Phase Gradient Effects in a BEC Interferometer

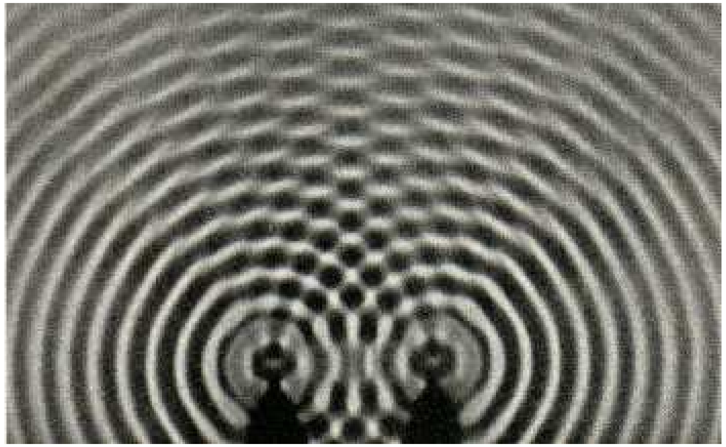
John H T Burke

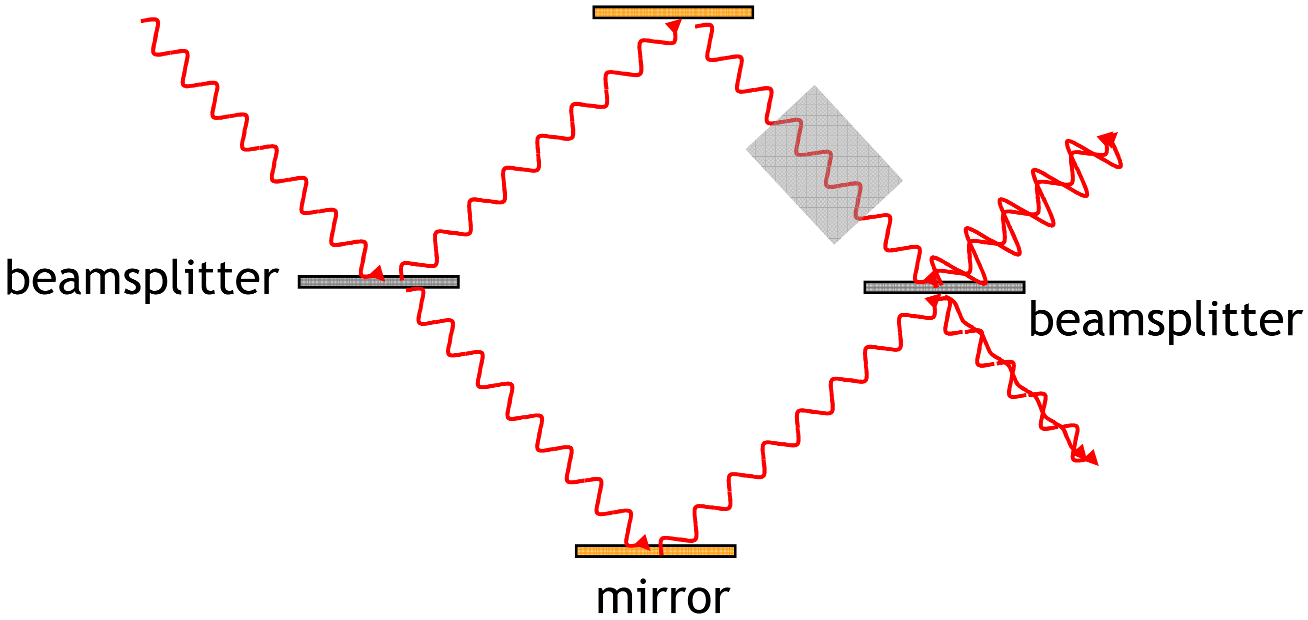
April 14th 2008

Acknowledgments:

- Cass Sackett, Ben Deissler, Jeramy Hughes,
  Eun Oh, Osvaldo Hernandez
- UVA, NSF, DARPA

Interferometry





Bose Einstein Condensate

- Theorized by Bose and Einstein in the 1920's
- Seen experimentally in 1995 by Eric Cornell, Carl Weiman, and Wolfgang Ketterle - they won the 2001 Nobel Prize
- Focus on wavelike nature of matter:
  - DeBroglie wavelength

$$\lambda_{dB} = \frac{h}{p} \propto 1/\sqrt{T}$$

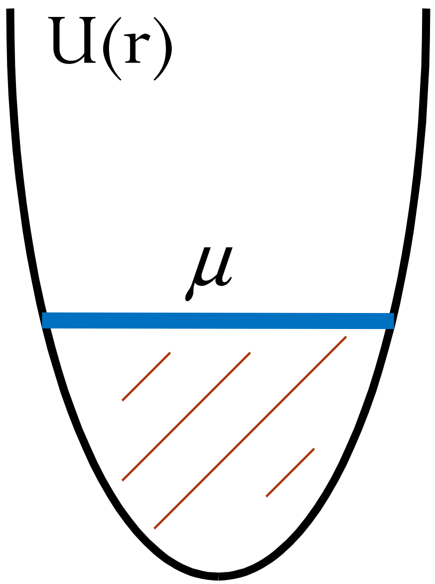
Bose Einstein Condensate (cont)

•When λ becomes bigger than the distance between atoms, the atoms' waves start to overlap.

•Waves add up coherently to create one macroscopic atom wave.

•Can do this by cooling atoms down below a critical temperature ~100nK for a wavelength ~1μm

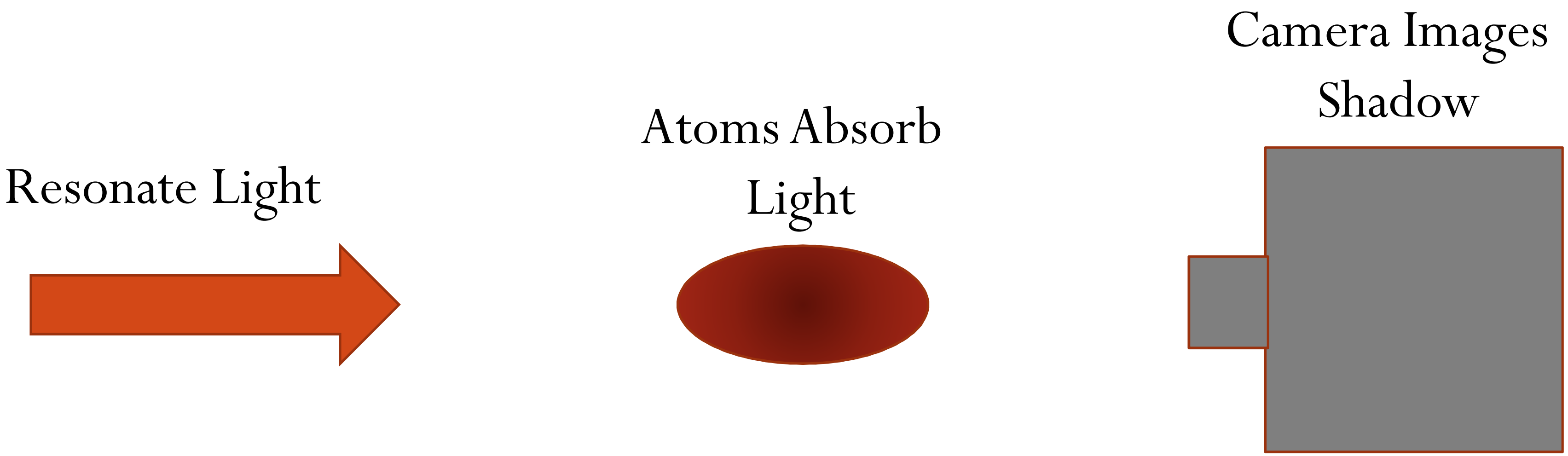
Bose Einstein Condensate (cont)

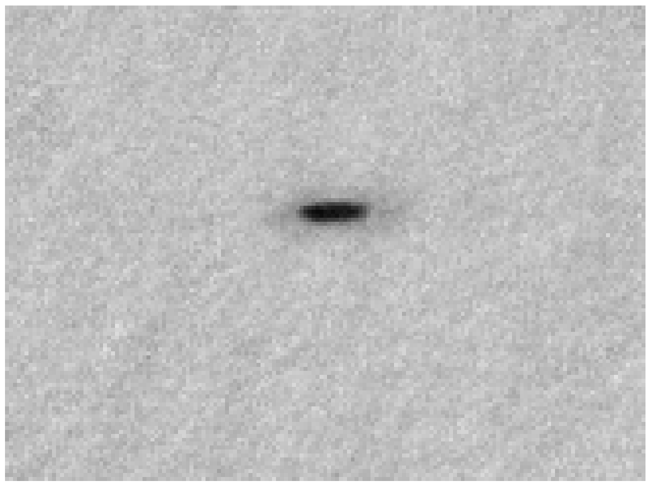


- Chemical potential, μ , increases with number due to interactions
- When N sufficiently high that $\mu >> \hbar\omega$ use Thomas-Fermi approximation

$$n_{TF}(\vec{r}) \propto \begin{cases} 1 - \frac{x^2}{L_x^2} - \frac{y^2}{L_y^2} - \frac{z^2}{L_z^2} & if > 0 \\ 0 & else \end{cases}$$

Imaging





Motivation

•BEC wave acquires phase via energy changes:

$$\phi = \frac{1}{\hbar}\int E(t)dt$$

•With an interferometer we can measure phases and learn about the environment the BEC experienced

•The energy is affected by environmental affects such as
Gravity Electric fields Rotations

•Note Photons don't interact as strongly as atoms.

