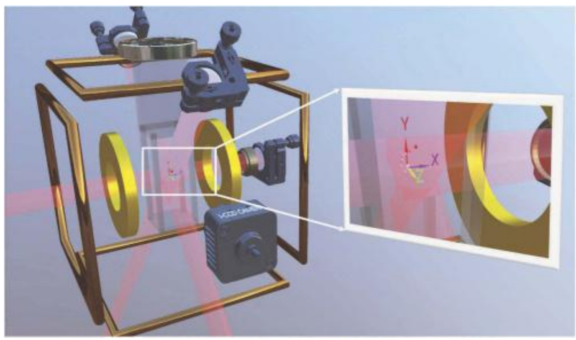
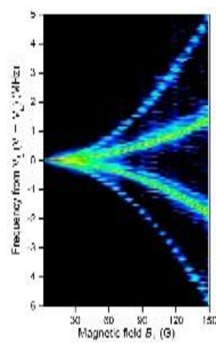
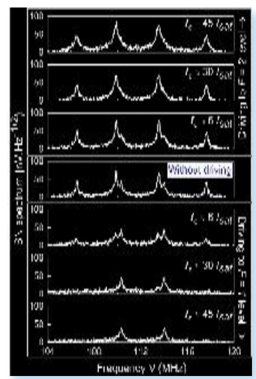
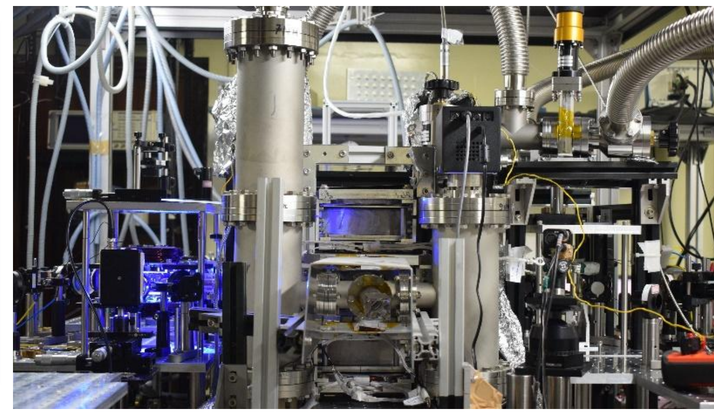
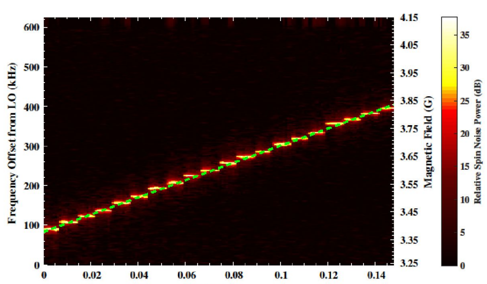
Experiments with Mixtures of cold atoms: **Quantum sensors**







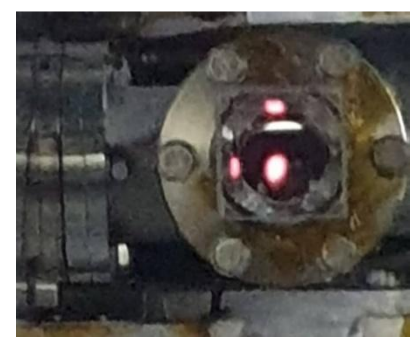




Saptarishi Chaudhuri

Raman Research Institute

10 May 2022



Plan of the talk

- A brief overview of our newly-built experimental machine at RRI to simultaneously cool and trap Sodium and Potassium atoms towards Quantum degeneracy (presently up to micro-Kelvin temperatures)

- A rather "detailed" discussion on our "spin noise spectroscopy" experiments on "Coherently driven" cold atoms: precision and time-resolved magnetic field sensing

References (Some recent, relevant articles from our lab):

1. Phys. Rev. Research 3, 043171 (2021) (On spin noise in cold atoms)
2. Optics Express 26, 32168 (2018). (On spin noise in thermal vapor)
3. IEEE Transactions on Instrumentation and Measurement, 70, 1 (2021) (On Magnetometry)
4. Optics Continuum 1 (2), 171-188 (2022) (On response of a cold atom in photon bath)
5. Optics Continuum 1 (5) (to appear) arXiv:2203.04852 (2022) (On Rydberg spectroscopy)

TEAM

Sanjukta Roy
(DST Scientist)

Supurna Sinha
(Theory collaborator, RRI)

Dibyendu Roy
(Theory collaborator, RRI)

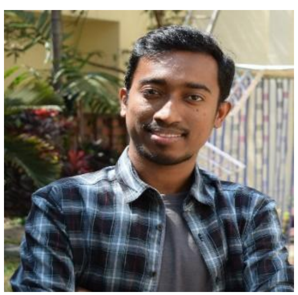
Sagar Sutradhar
(PhD Scholar)

Maheswar Swar
(PhD Thesis Submitted)

Subhajit Bhar
(PhD Synopsis submitted)

Silpa B. S.
(PhD Scholar)

Shreya Bagchi
(PhD Scholar)



Shovan Barik
(PhD Scholar)

Bidyut Bikash Boruah
(PhD Scholar)

Gourab Pal
(PhD Scholar)

Anirban
Misra
(PhD
Scholar)

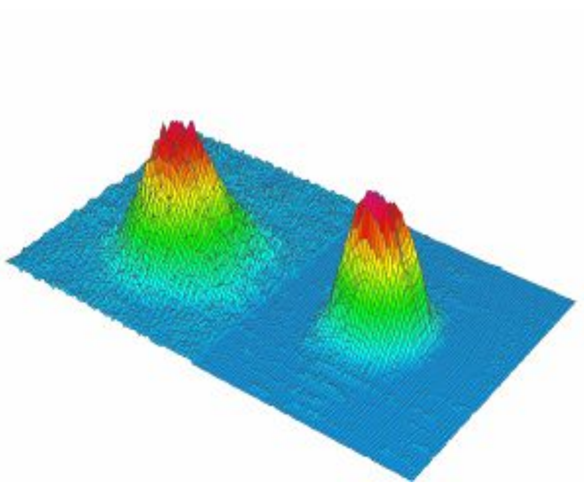
Sayari Majumdar
(PhD Scholar)

Swarnava Barui
(PhD Scholar)

The Quantum Mixture Lab @RRI

- **Aim: Multi species BEC and Fermi superfluid in Optical Lattices**

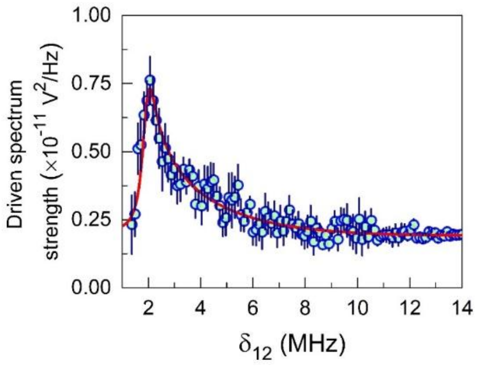
To primarily study quantum correlations:
By tuning interspecies interactions
And
Trap geometry and dimensionality

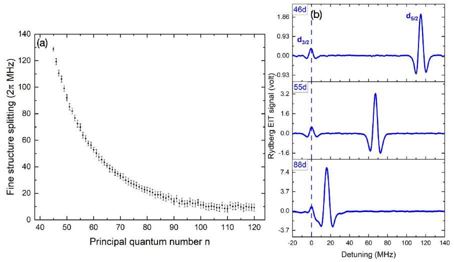


- **Atoms we cool**: Sodium (Bosons), Potassium (Fermions and Bosons), Rubidium (Bosons)

  - **Cold atoms** are also excellent systems for **precision measurements** and as **Sensors**

Sensors: Faraday rotation fluctuation measurements on cold atoms

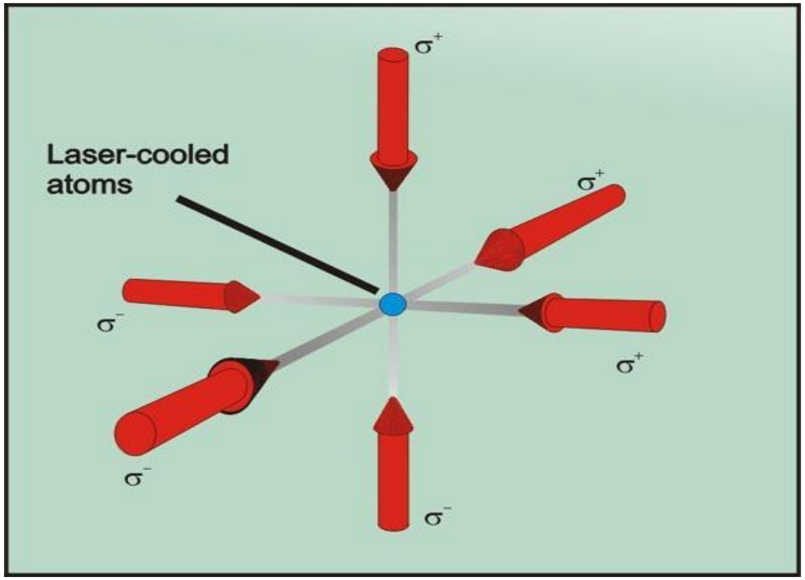


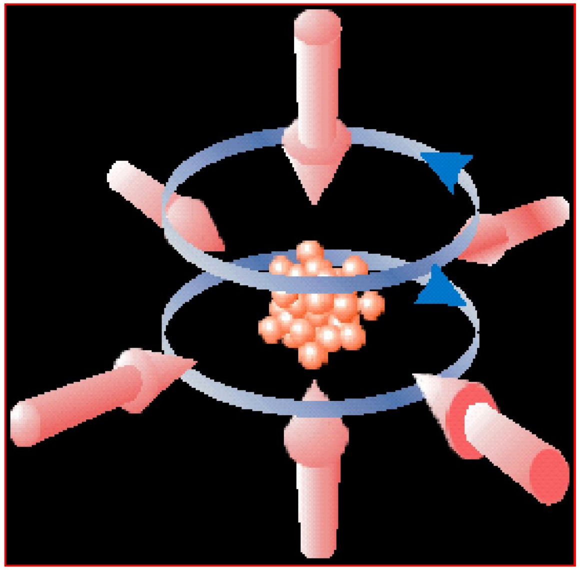


Precision measurements: Rydberg atoms

Laser cooling:

Strong damping of atomic motion

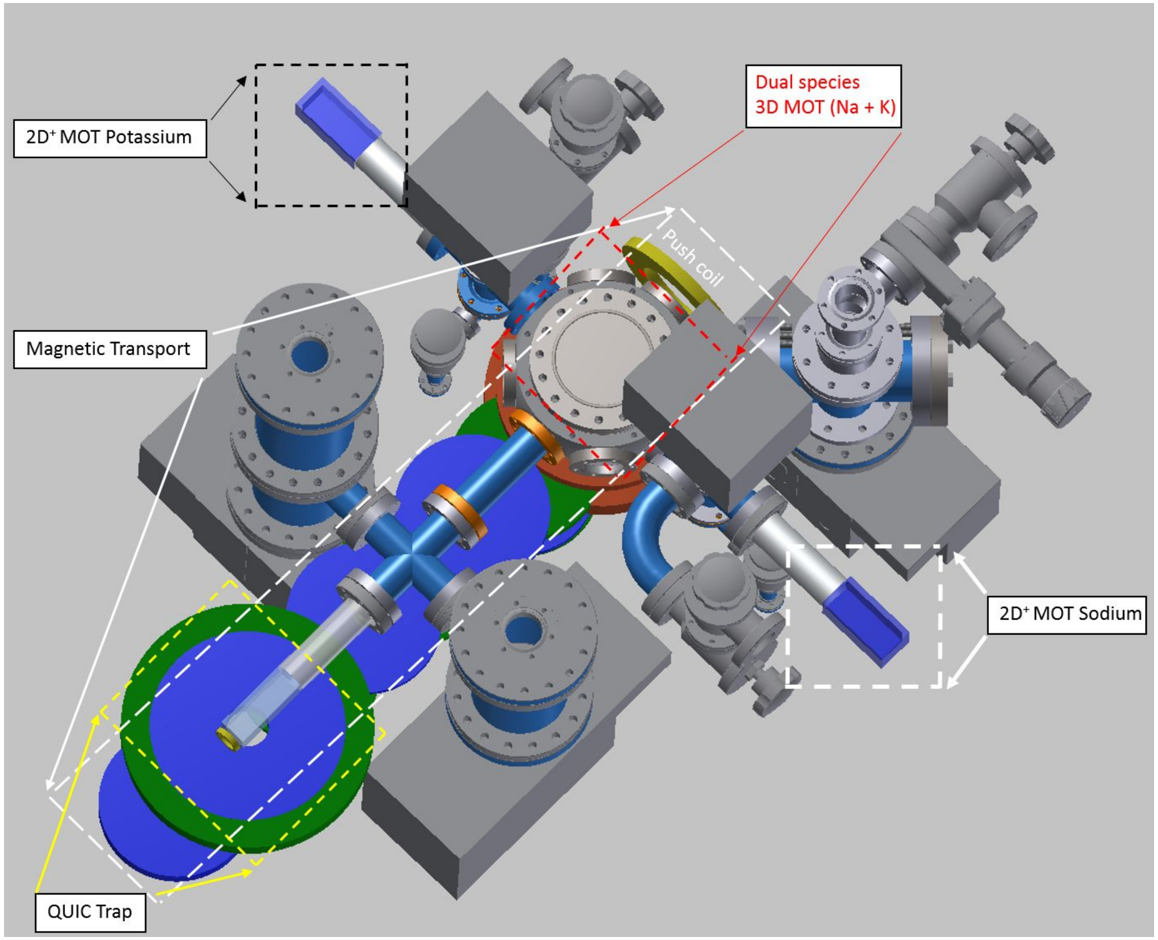




Atom feels viscous force within the Laser beams

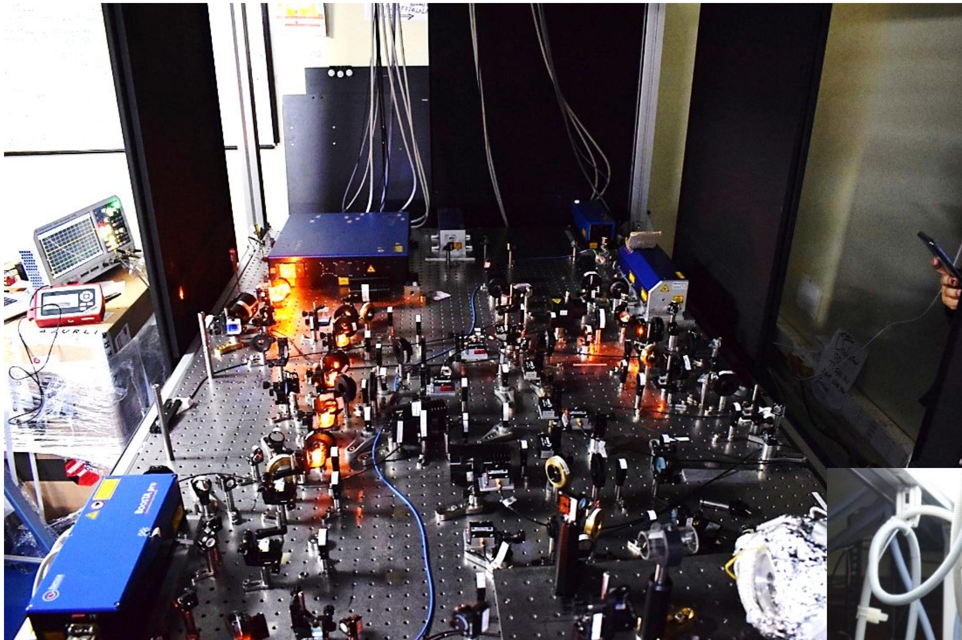
+ Trapping using spatially varying magnetic fiels

