Modeling nuclear matter with ultracold atomic gases

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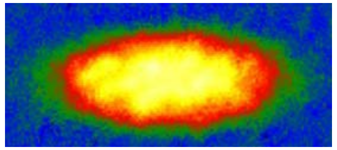
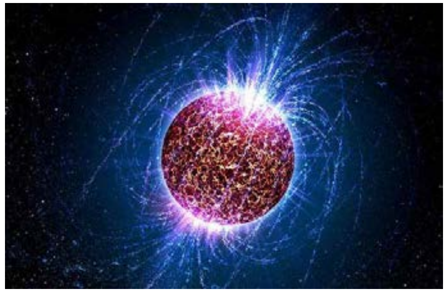
Motivation and Outline

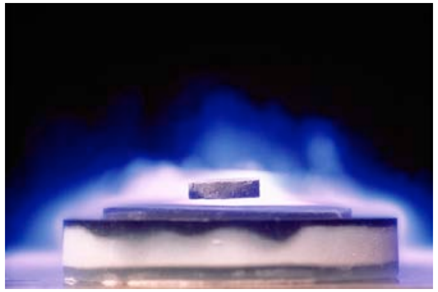
Strongly Interacting
Fermi Gas



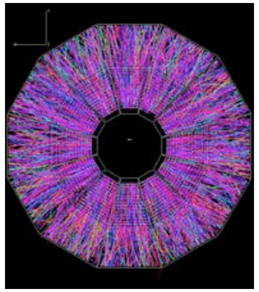


Neutron Matter

Optical Control
of Interactions



Superconductors



Quark Gluon Plasma

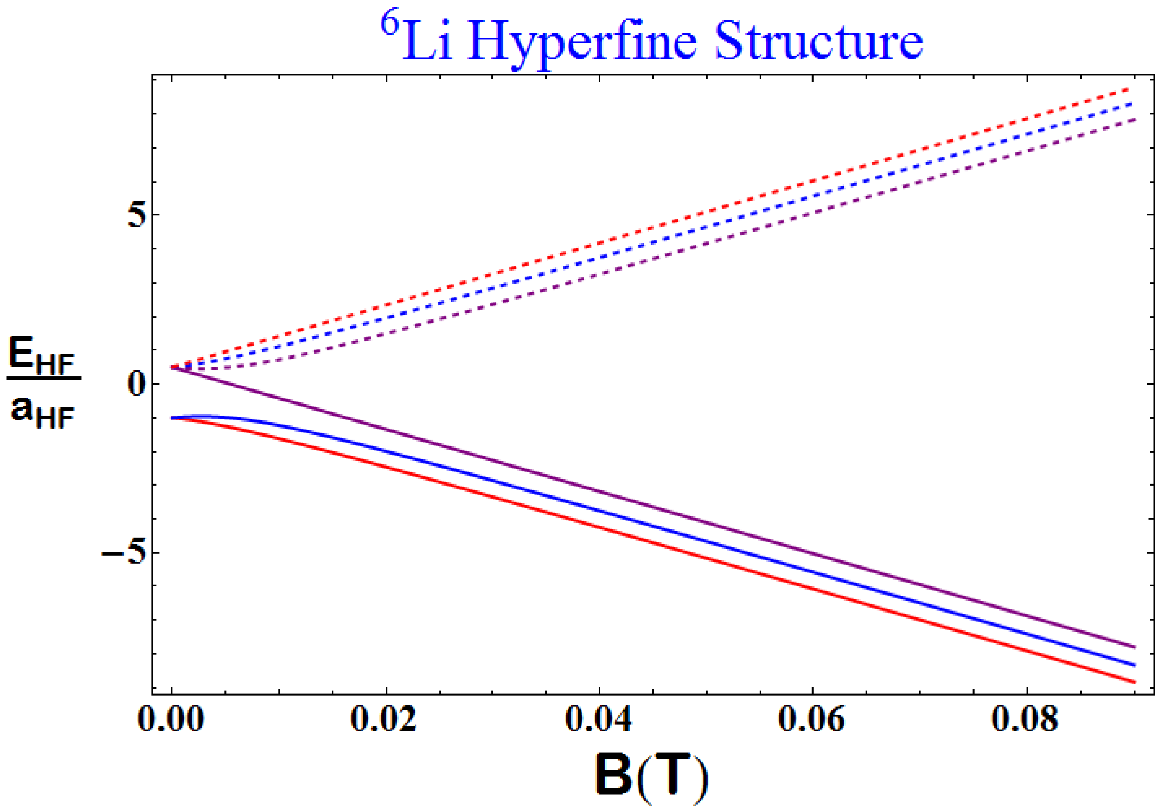
Hydrodynamics in
Boxes and Channels

Outline

- Hydrodynamics in a Unitary Fermi Gas
  - Local Shear Viscosity
  - Boxes and Channels
- Optical Control of Interactions
  - Scattering Length and Effective Range
  - Spatial Profile
- Conclusions

Fermionic Lithium ^{6}Li

^{6}Li One valance electron: $s = \frac{1}{2}$ Nuclear spin: $I = 1$



High Field Basis

$|s_z, I_z\rangle$

$|3\rangle \simeq |-1/2, -1\rangle$

$|2\rangle \simeq |-1/2, 0\rangle = \downarrow$

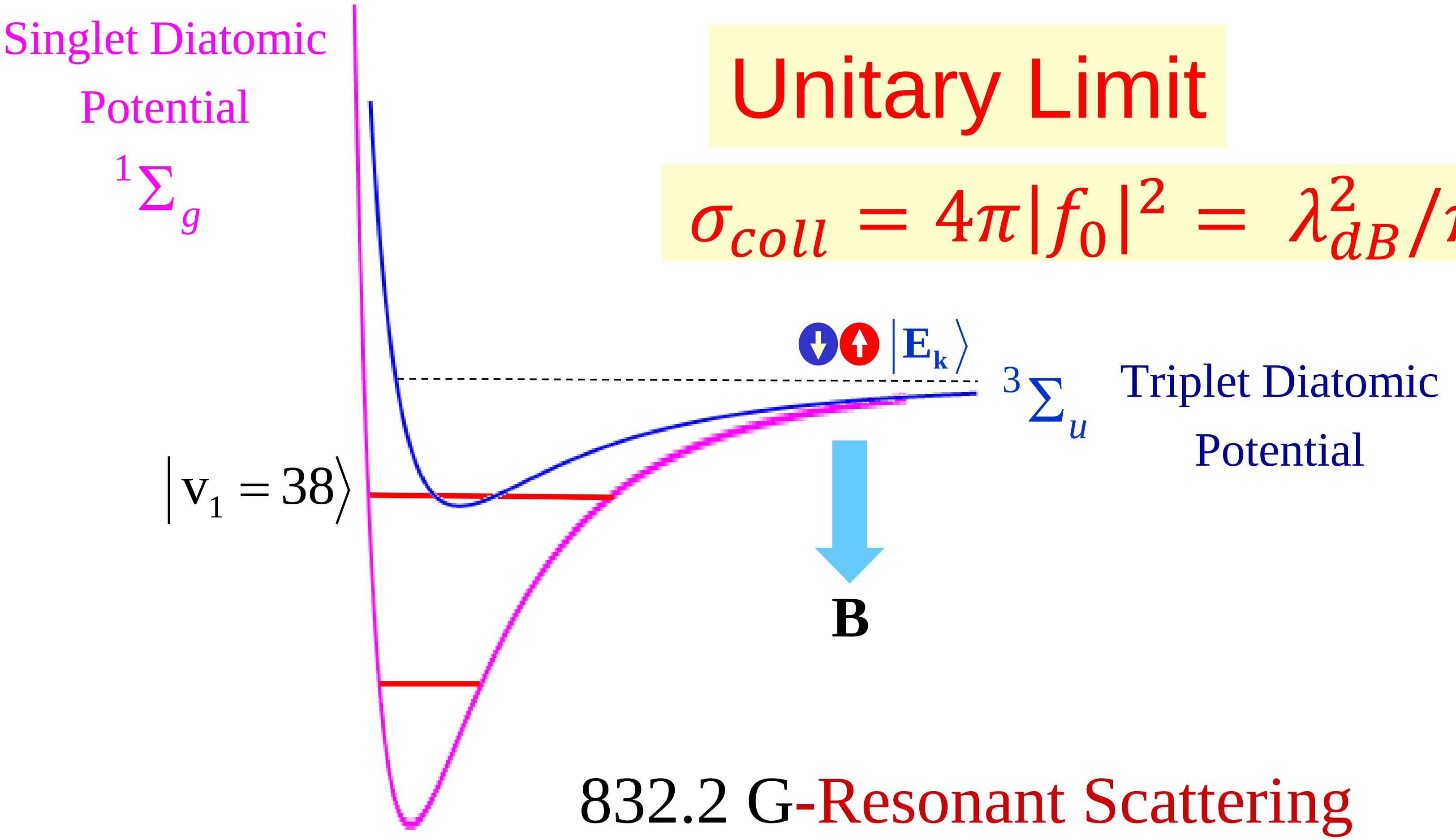
$|1\rangle \simeq |-1/2, 1\rangle = \uparrow$

