Locking a Local Oscillator Phase to an Atom Phase

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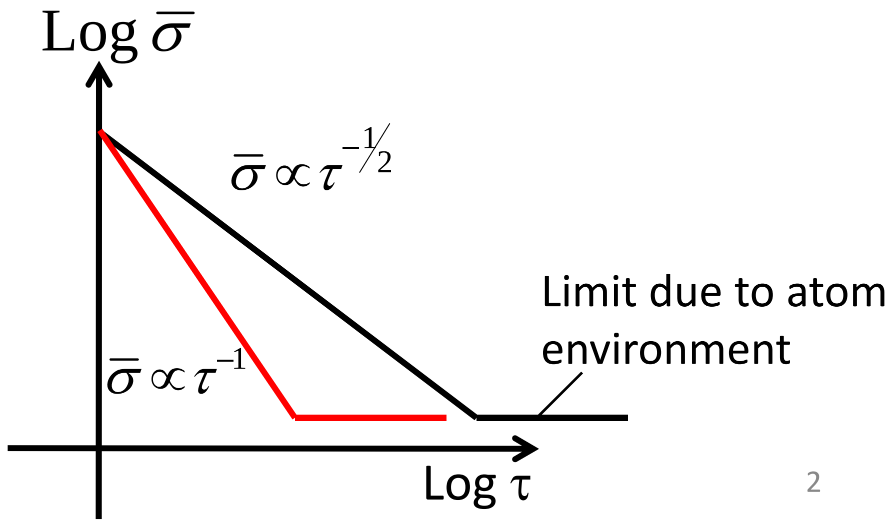
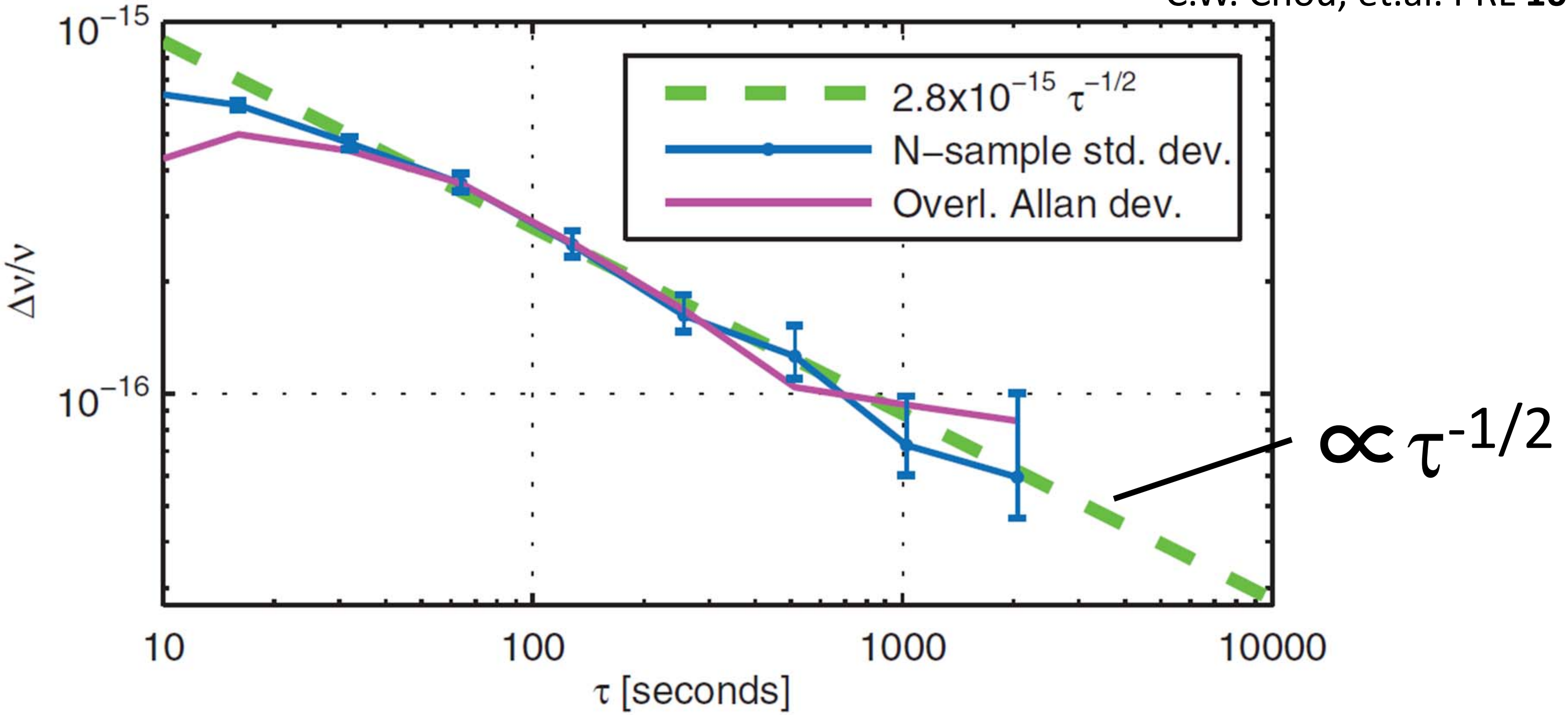
Abstract

We propose and aim to demonstrate the control method to reach the ultimate stability of atomic clock. Instead of locking laser **frequency** to atomic **frequency**, I will aim to lock laser **phase** to the atomic **phase**. **We estimate that atom phase lock can be achieved from 0.1sec to 10sec with 10^6 ions in a linear rf-trap.**



Stability of the best clock at the Al^{+} clock at NIST

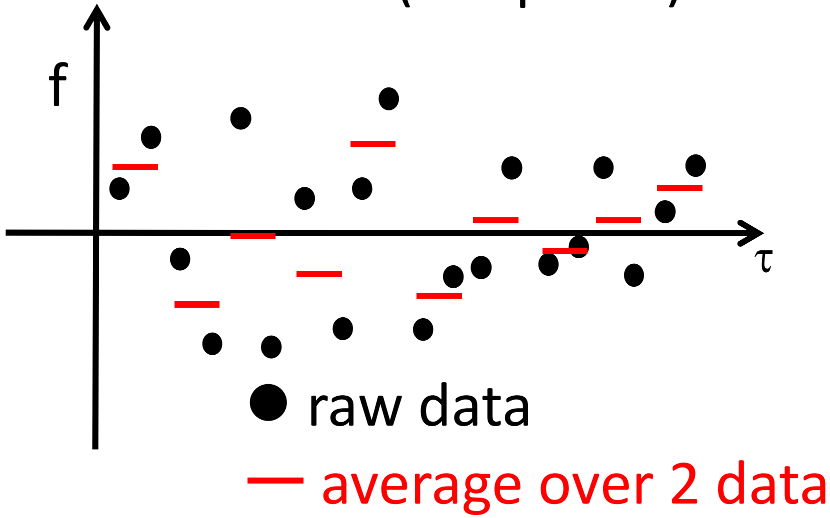
C.W. Chou, et.al. PRL **104**, 070802 (2010)

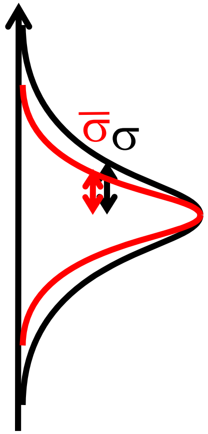


- This is the best atomic clock at the moment. What could be the next direction for further improvement?