The Experiment

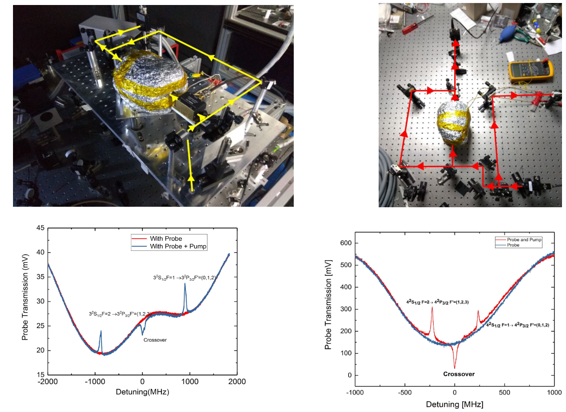


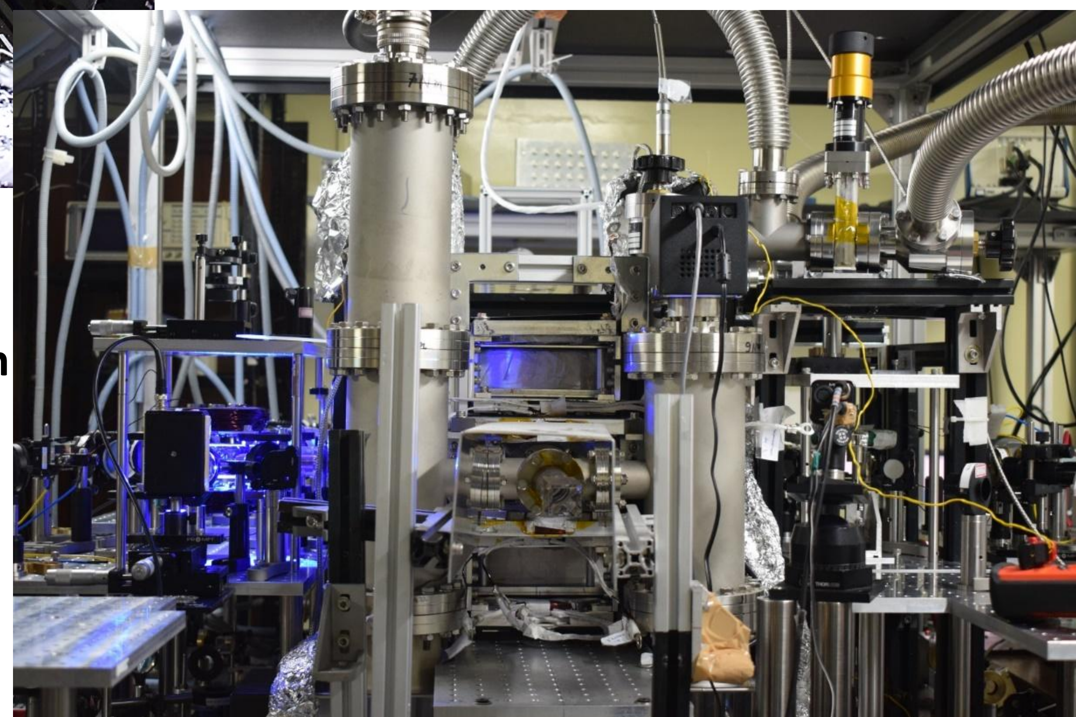
Heavily influenced by Star Trek Enterprise!

Preparing the Lasers and Vacuum system!



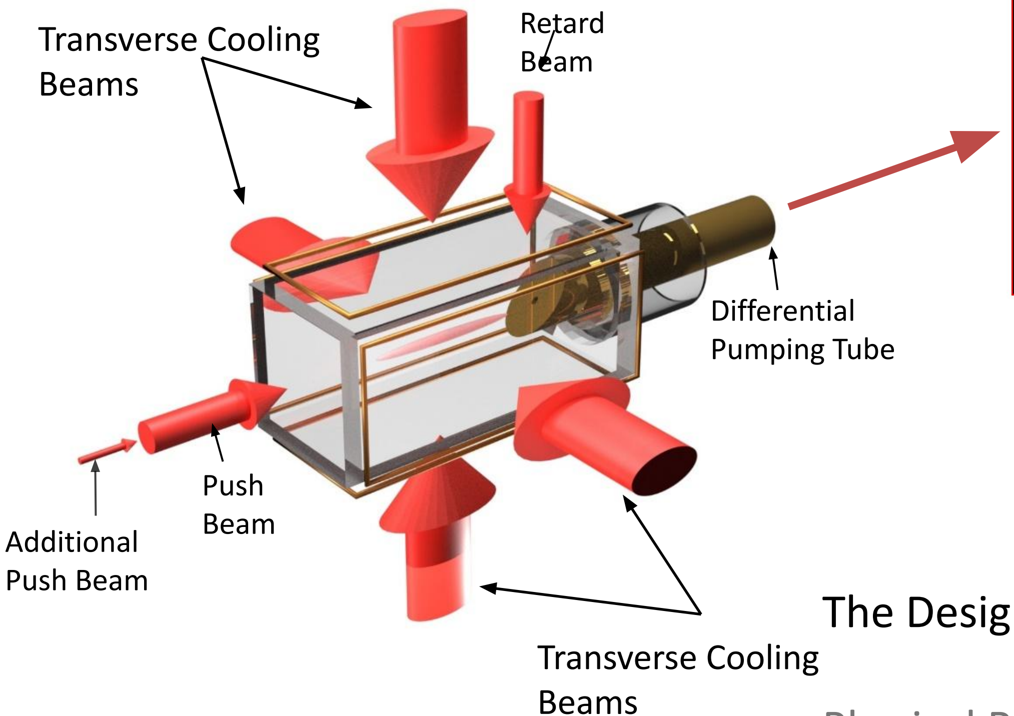
SPECTROSCOPY SET-UPS FOR COOLING

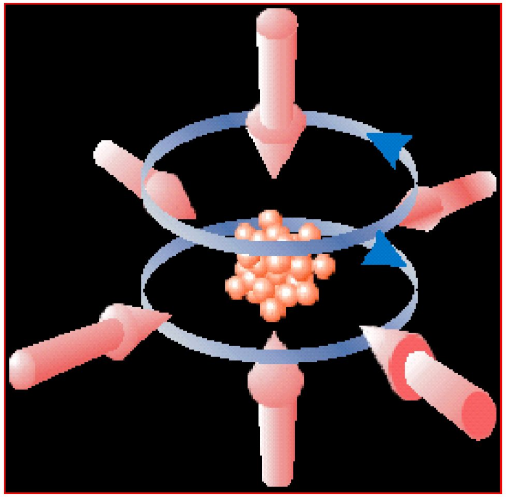




- **Ultra-high vacuum ~** 10^{-11} mBar
- Ultra precision **frequency stabilization** of lasers ~ 100 kHz linewidths
- Ultra-stable optical set-up
- High resolution (~ 2.4 μm) imaging

The cold atom sources





The Design based on our previous works:

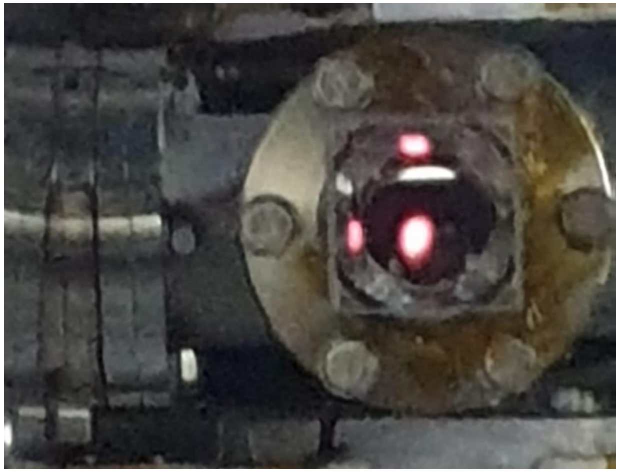
Physical Review A 74 (2), 023406 (2006)

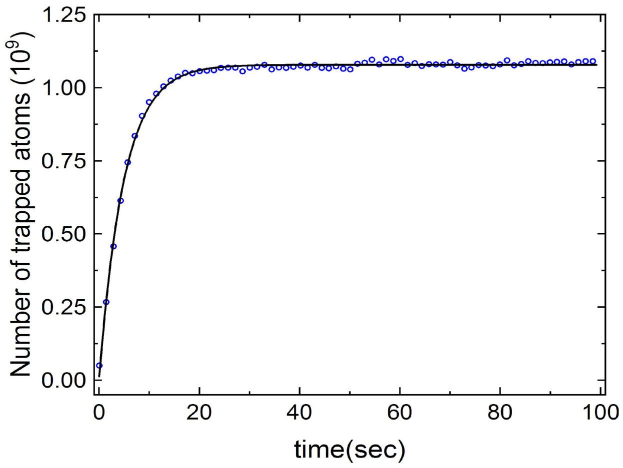
The European Physical Journal D 65 (1), 223-242 (2011)

The Potassium and Sodium cold atoms

^{23}Na MOT

^{39}K MOT





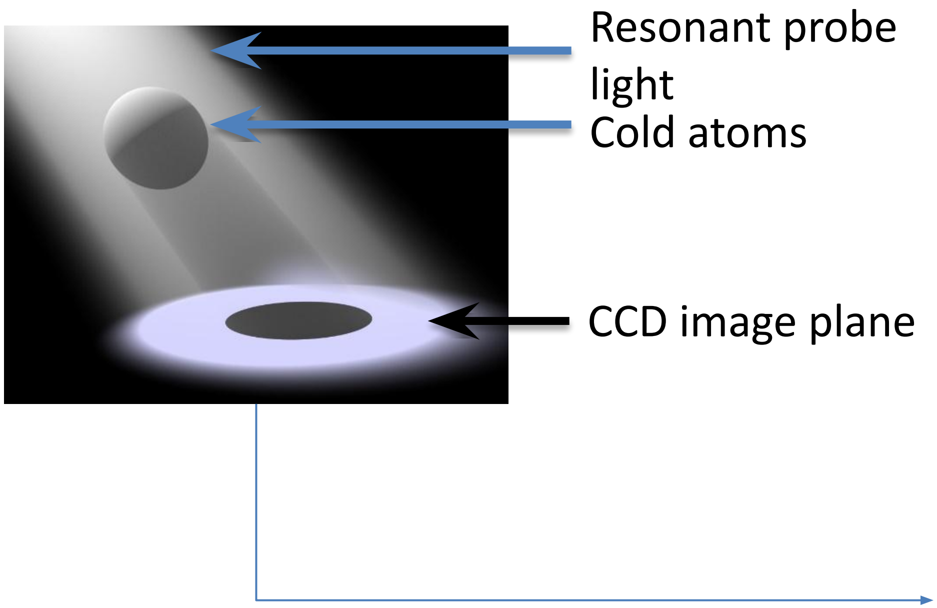
Detail characterization of the system and Manuscript in preparation.

