SAND2017-5824C

Spin Squeezing on Nanophotonic Waveguides

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2017-06-09

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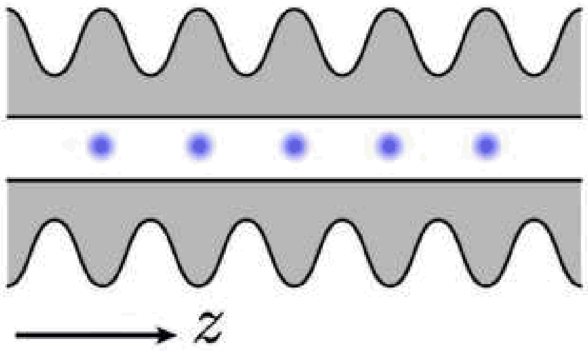
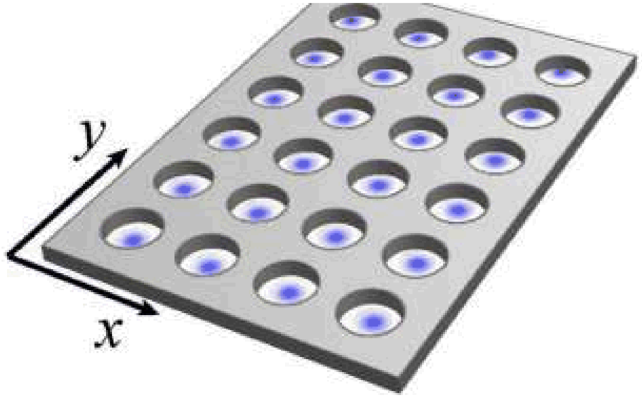
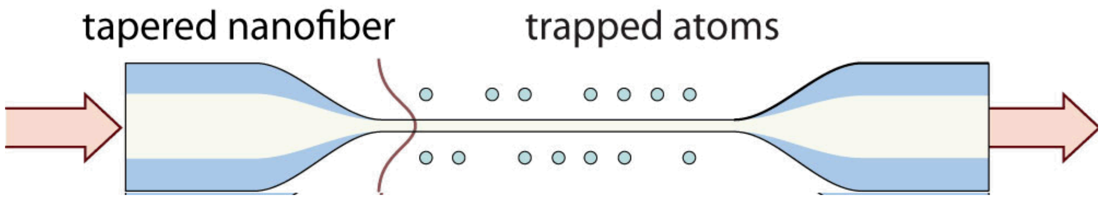
Quantum Atom-Light Interfaces with Nanophotonics





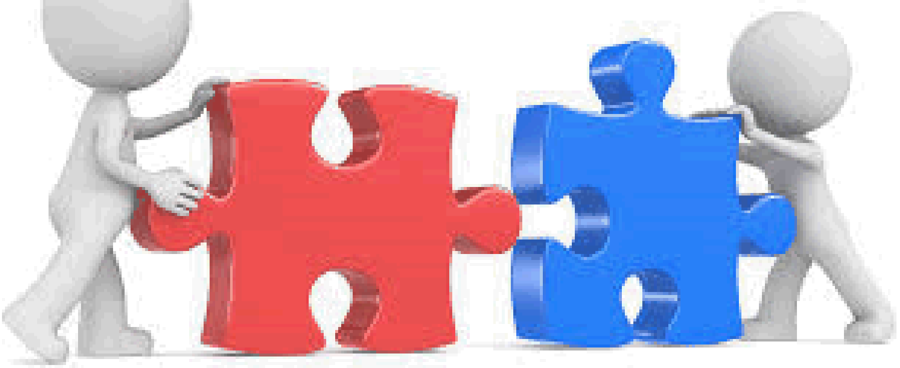
Proc Natl Acad Sci U S A. 113 (2016)



Phy Rev A 93, 023817 (2016)

Atom

Light



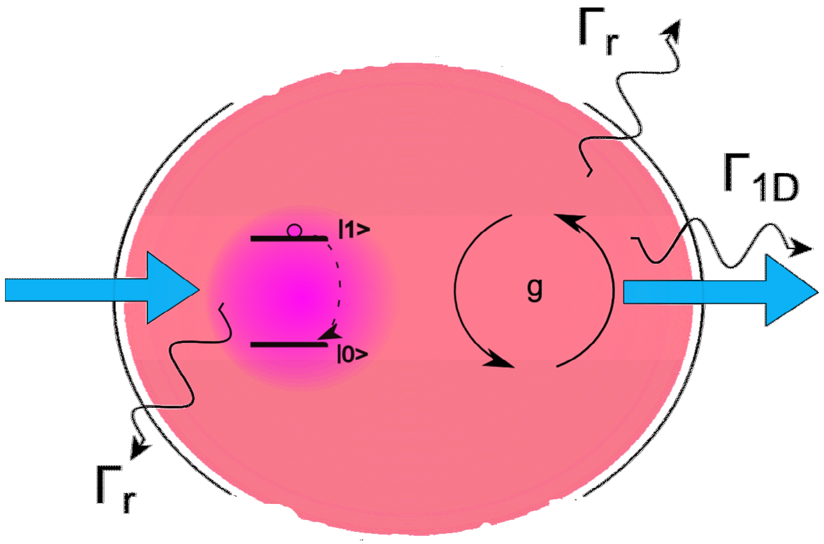
Entanglement

Cooperativity

Strong Atom-Photon Coupling in Photonics

Cooperativity:

$$C \equiv \mathscr{F}\frac{\Gamma_{1D}}{\Gamma_0} = \mathscr{F}\frac{\sigma_0}{A_{\mathrm{eff}}}$$



