Quantum gases with tunable interactions and non-perturbative measurements

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Raman Research Institute

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Group Members

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Analog Simulators

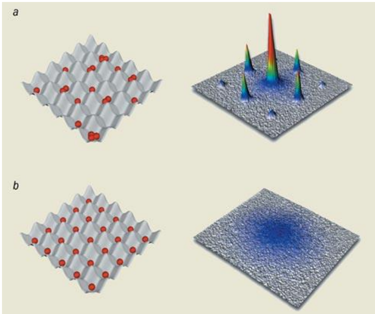
Classical

Prague Astronomy Clock, 1410

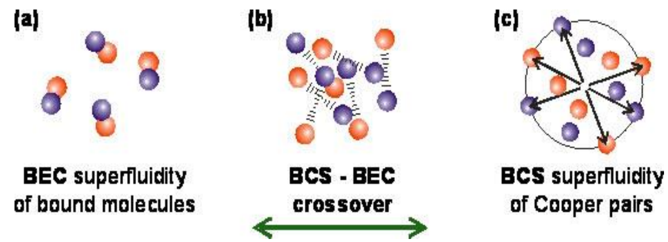
Quantum Simulator

"One controllable quantum system simulating another"
-Richard Feynman

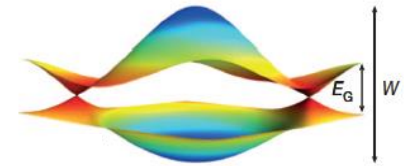
Cold Atoms as analog quantum simulators



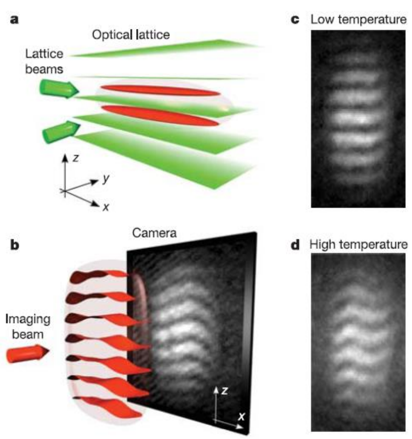
Superfluid-Mott insulator Transition
(MPQ Munich, ETH Zurich)



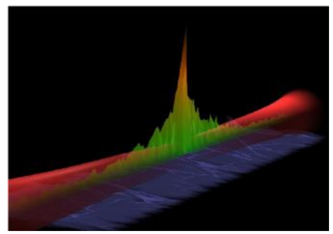
BEC-BCS crossover
(ENS, MIT, JILA, Innsbruck)



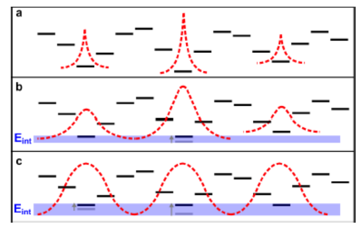
Controlling Dirac points with
Fermi gas in Honeycomb lattice
ETH Zurich



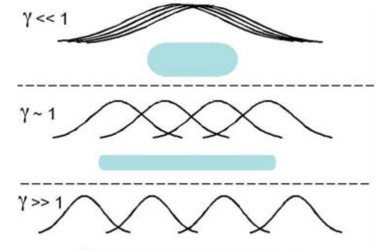
Berezinskii-Kosterlitz-
Thouless crossover
(ENS, NIST, JILA)



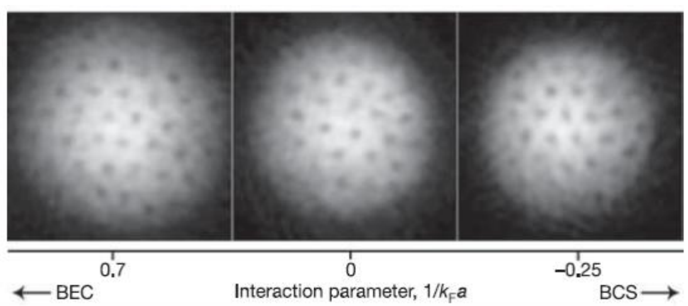
Anderson localization
(Florence, Orsay)



Bose-Glass
(Florence)



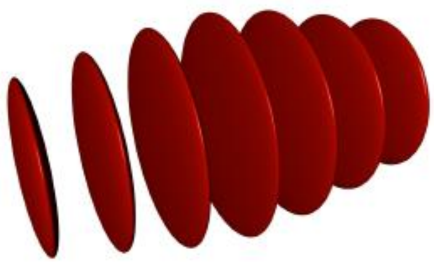
Tonks-Girardeau gas
(Mainz, Penn State)



Quantized vortices
in Fermion gases (MIT)

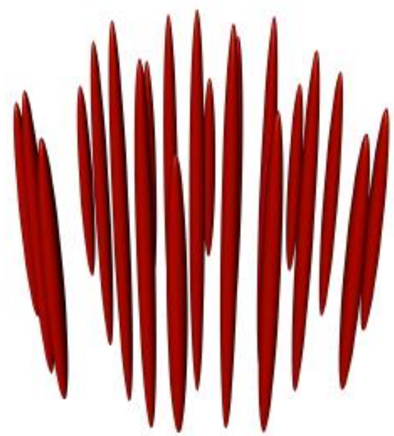
Optical Lattices: Artificial crystal of light

1D optical lattice



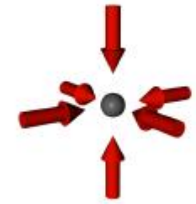
2D geometry

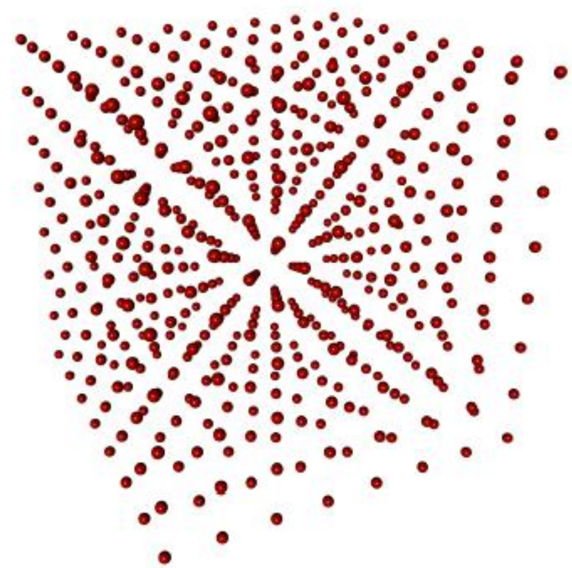
2D optical lattice



1D geometry

3D optical lattice

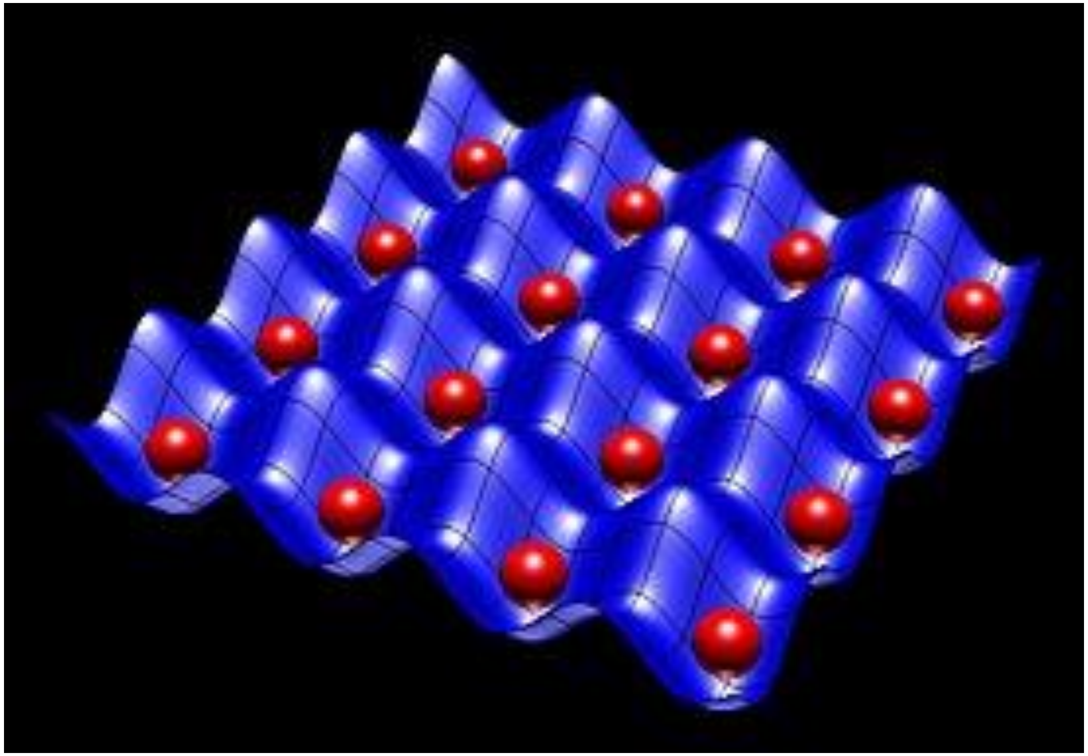




Spatial intensity modulation creates optical trapping potential for neutral atoms

$$\mathbf{U} \propto {}^{I}/_{\delta}$$

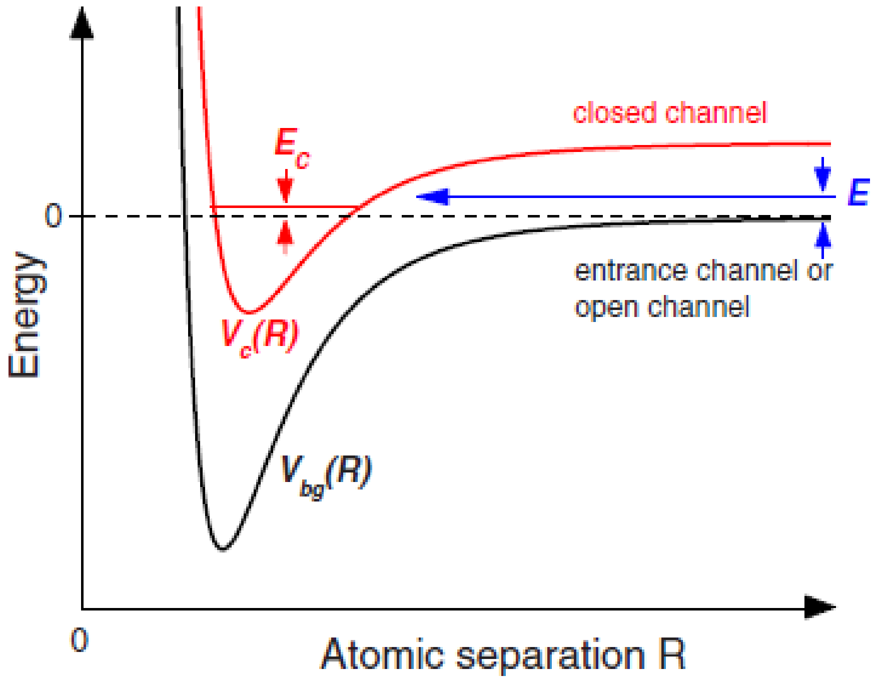
Optical Lattices: Artificial crystal of light

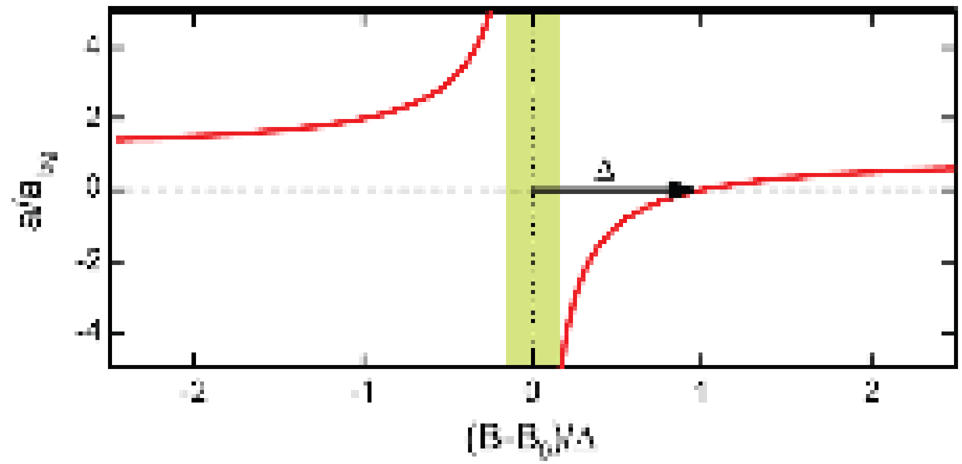


Quantum gases in optical lattices emulates electrons in a solid state lattice

Control of (*contact*) Interaction: Feshbach resonance

A control knob for tuning interaction

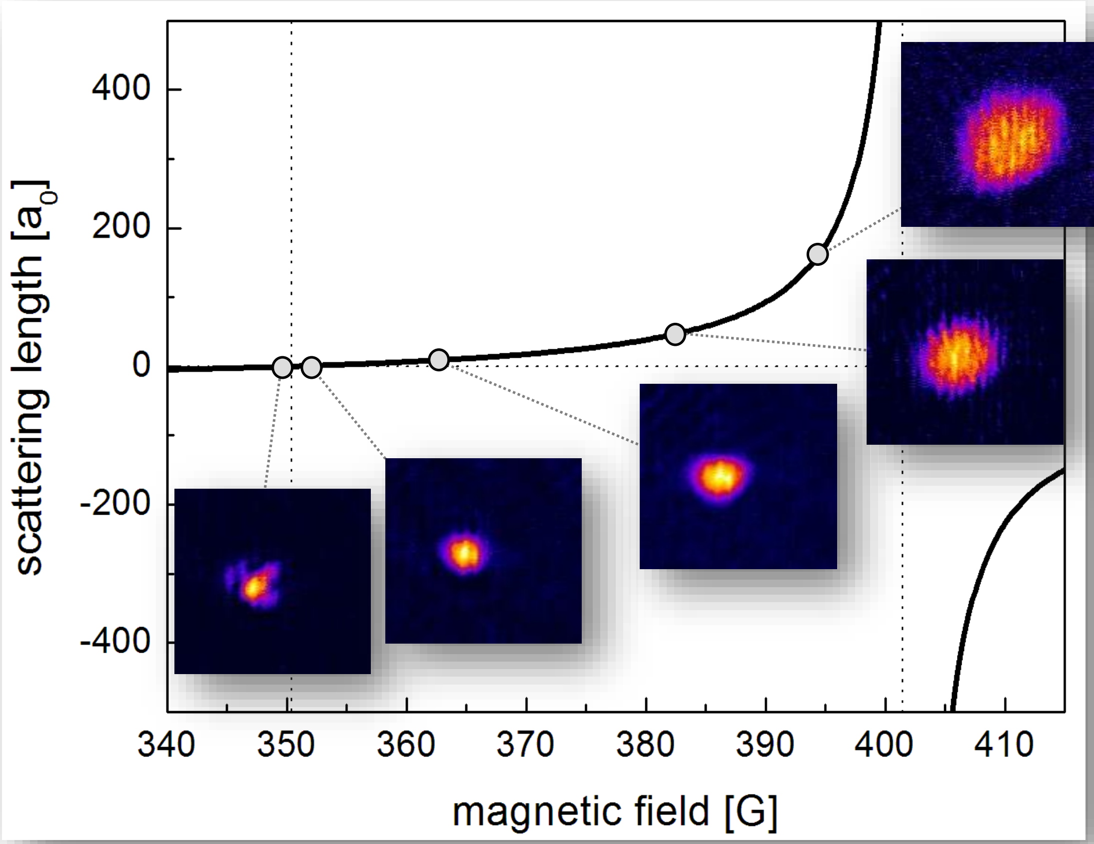




$$a(B) = a_{bg}\left(1 - \frac{\Delta}{B - B_0}\right)$$

➡ **magnetic tunability of scattering length a**

Control of (*contact*) Interaction: Feshbach resonance



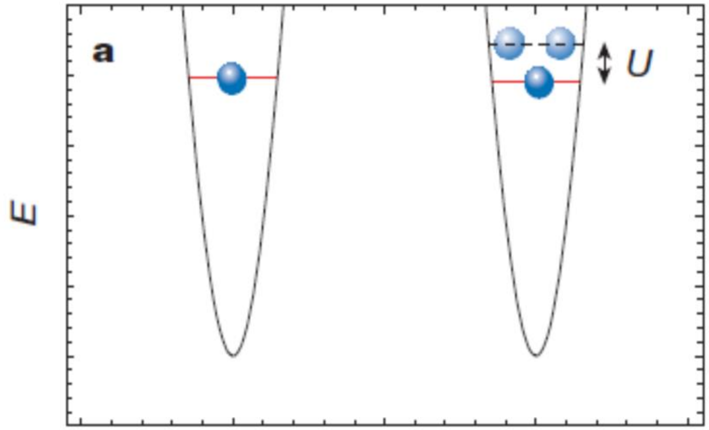
$$U = \frac{2\pi\hbar^2}{m} a \int |\varphi(x)|^4 \, d^3x$$

