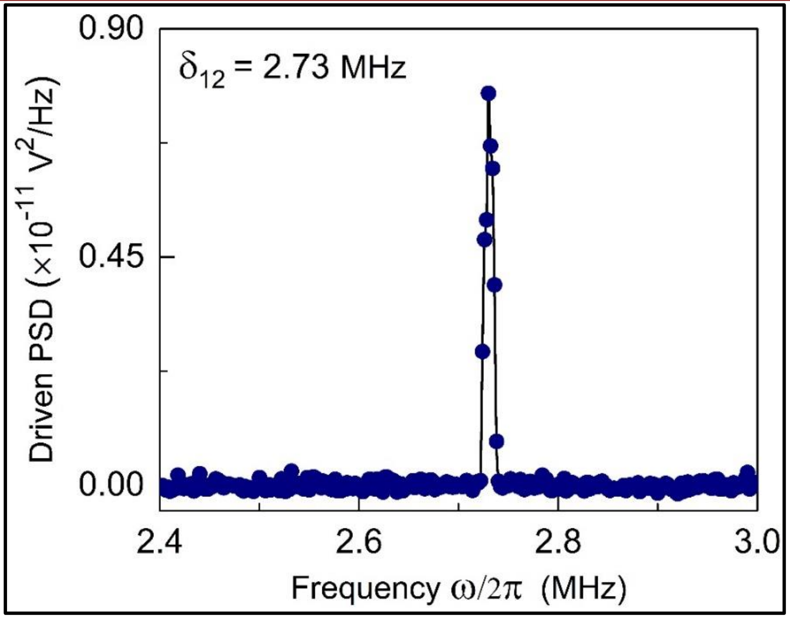
Raman beam polarization:
$(\pi_1)_x - (\sigma_2^+)_x$

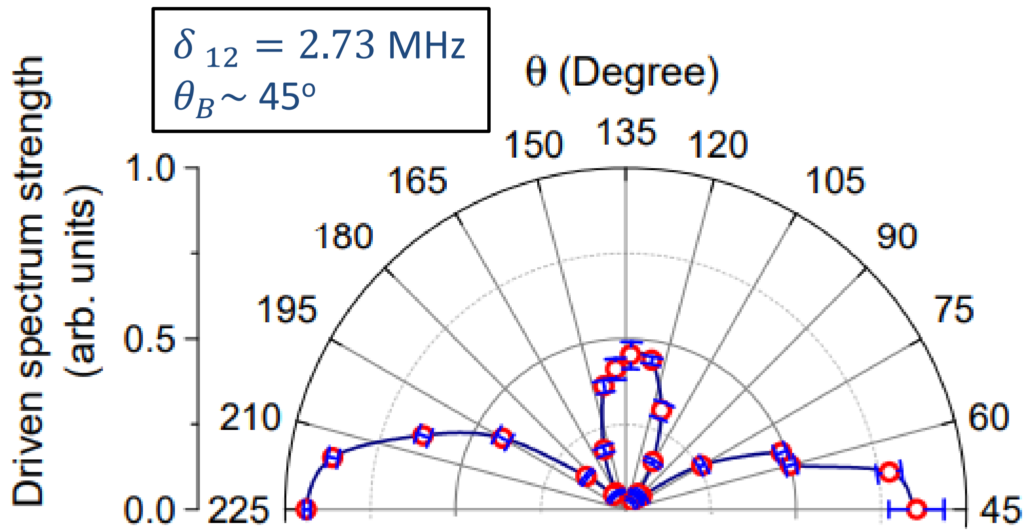
Probe beam diameter
$\sim 70\ \mu m$

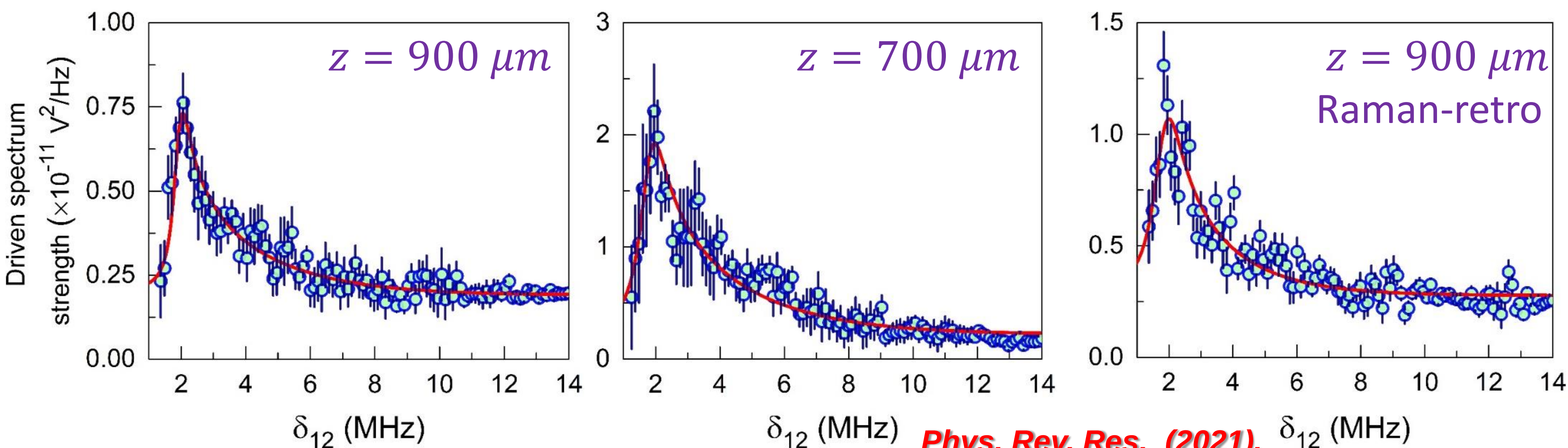
$\frac{\Omega}{\gamma} \sim 0.35$



Driven spectrum in cold atoms







Phys. Rev. Res. (2021).

Conclusions and outlook

- **A new state-of-the-art machine to experimentally study to ultra-cold atomic gases**
- **A novel measurement technique to explore spin dynamics at this regime**
- **Applications include quantum sensing with high precision and high time resolution**
- **Cold atoms in structured potential → Many body physics in arbitrary geometry and dimensionality**

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