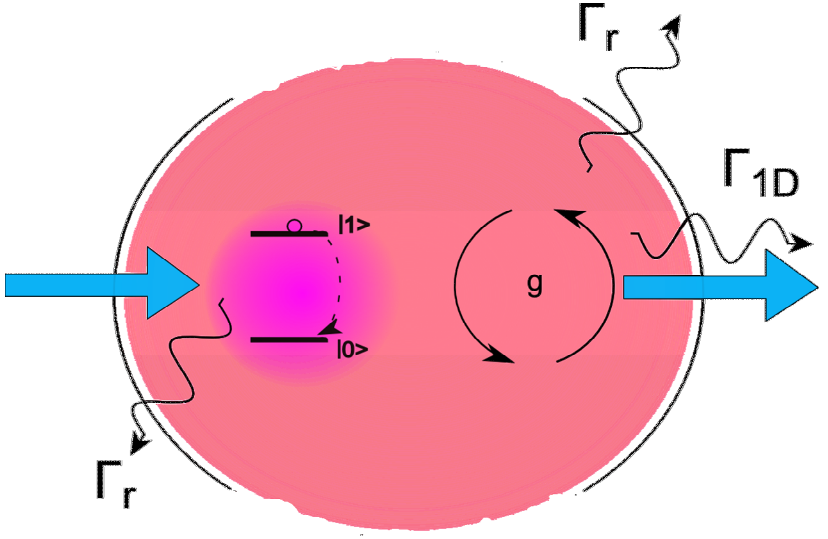
Cavity-QED

Strong Atom-Photon Coupling in Photonics

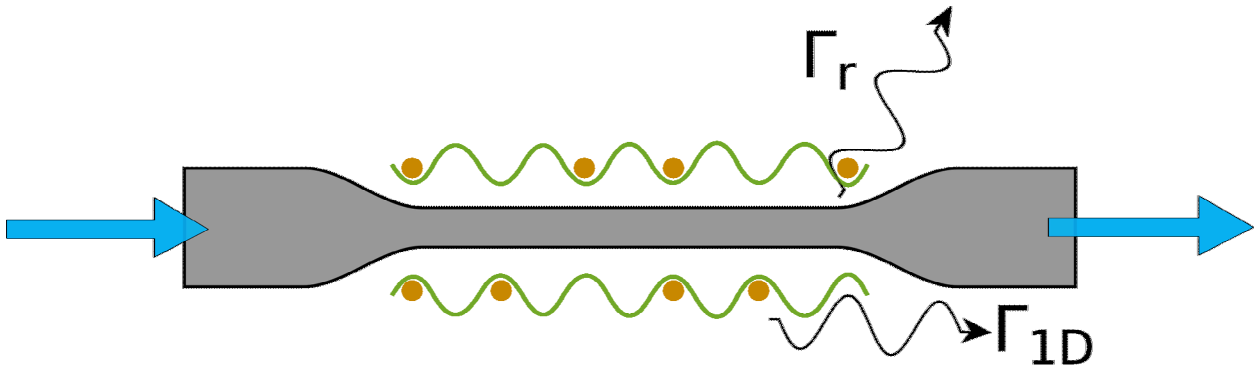
Cooperativity:

$$C \equiv \mathscr{F}\frac{\Gamma_{1D}}{\Gamma_0} = \mathscr{F}\boxed{\frac{\sigma_0}{A_{\mathrm{eff}}}}$$

$$C = N_A\frac{\Gamma_{1D}}{\Gamma_0} = N_A\boxed{\frac{\sigma_0}{A_{\mathrm{eff}}}} = N_A\boxed{\frac{\mathrm{OD}_{\mathrm{eff}}}{N_A}}$$

