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Single-ion Quantum Lock-in Amplifier

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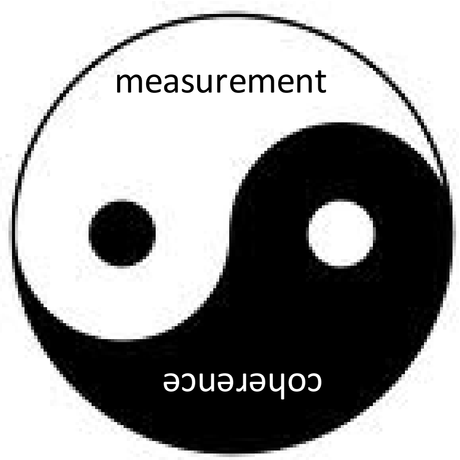
Information is Physical

<u>Information getters</u>

- Measurement probe
- Couples to its environment

<u>Information carriers</u>

- Physical memory
- transmission channels
- Weak coupling to the environment



Noise as a common enemy.

Radio transmission

- Transfer an audio-frequency electro-magnetic signal, f(t), over a noisy medium.
- AM: modulate f(t) with a frequency ω_m, outside the noise bandwidth:

$$f(t) \longrightarrow f(t)\sin(\omega_m t)$$

- At the receiver, mix the recieved signal with $A\sin(\omega_m t + \phi)$ and low-pass filter

- Recover at base-band frequencies the signal $Af(t)\cos(\phi)$

Lock-in amplifier and measurement

- Invented in the 50's by Princeton physicist, Robert Dicke

- Want to measure a (noisy) physical quantity Y

- Modulate Y at a frequency ω_m outside the noise bandwidth: $Y \Rightarrow Y\cos(\omega_m t)$

- Electronically mix the detected Y signal with: $A\sin(\omega_m t + \phi)$
  and low-pass filter

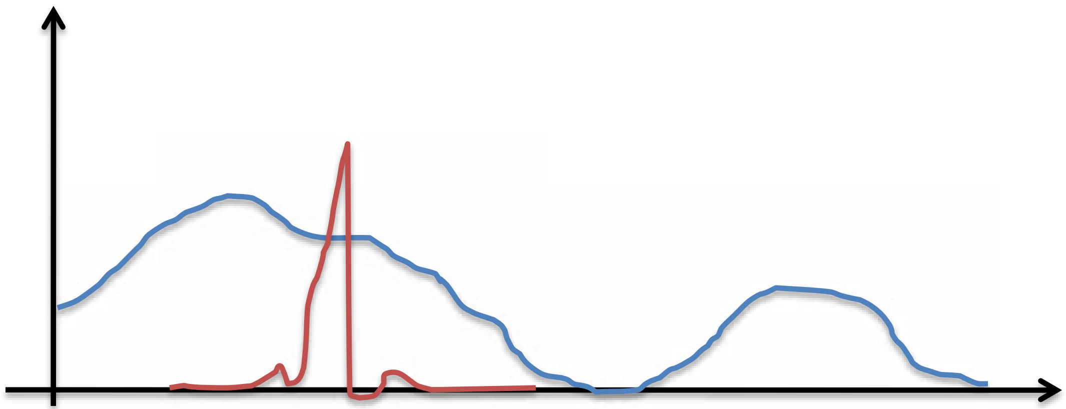
$$\frac{A}{T}\int_0^T Y\cos(\omega_m t)\cos(\omega_m t + \phi)dt \simeq \boxed{AY\cos(\phi)} + O(\frac{1}{\omega_m T})$$

"Quantum Radio": Dynamic de-coupling

- Protect coherence in a quantum system (e.g. qubit) which is subject to a noisy environment or coupled to a non-Markovian bath

- Engineer a time dependent system Hamiltonian: H(t)

- Decoherence rate is proportional to the spectral overlap of the system time evolution with the noise/bath spectrum.

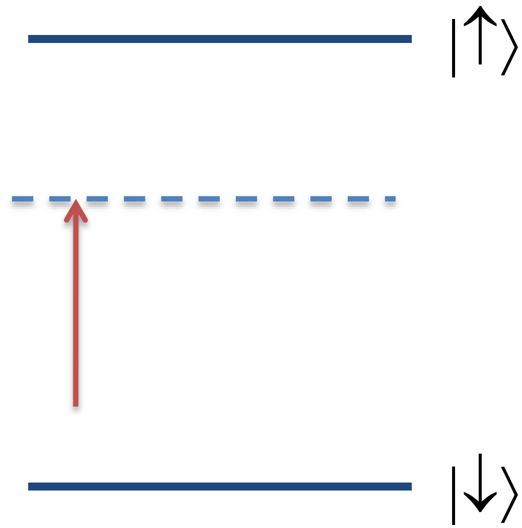


Gordon, Erez and Kurizki, J. of Phys. B, **40**, S75 (2007)
Sagi, Almog and Davidson, Phys. Rev. Lett., **104**, 253003 (2010)

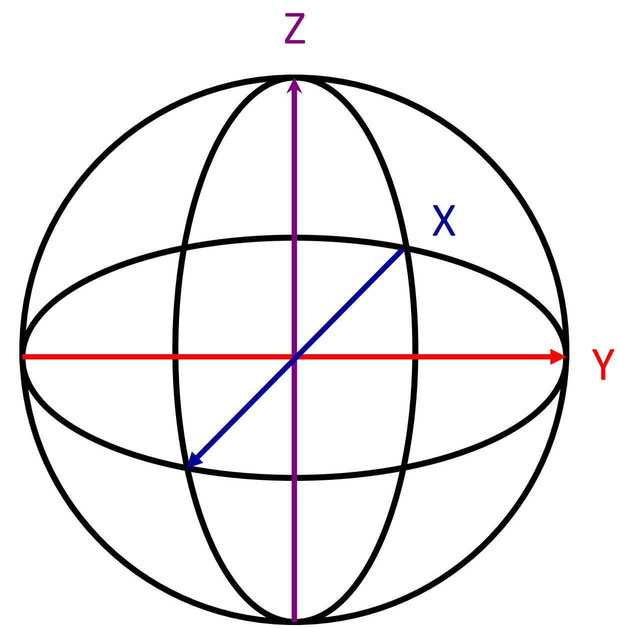
Quantum two-level probe

$\omega_L - \omega_0 = \delta(B)$

$\omega_0 = \omega_0(B)$



The Bloch sphere



$|\mathbf{Z}+\rangle = |\uparrow\rangle$ $\quad$ $|\mathbf{Z}-\rangle = |\downarrow\rangle$

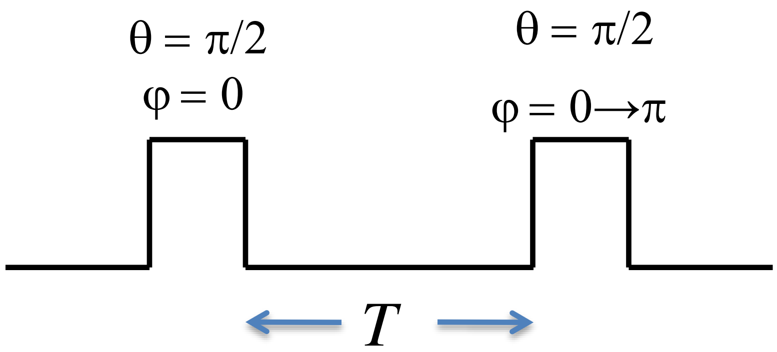
$|\mathbf{X}-\rangle = (|\uparrow\rangle + |\downarrow\rangle)/\sqrt{2}$ $\quad$ $|\mathbf{X}-\rangle = (|\uparrow\rangle - |\downarrow\rangle)/\sqrt{2}$

$|\mathbf{Y}+\rangle = (|\uparrow\rangle + i\,|\downarrow\rangle)/\sqrt{2}$ $\quad$ $|\mathbf{Y}-\rangle = (|\uparrow\rangle - i\,|\downarrow\rangle)/\sqrt{2}$

