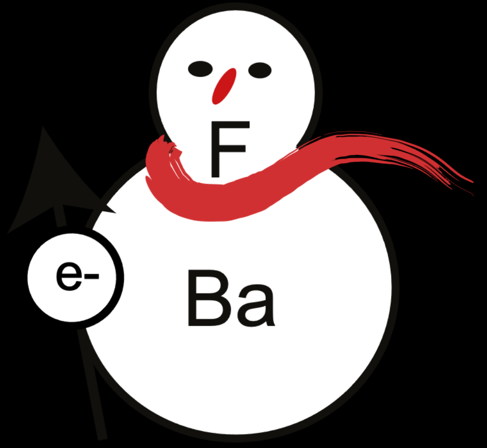


Searching for the *e*EDM with molecules

Alexander Boeschoten
on behalf of the NL-*e*EDM collaboration

Nikhef Jamboree 15/05/23

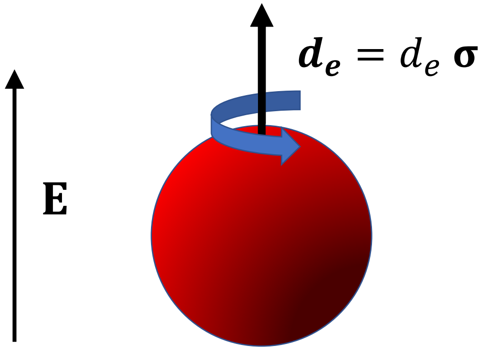
university of groningen
VRIJE UNIVERSITEIT AMSTERDAM
Nikhef
NWO

Elementary EDM

- ***e*EDM:** Parity and Time Reversal $(= CP)$ violating interaction between electron and electromagnetic field

- EFT operator: $$\mathcal{L}_{e\mathrm{EDM}} = -i\,\frac{d_e}{2}\,\overline{\Psi}_e\sigma^{\mu\nu}\gamma^5\Psi_e F_{\mu\nu}$$

- Hamiltonian: $$H_{e\mathrm{EDM}} = -d_e\,\boldsymbol{\sigma}\cdot\mathbf{E}$$



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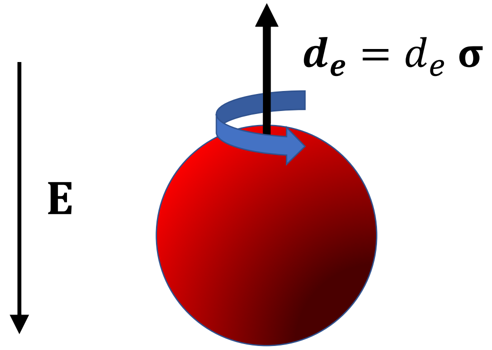

P

$$P H_{e\text{EDM}} P^{-1} = d_e\,\boldsymbol{\sigma}\cdot\mathbf{E}$$

$$-d_e\,\boldsymbol{\sigma}\cdot(-\mathbf{E}) = -H_{e\text{EDM}}$$

Elementary EDM

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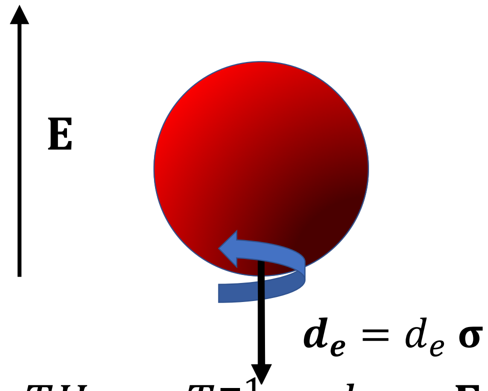


$$T H_{e\mathrm{EDM}} T^{-1} = d_e\,\boldsymbol{\sigma}\cdot\mathbf{E}$$

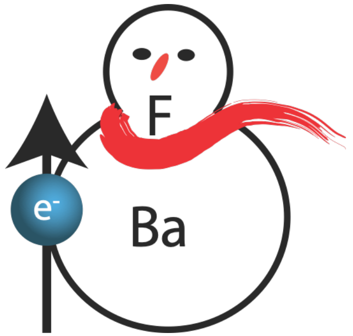
T

$$-d_e\,(-\boldsymbol{\sigma})\cdot\mathbf{E} = -H_{e\mathrm{EDM}}$$

P

$$-d_e\,\boldsymbol{\sigma}\cdot(-\mathbf{E}) = -H_{e\mathrm{EDM}}$$

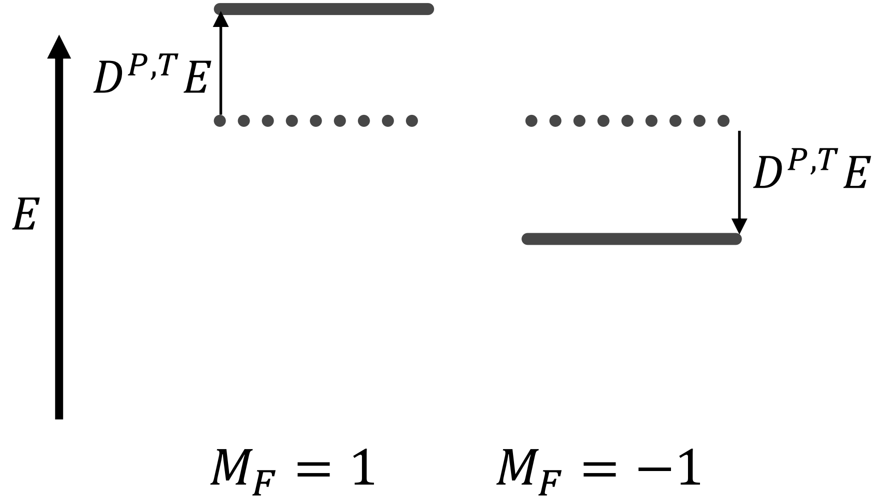
Molecular EDM



- d_e induces a **molecular EDM** $D^{P,T}$:

$$H_{\mathrm{EDM}} = -D^{P,T}(d_e)\mathbf{F}\cdot\mathbf{E}$$

- $D^{P,T}(d_e) \sim 10^5 d_e$ in BaF: *e*EDM is enhanced!



Molecular EDM

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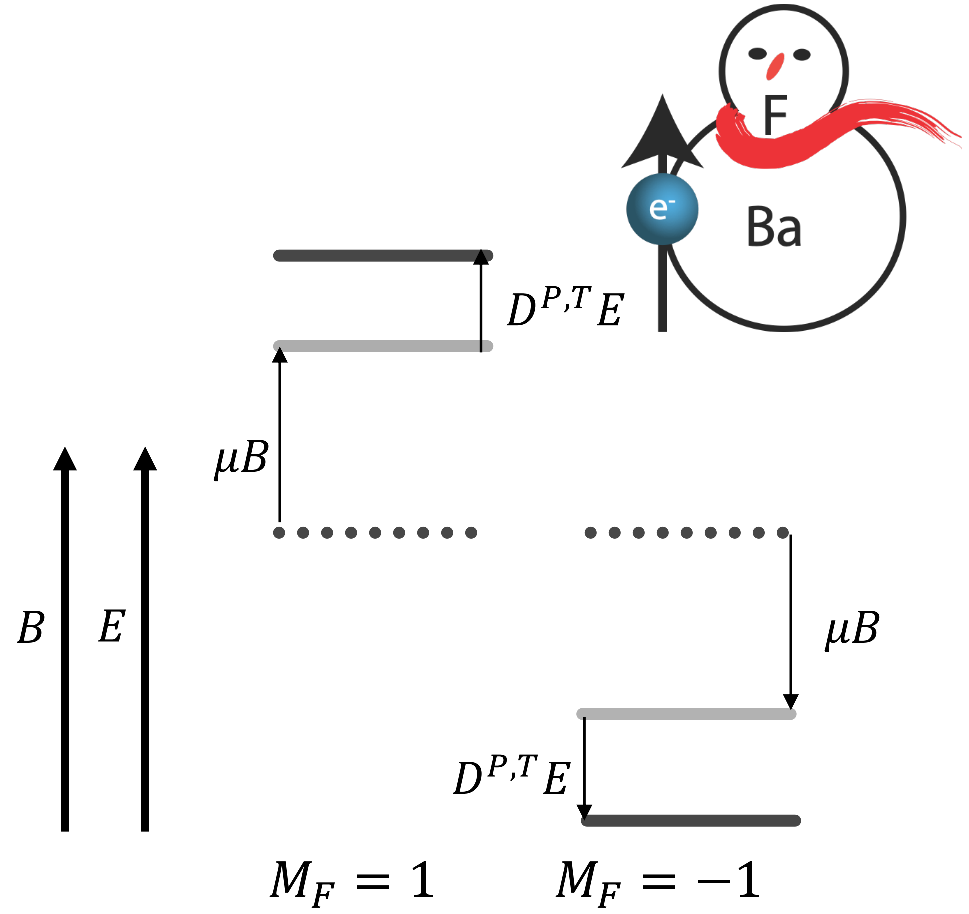
- $D^{P,T}(d_e) \sim 10^5 d_e$ in BaF: *e*EDM is enhanced!

- Zeeman effect:

$$H_{\text{Zeeman}} = -\mu\, \mathbf{F} \cdot \mathbf{B}$$

- Same shift, but larger!

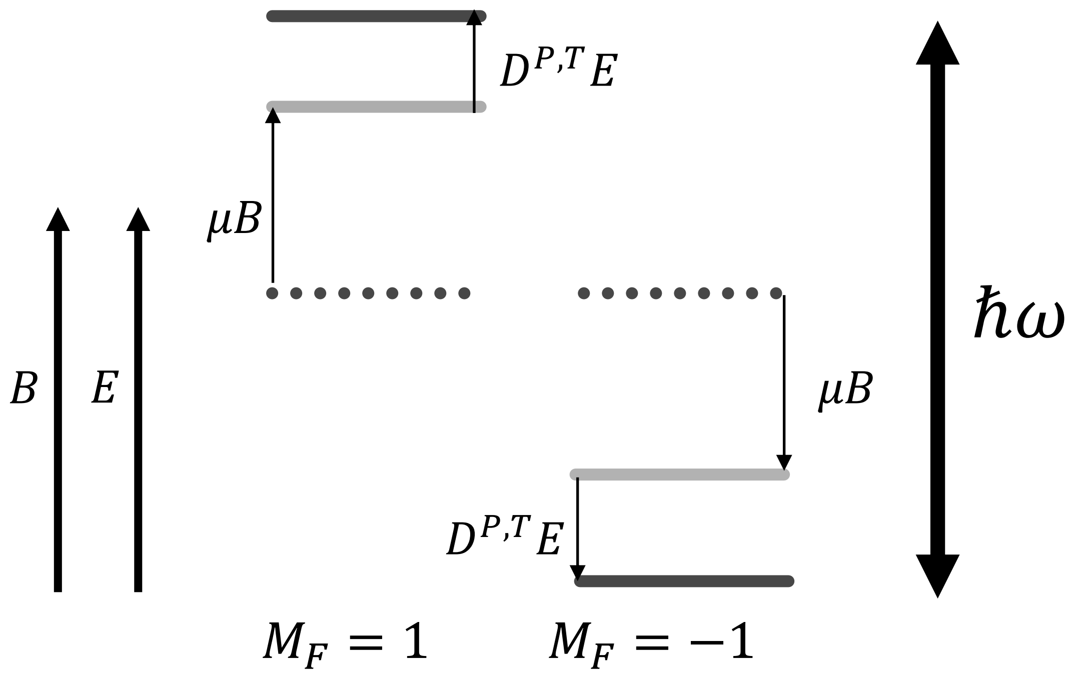
$$\frac{\Delta W_{\text{EDM}}}{\Delta W_{\text{Zeeman}}} \sim 10^{-7}$$