Feshbach Resonance: Unitary Fermi Gas

Resonant Coupling between Colliding Atom Pair – Bound Molecular State

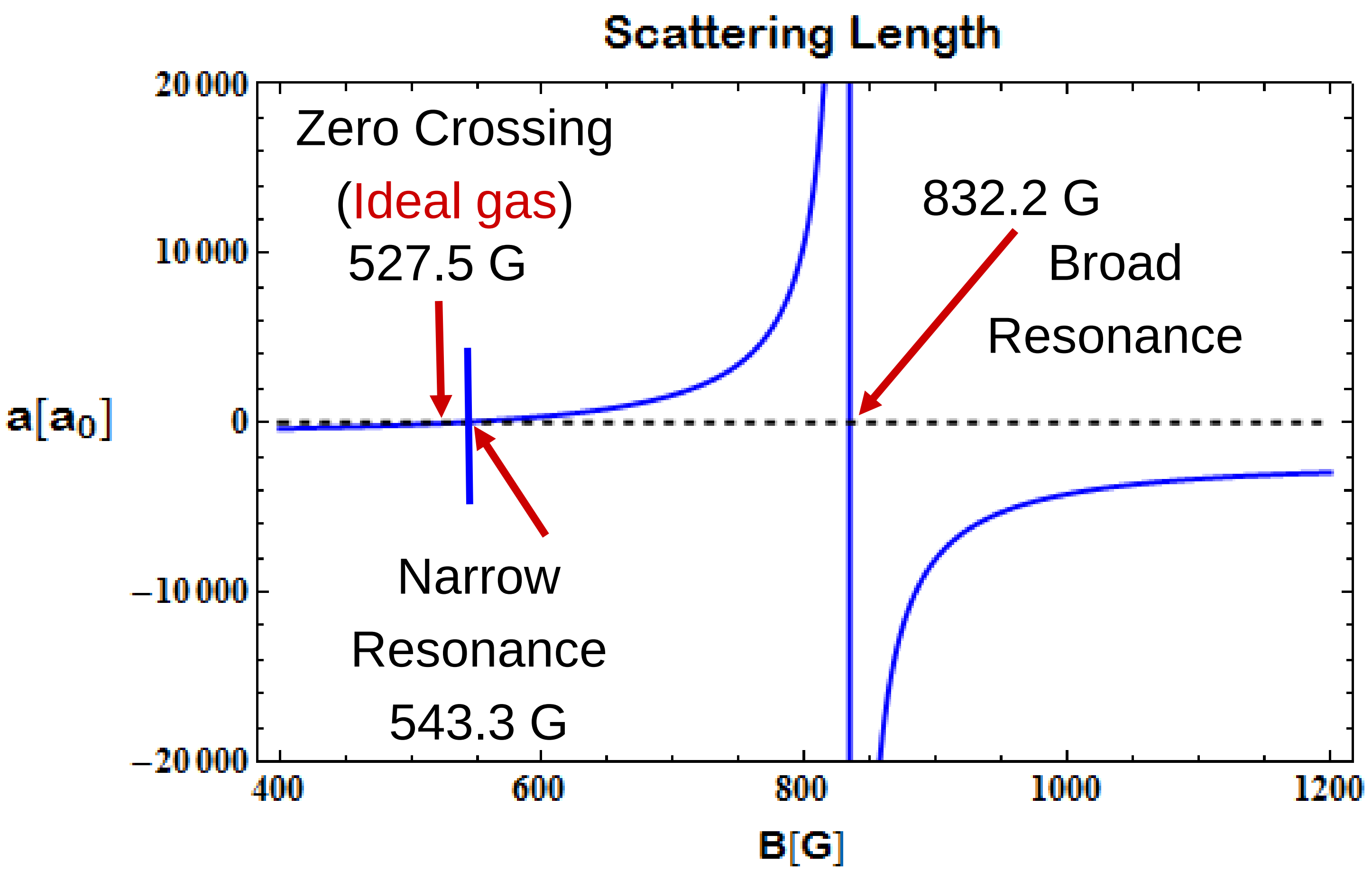
Unitary Limit

$$\sigma_{coll} = 4\pi|f_0|^2 = \lambda_{dB}^2/\pi$$

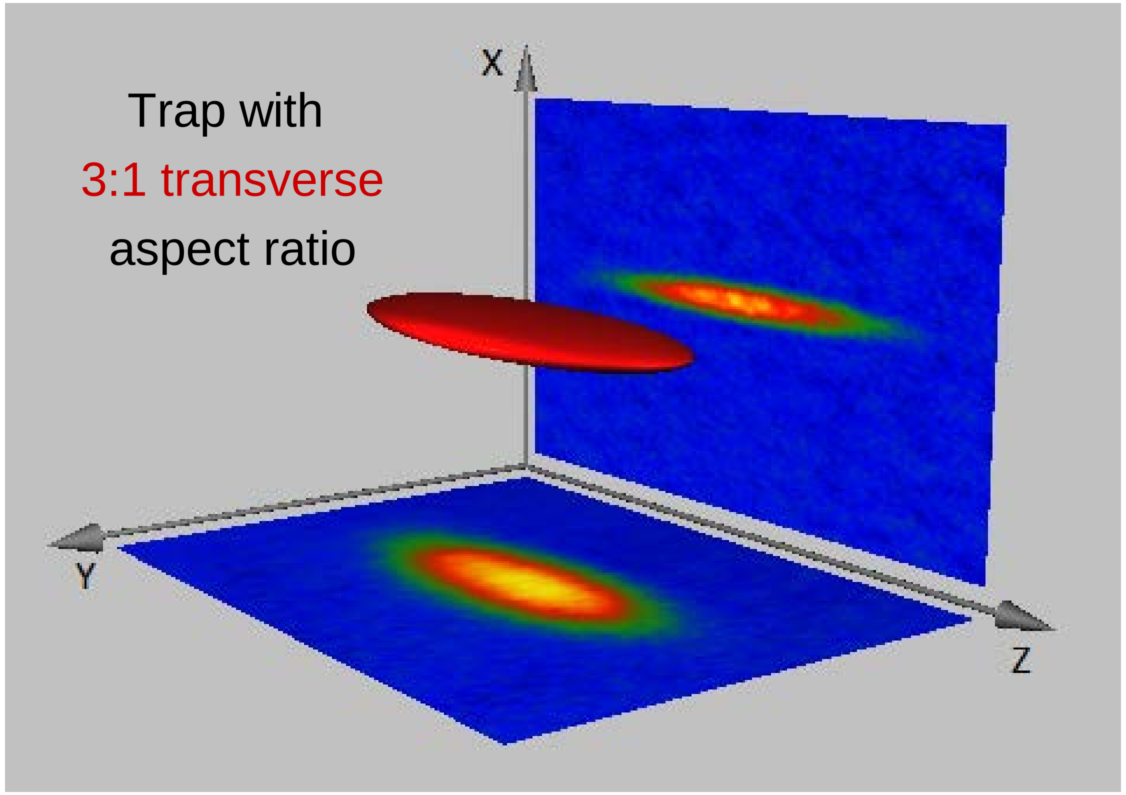


832.2 G-Resonant Scattering

Tunable Strong Interactions

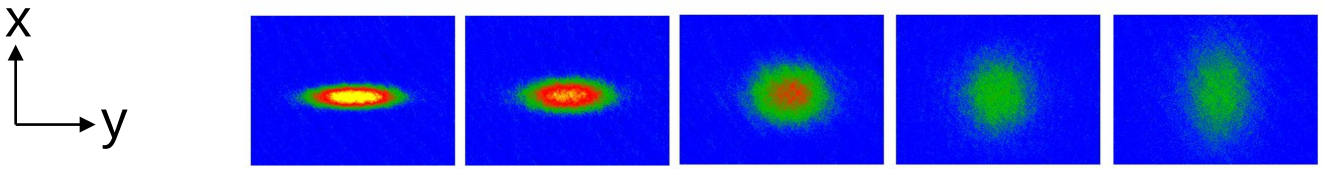


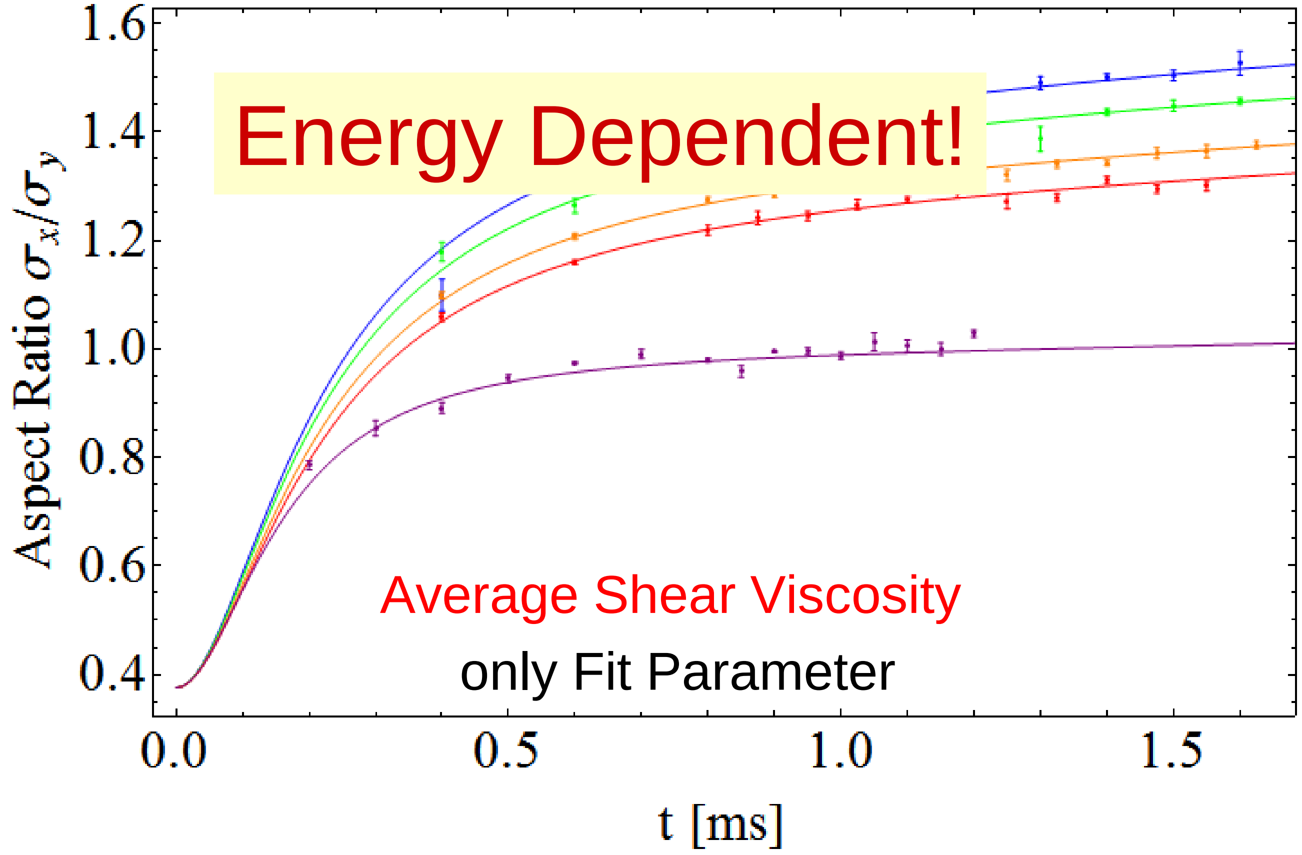
Hydrodynamics of the cloud in 3D



- Measure *all three* cloud radii using two cameras.

Aspect Ratio versus Expansion Time





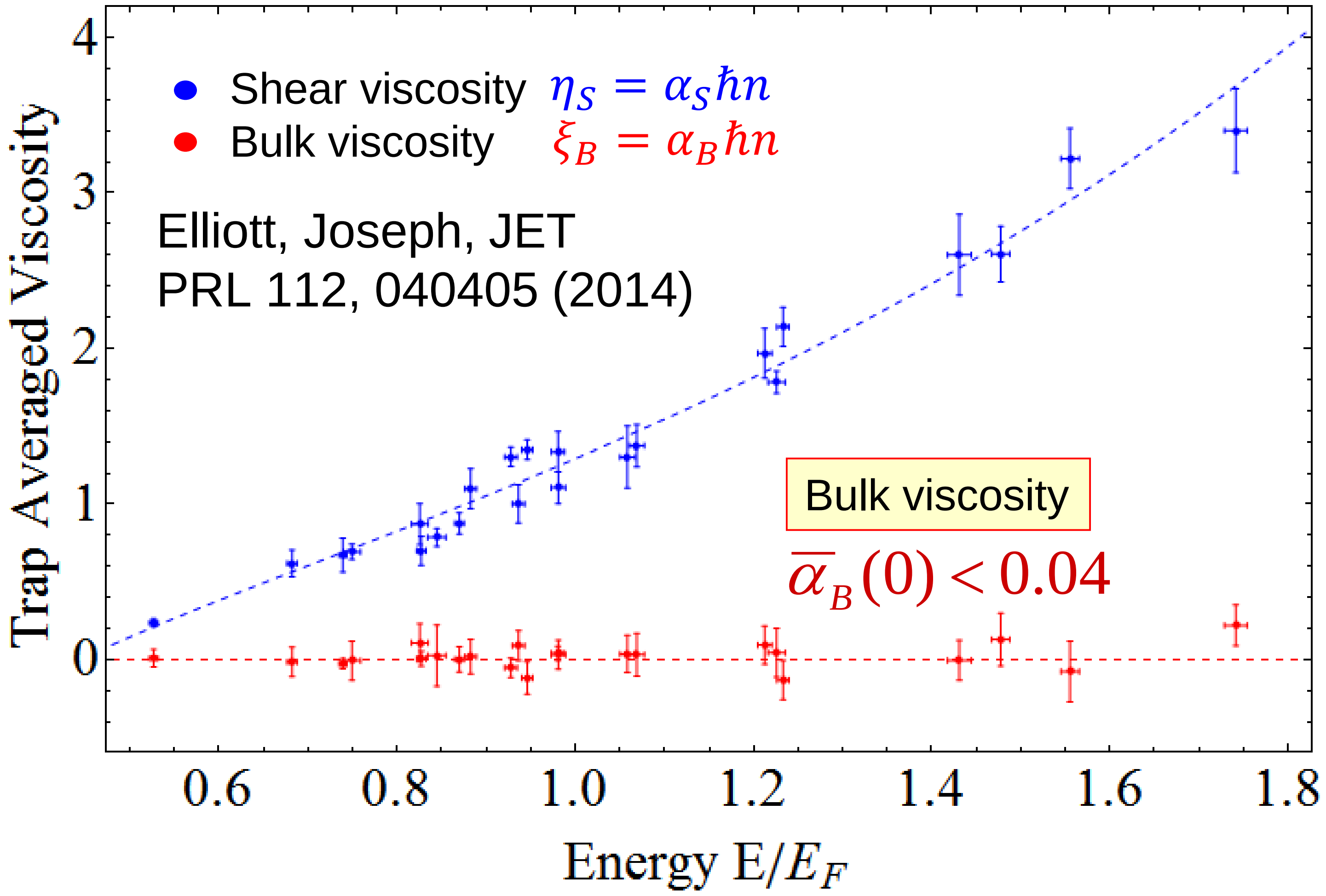
- $E/E_F=0.52$
- $E/E_F=0.75$
- $E/E_F=1.22$
- $E/E_F=1.69$

832 G

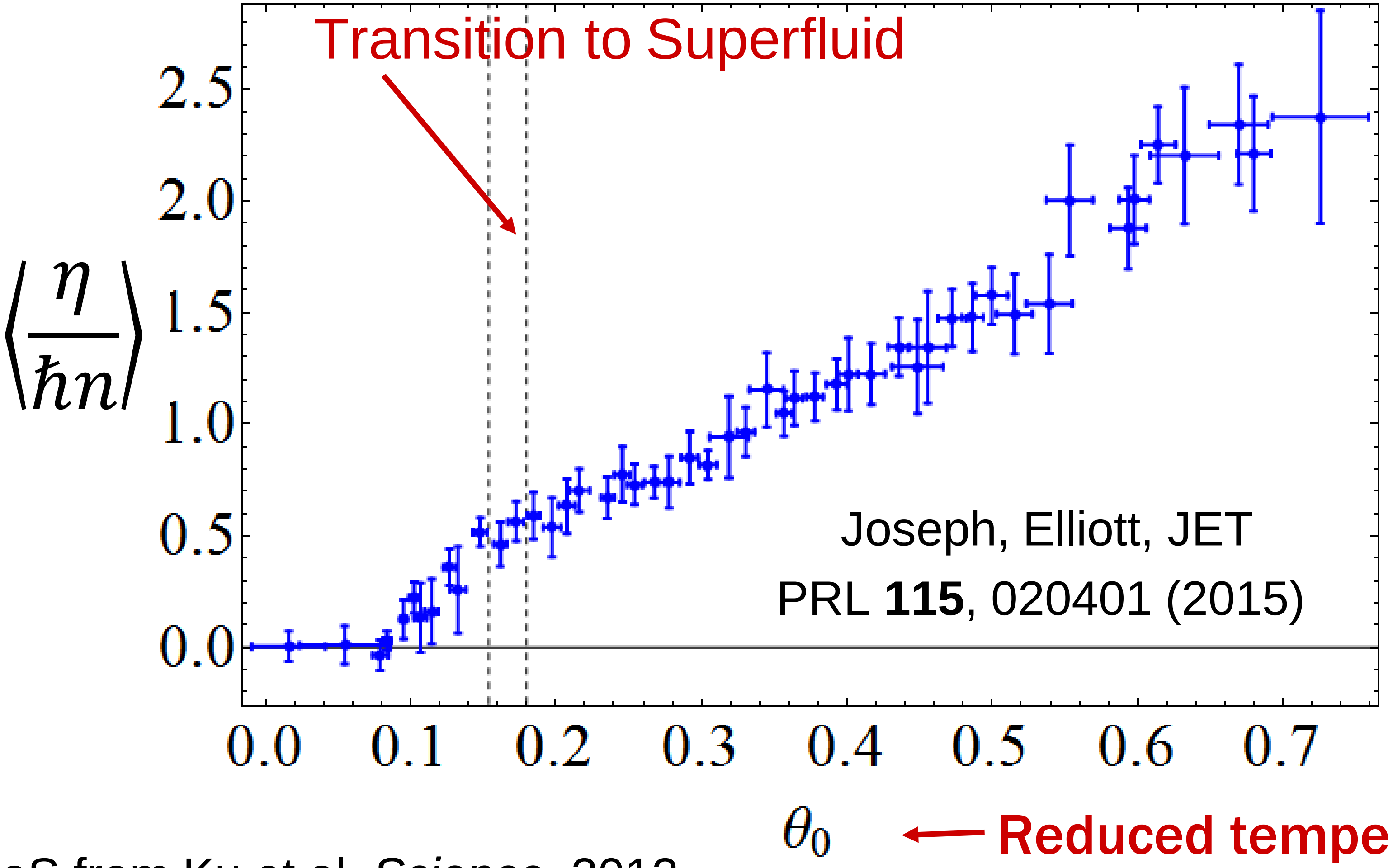
- *Ballistic* **527.5 G**

$$\frac{\sigma_x}{\sigma_y} = \frac{\omega_y}{\omega_x} \frac{b_x(t)}{b_y(t)}$$

Shear and Bulk Viscosity at Resonance



Cloud *Averaged* Shear Viscosity versus Temperature



$$\theta_0 \equiv \frac{T}{T_F(n_0)}$$

Reduced temperature at the trap center

*EoS from Ku et al., *Science*, 2012

Local Viscosity: Full 3D Hydro Fit

Bluhm, Hou, Schaefer: Expand shear viscosity in "diluteness"

$$\eta = \eta_0 \frac{(mk_B T)^{3/2}}{\hbar^2}[1 + \eta_2 (n\lambda_T^3) + \cdots]$$

Fit cloud expansion data with full 3D hydrodynamics

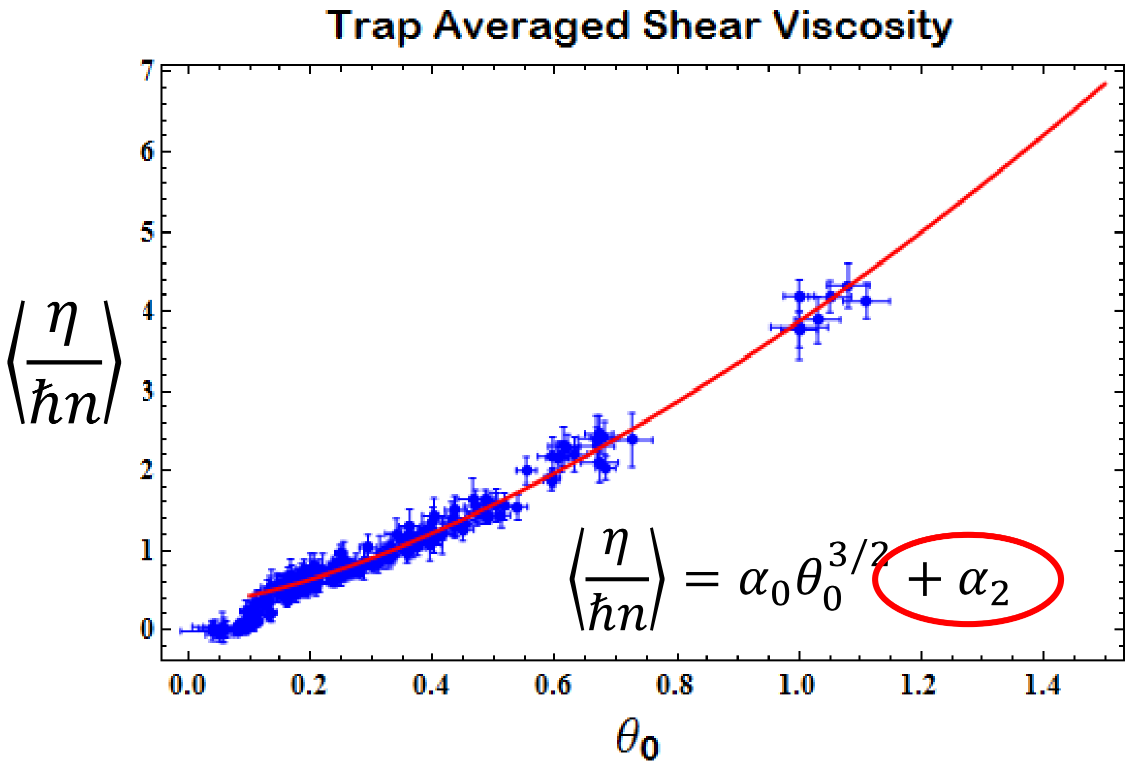
Second order hydrodynamics method extrapolates exactly to Boltzmann equation limit: hydro to ballistic region at the cloud edges.

