Neutron EDM and Dressed Spin

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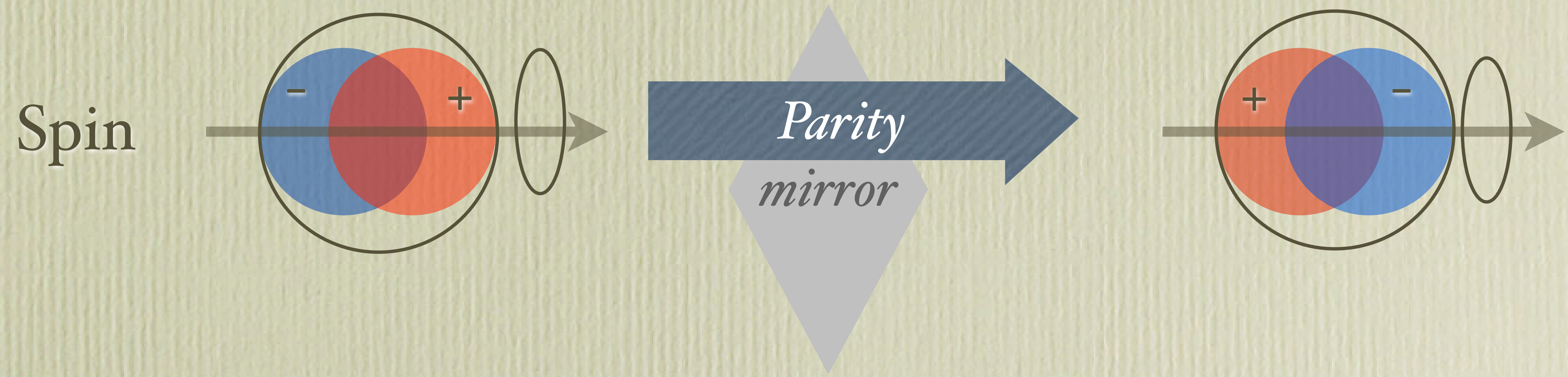
Outline

- History of neutron EDM search
- Review of neutron EDM technique
- Neutron EDM experiment at SNS at ORNL
- Measurement of dressed spin
- Theory of dressed spin
- Simulation of dressed spin and neutron EDM experiment

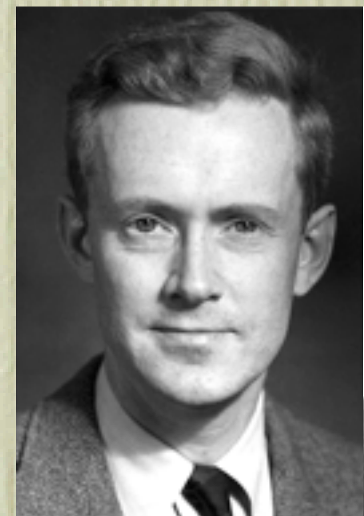
Neutron electric dipole moment

$$\vec{d_n} = \int dx^3 \rho \vec{x} = d_n \hat{S}$$



- Electric dipole moment (EDM) is the first moment of the charge distribution (ρ).
- The EDM (**vector**) is parallel to the **Spin (axial vector)** direction.
- A non-zero neutron EDM violates the parity symmetry.

Pioneers of neutron electric dipole moment



Purcell

Ramsey

- Purcell and Ramsey emphasized the possibility of a non-zero neutron EDM and the need to check it experimentally.
- They set an upper limit of 3×10^{-18} e cm from the neutron-nucleus scattering data (1950).
- They carried out a pioneering measurement of the upper limit of 5×10^{-20} e cm by using the separated oscillatory field at Oak Ridge (1950) (later slides).
- The parity violation was suggested by Lee and Yang(1956) and discovered by Wu, et al.(1957).
- Still no neutron EDM was observed.

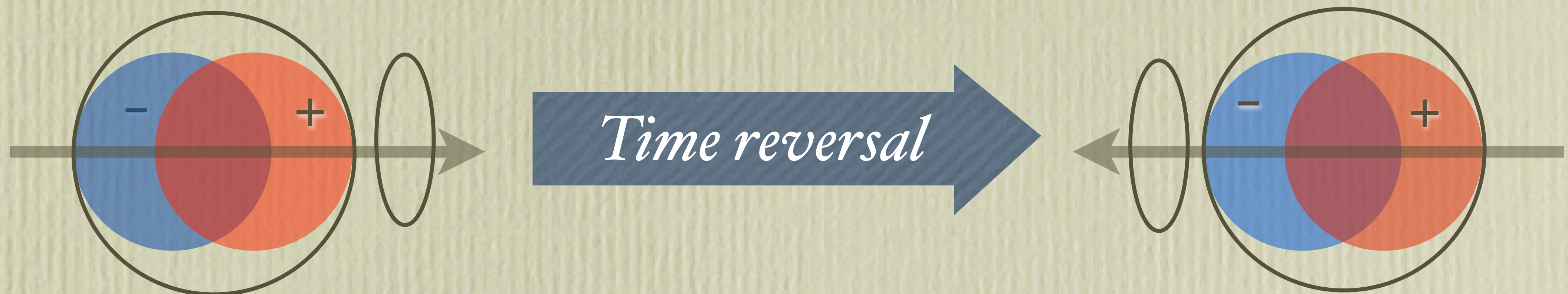
Yang

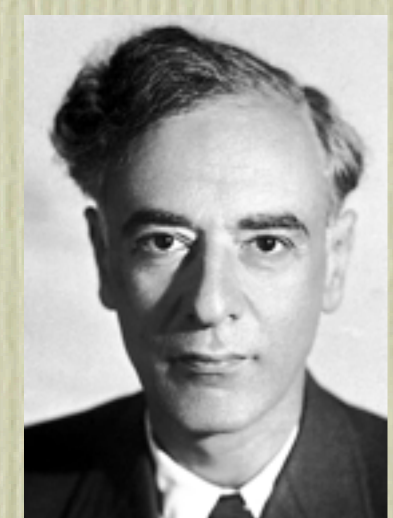
Lee

Wu

EDM and CP violation

Spin





Landau

$$\vec{d_n} = \int dx^3 \rho \vec{x} = d_n \hat{S}$$

Cronin **Fitch**

- Landau showed that particles cannot possess EDM from time-reversal invariance (1957).
- T violation implies **CP violation** if CPT holds.
- *No* neutron EDM experiments during 1957-1964.
- CP violation was discovered in **neutral Kaons decay** by Cronin and Fitch(1964).

Baryon asymmetry of Universe and CP violation

Sakharov

Kobayashi

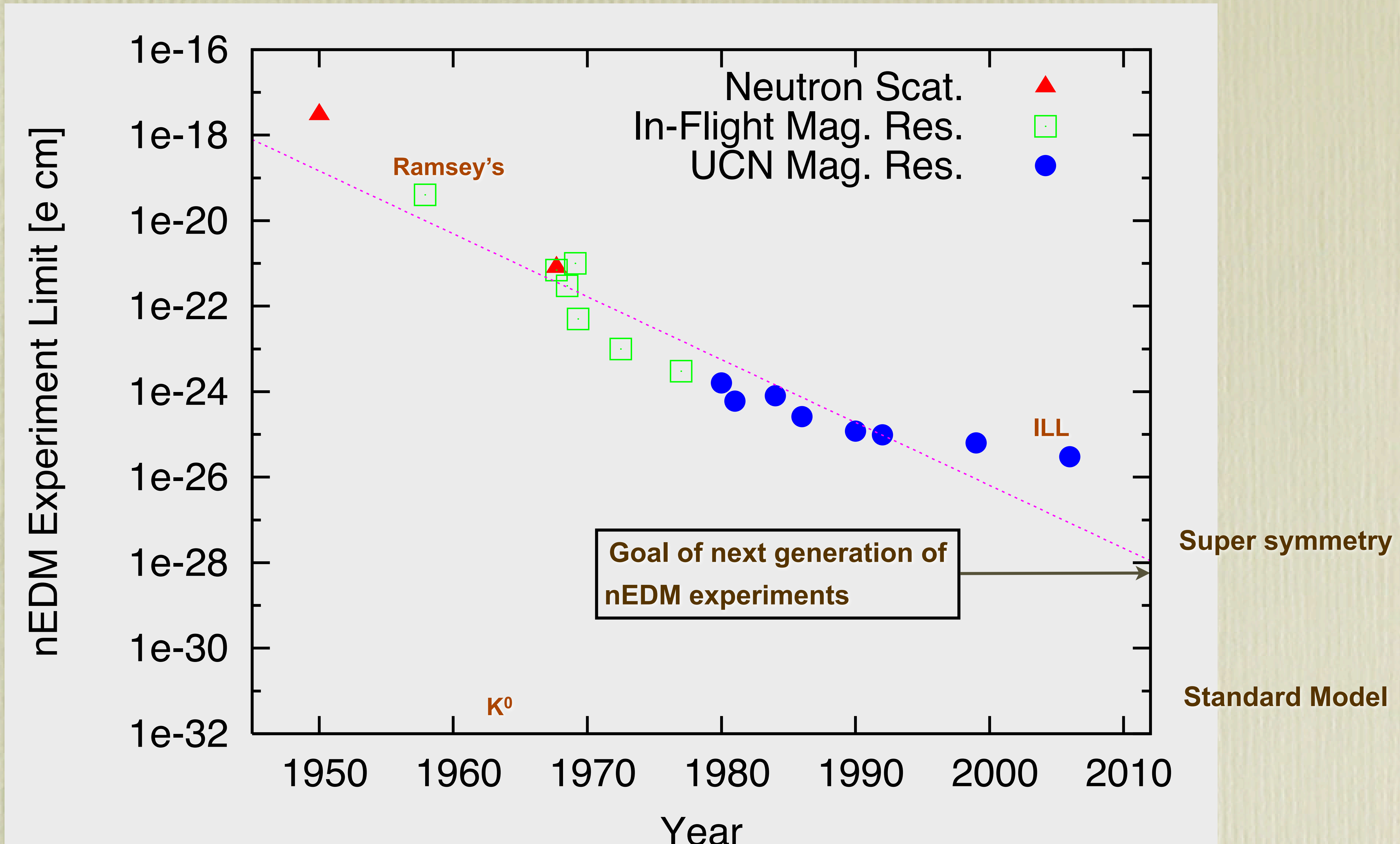
Maskawa

- Baryon asymmetry of universe (BAU) : baryon/photon~10^{-10}.
- Sakharov proposed CP violation as one of necessary ingredients(1967).
- CP violation has only been observed in **Kaon and B meson decays**,which can be explained by **Kobayashi-Maskawa mechanism** (CKM matrix) in SM(baryon/photon~10^{-18}).
- Require CP violation beyond the SM.

Neutron EDM in Standard Model

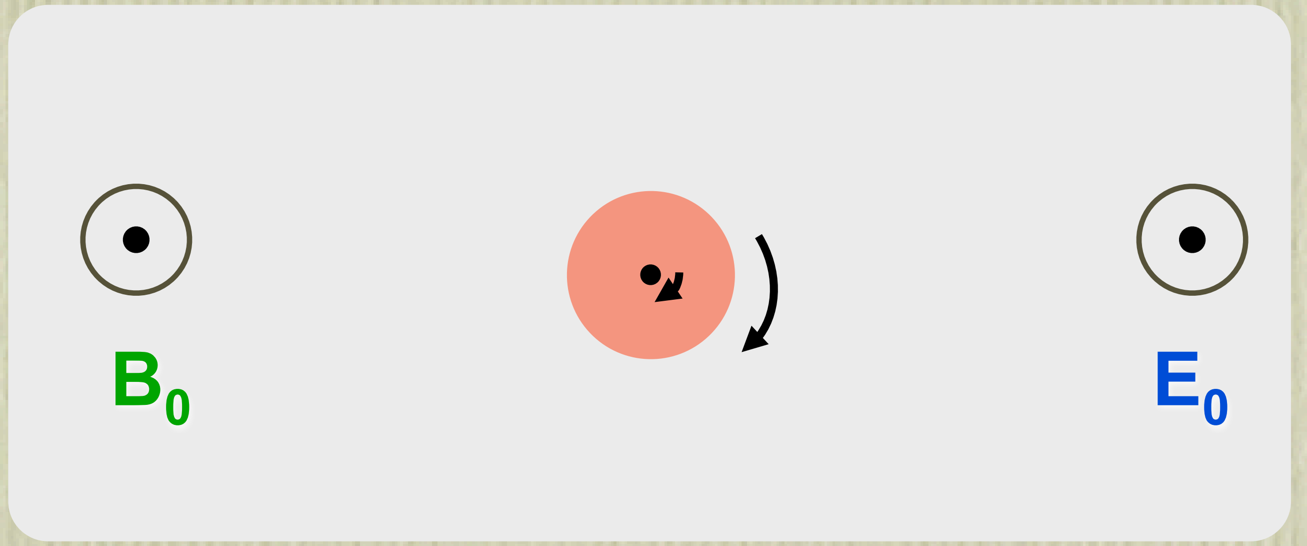
- Upper limit of neutron EDM (d_n)~3×10^{-26} e cm.
- Neutron EDM in Standard Model
  - **Strong interaction**: $d_n \sim \theta \times 10^{-15}$ e cm, where θ specifies the magnitude of CP violation in the QCD Lagrangian ($\theta < 10^{-10}$).
  - **Weak interaction**: Phase in CKM matrix: $d_n \sim 10^{-31}$ e cm
- Neutron EDM provides a strong constraint for new theories predicting CP violation.
- The neutron EDM searches can explore physics beyond SM complementary to LHC.

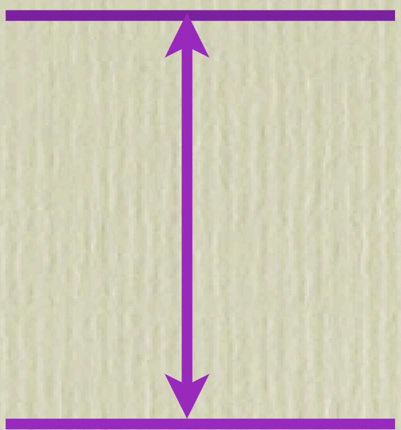
History of neutron EDM search



- Current neutron EDM upper limit: < 2.9 x 10^{-26} e cm (90% C.L.)
- Still no evidence for neutron EDM.

How to measure neutron EDM?



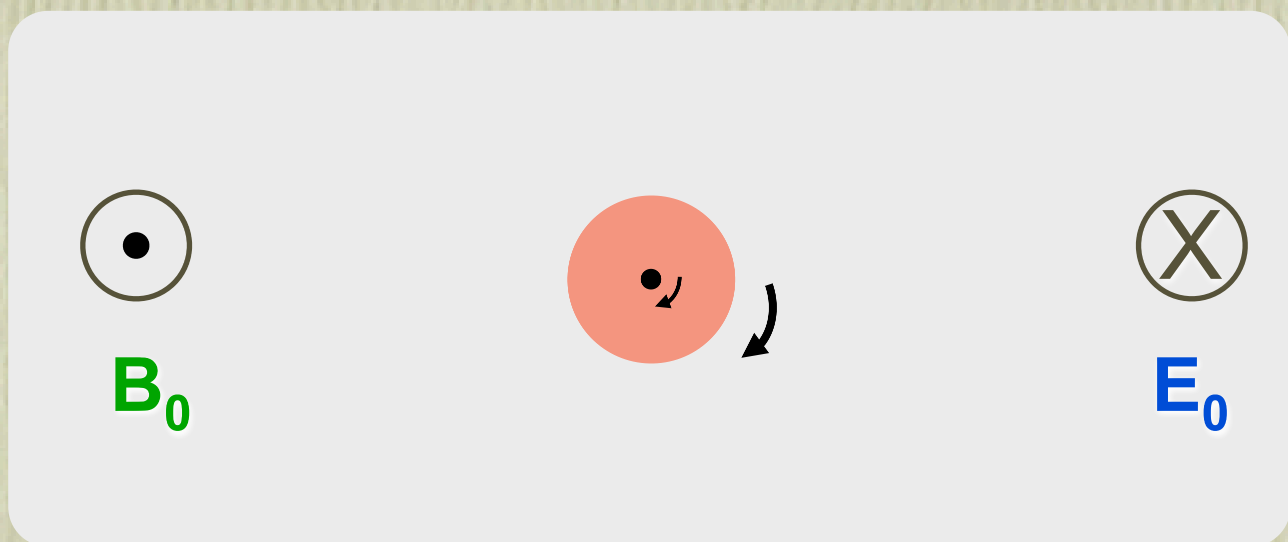


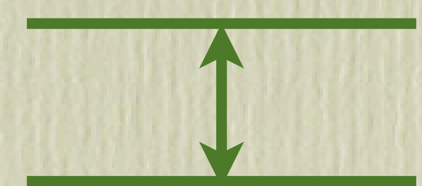
$$B_0 \uparrow E_0 \uparrow$$
$$\hbar\omega = 2(\mu_n B_0 + d_n E_0)$$

- Measure the **precession frequency** of neutron in B_0 and E_0.
- **Flip E_0**, get nEDM from precession frequency difference.

$$H = -(\vec{\mu}_n \cdot \vec{B}_0 + \vec{d}_n \cdot \vec{E}_0)$$
$$\vec{\mu}_n = \gamma_n \vec{S}, \quad \vec{d}_n = d_n \hat{S}$$
$$\rightarrow \omega = \gamma_n B_0 \pm 2 d_n E_0 / \hbar$$
$$\rightarrow \Delta\omega = 4 d_n E_0 / \hbar$$

How to measure neutron EDM?





$$B_0 \uparrow E_0 \downarrow$$
$$\hbar\omega = 2(\mu_n B_0 - d_n E_0)$$

- Measure the **precession frequency** of neutron in B_0 and E_0.
- **Flip E_0**, get nEDM from precession frequency difference.

$$H = -(\vec{\mu}_n \cdot \vec{B}_0 + \vec{d}_n \cdot \vec{E}_0)$$
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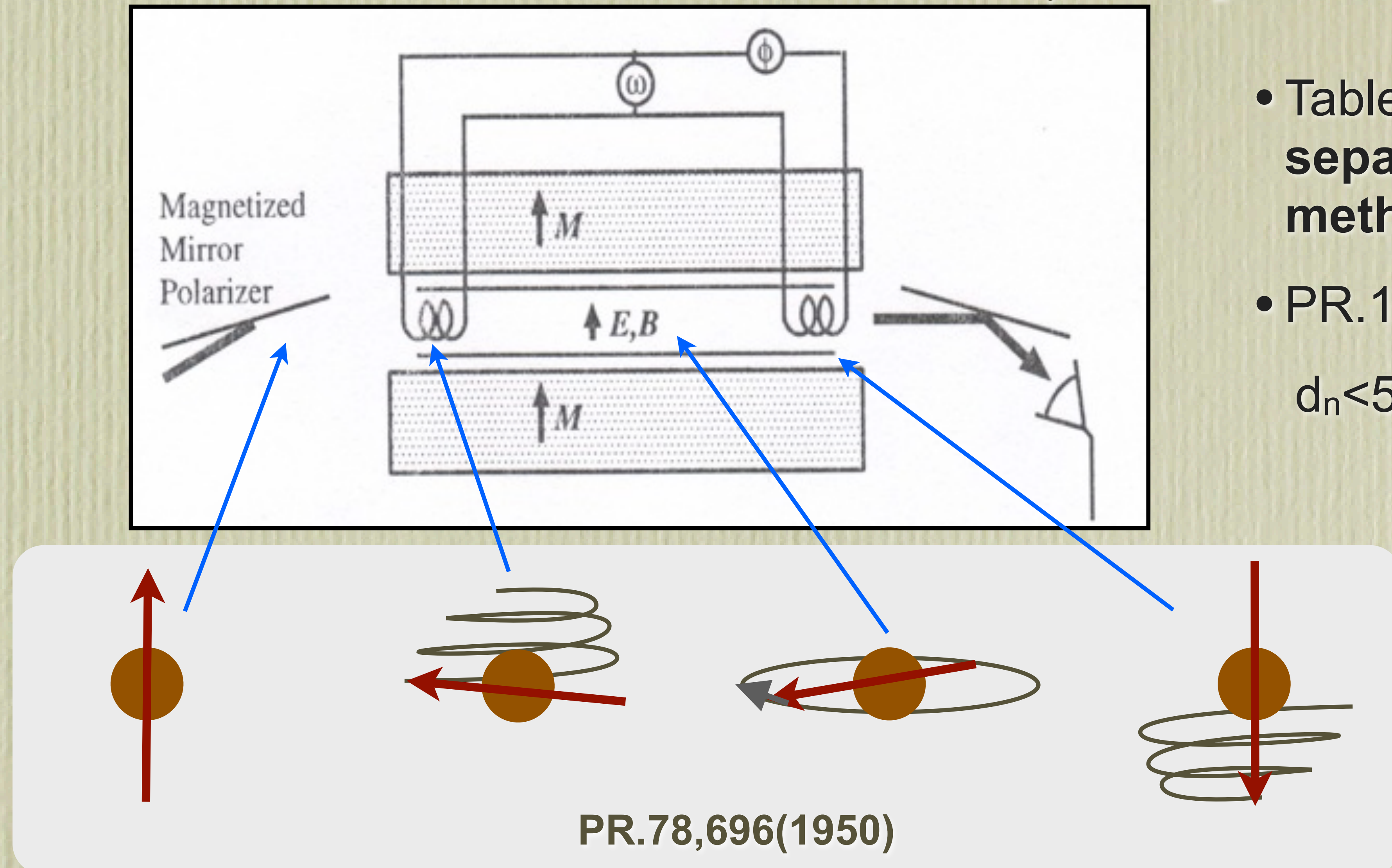
Purcell and Ramsey's experiment



PR.78,696(1950)

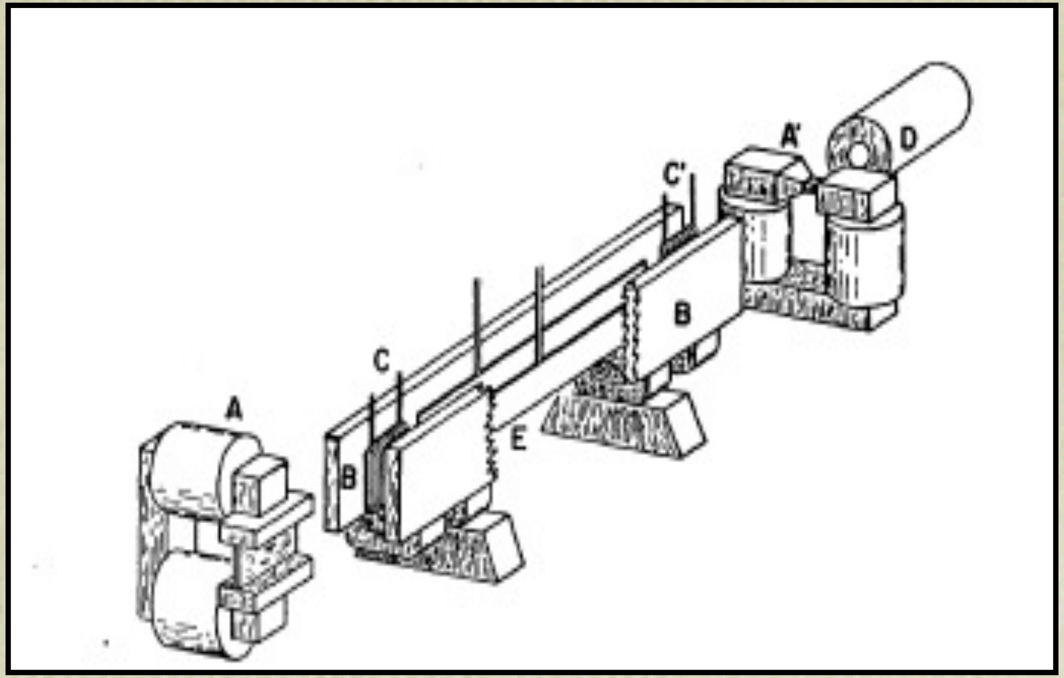
- Table-size experiment using **separated oscillatory fields method**.
- PR.108,120(1957):

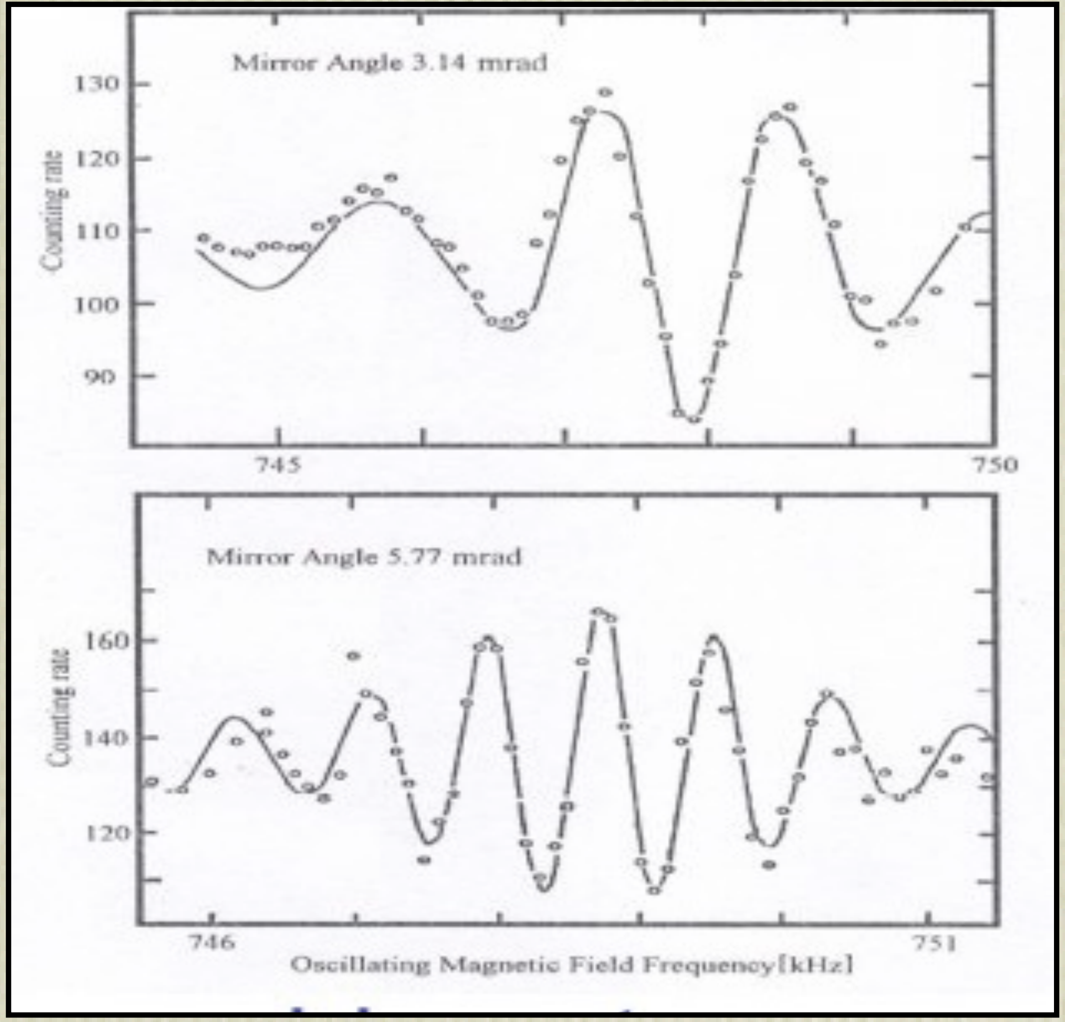
  $d_n < 5 \times 10^{-20}$ e cm

RF	off	on	off	on
	neutron spin is parallel to holding field	first $\pi/2$ pulse is applied; spin is rotated to be perpendicular to holding field	neutrons precess in B and E	second $\pi/2$ pulse is applied; spin is rotated to be anti-parallel to holding field

Purcell and Ramsey's experiment

- The peak location determines the precession frequency.
- Limitations:
  1. **Short duration** for observing the precession (~1 ms) due to short transit time of cold neutron beam in this region
  2. Systematic error due to **motional magnetic field (v x E)**
- Both can be improved by using **ultracold neutrons (UCN)** due to their slow velocities (~5 m/s)





Ultracold neutron (UCN)

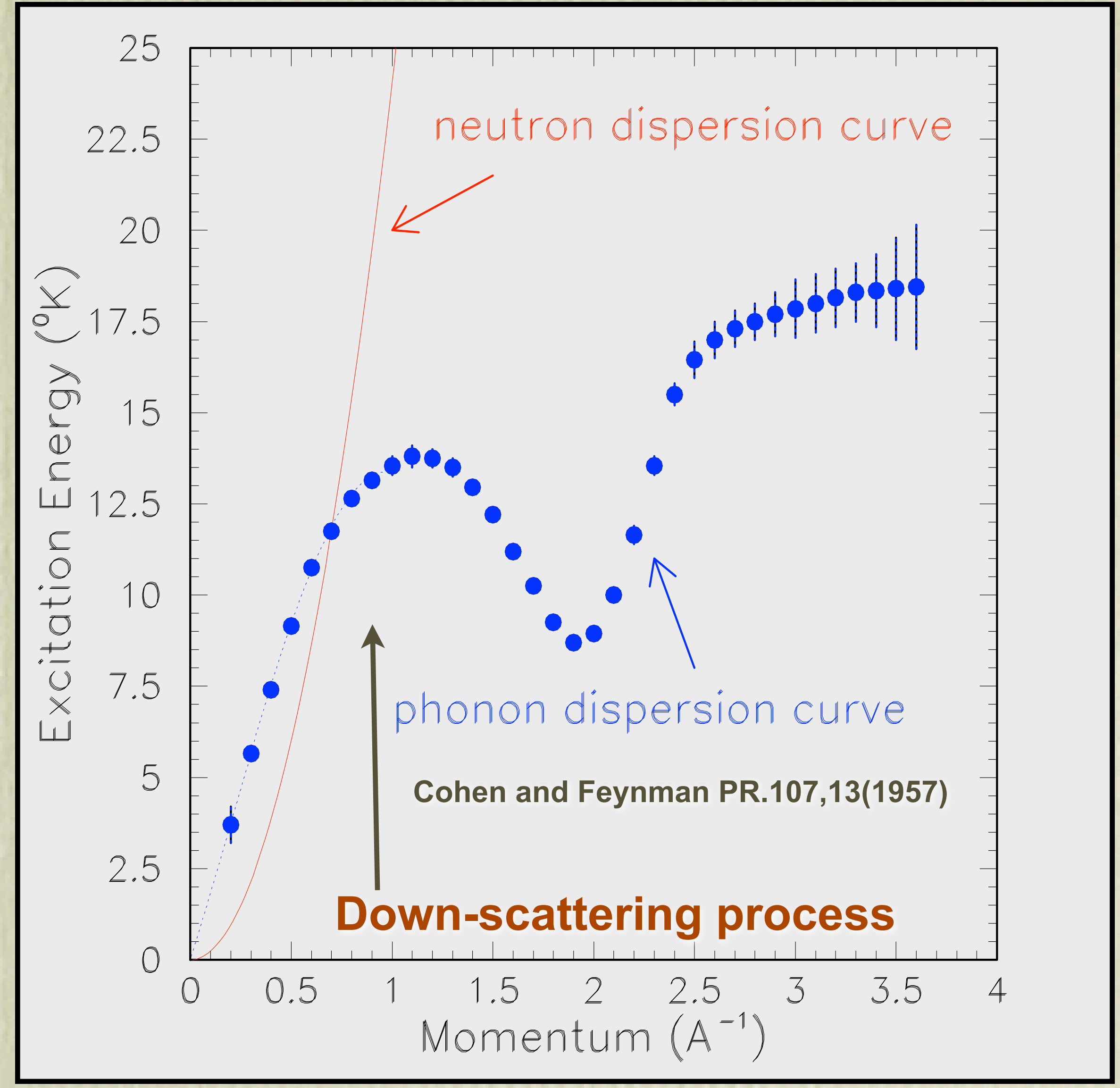
Fermi

- Fermi suggested that neutrons with very low energy can be stored in a bottle(1936).
- Many materials provide repulsive **Fermi potential U_F** around order of **200 neV** for neutrons.
- If neutron energy is *less* than the Fermi potential U_F, neutrons can be stored in a bottle.
- $U_F \sim 200$ neV, UCNs have velocities of order of 5 m/sec, wavelengths of order 500 °A and an effective temperature of order 2 mK.
- **Long storage time, low velocity**.
- Many experiments with UCN, like neutron life time measurement, **neutron EDM**, gravitational interactions of neutrons,etc.

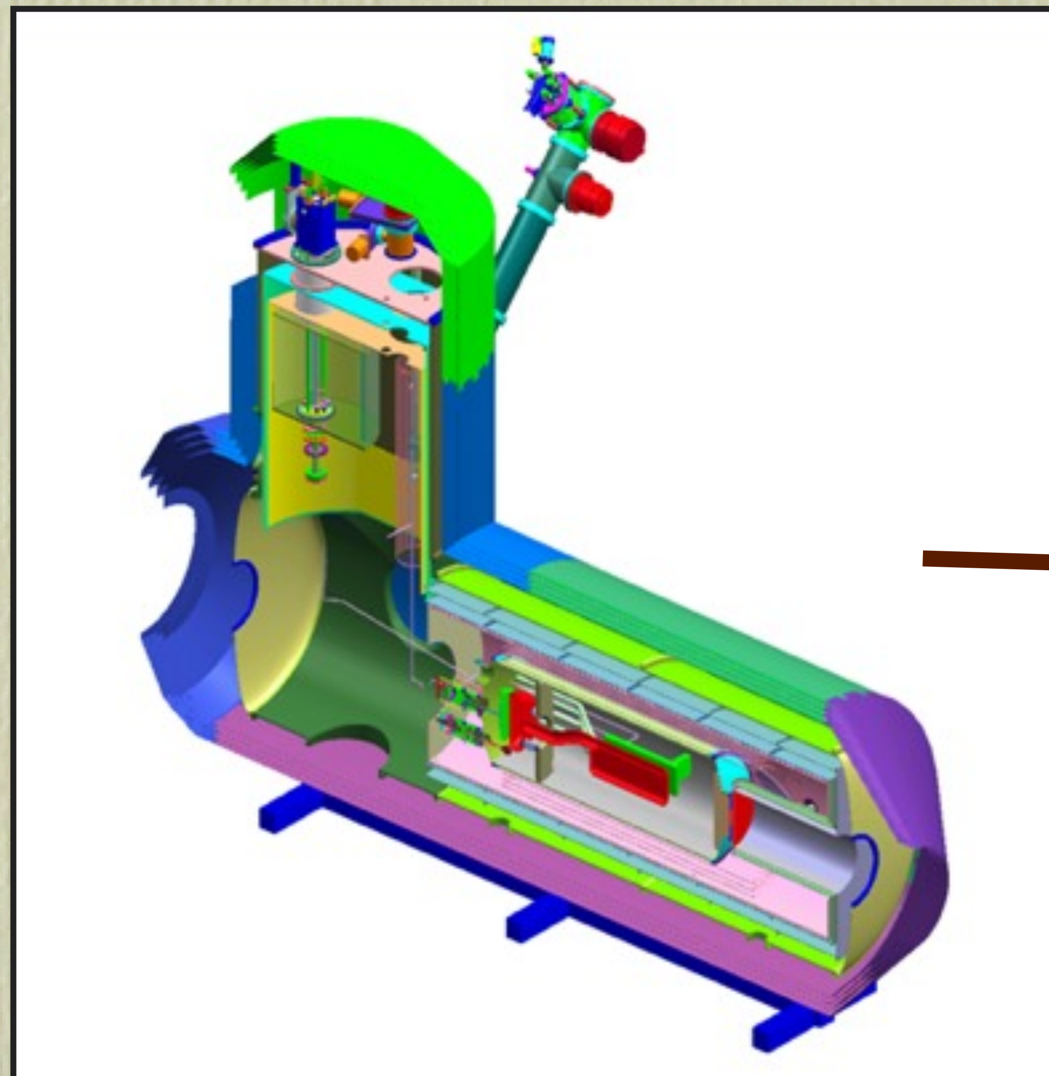
UCN production in superfluid ^{4}He

- UCN was extracted from the **low-energy tail** of the Maxwell-Boltzmann distribution of cold neutrons(~5 UCN/cm^3).
- A method was suggested by Golub and Pendlebury. Cold neutron with momentum of 0.7 A^{-1} (10^{-3} eV) can excite a phonon in superfluid ^{4}He and become an UCN via **down-scattering process**.

=>Much larger UCN density than conventional UCN sources



The new neutron EDM experiment
(based on UCN production in superfluid ^{4}He)



(Based on the idea originated by R. Golub and S. Lamoreaux in 1994)

Collaboration:

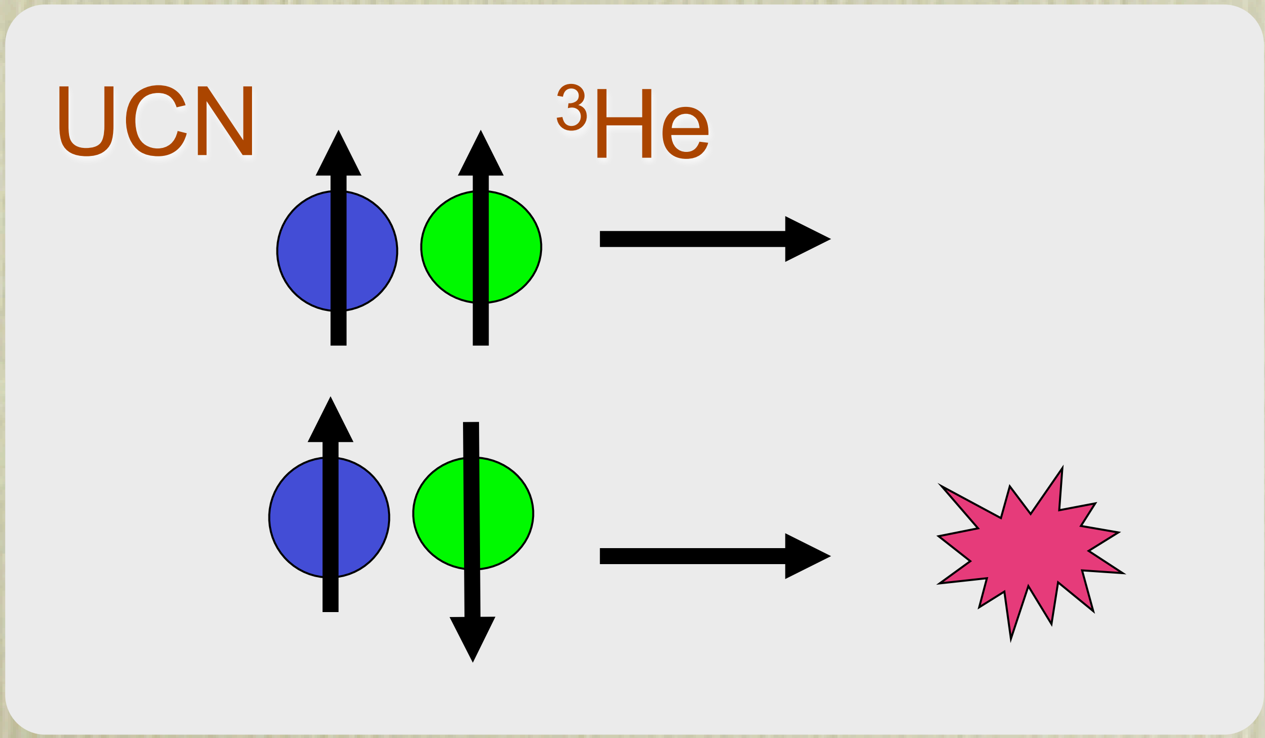
Arizona State, Berkeley, Brown, Boston, Caltech, Duke, Indiana,Illinois, Kentucky, LANL, Maryland, MIT, Mississippi State, NCSU, ORNL, Simon-Fraser, Tennessee, Virginia, Valparaiso, Yale

How to measure the precession of UCN in superfluid ^{4}He?

- Use polarized ^{3}He in the bottle as a spin analyzer.

$$n +^3 He \rightarrow p +^3 H + 764 KeV$$

- n – ^{3}He absorption is strongly spin-dependent.

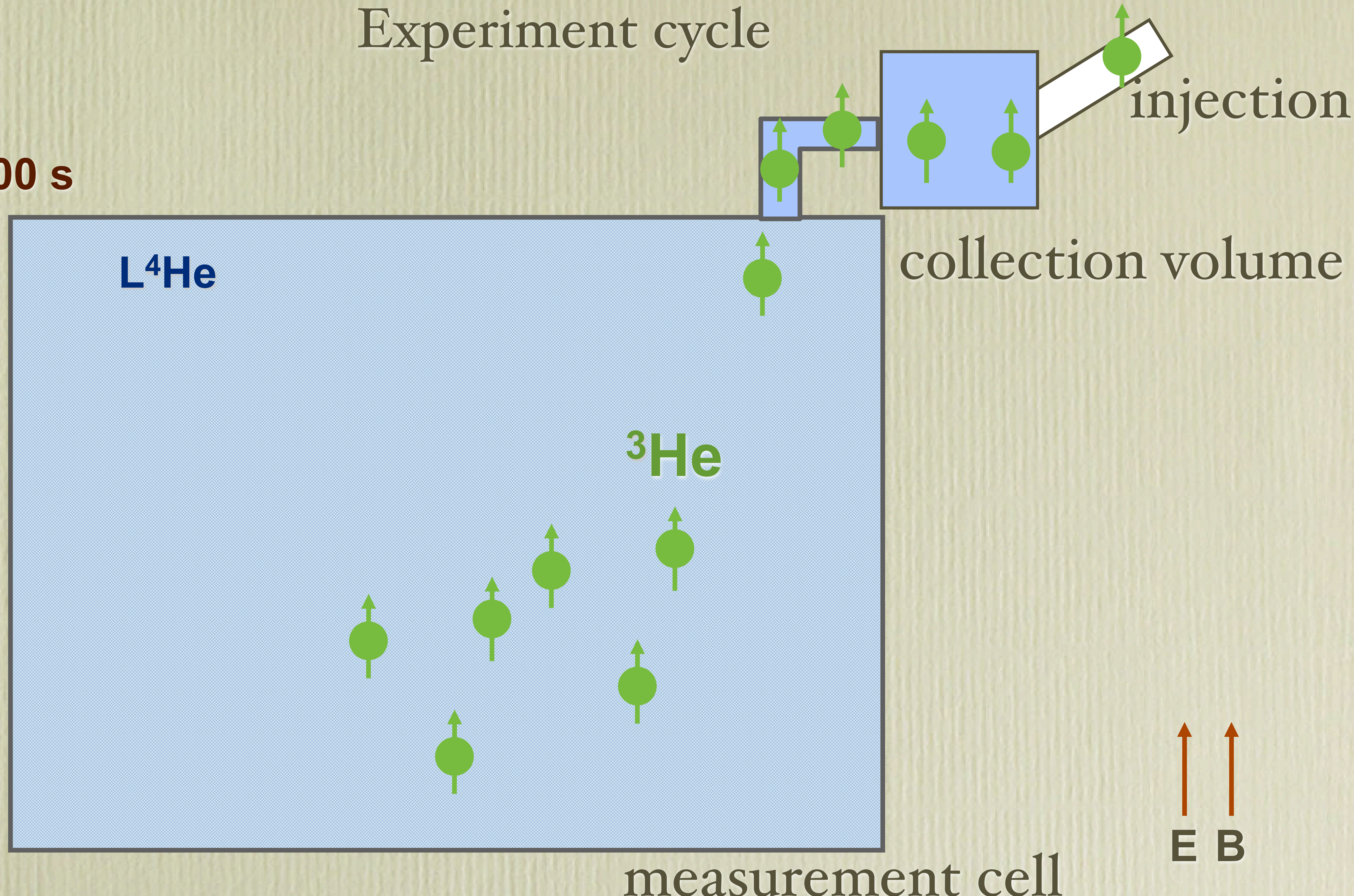


J=1, $\sigma \sim 0$

J=0, $\sigma_{abs} \sim 4.8 \times 10^6$ barns for v=5 m/s

Experiment cycle

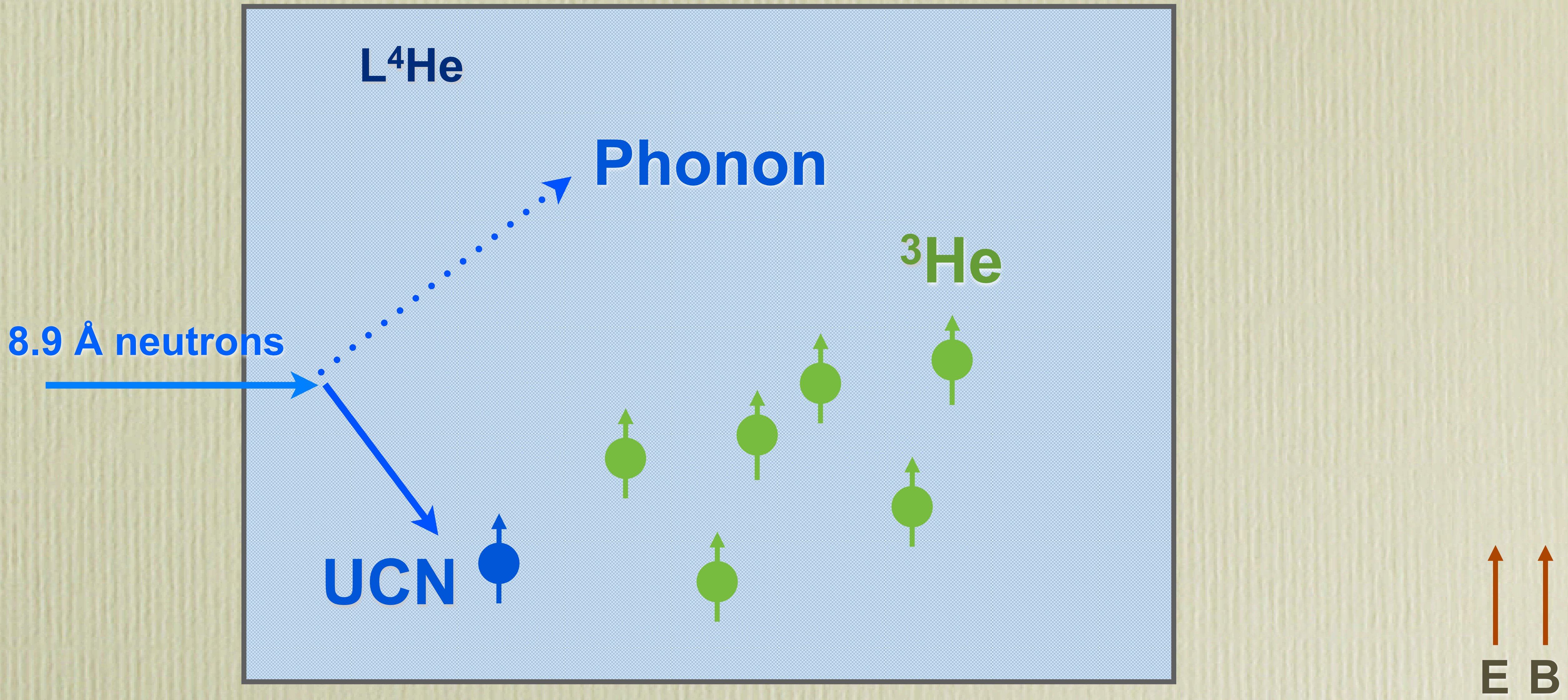
T = 0 - 100 s



Fill L^{4}He with polarized ^{3}He

Experiment cycle

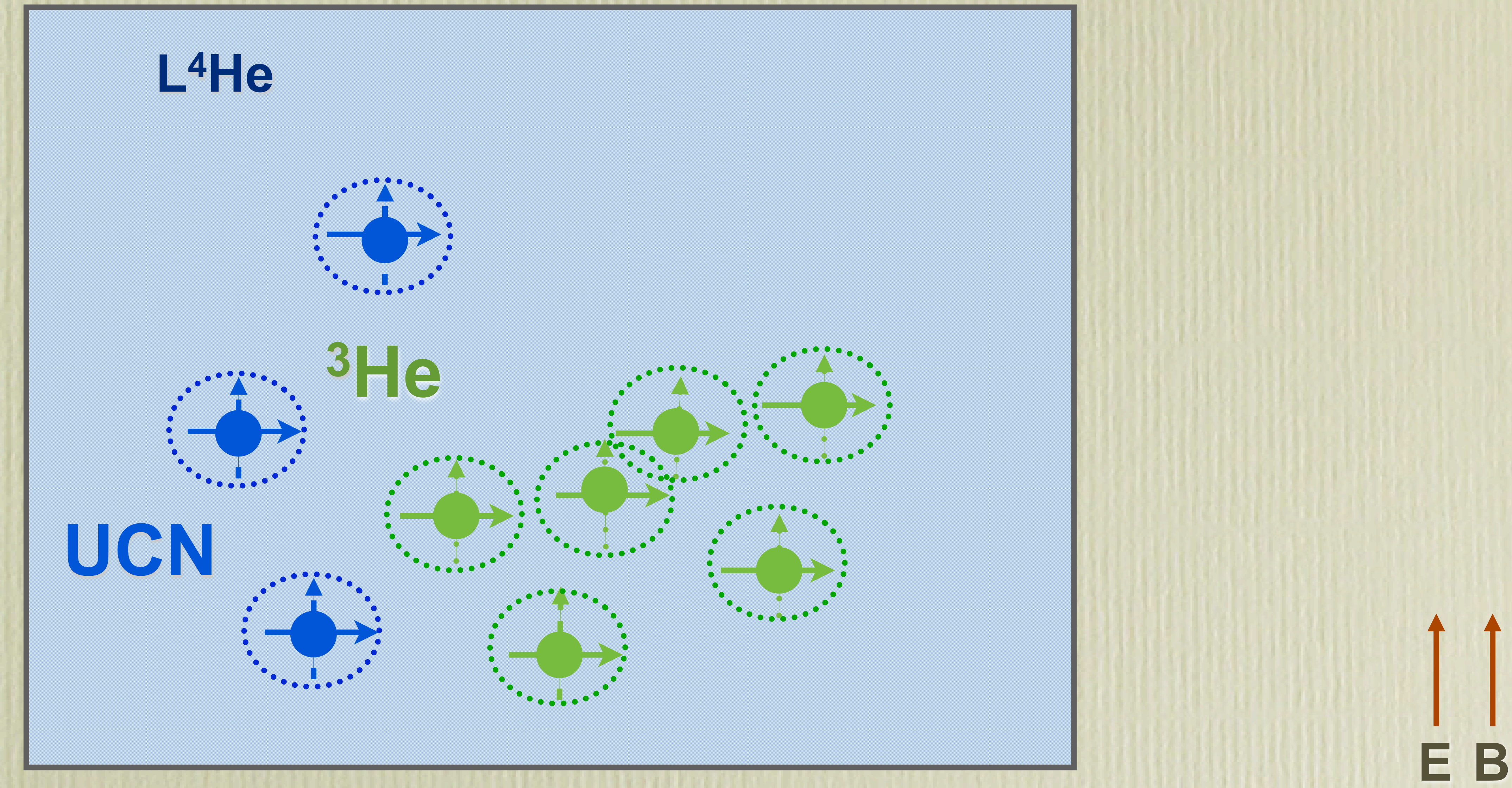
T = 100 - 1100 s



Produce polarized UCNs with polarized cold neutron beam

Experiment cycle

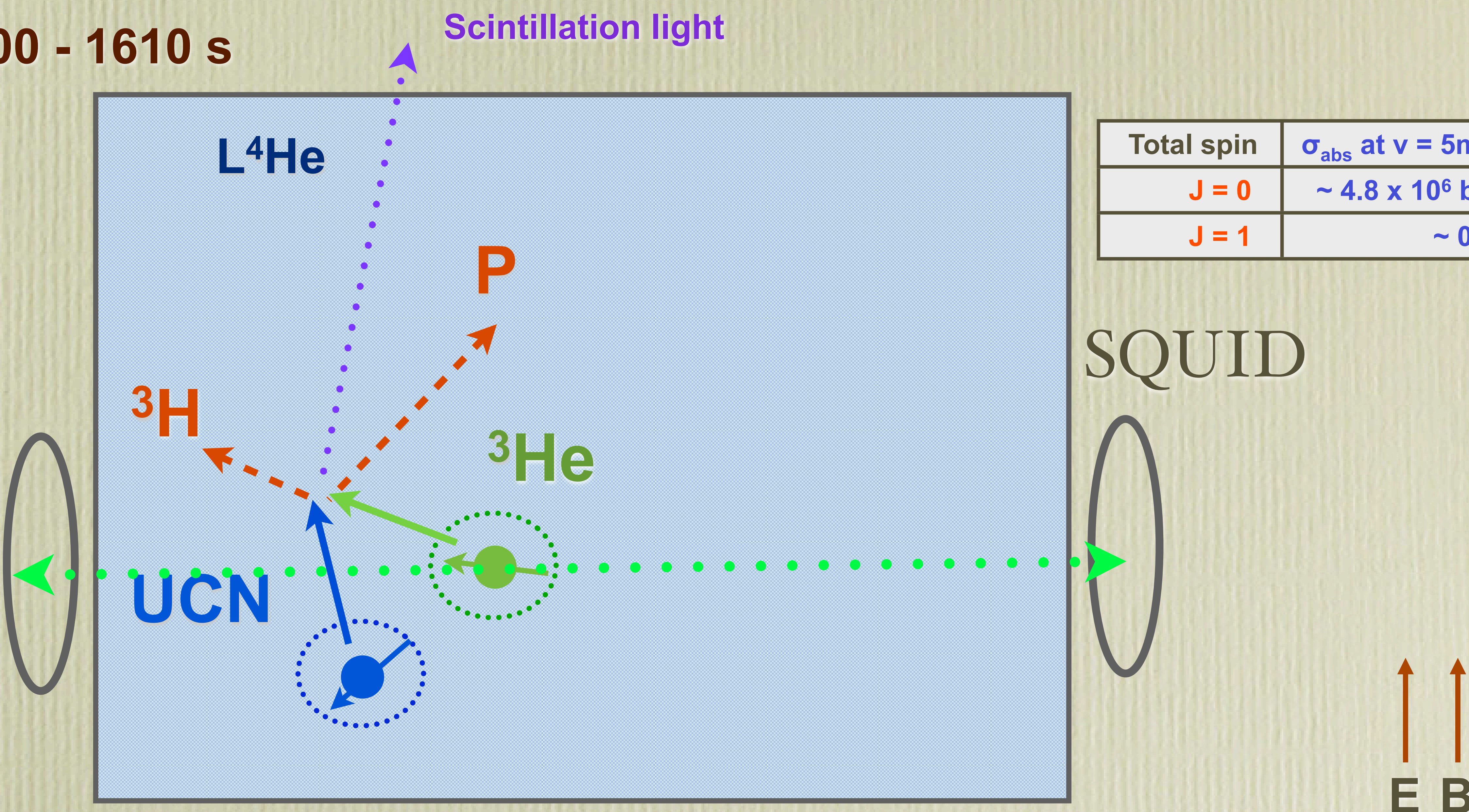
T = 1100 s



Flip neutron and ^3He spins by a π/2 RF coil

Experiment cycle

T = 1100 - 1610 s



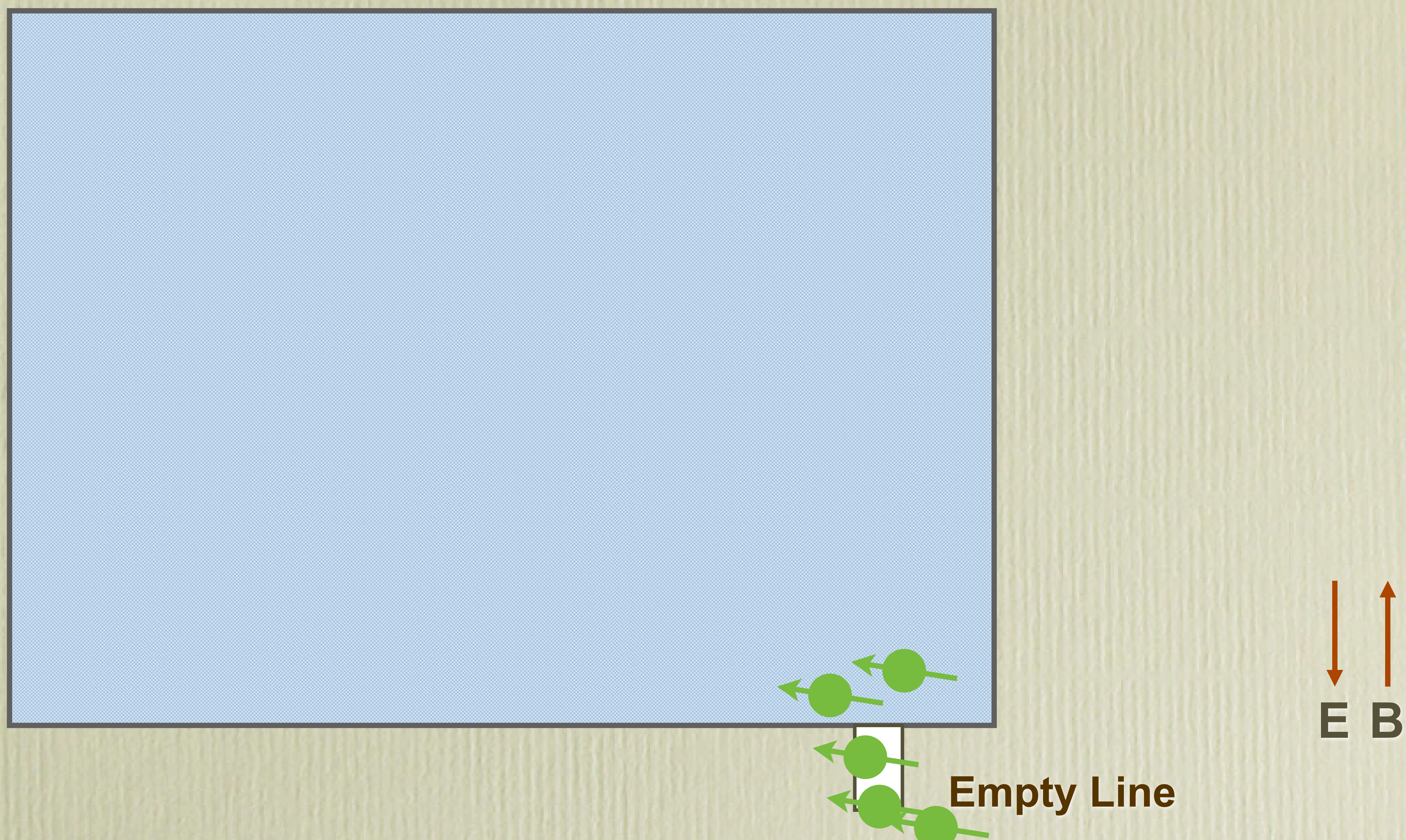
Total spin	σ_{abs} at v = 5m/sec
J = 0	~ 4.8 x 10^6 barns
J = 1	~ 0

