Precision Metrology with Bose-Einstein Condensates

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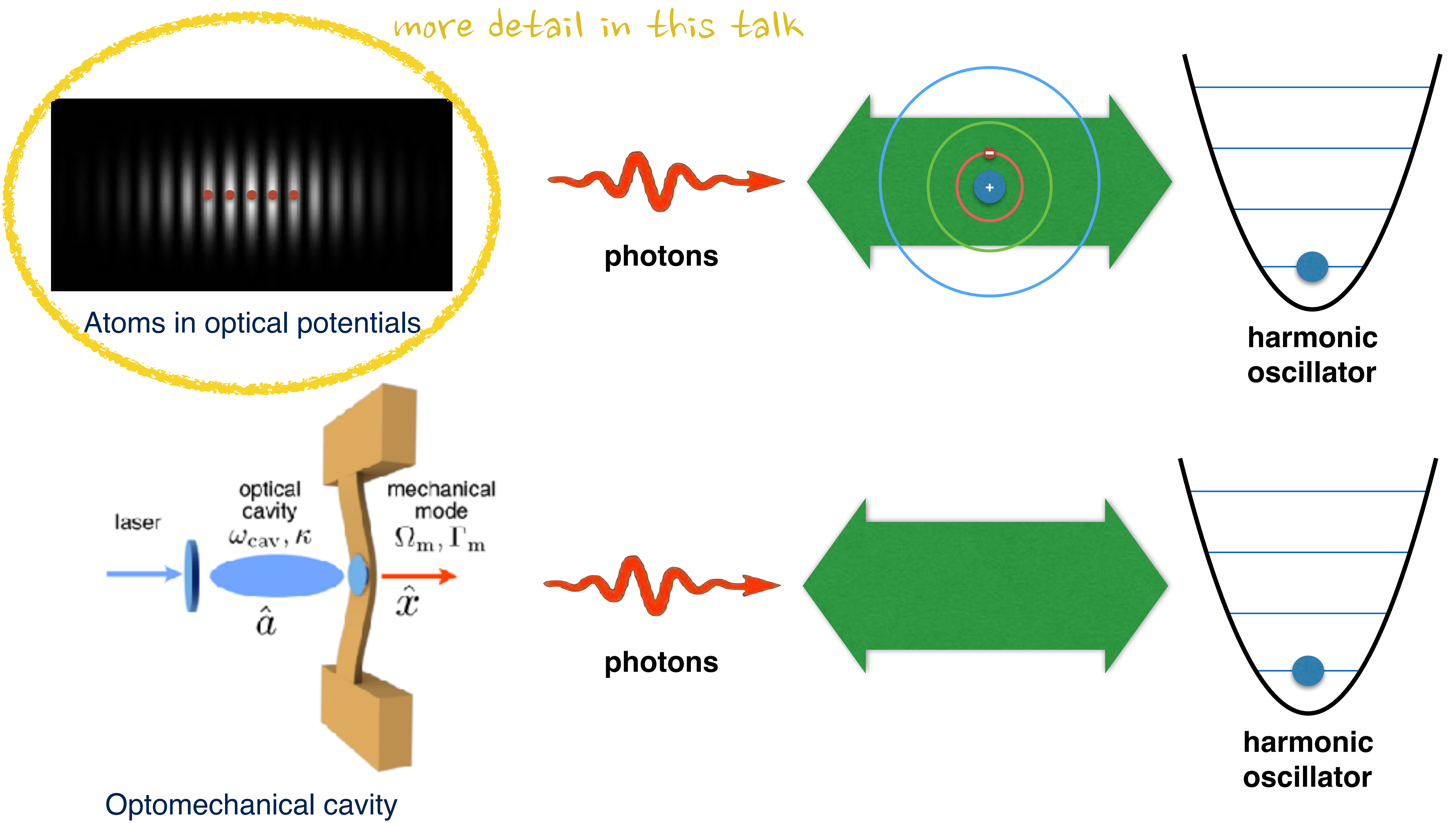
0. Why ultracold atoms?

1. Making BECs

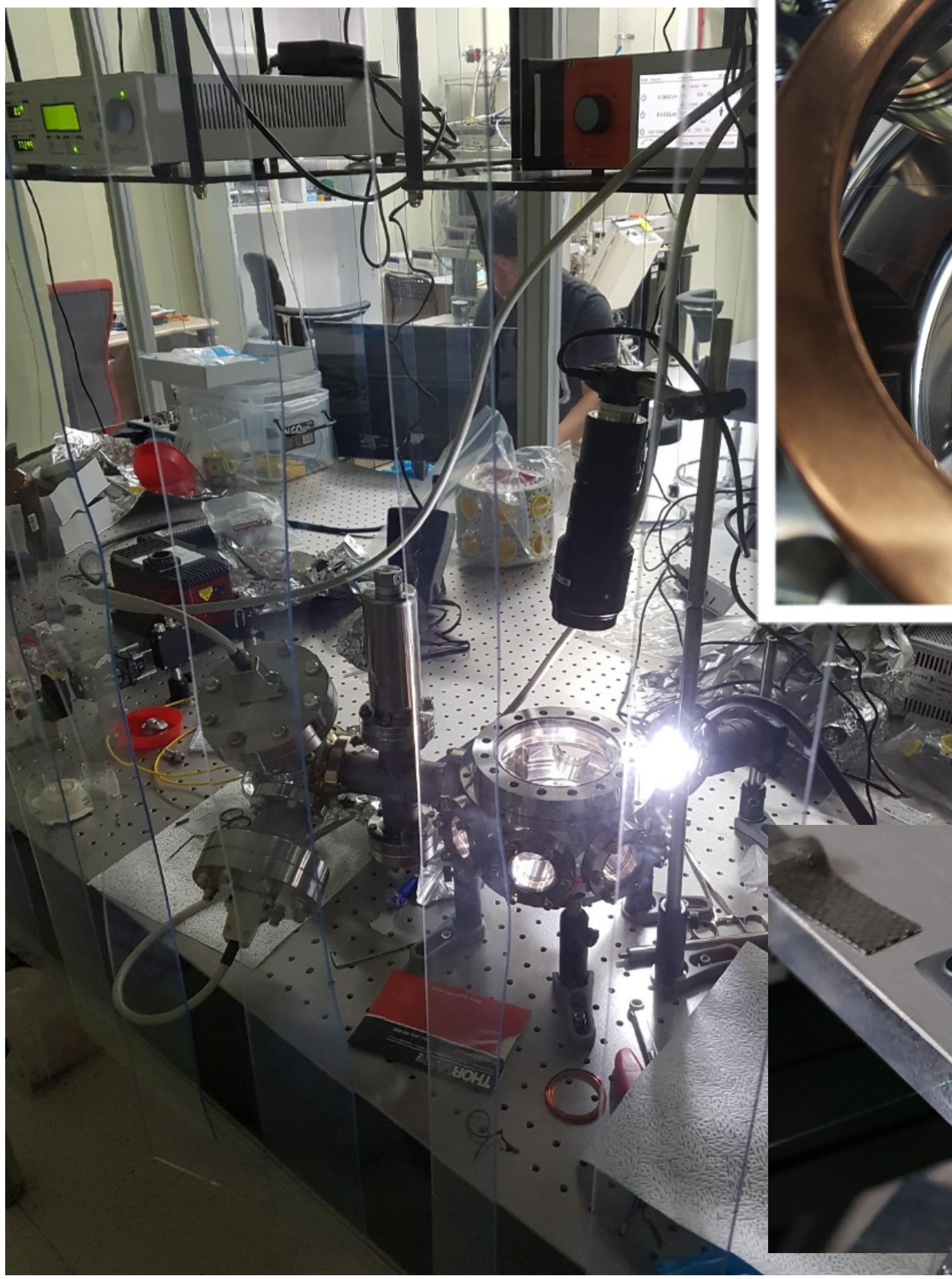
2. BEC matter wave interferometer

3. Quantum Simulator (Kondo lattice model)

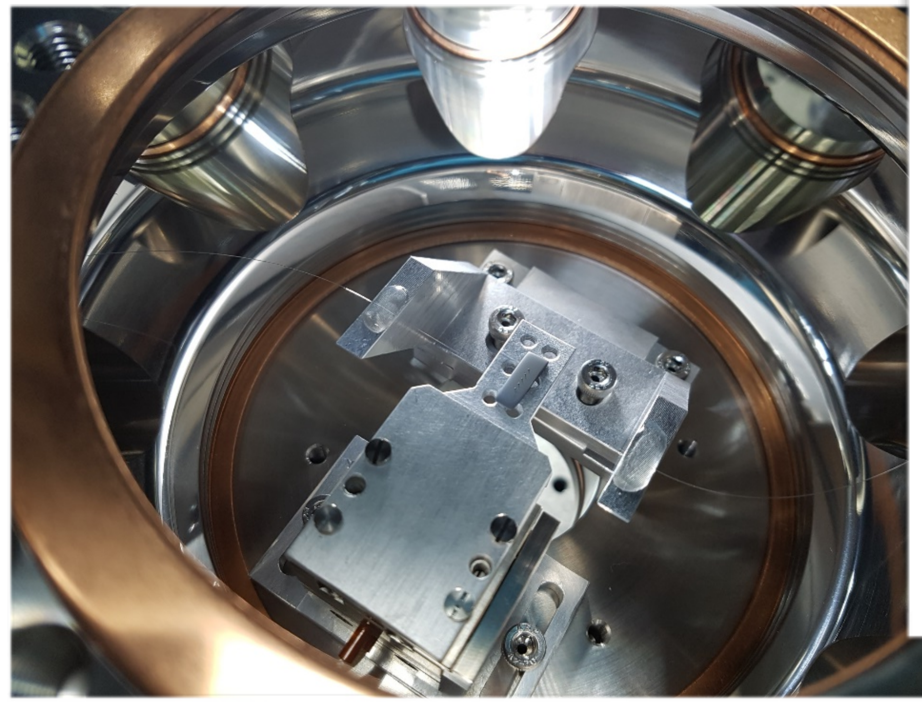
Cavity optomechanics

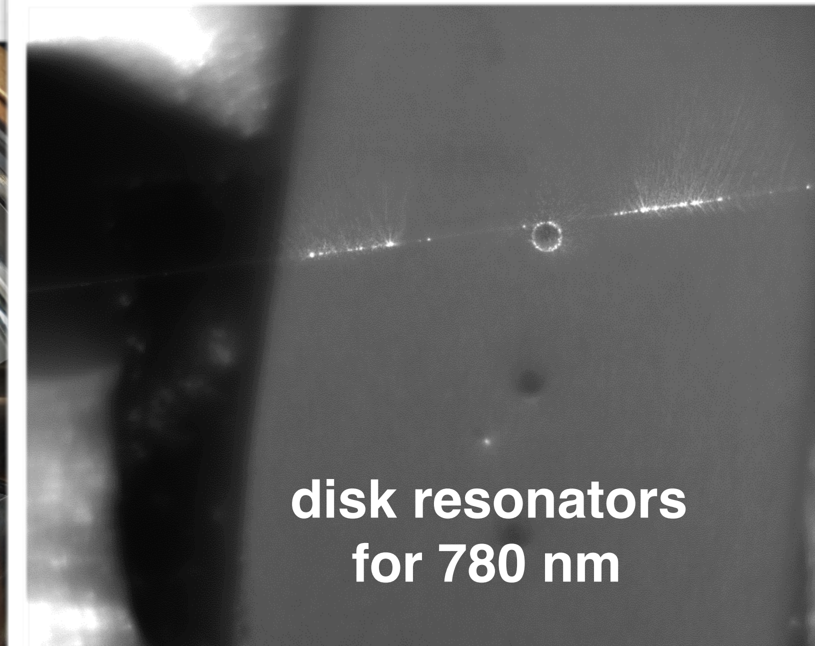


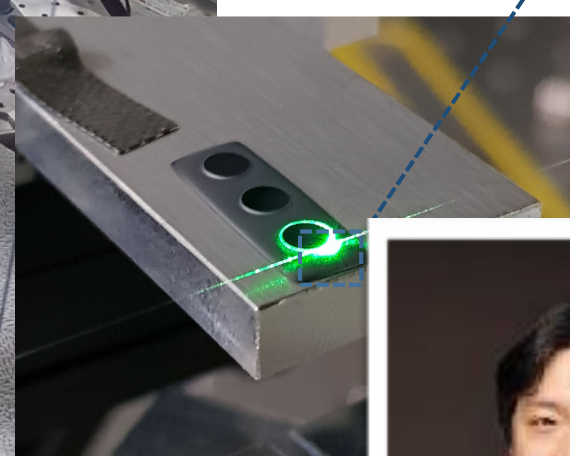
Quick recap of QND talk

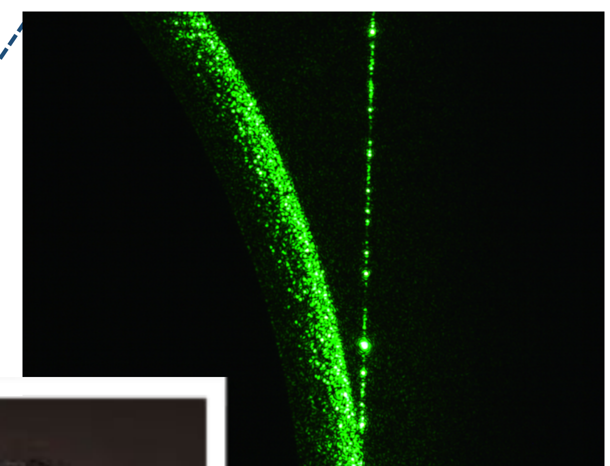


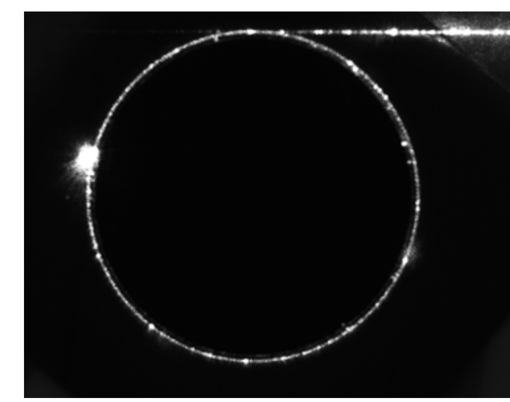
Vacuum Chamber setup



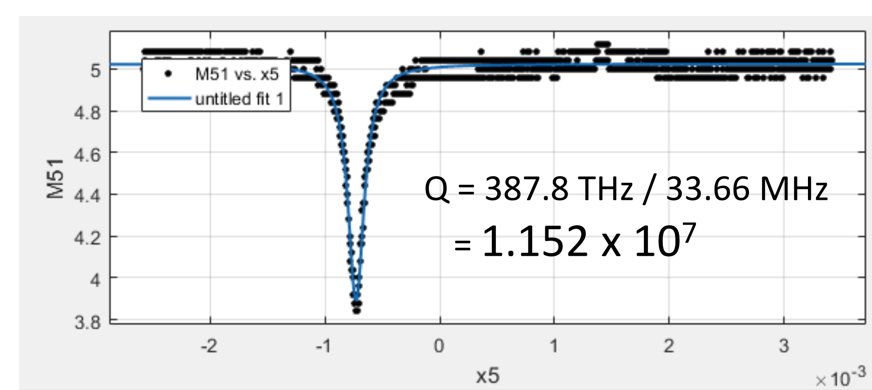






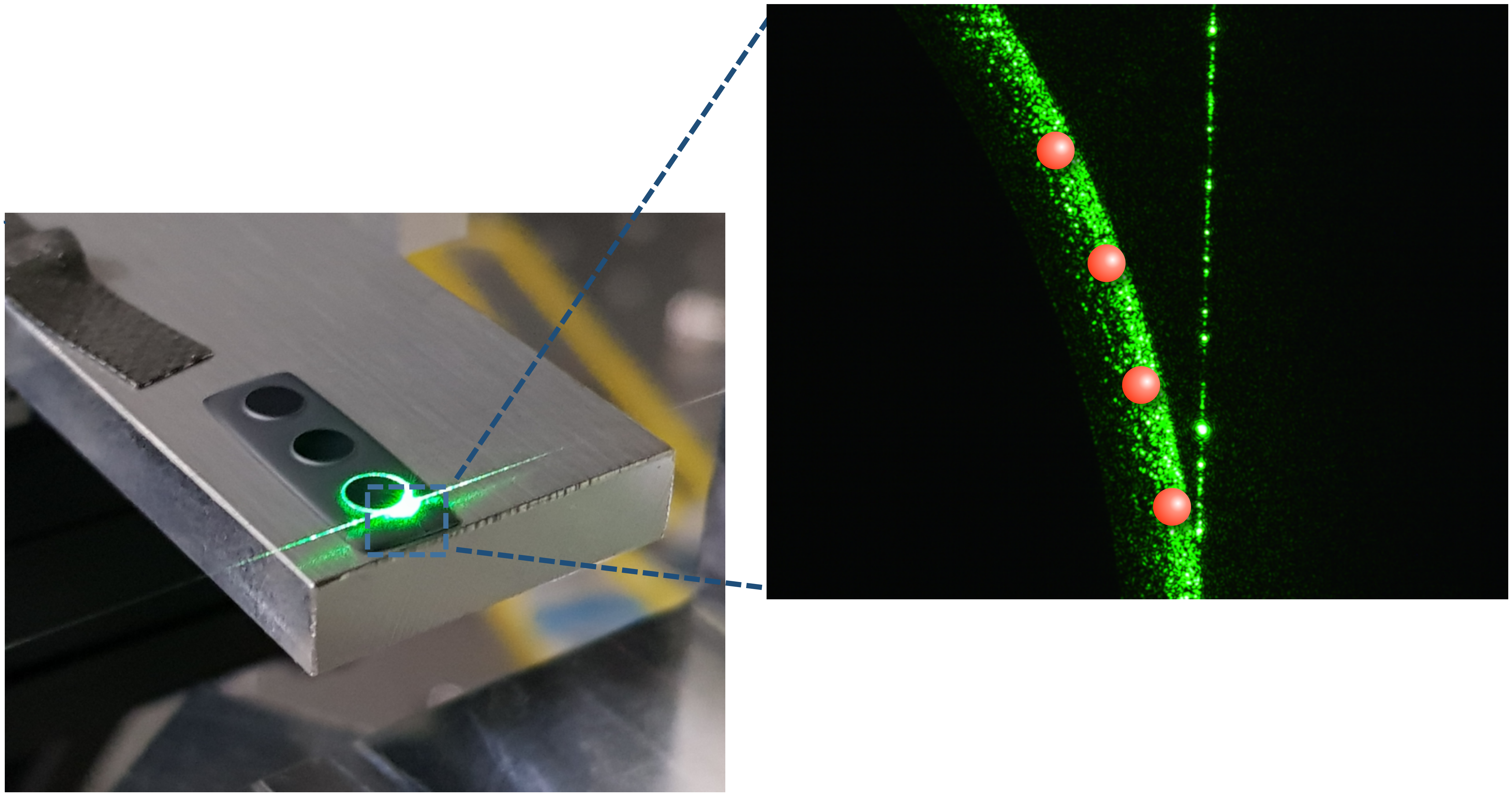


KAIST
이한석 교수



Quick recap of QND talk

atom + optomechanics



Ultracold Atoms

The Nobel Prize in Physics 1997

Photo from the Nobel Foundation archive.
Steven Chu
Prize share: 1/3

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Claude Cohen-Tannoudji
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William D. Phillips
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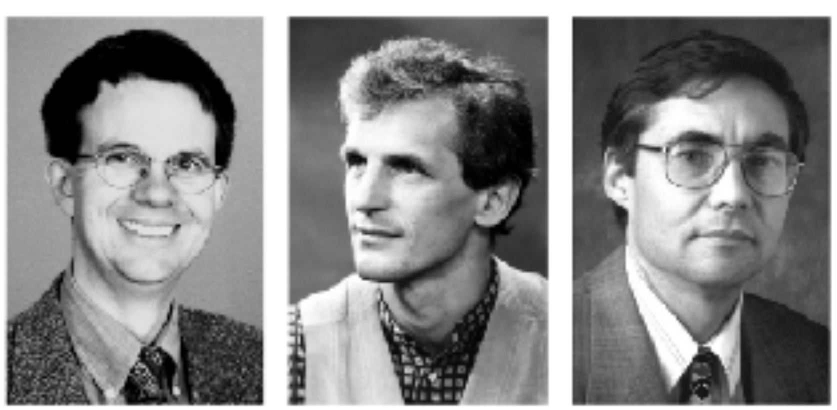
The Nobel Prize in Physics 2001