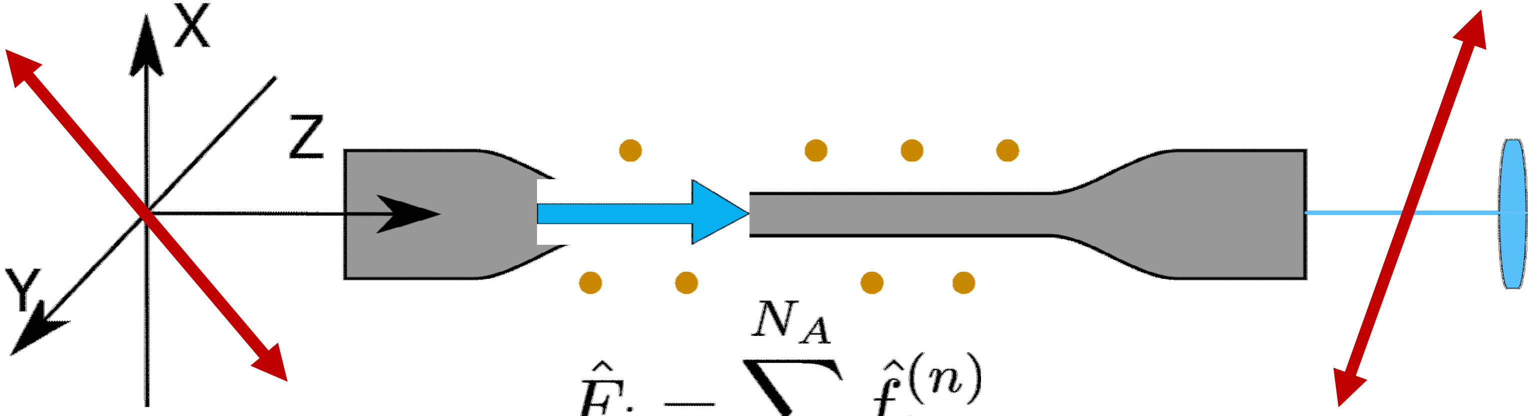


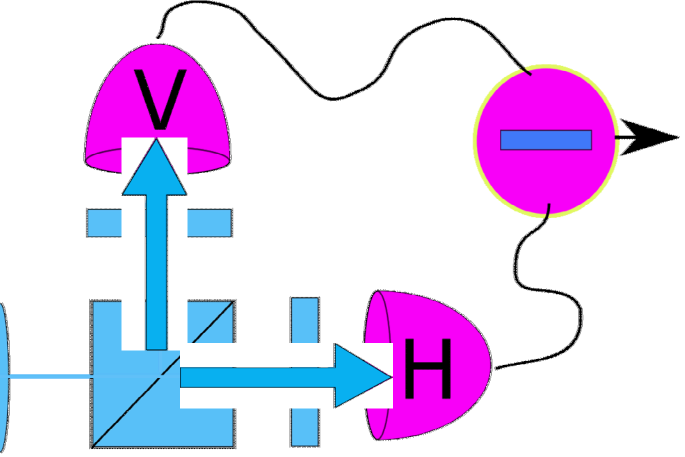
Cavity-QED



Nanophoronic waveguides

Faraday Effect Polarization Spectroscopy





$$\hat{F}_i = \sum_{n}^{N_A} \hat{f}_i^{(n)}$$

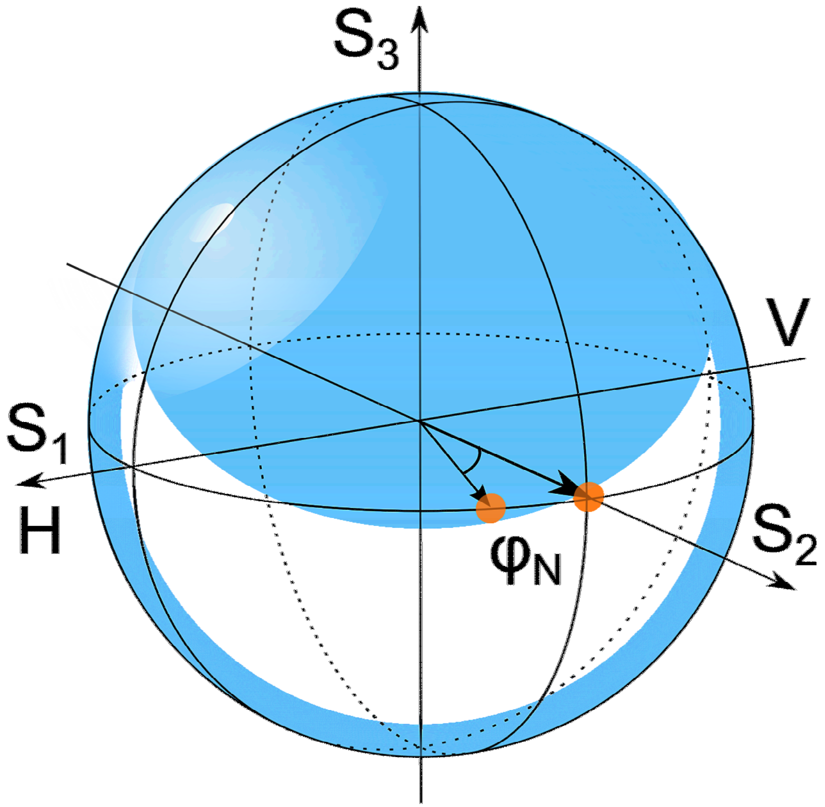