EDM measurement

1. Measure energy difference $\hbar\omega$ with high **precision**

$$\omega = 2\mu B + 2D^{P,T}E$$



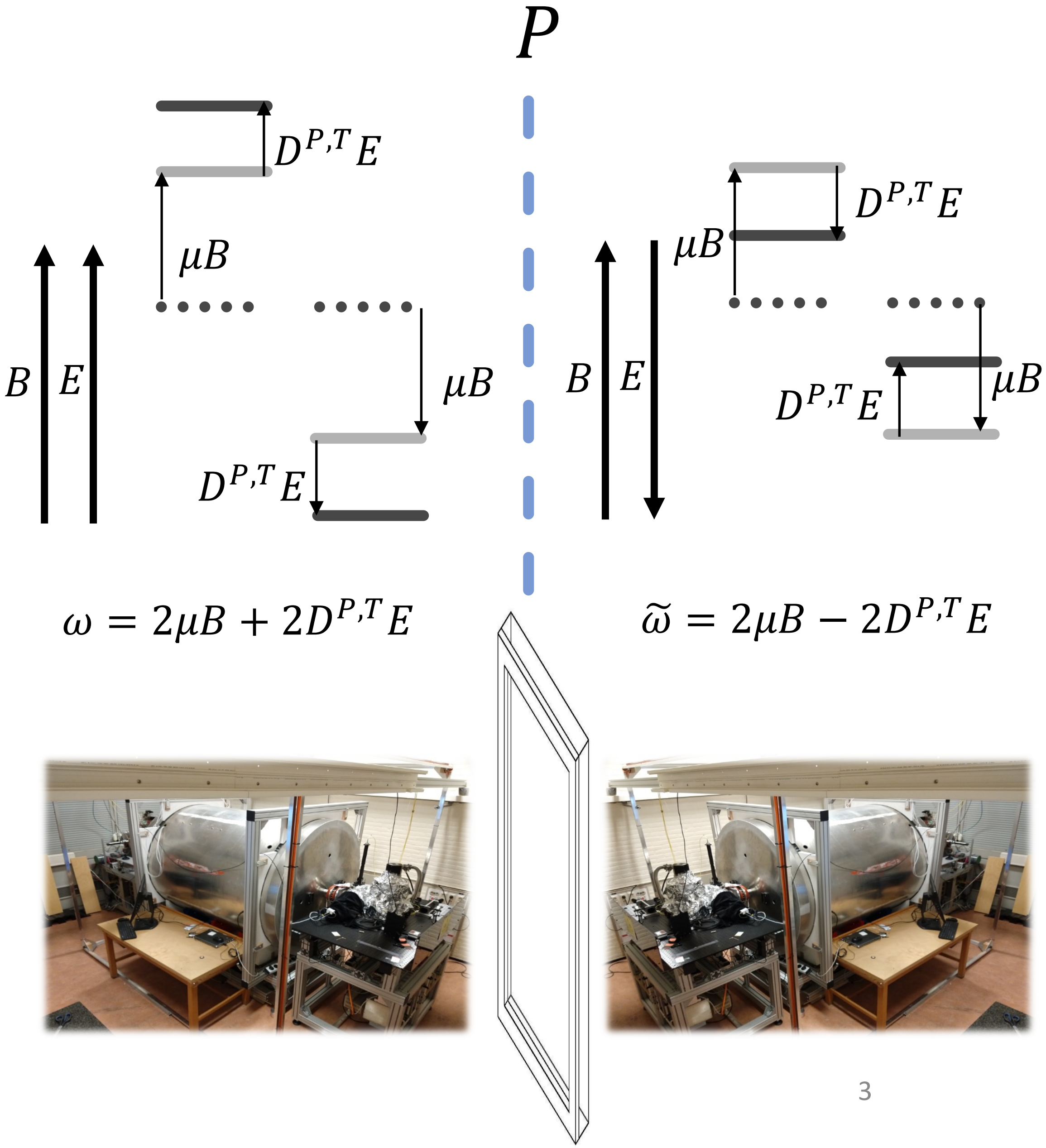
EDM measurement

1. Measure energy difference $\hbar\omega$ with high **precision**

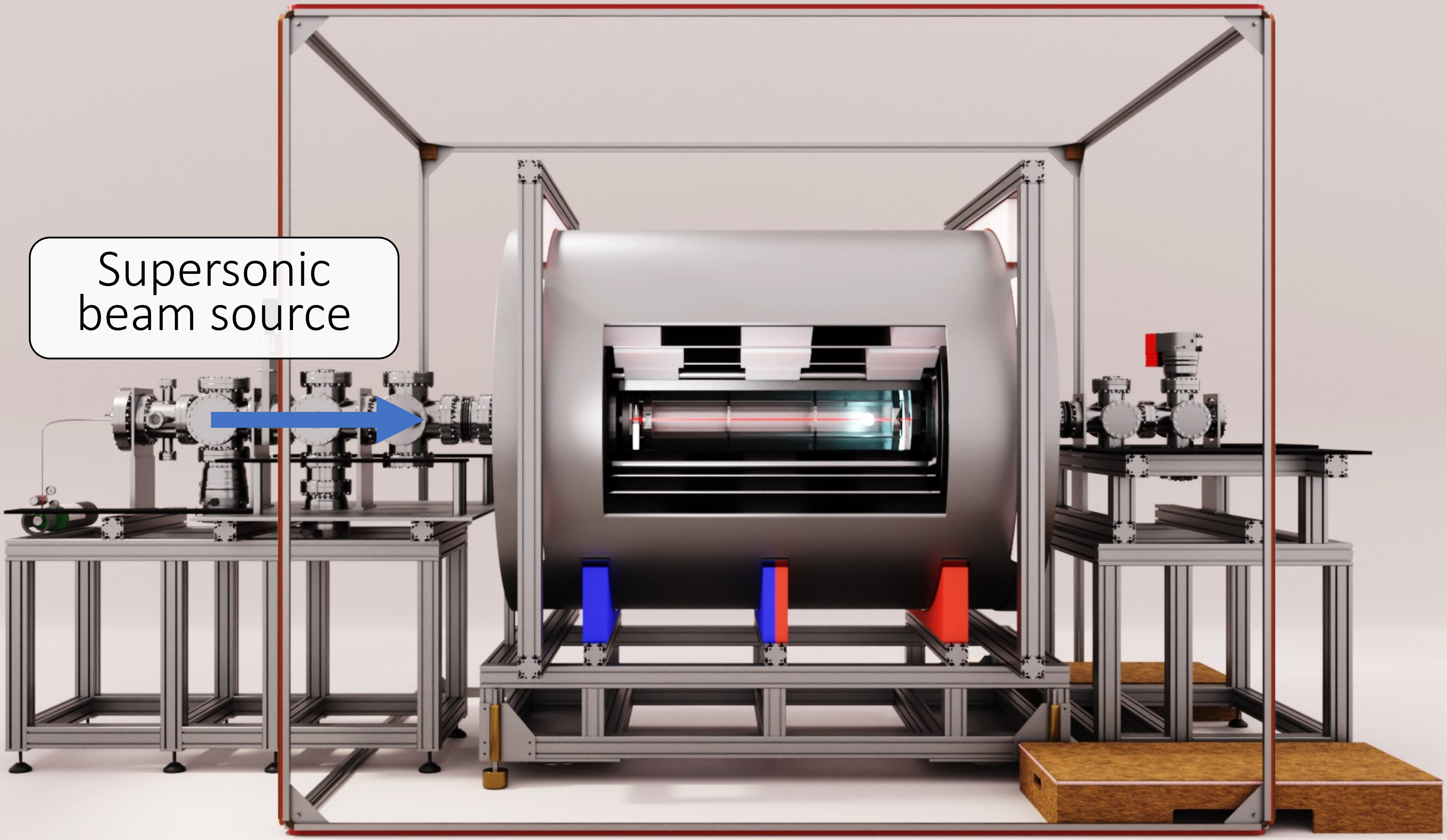
$$\omega = 2\mu B + 2D^{P,T}E$$

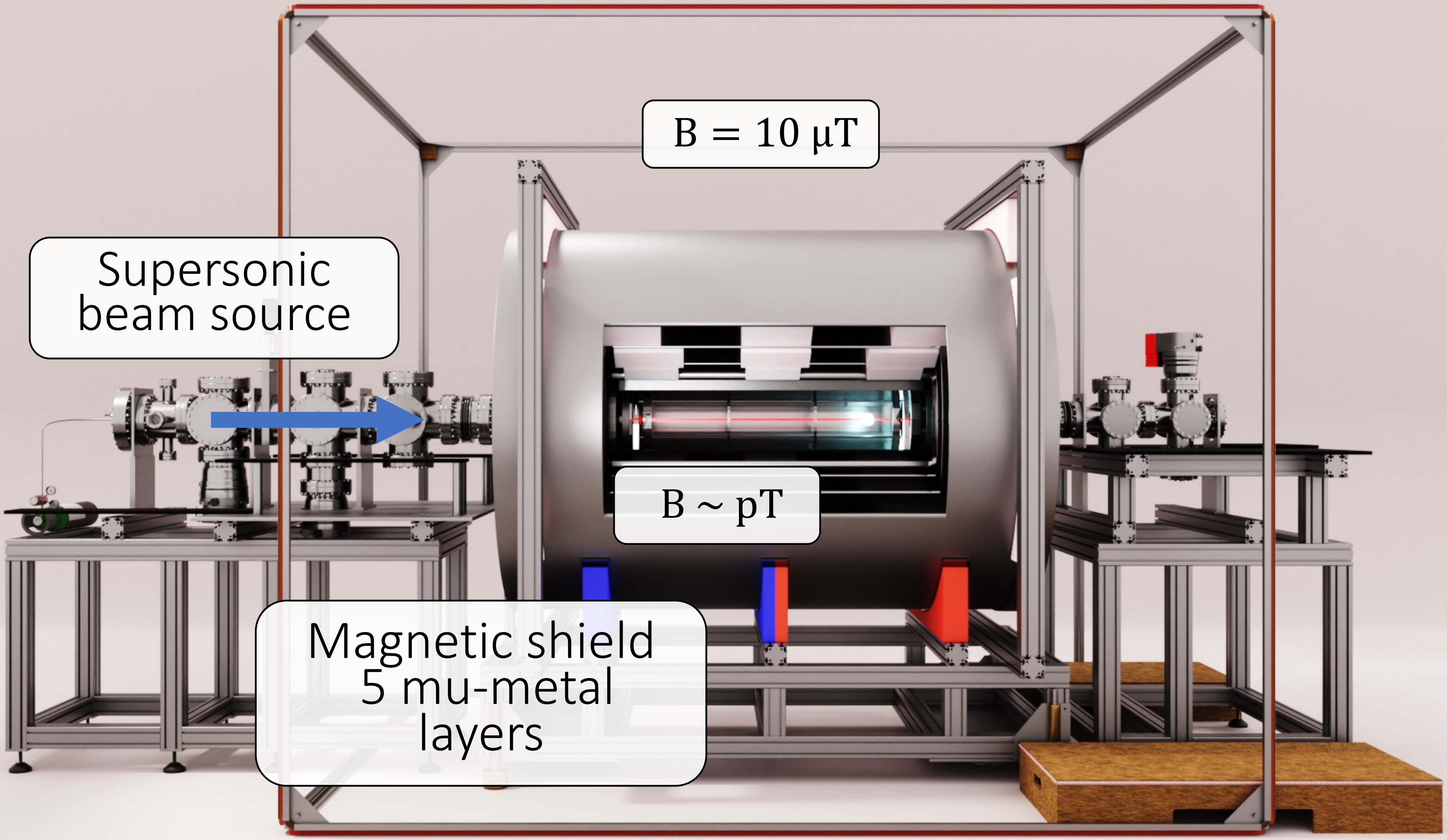
2. Do a *P* or *T* transformation with high **accuracy**