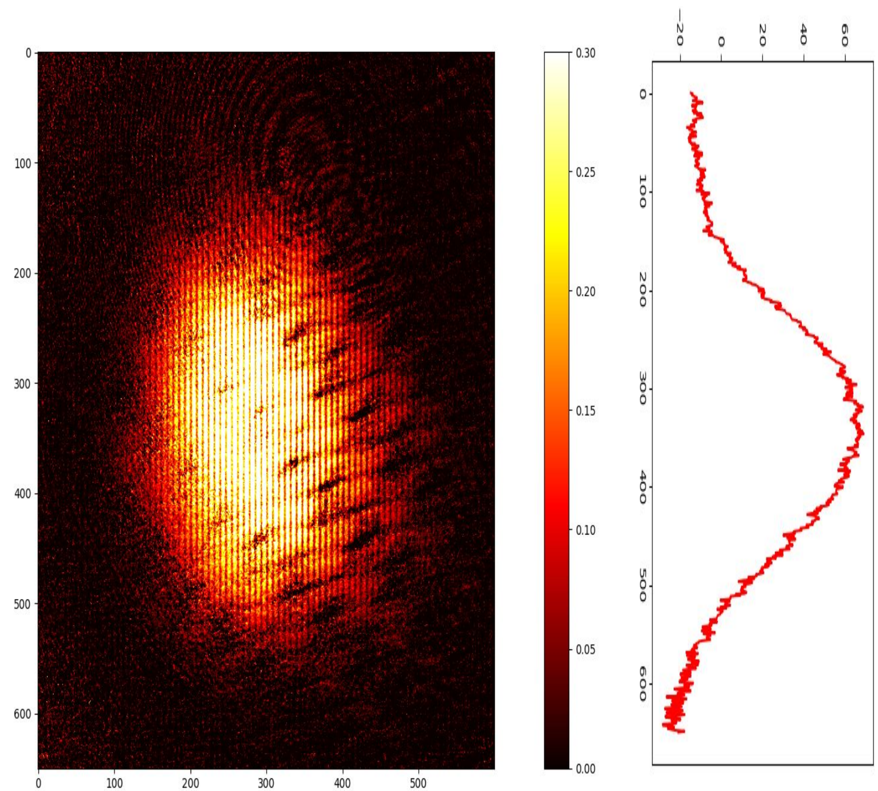
Status:

- Billion+ Potassium atoms cooled to T = 450 μK
- 10^7 Sodium trapped atoms (optimization stage)
- Optical traps and lattice lasers being installed

Detection Techniques

Absorption imaging:





Potassium absorption imaging

Spin correlation spectroscopy

A Quantum Non-Demolition (QND) measurement technique

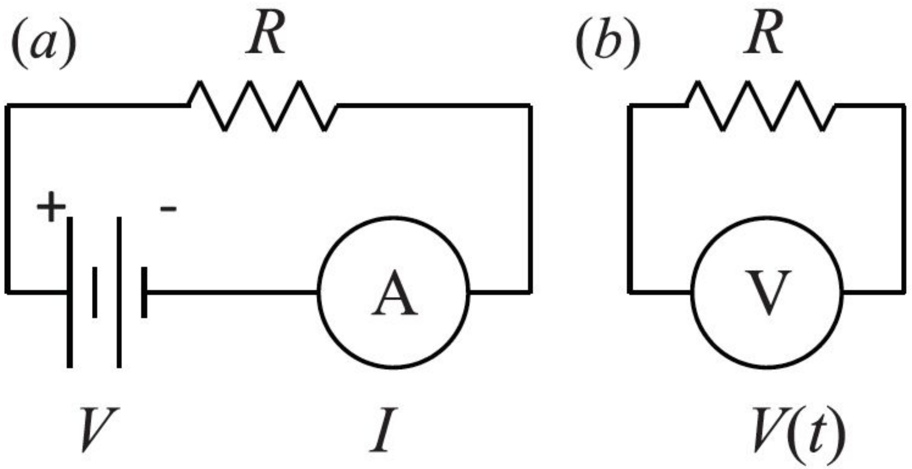
Sanjukta Roy, Dibyendu Roy, Maheswar Swar, Subhajit Bhar

Primary reference:

Phys. Rev. Research 3, 043171 (2021)

Measurement of Stochastic fluctuations

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

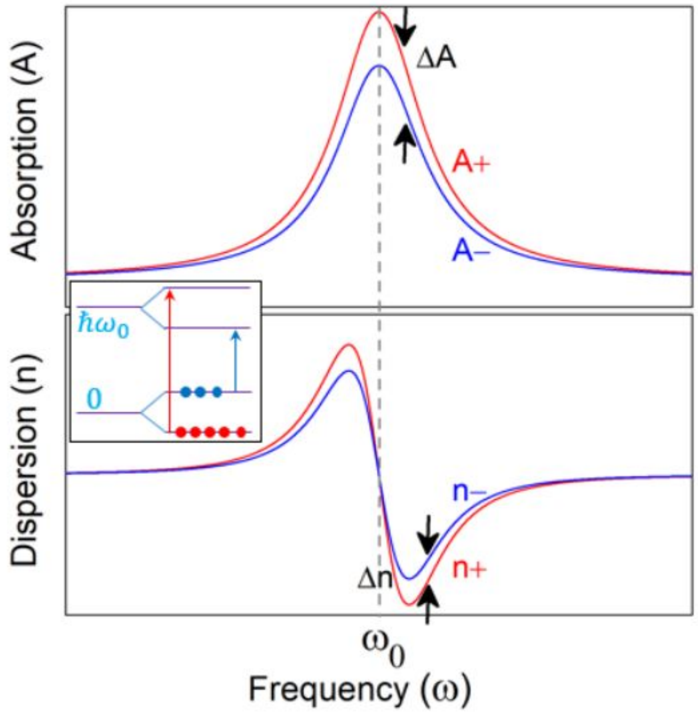
By measuring "fluctuations" we can sense Resistance value!

Lets do the same thing for Magnetic field measurements !

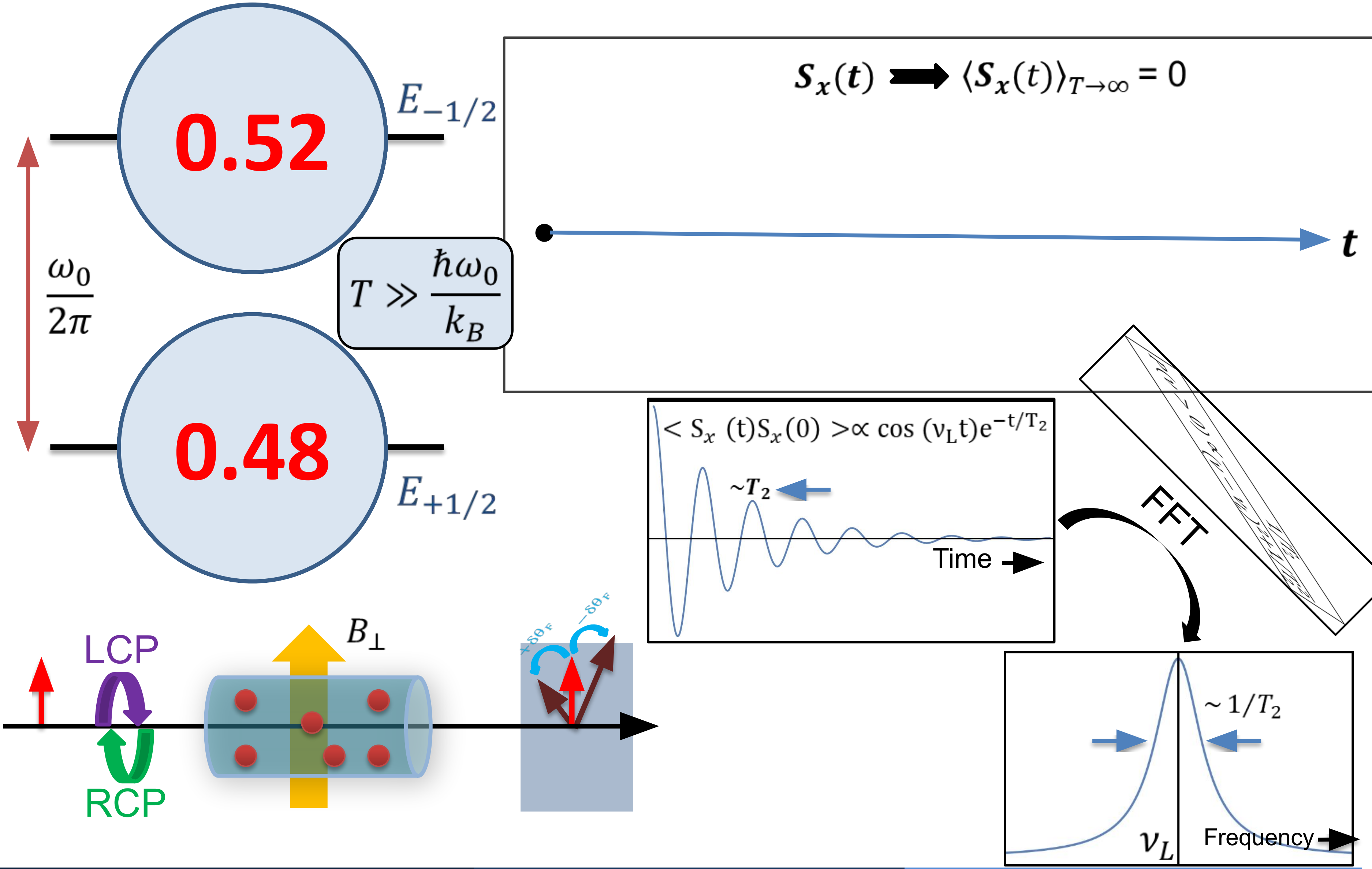
Measurement of Magnetization fluctuations

Basics of Spin Noise Spectroscopy:

- **Fluctuation-dissipation theorem:** Fluctuations in atomic population between different magnetic states causes dissipation in net magnetization of spin system.
- This leads to a correlated fluctuations in the real part of linear susceptibility (Re $[\chi^{(1)}]$) via Kramers-Kronig relations.
- A linearly polarized, far detuned, and weak probe laser detects magnetization fluctuation in its time resolved Faraday rotation angle as a "noise".
- A homogeneous magnetic field is applied across the probe laser to detect the spin coherence signal at Larmor frequency in its frequency spectrum.

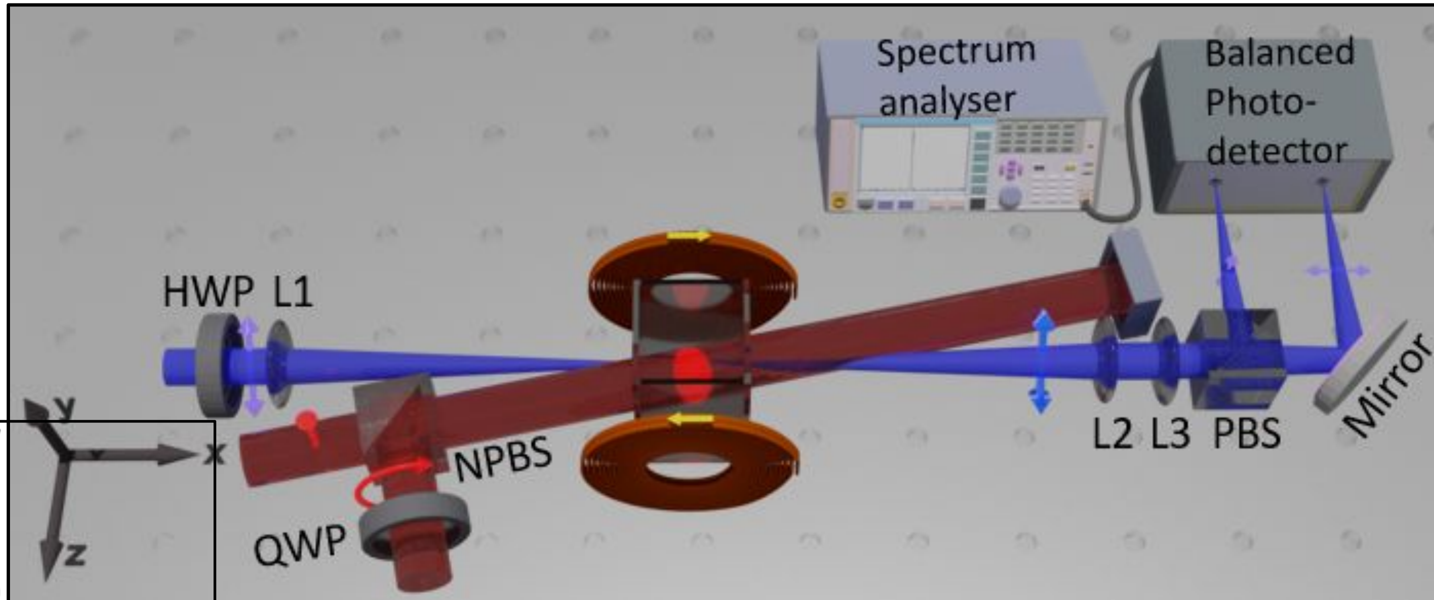


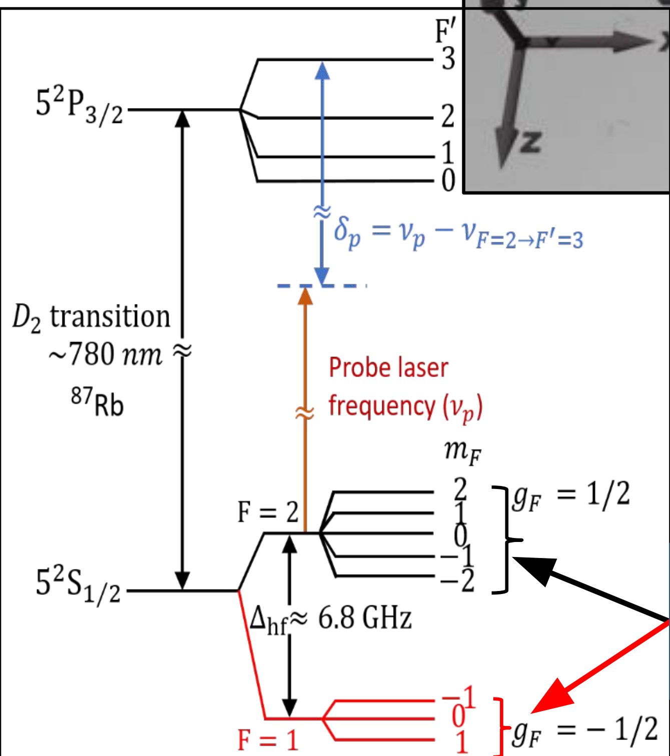
Introduction: basics of spin noise spectroscopy (SNS)



Intrinsic spin noise (SN) spectrum

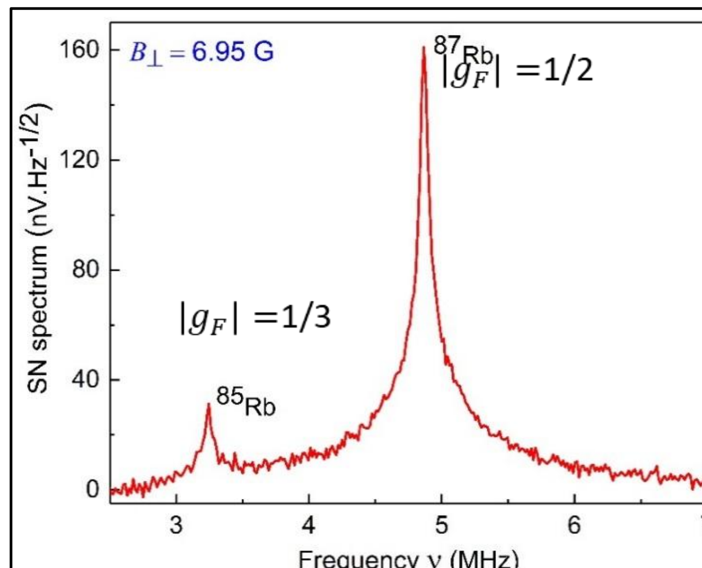
Reference:
Opt. Express **26**, 32168 (2018).