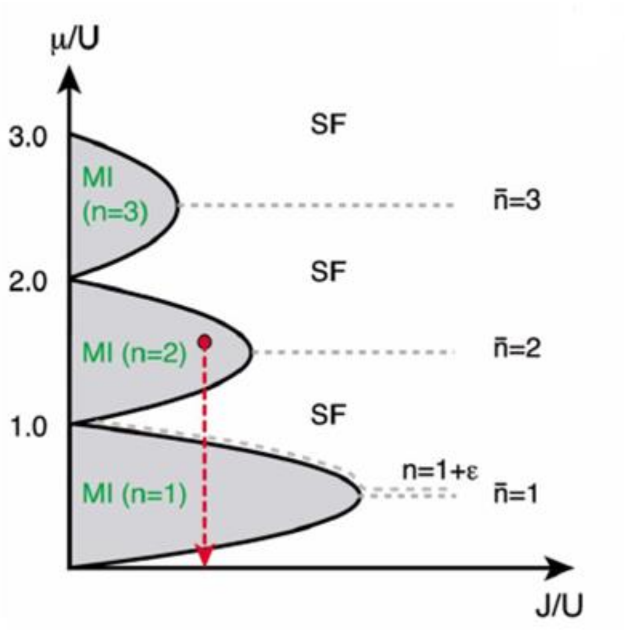
Roati et. al. (Florence)

Bose-Hubbard Model

$$\hat{H} = -J\sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \frac{U}{2}\sum_i \hat{n}_i(\hat{n}_i - 1) + \sum_i \varepsilon_i \hat{n}_i$$

Superfluid-Mott Insulator transition



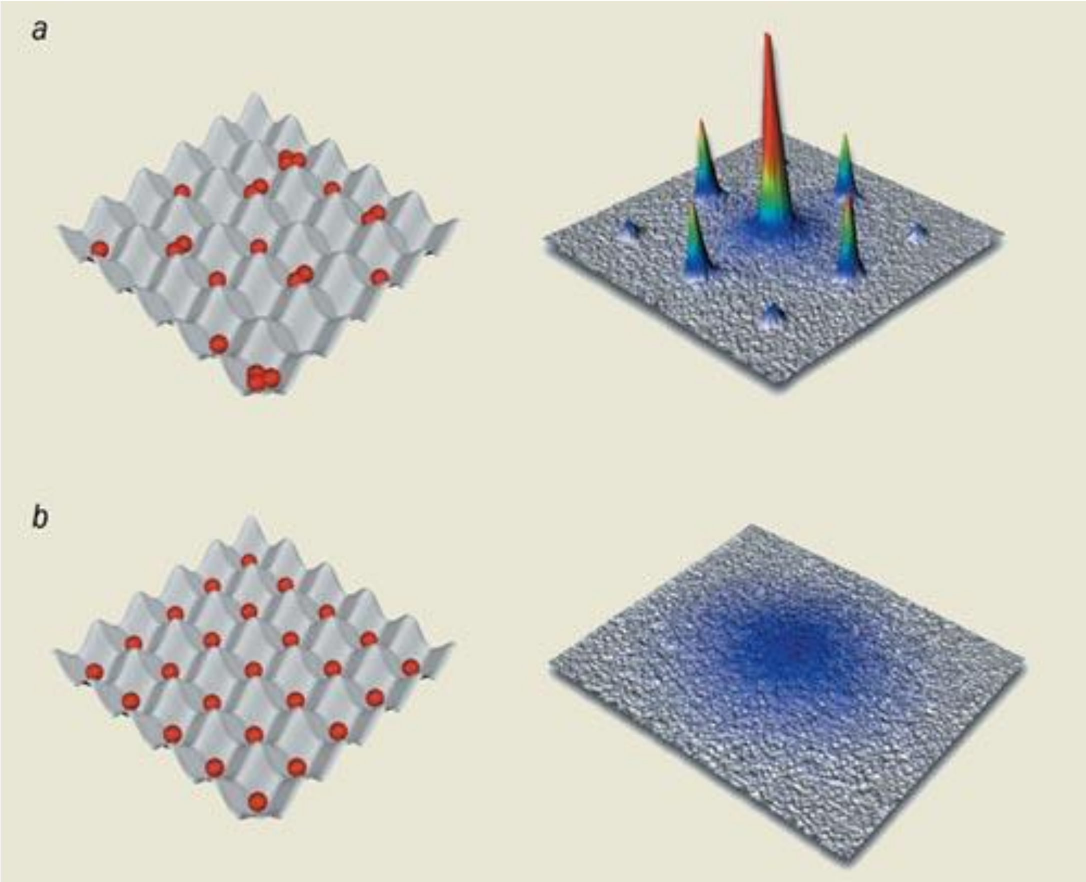


Removing an atom from a lattice site and adding it to neighboring lattice sites.

- Due to on-site repulsion between the atoms, this requires a finite amount U in energy and hopping of the atoms is therefore suppressed.

Bose-Hubbard Model

Sudden switching-off the optical lattice and absorption imaging of atomic cloud



Superfluid:

Complete phase coherence

Phase coherent matter wave interfere

Insulator:

Random phase site-to-site

No interference for incoherent insulator phase

I. Bloch et. al.

Limitation of neutral atom quantum gas simulators

- Only on-site interaction via $\frac{1}{R^6}$ potential

- e.g. Quantum magnetism can only be probed by super-exchange
  (nearest neighbor and exponentially small strength with lattice depth)

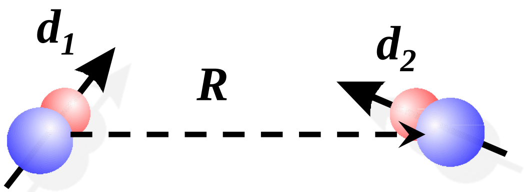
- Not fully applicable to a range of condensed matter phenomena involving long-range interactions

Possible solutions

↙ ↘

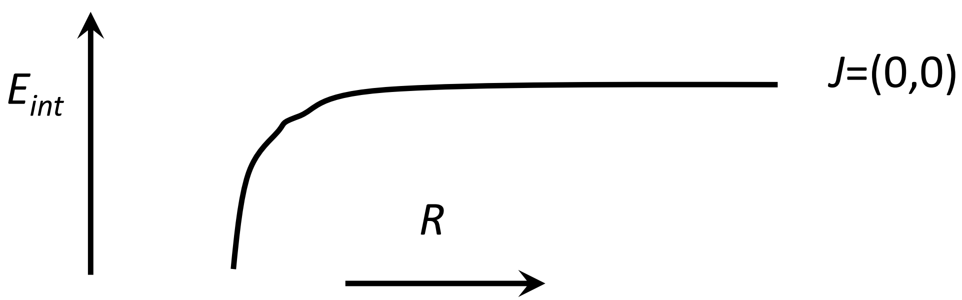
Cold ions — Cold dipolar molecules

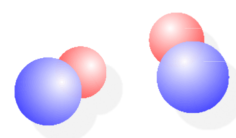
Long-range dipole-dipole Interaction



$$V = \frac{\boldsymbol{d_1} \cdot \boldsymbol{d_2}}{R^3} - \frac{3(\boldsymbol{d_1} \cdot \boldsymbol{R})(\boldsymbol{d_2} \cdot \boldsymbol{R})}{R^5}$$

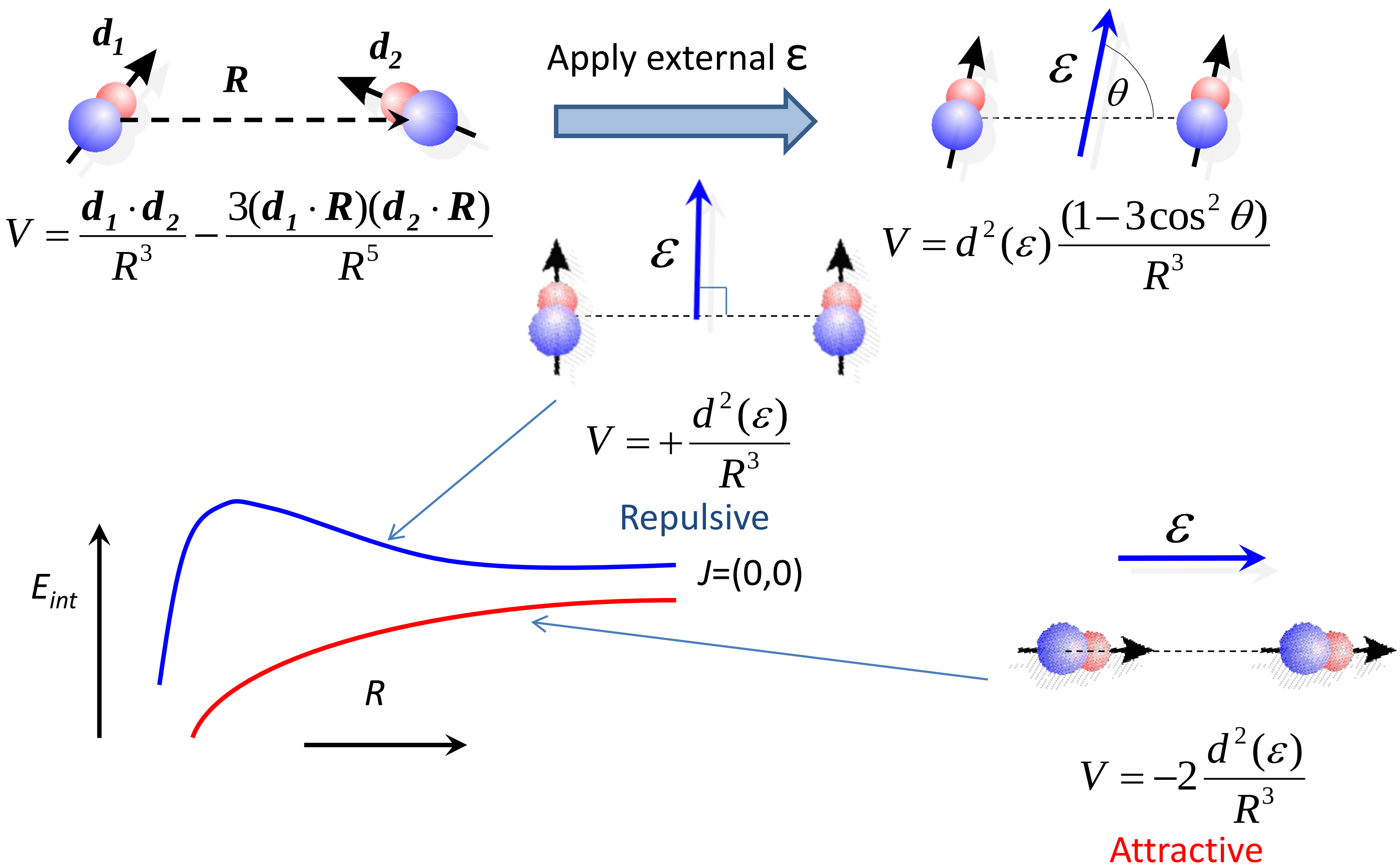
Absence of Polarizing Electric Field





$$V = -\frac{C_6}{R^6} = -\frac{d^4}{6BR^6}$$

Anisotropic dipole-dipole Interaction



$$V = \frac{\boldsymbol{d_1} \cdot \boldsymbol{d_2}}{R^3} - \frac{3(\boldsymbol{d_1} \cdot \boldsymbol{R})(\boldsymbol{d_2} \cdot \boldsymbol{R})}{R^5}$$

$$V = d^2(\varepsilon)\frac{(1-3\cos^2\theta)}{R^3}$$

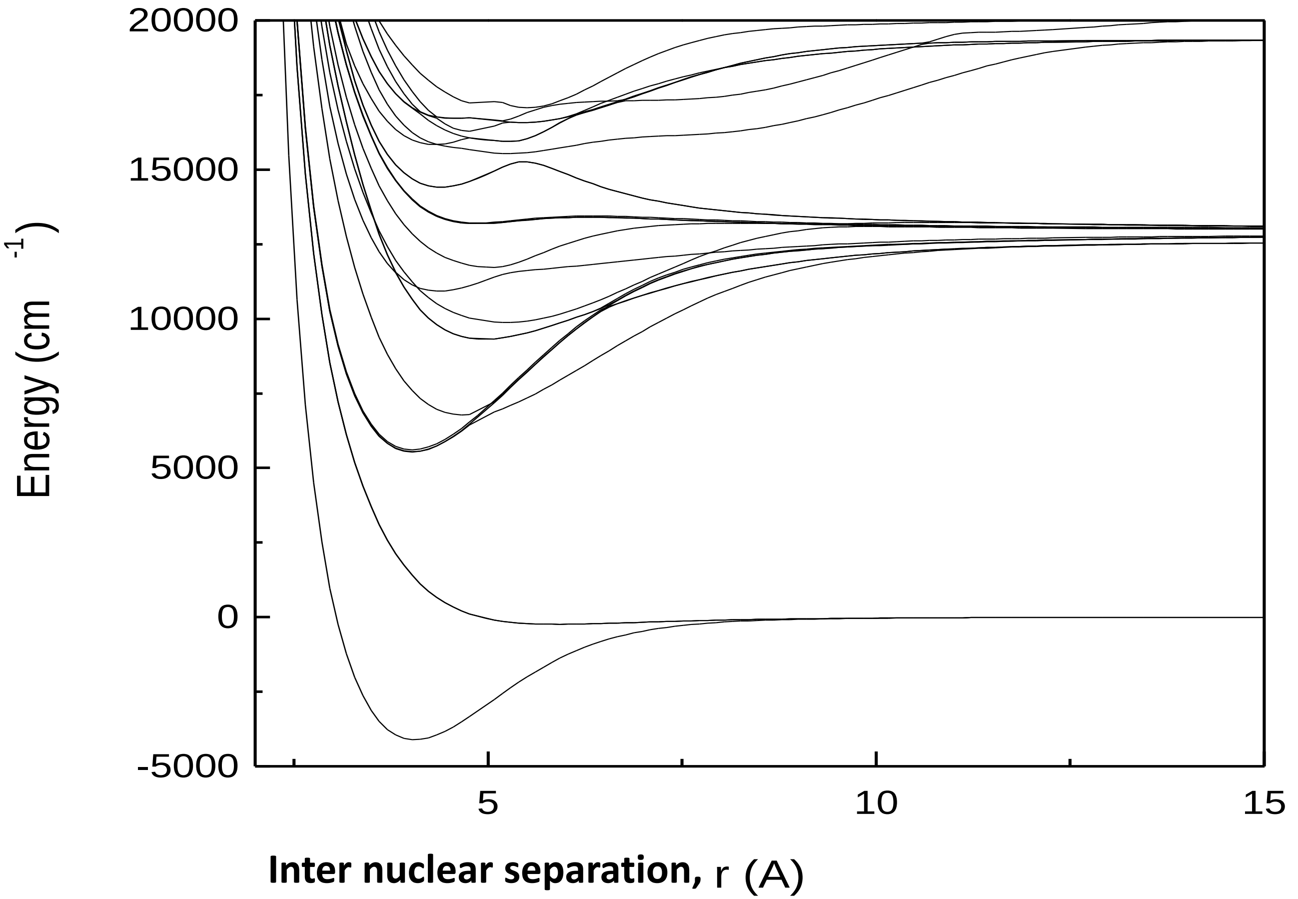
$$V = +\frac{d^2(\varepsilon)}{R^3}$$

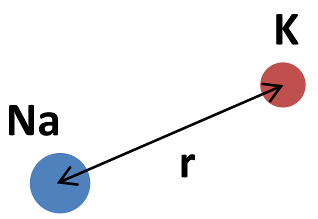
Repulsive

$$V = -2\frac{d^2(\varepsilon)}{R^3}$$

Attractive

The Challenge: molecular potentials





$$V = -\frac{C_6}{r^6}$$

Large number of energy levels (Includes rotational and vibrational splitting)