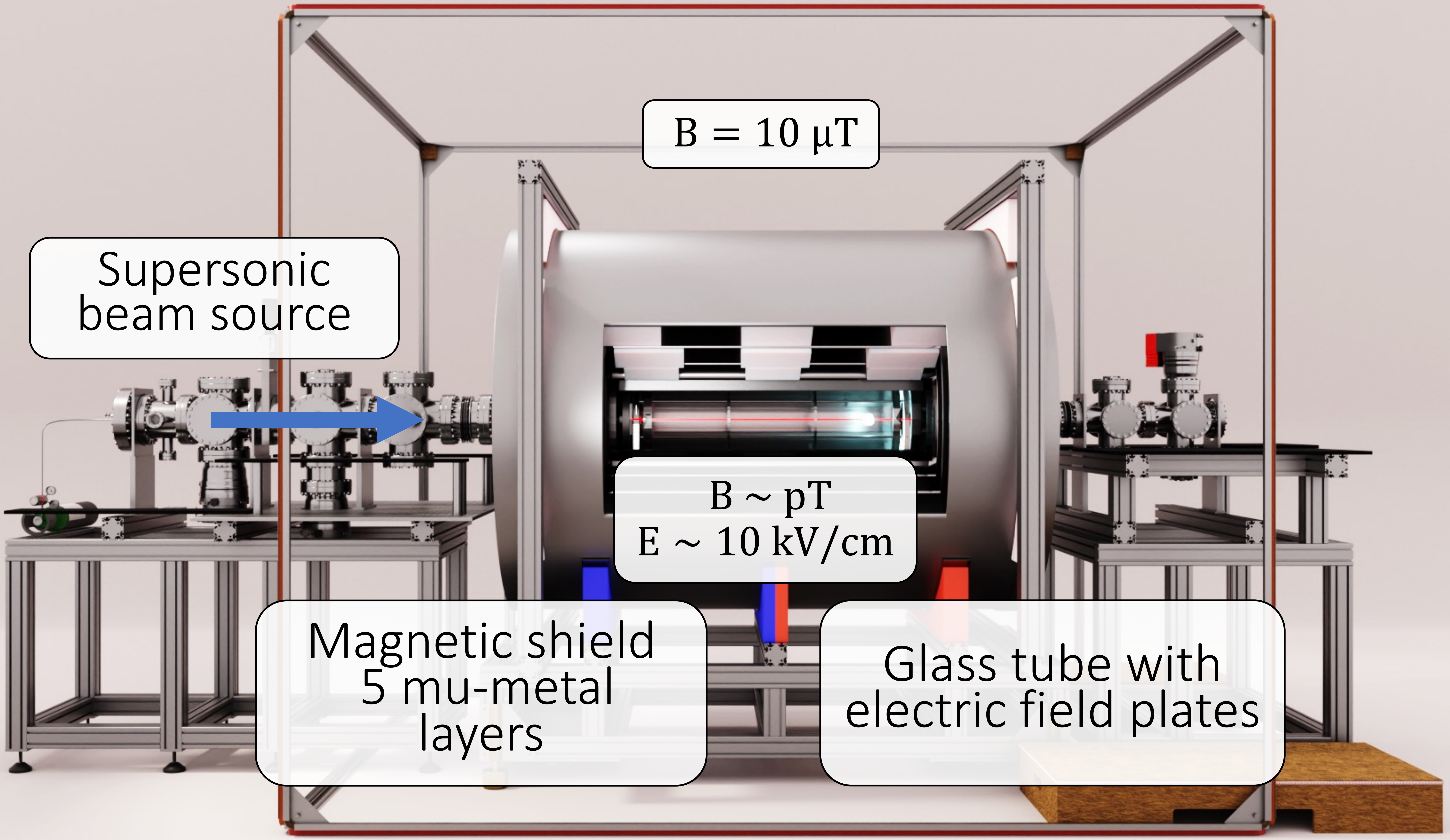
$$\omega - \tilde{\omega} = 4D^{P,T}E$$

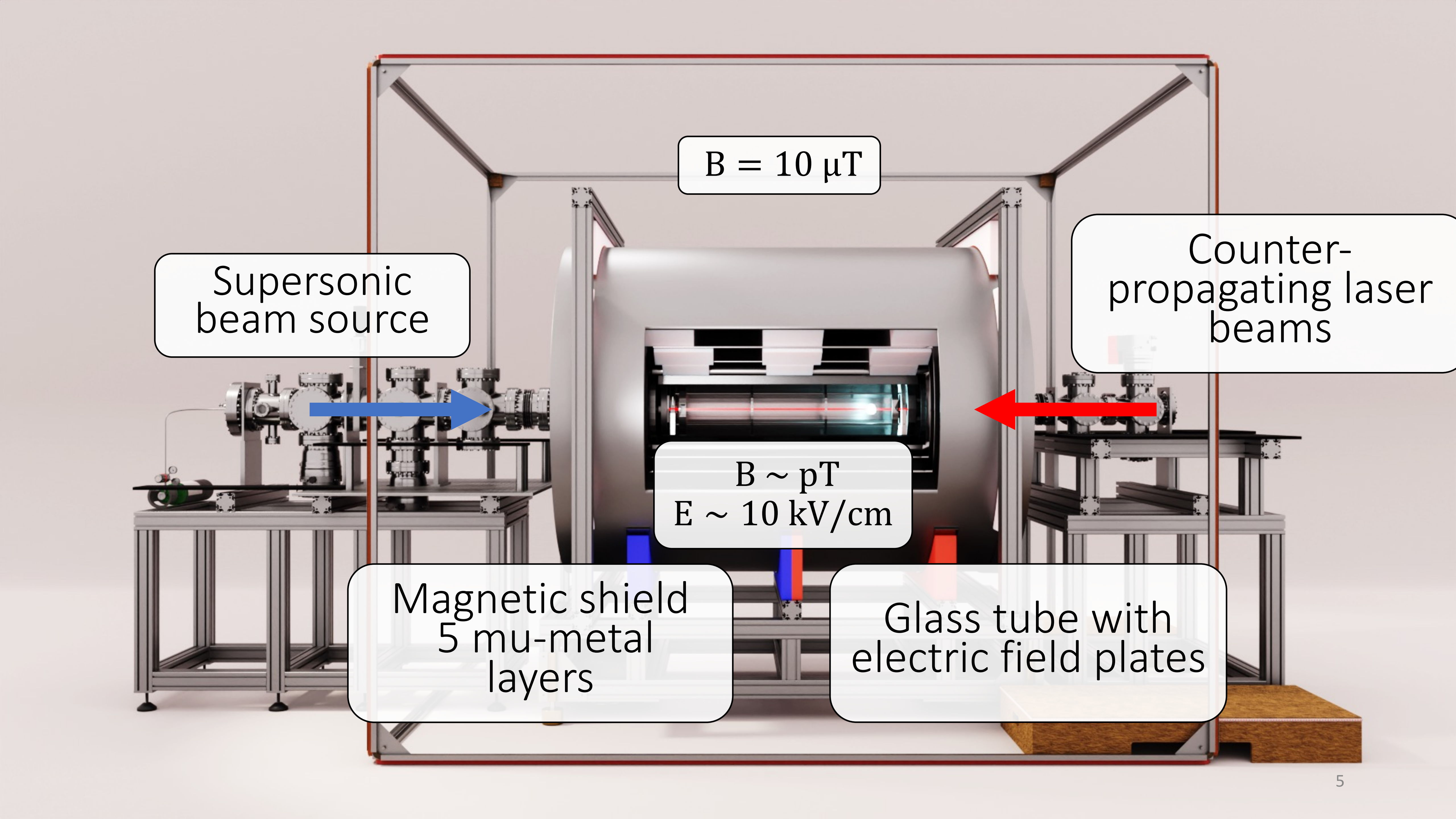


The NL-*e*EDM setup

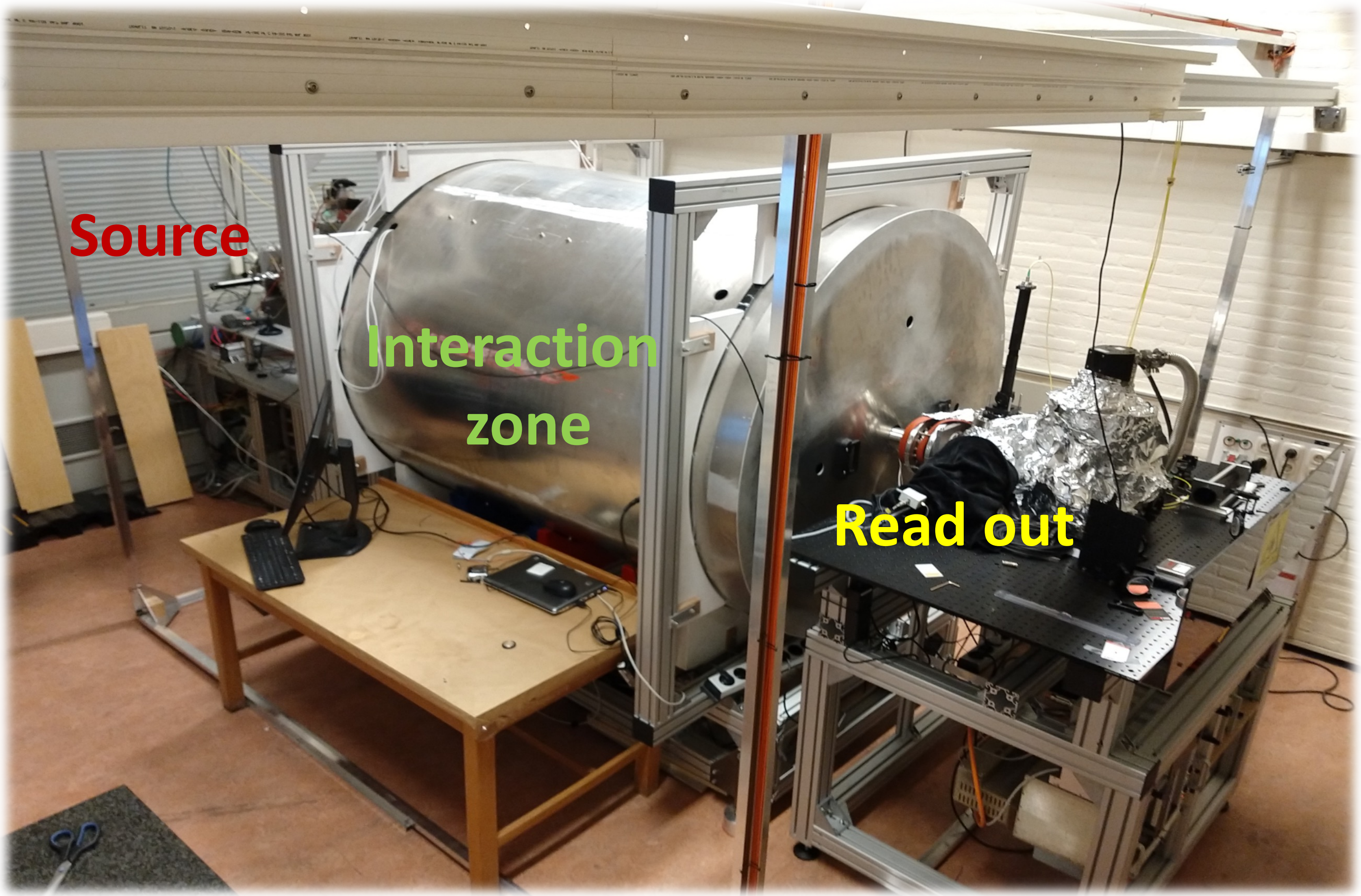

Supersonic
beam source


B = 10 μT
Supersonic beam source
B ~ pT
Magnetic shield 5 mu-metal layers


B = 10 μT
Supersonic beam source
B ~ pT
E ~ 10 kV/cm
Magnetic shield 5 mu-metal layers
Glass tube with electric field plates



B = 10 µT
Supersonic beam source
Counter-propagating laser beams
B ~ pT
E ~ 10 kV/cm
Magnetic shield 5 mu-metal layers
Glass tube with electric field plates



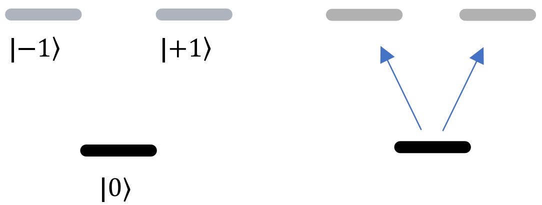
+ many lasers!

Principle of the experiment

Quantum interference measurement

Interference measurement

1. **Superposition creation**



$\Psi(t_0) = |0\rangle$

$$\Psi(t_1) = \frac{1}{\sqrt{2}}(|-1\rangle + | + 1)$$
$$= |x\rangle$$

bright state $|x\rangle \equiv \frac{1}{\sqrt{2}}(|-1\rangle + |+1\rangle).$

dark state $|y\rangle \equiv \frac{1}{\sqrt{2}}(|-1\rangle - |+1\rangle)$

Interference measurement

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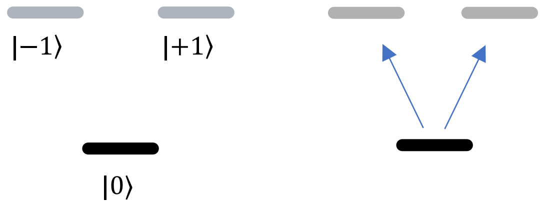

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2. Evolution in $\boldsymbol{E}$ and $\boldsymbol{B}$ field

$\Psi(t) = (e^{-i\phi/2}|-1\rangle + e^{i\phi/2}|+1\rangle)/\sqrt{2}$
$= \cos(\phi/2)|x\rangle - i\sin(\phi/2)|y\rangle$

$$\phi = 2(\mu B + D^{P,T} E)T$$

Interference measurement

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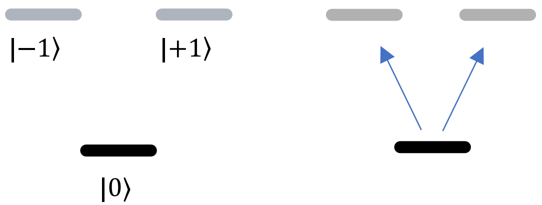

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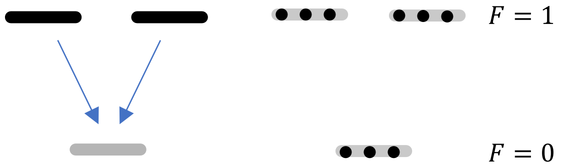
3. Read out



$\Psi(t_2) = \cos(\phi/2)|0\rangle - i\sin(\phi/2)|y\rangle$

$$P_{F=1} = |\langle y|\Psi(t)\rangle|^2 = \sin^2(\phi/2)$$
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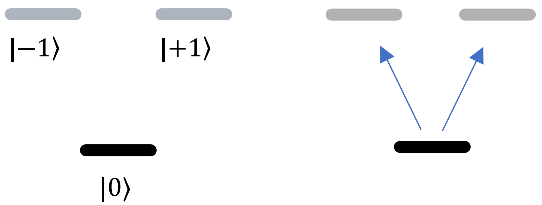

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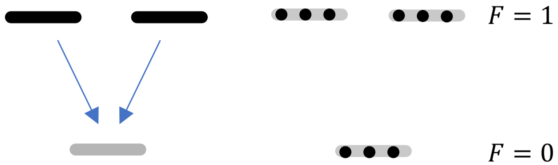

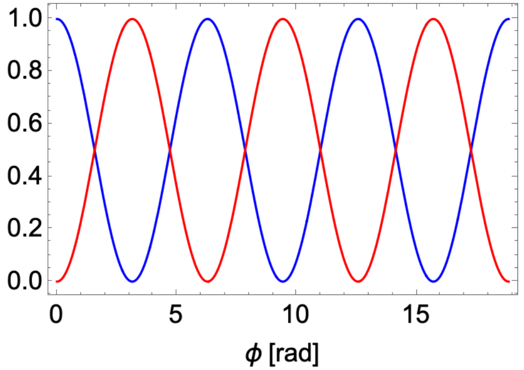

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Interference measurement

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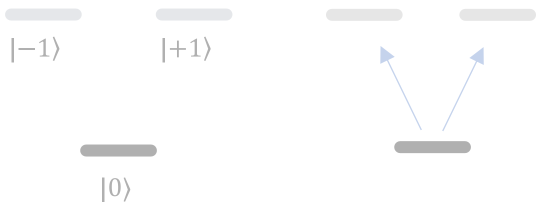

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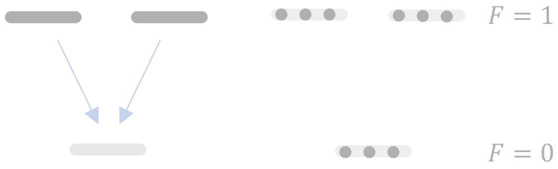

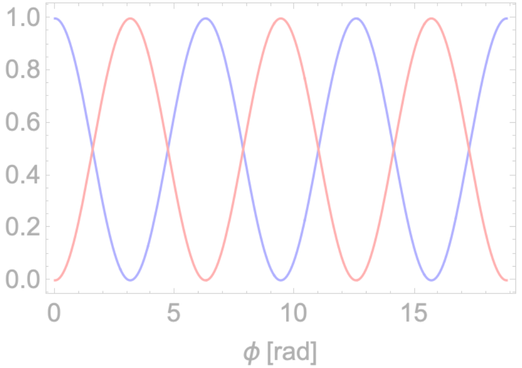

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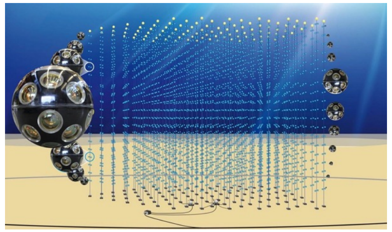
HEP: Neutrino oscillations: same physics!

