

Narrow opposite-parity level crossings in a diatomic free radical

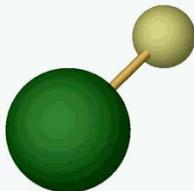
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- Motivation: nuclear spin-dependent parity violation
- PV measurement strategy: Zeeman-tuned rotational degeneracies
- Measurements: Stark-induced transitions near a rotational level crossing
- Outlook

DeMille



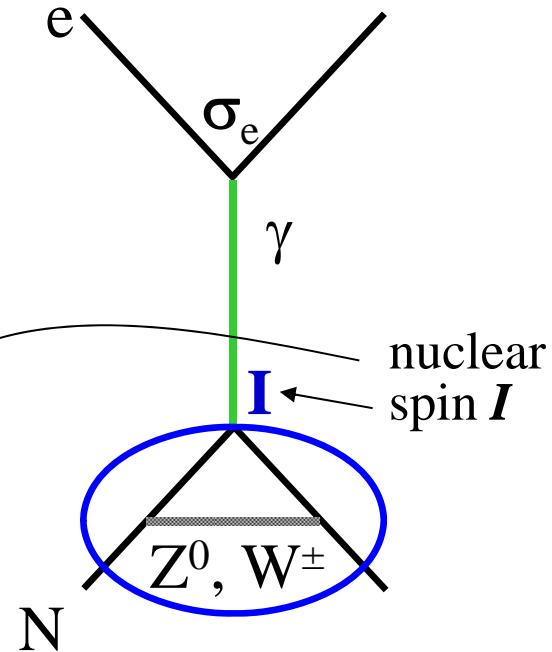
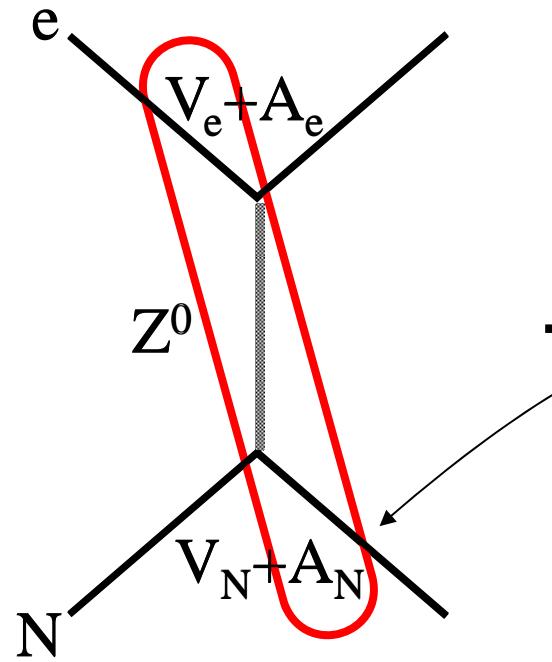
Group

Funding: NSF



Mechanisms for atomic/molecular parity violation

Electroweak coupling to nuclear spin: “NSD-PV”



$$H_W \propto (\kappa_Z + \kappa_{an}) \times (\vec{I} \cdot \vec{\sigma})(\vec{\sigma} \cdot \vec{p}) \delta^3(\vec{r})$$

Weak-interaction Hamiltonian H_W mixes hyperfine states with opposite parity

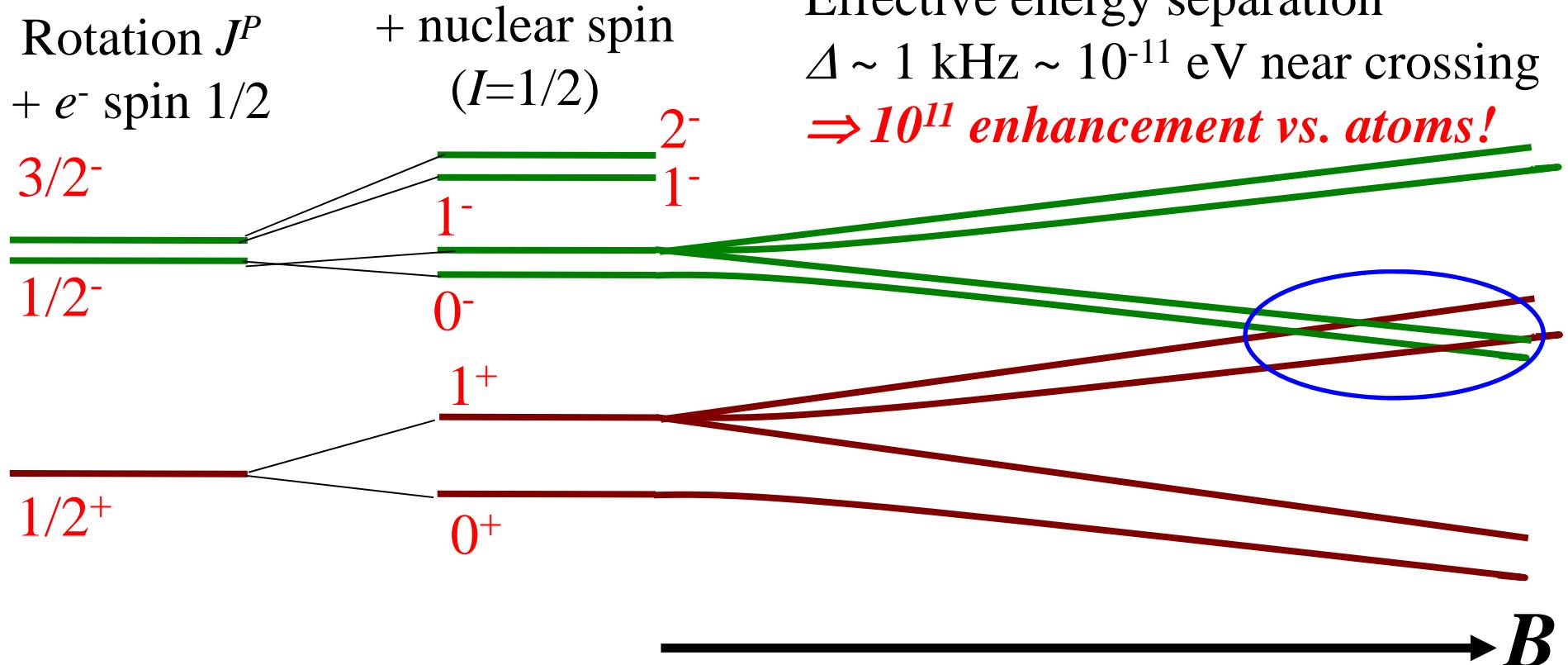
NSD-PV from direct Z^0 exchange: + numerically suppressed