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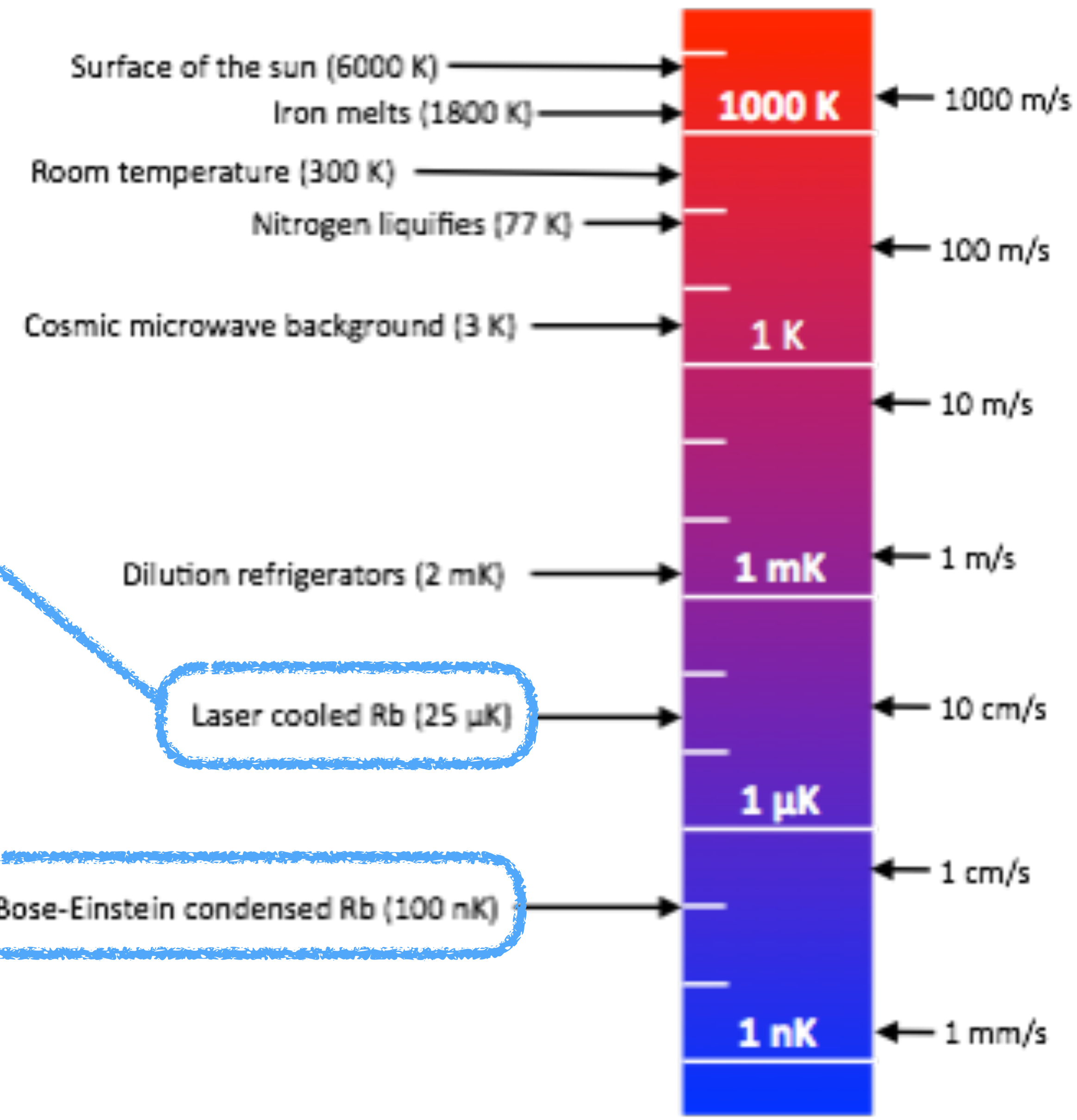
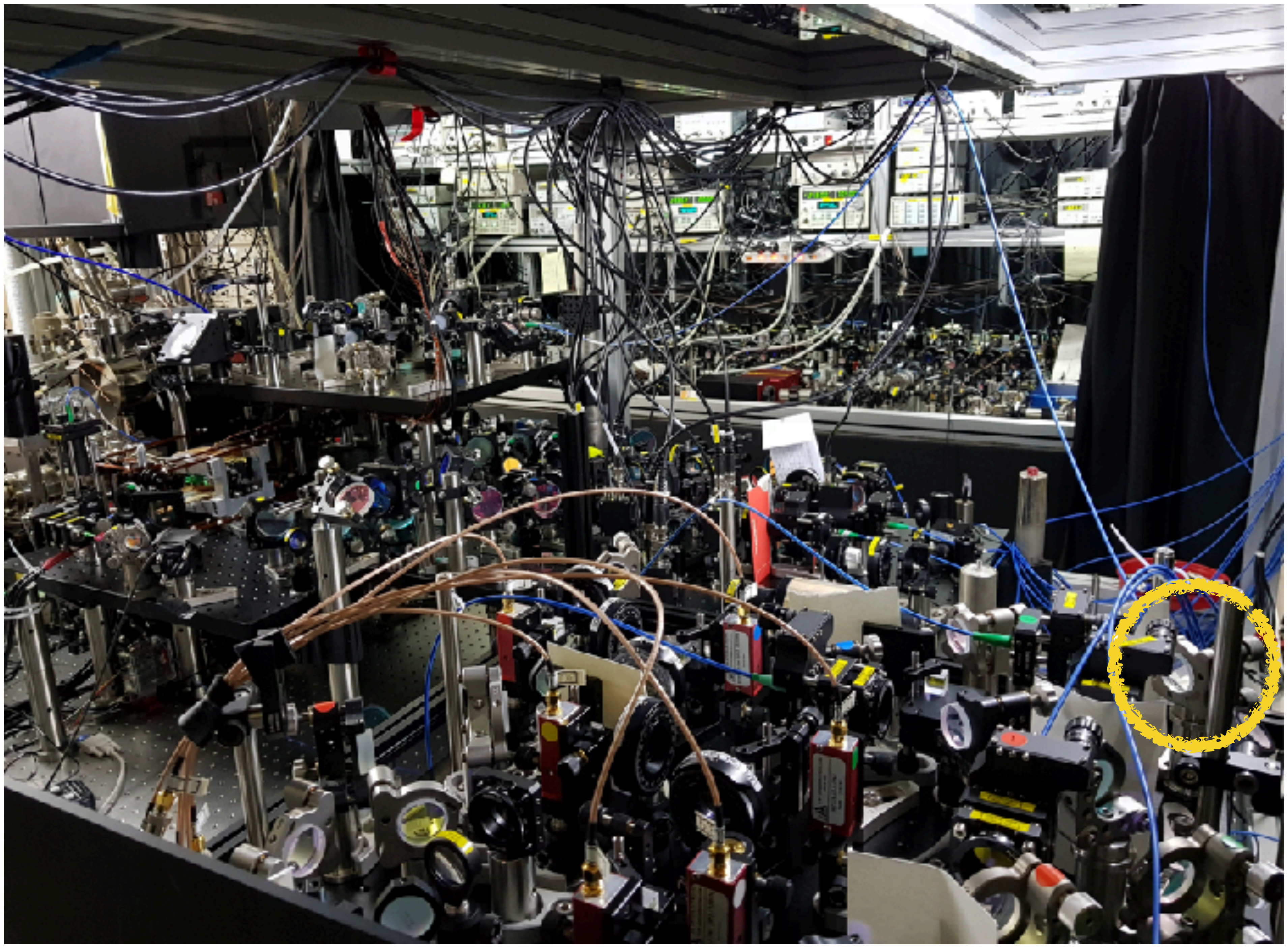
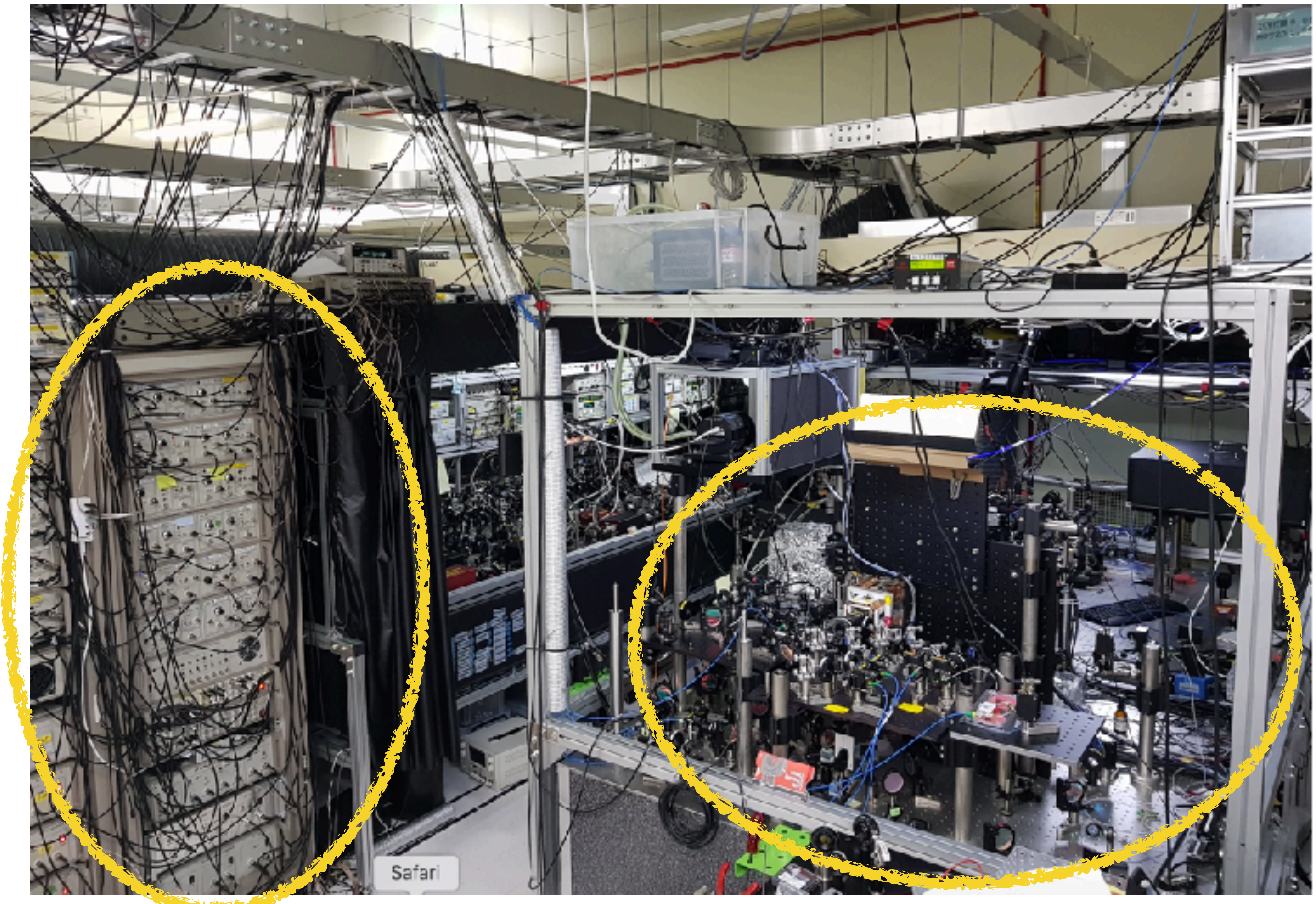


Ultracold atom experiments are hard/expensive

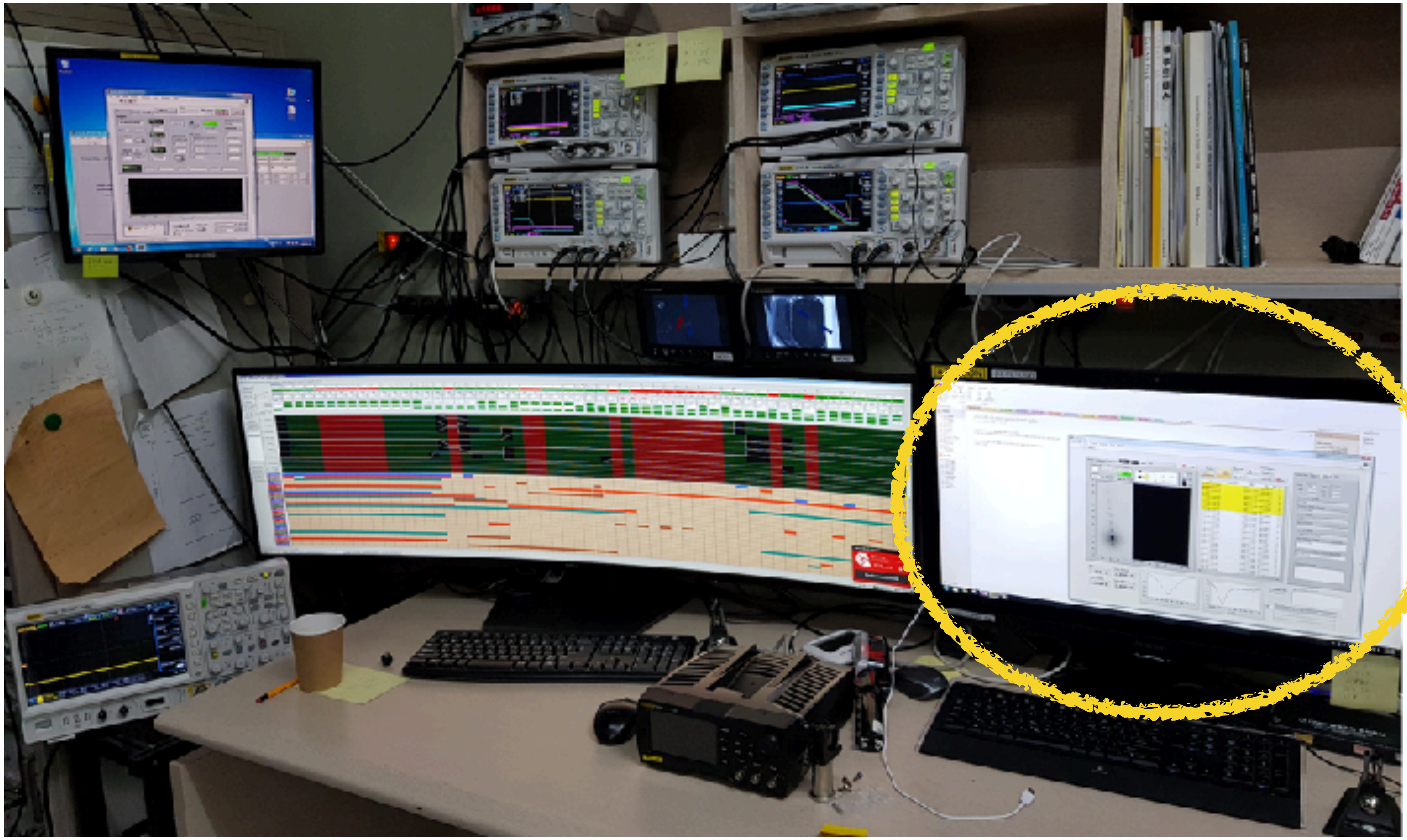


more than 500 optical components

Ultracold atom experiments are hard/expensive



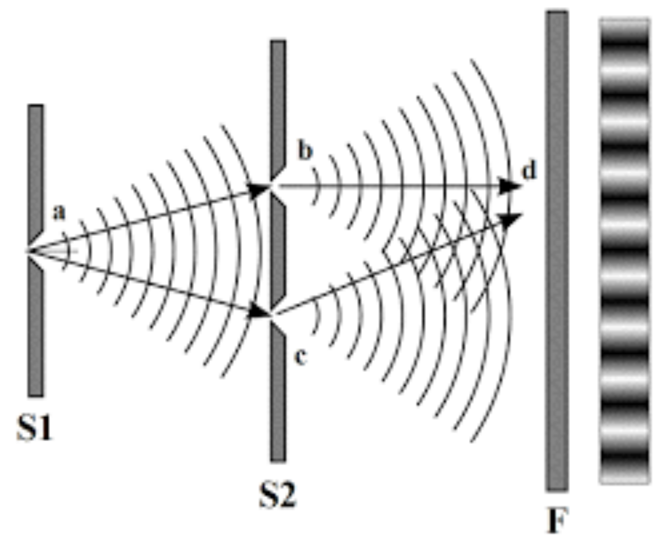
Ultracold atom experiments are hard/expensive



network of
10
computers

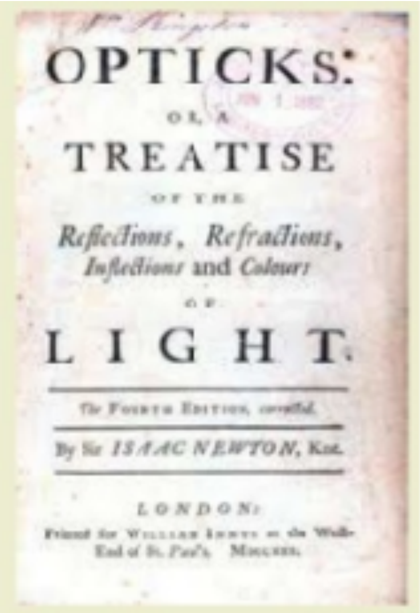
Why go through this pain?

Thomas Young (1801)



easy with laser…
but sunlight or candle?

Isaac Newton (1704)



light is a particle (corpuscle)
flying through void

Why go through this pain?

Thomas Young (1801)

to convince the audience
used water for presentation

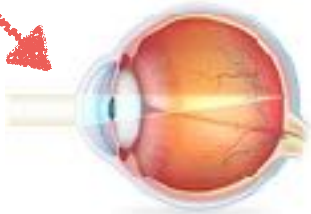
Why go through this pain?

Thomas Young (1801)

	water wave	light wave
λ	human scale (~cm)	sub micron
dynamics (frequency)	human scale (~20 Hz)	~500 THz
coherence	easy to observe	hard to observe (sun or candle)

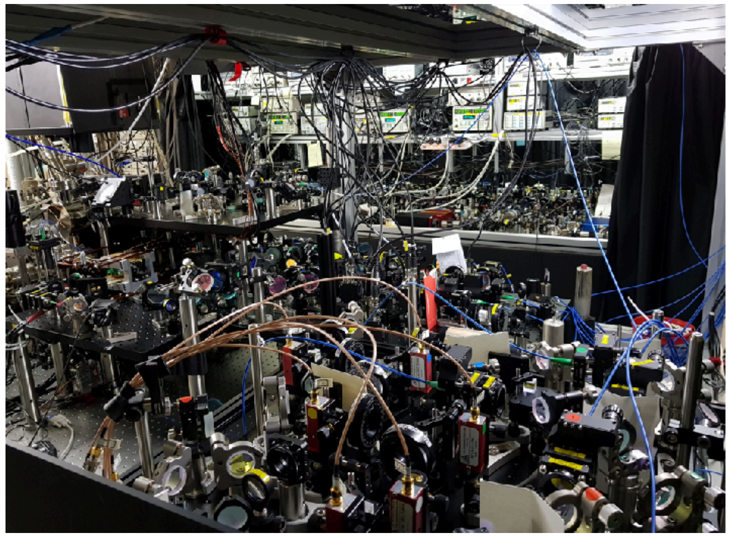
in order to explain **wave mechanics of light**
you need to understand **light fields (E)** and **human eye**

$$I = \frac{cn\varepsilon_0}{2}|E|^2$$



~10 Hz bandwidth detector

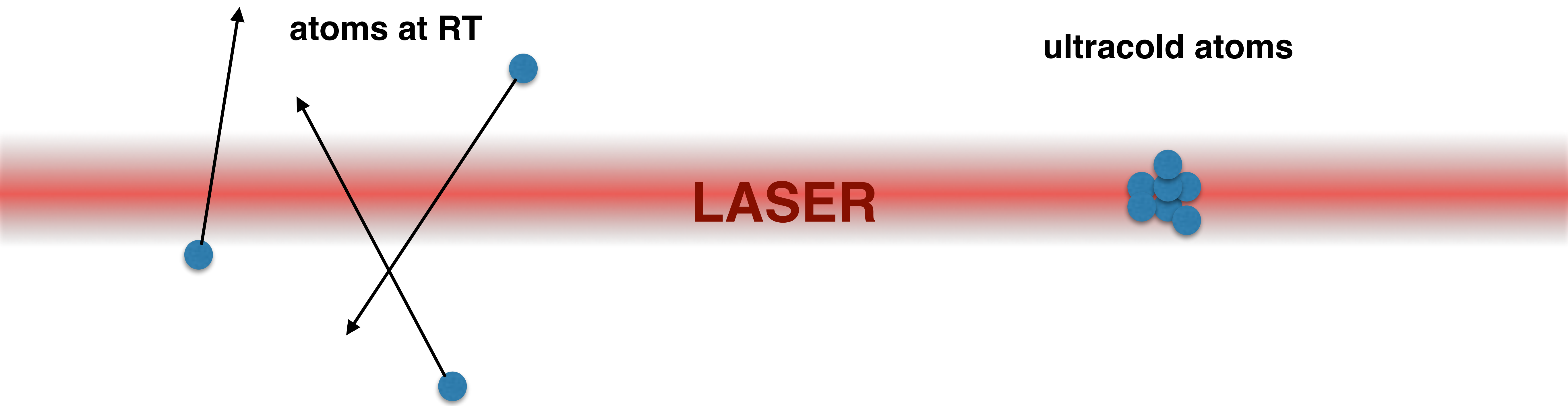
Why go through this pain?



	BEC (100 μK)	atom vapor (300 K)
λ (de Broglie)	~ 20 μm	~ 1 Å
dynamics (speed)	~ 1 mm/s	~100 m/s
coherence	easy to observe	hard to observe

Ultracold atom technology is a awesome tool to study Quantum Phenomena

Ultracold atoms : “quantumness” amplifier



interrogation limited by transient time

interrogation limited by gravity, photon scattering, background gas collision etc.

measurements!

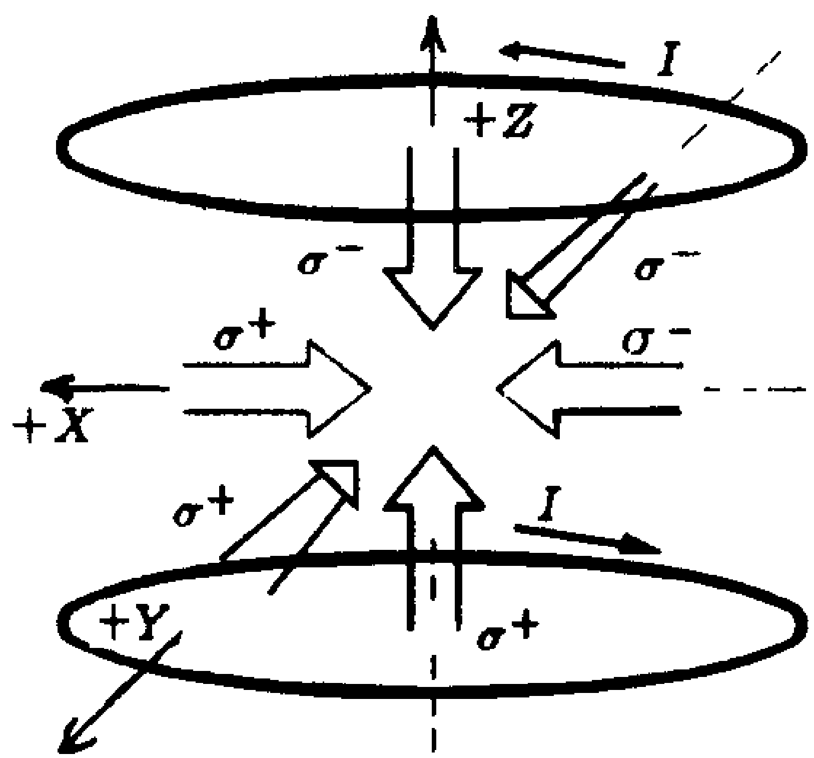
Ultracold atoms : “quantumness” amplifier

short interrogation time

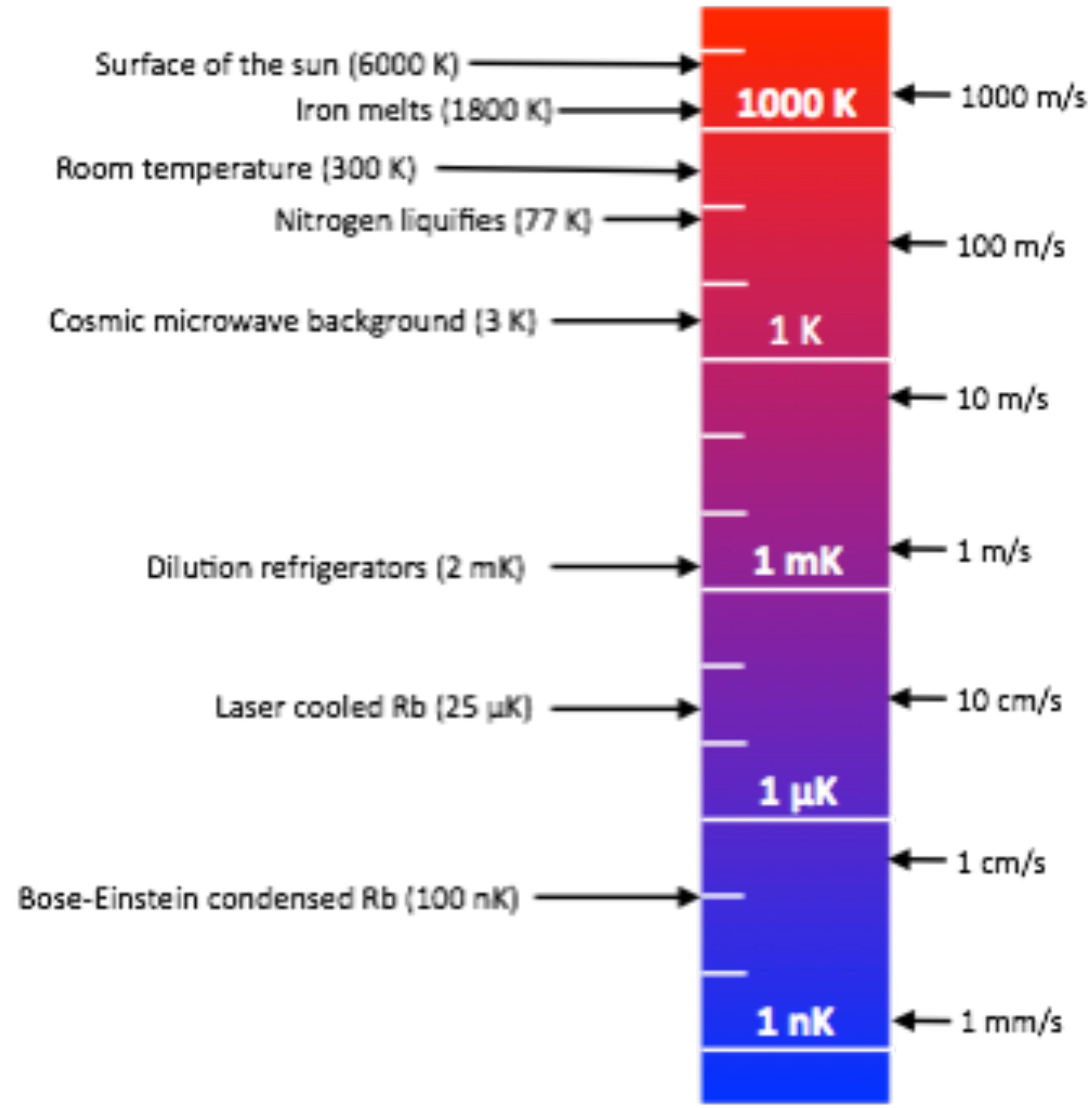
long interrogation time

How to make Ultracold Atoms

First, laser cooling



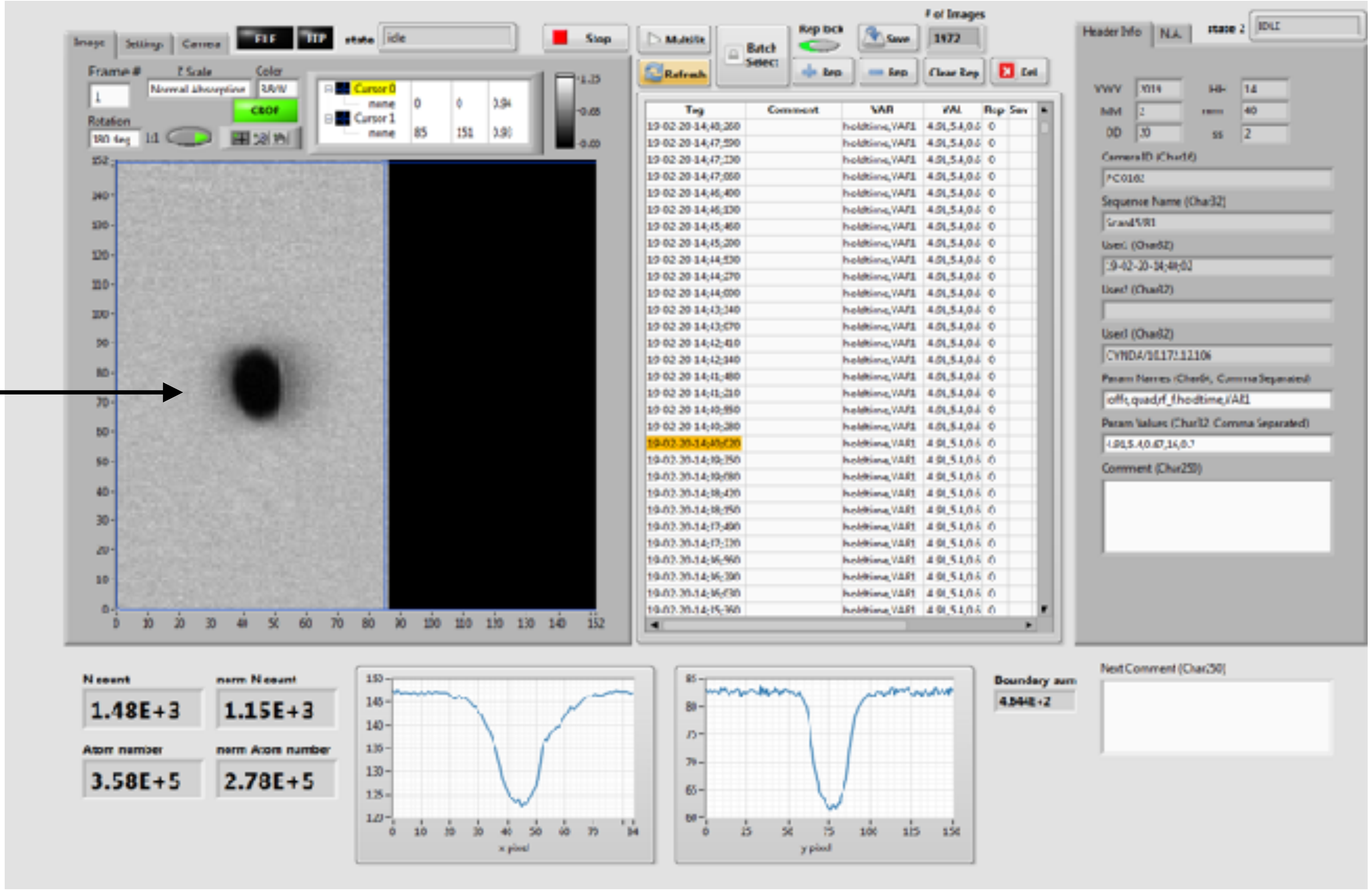
Further cooling
e.g. evaporative cooling