Precisely the reason why direct laser cooling is nearly impossible

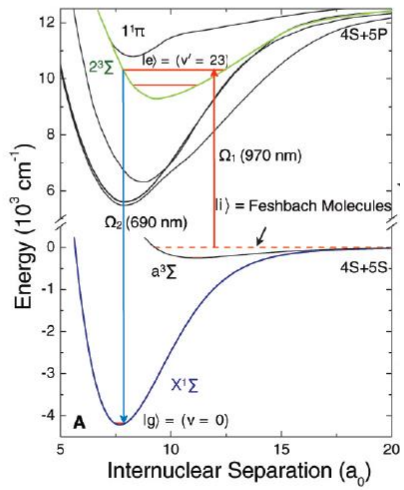
State of the art

- ***JILA (Jin, Ye) – $^{40}K^{87}Rb$ (Fermionic) , in 3D Lattice***

SCIENCE VOL 322 10 OCTOBER 2008

A High Phase-Space-Density Gas of Polar Molecules

K.-K. Ni,[1*] S. Ospelkaus,[1*] M. H. G. de Miranda,[1] A. Pe'er,[1] B. Neyenhuis,[1] J. J. Zirbel,[1] S. Kotochigova,[2] P. S. Julienne,[3] D. S. Jin,[1†] J. Ye[1†]



- ***Innsbruck (Nagerl, Grimm) - RbCs***

Towards the production of ultracold ground-state RbCs molecules: Feshbach resonances, weakly bound states, and coupled-channel model

Tetsu Takekoshi[1,2], Markus Debatin[1], Raffael Rameshan[1], Francesca Ferlaino[1], Rudolf Grimm[1,2], and Hanns-Christoph Nägerl[1]
[1] *Institut für Experimentalphysik, Universität Innsbruck, 6020 Innsbruck, Austria*
[2] *Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria*

C. Ruth Le Sueur and Jeremy M. Hutson
Department of Chemistry, Durham University, South Road, Durham DH1 3LE, United Kingdom

Paul S. Julienne
Joint Quantum Institute, NIST and University of Maryland, Gaithersburg, MD 20899, USA

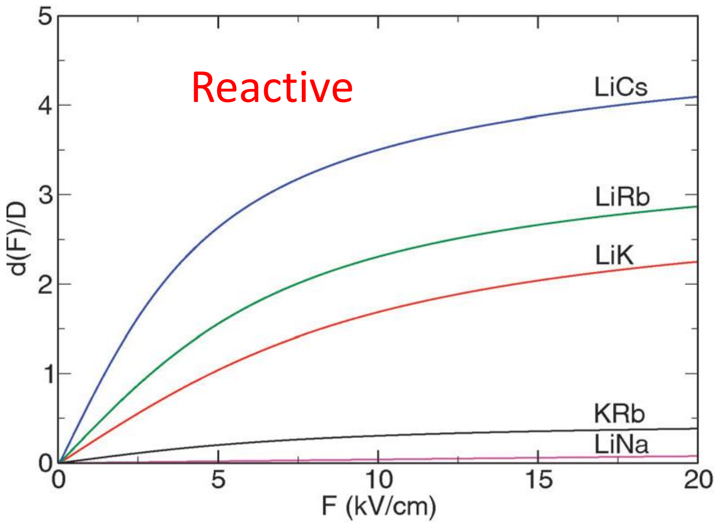
Svetlana Kotochigova
Physics Department, Temple University, Philadelphia, PA 19122-6082, USA

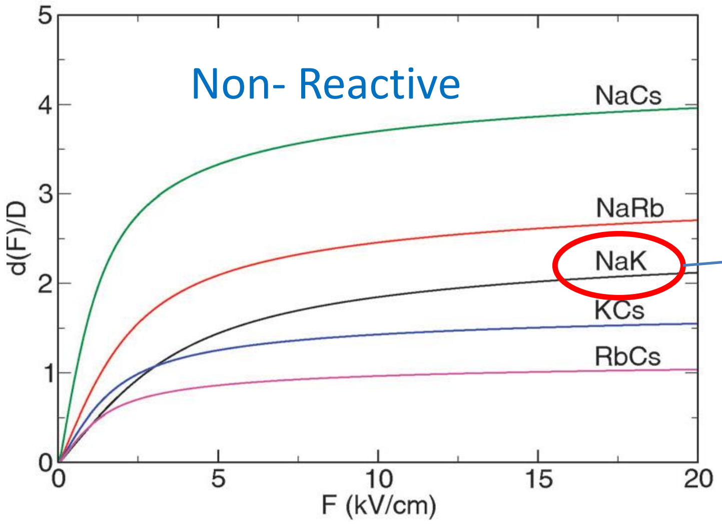
Eberhard Tiemann
Institute of Quantum Optics, Leibniz Universität Hannover, D-30167 Hannover, Germany
(Dated: January 9, 2012)

- Strong progress in theory

- Many other groups (MIT, Munich, Singapore, Florence…) on the way to realize degenerate polar molecules …

Why NaK?





Julienne et. al., 2011

Relatively easy to prepare
Degenerate Na and K

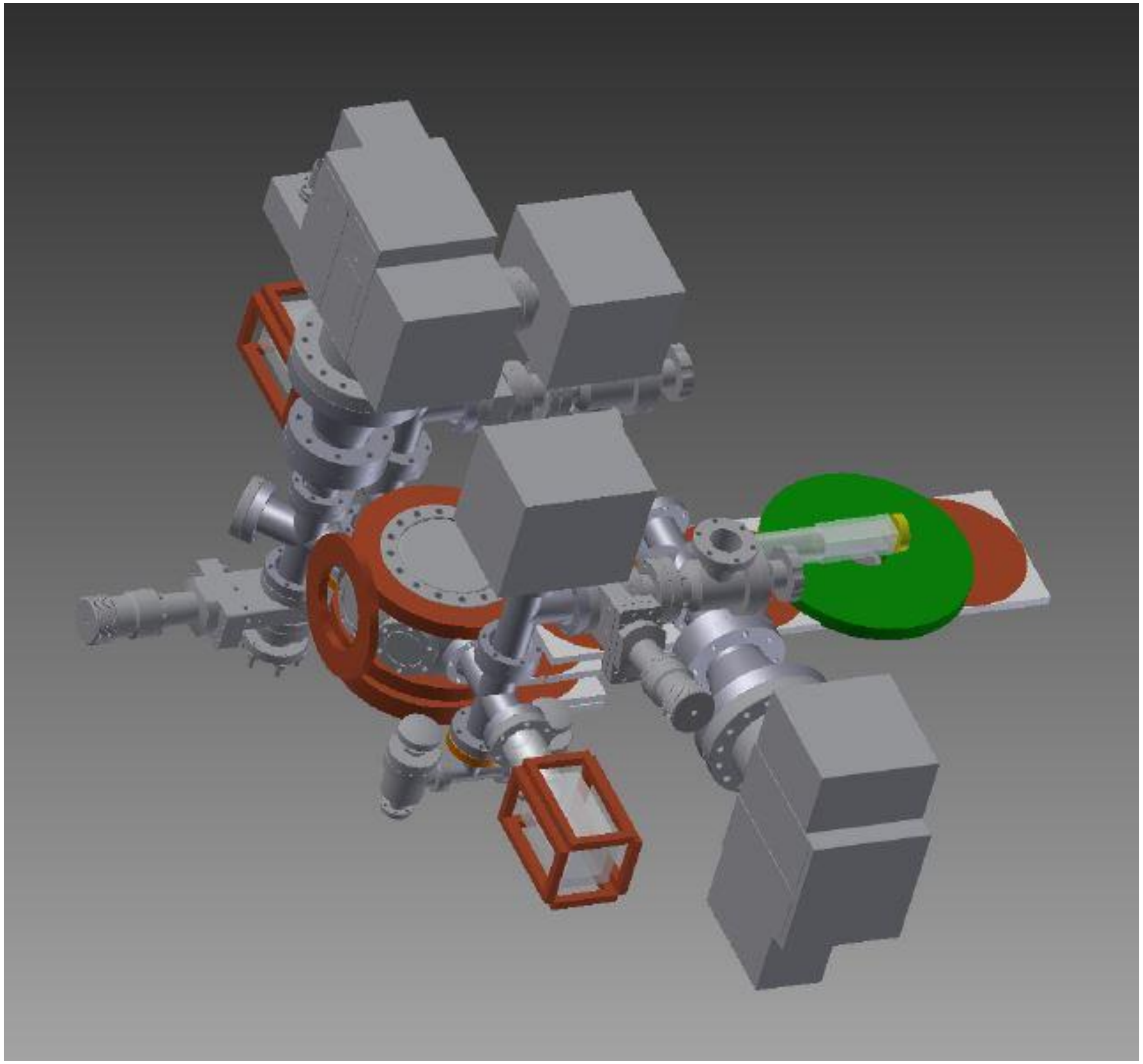
Chemically stable diatomic Molecules

- Physics of lighter boson mediated fermionic pairing (Similar to electron-phonon coupling)

Stable molecule with high dipole moment
With Both Fermion and Boson molecule
Formation possibilities

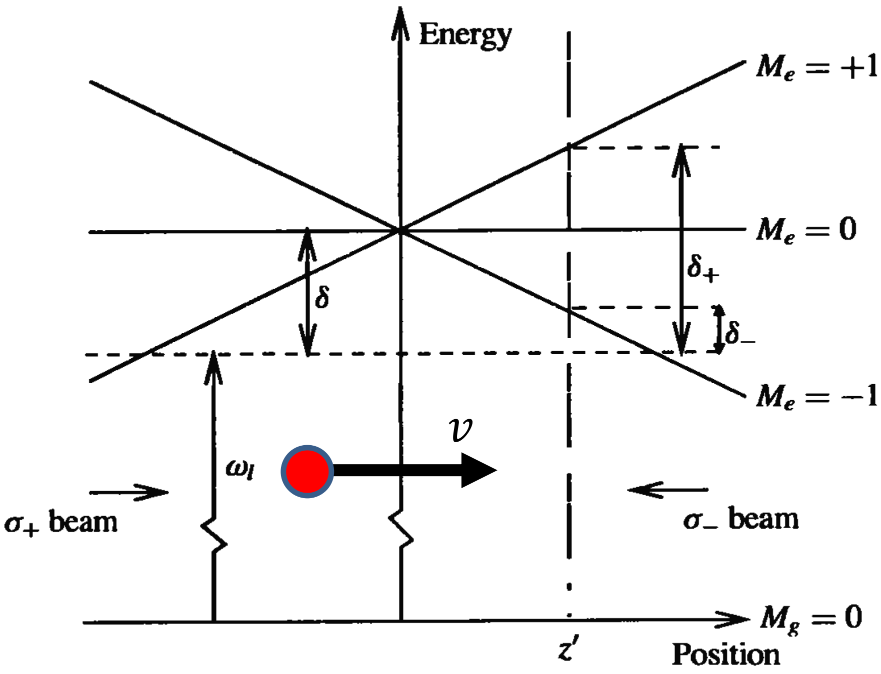
Huge Dipolar length,
a_{dd} ~ 1.5 μm or 30000 a_0

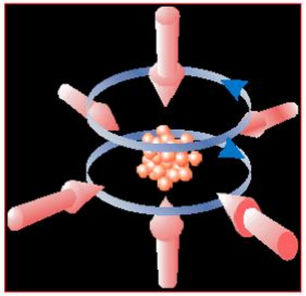
Our pathway to create ultra-cold dipolar molecules



- Laser cooling and trapping of Sodium and Potassium
- Evaporative cooling to dual degeneracy
- Feshbach association
- STIRAP to molecular ground state
- External electric field to polarize molecules

Laser Cooling and trapping

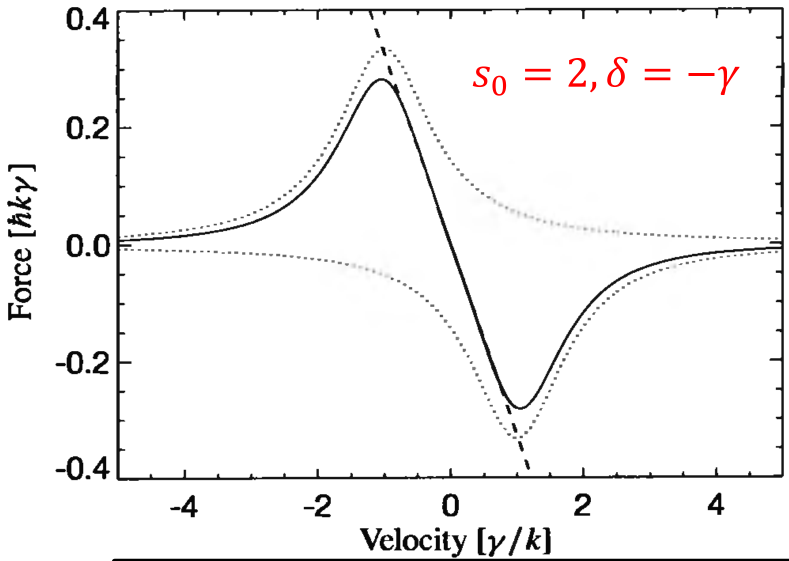




Typical values

density	n	10^9 - 10^{11} cm^{-3}
temperature	T	0.00001 K
size	Δx	0.1…10 mm

cooling and trapping in 3 dimensions



Total force on the atoms in MOT $\vec{F} = \vec{F}_+ + \vec{F}_-$

$$\vec{F}_\pm = \pm \frac{\hbar \vec{k} \gamma}{2} \frac{s_0}{1 + s_0 + (2\delta_\pm/\gamma)^2}$$

$$\delta_\pm = \delta \mp \vec{k} \cdot \vec{v} \pm \mu' B/\hbar.$$

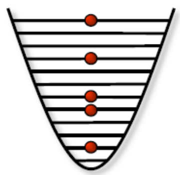
$$\vec{F} = -\beta \vec{v} - \kappa \vec{r} \qquad \kappa = \frac{\mu' A}{\hbar k} \beta \qquad \beta = \frac{8\, \hbar\, \delta\, s_0}{\gamma\,(1 + s_0 + (2\delta/\gamma)^2)^2}$$

Doppler limit Temperature $T_D = \frac{\hbar \gamma}{2\, K_B}$

$T_D \sim 235\ \mu K\ for\ Na,\ \ \gamma = 2\pi\ \ 9.79\ MHz$
$T_D \sim 145\ \mu K\ \ for\ 40K, \gamma = 2\pi\ \ 6.04\ MHz$

Quantum Degeneracy

Trapped Boson & Fermions in Harmonic Trap



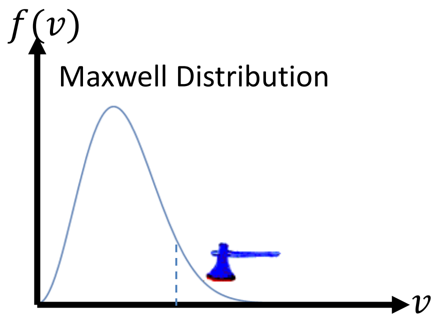
Bosons & Fermions at high T

Mean occupation numbers in energy state ϵ

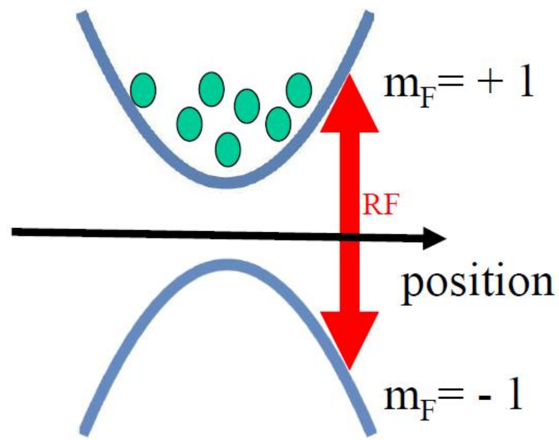
$$n_{BE}(\epsilon) = \frac{1}{e^{\frac{(\epsilon-\mu)}{K_B T}} - 1}$$

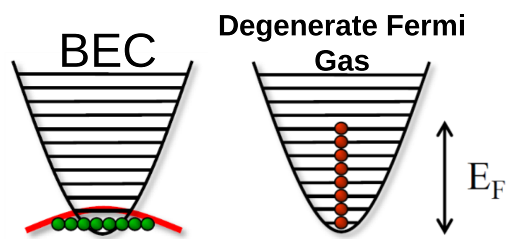
$$n_{Fermi}(\epsilon) = \frac{1}{e^{\frac{(\epsilon-\mu)}{K_B T}} + 1}$$

