$\tilde{\mathcal{G}}$ switch

Zhen Han,Peiran Hu

Outline

What is G switch

Theory for G switch: How it works

- Polarization of light under G switch
- Spin misalignment and EDM systematic
- Imperfect optical pumping
- G switch suppression

Historical Evidence for G switch

ACME III Field Plates requirements

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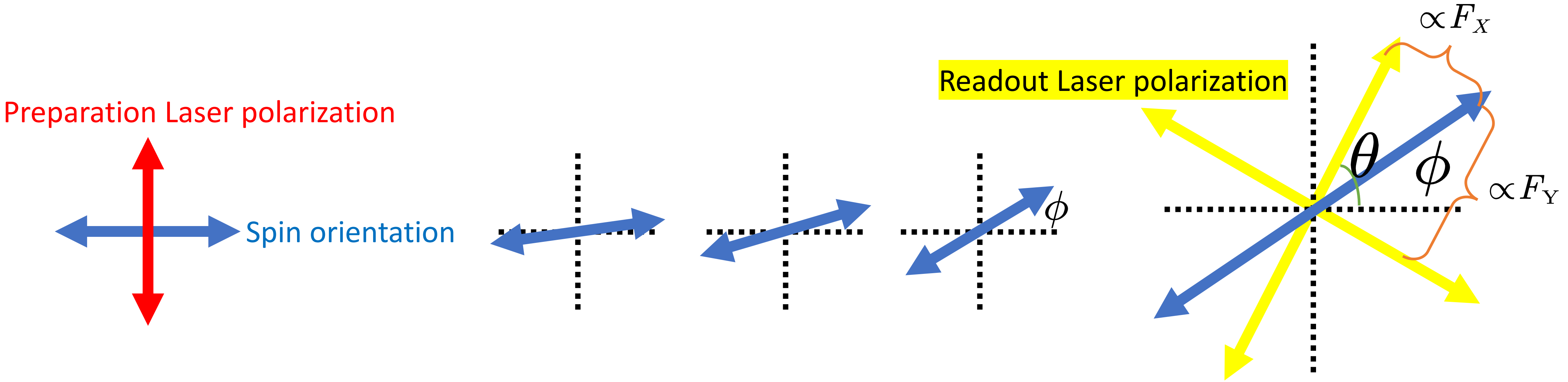
What is G switch $\tilde{\mathcal{G}}$



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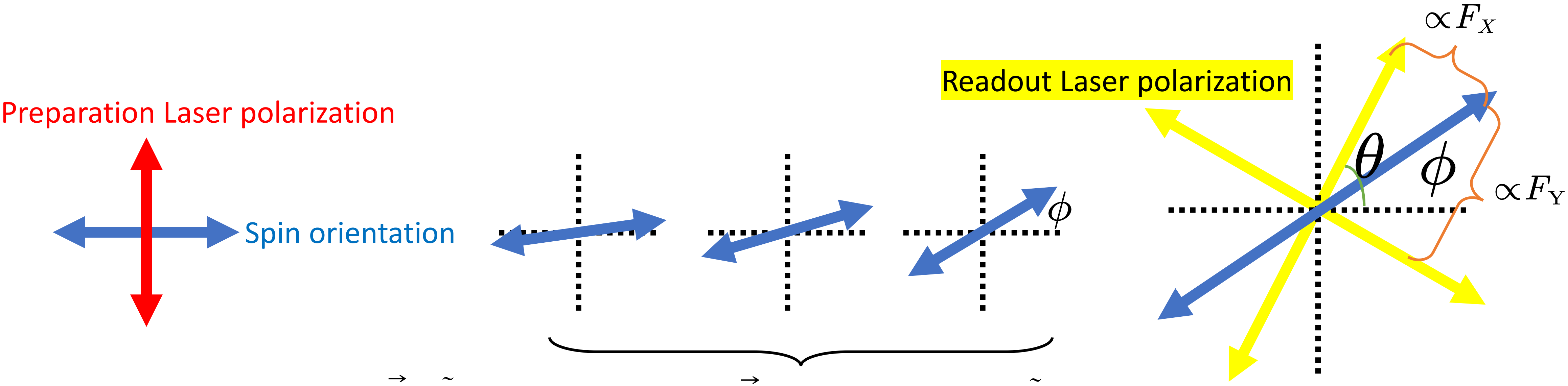


ThO orientation relative to $\vec{E}$: $\tilde{N}$

Electric field $\vec{E}$ along z axis: $\mathcal{E}\tilde{\mathcal{E}}$

Magnetic field $\vec{B}$ along z axis: $\mathcal{B}\tilde{\mathcal{B}}$

$\tilde{\mathcal{N}} \in \{-1, +1\}$

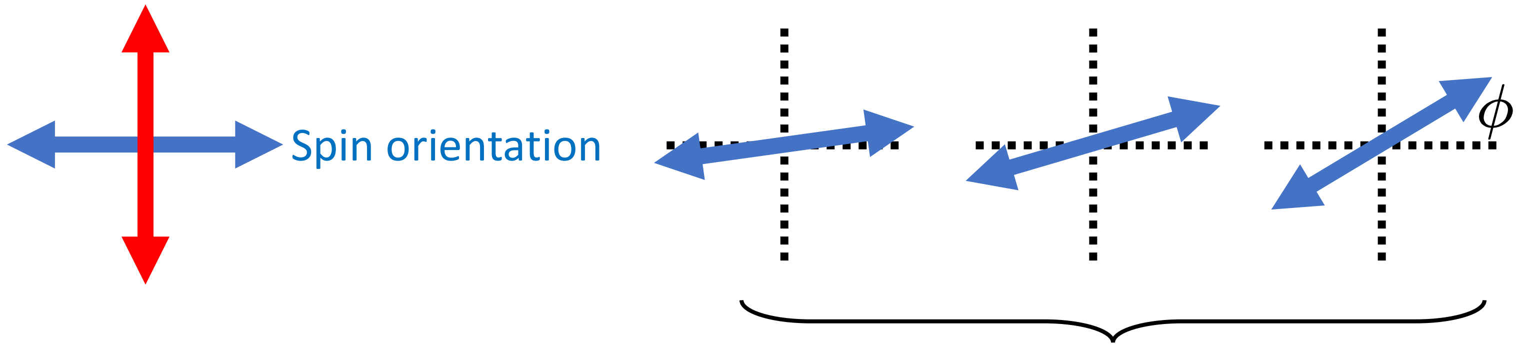
$\tilde{\mathcal{B}} \in \{-1, +1\}$

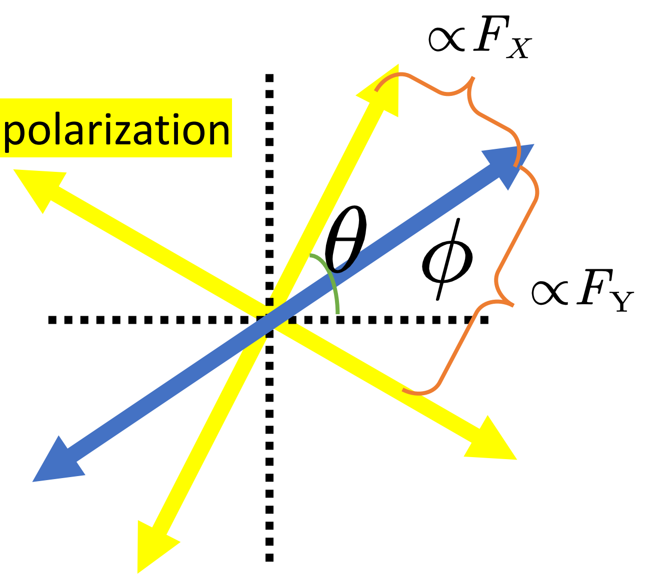
$\tilde{\mathcal{E}} \in \{-1, +1\}$

Precession phase: ϕ

ϕ measured as: $\Phi\left(\tilde{\mathcal{N}}, \tilde{\mathcal{E}}, \tilde{\mathcal{B}}\right)$

What is G switch $\tilde{\mathcal{G}}$





ThO orientation relative to $\vec{E}$: $\tilde{N}$

Electric field $\vec{E}$ along z axis: $\mathcal{E}\tilde{\mathcal{E}}$

Magnetic field $\vec{B}$ along z axis: $\mathcal{B}\tilde{\mathcal{B}}$

$$\tilde{\mathcal{N}} \in \{-1, +1\}$$

$$\tilde{\mathcal{B}} \in \{-1, +1\}$$

$$\tilde{\mathcal{E}} \in \{-1, +1\}$$

$$\Phi(\tilde{\mathcal{N}}, \tilde{\mathcal{E}}, \tilde{\mathcal{B}}) = \Phi^{\mathrm{nr}} + \Phi^{\mathcal{N}}\tilde{\mathcal{N}} + \Phi^{\mathcal{E}}\tilde{\mathcal{E}} + \Phi^{\mathcal{B}}\tilde{\mathcal{B}}$$

$$+ \Phi^{\mathcal{N}\mathcal{E}}\tilde{\mathcal{N}}\tilde{\mathcal{E}} + \Phi^{\mathcal{N}\mathcal{B}}\tilde{\mathcal{N}}\tilde{\mathcal{B}} + \Phi^{\mathcal{E}\mathcal{B}}\tilde{\mathcal{E}}\tilde{\mathcal{B}} + \Phi^{\mathcal{N}\mathcal{E}\mathcal{B}}\tilde{\mathcal{N}}\tilde{\mathcal{E}}\tilde{\mathcal{B}}.$$

EDM Channel

$$\tilde{\mathcal{N}} \in \{-1, +1\}$$

$$\tilde{\mathcal{B}} \in \{-1, +1\}$$

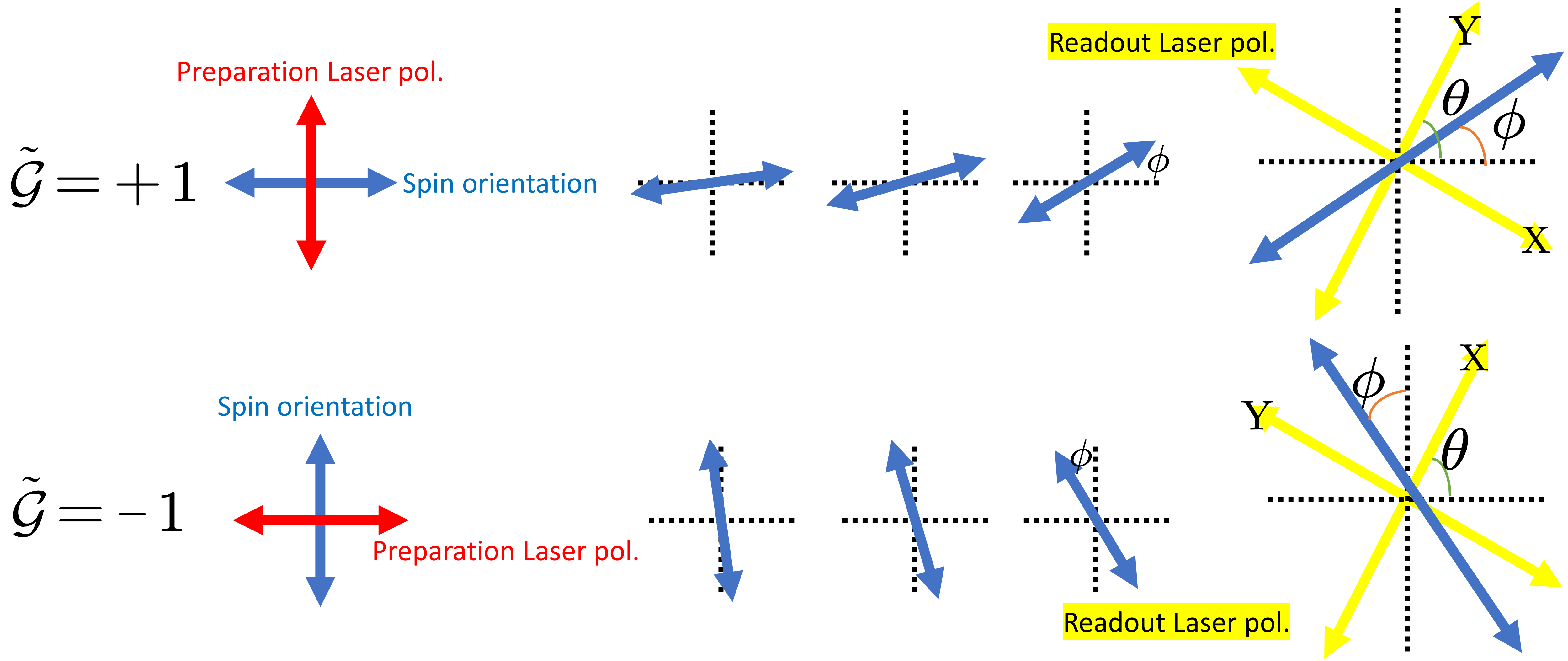
$$\tilde{\mathcal{E}} \in \{-1, +1\}$$

... (other ACME switches)

$$\tilde{\mathcal{G}} \in \{-1, +1\}$$

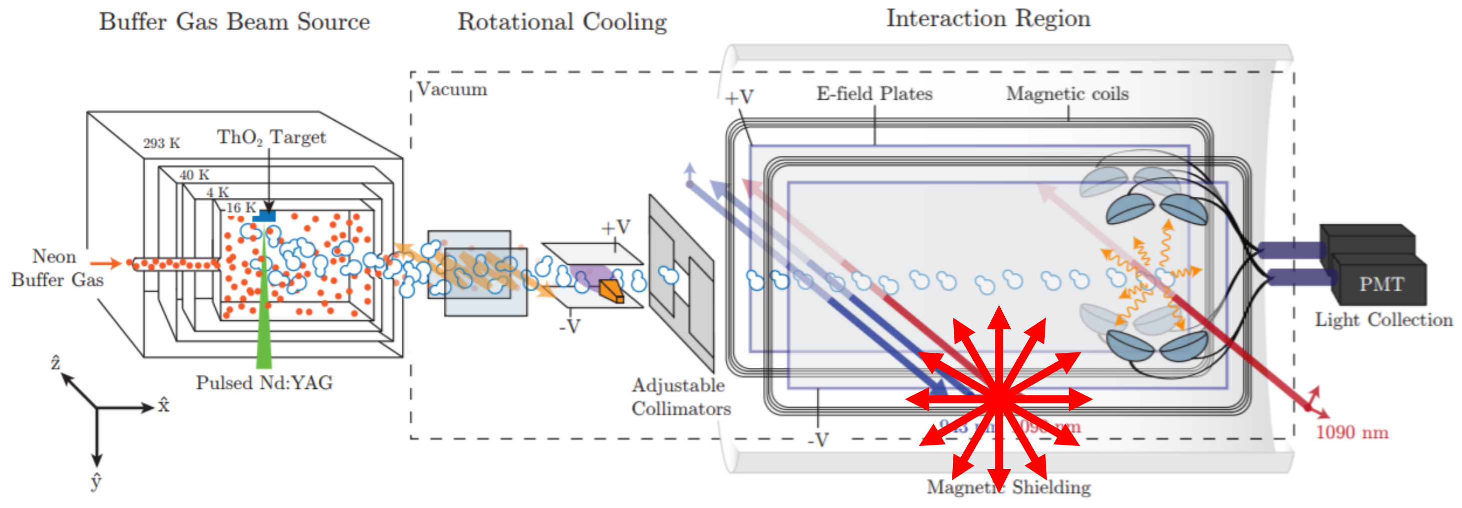
What is G switch

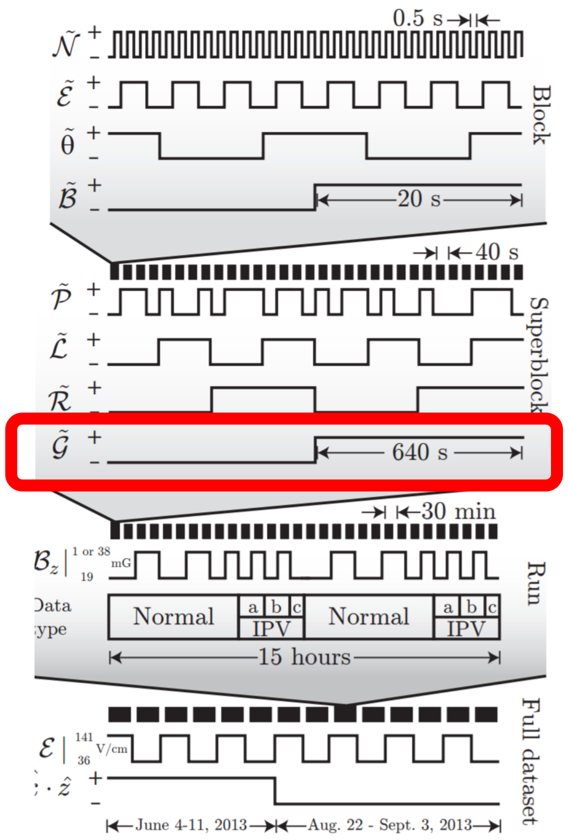
$\tilde{\mathcal{G}}$: Global 90° rot. of prep. (refine.) laser pol. and readout laser pol.