Applications

- Navigation devices (measure rotations)
- Oil exploration (gravitational sensing)
- Measure physical quantities (fun for scientists)

Technical Difficulties

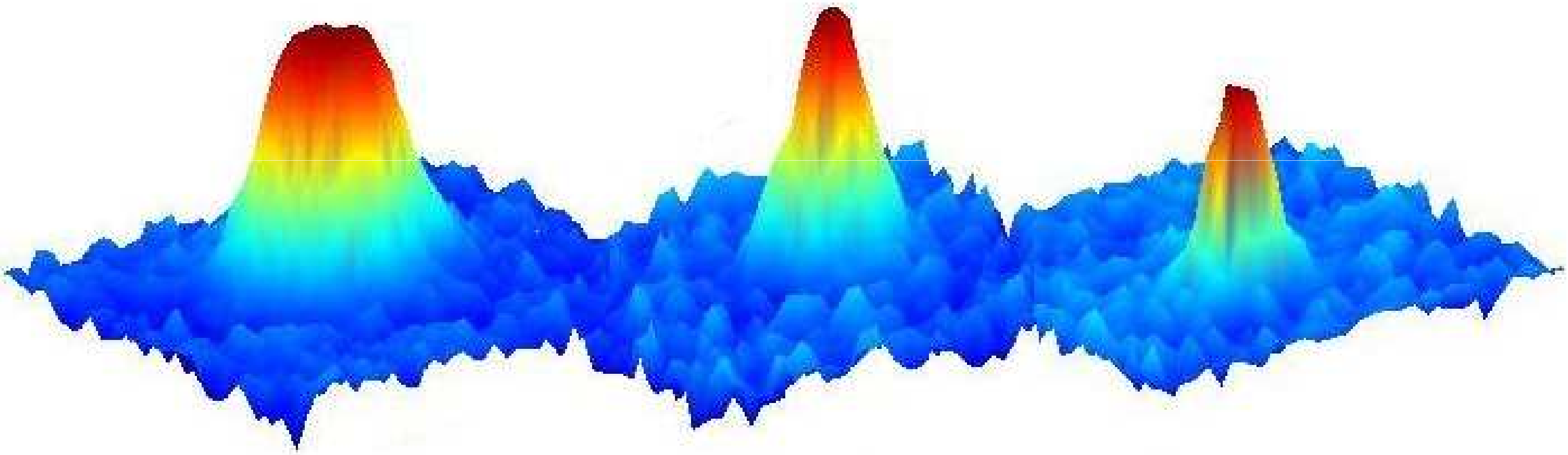
- Strong interactions
  - Difficult to isolate from external sources
- Low flux (10^5 atoms/s)
  - Bad signal to noise
- Hard to manipulate
  - Atoms in vacuum
  - Optical or mech. Gratings

Building Blocks

- Make BEC (we use ^{87}Rb)
- Gravitational support (atoms will fall)
- Velocity Manipulation

Making BEC

Use sequence of laser and evaporative cooling to reach 100nK.



Gravitational Support

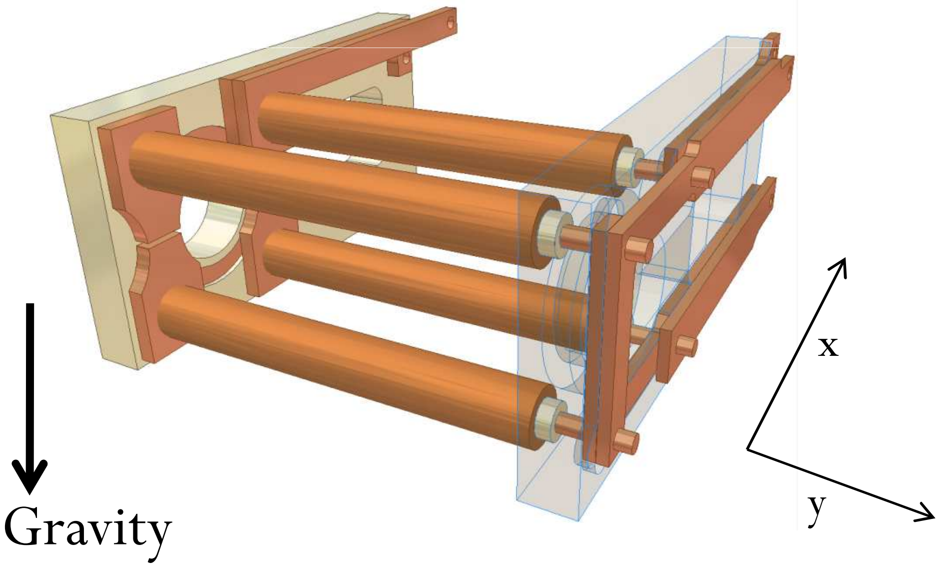
- Want to support atoms against gravity, but otherwise not affect them
- Use magnetic fields!
- Atoms have a dipole moment μ (acts like a bar magnet)
- Generate trap with magnetic fields:
  $U = -\boldsymbol{\mu} \cdot \mathbf{B} = g\mu_B m B$
- For $m > 0$, have confining potential around minimum of B field

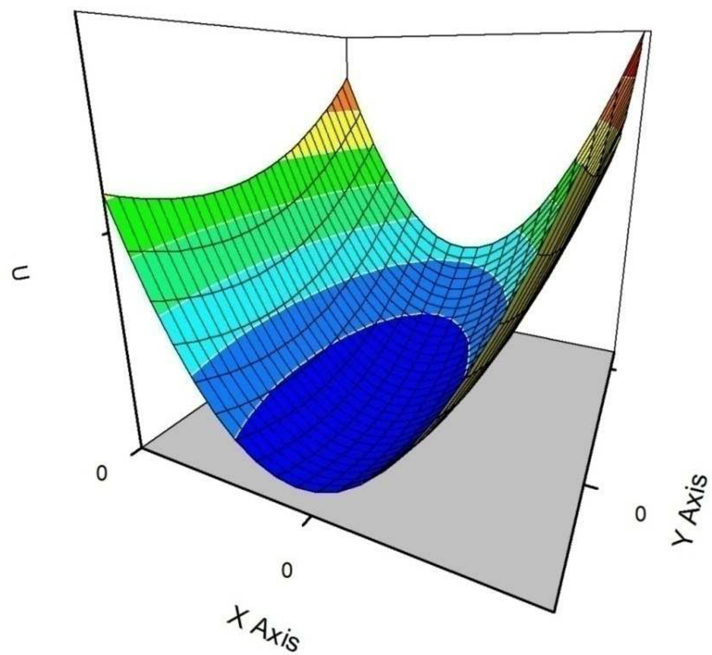
Waveguide

$$U_B = \frac{m}{2}\left(\omega_x^{\ 2} x^2 + \omega_y^{\ 2} y^2 + \omega_z^{\ 2} z^2\right)$$

$$\omega_x = 2\pi \times 6 \quad Hz$$
$$\omega_y = 2\pi \times 1 \quad Hz$$
$$\omega_z = 2\pi \times 3 \quad Hz$$

Spacing between rods ~1.5 cm





Velocity Control

Want to separate 'arms'

- far apart so we can expose them to different environments
- For a long time to accumulate a measurable phase