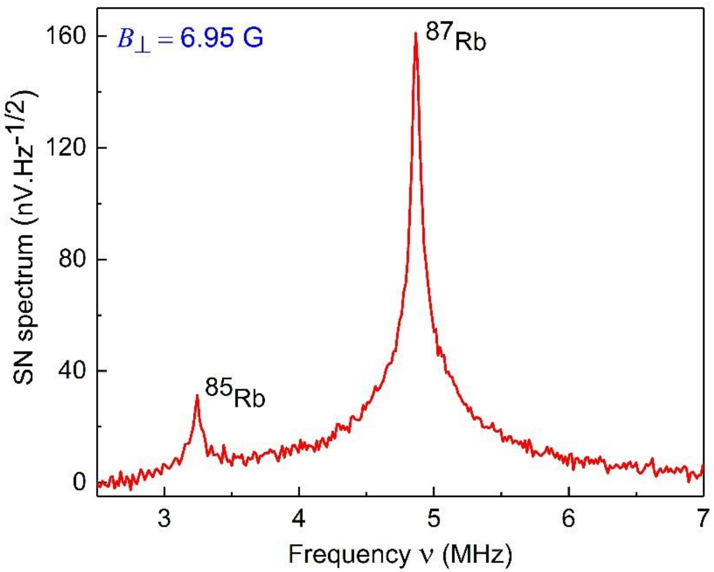


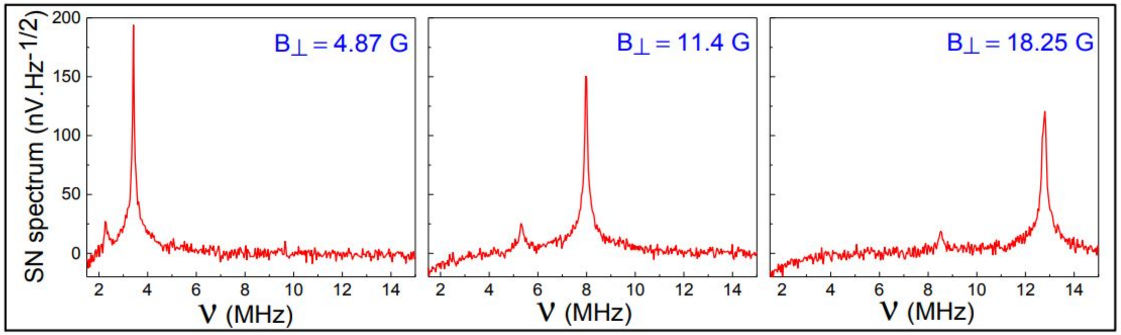
$$\Sigma = \int_0^\infty d\nu\, P(\nu) \propto \frac{I_p^2}{\delta_p^2}\left(\frac{n_0 l}{A}\right)$$

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

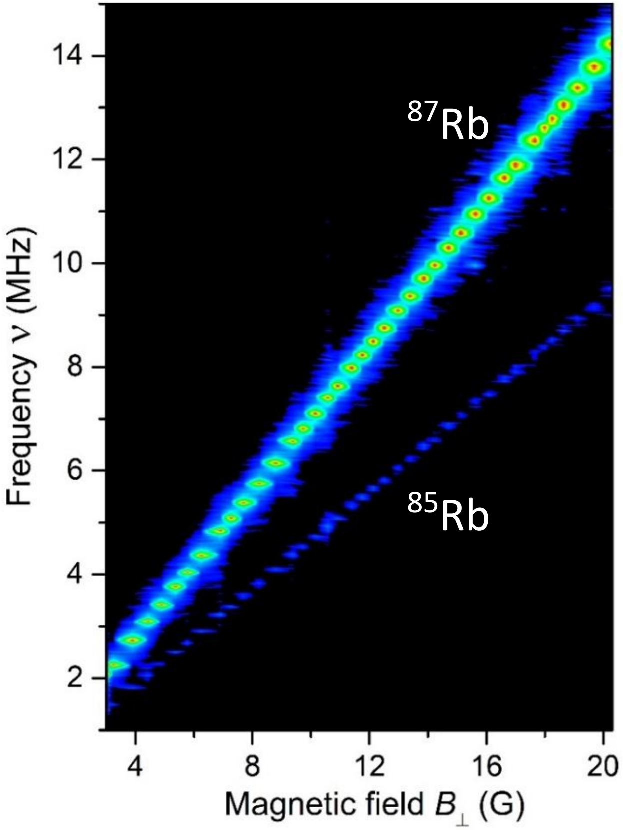


Applications of intrinsic SNS (linear Zeeman regime)



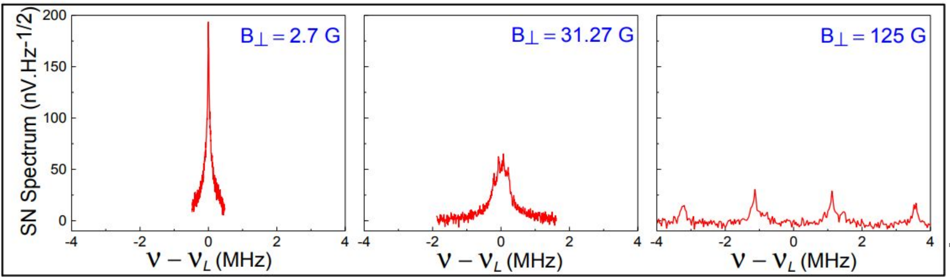


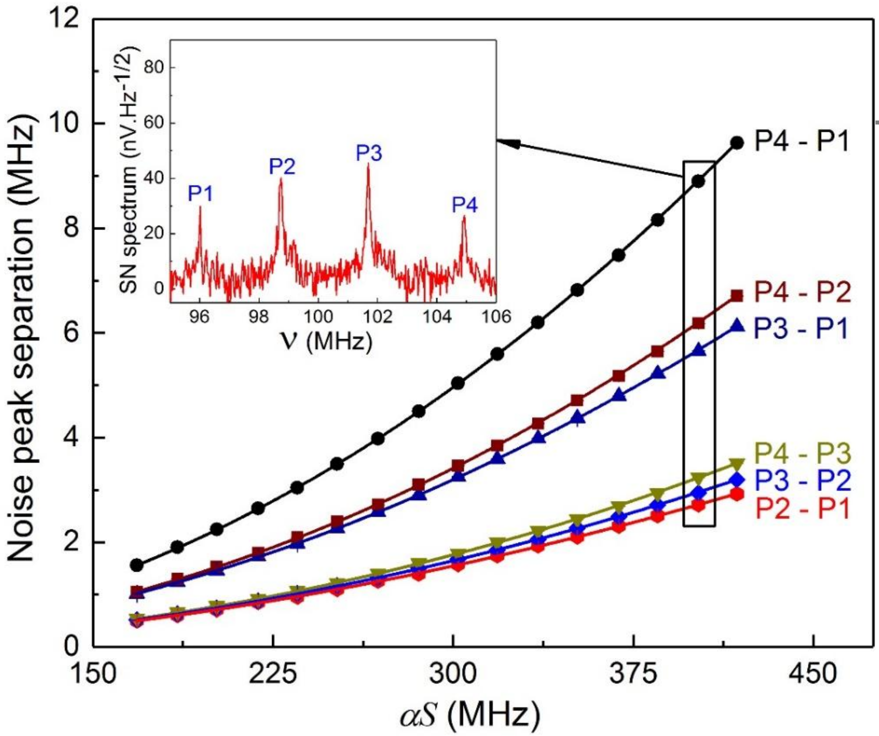
$$|g_F| = \frac{h\nu_L}{\mu_B B_\perp}$$

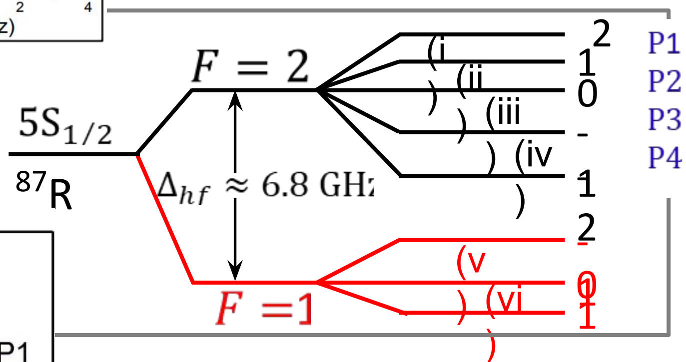


Parameters	Extracted value

Applications of intrinsic SNS (non-linear Zeeman regime)







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

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

$$S = P_1 + P_2 + P_3 + P_4 = \frac{\mu_B}{h}(3g_I + g_J)\,\boldsymbol{B_\perp}$$

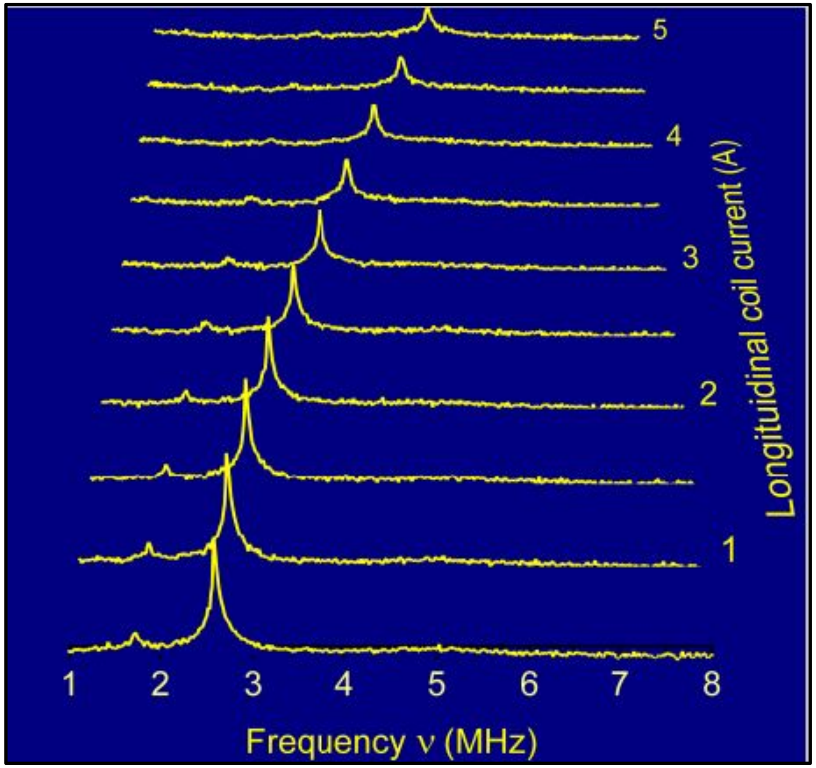
- Accuracy in $B_\perp$ measurement = 50 nT

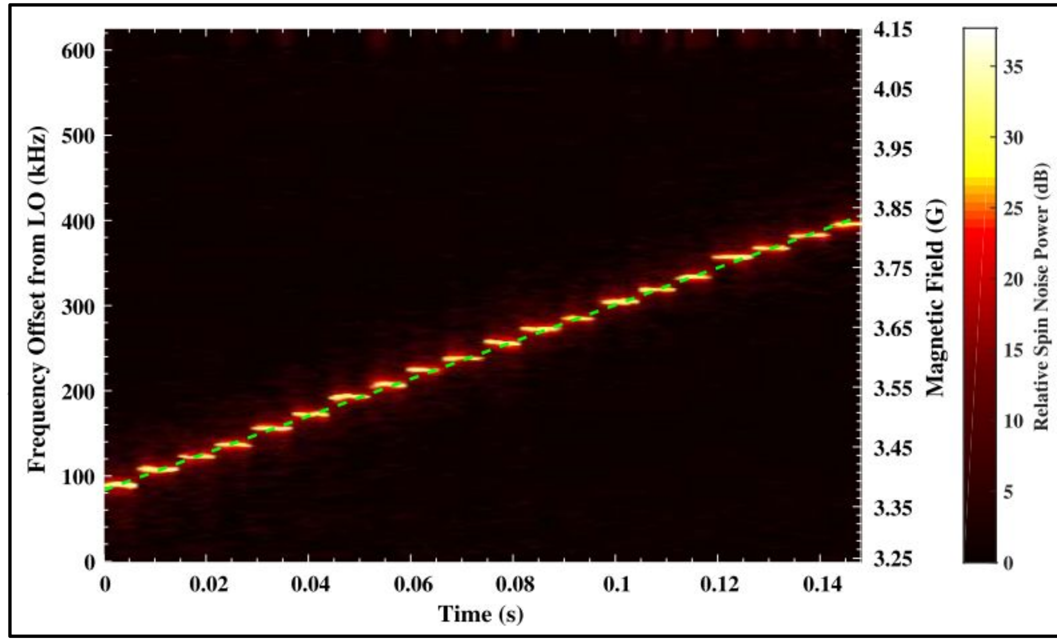
$$E_{F=2,m_F} = -\frac{h\Delta_{\rm hf}}{8} + \frac{hg_I}{(g_J - g_I)} m_F(\alpha S) + \frac{h}{2}\sqrt{\Delta_{hf}^2 + \Delta_{\rm hf}\, m_F(\alpha S) + (\alpha S)^2}$$