Light-atom interaction Hamiltonian

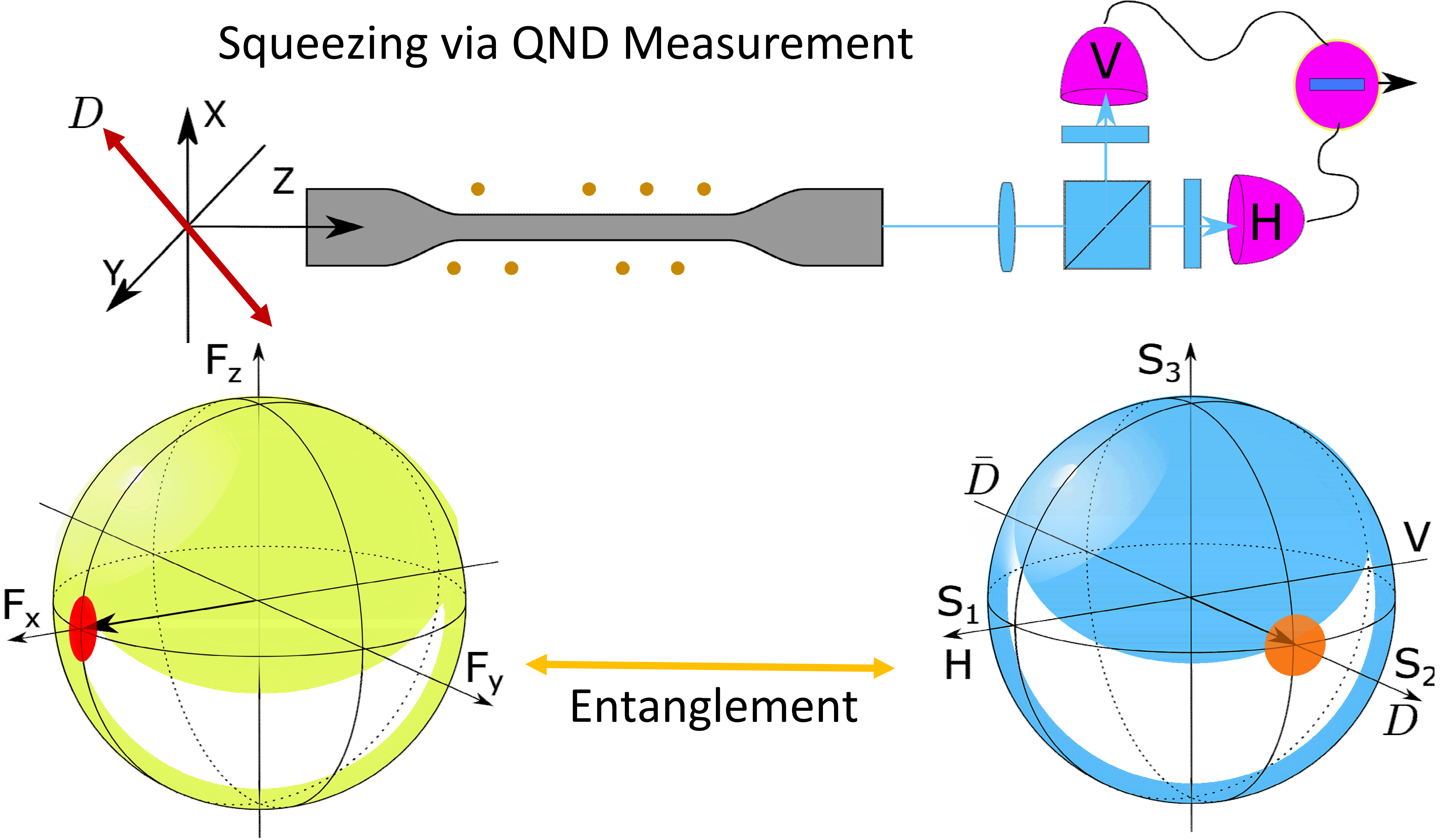
$$\hat{H}_{LS} = -\sum_{n=1}^{N_A} \hat{\mathbf{E}}^{(-)}(\mathbf{r}'_n) \cdot \hat{\overleftrightarrow{\boldsymbol{\alpha}}}^{(n)} \cdot \hat{\mathbf{E}}^{(+)}(\mathbf{r}'_n)$$