- UCN and ^3He precess in a uniform B field (~10mG) and a strong E field (~50KV/cm). Measure the precession of ^3He by using SQUID.
- Detect **scintillation light** from the reaction n + ^3He -> p + t (and from other sources, including neutron beta decays)
- θ_{n3} is the relative angle between neutron and ^3He.

$$\frac{d\phi(t)}{dt} = N_0 e^{-\Gamma_{tot} t}\left[\frac{1}{\tau_\beta} + \frac{1}{\tau_3}(1 - P_3 P_n \cos(\theta_{n3}))\right]$$

Experiment cycle

T = 1610 - 1710 s

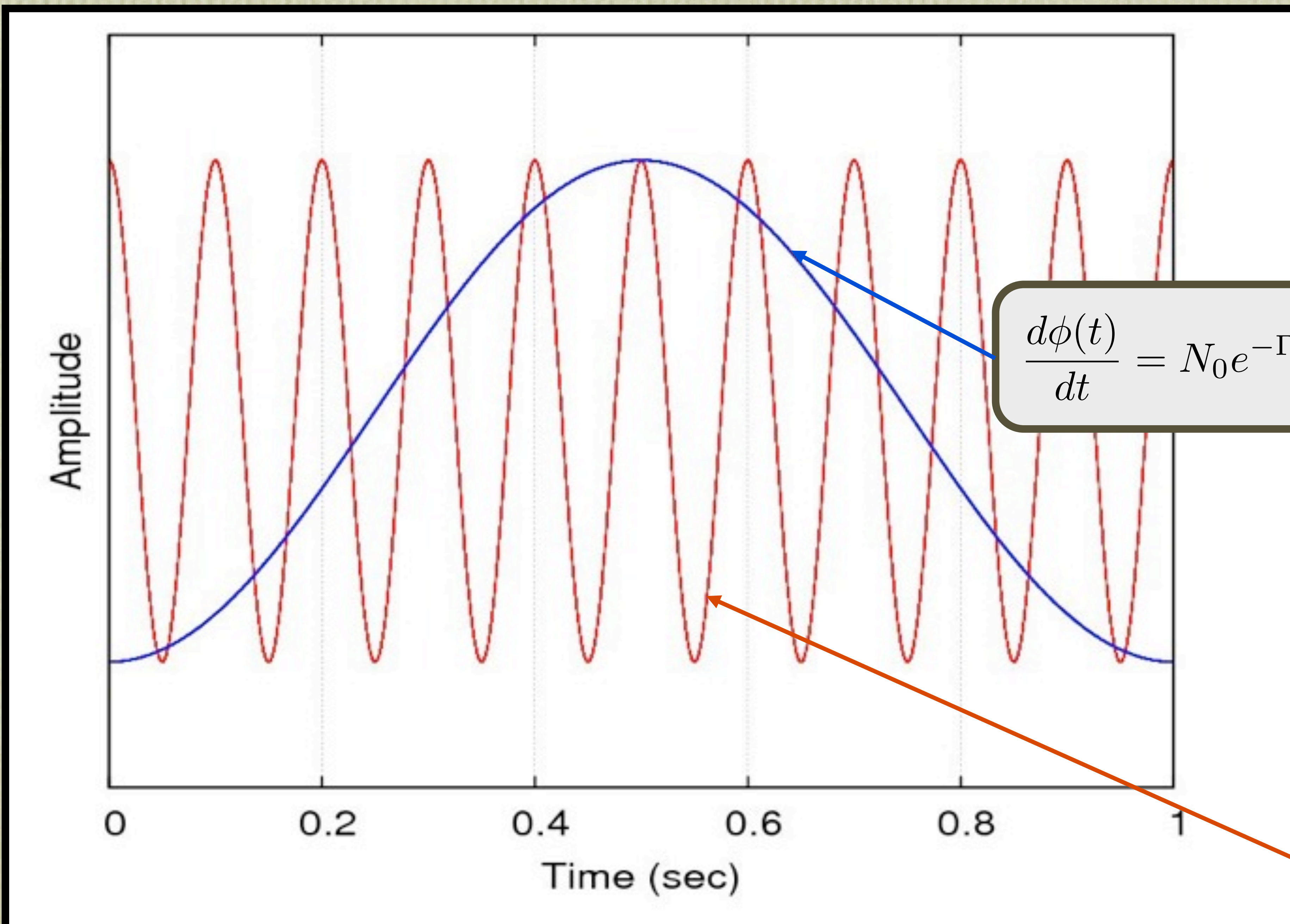


Empty the ^3He by using heat flush, change the electric field direction periodically and repeat the measurement

Two oscillatory signals

- Scintillation light from $n + {}^3He \rightarrow p + t$ with $\omega_\gamma = (\gamma_n - \gamma_3)B_0 \pm 2d_n E_0/\hbar$ where the relative angle $\theta_{n3} = \omega_\gamma t$.
- SQUID signal from the precession of ^{3}He with $\omega_3 = \gamma_3 B_0$.
- Thus, the precession of neutron can be known well.

comagnetometer:
reduce the error caused by B_o instability between measurements



Scintillation signal

$$\frac{d\phi(t)}{dt} = N_0 e^{-\Gamma_{tot} t}\left[\frac{1}{\tau_\beta} + \frac{1}{\tau_3}(1 - P_3 P_n \cos(\theta_{n3}))\right]$$

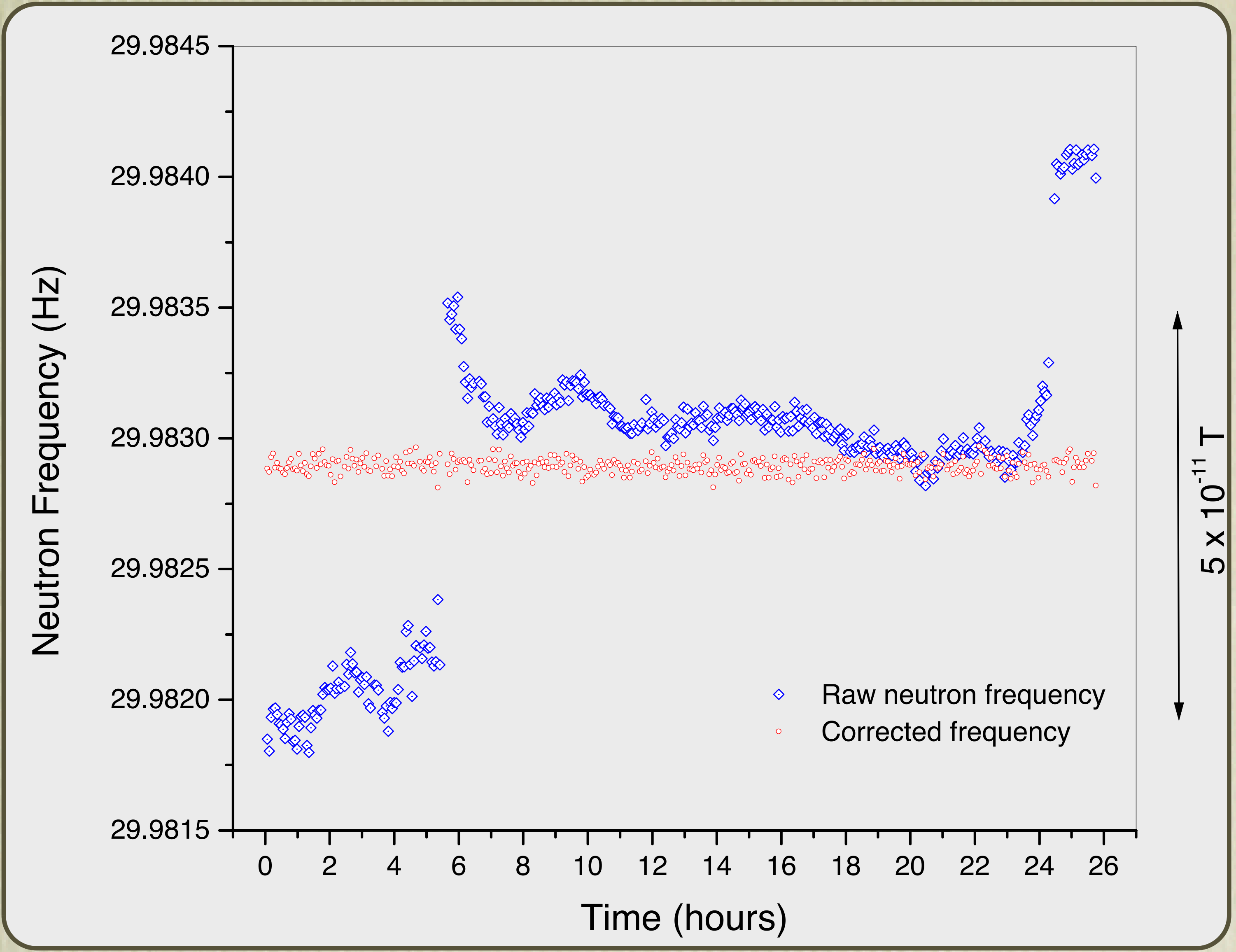
$$\gamma_3 \approx 1.1\gamma_n$$

SQUID frequency is ~10 times higher than scintillation frequency

SQUID signal

Application of comagnetometer

- The idea is to add **a polarized atomic species** to precess with neutrons.
- **The drift of the holding field** can be monitored by measuring the precession of the comagnetometer.
- ^{199}Hg was applied as a comagnetometer in ILL experiment (Phys.Rev.Lett. 97 (2006) 131801: $d_n < 2.9 \times 10^{-26}$ e cm). But it *cannot* be used in liquid ^4He.
- ^3He will be used for the new neutron EDM experiment in liquid ^4He at the SNS.



Dressed spin in nEDM

- Neutrons and ^{3}He naturally precess at different frequencies (different g factors)

- Applying a RF field (dressing field), $B_d\cos(\omega_d t)$, perpendicular to the constant B_0 field, the effective g factors of neutrons and ^{3}He will be **modified** (dressed spin effect)

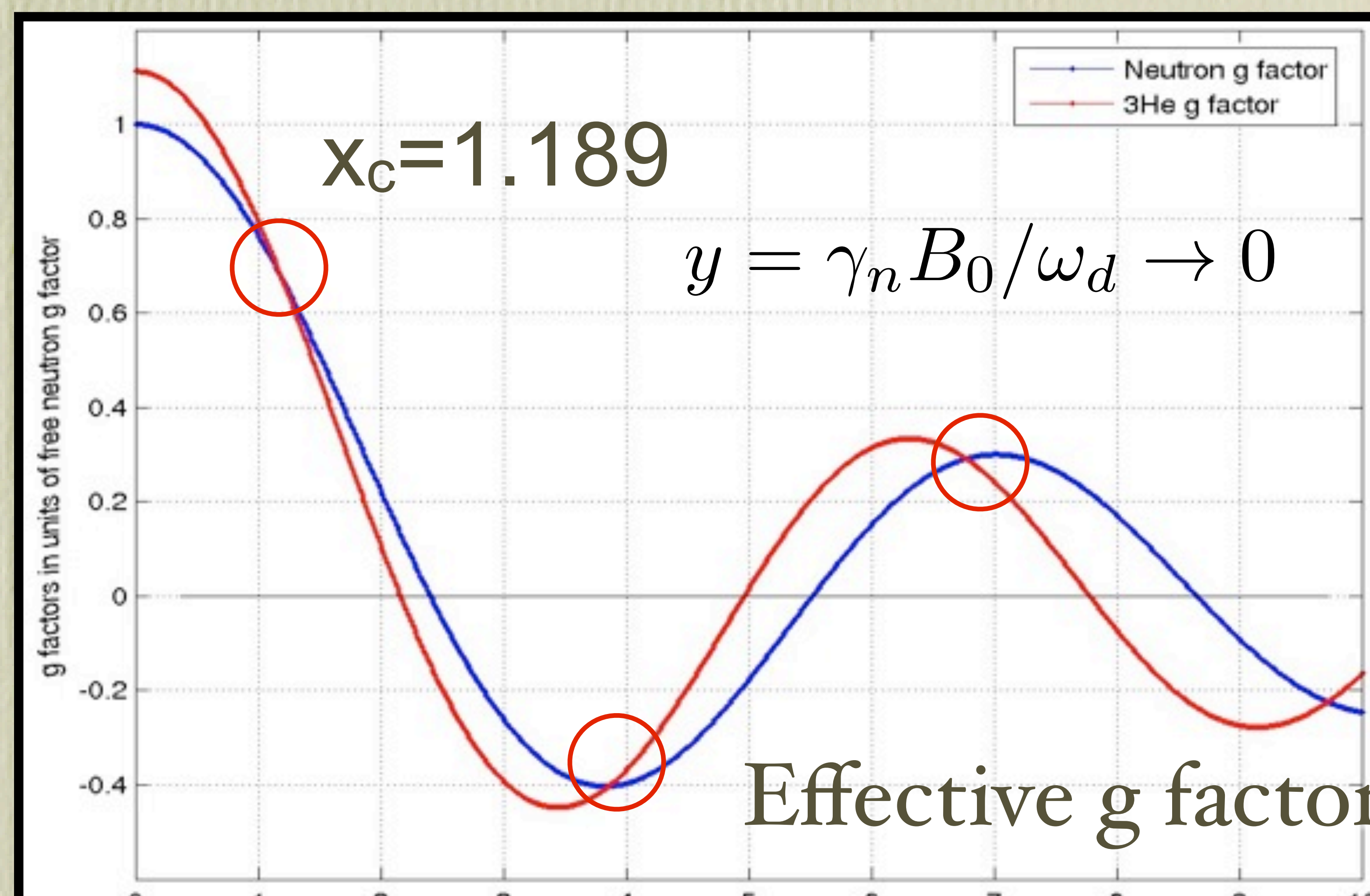
- At a **critical dressing field**, the effective g factors of neutrons and ^{3}He can be made **identical!**

$$\omega_\gamma = (\gamma_n - \gamma_3)B_0 \pm 2d_n E_0/\hbar \to \pm 2d_n E_0/\hbar$$

Critical dressing of neutron and ^{3}He

- The Larmor frequency is given as $\omega_{Larmor} = \omega_0 = \gamma B_0$
- γ is modified by the dressing field at the high frequency limit as $\gamma' = \gamma J_0(x)$
- The critical dressing is $\gamma'_n = \gamma'_3$
- Thus $J_0(x_c) = aJ_0(ax_c)$
- $a = \gamma_3/\gamma_n \approx 1.1$
- The proposal value is
  $B_0 = 10\ mG$,
  $x = 1.189$,
  $y = 0.01$.

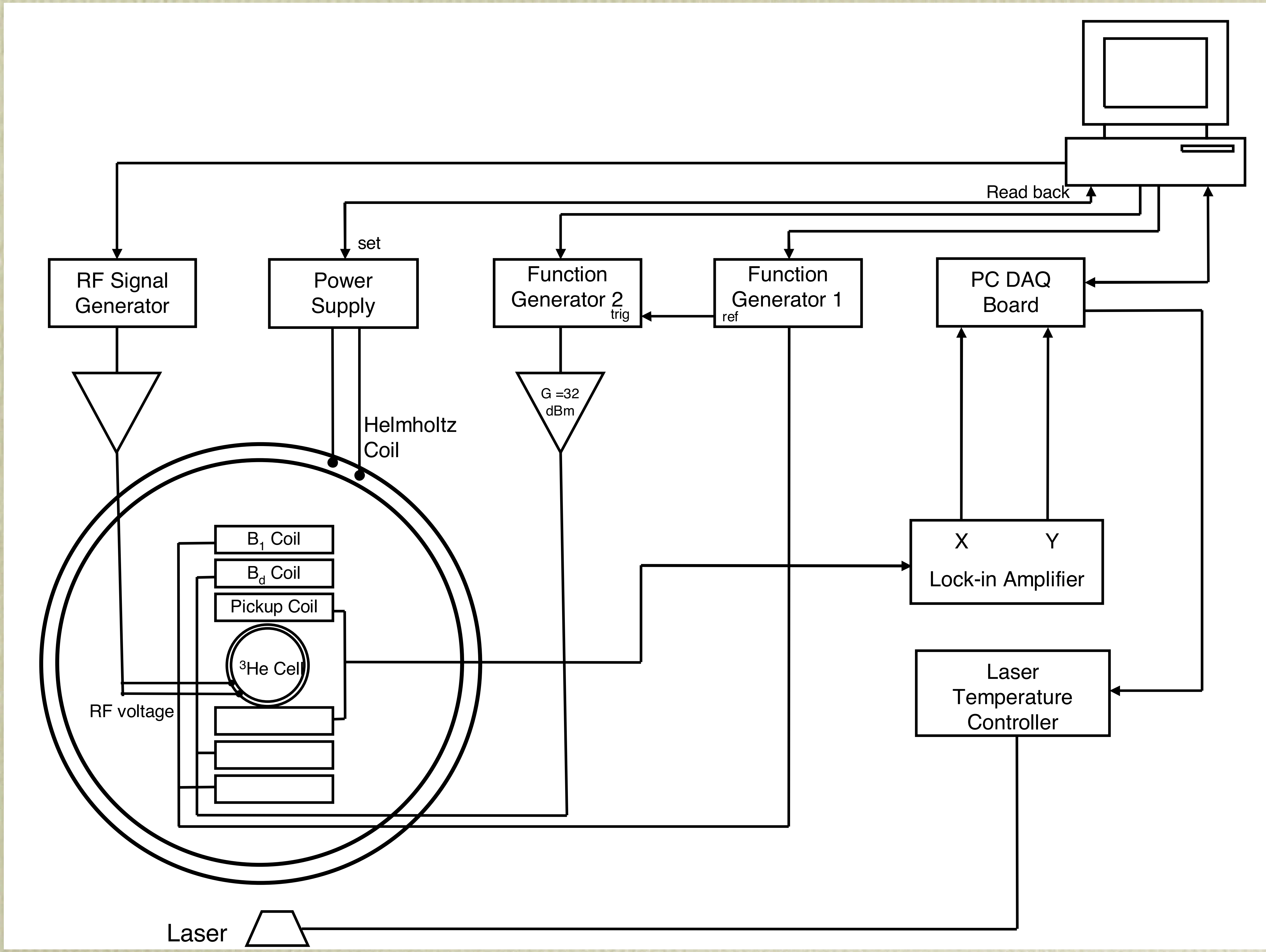
$$x \equiv \frac{\gamma_n B_d}{\omega_d}$$
$$y \equiv \frac{\gamma_n B_0}{\omega_d}$$



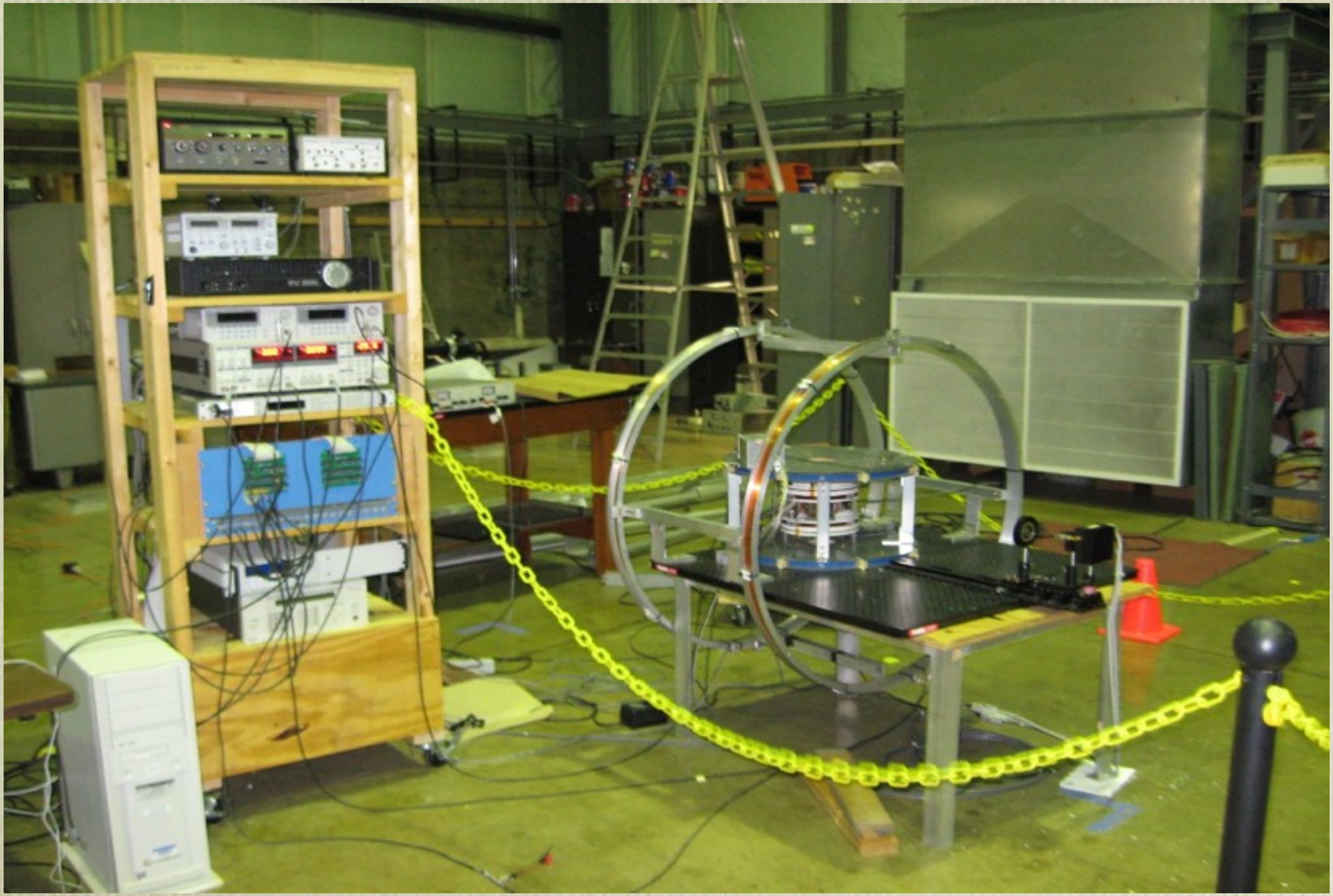
$x = \gamma_n B_d/\omega_d$

The goal of the UIUC measurement is to explore the dressed spin effect of polarized ^{3}He as a function of B_0, B_d and ω_d in a cell.

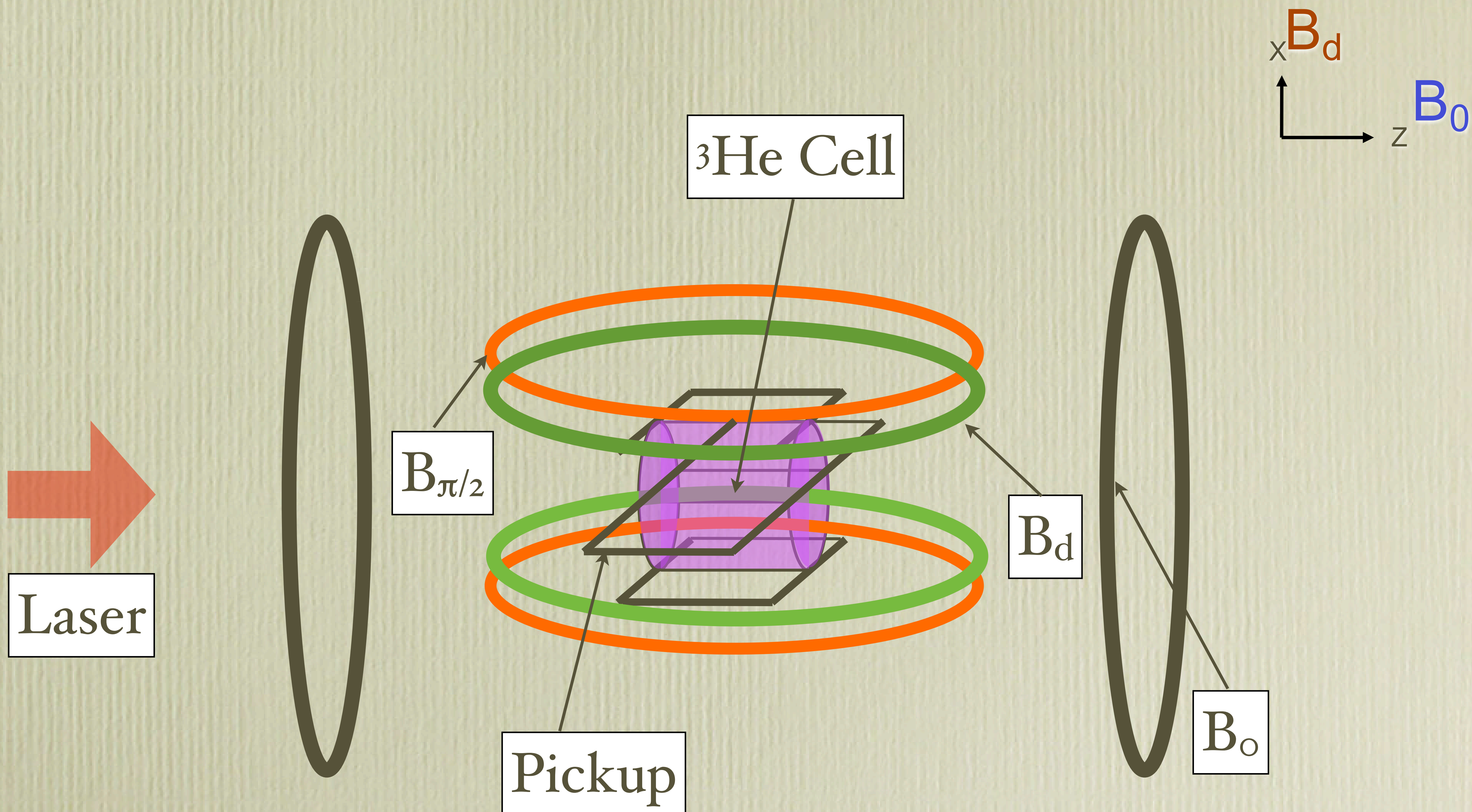
Experimental setup



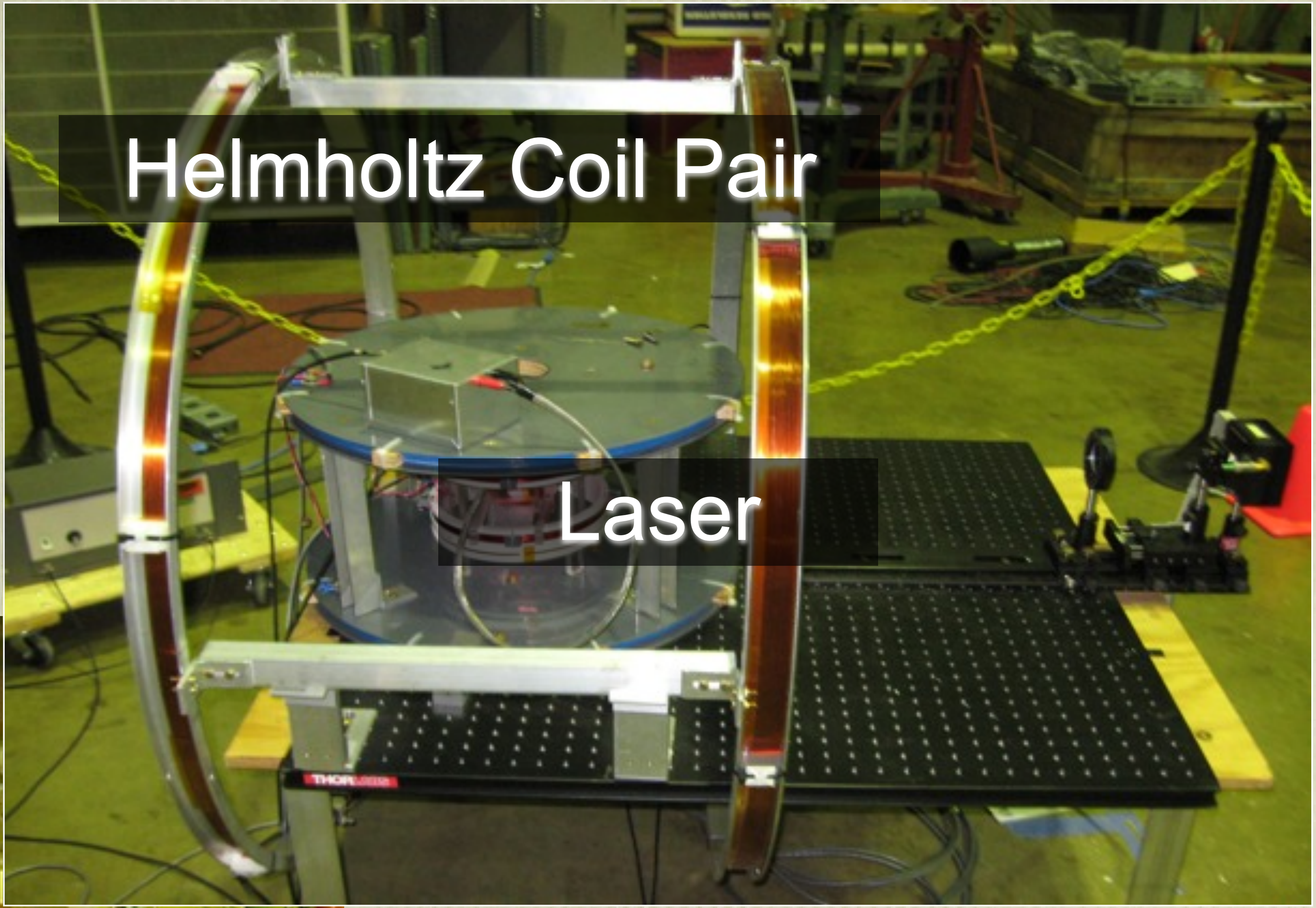
Experimental setup

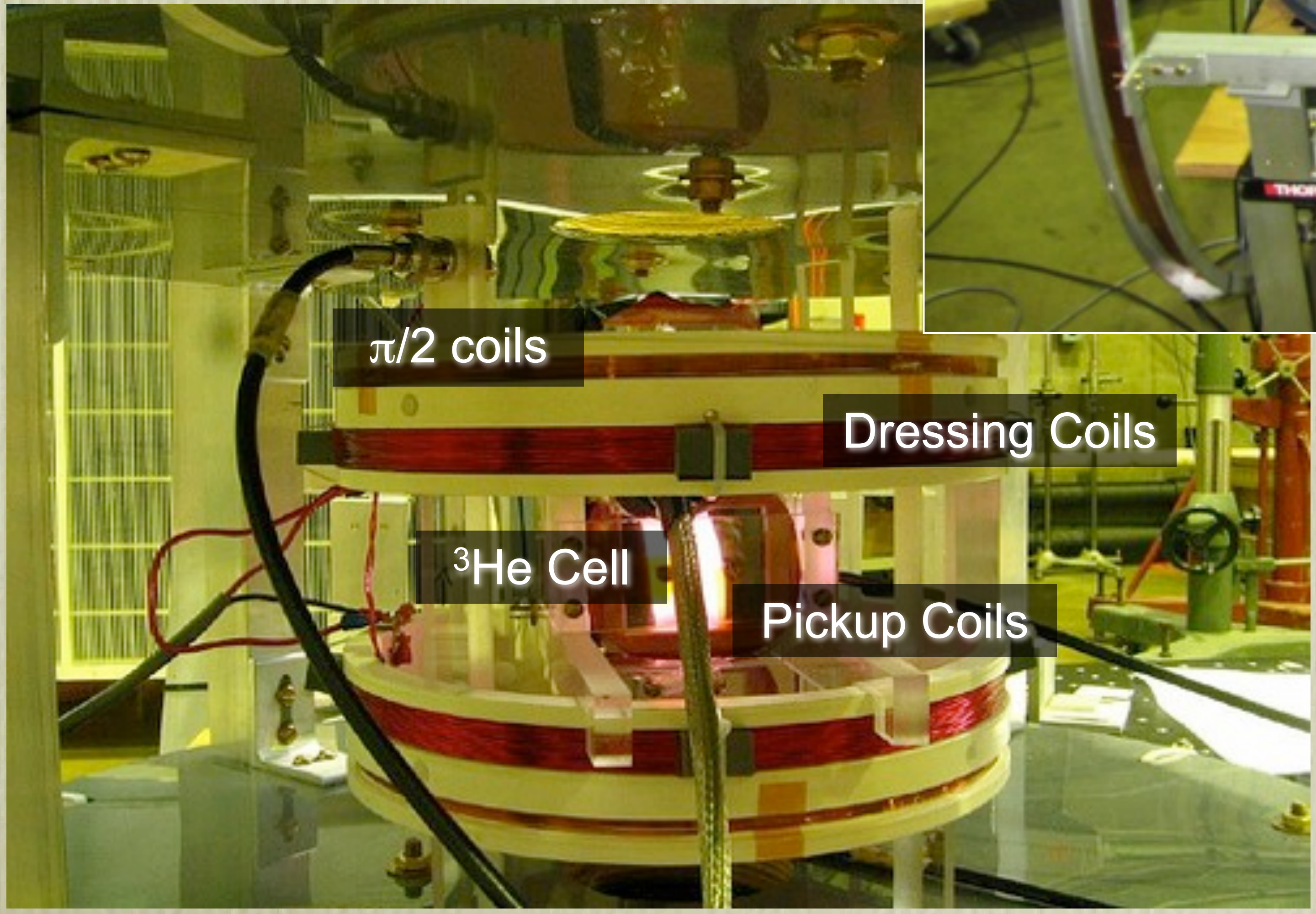


Experimental setup



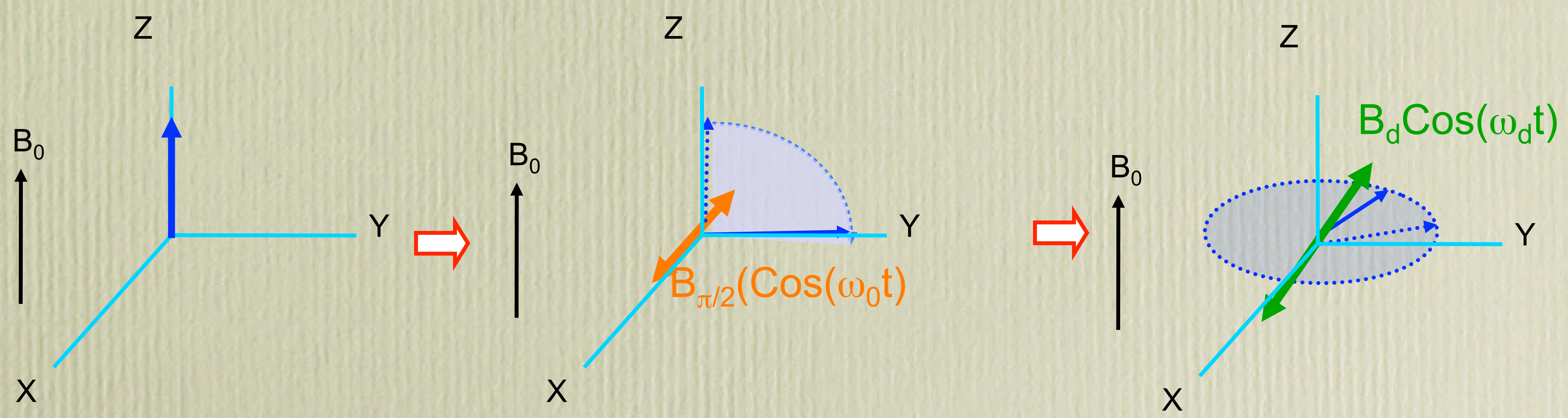
Experimental setup





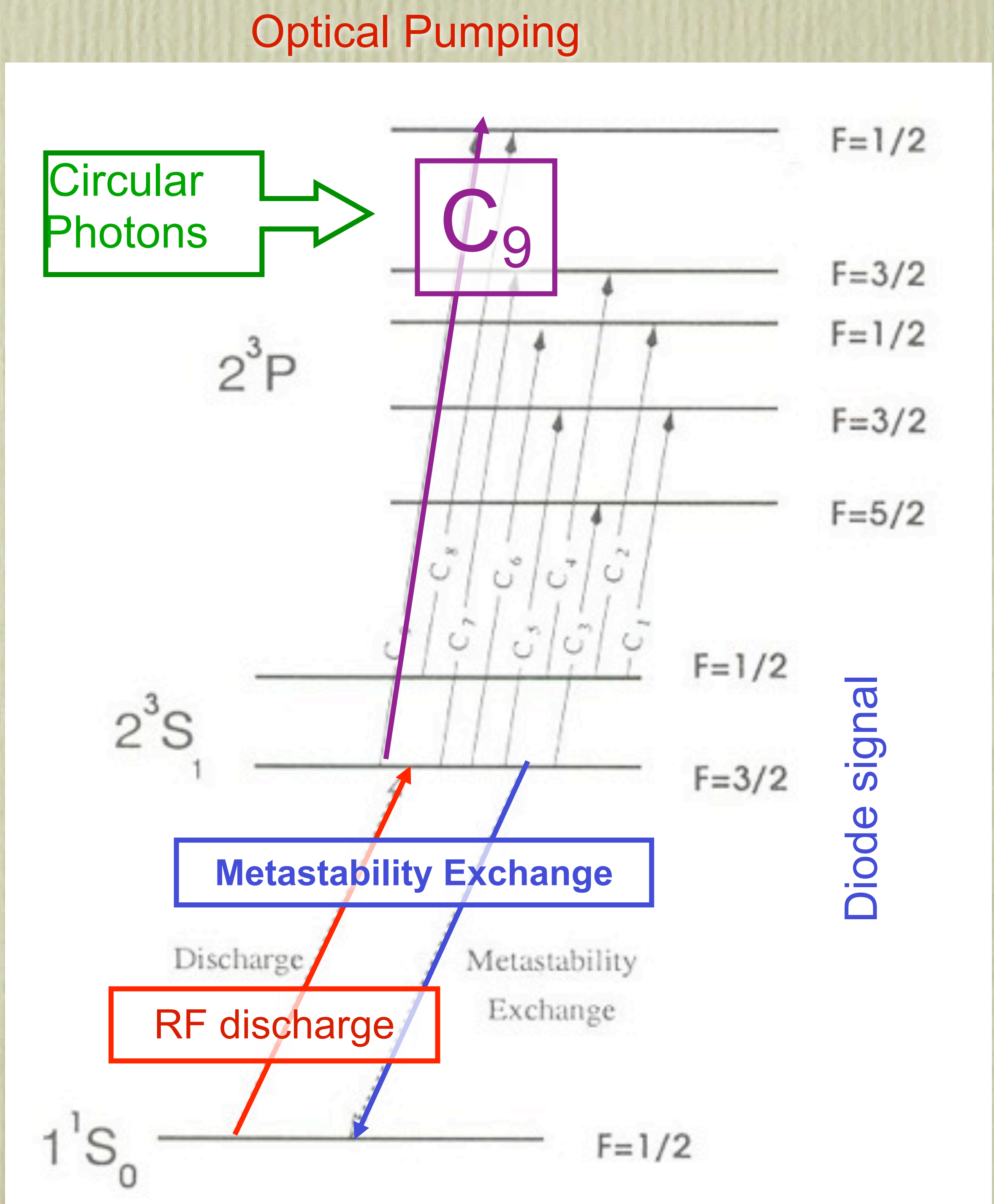
Experimental steps

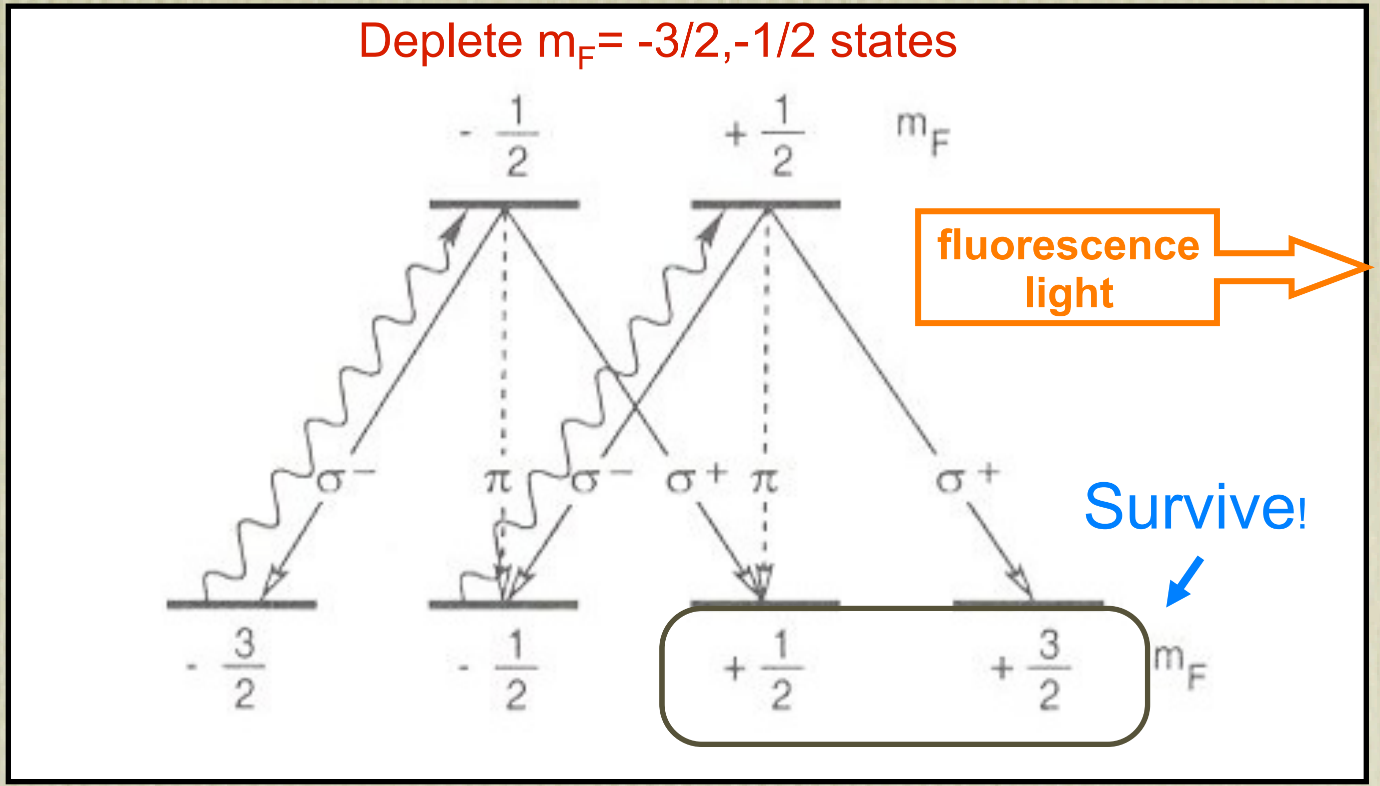
- Polarize ^{3}He nuclear spins. (Metastability exchange with optical pumping) (by **Laser** and $\mathbf{B_0}$)
- $\pi/2$ pulse to rotate the spin to x-y plane. (by $\mathbf{B_{\pi/2}Cos}(\omega_0 t)$)
- Apply a dressing field, $\mathbf{B_d Cos}(\omega_d t)$, and measure precession frequency by the **pickup coils** and **Lock-in amplifier**.

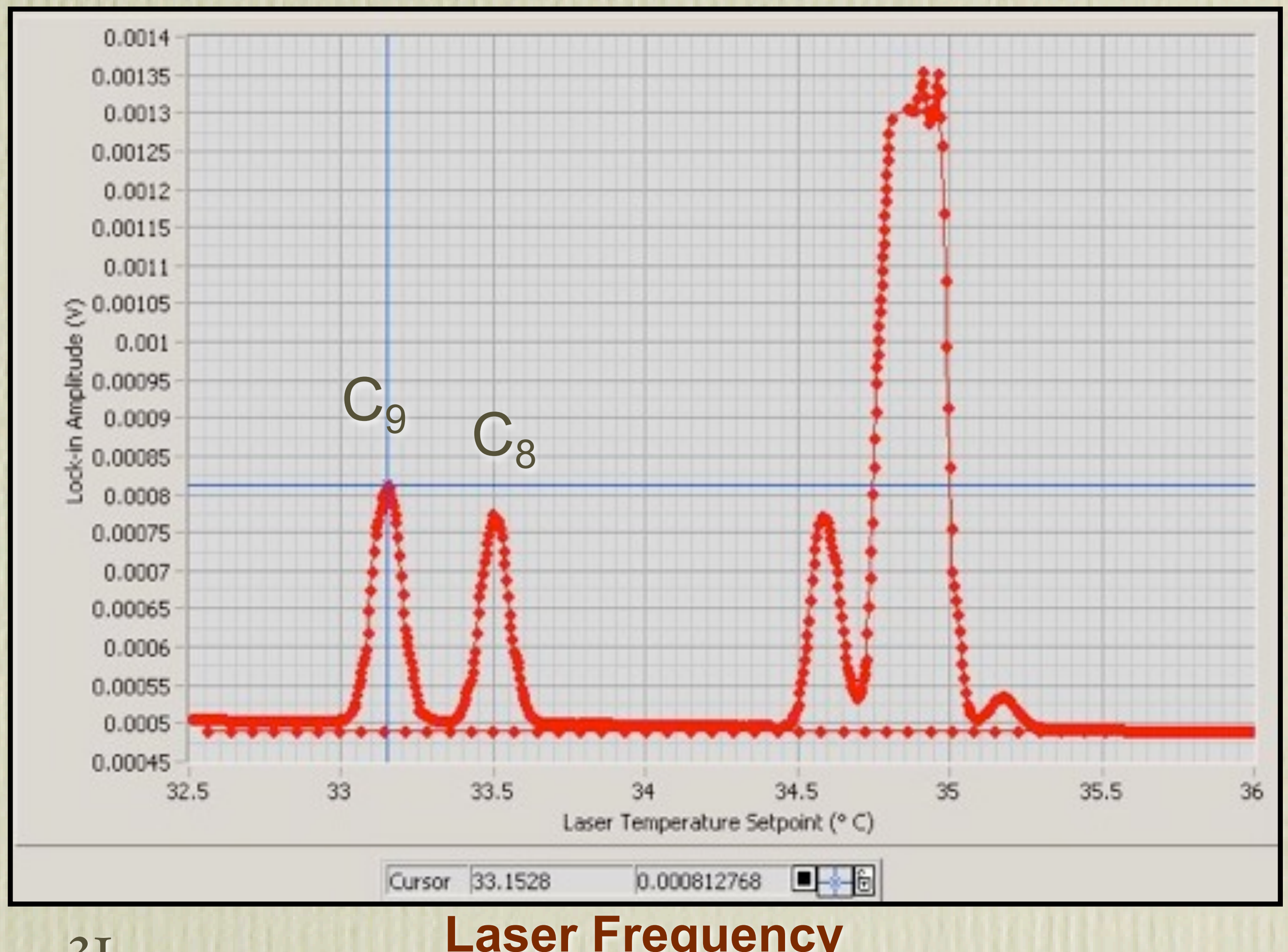


Polarized spins $\pi/2$ pulse   NMR signal

Polarize ^{3}He with metastability exchange



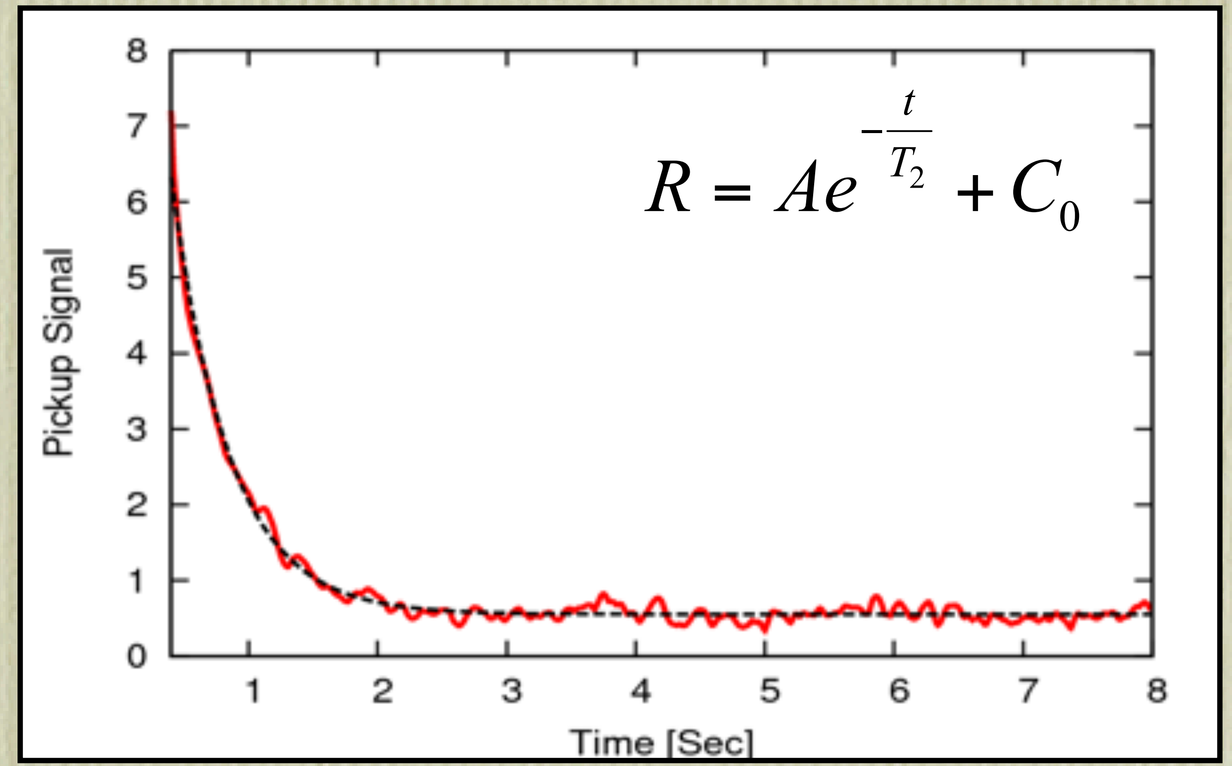


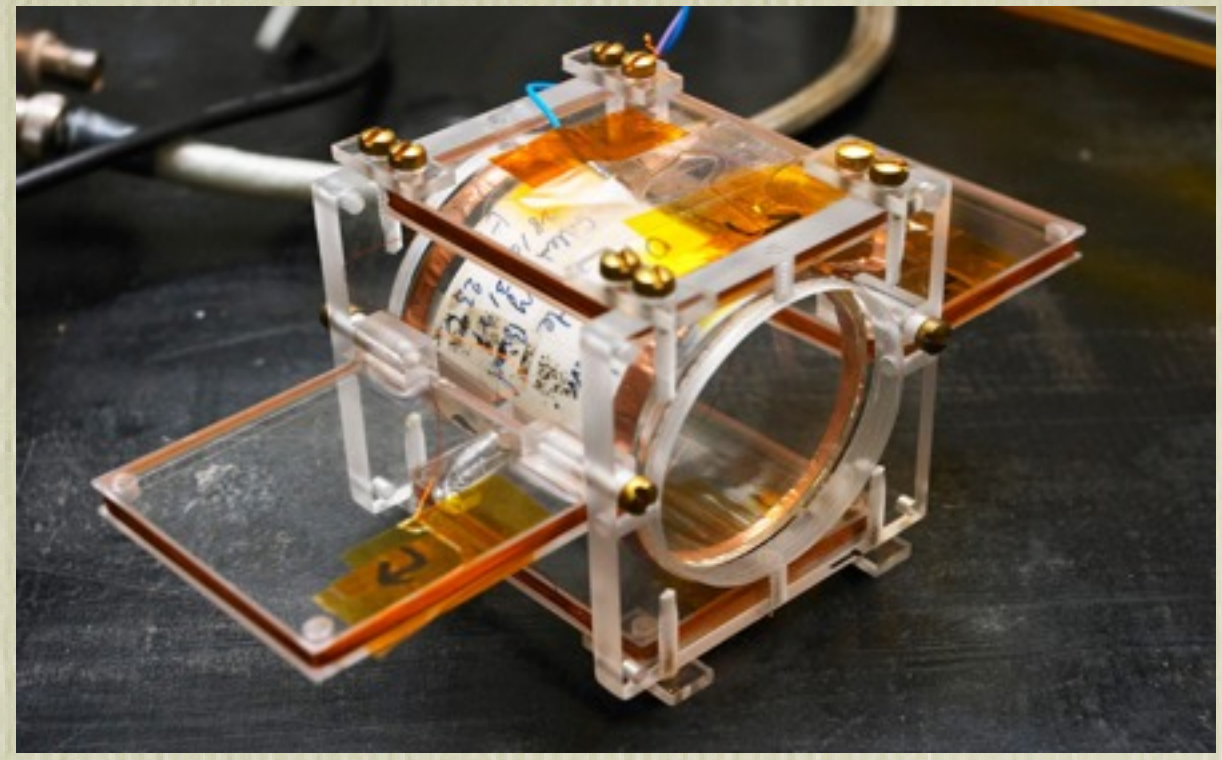


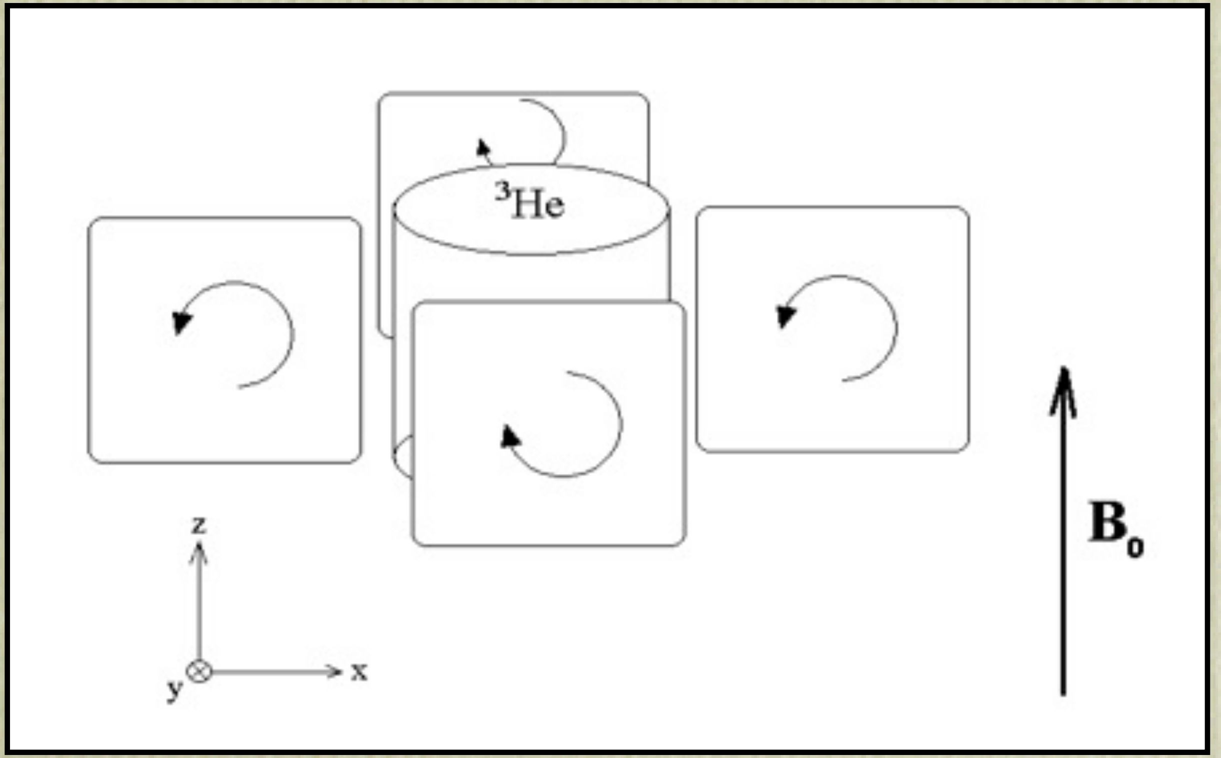
1)Transfer angular momentum of photon to atomic electrons