1. Neutrinos created in flavor eigenstate: superposition of energy eigenstates

$$|\nu_\alpha(0)\rangle = c_1|\nu_1\rangle + c_2|\nu_2\rangle$$

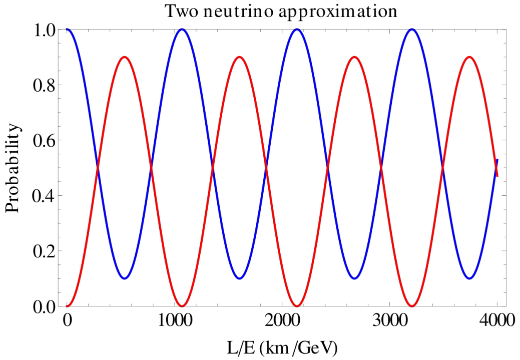
2. Neutrinos travel through space, acquire phase because of mass difference

$$|\nu_\alpha(L)\rangle = e^{-i\left(\frac{m_1^2}{2E}\right)L}|\nu_1\rangle + e^{-i\left(\frac{m_2^2}{2E}\right)L}|\nu_2\rangle$$

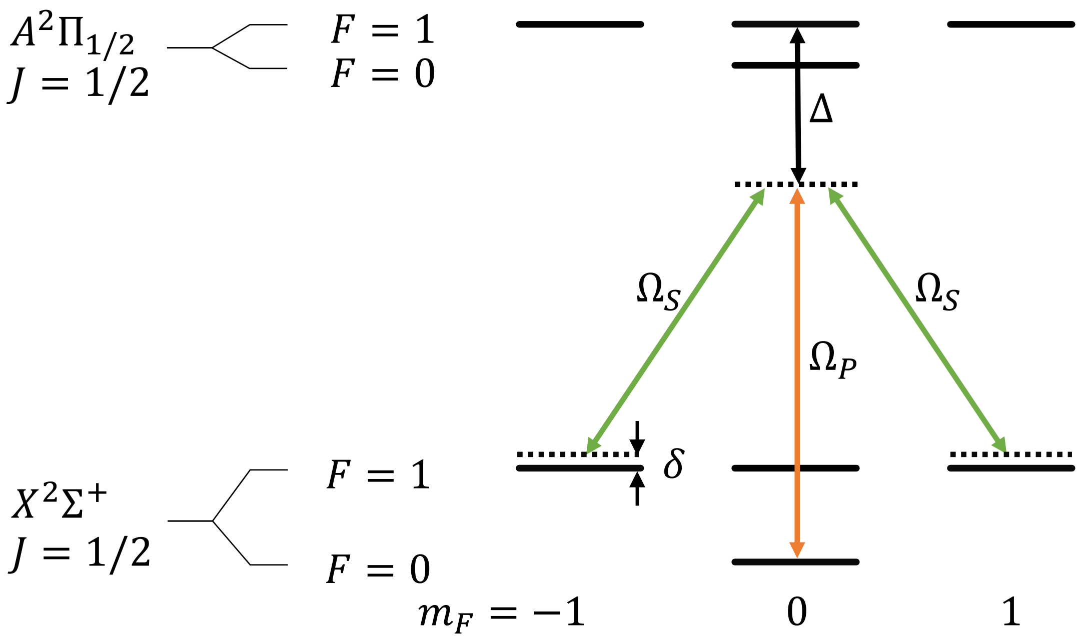


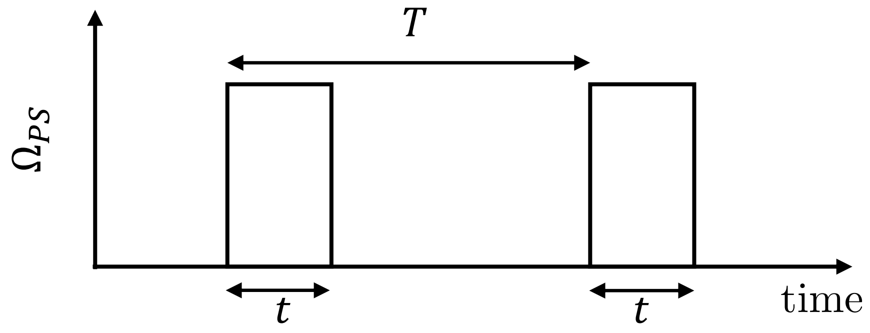
3. Neutrinos probed with flavor physics: collapse to flavor-eigenstate

$$P_\alpha = |\langle\nu_\alpha|\nu_\alpha(L)\rangle|^2 \propto \sin^2\phi$$
$$P_\beta = \left|\langle\nu_\beta|\nu_\alpha(L)\rangle\right|^2 \propto \cos^2\phi$$



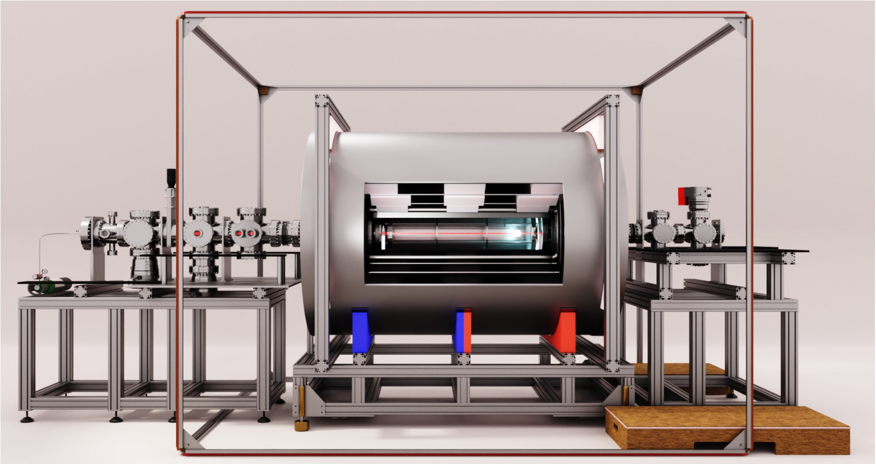
Our robust implementation





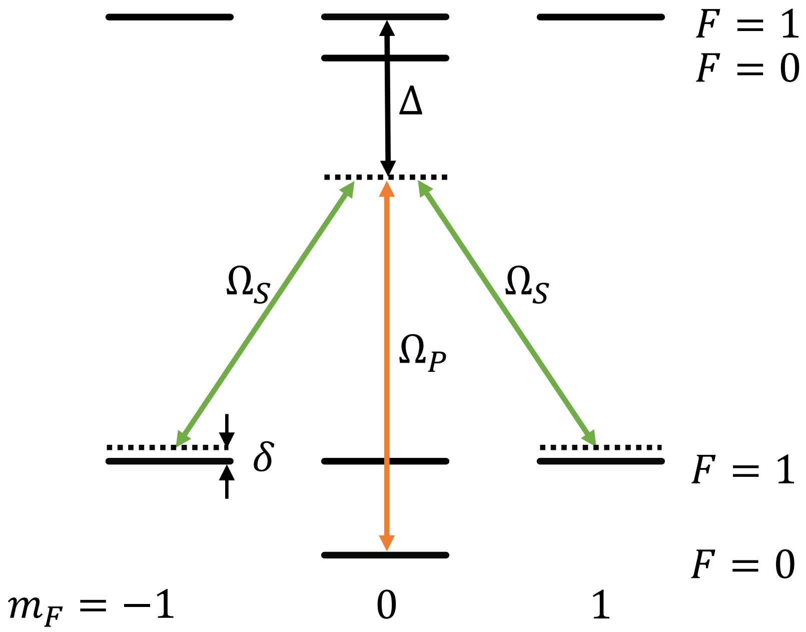
Optical implementation of superposition creation and read out

NL-*e*EDM experiment



- Experimental control over parameters
  - $\delta, \Delta, t, T, \Omega_{P/S}, \hat{e}_{P/S}, \Phi_{P/S}, \mathbf{E}, \mathbf{B}$
- Description of signal as function of parameters[1]
  - $P_{F=0,1}(\delta, \Delta, t, T, \Omega_{P/S}, \hat{e}_{P/S}, \Phi_{P/S}, \mathbf{E}, \mathbf{B})$

→ **Permits to make use of parameter space**



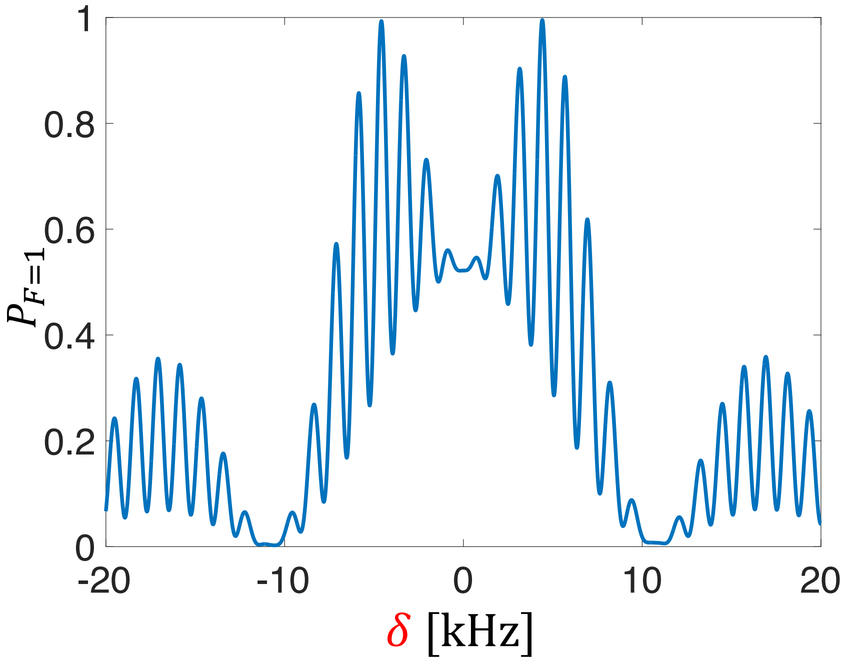
1) A.Boeschoten, PhD thesis 2023

New EDM-measurement method

NL-*e*EDM collaboration, *Novel spin-precession method for EDM searches*
https://doi.org/10.48550/arXiv.2303.06402

Measuring an EDM

- $P_{F=1}(\delta, \Delta, t, T, \Omega_{P/S}, \hat{e}_{P/S}, \Phi_{P/S}, \mathbf{E}, \mathbf{B})$
  - spin-precession spectrum
  - contains a lot of information
  - simultaneous measurement of parameters



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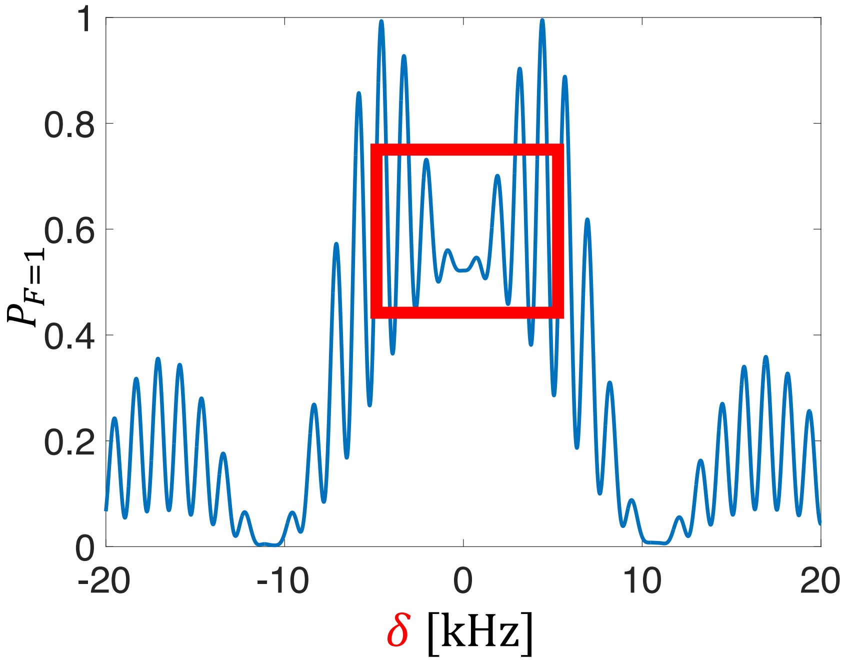
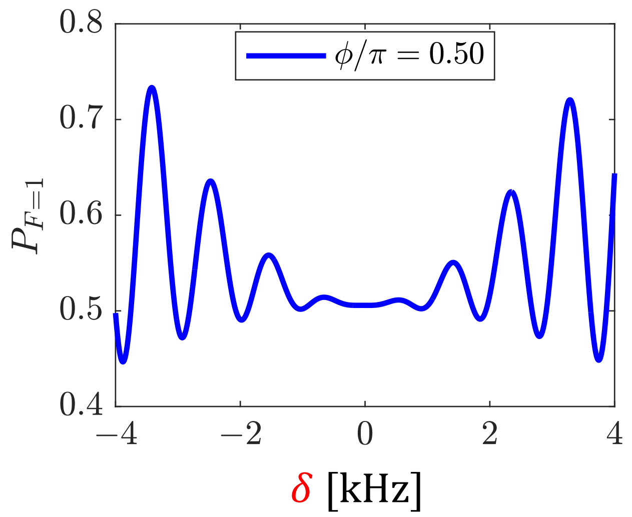


Disentangling the EDM

- $P_{F=1}(\delta, \Delta, t, T, \Omega_{P/S}, \hat{e}_{P/S}, \Phi_{P/S}, \mathbf{E}, \mathbf{B})$



Disentangling the EDM

- $P_{F=1}(\delta, \Delta, t, T, \Omega_{P/S}, \hat{e}_{P/S}, \Phi_{P/S}, \mathbf{E}, \mathbf{B})$

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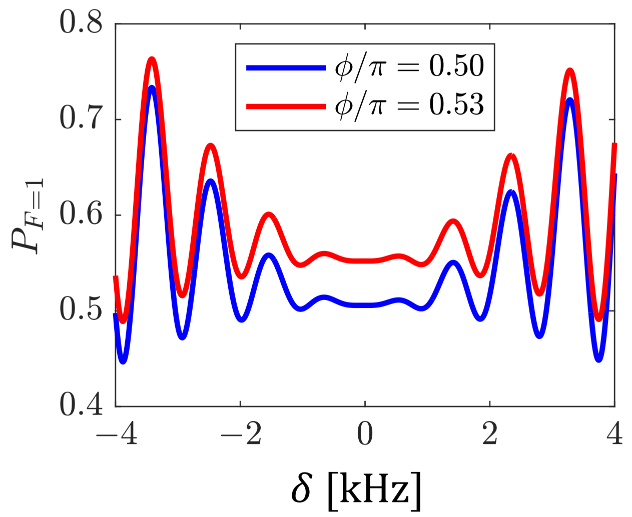