$$= \hbar \sum_{i,j} \chi_{ij} \hat{F}_i \hat{S}_j .$$

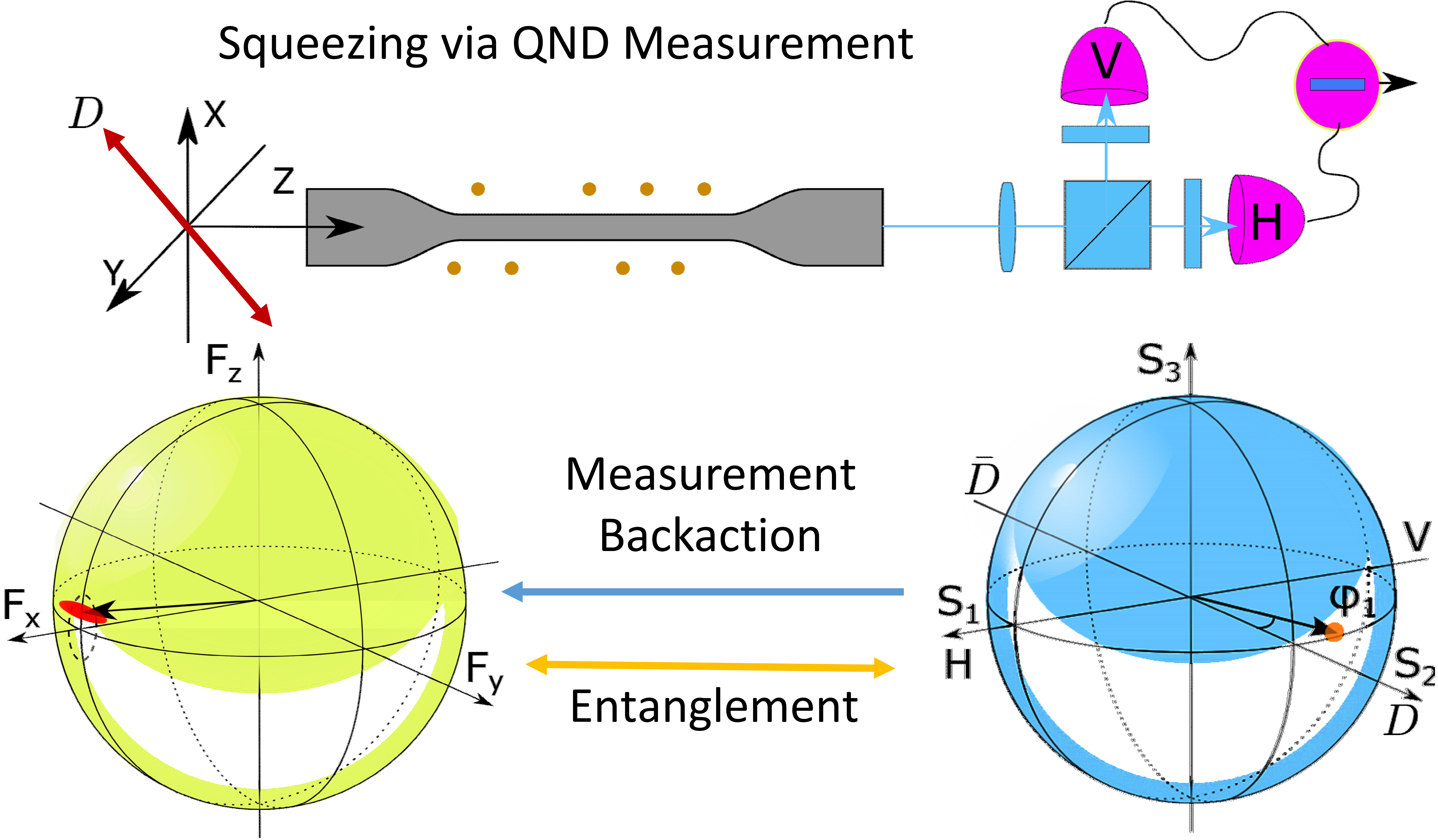
$$\rightarrow \hbar \chi_{33} \hat{F}_z \hat{S}_3$$

$\hat{S}_i$ are the Stokes vector operators.