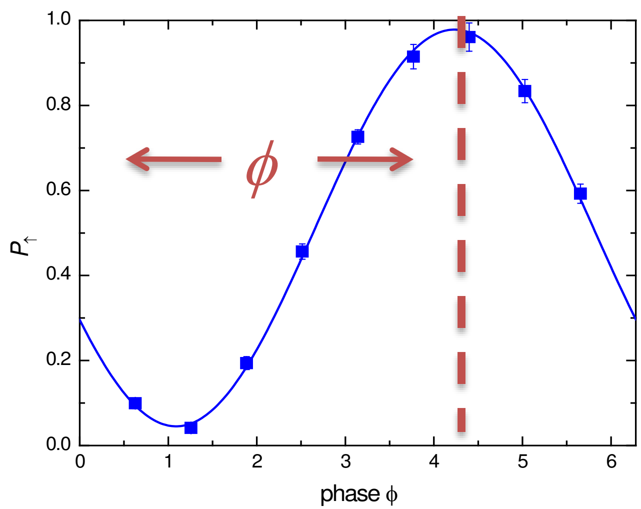
Quantum phase estimation

1st Ramsey pulse

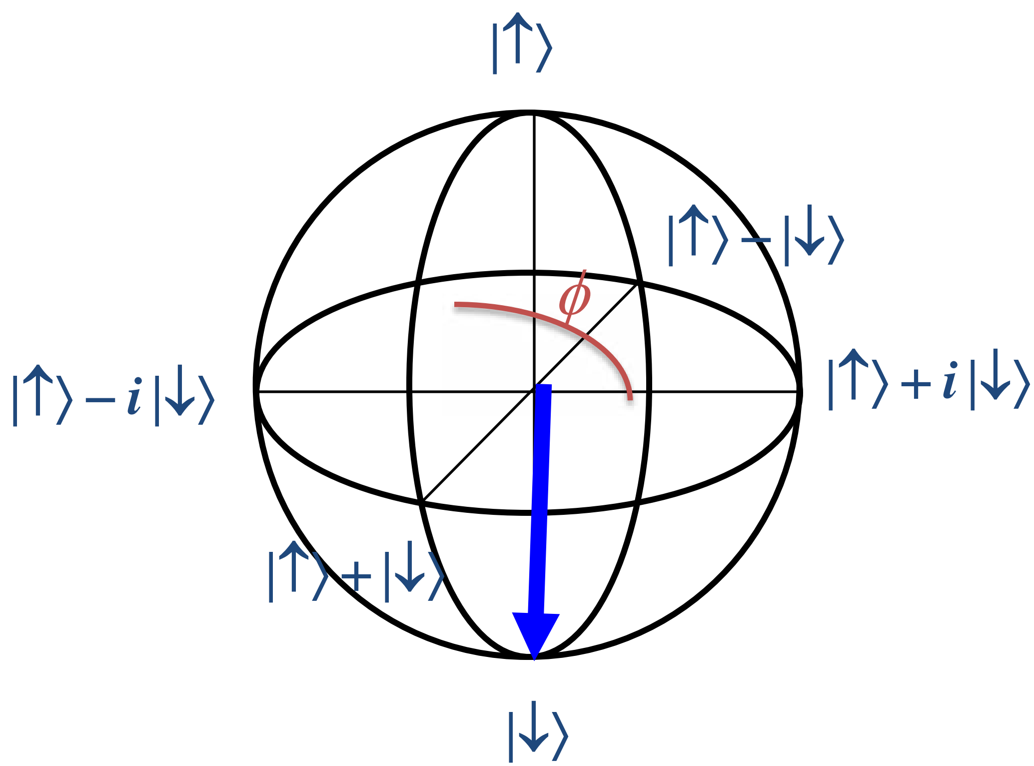
2nd Ramsey pulse



$$\phi = g \int_0^T B(t)dt$$

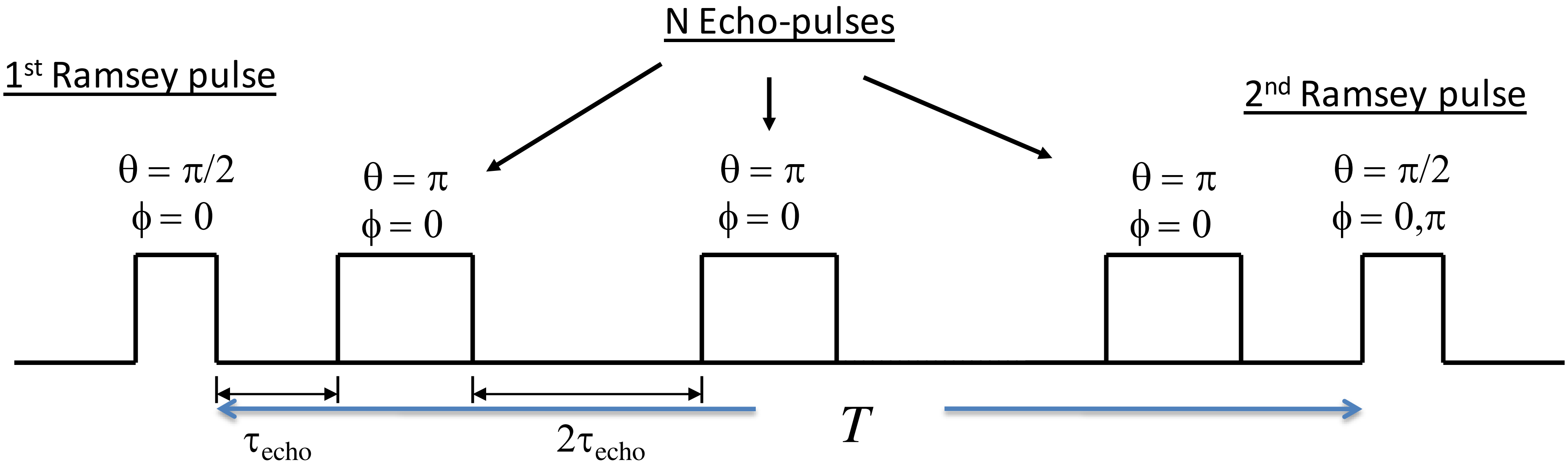


Bloch sphere



- Noise reduces fringe contrast
- Repeat the experiment many times
- Reduced contrast = more experiments

Quantum Lock-in



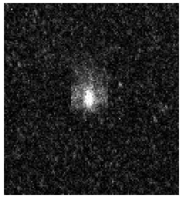
$$\phi = g\int_0^T B_0 \cos(\omega_m t) \times \sqcap\!\sqcup\!\sqcap\ldots\sqcup\!\sqcap \, dt$$