G switch ACME I & ACME II

- G switch was applied in ACME I, but NOT in ACME II
- In ACME I, the molecules are prepared into H state with optical pumping, laser go horizontally, having the freedom of choosing polarization.

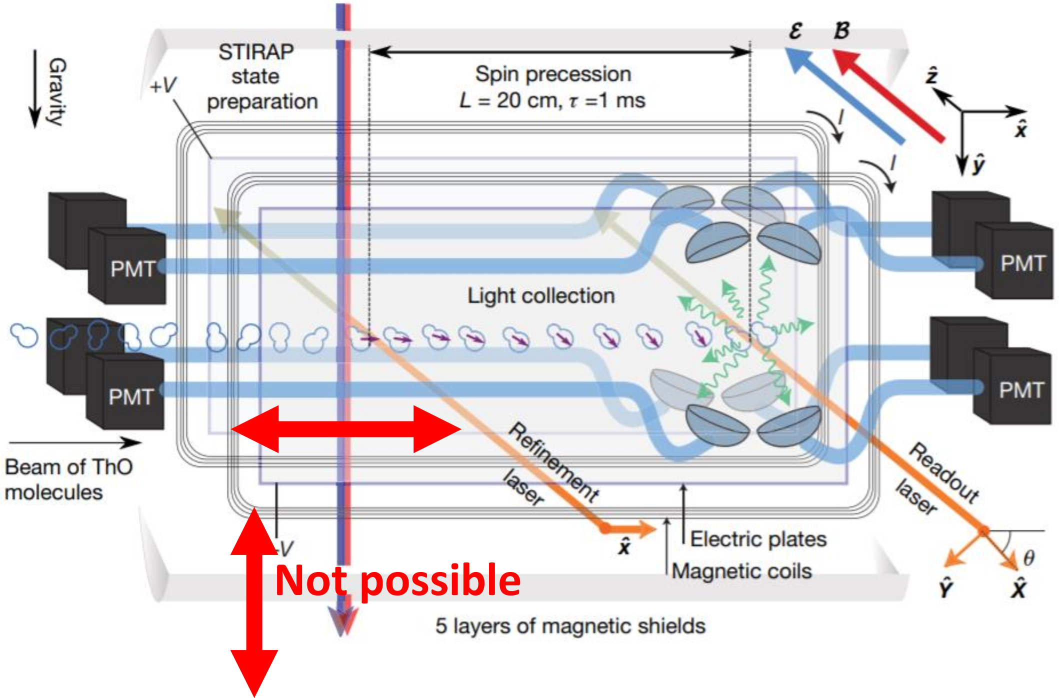




ACME I switches

G switch ACME I & ACME II

- G switch was applied in ACME I, but NOT in ACME II
- In ACME II, the molecules are prepared into H state with STIRAP, laser go vertically, under the specific STIRAP scheme there is only polarization in XZ plane can be prepared, no rotation in XY plane.



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Historical Evidence for G switch

ACME III Field Plates requirements

Long story short

$$\Phi^{\mathcal{NE}} = {\Phi_{\text{true EDM}}}^{\mathcal{NE}} + {\Phi_{\text{systematic}}}^{\mathcal{NE}}$$

$$\text{if } {\Phi_{\text{systematic}}}^{\mathcal{NE}} = \text{ Ellipticity } \times \text{ OtherFactor}^{\mathcal{NE}}$$

$$\text{under } \tilde{\mathcal{G}} \text{ switch:}$$

$$\tilde{\mathcal{G}} = +1 \rightarrow \tilde{\mathcal{G}} = -1$$

$$\text{Ellipticity } \rightarrow \text{ -Ellipticity}$$

$${\Phi_{\text{systematic}}}^{\mathcal{NE}}\left(\tilde{\mathcal{G}} = +1\right) = -{\Phi_{\text{systematic}}}^{\mathcal{NE}}\left(\tilde{\mathcal{G}} = -1\right)$$

$$\left(\Phi^{\mathcal{NE}}\left(\tilde{\mathcal{G}} = +1\right) + \Phi^{\mathcal{NE}}\left(\tilde{\mathcal{G}} = -1\right)\right)/2 = {\Phi_{\text{true EDM}}}^{\mathcal{NE}}$$

Long story long

Theory for G switch: How it works

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Theory for G switch: How it works (A brief look ahead)

- Polarization of light under G switch
- Spin misalignment and EDM systematic
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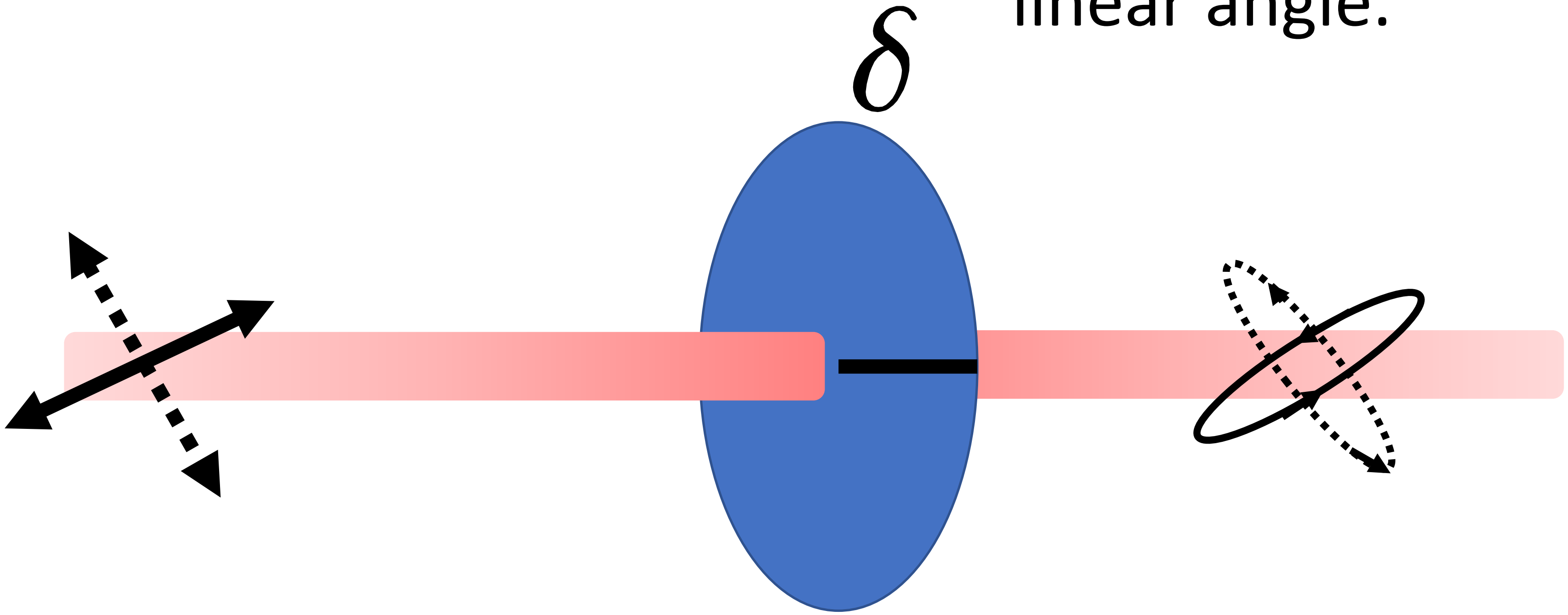
Show how **G switch** flip sign of ellipticity, and what is its effect on linear angle.



Theory for G switch: How it works (A brief look ahead)

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- **Spin misalignment and EDM systematic**
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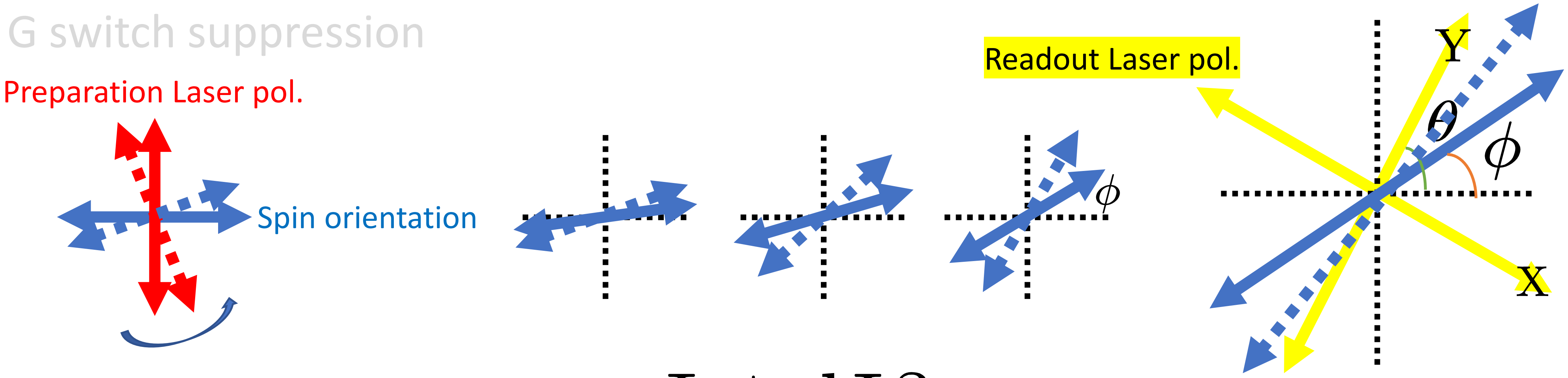

$$\Phi + \mathrm{d}\Phi?$$

Find out how **spin misalignment** gives **false EDM signal.**

Theory for G switch: How it works (A brief look ahead)

- Polarization of light under G switch
- Spin misalignment and EDM systematic
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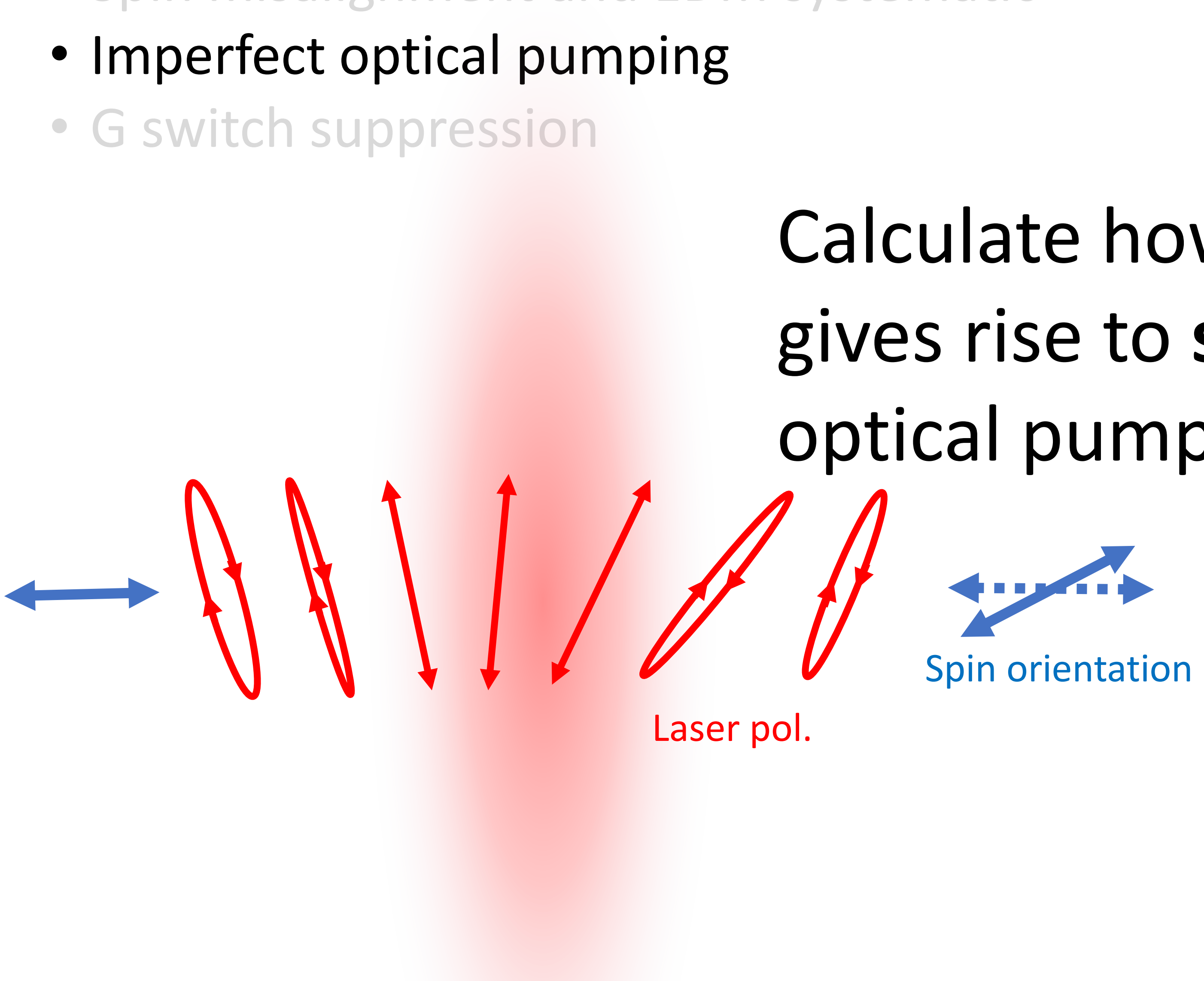
Calculate how **laser pol. imperfection** gives rise to **spin misalignment** in optical pumping.



Theory for G switch: How it works (A brief look ahead)

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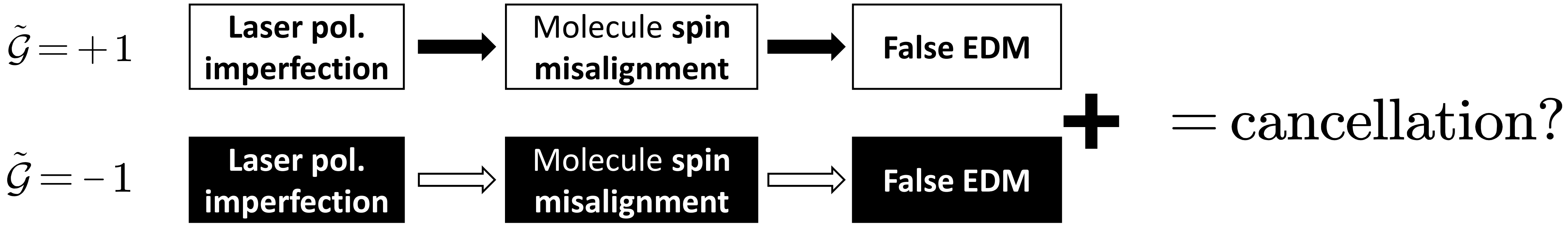
Exam how contribution to **false EDM** from **pol. imperfection** get canceled with G switch on and off.