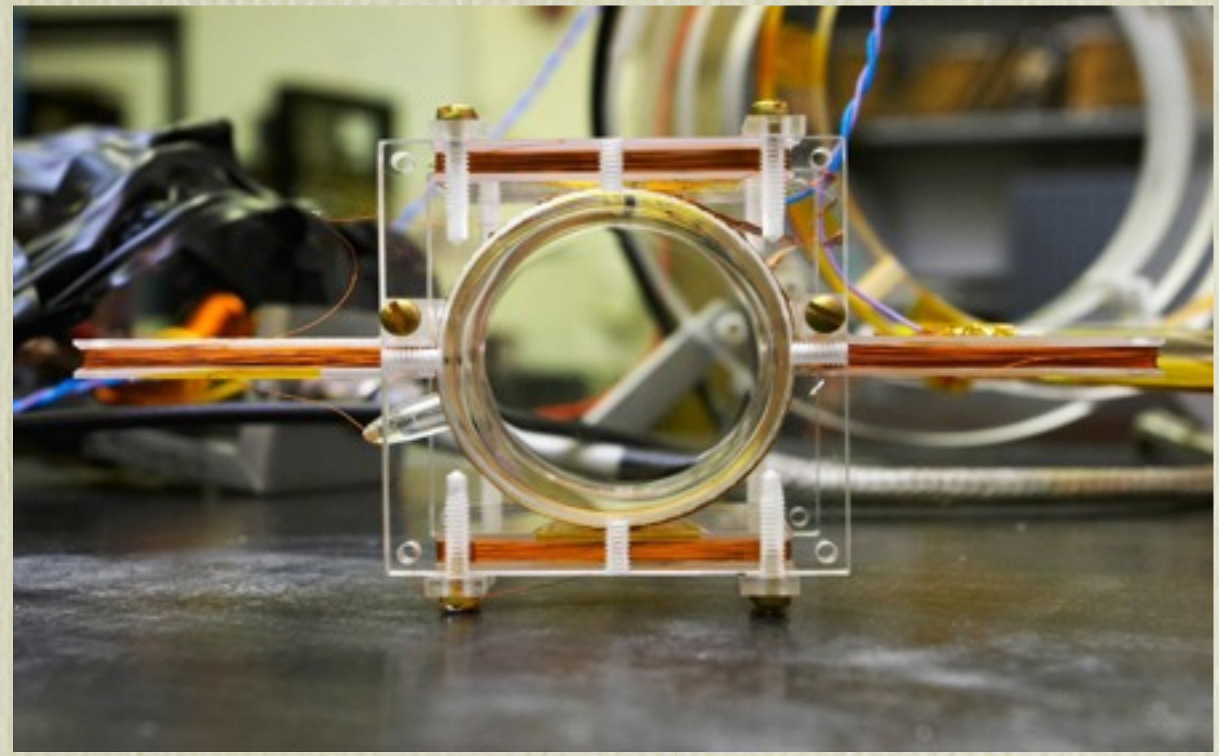
2) produce nuclear polarization via metastability exchange

Pickup coils signal

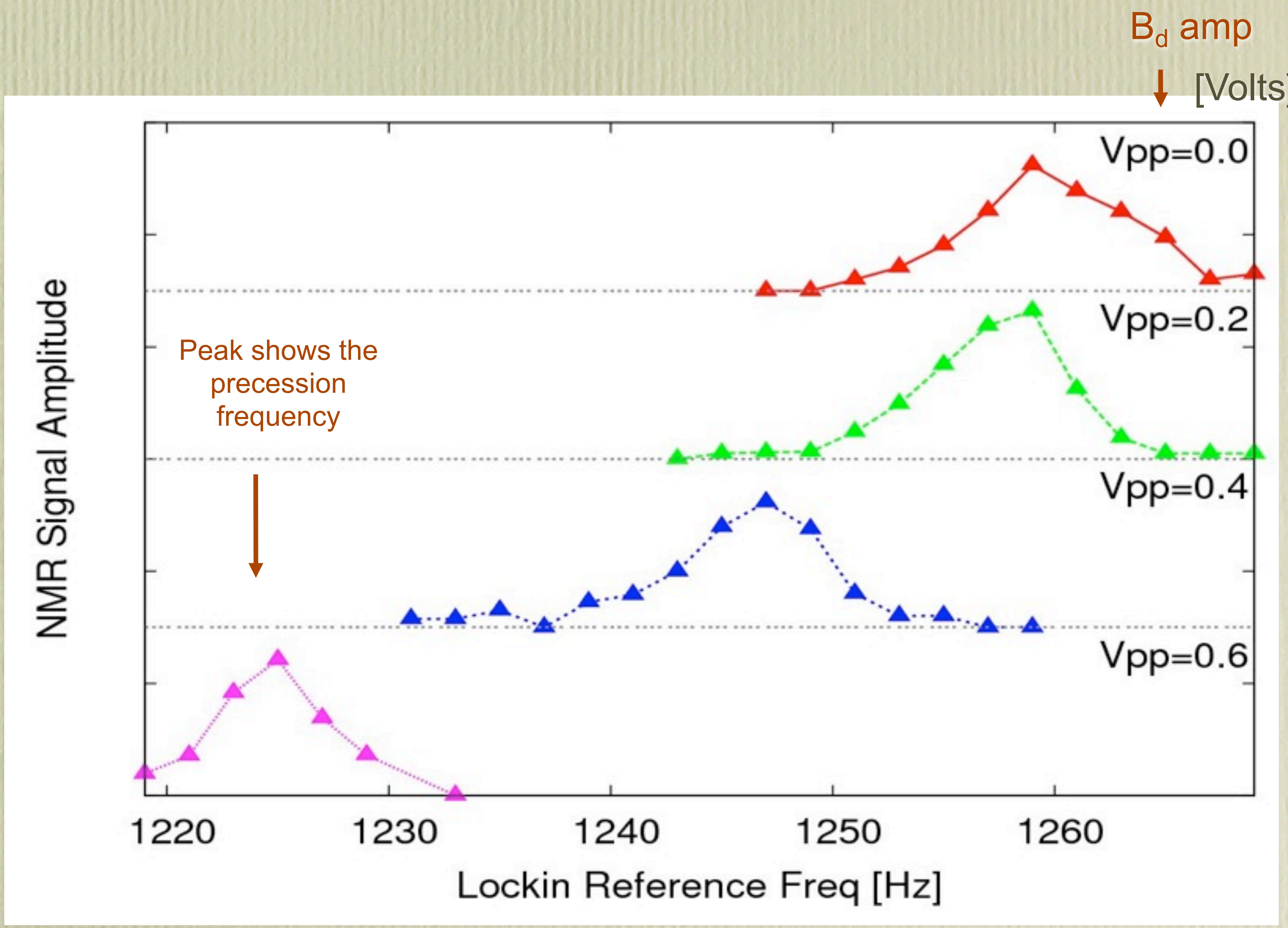






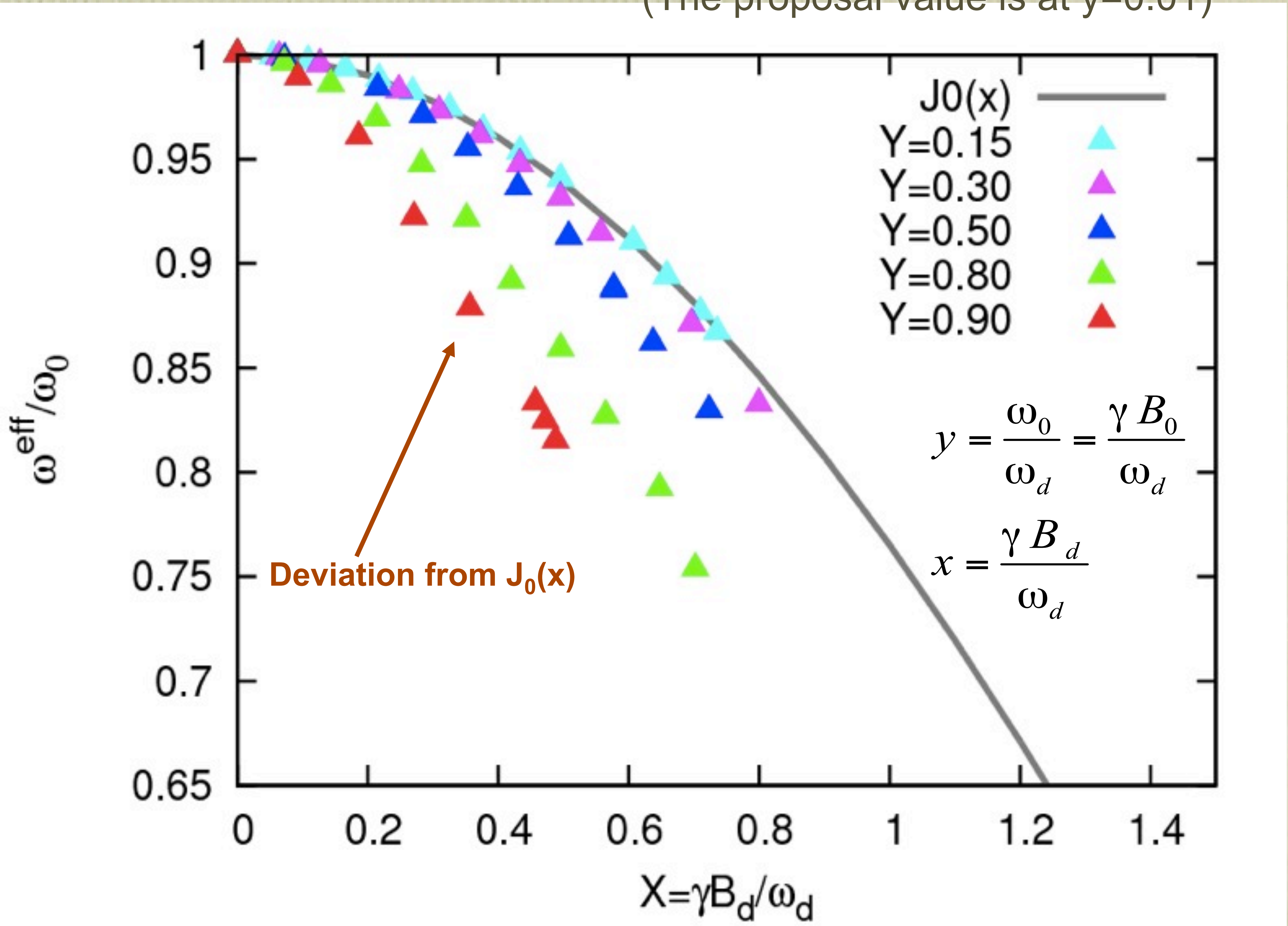


Precession frequency measurement by using Lock-in amplifier



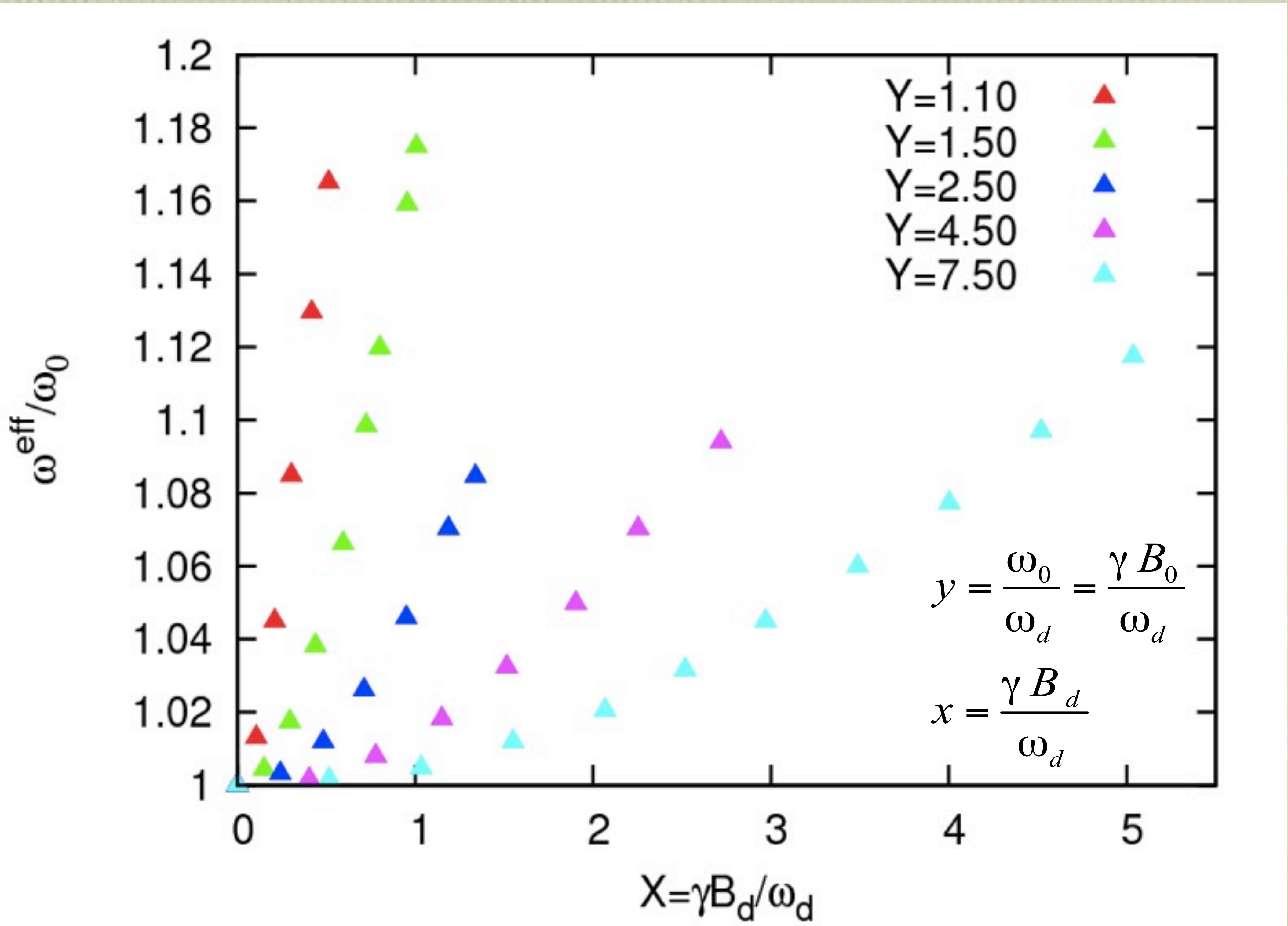
The effective precession frequency for different dressing field configuration for $y<1(\omega_0<\omega_d)$

(The proposal value is at y=0.01)



Precession slows down!

The effective precession frequency for different dressing field configuration for y>1 ($\omega_0 > \omega_d$)



Precession speeds up!

Quantum mechanical approach

$$H = H_M + H_{RF} + H_{int} = \hbar\omega_0 S_z + \hbar\omega_d a^\dagger a + \lambda S_x(a + a^\dagger)$$

$$\lambda = \hbar\gamma B_d / 2\bar{n}^{1/2}$$

Jaynes-Cummings Hamiltonian

$$Y = \frac{\gamma B_0}{\omega_d}$$

$$X = \frac{\gamma B_d}{\omega_d}$$

$$n \;=\; number\ of\ photons$$

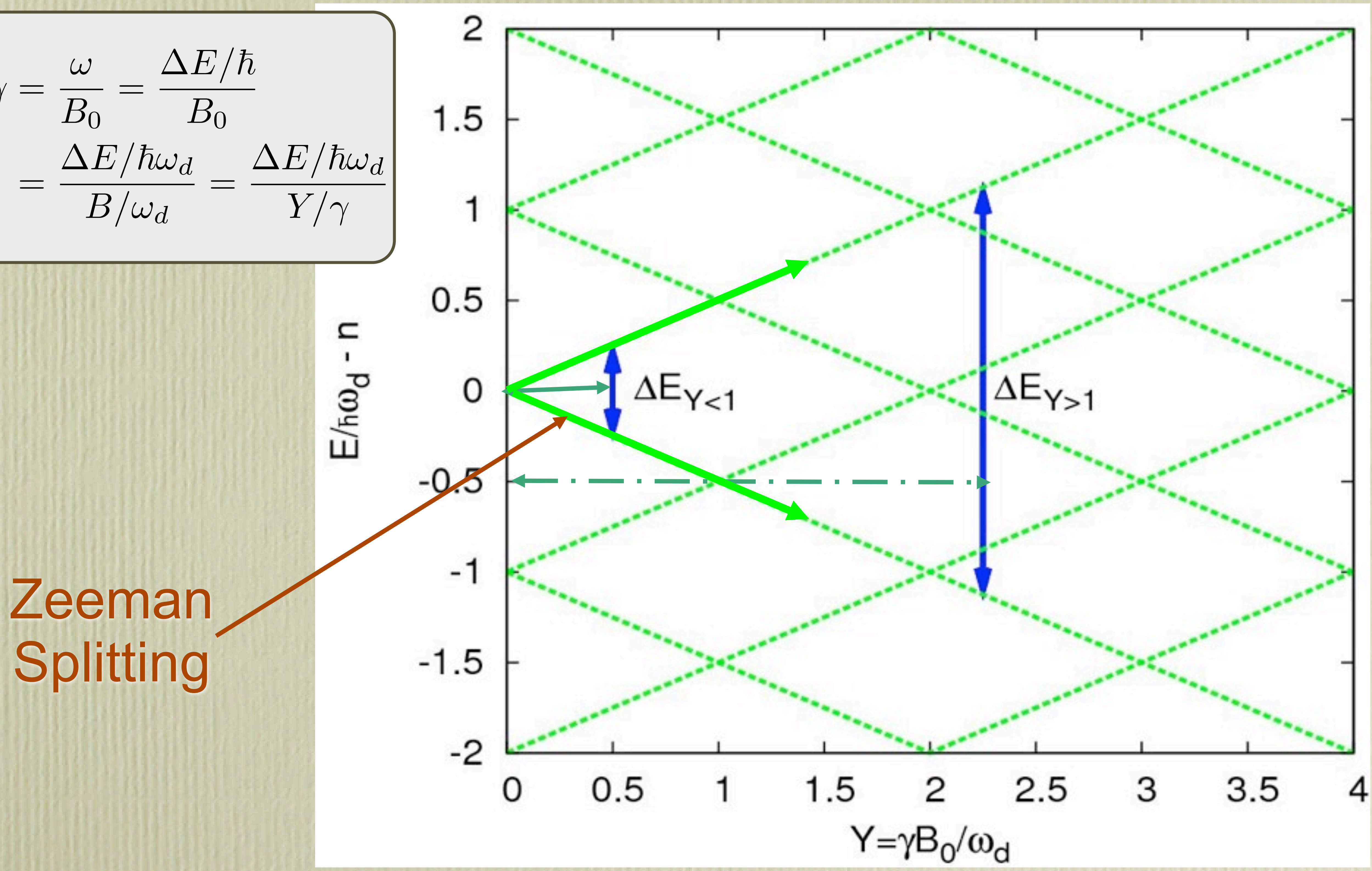
$$\hbar\omega_d \begin{bmatrix} n+1+\frac{Y}{2} & 0 & 0 & \frac{X}{4} & 0 & 0 \\ 0 & n+1-\frac{Y}{2} & \frac{X}{4} & 0 & 0 & 0 \\ 0 & \frac{X}{4} & n+\frac{Y}{2} & 0 & 0 & \frac{X}{4} \\ \frac{X}{4} & 0 & 0 & n-\frac{Y}{2} & \frac{X}{4} & 0 \\ 0 & 0 & 0 & \frac{X}{4} & n-1+\frac{Y}{2} & 0 \\ 0 & 0 & \frac{X}{4} & 0 & 0 & n-1-\frac{Y}{2} \end{bmatrix}$$

6x6

46x46

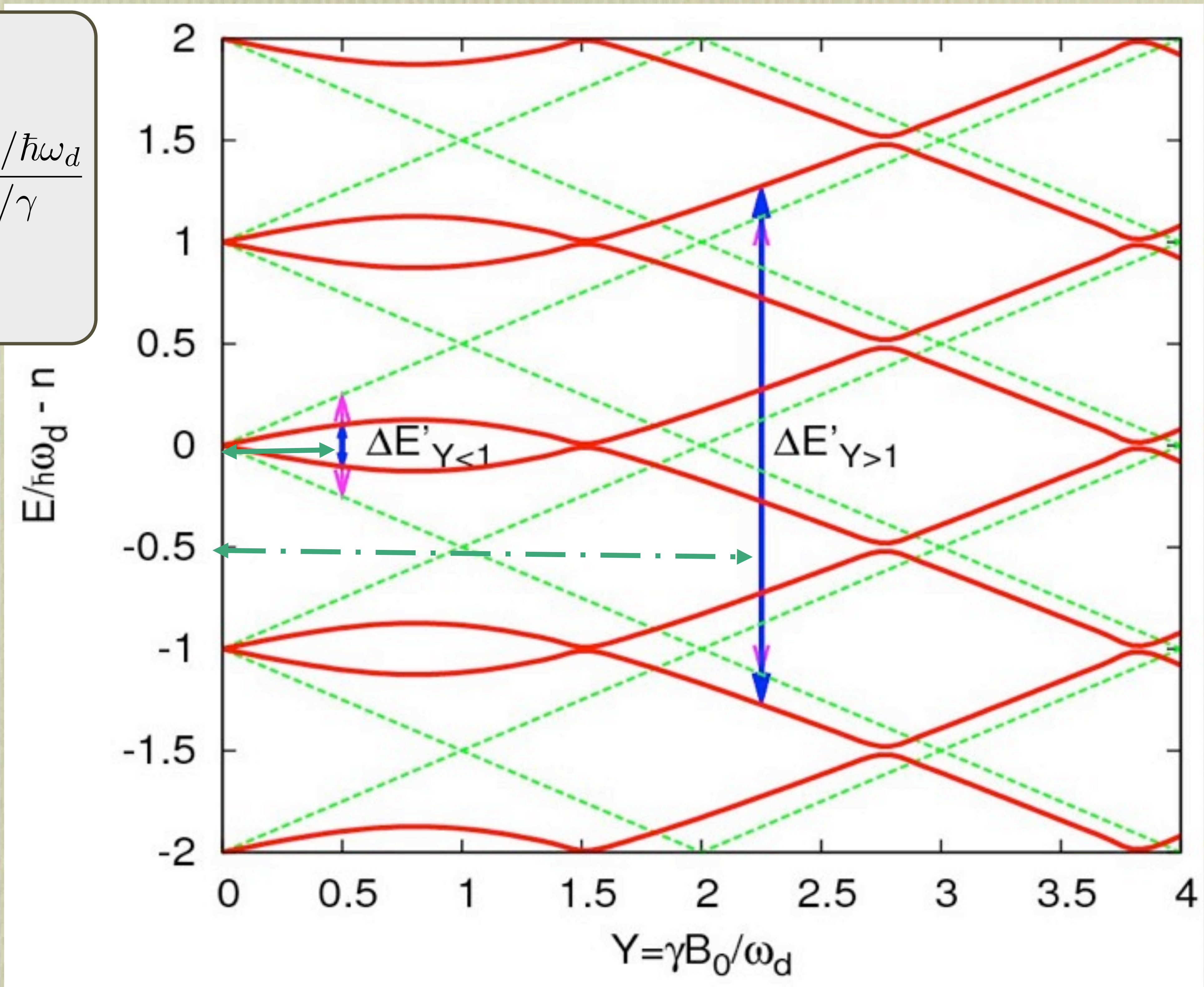
Dependence of effective γ in dressing field without dressing field

$$\gamma = \frac{\omega}{B_0} = \frac{\Delta E/\hbar}{B_0}$$
$$= \frac{\Delta E/\hbar\omega_d}{B/\omega_d} = \frac{\Delta E/\hbar\omega_d}{Y/\gamma}$$



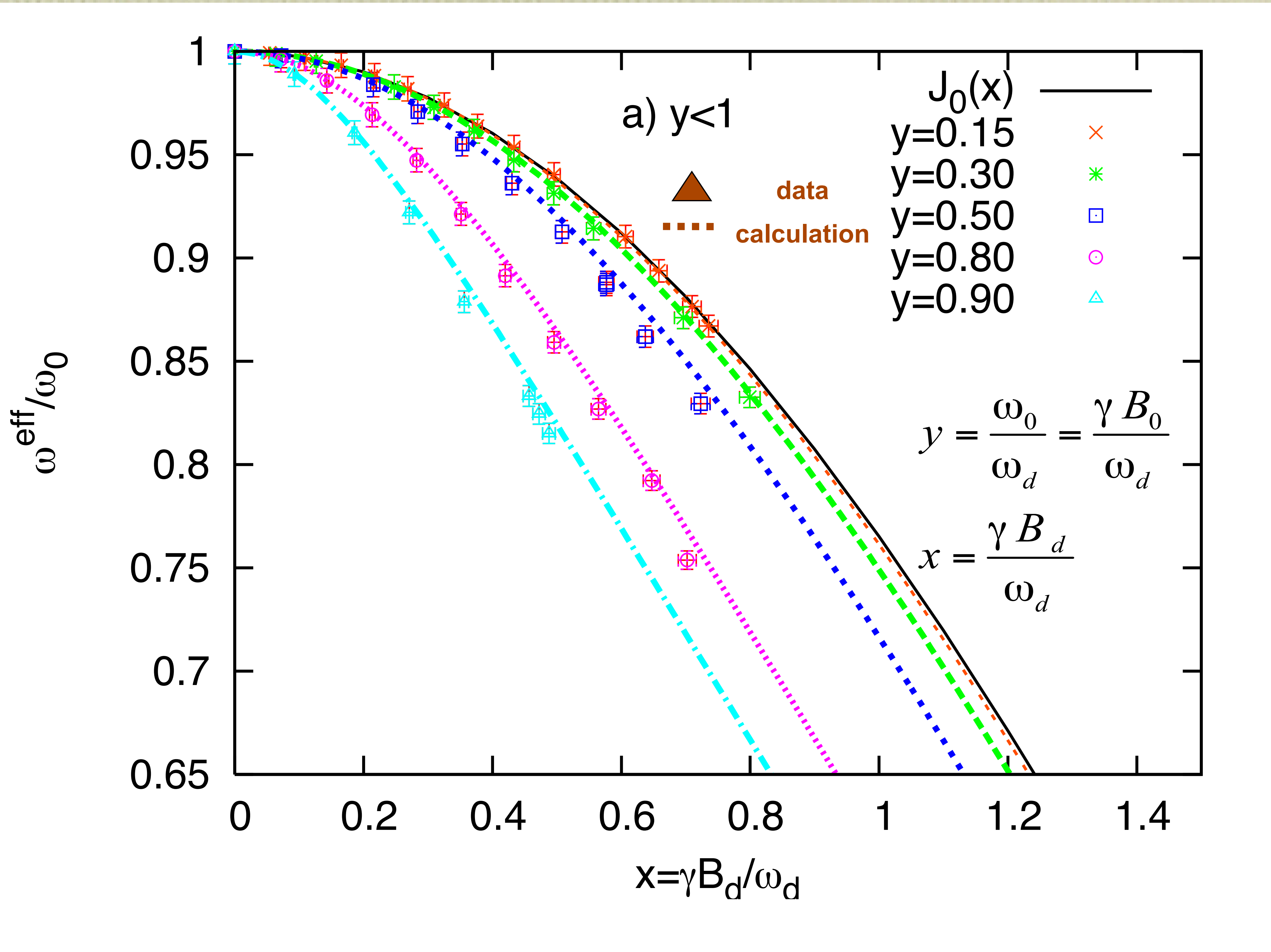
Dependence of effective γ in dressing field with dressing field

$$\gamma' = \frac{\omega}{B_0} = \frac{\Delta E'/\hbar}{B_0}$$
$$= \frac{\Delta E'/\hbar\omega_d}{B/\omega_d} = \frac{\Delta E'/\hbar\omega_d}{Y/\gamma}$$
$$\rightarrow \frac{\gamma'}{\gamma} = \frac{\Delta E'}{\Delta E}$$

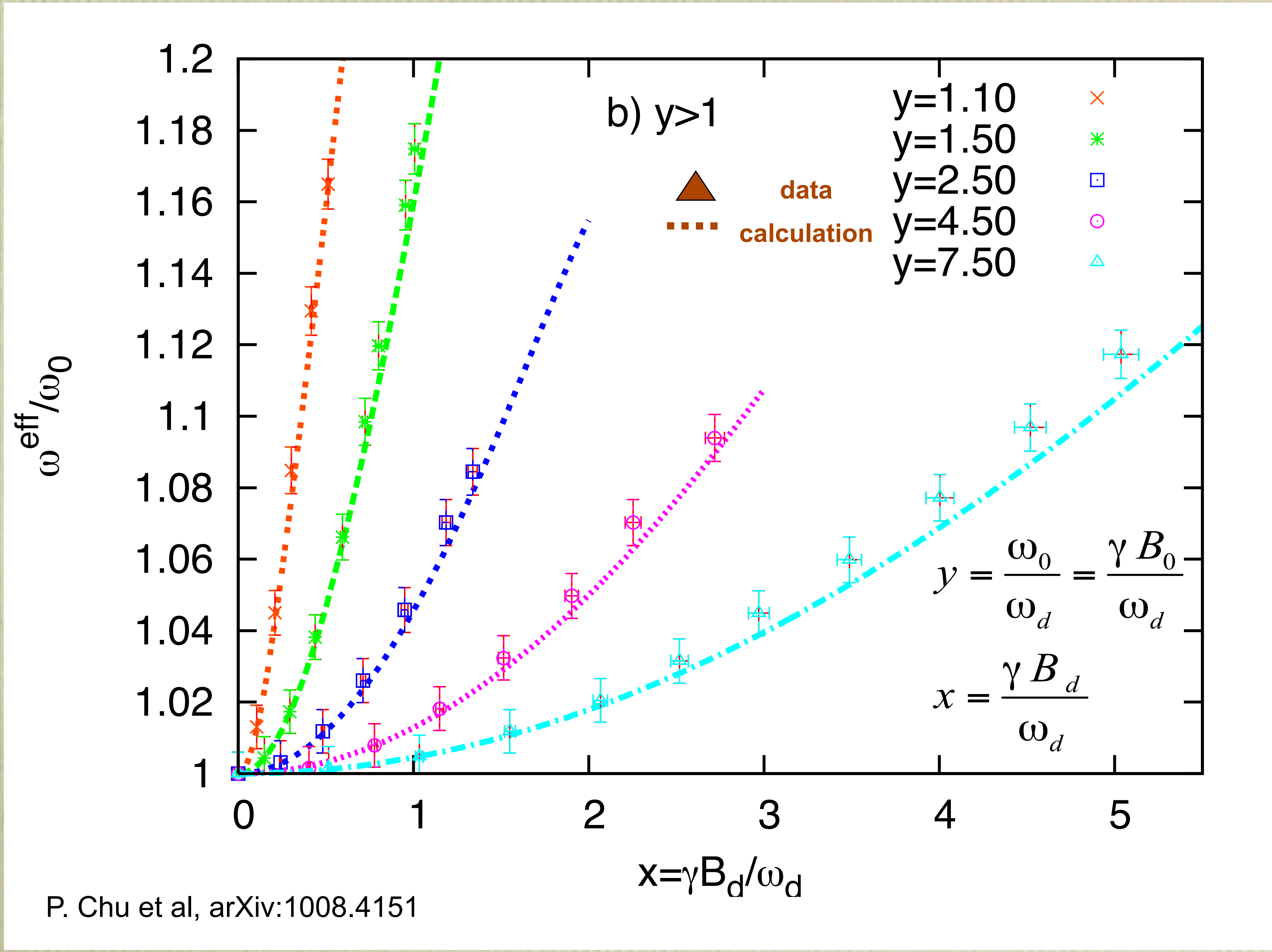


g ratio is equal to energy spacing ratio.

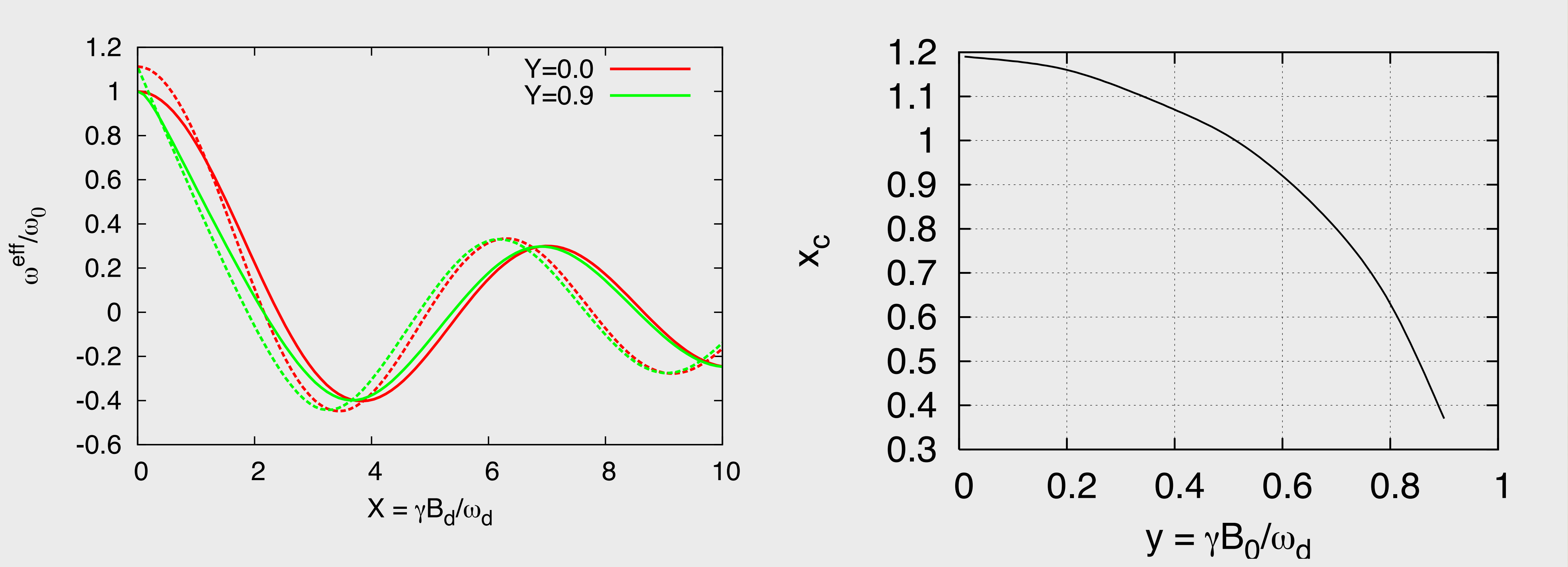
The effective precession frequency for different dressing field configuration for y<1 ($\omega_0<\omega_d$)



The effective precession frequency for different dressing field configuration for y>1 ($\omega_0 > \omega_d$)



Critical dressing for other y's(lower dressing frequencies)



- Other choices for the critical dressing?
- It may help the design of the dressing coils so that we don't need to run at the high dressing frequency condition.

Simulation of the dressed spin

- Simulation of the dressed spin dynamics is underway.
- Bloch equation simulation with the 4th order of the Runge-Kutta method is used to simulate the dressed spin,

$$\frac{d\vec{S}(t)}{dt} = \vec{S}(t) \times \gamma \vec{B}(t)$$
$$\vec{B}(t) = B_0 \hat{z} + B_d \cos \omega_d t \hat{x}$$

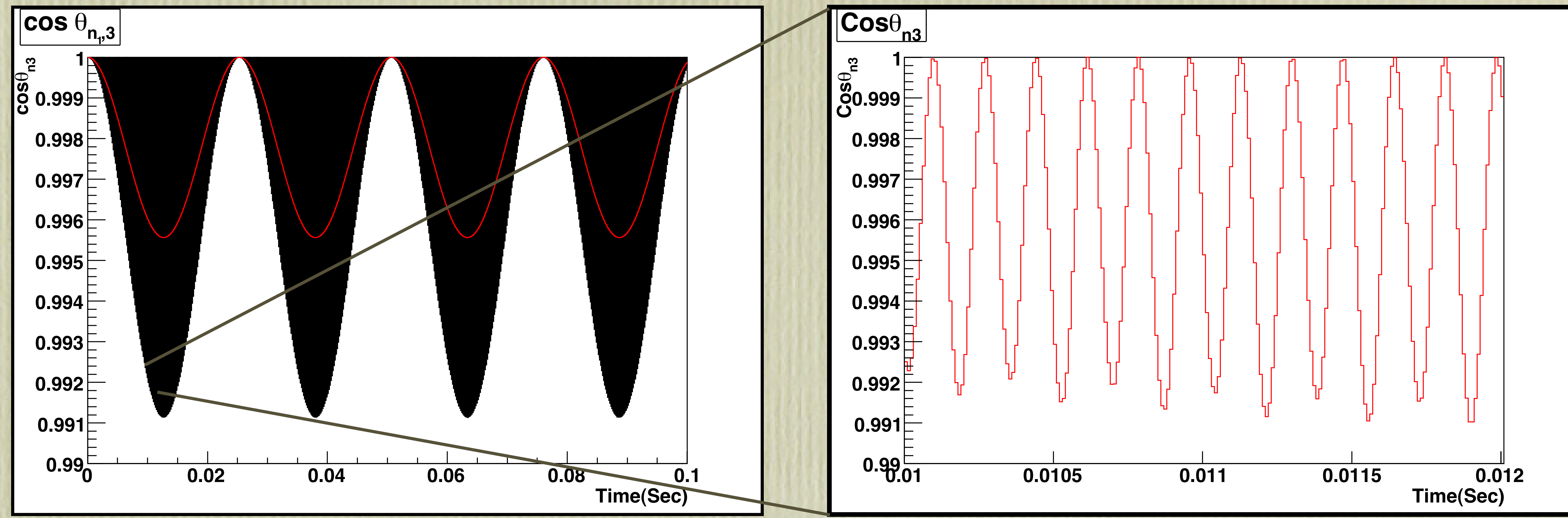
Bloch equation

- The time dependence of $\text{Cos}\theta_{n3}$, the relative angle between ^{3}He and neutron spins, is derived in Physics Report 237, 1-62(1994) as:

$$\cos\theta_{n3} = \frac{1}{2}[1 + J_0(x_n - x_3)]\cos[(\omega_n - \omega_3)t] + \frac{1}{2}[1 - J_0(x_n - x_3)]\cos[(\omega_n + \omega_3)t]$$
$$x_n = \frac{\gamma_n B_d}{\omega_d},\ x_3 = \frac{\gamma_3 B_d}{\omega_d},\ \omega_n = \gamma_n B_0 J_0(x_n),\ \omega_3 = \gamma_3 B_0 J_0(x_3)$$

- The first term of the analytical expression is a constant close to 1 at the critical dressing where $\omega_n=\omega_3$. The second term has an oscillatory pattern.

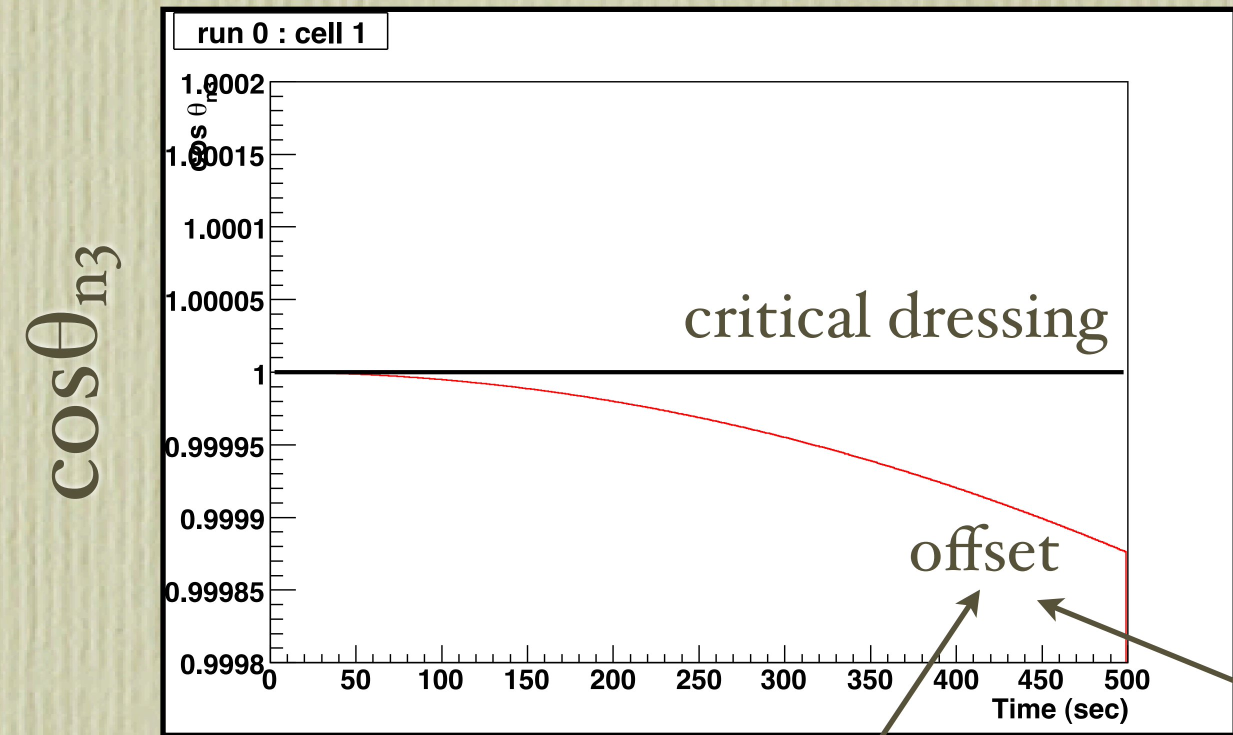
Simulation of the dressed spin

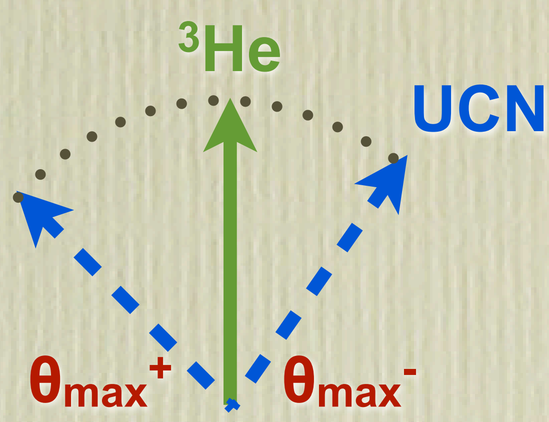


- Use the proposal values at y=0.01, x=1.189, B_0=10 mG, B_d =1189 mG, f_d=-2916.46954Hz, which is very close to the critical dressing.
- The black is the Bloch equation simulation. The red is the analytical expression, which is consistent with the time average of the simulation.
- The simulation also shows an additional oscillatory pattern at the dressing frequency and visualize the spin dynamics.

http://www.youtube.com/watch?v=xBL_jDjtojc

Idea of the feedback

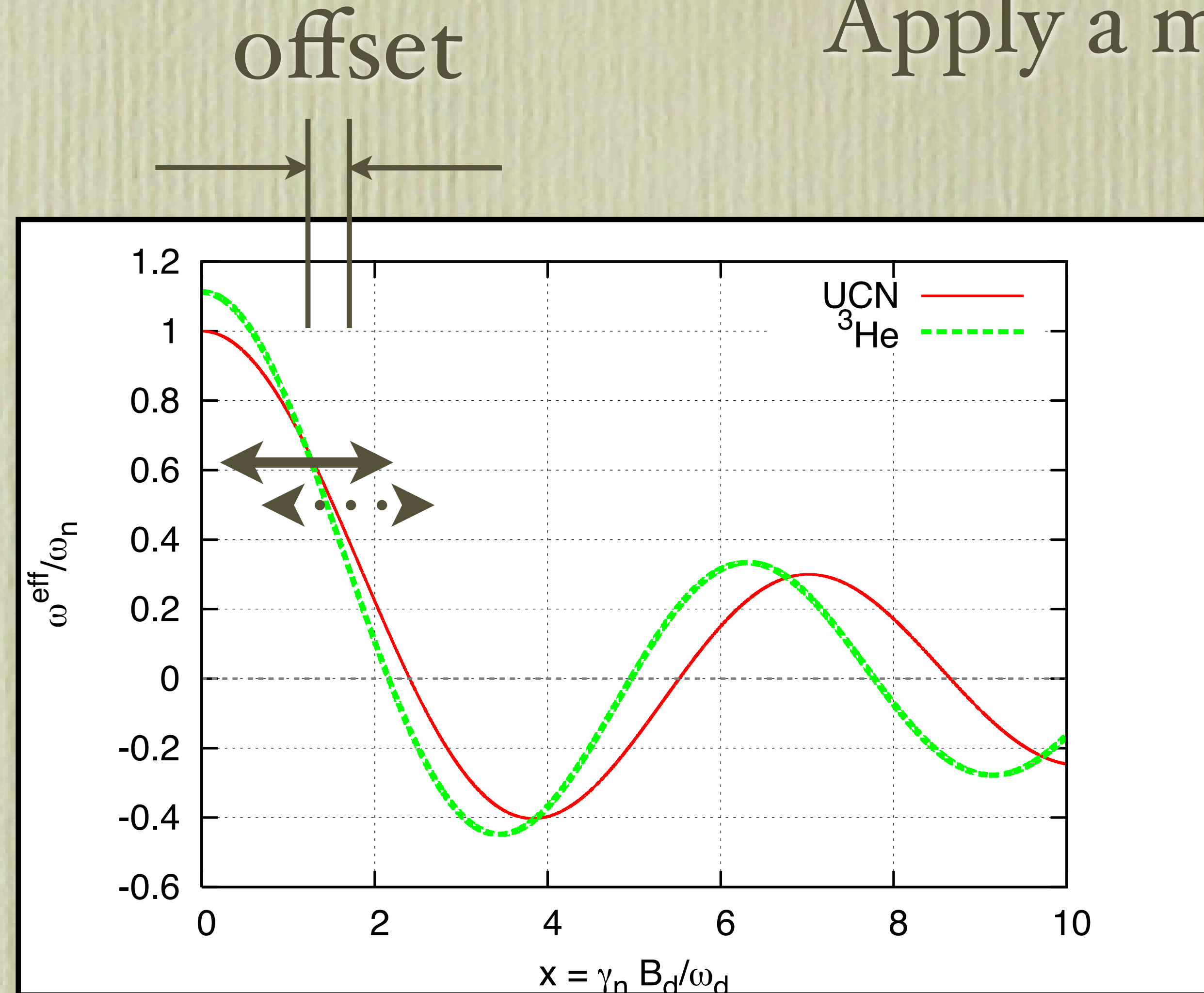




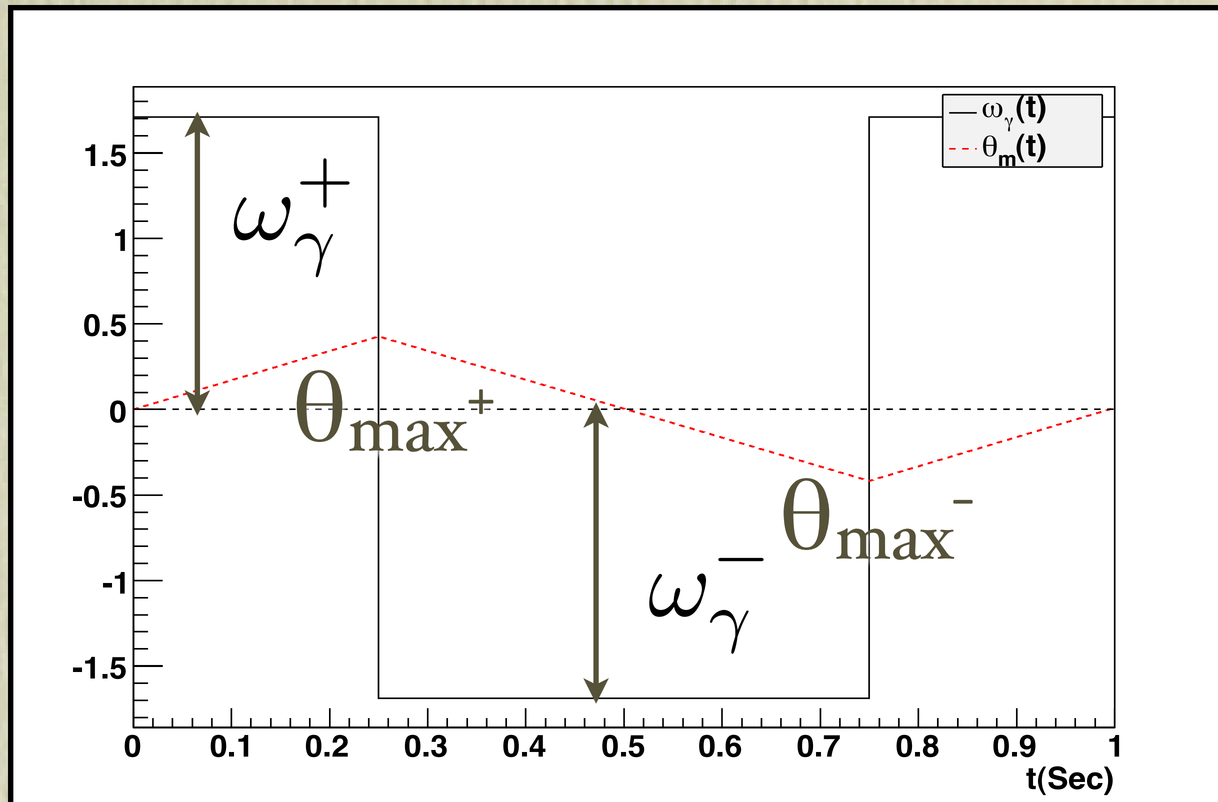
$$\cos\theta_{n3} \approx \frac{1}{2}[1 + J_0(\Delta x + x_n - x_3)]\cos[(\Delta\omega + \omega_n - \omega_3)t]$$

- If the dressing field deviates from the critical dressing, $\cos\theta_{n3}$ will have time dependence which will mix with the EDM signal.
- Apply a **feedback** to compensate the offset, initially proposed by Golub and Lamoreaux in 1994.
- Add a modulation to vary the angle between neutron and ^{3}He. Any difference between modulation angles in opposite directions (the scintillation light) will be the input to the feedback.