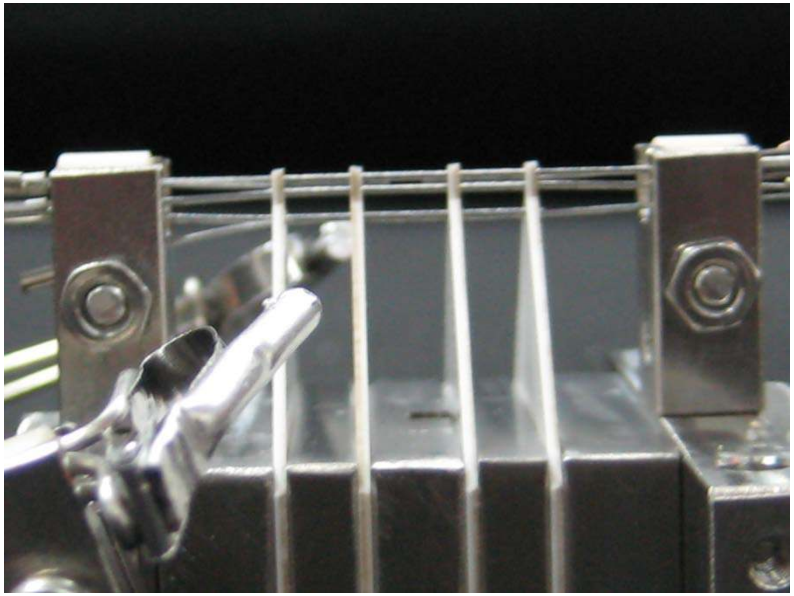
$$\phi \simeq g B_0 T$$

S. Kotler et. al. arXiv:1101.4885[quant-ph] (2011); accepted in Nature

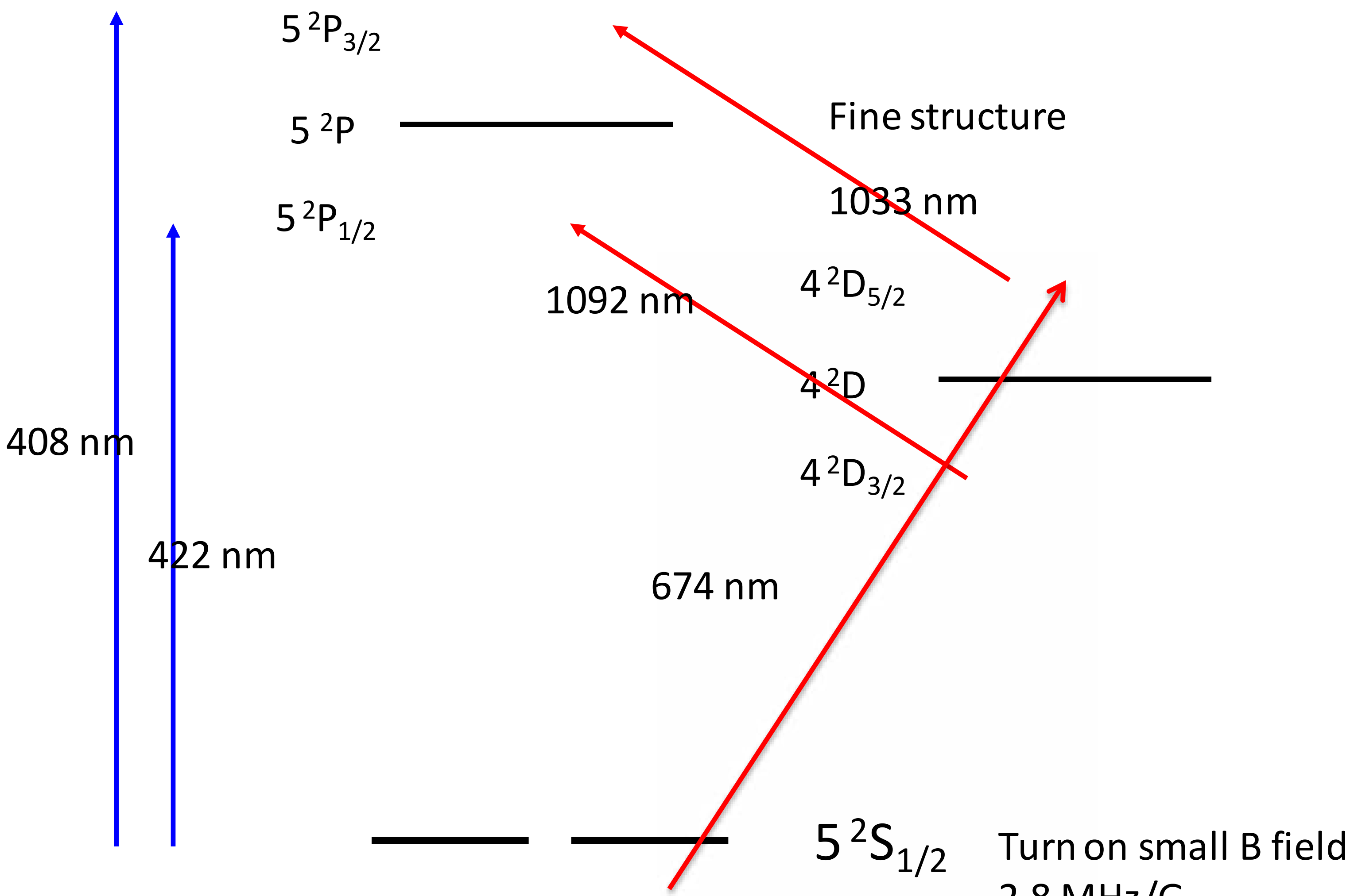
J. R. Mae et. al. Nature, 455, 644, (2008)