Theory for G switch: How it works

- Polarization of light under G switch
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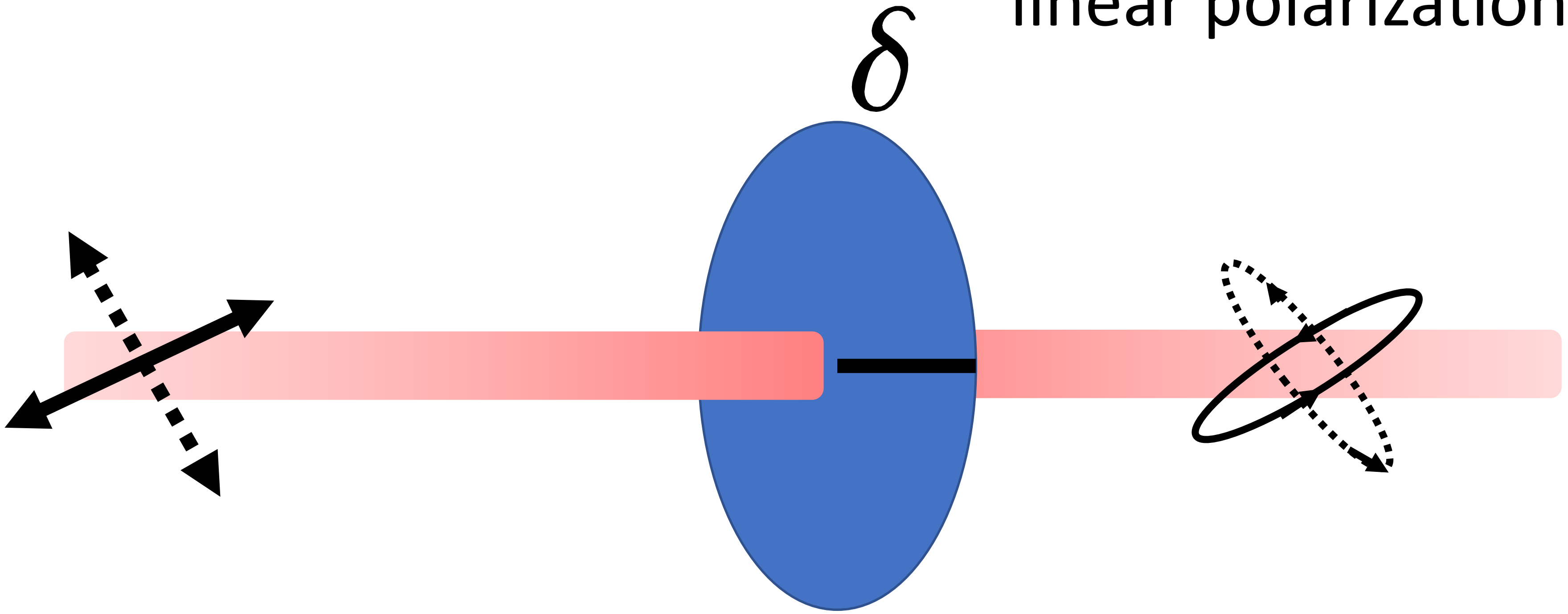
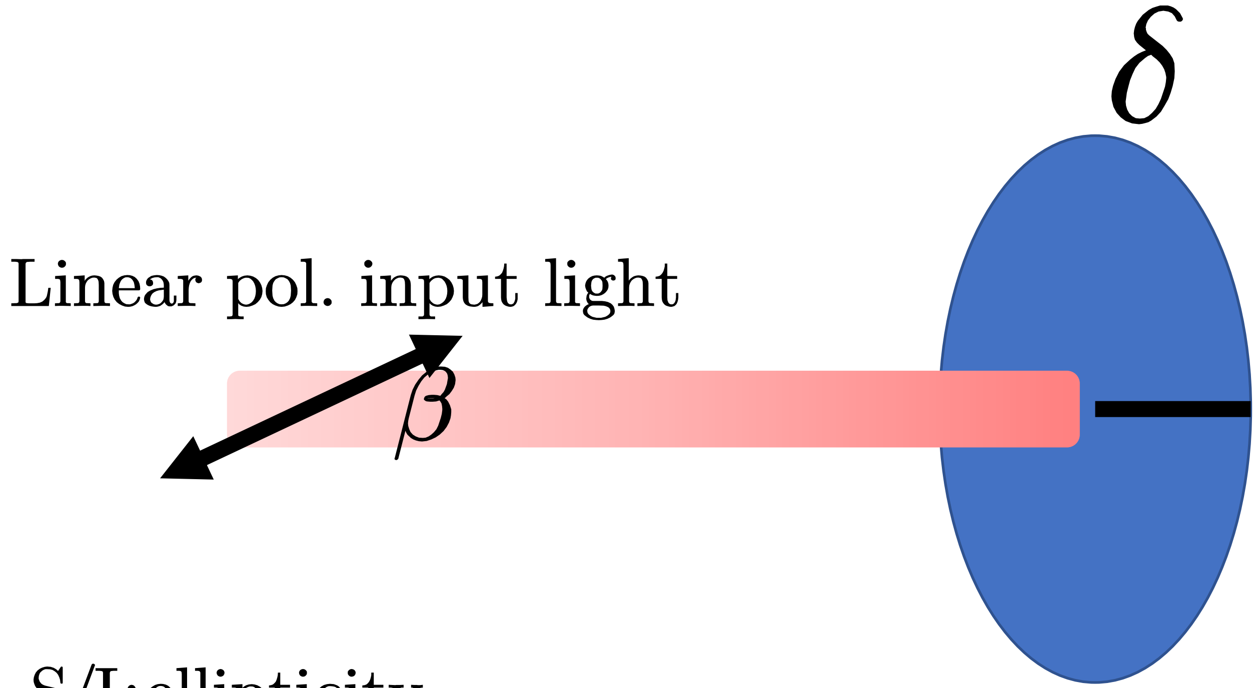
Show how **G switch** flip sign of ellipticity, and what is its effect on linear polarization component.



- Polarization of light under G switch



Ellipticity of outcoming light

$$S/I = \sin\delta \sin 2\beta$$

S/I:ellipticity

β:Incoming polarization relative to birefringence axis of optical system

δ: retardance of optical system

$$\tilde{\mathcal{G}} = +1 \rightarrow \tilde{\mathcal{G}} = -1$$

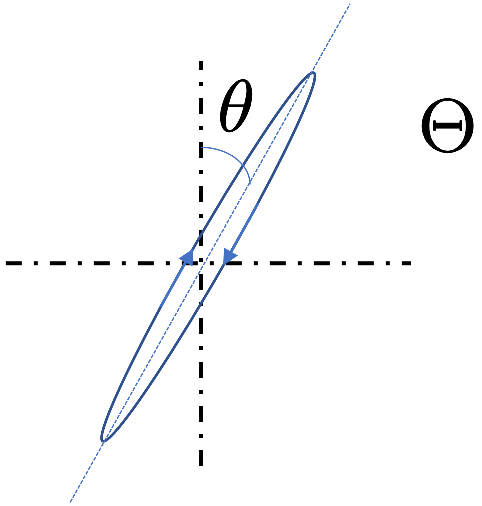
$$\beta \rightarrow \beta + \pi/2$$

$$S/I \rightarrow -S/I$$

- # Polarization of light under G switch

- Generation description of light polarization

$$\hat{\epsilon} = -e^{-i\theta}\cos\Theta\,\hat{\epsilon}_{+1} + e^{i\theta}\sin\Theta\,\hat{\epsilon}_{-1}$$

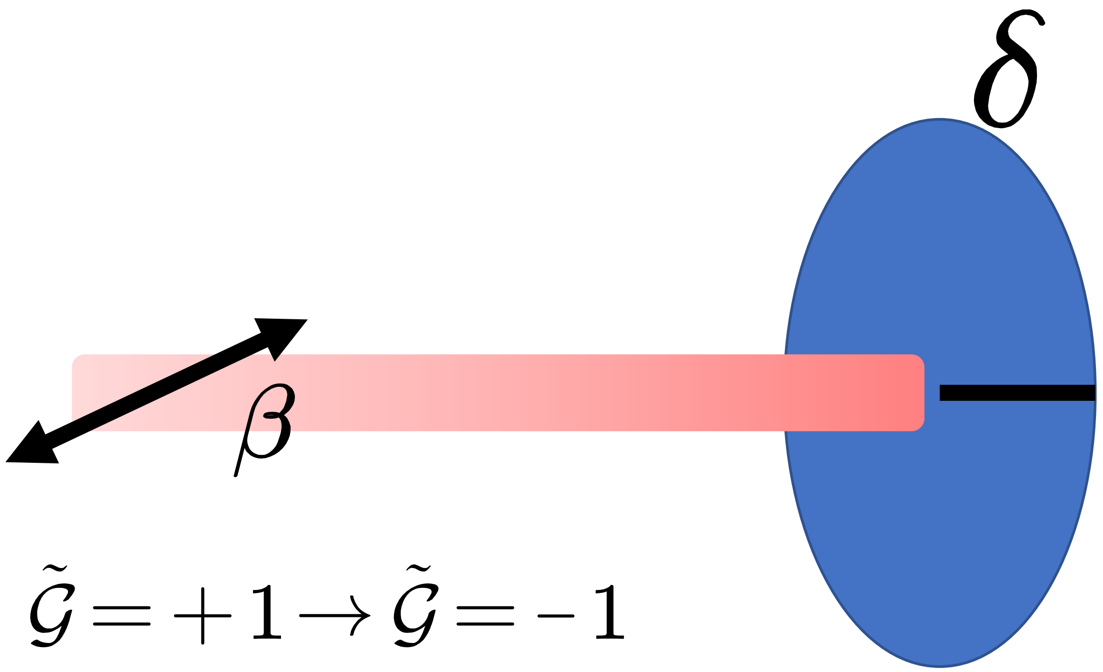


θ: orientation in XY plane

Θ: characterization of ellipticity,

$(S/I) = \cos 2\Theta$, when $\Theta \to \pi/4$ almost linear

- Polarization of light under G switch



$$\theta = \frac{1}{8}\sin(4\beta)\delta^2 + O(\delta^3)$$

$$\Theta = \frac{\pi}{4} - \cos\beta\sin\beta\cdot\delta + O(\delta^3)$$

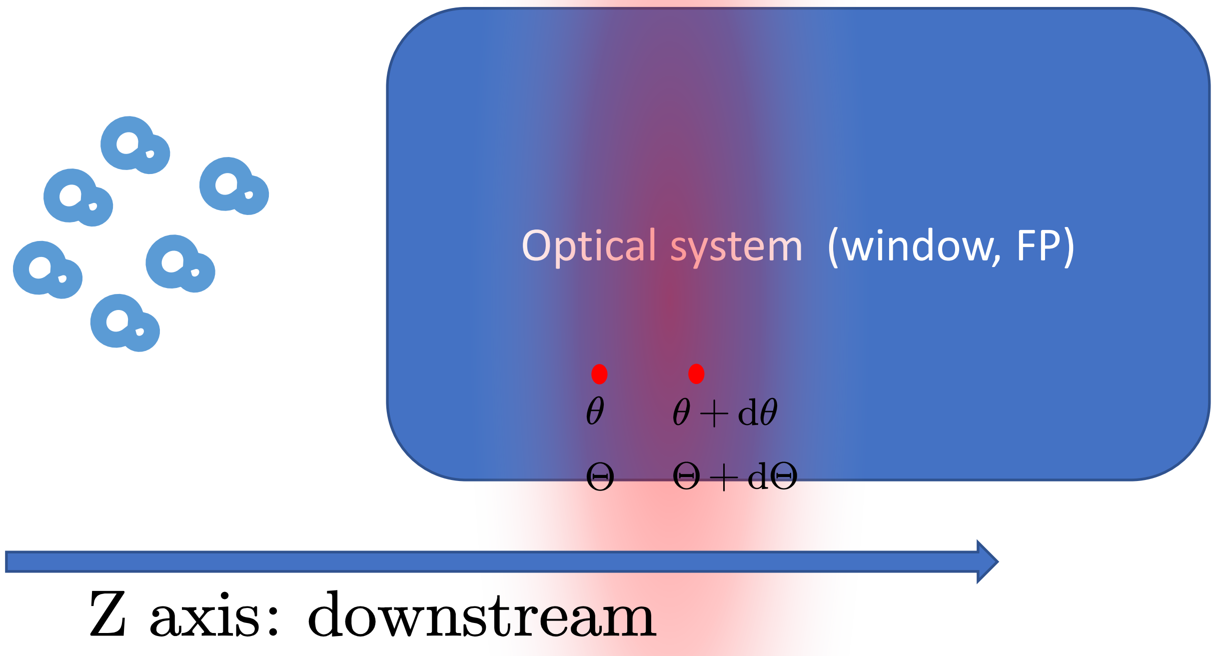
$$\tilde{\mathcal{G}} = +1 \rightarrow \tilde{\mathcal{G}} = -1$$

$$\beta \rightarrow \beta + \pi/2$$

θ not changing

$$\Theta = \frac{\pi}{4} - \cos\beta\sin\beta\cdot\delta + O(\delta^3) \;\rightarrow\; \Theta_{\text{output}} = \frac{\pi}{4} + \cos\beta\sin\beta\cdot\delta + O(\delta^3)$$

- Polarization of light under G switch



$\mathrm{d}\Theta$ is on the order of δ

$\mathrm{d}\theta$ is on the order of δ^2

if δ is small (typically $< 1\%$),

$\mathrm{d}\theta \sim \delta \times \mathrm{d}\Theta$ (Order Estimation)

$\tilde{\mathcal{G}} = +1 \rightarrow \tilde{\mathcal{G}} = -1$

$\mathrm{d}\Theta \rightarrow -\mathrm{d}\Theta$

$\mathrm{d}\theta$ no change

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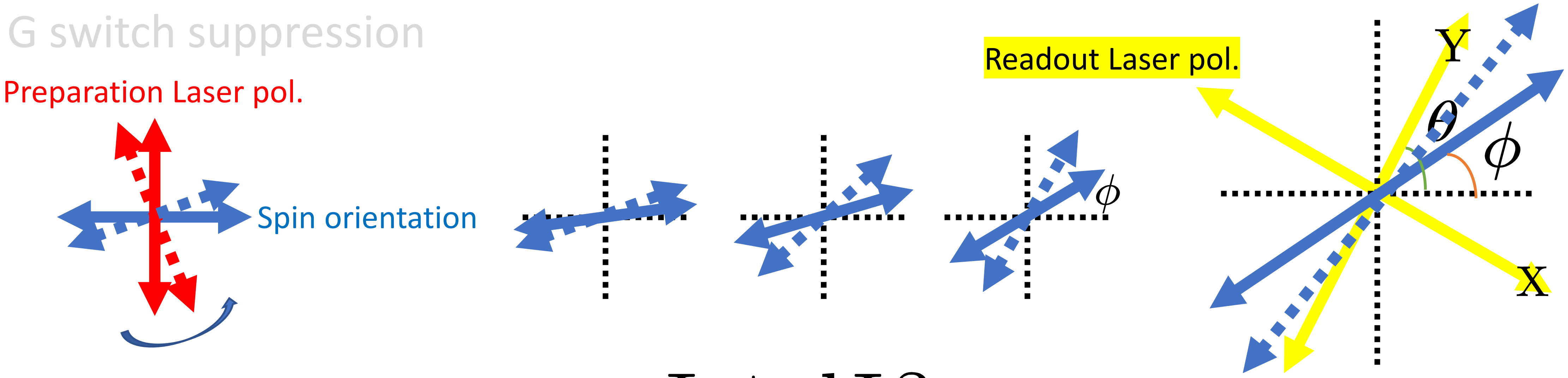


$$\Phi + \mathrm{d}\Phi ?$$

Find out how **spin misalignment** gives **false EDM signal.**

Way to represent spin misalignment

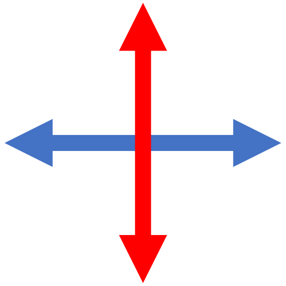
- One-to-one mapping between pumping light polarization and dark state of molecule

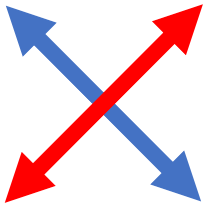
$$|B(\hat{\epsilon}_{\mathrm{prep}}, \tilde{\mathcal{N}}, \tilde{\mathcal{P}})\rangle = (\hat{\epsilon}^*_{+1} \cdot \hat{\epsilon}^*_{\mathrm{prep}})\,|+, \tilde{\mathcal{N}}\rangle - \tilde{\mathcal{P}}(\hat{\epsilon}^*_{-1} \cdot \hat{\epsilon}^*_{\mathrm{prep}})\,|-, \tilde{\mathcal{N}}\rangle\,,$$