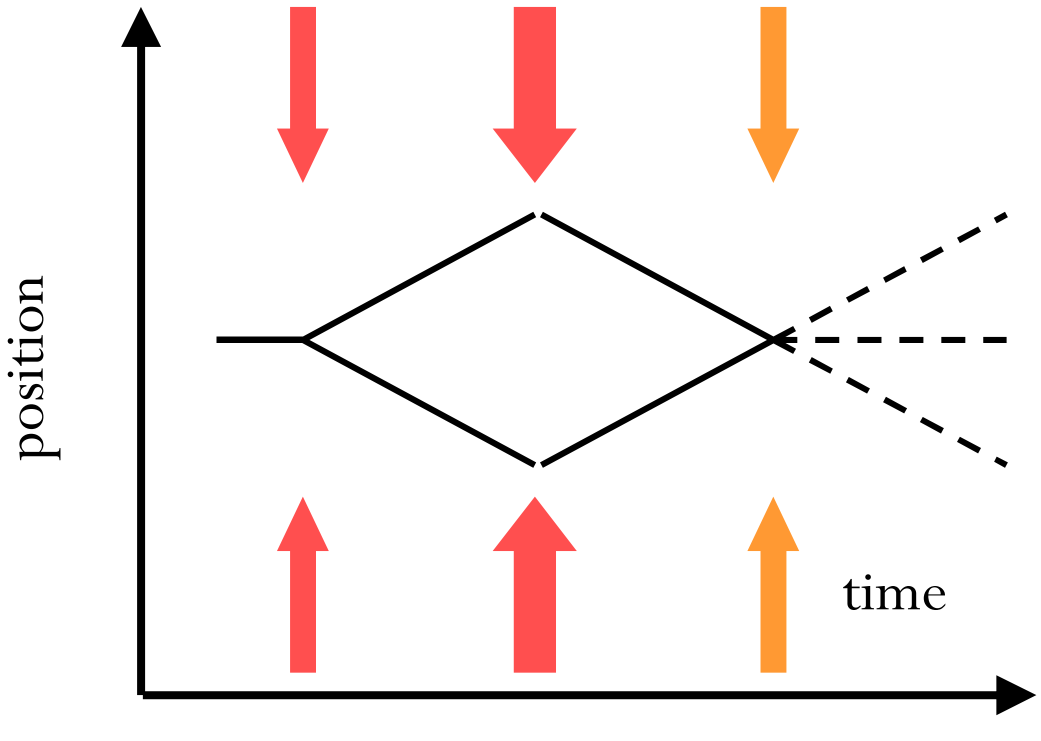


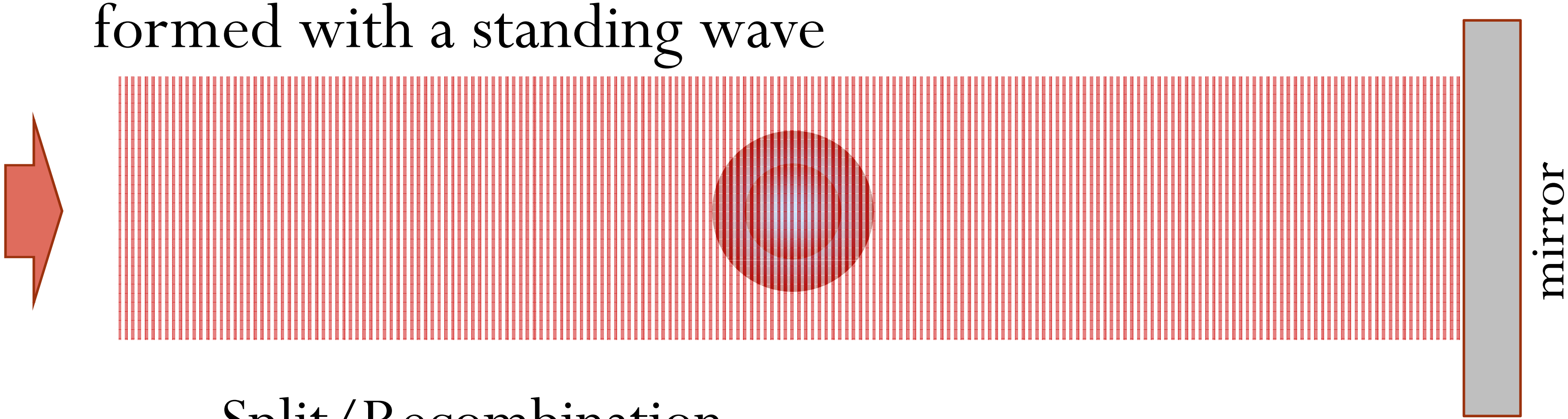
Figure of merit:

$$\chi \equiv \int_0^{t_{\max}} |\Delta y| dt$$

Measure of accumulated phase

Velocity Control

We can also diffract matter waves from 'optical grating' formed with a standing wave



Split/Recombination pulse drives

$$|0\rangle \leftrightarrow \frac{1}{\sqrt{2}}\left(|v_0\rangle + |-v_0\rangle\right)$$

Reflect pulse drives

$$|v_0\rangle \leftrightarrow |-v_0\rangle$$

$$v_0 = {}^{2h}\!/_{\lambda m} = 11.7\,{}^{mm}\!/_{s}$$

Phase adjust

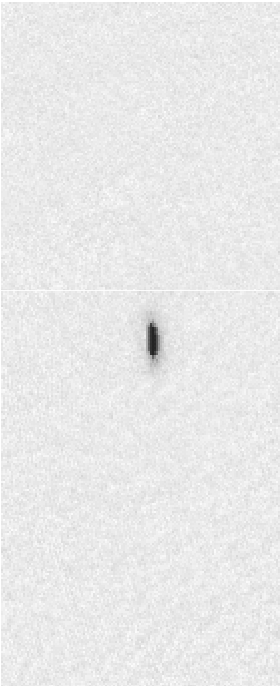
•Adjust interferometry phase by shifting relative phase of standing phase.