$\mu \rightarrow$ Chemical Potential of the system



Evaporative Cooling

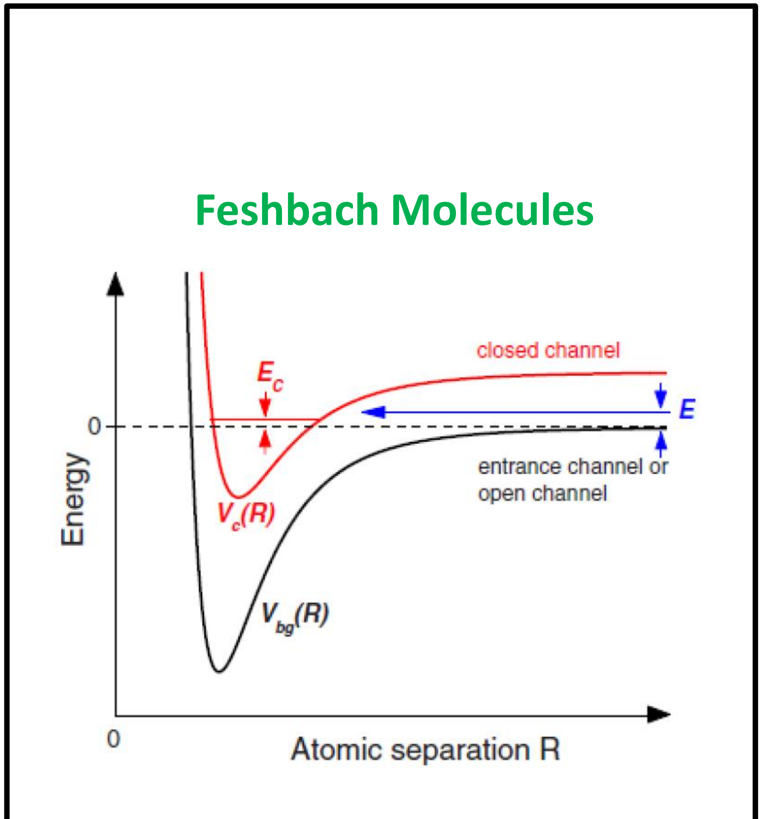




Bosons **Fermions**
at T=0

Degeneracy occurs when there is macroscopic population of particular energy state

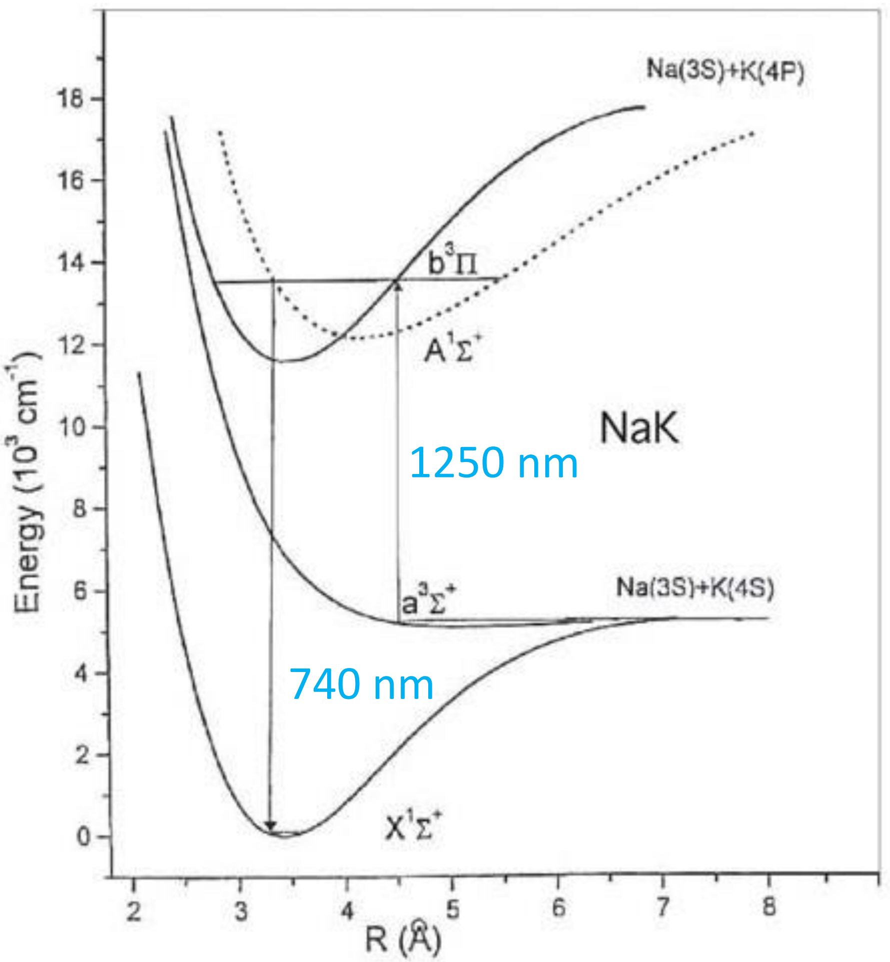
Feshbach Molecules and ground state transfer



$$a(B) = a_{bg}\left(1 - \frac{\Delta}{B - B_0}\right)$$

$23\ Na\ |F = 1, M_F = 1 > \ +40K\ |F = \frac{9}{2}, M_F = -\frac{5}{2} >$

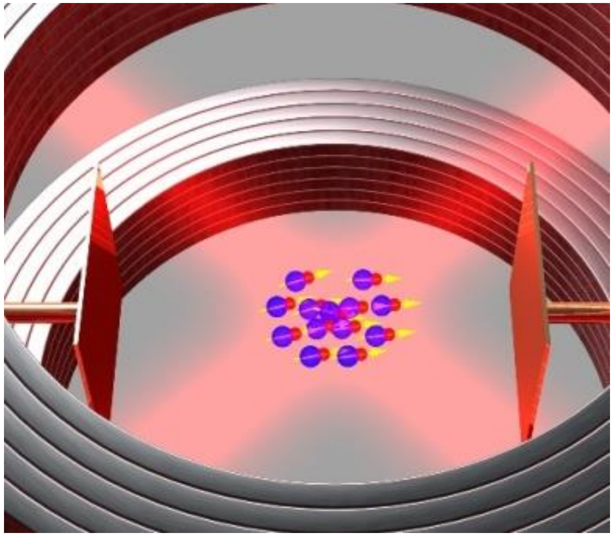
$B_0 = 138\ Gauss, \Delta = 30\ Gauss$

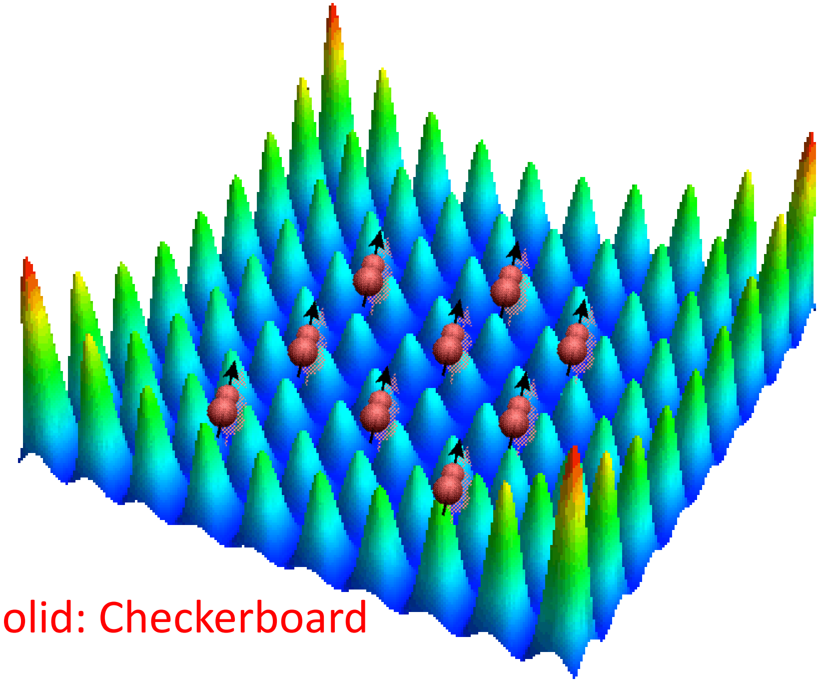


W. C. Stwalley, Eur. Phys. J. D 31, 221 (2004)

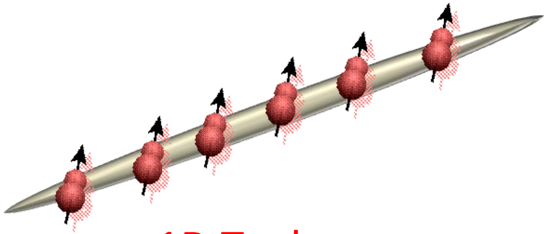
Once we get through the complexity …

There are interesting and novel physics to explore

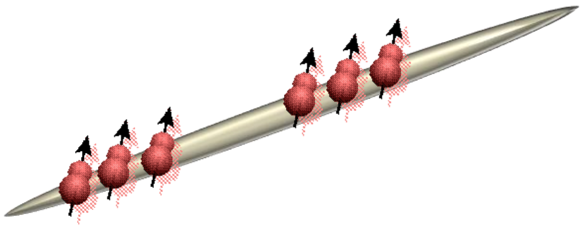




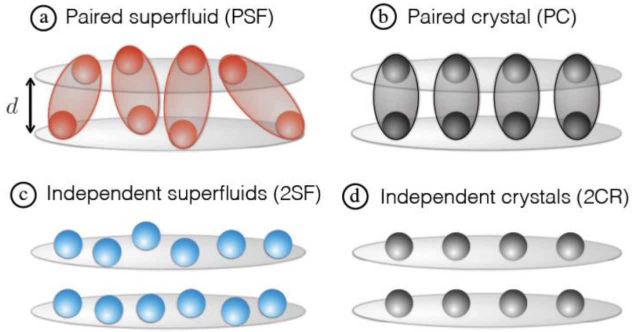
2D super-solid: Checkerboard



1D Tonks gas



Clustered state in 1D



Cinti et. al., 2017

For Review: T. Lahaye et. al., Rep. Prog. Phys. **72**, 126401 (2009)

How does one distinguish these quantum phases

- Traditionally using destructive imaging techniques (with many limitations)
- One possible alternative (with non-perturbative nature) :

Spin Correlation Spectroscopy

In Collaboration with:

Hema Ramachandran, Dibyendu Roy, Sanjukta Roy

Motivation:

- Polarization rotation in cold and quantum degenerate atoms → A new tool for non-destructive and non-perturbative detection (because it is off resonance measurement and detects the phase of probe light with negligible scattering)

- Atomic Polarization fluctuation → Intrinsic property of the system (Different phases will have different nature of fluctuation)

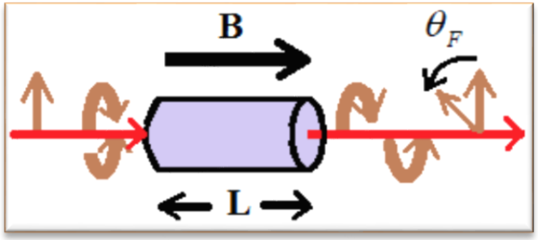
- True Many body physics can be probed → e. g. distinguishing between localized (insulator) and superfluid phases (Example: Interacting disordered quantum gases)

- In this talk → development and understanding the technique (using thermal atoms for the time being)

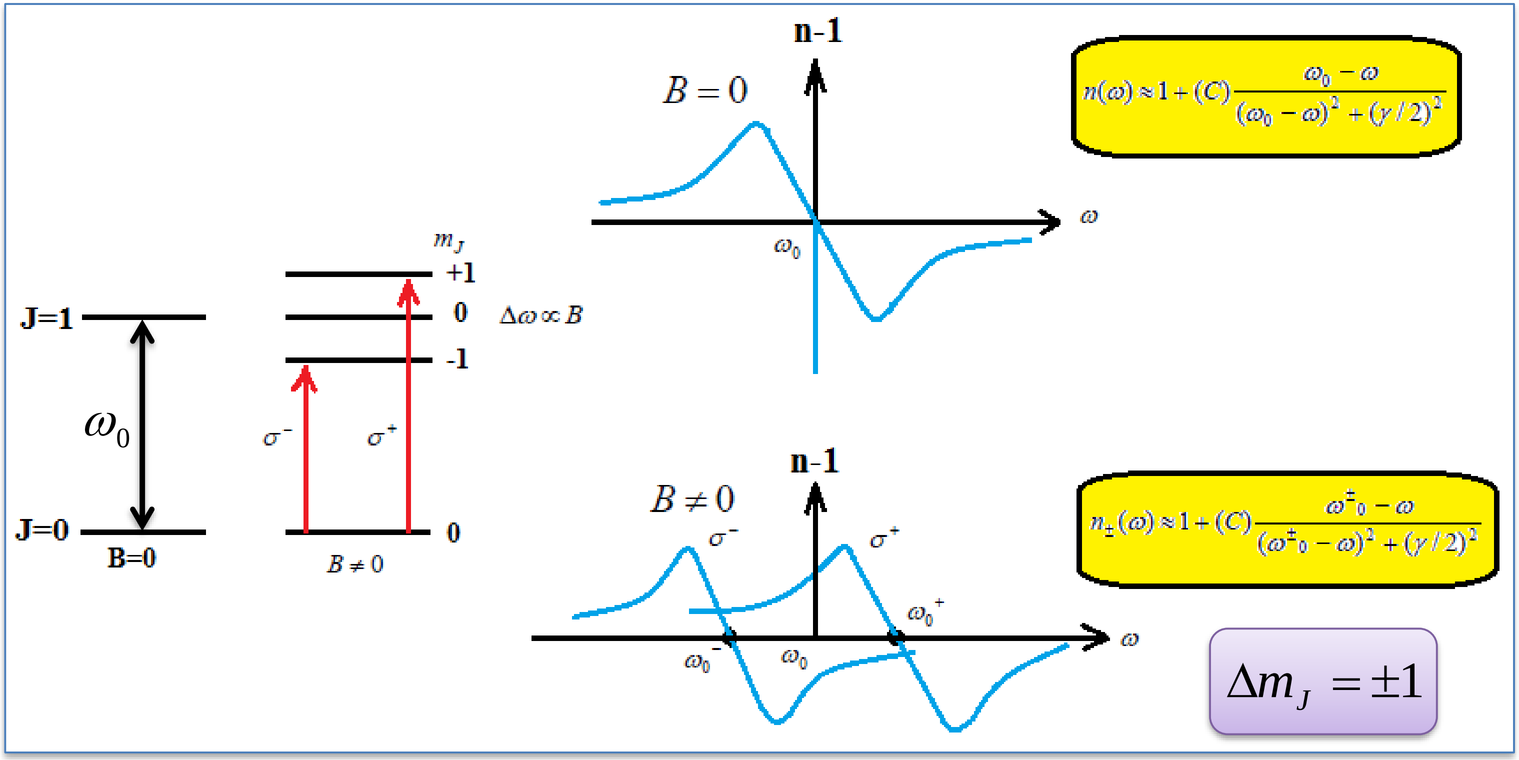
- Many recent publications signifying interest in the technique mainly from condensed matter community

The Basics:

Faraday (Polarization) Rotation



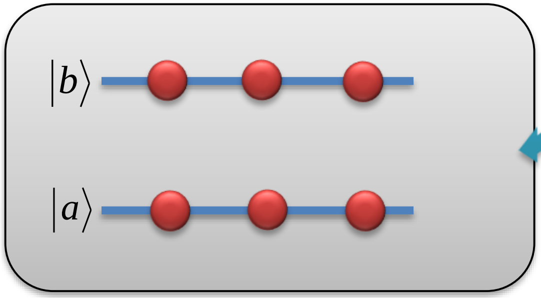
$$\theta_F = V(\omega)|B|L$$

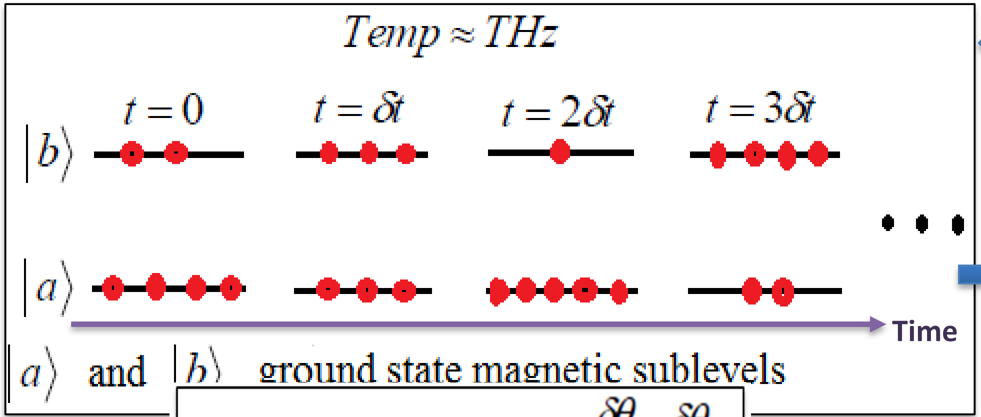


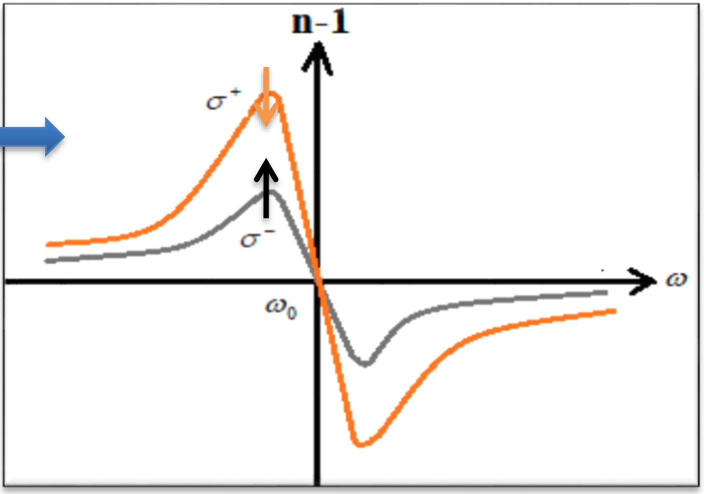
Polarization Fluctuation

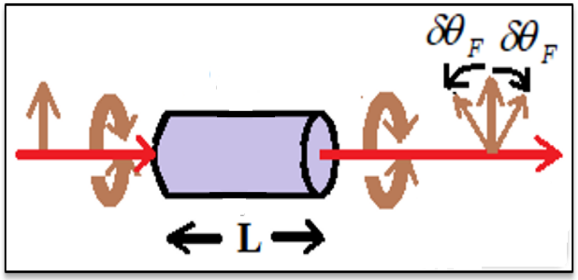
- Even in zero field (when no polarization rotation is present), atomic polarization can fluctuate due to its relaxation at thermal temperature.