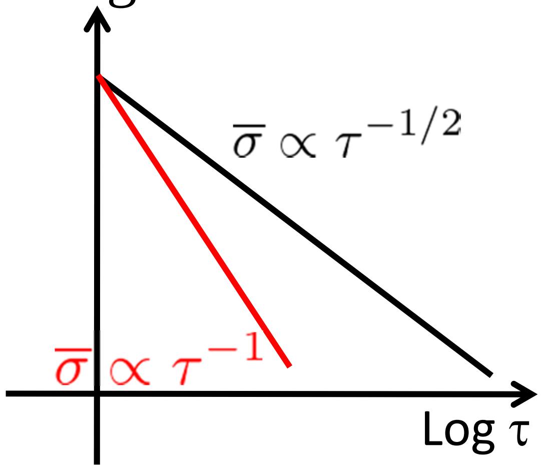
τ^{-1} is possible with "Good correlation"

No Correlation (Freq. lock)

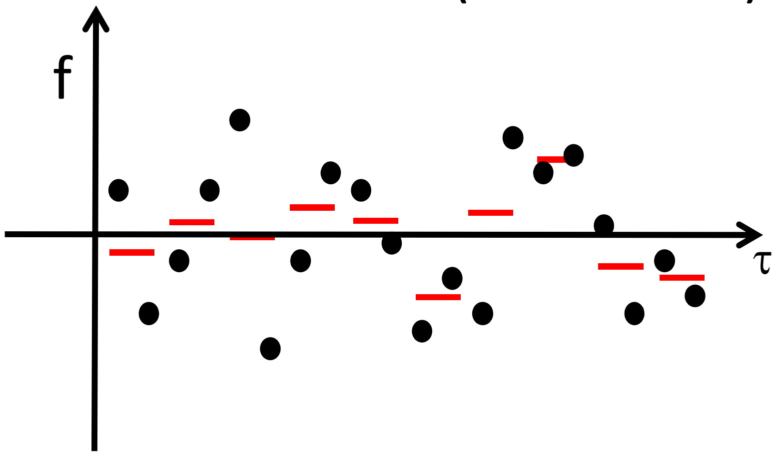


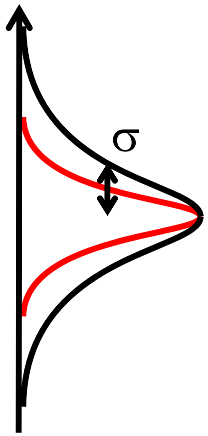


$$\bar{\sigma} = \frac{\sigma}{\sqrt{N}} \propto \frac{1}{\sqrt{\tau}}$$



Good Correlation (Phase lock)





$$\bar{\sigma} = \frac{\sigma}{N} \propto \frac{1}{\tau}$$

3 major path for further improvement of atomic clock

$$\sigma_y(\tau) = \frac{\Delta\omega_a}{\pi\omega_0}\sqrt{\frac{\tau_c}{2N\tau}} \approx \frac{1}{Q}\frac{1}{S/N}\sqrt{\frac{\tau_c}{\tau}}$$

τ: Total measurement time
τ_c: cycle time
$\Delta\omega_a$: spectral line width

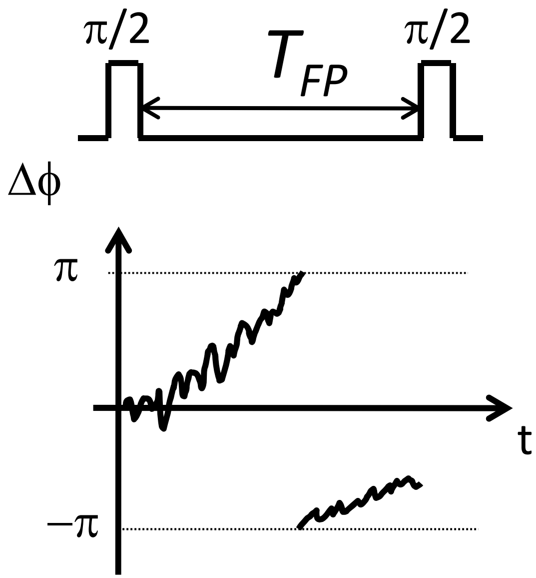
1. Choose a clock transition with higher frequency to increase ω_0.
2. Increase probe time (or free precession time for Ramsey) to decrease $\Delta\omega_a$.
3. Use squeezed state to increase S/N.

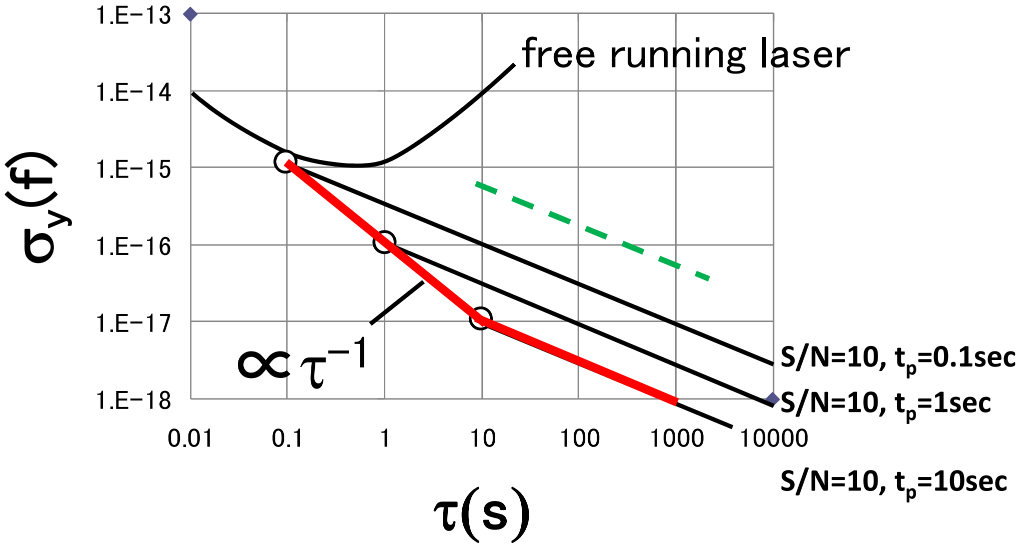
1. has contributed to the recent improvement of atomic clock by replacing the microwave transition to the optical transition.

2. and 3. has been difficult due to the (bad) noise of the LO.

Atom phase lock aims to improve the stability through 2. even under the LO limit.