Making a BEC

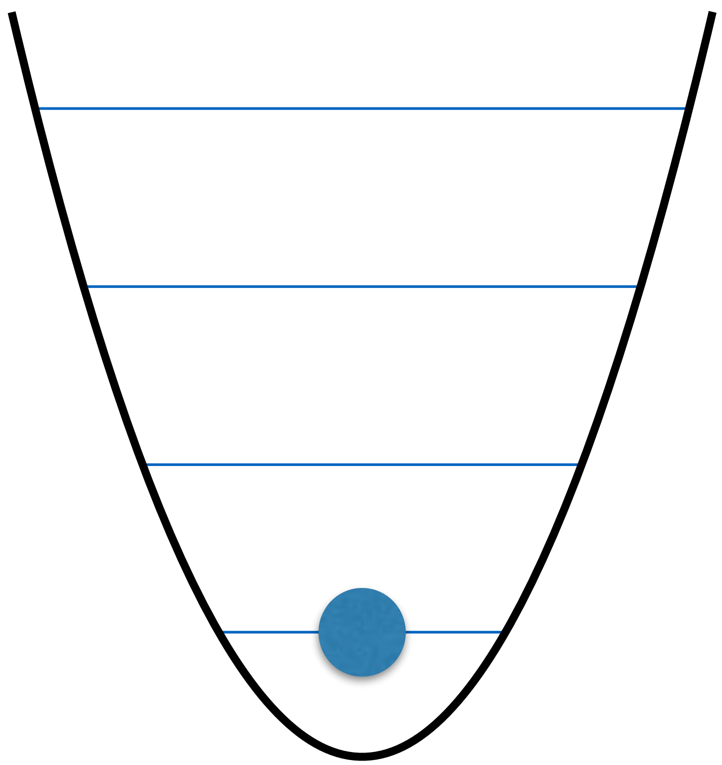
Making a BEC

shadow



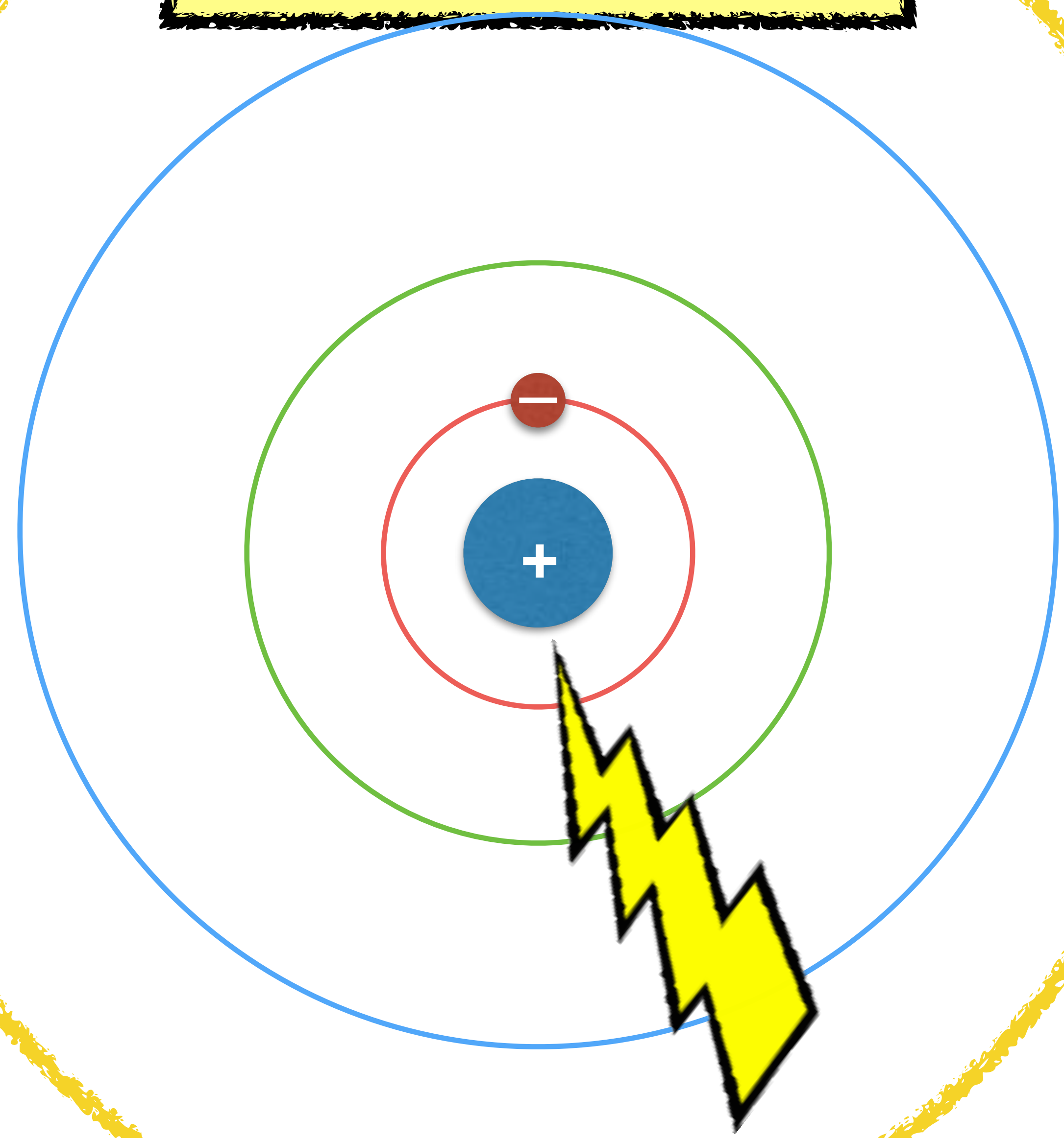
냉각 및 포획된 원자의 양자상태

Motional quantum state



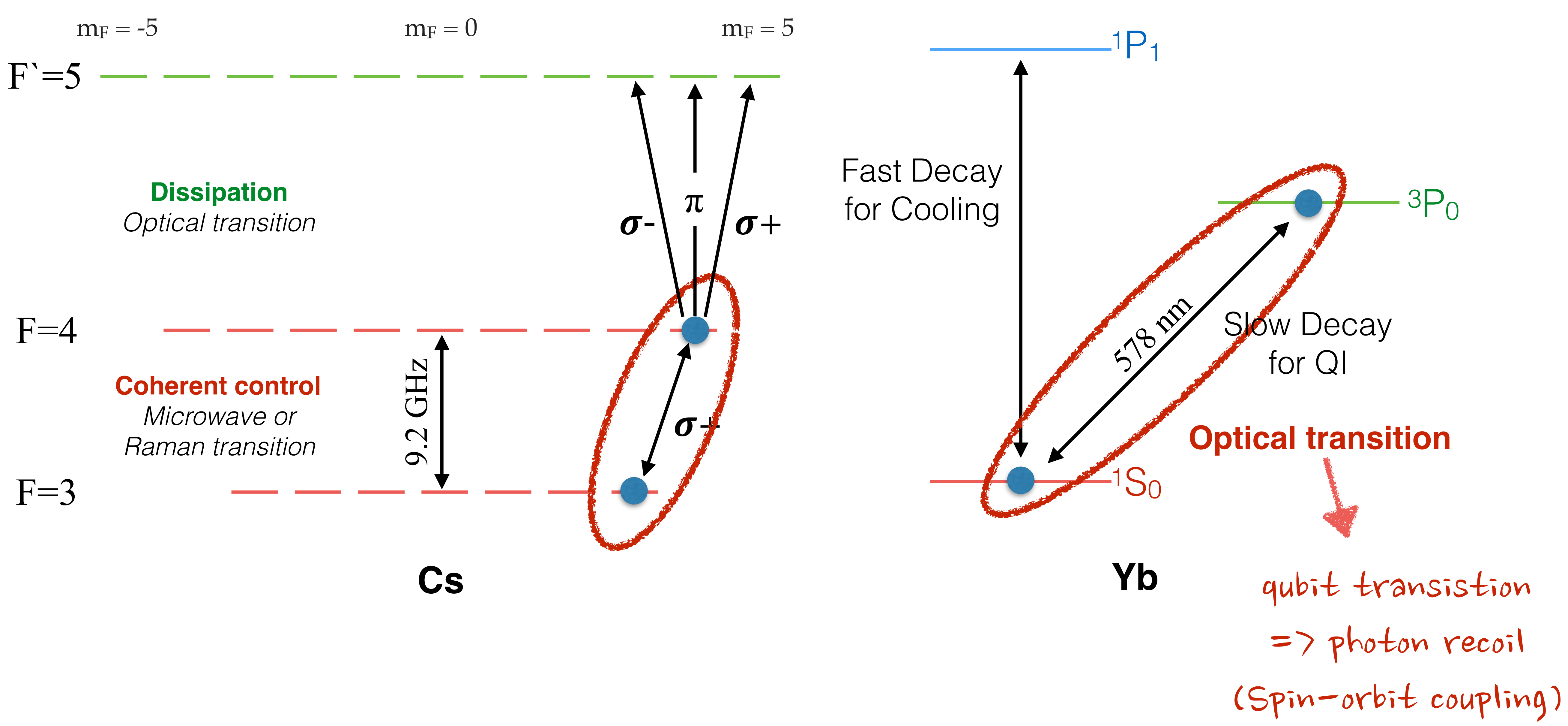
Electromagnetic
or
Magnetic **potential**
or
Electric

Internal quantum state

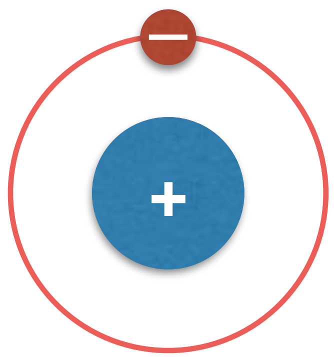


control with **lasers**, **microwaves**, and **B-fields**

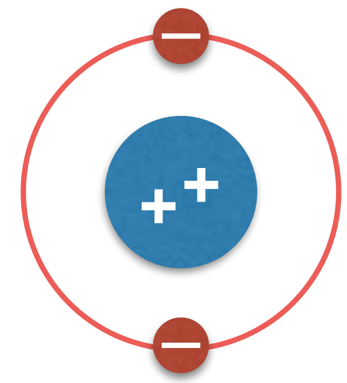
1. Making BECs



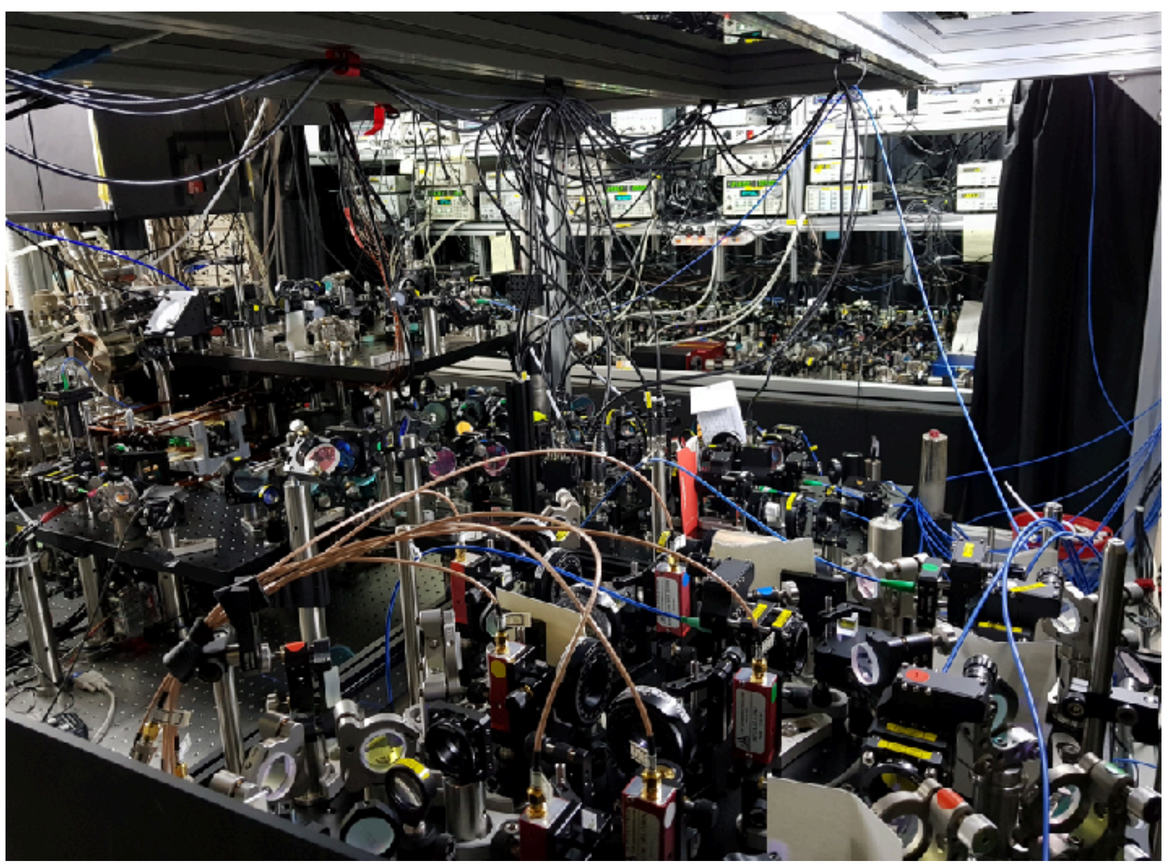
1. Making BECs



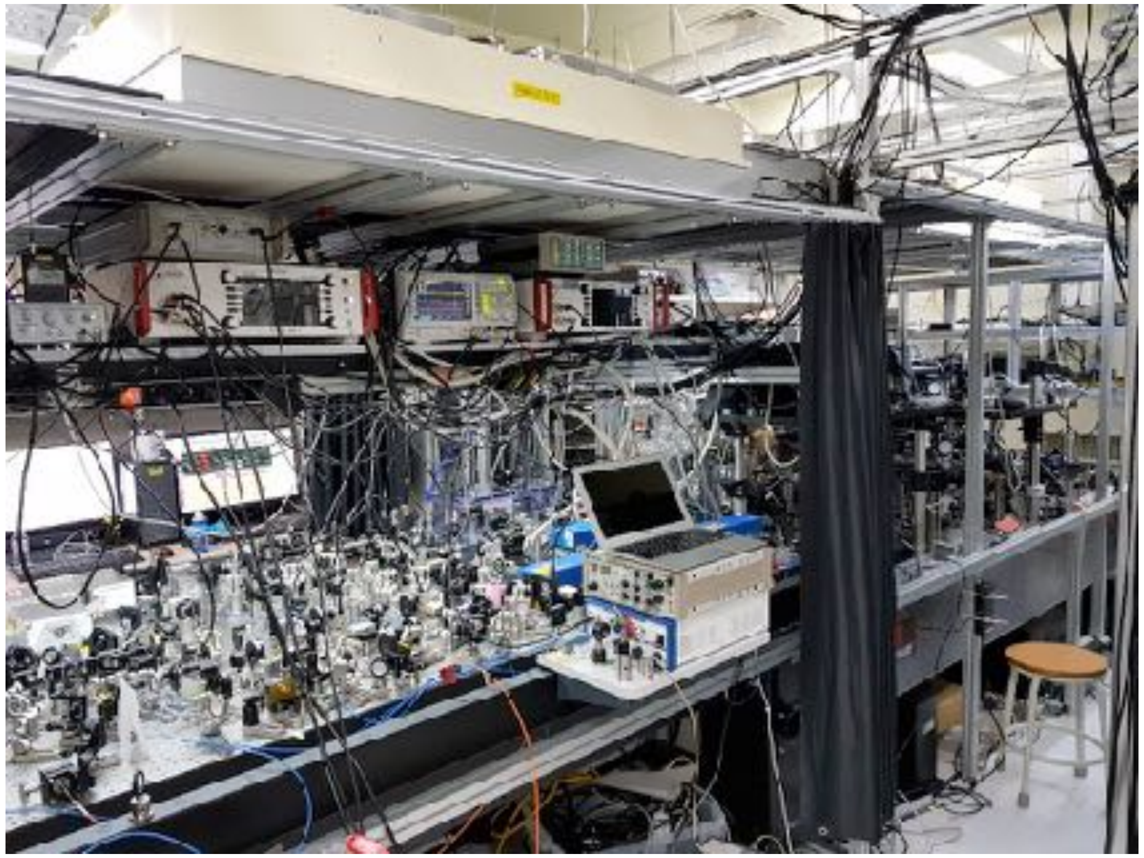
Alkali Atoms



Alkaline-Earth-Metal-like Atoms



Rb, K



Yb

Applying light to atoms

a little bit of math…

Rabi Frequency

$\omega_{\mathrm{R}} \equiv \vec{E}_0 \cdot \vec{\mu}_{ge}/\hbar$

Hamiltonian of BEC

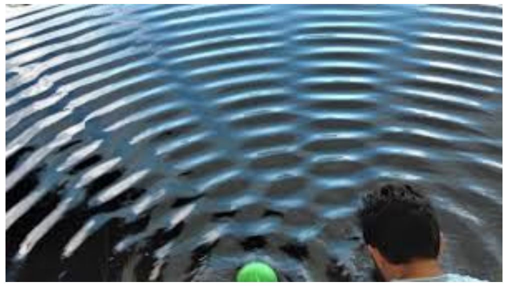
$$\hat{H}' = \frac{(\hat{\vec{p}}_{\mathrm{CM}})^2}{2M} + \hbar\omega_0 \left|e\right\rangle\left\langle e\right| + \frac{\hbar\omega_{\mathrm{R}}}{2} e^{i\vec{k}_{\mathrm{rec}}\cdot\hat{\vec{x}}_{\mathrm{CM}} - i\omega t} \left|e\right\rangle\left\langle g\right| + \frac{\hbar\omega_{\mathrm{R}}^*}{2} e^{-i\vec{k}_{\mathrm{rec}}\cdot\hat{\vec{x}}_{\mathrm{CM}} + i\omega t} \left|g\right\rangle\left\langle e\right|$$

K.E. — optical transition — dipole matrix elements

Transform using operator $\hat{T}(\omega) \equiv \left|g\right\rangle\left\langle g\right| + e^{i\omega t}\left|e\right\rangle\left\langle e\right|$ via $\hat{H}'(t) = \hat{T}(t)\hat{H}(t)\hat{T}^\dagger(t) + i\hbar\frac{d\hat{T}}{dt}\hat{T}^\dagger(t)$

$$\hat{H} = \frac{(\hat{\vec{p}}_{\mathrm{CM}})^2}{2M} + \frac{\hbar\omega_{\mathrm{R}}}{2} e^{i\vec{k}_{\mathrm{rec}}\cdot\hat{\vec{x}}_{\mathrm{CM}}} e^{-i\delta t} \left|e\right\rangle\left\langle g\right| + \frac{\hbar\omega_{\mathrm{R}}^*}{2} e^{-i\vec{k}_{\mathrm{rec}}\cdot\hat{\vec{x}}_{\mathrm{CM}}} e^{i\delta t} \left|g\right\rangle\left\langle e\right|$$

~10^{10} smaller than $\hbar\omega_0$ for ultracold atoms



2nd order perturbation $\hat{U} = \hbar\frac{|\omega_{\mathrm{R}}|^2}{4\delta}\left|g\right\rangle\left\langle g\right|$

AC stark shift

2. BEC matter wave interferometer

Diffraction by counter propagating beams

Schrodinger equation in the regime $\delta \gg \omega_{\mathrm{R}} \gg \omega_{\mathrm{rec}}$

$$i\hbar\frac{\partial\psi}{\partial t} = \hat{U}(x)\psi \quad \rightarrow \quad \hat{U} = \hbar\frac{|\omega_{\mathrm{R}}|^2}{4\delta}\,|g\rangle\langle g|$$

for counter propagating fields $E_0\hat{z}(e^{-ikx} + e^{ikx})$

$$i\hbar\frac{\partial\psi}{\partial t} = \hbar\omega_{\mathrm{R}}^{(2)}(t)\cos(2kx)$$

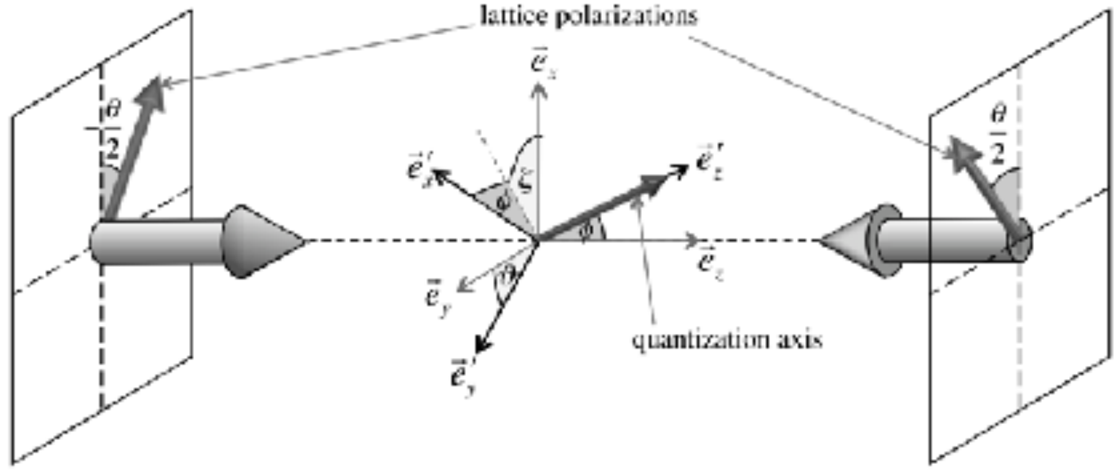
$$\psi(x,t) = \exp\left[i\left(\int_0^t dt'\,\omega_{\mathrm{R}}^{(2)}(t')\right)\cos(2kx)\right]\psi(x,0)$$

$$= \sum_{n=-\infty}^{\infty} i^n J_n(\theta)e^{i(2nk)x}$$

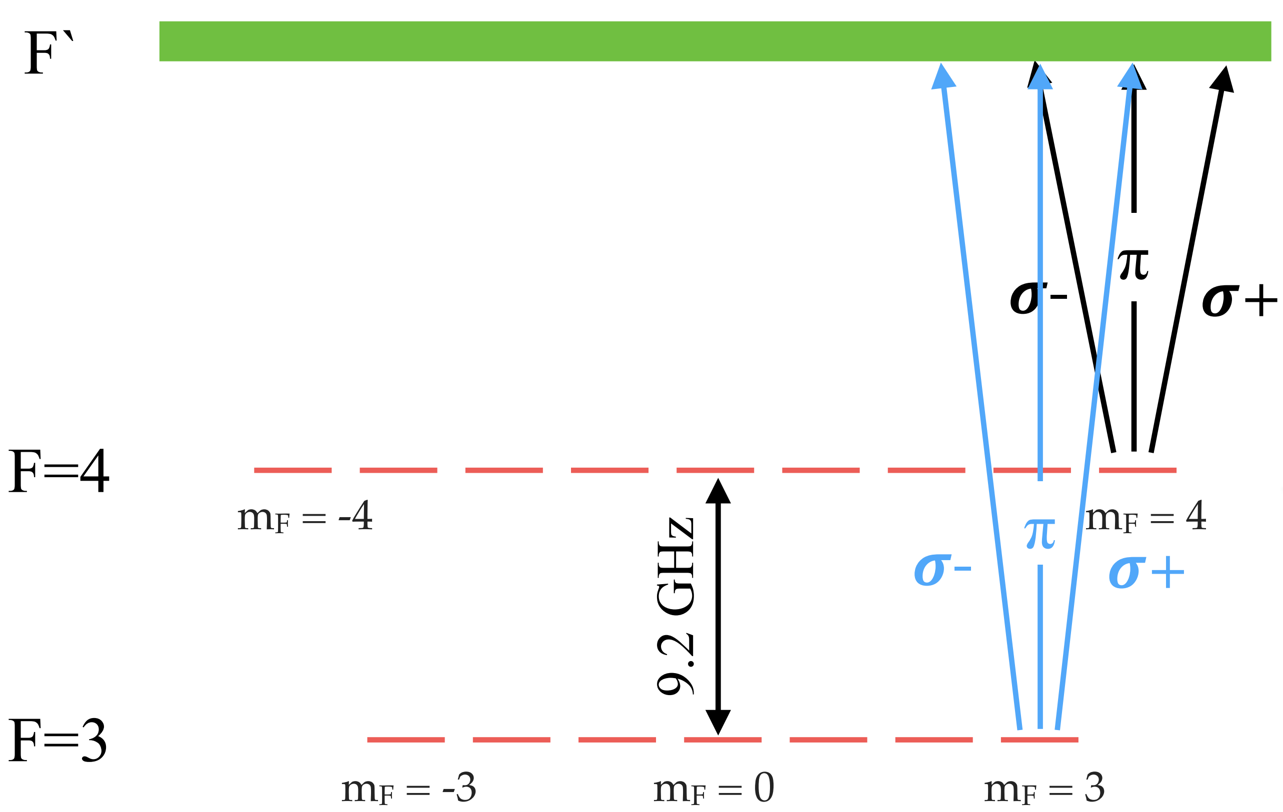
pulse area

photon recoil by multiples of $2\hbar k$

Bessel Function of 1st kind



we actually have hyperfine magnetic sub level structure and polarization of light