- Fluctuations of population between different magnetic states,
  ⇒ fluctuating magnetic circular birefringence.
  ⇒ fluctuating probe beam polarization angle.









Spin Noise: Theory

- **Fluctuation-Dissipation theorem (FDT):**

Response of a system to a small external perturbation $\equiv$ response to a spontaneous fluctuation.

- Average of the polarization $=$ Zero.

- S.D. of the polarization $\propto$ spin noise power $\neq$ Zero.

- **Wiener–Khinchin theorem:** Autocorrelation in the time domain $\equiv$ The power spectrum in the frequency domain.

$$P(\omega) = \int_0^\infty dt e^{i\omega t} \langle \delta\phi(t)\delta\phi(0) \rangle$$

$$\frac{\phi_N(\omega)}{\sqrt{\delta f}} = [P(\omega)]^{1/2}$$

$\sqrt{\delta f}$ = Resolution bandwidth of SA

Experimental considerations

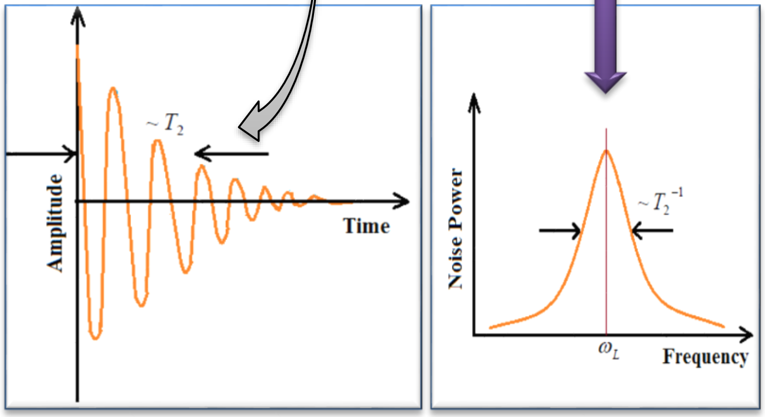
- It is easier for experiments to detect a noise peak shifted to Larmor frequency ω_L

  ⟹ We use a perpendicular magnetic field with respect to light propagation.

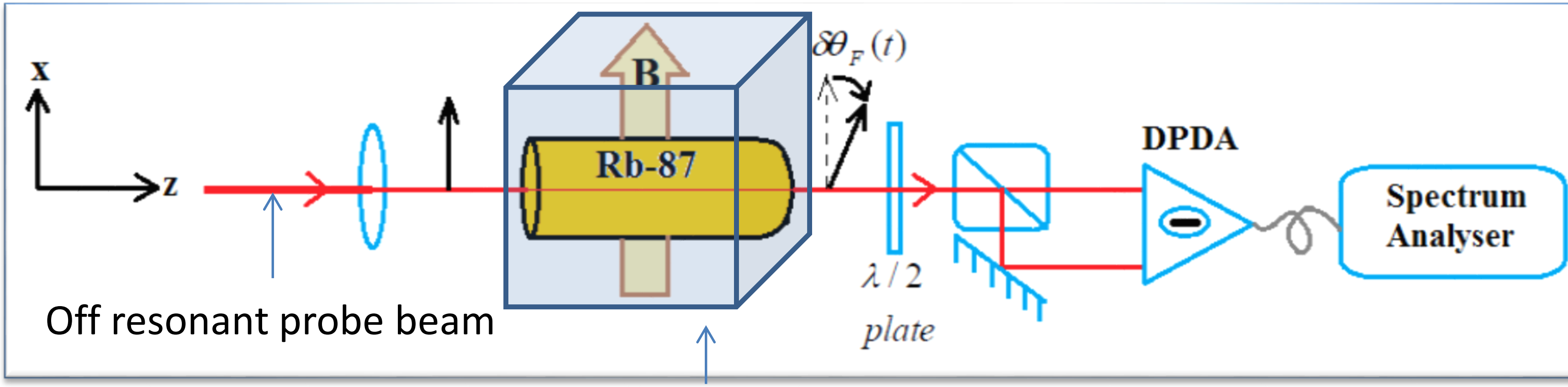
- Presence of perpendicular B-field ⟹ Fluctuating macroscopic magnetization along propagation direction start to precess at Larmor frequency ω_L with a characteristic decay time T_2 ⟹ $S_{au}(t) = < S_z(0) S_z(t) > \propto \cos(\omega_L t) e^{-t/T_2}$

- FT of autocorrelation function ⟹ Lorentzian peak centered at ω_L, with width $1/T_2$.

- Spin Noise Amplitude $\propto \left\langle \delta\theta_F^{\,2} \right\rangle^{1/2} = \frac{e^2 f\beta}{4mc\delta} \sqrt{\frac{N_0 L}{A}}$



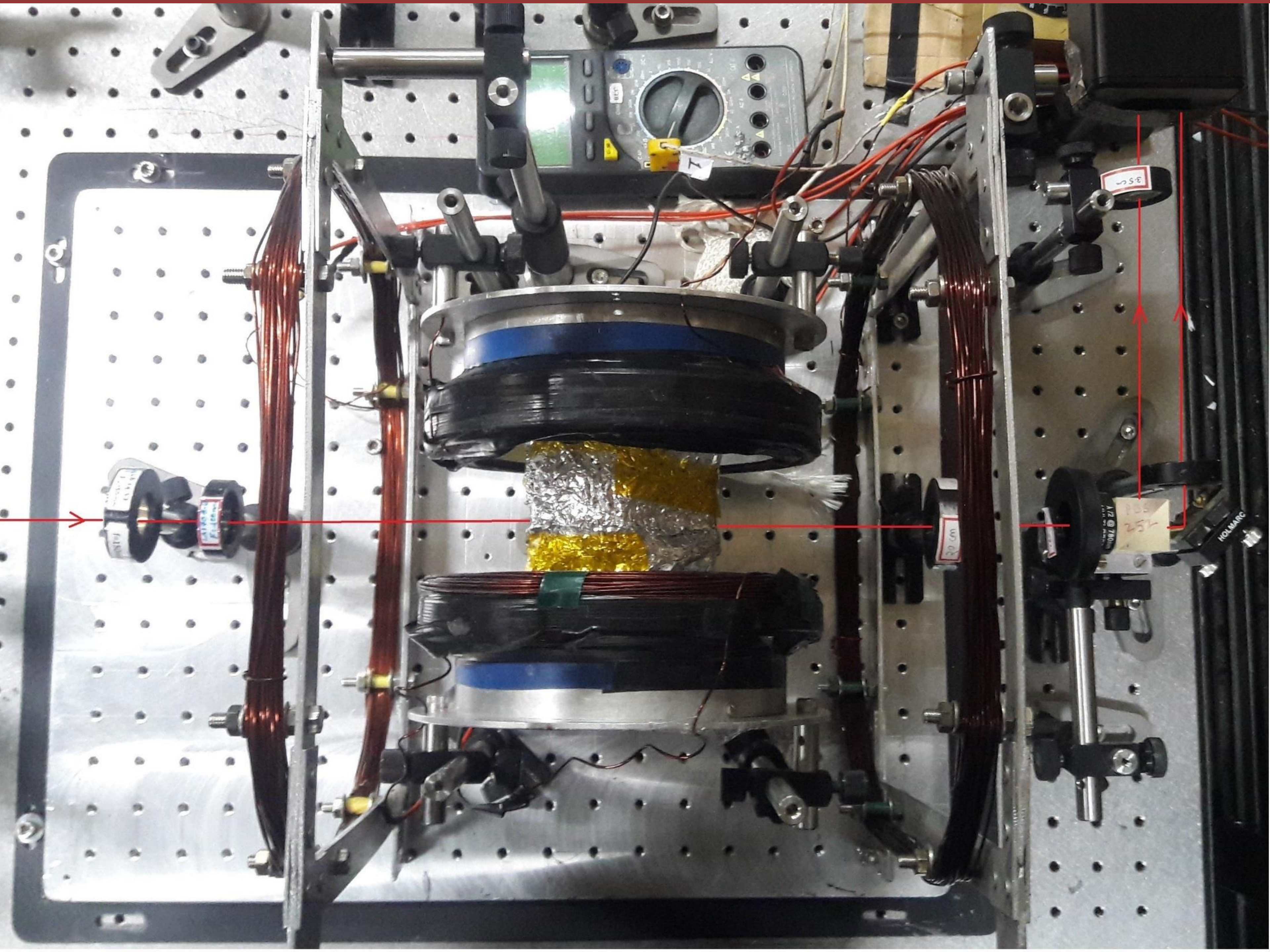
Experimental arrangement



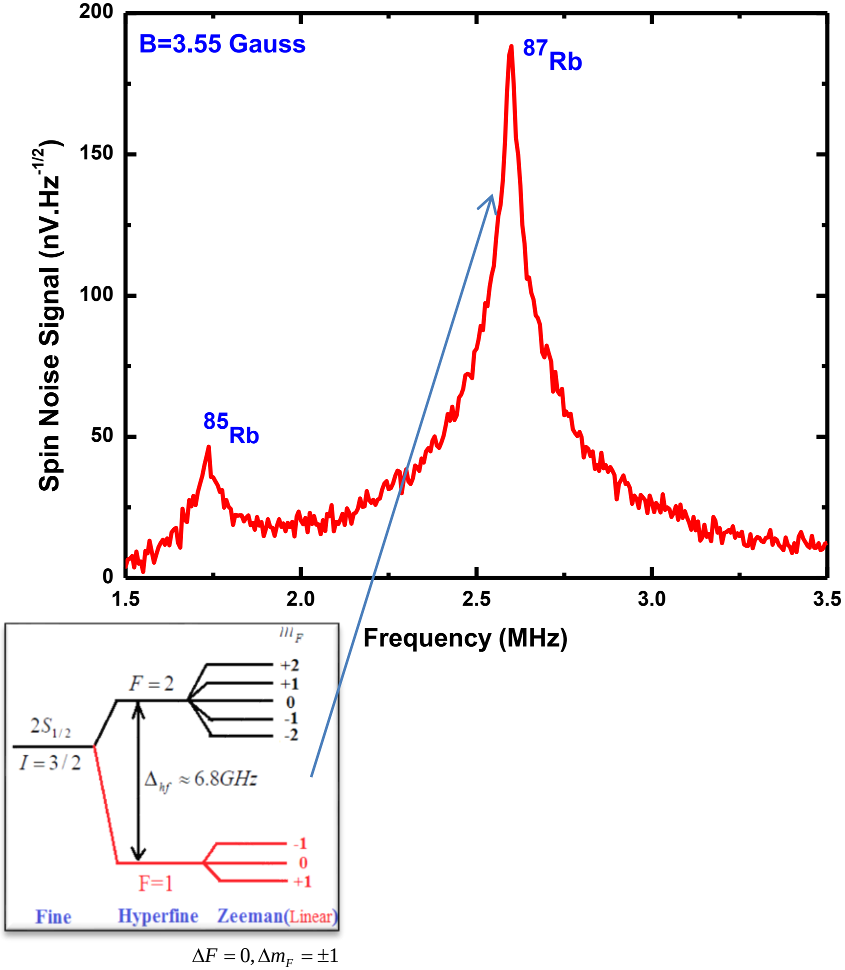
Off resonant probe beam

Magnetic Shielding

Detector: Balanced 80 MHz Bandwidth dual channel
Common mode rejection: 25 dB
Conversion gain: $2\text{x}10^4$ V/W



Spectrum

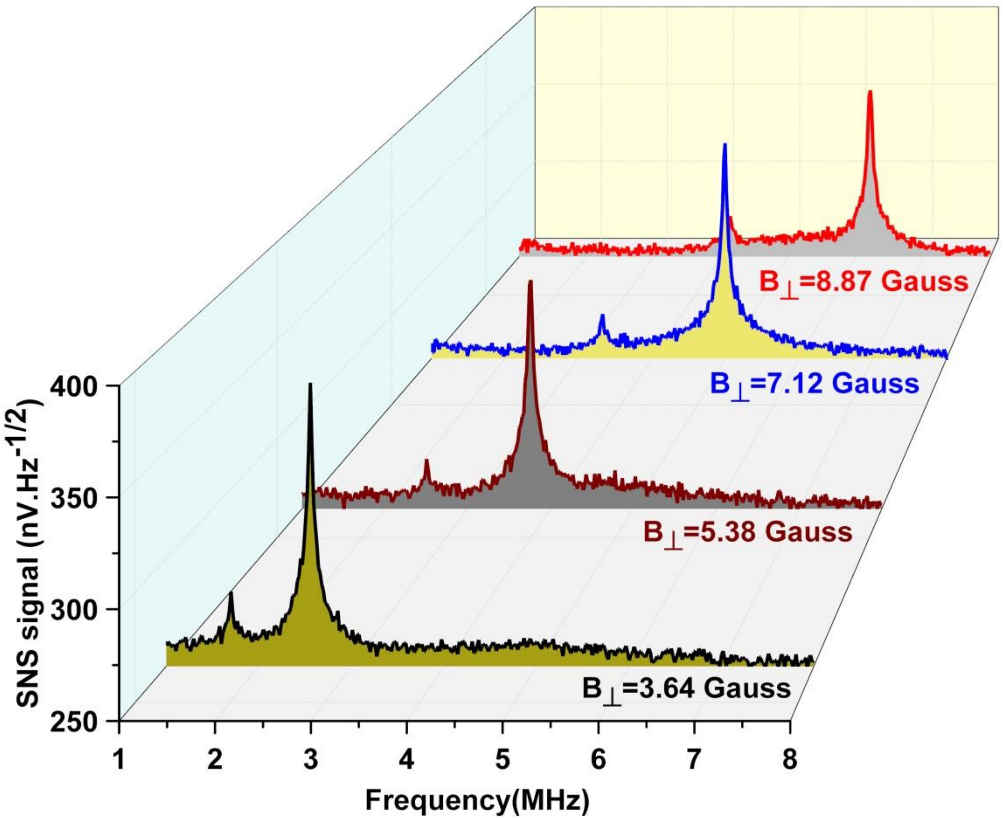


Salient features:

- Extremely narrow line-width (~40 KHz) [Much smaller than Doppler and pressure broadenings and even natural linewidth for optical transitions]
- High precision detection of isotope abundance
- Independent of probe laser line-width
- Spin state identification [more later]

Similar Results: Smith et. al.(Nature, 2004), Lucivero et. al. (PRA, 2017)