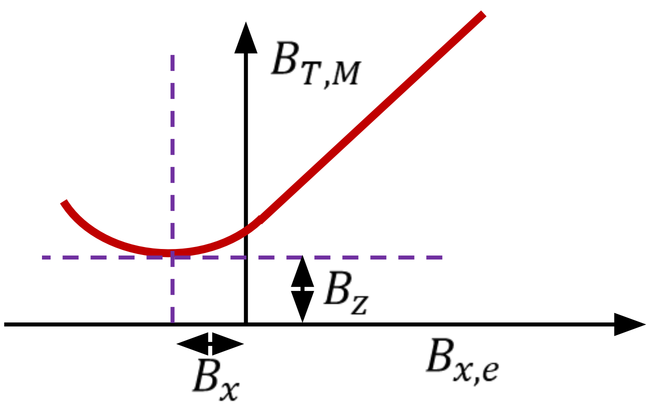
$$\alpha = (g_J - g_I)/(g_J + 3g_I)$$

- $\Delta_{hf} \sim$ 6805.5(7.2) MHz

Vector magnetometry and time-resolved magnetometry





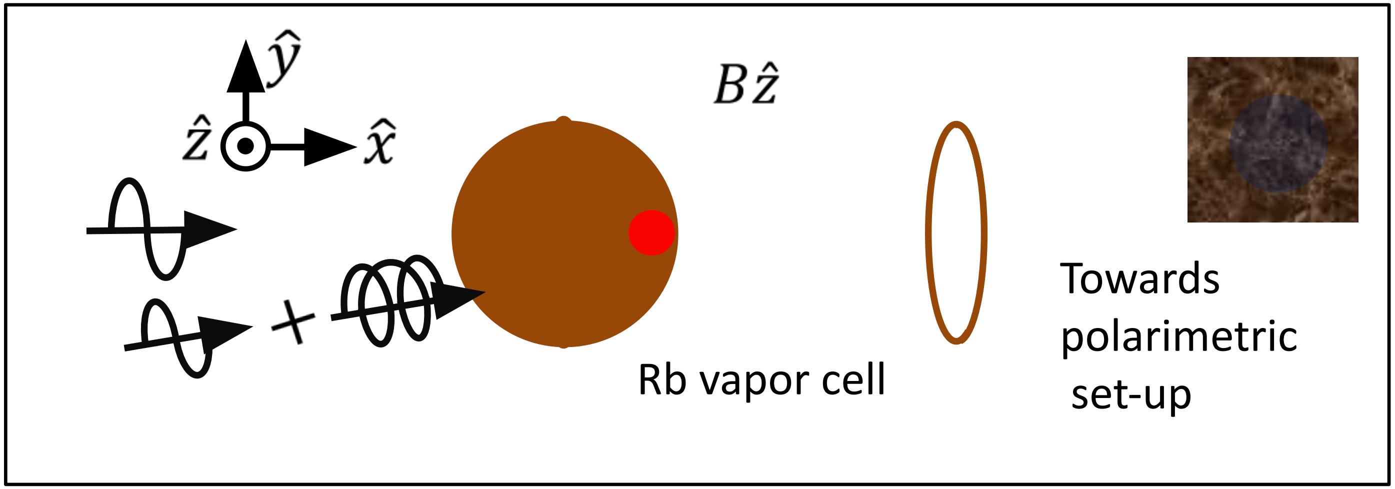


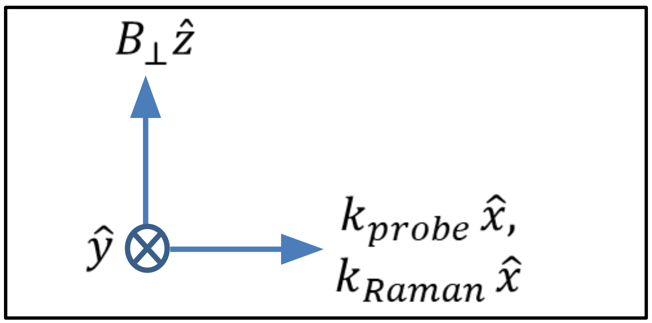
$$B_T = \sqrt{B_z^2 + B_x^2}$$

$$B_{T,M} = \sqrt{B_z^2 + \left(B_x + B_{x,e}\right)^2}$$

IEEE Transactions on Instrumentation and Measurement **70**, 1 (2021).

SNS with coherently driven atomic systems

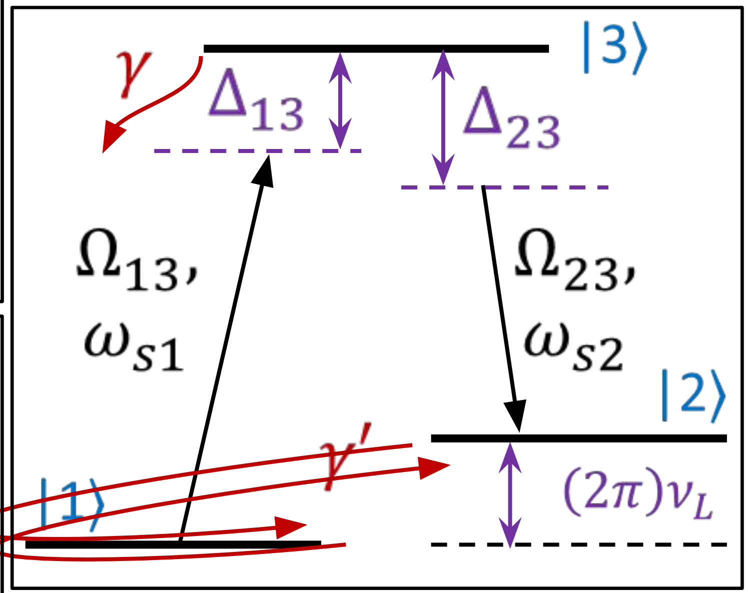




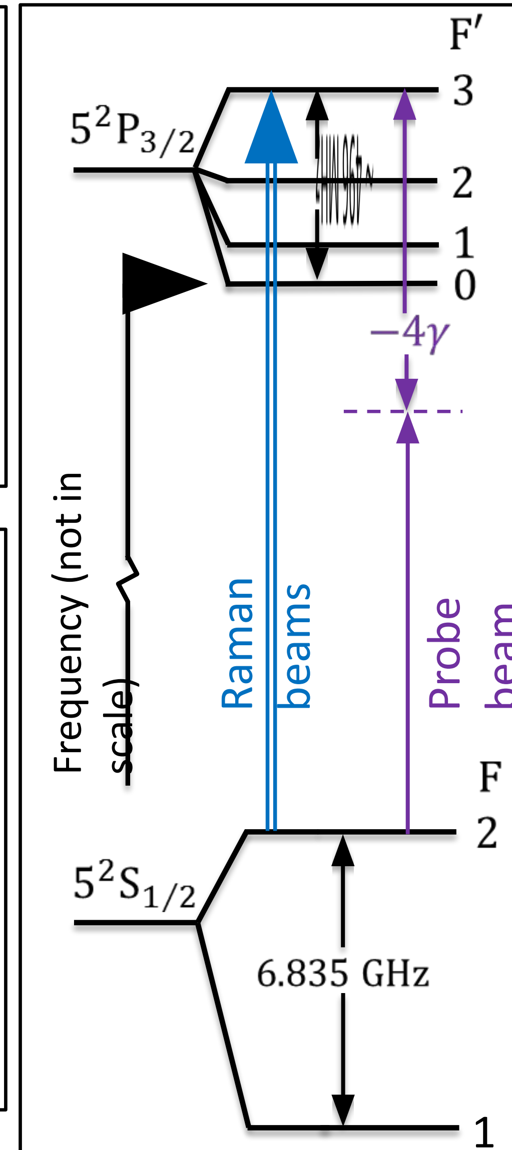
$|1\rangle \equiv |F = 2, m_F = -1\rangle$

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

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



Physical Review Research 3 (4), 043171 (2021).



Theoretical modelling

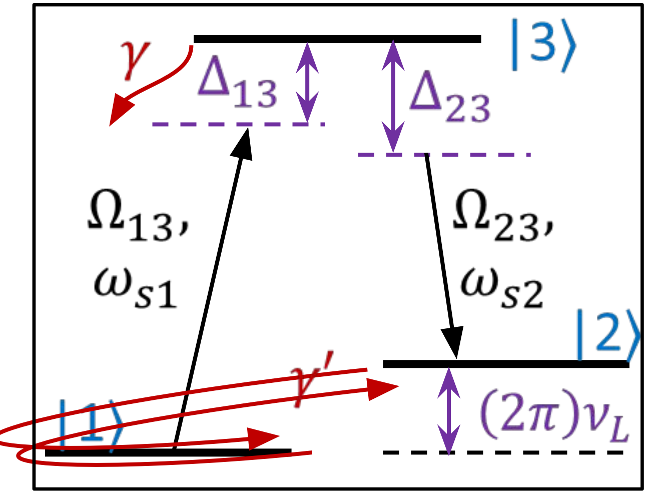
$$\frac{\mathcal{H}}{\hbar} = (\Delta_{23} - \Delta_{13})\mu^\dagger\mu - \Delta_{13}\sigma^\dagger\sigma - \Omega_{13}(\sigma + \sigma^\dagger) - \Omega_{23}(\mu + \mu^\dagger),$$

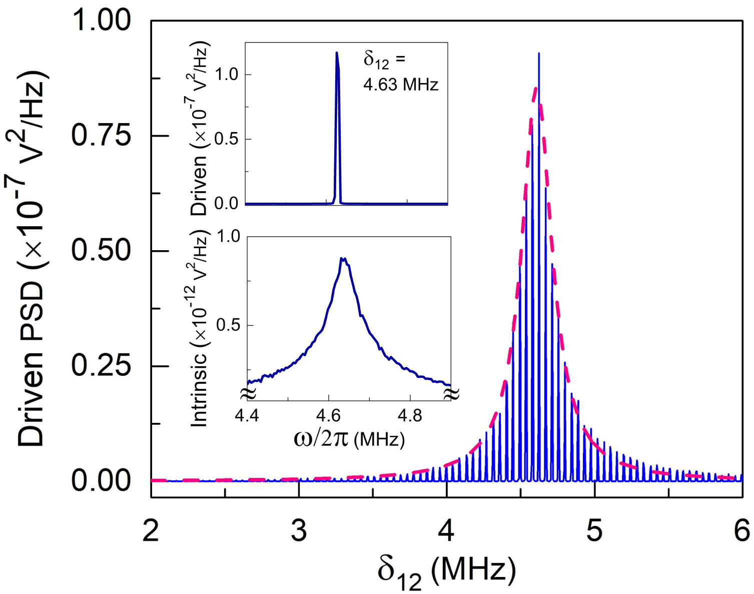
$$\sigma^\dagger = |1\rangle\langle 3|,\ \mu^\dagger = |2\rangle\langle 3|,\ \nu^\dagger = |1\rangle\langle 2|$$

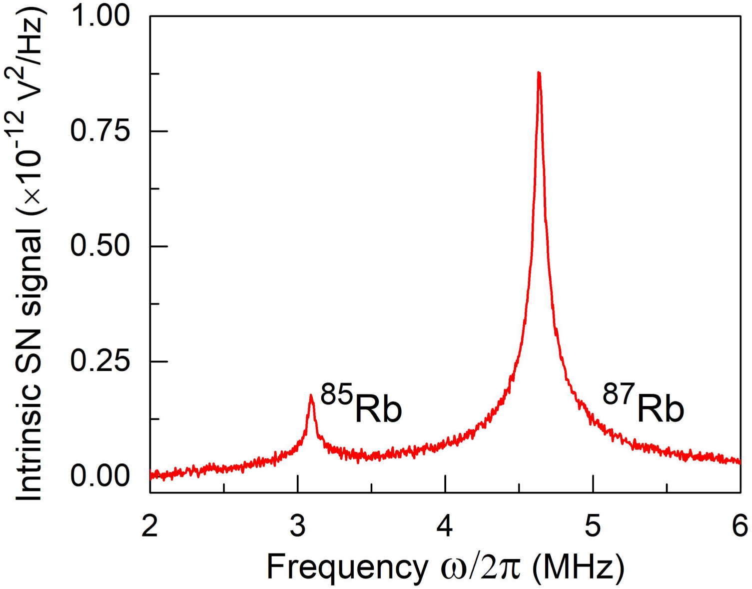
$$P(\omega) = \delta(\omega + \omega_{s2} - \omega_{s1})|\rho_{21}|^2$$