Cs

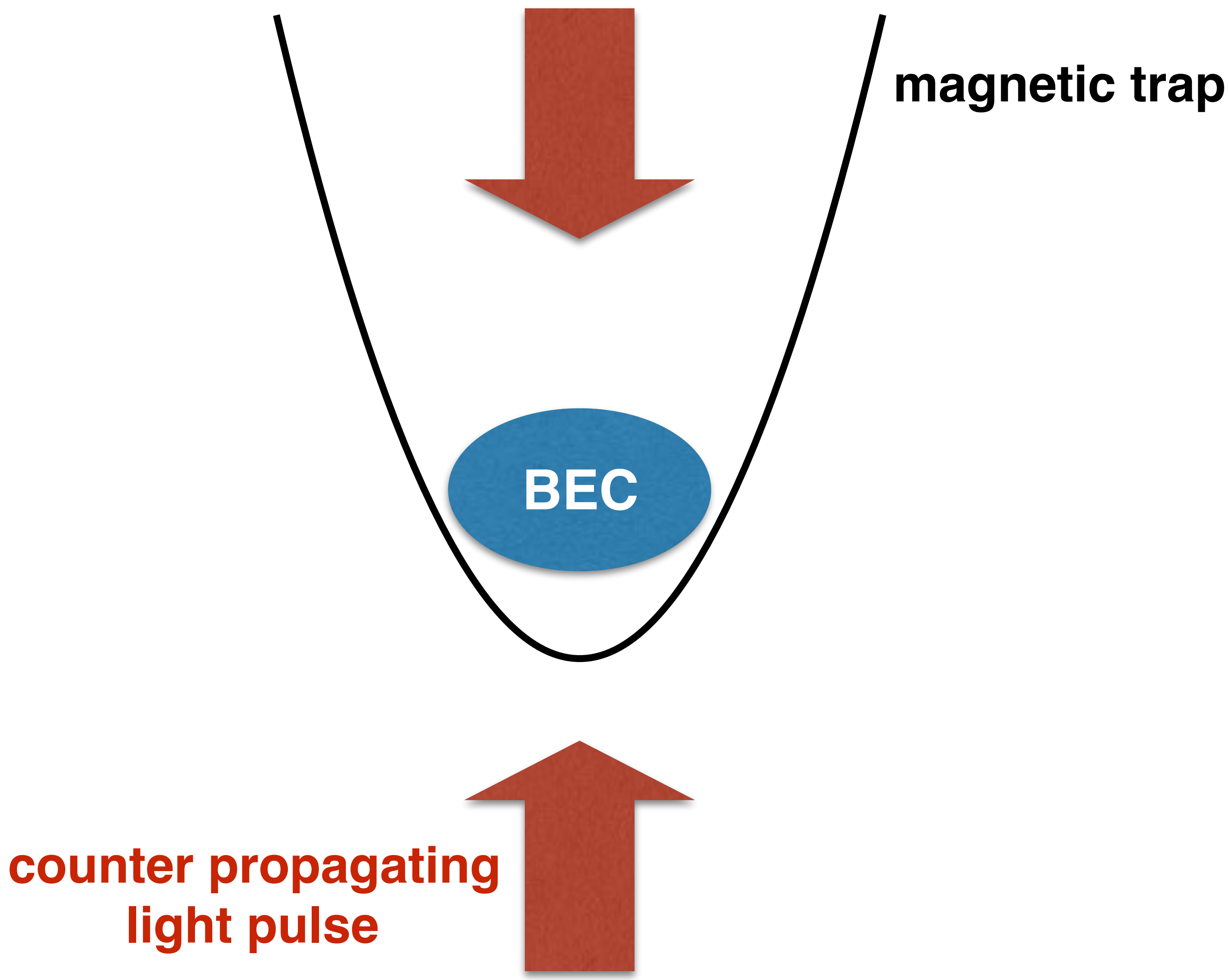
$$
\begin{aligned}
U_{(F,m_F)(F,m_F)}(x) &\equiv \langle F, m_F|\hat{U}(x)|F, m_F\rangle \\
&= -\frac{1}{4}\tilde{\alpha}\sum_{F'}\frac{\Delta_{45'}}{\Delta_{F,F'}}f_{F'F}\Big((c_{F,m'_F}^{F',m_F+1})^2|E_{+1}(x)|^2 \\
&\quad +(c_{F,m'_F}^{F',m_F-1})^2|E_{-1}(x)|^2+(c_{F,m'_F}^{F',m_F})^2|E_0(x)|^2\Big)
\end{aligned}
$$

$$U_{4,m_F}(x) = U_4^1\left(\frac{8+m_F}{12}|e_{+1}(x)|^2 + \frac{8-m_F}{12}|e_{-1}(x)|^2 + \frac{2}{3}|e_0(x)|^2\right)$$

$$U_{3,m_F}(x) = U_3^1\left(\frac{8-m_F}{12}|e_{+1}(x)|^2 + \frac{8+m_F}{12}|e_{-1}(x)|^2 + \frac{2}{3}|e_0(x)|^2\right)$$

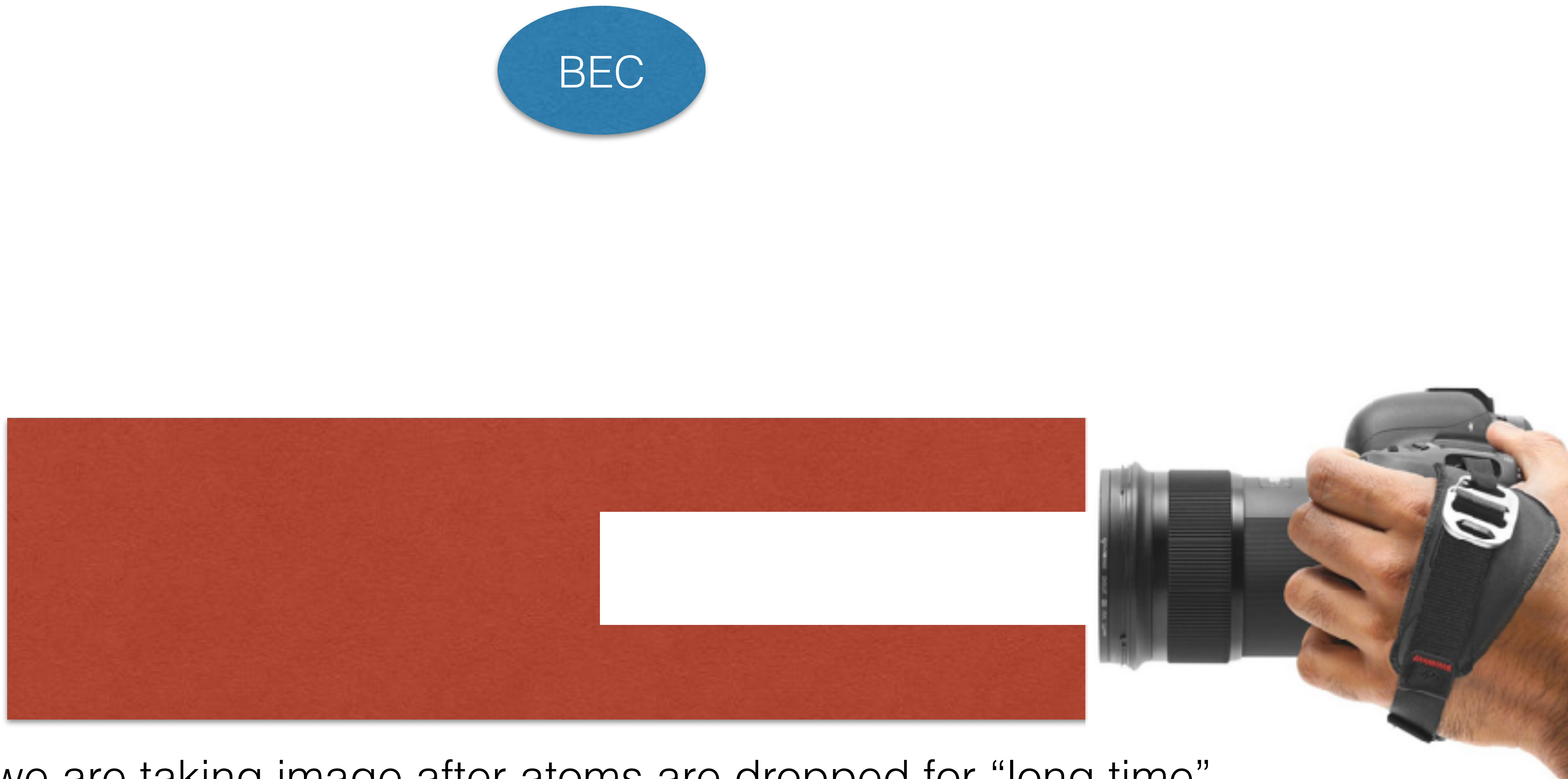
we can make different lattices for different internal states

2. BEC matter wave interferometer



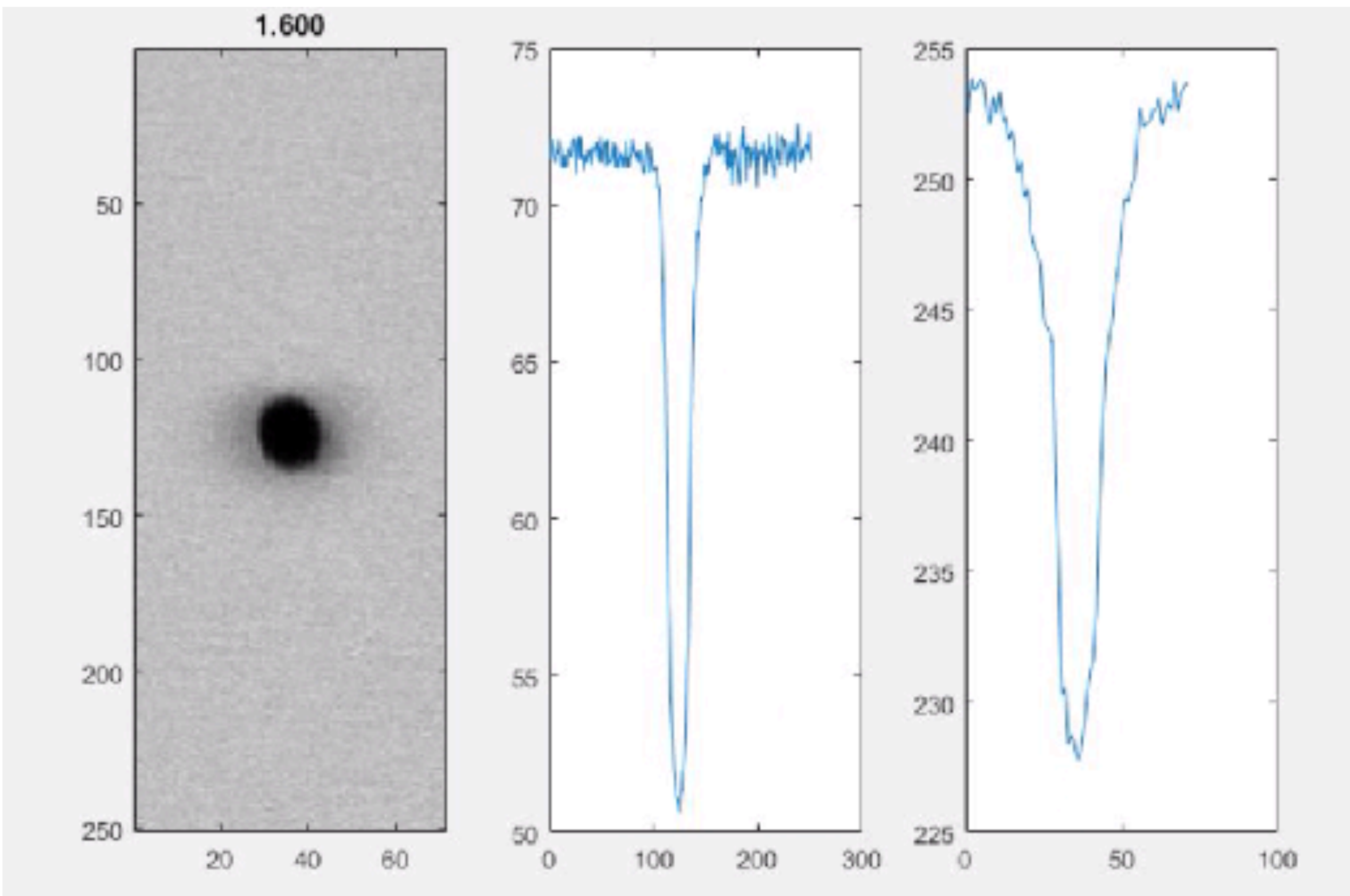
1. **magnetic trap** can be on or off during light pulse
2. we can apply one or many **light pulses**

2. BEC matter wave interferometer



we are taking image after atoms are dropped for “long time”
=> snap shot of **momentum**

2. BEC matter wave interferometer

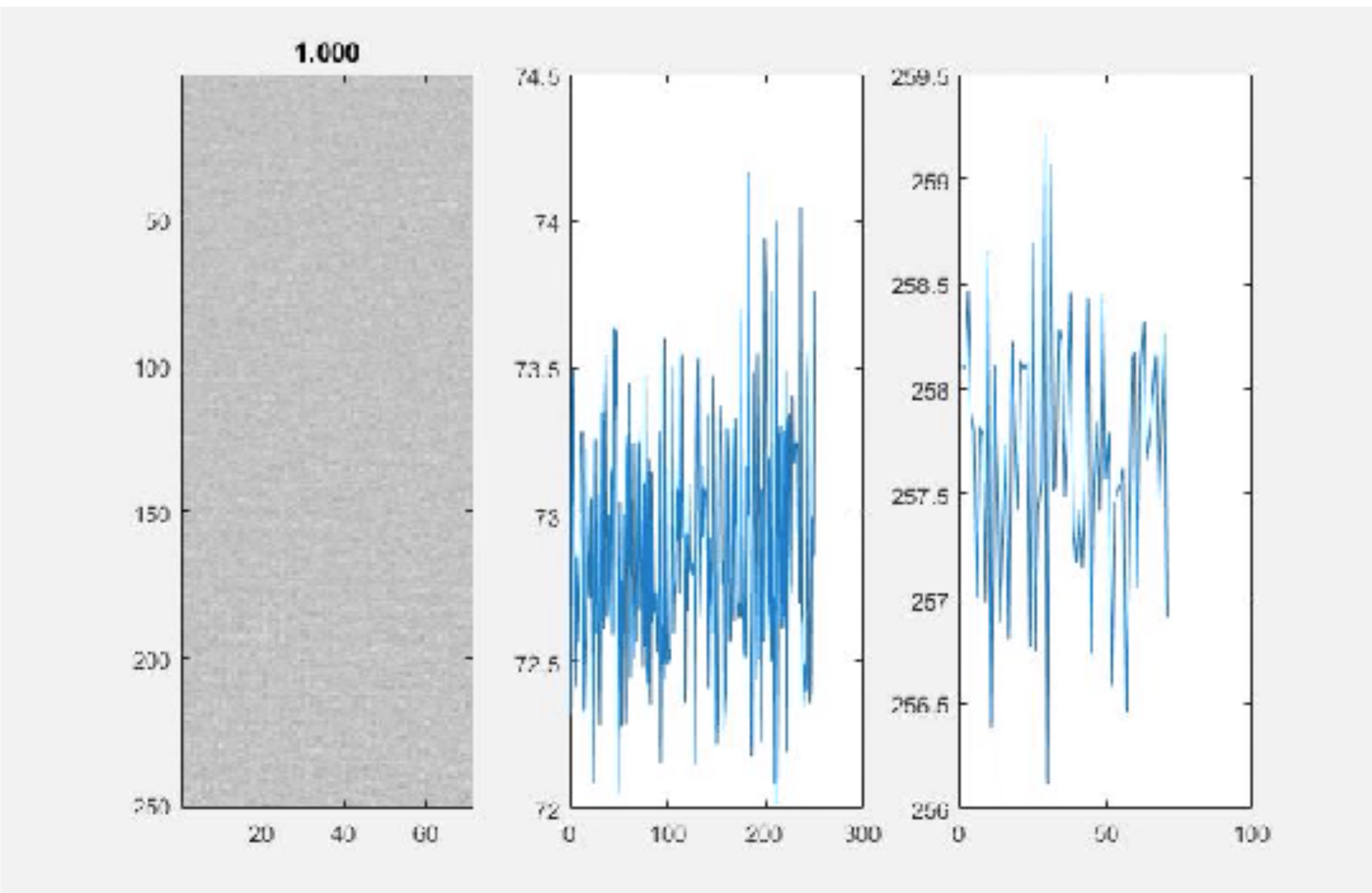


project image
to vertical axis

project image
to horizontal axis

2. BEC matter wave interferometer

stitching of many experiments
increasing **diffraction beam intensity**



project image
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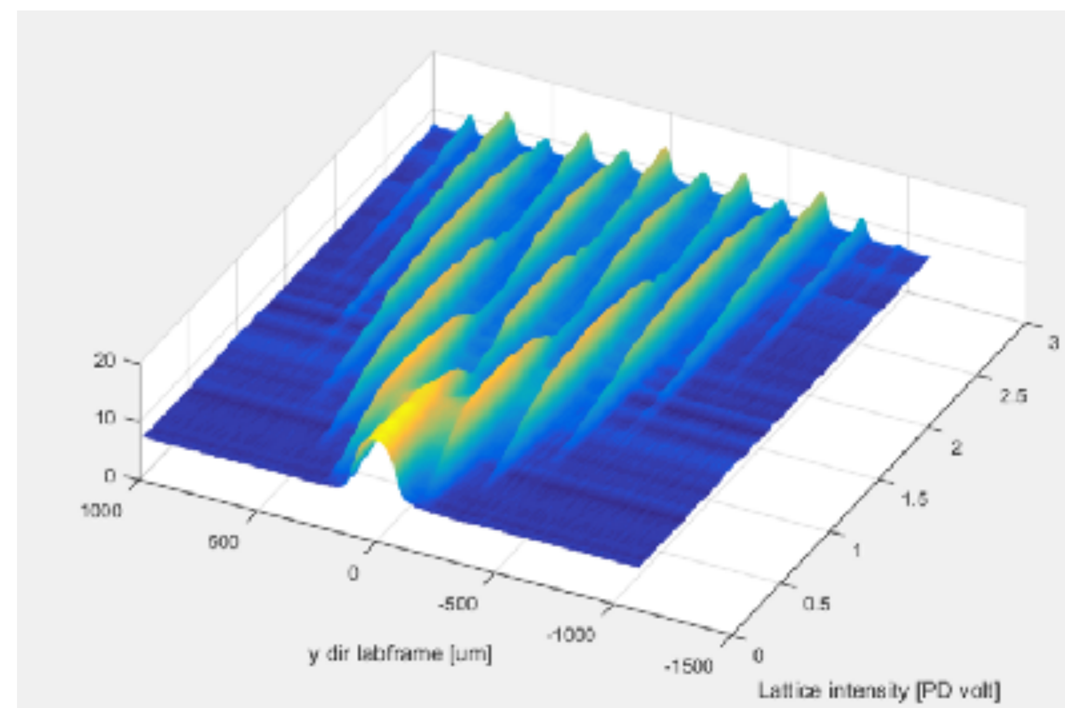
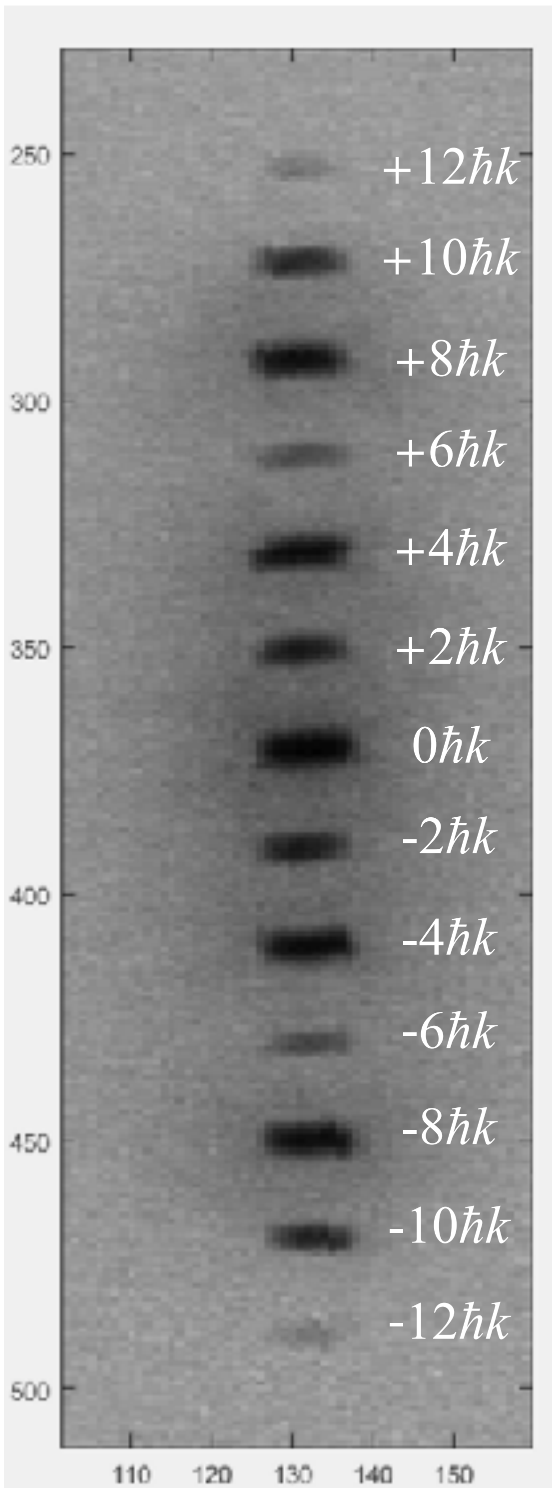
to horizontal axis



2. BEC matter wave interferometer



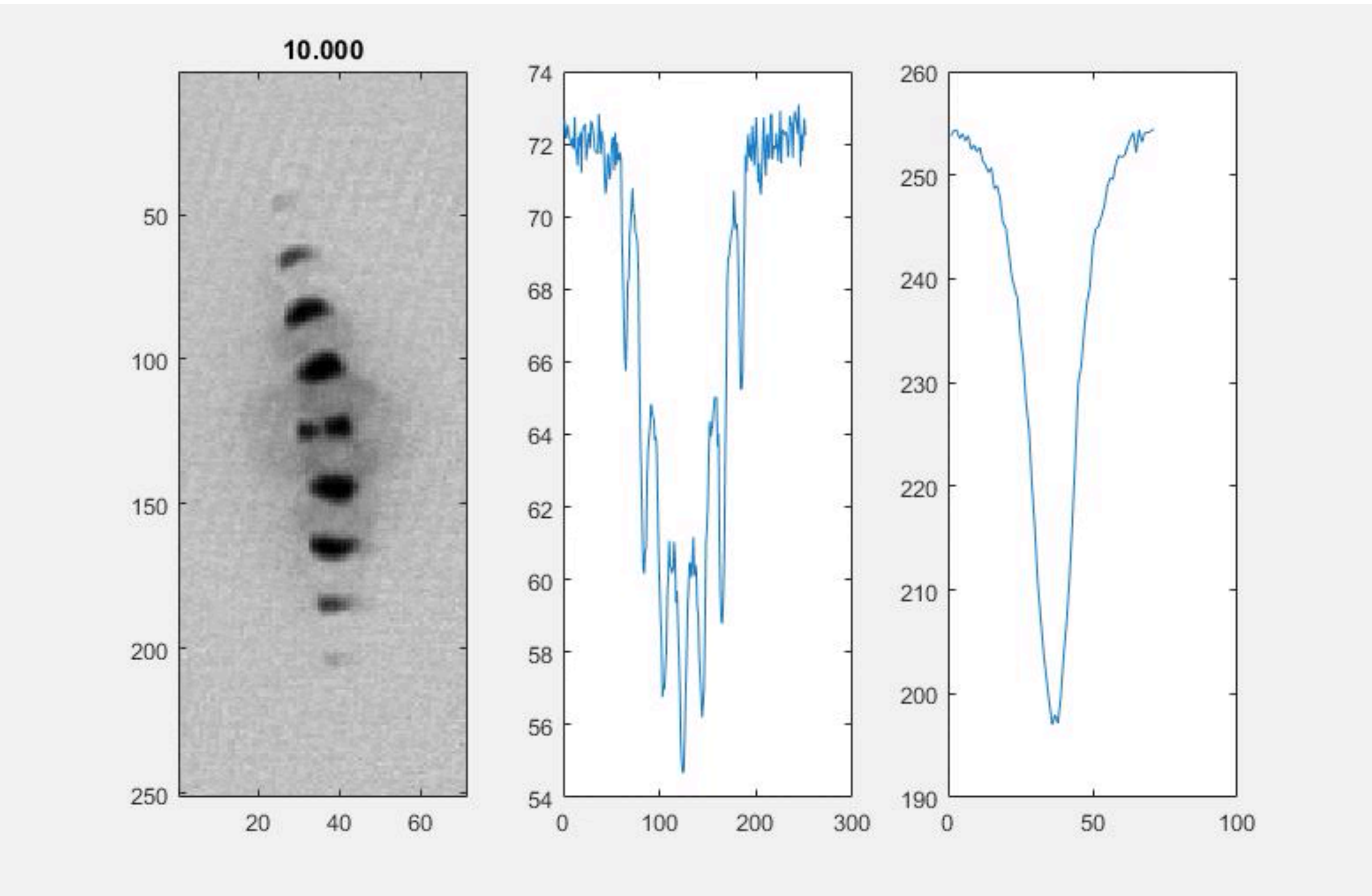
$$\hat{U} = \hbar \frac{|\omega_{\mathrm{R}}|^2}{4\delta} |g\rangle \langle g|$$