"Atom Phase Lock"

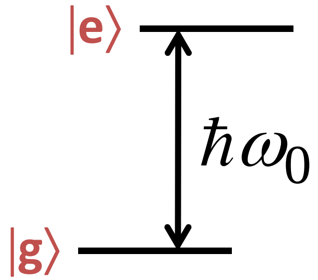




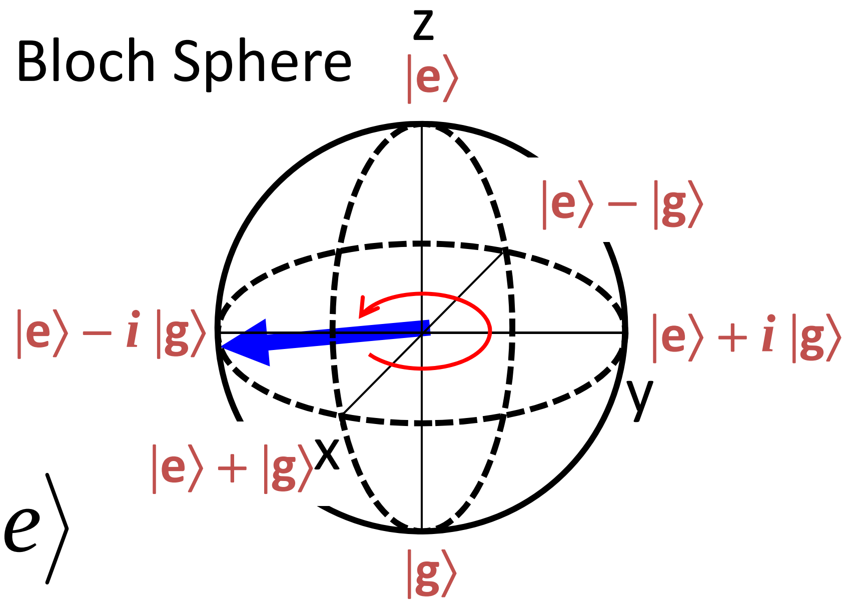
- Ramsey method measures the phase difference between LO and atom after free precession time T_{FP}.
- Q of the spectrum is improved by increasing the T_{FP}, but phase can only be measured between $-\pi$ to $+\pi$. Therefore, T_{FP} is limited by the stability of the LO.
- Main idea of "Atom phase lock" is to "monitor" the atom phase without destroying the coherence of the atom to keep the LO phase to be within $\pm\pi$ by feeding back to the LO phase.

What is the atomic Phase?

2-level system



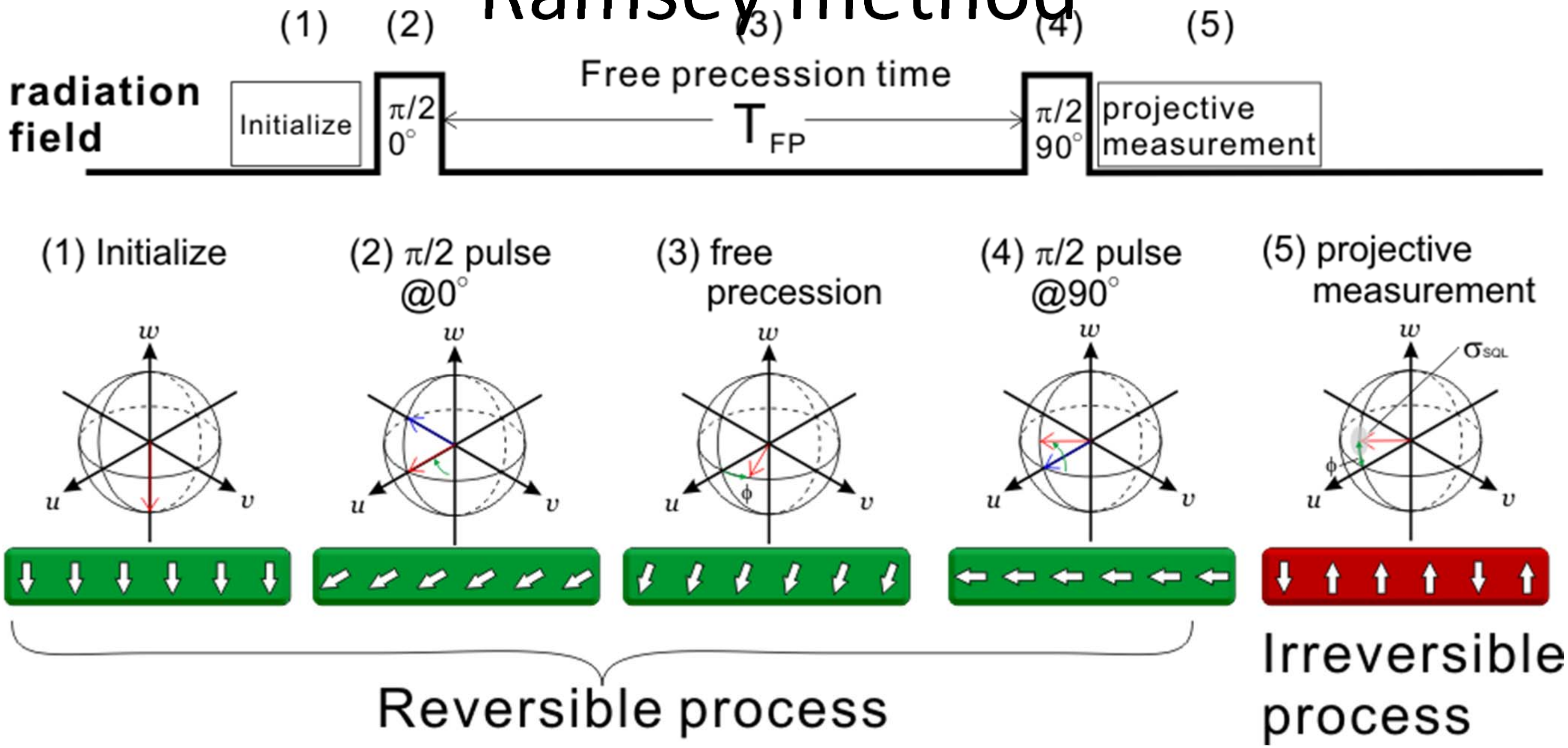
Bloch Sphere



$$\psi = C_g e^{i\omega_0 t}\left|g\right\rangle + C_e e^{-i\omega_0 t}\left|e\right\rangle$$