PV weak interactions *inside nucleus* induce nuclear “anapole moment” that couples to electron magnetically

Enhanced parity mixing via systematic level degeneracies in diatomic free radicals

Example: $^2\Sigma$ with single nuclear spin $I=1/2$ (e.g. ^{138}BaF)

Typically several crossings
for $B = 0.3 - 1 \text{ T}$



The ZOMBIES NSD-PV experiment at Yale

Zeeman-tuned

Optically prepared and detected

Molecular

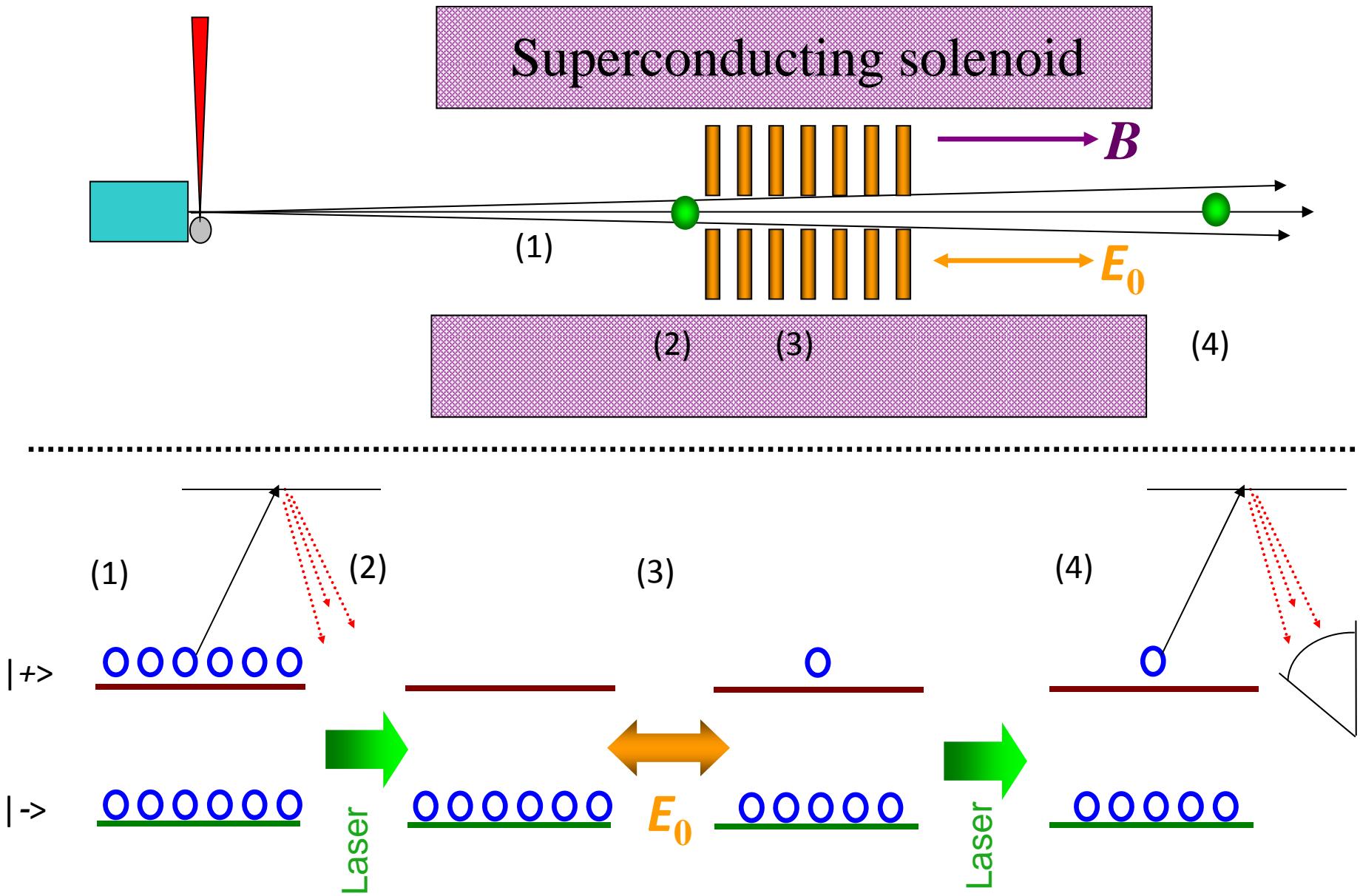
Beams for the

Investigation of

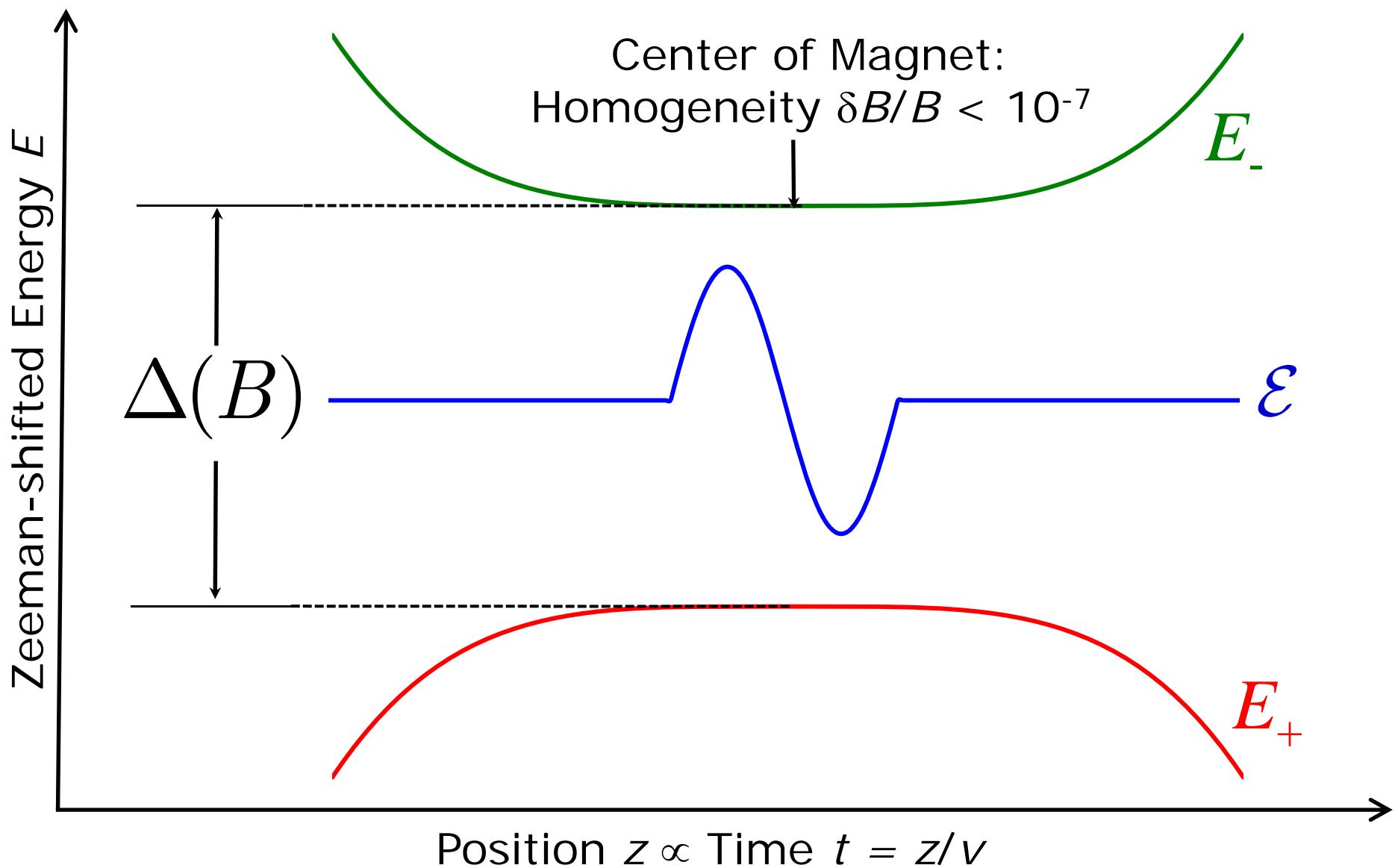
Electroweak effects using

Stark interference

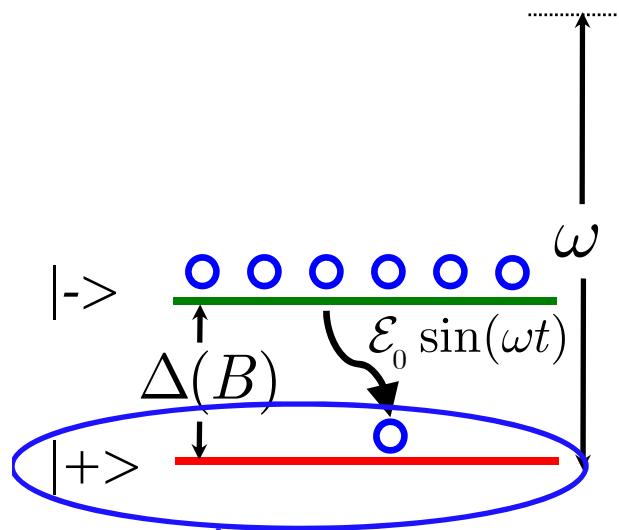
Molecule PV experimental schematic



*Stark interference method:
apply oscillating \mathcal{E} -field to mix nearly-degenerate levels*



Strategy to detect PV in near-degenerate levels



$$H = \begin{pmatrix} 0 & iH_W + d\mathcal{E}(t) \\ -iH_W + d\mathcal{E}(t) & \Delta \end{pmatrix}$$

$$\mathcal{E}(t) = E_0 \sin(\omega t)$$