Apply a modulation

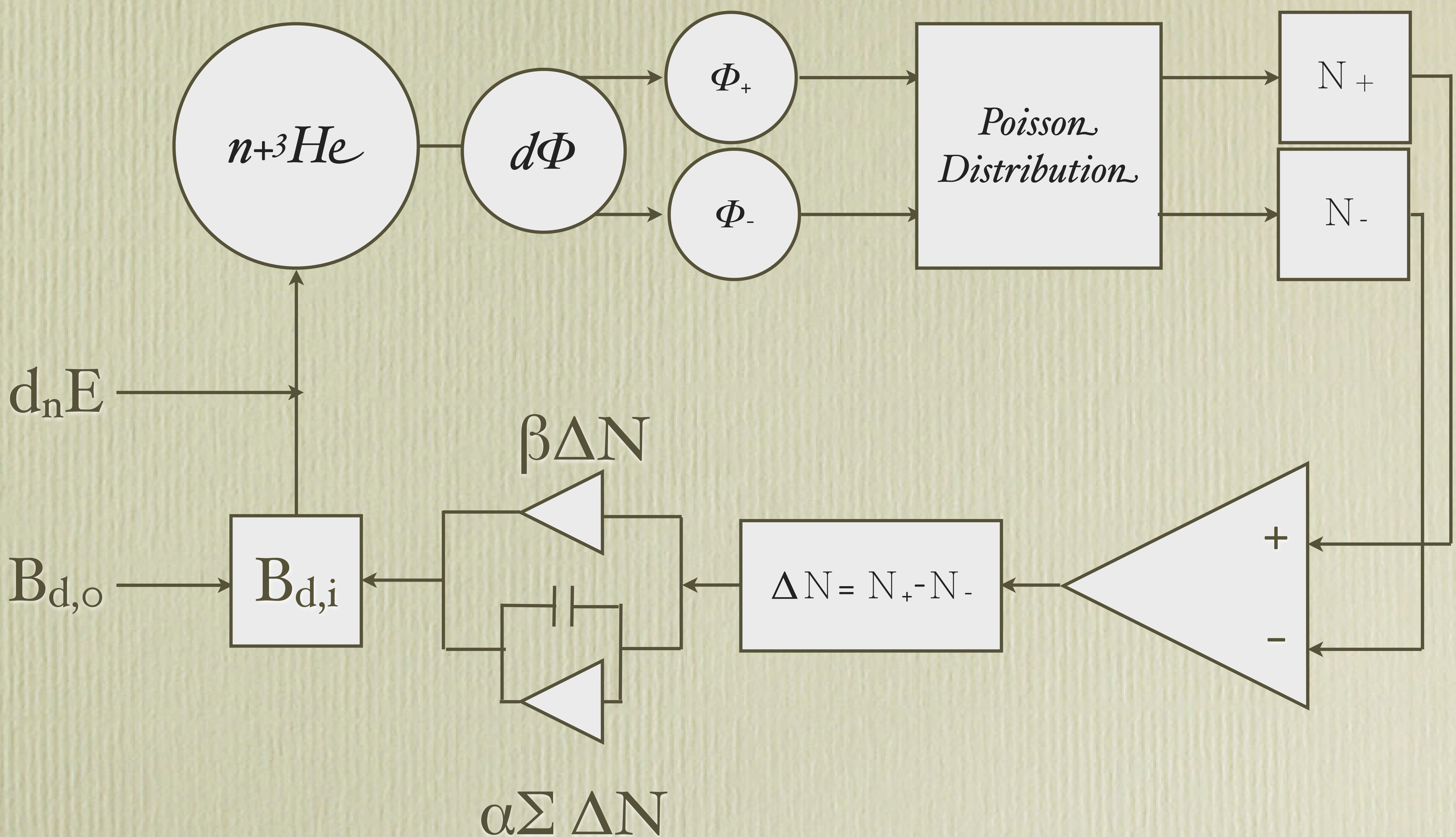


$$\omega_\gamma^\pm = \omega_0[J_0(x_c \pm x_m) - aJ_0(a(x_c \pm x_m))]$$

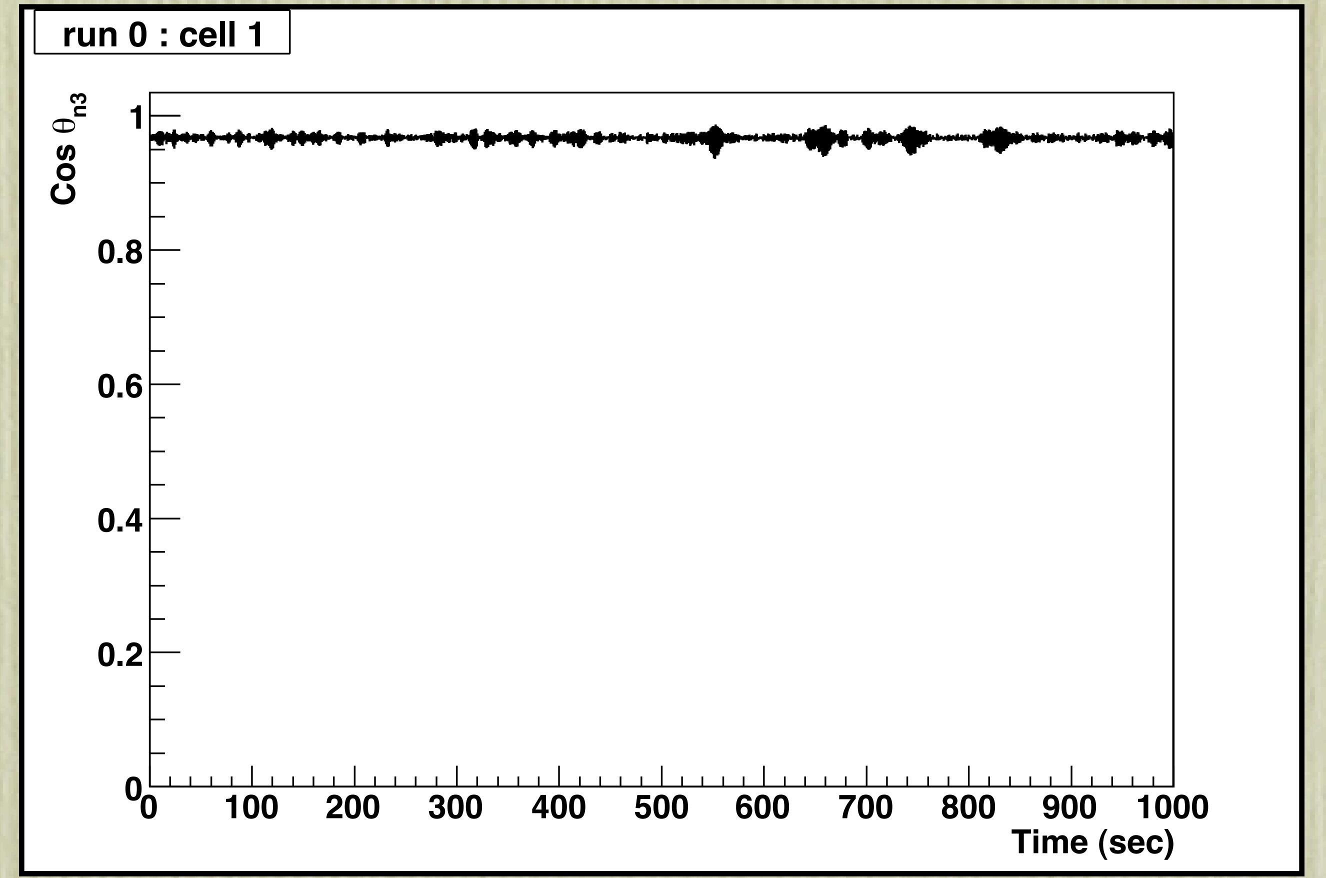


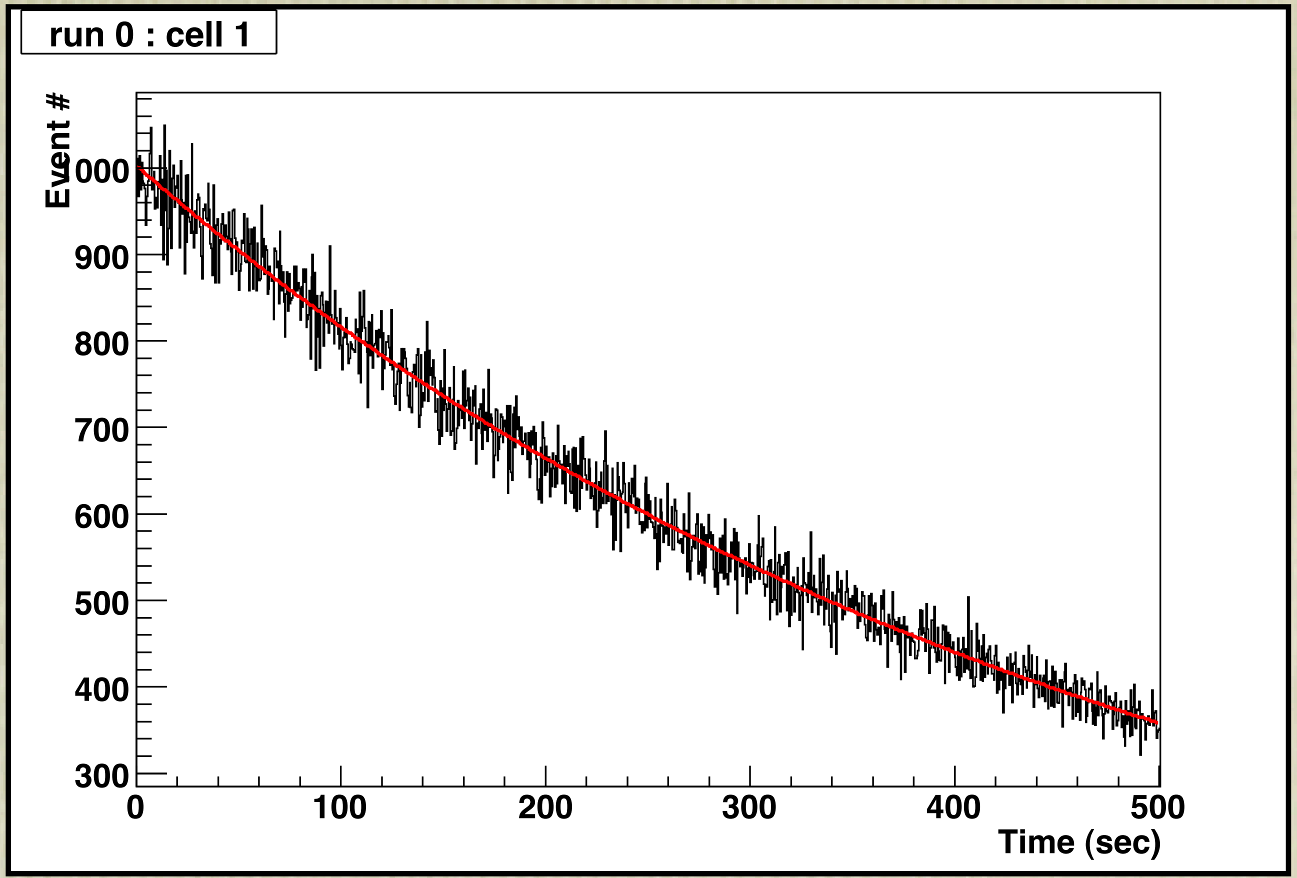
- Add a modulation on the dressing field so that $x_c \rightarrow x_c \pm x_m$
- The relative angle between neutron and ^{3}He is varied between θ_{max}^+ and θ_{max}^-. $\theta_{max}^+ = \theta_{max}^-$ at the critical dressing.
- Any offset will cause difference in θ_{max}^+ and θ_{max}^-.
- Measure the scintillation light difference in opposite modulation directions.

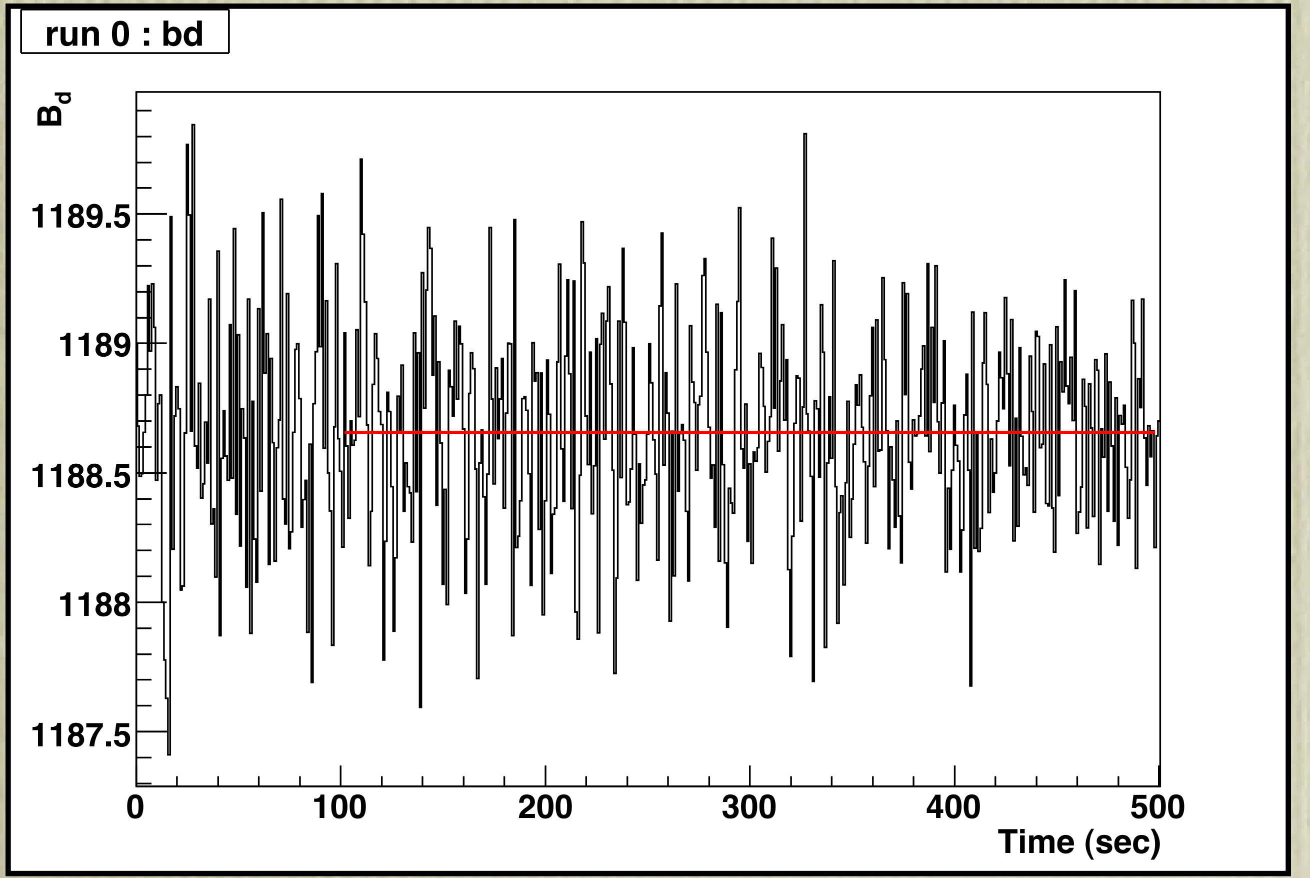
Schematic of feedback loop



Monte Carlo for the feedback loop





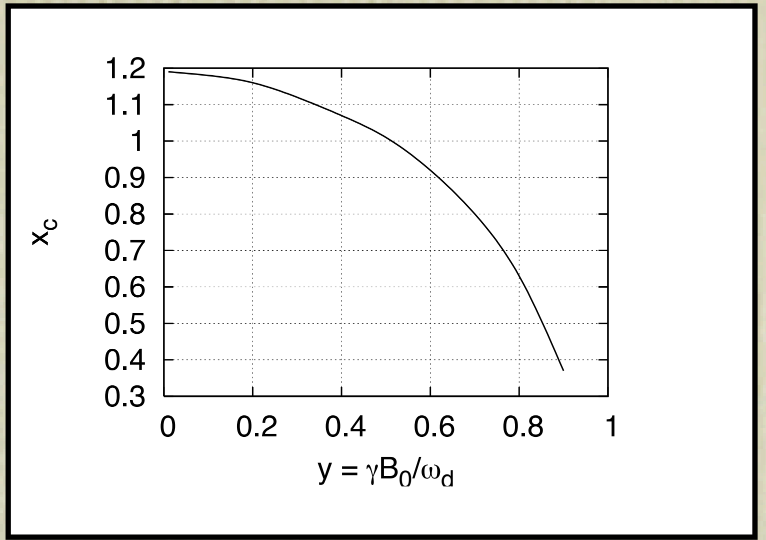


- $\cos\theta_{n3}$ is kept at a constant.
- The signal is kept at the critical dressing.
- Relate the EDM effective field to $B_{d,\,fit}$.
- The feedback can be only applied in a single measurement cell in the SNS experiment(since both two cells share the same dressing coils).
- Many parameters remain to be optimized

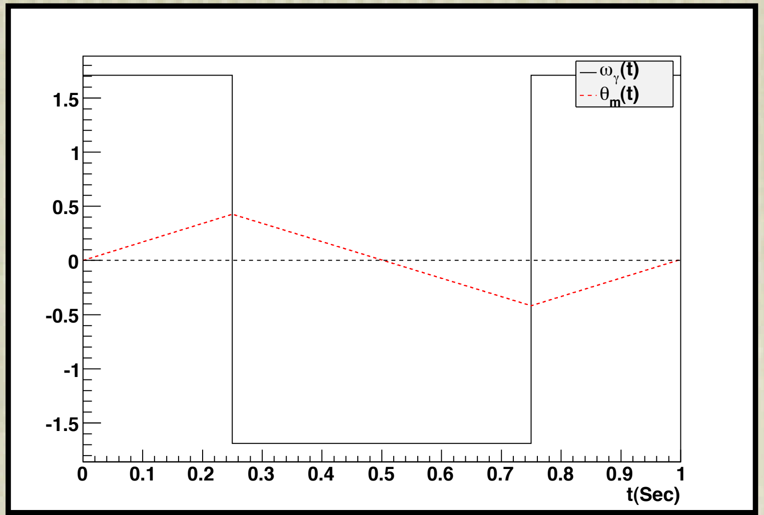
Parameters for dressing/modulation/feedback

- Several parameters should be considered and optimized.

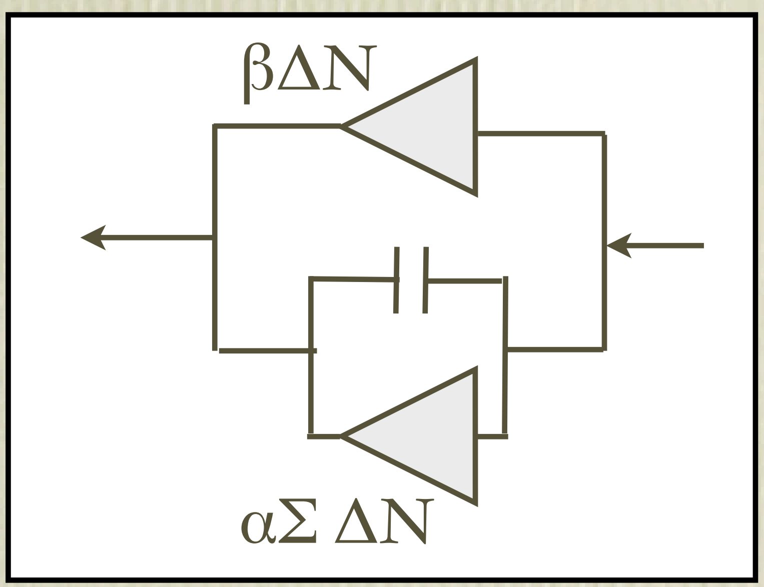
  - x and y are discussed in the dressed spin study. There are critical points for different y's.



  - Modulation amplitude B_m and period τ_m should be carefully determined since it is related to the input signal.



  - The feedback parameters α and β are important for the feedback loop to succeed.



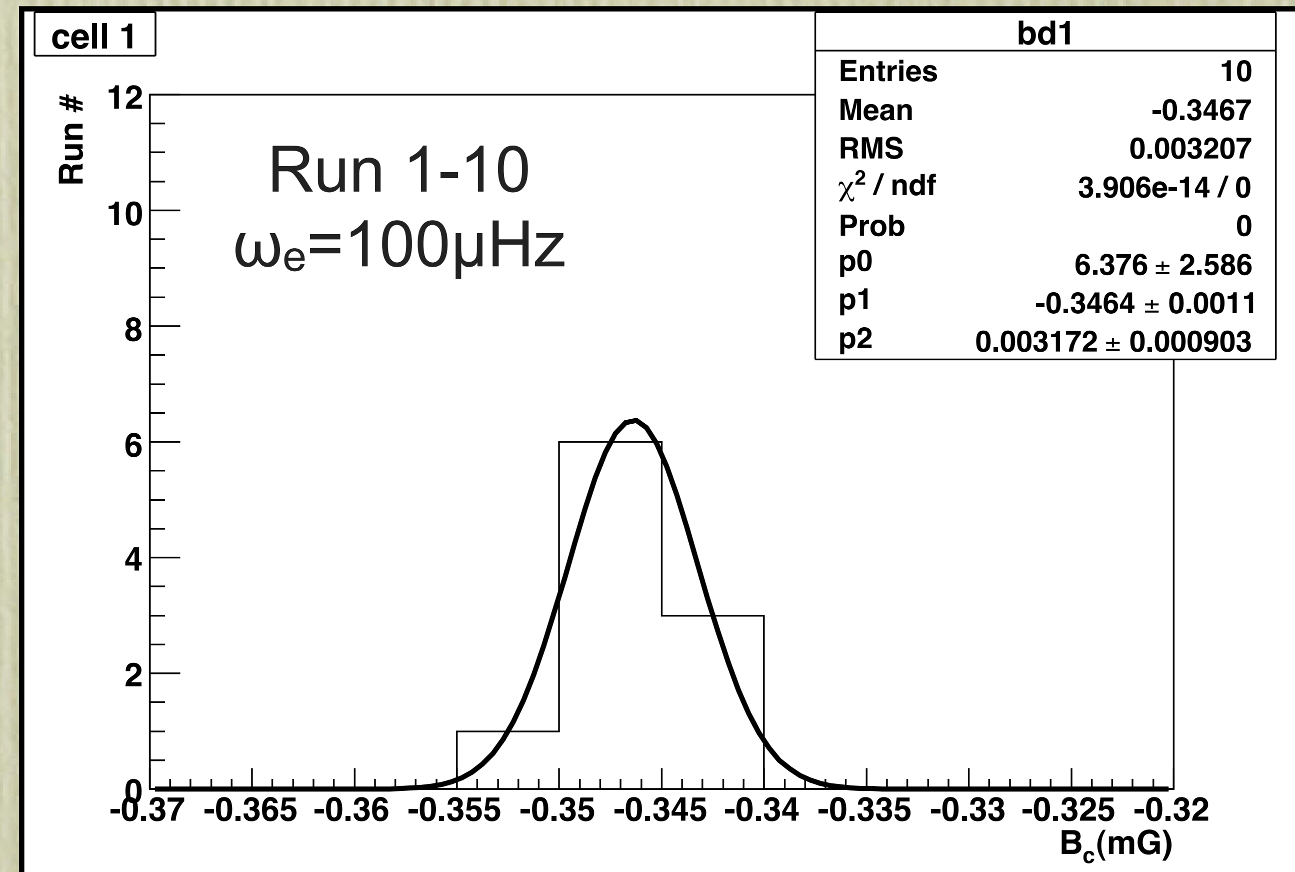
- The optimization is still ongoing.

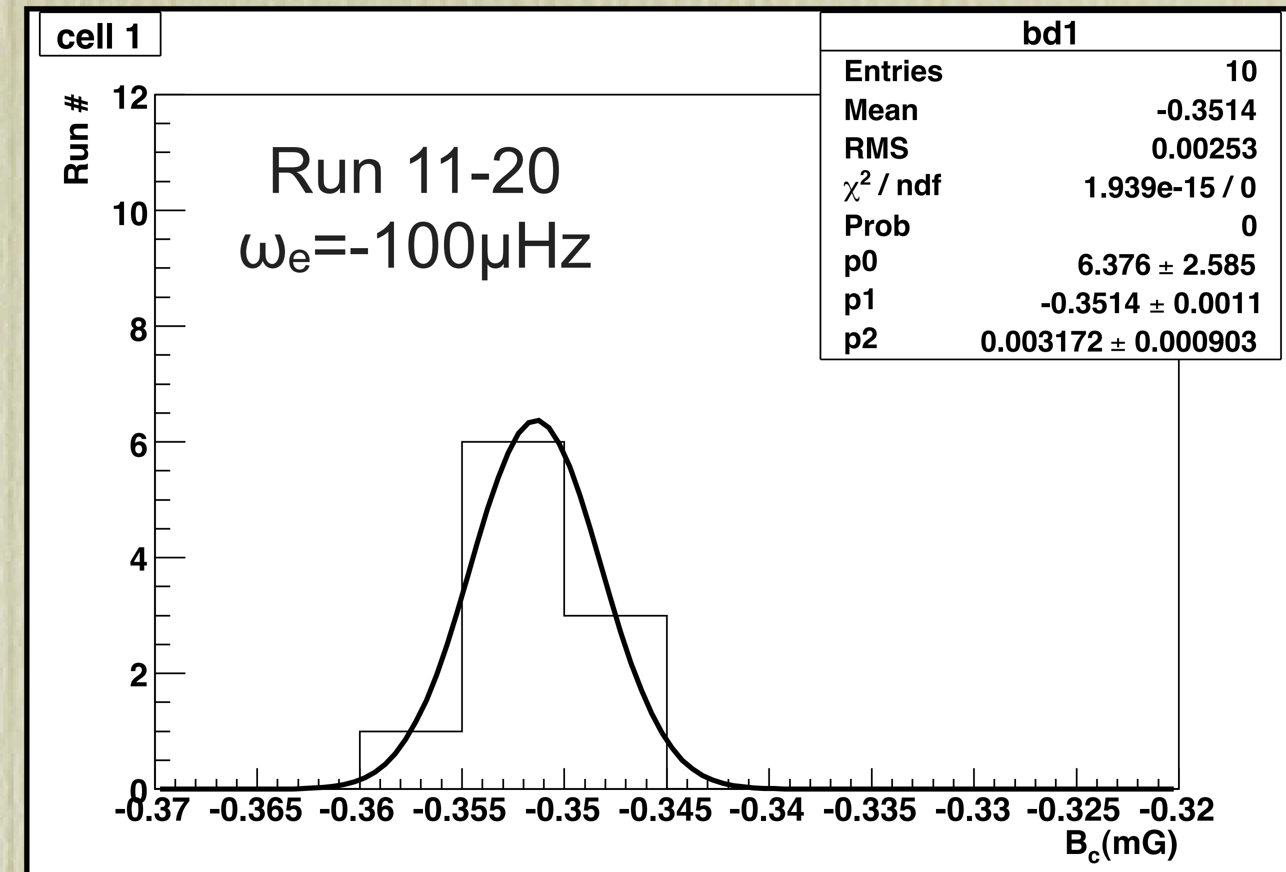
Summary

- Neutron EDM is a powerful tool searching for physics beyond SM.
- The goal of next generation experiments is to reach the sensitivity at 10^{-28} e cm.
- A new neutron EDM experiment uses ultracold neutron produced in superfluid ^4He, with ^3He as a spin analyzer and a comagnetometer. The dressed spin technique will be applied to reduce the systematic uncertainty.
- The dressed spin phenomena have been studied over a broad range of dressing field configuration in UIUC. The observed effects are compared with calculations based on quantum optics formalism
- The optimal implementation of the dressed spin technique for the neutron EDM experiment is still ongoing.

Back-up slides

Monte Carlo for the feedback loop





- Apply an electric field in different direction for different runs. Assume ω_e=100μHz.
- The correction field $B_c = B_{d,fit} - B_{d,0}$ for Run1-10 is -0.3467mG and for Run 11-20 is -03514mG, which include both the offset and the EDM effective field. Thus ΔB_c =0.0047 mG.
- Use the relation between the correction field and the EDM effective field:

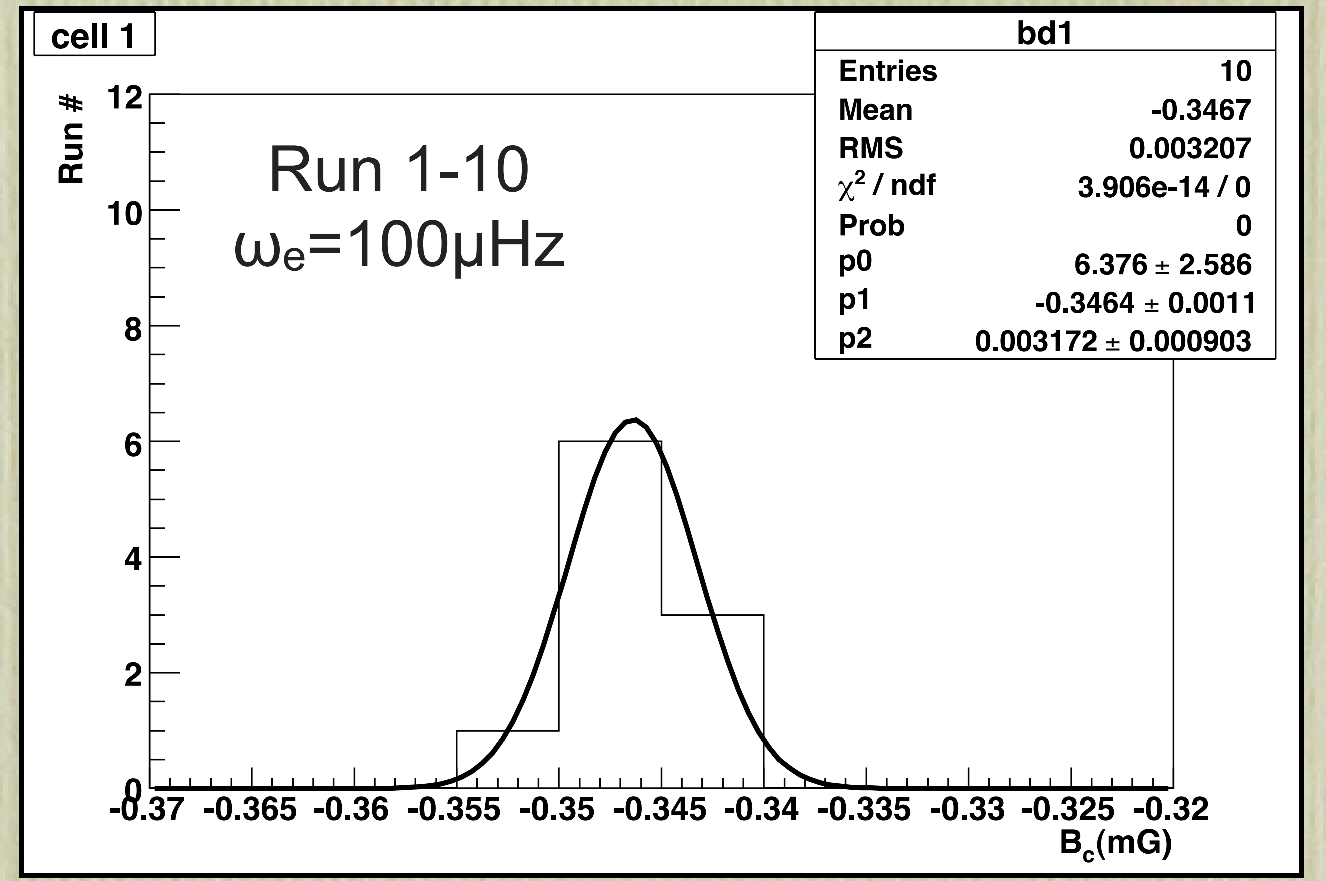
$$\Delta\omega_\gamma = \omega_0[J_0(x_c+\Delta x) - \gamma_3/\gamma_n J_0(\gamma_3/\gamma_n(x_c+\Delta x))]$$

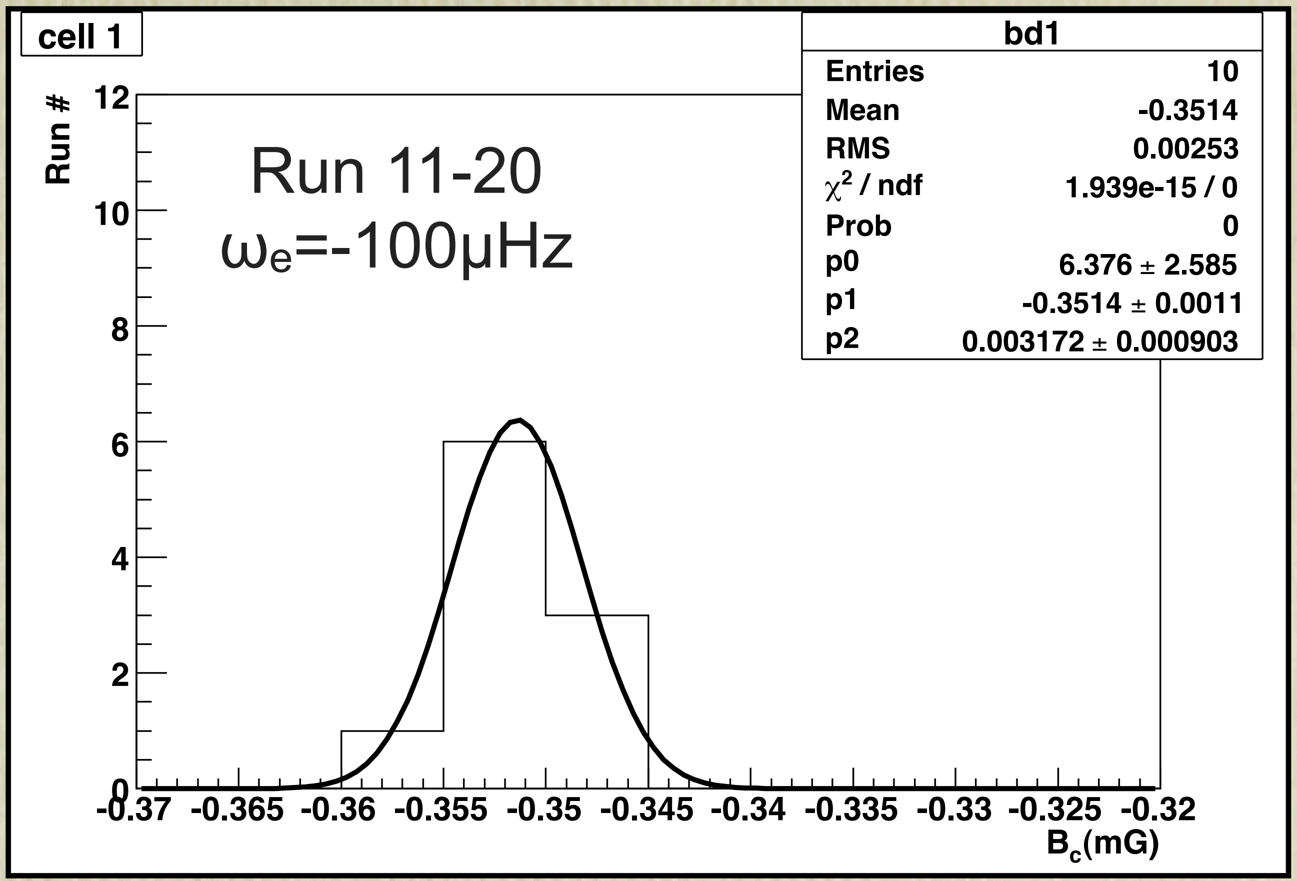
$$= 0.156077\omega_n \Delta x = 0.156077\omega_n \frac{\gamma_n B_c}{\omega_d} = -0.0286007 B_c = \omega_e J_0(x_c)$$

$$\omega_e = -0.0422713 B_c$$

$\boxed{\Delta\omega_e = 198.675\mu\text{Hz}}$

Sensitivity of the feedback method

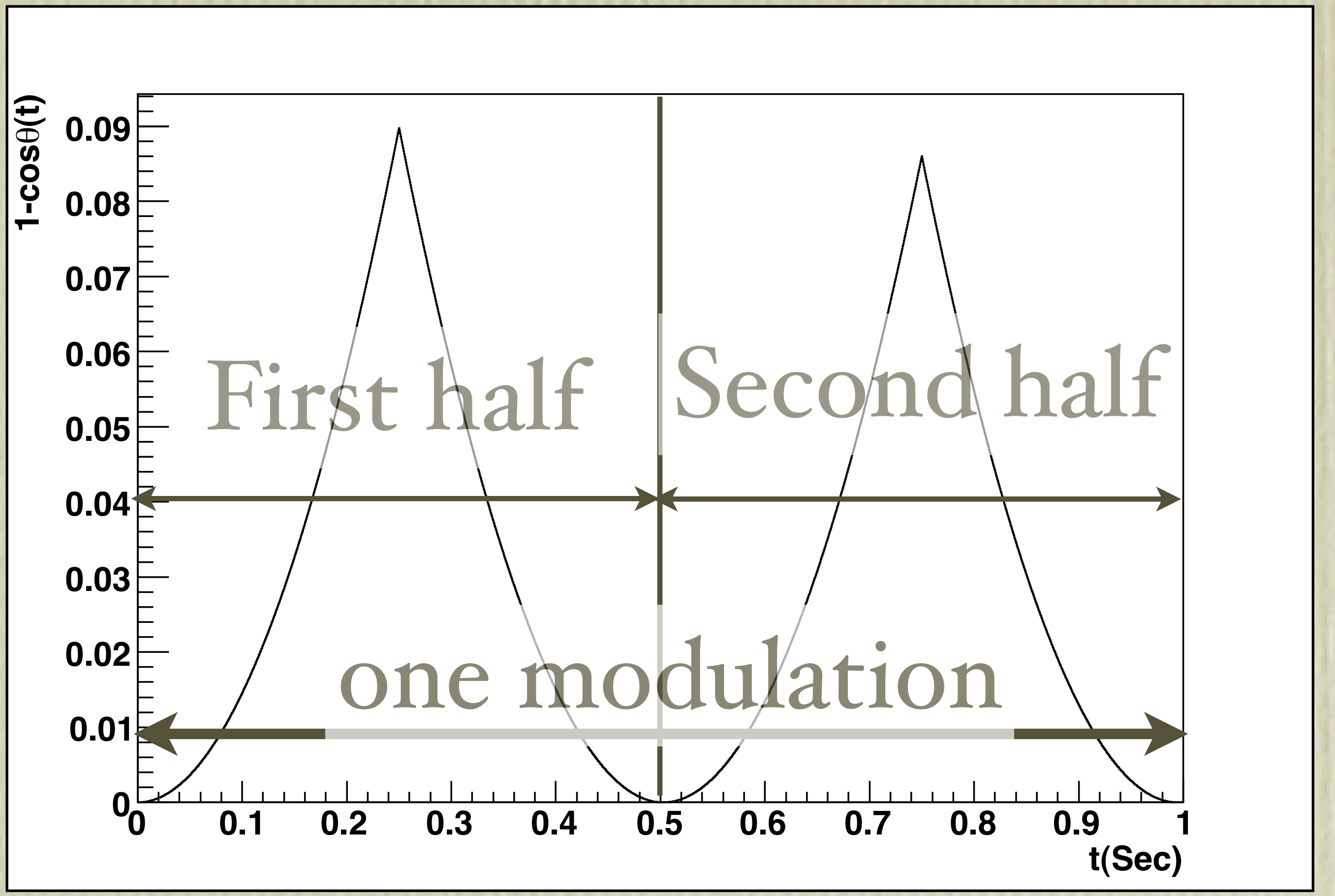




- The RMS for 20 runs is 0.0028884 mG.
- Thus, the sensitivity for the EDM is σ_{fe} = 19.4323μHz.
- Comparing with the case without the dressing field which is around 2.7μHz, the feedback method still needs optimization(x and y, modulation parameters, feedback parameters,etc.).

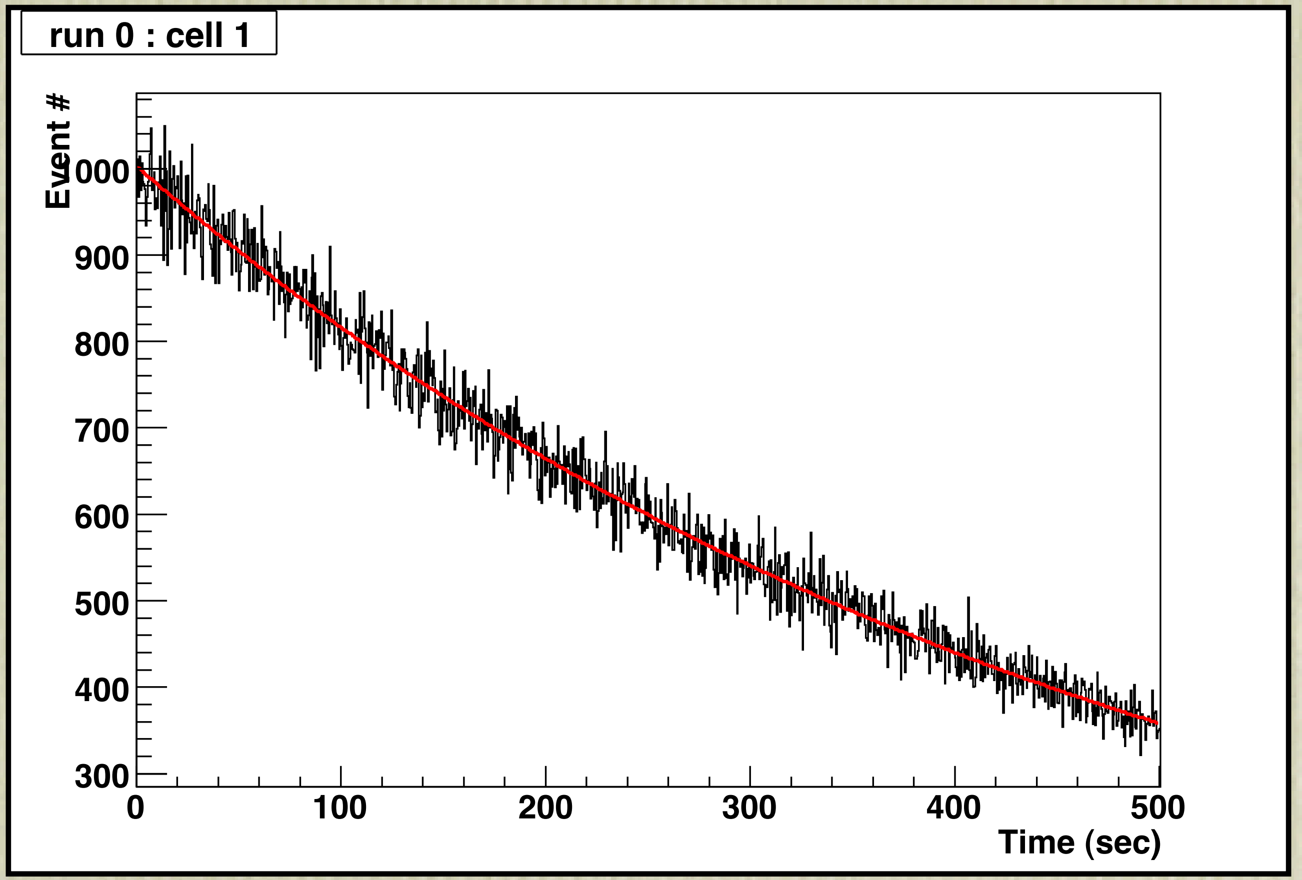
Modulation signal

The distribution function = $(d\varphi/dt)/N_0$ depends on $1\text{-}\cos\theta_{n3}$.



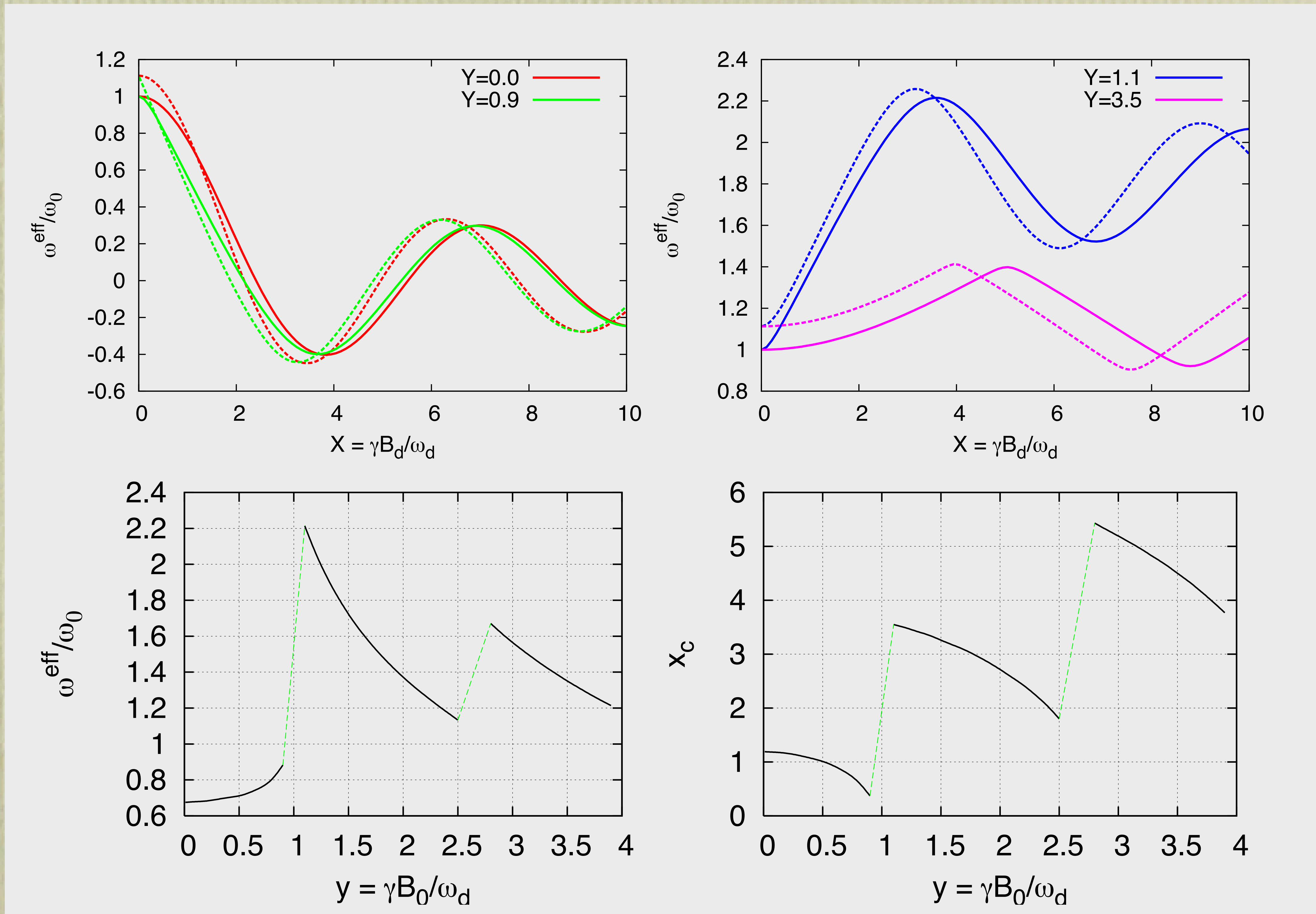
- The scintillation light rate is $\dfrac{d\phi(t)}{dt} = N_0 e^{-\Gamma_{tot} t}\left[\dfrac{1}{\tau_\beta} + \dfrac{1}{\tau_3}(1 - P_3 P_n \cos(\theta_{n3}))\right]$
- The counts in the **first half** and the **second half** of a modulation cycle should be *identical* at the critical dressing.
- The difference in the counts will be the input to the feedback.

Monte Carlo for the feedback loop



- Example of the simulation for the scintillation events with modulation/feedback scheme.
- many parameters remain to be optimized

Critical dressing for other y's(lower dressing frequencies)



- Other choices for the critical dressing. Consider the possibility once we realize the dressed spin technique. It may help to the design of the dressing coils so that we don't need to run at the high dressing frequency condition.

Apply a modulation

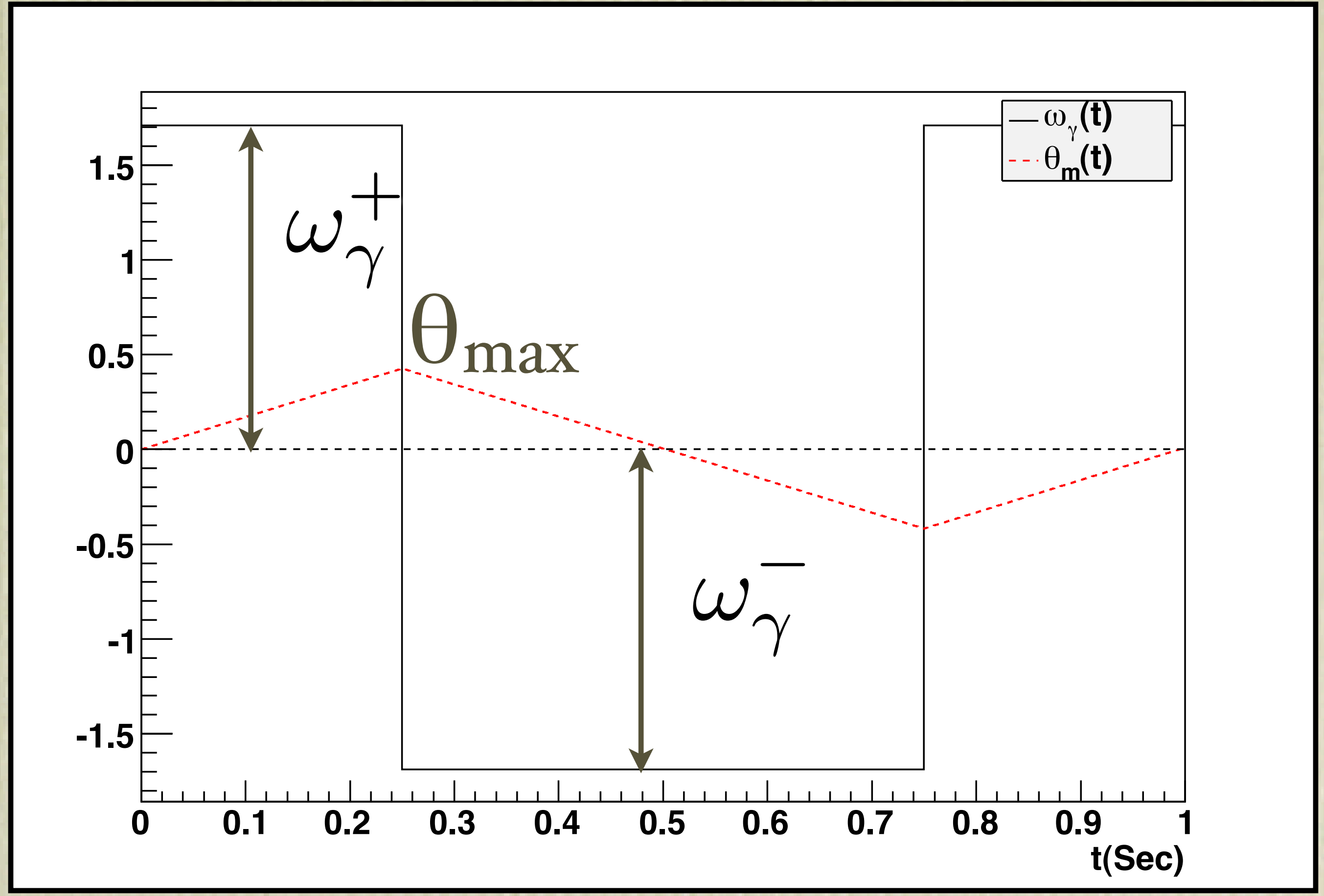
- At the critical dressing, no signal from the ^3He capture. Add a modulation.
- The relative precession frequency between neutron and ^3He at the critical dressing is

$$\omega_\gamma = \omega_0[J_0(x_c) - aJ_0(a(x_c))] = 0$$

- Apply a **cos square modulation** onto the dressing field such as

$$B_d(t) = [B_{d,c} + B_m Sign(\cos(\omega_m t))] \cos \omega_d t$$

$$x = x_c \pm x_m$$



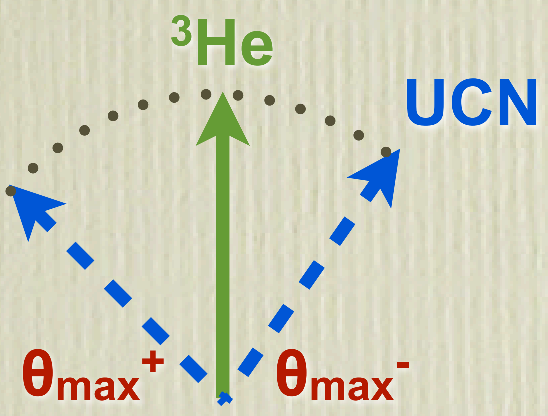
- The **relative precession frequency** becomes

$$\omega_\gamma^\pm = \omega_0[J_0(x_c \pm x_m) - aJ_0(a(x_c \pm x_m))]$$

- The maximum **relative angle** becomes

$$\theta_{max}^\pm = \omega_\gamma^\pm \tau_m / 4$$

- The result can be also simulated by using Bloch equation.

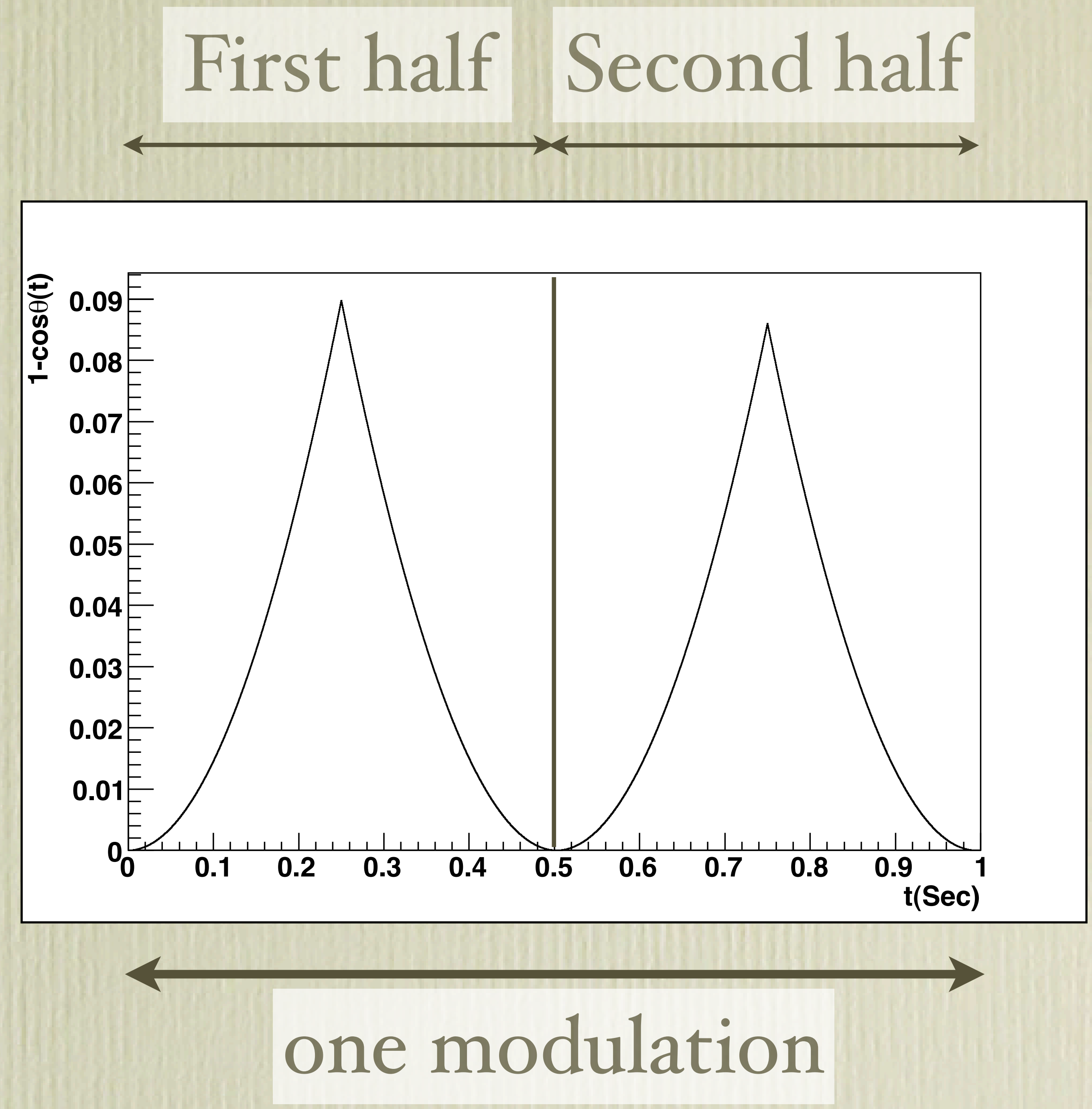


Apply the feedback loop

- The scintillation light is

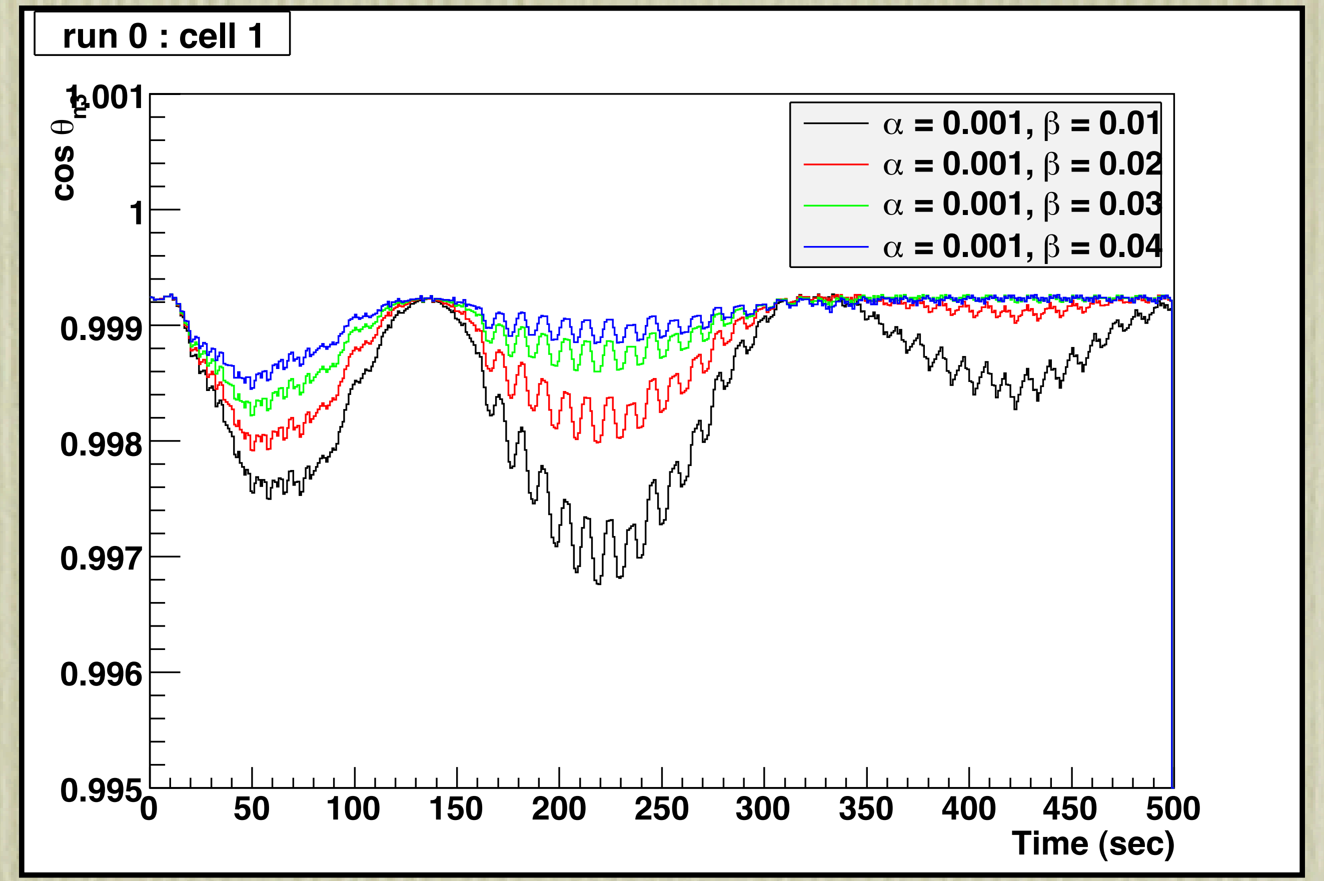
$$\frac{d\phi(t)}{dt} = N_0 e^{-\Gamma_{tot}t}[\frac{1}{\tau_\beta} + \frac{1}{\tau_3}(1 - P_3 P_n \cos(\theta_{n3}))]$$

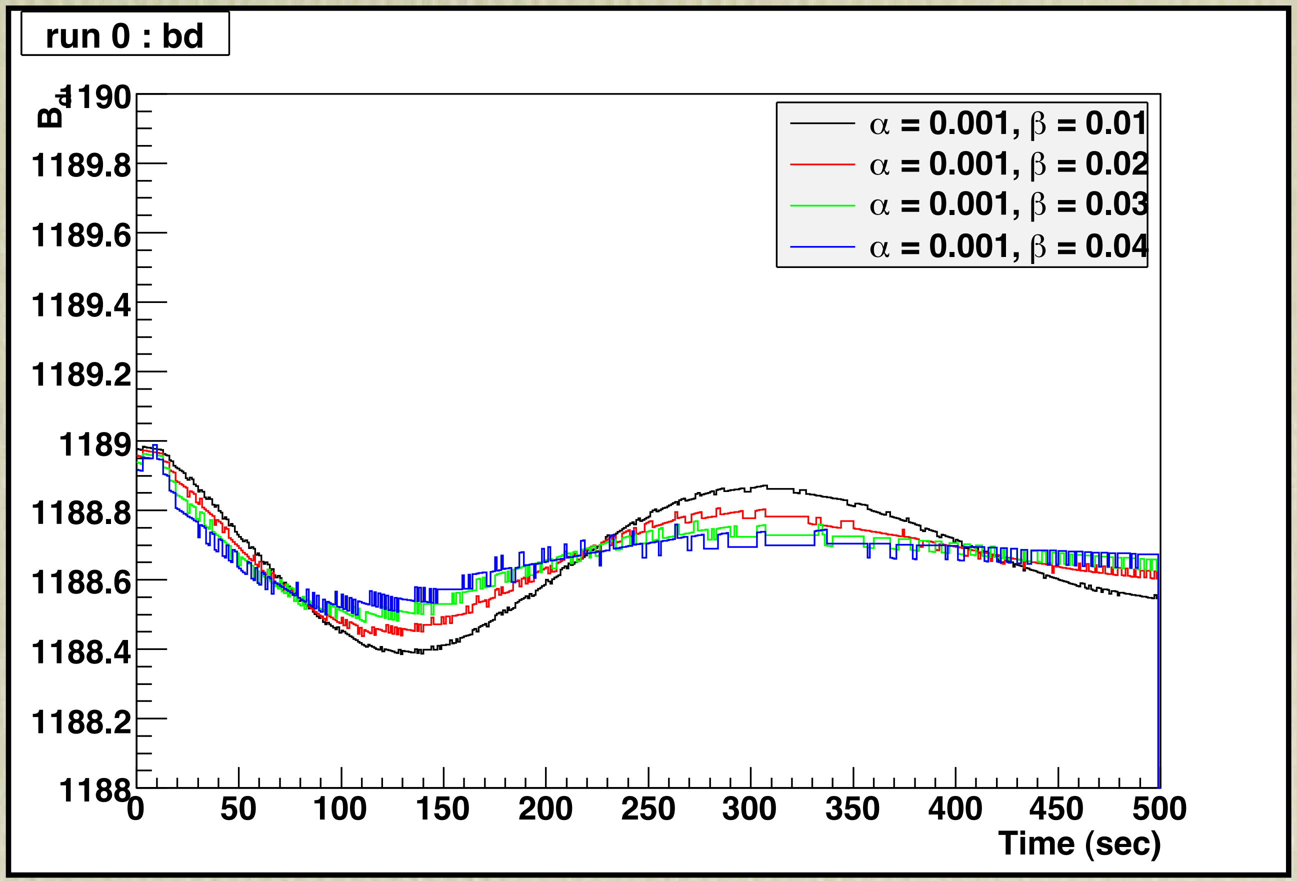
- The total light in the **first half** and the **second half** modulation should be *identical* at the critical dressing.
- The difference of the light in two periods will be the input of the feedback loop.
- The difference may come from **the offset of the dressing field** or **the EDM effective field.**
- The correction field can compensate the offset or the EDM effective field. Thus, the EDM can be obtained from **the correction field** in different runs.