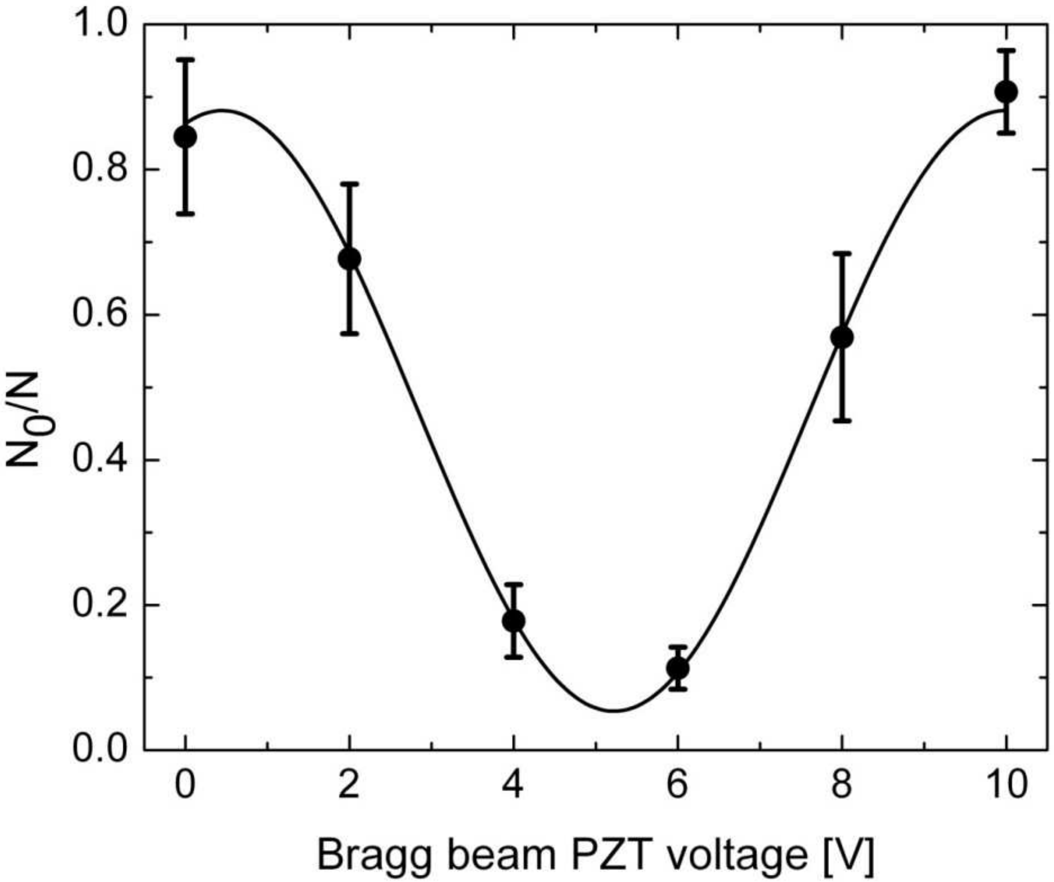
•Change its frequency slightly

$$\frac{N_0}{N} = \frac{1}{2}\left(1 + V\cos(\theta_{applied})\right)$$

For Visibility V

Working Interferometer

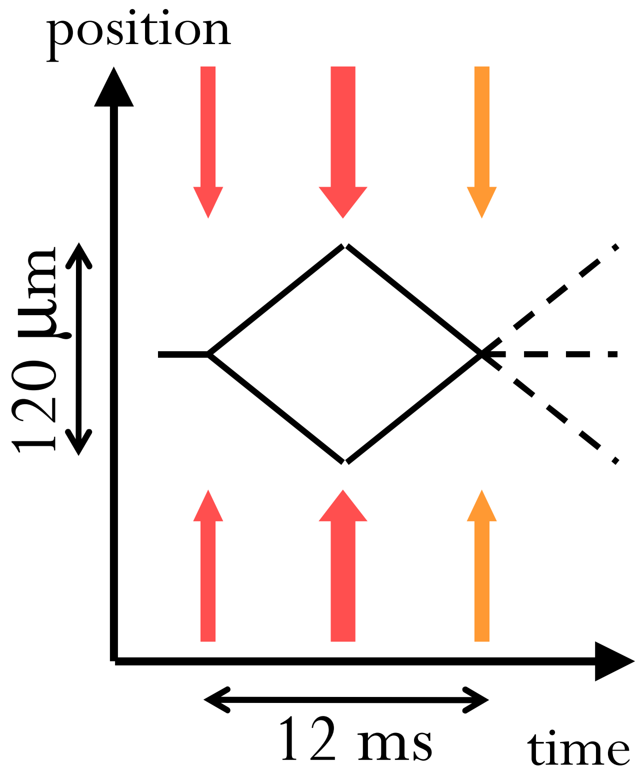


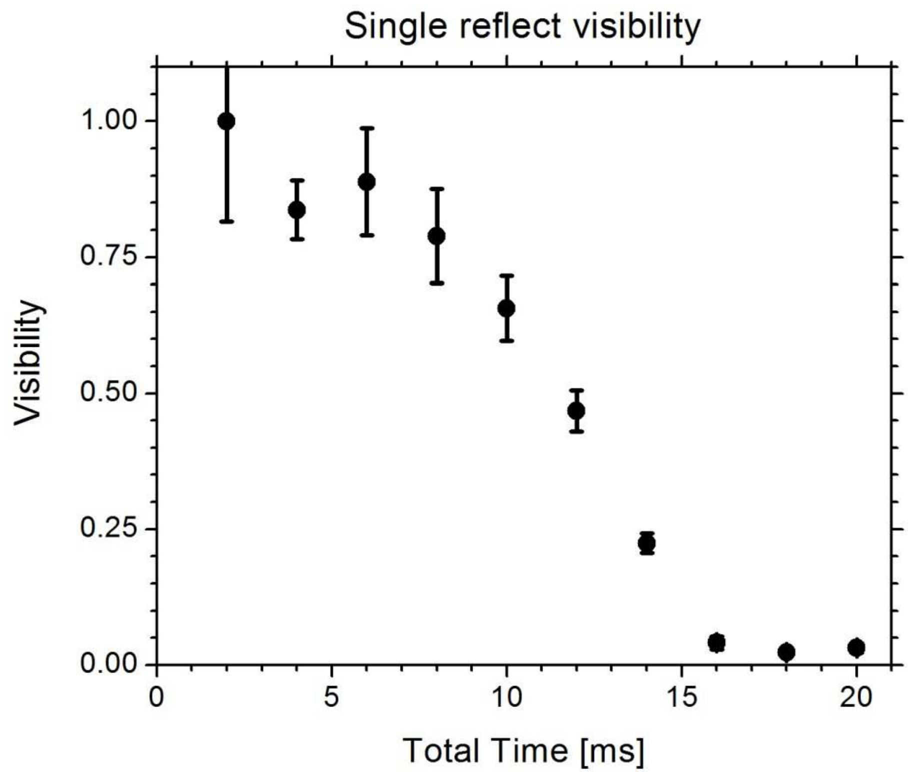


interferometer.avi

Interferometer Geometry

Single Reflect: $\chi = 0.7\ \mu$m-s

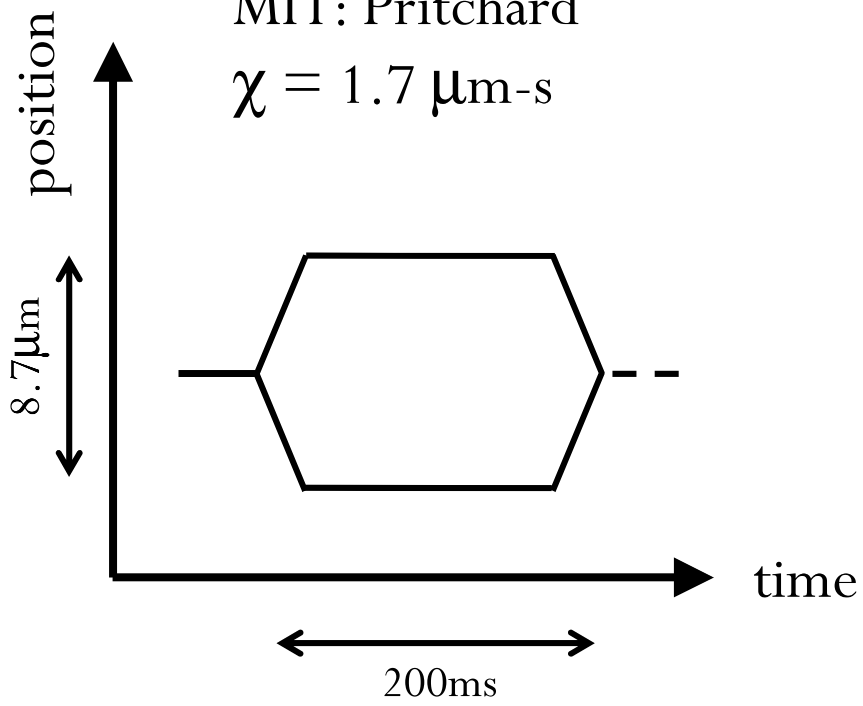




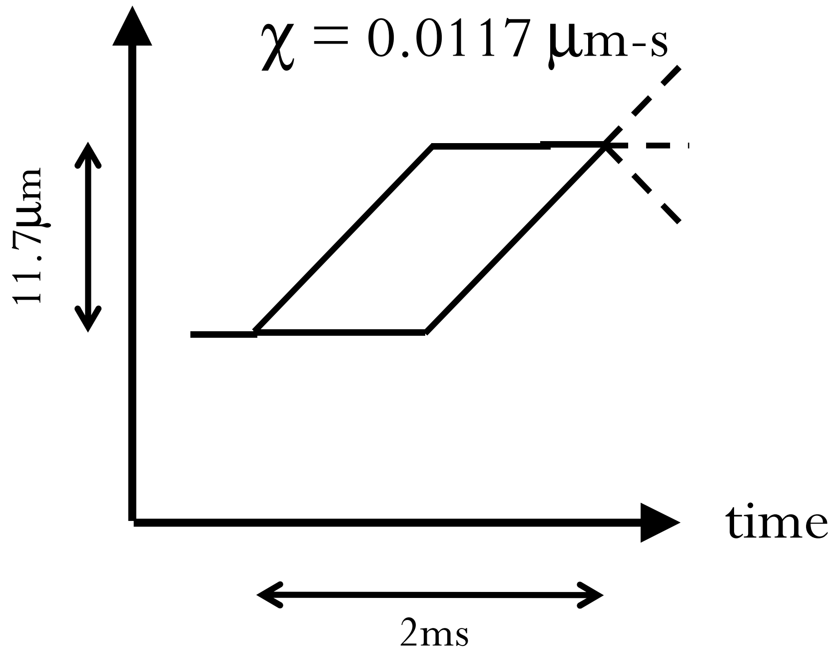
Other Geometries

Virginia: Sackett $\chi = 0.7\ \mu$m-s
Colorado: Anderson $\chi = 0.0012\ \mu$m-s
Harvard: Prentis $\chi = 2\ \mu$m-s

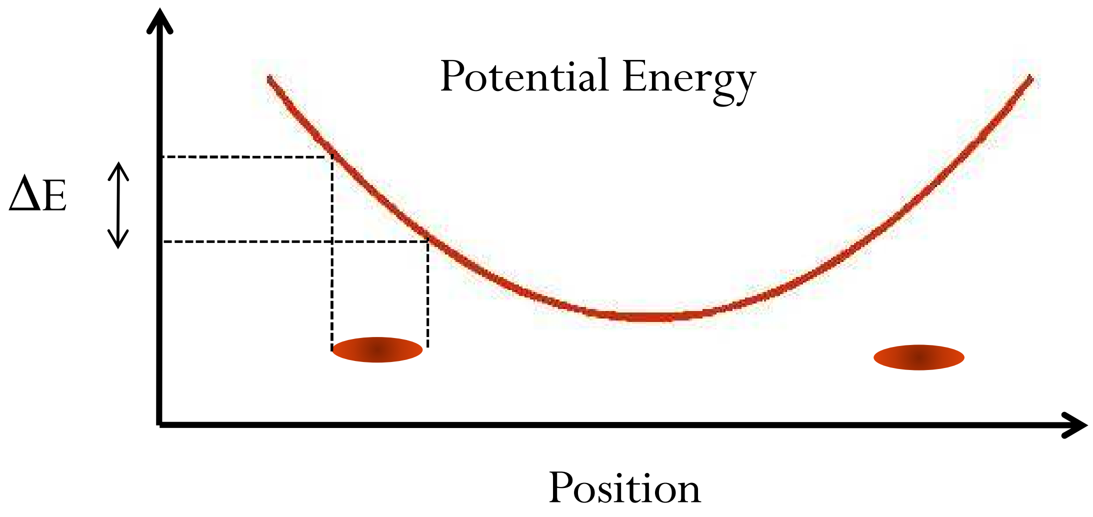
MIT: Pritchard
$\chi = 1.7\ \mu$m-s



Japan: Nakagawa
$\chi = 0.0117\ \mu$m-s

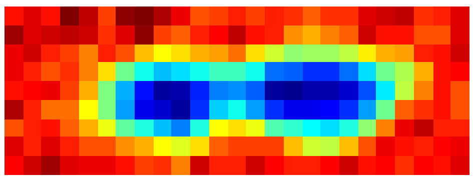


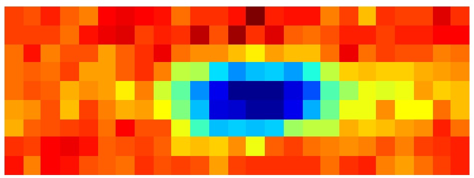
Problem: Phase Gradients

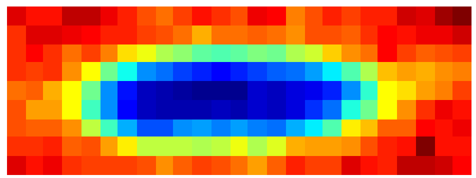


Energy gradient across cloud creates a phase gradient across cloud

When atoms are recombined, N_0/N depends on position







Semi-Classical Theory

$$U_1(\vec{r}_1,t) = \underbrace{\frac{m}{2}\left(\omega_y{}^2 y(t)^2\right)}_{Confinement} - \underbrace{\mu n_{TF}(\vec{r}_2,t)}_{Interactions}$$

$$y(t) = y_1 \pm Y_{CM}(t)$$

Where Y is the center of mass motion

$$\Delta\varphi(\vec{r},T) = \int_0^T dt\left\{U_1(\vec{r},t) - U_2(\vec{r},t)\right\}$$

Note here we are assuming the condensate is a rigid body

Trajectory

$$Y(t) = \frac{v_0}{\omega}\sin(\omega t) \quad 0 < t < T_{reflect}$$

Cloud slows down as it moves to higher potential.
"Reflect" pulse actually applies a $-2v_0$ kick

$$Y(t) = \frac{v_0}{\omega}\left(\sin(\omega t) - 2\sin\left(\omega\left[t - T_{reflect}\right]\right)\right) \quad T_{reflect} < t < T_{recombine}$$