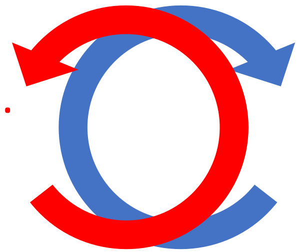
Bright state

$$|D(\hat{\epsilon}_{\mathrm{prep}}, \tilde{\mathcal{N}}, \tilde{\mathcal{P}})\rangle = (\hat{\epsilon}^*_{+1} \cdot \hat{\epsilon}_{\mathrm{prep}})\,|+, \tilde{\mathcal{N}}\rangle + \tilde{\mathcal{P}}(\hat{\epsilon}^*_{-1} \cdot \hat{\epsilon}_{\mathrm{prep}})\,|-, \tilde{\mathcal{N}}\rangle\,.$$

Dark state

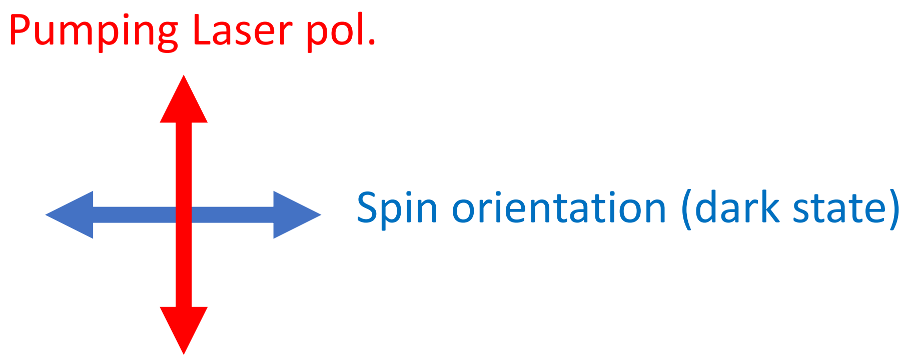


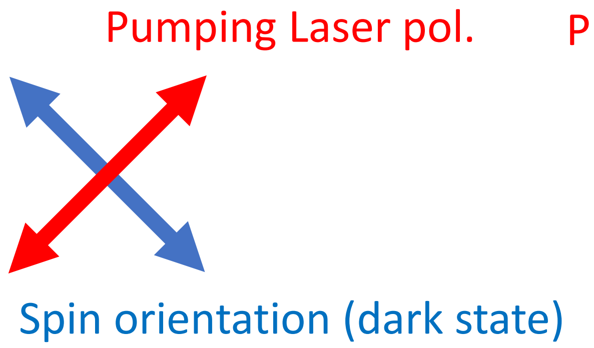


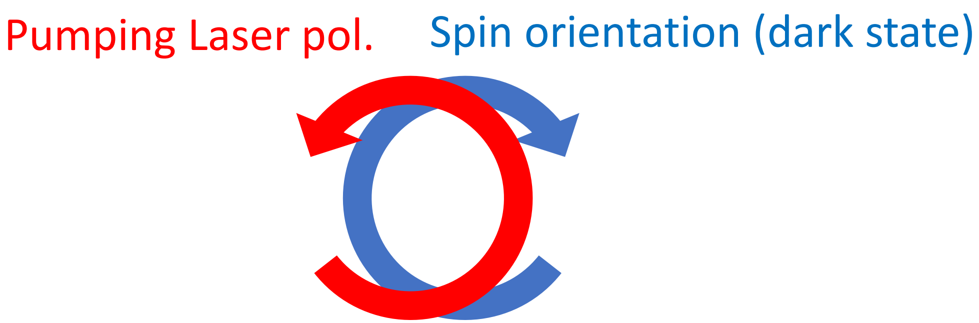


Way to represent spin misalignment

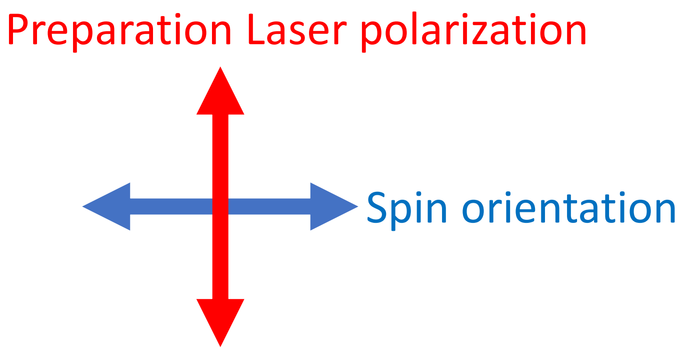
- In the following slides, I will use the pol. of pumping light that have the dark state with same molecule spin orientation to represent spin direction.

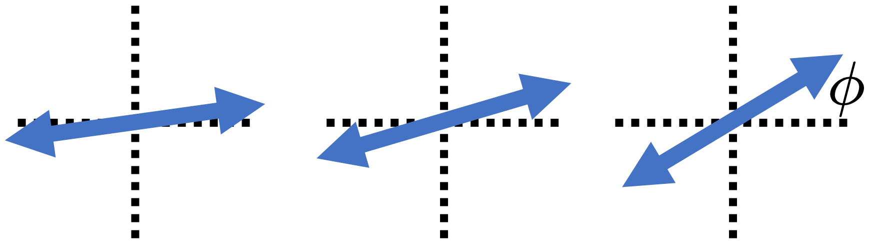


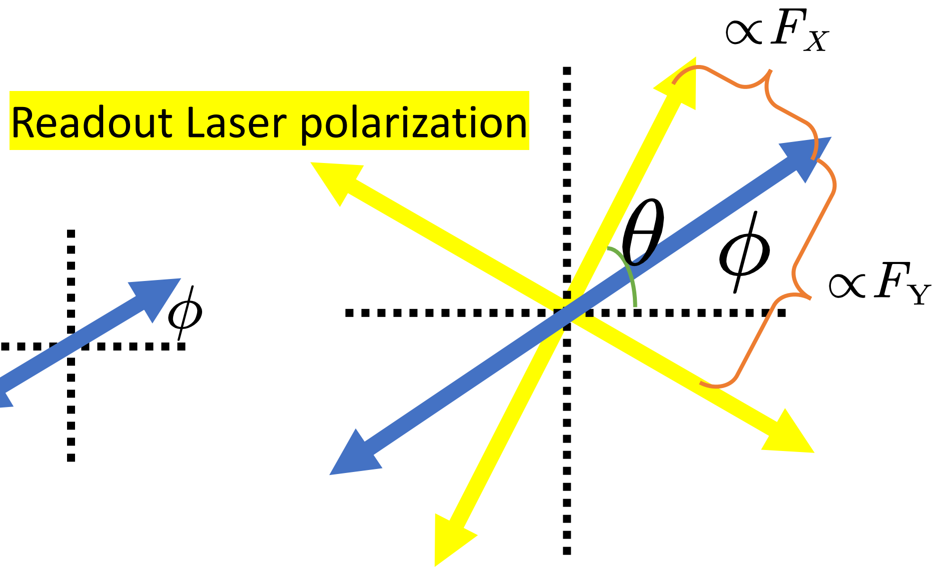




ACME - ideal







1.
Use optical pumping to pump out the "bright state" defined by preparation laser polarization,

Prepare spin of ThO molecule into the dark state **(orthogonal to preparation laser polarization)**

2.
Spin state of ThO molecule precesses under E and B field.

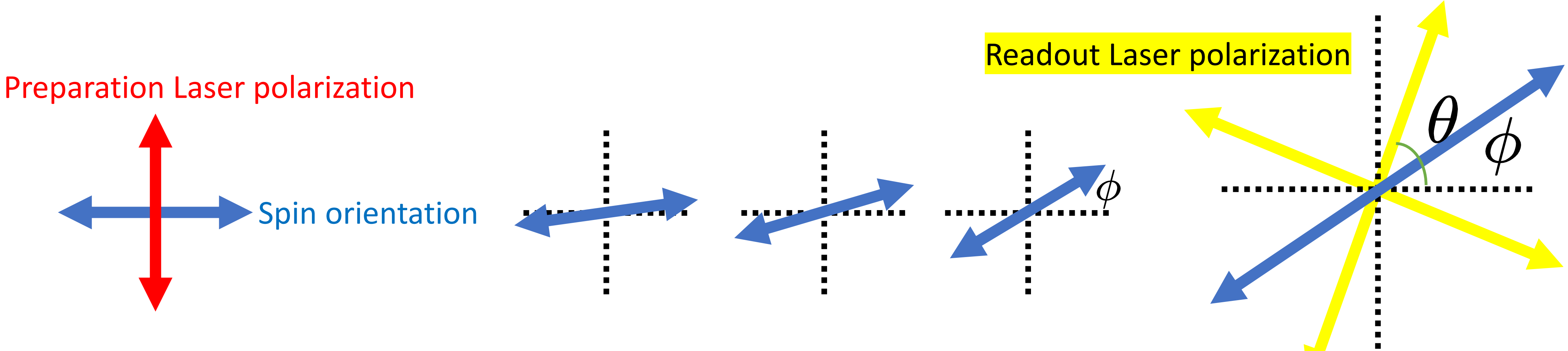
The precession angle ϕ contains information about eEDM

3.
Readout precessed spin by using two orthogonal readout laser and measure photon counts F_X, F_Y and calculate asymmetry

$$\mathcal{A} = \frac{F_X - F_Y}{F_X + F_Y} \propto \cos(2(\phi - \theta))$$

And then solve for ϕ, find out eEDM

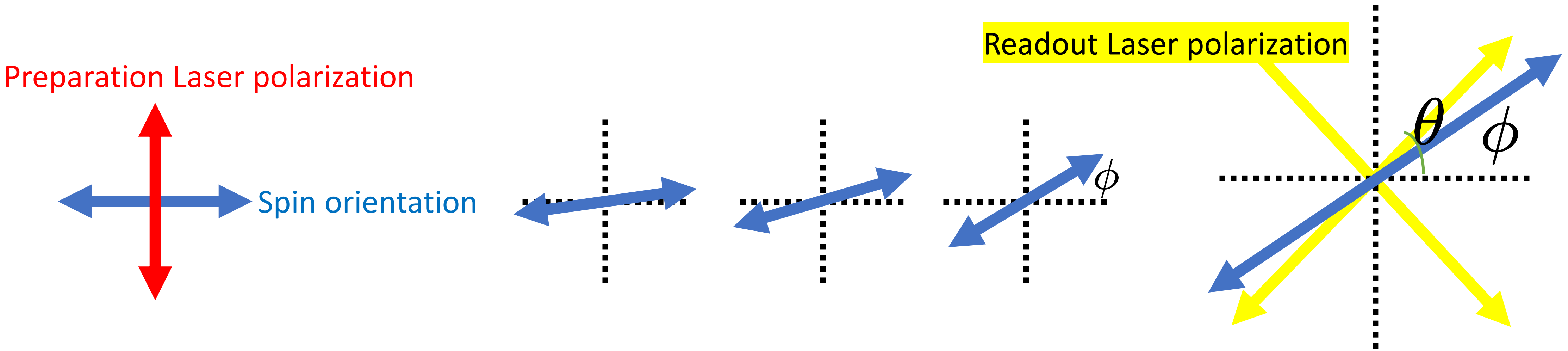
ACME - ideal



In ideal case: Preparation Laser and Readout Laser needs to be **perfectly linear polarized.**

Two readout Laser (X and Y) need to be perfectly orthogonal.

ACME – what will happen in non-ideal case



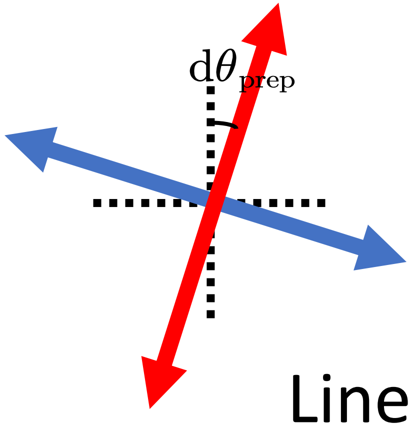
ϕ: True precession phase

Φ: Precession phase calculated from $\mathcal{A}$ we actually measured

$$\text{If imperfection exist: } \Phi = \phi + \text{imperfection}$$

ACME – possible non-ideal case

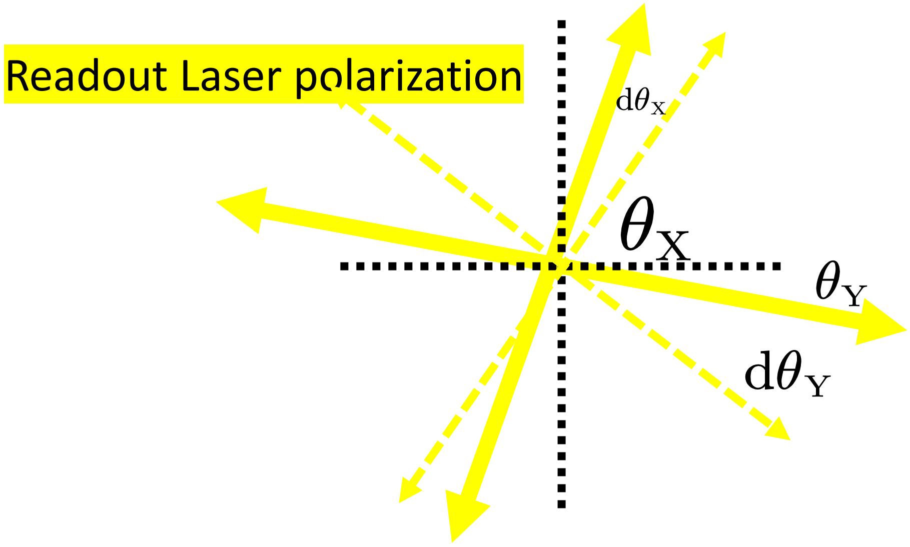
Preparation Laser polarization



Spin orientation

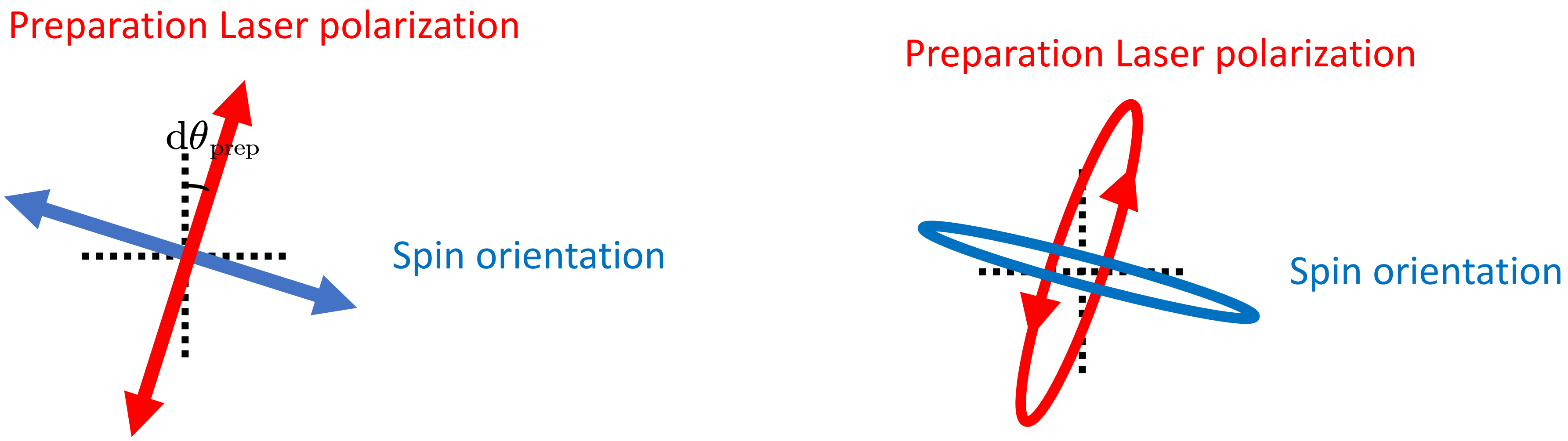
Linear pol. orientation of prep. laser, θ_{prep}
deviate from where it suppose to be,
Becoming $\theta_{\mathrm{prep}} + \mathrm{d}\theta_{\mathrm{prep}}$

ACME – possible non-ideal case



Linear polarization orientation of Readout lasers, θ_X, θ_Y deviate from where it suppose to be,
Becoming $\theta_X + d\theta_X, \theta_Y + d\theta_Y$

ACME – possible non-ideal case



Θ_{prep}: nominal ellipticity angle for prep. laser, (should be $\pi/4$)

$d\Theta_{\mathrm{prep}}$: deviation of ellipticity angle for prep. laser (imperfection)

$\Theta_{\mathrm{X(Y)}}$: nominal ellipticity angle for readout X(Y) laser, (should be $\pi/4$)