The distribution function = $(d\varphi/dt)/N_0$ depends on $1\text{-}\cos\theta_{n3}$.

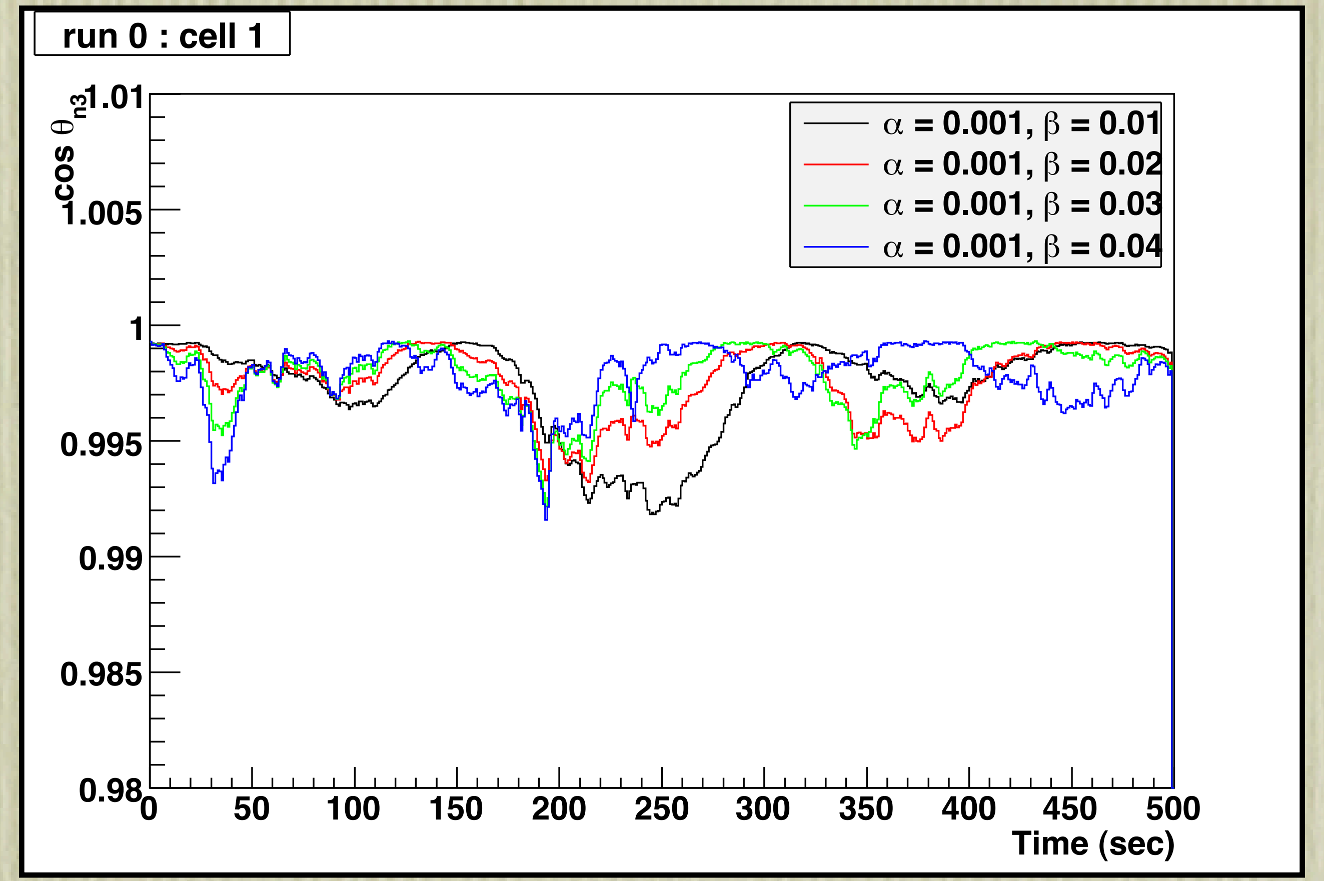
Simulation of modulation/feedback

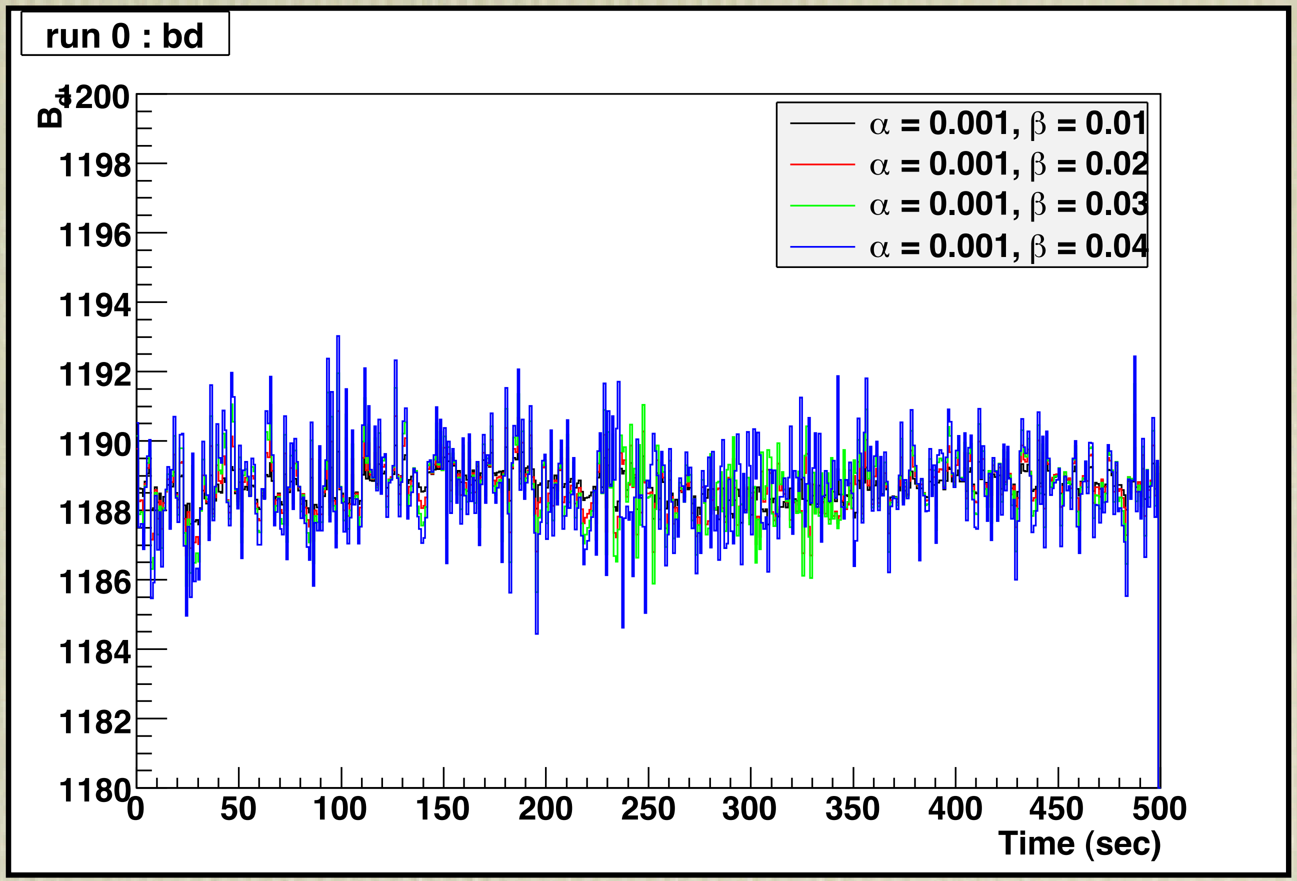




- One example *without* fluctuation with different α and β. Set x=1.189, $B_m/B_d = 0.05$ and f_m=1 Hz.
- $\cos\theta_{n3}$ can be tuned to be a constant.
- The system can be tuned to be the critical dressing.
- The feedback can be only applied in a single measurement cell in the SNS experiment(since both two cells share the same dressing coils).

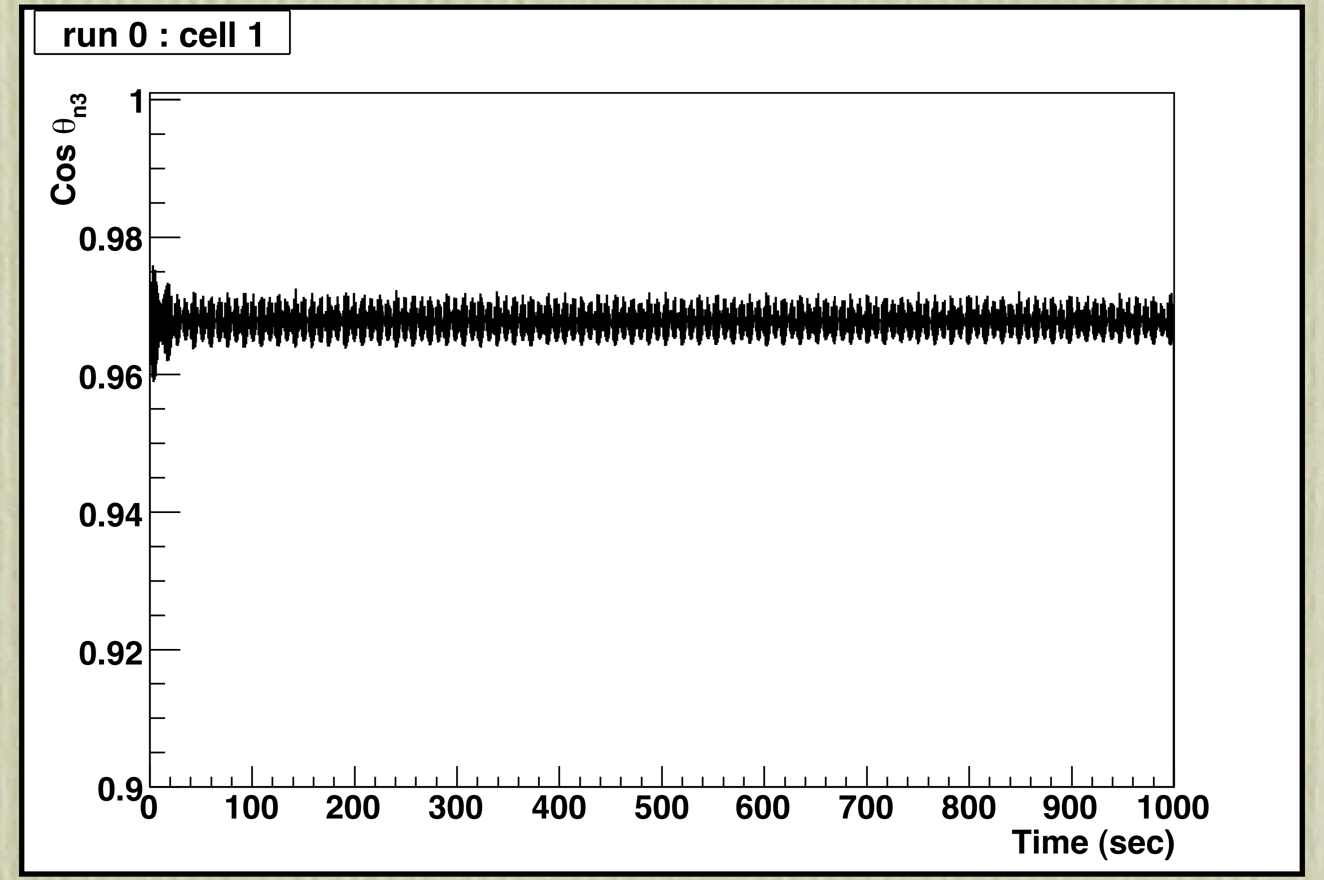
Monte Carlo for the feedback loop

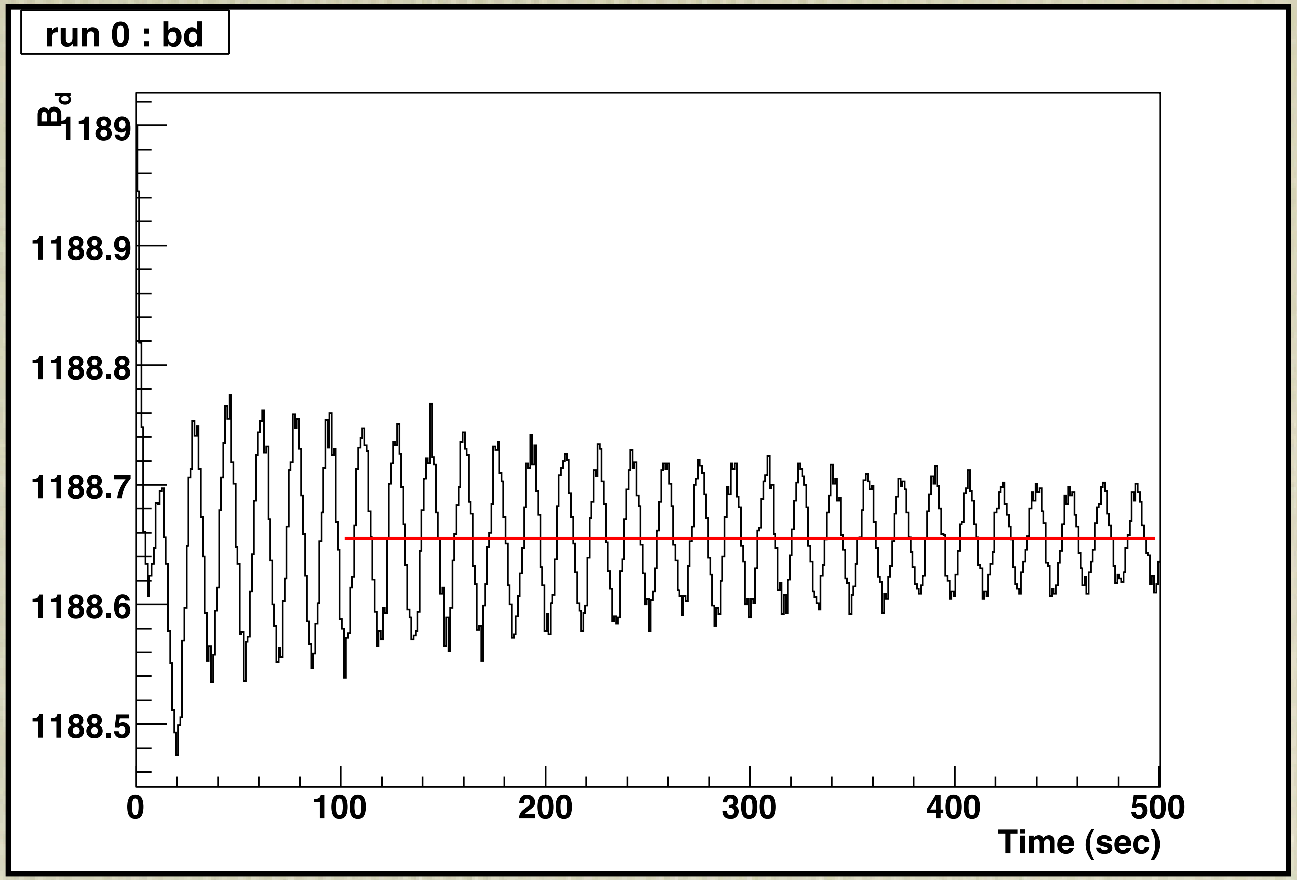




- One example *with* fluctuation with different α and β. Set x=1.189, B_m/B_d = 0.05 and f_m=1 sec.
- $\text{Cos}\theta_{n3}$ is (roughly) kept at a constant.
- Fit the dressing field *within* the final range. We use the time window t=100-500 sec.
- Relate the EDM effective field to $B_{d,\,fit}$.

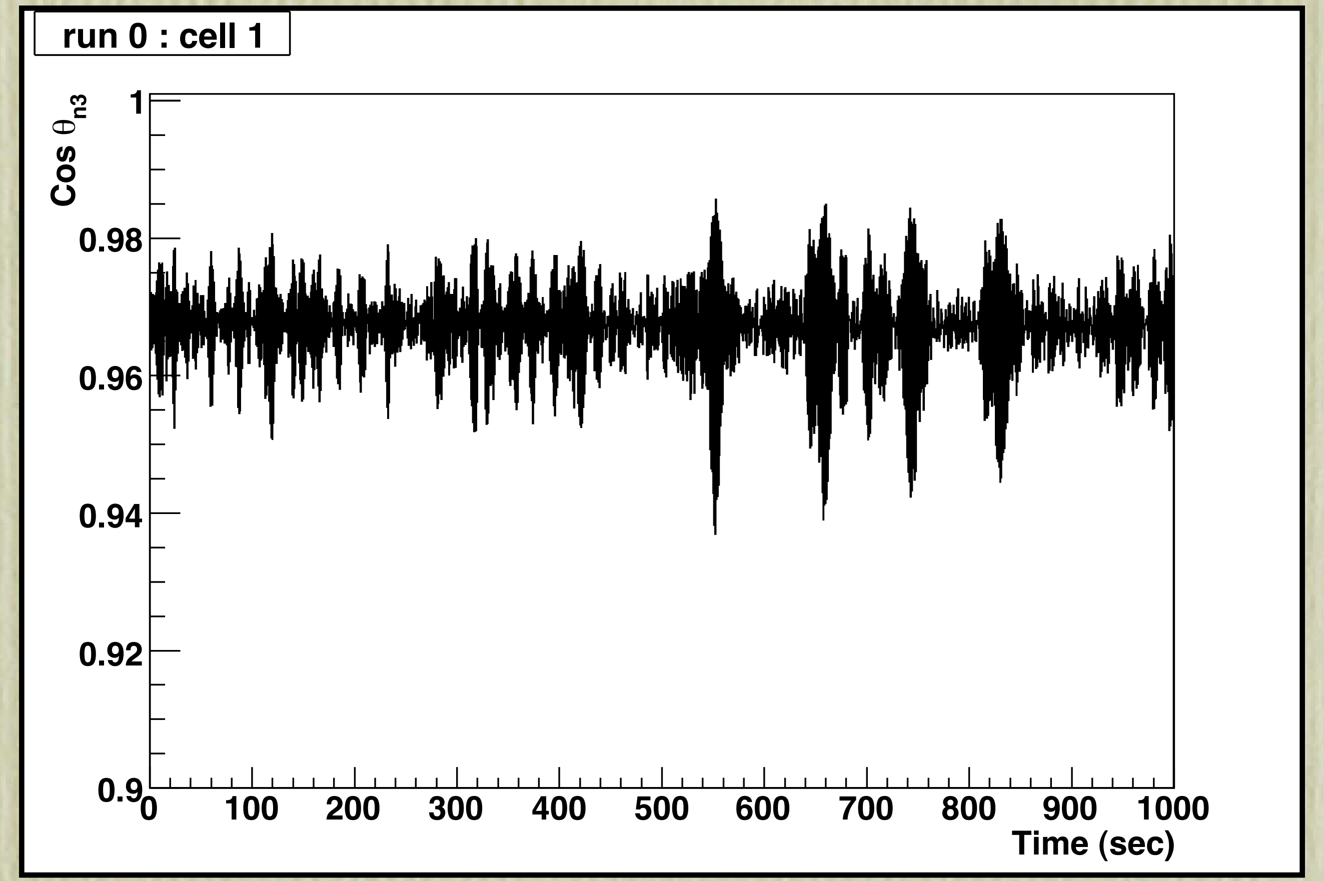
Simulation for the feedback loop

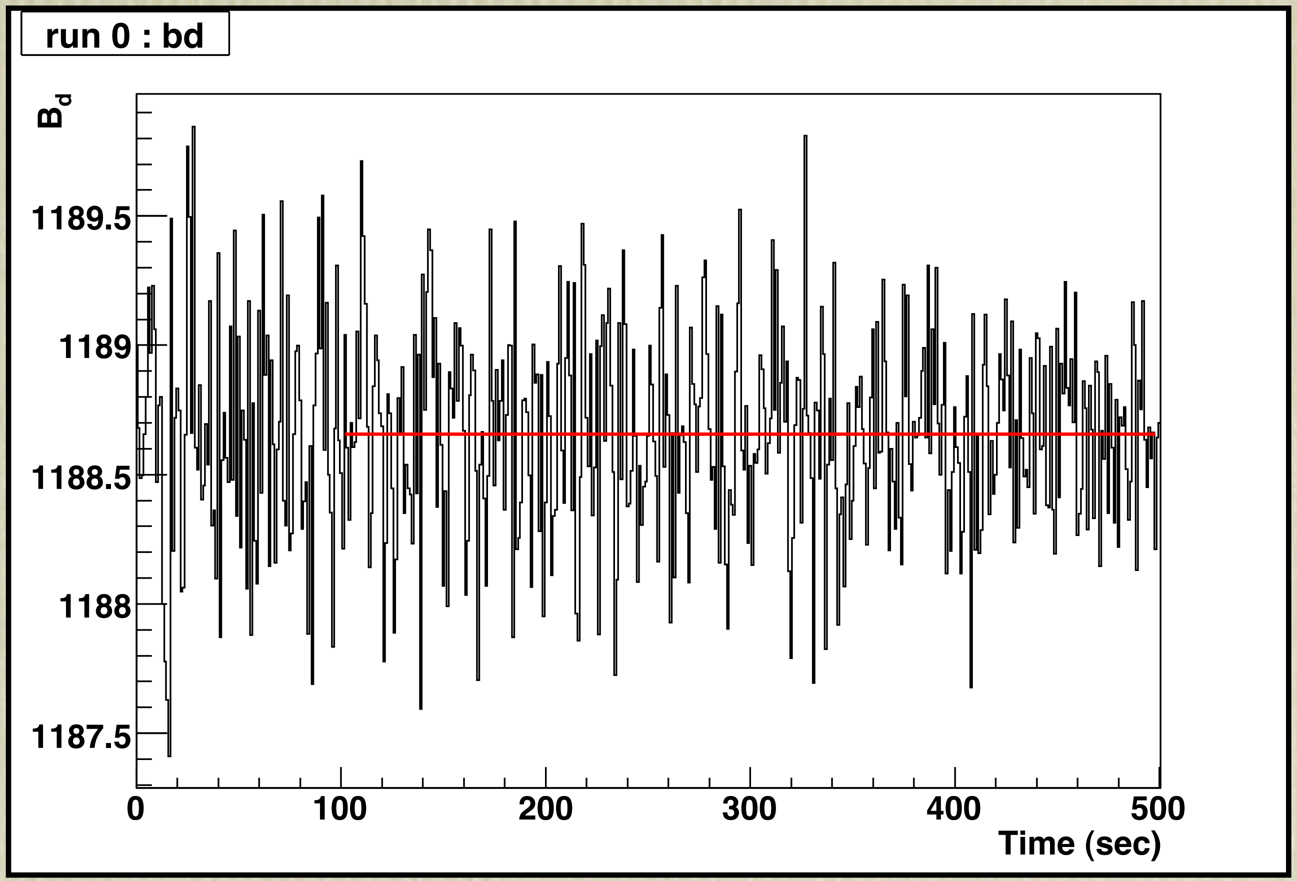




- One example *without* fluctuation with α=0.001 and β=0.01. Set x=1.189, B_d = 1189 mG, B_m/B_d = 0.05 and f_m=1 Hz.
- $\cos\theta_{n3}$ can be tuned to be a constant.
- The system can be tuned to be the critical dressing.
- The feedback can be only applied in a single measurement cell in the SNS experiment(since both two cells share the same dressing coils).

Monte Carlo for the feedback loop



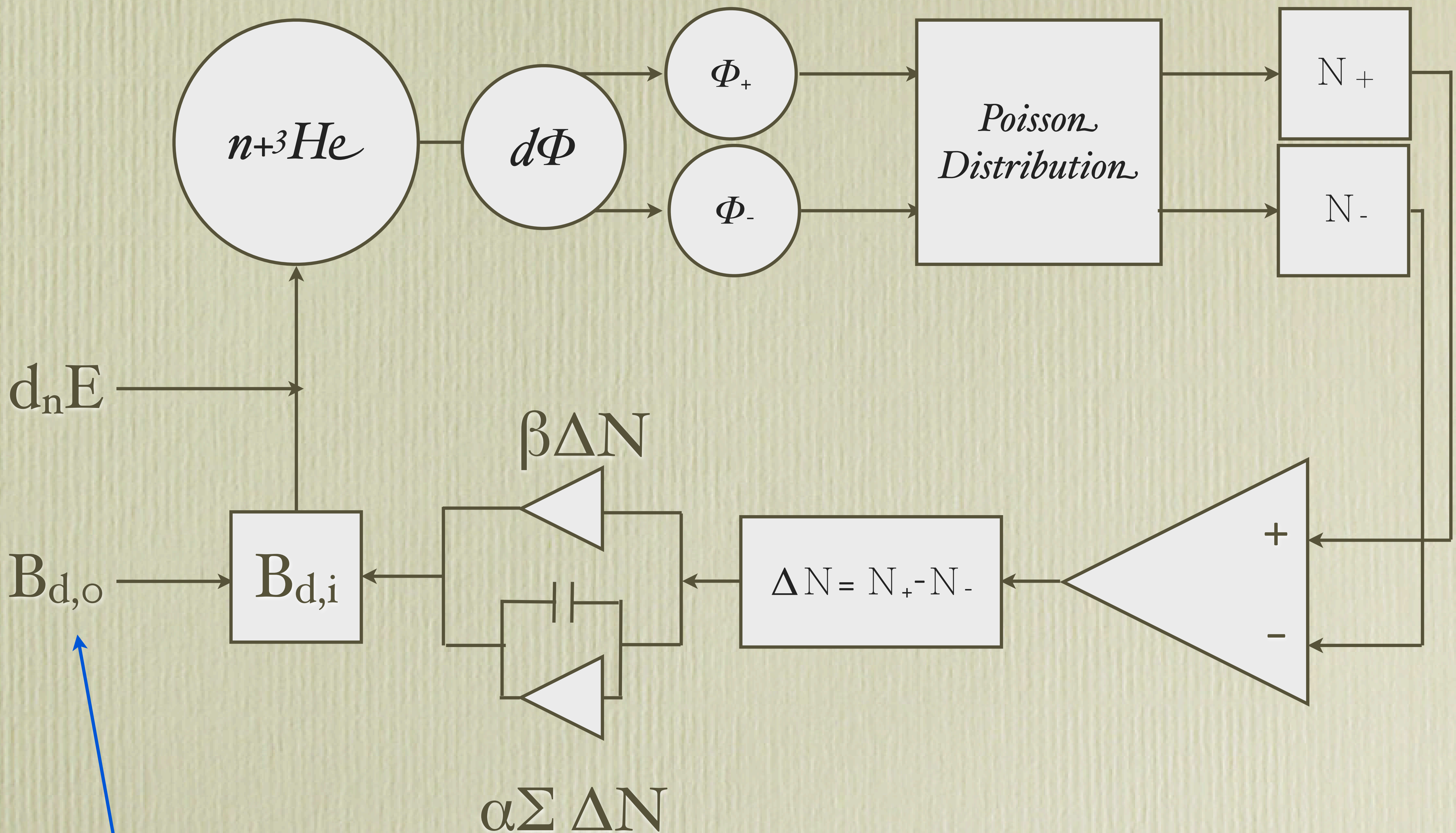


- One example *with* fluctuation with different α and β. Set x=1.189, B_m/B_d = 0.05 and f_m=1 sec.
- $\cos\theta_{n3}$ is (roughly) kept at a constant.
- Fit the dressing field *within* the final range. We use the time window t=100-500 sec.
- Relate the EDM effective field to $B_{d,\ fit}$.

Simulation of the dressed spin

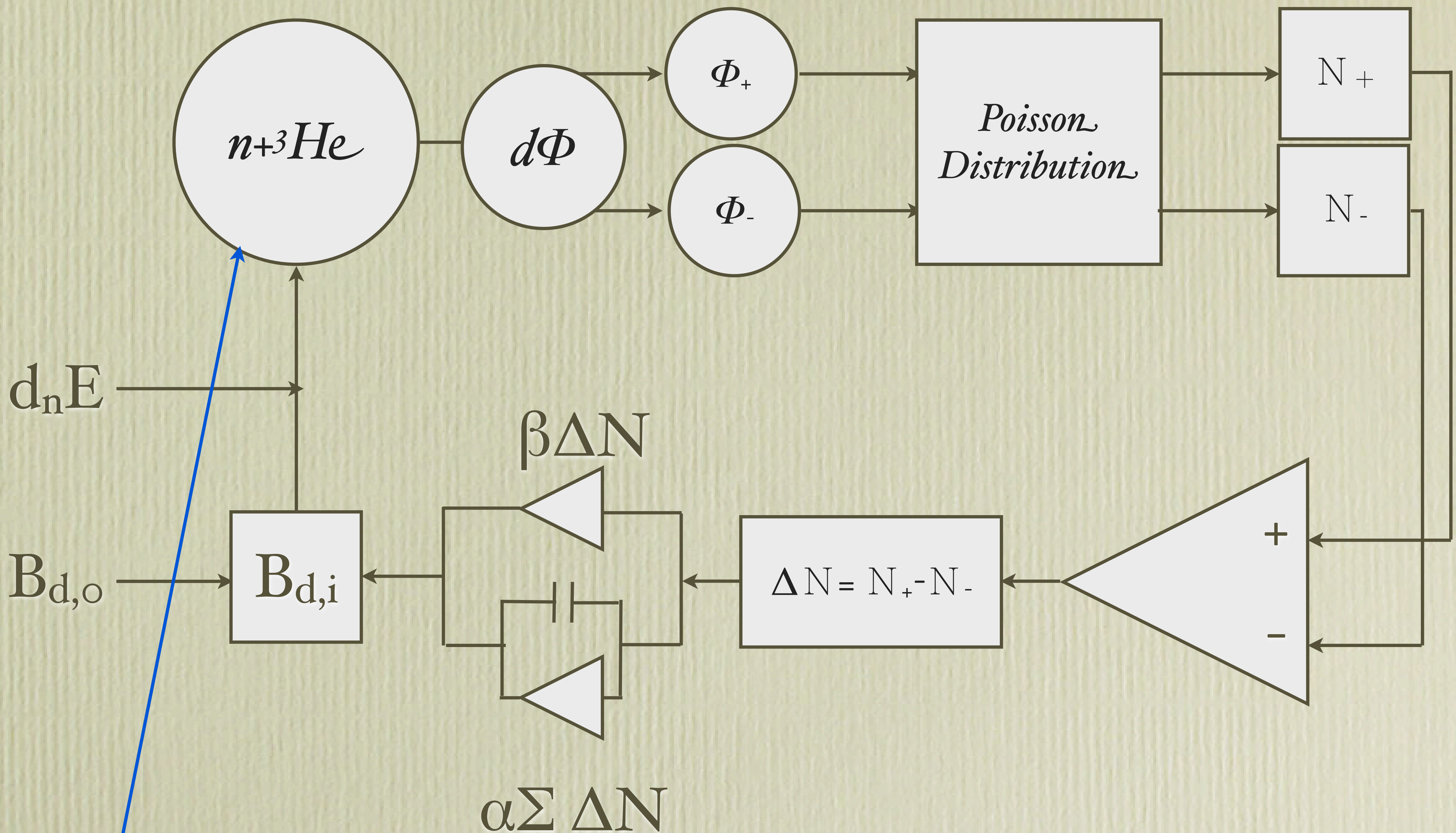
- The simulation result is consistent with the analytic solution.
- The simulation can be applied in any magnetic fields and spin dynamics. It will be used for **the feedback loop study** (proposed by Golub and Lamoreaux in 1994).
- It can be also used for
  - **Optimization of π/2 pulse for both neutron and 3He,**
  - the systematic effect of **the pseudomagnetic field**, and
  - the systematic effect of **the initial polarization and the relative angle.**
- Together with **Monte Carlo**, we have a tool to study **the statistic error and systematic error** of the dressed spin technique.

Schematic of feedback loop



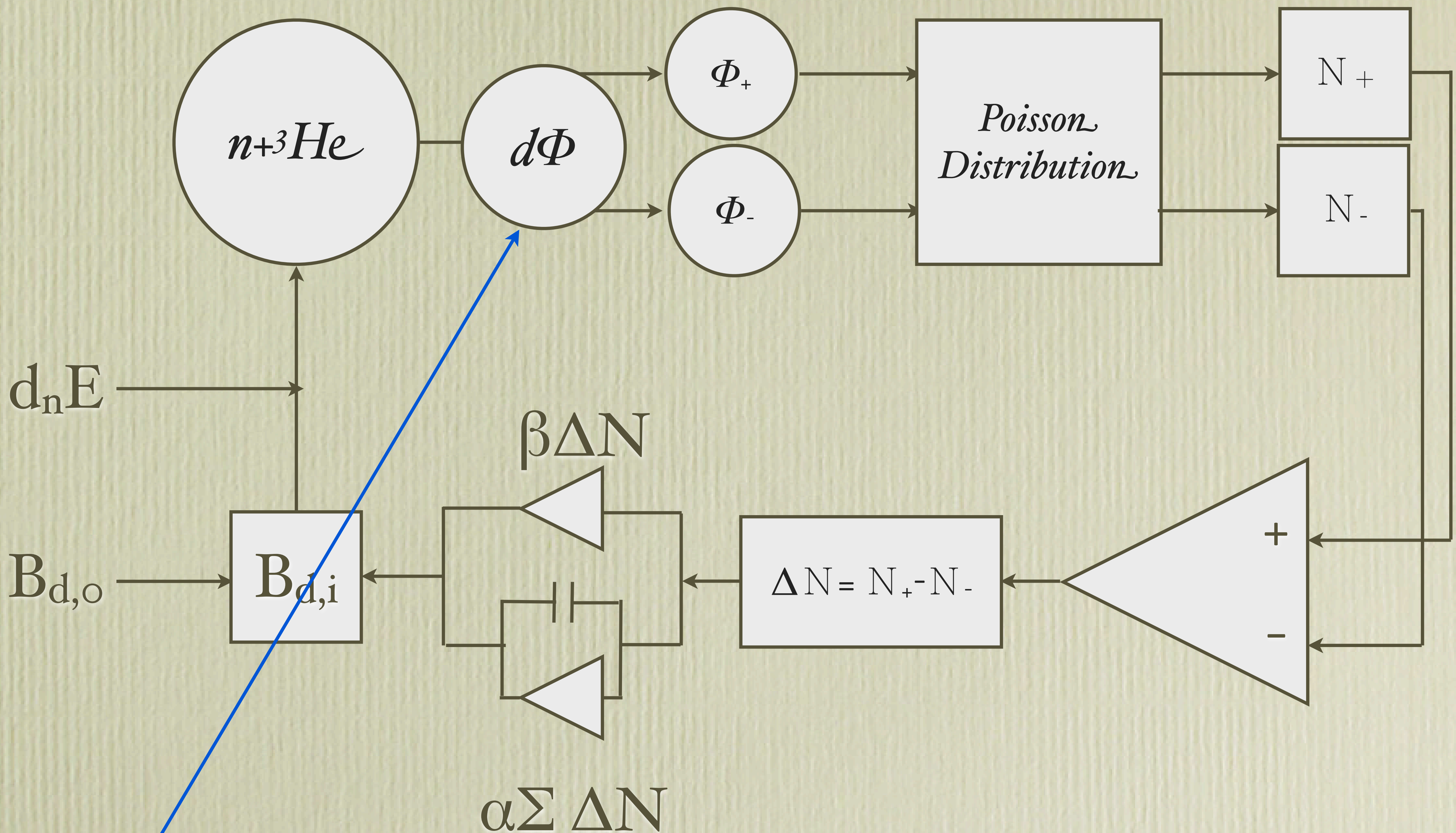
1. The initial value of B_d is $B_{d,0}$.

Schematic of feedback loop



2. For given $B_{d,i}$, simulate n+^{3}He interaction. Use the Bloch equation to calculate $\cos\theta_{n3}$ within the time window $t = [t_i, t_i + \tau_m]$, corresponding to one modulation cycle.

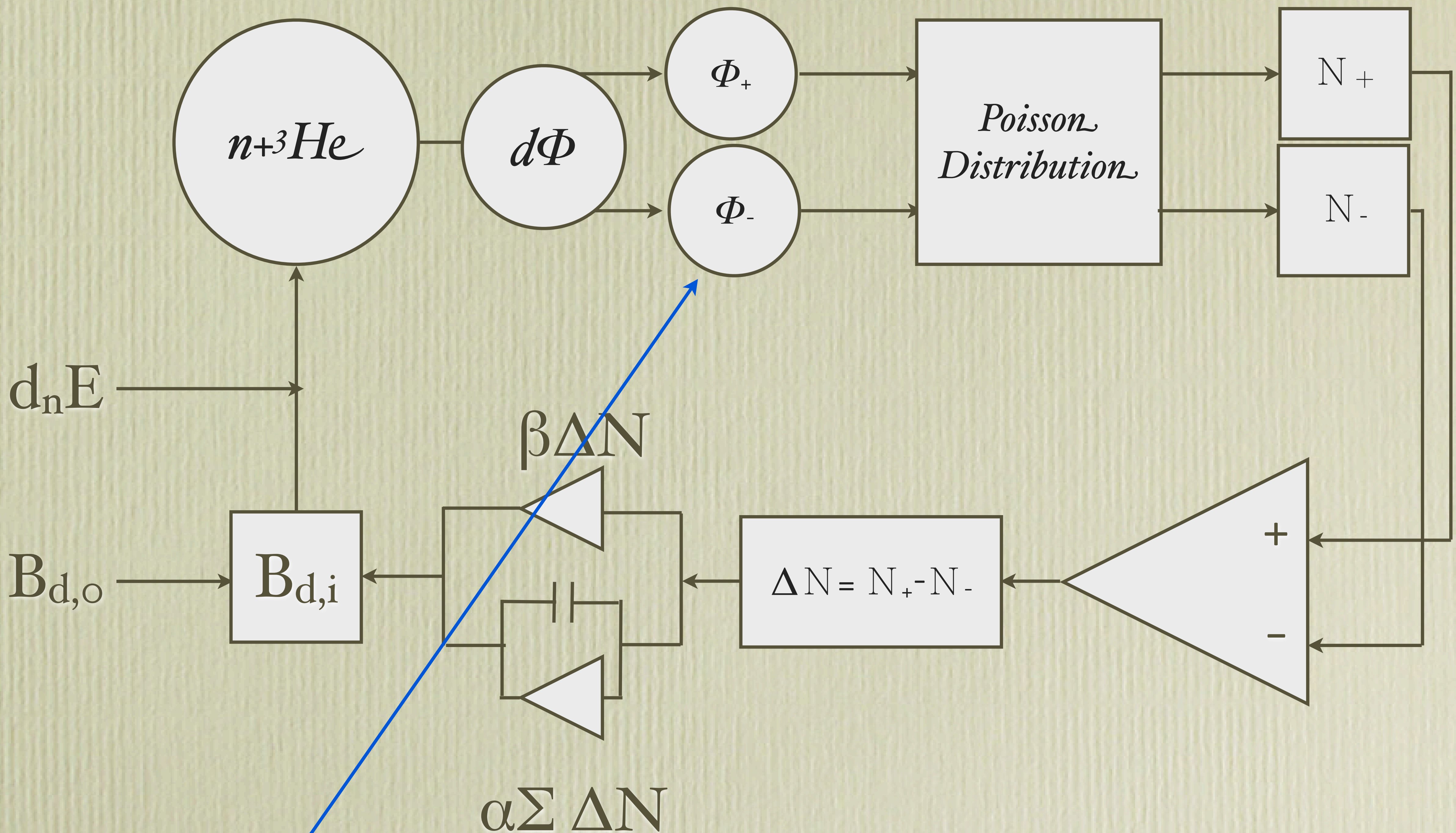
Schematic of feedback loop



3. Insert $\cos\theta_{n3}$ into the distribution function,

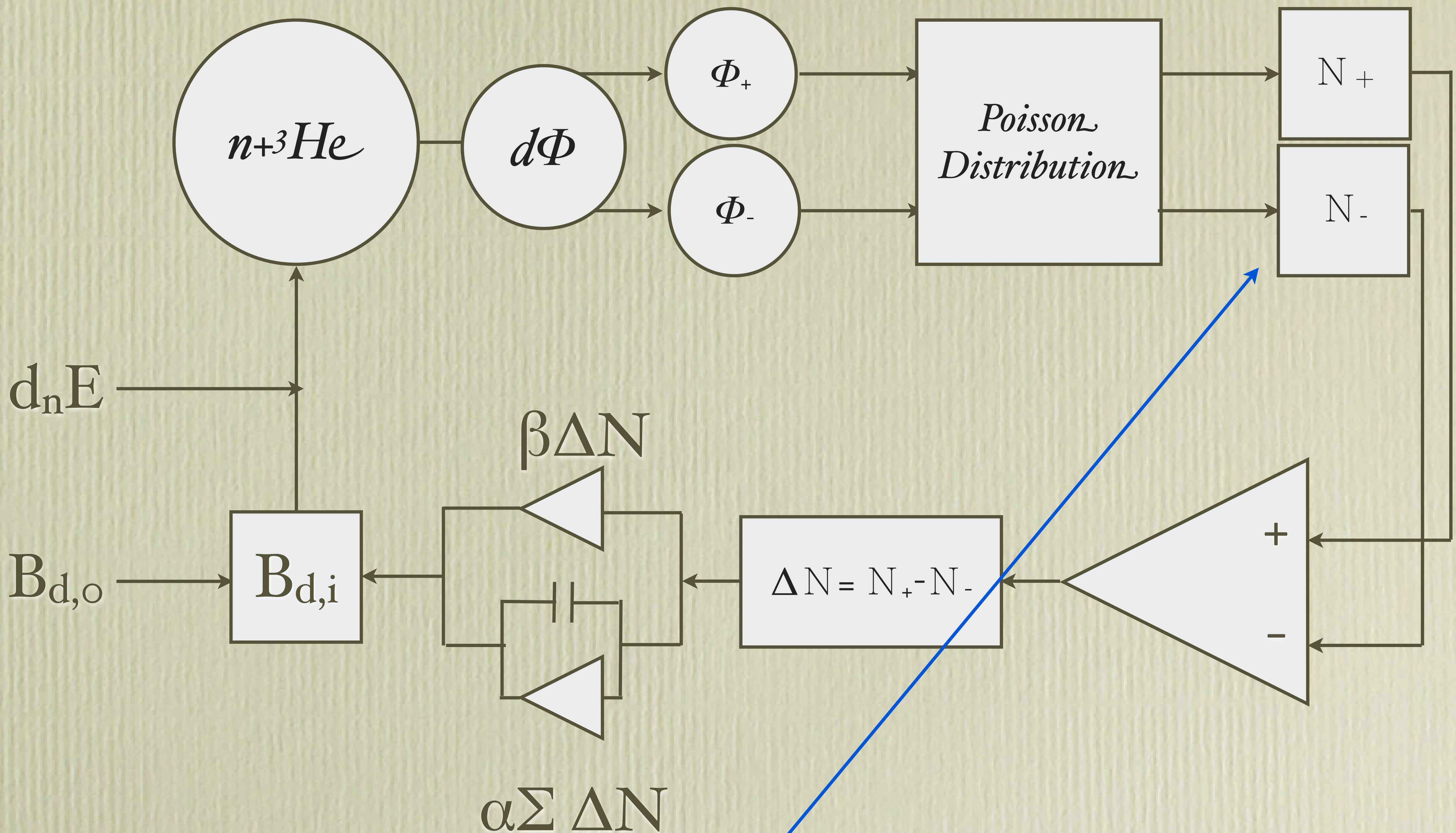
$$\frac{d\Phi}{dt} = N_0 e^{-\Gamma_{tot} t}[\frac{1}{\tau_\beta} + \frac{1}{\tau_3}(1 - P_3 P_n \cos(\theta_{n3}))].$$

Schematic of feedback loop



$$4.\ \Phi_{+,i} = \int_{t_i}^{t_i+\tau_m/2} \frac{d\Phi}{dt}dt, \quad \Phi_{-,i} = \int_{t_i+\tau_m/2}^{t_i+\tau_m} \frac{d\Phi}{dt}dt$$

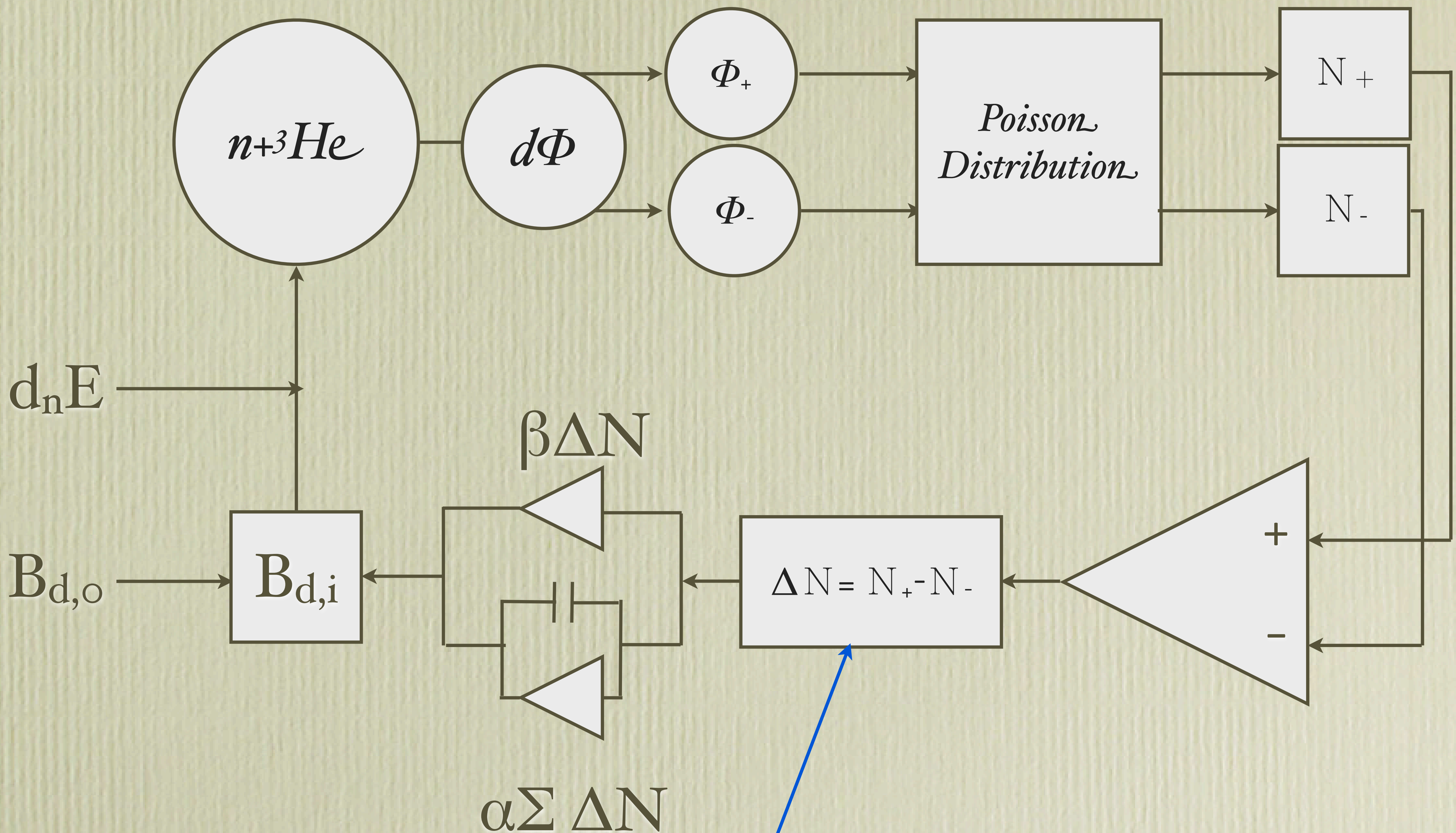
Schematic of feedback loop



5. Generate Monte Carlo:

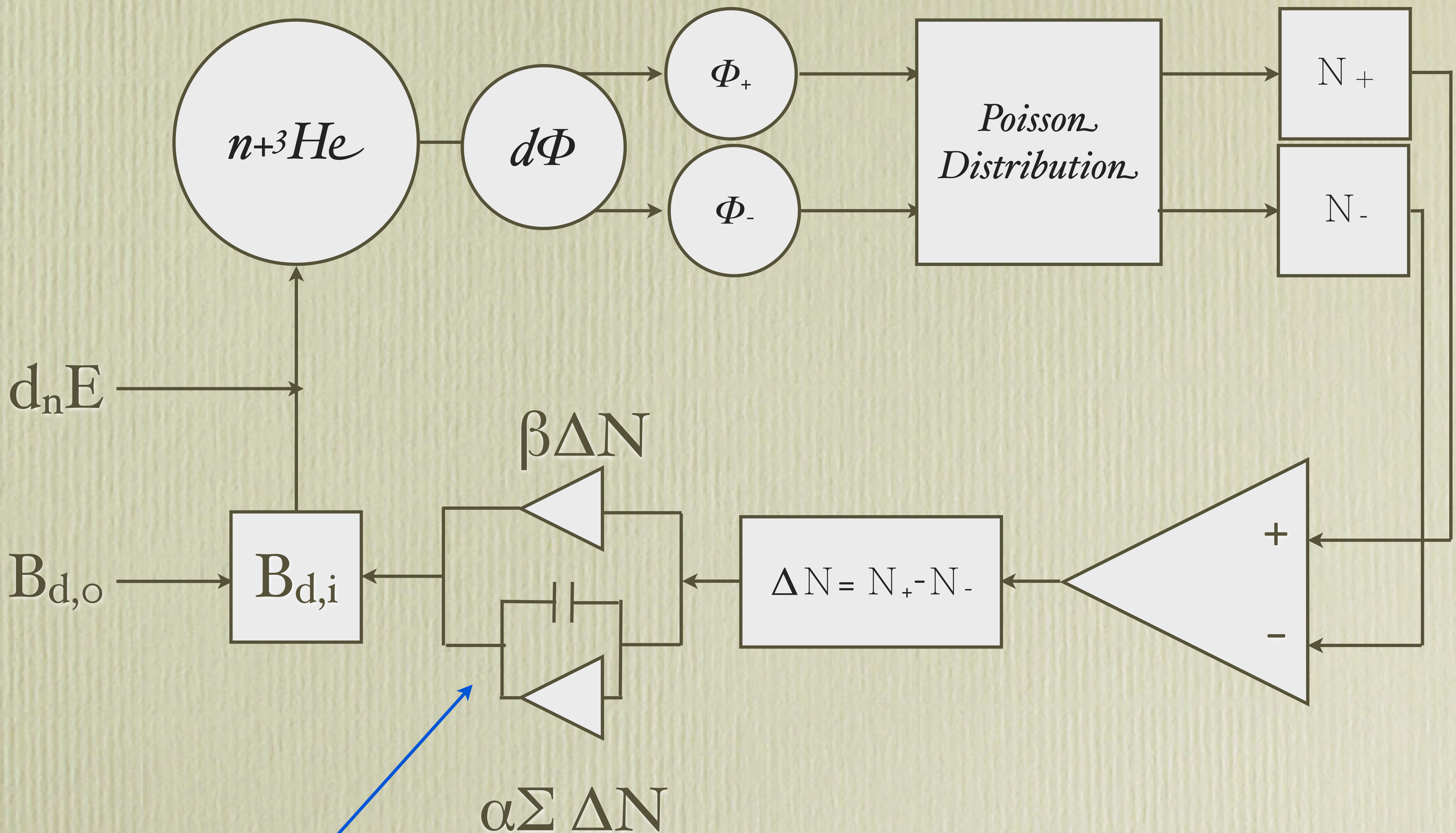
$$N_{+,i} = Poisson(\Phi_{+,i}) \text{ and } N_{-,i} = Poisson(\Phi_{-,i})$$

Schematic of feedback loop



6. Calculate $\Delta N_i = N_{+,i} - N_{-,i}$.

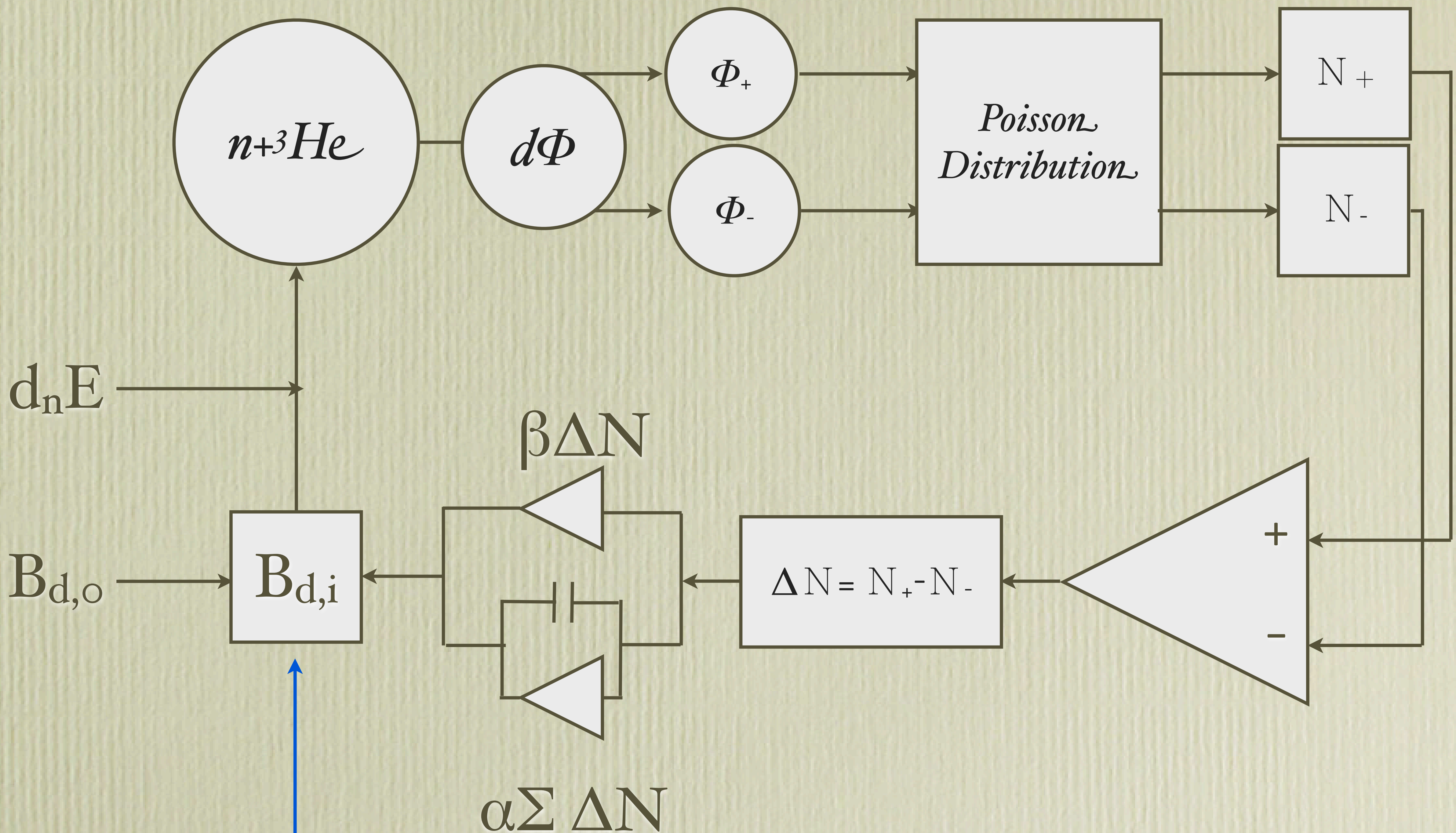
Schematic of feedback loop



7. Run the feedback loop process and obtain the modified dressing field.

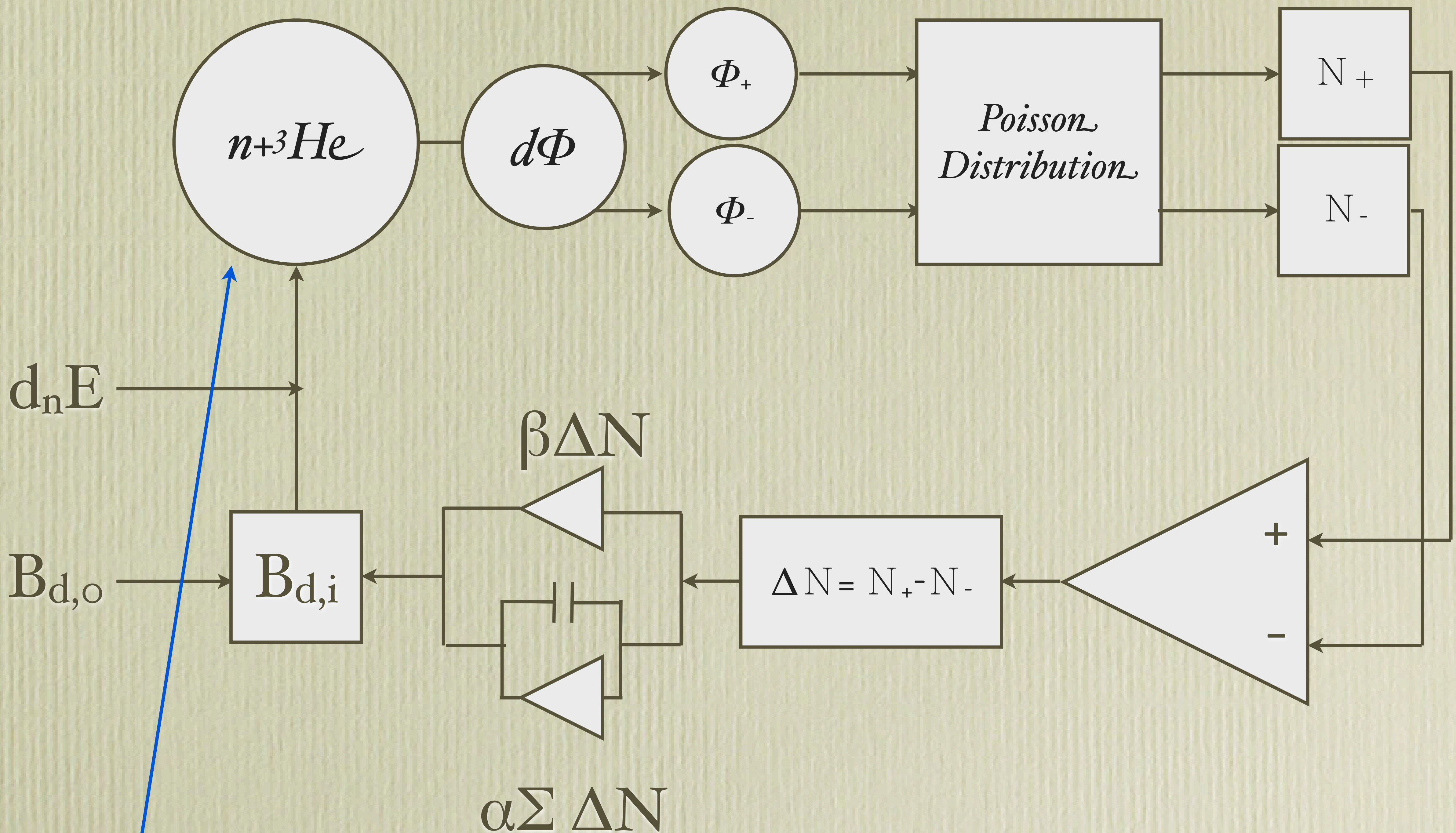
- Low Pass Integrator: $B_{c,0,\alpha} = B_{d,0}$, $B_{c,i,\alpha} = B_{c,i-1,\alpha} - \alpha\Delta N_i$.
- Amplifier: $B_{c,i,\beta} = -\beta \times \Delta N_i$.