Fit: $\eta_0 = 0.265(0.02)$ $\eta_2 = 0.065(0.02)$ $\eta_3 = -5 \times 10^{-4}$

Compare to variational Boltzmann result:
Bruun, Smith, PRA 75, 043612 (2007)

$$\eta_0 = \frac{15}{32\sqrt{\pi}} = 0.264$$

Cloud-Averaged Shear Viscosity: Comparison of Second Coefficient with 3D Hydrodynamics



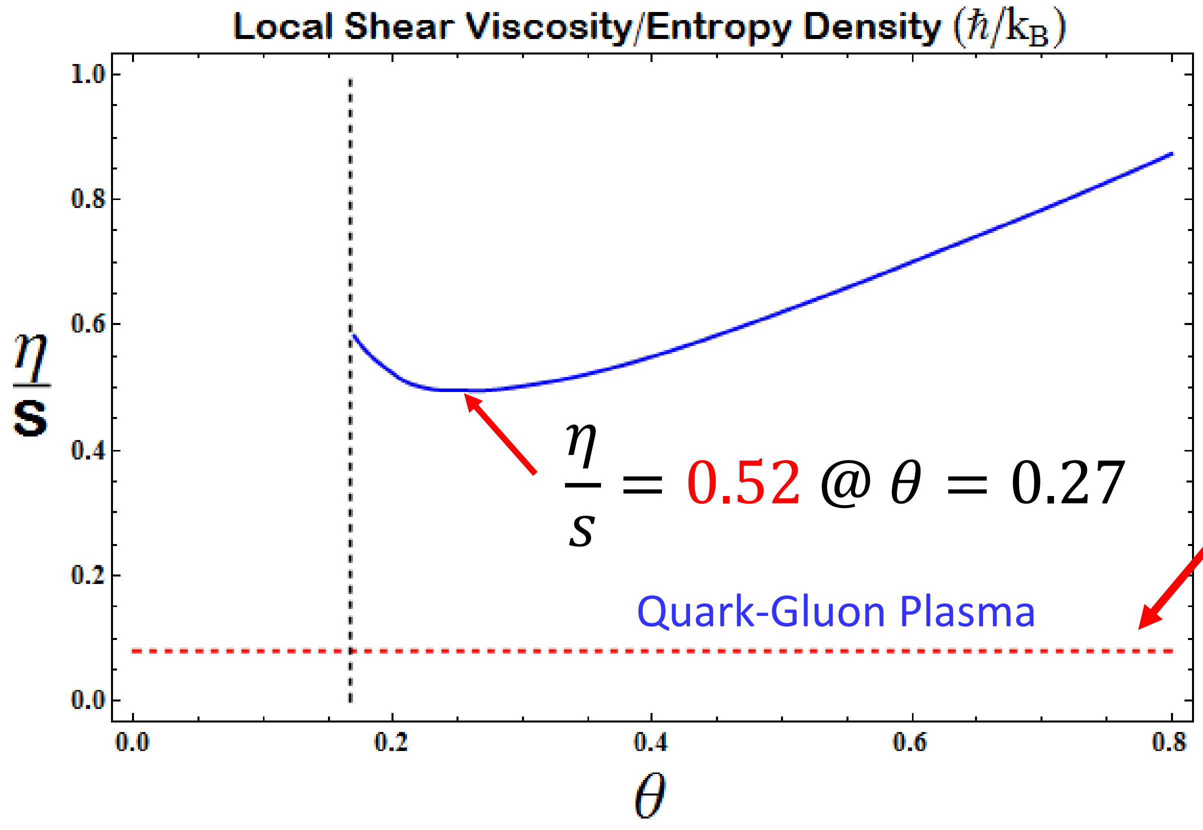
$\alpha_0 = 3.55(15)$

$\alpha_2 = 0.31(4)$

$\eta_0 = 0.265(0.02)$ *Uniform gas*: $\alpha_0 = \frac{3\pi^2}{\sqrt{8}} \eta_0 = 2.77$

$\eta_2 = 0.065(0.02)$ *Diluteness fit*: $\alpha_2 = (2\pi)^{3/2} \eta_0 \, \eta_2 = 0.27(8)$

Ratio: Local Shear Viscosity / Entropy Density*



$\frac{\text{Bluhm} - \text{Schaefer}}{\text{Ku} - \text{Zwierlein}}$

KSS Limit

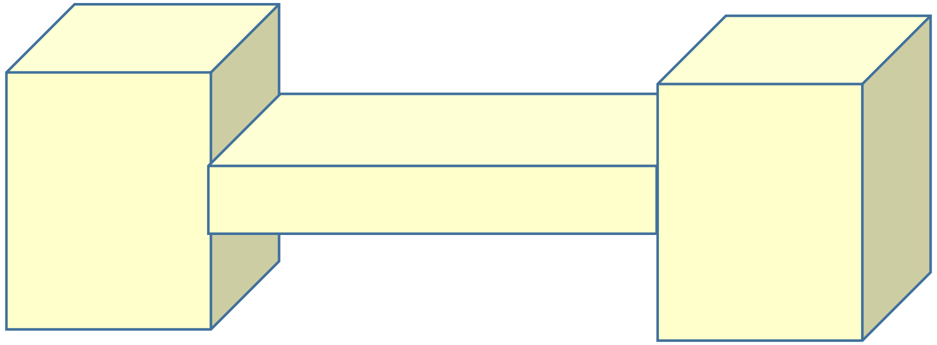
$\frac{1}{4\pi} \approx 0.08$

*EoS from Ku et al., *Science*, 2012

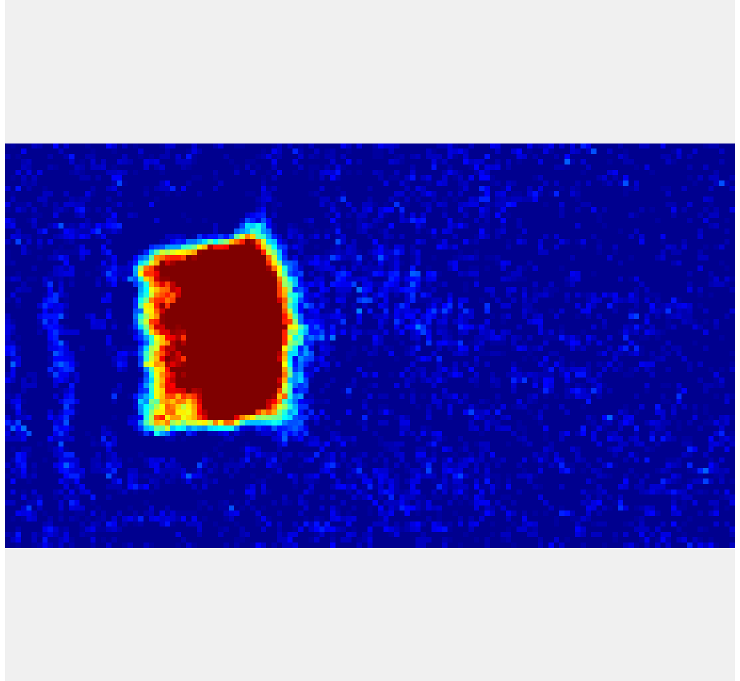
Hydrodynamics in Boxes and Channels

Dynamically controlled repulsive box potentials created by two micro-mirror arrays

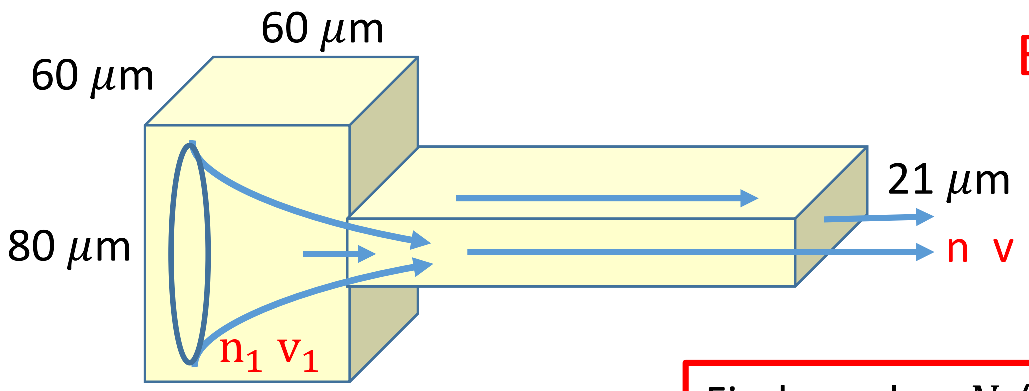
Energy and particle flow



$N_1(0) = N_{10}$ $N_2(0) = 0$



Hydrodynamics in Boxes and Channels



Reservoir volume
$V_1 = 60 \times 60 \times 80\ \mu\mathrm{m}^3$

Expansion into a vacuum

Exit area $A = 60 \times 21\ \mu\mathrm{m}^2$

Find number N_1(t) in reservoir
and compare to measurements

Exiting number per second

$$\dot{N} = n\, v\, A = n_1\, A\, \frac{n}{n_1} v$$

Assume adiabatic hydrodynamics:
Kinetic energy per unit mass
plus Enthalpy per unit mass
is conserved along streamlines.

$$\frac{v^2}{2} + \frac{h}{mn} = \frac{v_1^2}{2} + \frac{h_1}{mn_1}$$

Enthalpy density
for Unitary Fermi gas

$$h = p + \varepsilon = \frac{5}{3}\varepsilon = n\, \epsilon_F(n)\, f_E(\theta)$$

From local equation of state
Ku et al.,*Science*, 2012

$f_E(0) = \xi_{Bertsch}$ = 0.376

Hydrodynamic flow through a channel

For adiabatic hydrodynamics
$f_E(\theta) = constant$

$$\frac{h}{h_1} = \left(\frac{n}{n_1}\right)^{5/3}$$

For $v_1 \ll v$ $\quad v = \sqrt{\frac{2h_1}{mn_1}}\sqrt{1-\left(\frac{n}{n_1}\right)^{2/3}}$

Flow rate $\quad \dot{N} = A\sqrt{\frac{2n_1 h_1}{m}\left(\frac{n}{n_1}\right)^2\left[1-\left(\frac{n}{n_1}\right)^{2/3}\right]}$

$$\dot{N}_{max} = A\sqrt{\frac{h_1}{m}}\left(\frac{3}{4}\right)^2\sqrt{\frac{2}{3}}$$

Maximum flow rate
for $\frac{n}{n_1} = \left(\frac{3}{4}\right)^{3/2}$

Fixed reservoir volume V_1

$$n_1 h_1 = n_{10} h_{10}\left(\frac{n_1}{n_{10}}\right)^{8/3} = n_{10} h_{10}\left(\frac{N_1}{N_{10}}\right)^{8/3} = n_{10}^2\,\frac{m\,v_{F10}^2}{2}\,f_E(\theta_{10})\left(\frac{N_1}{N_{10}}\right)^{8/3}$$

$$\frac{d}{dt}\left(\frac{N_1}{N_{10}}\right) = -\,\Gamma\left(\frac{N_1}{N_{10}}\right)^{4/3}$$

$$\Gamma = \frac{3}{16}\frac{A\,v_{F10}}{V_1}\sqrt{3 f_E(\theta_{10})}$$

$$\frac{N_1(t)}{N_1(0)} = \frac{1}{\left(1+\frac{\Gamma}{3}t\right)^3}$$

Number N_1 in reservoir versus time

Hydrodynamic flow through a channel

$$\Gamma = \frac{3}{16}\frac{A\,v_{F10}}{V_1}\sqrt{3 f_E(\theta_{10})}$$

For one spin state: N_{10} = 18,000

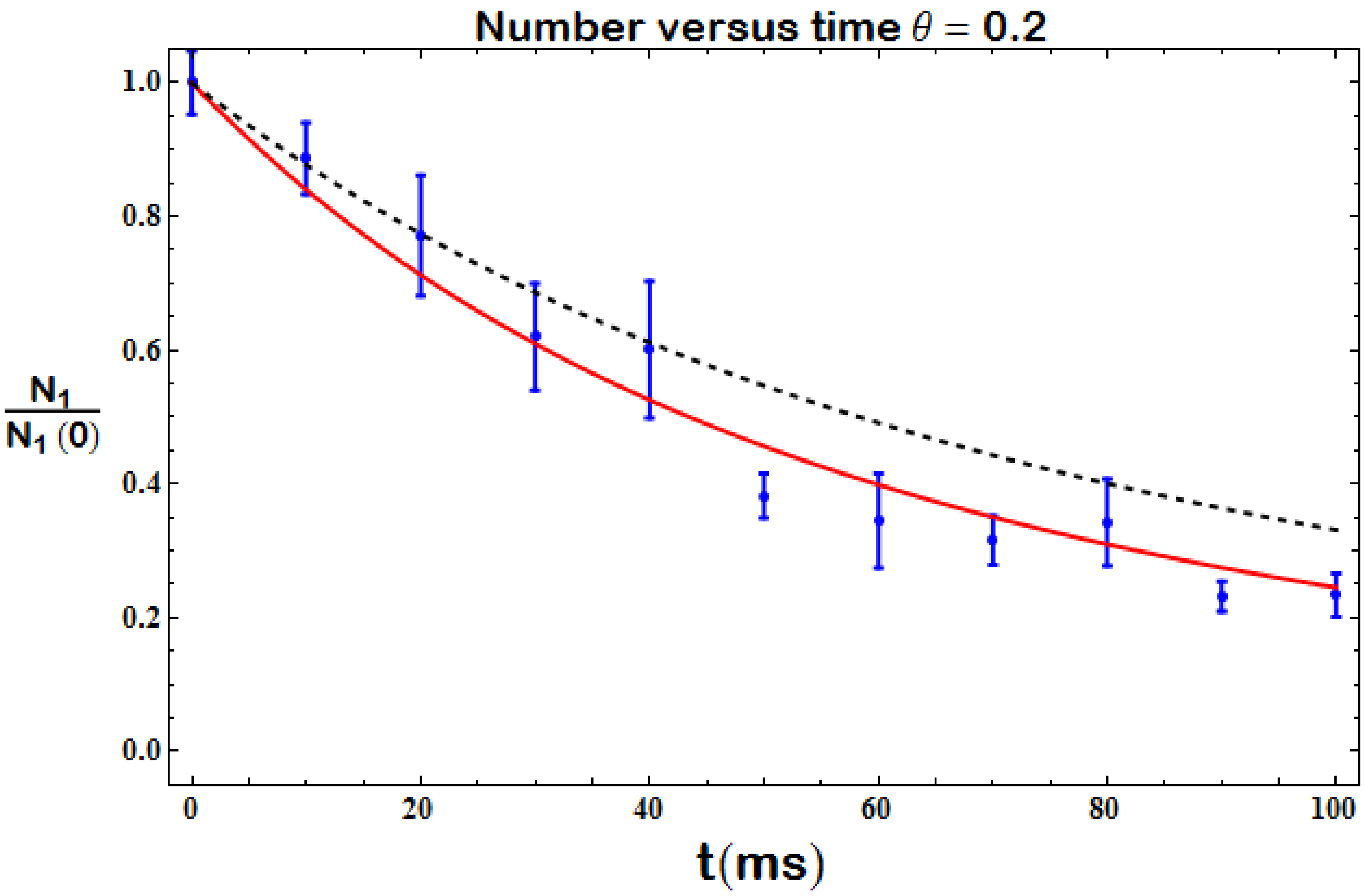
$n_{10} = \frac{N_{10}}{V_1} = 6.2 \times 10^{10}$ atoms/cm

$\epsilon_F = 0.1\mu K$; v_{F10} =1.63 cm/s

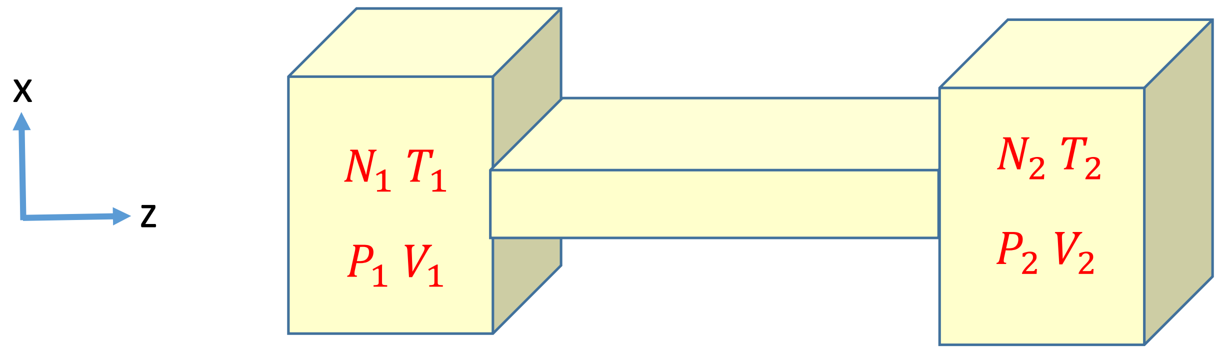
$$\frac{3}{16}\frac{A\,v_{F10}}{V_1} = \frac{1}{74.8\text{ ms}}$$

$$\frac{N_1(t)}{N_1(0)} = \frac{1}{\left(1+\frac{\Gamma}{3}t\right)^3}$$

$f_E(0.2) = 0.6$



Applications of Dynamically-Controlled Boxes and Channels



Flowing systems

Density profile n(x,z)

Stream velocity v(x,z)