A single trapped ion

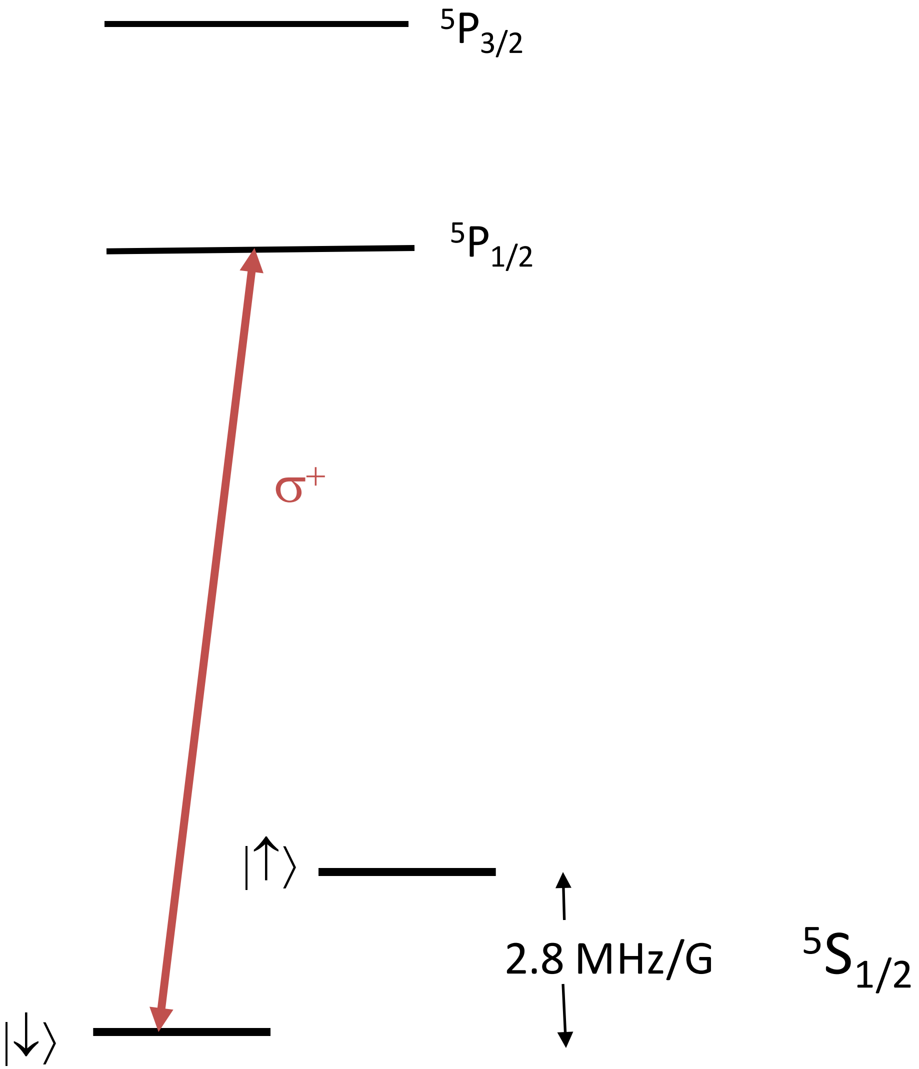




Electronic levels in $^{88}Sr^+$



Probe initialization



Optical pumping

Fidelity > 0.9999

Coherent probe rotations

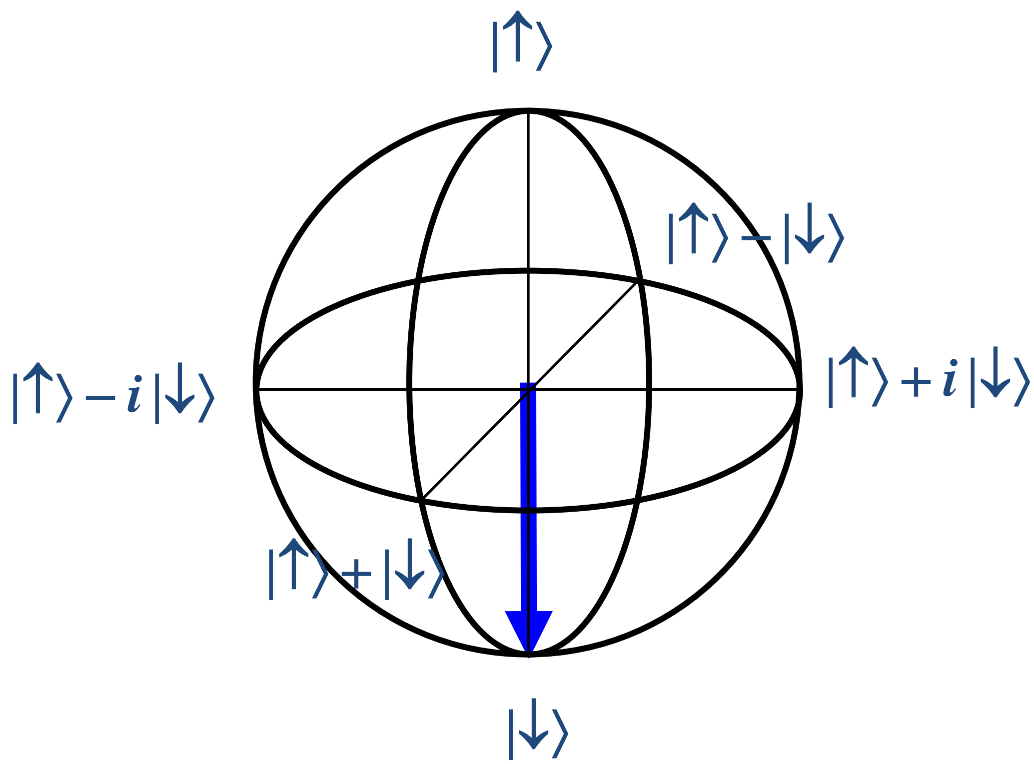
Pulse time

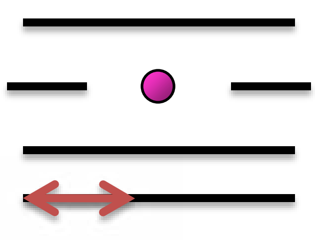
RF phase

$$R(\theta, \phi)$$

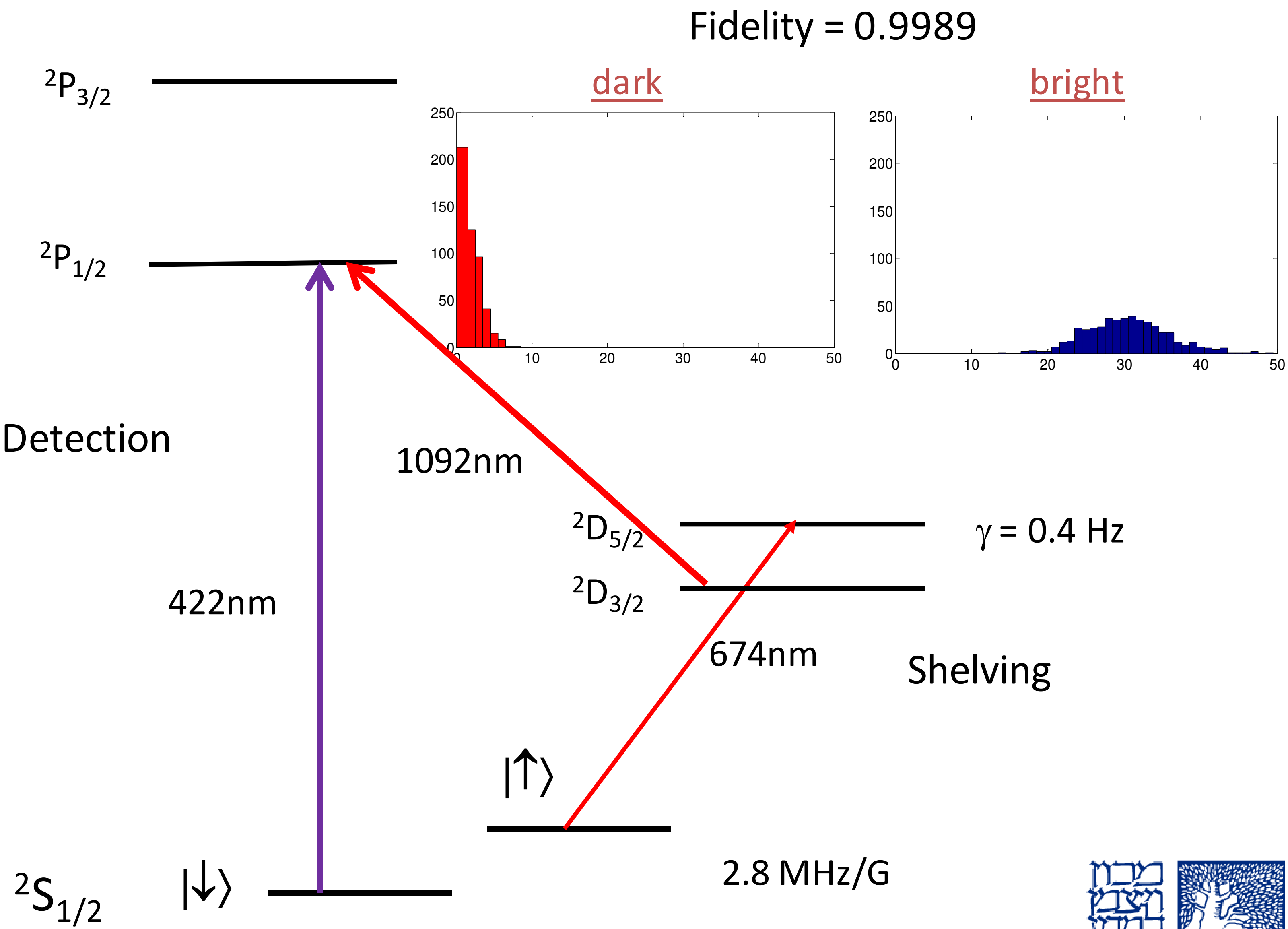
$$R(\pi, 0)$$

Bloch sphere

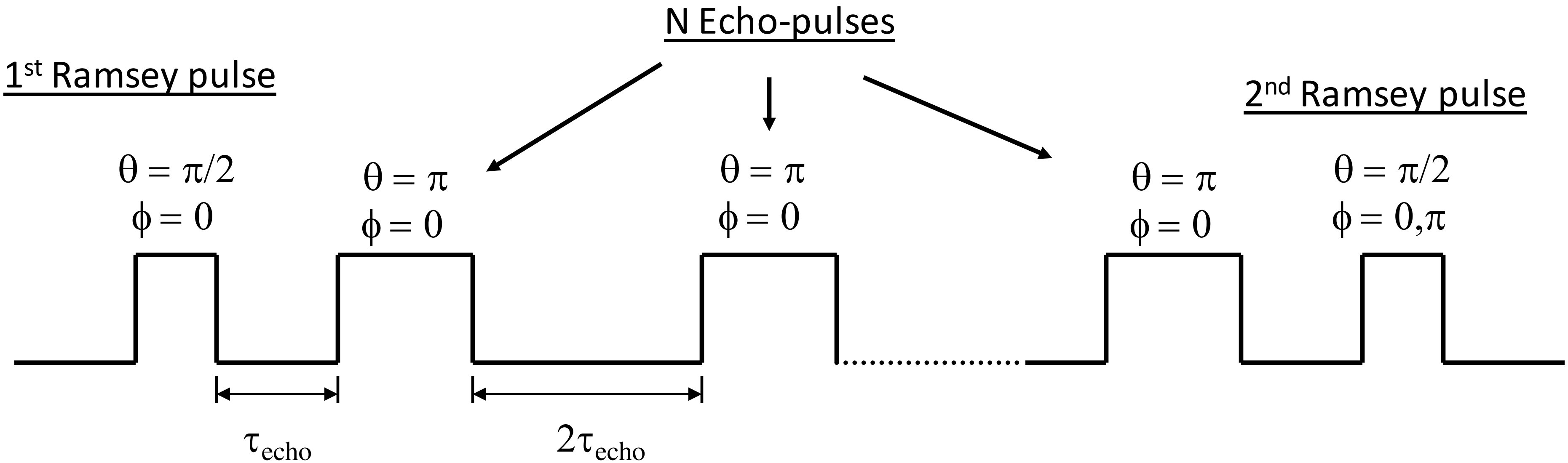


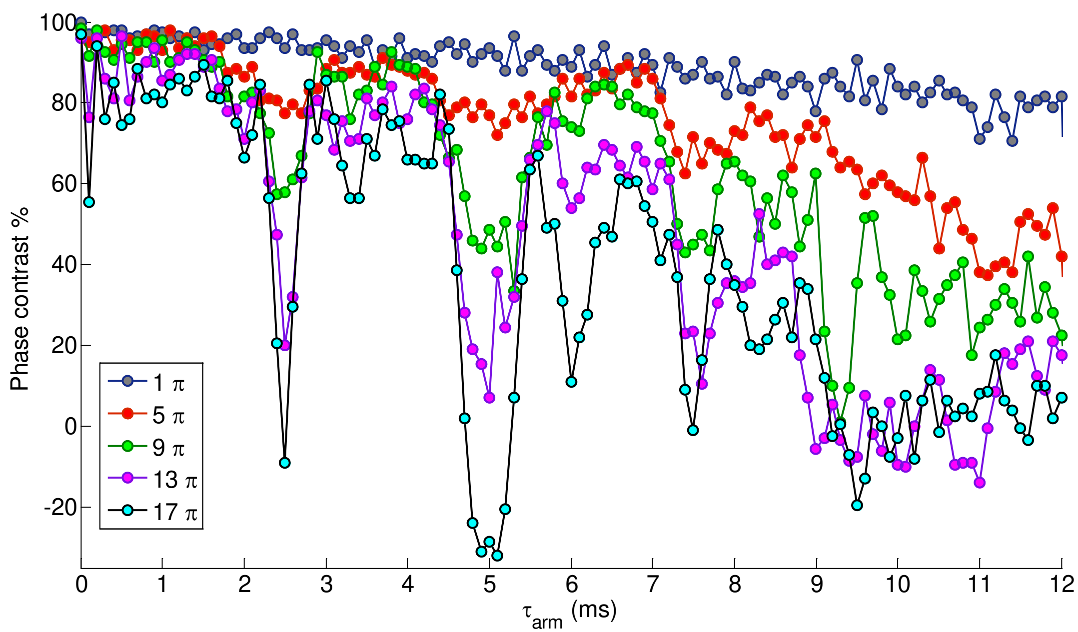


Qubit Detection