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

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





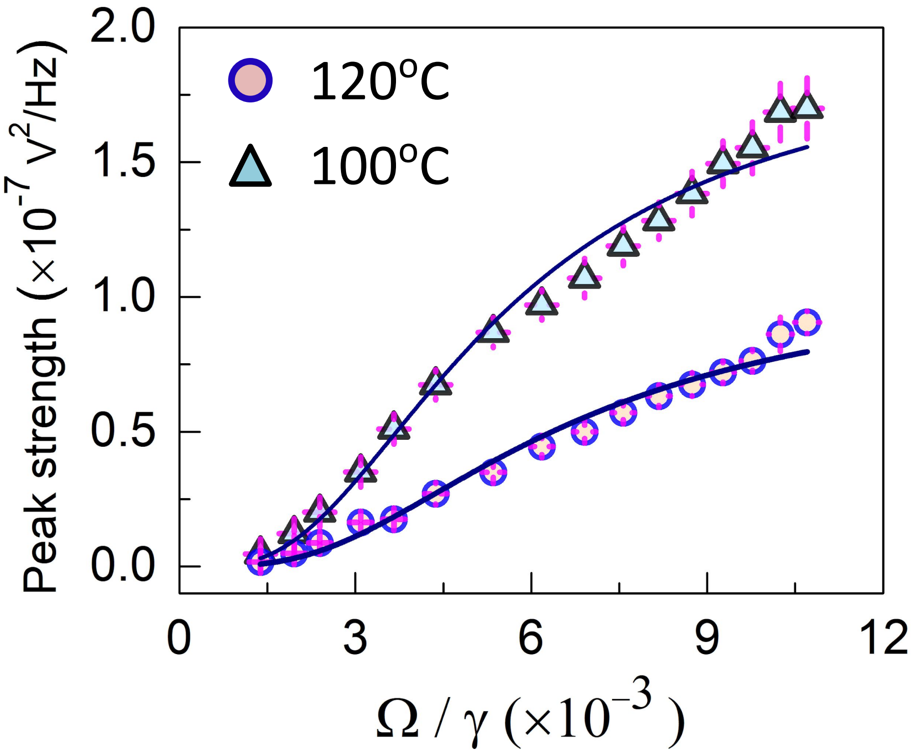


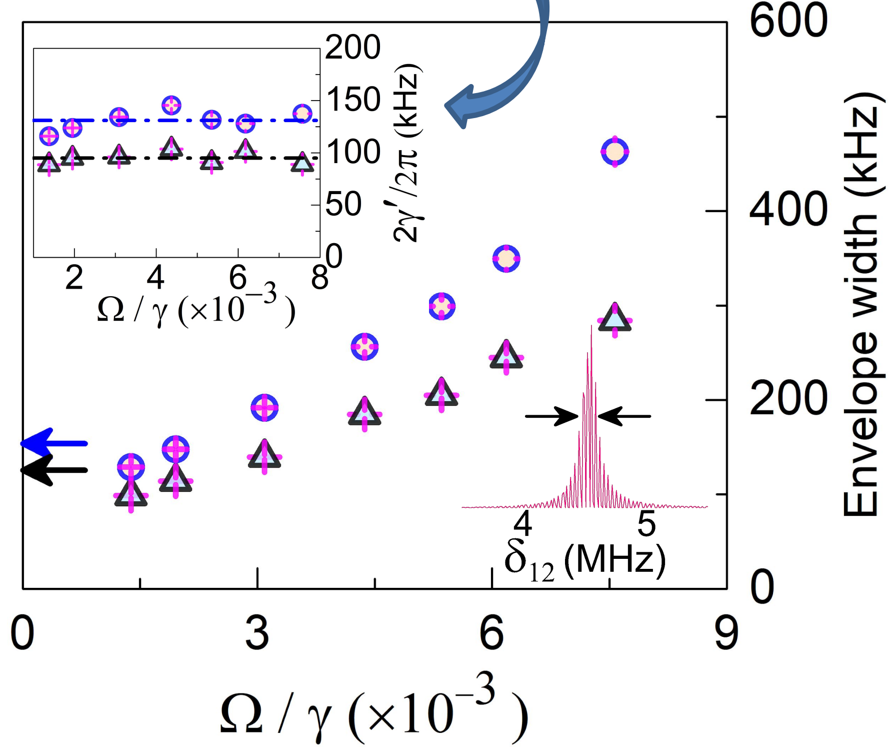
Intrinsic spin-coherence rate from driven spectrum

Temperature	Intrinsic width (kHz)	
100°C		
120°C		

$$|\rho_{21}|^2_{\Delta=0} = \frac{\gamma^2\Omega^4}{(\gamma'\gamma^2 + (3\gamma' + 2\gamma)\Omega^2)^2}$$

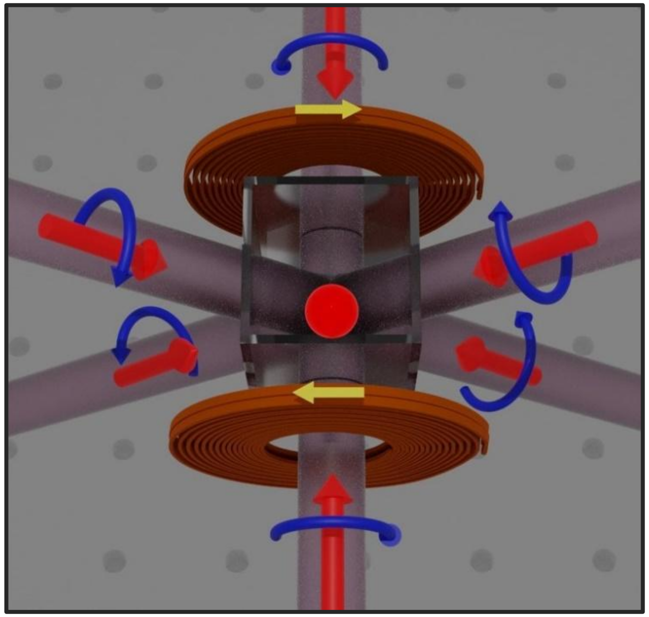
$|\rho_{21}|^2$ fitted with Ω/γ to extract $2\gamma'$

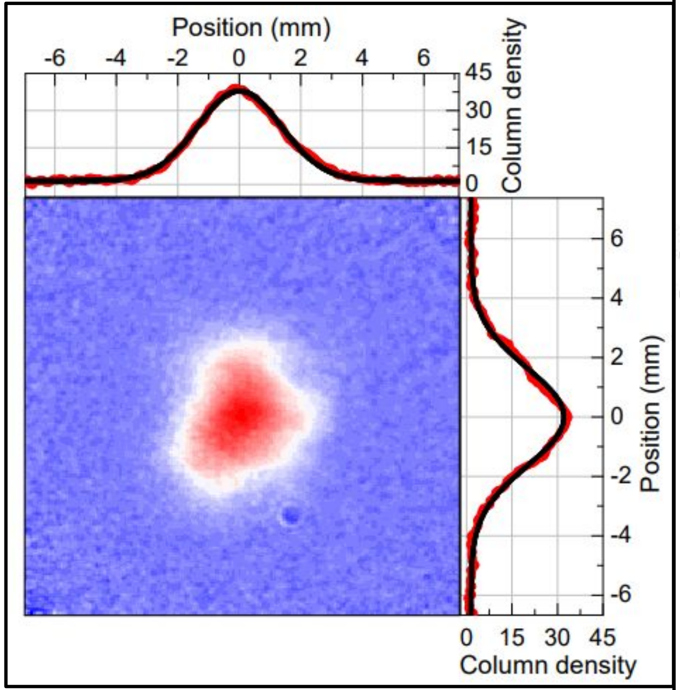


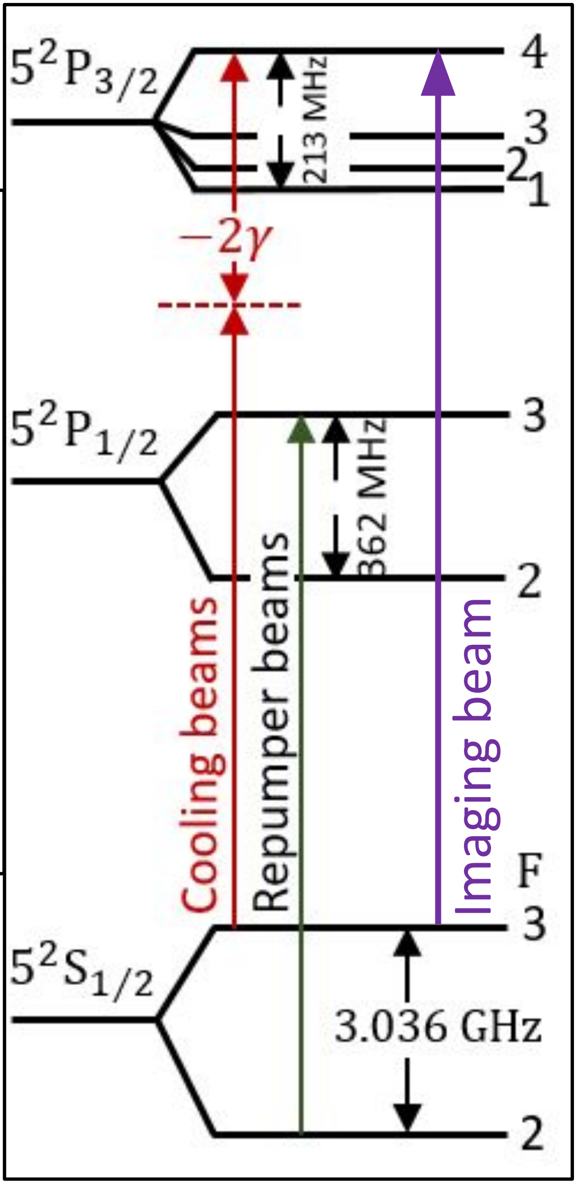


The Rubidium cold atom machine

Standard vapor loaded Magneto Optical Trap for Rubidium atoms







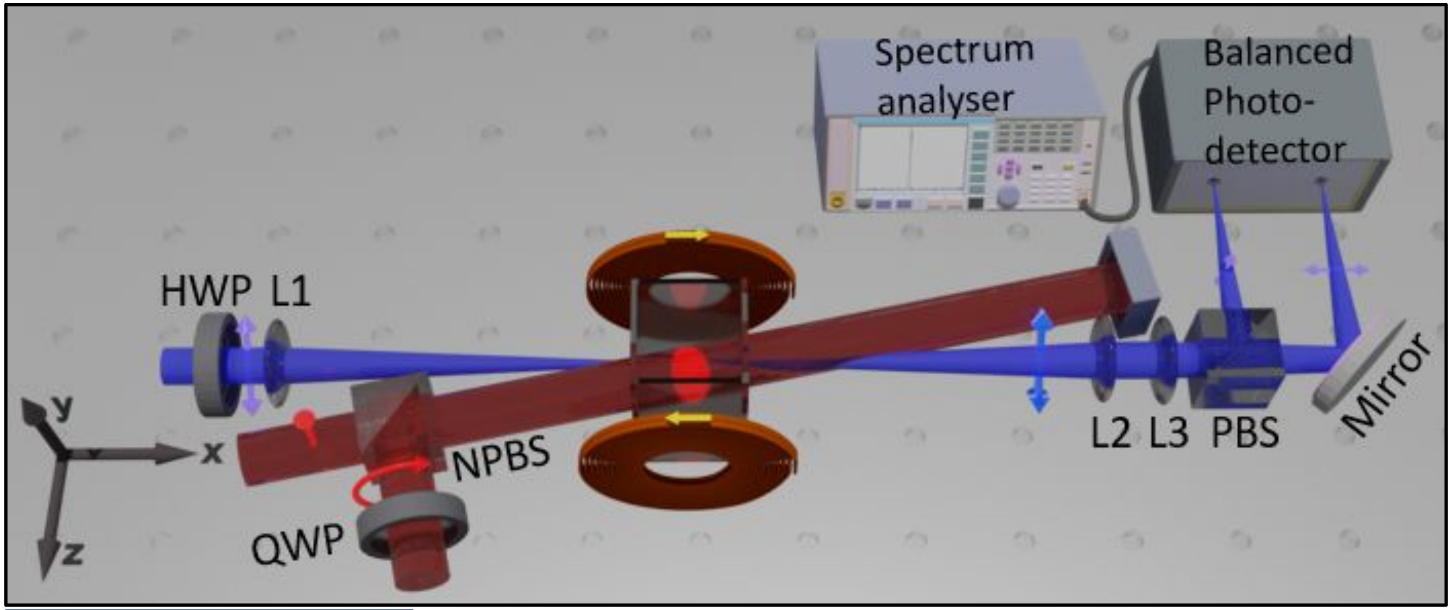
$$\vec{F}_{MOT} \propto -\alpha\vec{v} - k\vec{r}$$

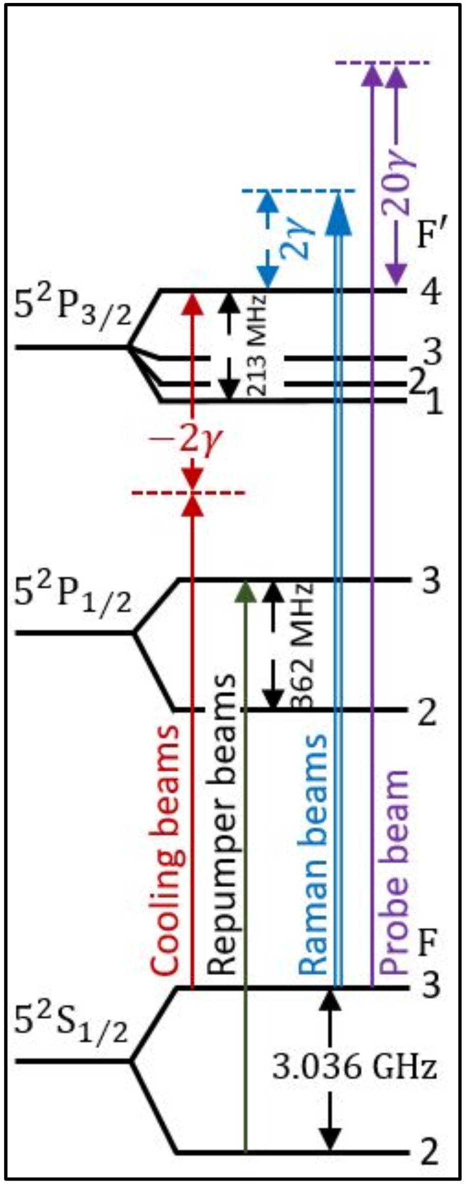
$$2\partial_x B(r) = 2\partial_y B(r) = -\partial_z B(r)$$

Atom number ~ 10^7
MOT size ~ 4 mm
Temperature ~ 150 μK

More details: Optics Continuum 1 (2), 171-188 (2022)