Local transport properties

Perturbed initially static systems

Sound waves

Propagation of density perturbations

Shock waves

Two temperature systems

Thermal conductivity

Energy flow without particle flow: Balanced pressures

Density profiles in linear potential

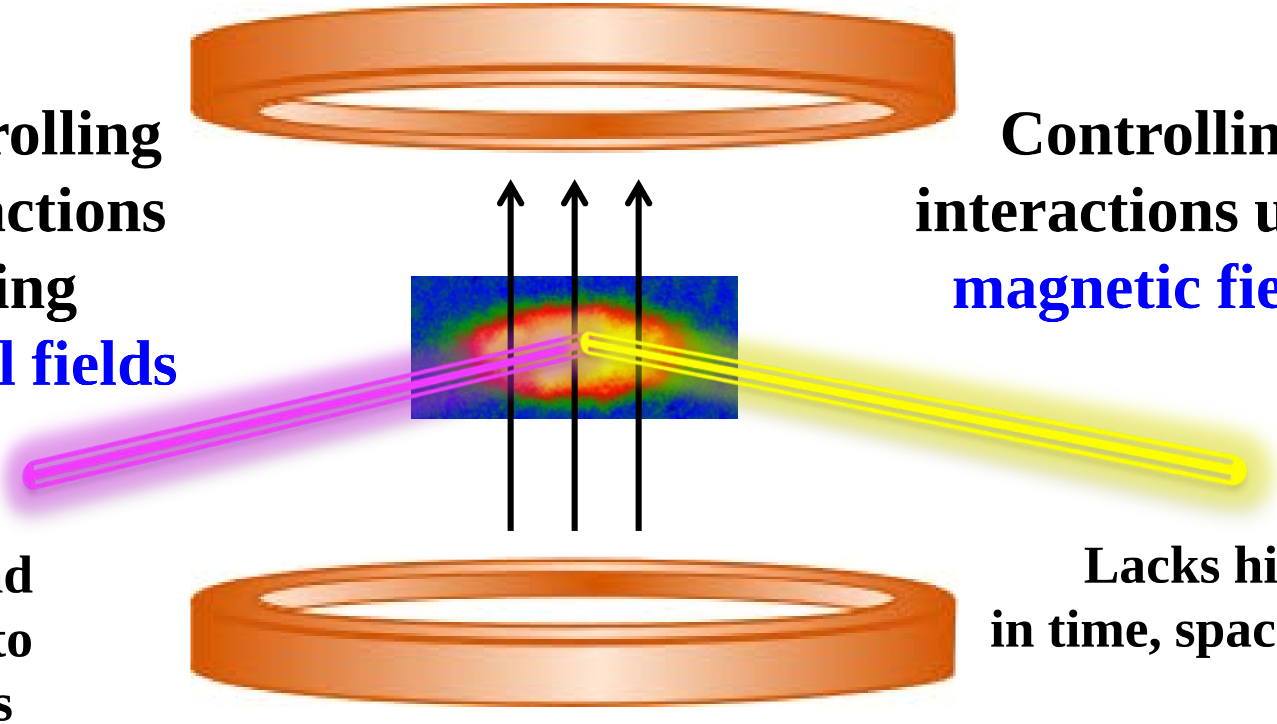
Thermodynamic photos of n(μ,T)

Optical Control of Interactions

Tunable interactions in ultracold gases

Controlling interactions using optical fields

Controlling interactions using magnetic fields



Atom loss and heating due to spontaneous scattering

Lacks high-resolution in time, space and momentum

Two-field optical method – loss suppression through destructive quantum interference

Better neutron matter models by optical control

Optical control of the scattering phase shift $\delta_0(k)$

$$k \cot \delta_0(k) = -\frac{1}{a} + \frac{k^2}{2} r_e$$

Independent control of the zero energy scattering length a and effective range r_e

Neutron Star Crust

a = - 18.5 fm

r_e = + 2.7 fm

$k_F \simeq 1 \text{ fm}^{-1}$

Schwenck, Pethick, PRL **95,** 160401 (2005)

Pressure: Fugacity expansion

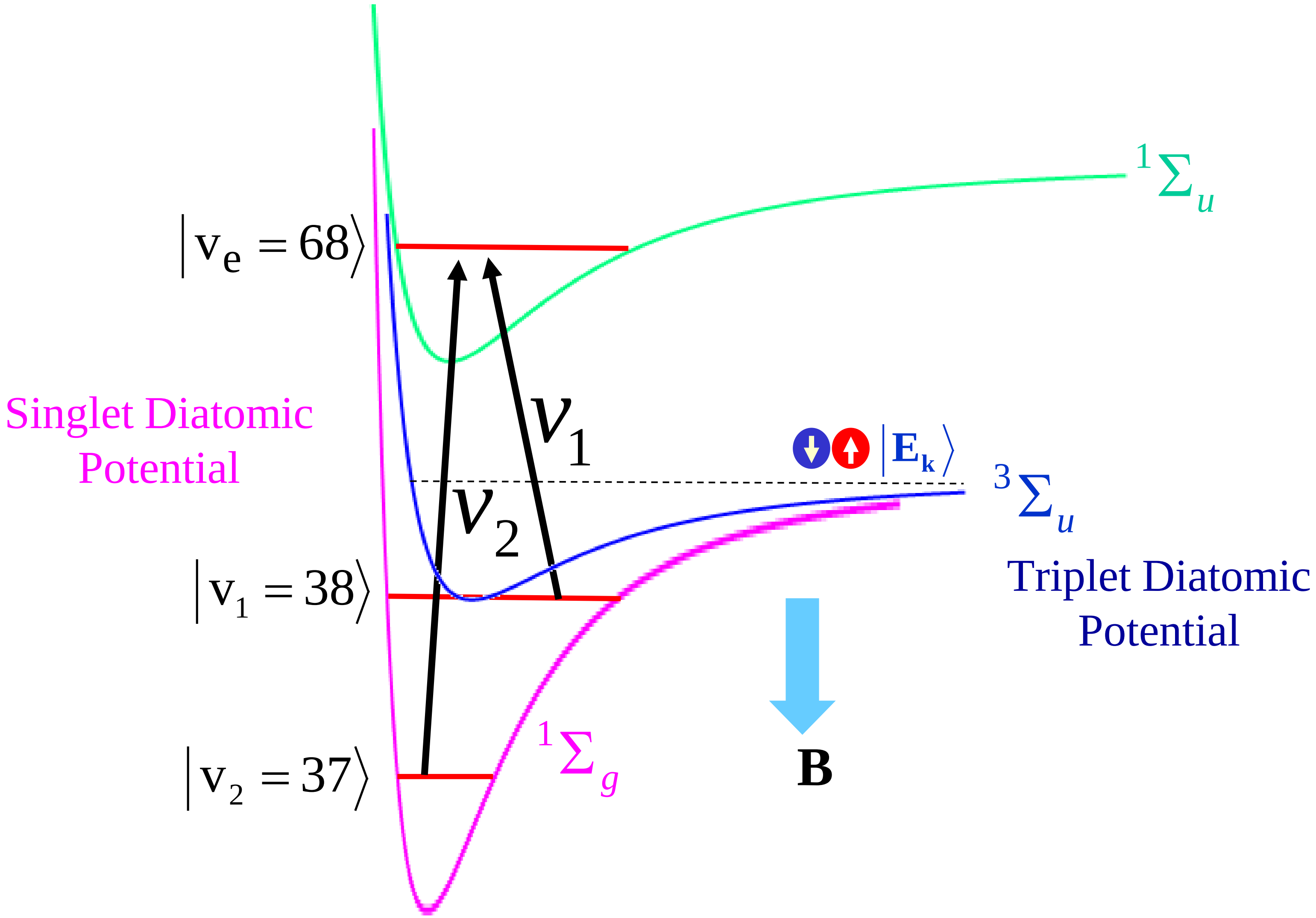
$$p = \frac{2k_BT}{\lambda_T^3}\left(z - 2^{-\frac{5}{2}} z^2 + \sqrt{2}\ b_2\ z^2\right)$$

$$b_2 = \sum_b e^{\frac{|E_b|}{k_BT}} + \int_0^\infty \frac{dk}{\pi}\frac{\partial \delta_0(k)}{\partial k} e^{-\frac{\hbar^2 k^2}{mk_BT}}$$

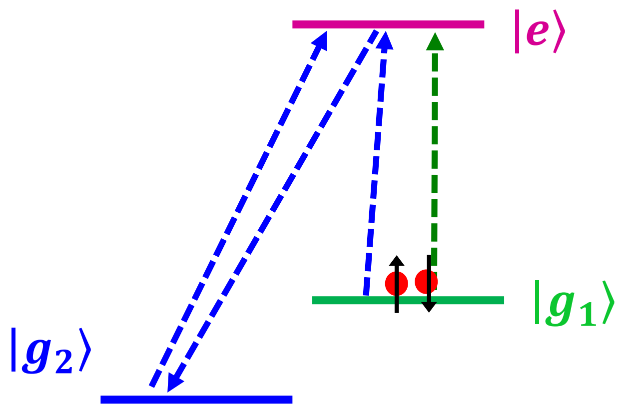
Optical control of the second virial coefficient b_2

Two-Field Optical Control of Magnetic Feshbach Resonances

Jagannathan, Arunkumar, Joseph, JET, Phys. Rev. Lett. 116, 075301 (2016)



Quantum interference – Simple picture

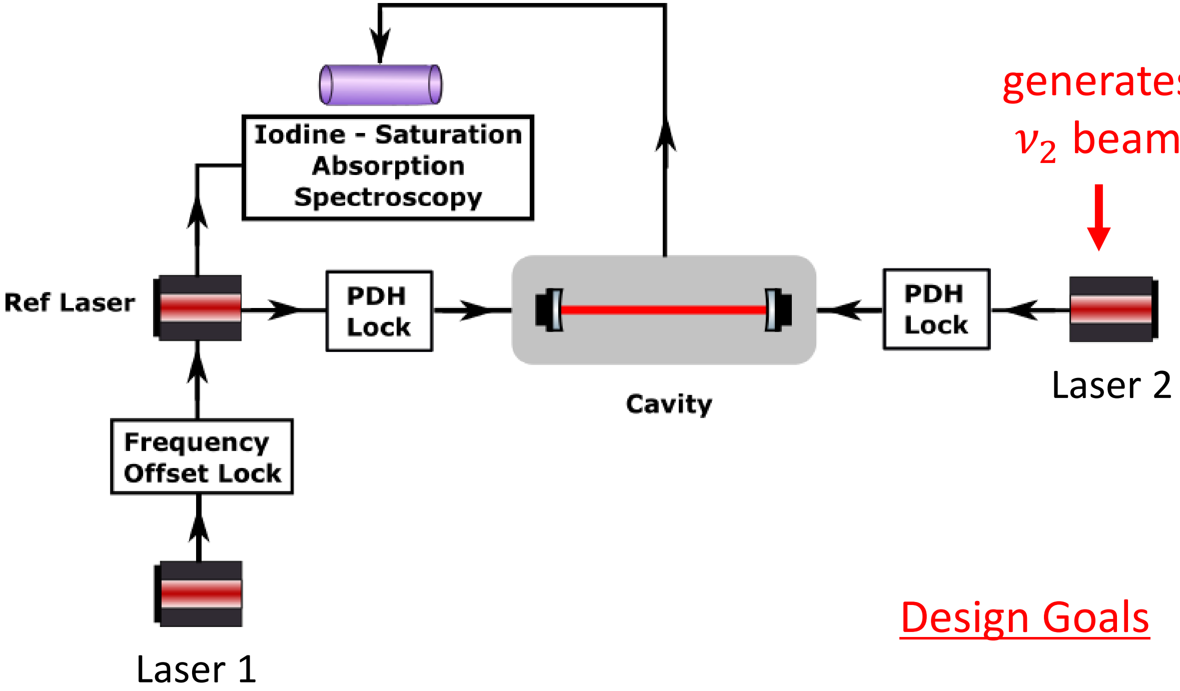


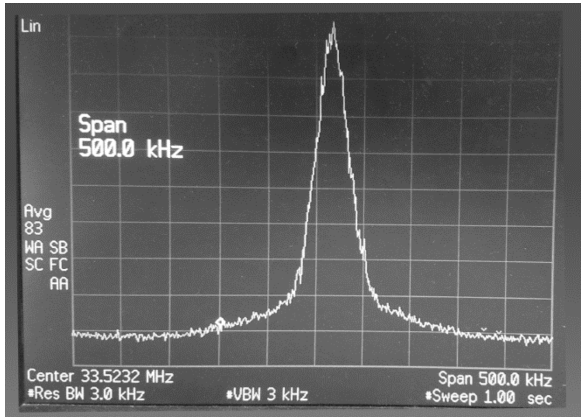
Path 1: $|g_1\rangle \rightarrow |e\rangle$

Path 2: $|g_1\rangle \rightarrow |e\rangle \rightarrow |g_2\rangle \rightarrow |e\rangle$

Optical System

generates ν_2 beam





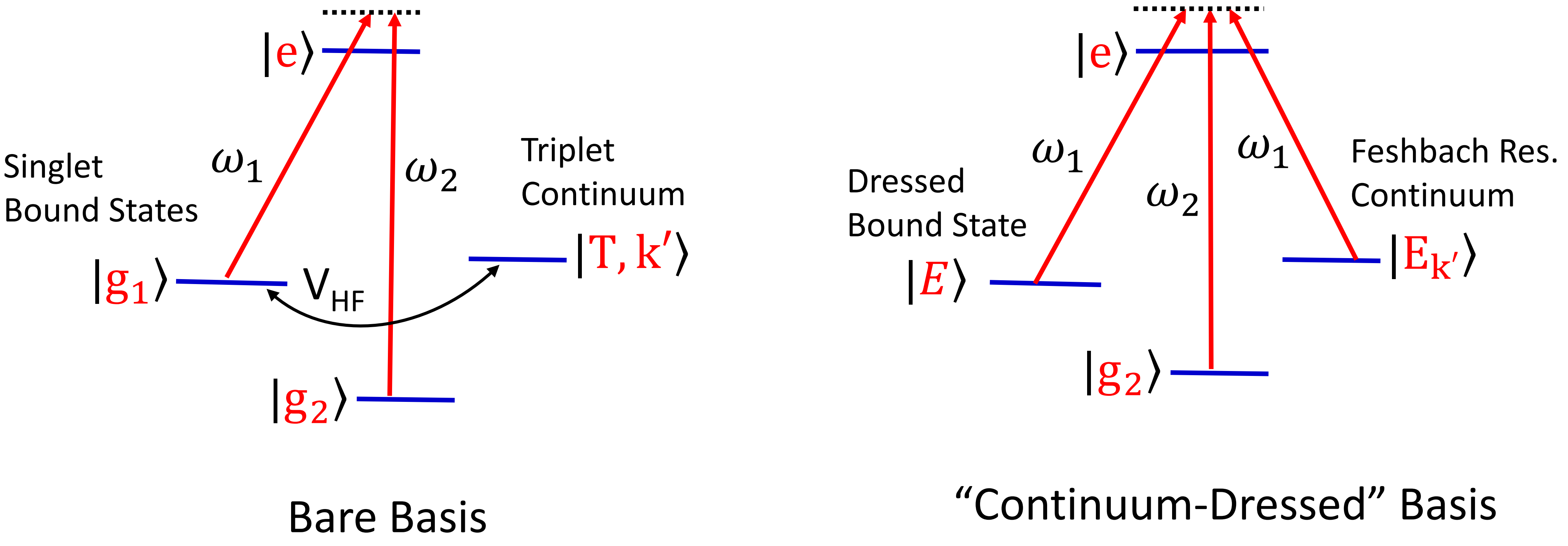
generates ν_1 beam

Tuning range $\sim$ 1 GHz

Design Goals

- Large frequency offset between ν_1 and ν_2 beams. ✓
- Wide frequency tunability of ν_1 beam. ✓
- Good frequency stability between ν_1 and ν_2 beams. ✓