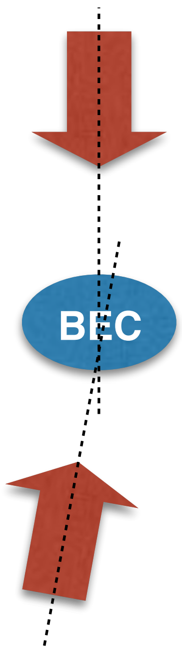
2-photon transition

2. BEC matter wave interferometer

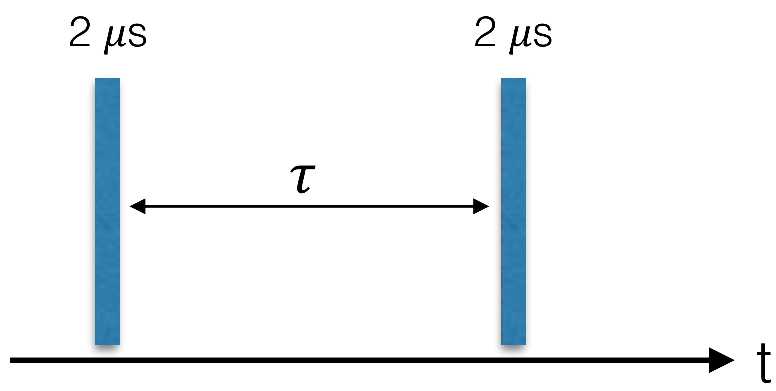
misalignment with k-vector along horizontal direction

increasing **pulse area**





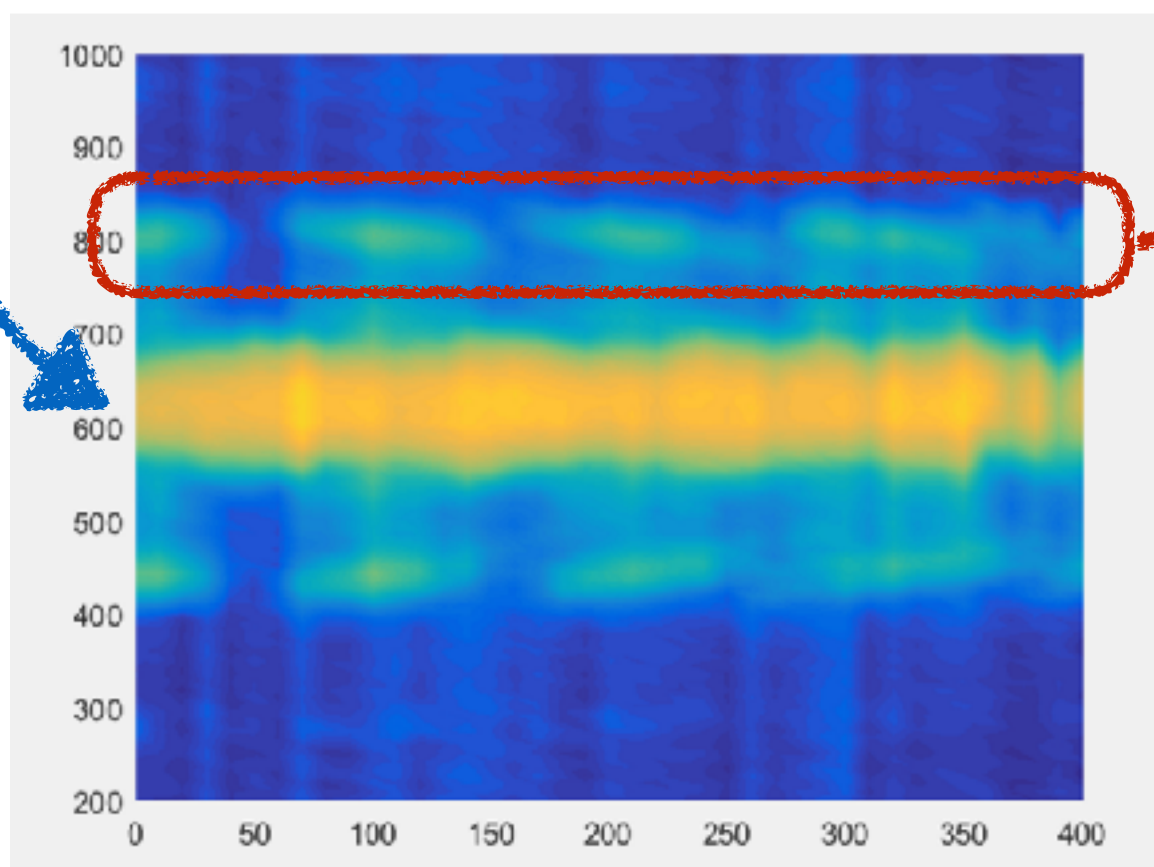
2. BEC matter wave interferometer



Kapitza-Dirac Interferometer

wave function $$|\psi(\tau)\rangle = |\psi_o\rangle[J_1(\theta)|\pm 2n\hbar k\rangle e^{-i4n^2\omega_{rec}\tau} + J_0(\theta)|0n\hbar k\rangle]$$

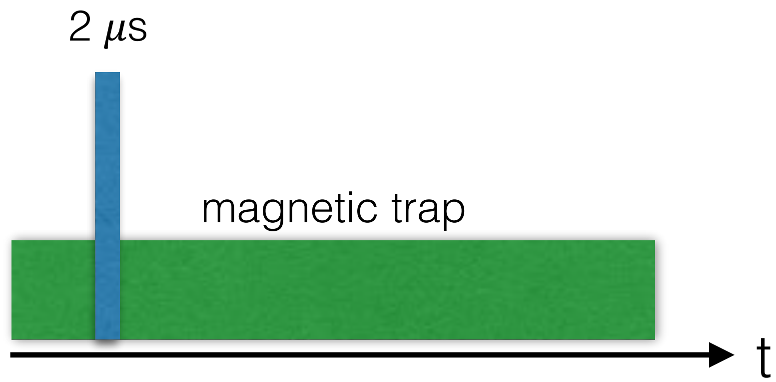
population of 0th order $$\rho_0 = J_0^4(\theta) + 4[J_0^2(\theta)J_1^2(\theta) + J_1^4(\theta)]\cos(4n^2\omega_{rec}\tau)$$



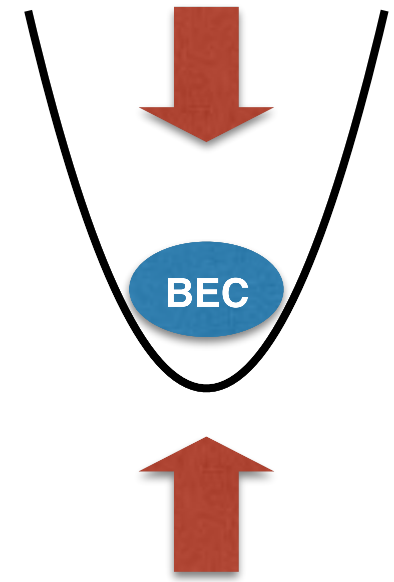
time [us]

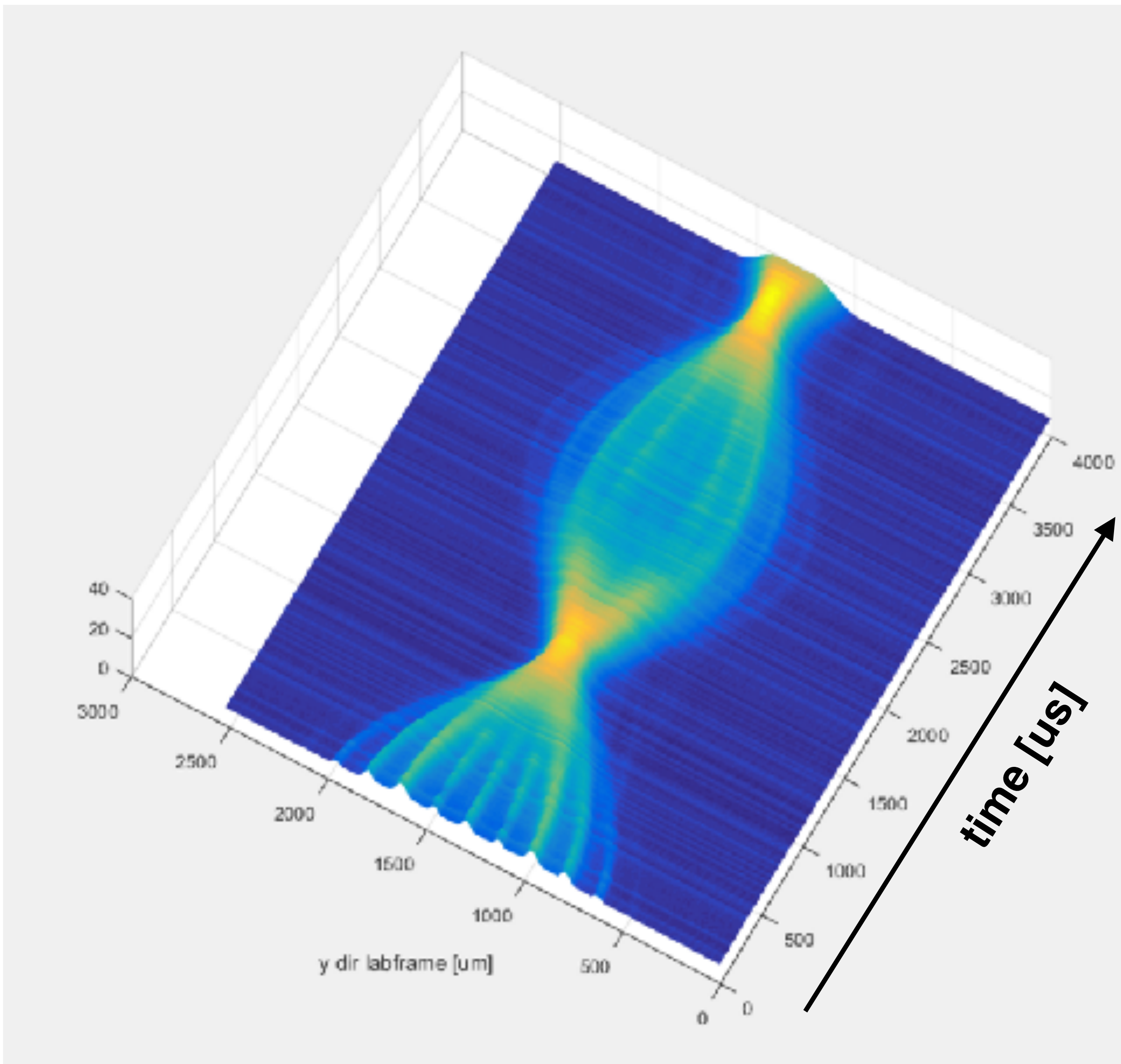
oscillation in population

2. BEC matter wave interferometer

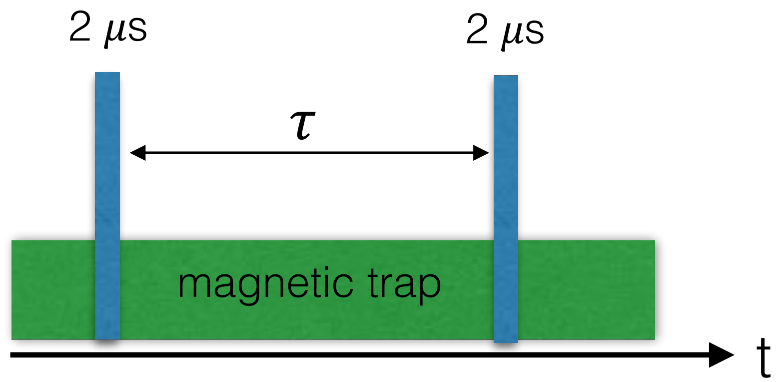


measure magnetic trap oscillation frequency

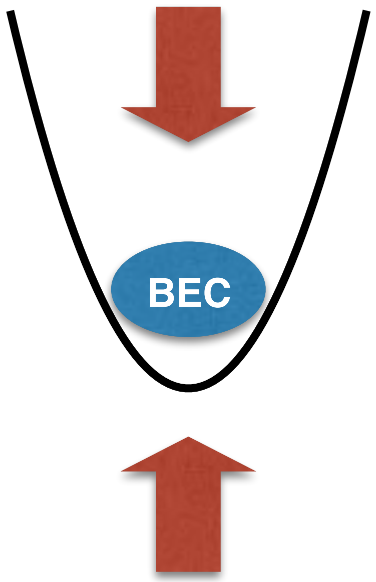


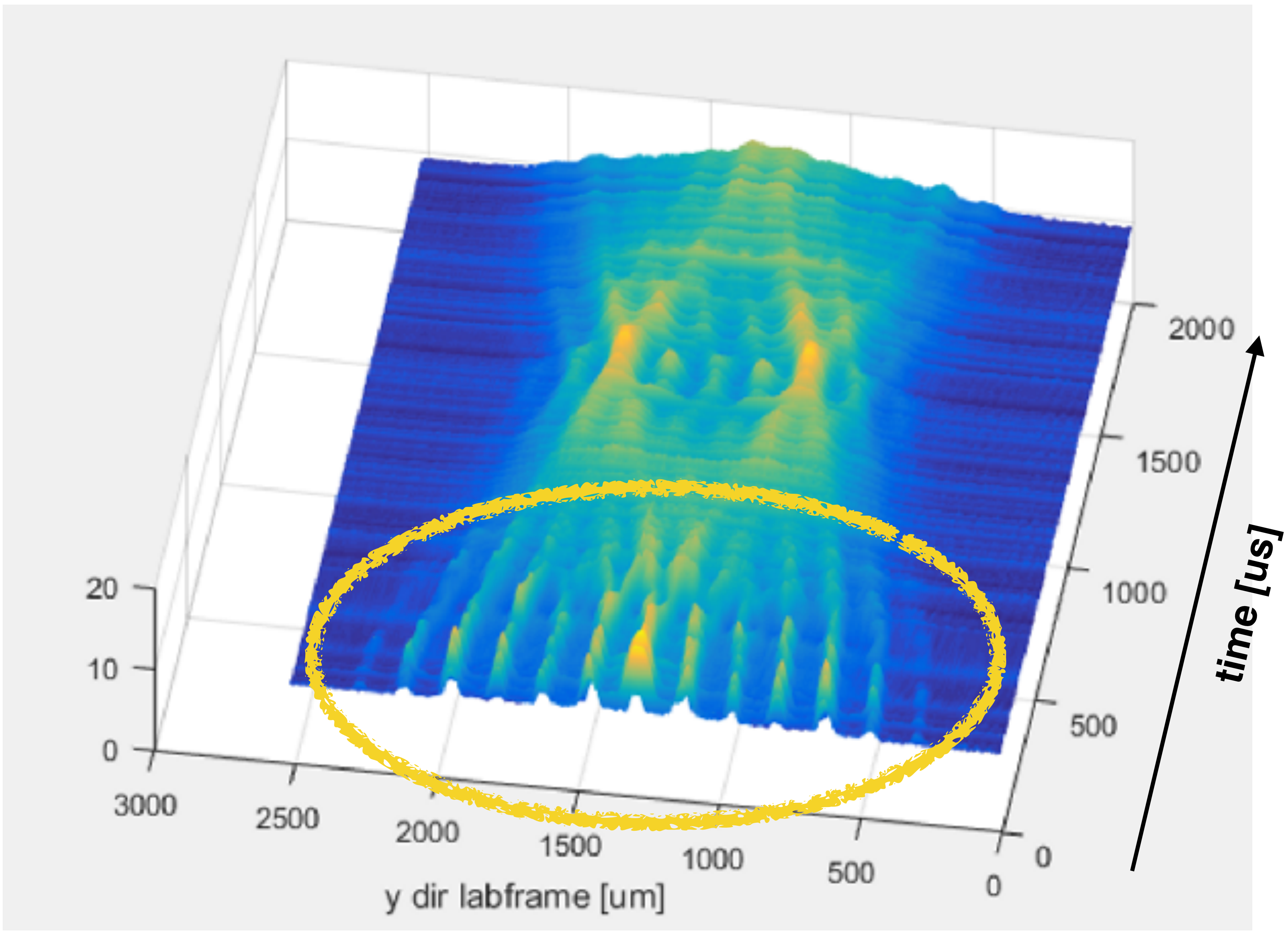


2. BEC matter wave interferometer

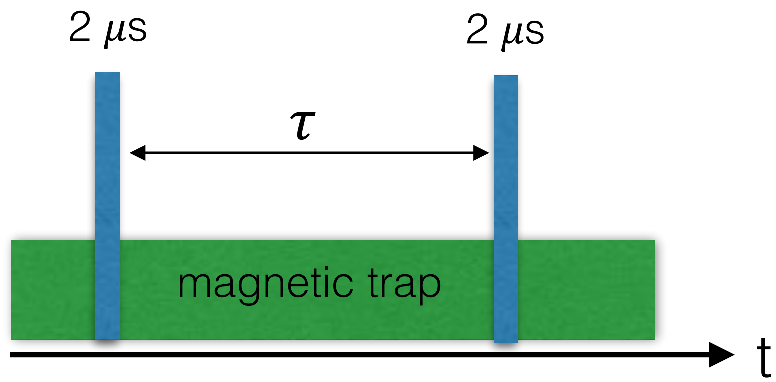


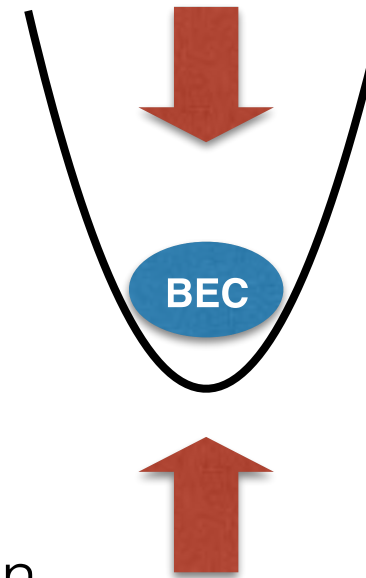
Kapitza-Dirac Interferometer



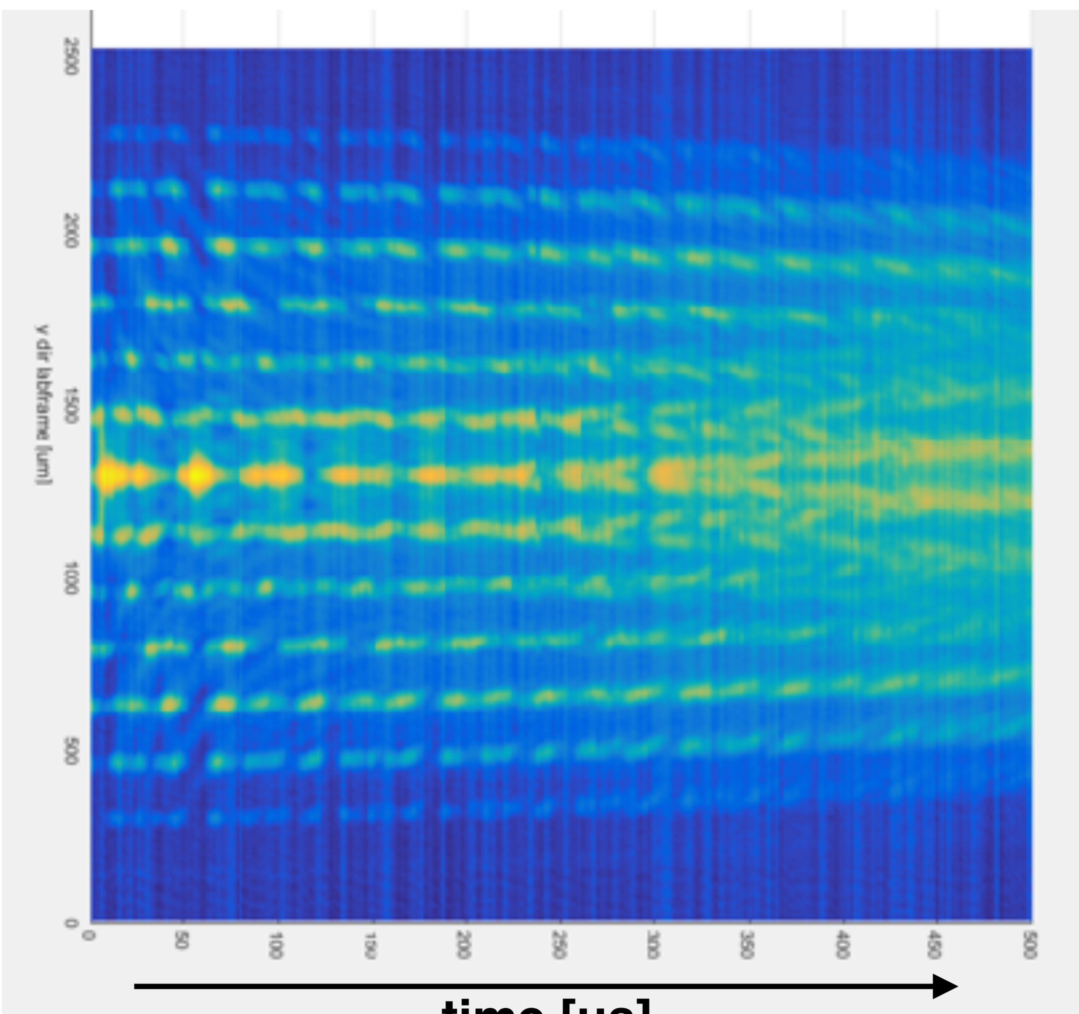


2. BEC matter wave interferometer

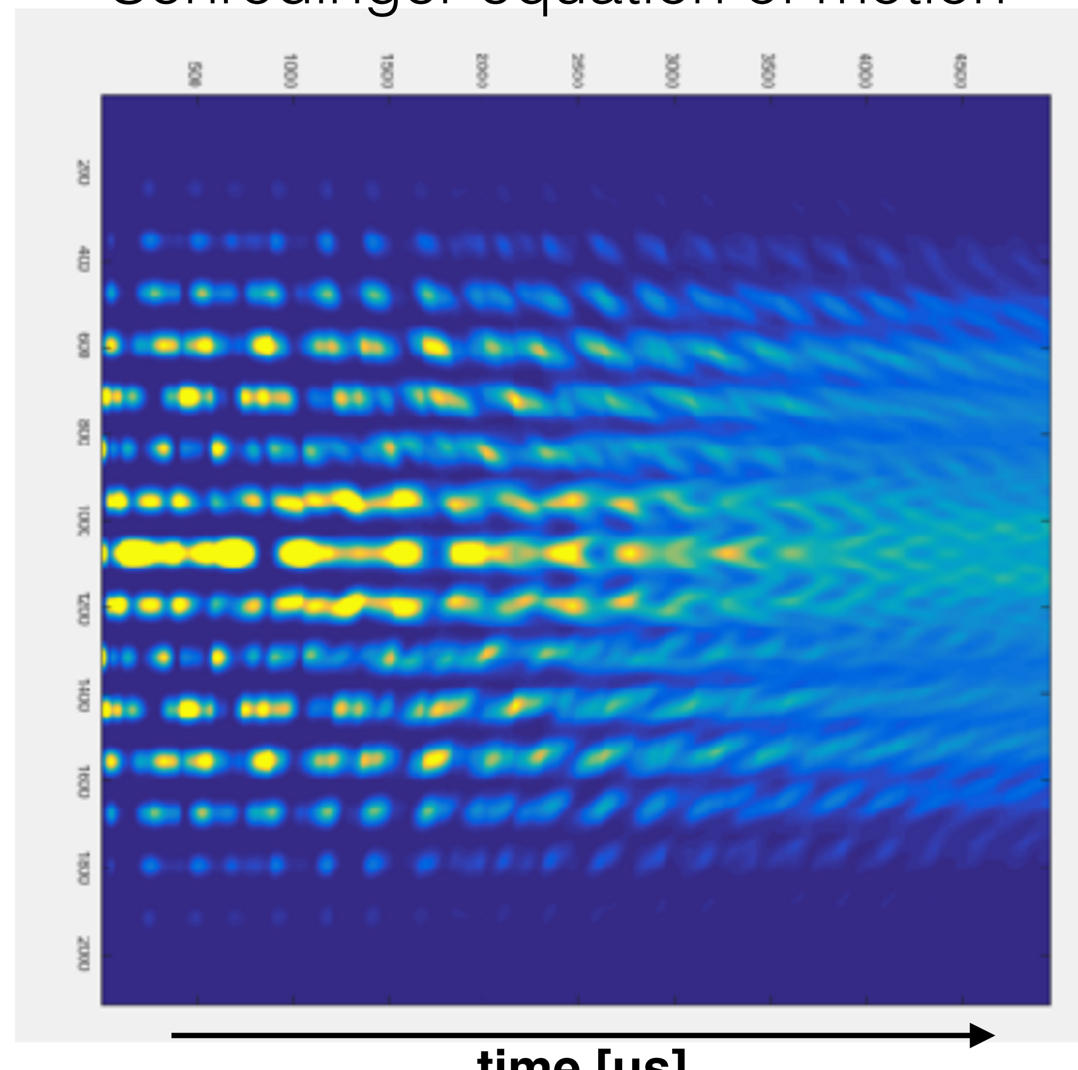




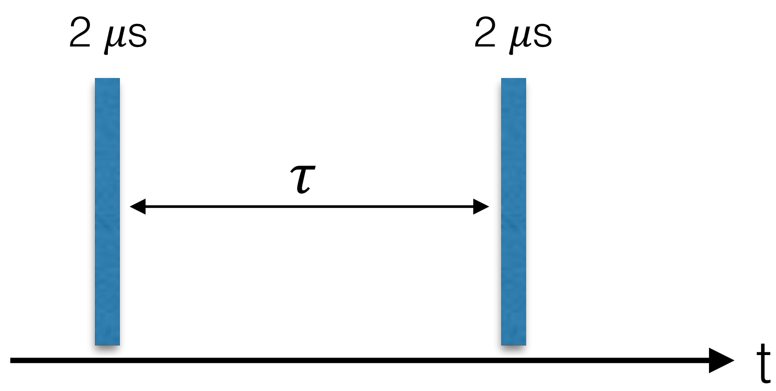
interference related to
relative speed of interfering BECs