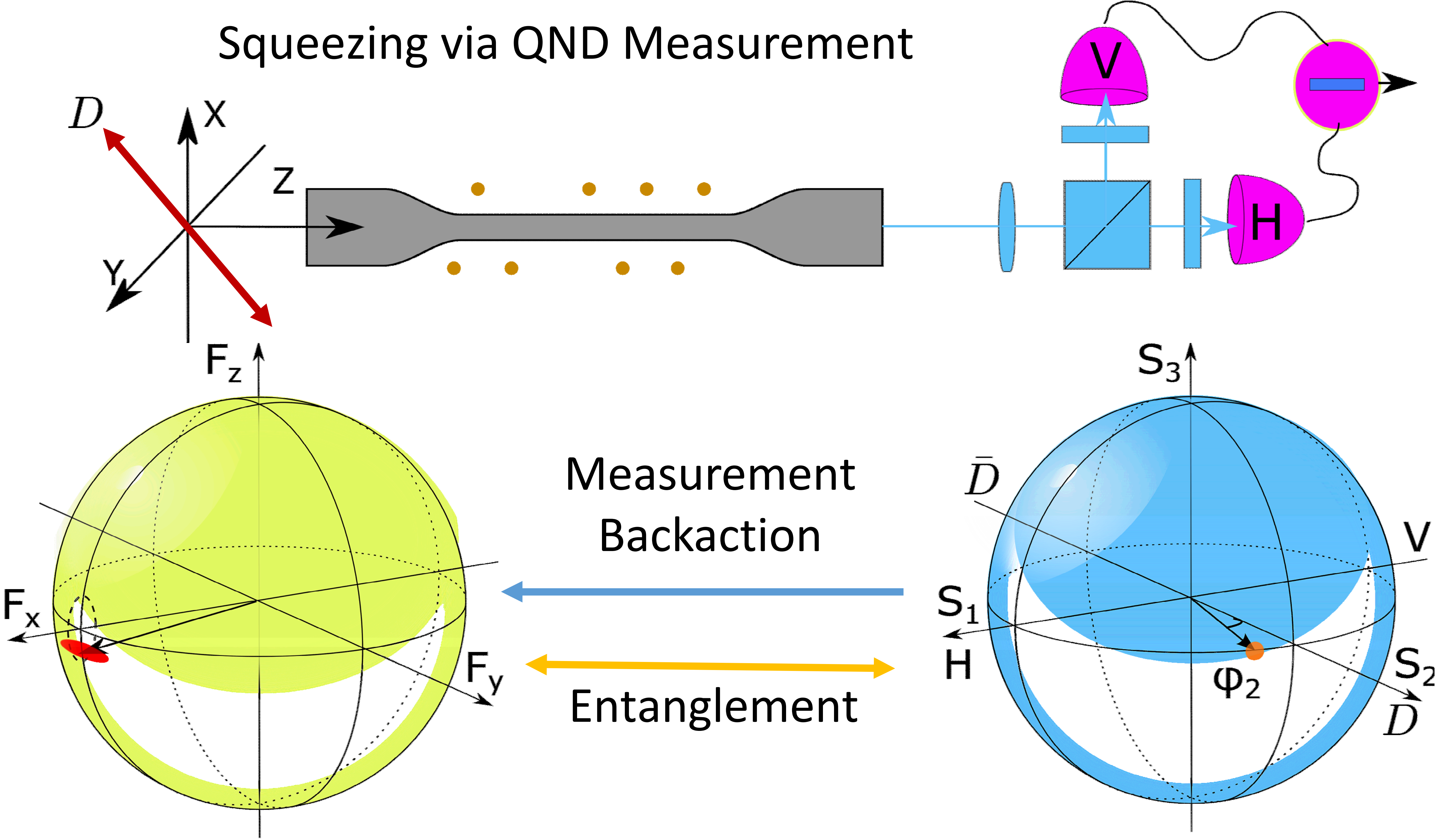




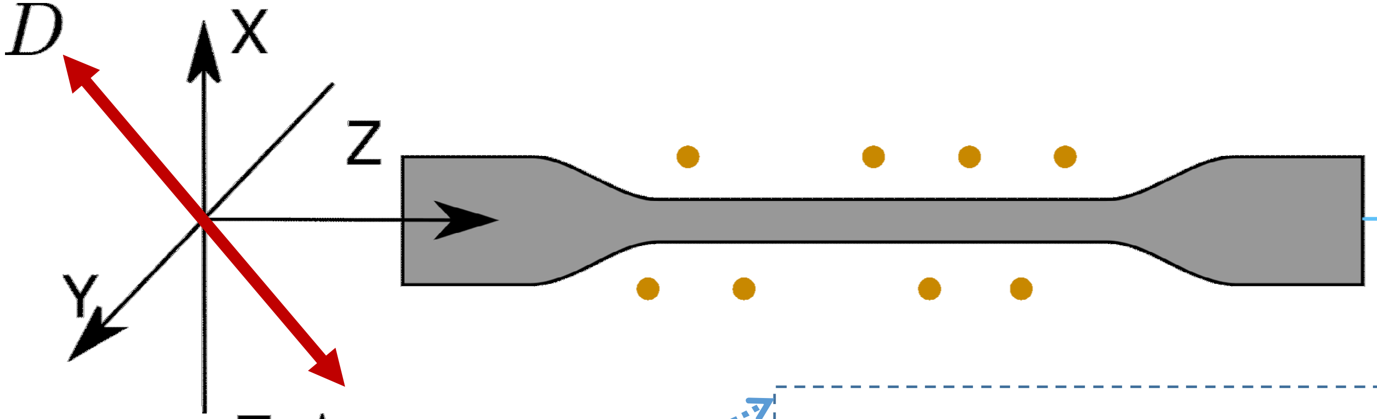
Squeezing via QND Measurement
D
X
Z
Y
V
H
F_z
F_x
F_y
S_3
$\bar{D}$
V
S_1
H
S_2
D
Entanglement

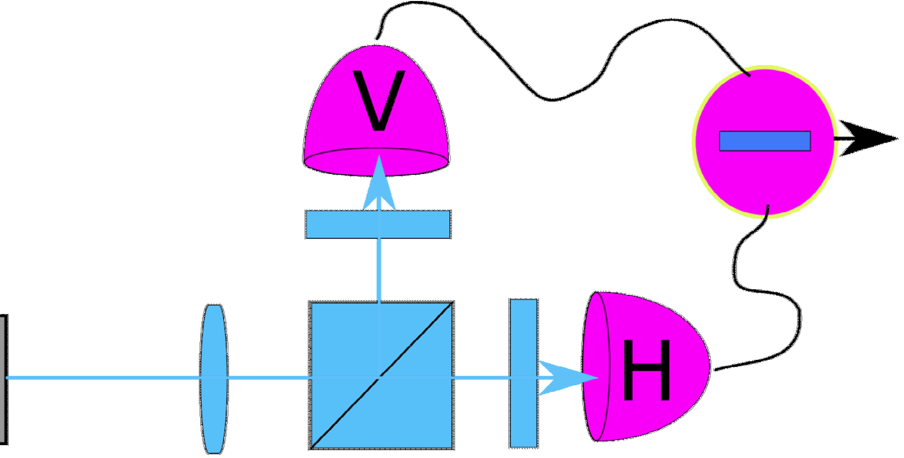

Squeezing via QND Measurement
D
X
Z
Y
V
H
F_z
F_x
F_y
Measurement
Backaction
Entanglement
S_3
$\bar{D}$
V
S_1
H
φ_1
S_2
D