$$[\omega \gg \Delta, dE_0]$$

$$S = \left| \langle + | \psi(T) \rangle \right|^2 = 4 \sin^2 \left(\frac{\Delta T}{2} \right) \left[\left(\frac{dE_0}{\omega} \right)^2 + 2 \frac{H_W}{\Delta} \frac{dE_0}{\omega} \right]$$

D.D., S.B. Cahn, D. Murphree, D.A. Rahmlow, and M.G. Kozlov
 Phys. Rev. Lett. **100**, 023003 (2008)

Large Stark Term Even in \mathcal{E}_0 *Small Weak Term Odd in \mathcal{E}_0*

Signal, Asymmetry, Sensitivity

--Measure signal $S(\mathcal{E}_0) \approx 4N_0 \sin^2\left(\frac{\Delta T}{2}\right) \left[\left(\frac{d\mathcal{E}_0}{\omega} \right)^2 + 2 \frac{H_W}{\Delta} \frac{d\mathcal{E}_0}{\omega} \right]$
with opposite-sign \mathcal{E} -fields $+ \mathcal{E}_0, - \mathcal{E}_0$

--Form asymmetry to extract H_W in terms of known quantities:

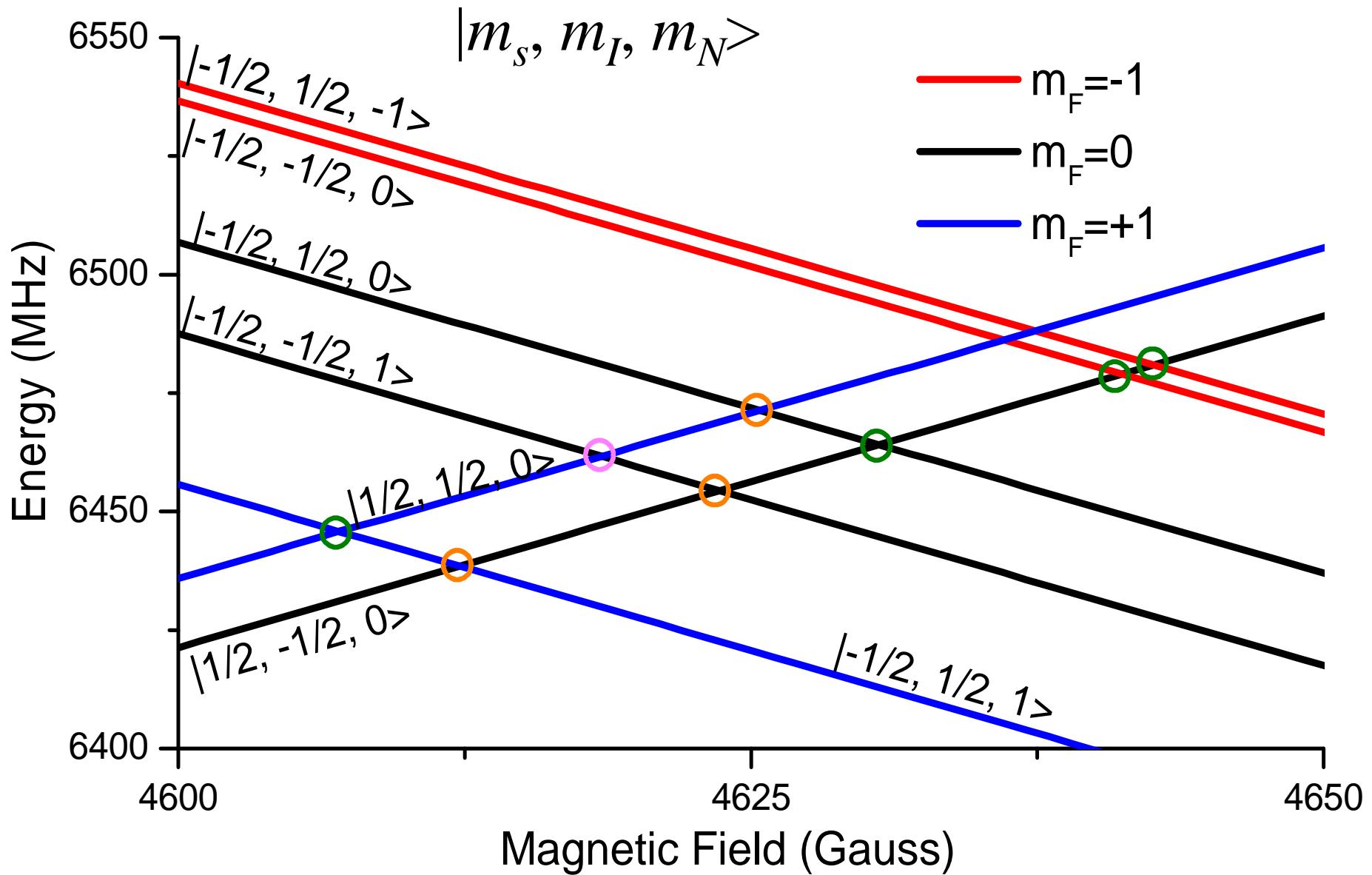
$$\mathcal{A} = \frac{S(+\mathcal{E}_0) - S(-\mathcal{E}_0)}{S(+\mathcal{E}_0) + S(-\mathcal{E}_0)} \approx \frac{H_W}{\Delta} \frac{\omega}{d\mathcal{E}_0}$$