Two-Field Optical Control Model



Determine $k \cot \delta_0(\omega_1, \Omega_1, \omega_2, \Omega_2, k)$

Physics: 1) Two-field optical dressed states

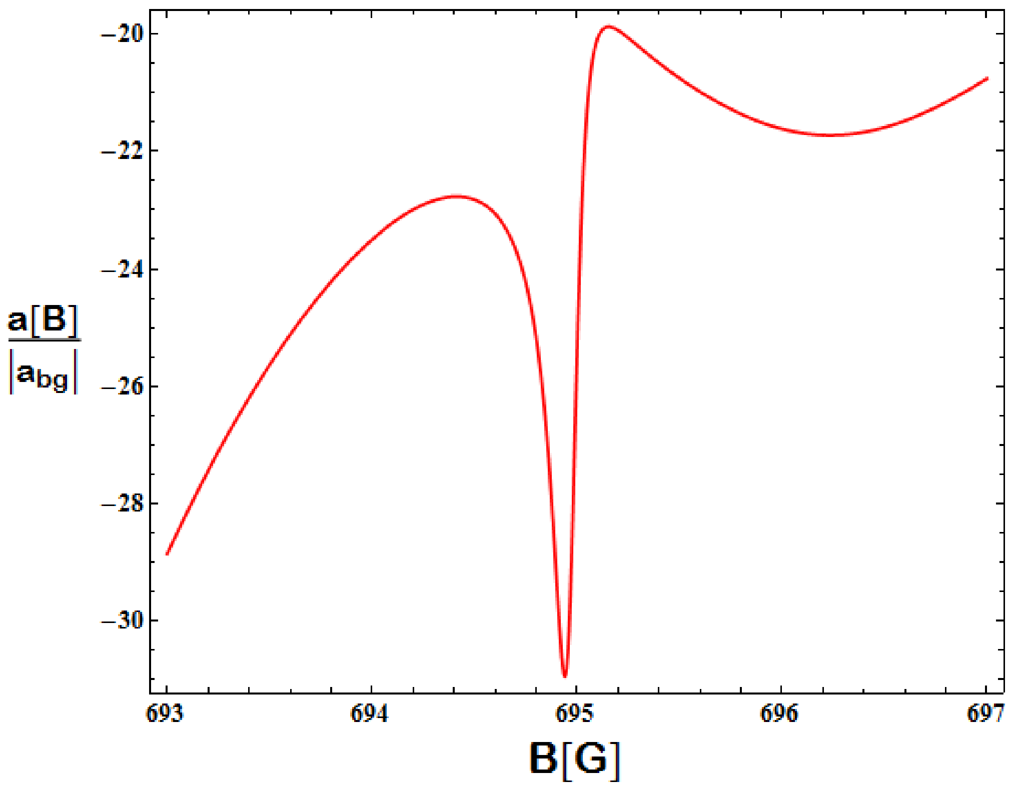
2) Anomalous optical shifts arising from the k-continuum

Optical Control of the 1-3 Broad Resonance

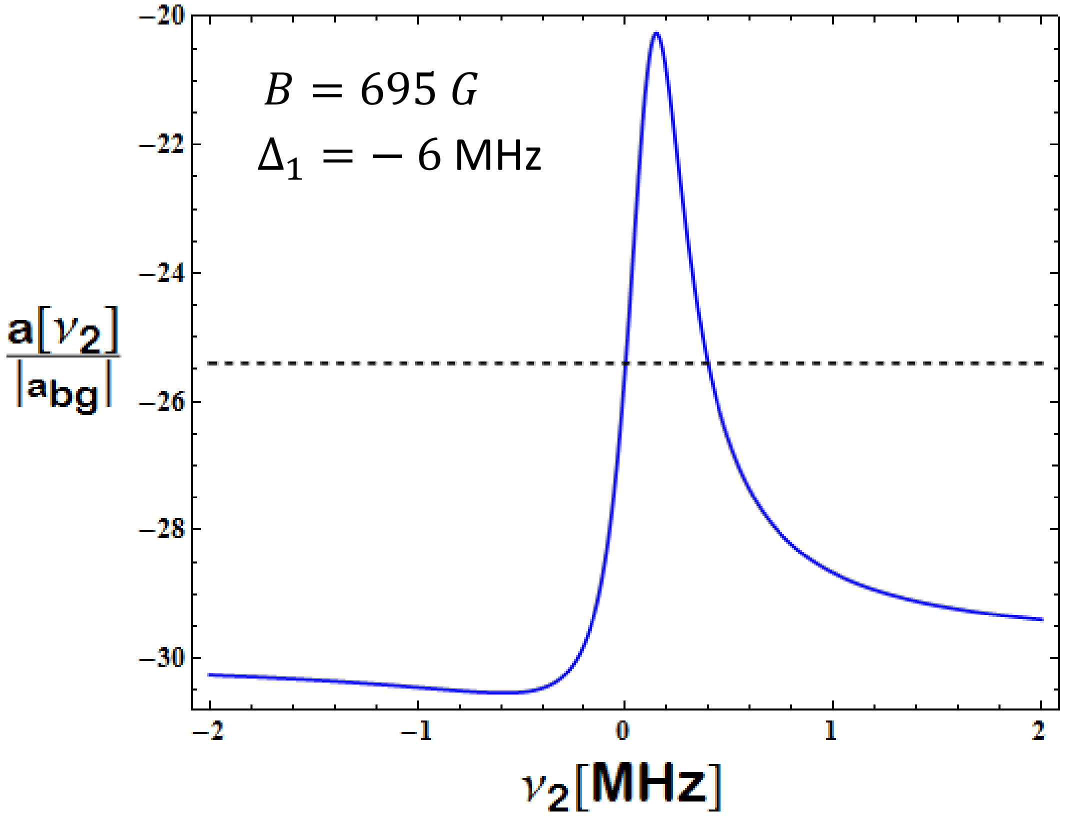
$B_{13\infty} = 690\ G$ $\Delta B_{13} = 122\ G$

$\Omega_1 = 1\,\gamma_e$ $\Omega_2 = 0.2\,\gamma_e$ $\gamma_e = 2\pi \times 11.8$ MHz