Confinement

$$\Delta\varphi_B(y,T) = y\frac{2mv_0}{\hbar}\left[1+\cos(\omega T)-2\cos\left(\frac{\omega T}{2}\right)\right]$$

$$\left.\frac{\partial\Delta\varphi_B}{\partial y}\right|_{T=5ms} \approx 1\frac{rad}{2L_y}$$

$$\left.\frac{\partial\Delta\varphi_B}{\partial y}\right|_{T=10ms} \approx 4\frac{rad}{2L_y}$$

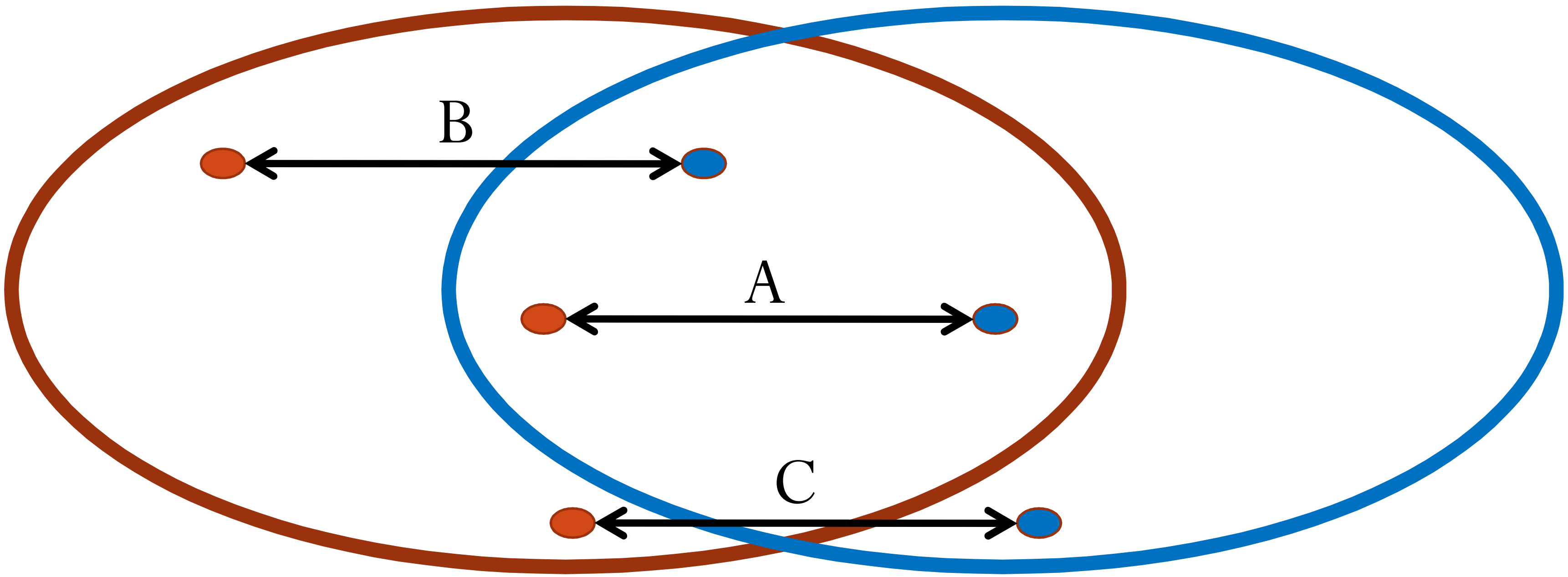
Interactions

For Given x, y, z, and t could have 3 possibilities between that point and its counterpart point:

A: Both interacting

B: One interacting but not other

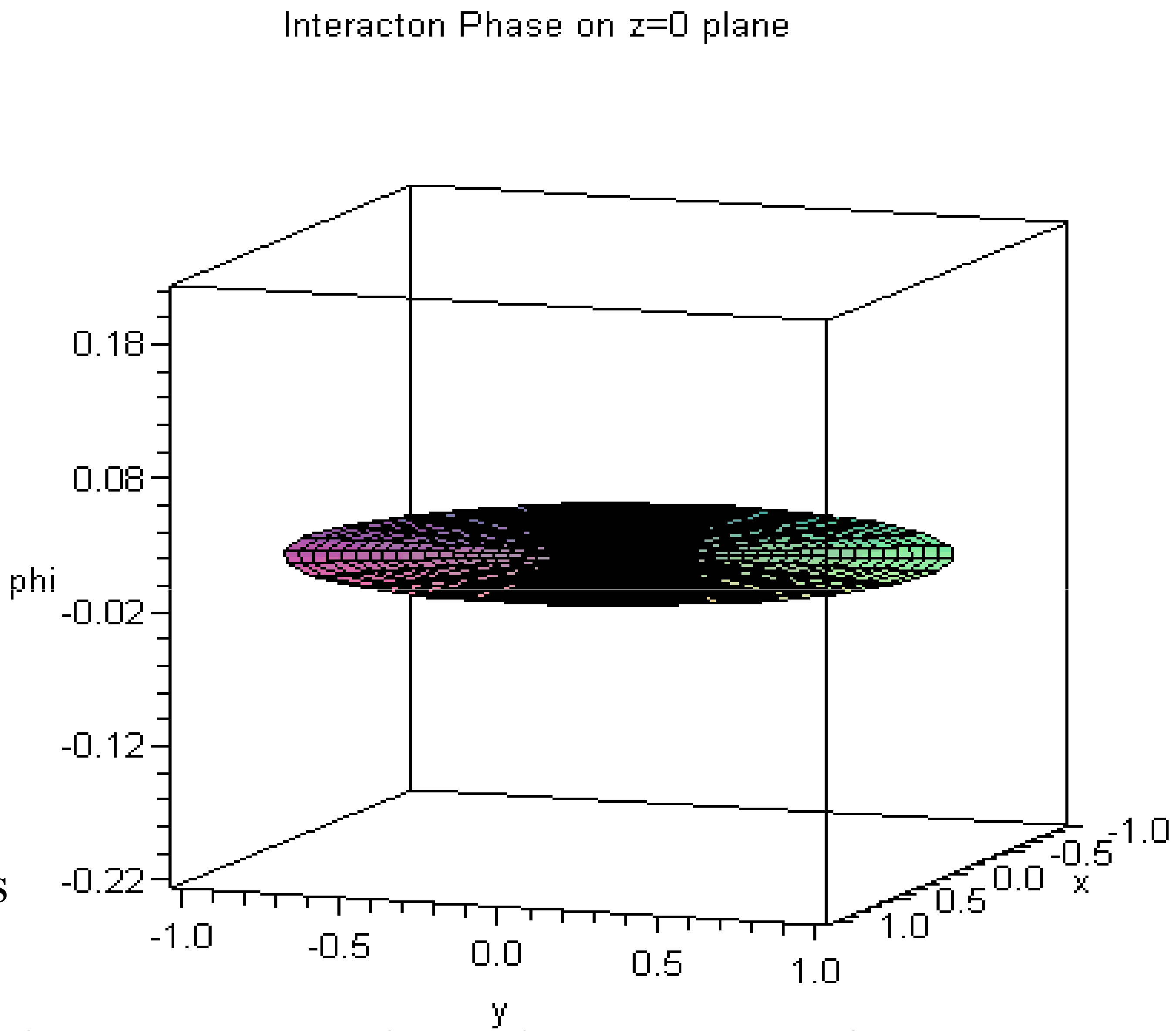
C: Neither interacting



Approximations

- During separation $\omega t << 1 \rightarrow Y_{cm}(t) \approx \pm v_0 t$
- Ignore interaction's repulsive effect in $Y_{cm}(t)$

Result



Time from 0 to 5 ms

Clouds completely separate at 4.6 ms

Max Gradient is 0.6 rad/2L

Compare to 1 rad/2L at 5ms and 4 rad/2L at 10ms for confinement

Visibility

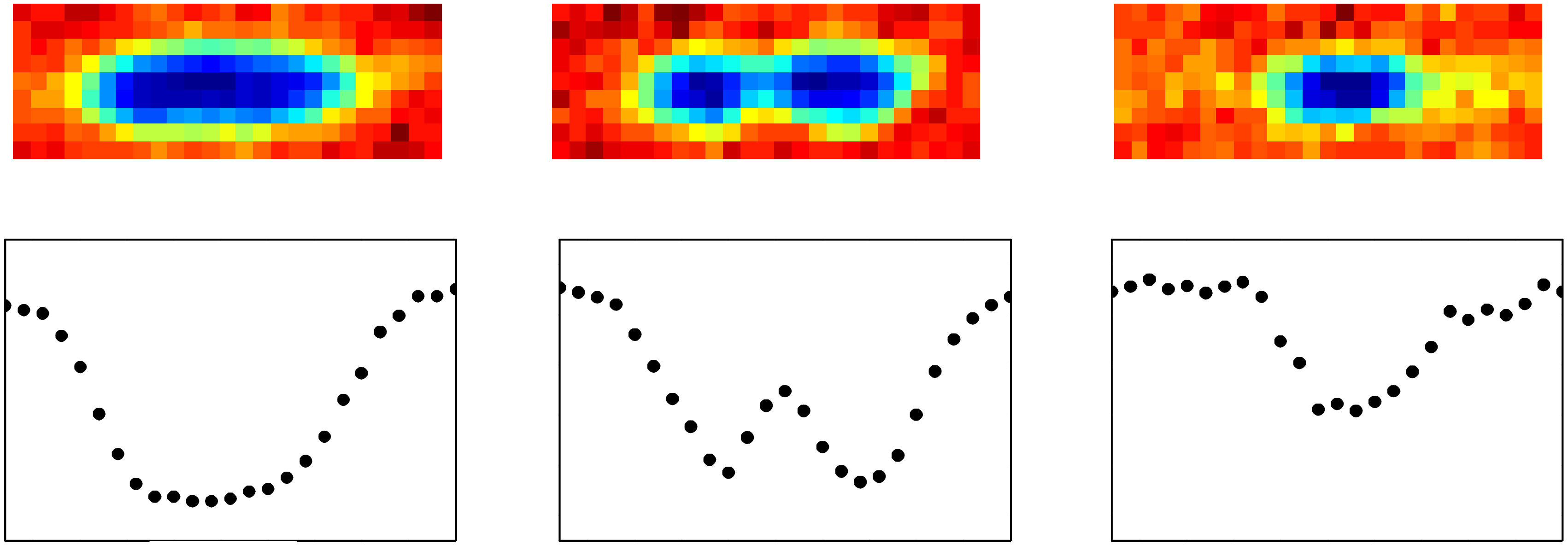
Measures how well we can see interference.