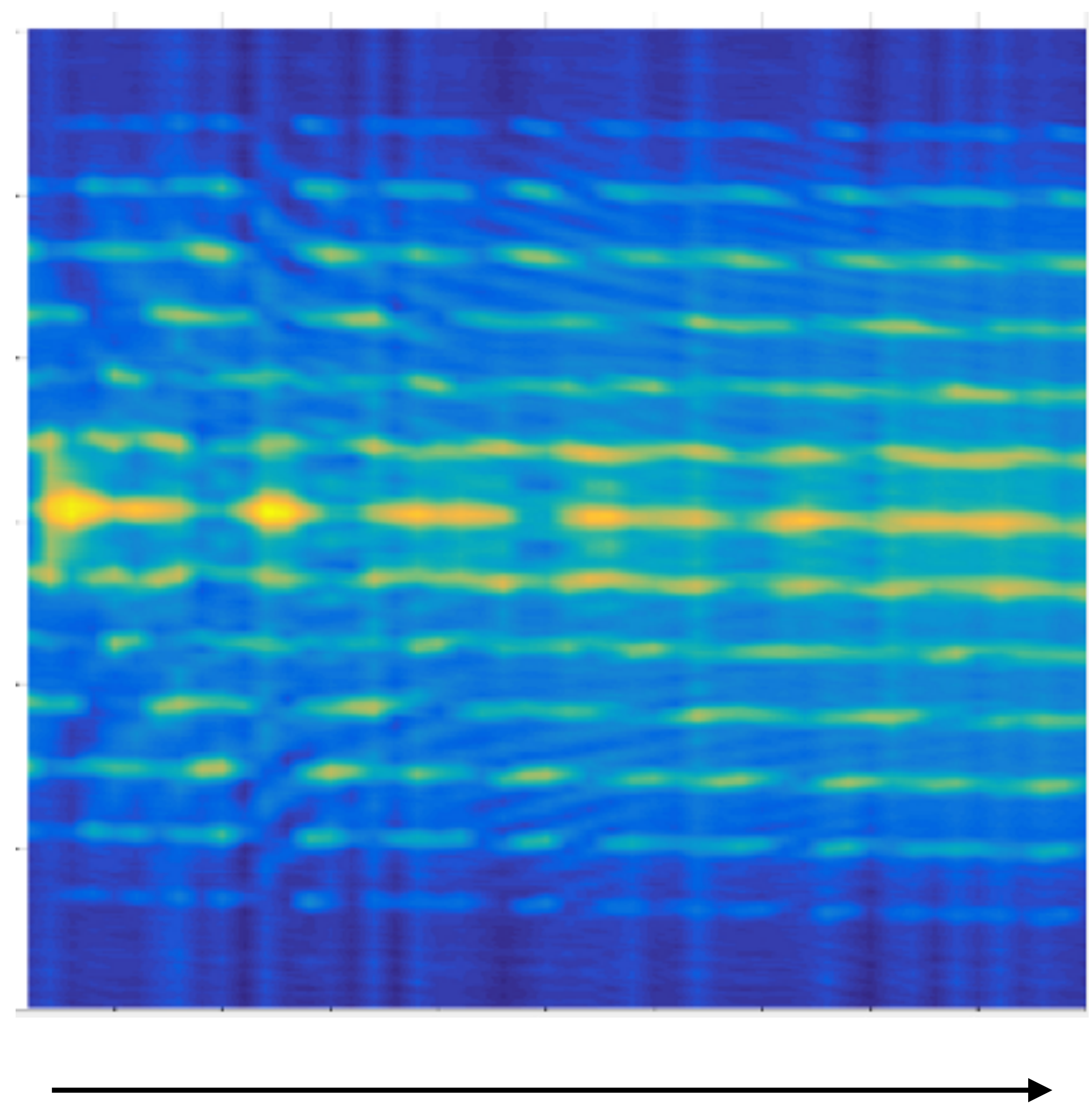
Calculation solving for
Schrodinger equation of motion



2. BEC matter wave interferometer

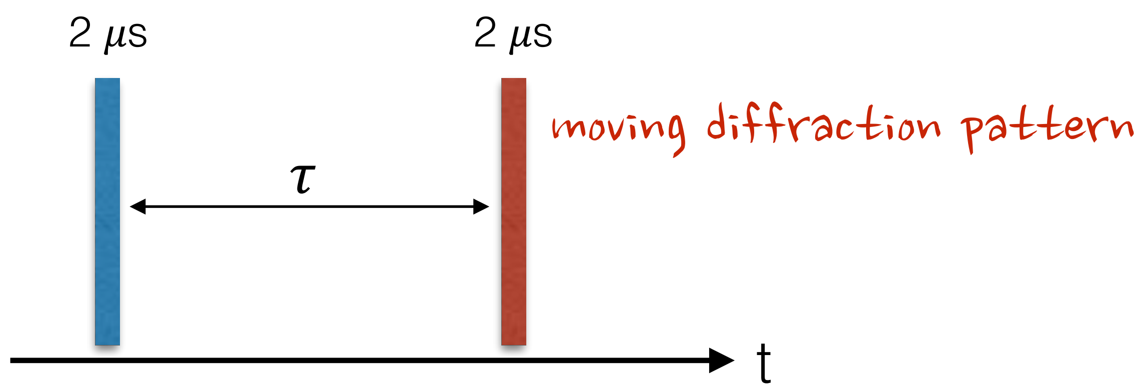


no magnetic trap



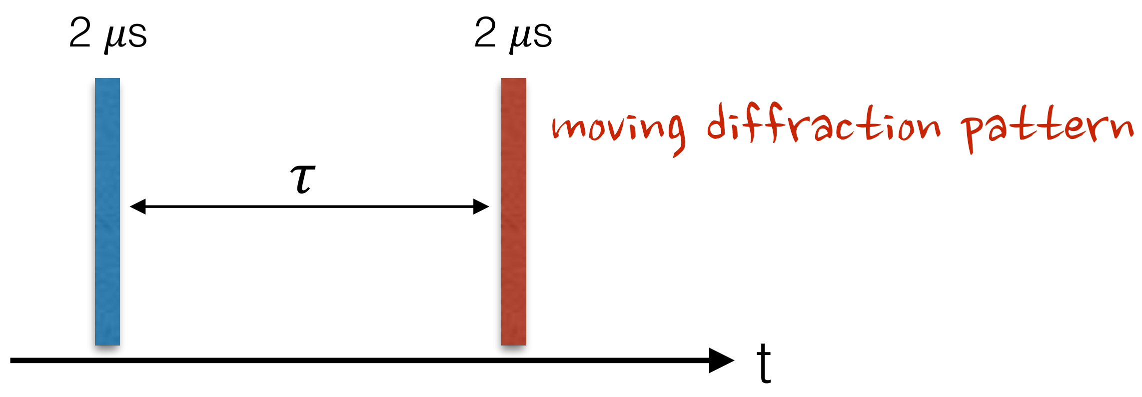
time [us]

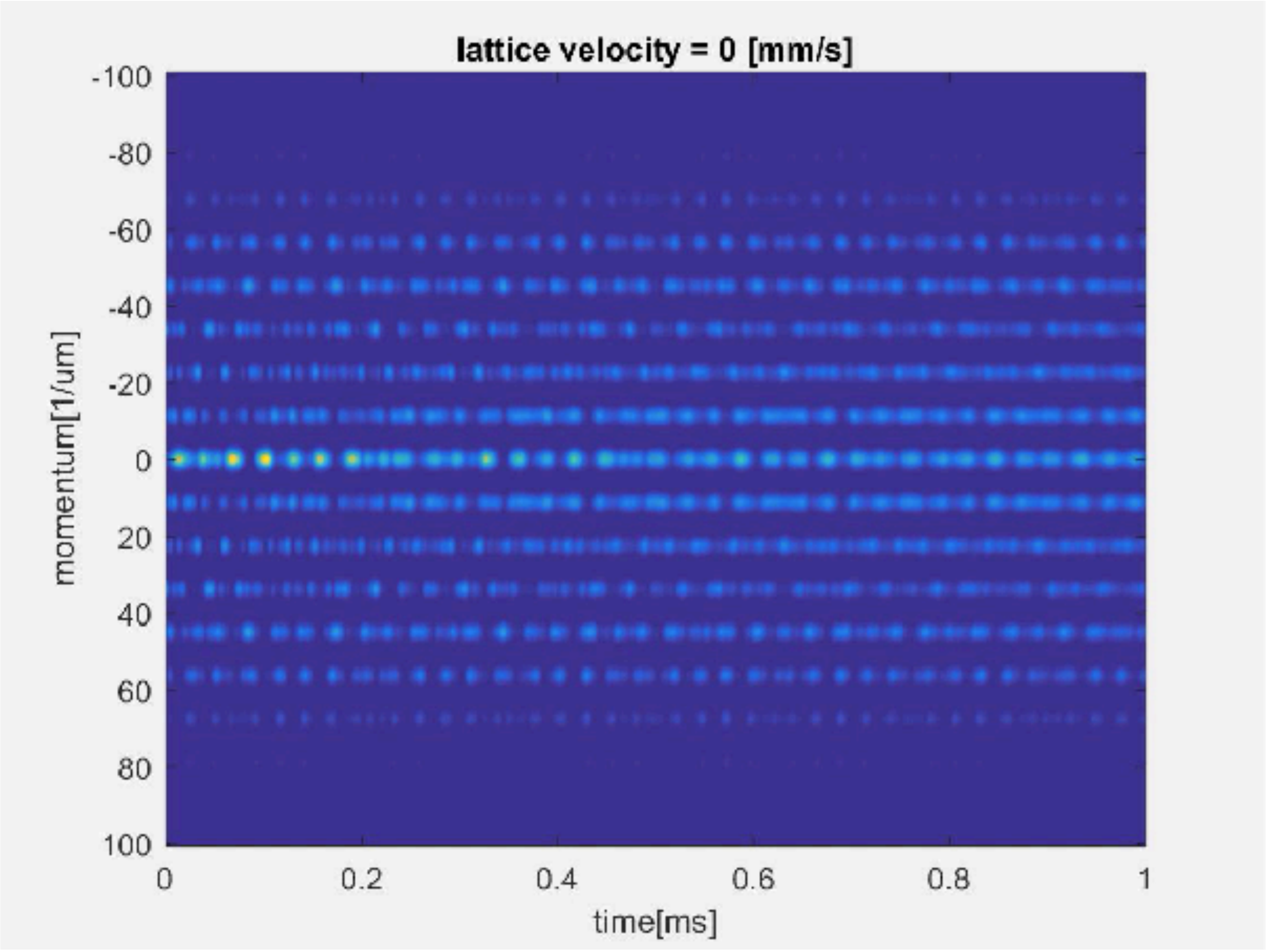
2. BEC matter wave interferometer



only calculation for now…

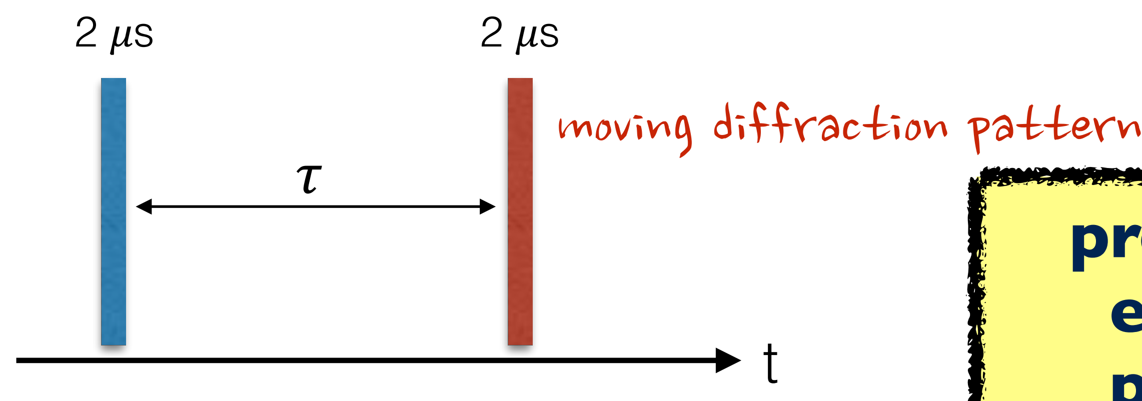
2. BEC matter wave interferometer



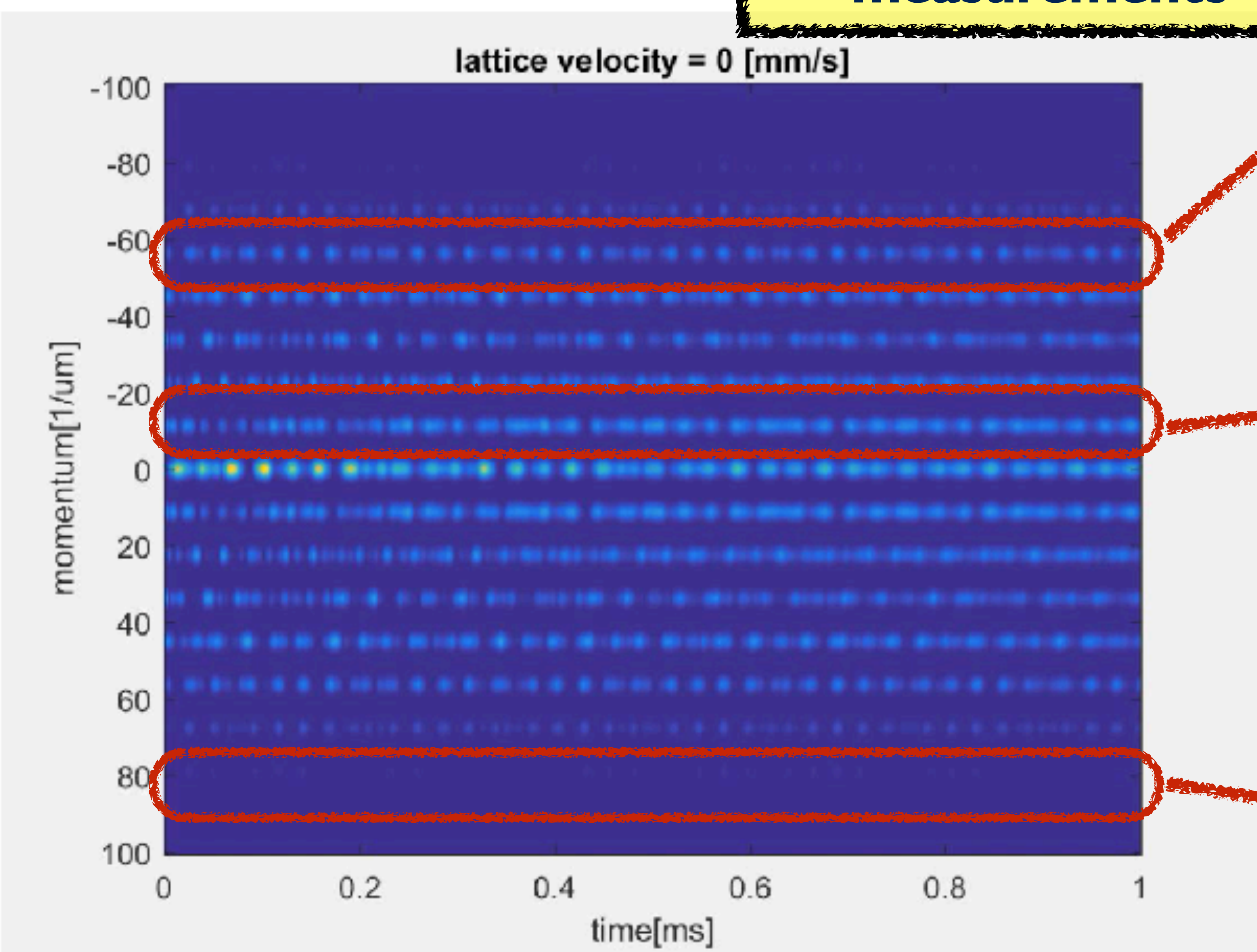


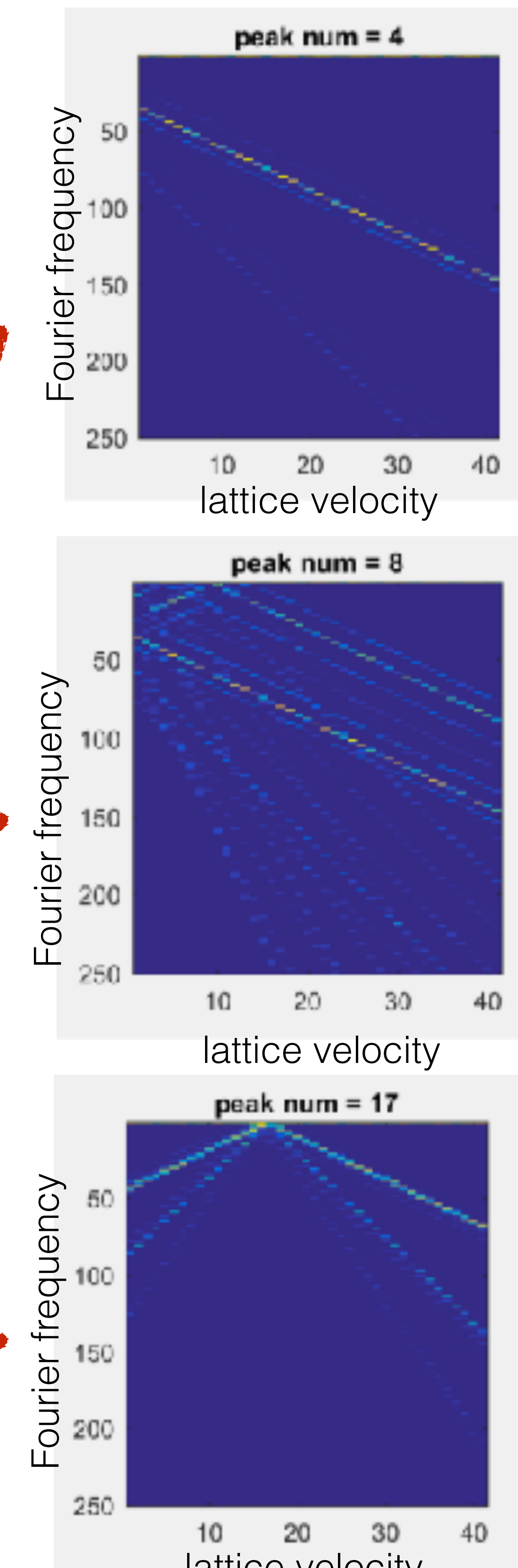
calculation for asymmetric pulse sequence interferometer

2. BEC matter wave interferometer

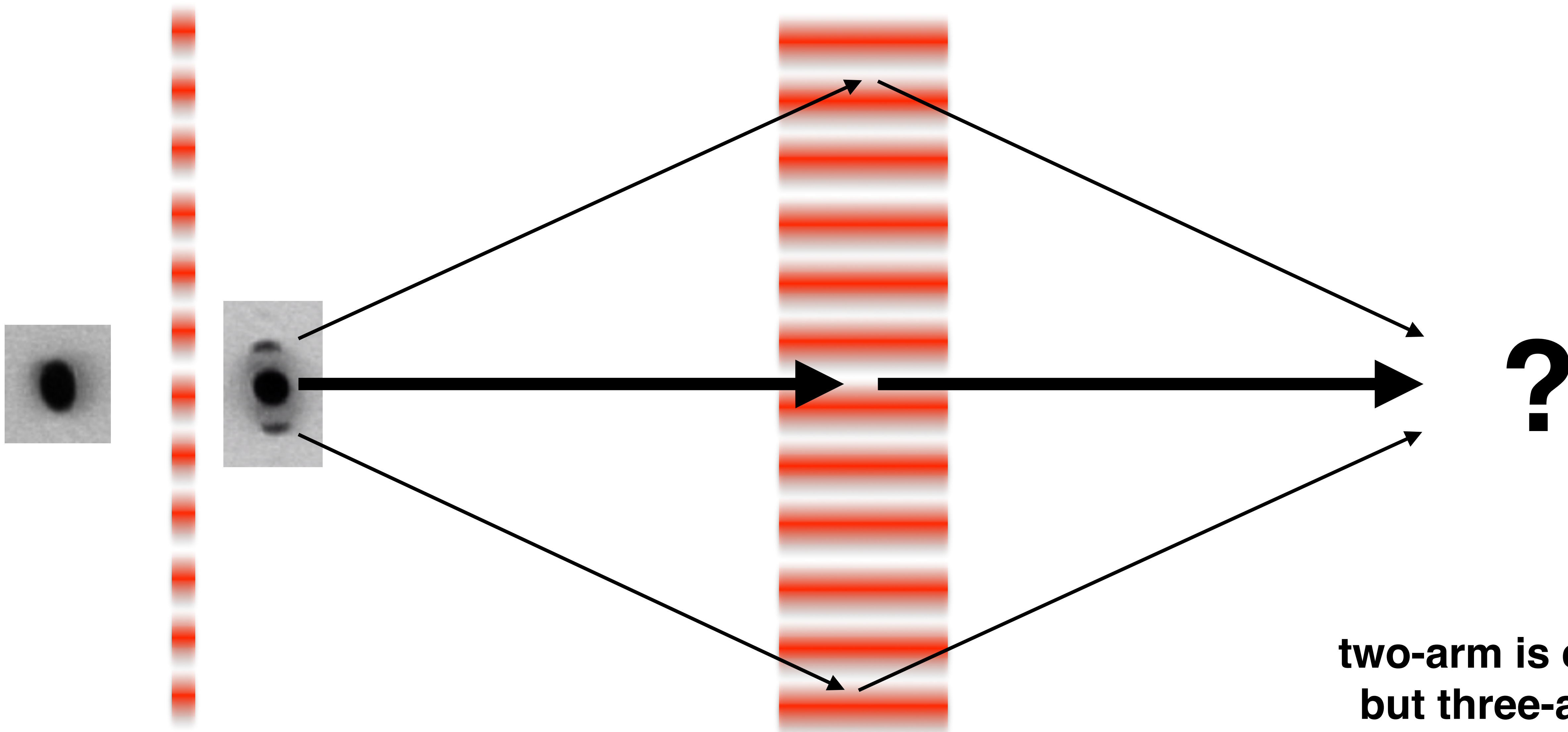


preparing for this experiment for precision recoil measurements





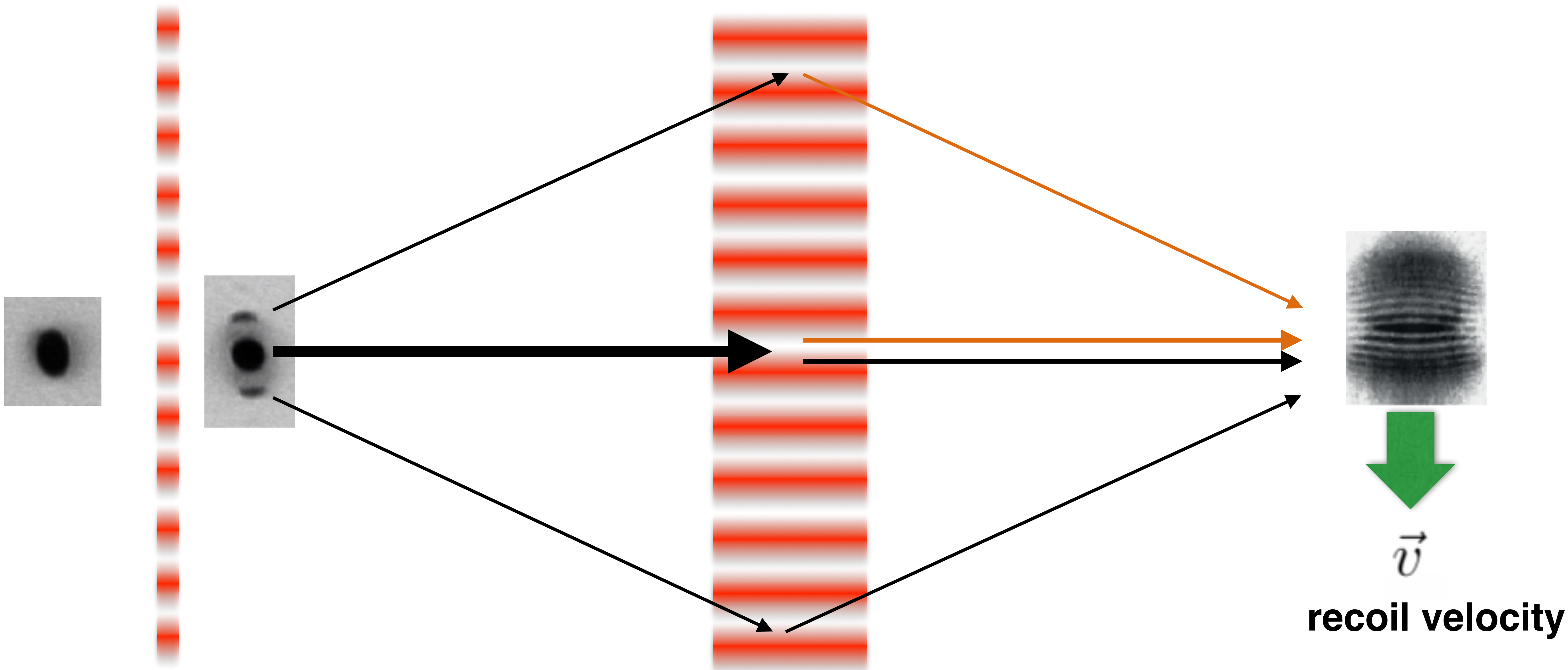
Contrast Interferometer
(symmetric three-arm interferometer)