$d\Theta_{\mathrm{X(Y)}}$: deviation of ellipticity angle for readout X(Y) laser (imperfection)

ACME – possible non-ideal case

$$\text{linear polarization orientation misalignment: } \mathrm{d}\theta_{\mathrm{prep}},\ \mathrm{d}\theta_{\mathrm{X}}\ , \mathrm{d}\theta_{\mathrm{Y}}$$

$$\text{ellipticity: } \mathrm{d}\Theta_{\mathrm{prep}},\ \mathrm{d}\Theta_{\mathrm{X}}\ , \mathrm{d}\Theta_{\mathrm{Y}}$$

Spin misalignment and EDM systematic

linear polarization orientation misalignment: $\mathrm{d}\theta_{\mathrm{prep}}$, $\mathrm{d}\theta_{\mathrm{X}}$,$\mathrm{d}\theta_{\mathrm{Y}}$

ellipticity: $\mathrm{d}\Theta_{\mathrm{prep}}$, $\mathrm{d}\Theta_{\mathrm{X}}$,$\mathrm{d}\Theta_{\mathrm{Y}}$

$$\Phi = \phi + \kappa\left(d\theta_{\mathrm{prep}} - \frac{1}{2}(d\theta_X + d\theta_Y)\right) - \kappa^2 \tilde{\mathcal{P}}_{\mathrm{prep}} \tilde{\mathcal{P}}_{\mathrm{read}} d\Theta_{\mathrm{prep}} (d\Theta_X - d\Theta_Y) + O\left(\kappa^3\right),$$

The phase we measured

what we supposed to measure

first order to linear misalignment

second order to constant ellipticity

κ: pertubation coefficient

$\tilde{P}_{\mathrm{prep}}, \tilde{P}_{\mathrm{read}}$: quantity related with parity of prep and read state, value from $\{-1, +1\}$

Spin misalignment and EDM systematic

what we have:

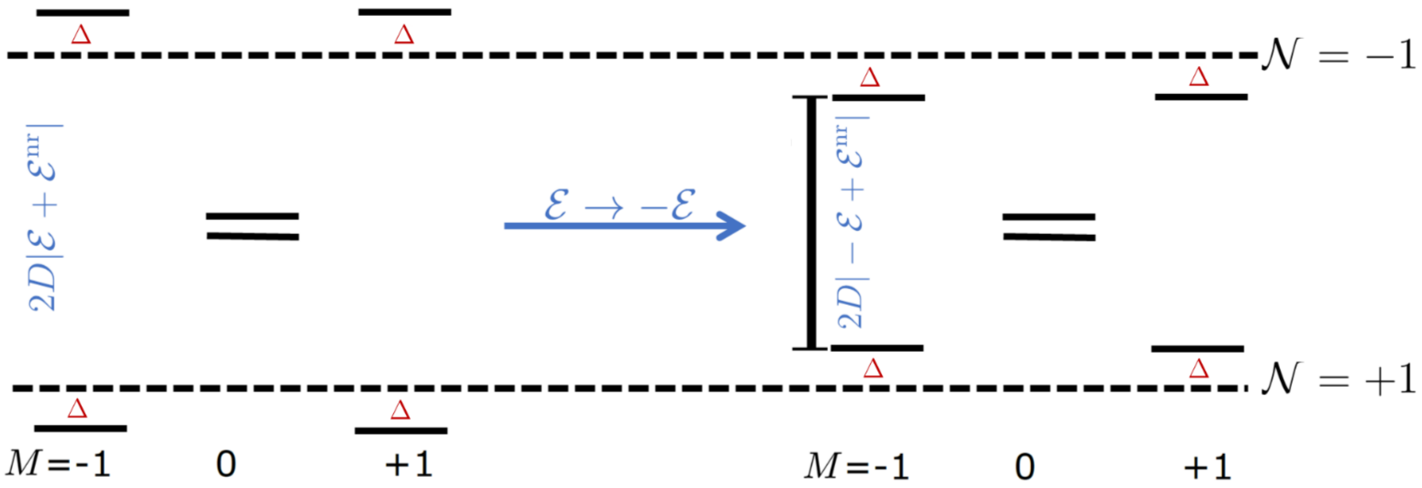
$$\Phi = \phi + \kappa\left(\mathrm{d}\theta_{\mathrm{prep}} - \frac{1}{2}\left(\mathrm{d}\theta_{\mathrm{X}} + \mathrm{d}\theta_{\mathrm{Y}}\right)\right) - \kappa^2(....)$$

what we really care about:

$$\Phi^{\mathcal{NE}} = \phi^{\mathcal{NE}} + \kappa\left(\mathrm{d}\theta_{\mathrm{prep}}{}^{\mathcal{NE}} - \frac{1}{2}\left(\mathrm{d}\theta_{\mathrm{X}}{}^{\mathcal{NE}} + \mathrm{d}\theta_{\mathrm{Y}}{}^{\mathcal{NE}}\right)\right) - \kappa^2(....^{\mathcal{NE}})$$

Where does $^{\mathcal{NE}}$ dependence of $\mathrm{d}\theta$ comes from?

Non-reversing E field



$$\Delta = f^N - \Delta^{\mathcal{N}}_{\rm Stark}$$

$$= \Delta_0 + (D_H|\mathcal{E}_0| - f^{\mathcal{N}})\tilde{\mathcal{N}} + D_H\mathcal{E}^{\rm nr}\tilde{\mathcal{N}}\tilde{\mathcal{E}}$$

$$= \Delta_0 + \Delta^{\mathcal{N}}\tilde{\mathcal{N}} + \Delta^{\mathcal{N}\mathcal{E}}\tilde{\mathcal{N}}\tilde{\mathcal{E}},$$

Spin misalignment and EDM systematic

what we have:

$$\Phi = \phi + \kappa\left(\mathrm{d}\theta_{\mathrm{prep}} - \frac{1}{2}(\mathrm{d}\theta_{\mathrm{X}} + \mathrm{d}\theta_{\mathrm{Y}})\right) - \kappa^2(....)$$

what we really care about:

$$\Phi = \phi + \kappa\left(\mathrm{d}\theta_{\mathrm{prep}}{}^{\mathcal{N}\mathcal{E}} - \frac{1}{2}(\mathrm{d}\theta\,{}_{\mathrm{X}}{}^{\mathcal{N}\mathcal{E}} + \mathrm{d}\theta\,{}_{\mathrm{Y}}{}^{\mathcal{N}\mathcal{E}})\right) - \kappa^2(....{}^{\mathcal{N}\mathcal{E}})$$

if $\mathrm{d}\theta_{\mathrm{prep}}(\Delta)$, then $\Delta^{\mathcal{N}\mathcal{E}}$ could have an effect

same for $\mathrm{d}\theta_{\mathrm{X}}$ and $\mathrm{d}\theta_{\mathrm{Y}}$

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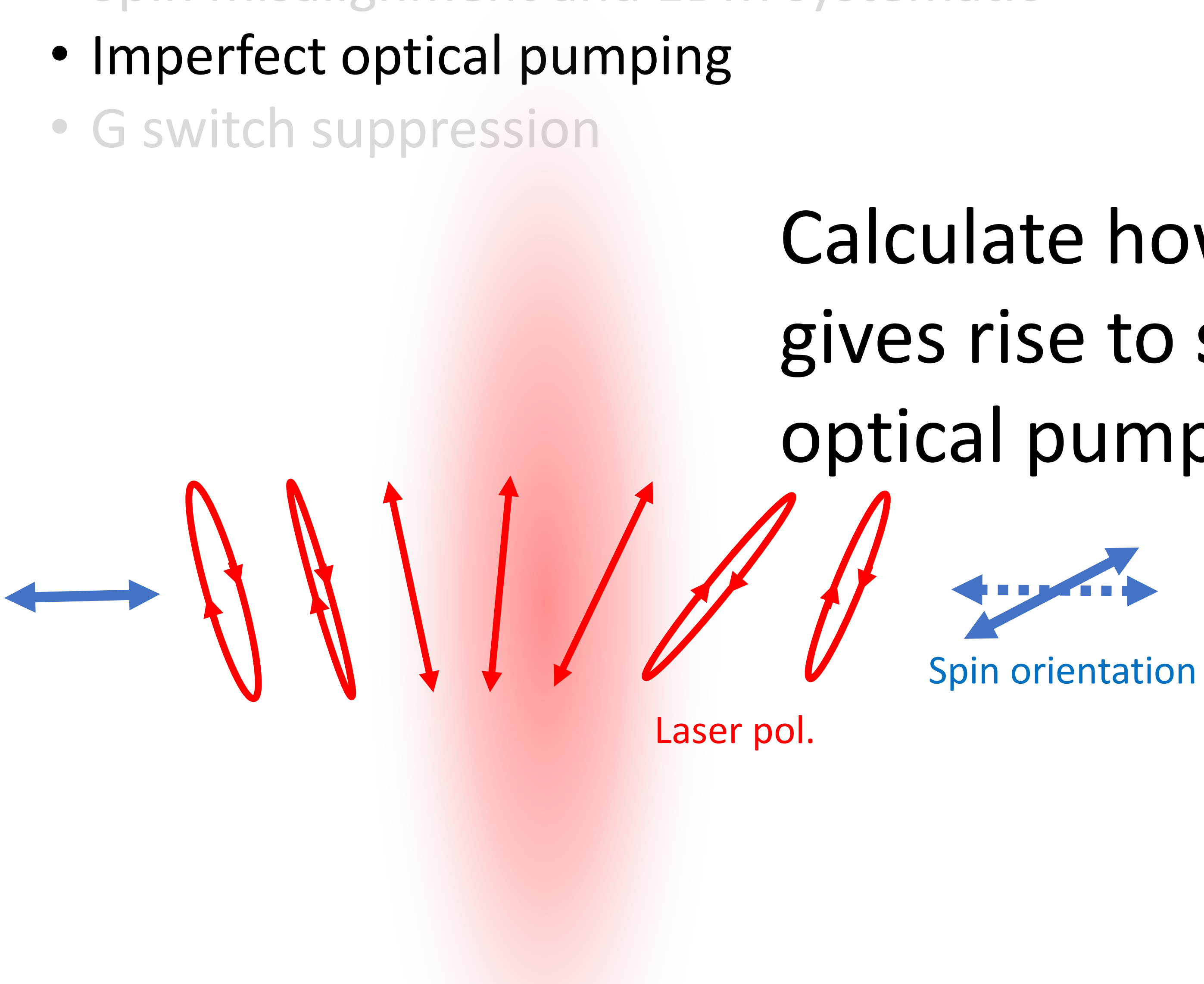
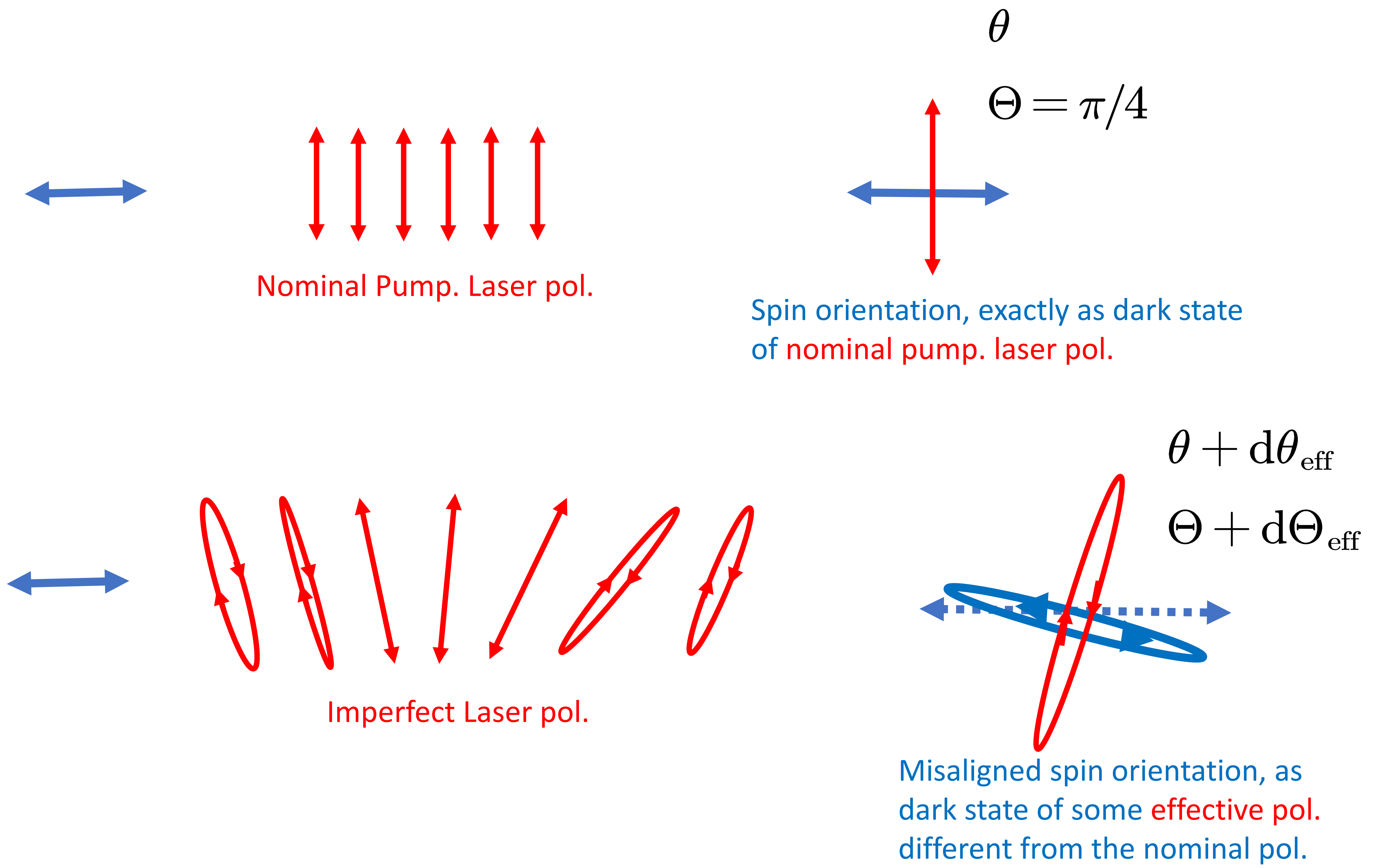
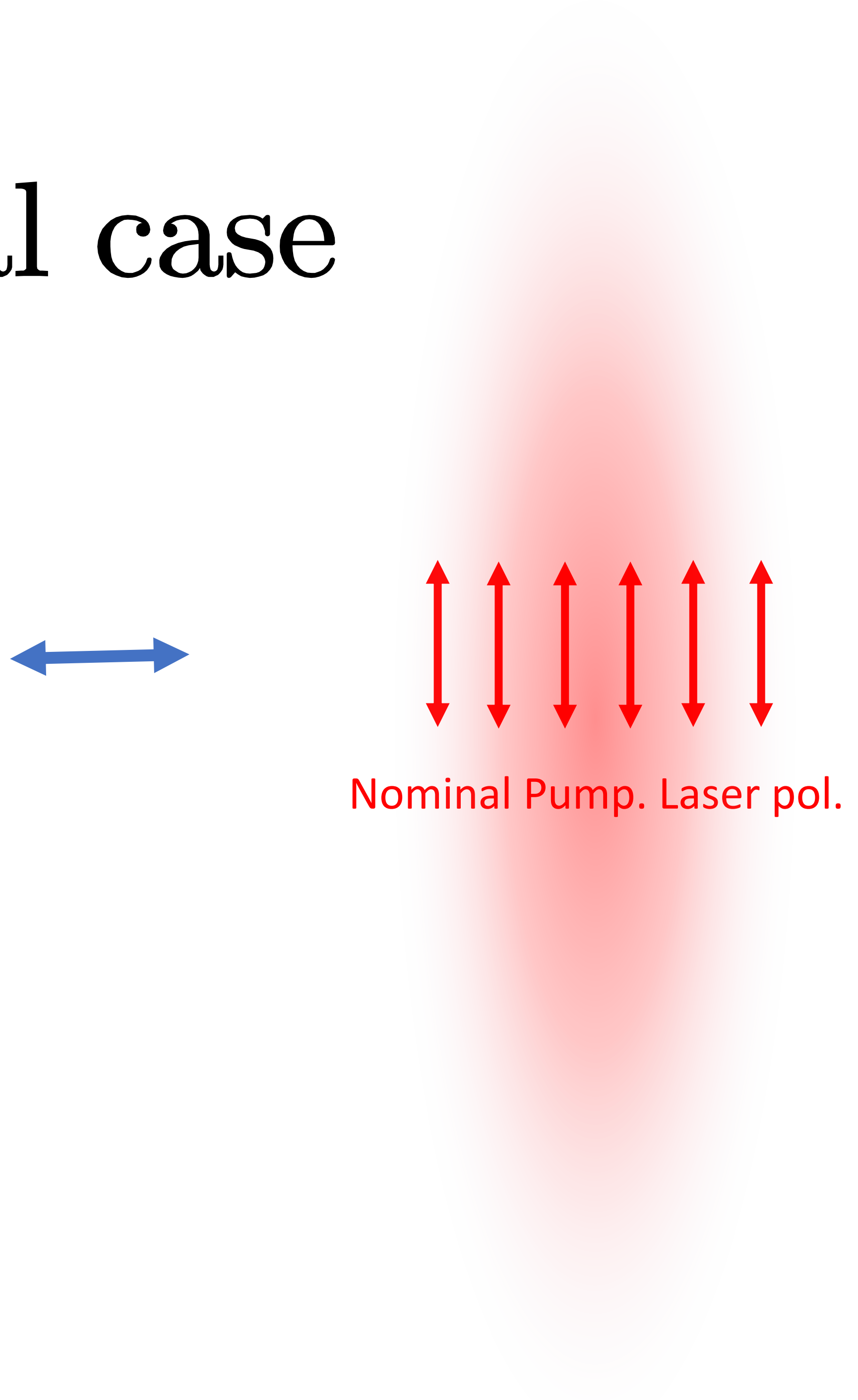
Calculate how **laser pol. imperfection** gives rise to **spin misalignment** in optical pumping.