Spin correlation experimental scheme in MOT

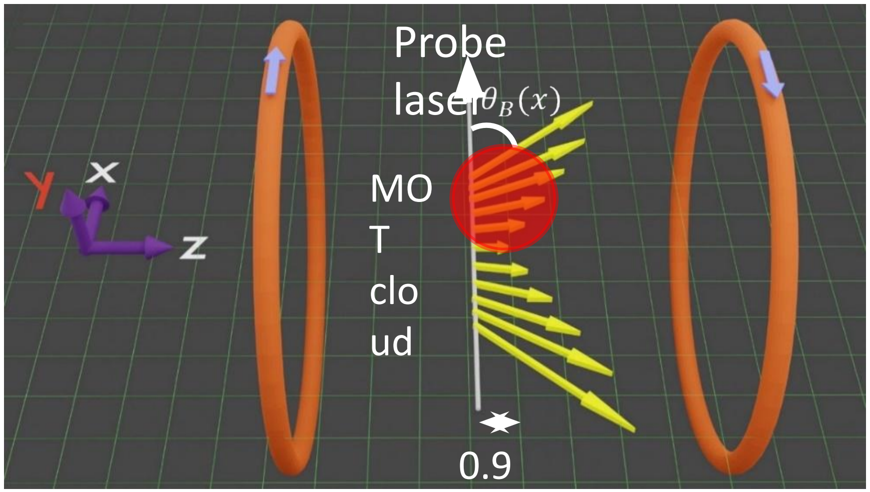




Raman beam polarization: $(\pi_1)_x - (\sigma_2^+)_x$

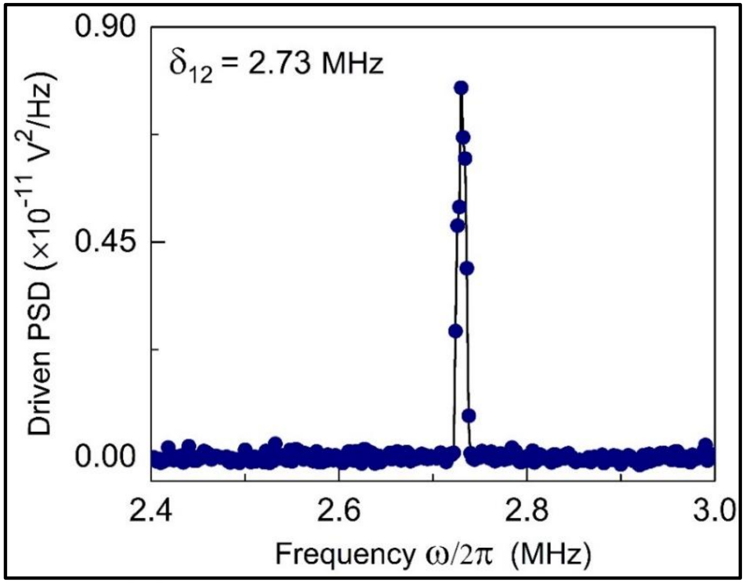
Probe beam diameter $\sim 70\ \mu m$

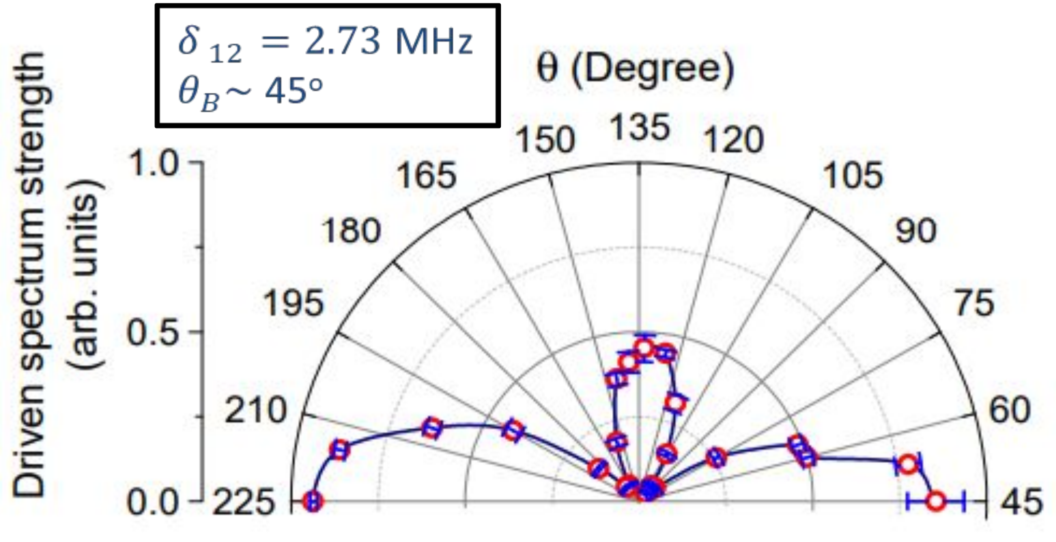
$\frac{\Omega}{\gamma} \sim 0.35$

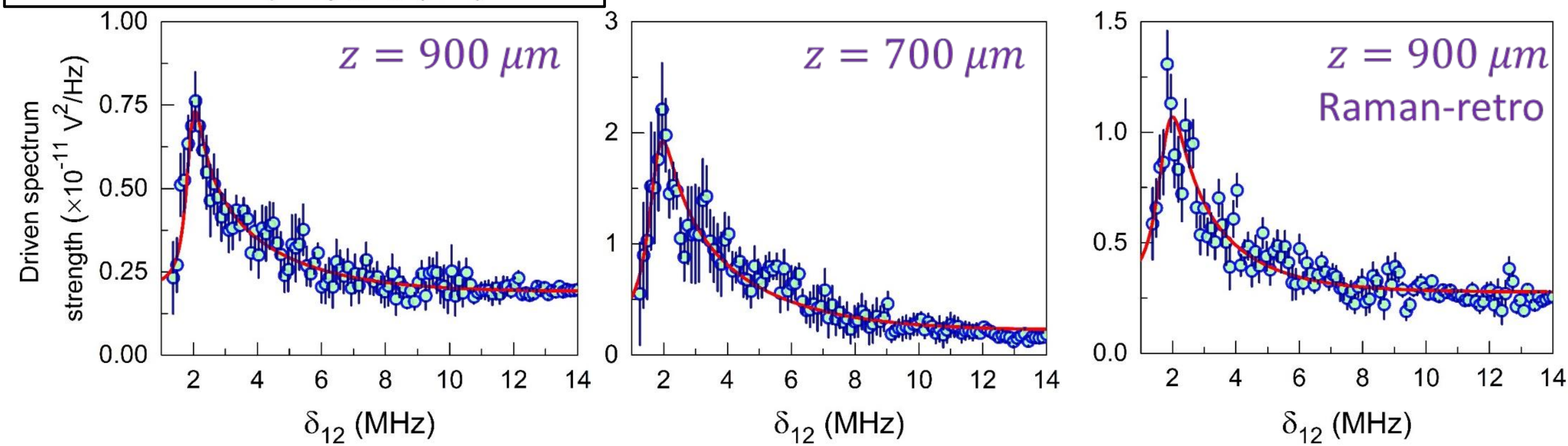


Physical Review Research 3 (4), 043171 (2021).

Driven spectrum in cold atoms

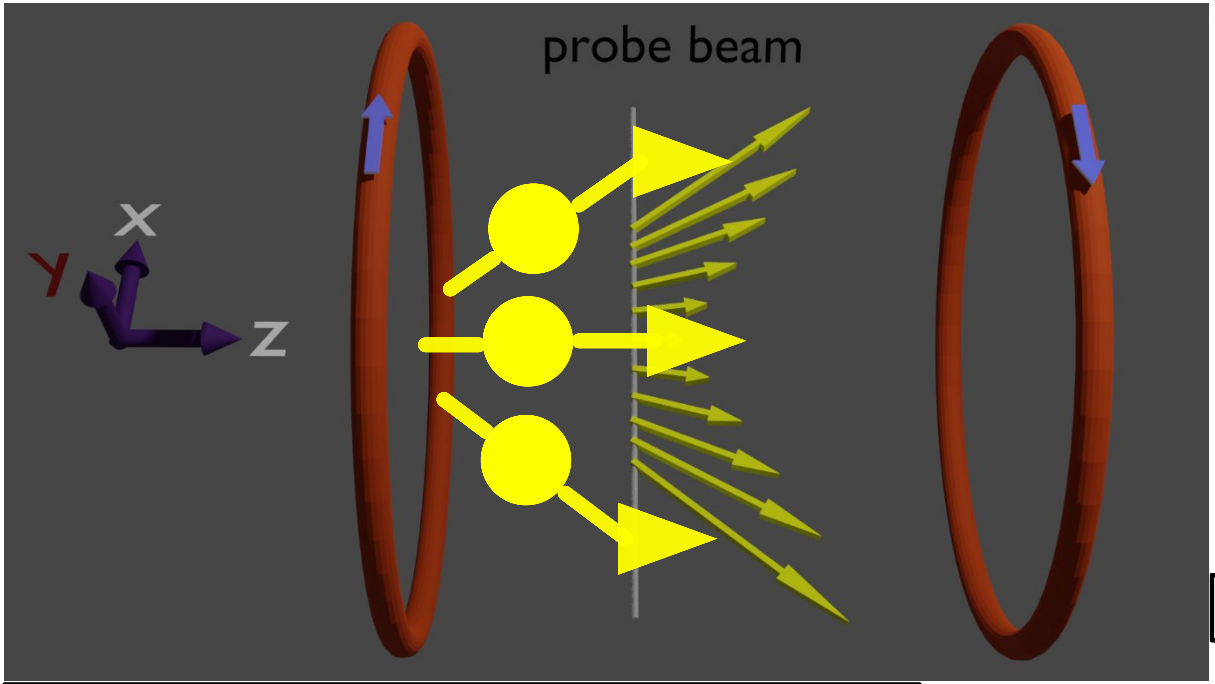


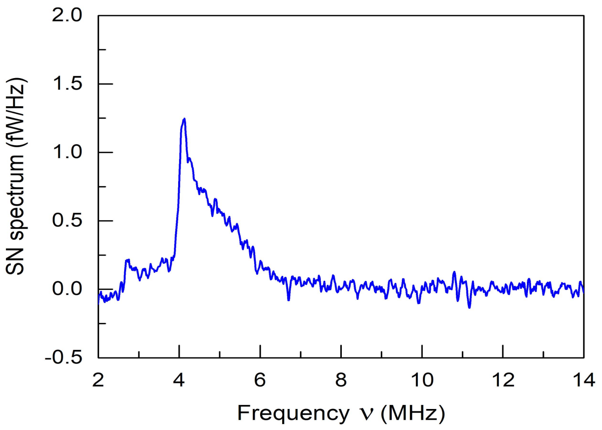




Physical Review Research 3 (4), 043171 (2021).

Simulation to fit driven spectrum and extracted γ'

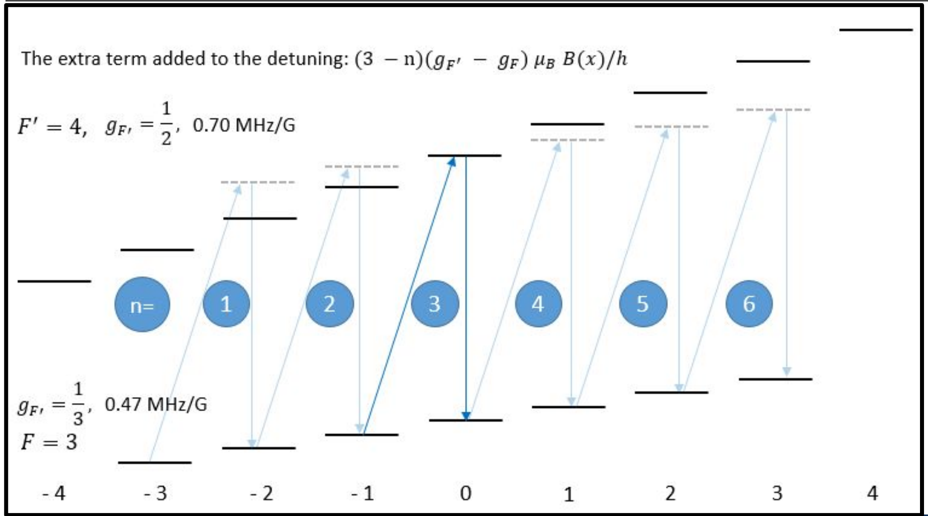


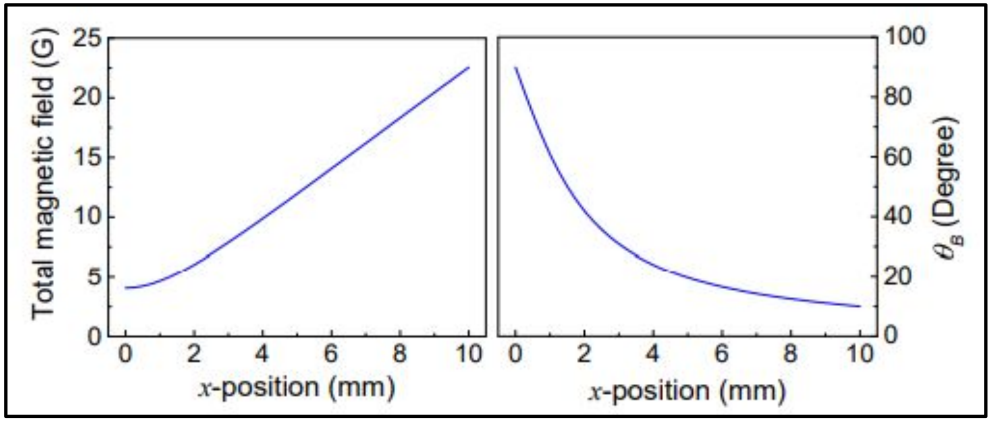


$$|\rho_{21}(x)|^2 = |\rho_{21}(\Omega(x))|^2 n(x) \sin^2 \theta_B(x).$$

$$\Delta_{23}(n) = 2\gamma + (3-n)(g_{F'} - g_F)\mu_B B(x)/h$$

$$\gamma' \sim 3 \times 10^3\ s^{-1}$$





Highlights, Outlooks

- Faraday rotation fluctuation measurement based magnetometer
  - Demonstrated Precision <50 nT (atomic vapor), < 1 nT (cold atoms, proof of principle)
  - Time-resolved magnetometry □ ~80 nT precision, 100 msec time resolution
- This technique is immune to laser intensity, polarization, alignment noise hence far superior than traditional Faraday rotation based magnetometry
- Cold atoms shows longer (at least 100 times) spin coherence time
  □ can be exploited for spin based quantum computation protocols
  (we'll be happy to collaborate with experts in QIP on this)
- Natural extension is to explore spin fluctuations in strongly correlated and many body Quantum systems such as BECs in optical lattices and explore quantum phase transitions using spin correlation measurements.