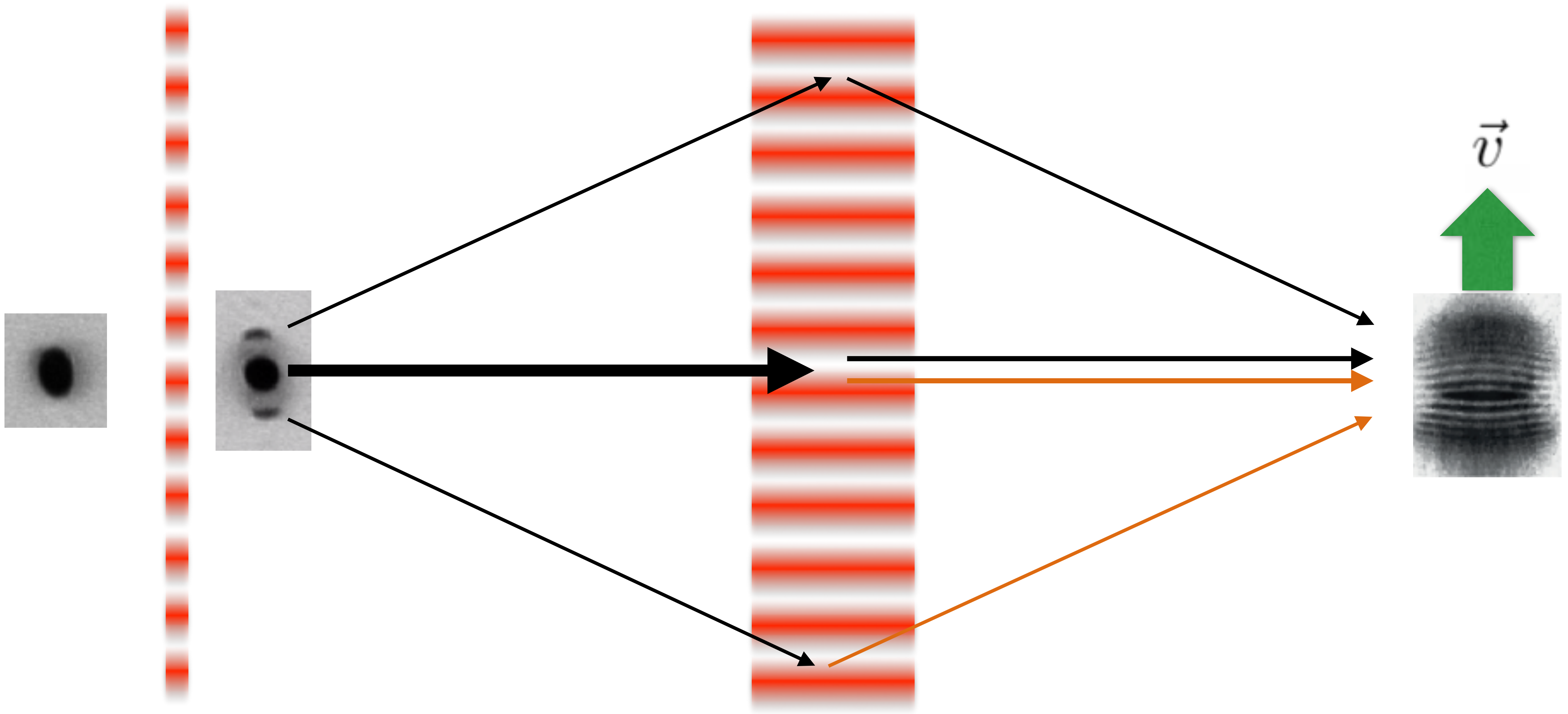
two-arm is easy..
but three-arm..

MIRROR pulse
low intensity
long pulse (w.r.t. recoil)

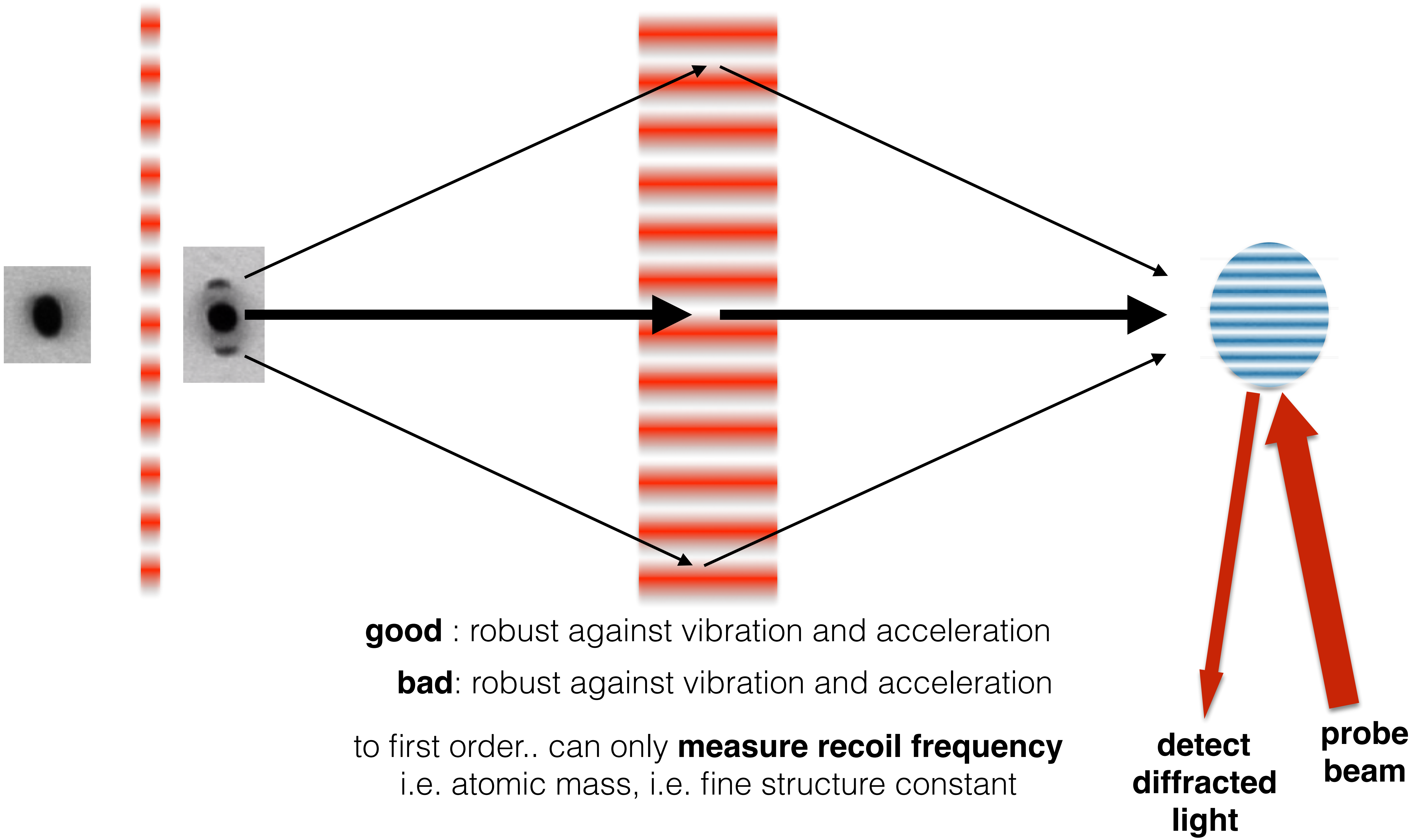
Contrast Interferometer
(symmetric three-arm interferometer)



Contrast Interferometer
(symmetric three-arm interferometer)



Contrast Interferometer
(symmetric three-arm interferometer)

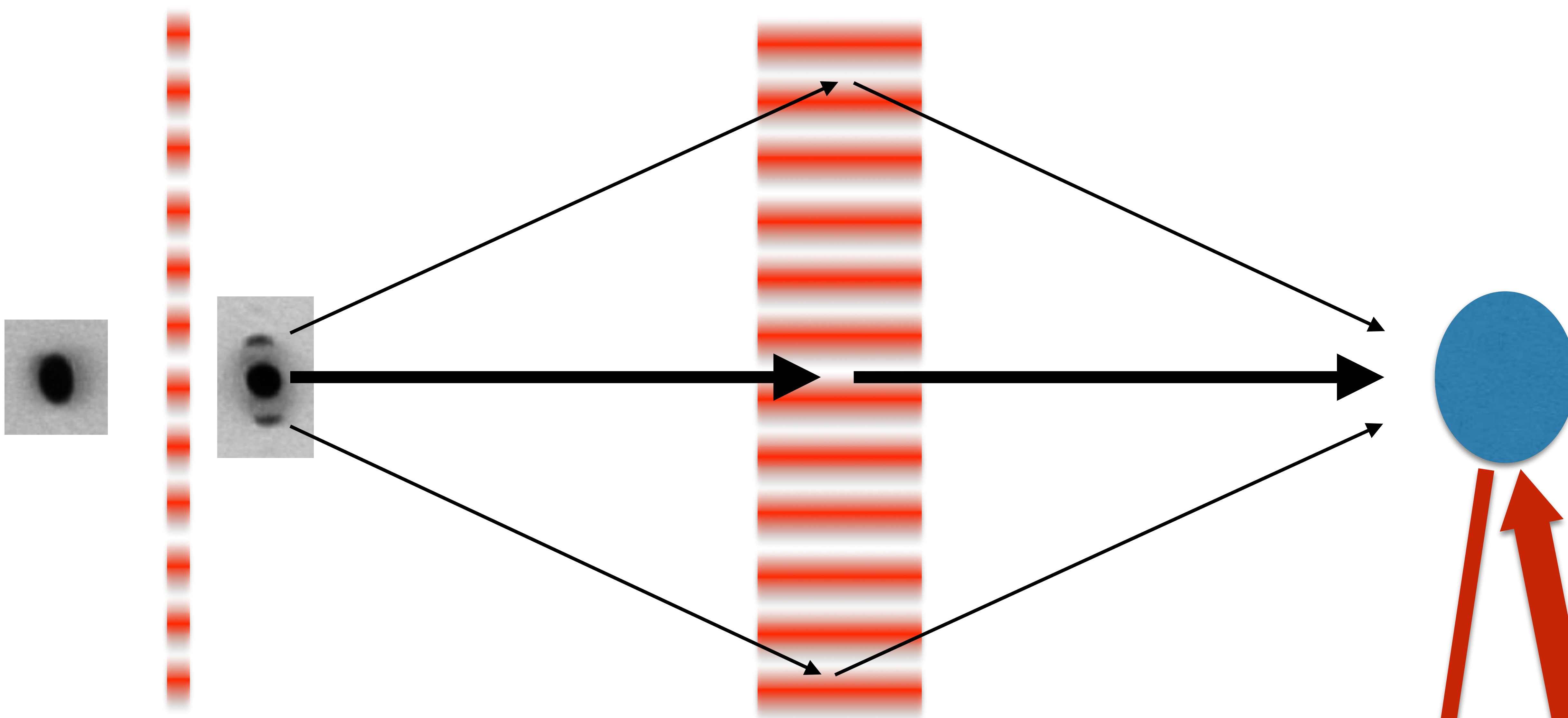


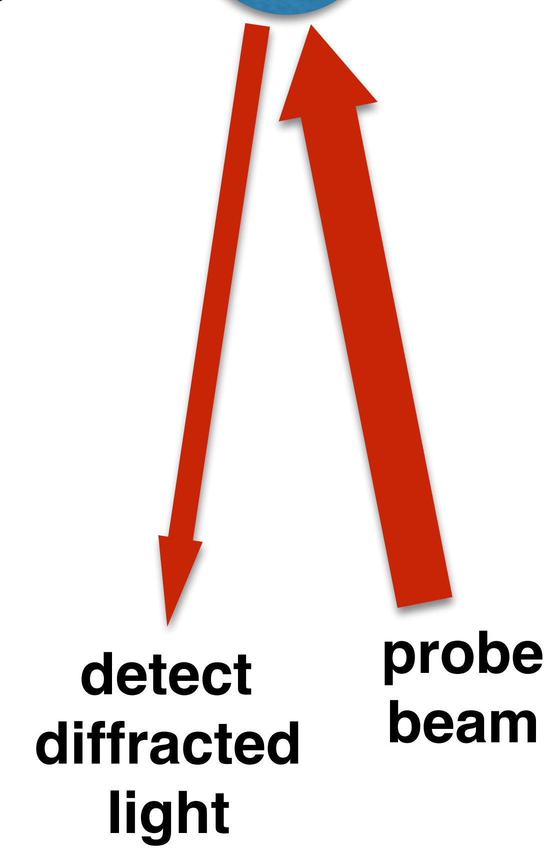
good : robust against vibration and acceleration

bad: robust against vibration and acceleration

to first order.. can only **measure recoil frequency**
i.e. atomic mass, i.e. fine structure constant

Contrast Interferometer
(symmetric three-arm interferometer)

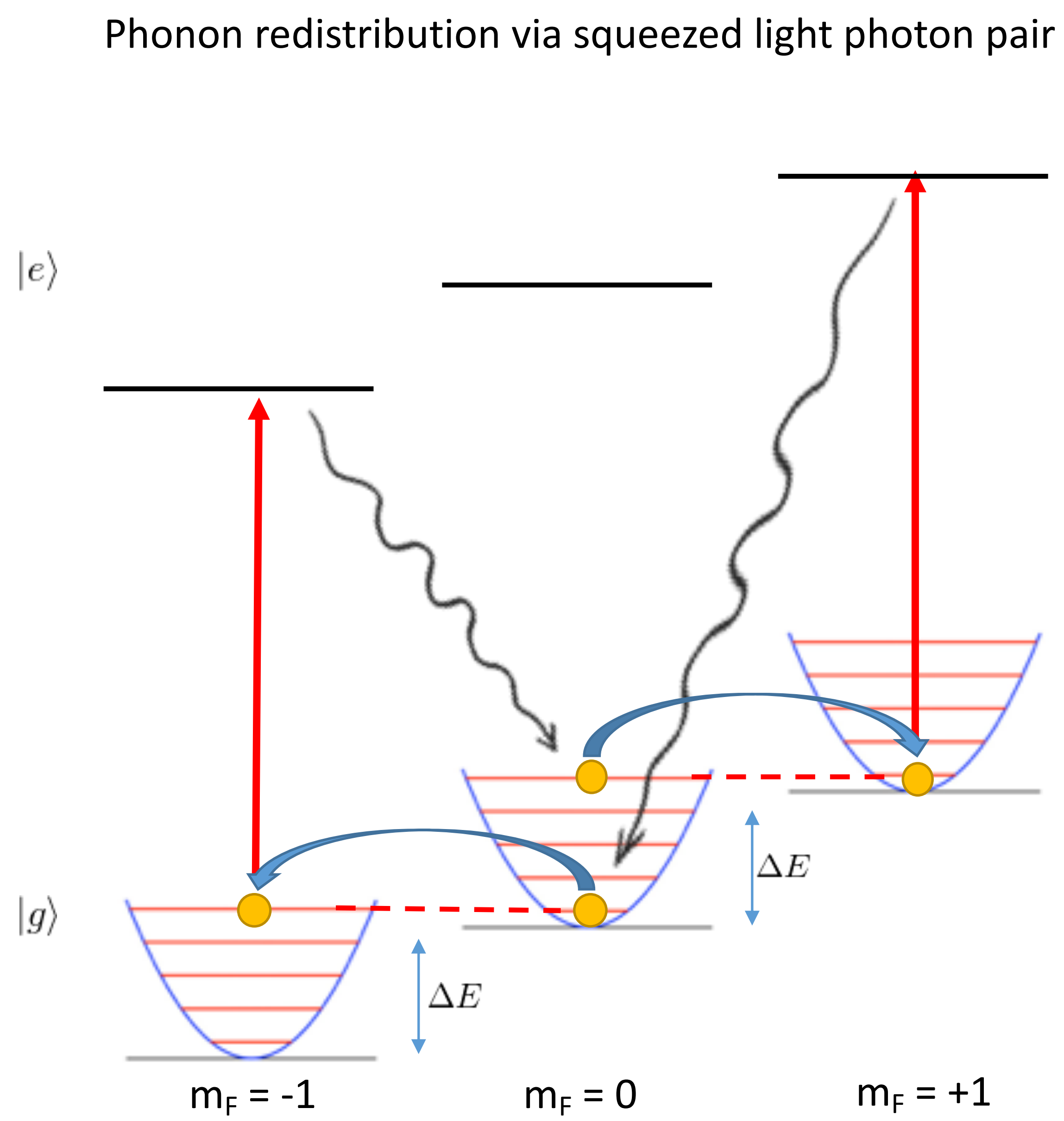




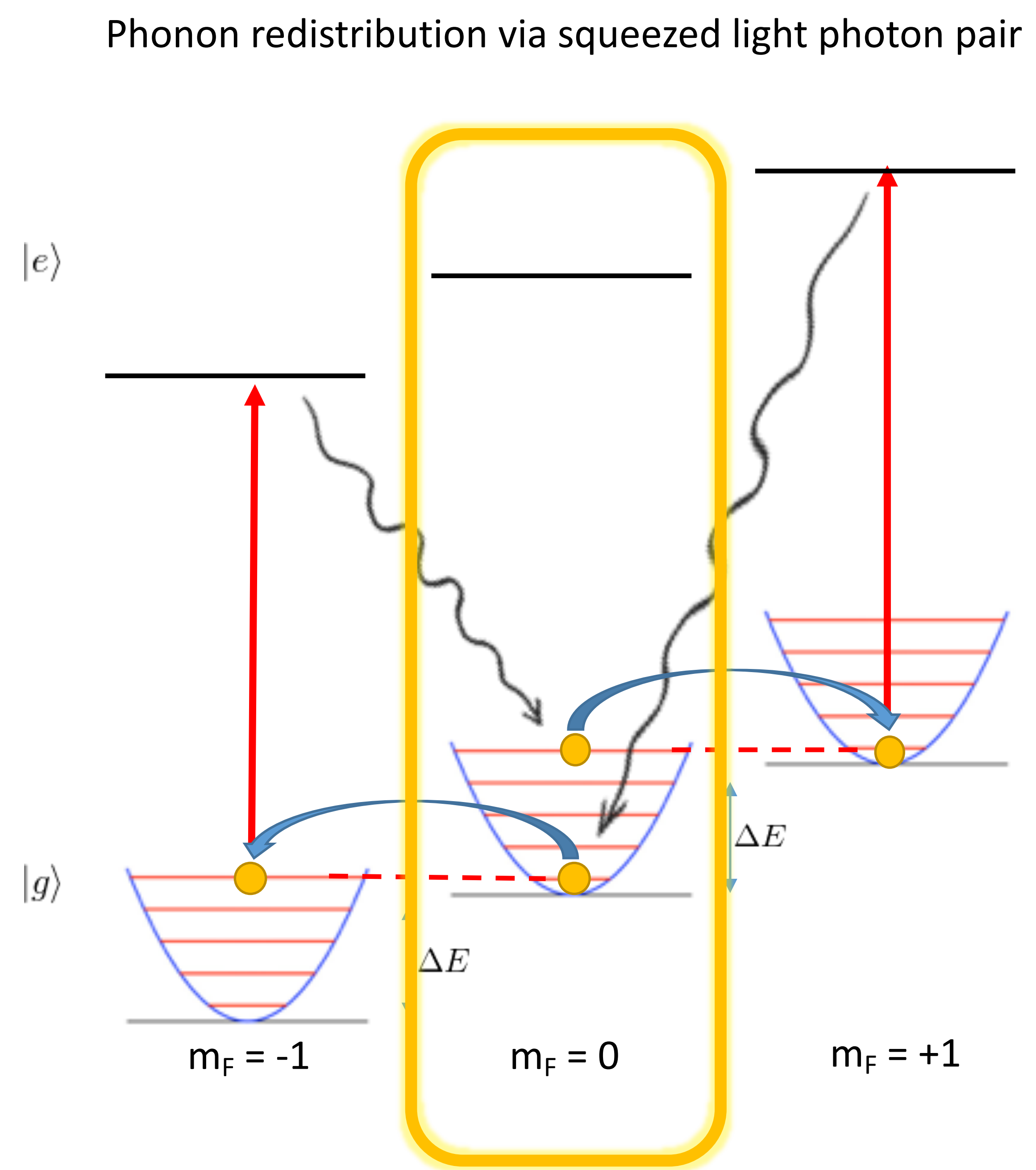
3 things to pursue…

1. state dependent lattice (accelerate symmetric paths)
2. direction along gravity (measure Δg, second order)
3. non-Gaussian states for quantum enhancement