Statistical Uncertainty

$$\delta H_W = \frac{1}{2\sqrt{2}} \frac{1}{\sqrt{N_0}} \frac{1}{T}$$

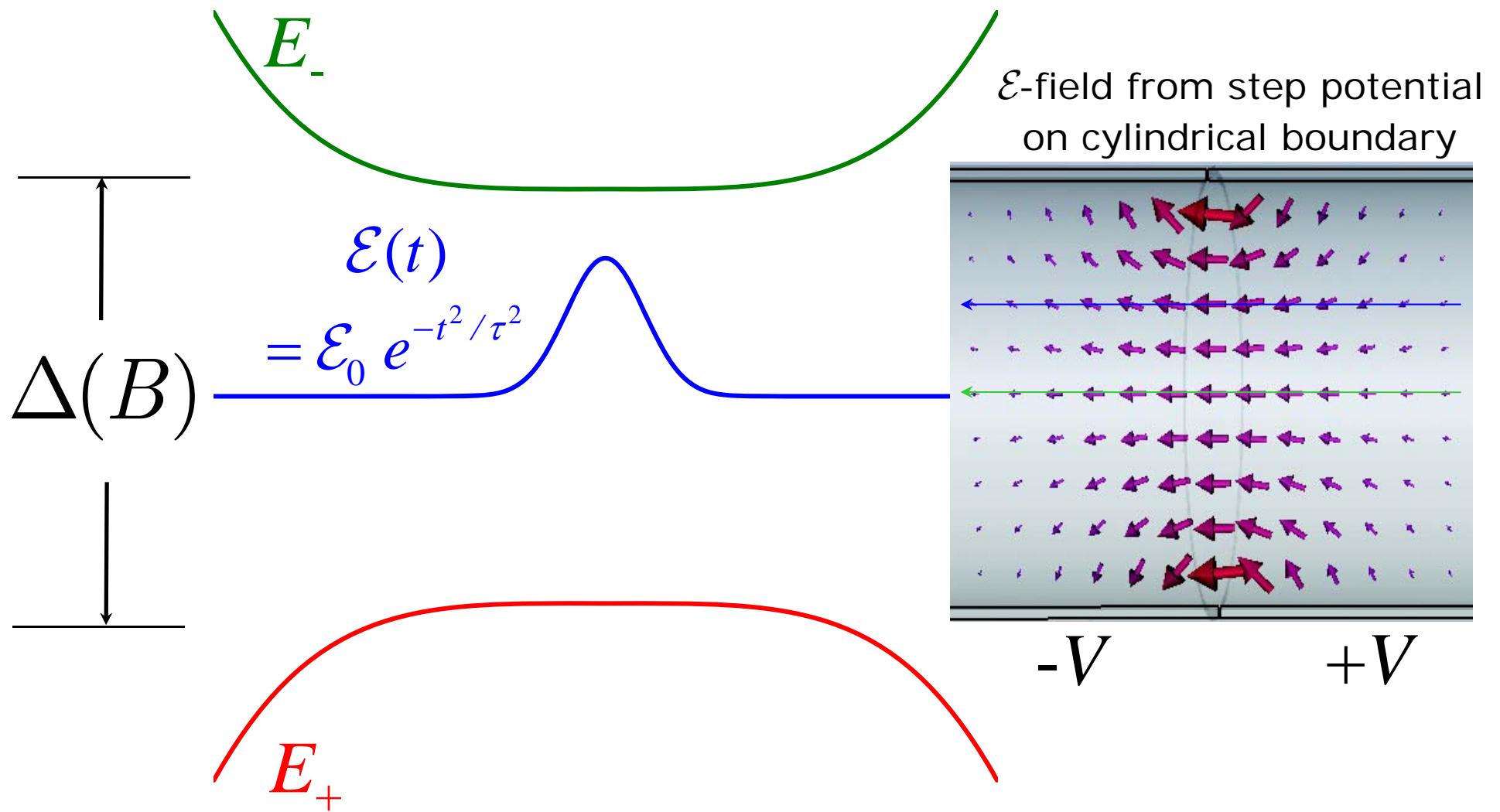
best sensitivity from
large interaction time T
with constant Δ

*Experimental study of Stark-induced transitions
at level crossings in ^{138}BaF*