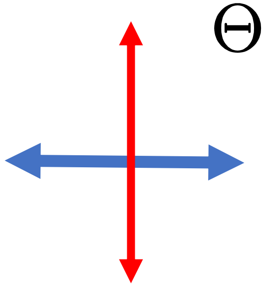

θ
$\Theta = \pi/4$
Nominal Pump. Laser pol.
Spin orientation, exactly as dark state
of nominal pump. laser pol.
$\theta + d\theta_{eff}$
$\Theta + d\Theta_{eff}$
Imperfect Laser pol.
Misaligned spin orientation, as
dark state of some effective pol.
different from the nominal pol.

Ideal case



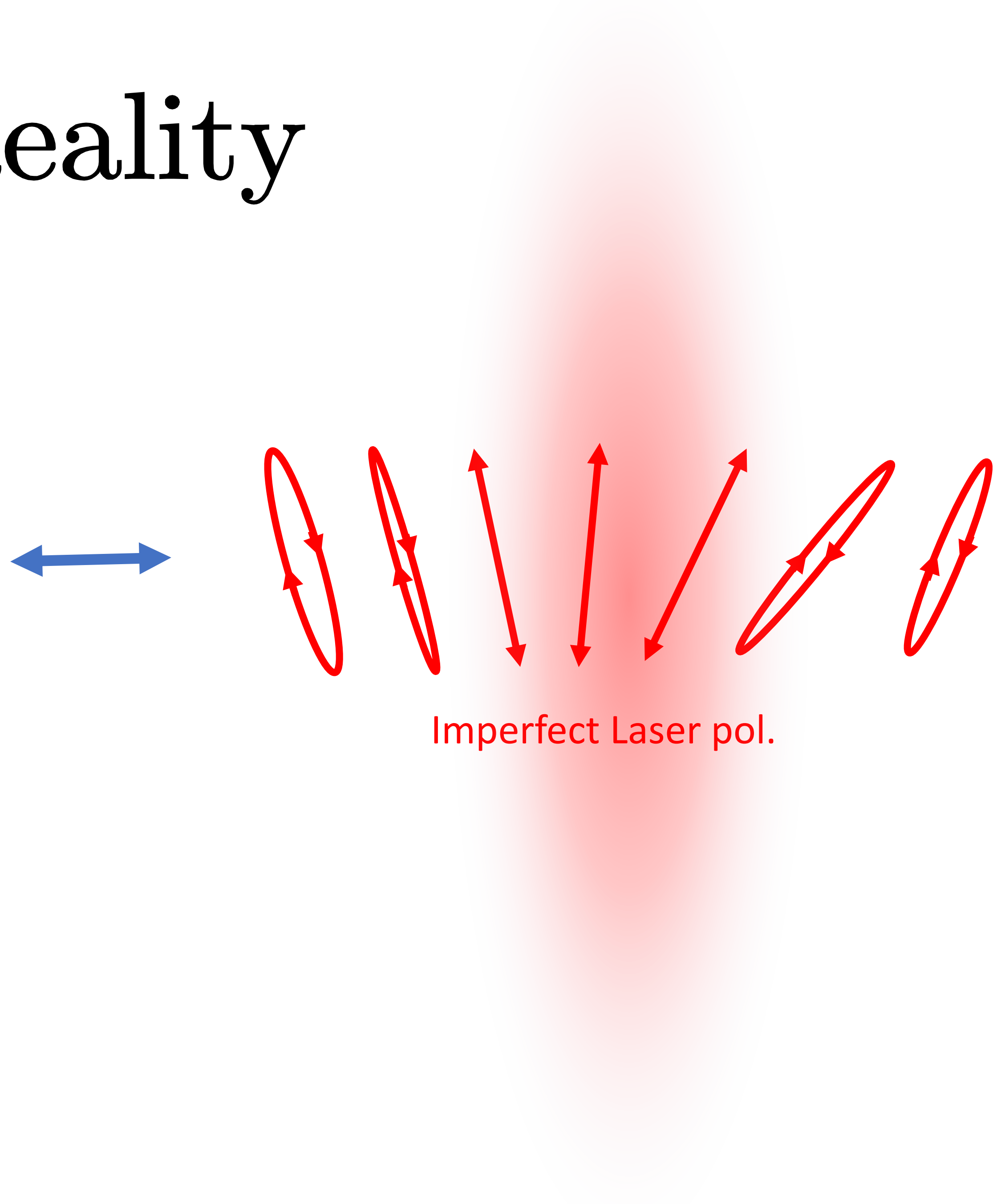
θ

$\Theta = \pi/4$



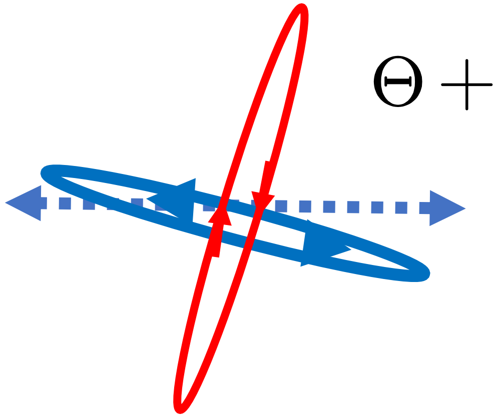
Spin orientation, exactly as dark state of nominal pump. laser pol.

Reality



$\theta + \mathrm{d}\theta_{\mathrm{eff}}$

$\Theta + \mathrm{d}\Theta_{\mathrm{eff}}$



Misaligned spin orientation, as dark state of some effective pol. different from the nominal pol.

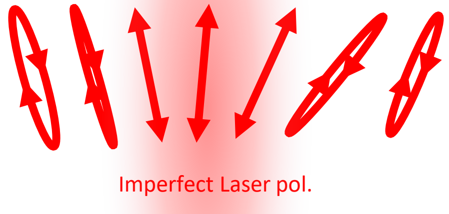
$$d\theta_{\mathrm{prep}},\ d\theta_{\mathrm{X}}\ ,d\theta_{\mathrm{Y}} \quad\longrightarrow\quad d\theta_{\mathrm{eff\ prep}},\ d\theta_{\mathrm{eff\ X}}\ ,d\theta_{\mathrm{eff\ Y}}$$

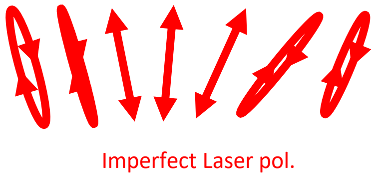
$$d\Theta_{\mathrm{prep}},\ d\Theta_{\mathrm{X}}\ ,d\Theta_{\mathrm{Y}} \quad\longrightarrow\quad d\Theta_{\mathrm{eff\ prep}},\ d\Theta_{\mathrm{eff\ X}}\ ,d\Theta_{\mathrm{eff\ Y}}$$

$d\theta_{\mathrm{eff\ prep}}$ depends on the spatial distribution of polarization imperfection

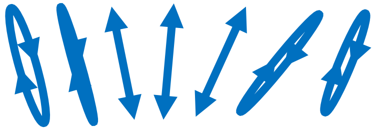
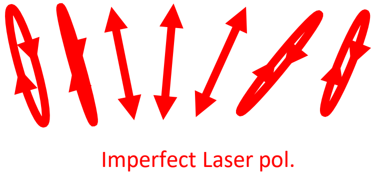
To get $\mathrm{d}\theta_{\mathrm{eff}}, \mathrm{d}\Theta_{\mathrm{eff}}$:

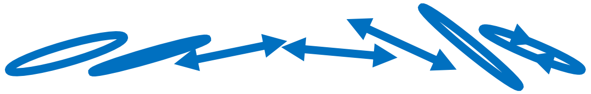
Solve

H (

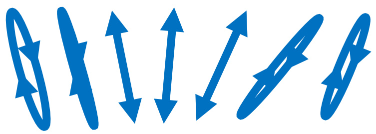
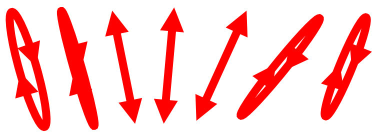
) under the basis of 

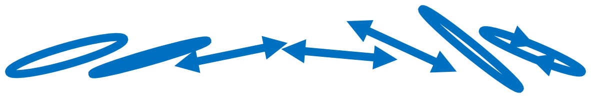
$|C\rangle$ excited state

$|B\rangle$ bright state  defined by 

$|D\rangle$ dark state  (time − dependent basis)

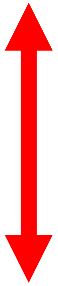
$|C\rangle$ excited state

$|B\rangle$ bright state  defined by 

$|D\rangle$ dark state  $(\mathrm{time-dependent\ basis})$

same at first order

$|C\rangle$ excited state

$|B\rangle$ bright state  defined by 

$|D\rangle$ dark state  $(\mathrm{time-independent\ basis})$

$$\Omega_r(t)$$

$$\chi(t)$$

$$\tilde{H} = \begin{pmatrix} \Delta & \frac{1}{2}\Omega_{\mathrm{r}} & 0 \\ \frac{1}{2}\Omega_{\mathrm{r}} & 0 & i\dot{\chi} \\ 0 & -i\dot{\chi}^* & 0 \end{pmatrix} \begin{matrix} |C\rangle \\ |B\rangle \\ |D\rangle \end{matrix}$$

$$\mathrm{d}\chi = \mathrm{d}\Theta - i\left(\mathrm{d}\theta - g_1\mu_B\mathcal{B}_z\tilde{\mathcal{B}}t\right)$$

$\mathrm{d}\chi$: complex combination of pol. imperfections

real part: Ellipticity imperfection

img part: Linear imperfection

$$\tilde{H} = \begin{pmatrix} \Delta & \frac{1}{2}\Omega_r & 0 \\ \frac{1}{2}\Omega_r & 0 & i\dot{\chi} \\ 0 & -i\dot{\chi}^* & 0 \end{pmatrix} \begin{matrix} |C\rangle \\ |B\rangle \\ |D\rangle \end{matrix}$$

diagonalize $\tilde{H}(t)$ with transformation $U(t)$

↓

Under new basis, $H' = U^\dagger \tilde{H} U - i\dot{U}U$

is close to diagonal, apply pertubation theory

solve for $c_{C'}, c_{B'}, c_{D'}$

↓

Use U to transform back to c_D, c_B, c_D

↓

Find corresponding $d\theta_{eff}, d\Theta_{eff}$ that has dark/birght state as c_B and c_D

$$d\theta_{\text{prep,eff}} = -\, d\Theta_{\text{prep}} \text{Im}\Pi + (d\theta_{\text{prep}} - g_1 \mu_{\text{B}} \mathcal{B}_z \tilde{\mathcal{B}} t)\text{Re}\Pi,$$
$$d\Theta_{\text{prep, eff}} = -\, d\Theta_{\text{prep}} \text{Re}\Pi - (d\theta_{\text{prep}} - g_1 \mu_{\text{B}} \mathcal{B}_z \tilde{\mathcal{B}} t)\text{Im}\Pi,$$

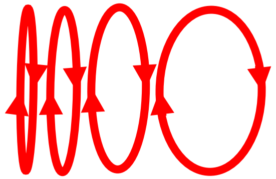
$$\mathrm{d}\chi = \mathrm{d}\Theta - i\left(\mathrm{d}\theta - g_1 \mu_B \mathcal{B}_z \tilde{\mathcal{B}} t\right)$$

$$\Pi = \sum_{\pm} (\kappa_{\mp})^2 e^{-iE_{B\pm}t} \int_0^t dt' \, \frac{\dot{\chi}(t')}{d\chi} e^{iE_{B\pm}t'}.$$

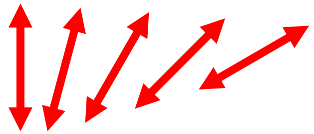
$$E_{B\pm} = \frac{1}{2}\left(\Delta \pm \sqrt{\Delta^2 + \Omega_{\mathrm{r}}^2}\right)$$

$$\kappa_{\pm} = \frac{1}{\sqrt{2}} \sqrt{1 \pm \frac{\Delta}{\sqrt{\Delta^2 + \Omega_{\mathrm{r}}^2}}}.$$

Too complicated?

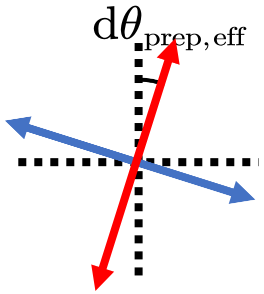


× some factor



× some factor

$$d\theta_{\mathrm{prep,eff}} = -\,d\Theta_{\mathrm{prep}}\mathrm{Im}\Pi + (d\theta_{\mathrm{prep}} - g_1\mu_{\mathrm{B}}\mathcal{B}_z\tilde{\mathcal{B}}t)\mathrm{Re}\Pi,$$



ellipticity gradient

linear angle gradient

(rotation due to B field substracted)

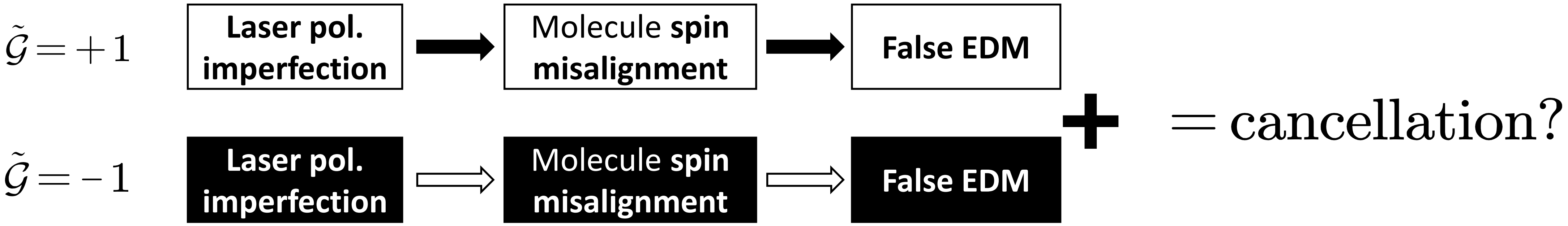
angular misalignment of spin

$$\Pi(\Delta, \Omega_{\mathrm{r}}, \ldots)$$

Theory for G switch: How it works (A brief look ahead)

- Polarization of light under G switch
- Spin misalignment and EDM systematic
- Imperfect optical pumping
- G switch suppression

Exam how contribution to **false EDM** from **pol. imperfection** get canceled with G switch on and off.