Spectrum

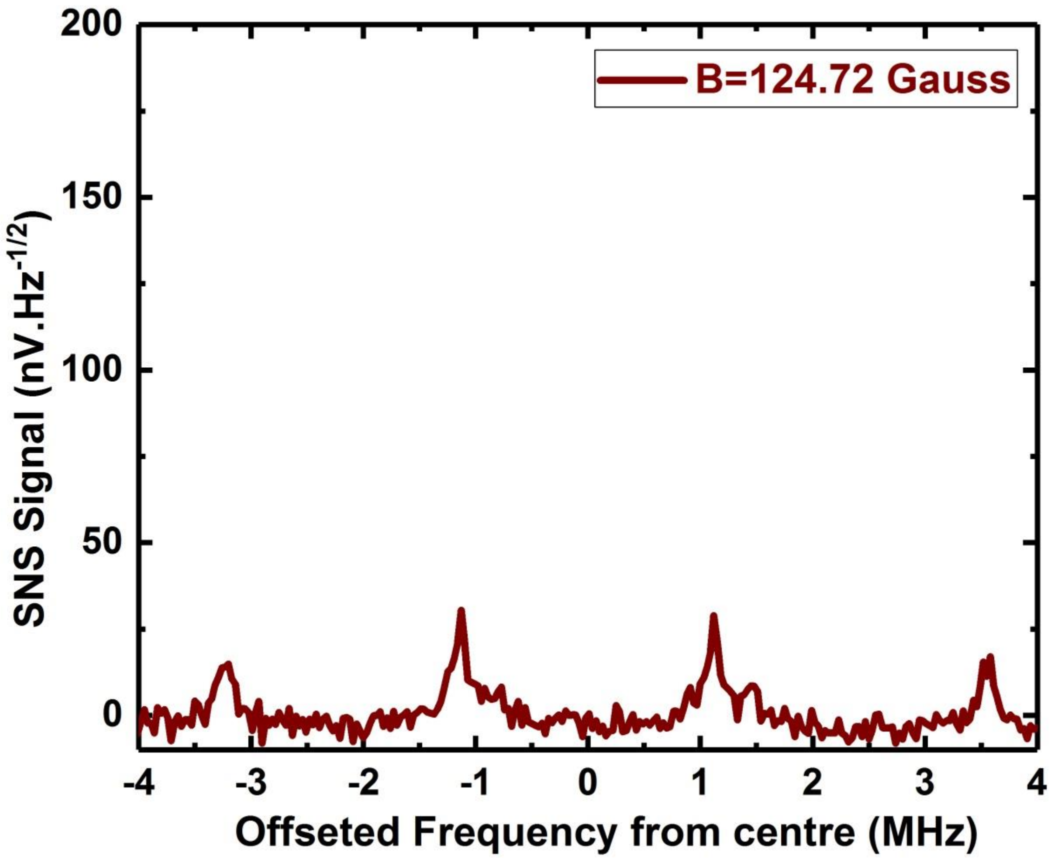


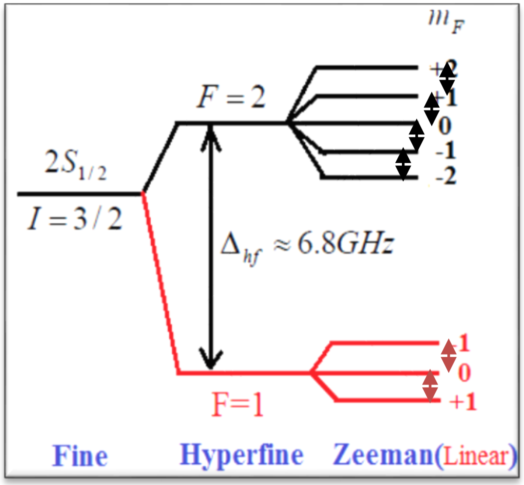
- High precision detection of small magnetic field
- Precision measurement of g factor

[extracted value from these Measurements:
gF = 0.500(1) for Rb-87
gF = 0.333(1) for Rb-85]

Quadratic Zeeman Effect

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

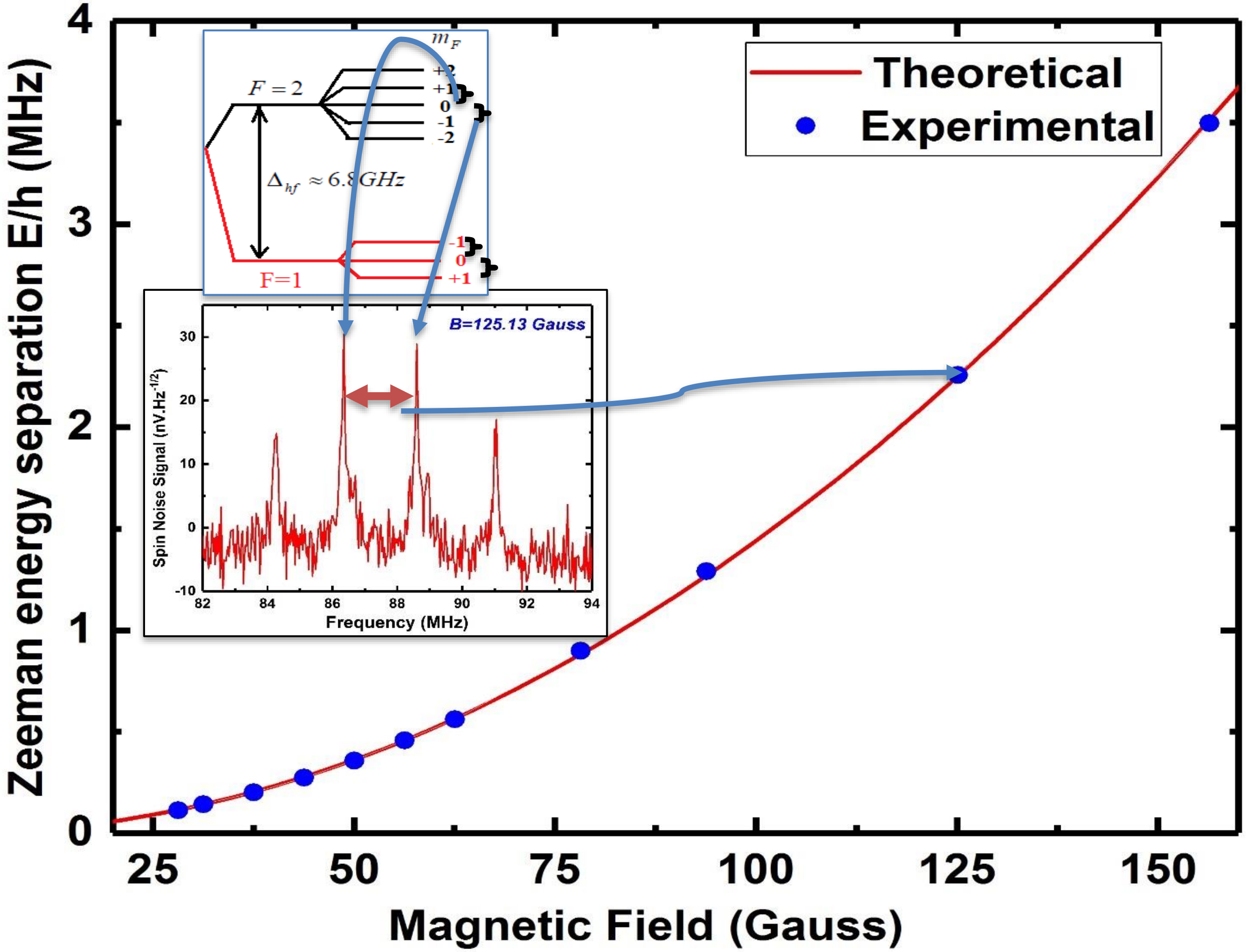




$\Delta F = 0, \Delta m_F = \pm 1$

Measurement of hyperfine constant

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



Measured hyperfine Constant =

6.808(59) GHz

Less than 1% error

CODATA value =

6.83468261090429(9) GHz

Nuclear Zeeman(Transition peaks)

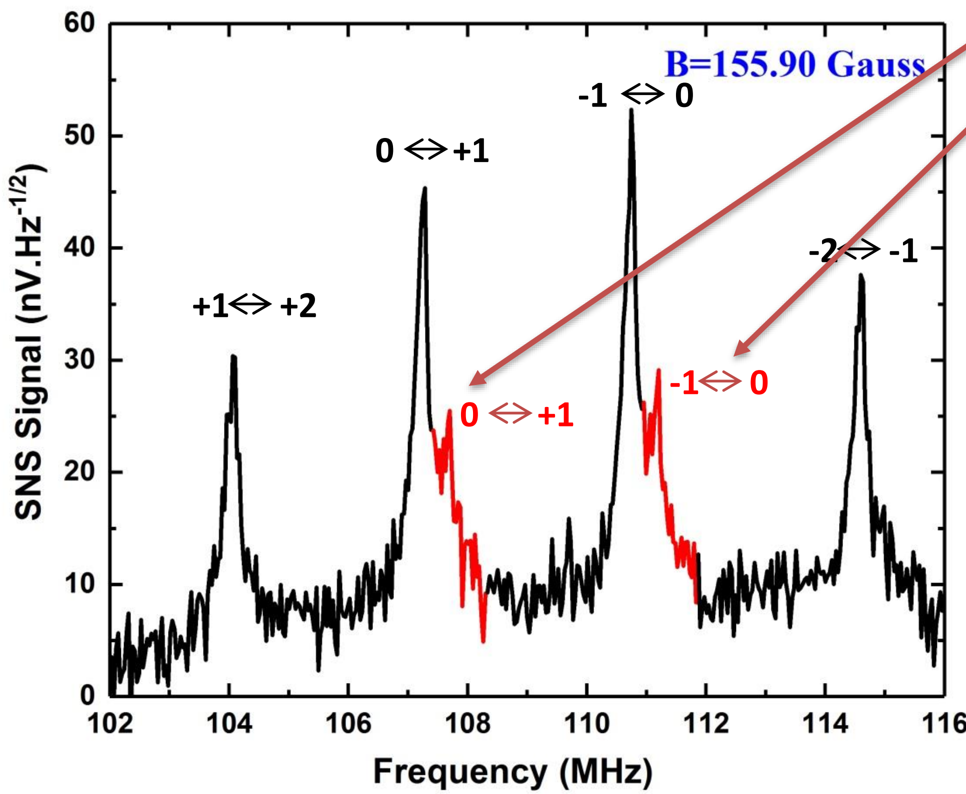
$$E_{F,m_F} = \frac{-\Delta_{hf}}{2(2I+1)} + g_I \mu_B B m_F \pm \frac{\Delta_{hf}}{2}\sqrt{1+\frac{4m_F}{2I+1}x + x^2}$$

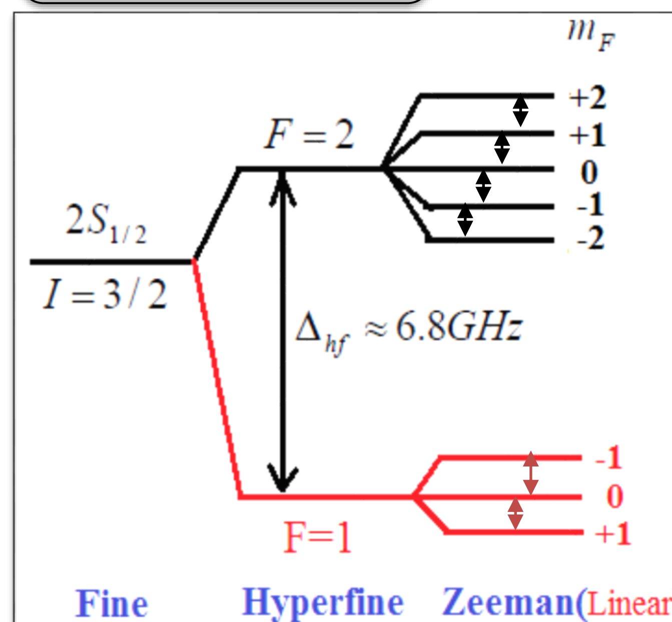
Nuclear Zeeman

Quadratic Zeeman

$$x = \frac{(g_j - g_I)\mu_B B}{\Delta_{hf}}$$

$$F = I \pm 1/2$$





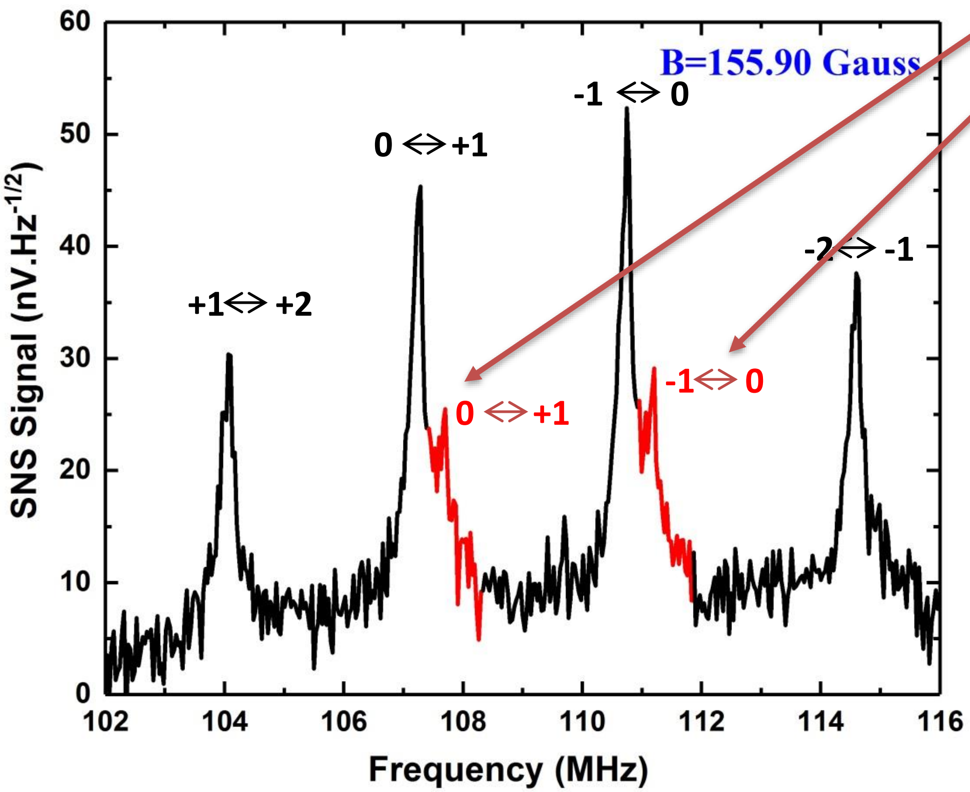
$$\Delta F = 0, \Delta m_F = \pm 1$$

Nuclear Zeeman(Transition peaks)