Rydberg spectroscopy

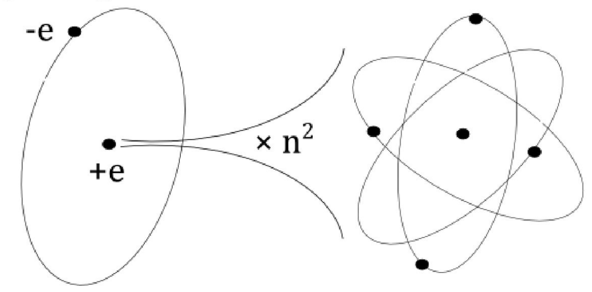
A new system for sensing electric field and also Mesoscopic quantum entanglement studies

Sanjukta Roy, Silpa B S, Shovan Kanti Barik

Primary reference: Optics Continuum 1 (5) (to appear)

Rydberg atoms

Atoms excited to high principal quantum levels (n) are called Rydberg atoms.



The fact that the outer electron is on average so far from the core makes it very weakly bound, and hence very sensitive to external electric fields, including fields induced by nearby Rydberg atoms .

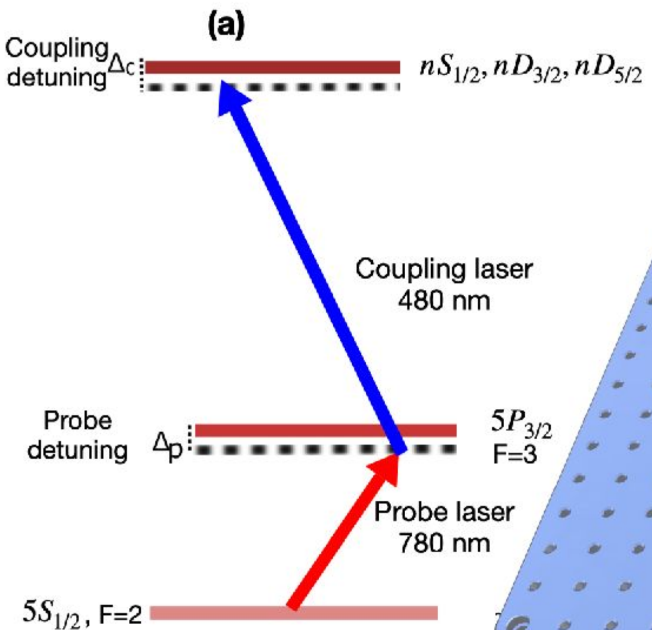
Rydberg atoms has exaggerated properties:

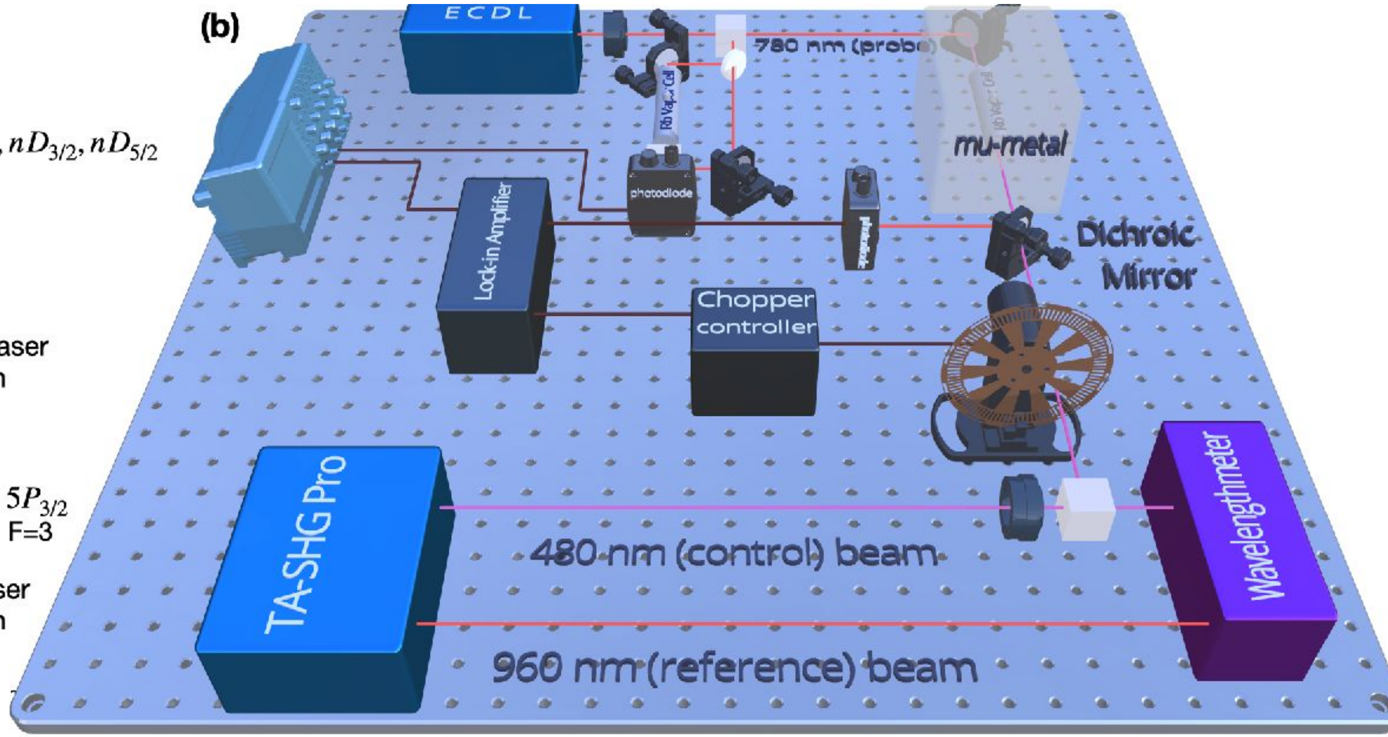
- Strong dipole-dipole interactions ~ n^4
- Large values of polarizability ~ n^7
- Long Life time ~ n^3
- Large Size ~ n^2 (~ µm for n > 100!)

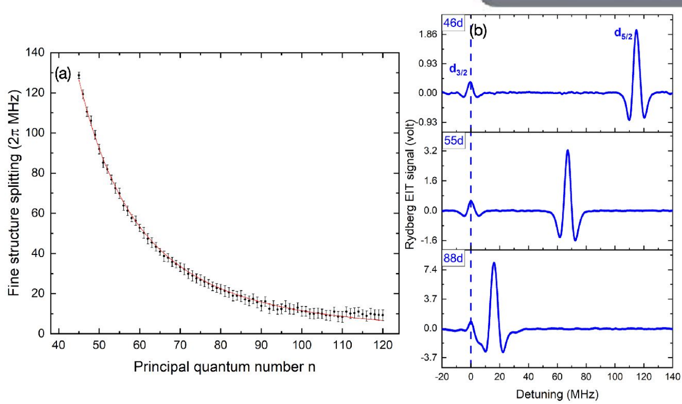
Applications in:

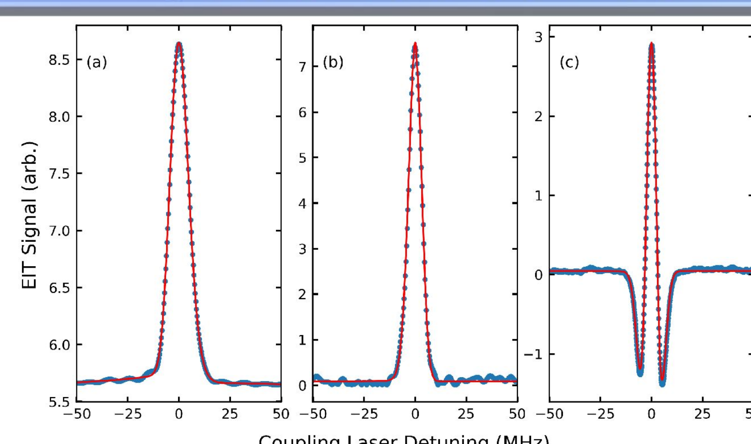
- Quantum sensing (electric fields)
- Quantum Information processing
- Quantum Simulations

7.1. Experiments on atomic vapor



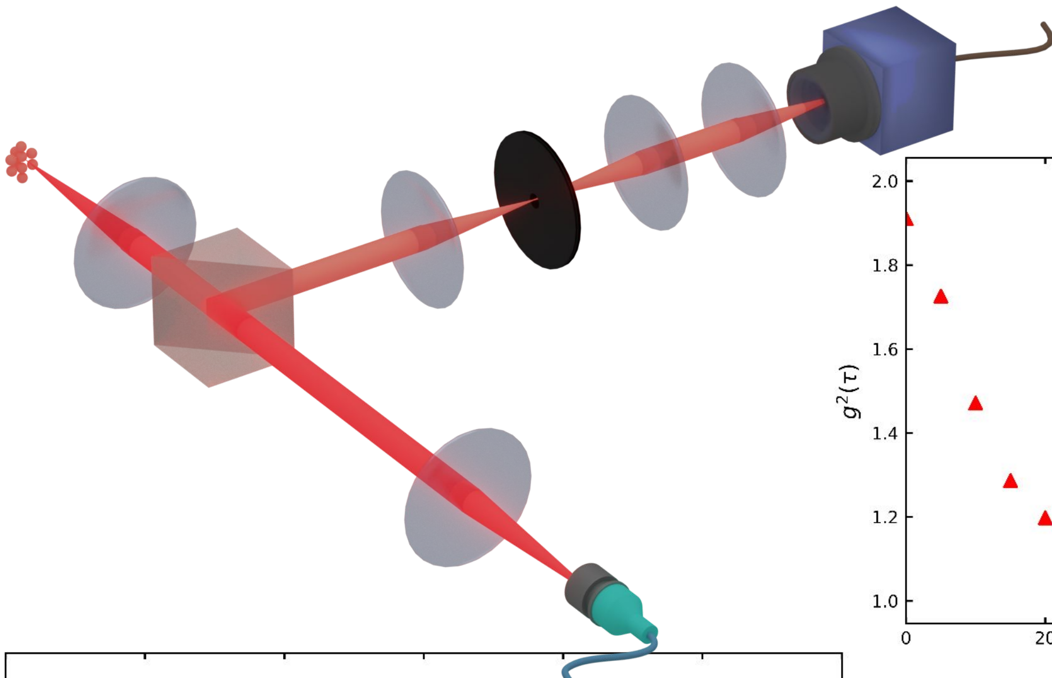


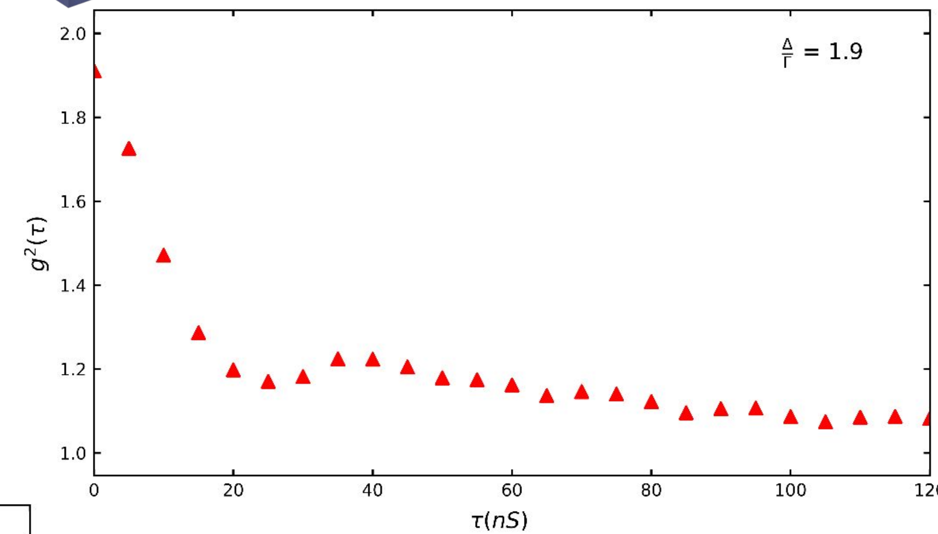


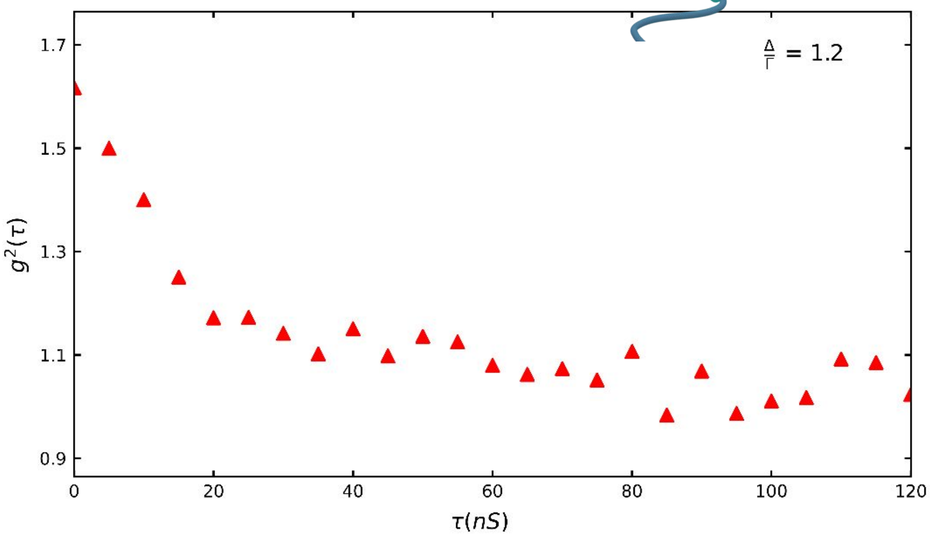


[Optics Continuum 1 (5) (to appear)]

Experiments on cold atoms







- Photon arrival statistics measurements
- Home build high efficiency detector
- Presently exploring modification of g^2 correlation in presence of Rydberg excitation

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**
- **Rydberg atoms for applications in Quantum Information Processing and sensing of weak electric fields.**