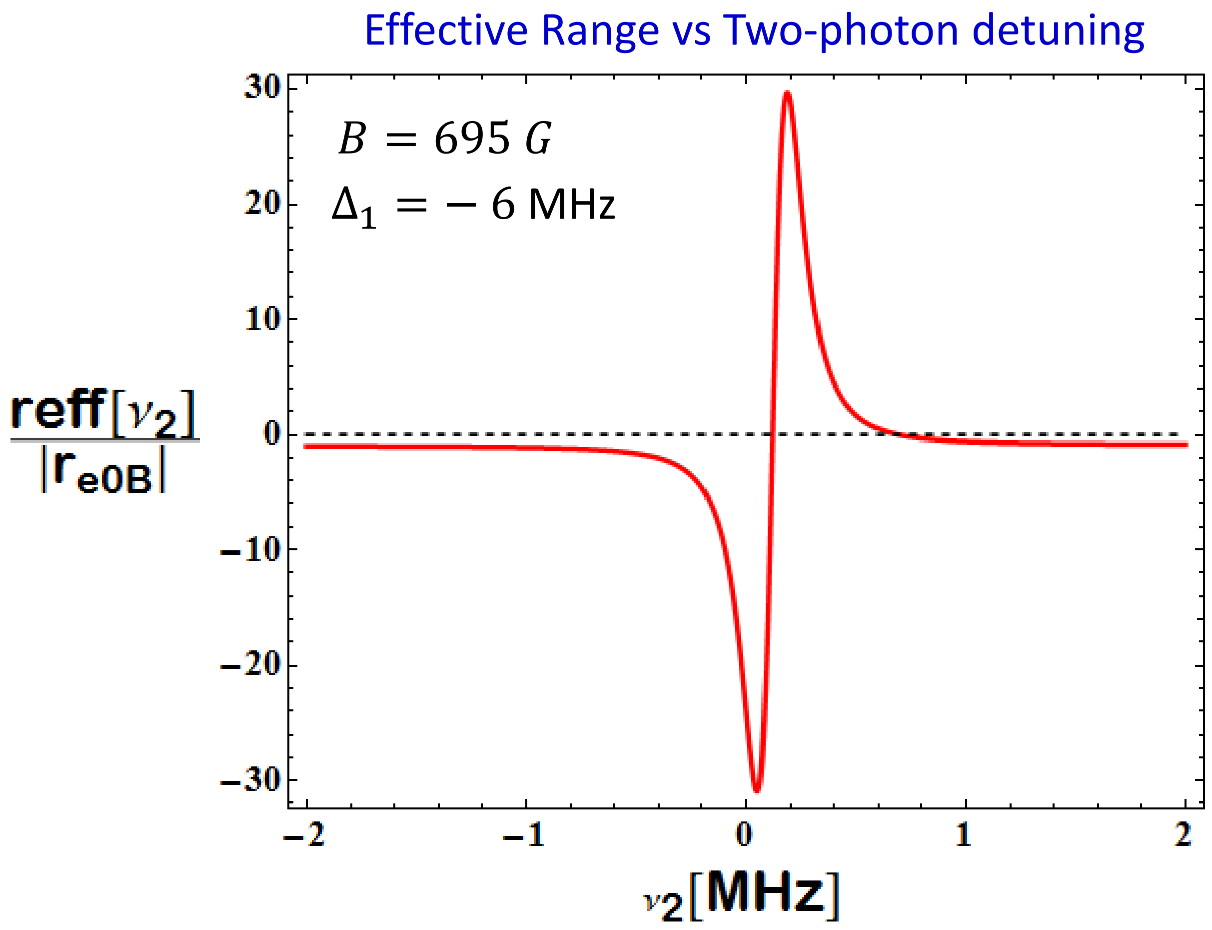
Scattering Length vs B-Field

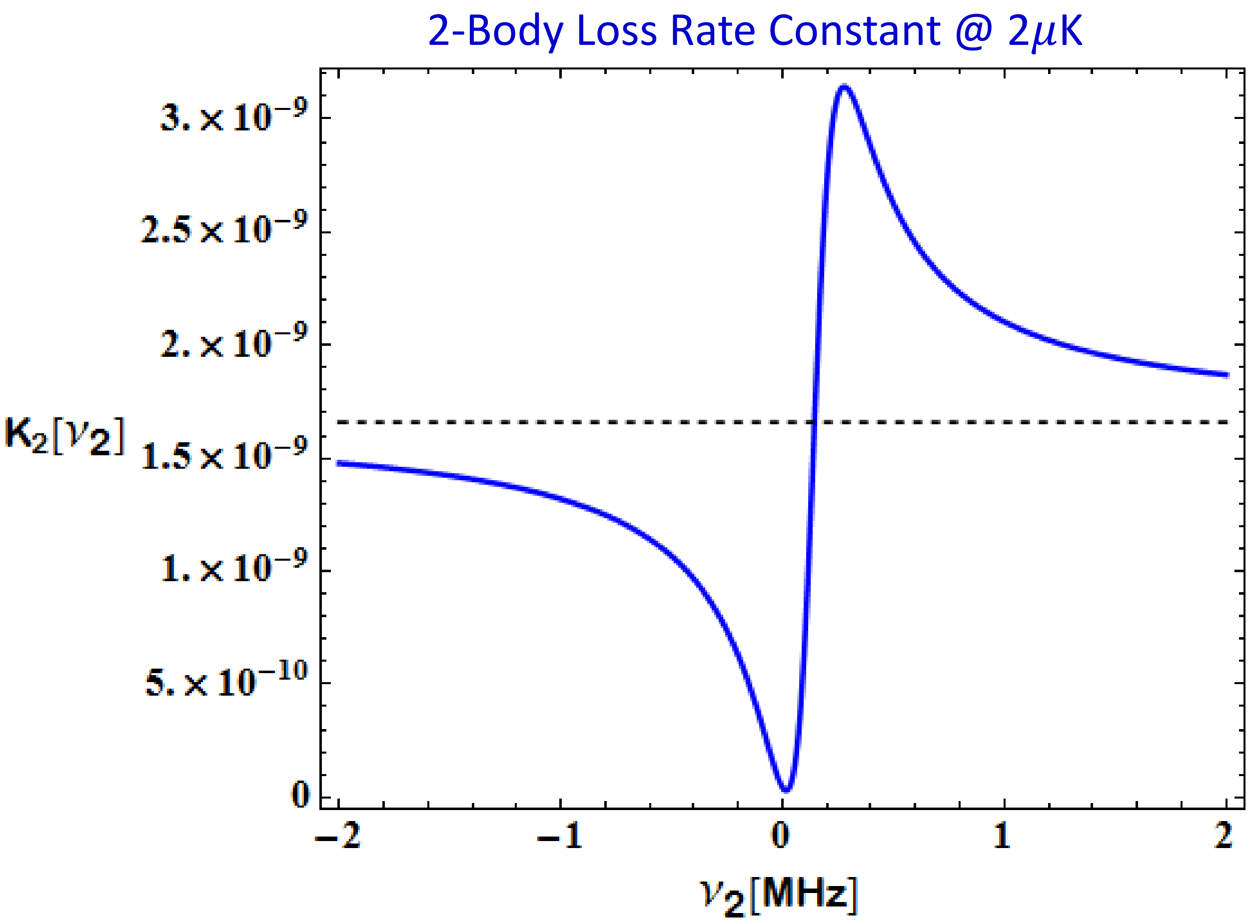


Scattering Length vs Two-photon detuning

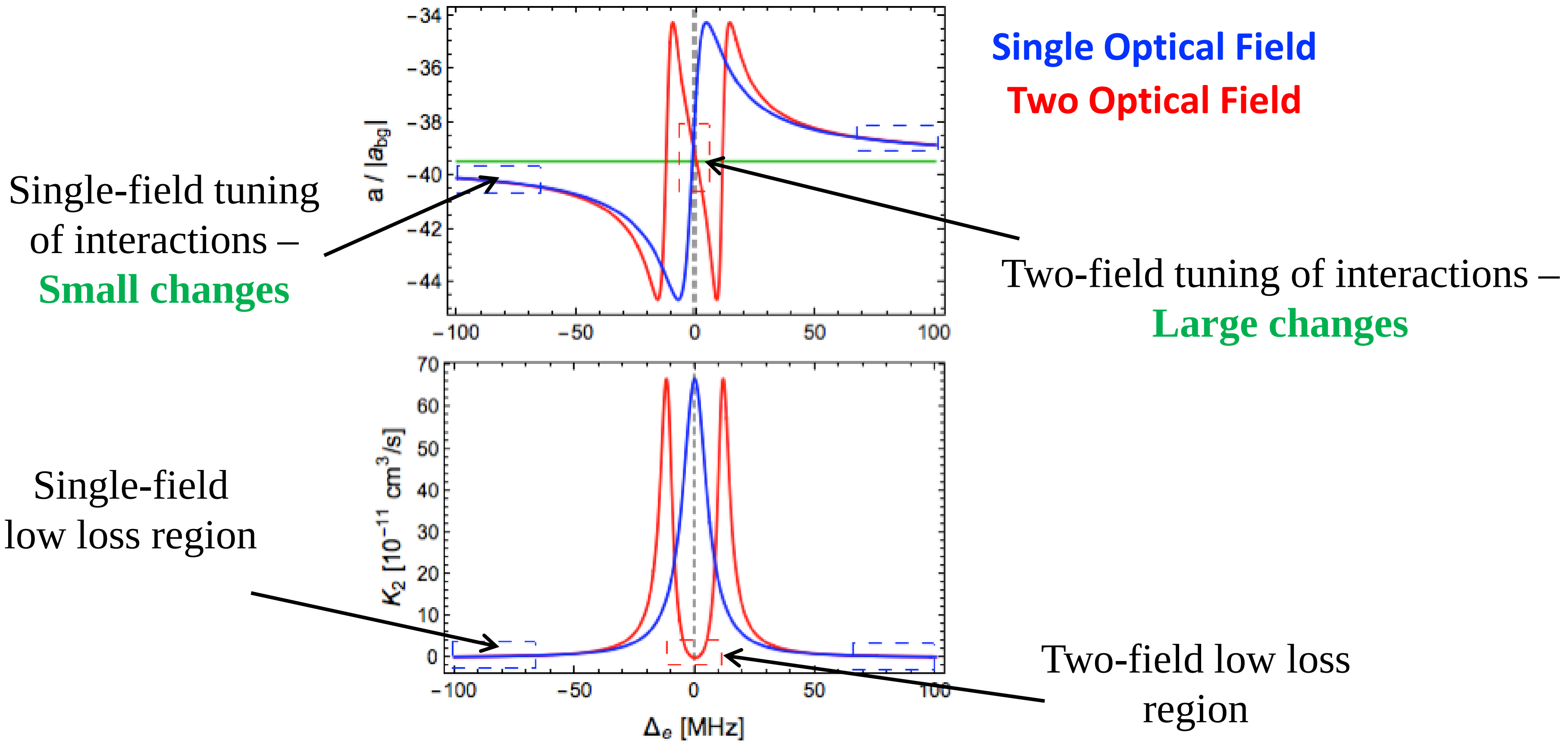


Controlling the Effective Range



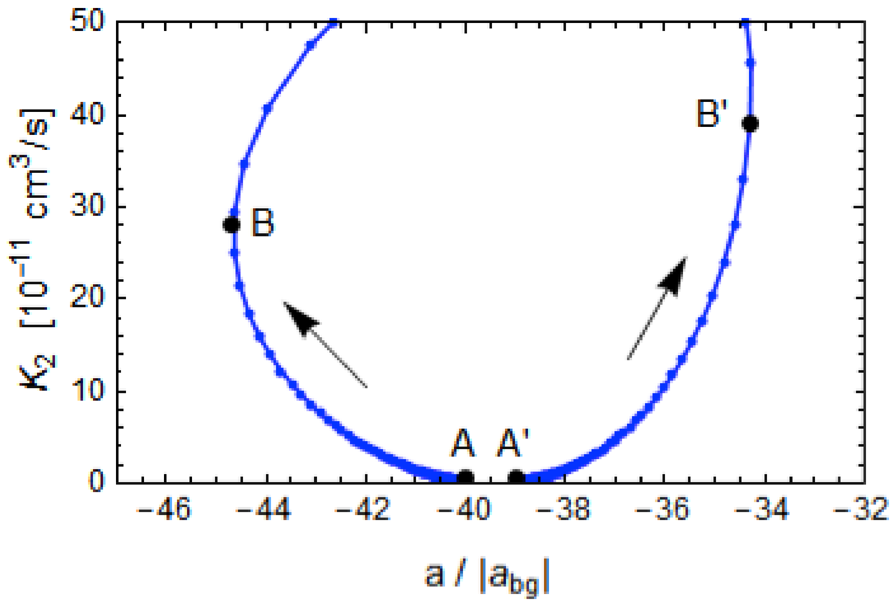


Advantages of Two-Field Optical Method



K_2 vs a for Single and Two-Field Methods

Single-field K_2 vs a



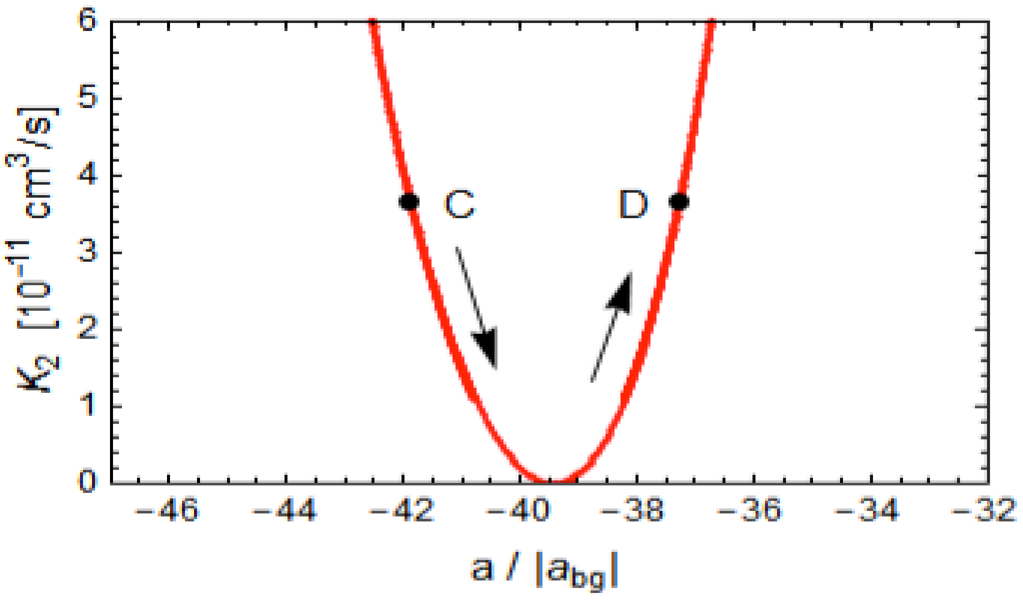
$\Delta a = 5\ a_{bg}$

$A \rightarrow B$: $\Delta_e = -100$ MHz to $-$ 7.5 MHz

or $A' \rightarrow B'$: $\Delta_e = +100$ MHz to $+$ 7.5 MHz

B: $K_2 = 27 \times 10^{-11}\text{cm}^3/s$

Two-field K_2 vs a



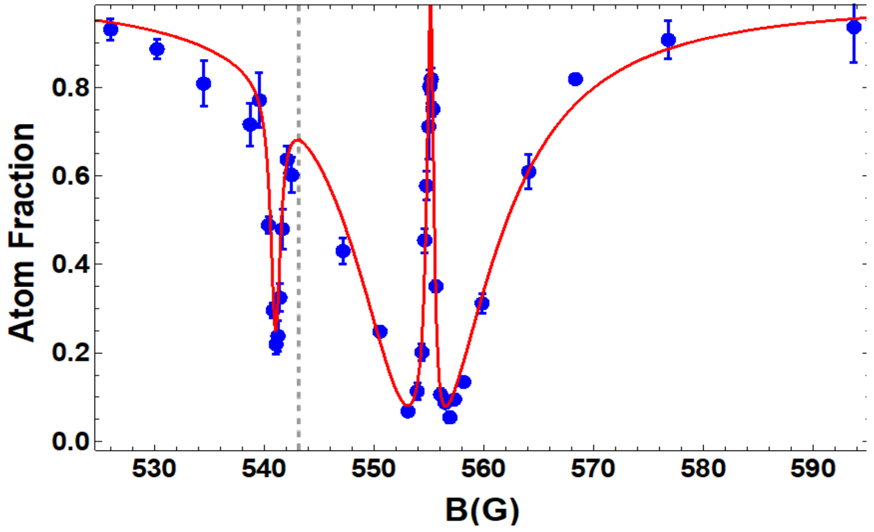
$C \rightarrow D$: $\Delta_e = -4.6$ MHz to 4.6 MHz

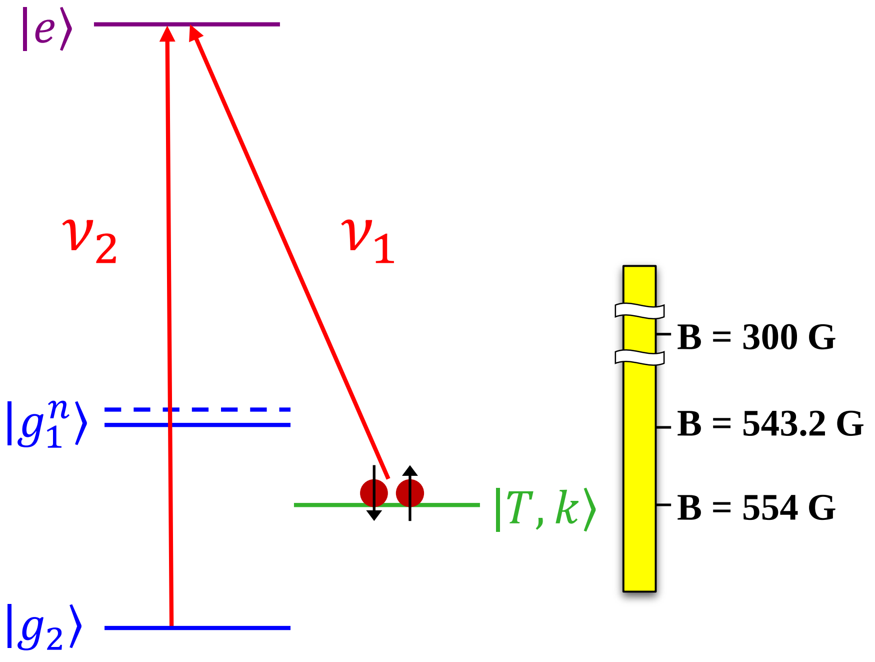
C, D: $K_2 = 3.6 \times 10^{-11}\text{cm}^3/s$

K_2 is less by a factor of 7 and requires a much smaller frequency change for the same Δa

Experiment 1 : Optical Control of Magnetic Feshbach Resonances

Loss Suppression at the 1-2 Broad Peak – Two Optical Fields



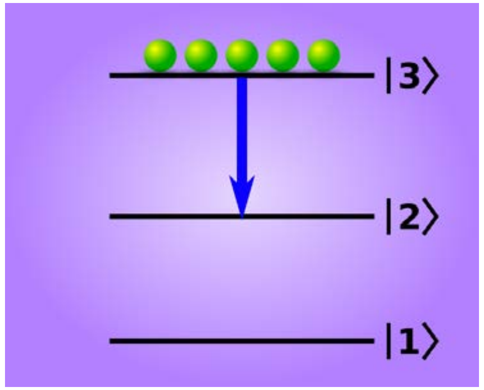


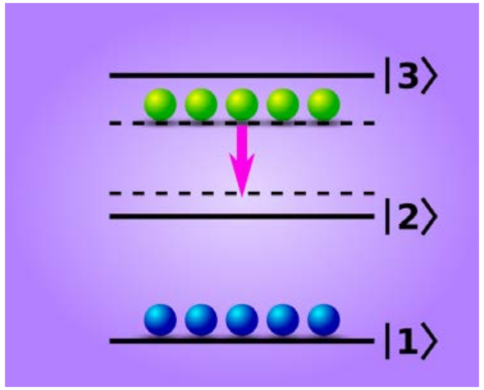
$0.5\, ms \rightarrow 0.5\, sec$

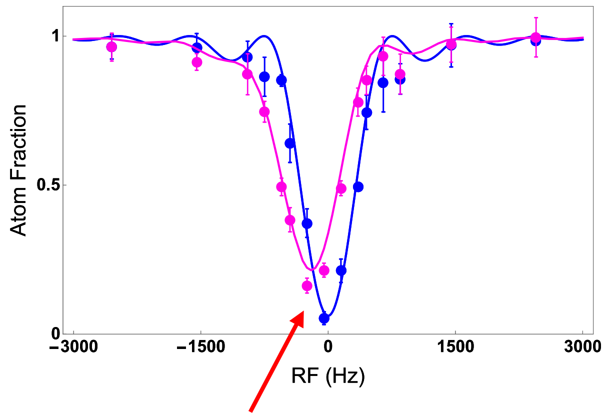
Experiment 2 : Optical Control of Two-Body Scattering Length a_{12}

Narrow 12 Resonance in ^{6}Li

Mean-Field Shift: RF Spectroscopy







Shift ∝ Density of atoms

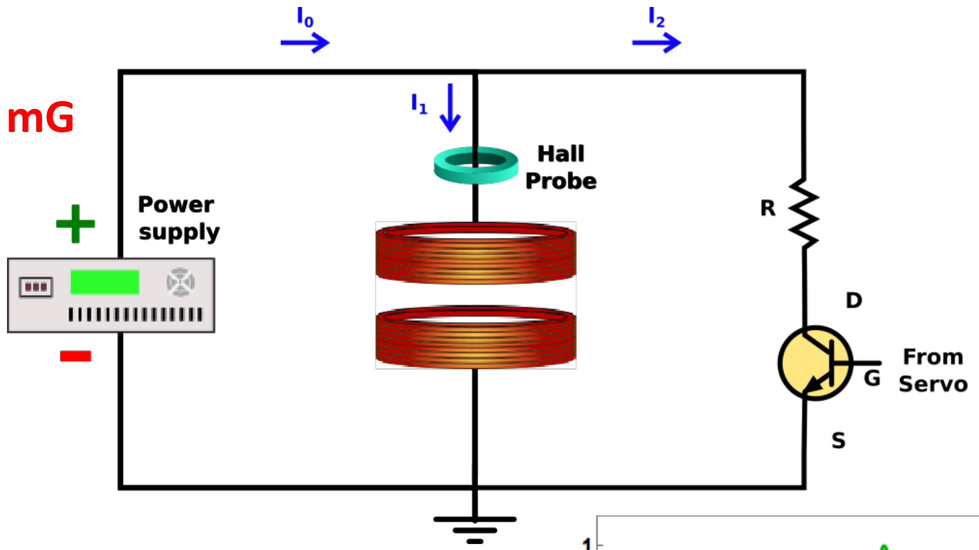
$$\Delta\nu = \frac{2h}{m} n_{3D}(\boldsymbol{r})[a_{13} - \overline{a_{12}}(B)]$$

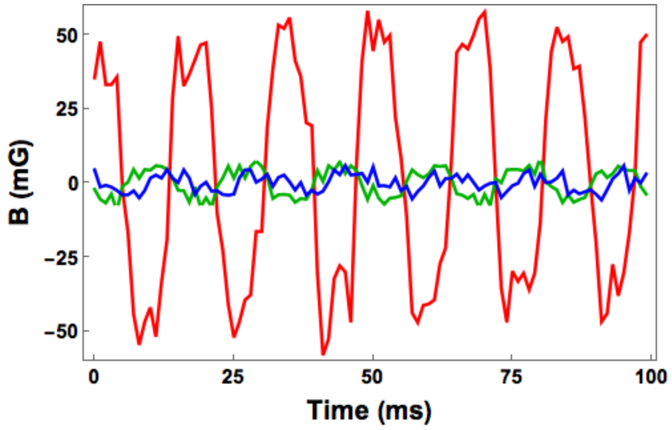
Near B ~ 543 G

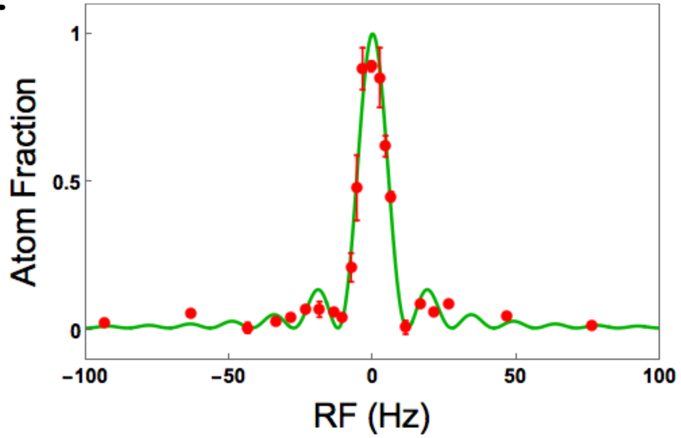
- $a_{13} = -270\, a_0$ - $|1\rangle$ - $|3\rangle$ Feshbach resonance at 690 G
- $a_{12} \cong a_{bg} = 62\, a_0$ - $|1\rangle$ - $|2\rangle$ Feshbach resonance near 543 G

Magnetic Field Stabilization

10 mG





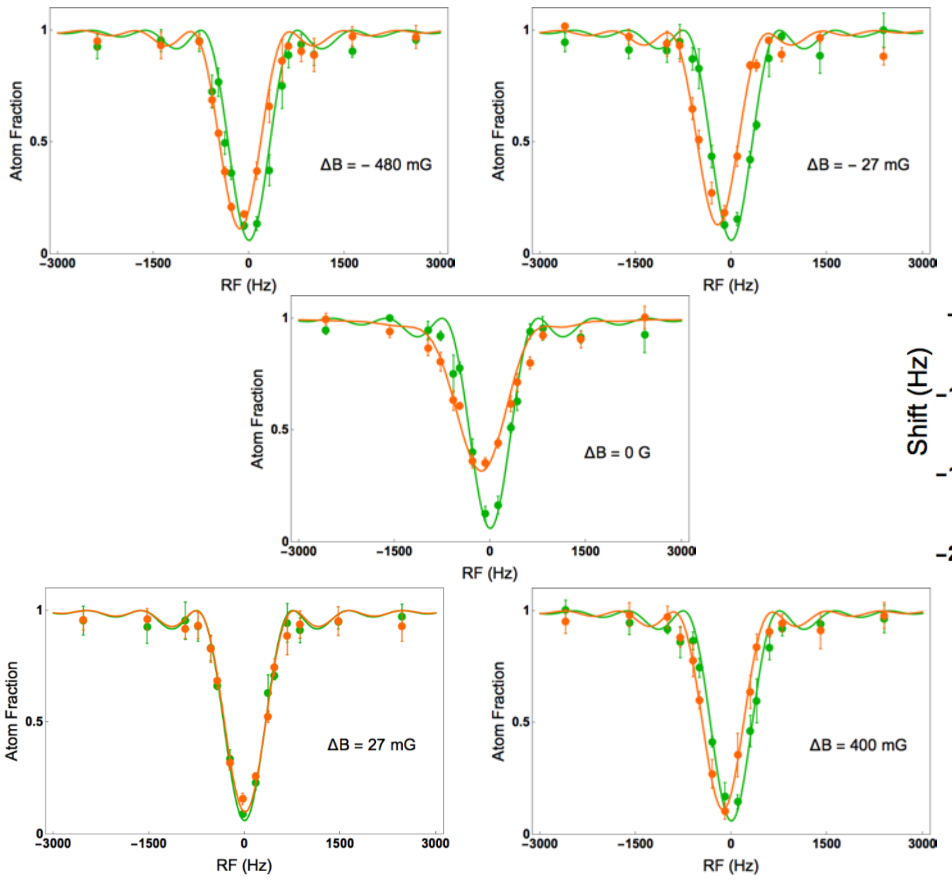


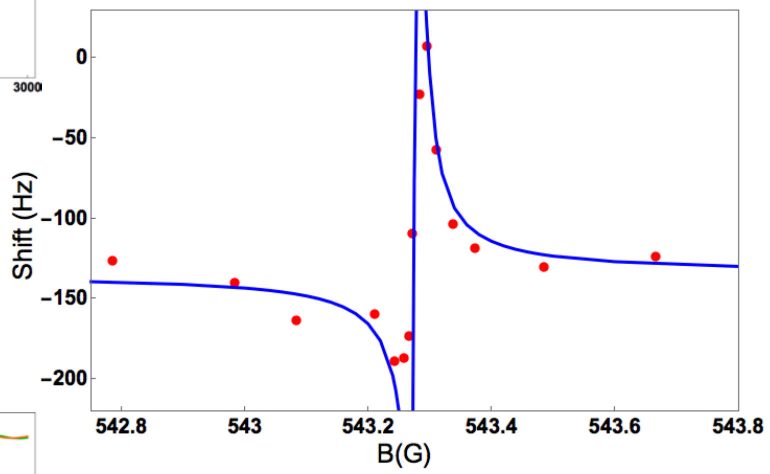
FWHM = 10 Hz

3mG
(at B = 530 G)