G switch suppression

$$d\theta_{\text{prep,eff}} = -d\Theta_{\text{prep}}\,\text{Im}\Pi + d\theta_{\text{prep}}\,\text{Re}\Pi - g_1\mu_B\mathcal{B}_z\tilde{\mathcal{B}}t\,\text{Re}\Pi$$

We actually care about: $\dfrac{\partial(d\theta_{\text{prep,eff}})}{\partial\Delta^{\mathcal{N}\mathcal{E}}}$

G switch suppression

$$d\theta_{\text{prep,eff}} = -\boxed{d\Theta_{\text{prep}}\,\text{Im}\Pi} + d\theta_{\text{prep}}\,\text{Re}\Pi - g_1\mu_B\mathcal{B}_z\tilde{\mathcal{B}}t\,\text{Re}\Pi$$

dominant

We actually care about: $\dfrac{\partial(d\theta_{\text{prep,eff}})}{\partial\Delta^{\mathcal{NE}}}$

1. show $d\Theta_{\text{prep}}\,\text{Im}\Pi \gg d\theta_{\text{prep}}\,\text{Re}\Pi$
2. show $d\Theta_{\text{prep}}\,\text{Im}\Pi$ term can be cancelled by G switch
3. show $g_1\mu_B\mathcal{B}_z\tilde{\mathcal{B}}t\,\text{Re}\Pi$ term can be suppressed by B switch

G switch suppression

$$d\theta_{\text{prep,eff}} = -\,d\Theta_{\text{prep}}\,\text{Im}\Pi + d\theta_{\text{prep}}\,\text{Re}\Pi - g_1\mu_B\mathcal{B}_z\tilde{\mathcal{B}}t\,\text{Re}\Pi$$

small

We actually care about: $\dfrac{\partial(d\theta_{\text{prep,eff}})}{\partial\Delta^{\mathcal{NE}}}$

Conclusion:

with G switch we can surpress $\dfrac{\partial(d\theta_{\text{prep,eff}})}{\partial\Delta^{\mathcal{NE}}}$

down to the level $\dfrac{\partial(d\theta_{\text{prep}}\text{Re}\Pi)}{\partial\Delta^{\mathcal{NE}}}$,

which is at least one $d\Theta$ order smaller than $\dfrac{\partial(d\theta_{\text{prep,eff}})}{\partial\Delta^{\mathcal{NE}}}$

G switch suppression

$$d\theta_{\mathrm{prep,eff}} = -d\Theta_{\mathrm{prep}}\,\mathrm{Im}\Pi + d\theta_{\mathrm{prep}}\,\mathrm{Re}\Pi - g_1\mu_B\mathcal{B}_z\tilde{\mathcal{B}}t\,\mathrm{Re}\Pi$$

dominant

We actually care about: $\dfrac{\partial(d\theta_{\mathrm{prep,eff}})}{\partial\Delta^{\mathcal{NE}}}$

2. show $d\Theta_{\mathrm{prep}}\,\mathrm{Im}\Pi$ term can be cancelled by G switch

$\tilde{\mathcal{G}} = +1 \rightarrow \tilde{\mathcal{G}} = -1$

$d\Theta \rightarrow -d\Theta$

$d\theta$ no change

$$d\Theta_{\mathrm{prep}}\,\mathrm{Im}\Pi \rightarrow -d\Theta_{\mathrm{prep}}\,\mathrm{Im}\Pi$$

G switch suppression

$$\mathrm{d}\theta_{\mathrm{prep,eff}} = -\mathrm{d}\Theta_{\mathrm{prep}}\,\mathrm{Im}\Pi + \mathrm{d}\theta_{\mathrm{prep}}\,\mathrm{Re}\Pi - g_1 \mu_B \mathcal{B}_z \tilde{\mathcal{B}} t\,\mathrm{Re}\Pi$$

We actually care about: $\frac{\partial(\mathrm{d}\theta_{\mathrm{prep,eff}})}{\partial \Delta^{\mathcal{NE}}}$

3. show $g_1 \mu_B \mathcal{B}_z \tilde{\mathcal{B}} t\,\mathrm{Re}\Pi$ term can be suppressed by B switch

Obvious.

G switch suppression

$$\mathrm{d}\theta_{\mathrm{prep,eff}} = -\mathrm{d}\Theta_{\mathrm{prep}}\mathrm{Im}\Pi + \mathrm{d}\theta_{\mathrm{prep}}\mathrm{Re}\Pi - g_1\mu_B\mathcal{B}_z\tilde{\mathcal{B}}t\,\mathrm{Re}\Pi$$

1. show $\mathrm{d}\Theta_{\mathrm{prep}}\mathrm{Im}\Pi \gg \mathrm{d}\theta_{\mathrm{prep}}\mathrm{Re}\Pi$

$\mathrm{d}\theta_{\mathrm{prep}} \sim \delta^2$

$\mathrm{d}\Theta_{\mathrm{prep}} \sim \delta$

δ: retardance of optical system the laser been through

ACME I: ~20%

ACME II: ~10%

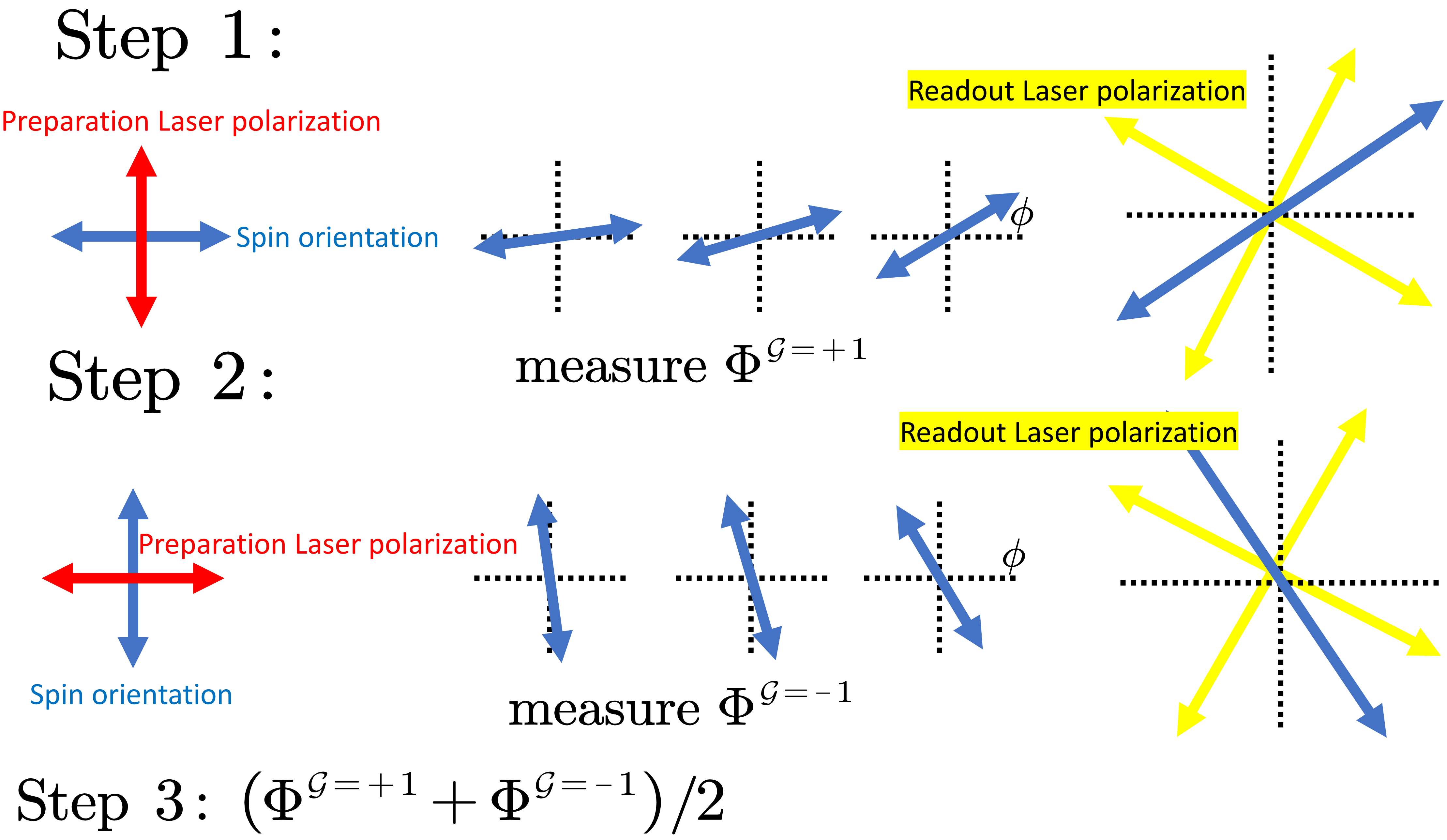
ACME III: ~1%

(major improvement will come from SF vacuum windows)

G switch suppression

$$\mathrm{d}\theta_{\mathrm{prep,eff}} = -\,\mathrm{d}\Theta_{\mathrm{prep}}\,\mathrm{Im}\Pi + \mathrm{d}\theta_{\mathrm{prep}}\,\mathrm{Re}\Pi - g_1\mu_B\mathcal{B}_z\tilde{\mathcal{B}}t\,\mathrm{Re}\Pi$$

small



Step 1:
Preparation Laser polarization
Spin orientation
measure $\Phi^{\mathcal{G}=+1}$
Readout Laser polarization
ϕ
Step 2:
Preparation Laser polarization
Spin orientation
measure $\Phi^{\mathcal{G}=-1}$
Readout Laser polarization
ϕ
Step 3: $(\Phi^{\mathcal{G}=+1}+\Phi^{\mathcal{G}=-1})/2$

Outline

What is G switch

Theory for G switch: How it works

- Polarization of light under G switch
- Spin misalignment and EDM systematic
- Imperfect optical pumping
- G switch suppression

Historical Evidence for G switch

ACME III Field Plates requirements

G switch in ACME I

Some reasonable questions to be asked:

Q1 Is there any (experiment) evidence that $\mathcal{G}$ switch helped?

Q2 Readout lasers are being switched as well, is there a similar effect?

Q3 In ACME I, $\mathcal{G}$ switch is applied, what's left there?

Q1 Is there any (experiment) evidence that $\mathcal{G}$ switch helped?

Ben spaun thesis for ACME I

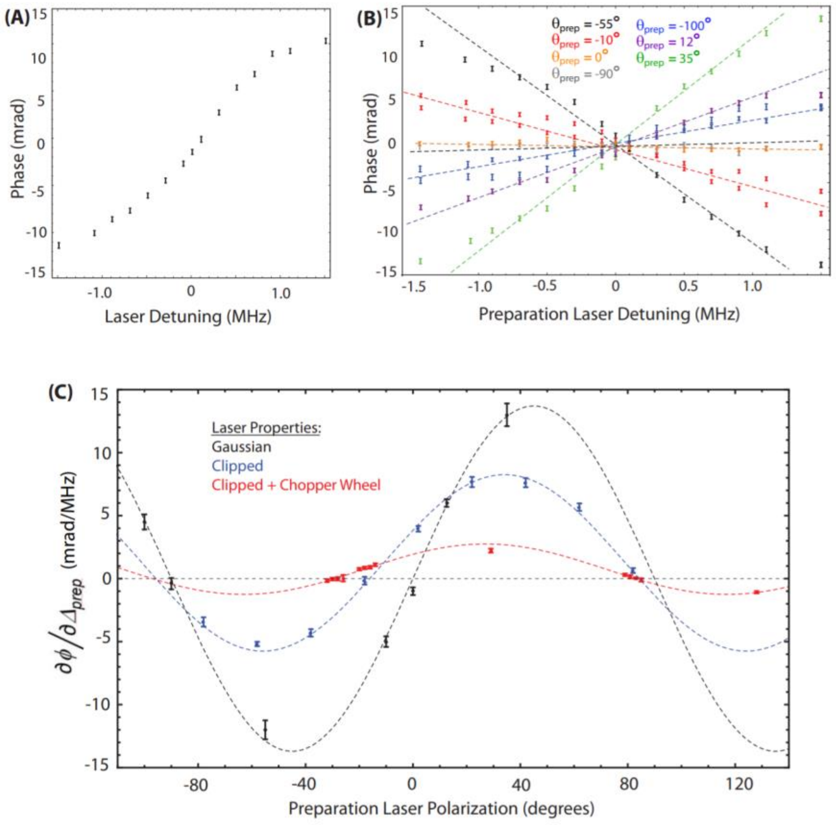
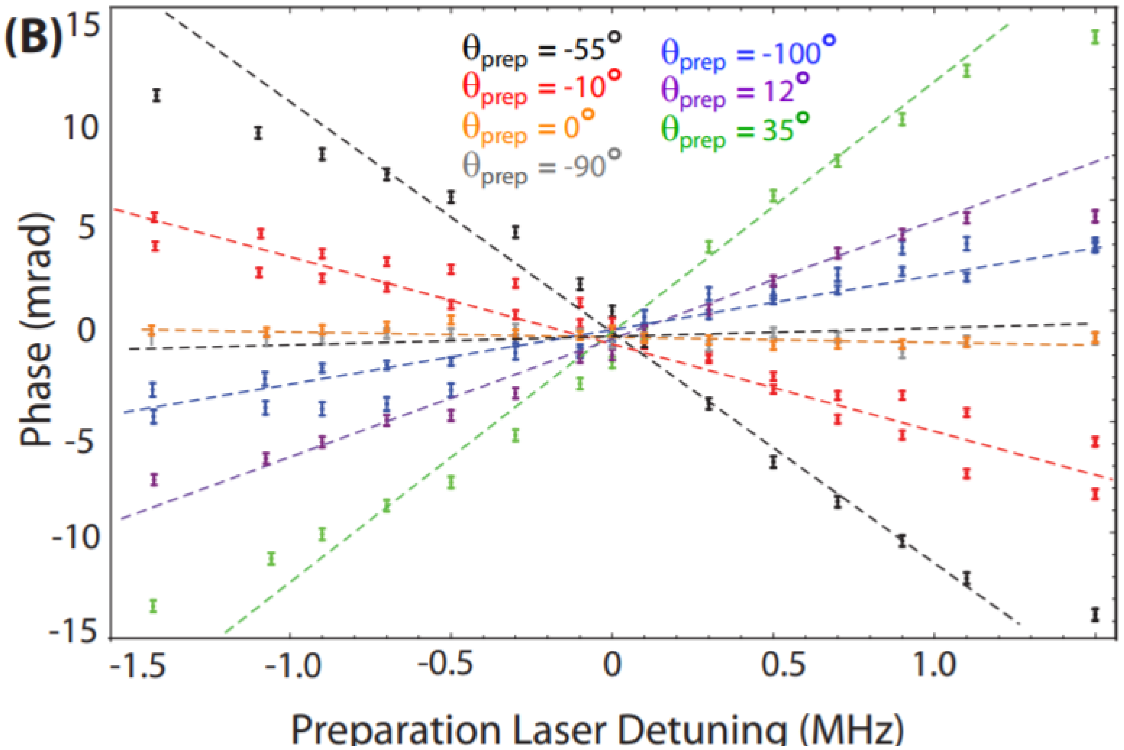


Figure 7.5: **(A)** Molecule phase as a function of preparation laser detuning. The slope agrees with originally observed $\phi^{\mathcal{NE}}$ dependence on $\Delta^{\mathcal{NE}}$. **(B)** Phase dependence on detuning for multiple preparation laser polarization angles. **(C)** $\partial\phi/\partial\Delta_0$ shows clear sinusoidal dependence on preparation laser polarization. The magnitude of $\partial\phi/\partial\Delta_0$ decreases for all polarization angles when the Gaussian beam tails are clipped (blue) and the laser power is reduced (red).

Q1 Is there any (experiment) evidence that $\mathcal{G}$ switch helped?



when θ_{prep} is 90° different,

Phase dependency on Detuning Δ flip sign.