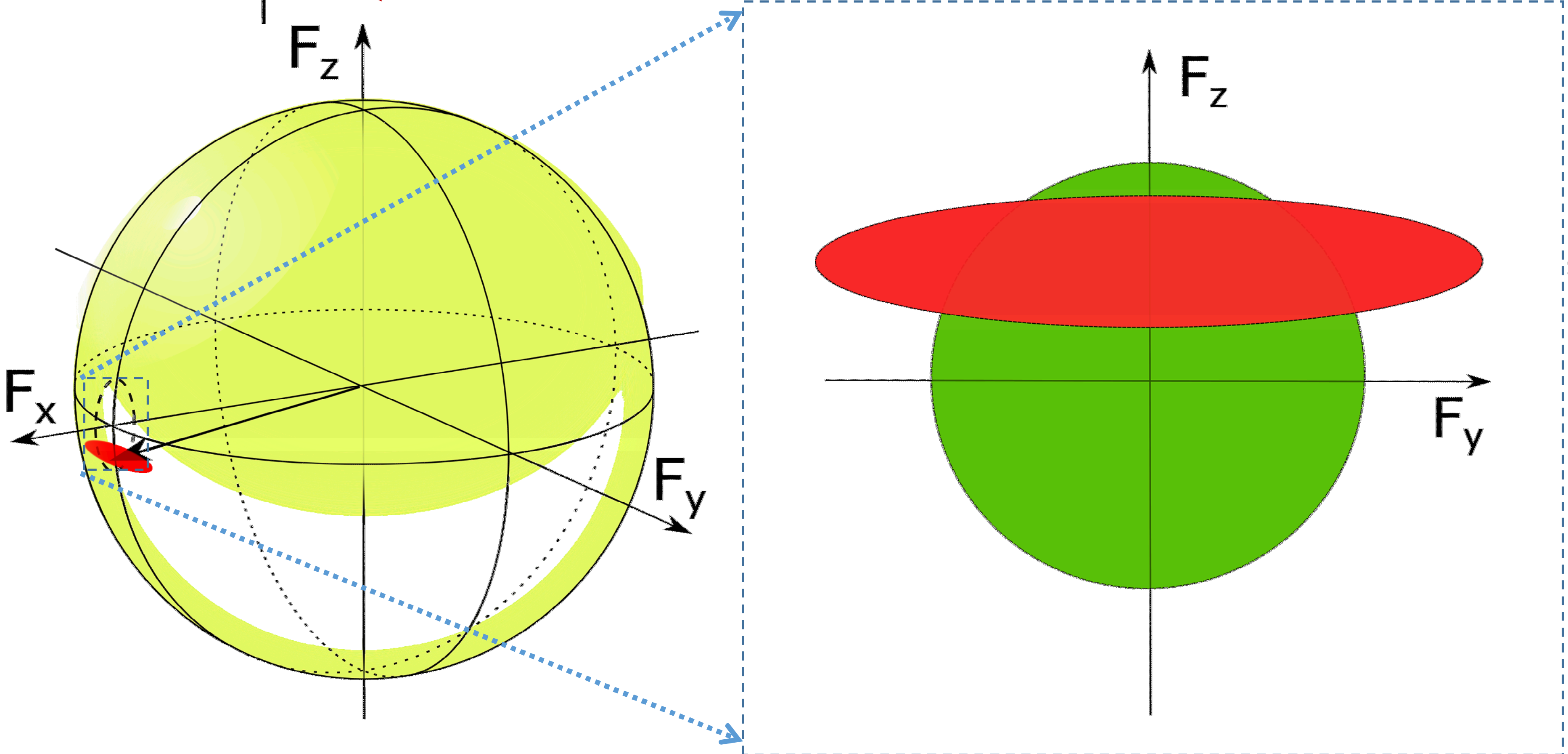
Squeezing via QND Measurement



Wineland Squeezing Parameter







$$\xi^2 = \frac{2N_A}{f}\frac{\Delta F_z^2}{\left|\langle \hat{F}_x \rangle\right|^2}$$