Schematic of feedback loop



8. Modified field: $B_{d,i+1} = B_{c,i,\alpha} + B_{c,i,\beta}$.

Schematic of feedback loop



9. Go to 2 and repeat the loop.

Approach of the feedback method

- The feedback method is under investigation. Several factors should be considered.
- The modulation amplitude and period cannot be too short since there will not be enough events for the feedback loop.
- The modulation amplitude cannot be too large since the Bessel function is not symmetric at the critical point if the modulation is too large.
- The modulation period cannot be too long either since the decay effect will be involved and there is no enough time to correct the dressing field.
- One dominate factor is **the decay** which can affect the sensitivity a factor of 5 from the Monte Carlo study.
- **Correction factors** for α and β are necessary to compensate the decay effect.
- The feedback method can only be applied to a **single cell** since two cells have the same dressing coils.
- Although the feedback loop can self-correct, different kinds of systematic error, including the pseudomagnetic field, the polarization of neutron and ^{3}He, the neutron and ^{3}He density,etc., should be studied.

Summary

- The dressed spin measurement is consistent with the prediction. We can apply the theory to estimate the critical dressing at different magnetic field setups.
- It may help to the design of the dressing coils since we may not need to run at the high dressing frequency condition.
- It will be of interest to extend the measurement to higher x range.
- The Bloch equation simulation can simulate the spin dynamics in any magnetic fields. It can be used in many subjects of the nEDM, like the $\pi/2$ optimization, the pseudomagnetic field.
- The Monte Carlo study can help to study the statistic sensitivity of the feedback loop. It will be done in months.

Pseudomagnetic field

- The pseudomagnetic moment, which is originated from the real part of n-^3He scattering length (spin-dependent), like magnetic dipole moment, can produce the pseudomagnetic field, along the ^3He spin direction.
- Ref : Nuclear Magnetism:order and disorder, A. Abragam and M. Goldman and Physics Report(1994)
- B_a is around 1000 times larger than the ^3He magnetization.
- B_a is proportional to P_3, which is time dependent.

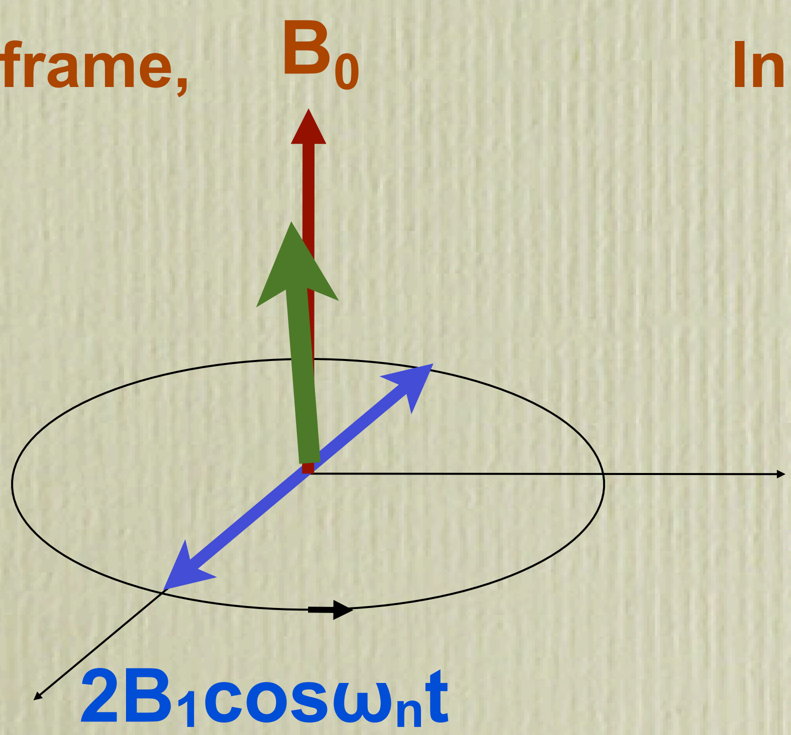
π/2 Pulse

- Apply a linear oscillatory RF magnetic field along the x-axis.
- The frequency is expected at the Larmor frequencies of neutron (ω_n).

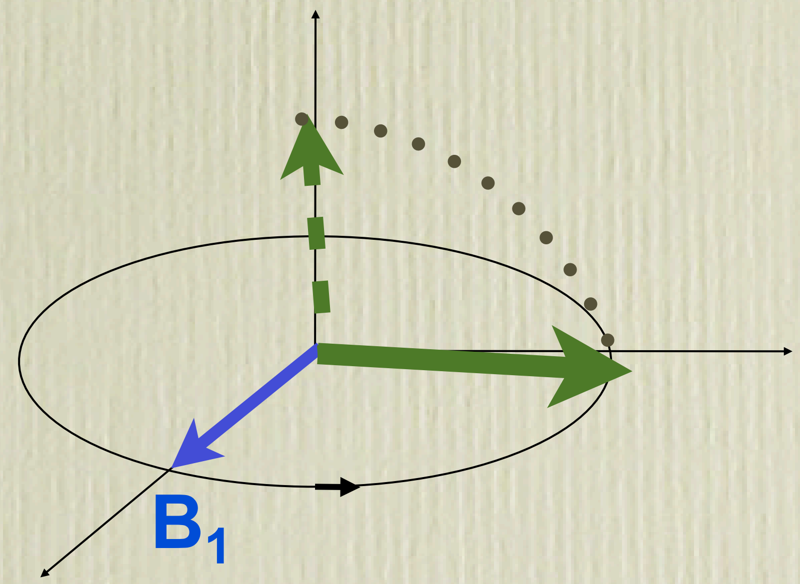
$$B_{RF}(t) = 2B_1 \cos \omega_n t \hat{x} = B_1(\cos(\omega_n t)\hat{x} - \sin(\omega_n t)\hat{y}) + B_1(\cos(\omega_n t)\hat{x} + \sin(\omega_n t)\hat{y})$$

- In the rotating frame, only a constant B_1 along the x-axis and another high frequency field. Ignore the high frequency term. The constant B_1 field can rotate the spin from the z-axis to the x-y plane within a period of time.

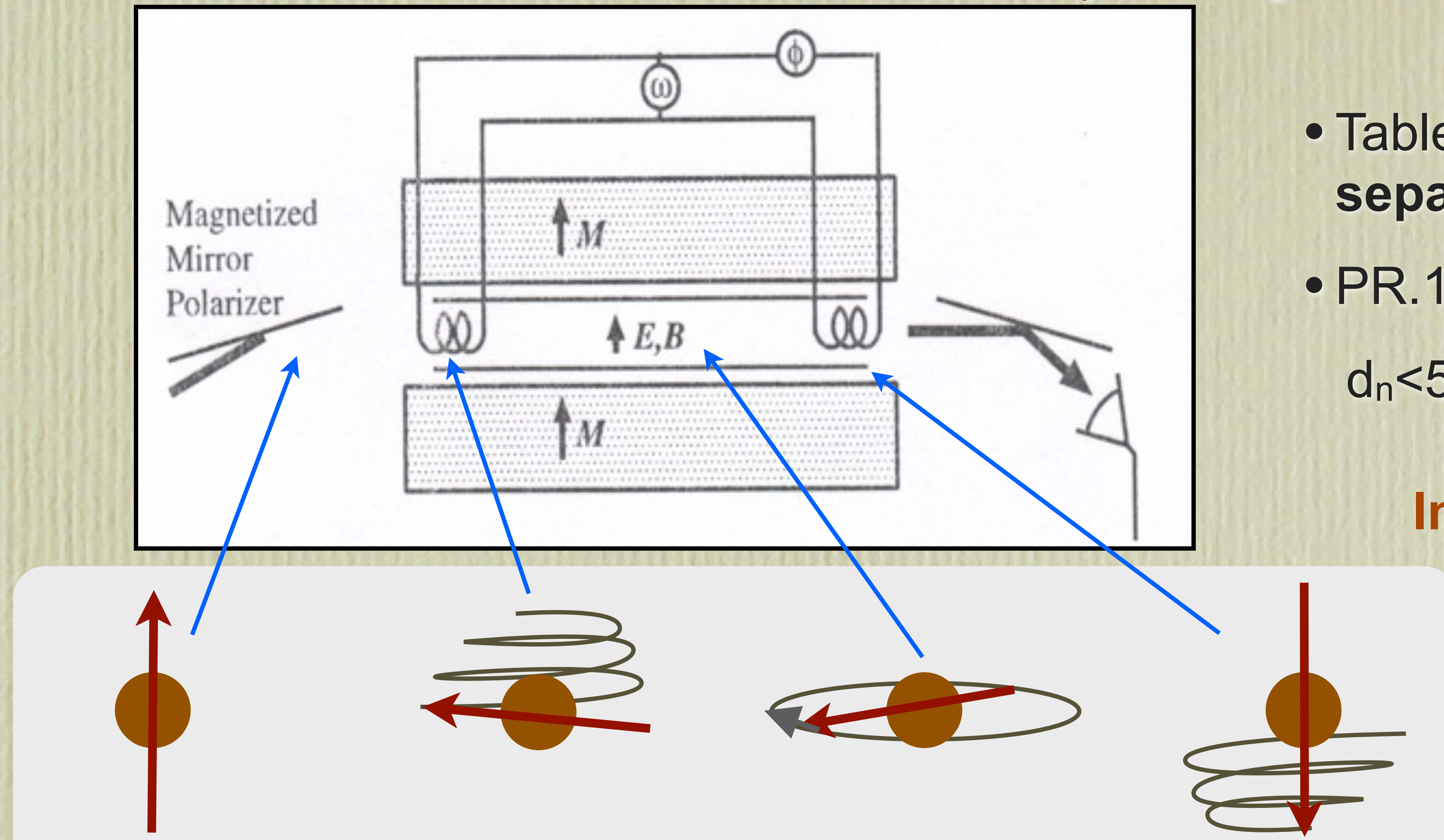
In lab frame,



In rotating frame,



Purcell and Ramsey's Experiment

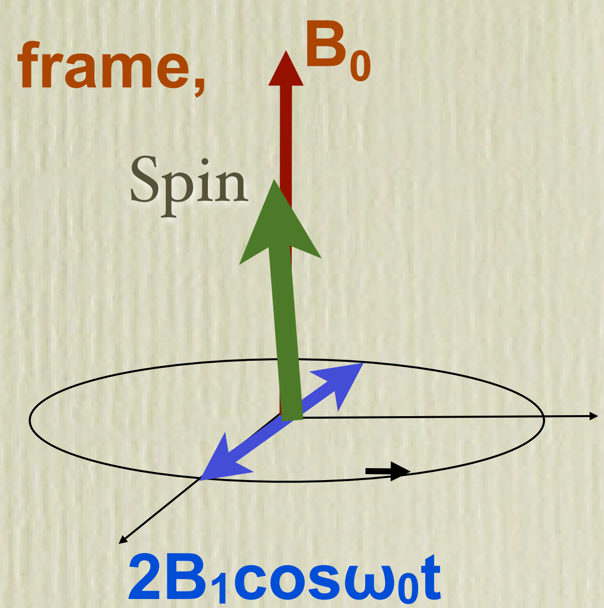


PR.78,696(1950)

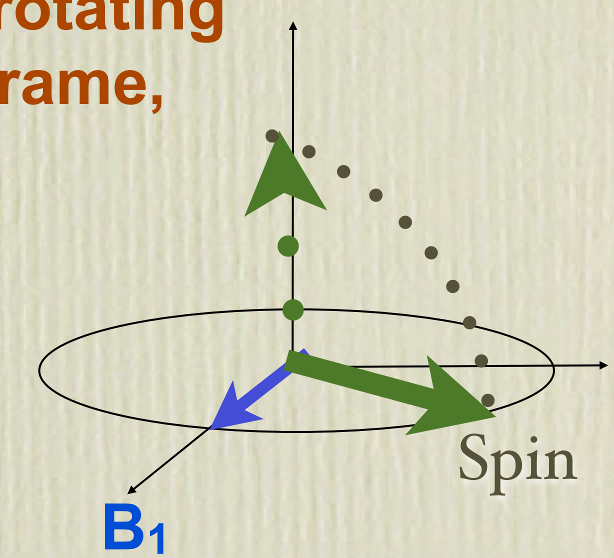
- Table-size experiment using **separated oscillatory field**.
- PR.108,120(1957):

  $d_n < 5 \times 10^{-20}$ e cm

In lab frame,



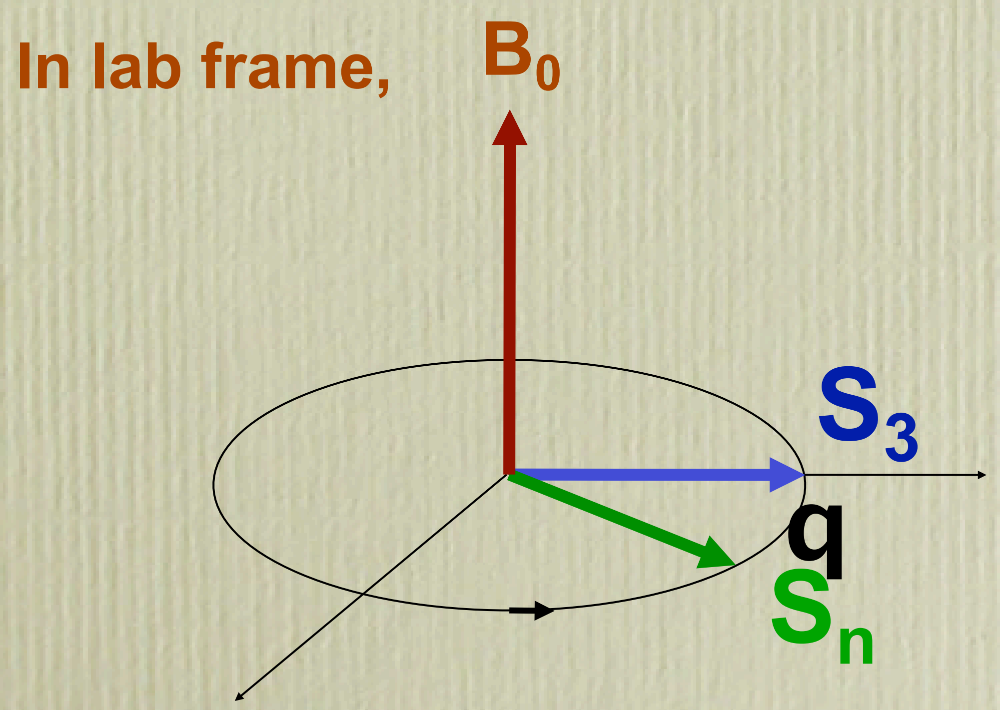
In rotating frame,

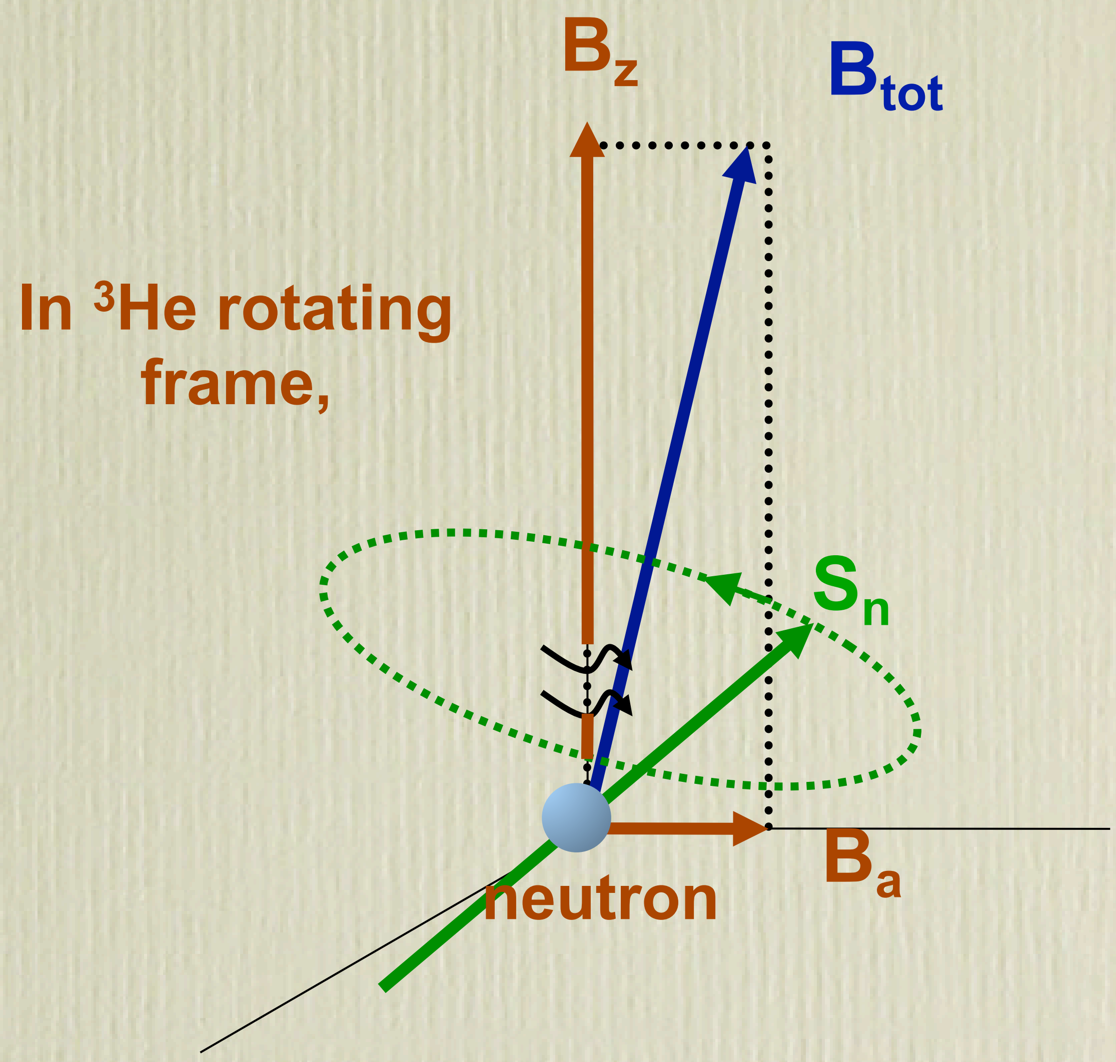


RF	off	on	off	on
	neutron spin is parallel to holding field	first $\pi/2$ pulse is applied; spin is rotated to be perpendicular to holding field	neutrons precess during storage time	second $\pi/2$ pulse is applied; spin is rotated to be anti-parallel to holding field

Pseudomagnetic field

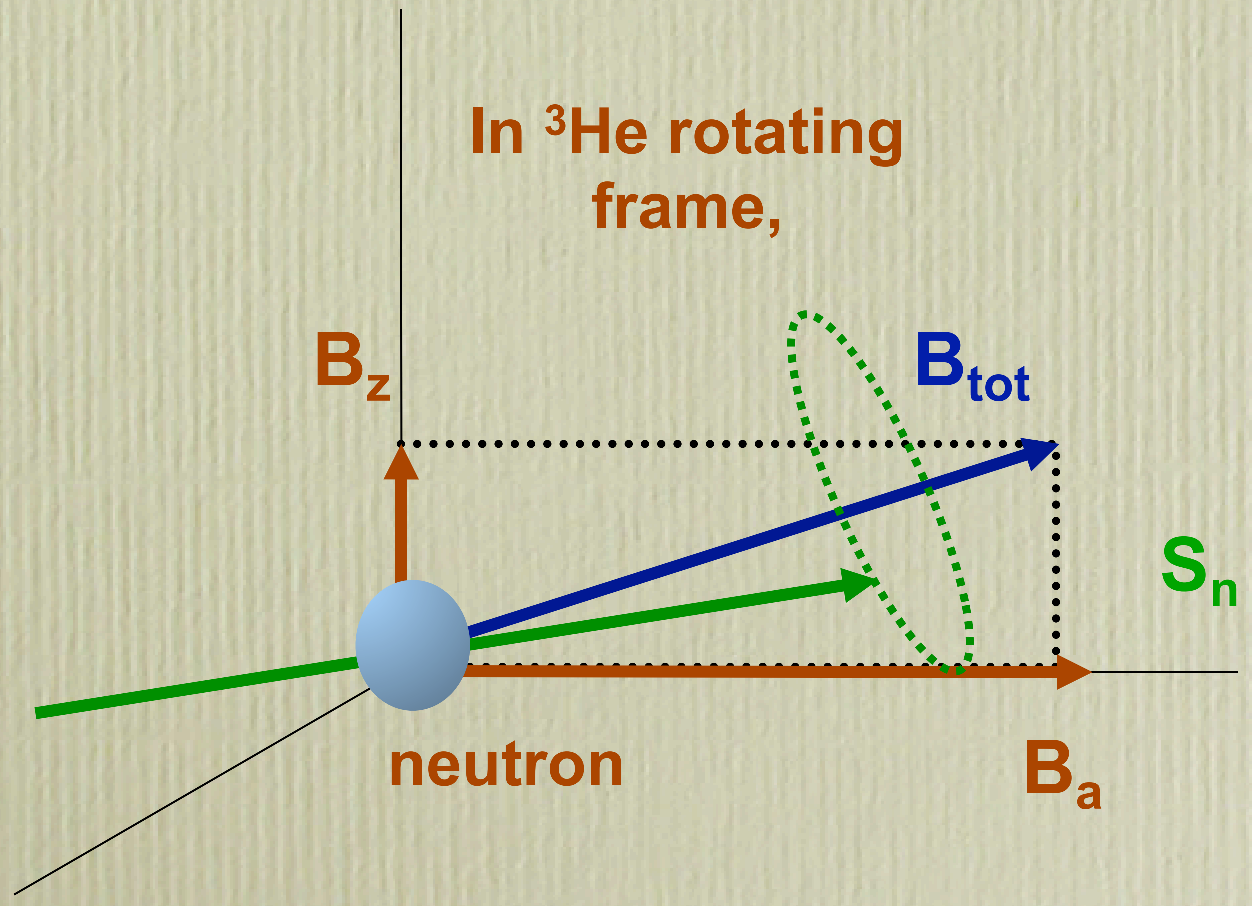
- The pseudomagnetic moment, which is originated from the real part of n-^{3}He scattering length (spin-dependent), like magnetic dipole moment, can produce the pseudomagnetic field, along the ^{3}He spin direction.
- Ref : Nuclear Magnetism:order and disorder, A. Abragam and M. Goldman and Physics Report(1994)
- B_a is around 1000 times larger than the ^{3}He magnetization.
- B_a is proportional to P_3, which is time dependent. The pseudomagnetic field is along the spin direction of ^{3}He. In the ^{3}He Larmor frequency rotating frame, the magnetic field is





Dressing field plus pseudomagnetic field

- At the critical dressing($g'_3=g'_n$), the constant field becomes very small in the rotating frame.
- The neutrons spin direction will be confined in a small cone around the ^{3}He spin direction.
- The EDM signal will be reduced by the pseudomagnetic field.
- Modulation and feedback of the dressing field are proposed to overcome this problem (discussed in the Physics Report).



The schematic plot for the feedback loop(by Golub and Lamoreaux)

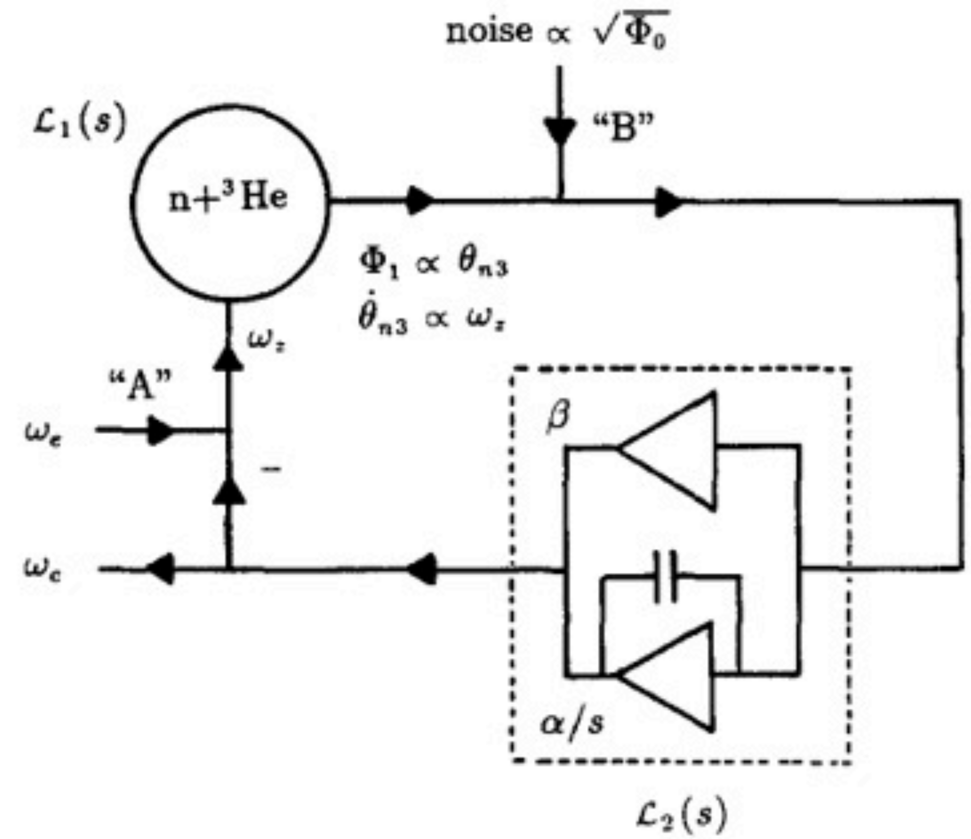


Fig. 7. Schematic of a feedback system following standard phaselock techniques. ω_z represents the total magnetic field seen by the UCN.

Generate Monte Carlo for the feedback loop

1. The initial value of B_d is $B_{d,0}$.

2. For given $B_{d,i}$, use the Bloch equation to calculate $\cos\theta_{n3}$ within the time window $t = [t_i, t_i + \tau_m]$, corresponding to one modulation cycle.

3. Insert $\cos\theta_{n3}$ into the distribution function, $\frac{d\Phi}{dt}$.

4. Calculate:

$$\Phi_{+,i} = \int_{t_i}^{t_i+\tau_m/2} \frac{d\Phi}{dt} dt,$$
$$\Phi_{-,i} = \int_{t_i+\tau_m/2}^{t_i+\tau_m} \frac{d\Phi}{dt} dt,$$

5. Generate Monte Carlo $N_{+,i} = Poisson(\Phi_{+,i})$ and $N_{-,i} = Poisson(\Phi_{-,i})$

6. Calculate $\Delta N_i = N_{+,i} - N_{-,i}$.

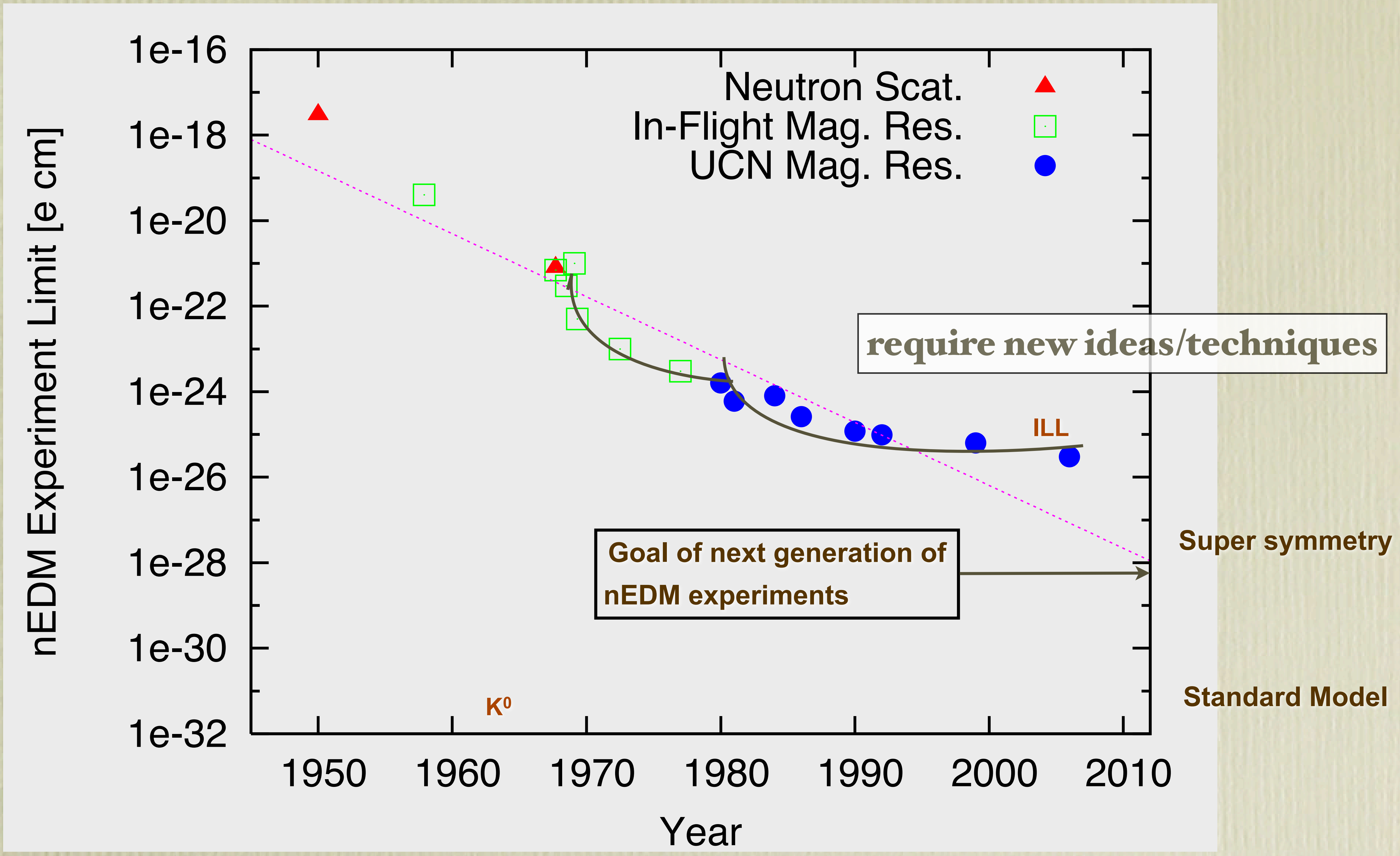
7. Run the feedback loop process and obtain the modified dressing field.

    - Low Pass Integrator: $B_{c,0,\alpha} = B_{d,0}$, $B_{c,i,\alpha} = B_{c,i-1,\alpha} - \alpha \Delta N_i$.
    - Amplifier: $B_{c,i,\beta} = -\beta \times \Delta N_i$.
    - Modified field: $B_{d,i+1} = B_{c,i,\alpha} + B_{c,i,\beta}$.

α,β are feedback parameters.

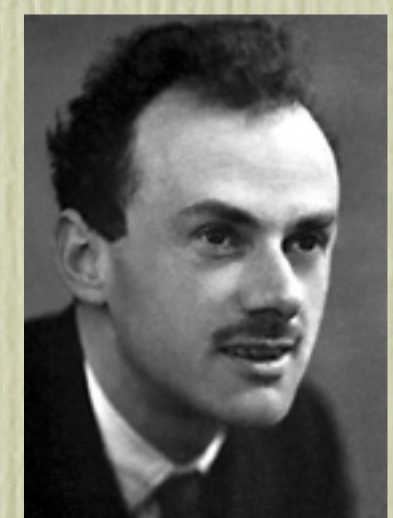
8. Go to 2 and repeat the loop.

History of neutron EDM search



- Current neutron EDM upper limit: < 2.9 x 10^{-26} e cm (90% C.L.)
- Still no evidence for neutron EDM.

Neutron electric dipole moment (Early history)



Dirac

$$\vec{d_n} = \int dx^3 \rho \vec{x} = d_n \hat{S}$$

- Electric dipole moment (EDM) is the first moment of the charge distribution (ρ).
- Dirac's **magnetic monopole** can generate an EDM (1948).
- The EDM (**vector**) is parallel to the **Spin (axial vector)** direction.
- EDM is **Parity-odd** but spin is **Parity-even**.

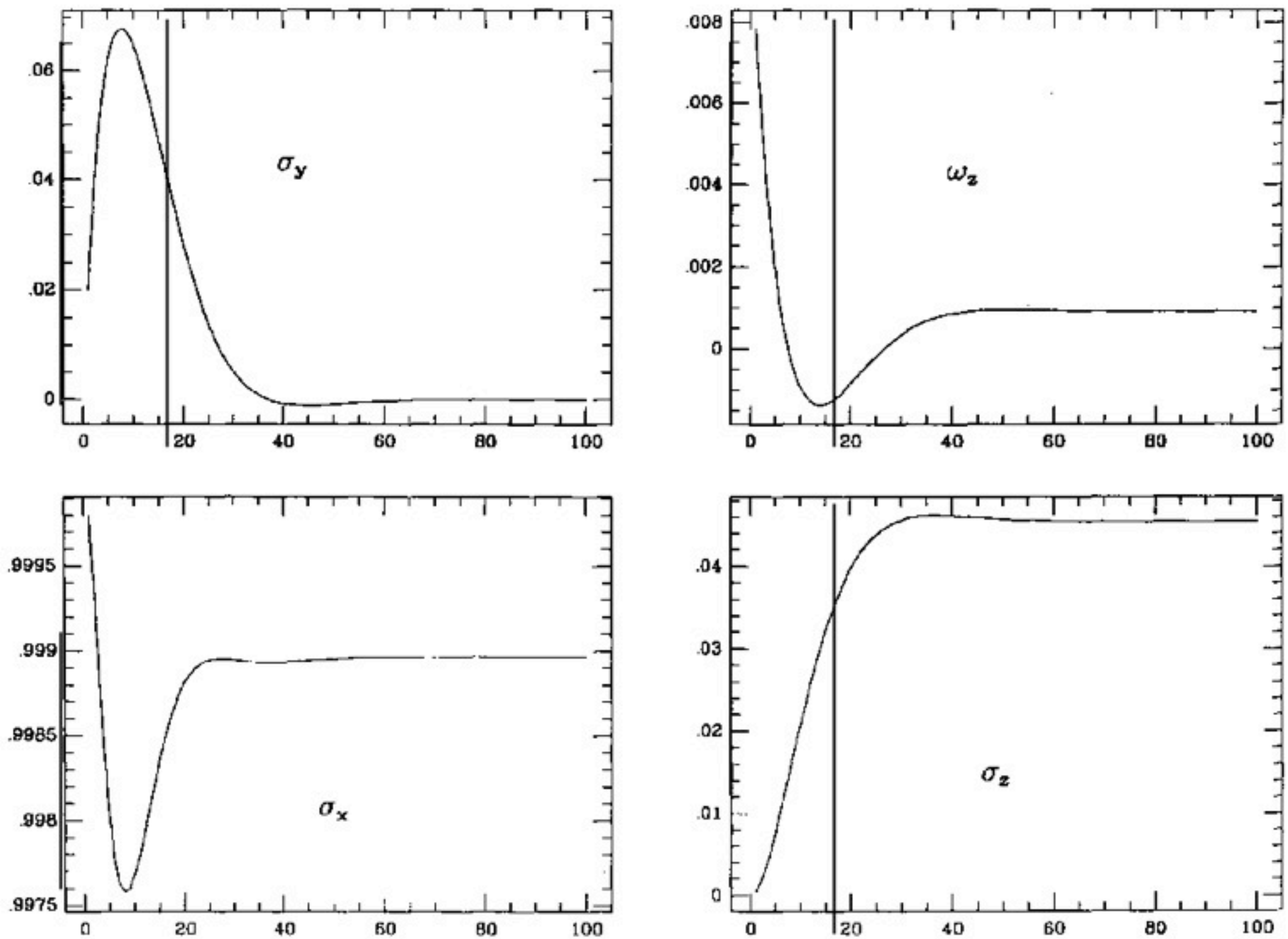
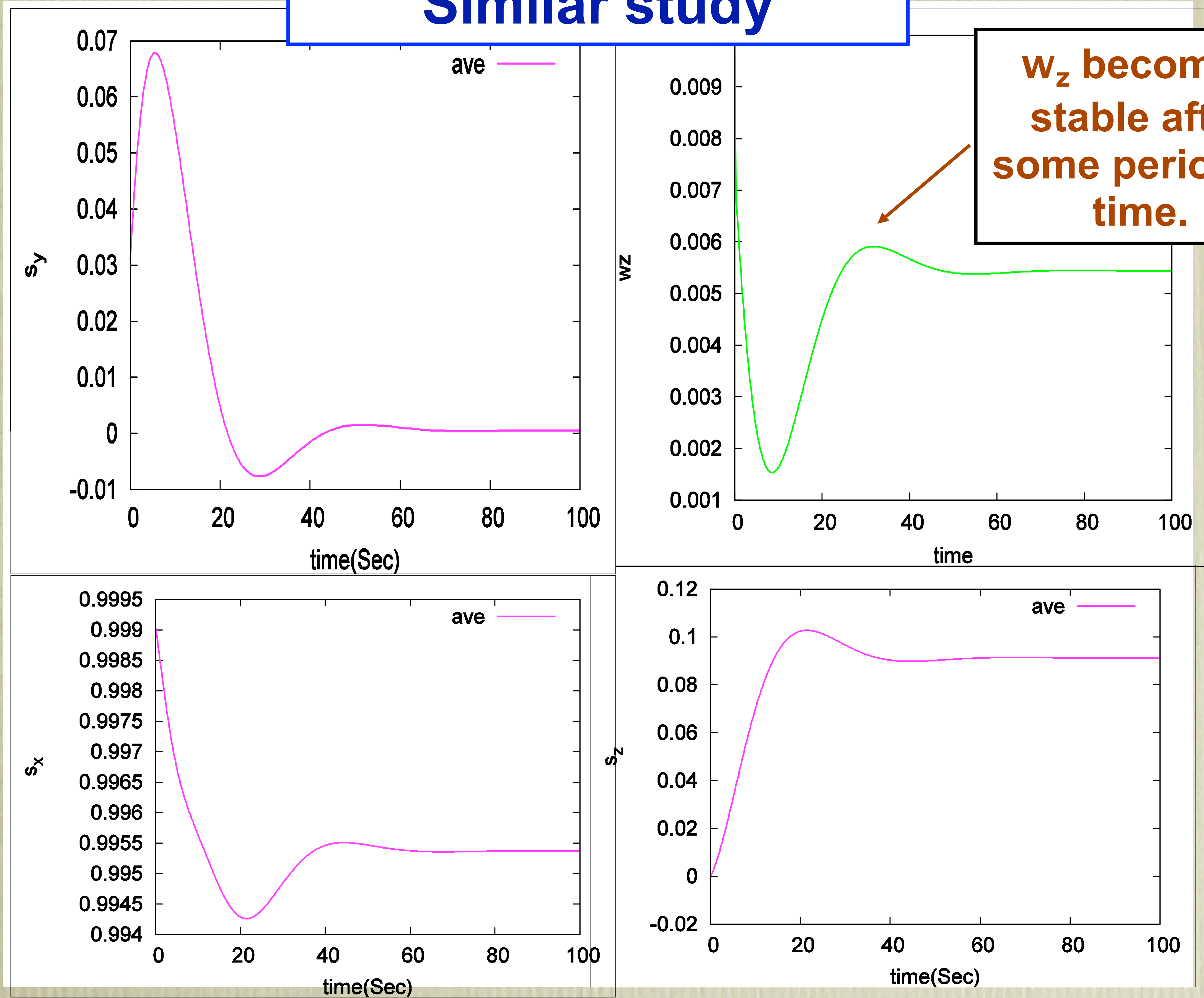


Fig. 8. Response of the system when τ_L is rather long and with no UCN loss. The modulation period $\tau = 0.1$ s. The interesting feature is that $\omega_z \neq 0$, which implies that there is an error in the correction signal, after the system has reached equilibrium.

Similar study



w_z becomes stable after some period of time.

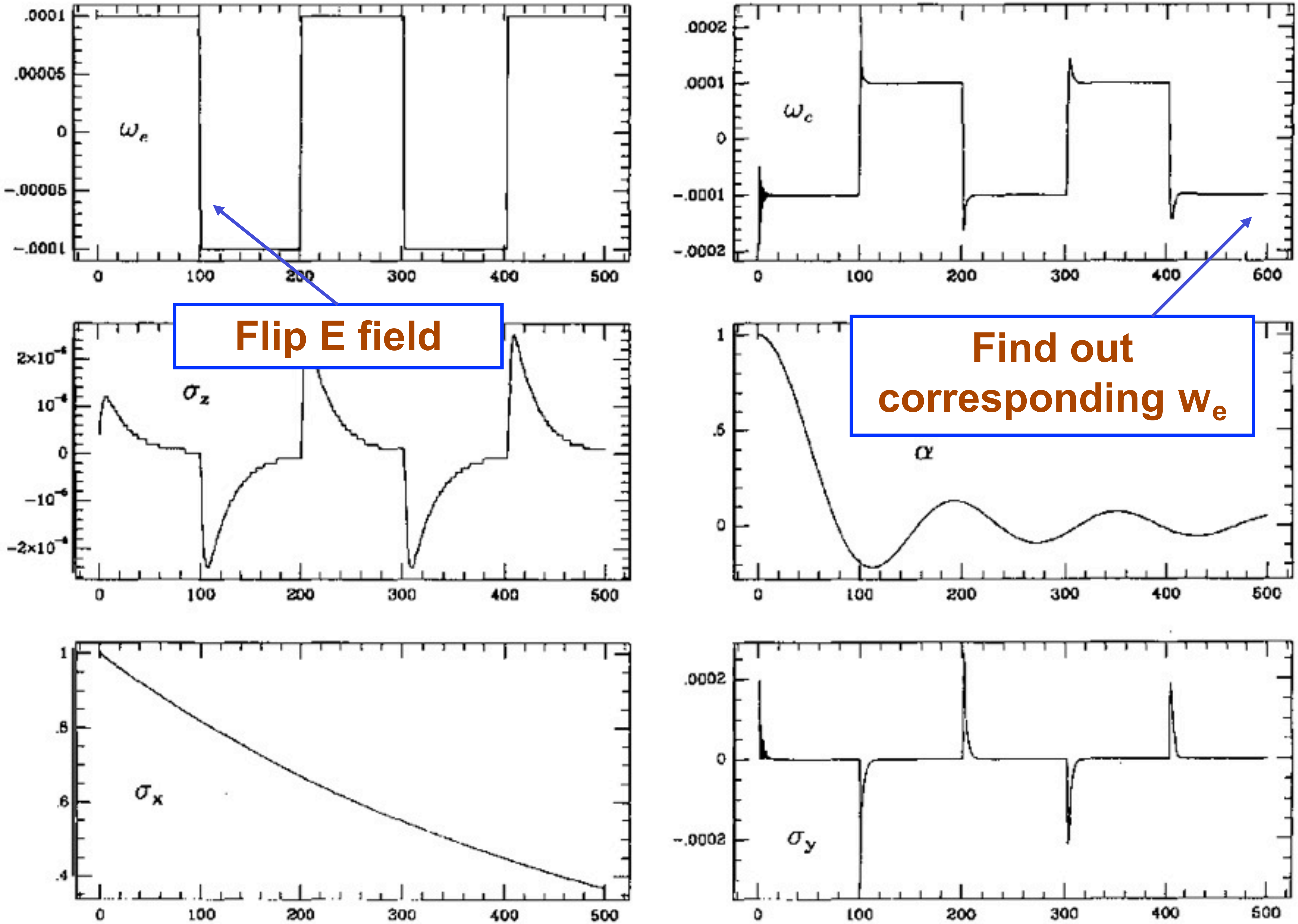
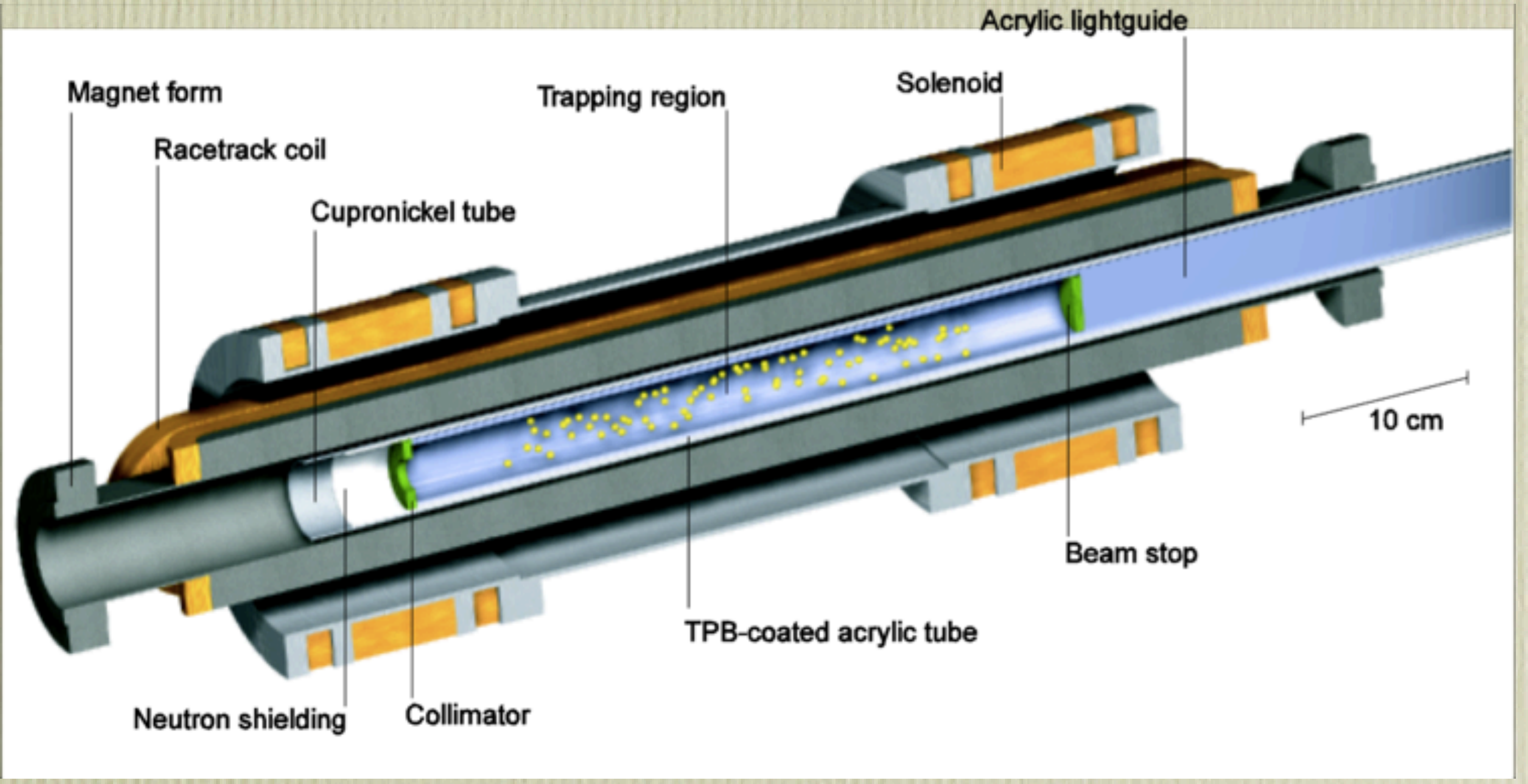


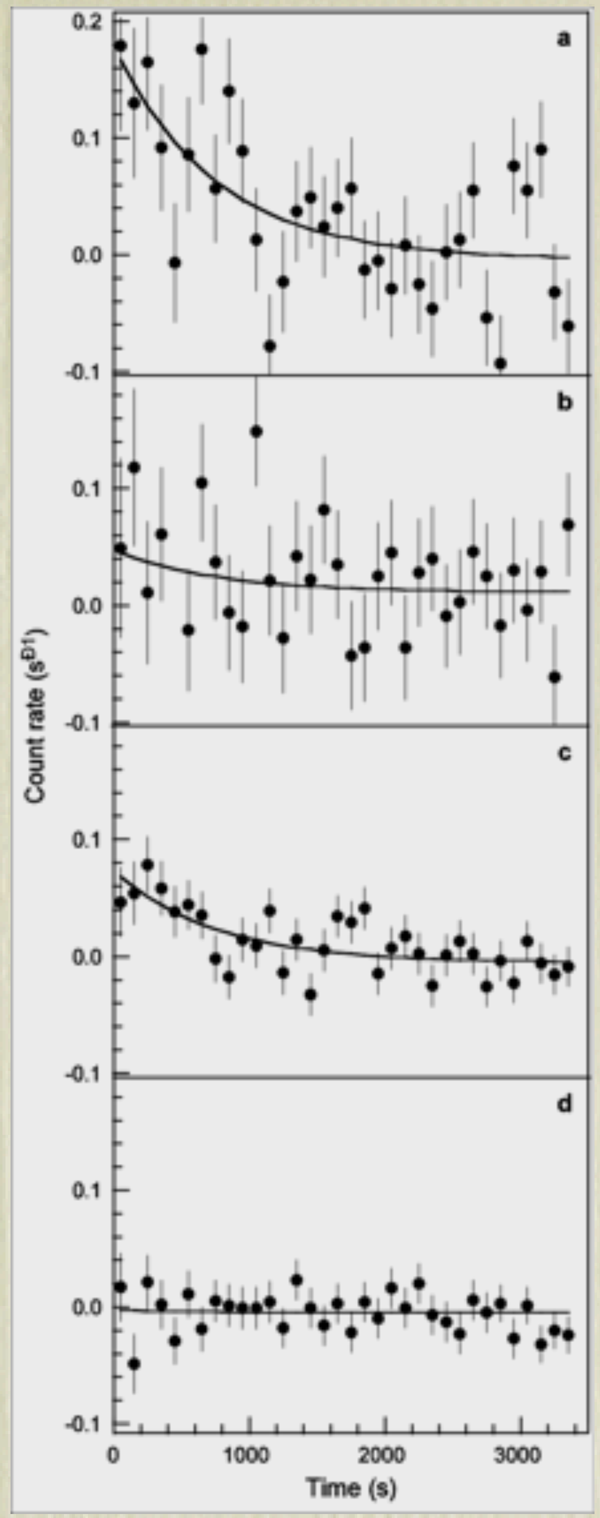
Fig. 10. Simulation including spin-dependent losses with $\omega_e = +1 \times 10^{-4}$, reversed every 50 s. The loop is initially underdamped but becomes overdamped due to the gain reduction from neutron losses. The $\sin\alpha/\alpha$ reduction factor is shown to indicate the loss of sensitivity expected when feedback is not used; such a reduction is absent from the correction signal ω_c. Also, the component of σ_z due to the finite loop response time decays faster than σ_x; this is due to spin-dependent losses.