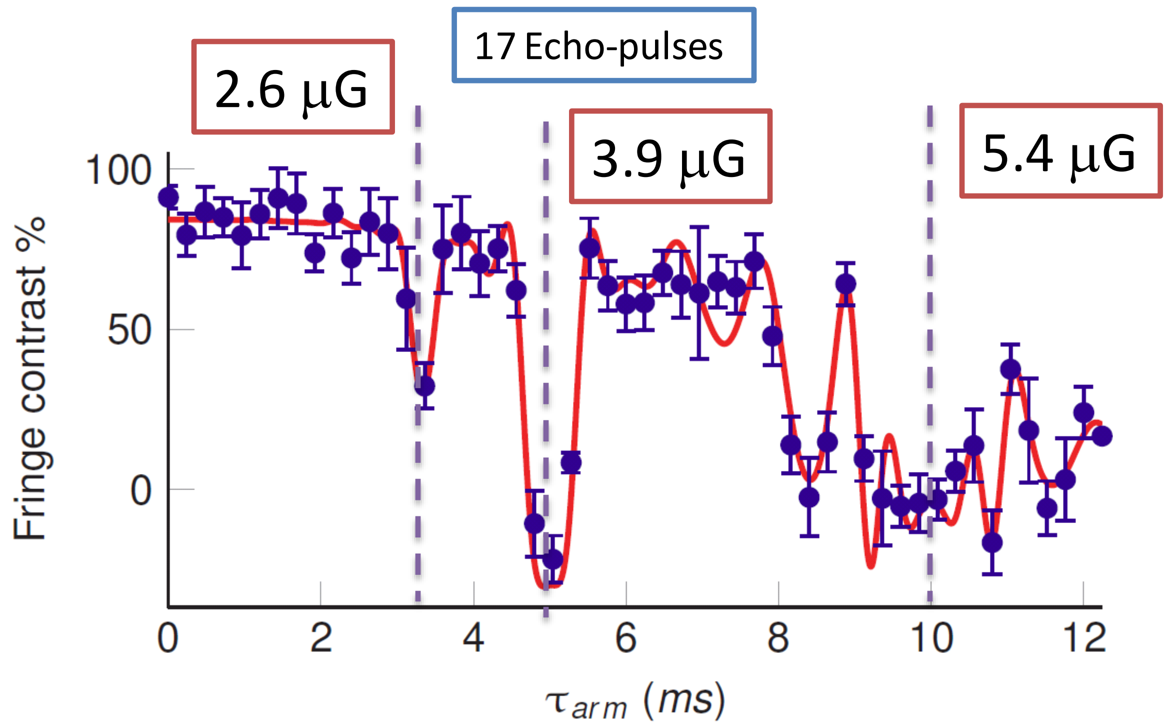
Echo Pulse Train





Long Coherence time and Measurement Sensitivity

$$vis(\tau_{arm}) = \prod_n J_0\left(\frac{-4\eta B_n}{f_n}\sin^2(\frac{\omega_n\tau_{arm}}{2})\frac{\sin(N\omega_n\tau_{arm})}{\sin(\omega_n\tau_{arm})}\right)$$

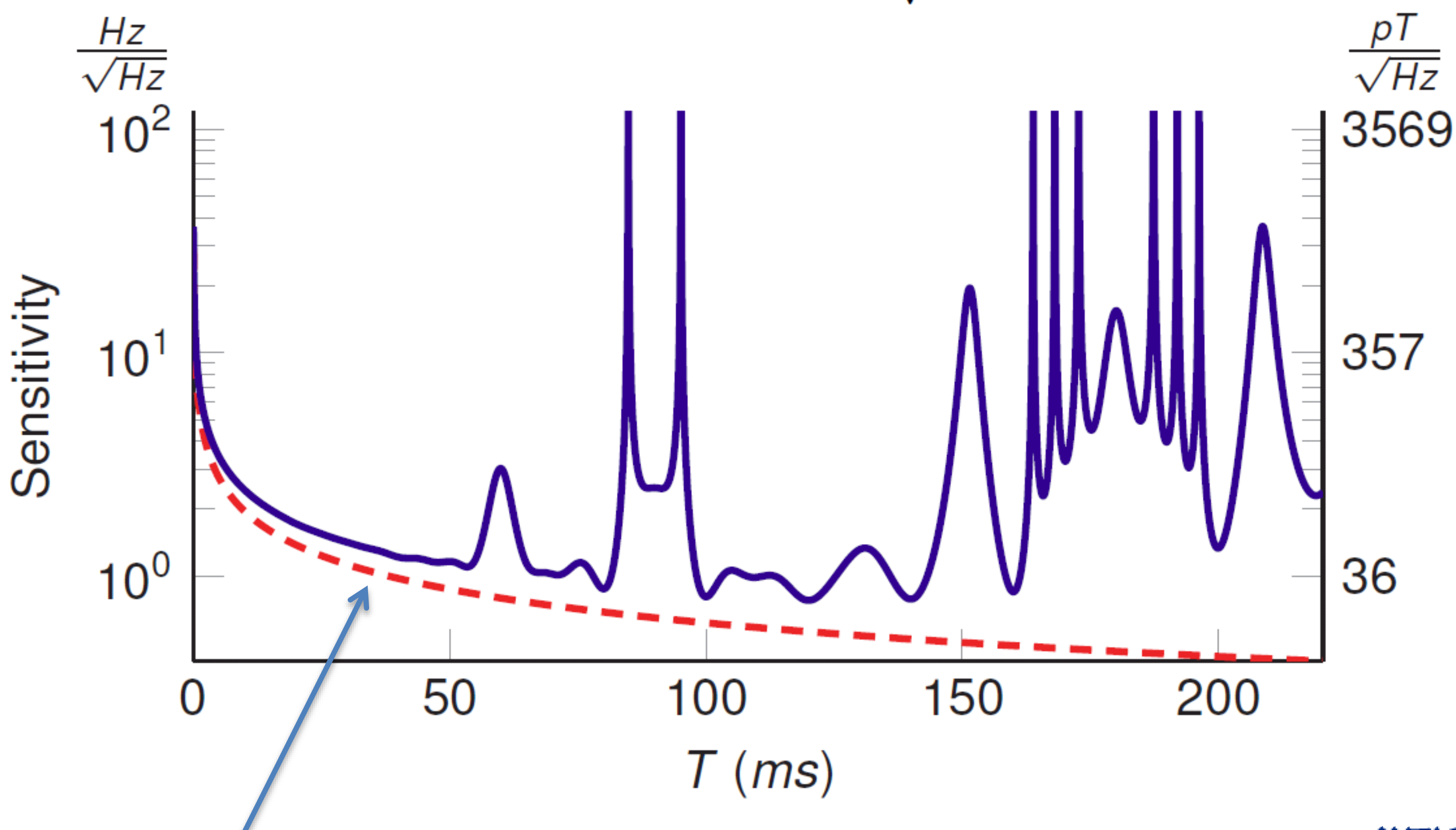


$$s = \frac{1}{2\pi}\sqrt{\frac{4-A^2}{2A^2T}}\frac{Hz}{\sqrt{Hz}}$$

A = contrast

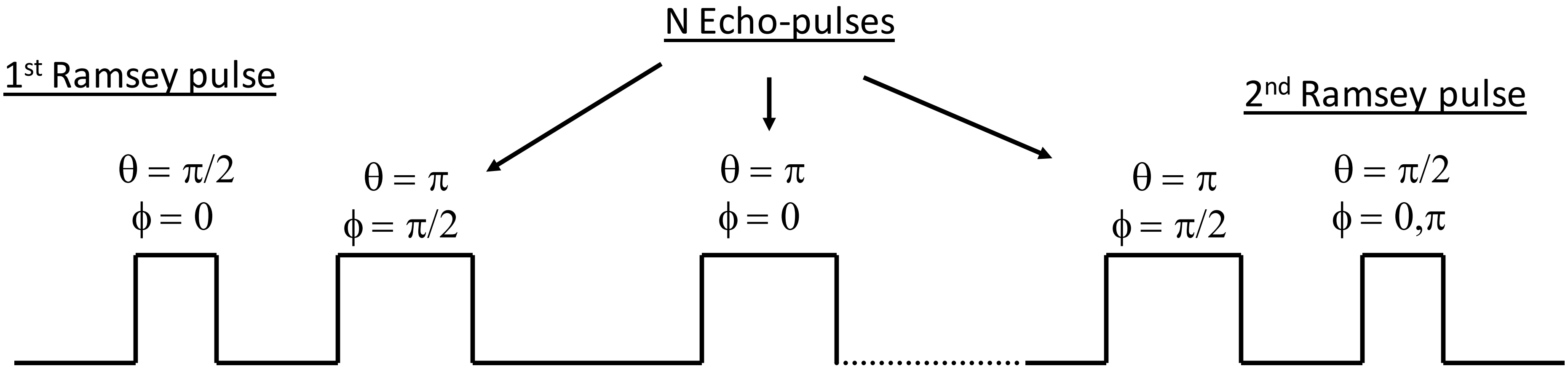
Long Coherence time and Measurement Sensitivity