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

Nuclear Zeeman

Quadratic Zeeman



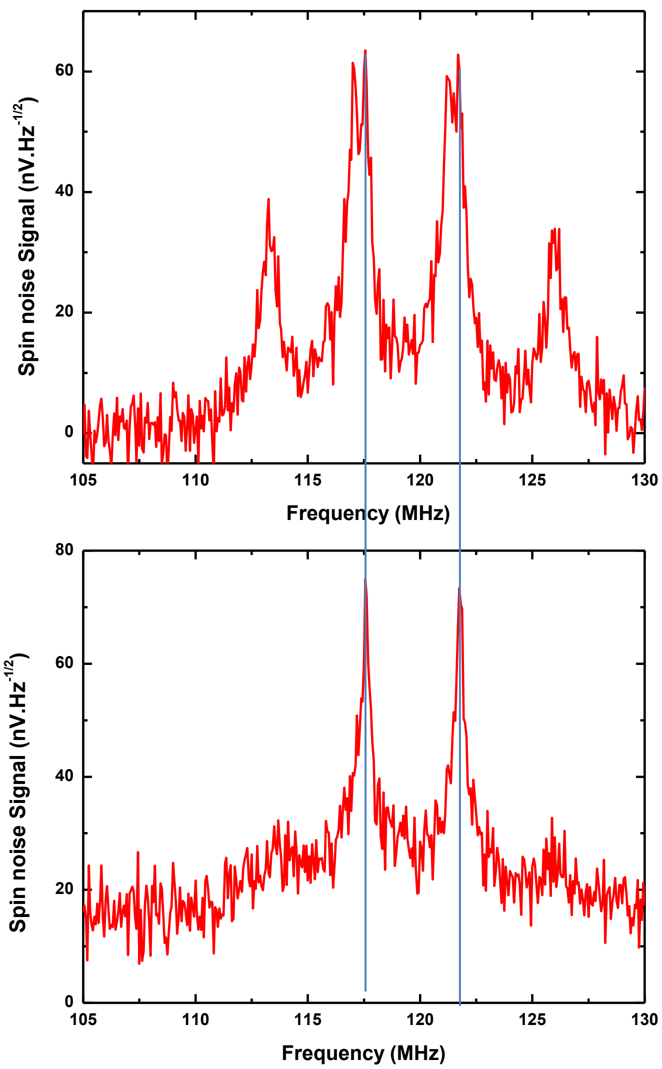
Measured g_I =

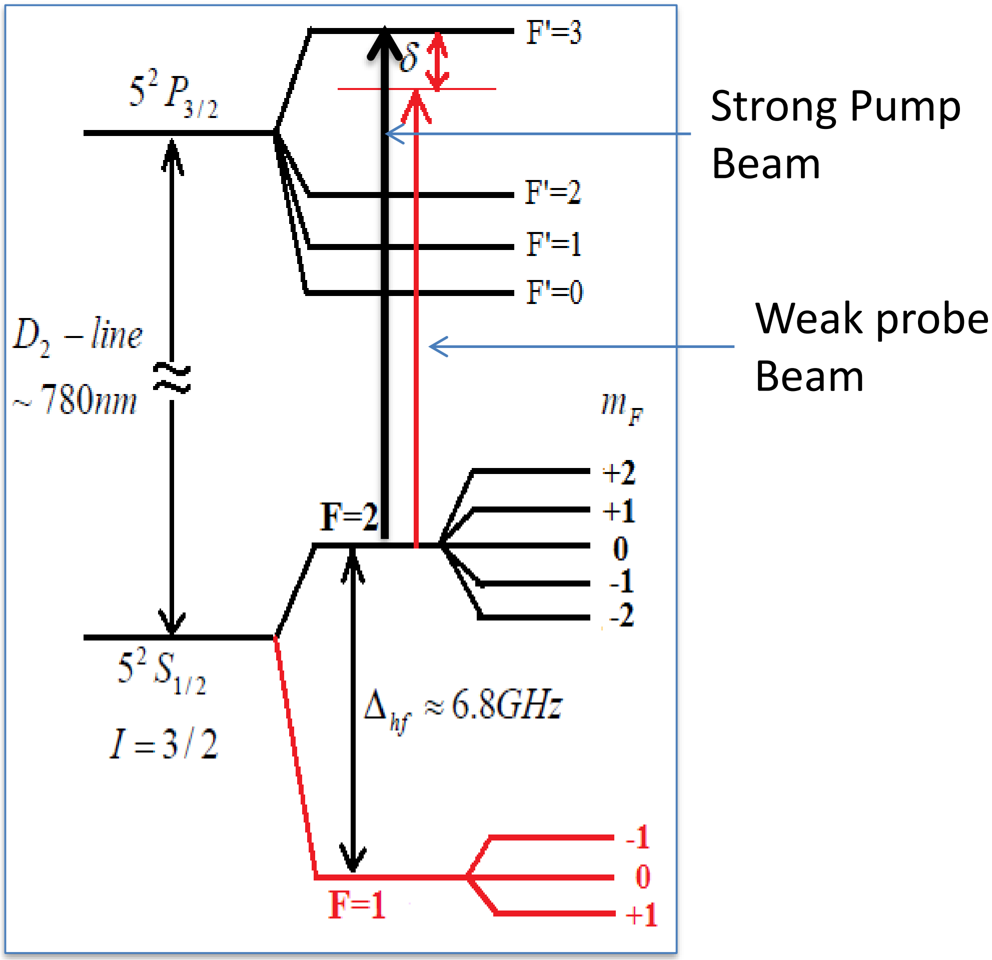
-0.00100627(2558)

CODATA value =

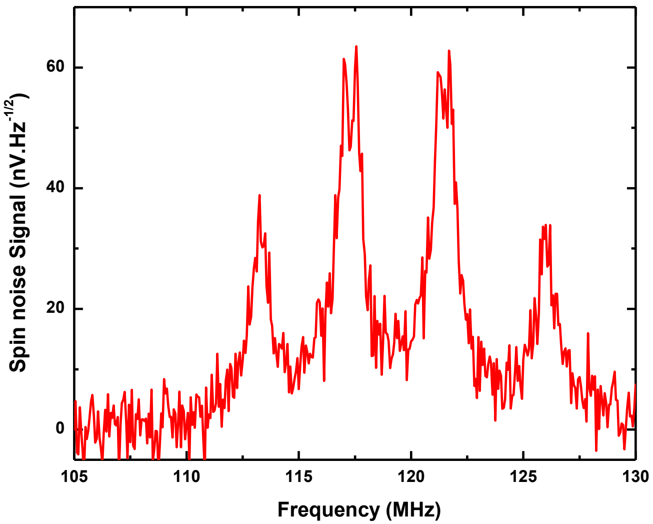
-0.0009951414(10)

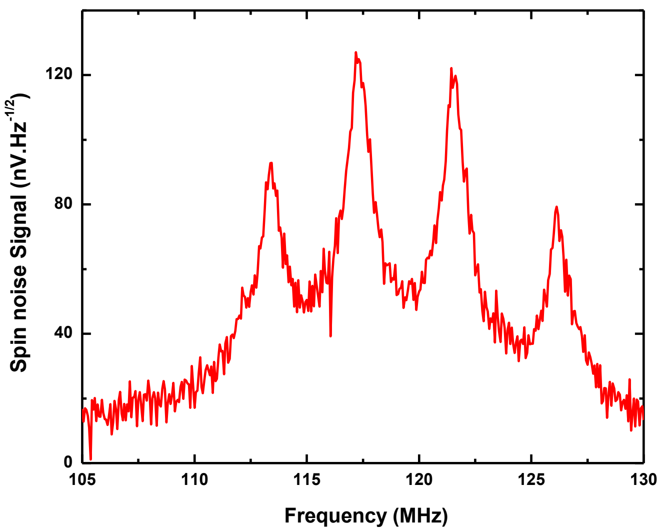
Effect of Optical Pumping

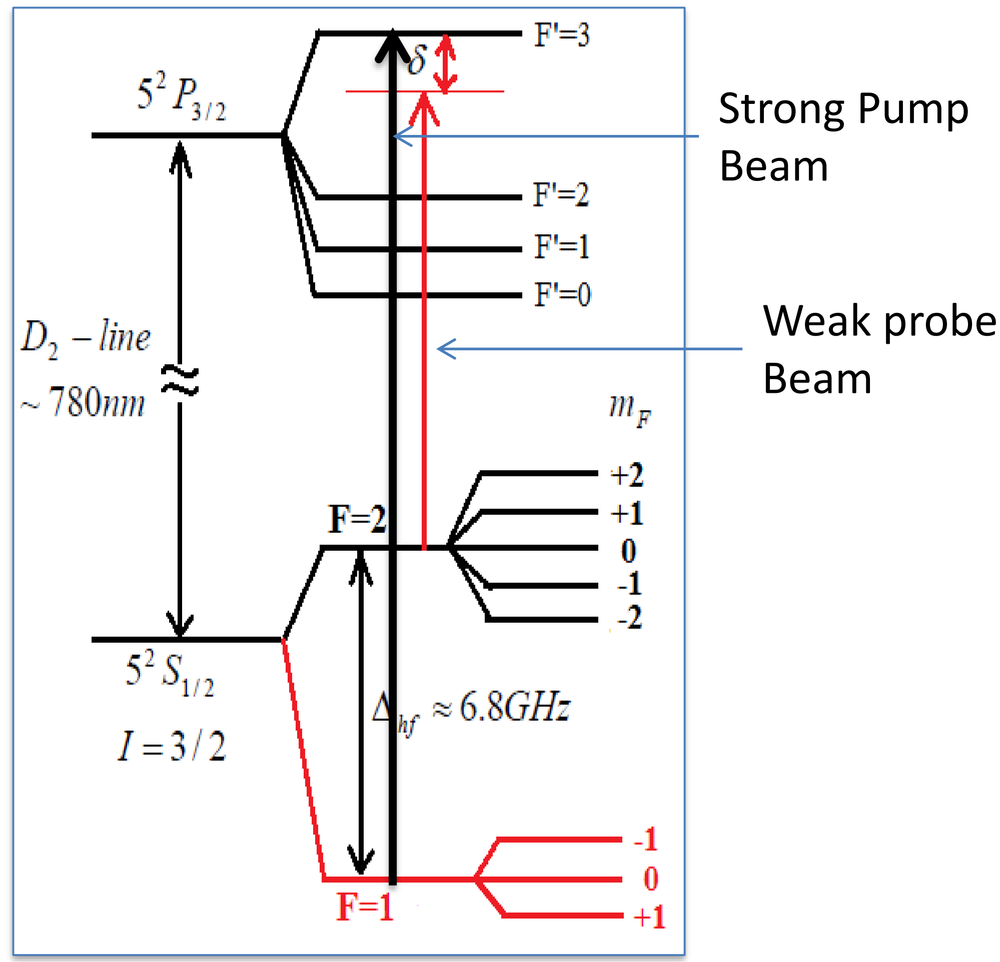




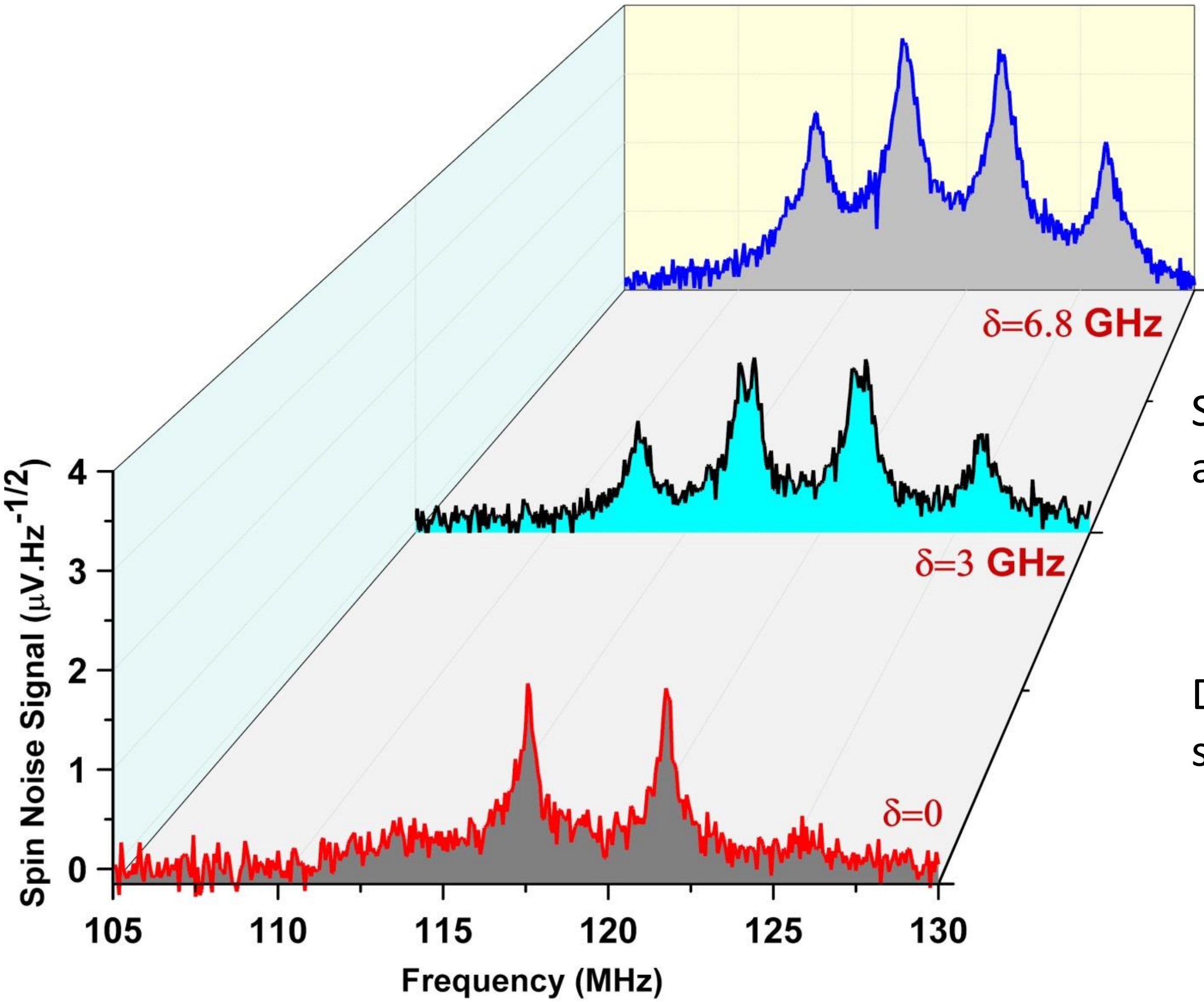
Effect of Optical Pumping







Partially polarizing the atoms



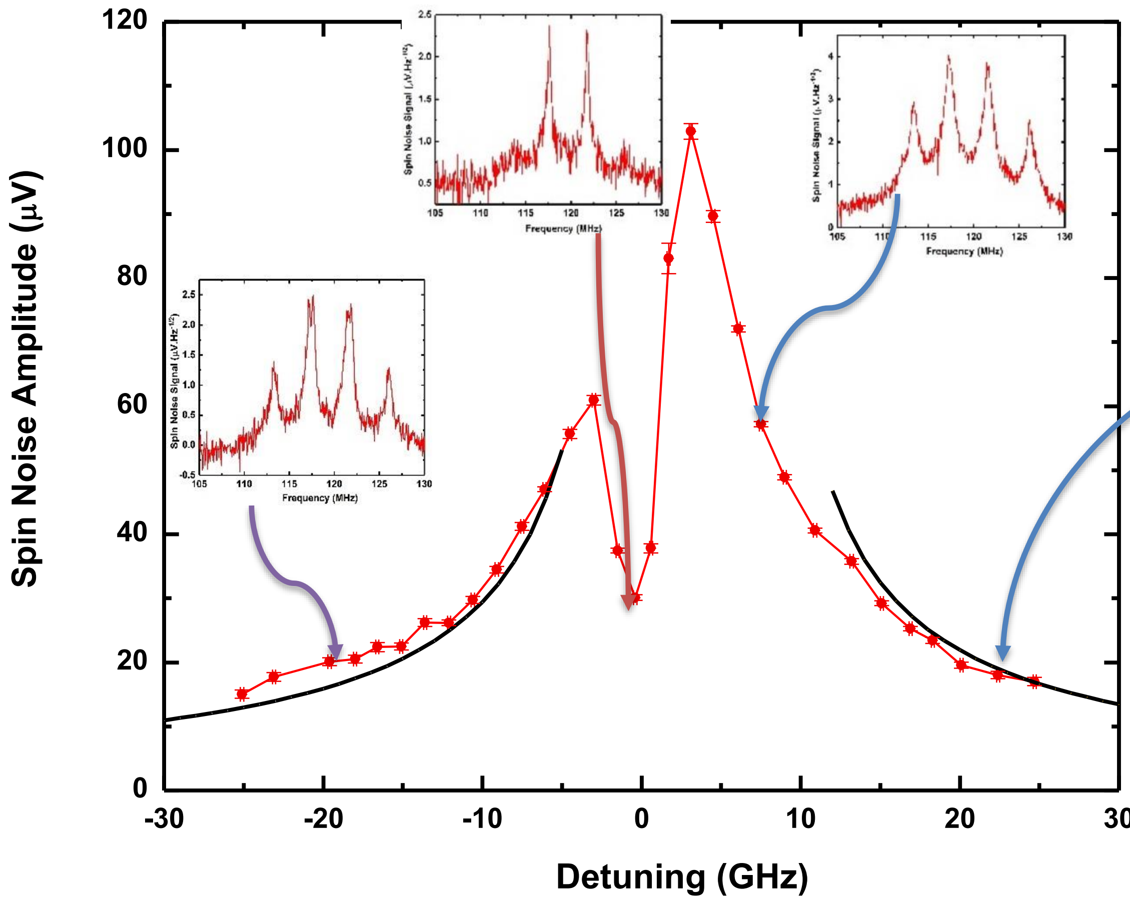
Spin dynamics can be affected by optical pumping