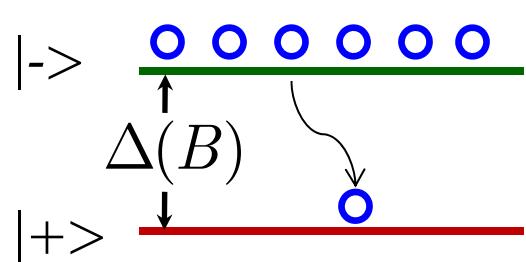


Opposite-parity level crossing spectroscopy

Apply unipolar E -field pulse



Simple Stark-induced transition at a level crossing



$$H = \begin{pmatrix} 0 & d\mathcal{E}(t) \\ d\mathcal{E}(t) & \Delta \end{pmatrix}$$

$$\mathcal{E}(t) = \mathcal{E}_0 e^{-t^2/\tau^2}$$

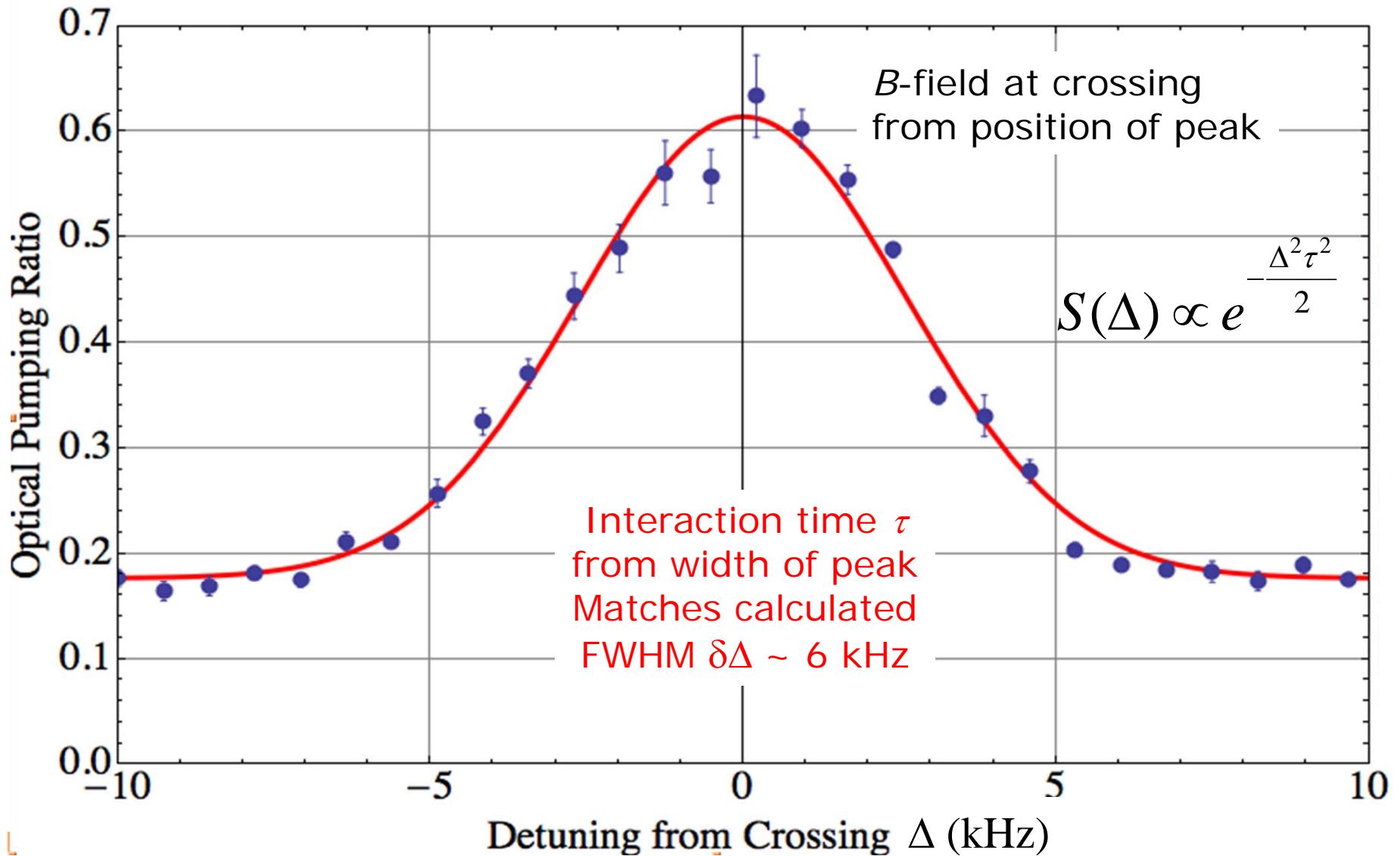
for weak excitation ($dE_0\tau \ll 1$), Gaussian lineshape:

$$S(\Delta) = |c_+(t \rightarrow \infty)|^2 = \pi d^2 \mathcal{E}_0^2 \tau^2 e^{-\frac{\Delta^2}{(2/\tau^2)}} \quad \text{Linewidth} \propto 1/\tau$$

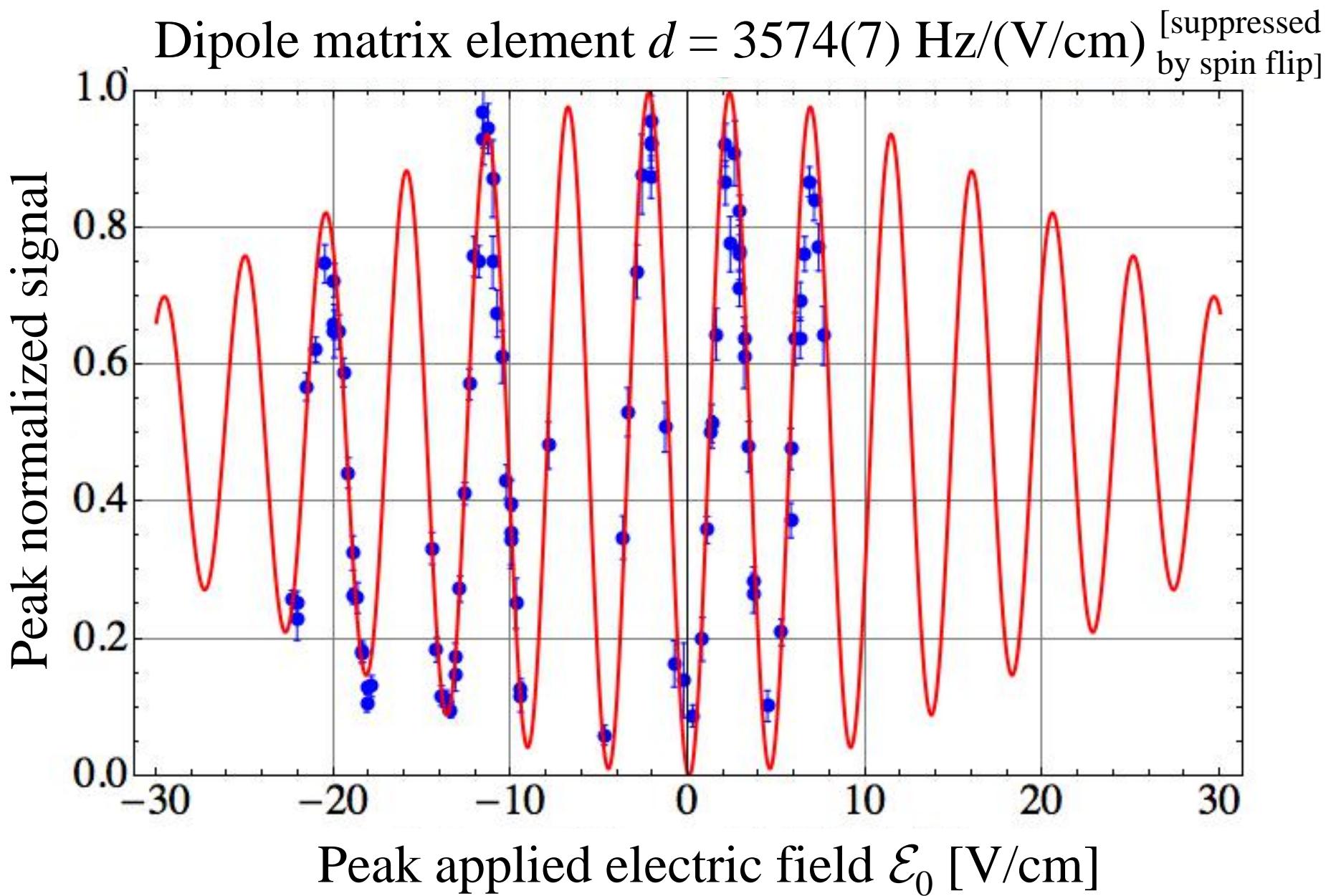
on resonance w/arbitrary excitation strength: Rabi flopping