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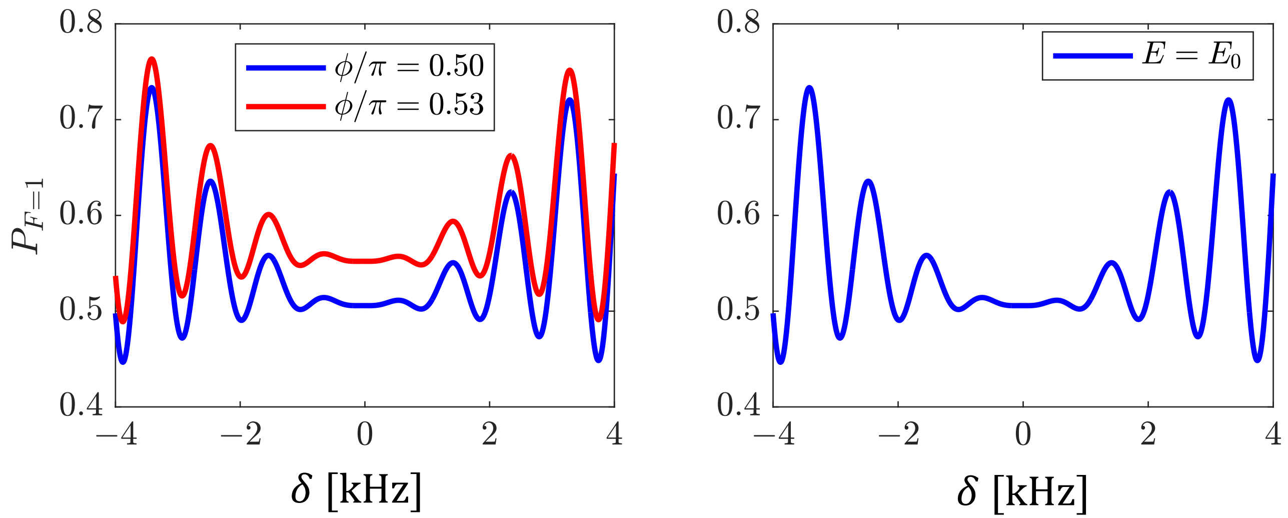

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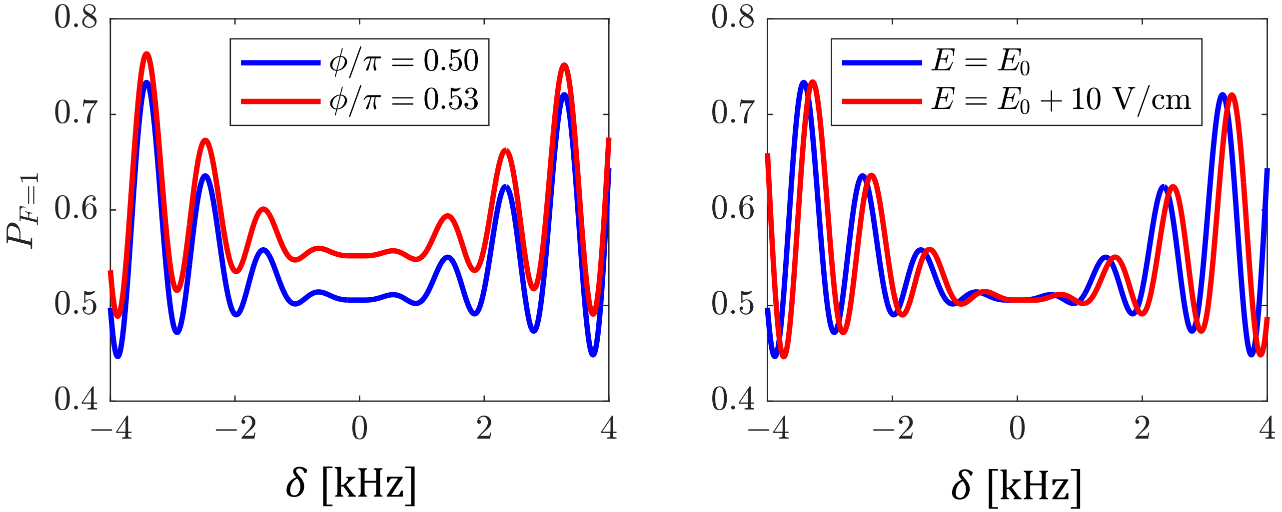

ϕ and *E:* different signature!

Disentangling the EDM

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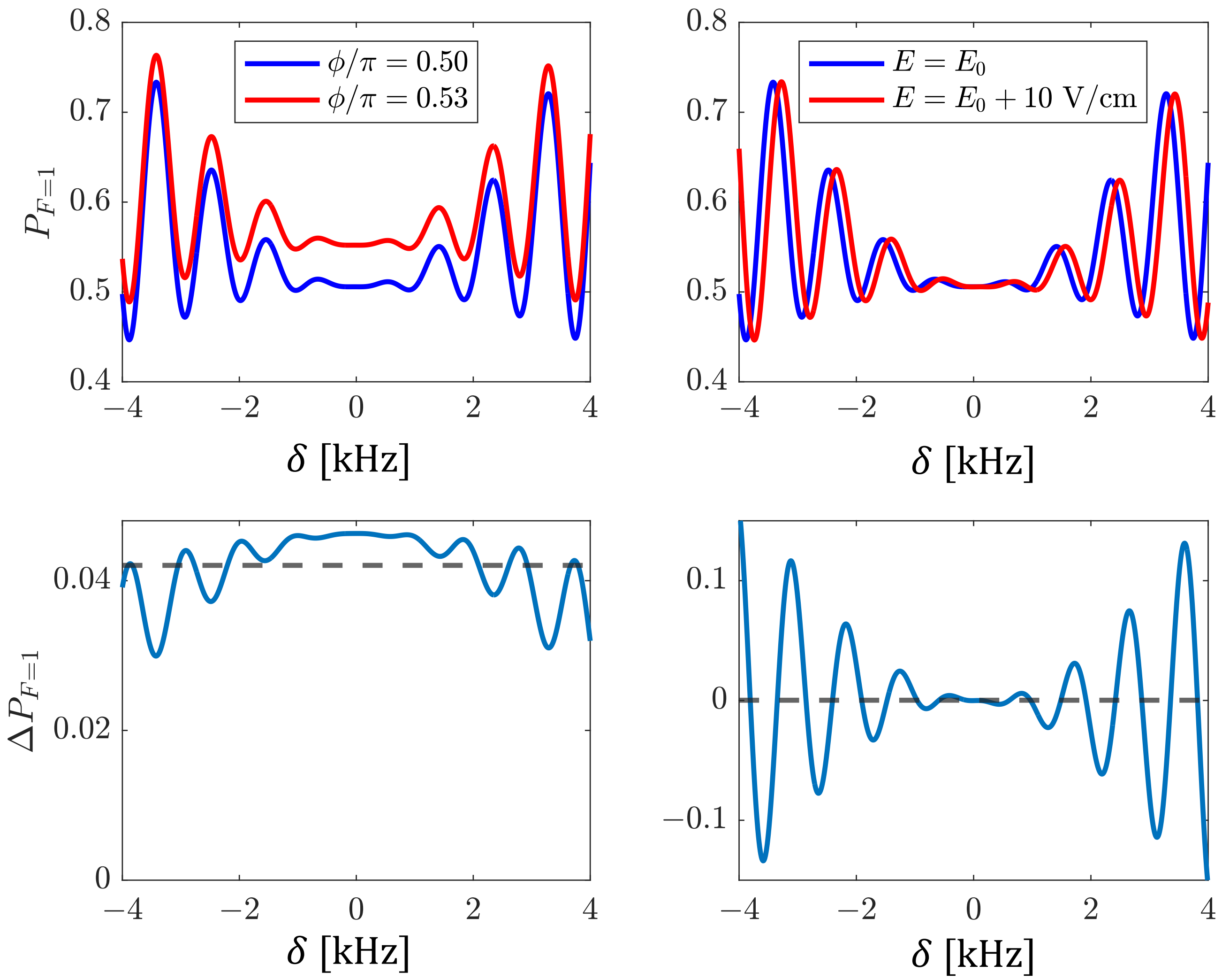
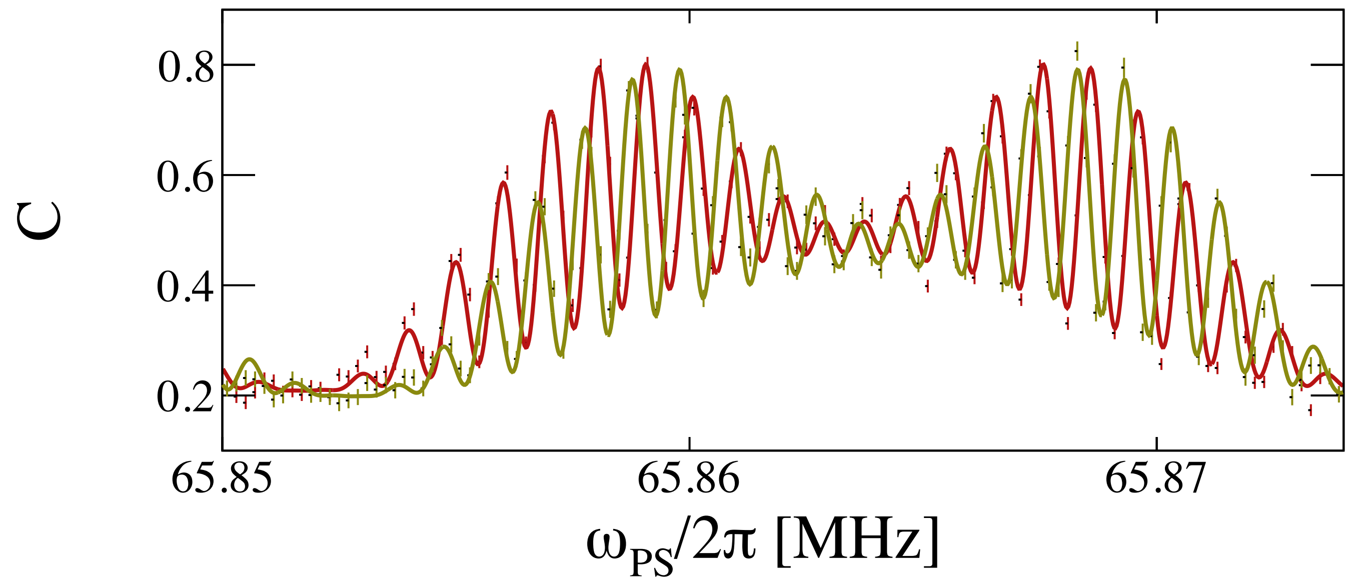
ϕ and *E:* different signature!

Systematic errors can be detected from EDM itself!



Experiment: excellent quantitative agreement



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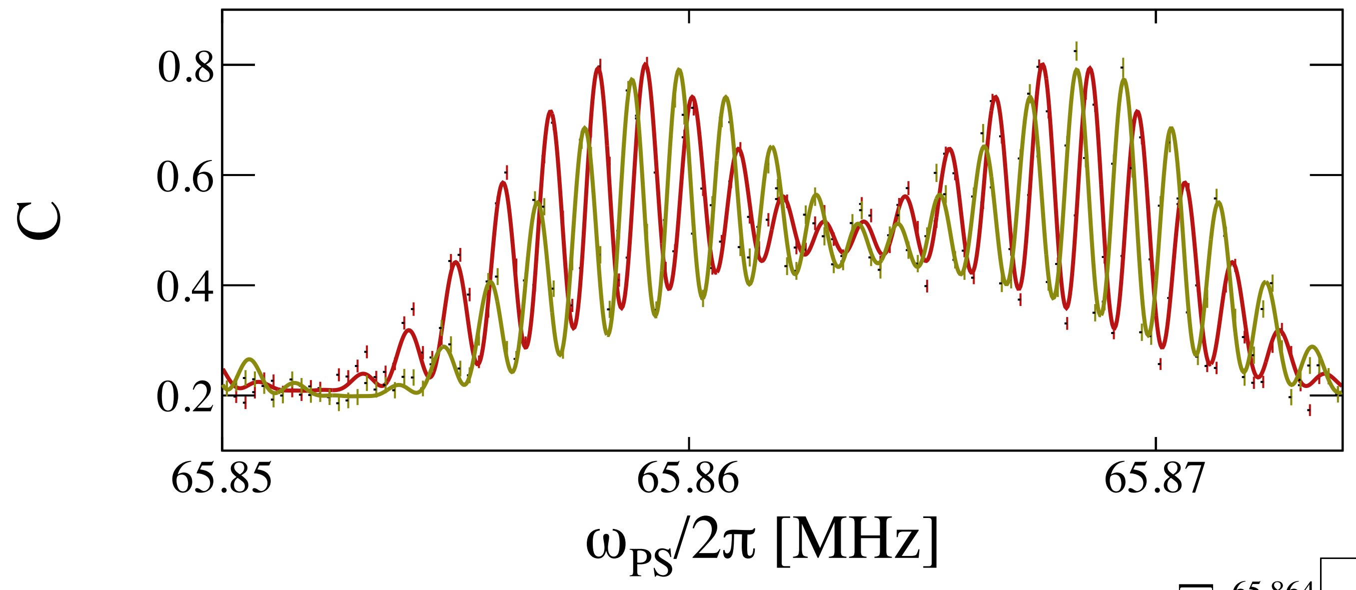
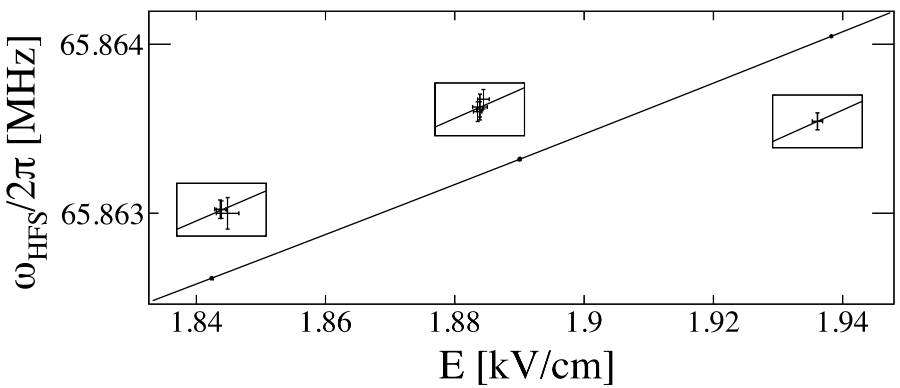
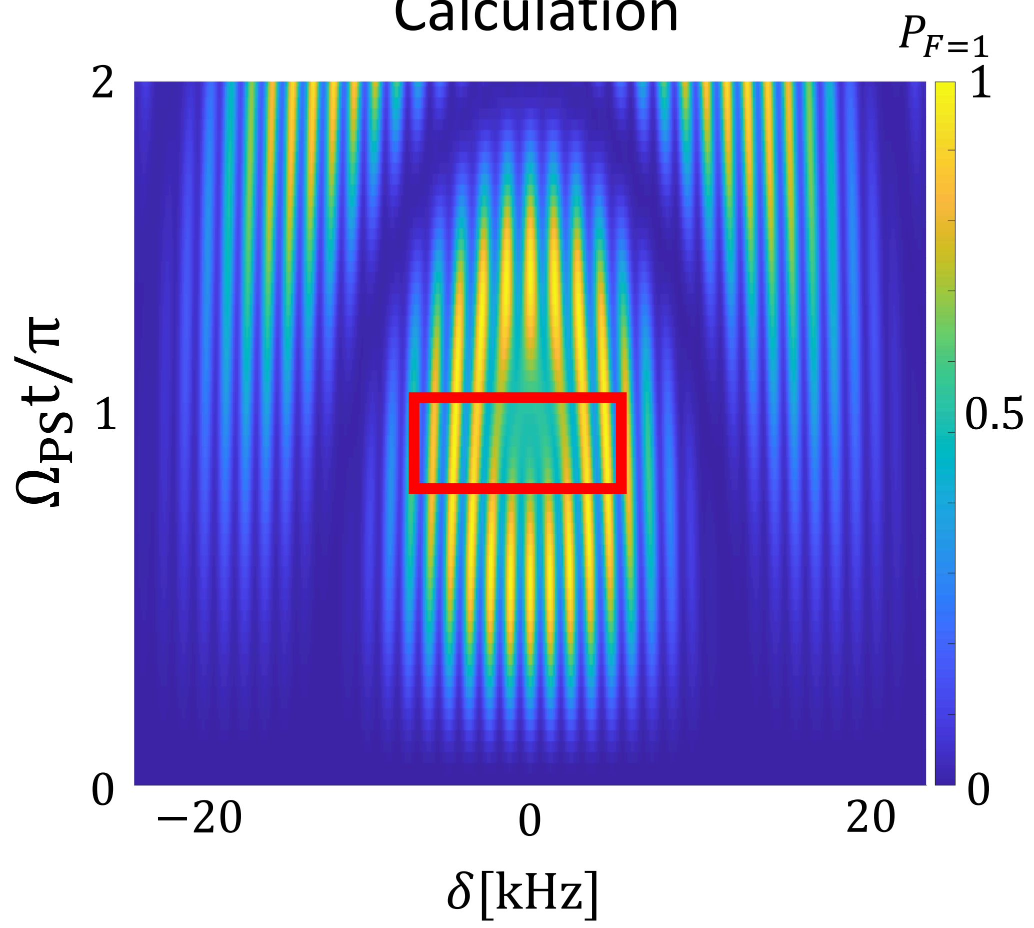