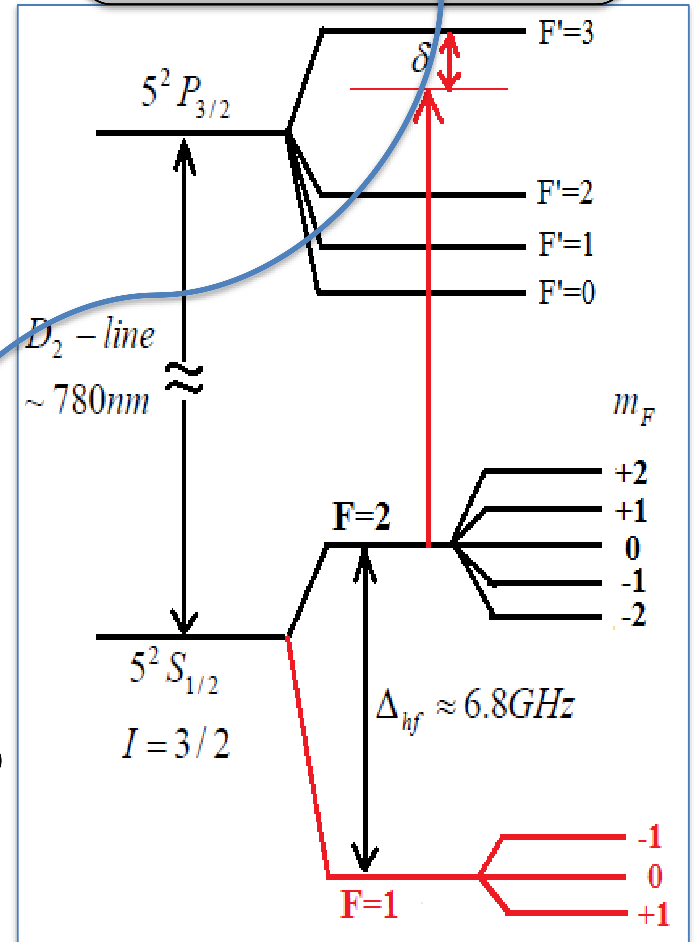
And

Detected by spin correlation spectroscopy

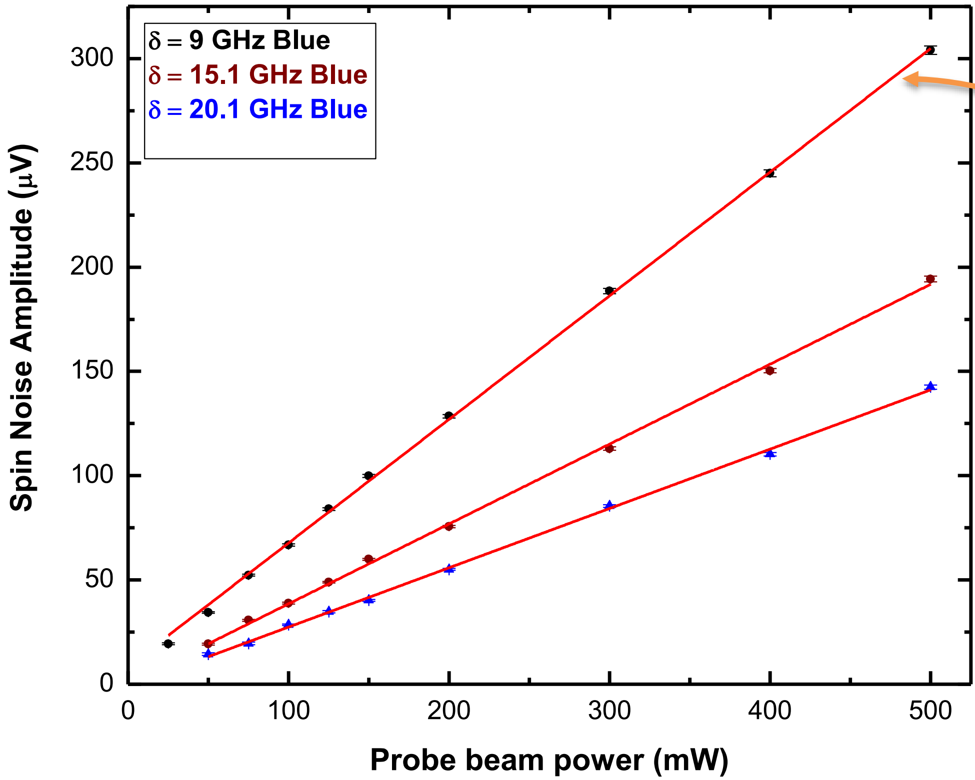
Spin Noise Amplitude vs probe detuning

$$\left\langle \delta\theta_F^{\,2} \right\rangle^{1/2} = \frac{e^2 f\beta}{4mc\delta}\sqrt{\frac{N_0 L}{A}}$$





Spin Noise Amplitude vs Probe power

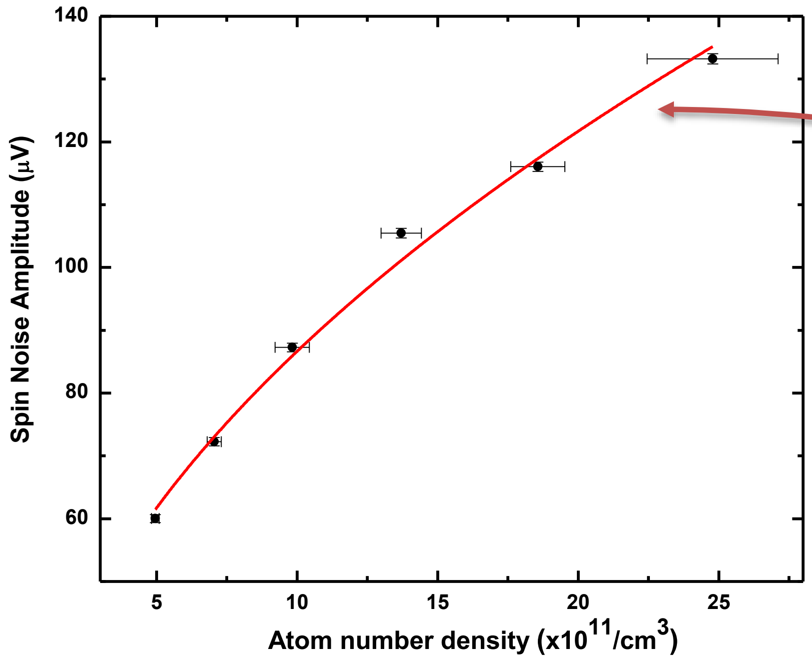


$$\left\langle \delta\theta_F^{\ 2} \right\rangle^{1/2} = \frac{e^2 f \beta}{4mc\delta} \sqrt{\frac{N_0 L}{A}}$$

Probe beam does perturb the system slightly, however for small probe power we recover intrinsic (unperturbed) noise amplitude

Spin Noise Amplitude vs atom density

We can vary the number of atoms in vapor simply by heating the cell

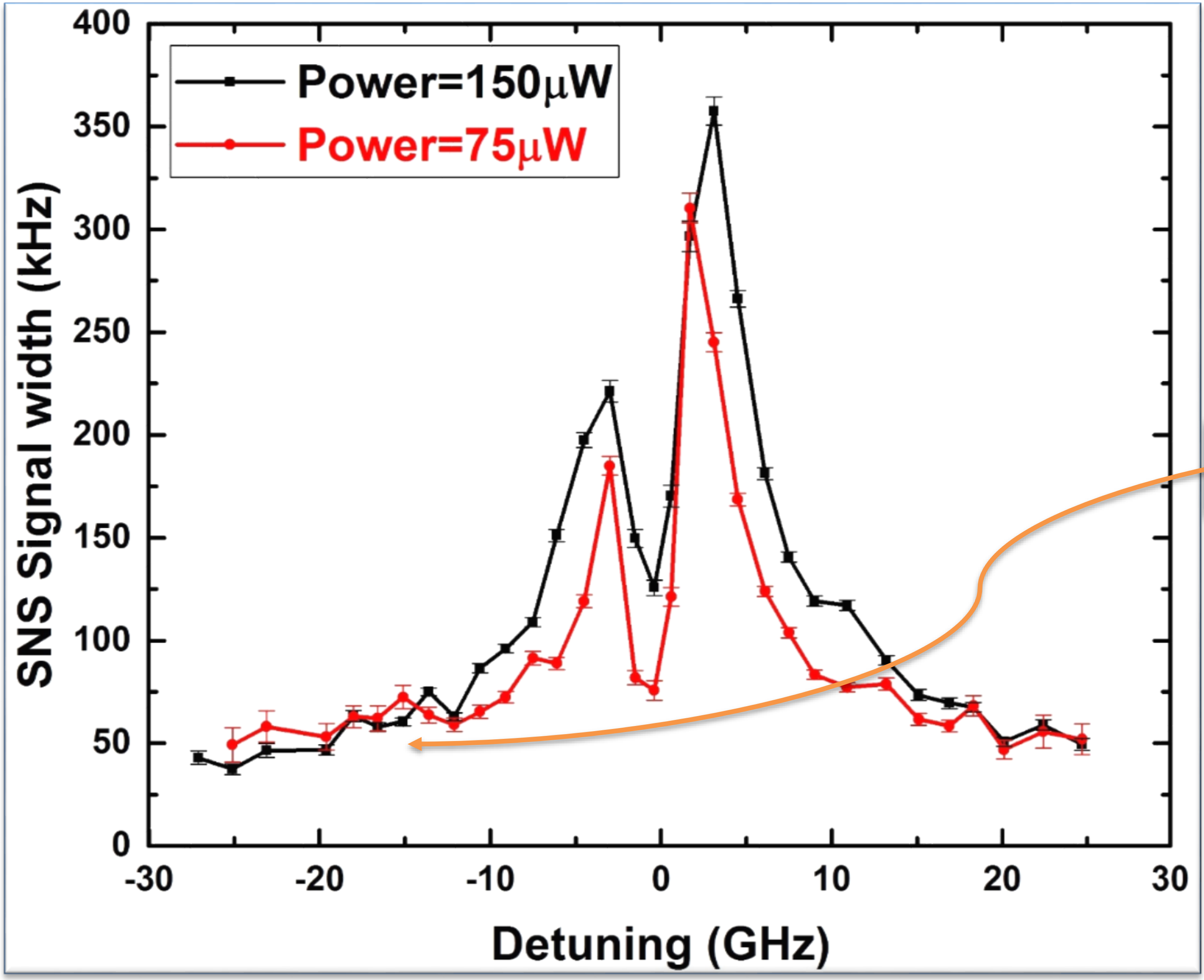


$$\left\langle \delta\theta_F{}^2 \right\rangle^{1/2} = \frac{e^2 f\beta}{4mc\delta}\sqrt{\frac{N_0 L}{A}}$$

Noise amplitude scales as **(number of available spin)**$^{1/2}$

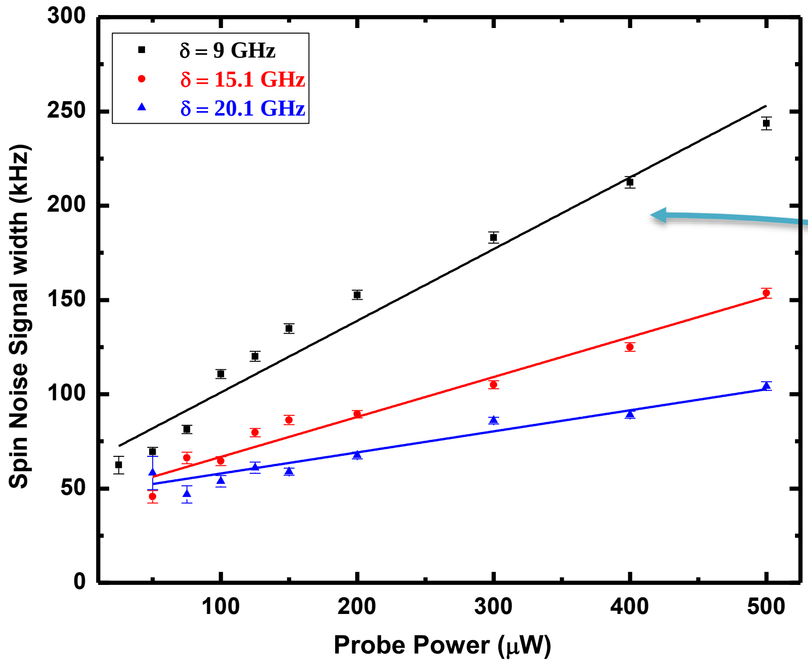
As one would expect for random noise

Spin Noise Line Width vs Detuning



$$\frac{1}{T_2} = \Gamma_0 + \alpha n + \gamma P + \xi f(\delta)$$

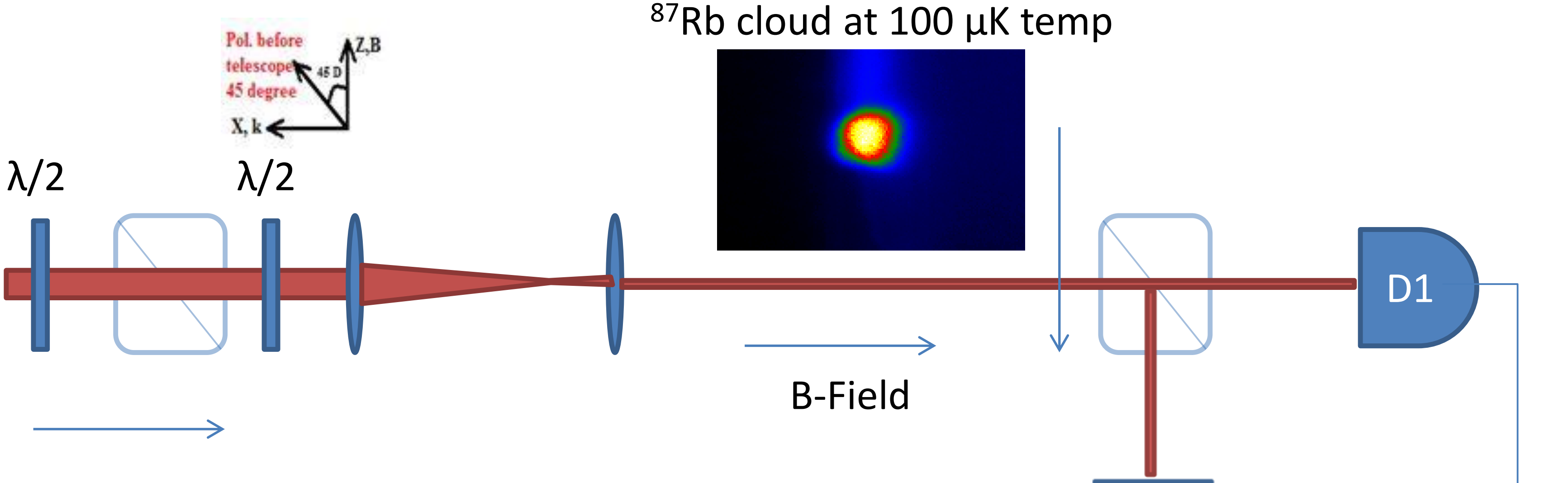
Spin Noise Line Width vs Probe power

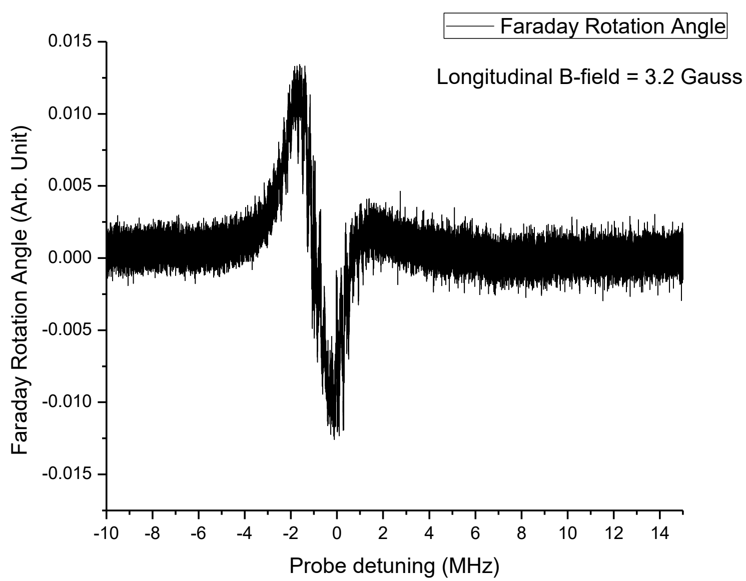


$$\frac{1}{T_2} = \Gamma_0 + \alpha n + \gamma P + \xi f(\delta)$$

Faraday Rotation in cold atoms

^{87}Rb cloud at 100 μK temp





See also:

Gazdacz et. al. (2013)

Kristensen et. al. (2017)

Conclusion and perspective

- A new experiment is being set-up to investigate physics of quantum gas mixtures
- Analog simulation of condensed matter systems with long-range interaction is the focus of this experiment
- A novel non-perturbative detection technique is being developed