$$S(\Delta = 0; \mathcal{E}_0) = \sin^2(\sqrt{\pi} d\mathcal{E}_0 \tau)$$

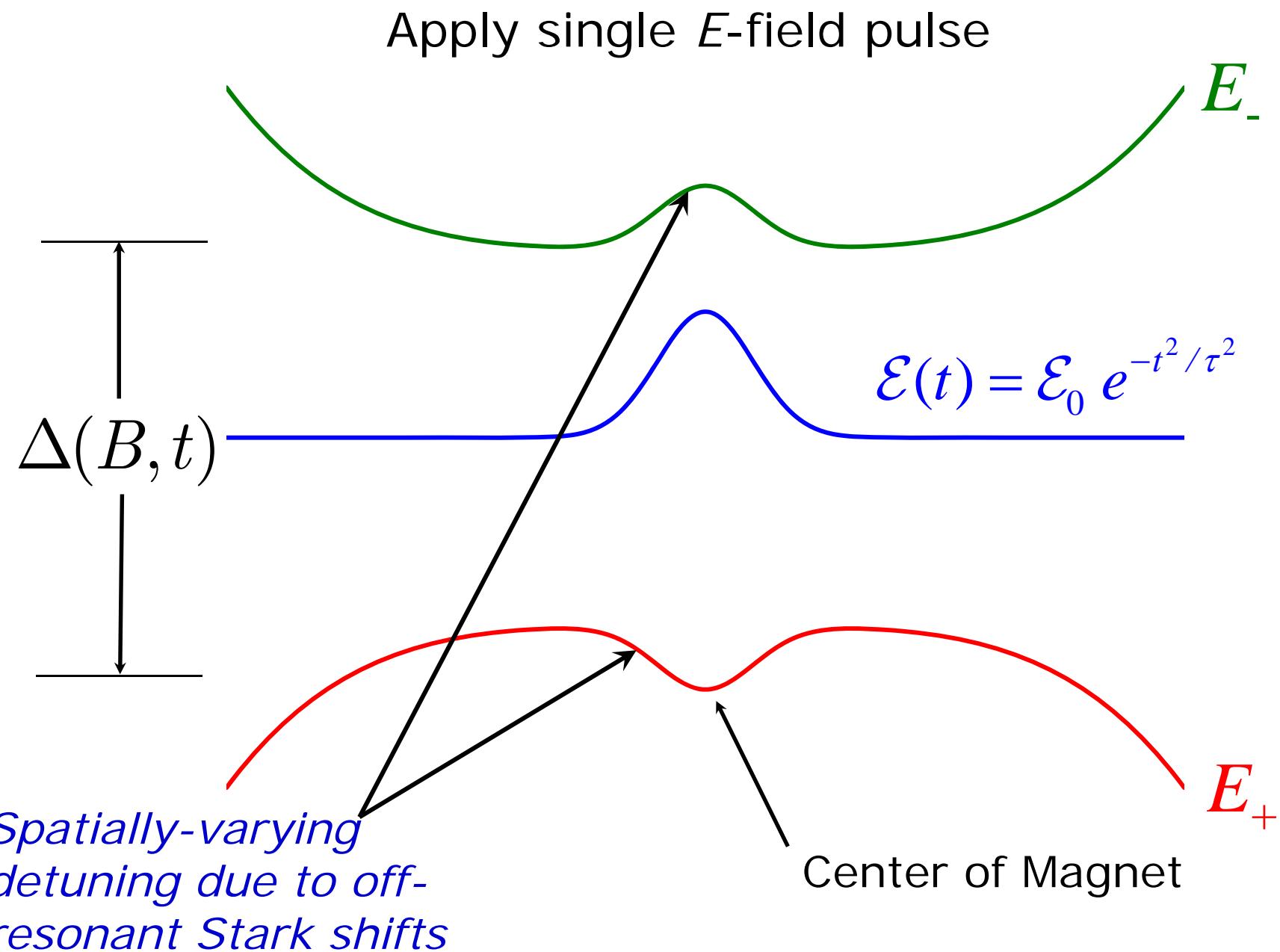
Typical level-crossing data: lineshape & position