Laser intensity

$$P_{F=1}(\delta, \Delta, t, T, \Omega_{P/S}, \hat{e}_{P/S}, \Phi_{P/S}, \mathbf{E}, \mathbf{B})$$

Calculation



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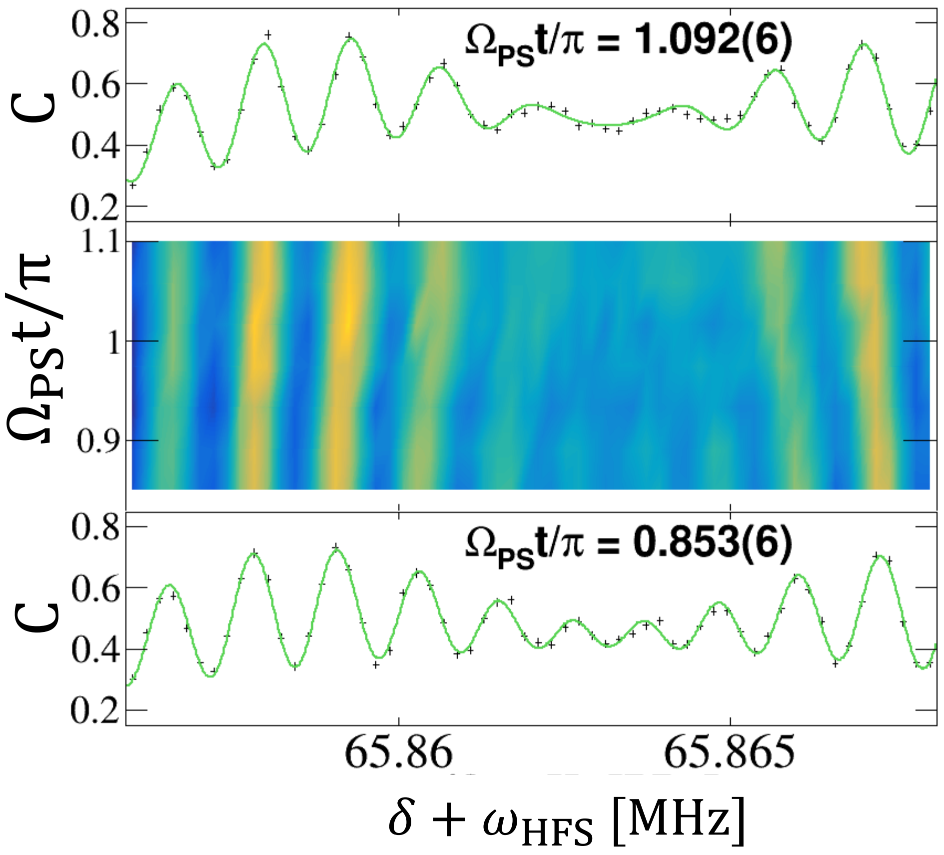


Conclusion

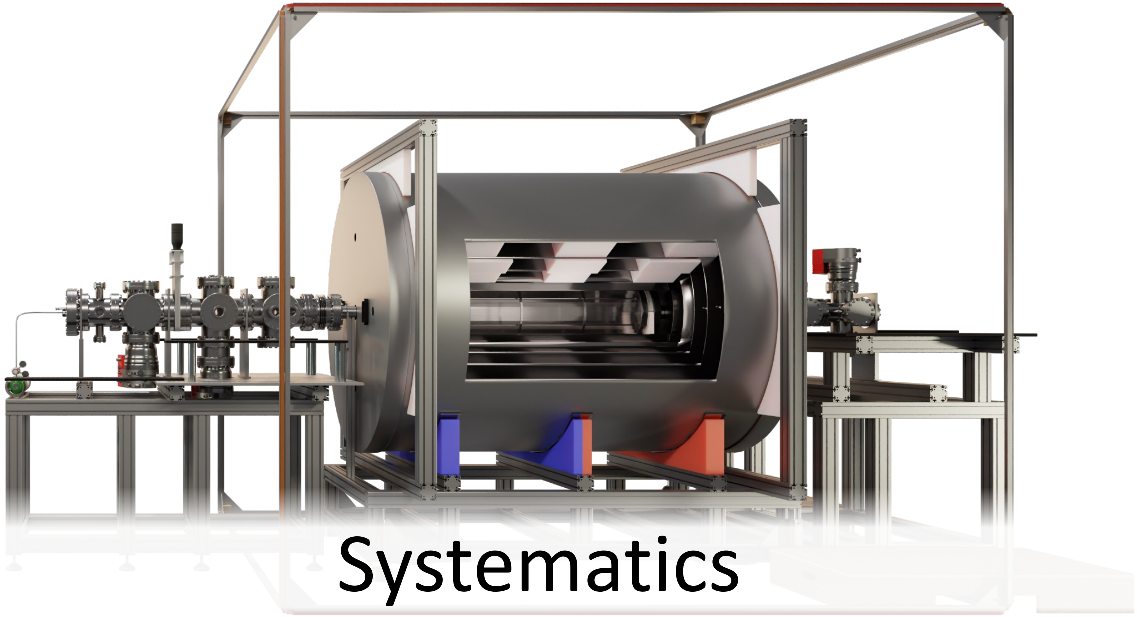
- Measurement of EDM requires precise measurement of Zeeman shift in combination with accurate E field reversal
- NL-*e*EDM experiment has control over parameters and description of signal in terms of these parameters
- New method allows to measure accuracy (systematic biases) simultaneously with EDM
- In the NL-*e*EDM experiment we can limit systematic errors without losing statistics on the EDM: **increased accuracy and precision**

Backup slides

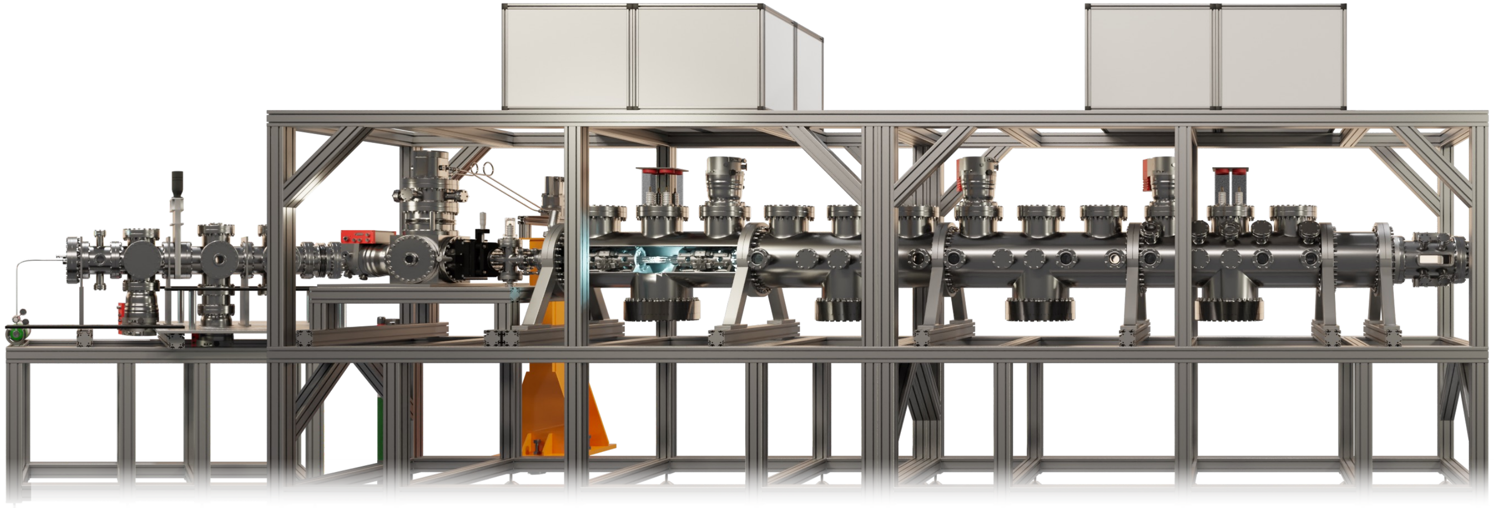
Fast beam

Supersonic beam (600 m/s)

Spin-precession measurement



Systematics



Statistics

Slow beam

Cryogenic beam (200 m/s)

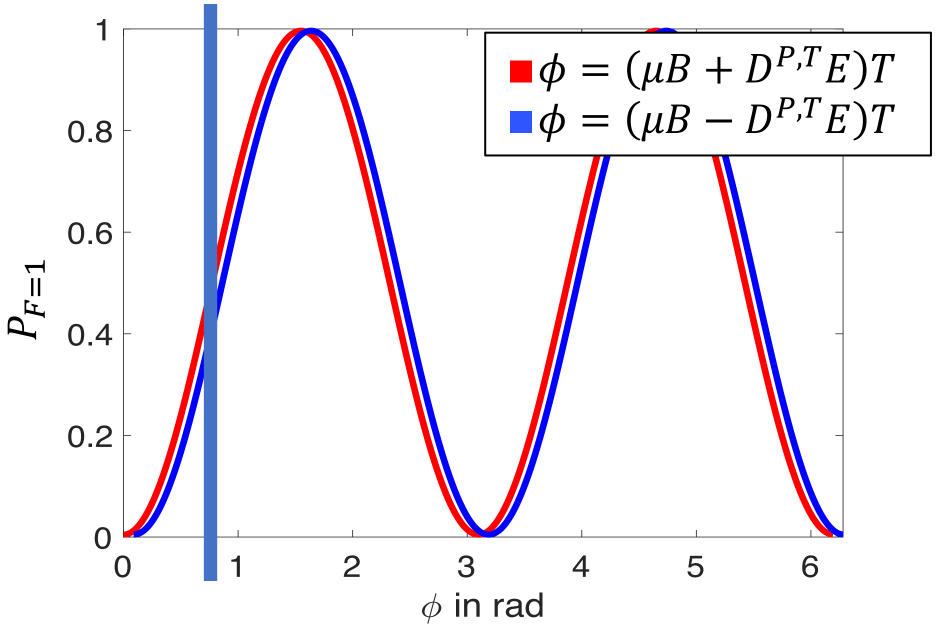
Stark decelerator (30 m/s)