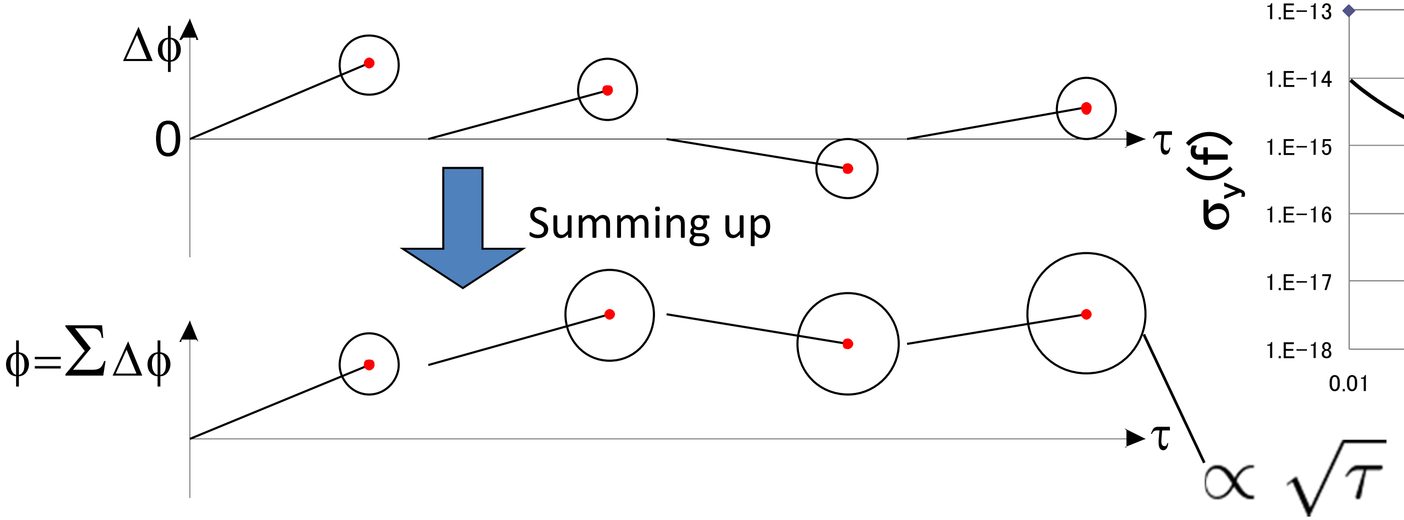
The super position of the 2-level system can be projected to “Bloch Sphere” and the vector is called “spin.” The coefficients of the super position state has phase term that evolves at ω_0 which corresponds the energy spacing.

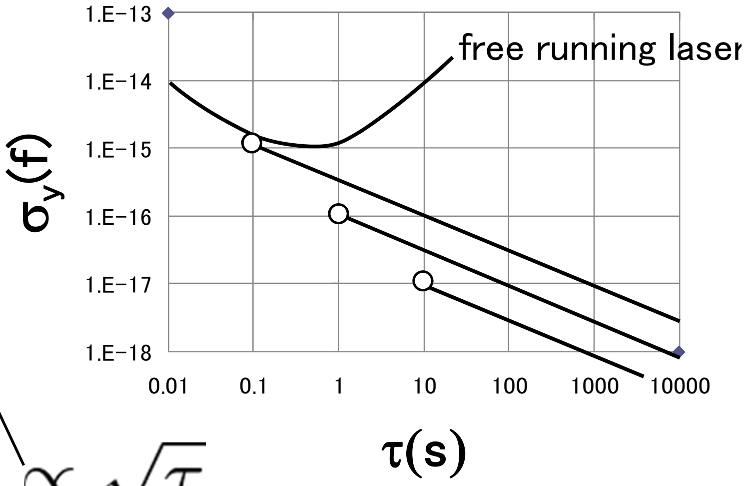
How to measure the phase of atom - Ramsey method-



- We emphasize here that the atom phase is completely destroyed by the mere projective measurement.

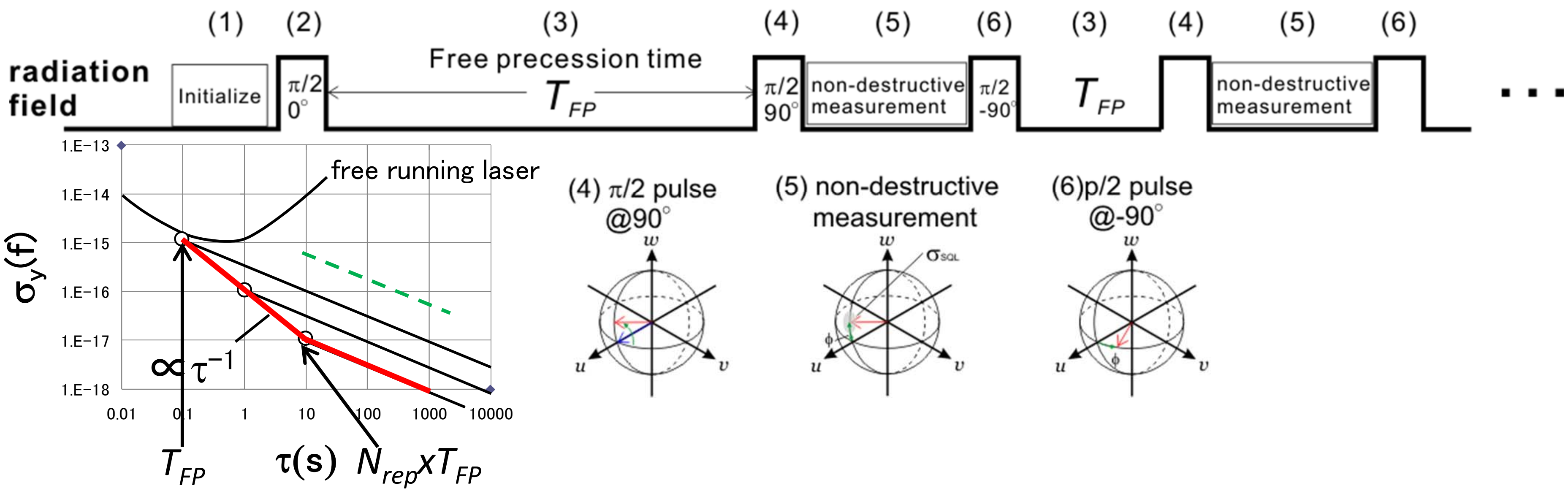
(Destructive) Measurement prevent us from Phase Lock…





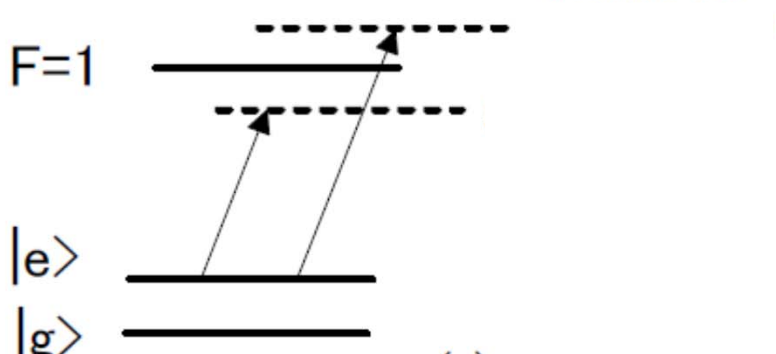
φ can be calculated from Δφ, but uncertainty grows as you take sum. This growth actually comes from the fact that the measurement destroys the atomic superposition state, and we initialize the phase at each cycle.