$$s = \frac{1}{2\pi}\sqrt{\frac{4-A^2}{2A^2T}}\,\frac{Hz}{\sqrt{Hz}}$$



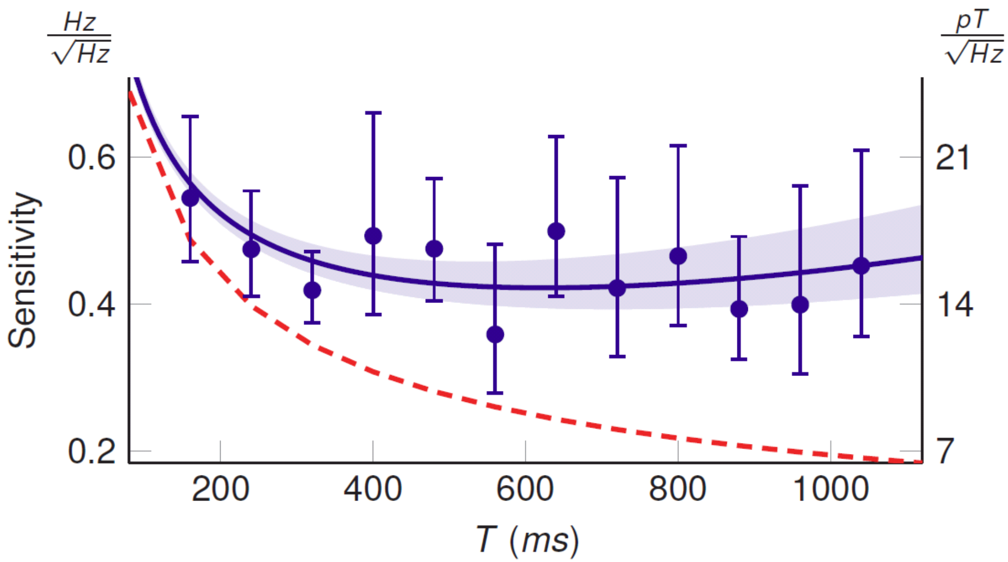
A=1; Standard Quantum Limit

Fast Lock-in Modulation

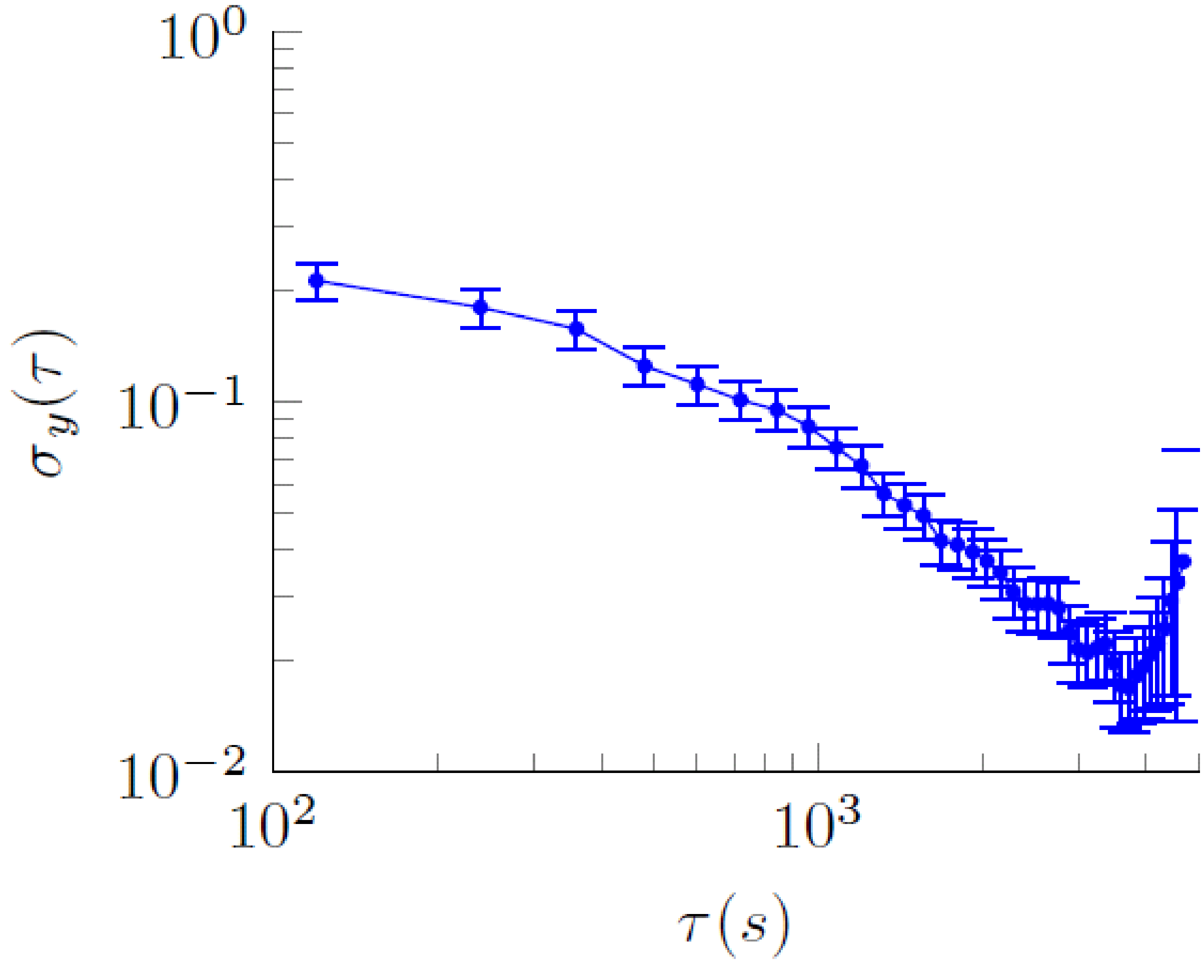


Modulation at 312.5 Hz

Sensitivity= 0.4 Hz/Hz$^{1/2}$ =0.15 μG/Hz$^{1/2}$

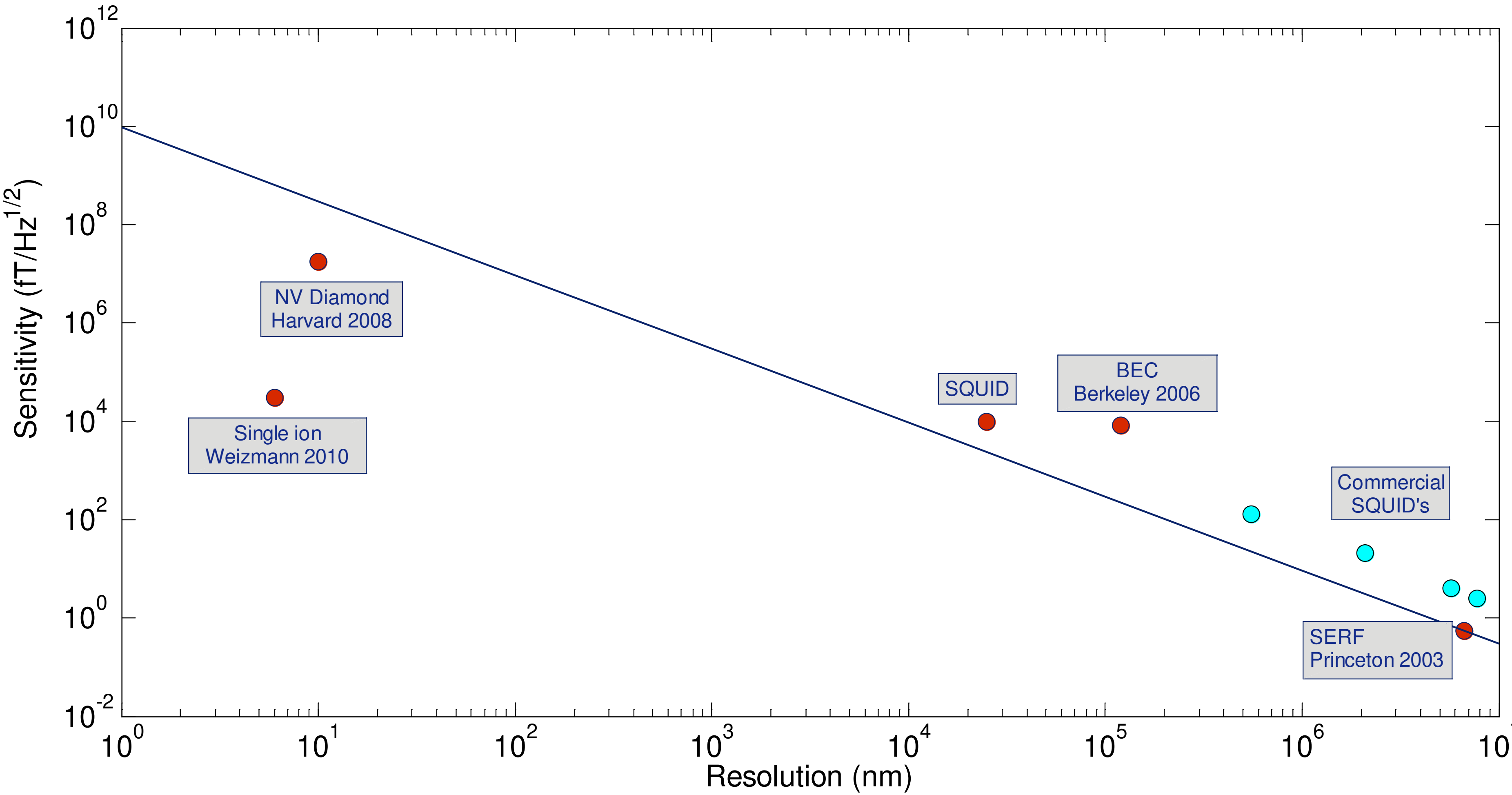


Allen deviation analysis

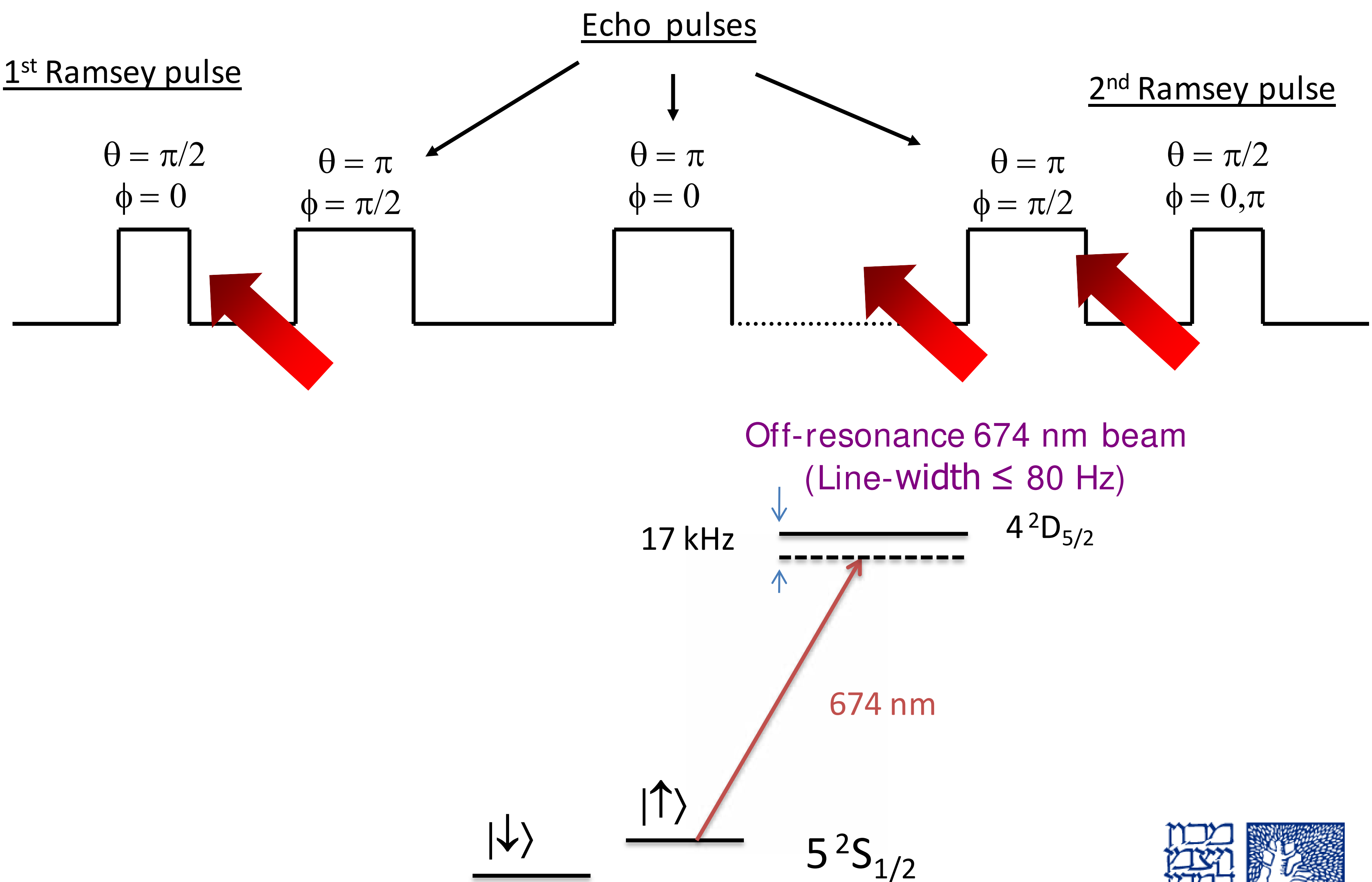


Minimum uncertainty: *9 mHz (3 nG)* after *3720 sec*

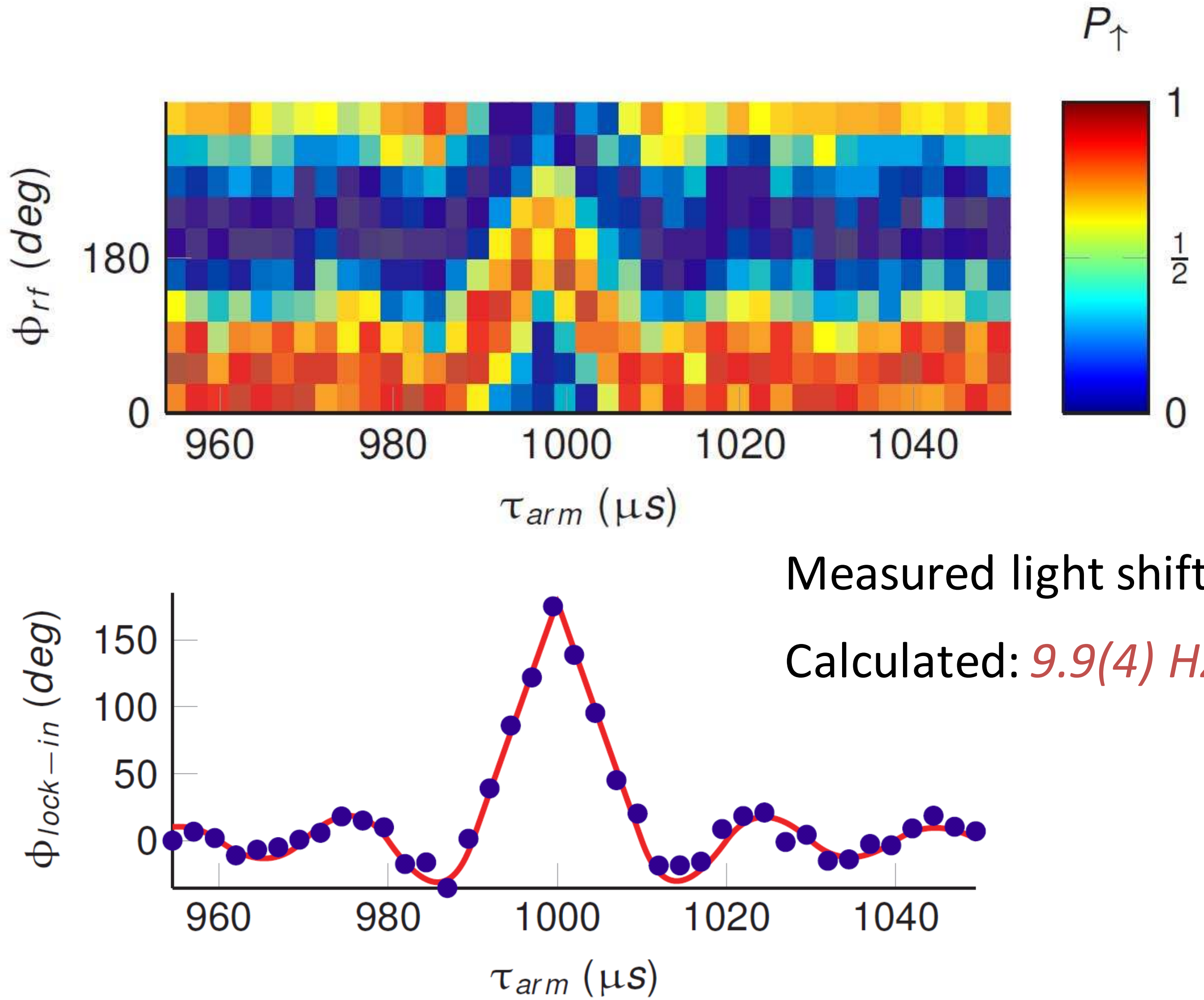