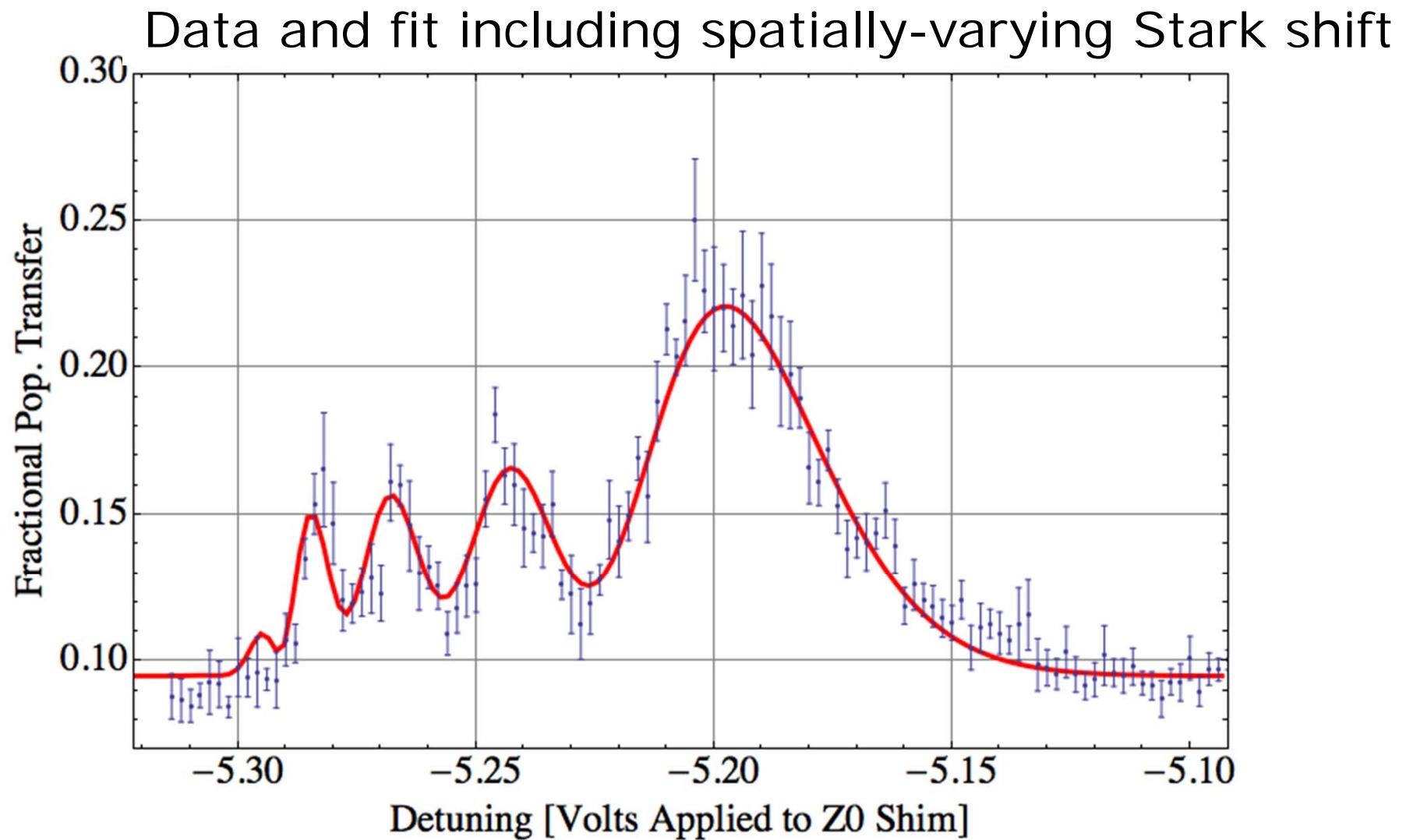
Rabi flopping: period vs. \mathcal{E}_0 determines d



Complex lineshapes from off-resonant Stark shifts

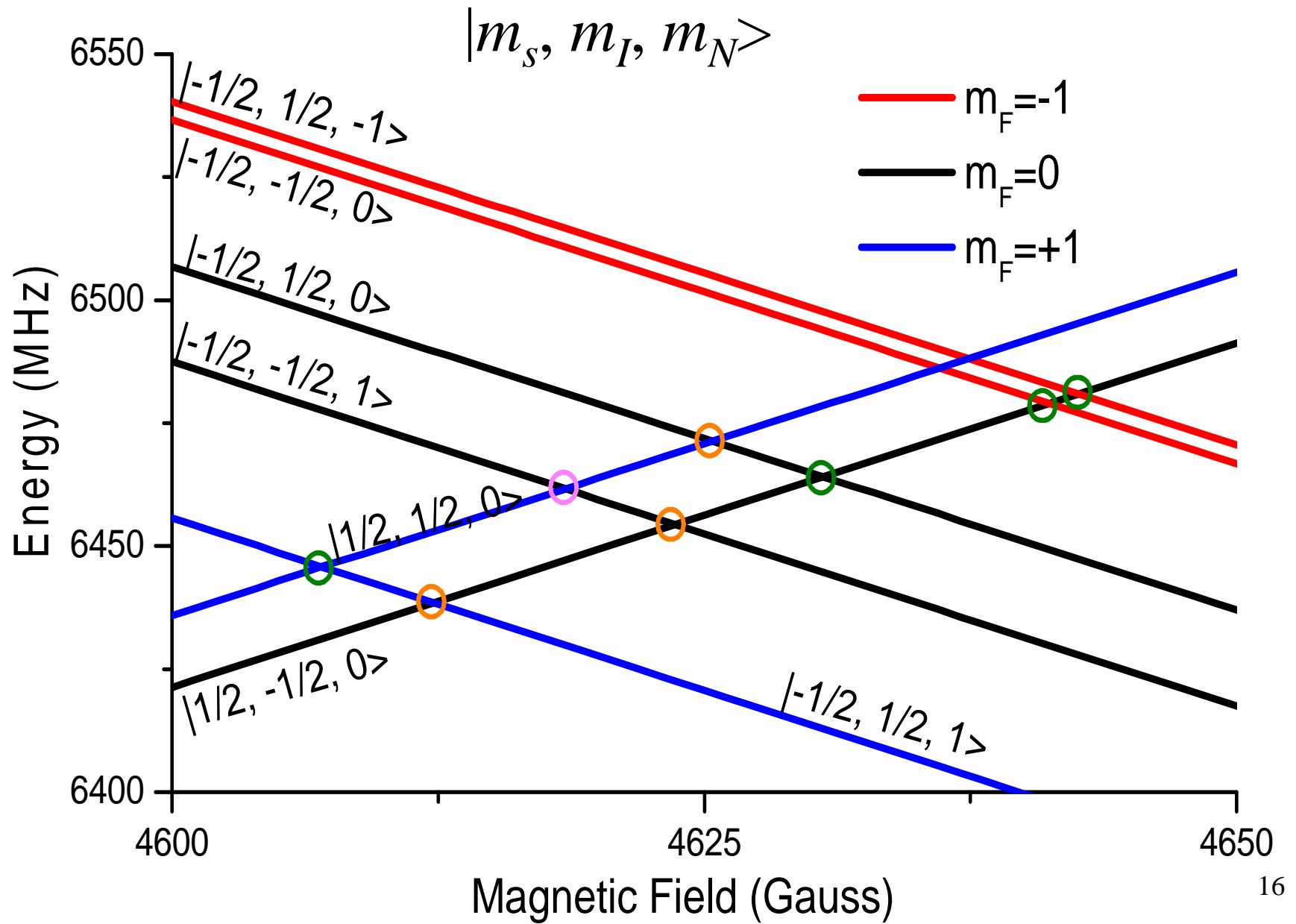


Data: lineshapes from off-resonant Stark shifts



Fit at several different \mathcal{E}_0 values determines crossing position vs. B, and Stark shift strength