Transverse laser cooling

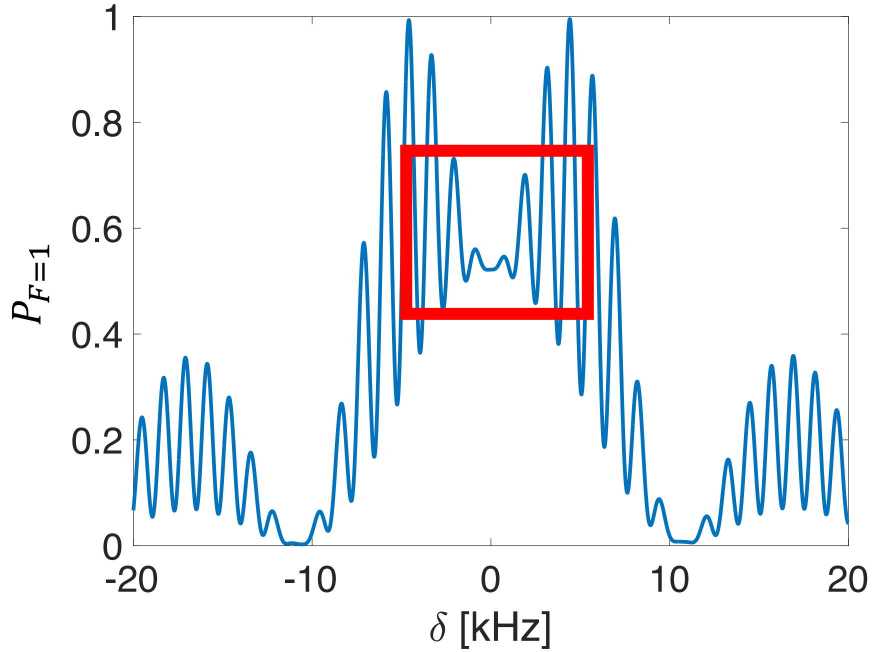
Intense and cold beam

Measuring the EDM

- $P_{F=1}(\phi)$
  - Traditional approach
  - Measure at one point in parameter space
  - Auxiliary measurements needed for other parameters

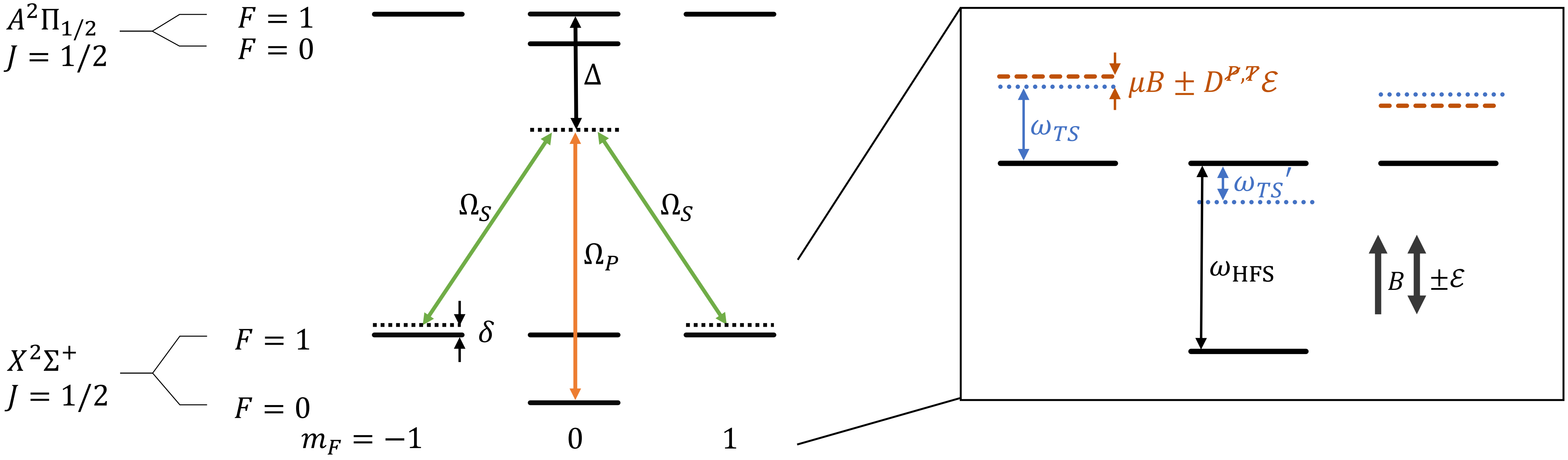


- $P_{F=1}(\delta)$
  - Spin-precession spectrum
  - Contains more information: simultaneous measurement of other parameters

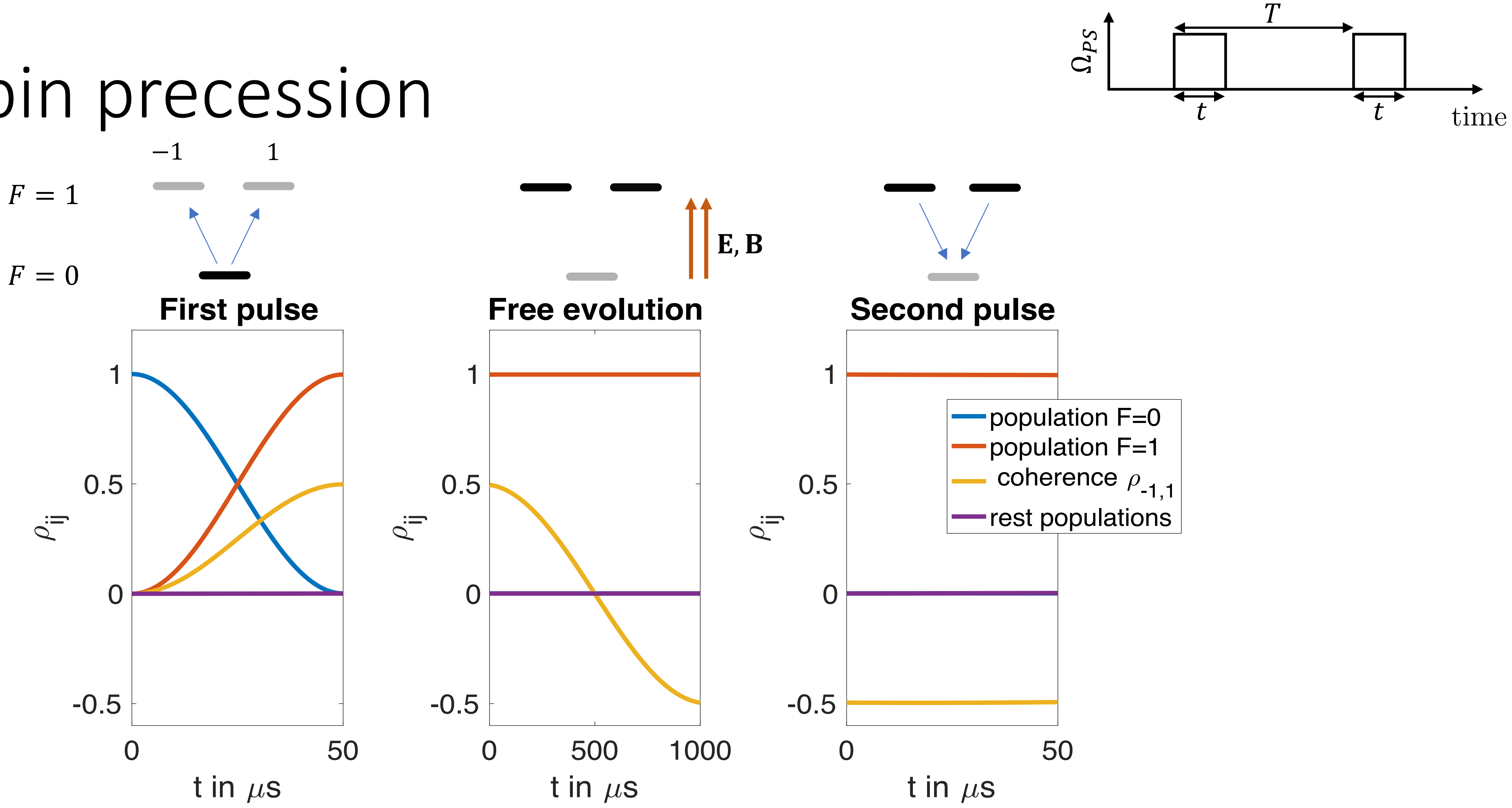


Description: Optical Bloch equations

- $i\hbar \frac{\partial}{\partial t}\rho = [H(t), \rho] + L_{\text{relax}}(\rho)$



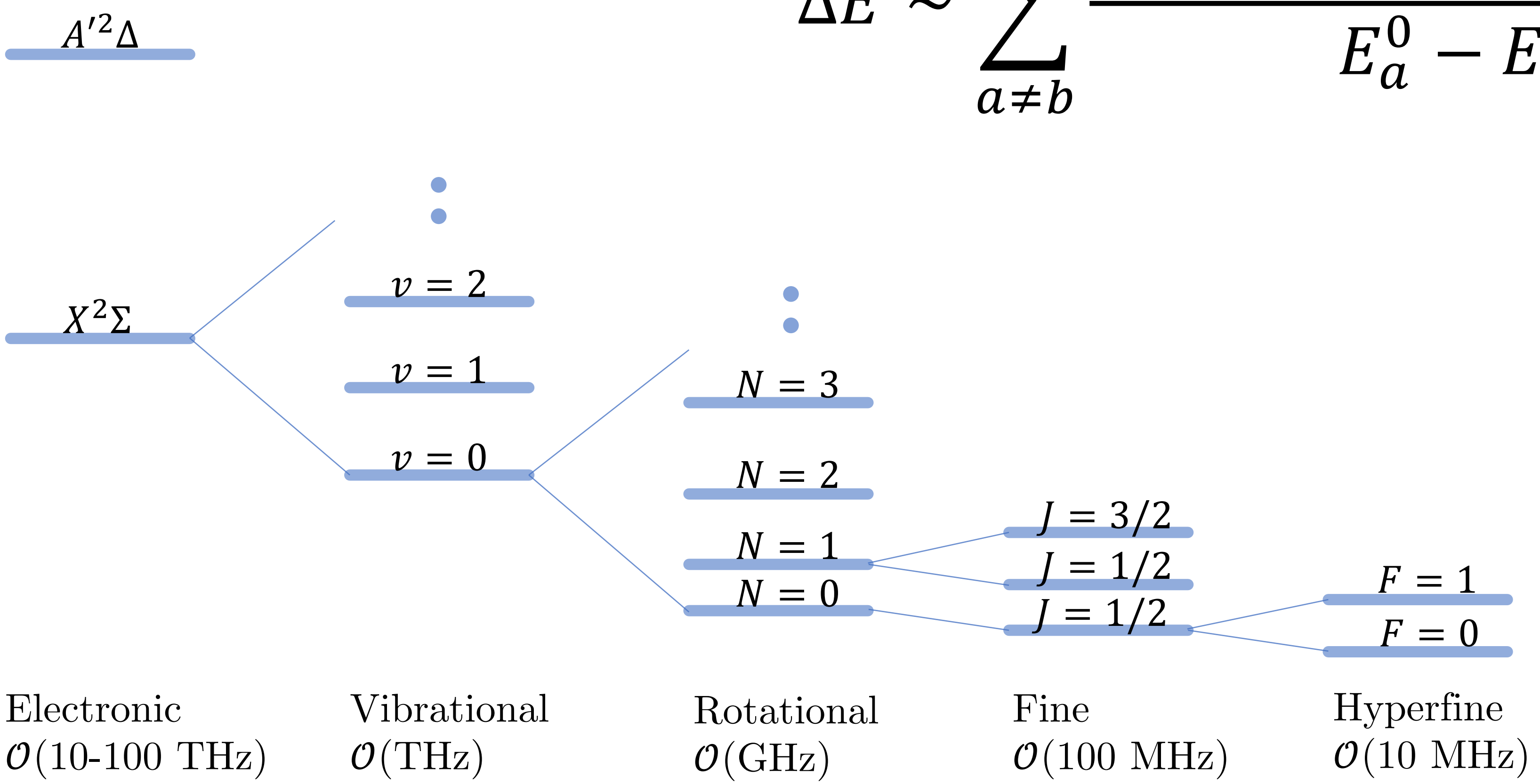
Spin precession



$$P_{F=0,1}(t+T+t) \ = P_{F=0,1}(\delta, \Delta, \Omega_{P/S}, \hat{e}_{P/S}, \Phi_{P/S}, \mathbf{E}, \mathbf{B}, t, T)$$

Extra slide with perturbation theory?

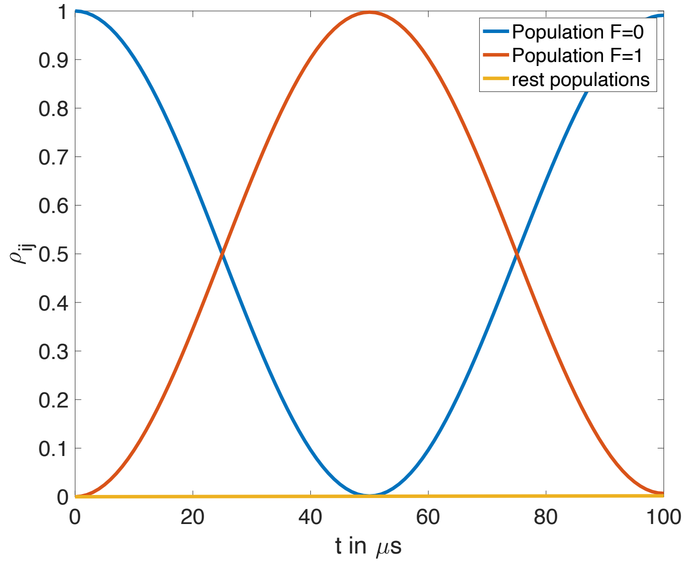
$$\Delta E \sim \sum_{a \neq b} \frac{\langle a | H^{e\text{EDM}} | b \rangle \langle b | H^{\text{Stark}} | a \rangle}{E_a^0 - E_b^0} \propto \frac{Z^3}{E_a^0 - E_b^0}$$