$$\frac{N_0}{N} = \frac{1}{2}\left[1 + V(T)\cos(\theta_{app})\right]$$

$$V(T) = \int d^3\vec{r}\left\{n_{TF}(\vec{r})\cos\left[\Delta\varphi(\vec{r},T)\right]\right\}$$

Integral is difficult – do numerically

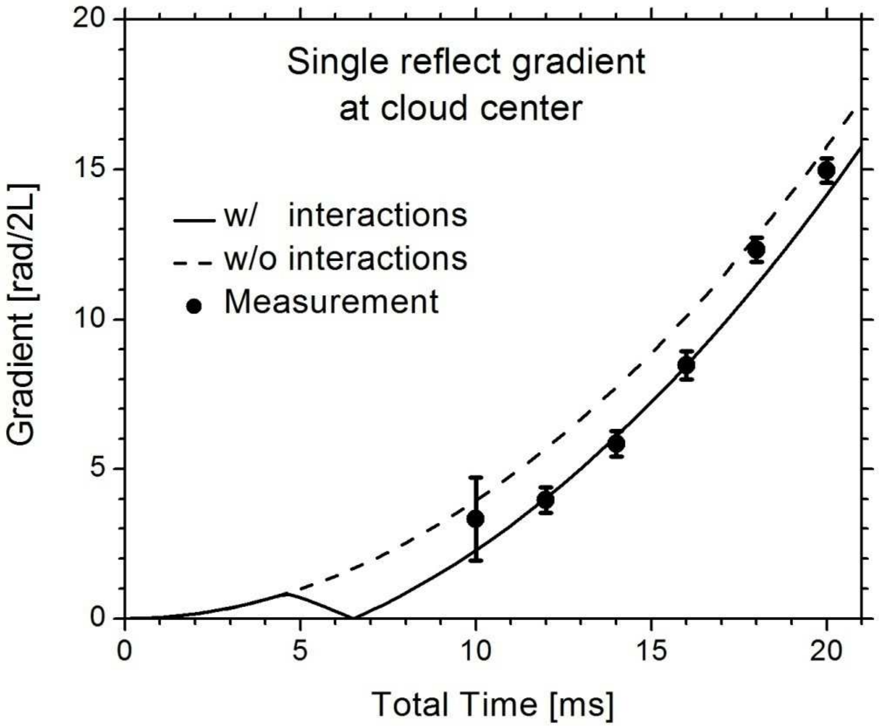
Phase Gradient Measurement

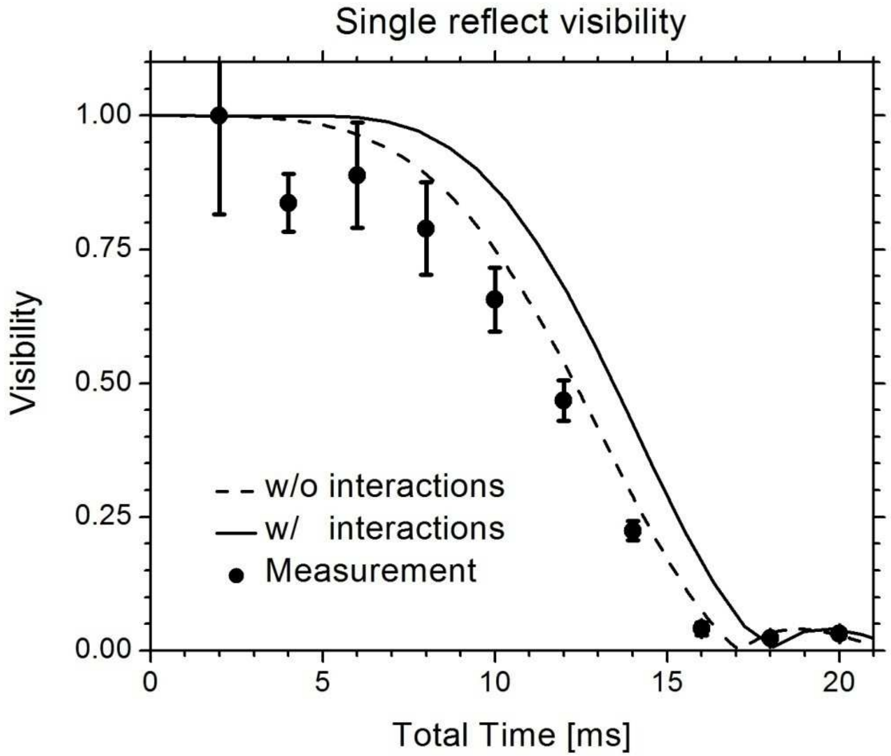


Integrate transverse direction

fit profile with modified Thomas Fermi function

Single Reflect Results

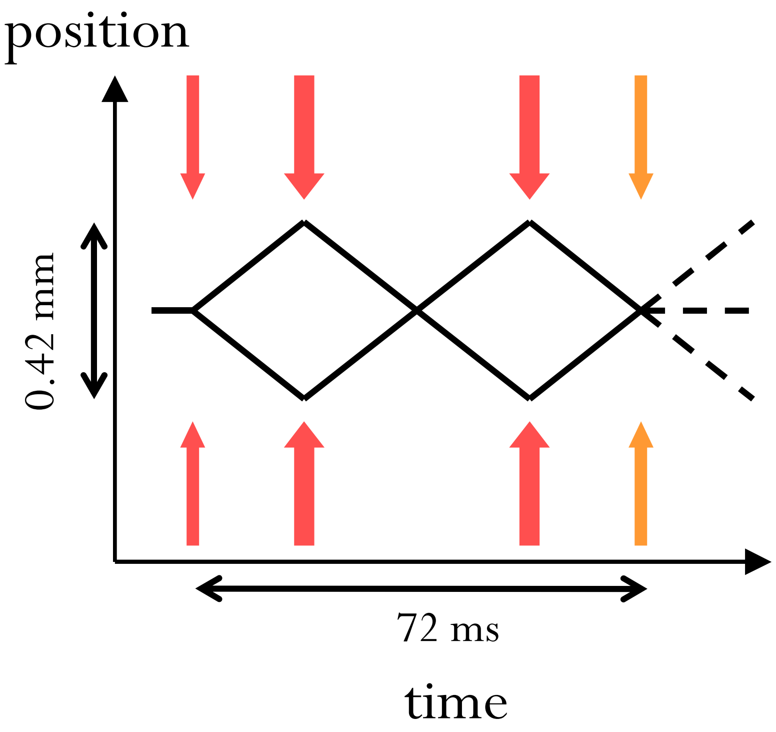


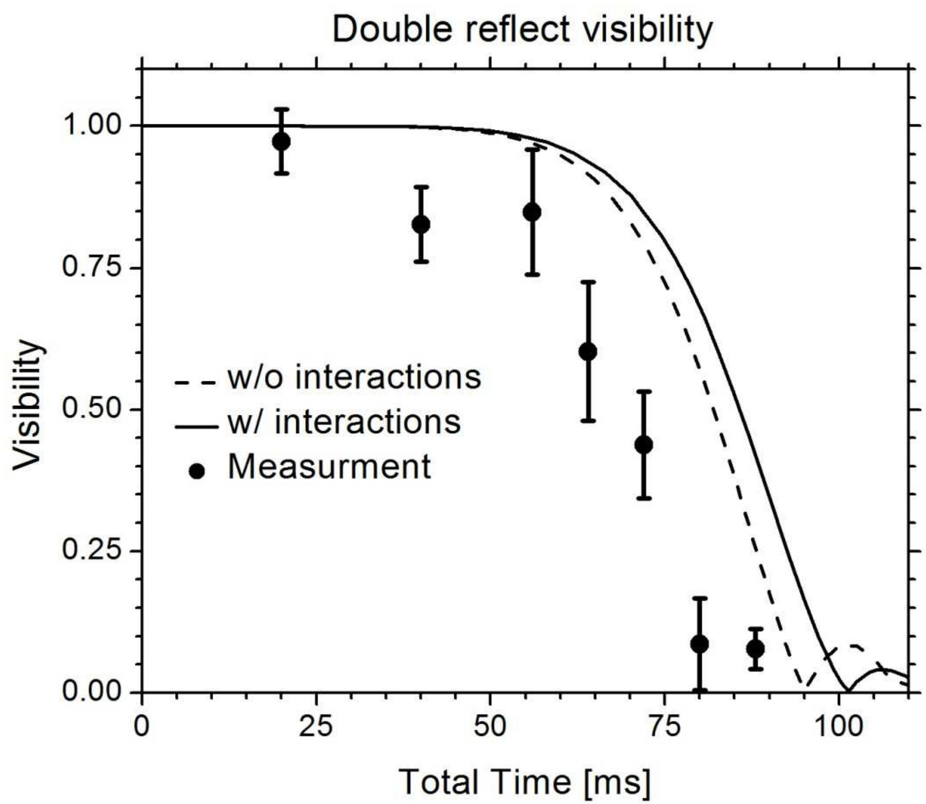


Symmetric Geometry (Double Reflect)