Calculated level crossings in ^{138}BaF

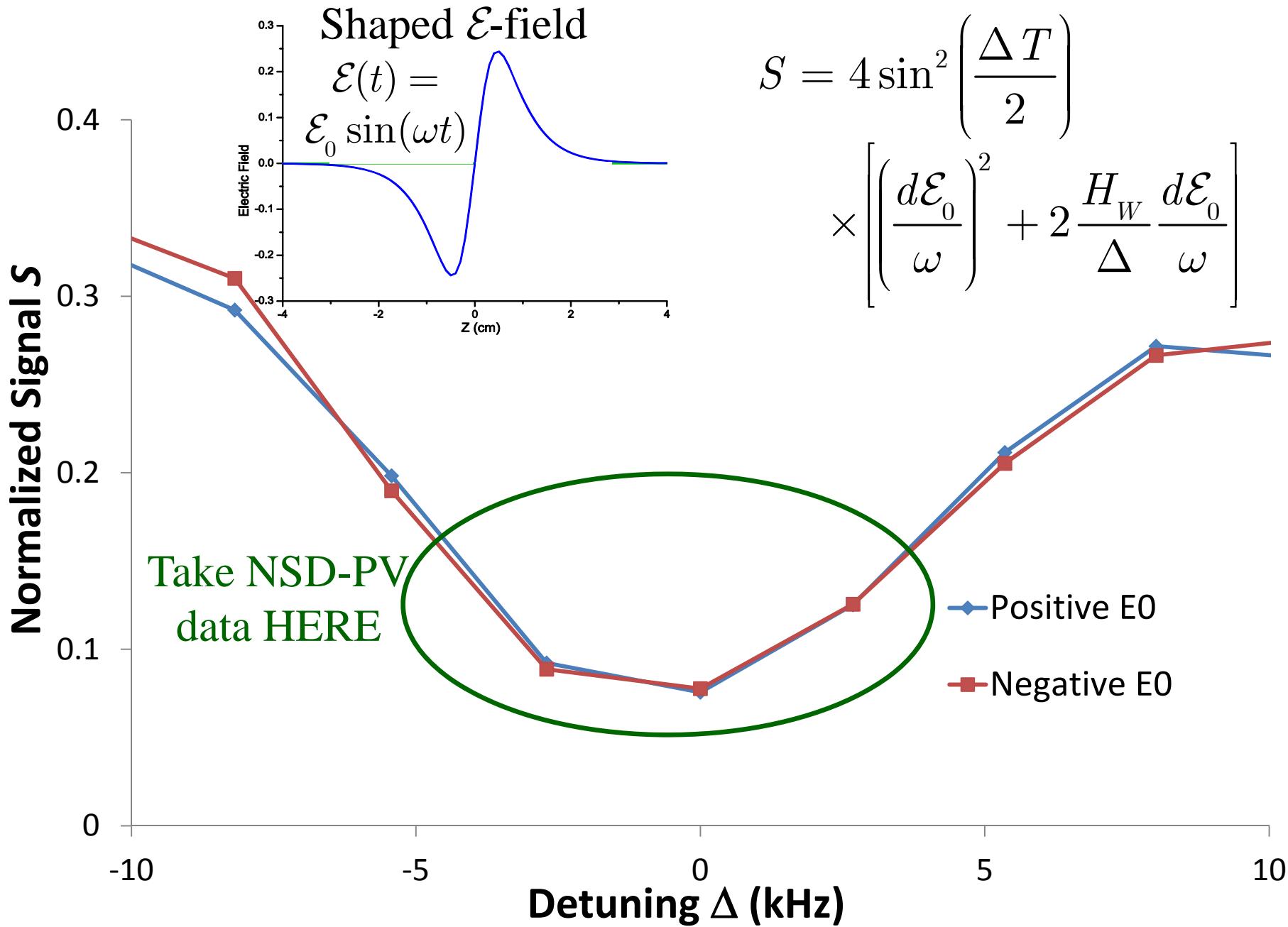


*Extracted data from ^{138}BaF crossings:
crossing positions & dipole matrix elements*

Type	Initial	Calc.X (Gauss)	Obs. X (Gauss)	Calc. d (Hz/V/cm)	Obs. d (Hz/V/cm)	Unc.obs. (Hz/V/cm)
$\Delta m=0$	1	4604.7	4604.8402	-3422	3456	39
$\Delta m=1$	0	4609.91	0	-16.	0	0
$\Delta m=-1$	1	4616.05	4616.138	-4700.	4150	2000
$\Delta m=0$	0	4621.25	4621.265	-150.	100	50
$\Delta m=-1$	1	4623.01	0	-65.	0	0
$\Delta m=0$	0	4628.2	4628.212	-3500.	3574	6.8
$\Delta m=-1$	0	4638.83	4638.674	-960.	800	400
$\Delta m=-1$	0	4640.2	4640.068	-4500.	4000	2000

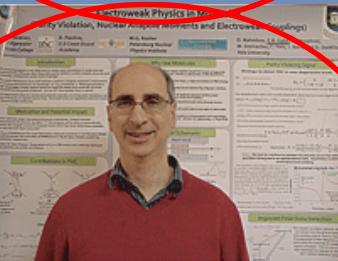
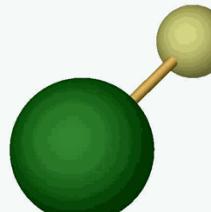
Generally excellent agreement with all predictions from standard spin/rotation/hyperfine + Zeeman Hamiltonian treatment;
some details still to be completed in fit

Initial, very preliminary NSD-PV data in ^{138}BaF



Conclusions & Outlook: Parity Violation with Diatomic Free Radicals

- Opposite-parity level-crossing spectroscopy: linewidth (as small as 4 kHz), lineshapes, positions, matrix elements, etc. all in agreement with theory
- Molecular systems very promising for study of NSD-PV: excellent S/N & systematics, leverage from developed techniques
- Multiple nuclei available for anapole moment determination (we will use ^{137}Ba in ^{137}BaF first; ^{19}F in ^{138}BaF now for testing)
- Measurements of fundamental Z^0 couplings possible in long term?
- Likely extensions with new molecular data, improved molecular beams, laser cooling, etc: an “anapole factory”...?
- n.b. same level crossings suggested for simulation of conical intersections in trapped ultracold molecules [Hutson, Krems, etc.]

			
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