UCN Production in superfluid 4He

Magnetic Trapping of UCN at NIST

(Nature 403 (2000) 62)





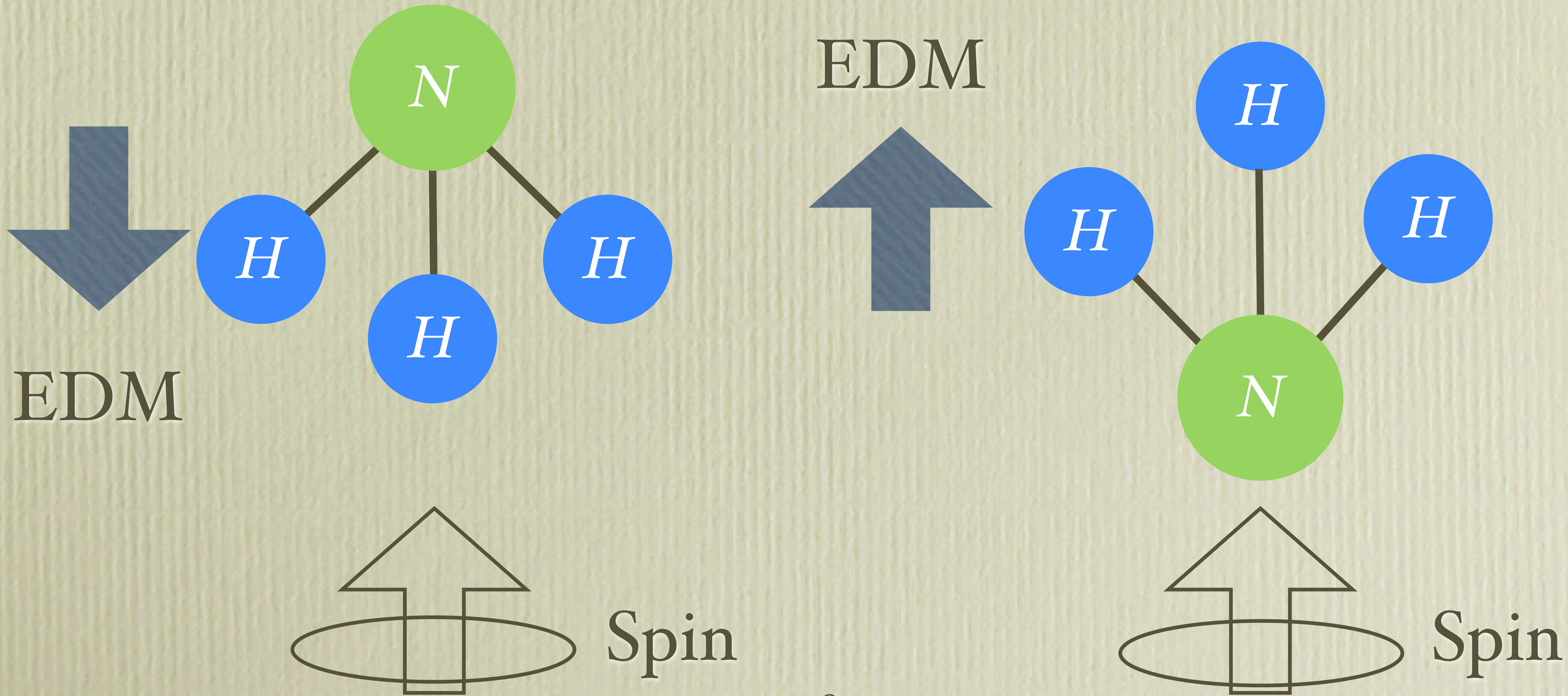
560 ± 160 UCNs trapped per cycle (observed)

480 ± 100 UCNs trapped per cycle (predicted)

The experiment helps to approve the neutron EDM proposal.

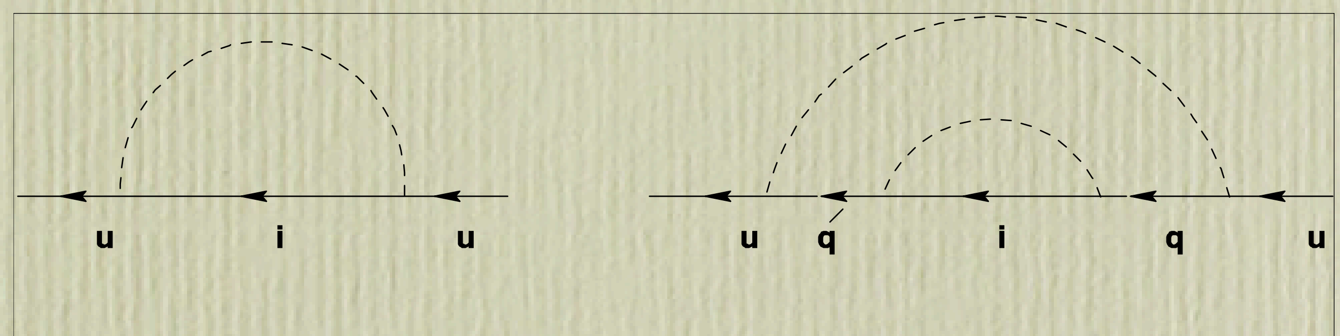
Why permanent EDMs exist without violating P and T?

- Consider a diatomic polar molecule. The only possible orientation of the EDM is along the molecular axis, but the rotation (spin) is directed perpendicular to the axis.
- For polyatomic molecules (like NH_3), the +k and −k (k is the spin projection) are degenerate states with opposite sign of EDM. The superposition of these two states would give zero EDM.



Electroweak Process

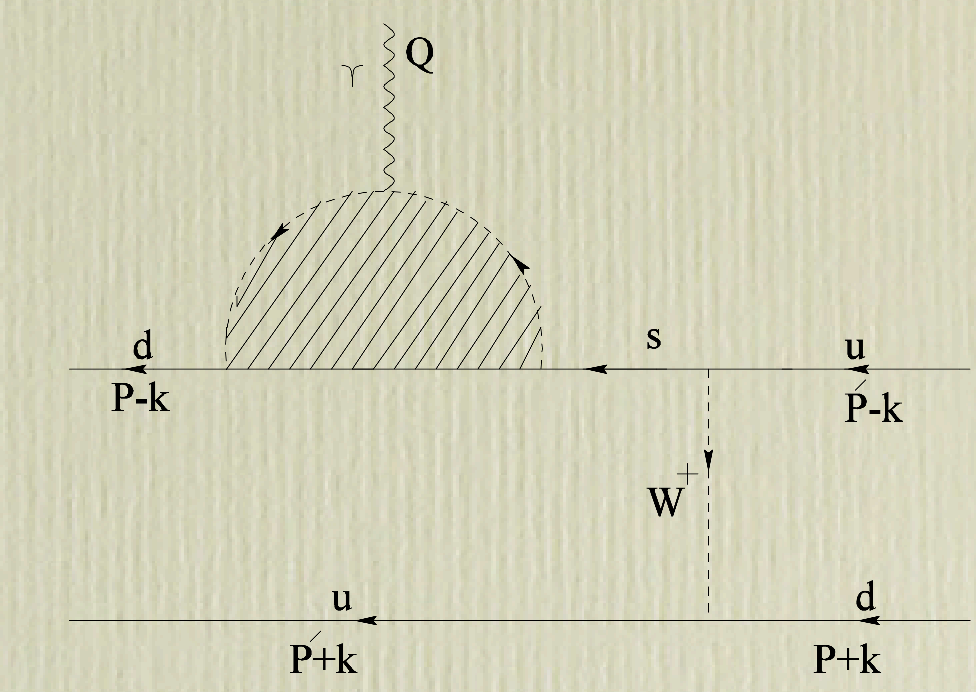
a) Contributions from single quark's EDM:



$$d_n \approx \frac{1}{3} d_u - \frac{4}{3} d_d$$

One and two-loop contributions are zero. Three-loop contribution is ~10^{-34} *e•cm*

b) Contributions from diquark interactions:



$$d_n = \frac{38}{9\pi^3} (G_F m_N^2)^2 \frac{m_t^2}{m_s^2} \frac{m_N^2}{m_W^2} \frac{\Lambda}{m_N^4} \frac{e}{m_N} (\mathrm{Im} V)$$

$$\mathrm{Im} V = c_1 s_1^2 c_2 s_2 c_3 s_3 \sin(\delta)$$

$d_n \sim 10^{-32}$ *e•cm*

(hep-ph/0008248)

Strong Interaction

- Θ term in the QCD Lagrangian :

$$L_\theta = \frac{\theta \; g_s^2}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

$$d_n = \frac{e}{m_p} \frac{g_{\pi NN} \bar{g}_{\pi NN}}{4\pi^2} \ln \frac{m_\rho}{m_\pi}$$

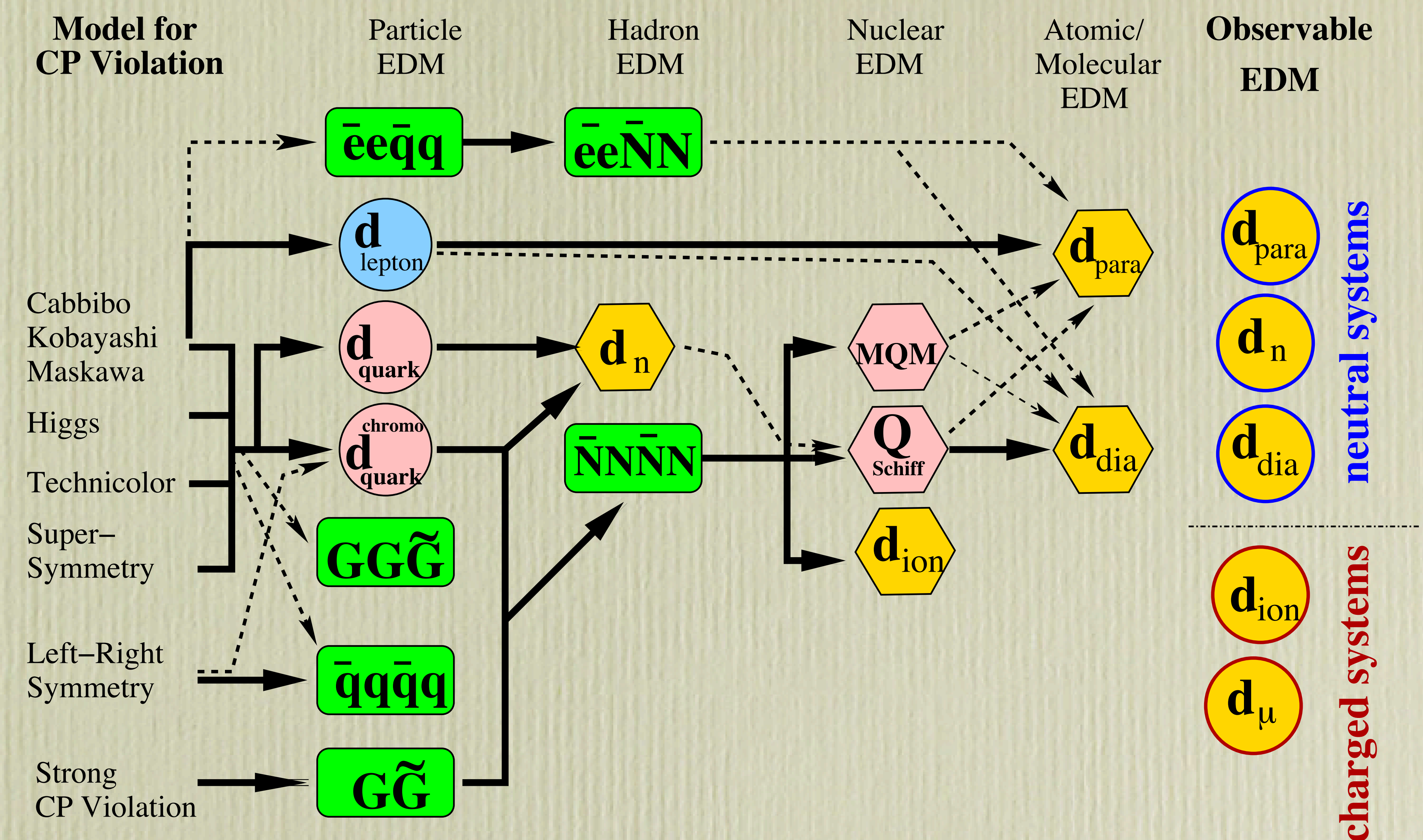
- Θ term's contribution to the neutron EDM :

$$\bar{g}_{\pi NN} = -\theta \frac{m_u m_d}{m_u + m_d} \frac{\sqrt{2}}{f_\pi} \frac{M_\Xi - M_\Sigma}{m_s}$$

$$d_n < 10^{-25} \; e \bullet cm \rightarrow |\theta| < 3 \times 10^{-10}$$

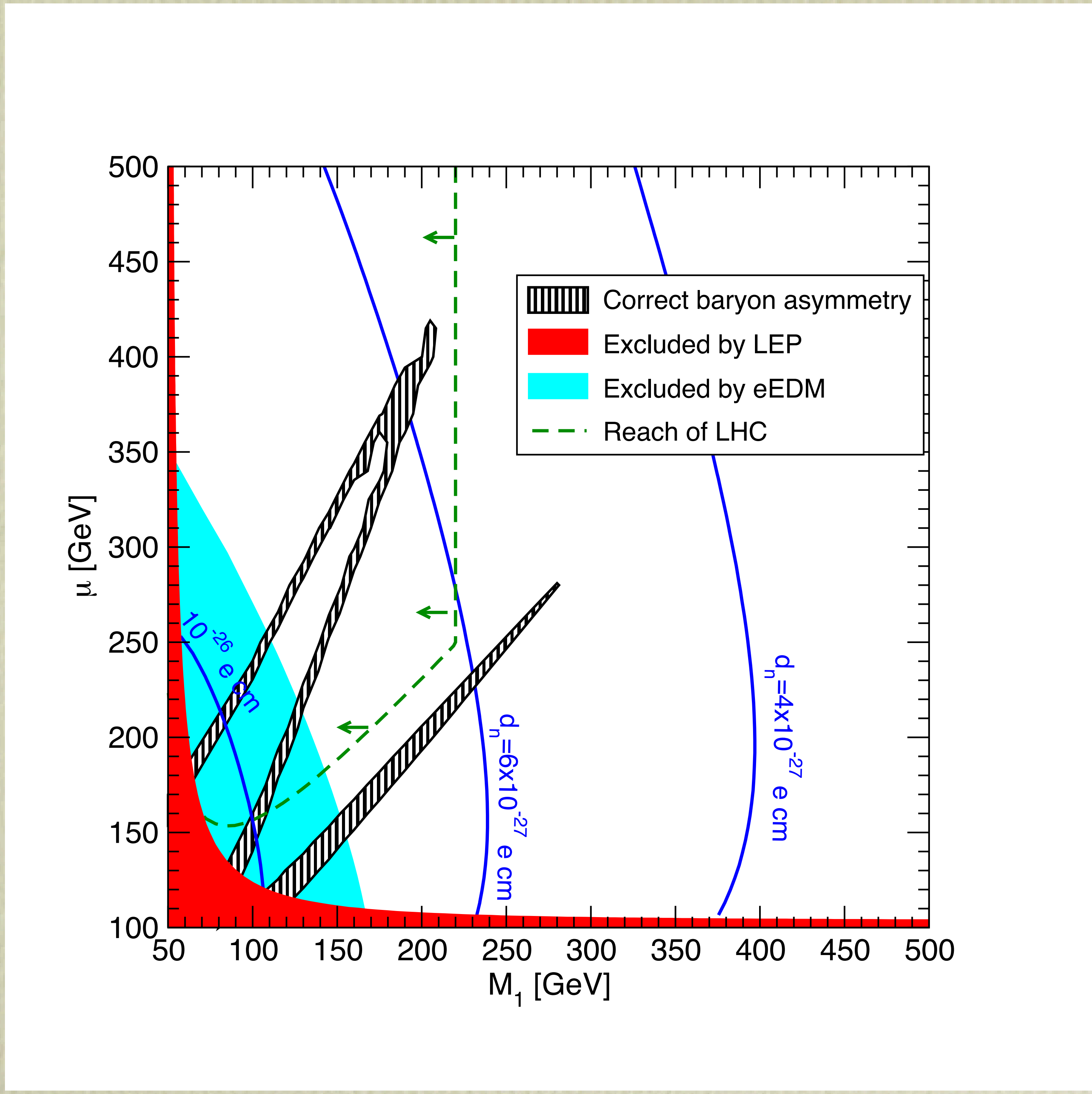
- Spontaneously broken Pecci-Quinn symmetry? No evidence of a pseudoscalar axion!

Physics beyond SM



•There are many new CP sources generating observable EDMs.
•Observed EDMs are a combination of different CP-violating sources.
•To explain the strong CP violation or the new CP sources, it is needed to check the relation between different systems.

One example of minimum supersymmetry model

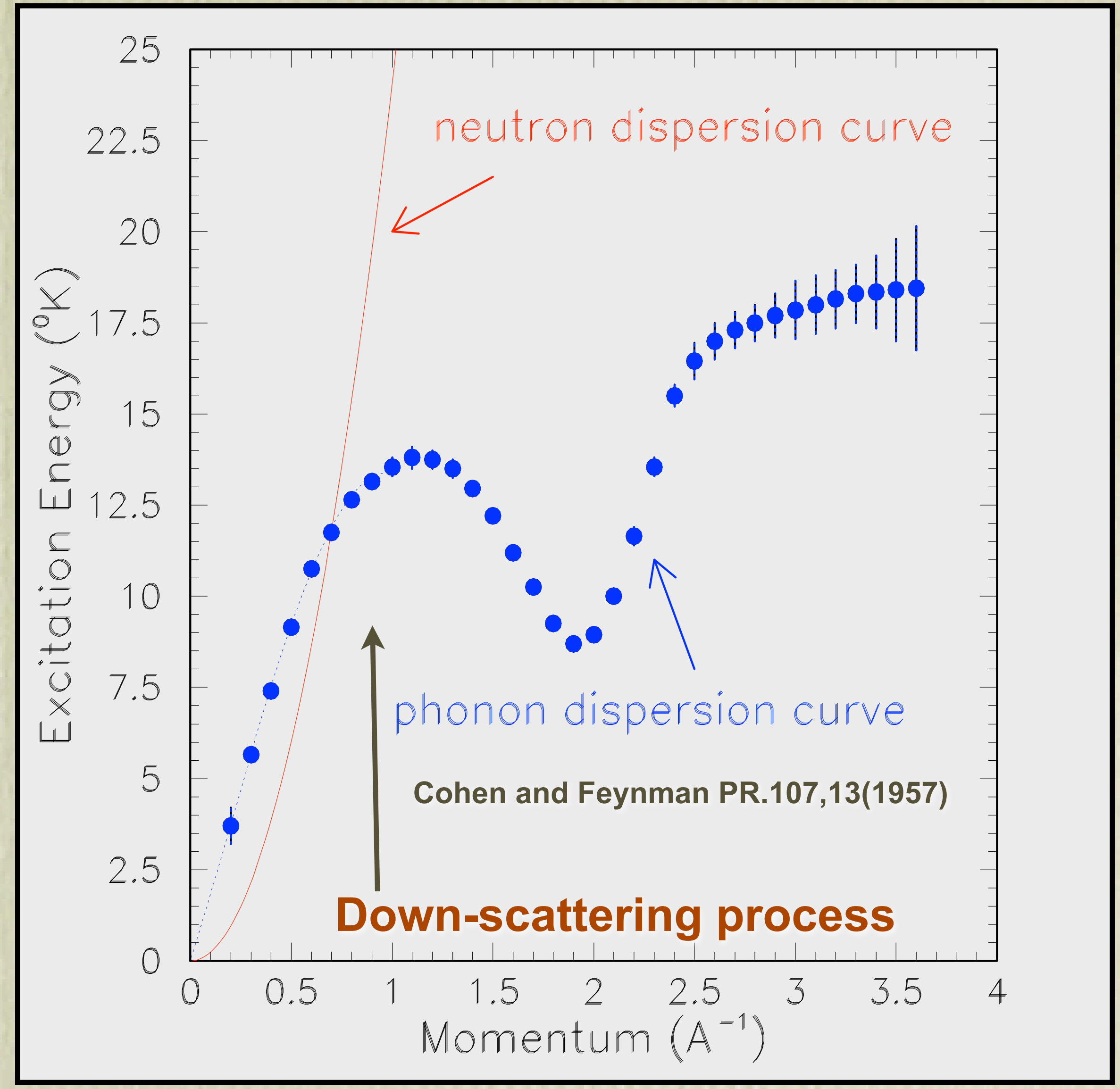


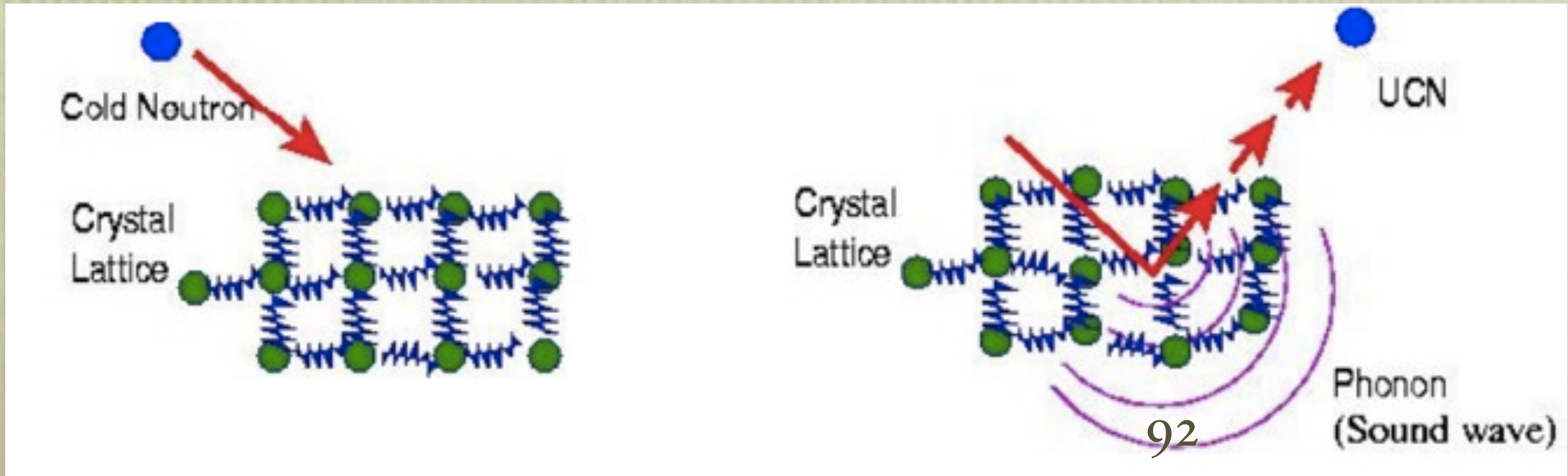
- LHC can only test one branch of parameter phase space of MSSM for the correct baryon asymmetry.
- Neutron EDM can be applied to exam the other region of the phase space.

Superthermal Method--UCN production in superfluid ^{4}He

- UCN was extracted from the **low-energy tail** of the Maxwell-Boltzmann distribution of cold neutrons(~5 UCN/cm^3).
- A new method suggested by Golub and Pendlebury. Cold neutron with momentum of 0.7 A^{-1} (10^{-3} eV) can excite a phonon in ^{4}He and become an UCN via **down-scattering process**.

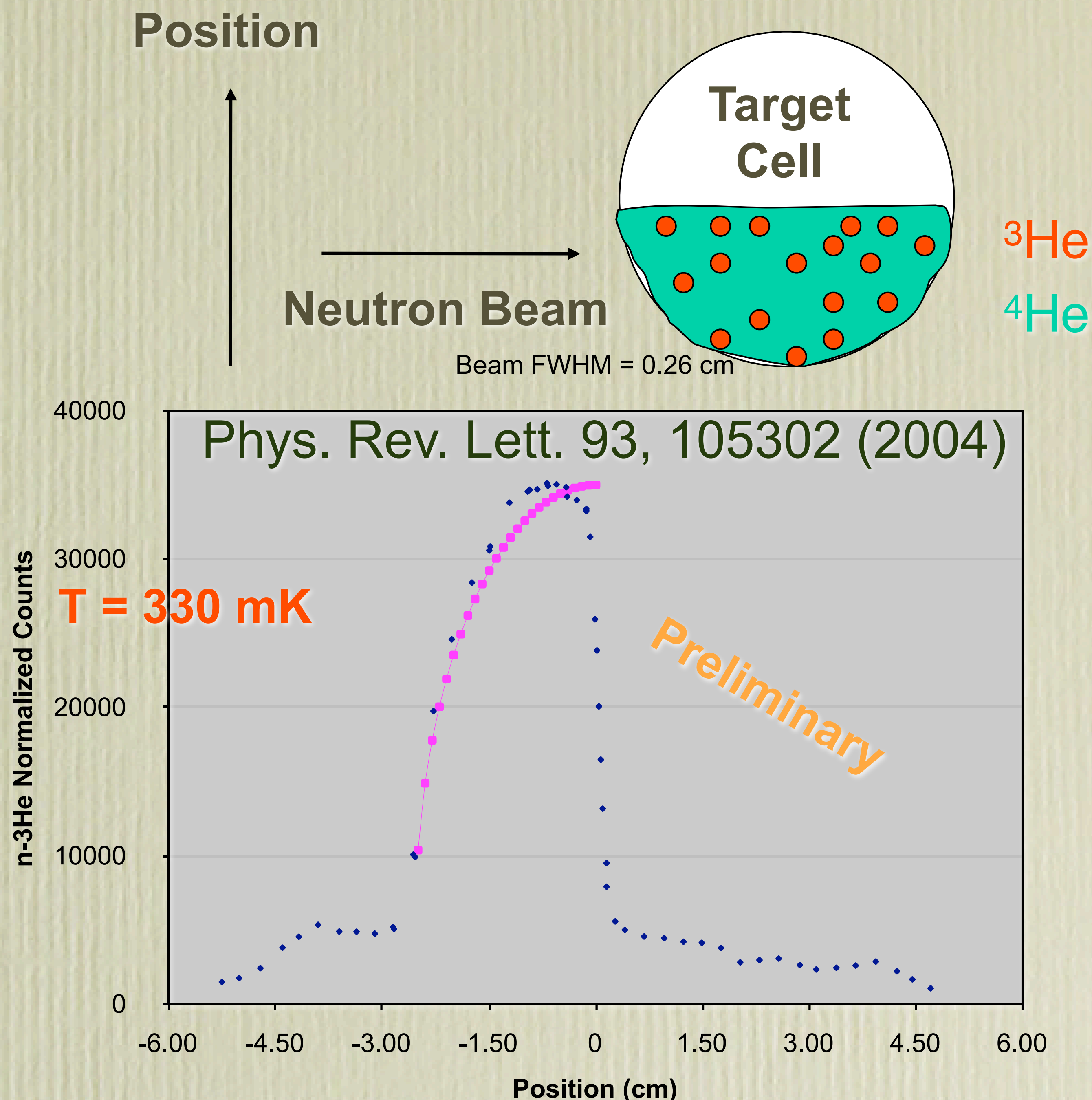
=>100 times larger UCN density than conventional UCN sources





3He Distributions in Superfluid 4He

Dilution Refrigerator at LANSCE Flight Path 11a

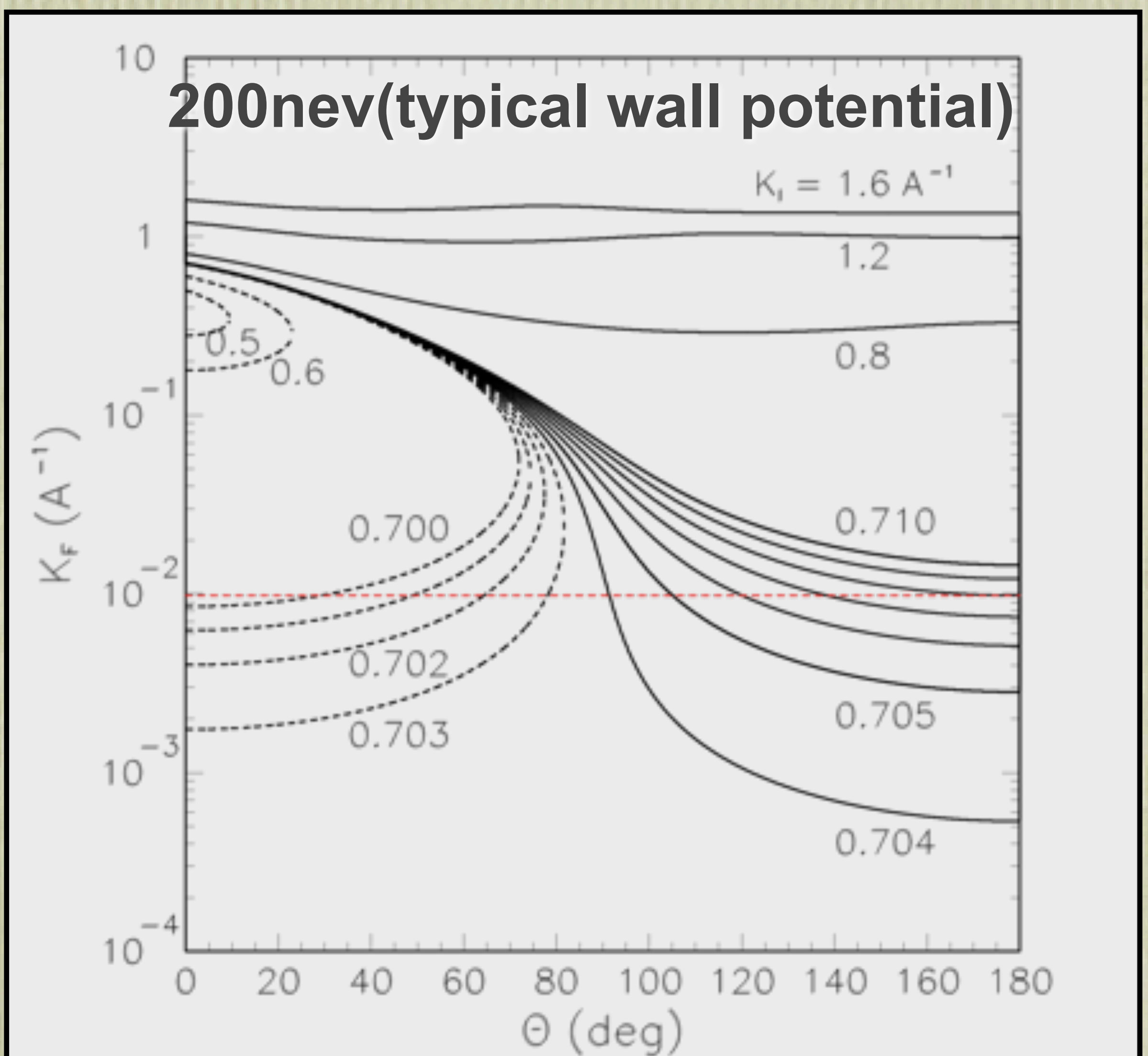


- The experiment shows neutrons distribute uniformly in the superfluid 4He. The result confirms the availability of 3He as a comagnetometer.

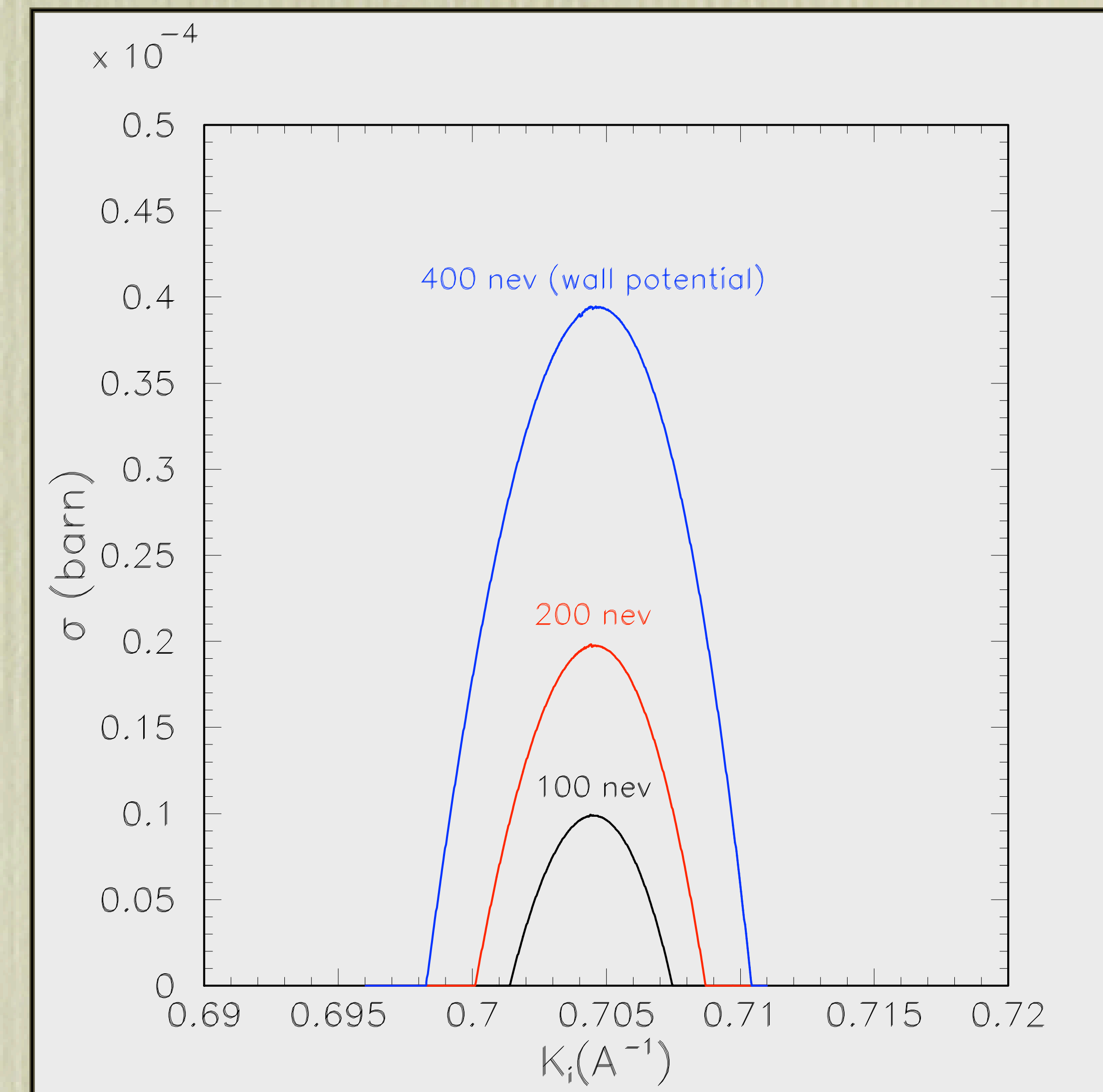
Production of UCN in superfluid 4He

$$\vec{Q} = \vec{k}_i - \vec{k}_f,$$
$$\frac{\hbar^2 k_i^2}{2m} = \frac{\hbar^2 k_f^2}{2m} + E(Q),$$

E(Q) is the phonon dispersion relation



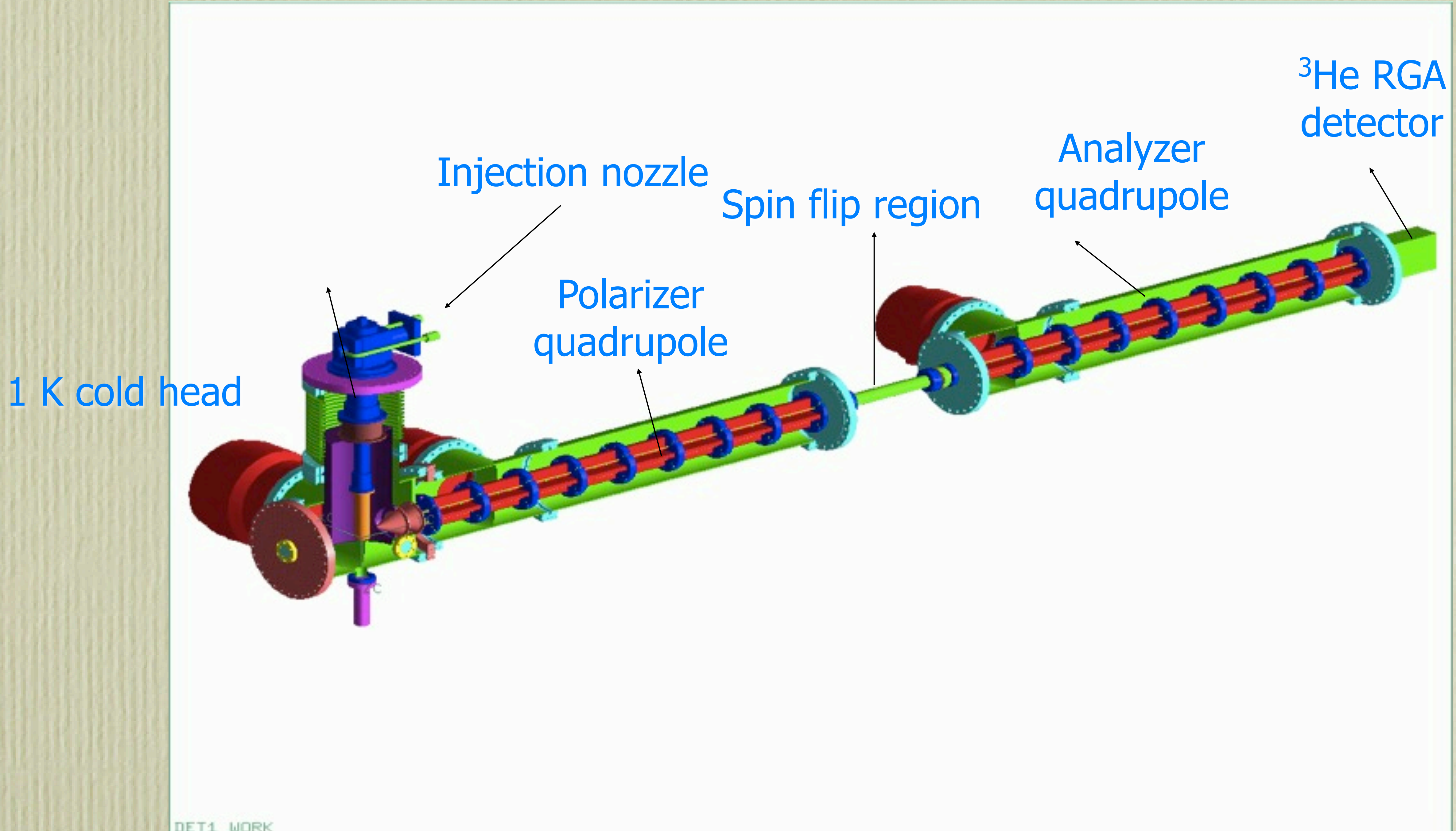
θ is neutron's scattering angle



For 1 mev neutron beam, σ(UCN)/σ(tot) ~ 10^{-3} for 200 nev wall potential

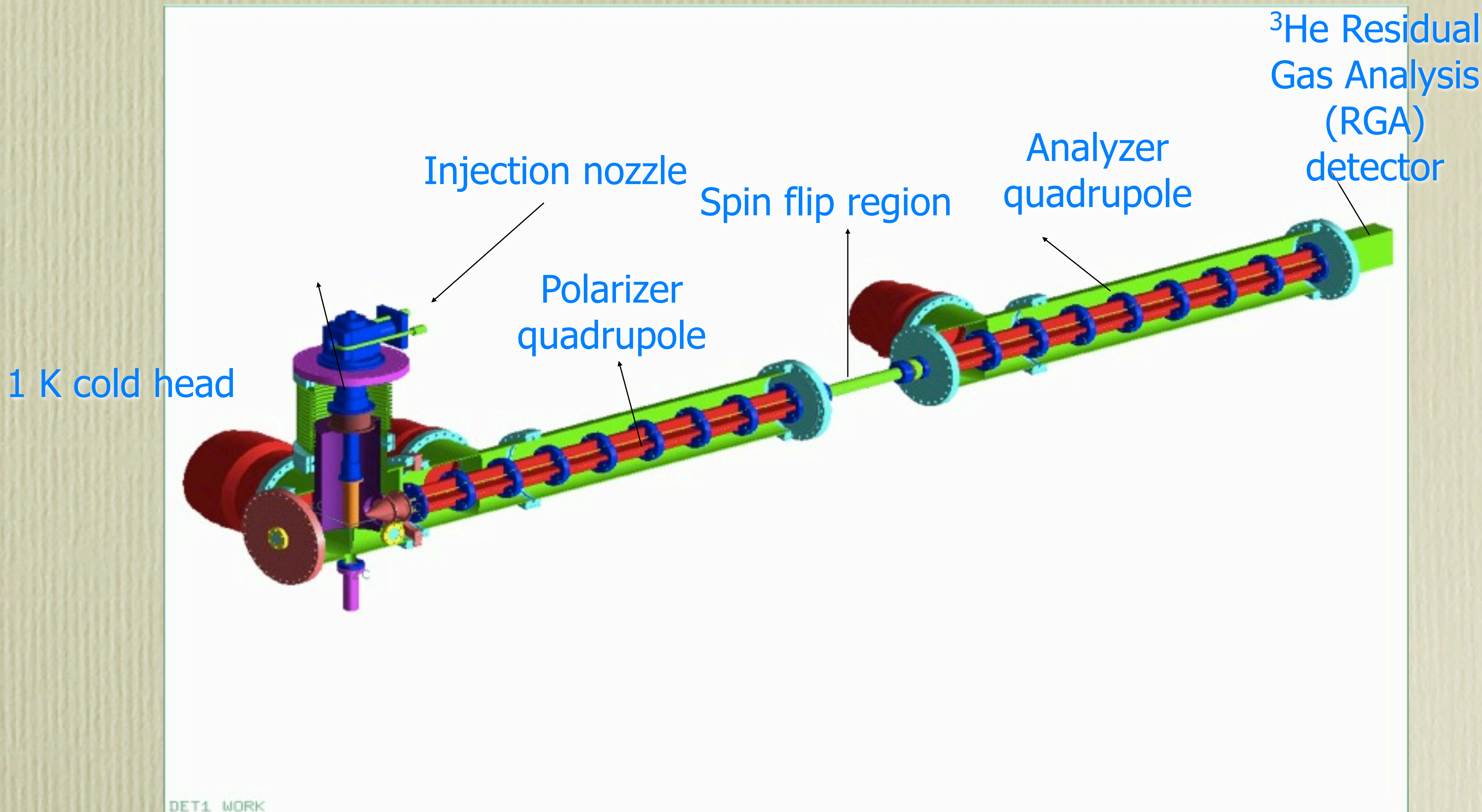
Mono-energetic cold neutron beam with ΔKi/Ki ~ 2%

Polarized 3He Atomic Beam Source

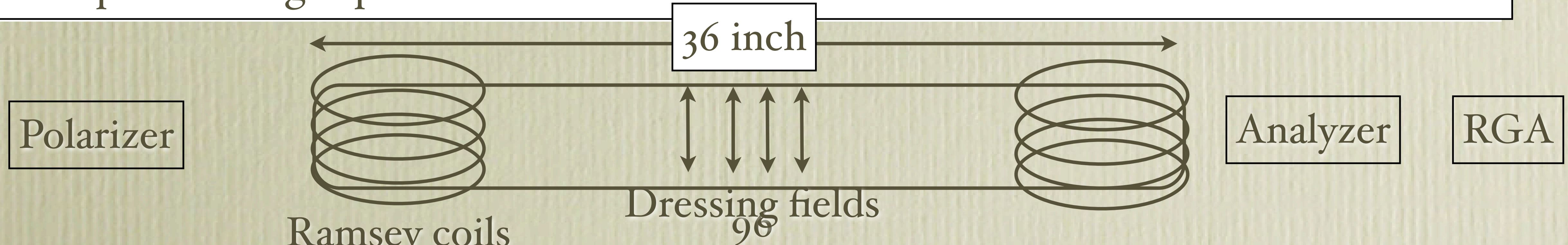


- Produce polarized 3He with 99.5% polarization at a flux of 2×1014/sec and a mean velocity of 100 m/sec

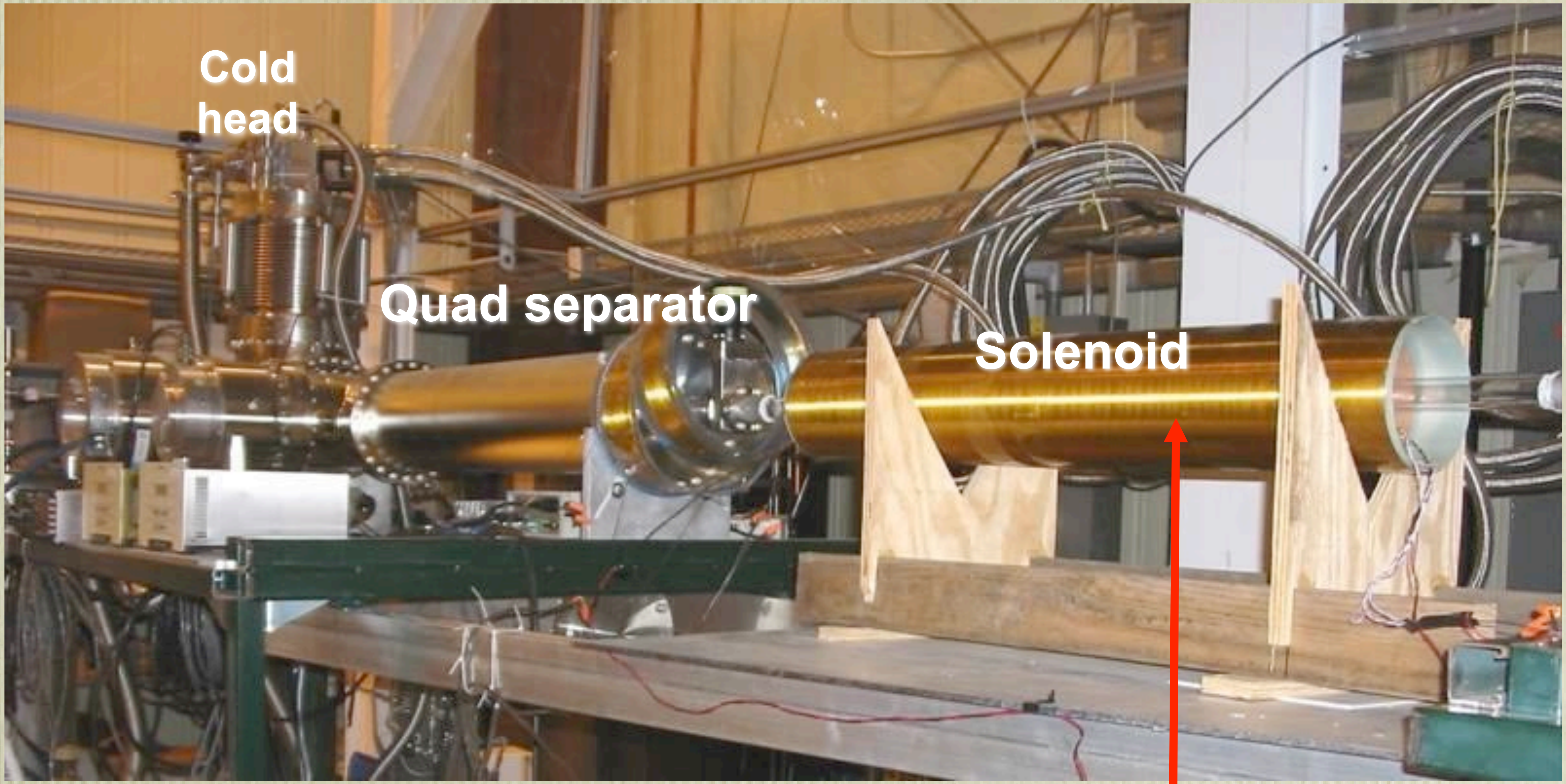
Los Alamos Polarized 3He Source



•3He Spin dressing experiment

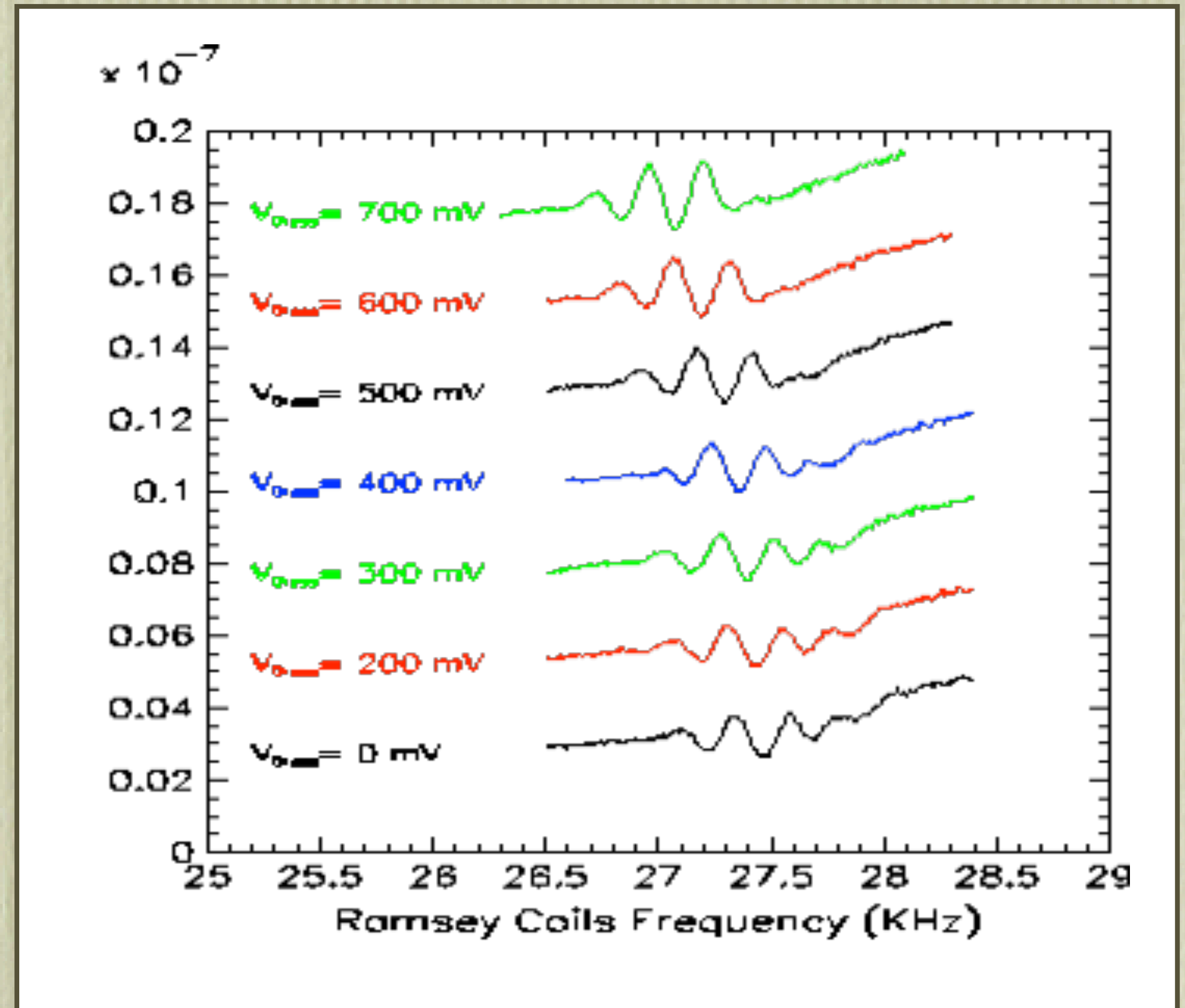


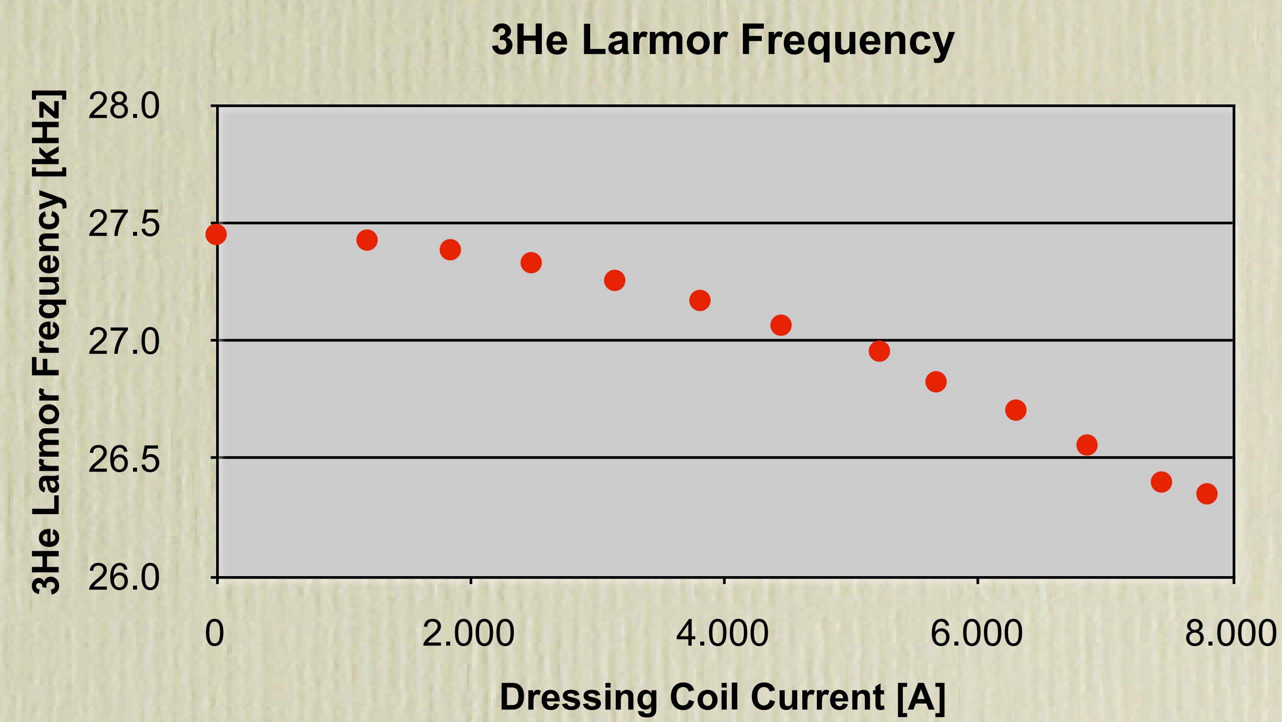
Mapping the dressing field



Spin-flip coils and dressing coils used inside the solenoid.