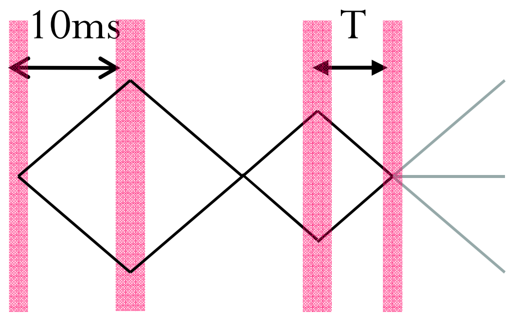
$\chi = 15\ \mu\text{m-s}$

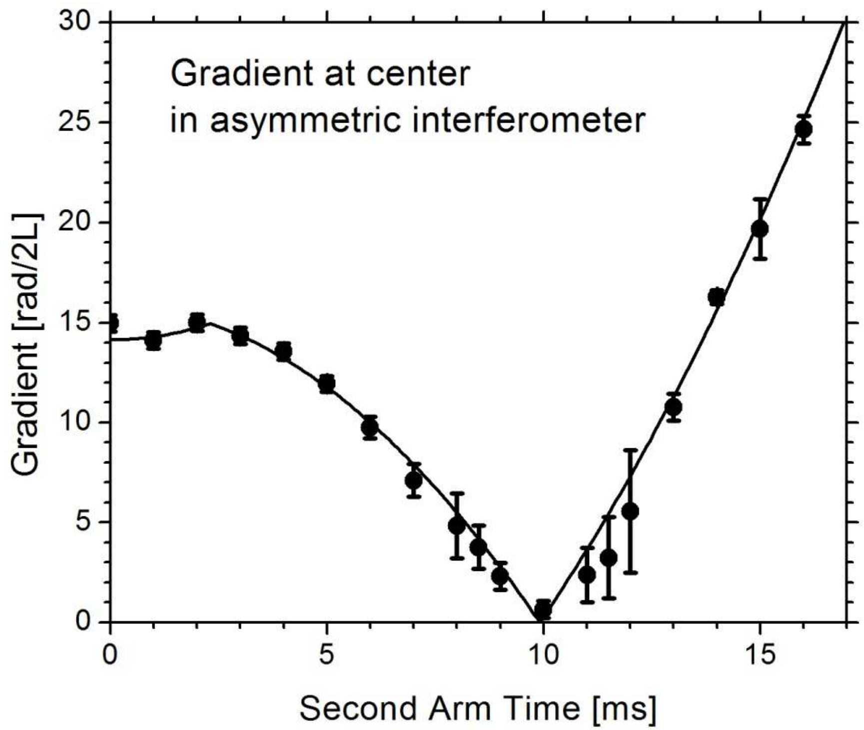
Gradient Partially Cancels

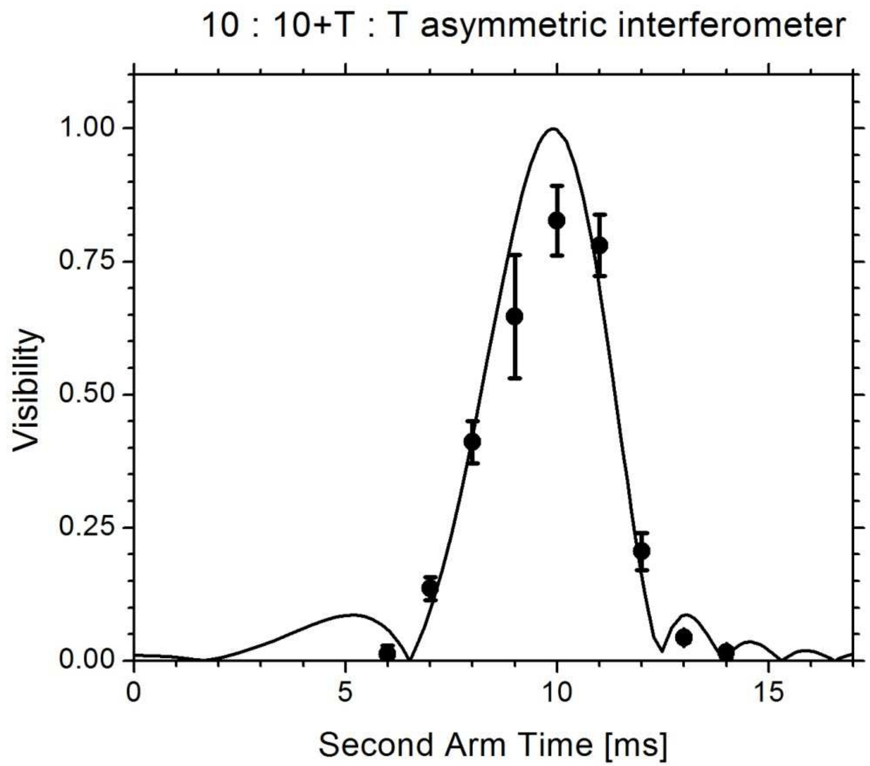




Asymmetric Interferometer





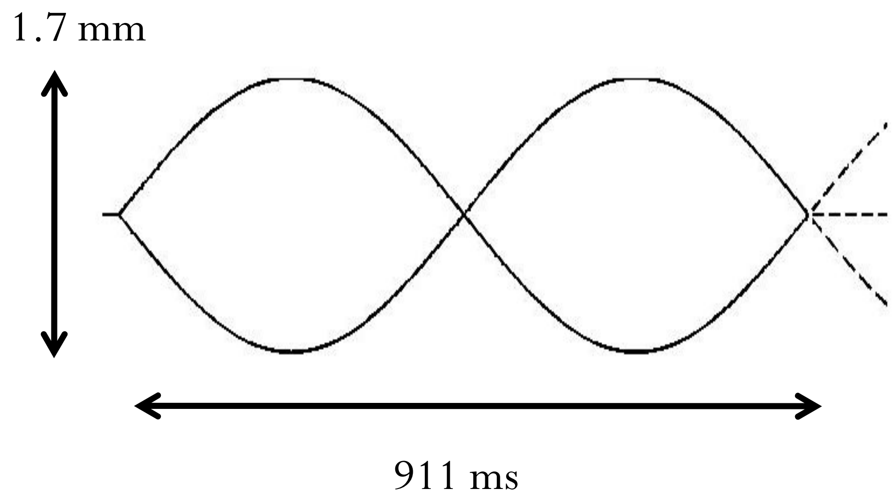


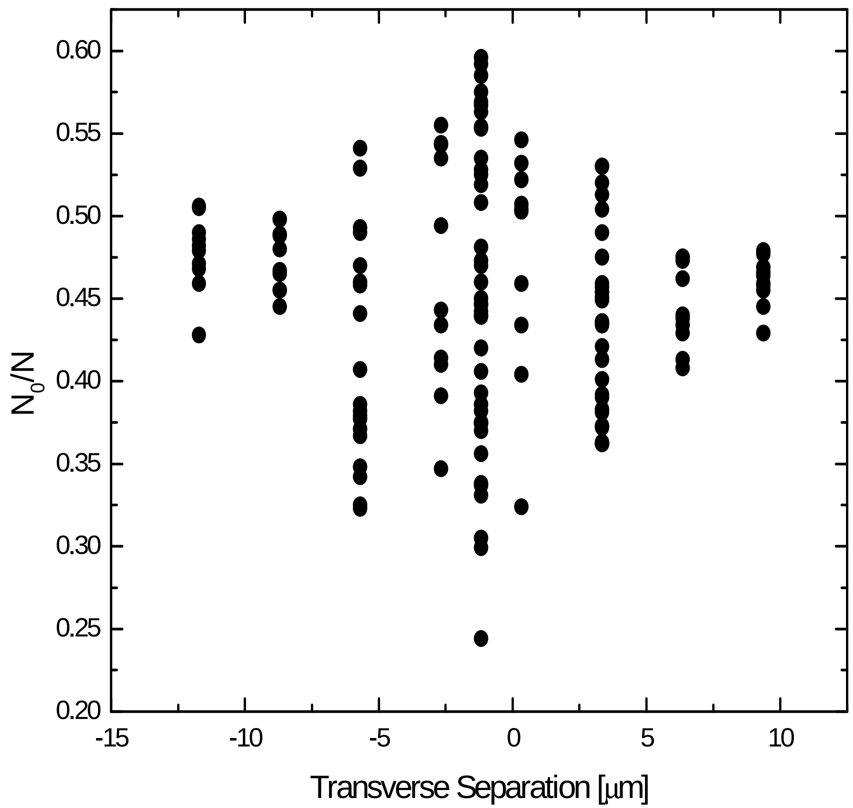
Free Oscillation (No Reflect)