Figure 7.5: **(A)** Molecule phase as a function of preparation laser detuning. The slope agrees with originally observed $\phi^{\mathcal{NE}}$ dependence on $\Delta^{\mathcal{NE}}$. **(B)** Phase dependence on detuning for multiple preparation laser polarization angles. **(C)** $\partial\phi/\partial\Delta_0$ shows clear sinusoidal dependence on preparation laser polarization. The magnitude of $\partial\phi/\partial\Delta_0$ decreases for all polarization angles when the Gaussian beam tails are clipped (blue) and the laser power is

Q2 Readout lasers are being switched as well, is there a similar effect?

$$\Phi = \phi + \kappa(d\theta_{\mathrm{prep\ eff}} \frac{1}{2}(d\theta_{X_{\mathrm{eff}}} + d\theta_{Y_{\mathrm{eff}}})) - \kappa^2 \tilde{\mathcal{P}}_{\mathrm{prep}} \tilde{\mathcal{P}}_{\mathrm{read}} d\Theta_{\mathrm{prep_{eff}}} (d\Theta_{X_{\mathrm{eff}}} - d\Theta_{Y_{\mathrm{eff}}}) + O\left(\kappa^3\right),$$

$$\theta_{\mathrm{X}} \perp \theta_{\mathrm{Y}}$$

$$\mathrm{d}\Theta_{\mathrm{X}} = -\,\mathrm{d}\Theta_{\mathrm{Y}}$$

$$\mathrm{d}\theta_{\mathrm{X,eff}} = -\,\mathrm{d}\Theta_{\mathrm{x}}\,\mathrm{Im}\Pi$$

$$\mathrm{d}\theta_{\mathrm{Y,eff}} = -\,\mathrm{d}\Theta_{\mathrm{y}}\,\mathrm{Im}\Pi = \mathrm{d}\Theta_{\mathrm{x}}\,\mathrm{Im}\Pi = -\,\mathrm{d}\theta_{\mathrm{X,eff}}$$

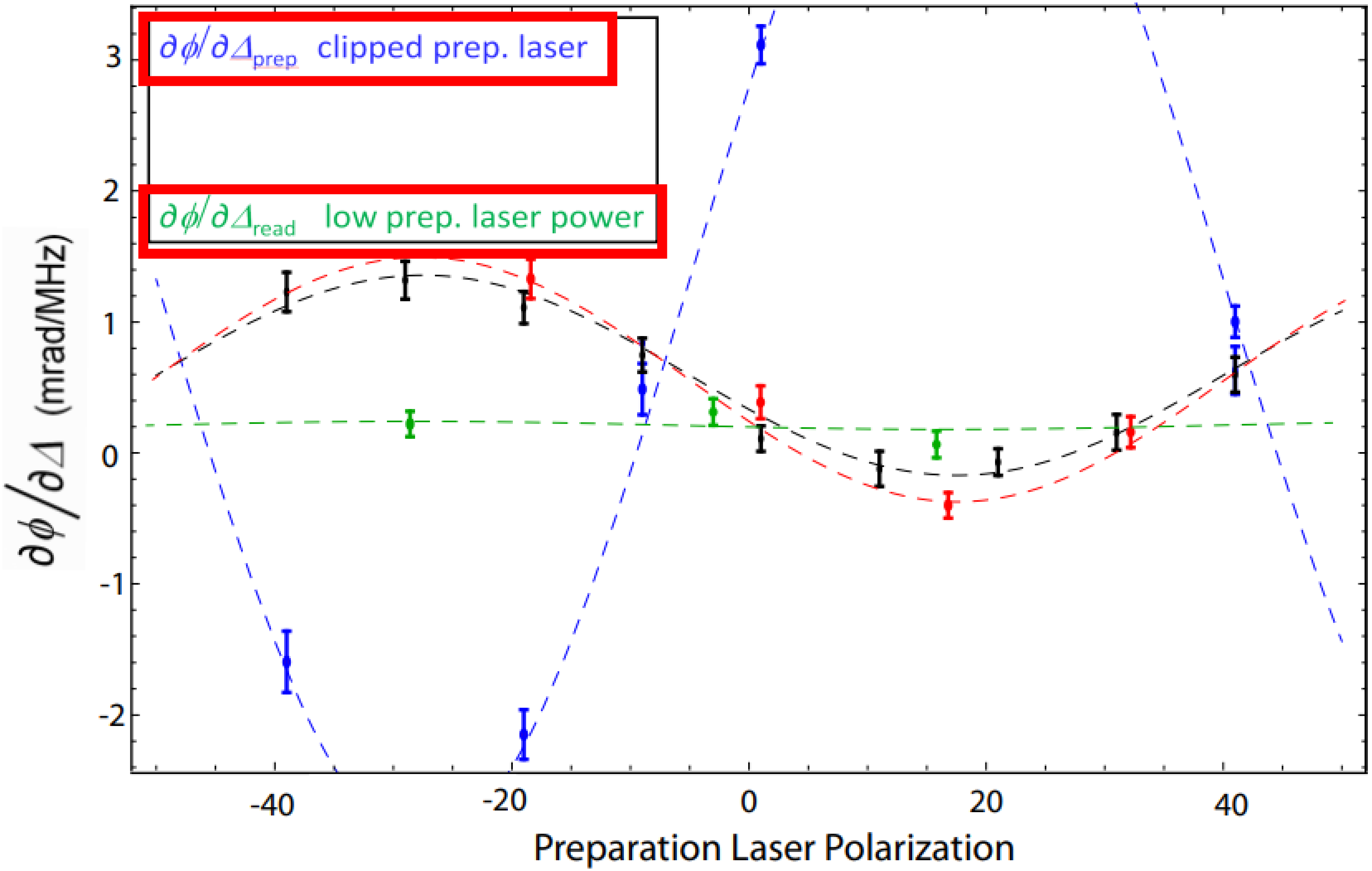
$\mathrm{d}\theta_{\mathrm{Xeff}} + \mathrm{d}\theta_{\mathrm{Yeff}}$ has no Δ first order dependence

$$F_Y = N_0\left[\frac{\quad}{2} + \mathcal{C}\sin(\phi - \theta + \phi_{\text{shift}})\right]. \tag{7.9}$$

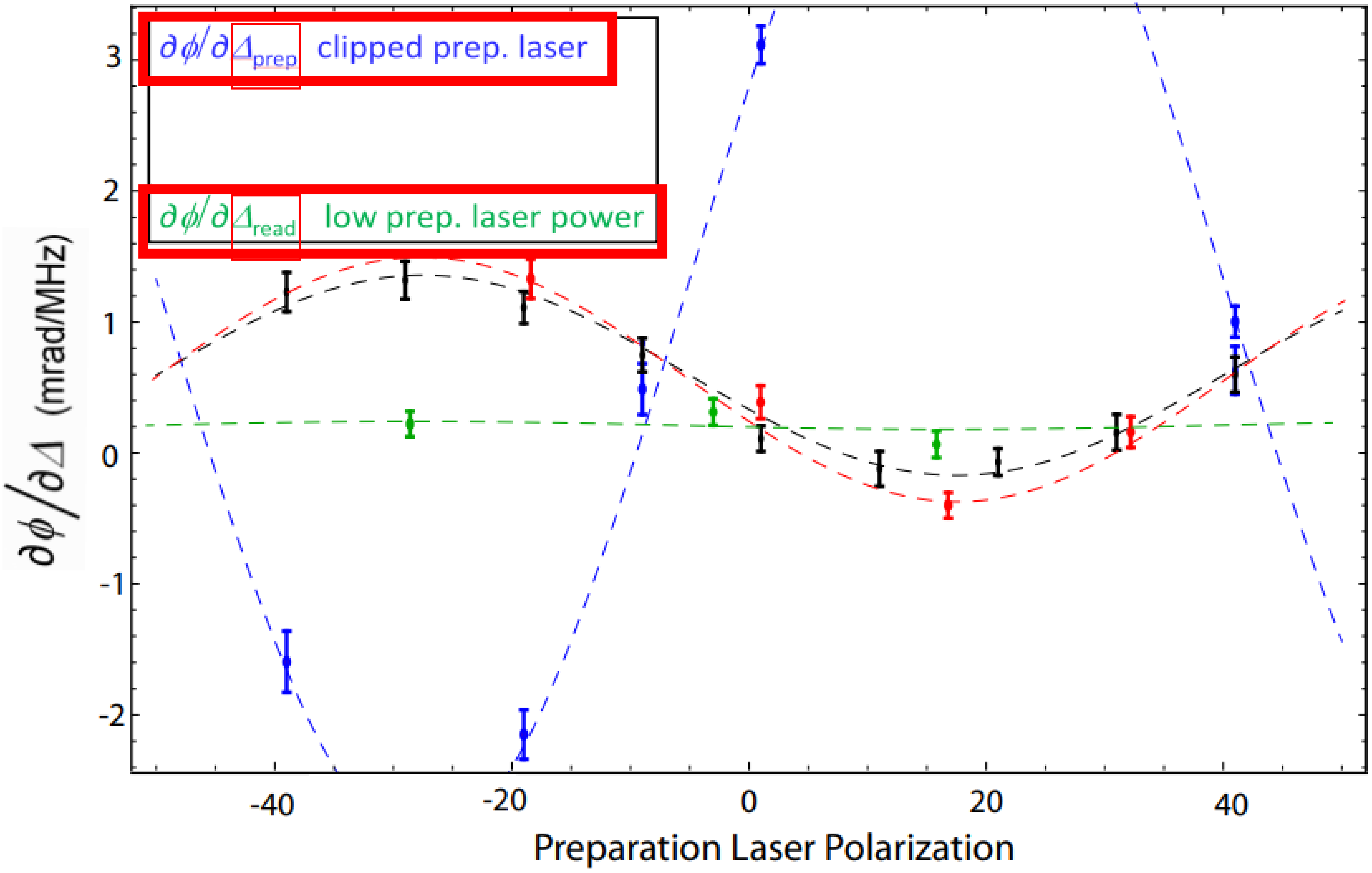
Where ϕ is the molecule precession phase, θ is the polarization of the $\hat{X}$ beam, and ϕ_{shift} is the systematic phase shift. When these fluorescence signals are combined to form asymmetry, the phase shifts are suppressed:

$$\mathcal{A} = \frac{F_X - F_Y}{F_X + F_Y} \approx \mathcal{C}\cos(2\phi + 2\theta) + \mathcal{C}^2\sin(4\phi + 4\theta)\phi_{\text{shift}}. \tag{7.10}$$

Here it is assumed that $\phi_{\text{shift}} << \phi + \theta$. Since we operate on the side of the asymmetry fringe with $\phi + \theta \approx \pi/4$, the contribution of ϕ_{shift} is largely suppressed. Indeed, all data indicated that $\partial\phi/\partial\Delta_{\text{read}}$ was completely independent of the readout laser polarization, and instead depended on θ_{prep}. Figure 7.7 shows $\partial\phi/\partial\Delta_{\text{read}}$ as a function

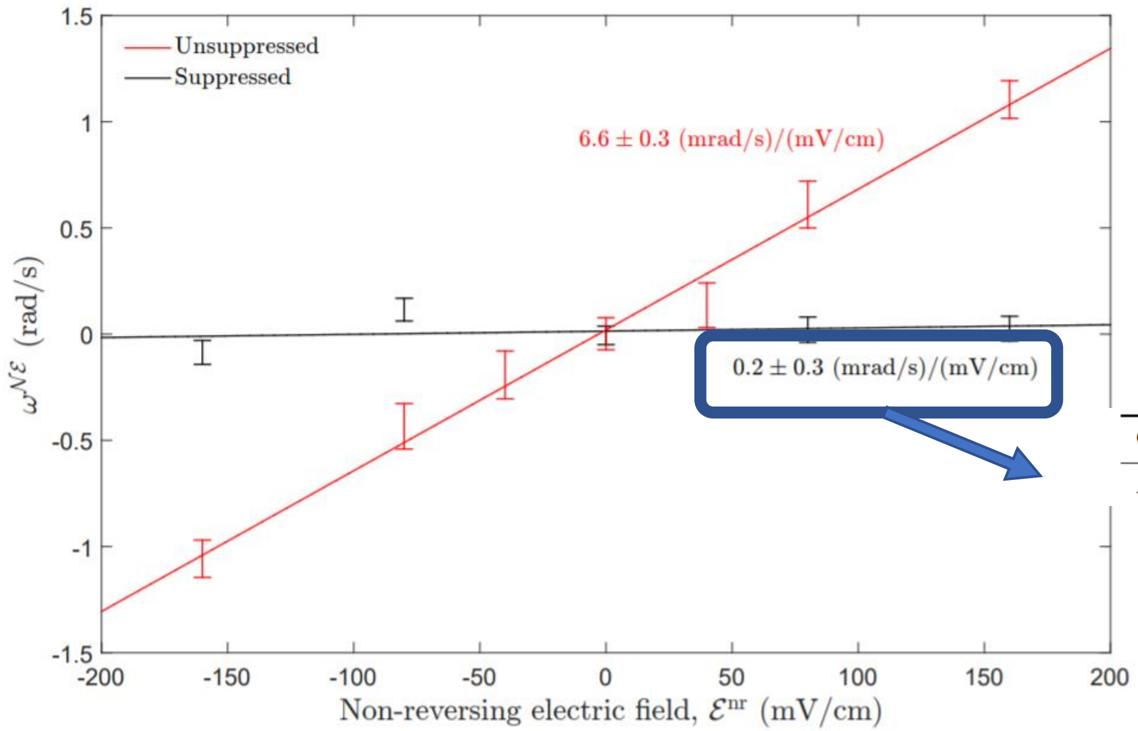


$\partial\phi/\partial\Delta_{prep}$ clipped prep. laser
$\partial\phi/\partial\Delta_{read}$ low prep. laser power
$\partial\phi/\partial\Delta$ (mrad/MHz)
3
2
1
0
-1
-2
-40
-20
0
20
40
Preparation Laser Polarization



$\partial\phi/\partial\Delta_{prep}$ clipped prep. laser
$\partial\phi/\partial\Delta_{read}$ low prep. laser power
$\partial\phi/\partial\Delta$ (mrad/MHz)
Preparation Laser Polarization
3
2
1
0
-1
-2
-40
-20
0
20
40

Q3 In ACME I, $\mathcal{G}$ switch is applied, what's left there?



Class	Parameter	Shift (mrad/s)	Uncertainty (mrad/s)
A	$\mathcal{E}^{nr}$ correction	−0.81	0.66

Figure 33: Linear dependence of the $\omega^{\mathcal{N}\mathcal{E}}$ channel on an applied non-reversing electric field observed before (red) and after (black) we suppressed the known AC Stark shift phase by optimizing the preparation laser beam shape, time-averaged power and polarisation.

Consistent with 'zero' under ACME I statistical uncertainty

Statistical uncertainty error bar is too large when doing systematic check, unable to reduce the uncertainty

Outline

What is G switch

Theory for G switch: How it works

- Polarization of light under G switch
- Spin misalignment and EDM systematic
- Imperfect optical pumping
- G switch suppression

Historical Evidence for G switch

ACME III Field Plates requirements

ACME III Field Plates requirements

Expected E^{nr} systematic level for ACME III

$$\frac{\Delta_{\text{sys}(E^{nr})\ \text{ACME III}}}{\Delta_{\text{sys}(E^{nr})\ \text{ACME II}}} = \text{Improvement on glass} \times \text{G switch suppression} \times \text{Natural gain}\,(5)$$

$$S\,(\text{success rate}) = S_{\text{glass}} \times S_{\text{G switch}} \times 1$$

spin misalignment: $d\theta$

precession time: $t \rightarrow 5t$

precession velocity uncertainty: $\frac{\mathrm{d}\theta}{t} \rightarrow \frac{1}{5}\frac{\mathrm{d}\theta}{t}$

ACME III Field Plates requirements

Expected $E^{\rm nr}$ systematic level for ACME III

$$\frac{\Delta_{\text{sys}(E^{nr})\ \text{ACME III}}}{\Delta_{\text{sys}(E^{nr})\ \text{ACME II}}} = \text{Improvement on glass} \times \text{G switch suppression} \times \text{Natural gain}\,(5)$$

$$S\,(\text{success rate}) = S_{\text{glass}} \times S_{\text{G switch}} \times 1$$

$S_{\text{G switch}}$ is determined by success rate of :

horizontal STIRAP

or STIRAP P switch (concept in ACME II)

or any prerequisite steps for G to be possible

Worth spending more time looking at

ACME III Field Plates requirements

Expected E^{nr} systematic level for ACME III

$$\frac{\Delta_{\mathrm{sys}(E^{nr})\ \mathrm{ACME\ III}}}{\Delta_{\mathrm{sys}(E^{nr})\ \mathrm{ACME\ II}}} = \text{Improvement on glass} \times \text{G switch suppression} \times \text{Natural gain}\,(5)$$

$$S\,(\text{success rate}) = S_{\mathrm{glass}} \times S_{\mathrm{G\ switch}} \times 1$$

Corning 7980 field plates plan:

Improvement on glass: slightly lower than SF plan

S_{glass}: higher than SF plan

SF field plates plan:

Improvement on glass: slightly better than Corning 7980 plan

S_{glass}: lower because epoxy

Major source for birefringence improvement:

- Using SF for vacuum windows
- Better Field Plate mounts

Minor source for birefringence improvement:

- Using SF instead of Corning 7980 for FP