Coherence preserved Ramsey method

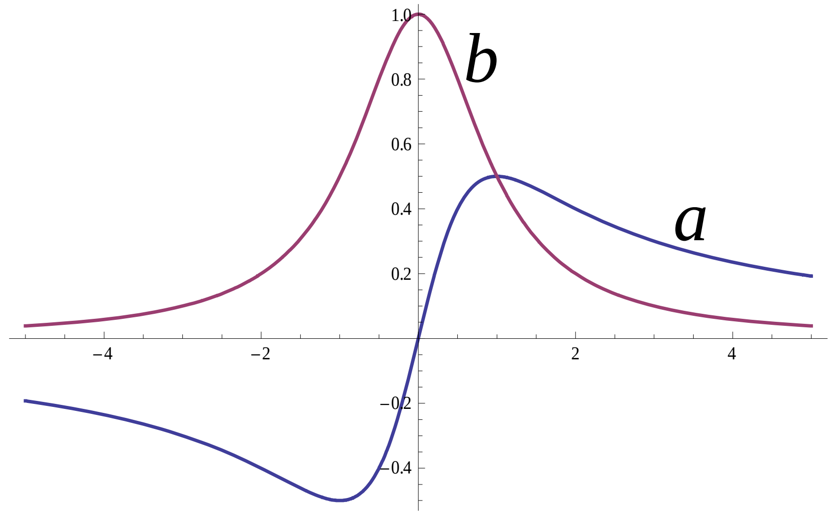


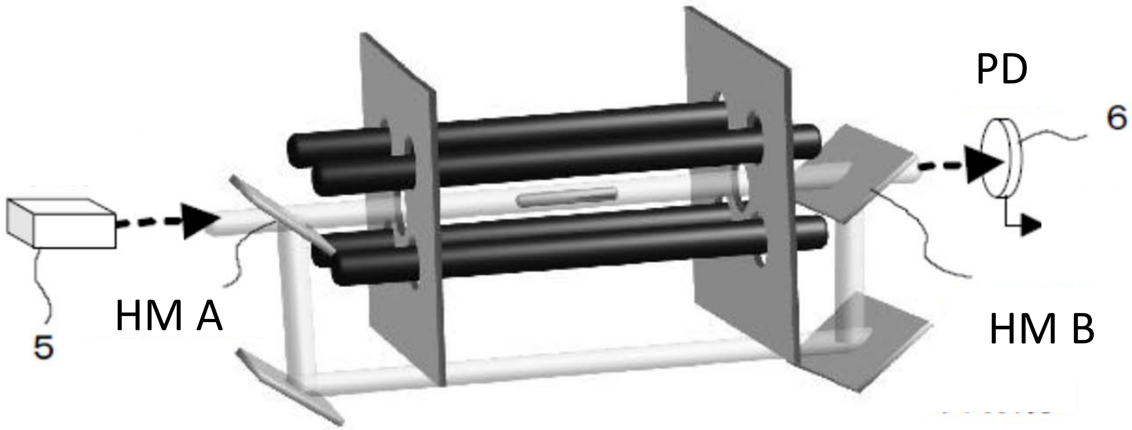
- Atom phase is monitored after every T_{FP} and then brought back to the original position.
- Repeating this would allow us to monitor the phase at τ without uncertainty being piled up.
- Atom phase lock is achieved as long as coherence of the atom is maintained
- Dick effect is valid, so (4)-(6) should be relatively quick.

Non-destructive measurement（Mach-Zender type）



(a)

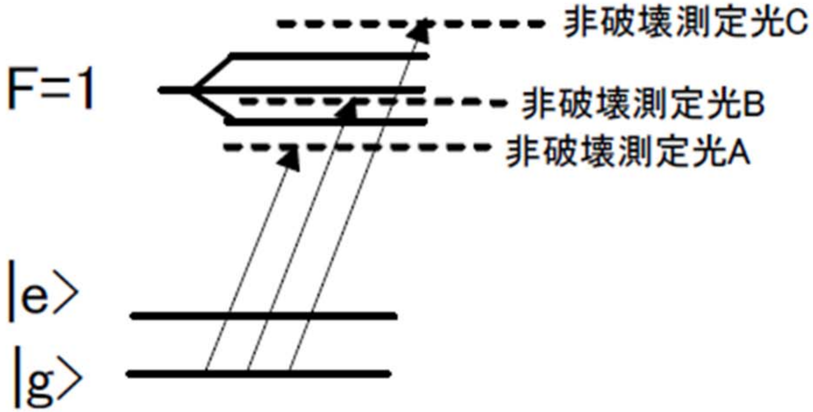


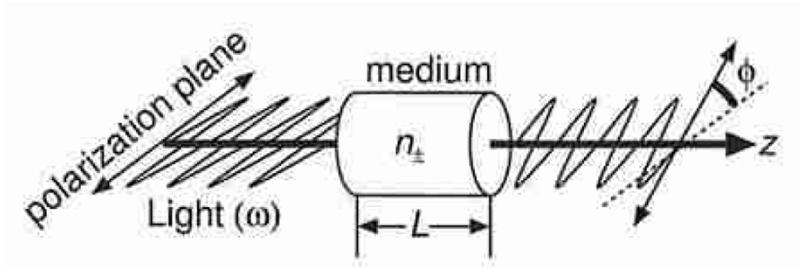


(b)

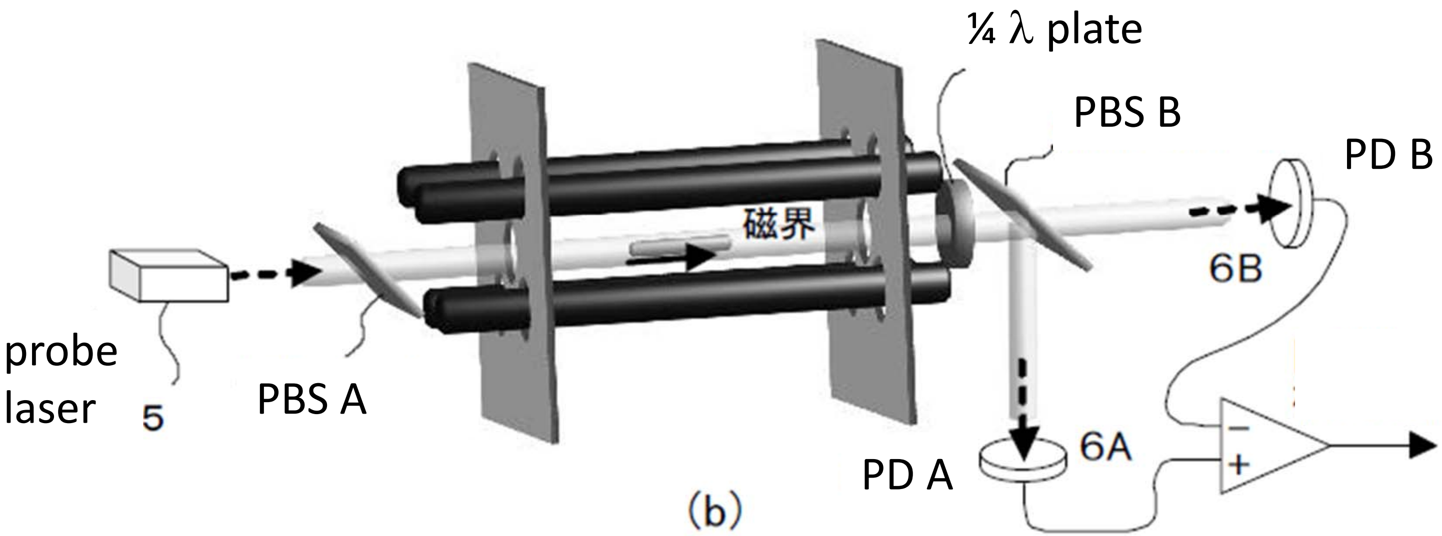
- We can monitor the population of the excited state by measuring the dispersion of the probe beam.