$\chi = 850\ \mu\text{m-s}$

Not repeatable yet

Gradient Completely Cancels

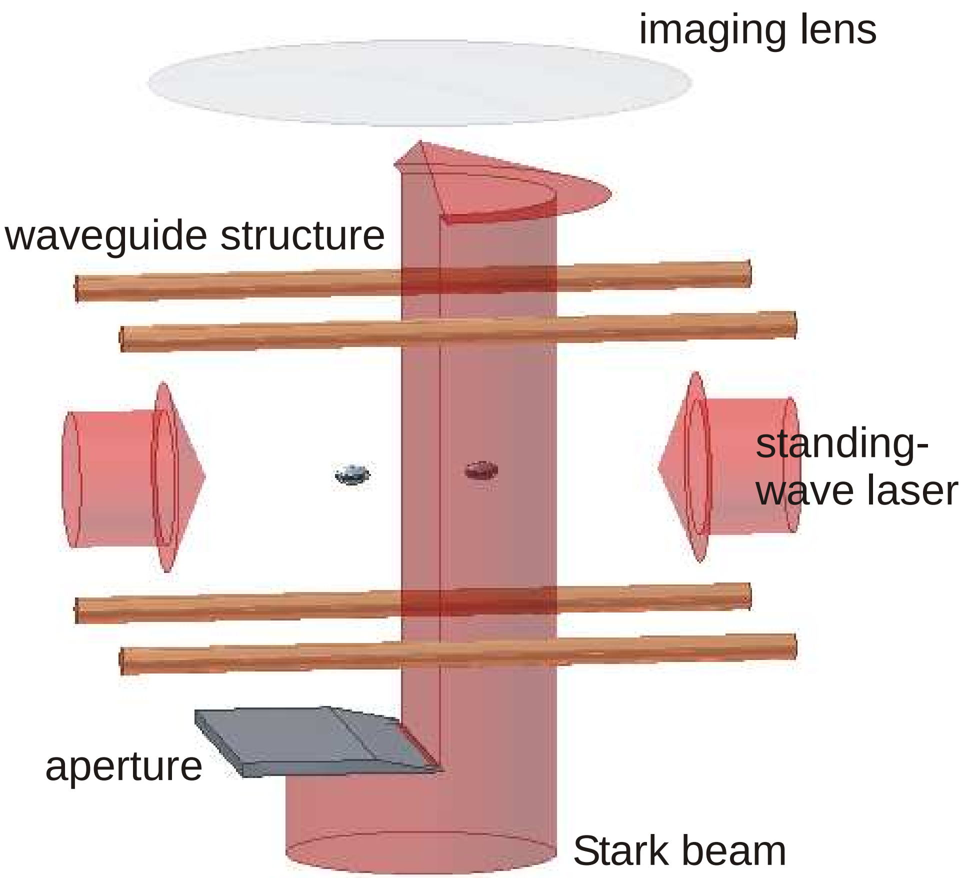




Recap

- Use waveguide to support atoms against gravity
    - Caused phase gradients
- Double reflect interferometer is better
    - Better arm separation by factor of 4
    - Better measurement time by factor of 5
- Understand that a waveguide with less confinement is desirable (in progress)
- Ready to use interferometer to make measurements

Recent Measurements
Dynamic AC Stark Shift



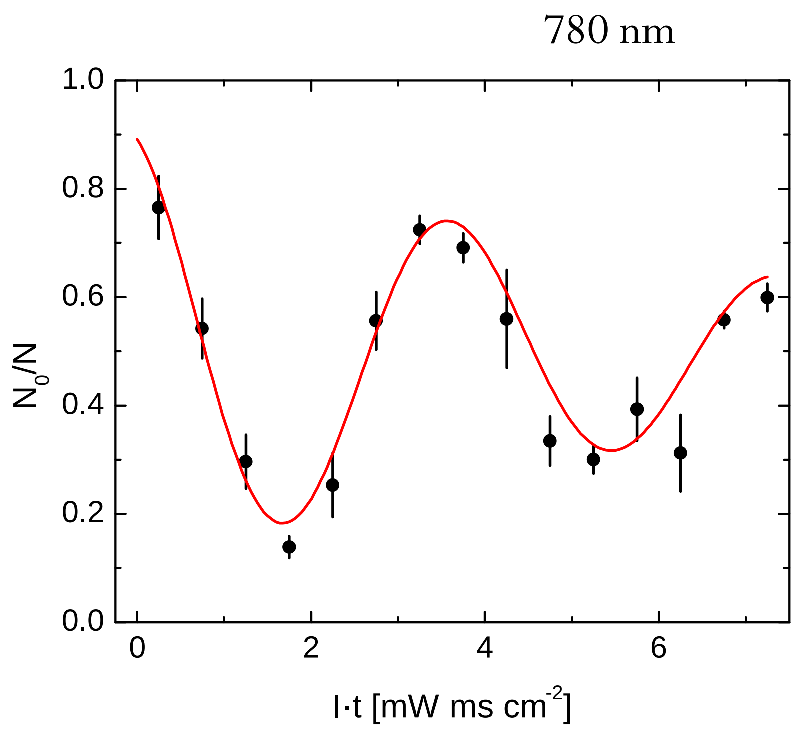
$$\Delta\phi = \frac{\alpha}{2c\hbar\varepsilon_0} It$$

α polirizability

I Intensity of pulse

t duration of pulse

AC Polarizability - Results

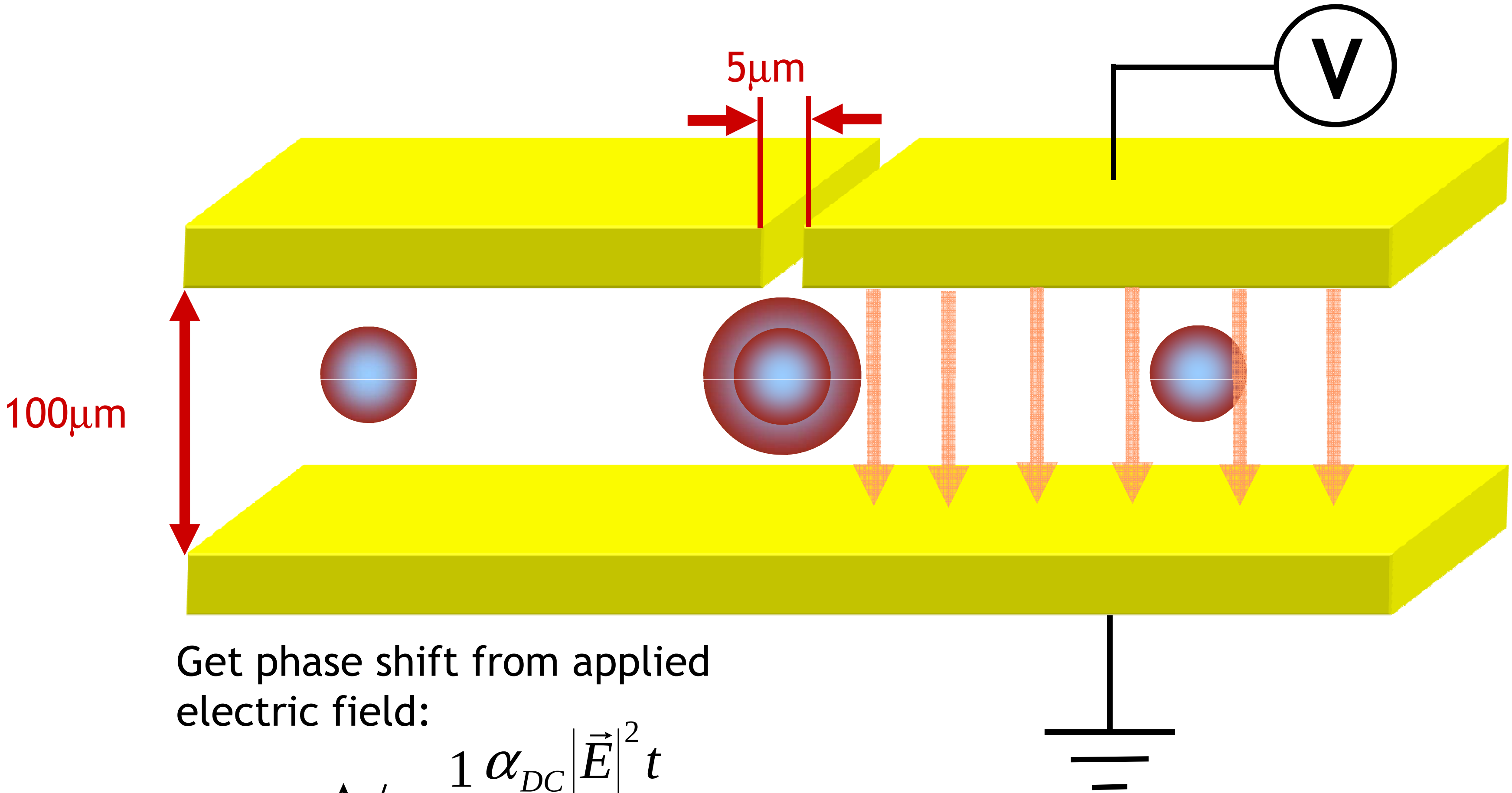


- Visibility falls of due to intensity gradients
- Limited by calibration in measurement of intensity of beam

$$\alpha_{\mathrm{exp}} = (8.37 \pm 0.24) \times 10^{-25}\,\mathrm{m}^{-3}$$

$$\alpha_{\mathrm{th}} = 8.67 \times 10^{-25}\,\mathrm{m}^{-3}$$

Future Measurements:
DC Polarizability



Get phase shift from applied electric field:

$$\Delta\phi = \frac{1}{2}\frac{\alpha_{DC}\left|\vec{E}\right|^2 t}{\hbar}$$

Special motivation: atomic clocks

SI second currently defined by Cs hyperfine transition freq

But Cs atoms don't work well at low temperatures:

- Rb atoms give better performance

Rb being considered as new standard

One limitation: black-body shift

Transition shifted by thermal radiation

effect ~ α_{dc}

Need to account for this, but α not known well enough

Better measurement would help resolve problem