Magnetometer Performance



Light shift Detection



Small Signal Lock-in Detection

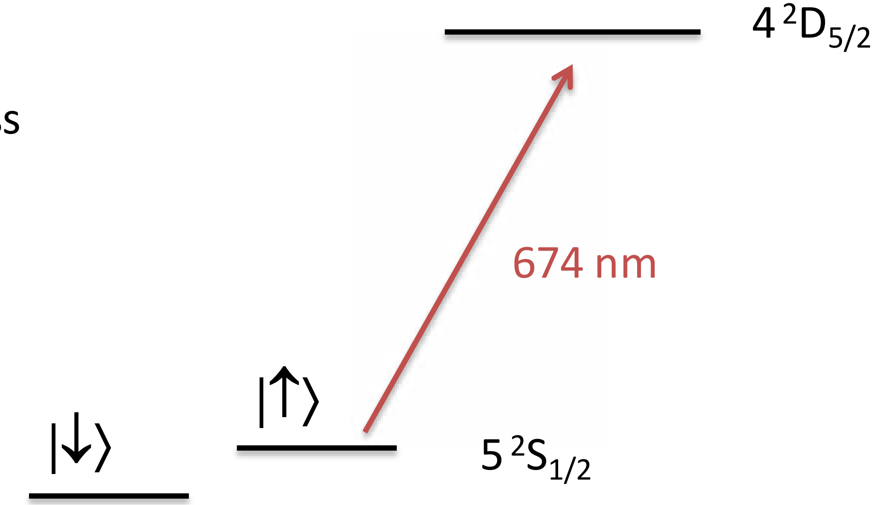


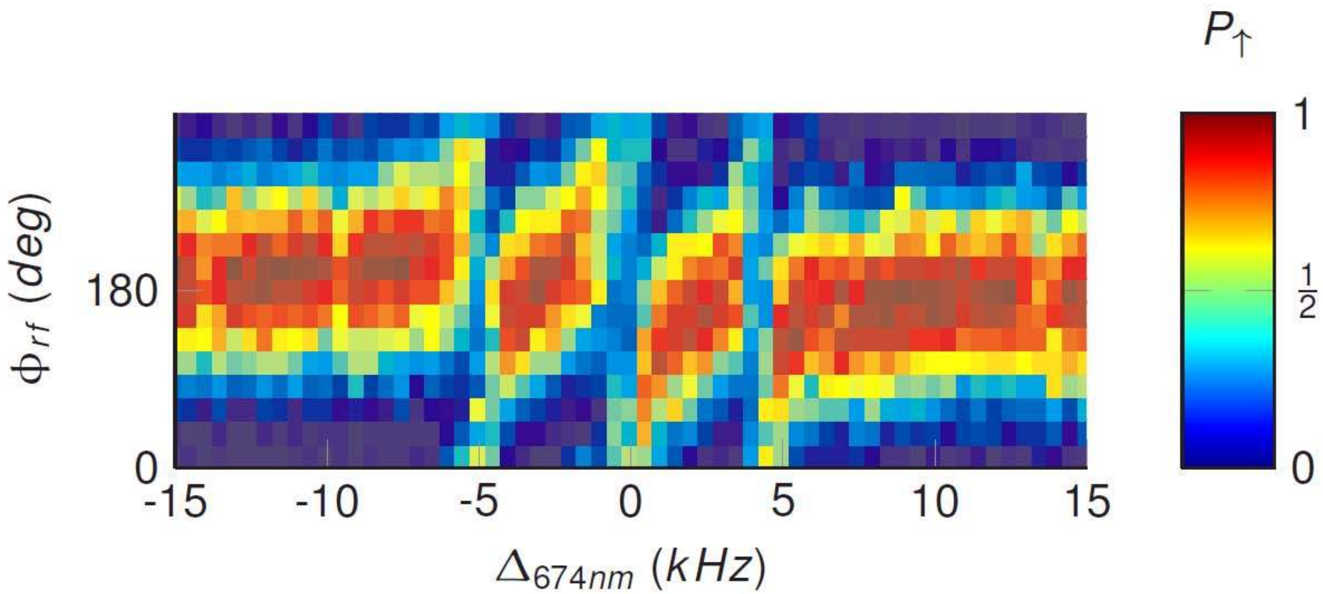
Measured light shift: *9.7(4) Hz*

Calculated: *9.9(4) Hz*

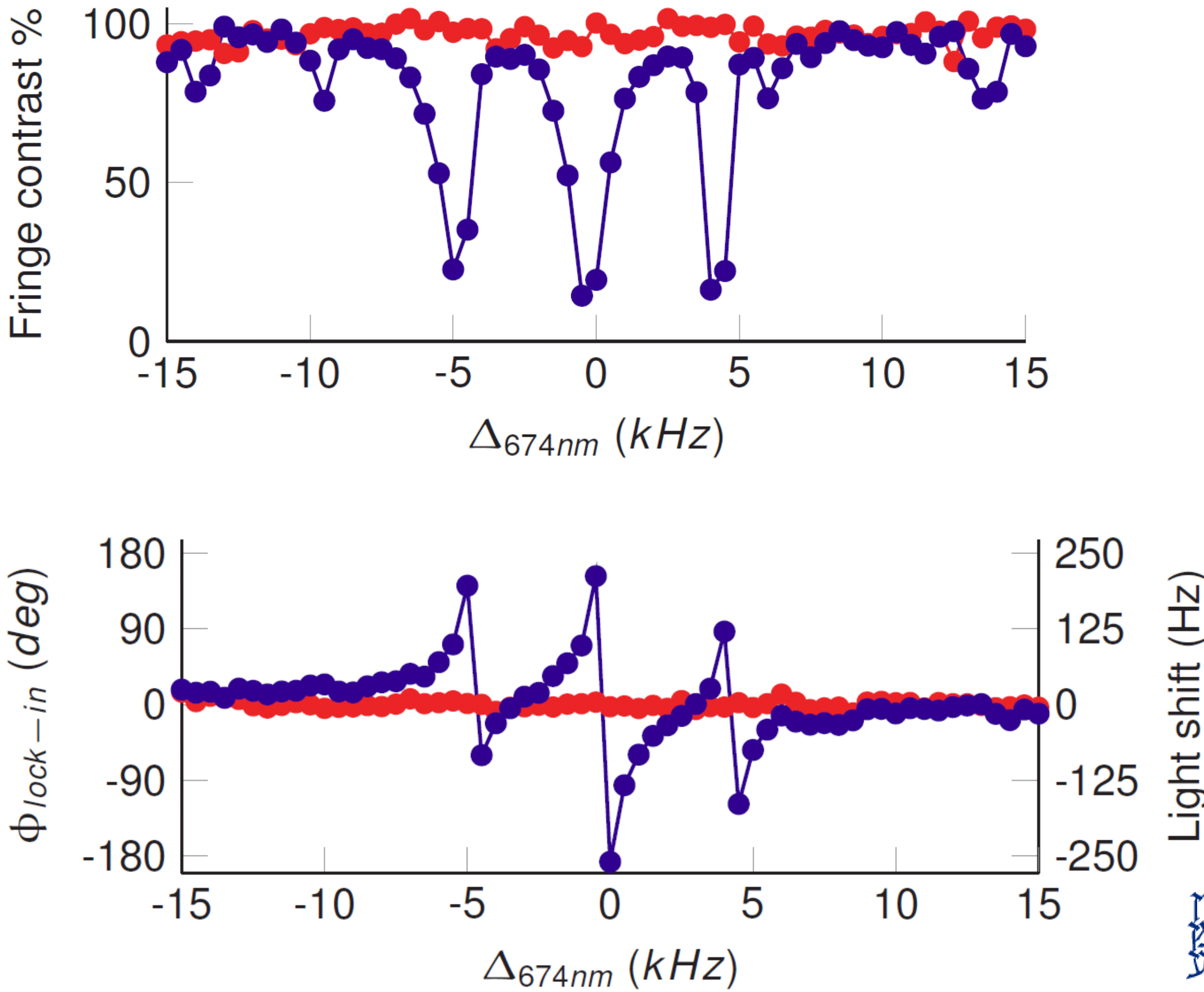
Light shift Spectroscopy

- Scan the laser frequency across the S →D transition





Light shift Spectroscopy



Summary

- Quantum Lock-in amplifier: Dynamic coupling/de-coupling can improve on measurement SNR

With a single trapped ion coupled to a magnetically noisy environment:

- A long coherence time: *1.4 sec*.
- Frequency shift measurement sensitivity : *0.4 Hz/Hz$^{1/2}$* *(15 pT/Hz$^{1/2}$)*
- Frequency shift measurement uncertainty: *9 mHz* *(300 fT)* after 1 hour integration time
- Applications: magnetometery; direct magnetic spin-spin coupling
- Applications: Precision measurements; frequency metrology.

S. Kotler et. al. arXiv:1101.4885[quant-ph] (2011); accepted in Nature.

Thank you

Yoni

Ziv

Elad