Non-destructive measurement
（Faraday Rotation type）





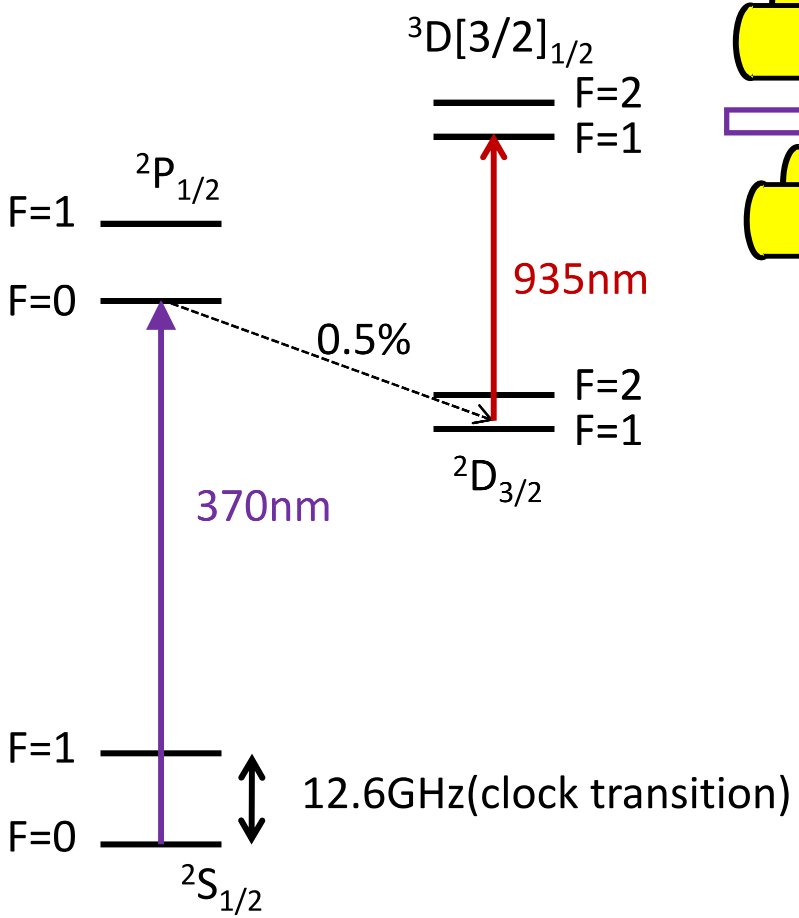
(a)

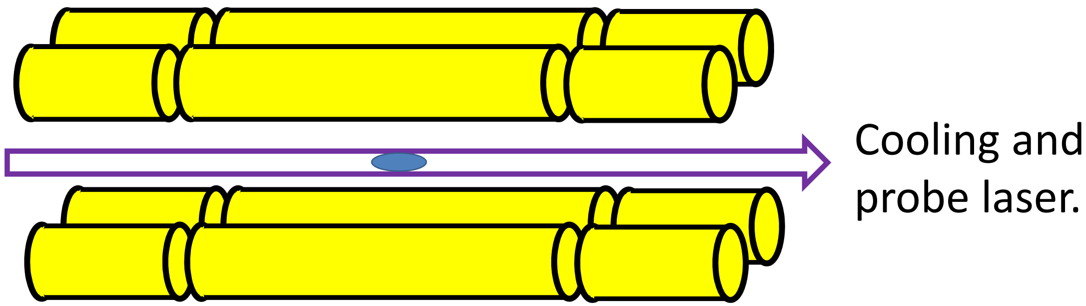


(b)

Experimental Set up

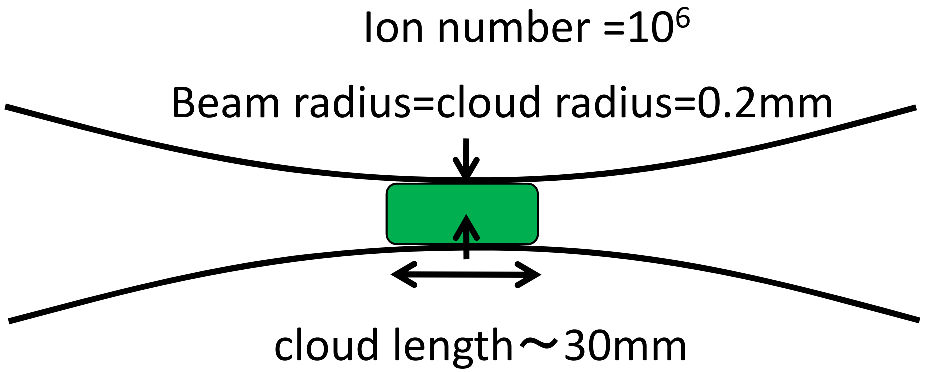
$^{171}Yb^{+}$ Energy diagram

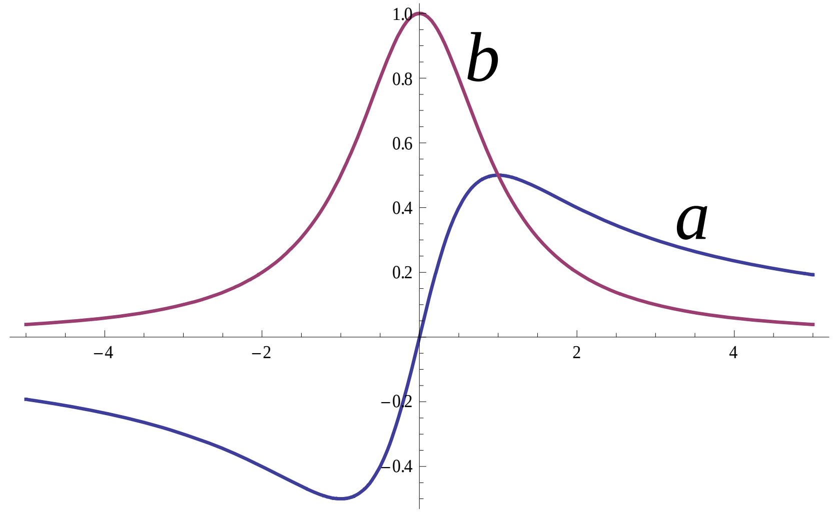


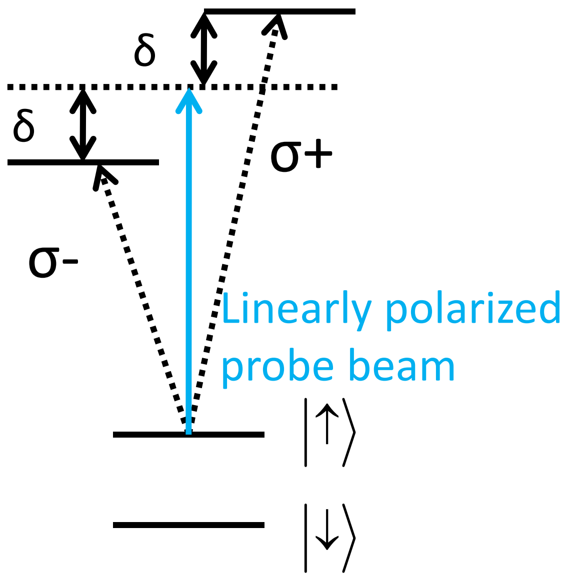


- Photo ionization 399nm
- Cooling and probe 370nm
- repump 935nm
- Can be prepared with ECDL