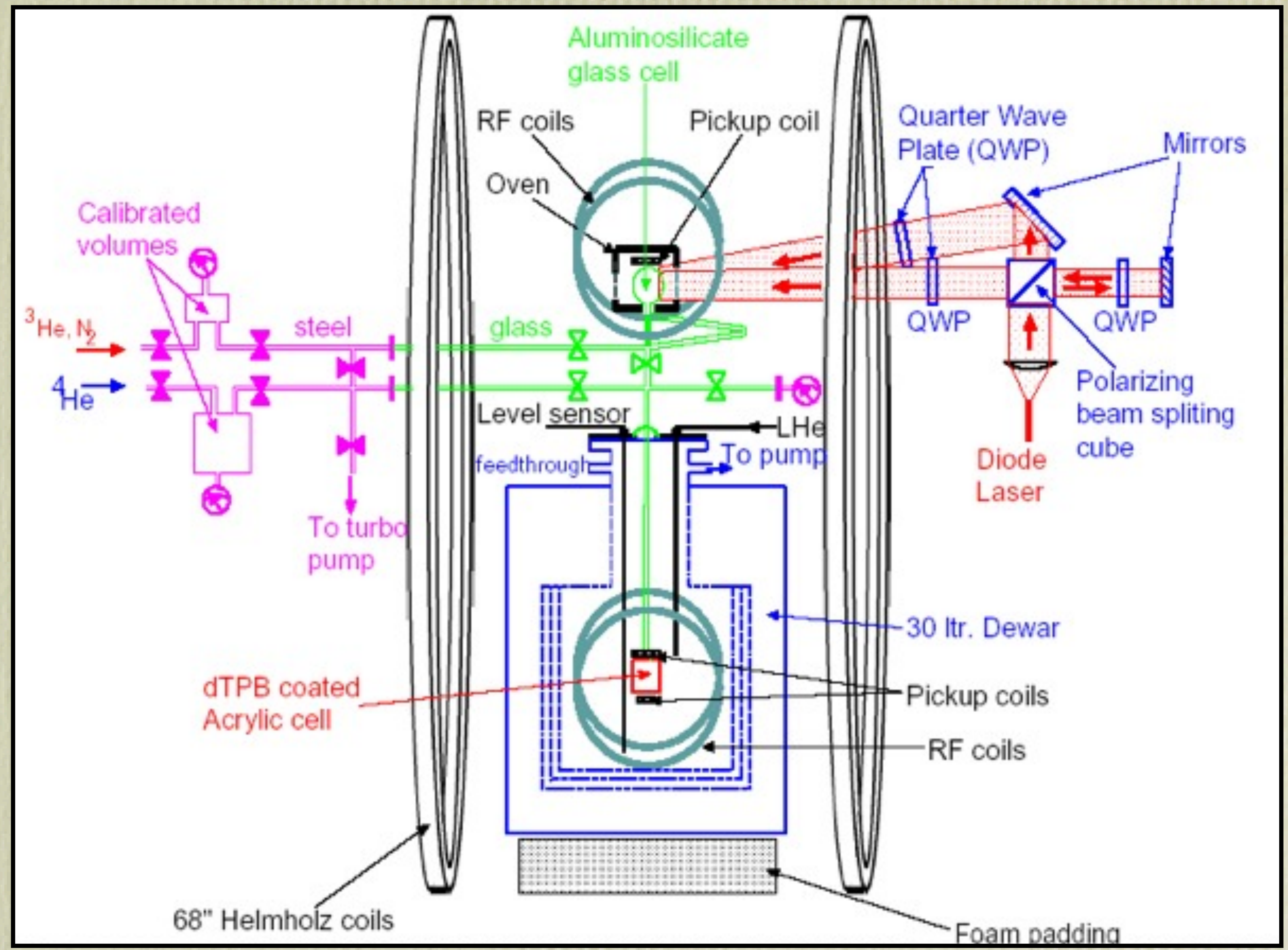
Experiment result





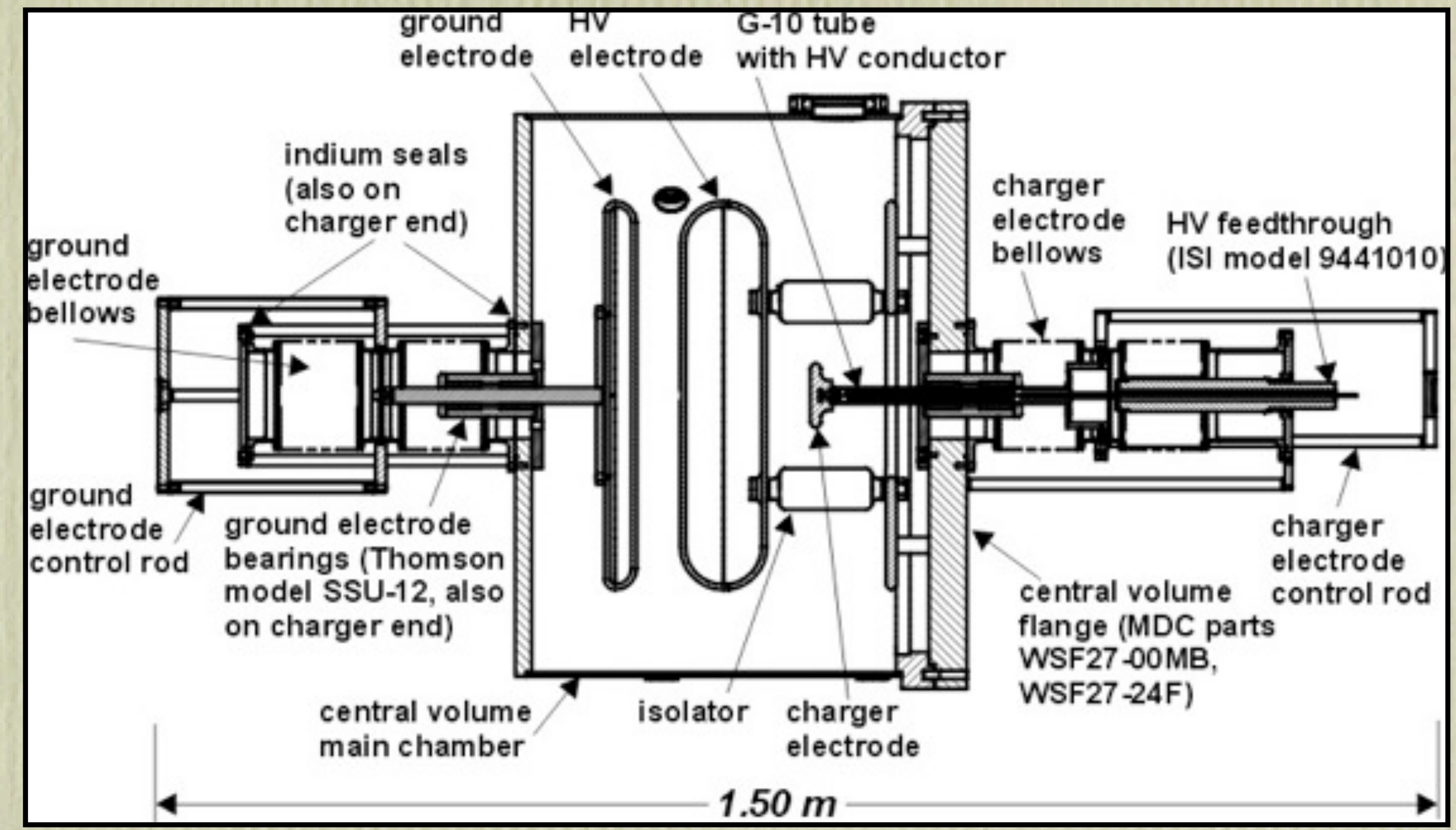
Esler, Peng, Lamoreaux, et al. Nucl-ex/0703029 (2007)

3He relaxation test



- T1 > 3000 seconds in 1.9K superfluid 4He
- Acrylic cell coated with dTPB
- H. Gao, R. McKeown, et al, arXiv:Physics/0603176
- Test has also been done at 600 mK at UIUC

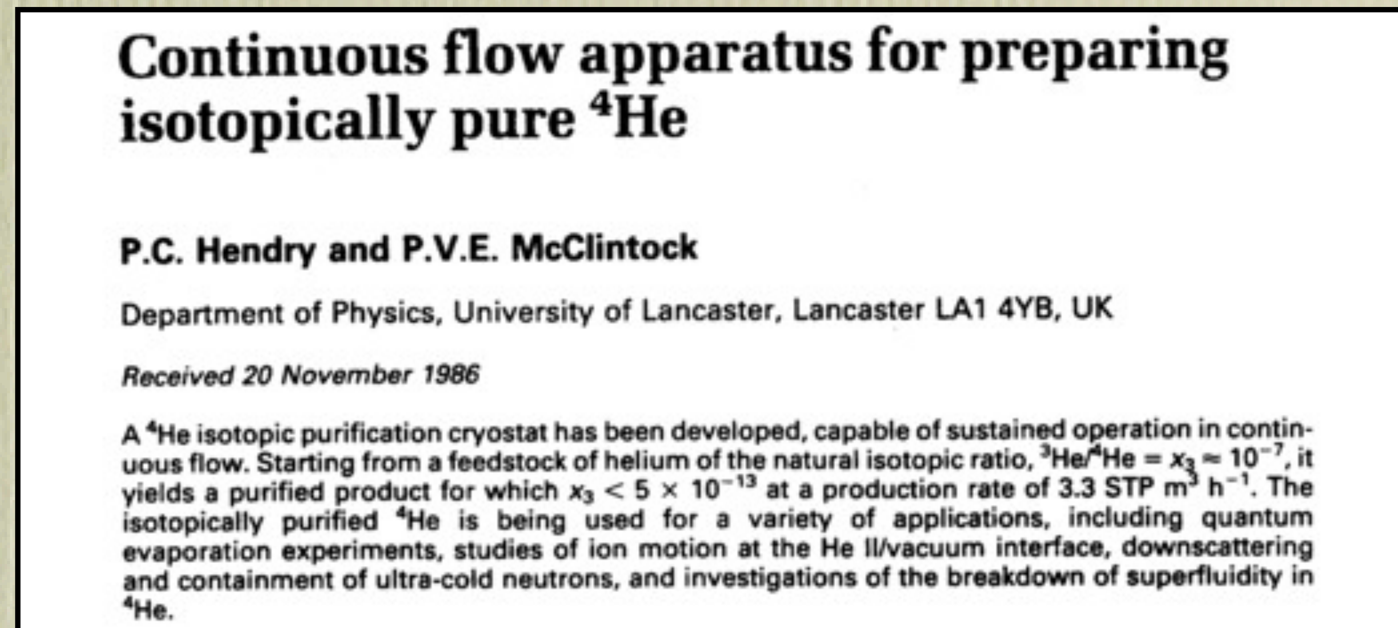
High voltage test



- Goal is 50 kV/cm
- 200 liter LHe. Voltage is amplified with a variable capacitor
- 90 kV/cm is reached for normal state helium. 30 kV/cm is reached below the λ-point
- J. Long et al., arXiv:physics/0603231

Heat flash

- The helium extracted from gas contains $^3He/^4He = 10^{-7}$.
- The heat flash technique can purify the helium to $^3He/^4He = 10^{-12}$.
- ^3He atoms in He II form part of the normal fluid component and tend to move to colder end of the apparatus.
- The normal fluid component, flowing away from the heater, will tend to carry with any 3He atoms and to prevent others from entering.
- The isotopically pure superfluid component can be drawn off in the opposite direction.



Continuous flow apparatus for preparing isotopically pure ^4He

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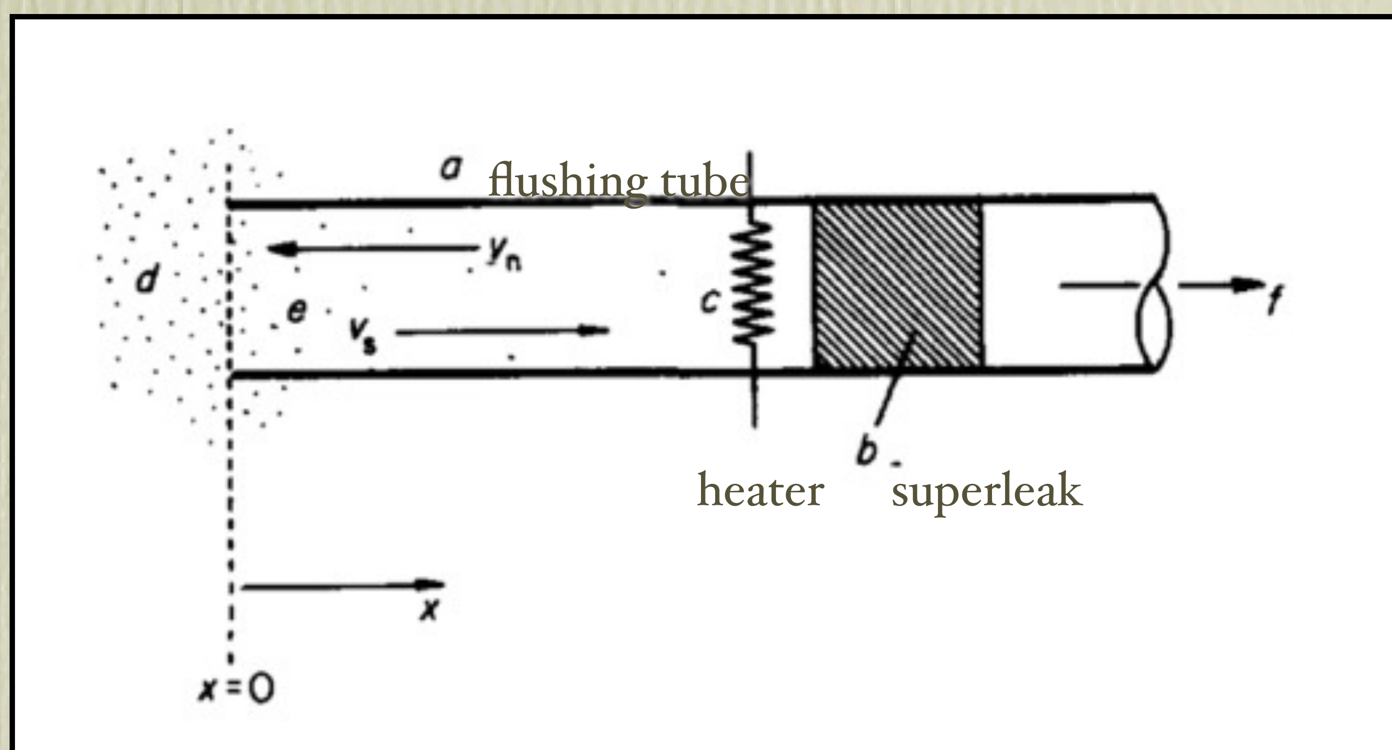
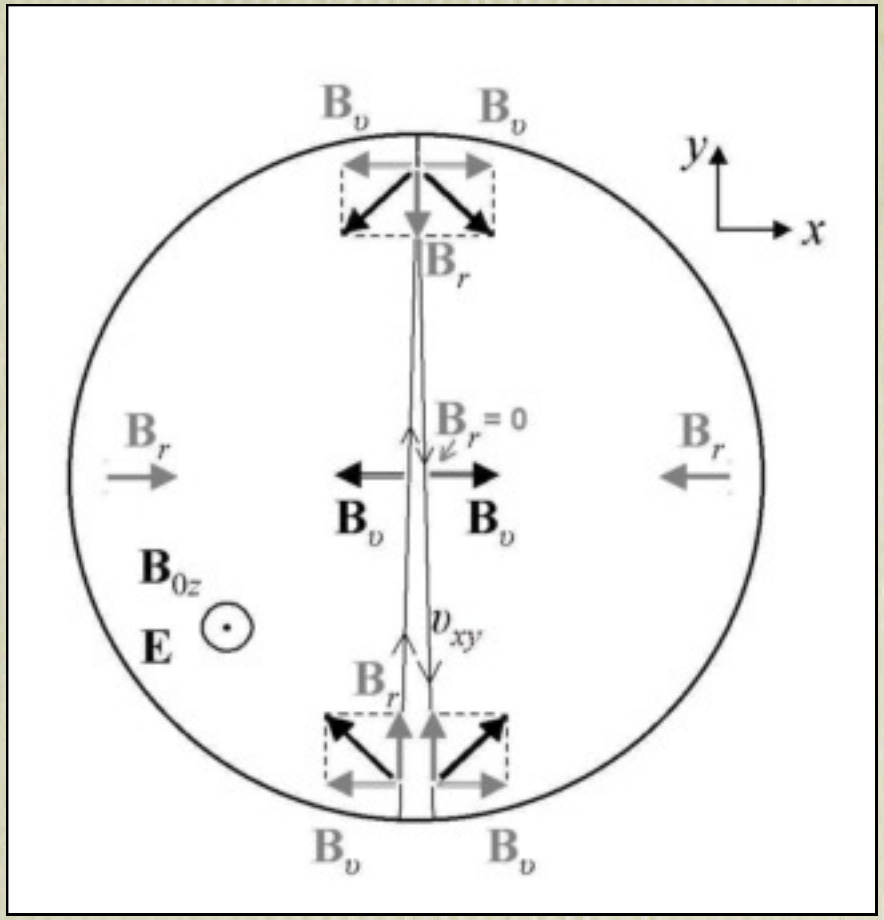
Received 20 November 1986

A ^4He isotopic purification cryostat has been developed, capable of sustained operation in continuous flow. Starting from a feedstock of helium of the natural isotopic ratio, $^3He/^4He = x_3 \approx 10^{-7}$, it yields a purified product for which $x_3 < 5 \times 10^{-13}$ at a production rate of 3.3 STP $m^3 h^{-1}$. The isotopically purified ^4He is being used for a variety of applications, including quantum evaporation experiments, studies of ion motion at the He II/vacuum interface, downscattering and containment of ultra-cold neutrons, and investigations of the breakdown of superfluidity in ^4He.



Geometric phase

- The false EDM can arise from geometric phases.
- The effect between vxE and a vertical gradient in the magnetic field.
- Gives a radial field $$B_r = -\frac{r}{2} \cdot \frac{\partial B}{\partial z}$$
- The radial field as well as to the sideways vxE component, yielding a diagonal resultant.
- The net effect that the additional effective field continues to rotate in the same direction.
- The shift in frequency is proportional to E, mimicking an EDM signal.



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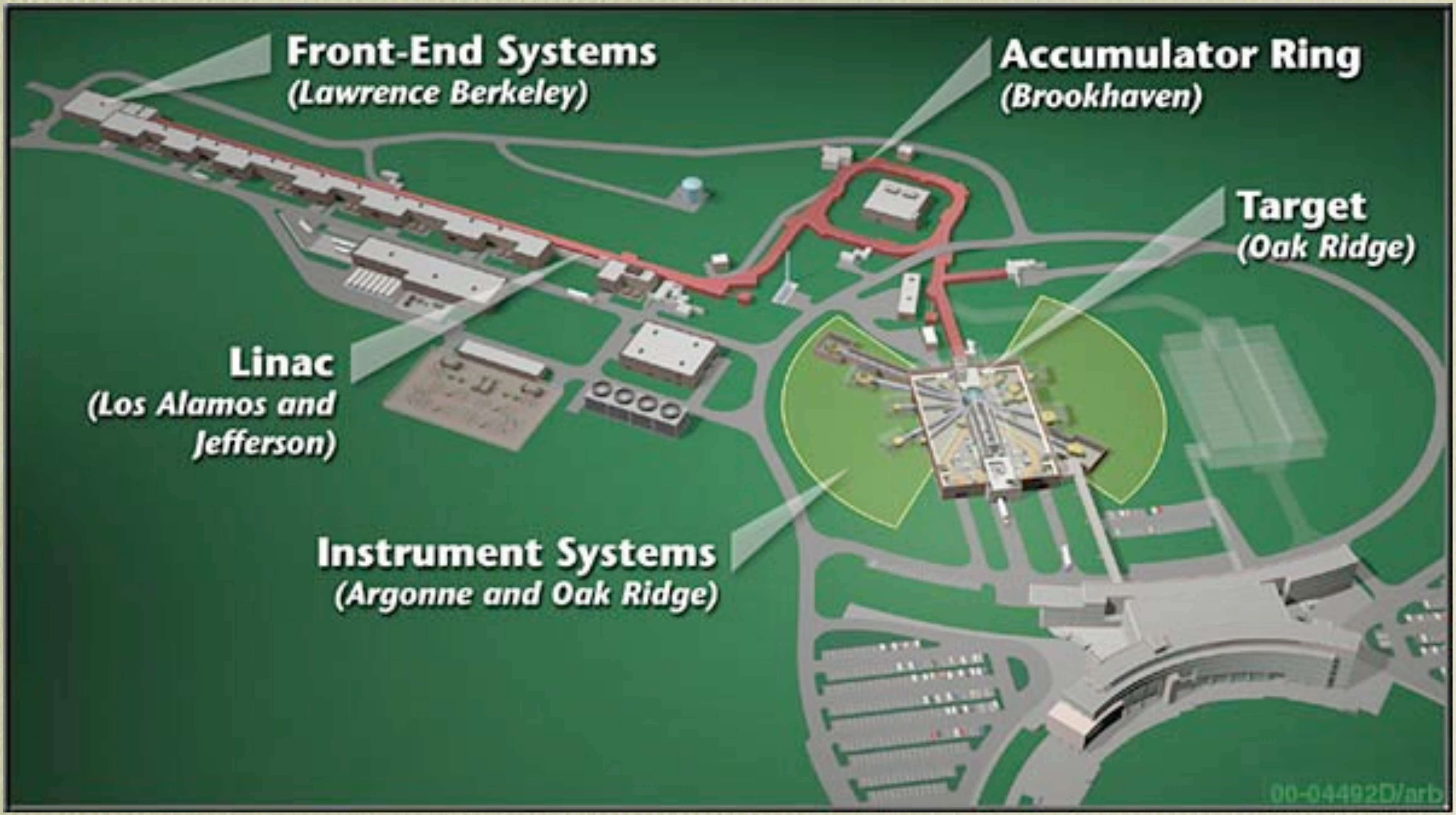
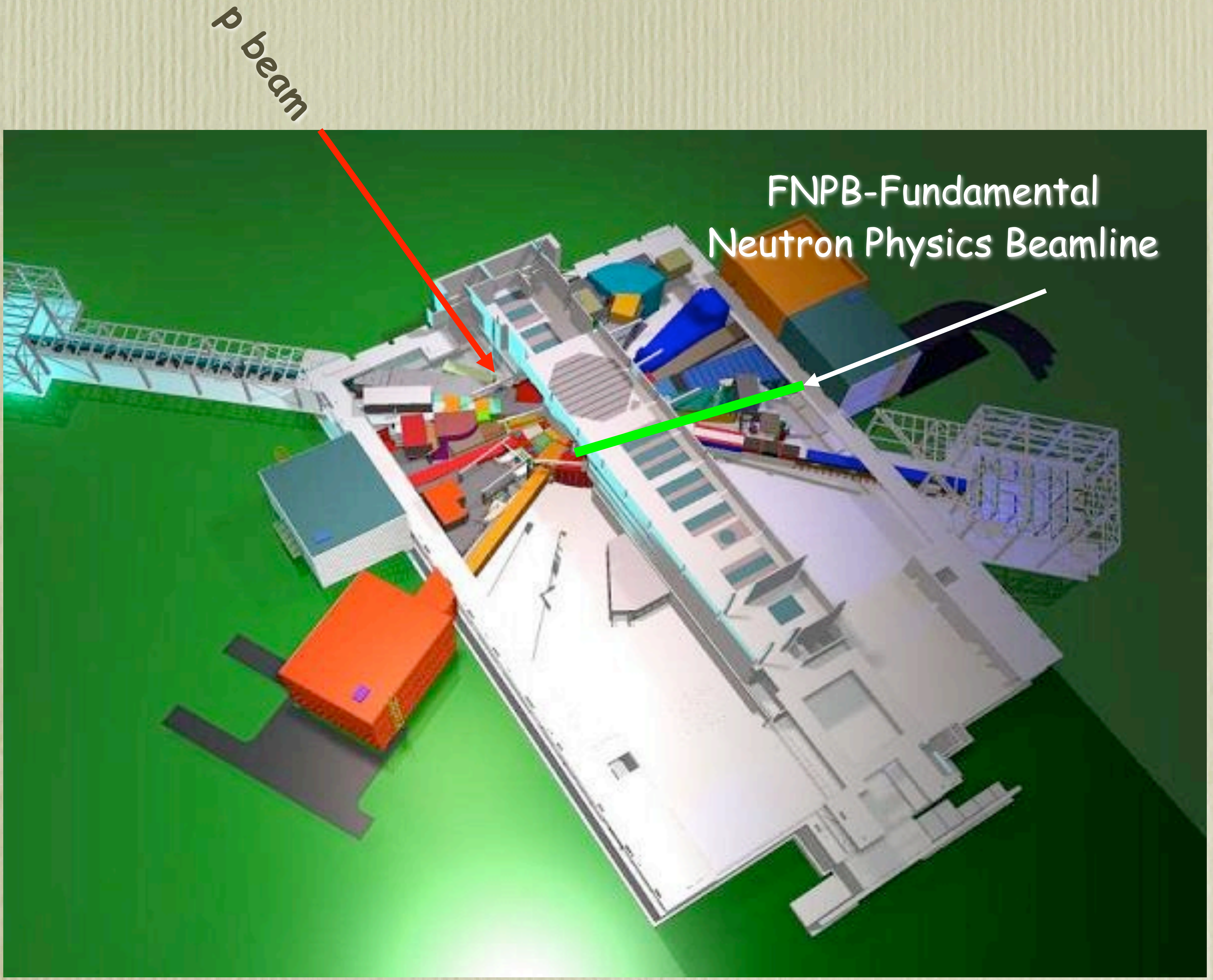
1.4 MW Spallation Source (1GeV proton, 1.4mA)

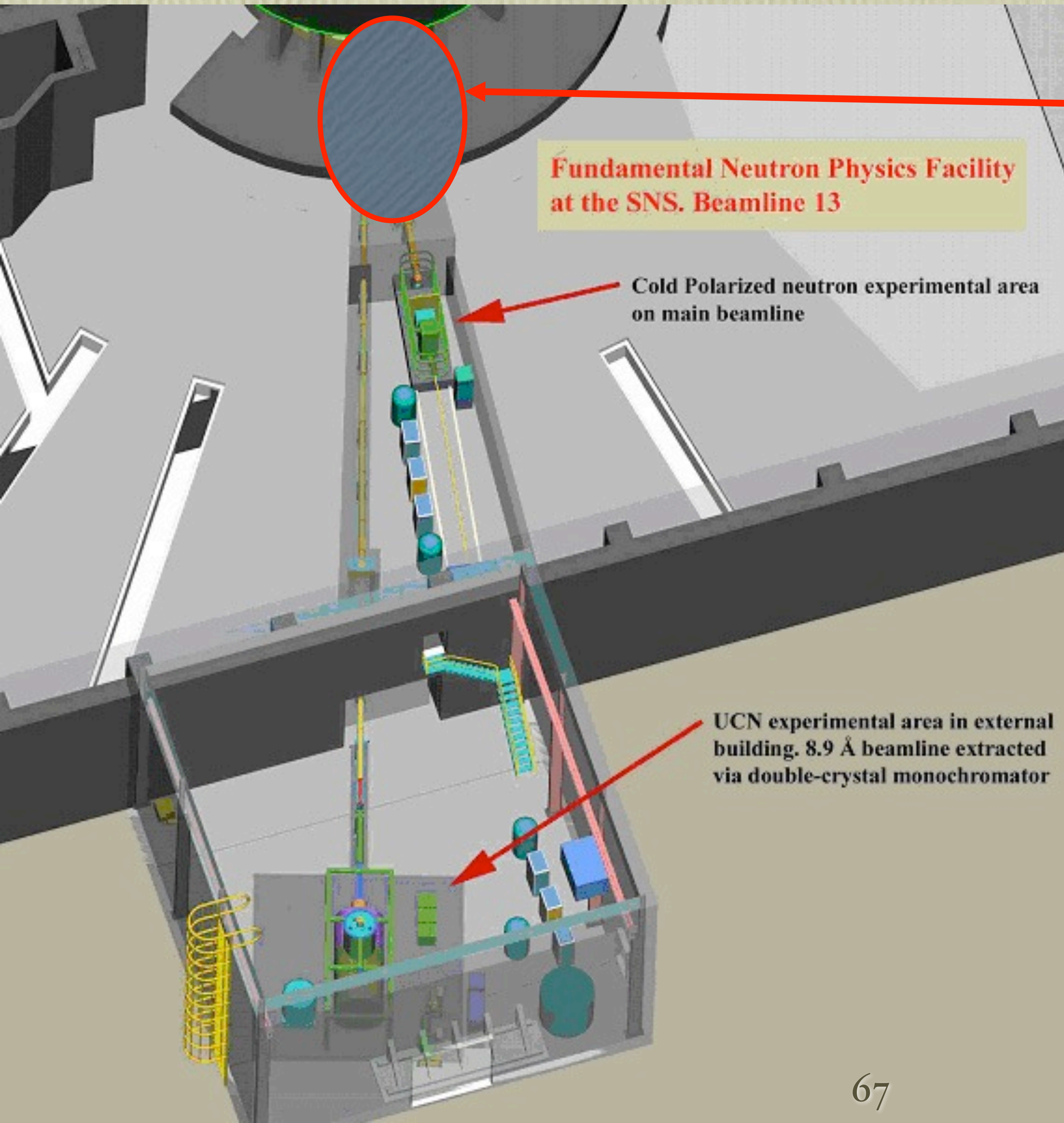


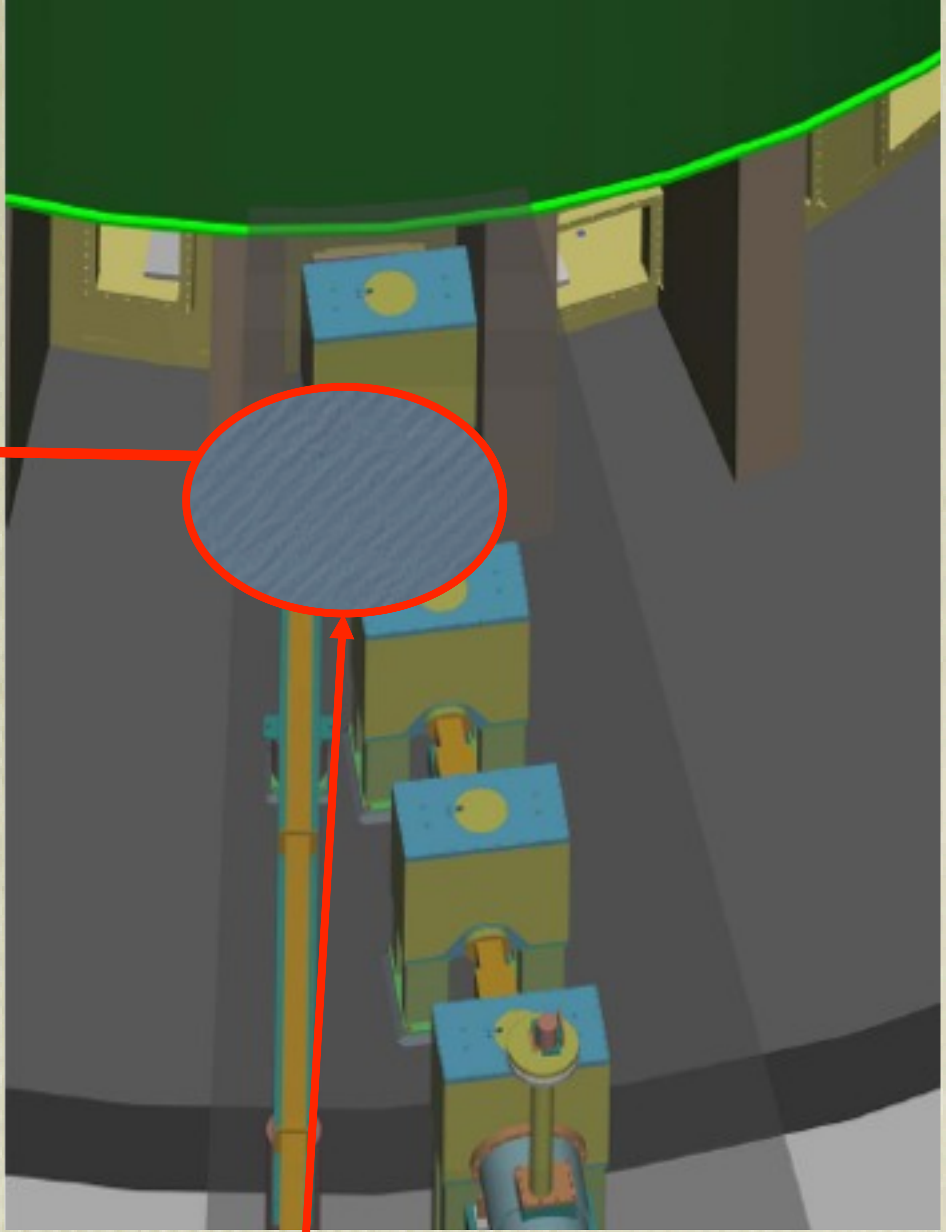


FNPB construction underway

Cold beam available ~2007

UCN line via LHe ~2009





Double
monochrometer

Selects 8.9 Å
neutrons
for UCN via LHe

History of neutron EDM experimetns

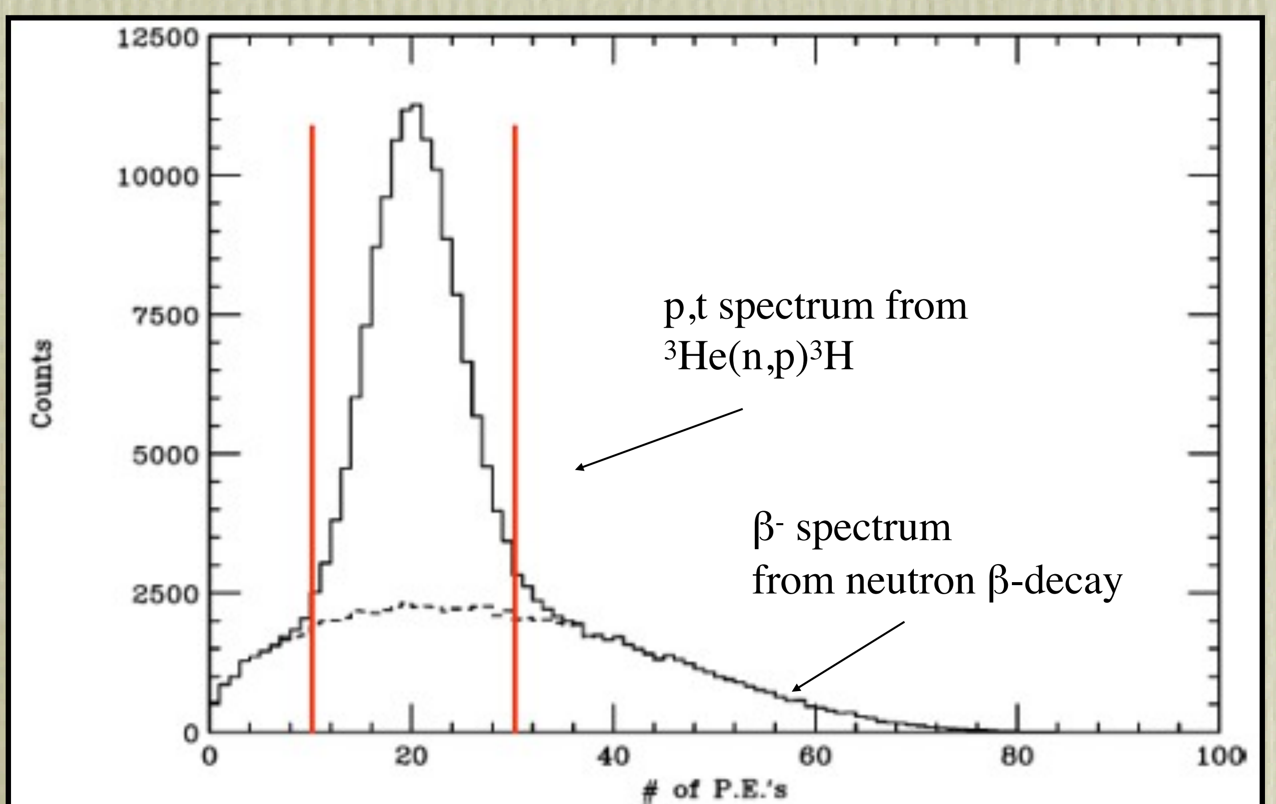
Ex. Type	<v>(m/cm)	E (kV/cm)	B (Gauss)	Coh. Time (s)	EDM (e.cm)	year
Scattering	2200	10^{25}	--	10^{-20}	< 3 x 10^{-18}	1950
Beam Mag. Res.	2050	71.6	150	0.00077	< 4x 10^{-20}	1957
Beam Mag. Res.	60	140	9	0.014	< 7 x 10^{-22}	1967
Bragg Reflection	2200	10^{9}	--	10^{-7}	< 8 x 10^{-22}	1967
Beam Mag. Res.	130	140	9	0.00625	< 3 x 10^{-22}	1968
Beam Mag. Res.	2200	50	1.5	0.0009	< 1 x 10^{-21}	1969
Beam Mag. Res.	115	120	17	0.015	< 5 x 10^{-23}	1969
Beam Mag. Res.	154	120	14	0.012	< 1 x 10^{-23}	1973
Beam Mag. Res.	154	100	17	0.0125	< 3 x 10^{-24}	1977
UCN Mag. Res.	<6.9	25	0.028	5	< 1.6 x 10^{-24}	1980
UCN Mag. Res.	<6.9	20	0.025	5	< 6 x 10^{-25}	1981
UCN Mag. Res.	<6.9	10	0.01	60-80	< 8 x 10^{-25}	1984
UCN Mag. Res.	<6.9	12-15	0.025	50-55	< 2.6 x 10^{-25}	1986
UCN Mag. Res.	<6.9	16	0.01	70	< 12 x 10^{-26}	1990
UCN Mag. Res.	<6.9	12-15	0.018	70-100	< 9.7 x 10^{-26}	1992
UCN Mag. Res.	<6.9	4.5	0.01	120-150	< 6.3 x 10^{-26}	1999

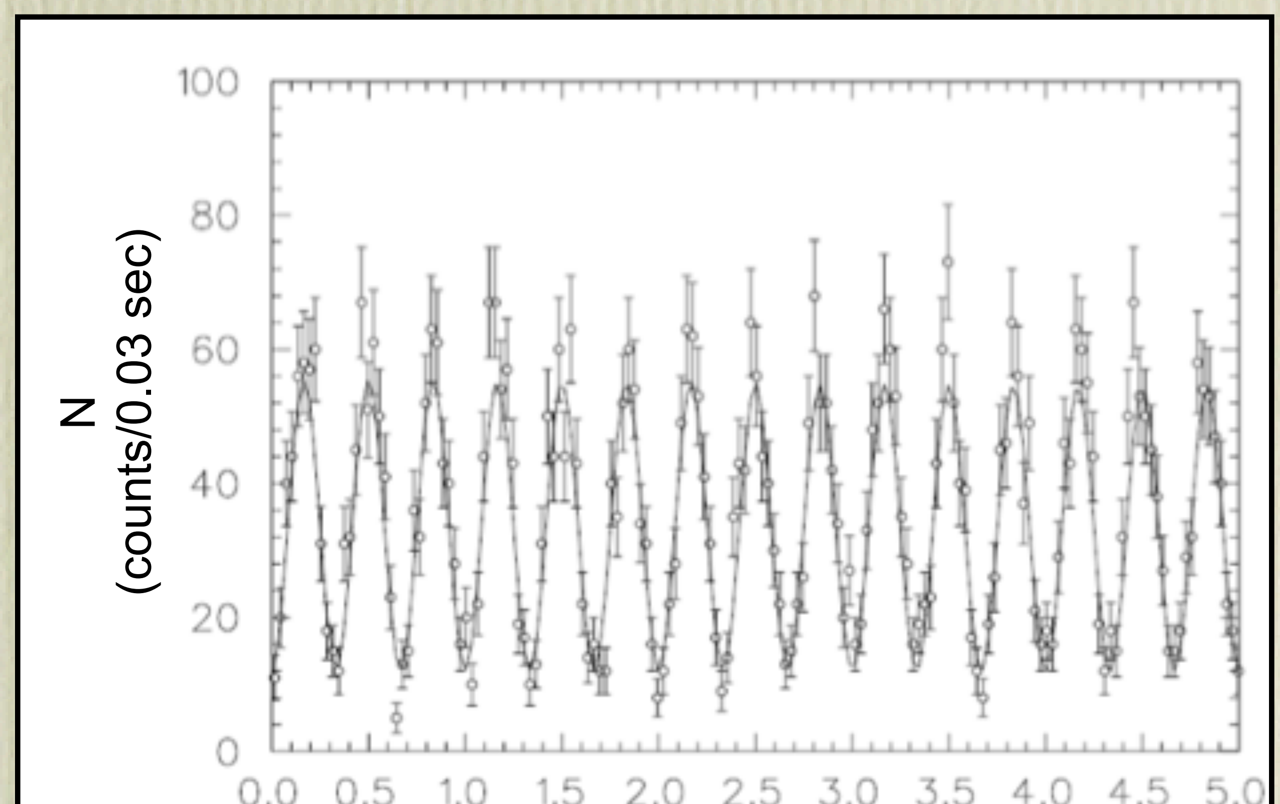
- B = 1mG => 3 Hz neutron precession freq.
- d = 10^-26 e•cm, E = 10 KV/cm => 10^-7 Hz shift in precession freq.

nEDM statistical sensitivity

- 300 live days over 3 years (due to accelerator/experiment uptime)
- Optimal projected sensitivity (@ 90% CL) : d = 7.8 x 10^-28 e cm
- Width of neutron capture signal given by number of photoelectrons
- Capture light is partially quenched compared to β-decay electrons
- σ_d depends on σ_f

$$\sigma_{d_n} = \hbar \frac{1.64\sigma_f}{4E_0}\sqrt{2}$$





nEDM systematic uncertainty

(Brad Filippone)

- Pseudomagnetic field
  - Due to spin-dependence of n-3He scattering length – gives frequency shift as $\sigma_n \cdot \sigma_3$ varies
  - Gives frequency noise if $\pi/2$ pulse varies
  - Precision spin flip needed anyway if we want to fix the phase
  - 10^-3 reproducibility with both cells < 5% different is sufficient for 10^-28 e cm

- Gravitational effects
  - 10^-29 e cm if leakage ~ 1 nA for ~ 10 cm cell
  - Thermal offsets could give larger effects

- Quadratic vxE effect
  - < 10-28 e cm if E-field reversal is good to 1%

- Geometric Phase – linear vxE effect
  - From Golub, Swank & Lamoreaux
  - Probably biggest potential systematic issue

nEDM systematic uncertainty

(Brad Filippone)

- Significantly different effects for neutron vs 3He
  - Neutron has $\omega_o >> \omega_L$ (ω_L is cell traversal frequency) and is largely independent of cell geometry.
    - Can use previous analysis of geometric phase
  - 3He has $\omega_o << \omega_L$ and is sensitive to cell geometry
    - Depends on diffusion time to walls (geometry & temperature)
    - False EDM in rectangular geometry: Golub,Swank & Lamoreaux arXiv:0810.5378
- Effect depends on Magnetic Field gradients (B_o along x-direction)

nEDM systematic uncertainty

(Brad Filippone)

Error Source	Systematic	Comments
Linear vxE (geometric phase)	$< 2 \times 10^{-28}$	Uniformity of B0 field
Quadratic vxE	$< 0.5 \times 10^{-28}$	E-field reversal to <1%
Pseudomagnetic Field Effects	$< 1 \times 10^{-28}$	pi/2 pulse, comparing 2 cells
Gravitational offset	$< 0.1 \times 10^{-28}$	With 1 nA leakage currents
Leakage currents	$< 1 \times 10^{-28}$	< 1 nA
vxE rotational n flow	$< 1 \times 10^{-28}$	E-field uniformity < 0.5%
E-field stability	$< 1 \times 10^{-28}$	$\Delta E/E < 0.1\%$
Miscellaneous	$< 1 \times 10^{-28}$	Other vxE, wall losses

Possible upgrade paths

(Brad Filippone)

Once experiment demonstrates that it's sensitivity is limited by neutron flux (first phyiscs result) ...

- Could "move" experiment to cold beam at FNPB (or vice versa)
  - Choppers instead of monochromator could increase

    8.9 Å flux by ~ 6x ($d_n < 4 \times 10^{-28}$ e-cm)
- Could "move" experiment to planned 2nd target station at SNS
  - 1 MW, optimized for long wavelength neutrons
  - Could increase 8.9 Å flux by > 20 ($d_n < 2 \times 10^{-28}$ e-cm)

CD0 – 1/09

Also NIST or PULSTAR possible

Active worldwide effort to improve neutron EDM sensitivity

(Brad Filippone)

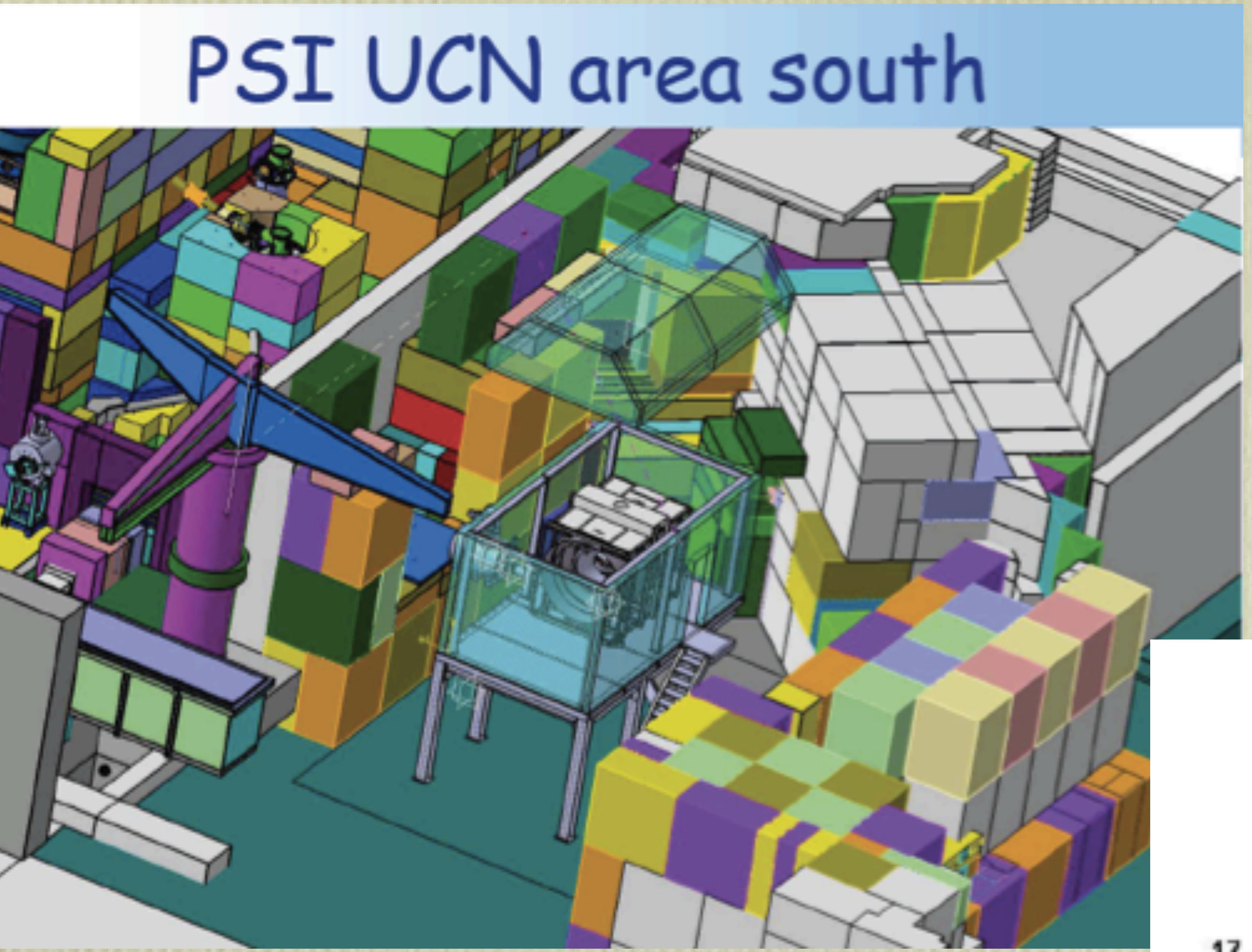
Exp	UCN source	cell	Measurement techniques	σ_d (10^{-28} e-cm)
ILL CryoEDM	Superfluid ^4He	^4He	Ramsey technique for ω External SQUID magnetometers	Phase1 ~ 50 Phase2 < 5
PNPI – I LL	ILL turbine PNPI/Solid D_2	Vac.	Ramsey technique for ω E=0 cell for magnetometer	Phase1<100 < 10
ILL Crystal	Cold n Beam		Crystal Diffraction	< 100
PSI EDM	Solid D_2	Vac.	Ramsey technique for ω External Cs & ^3He magnetometers Hg co-mag for P1, Xe for P2?	Phase1 ~ 50 Phase2 ~ 5
SNS EDM	Superfluid ^4He	^4He	^3He capture for ω ^3He comagnetometer SQUIDS & Dressed spins	~ 8
TRIUMF/JPARC	Superfluid ^4He	Vac.	Under Development	?

Comparison of worldwide

(Brad Filippone)

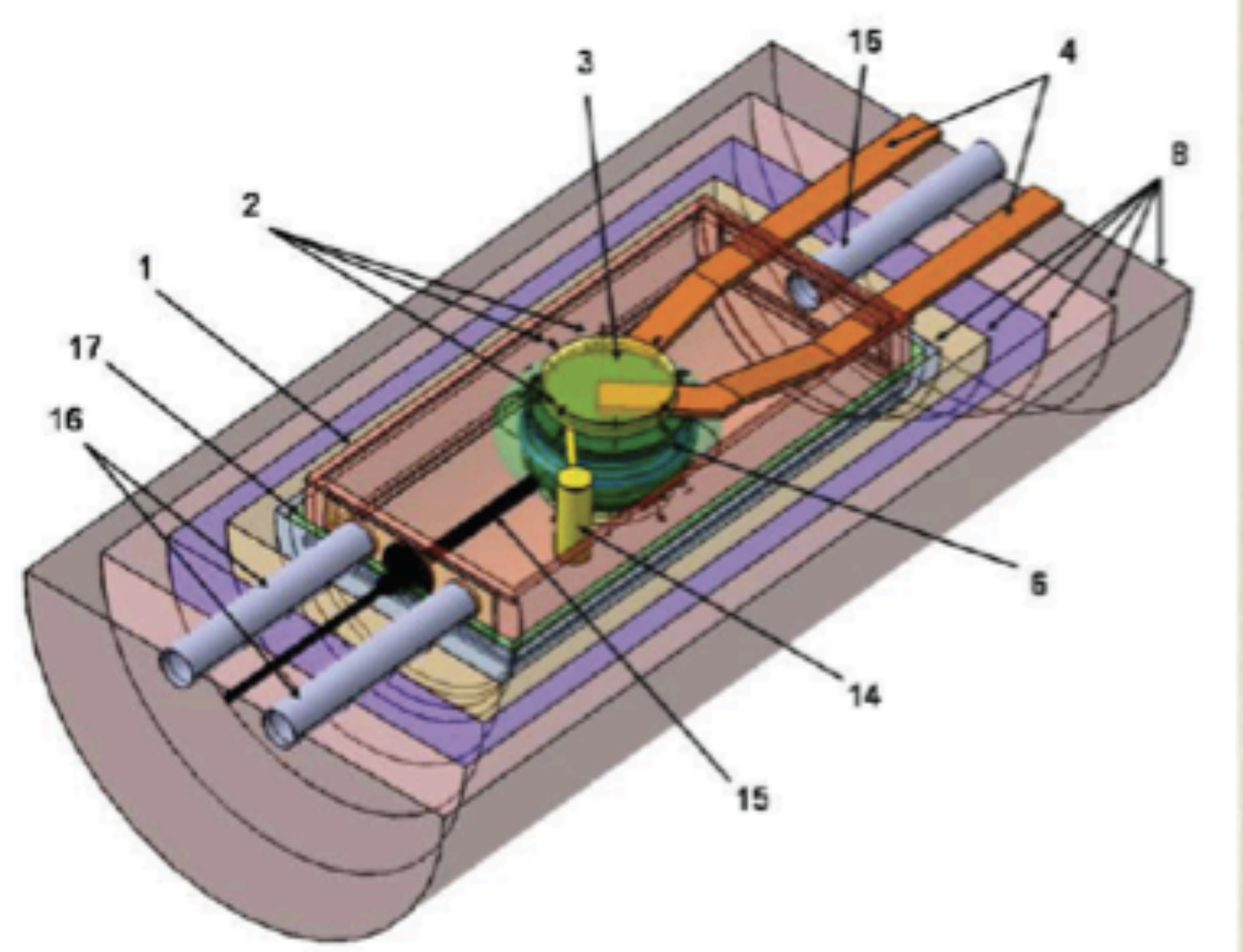
- Comparing sensitivities from different experiments is somewhat qualitative(depends on many assumptions)
- At present, ILL CryoEDM and PSI-nEDM appear to be the most competitive with SNS nEDM
- Both ILL-CryoEDM and PSI-nEDM have 2 phases of measurement with some construction between the data periods

PSI high flux UCN source



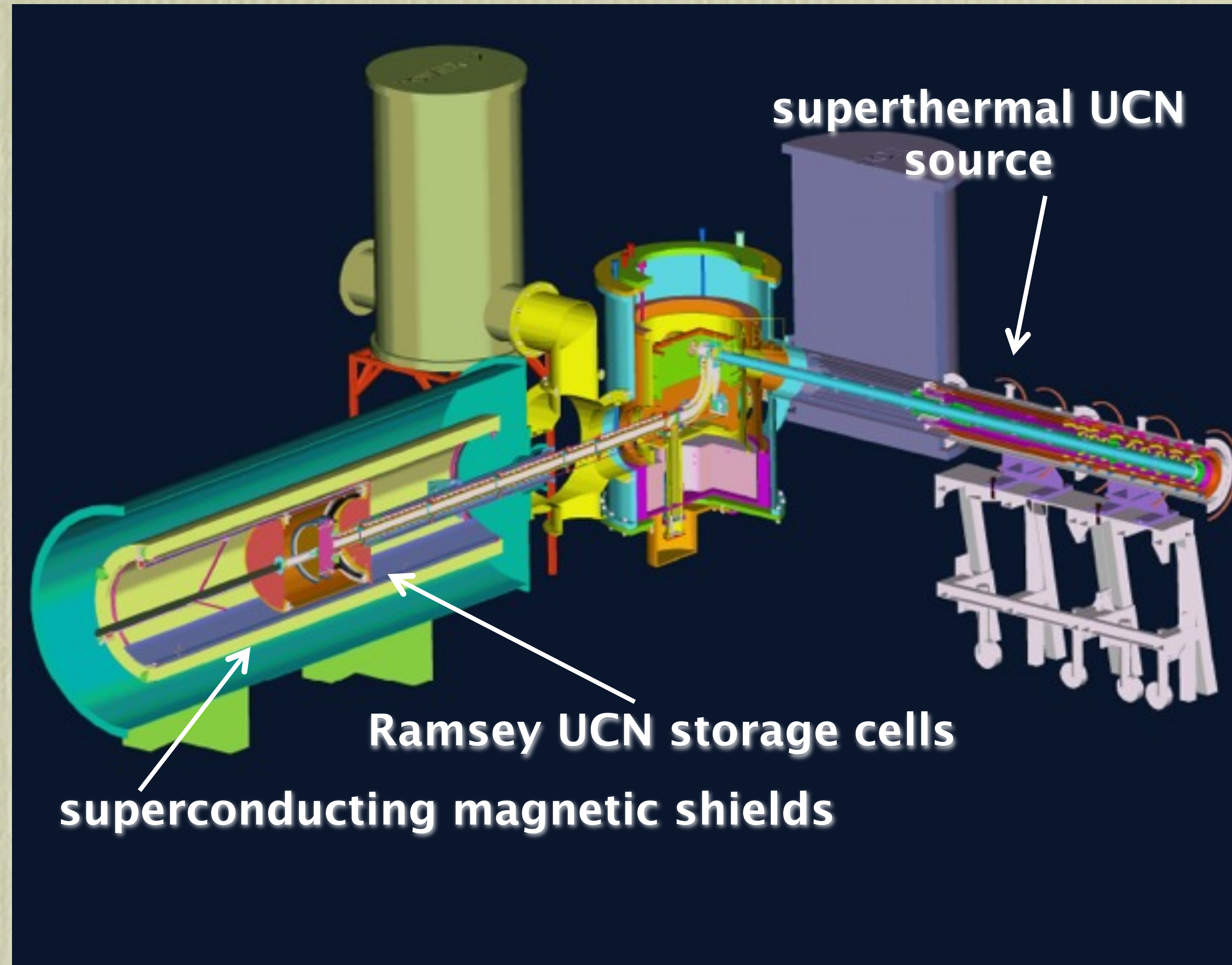
(Brad Filippone)

- Initial data will use original apparatus from ILL with magnetic upgrades
- New apparatus being designed for higher sensitivity



CryoEDM@ILL (Brad Filippone)

superthermal UCN source



whole experiment in superfluid He at 0.5 K

- production of UCN
- storage & Larmor precession of UCN
- SQUID magnetometry
- detection of UCN

Ongoing nEDM experiments schedules and sensitivities

(Brad Filippone)

Exp	Status	Schedule	Claimed Sensitivity (e-cm)
ILL CryoEDM	Phase 1 – underway Phase 2 – new beamline	2010-12 2012-15	$< 5 \times 10^{-27}$ $< 5 \times 10^{-28}$
PNPI-EDM	PNPI @ ILL Move to PNPI UCN	2010 ?	$\sim 10^{-26}$ $< 10^{-27}$
PSI EDM	Initial phase underway (using old ILL apparatus) New exp.	2010-13 2015	$\sim 5 \times 10^{-27}$ $\sim 5 \times 10^{-28}$
SNS EDM	Preparing Baseline	2016 2018	Commissioning $\sim 8 \times 10^{-28}$

Other factors

(Brad Filippone)

- The "known" systematic effects are part of the experimental design
- Tackling the unknown effects requires unique handles in the experiment that can be varied
- The significance of a non-zero result requires multiple approaches to unforeseen systematics
- nEDM @ SNS is unique in its use of a polarized ^{3}He co-magnetometer, characterization of geometric phase effects via temperature variation, as well as the dressed spin capability

Comparison of capabilities

(Brad Filippone)

■ (green) = included
■ (red) = not included

	CRYOEDM 1	CRYOEDM 2	PSIEDM 1	PSIEDM 2	SNSEDM
Δω via accumulated phase in n polarization	included	included	included	included	not included
Δω via light oscillation in ^{3}He capture	not included	not included	not included	not included	included
Co-magnetometer	not included	not included	included	?	included
Superconducting B-shield	included	included	not included	not included	included
Dressed Spin Technique	not included	not included	not included	not included	included
Horizontal B-field	included	included	not included	not included	included
Multiple EDM cells	not included	included	not included	included	included

Note that red vs green does not necessarily signify good vs bad. But understanding systematics requires mix of red & green.