Magnetically Tuning Interactions: Narrow Feshbach Resonance

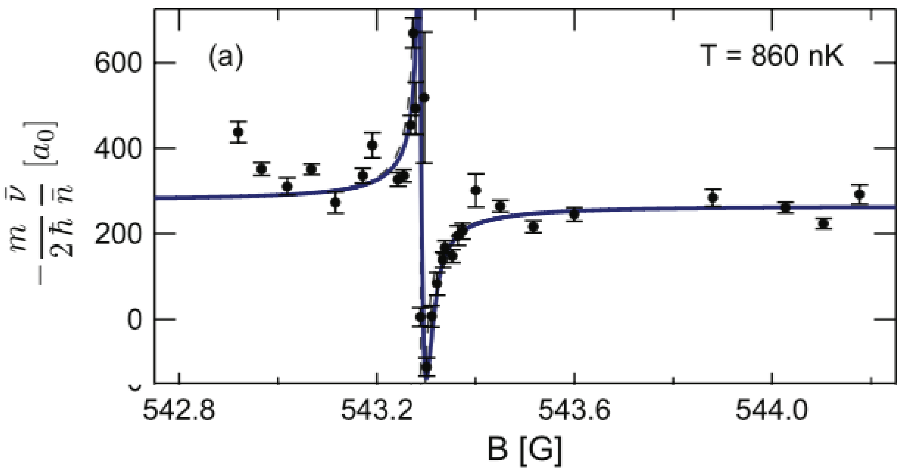
RF pulse - $|3\rangle \rightarrow |2\rangle$ for $t = 1.2$ ms

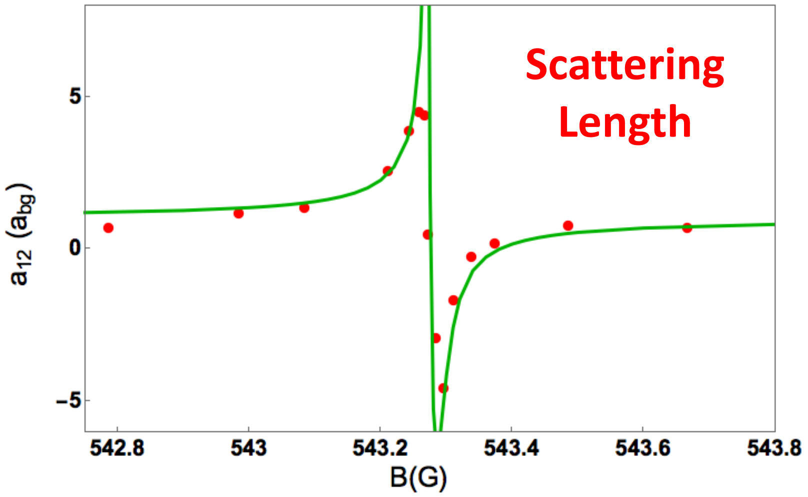




Scattering Length – Narrow Feshbach Resonance

Phys. Rev. Lett. 108, 045304 (2012)



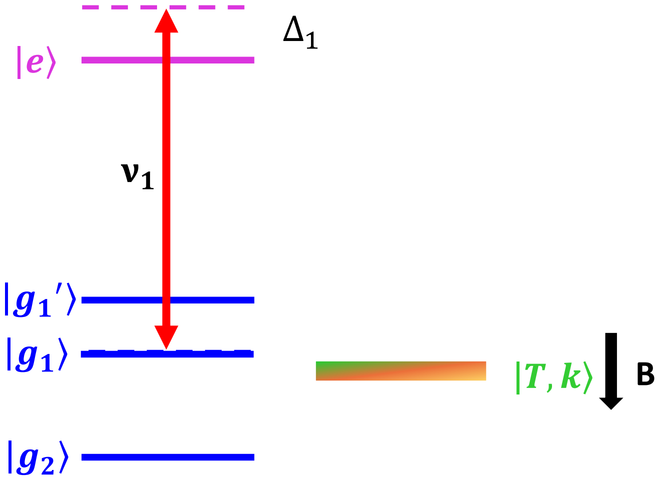


$$\Delta\nu_{meas} = \frac{2h}{m}\ \overline{n_{3D}}\ [a_{13} - \overline{a_{12}}(B)]$$

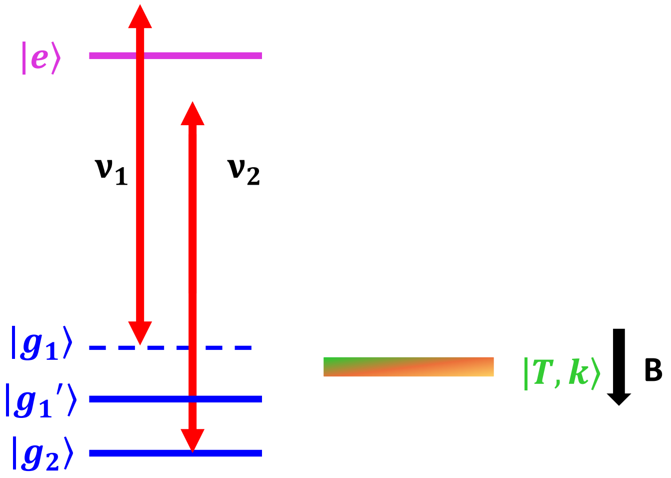
$a_{13} = -270\ a_0$ $\qquad$ $a_{12} \cong a_{bg} = 62\ a_0$ $\qquad$ $\overline{n_{3D}} = 3.6 \times 10^{11}\ cm^{-3}$

Controlling Interactions Using Two Optical Fields

$|\boldsymbol{g_1}\rangle$ tuning – with only $\mathbf{v_1}$ beam



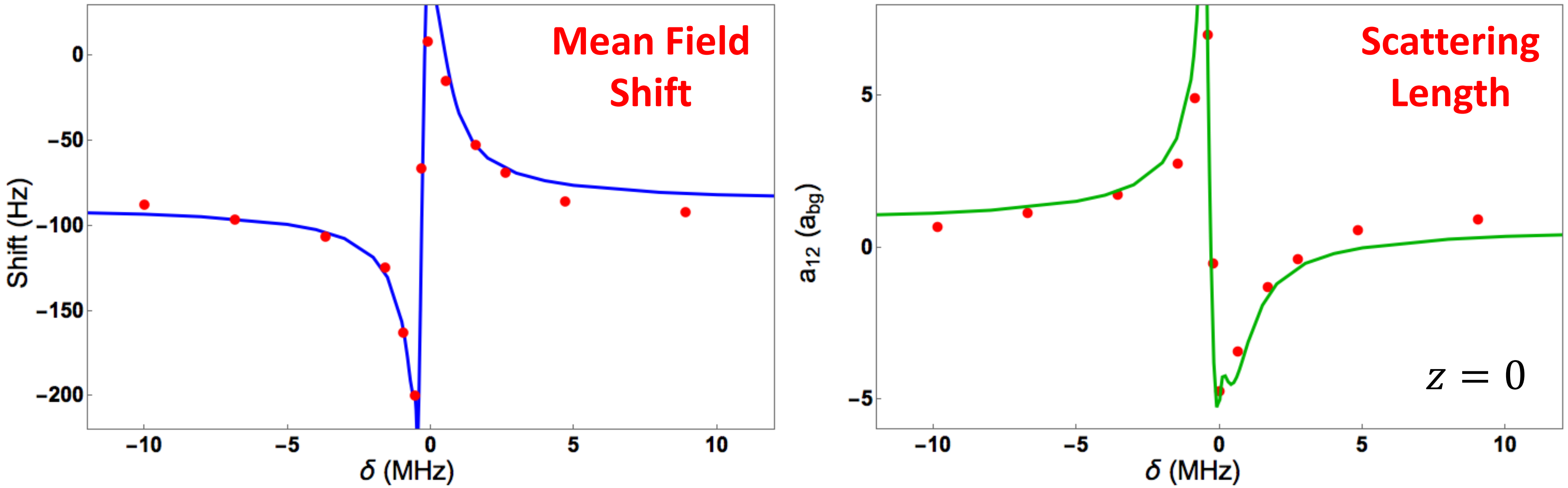
$|\boldsymbol{g_1}\rangle$ tuning – with both $\mathbf{v_1}$ and $\mathbf{v_2}$ beams



When $\delta = \Delta_2 - \Delta_1 = 0$,
$|\boldsymbol{g_1}'\rangle$ becomes $|\boldsymbol{g_1}\rangle$

Optically Controlled Scattering length

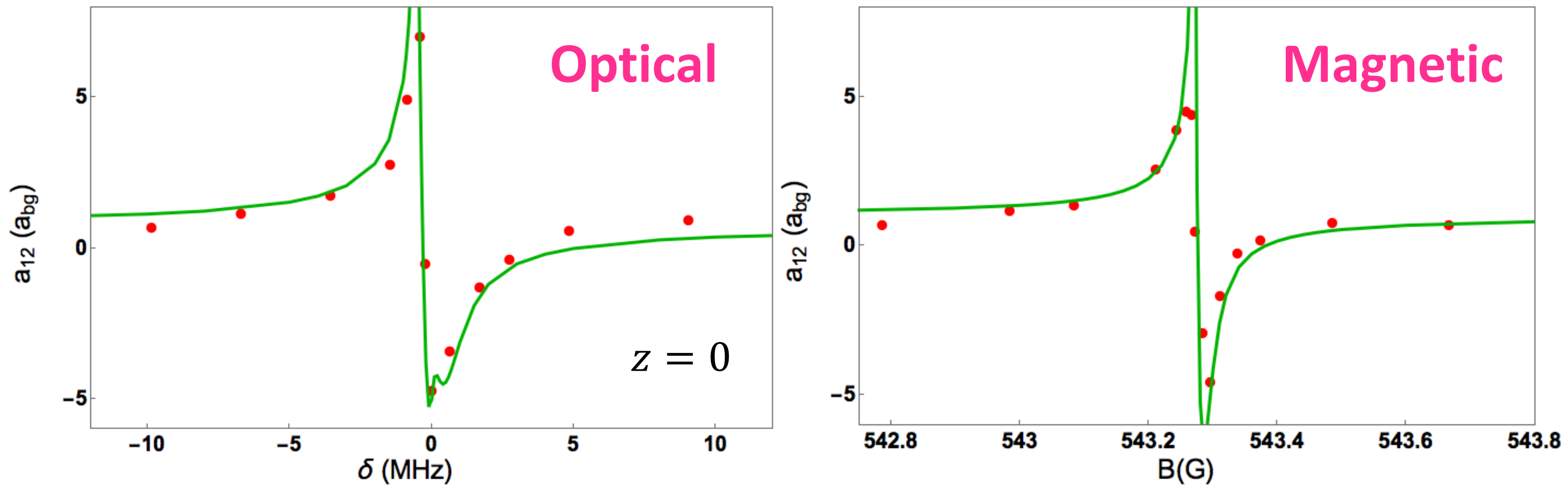
$B = B_{res} + 10\ mG$



$$\Delta\nu_{meas} = \frac{2h}{m}\ \overline{n_{3D}}\ \left[a_{13} - \overline{a_{12}^{opt}}(B, \delta, \Omega_2(z))\right]$$

$$\overline{n_{3D}} = 1.5\ \times\ 10^{11}\ cm^{-3}$$

Comparison of Magnetic and Optical Tuning



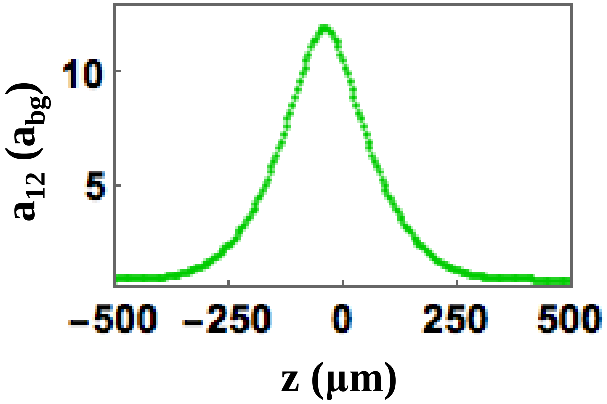
How did we achieve same level of tunability in scattering length?

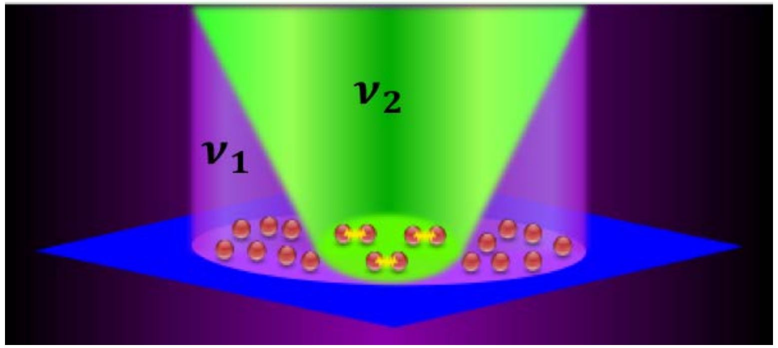
- Initial magnetic field – close to B_{res}
- At $\delta = 0$ - minimum loss
  - $|g_1'\rangle$ is tuned to unshifted position of $|g_1\rangle$ and becomes degenerate with $|T, k\rangle$

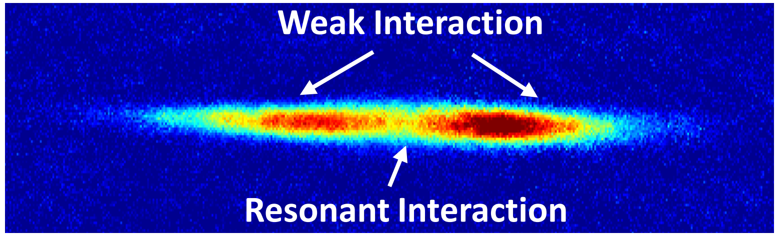
Experiment 3 : Spatial Control of Interactions in Ultracold Gases

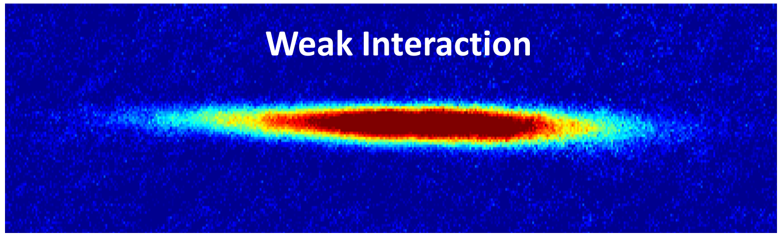
Realizing an Interaction Sandwich

- Prepare $|1\rangle - |3\rangle$ mixture at $B_{res} + 10\ mG$
- Apply optical beams $\boldsymbol{\nu_1}$ and $\boldsymbol{\nu_2}$
- Apply RF pulse $|3\rangle \rightarrow |2\rangle$ for 1.2 ms and image atoms in $|2\rangle$
- Weak interactions – Maximum atom transfer