Decoherence due to Absorption







$$a = \frac{\sigma}{2A}\frac{2\delta/\gamma}{1+(2\delta/\gamma)^2}$$

$$b = \frac{\sigma}{A}\frac{1}{1+(2\delta/\gamma)^2}$$

γ : Natural line width

δ : Detuning

σ : Absorption cross section at resonance

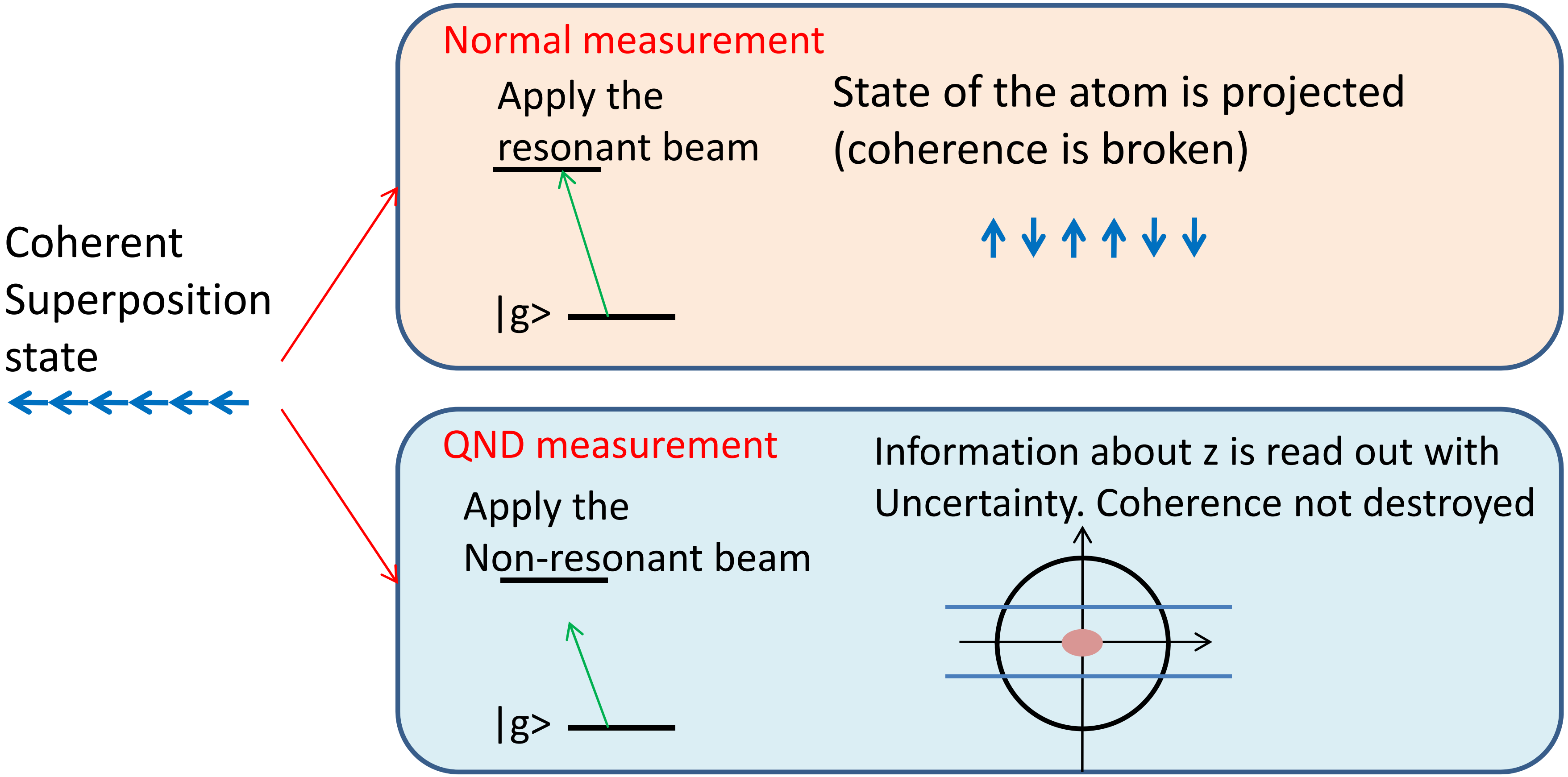
Number of photons N_{ph} needed for S/N=10	$N_{ph} = \frac{(S/N)^2}{4a^2N^2} = 1400\,photons$
Absorption probability P_{abs} with N_{ph} photons	$P_{abs} = bN_{ph} = 3.8\times10^{-4}$

We estimated that we can operate non-destructive measurement for ~100 times before 10% of the ions are absorbed.

Linear Paul trap under construction

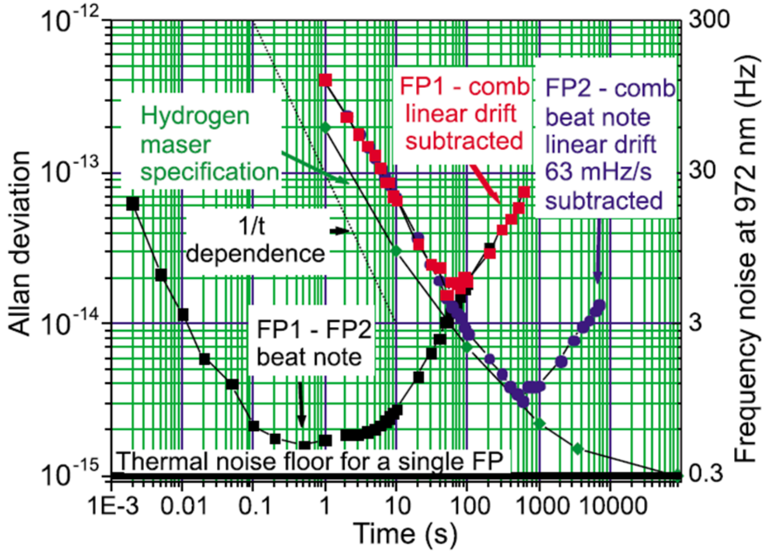
- Basic component is built. electronic wiring needs to be done.