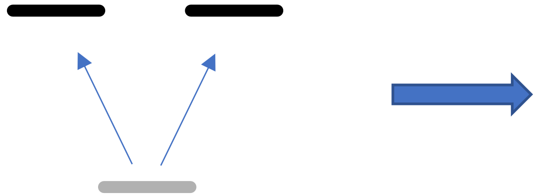


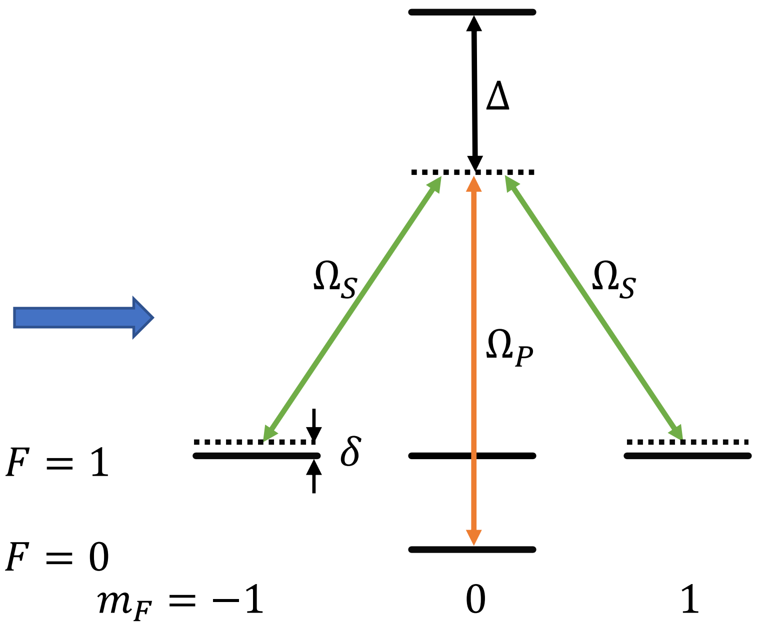
Superposition creation

- Laser detunings: $\Delta \sim \text{GHz}$,
  $\delta = 0$: Two-photon resonance
- Laser intensities: $I_P = I_S = 40\ I_{\text{sat}}$

→ **Rabi oscillations**







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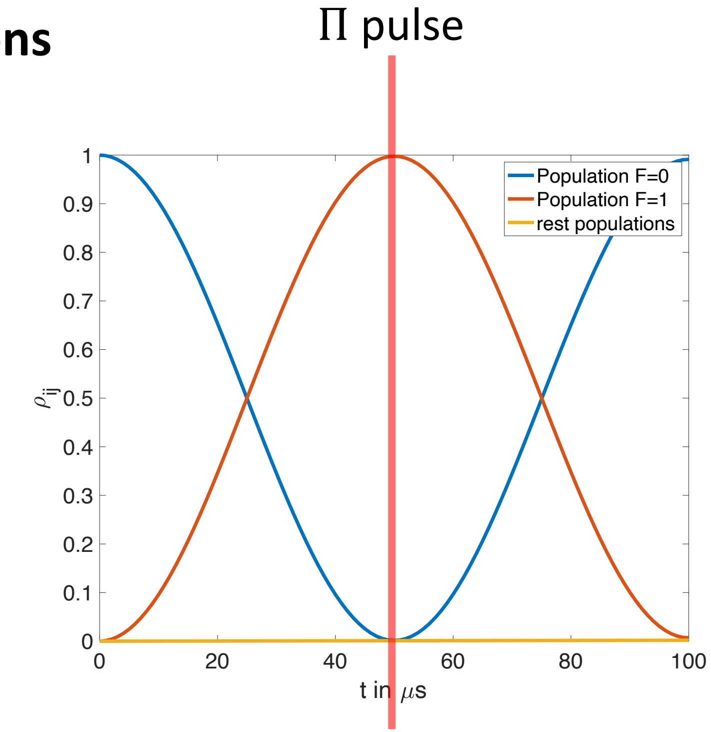

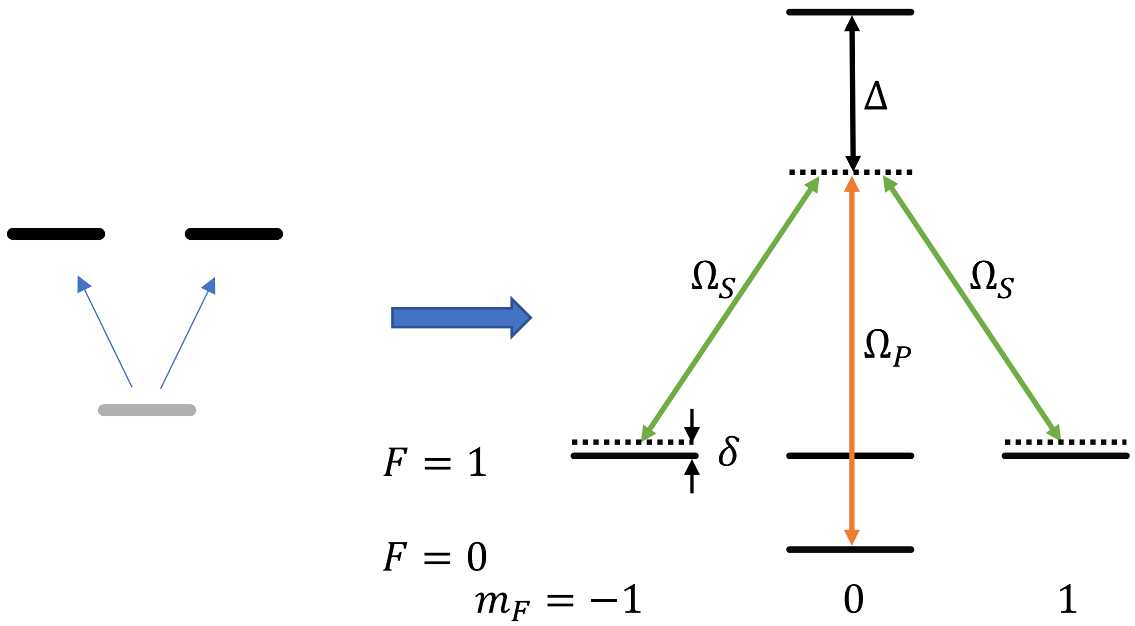

- At $t = 50\ \mu s$: transfer from $F = 0$ to $F = 1$
- No population in other states

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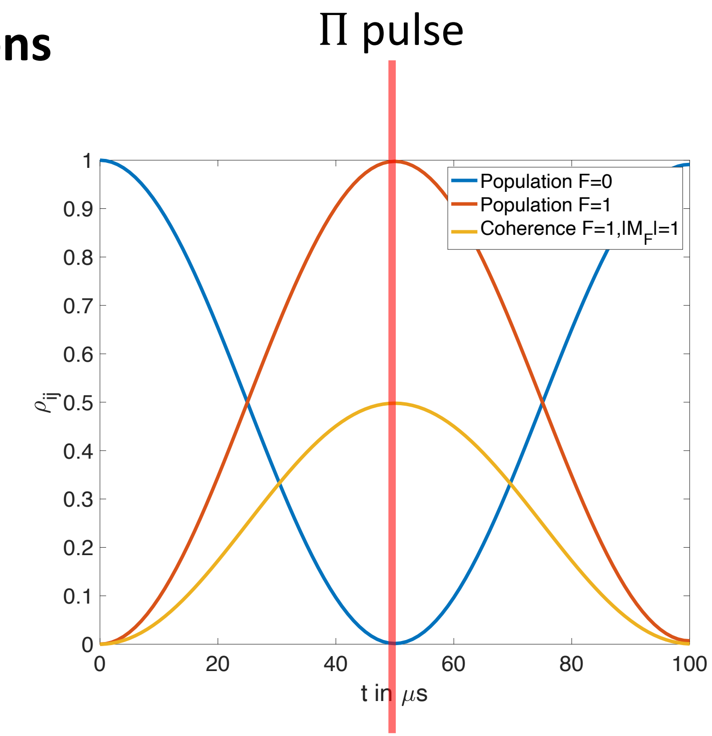

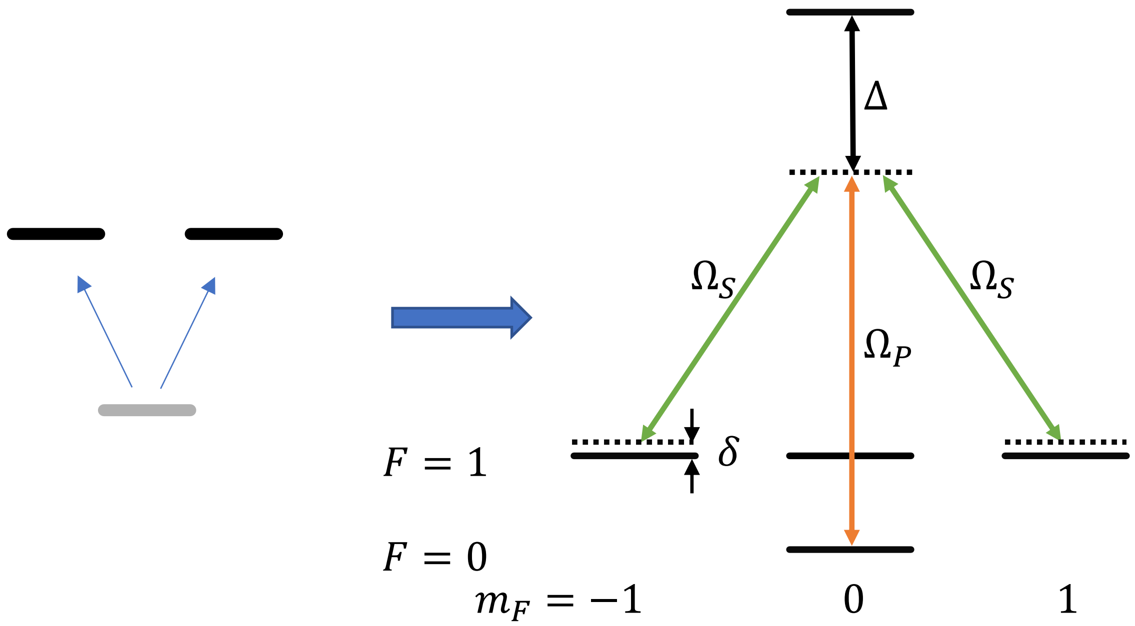

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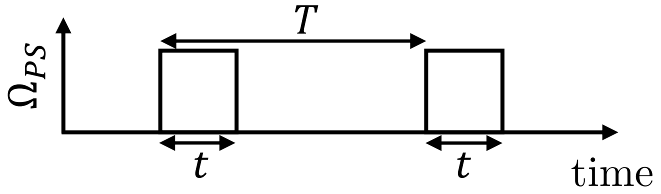
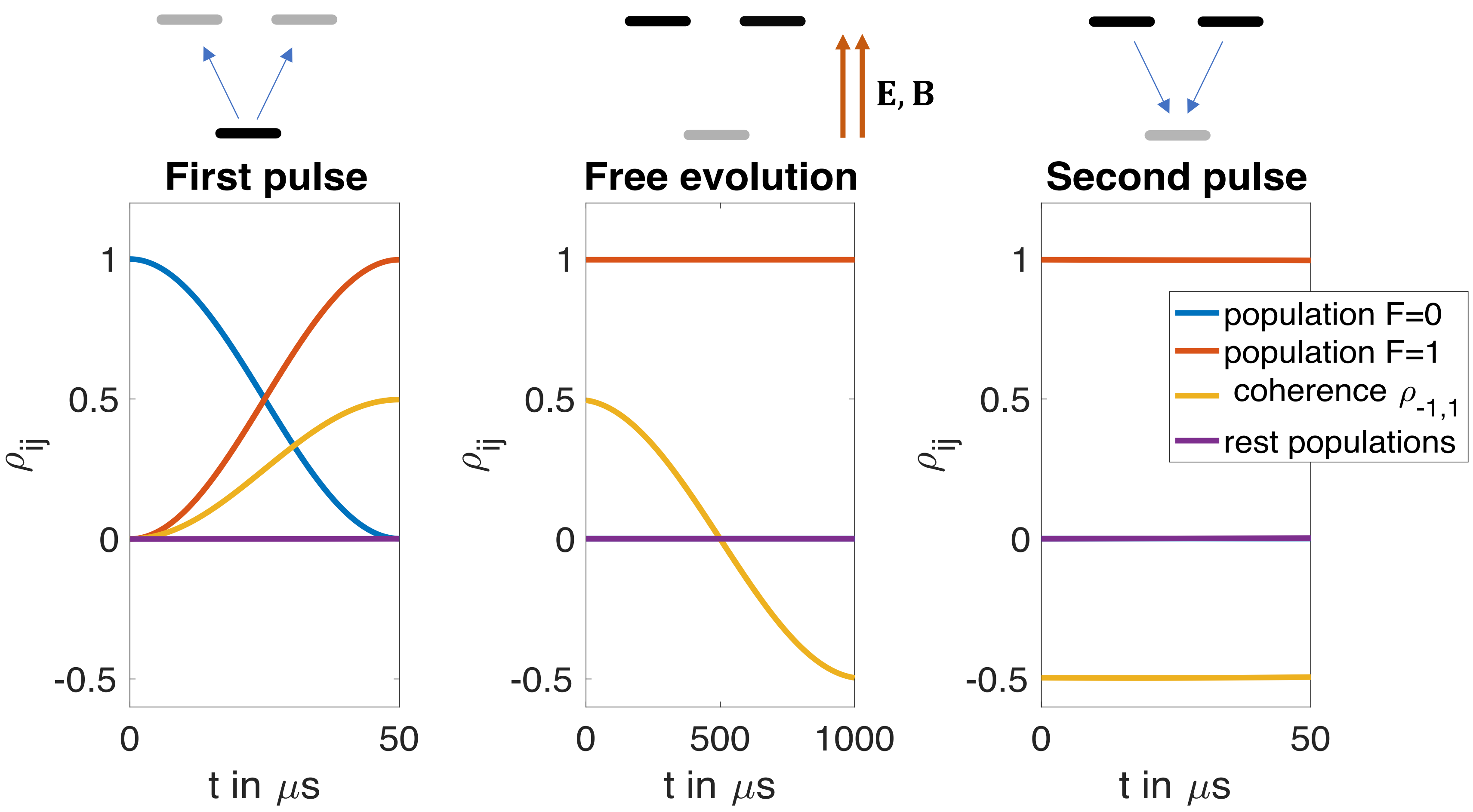
- No population in other states

- $\rho_{-1,1} = c_{-1}c_1^* \approx 0.5$
  coherence between states $|1,-1\rangle$ and $|1,1\rangle$:
  $$\rightarrow\ |\psi\rangle \approx \frac{1}{\sqrt{2}}(|1,-1\rangle + |1,+1\rangle)$$

Spin precession





$$P_{F=0,1}(t+T+t) \;= P_{F=0,1}(\delta,\Delta,\Omega_{P/S},\hat{e}_{P/S},\Phi_{P/S},\boldsymbol{E},\boldsymbol{B},t,T).$$