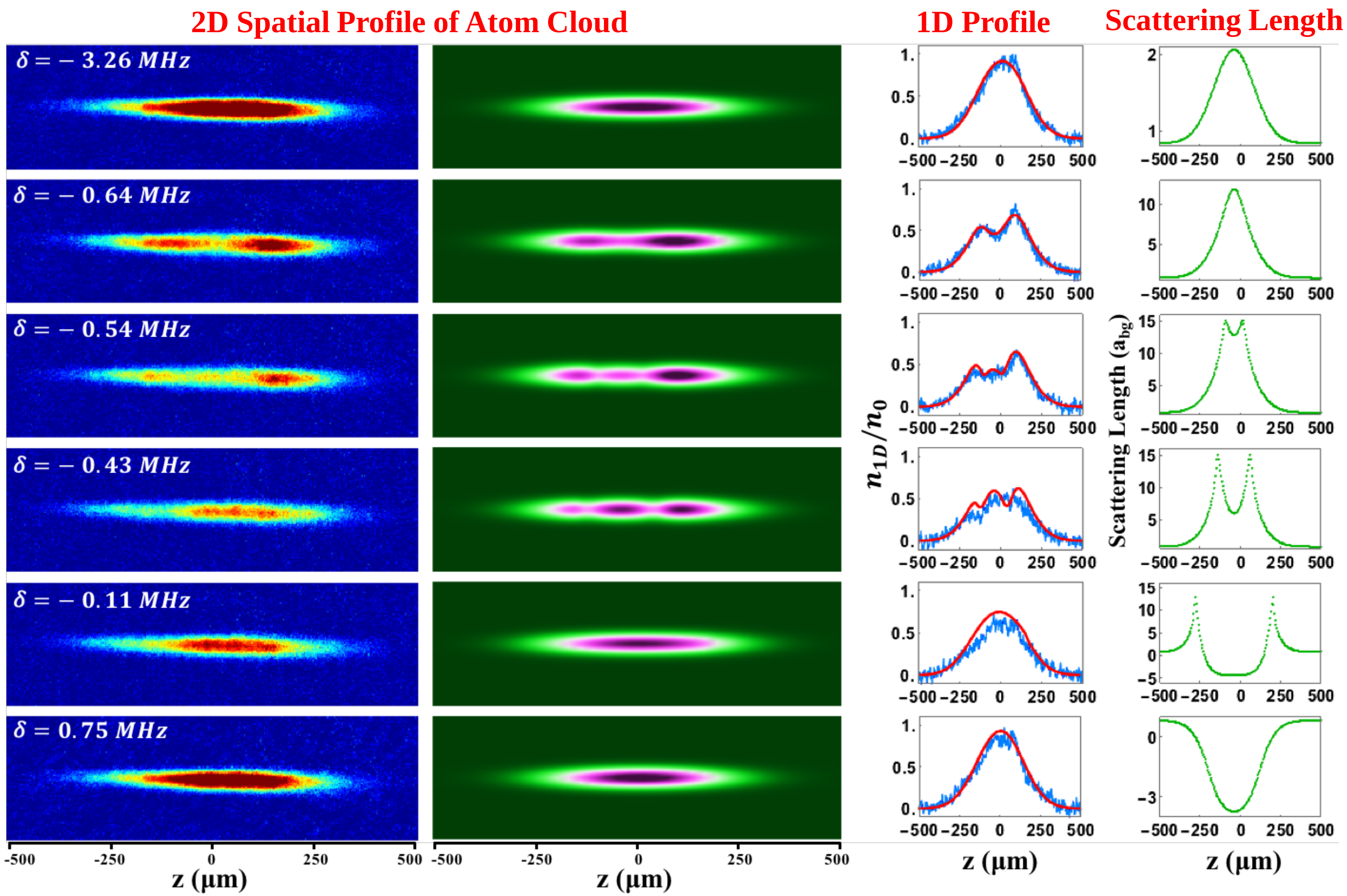








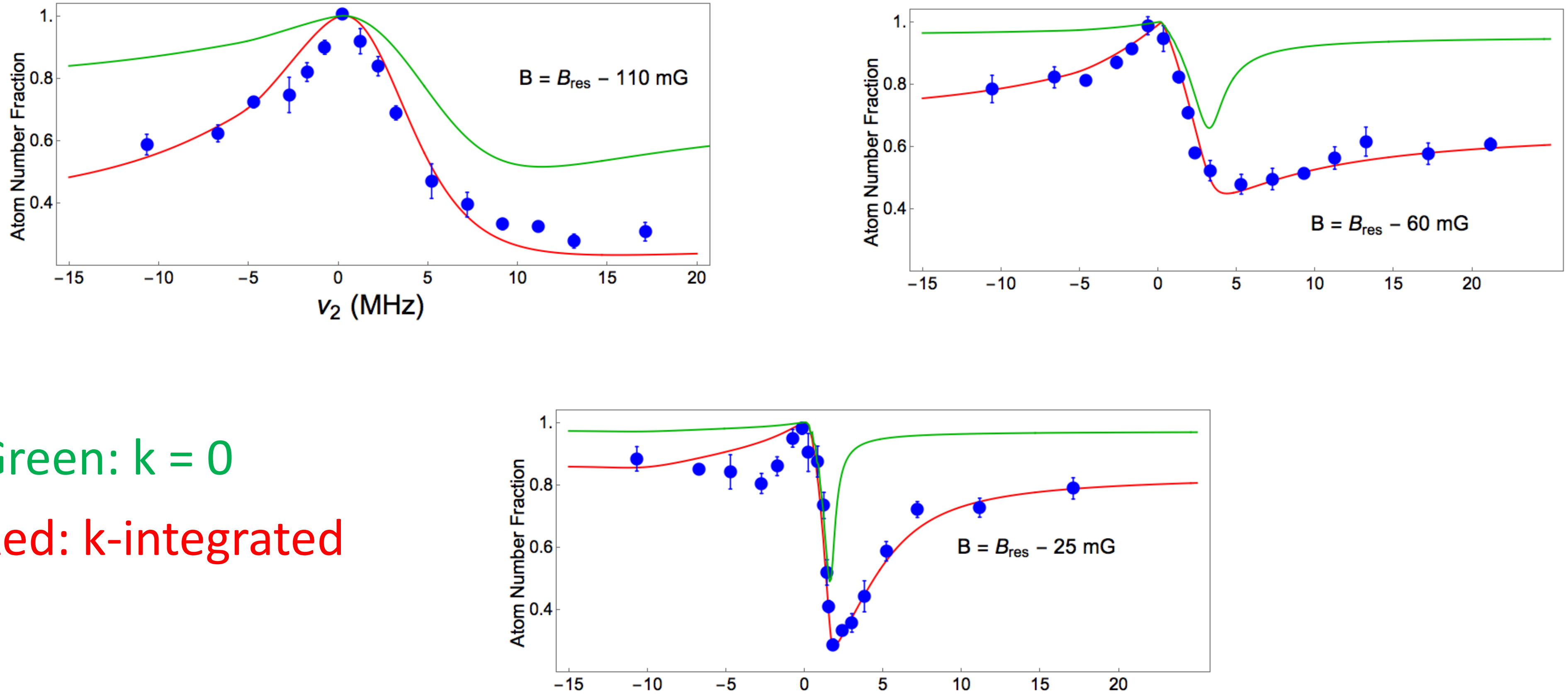
Manipulating Interaction Profiles on a Atomic Cloud



Experiment 4 : Two-Field Loss Spectra

Loss vs Two-Photon Detuning

B-field below Resonance: Theory vs Experiment

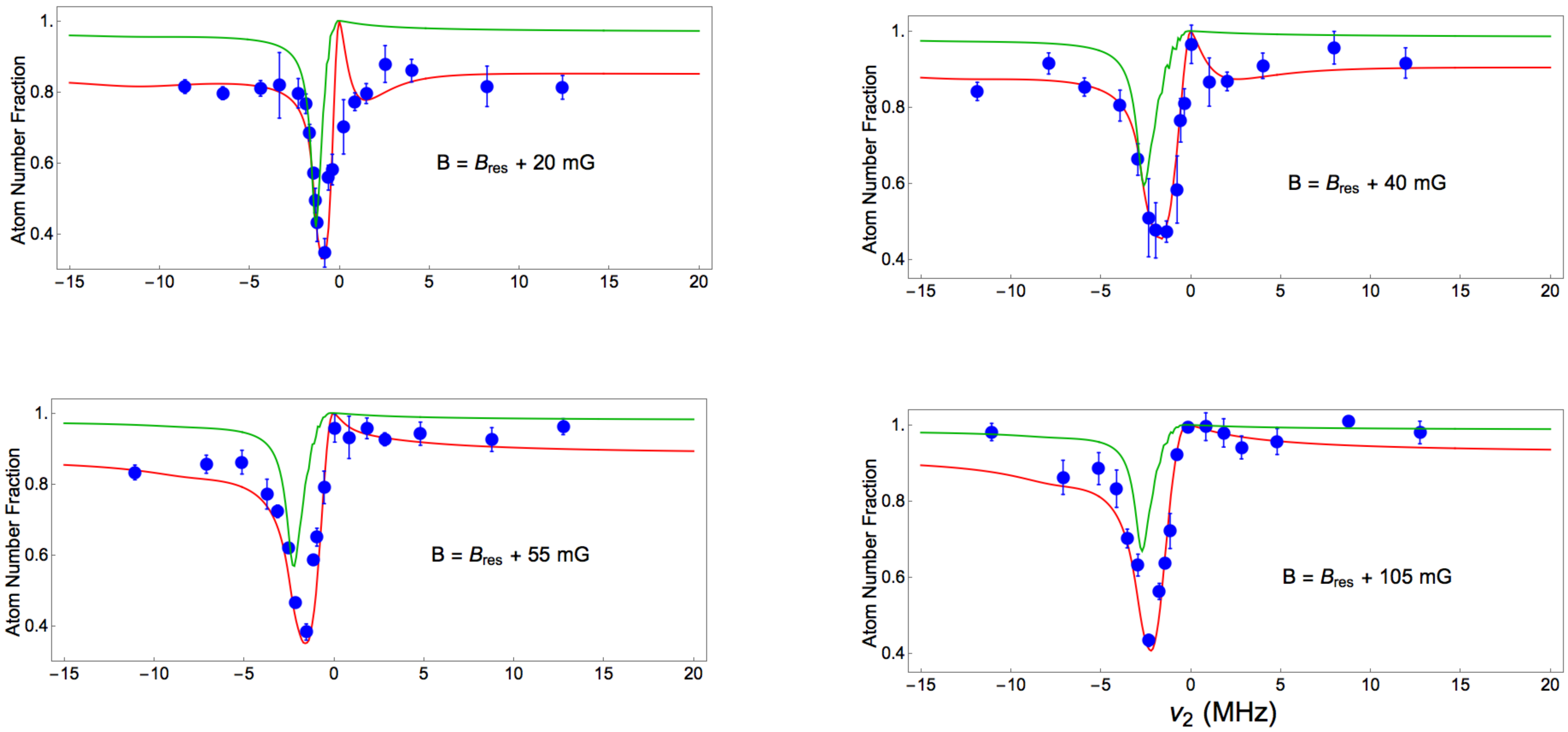


Green: k = 0

Red: k-integrated

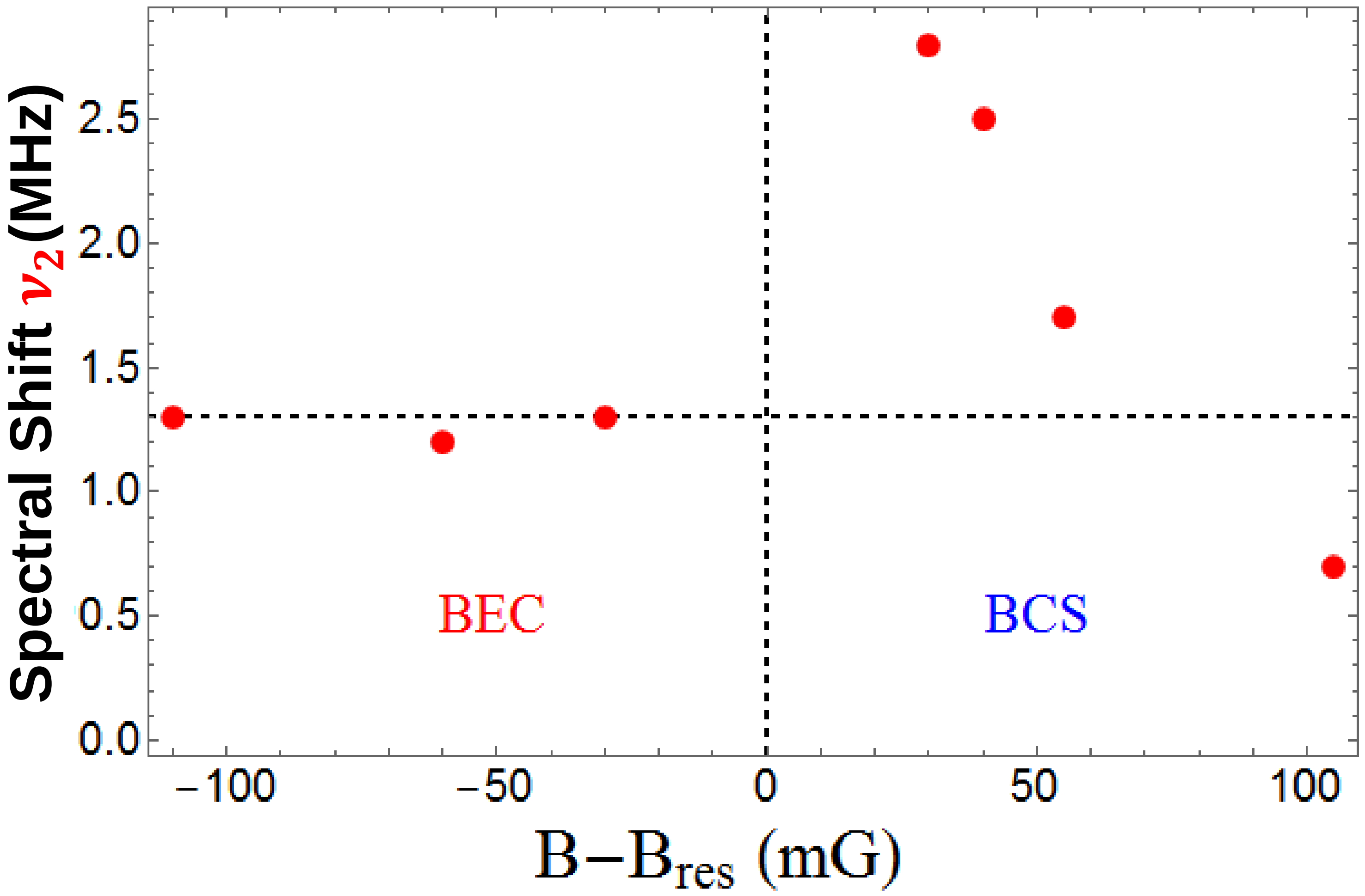
Loss vs Two-Photon Detuning

B-field above Resonance: Theory vs Experiment

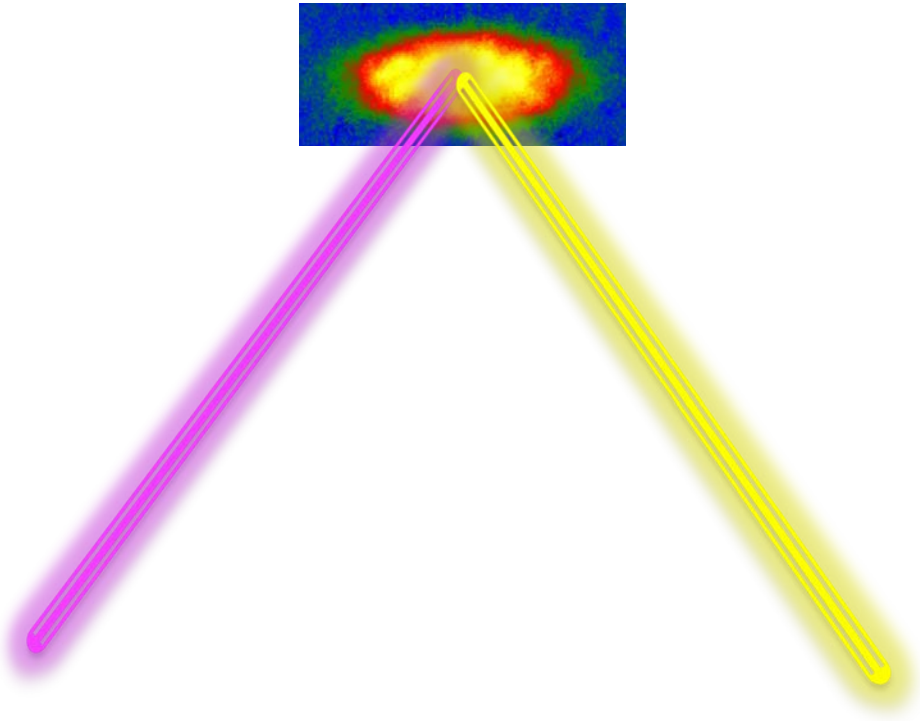


Anomalous “Anomalous” Shift!

Shapes agree, Spectral Shift of Experiment wrt Theory



Applications: Optical Control of Interactions



Two-body interactions

S-wave, P-wave…

Dynamical control of the effective range

Few body physics

Spatial control

Momentum - selective control

3 - state mixtures

Dynamical control of stability

Symmetrized interaction strength

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Thank You!