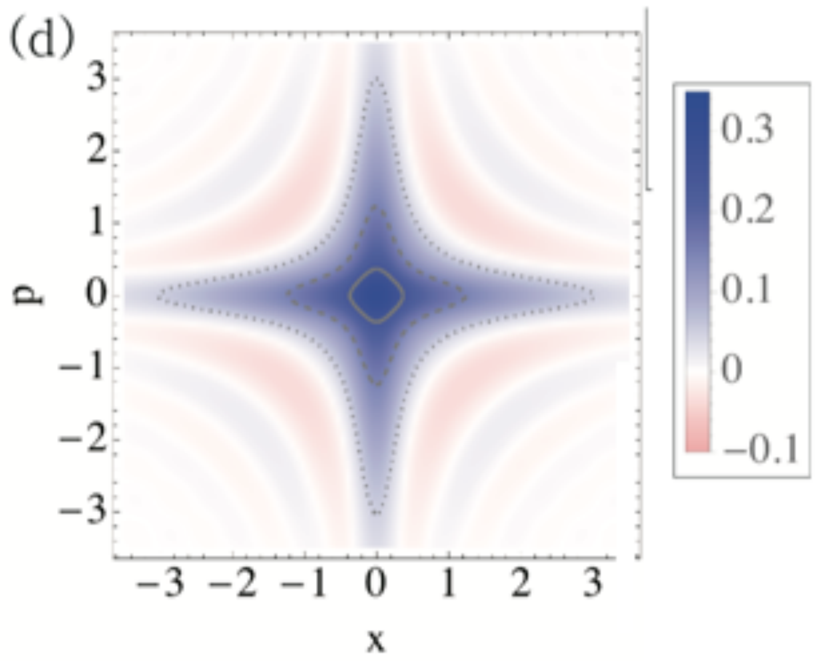
non-Gaussian state metrology

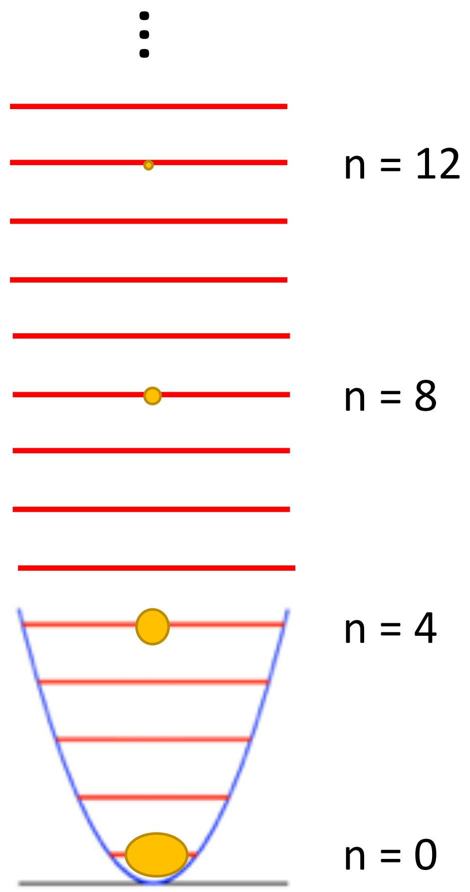


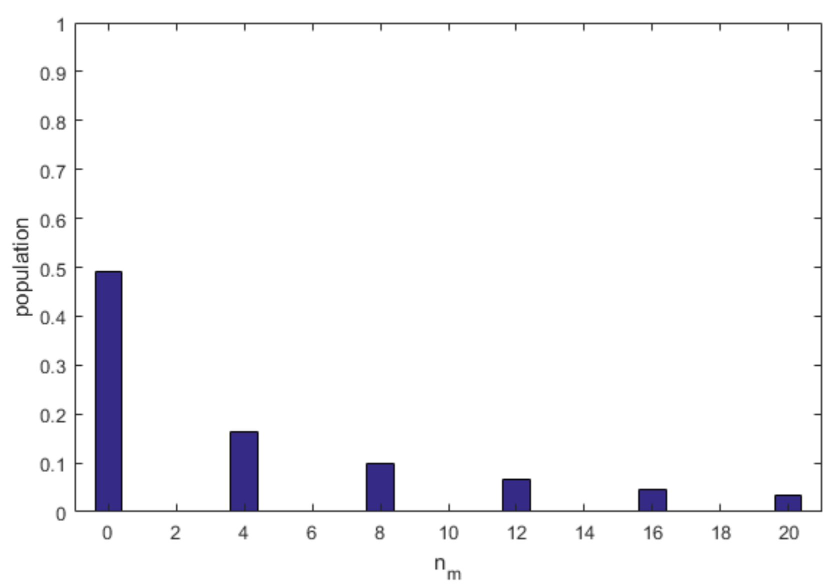
non-Gaussian state metrology



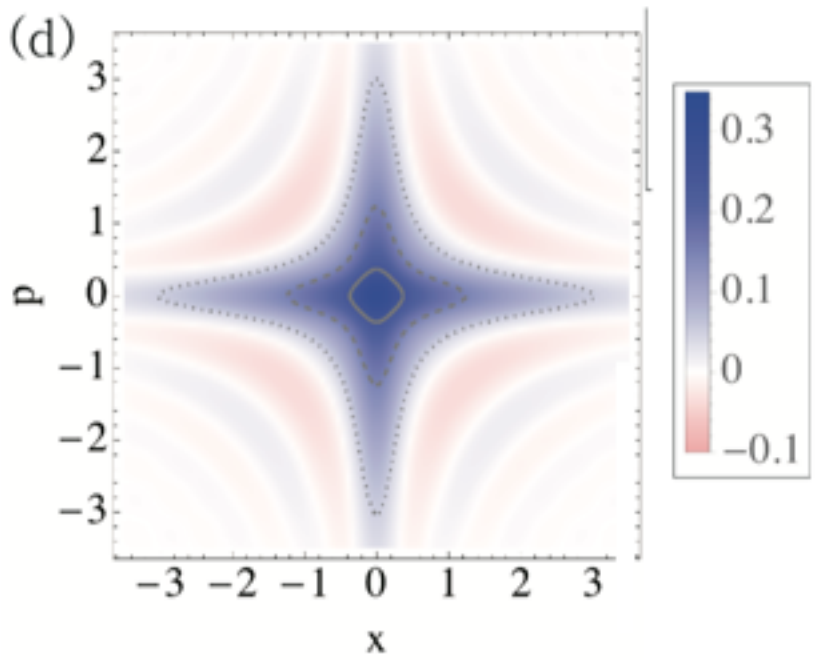
non-Gaussian state metrology







non-Gaussian state metrology



Typical quadrature

$$\hat{X}_1 = \frac{1}{2}(\hat{b}e^{-i\theta/4} + \hat{b}^\dagger e^{i\theta/4})$$

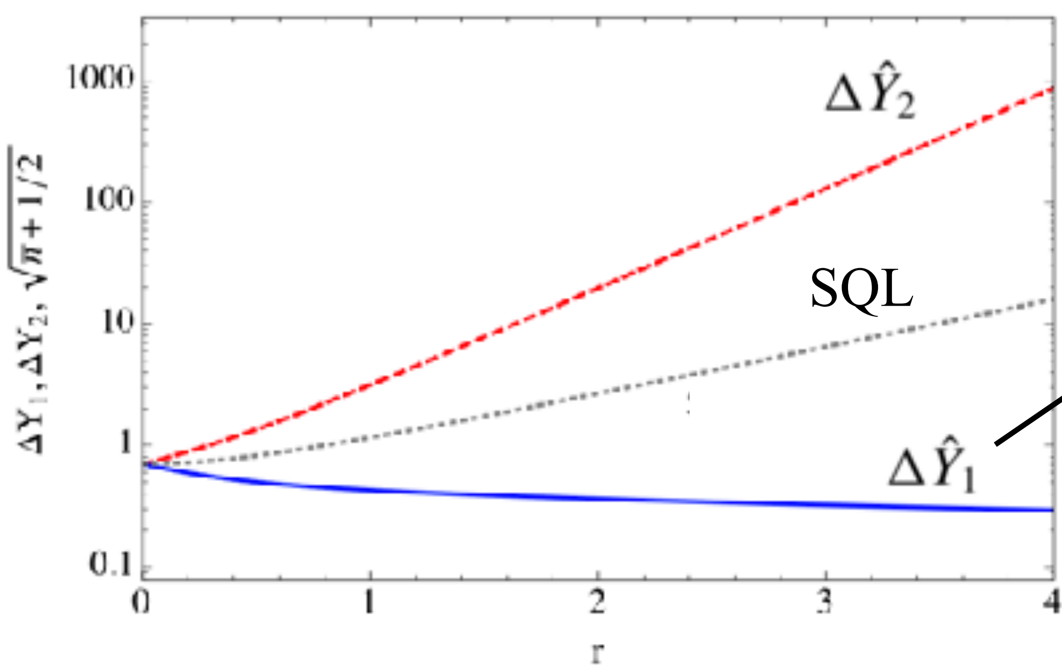
$$\hat{X}_2 = \frac{1}{2i}(\hat{b}e^{-i\theta/4} - \hat{b}^\dagger e^{i\theta/4})$$

Amplitude squared quadrature

$$\hat{Y}_1 = \frac{1}{2}(\hat{b}^2 e^{-i\theta/2} + \hat{b}^{\dagger 2} e^{i\theta/2})$$

$$\hat{Y}_2 = \frac{1}{2i}(\hat{b}^2 e^{-i\theta/2} - \hat{b}^{\dagger 2} e^{i\theta/2})$$

$$\Delta\hat{Y}_1 \Delta\hat{Y}_2 \geq \bar{n} + \frac{1}{2}$$



$$\hat{Y}_1 = \hat{x}\hat{p} + \hat{p}\hat{x}$$

quantum enhanced correlation measurement

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Quantum Simulators

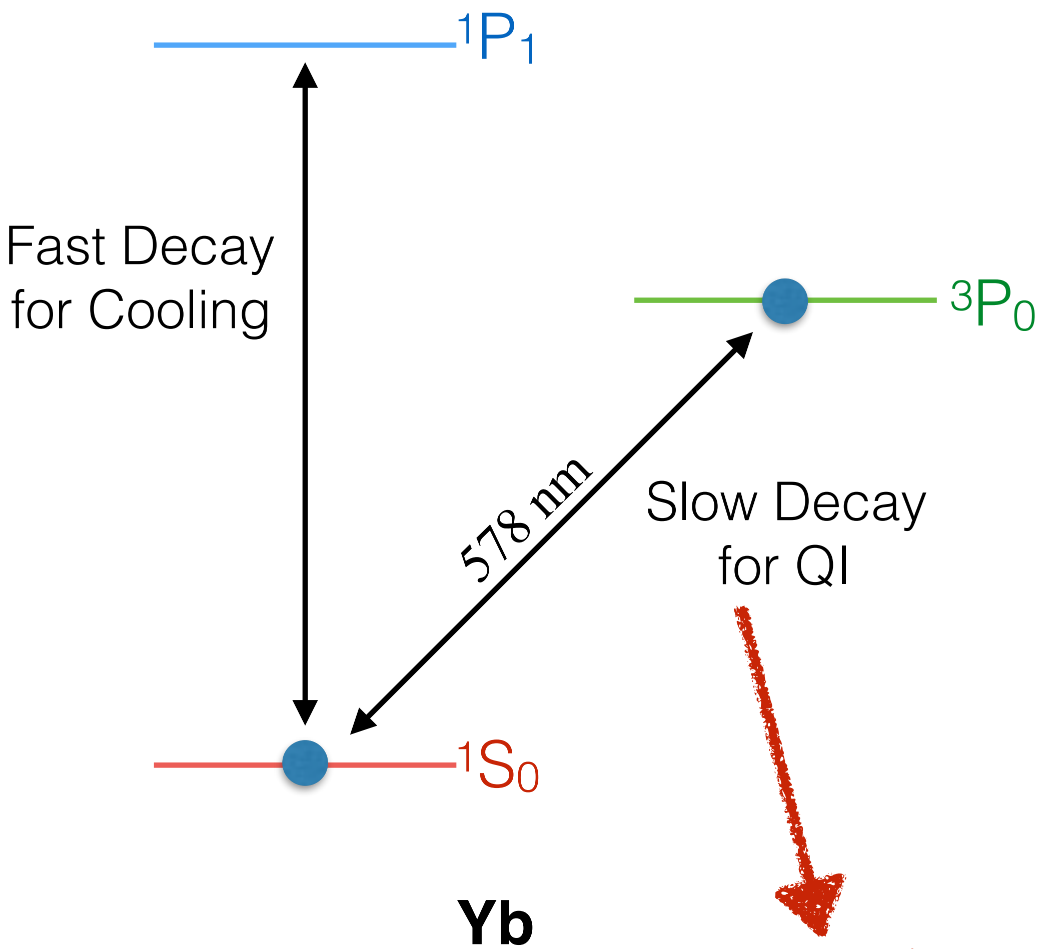
Thomas Young (1801)

to convince the audience
used water for presentation

Feynmann ‘simulating physics with computers’

“Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.”

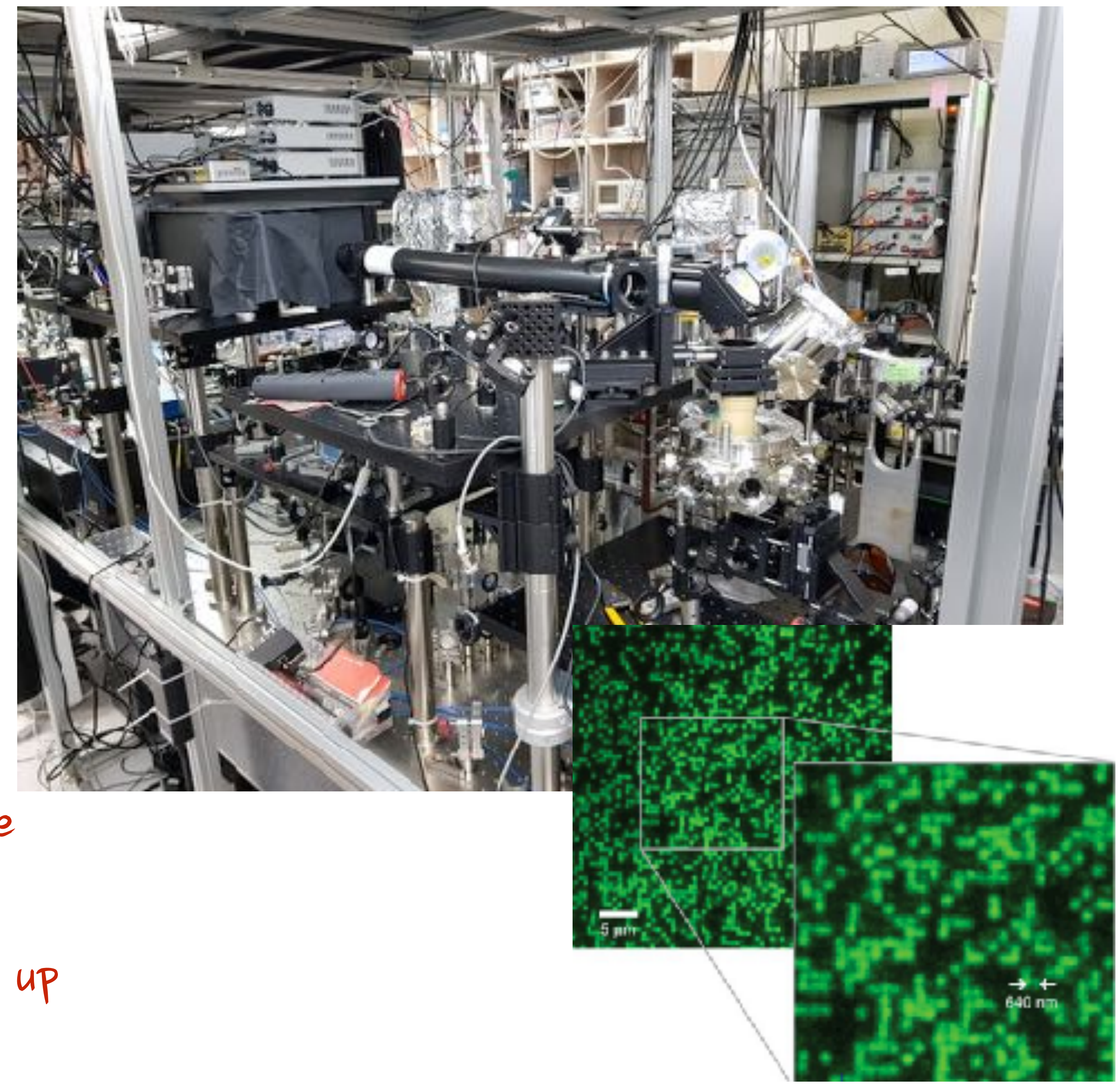
Yb Quantum Gas Microscope



long lifetime

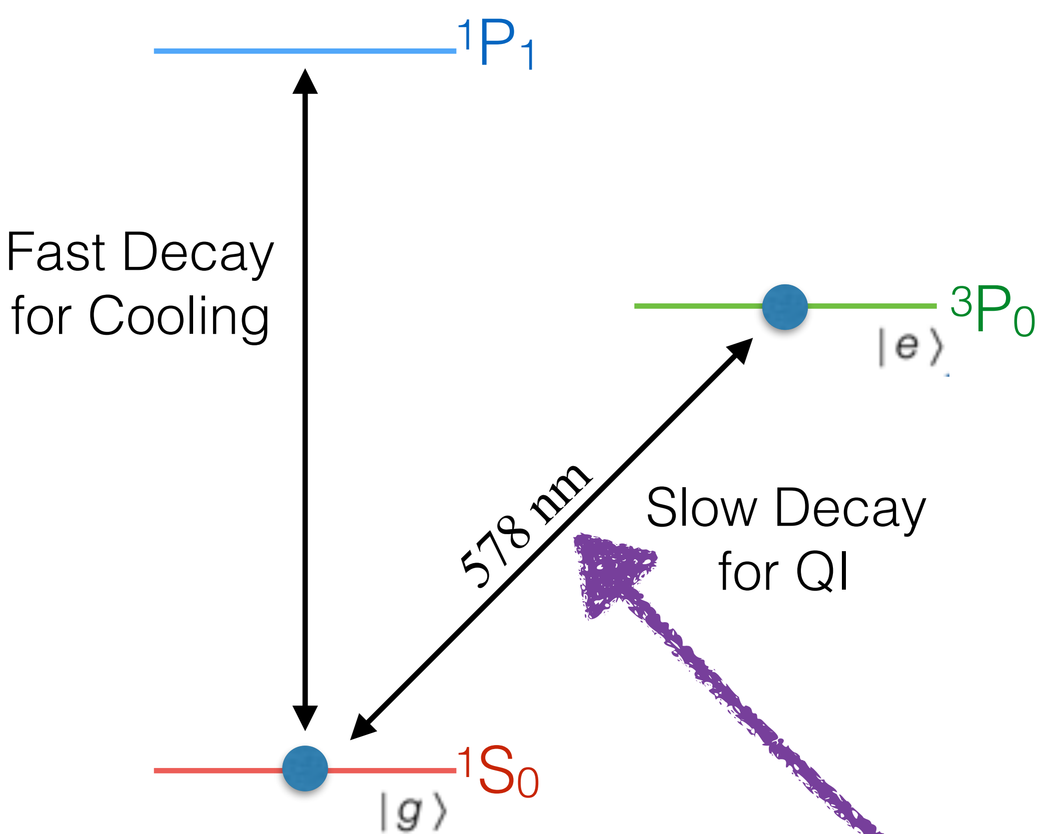
long simulation time

c.f. alkali atoms heat up

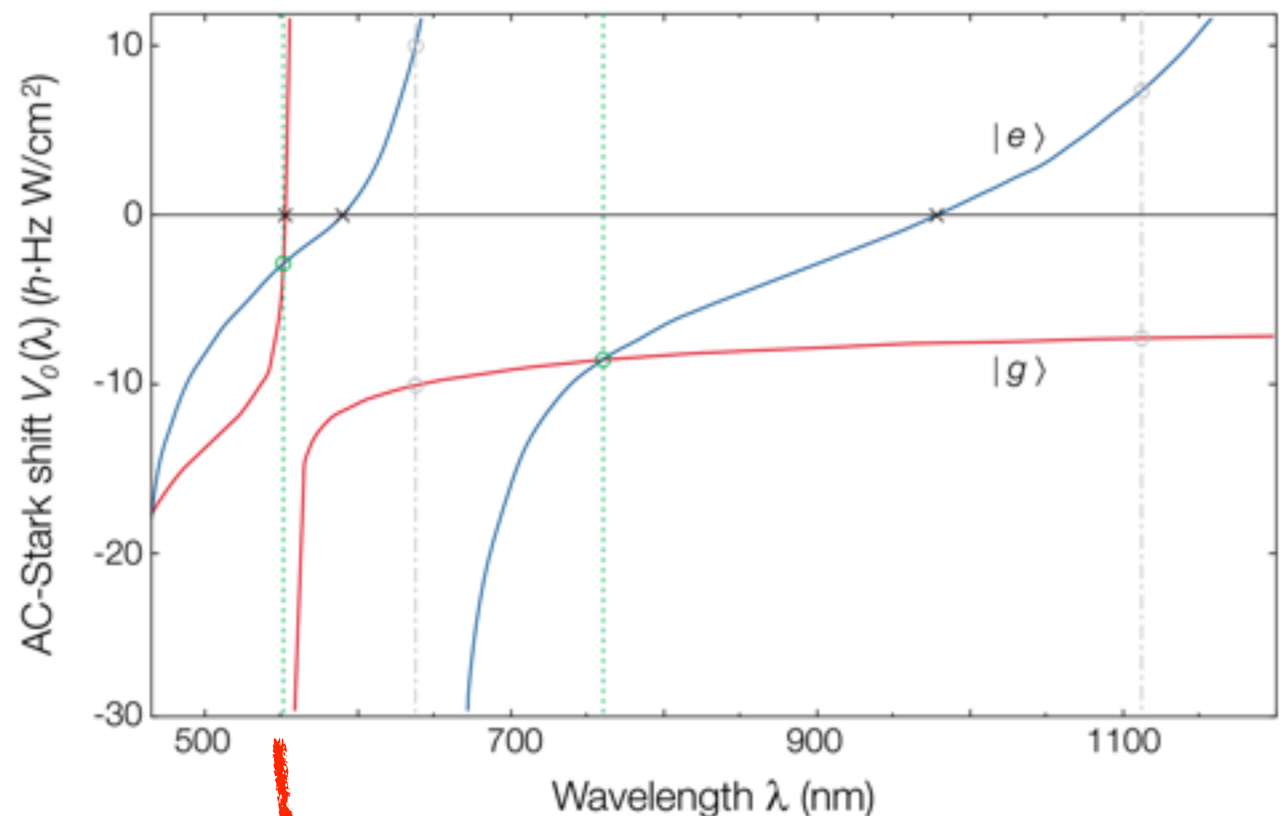


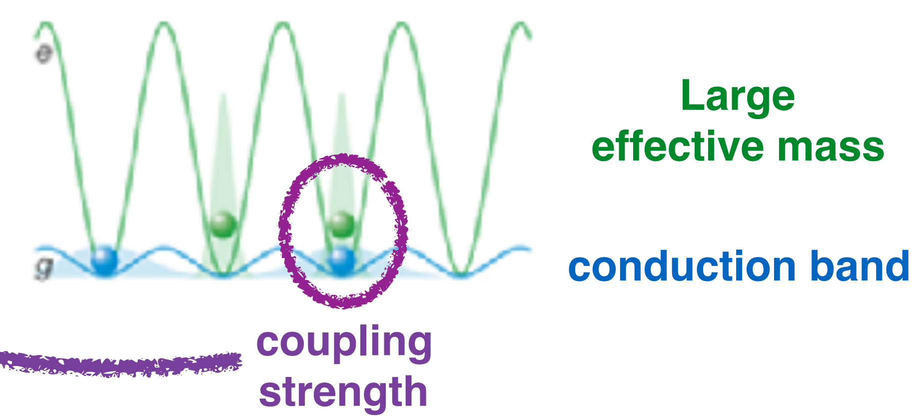
Greiner group

Kondo Lattice Model



$$\hat{U} = \hbar \frac{|\omega_R|^2}{4\delta} |g\rangle \langle g|$$





$$\hat{H}_{\mathrm{KLM}} = -J_g \sum_{\langle i,j\rangle\, m} \hat{c}^{\dagger}_{gim}\hat{c}_{gjm} + V_{\mathrm{ex}} \sum_{jmm'} \hat{c}^{\dagger}_{gjm}\hat{c}^{\dagger}_{ejm'}\hat{c}_{gjm'}\hat{c}_{ejm}$$

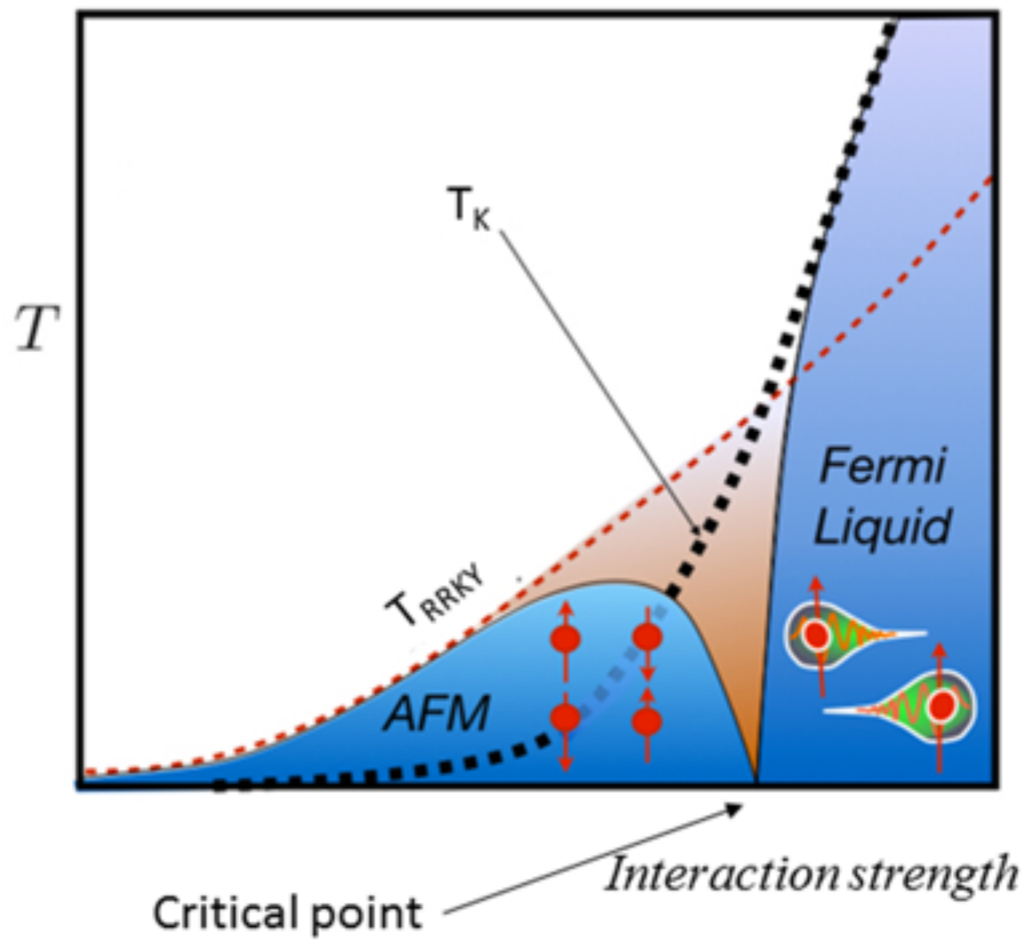
tunneling — spin interaction

core parameter: $V_{\mathrm{ex}} / J_{\mathrm{g}}$

Kondo Lattice Model

study of
heavy fermion material

quantum phase
quantum criticality
topological effects
.
.



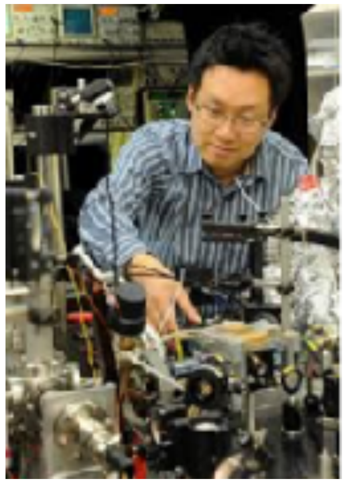
hopefully, we can contribute to understanding quantum phenomena in **condensed matter**

Acknowledgements

Thank you!

looking for 포닥 & 정규직

문종철 (KRISS)



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서준호 (KRISS)

이한석(KAIST)