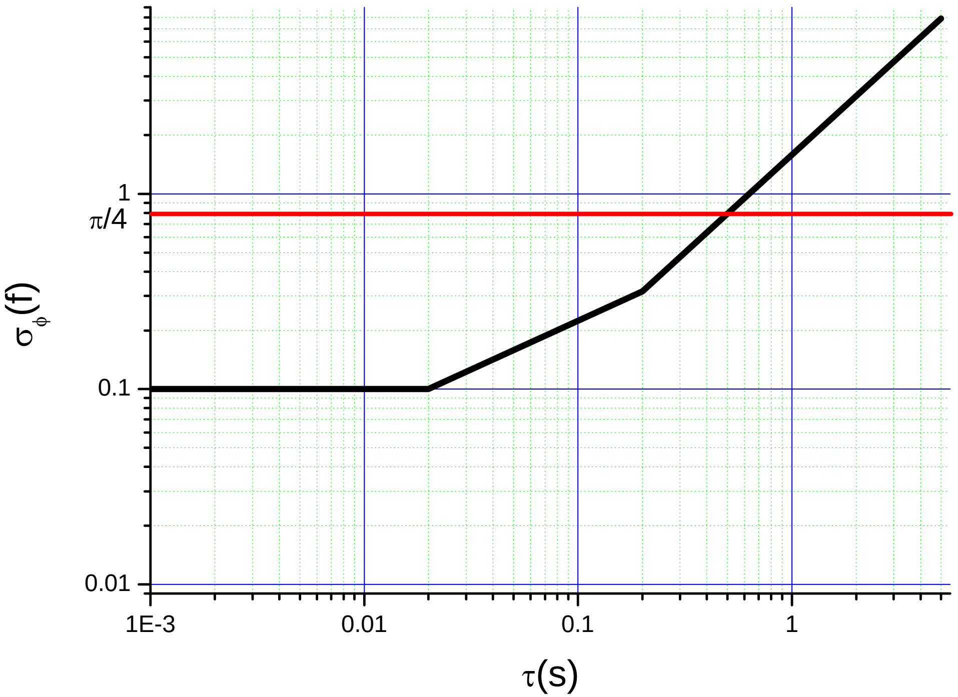
Normal measurement and QND measurement



- QND measurement (sort of) maintains the coherence of the spin at the cost of increased uncertainty of x direction.

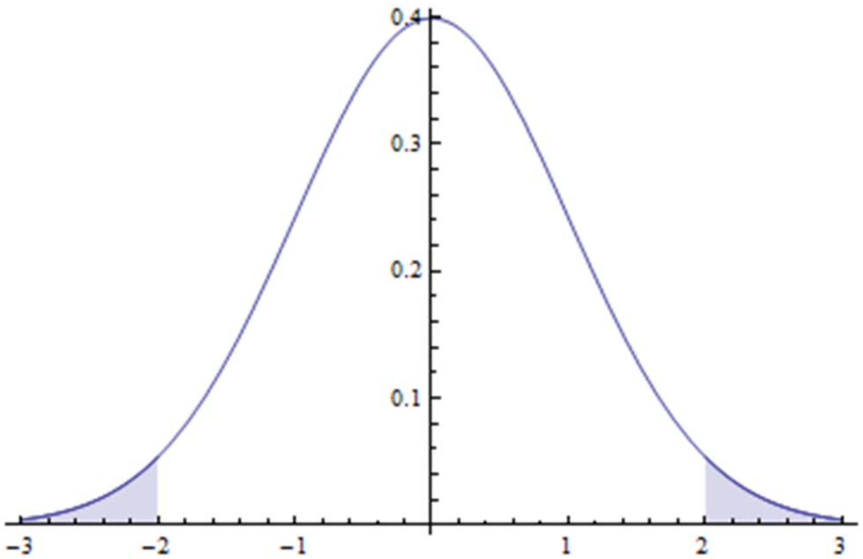
Phase deviation of LO

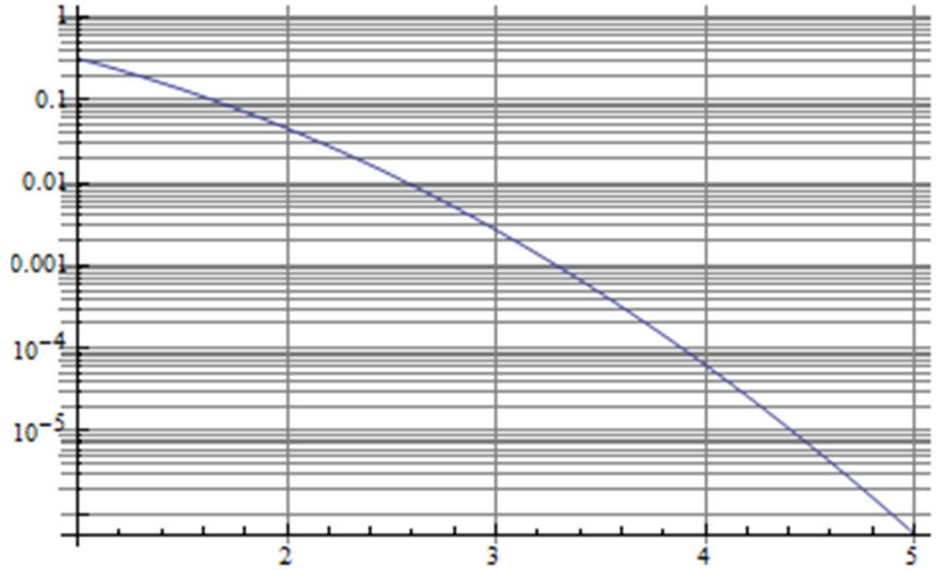




- Phase deviation accumulates $\pi/10$ in 0.2 sec.

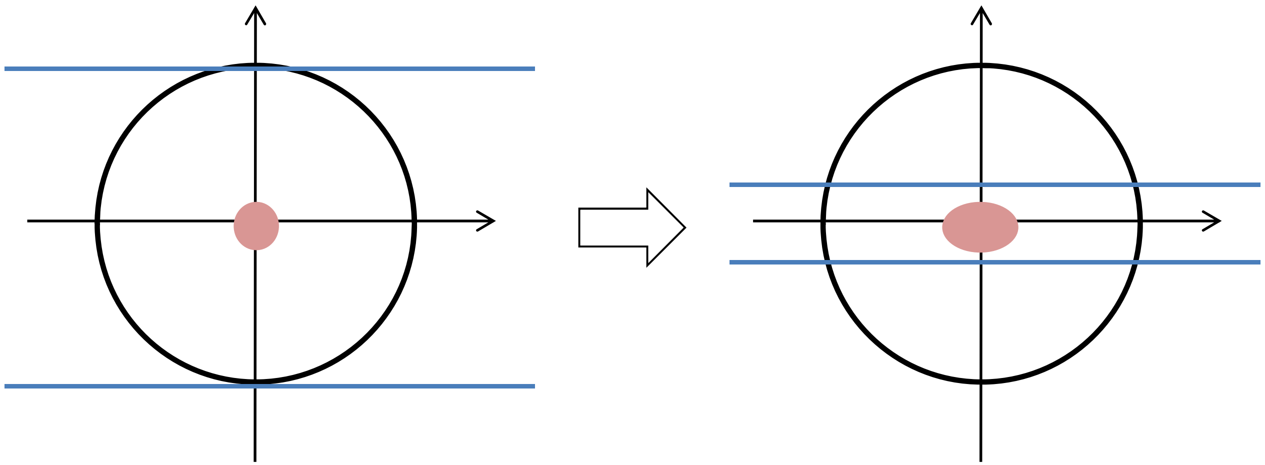
S/N=10 gives error rate of $<10^{-6}$





- S/N=10 means that Ramsey signal has chance of exceeding +-$\pi/2$ limit with chance of 10^{-6}.

Back action is still much smaller than absorption with 10^6 ions



$$\left\langle S_y^2 \right\rangle \sim \frac{N}{4}\left(1+\frac{(S/N)^2}{2N^2}\right)=\frac{N}{4}(1+5\times10^{-11})$$

- Non-destructive measurement comes with back action but it’s very small when S/N=10 and N=10^6.