Wineland squeezing parameter

Modeling Spin Squeezing Dynamics

- Spin squeezing parameter

$$\xi^2 = \frac{2N_A}{f} \frac{\Delta F_z^2}{|\langle \hat{F}_x \rangle|^2}$$

- One-body and two-body operators that matter

$$\Delta F_z^2 = \boxed{N_A \left(\Delta \hat{f}_z^{(1)}\right)^2} + \boxed{N_A (N_A - 1) \langle \Delta \hat{f}_z^{(1)} \Delta \hat{f}_z^{(2)} \rangle}$$

$$\langle \hat{F}_x \rangle = \boxed{N_A \langle \hat{f}_x^{(1)} \rangle}$$

Dynamics of QND Measurement with Decoherence

- Stochastic master equation

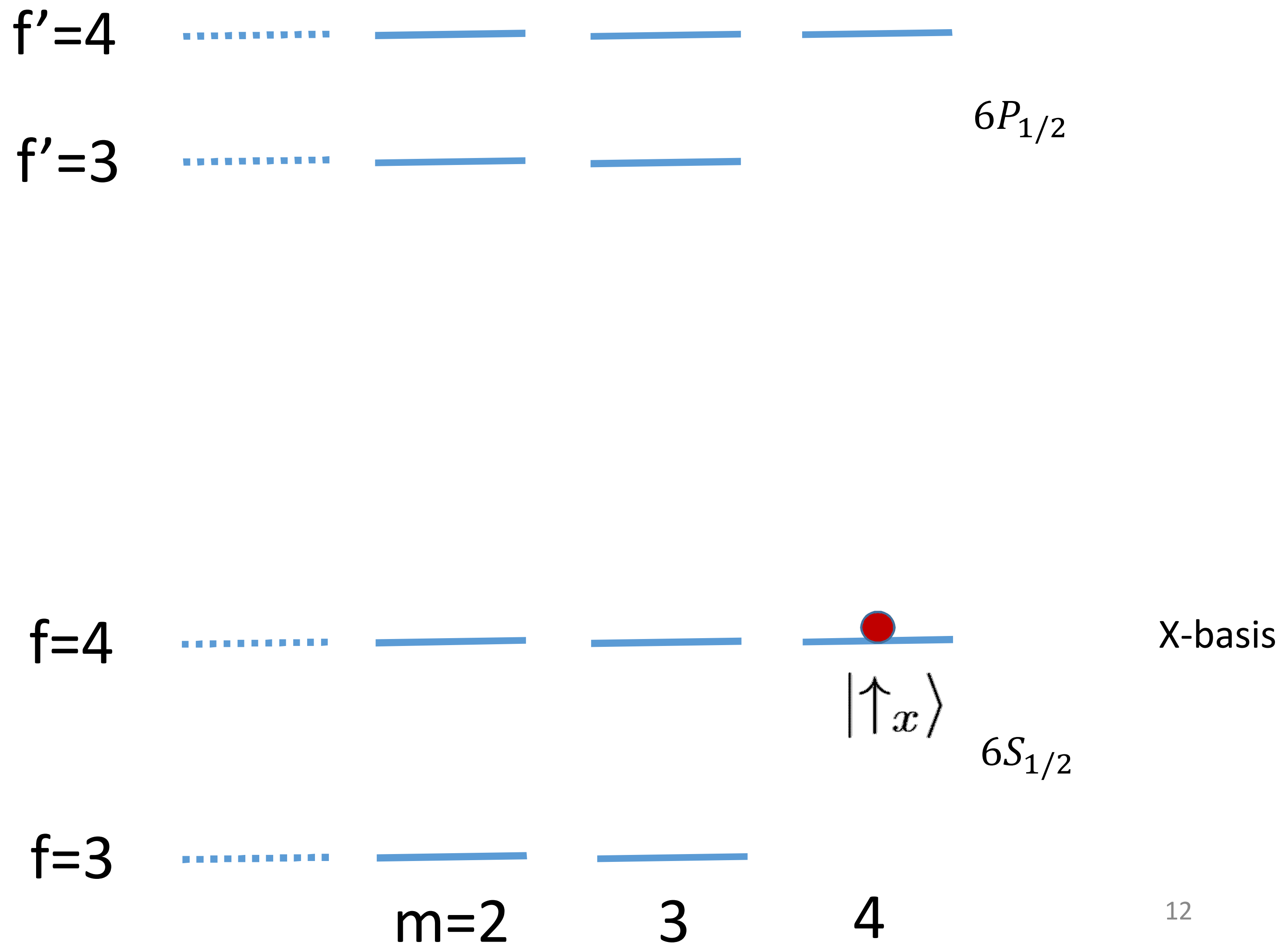
$$\mathcal{H}[\hat{\rho}] = \hat{F}_z\hat{\rho} + \hat{\rho}\hat{F}_z - 2\langle\hat{F}_z\rangle\hat{\rho}, \qquad \mathcal{L}[\hat{\rho}] = -\tfrac{1}{2}\left(\hat{\rho}\hat{F}_z^2 + \hat{F}_z^2\hat{\rho}\right) + \hat{F}_z\hat{\rho}\hat{F}_z.$$

$$d\hat{\rho} = \underbrace{s\sqrt{\frac{\kappa}{4}}\mathcal{H}[\hat{\rho}]dW + \frac{\kappa}{4}\mathcal{L}[\hat{\rho}]dt}_{\text{collective measurement}} \quad + \quad \underbrace{\gamma_s\sum_n \mathcal{D}_n[\hat{\rho}]dt}_{\text{optical pumping}},$$

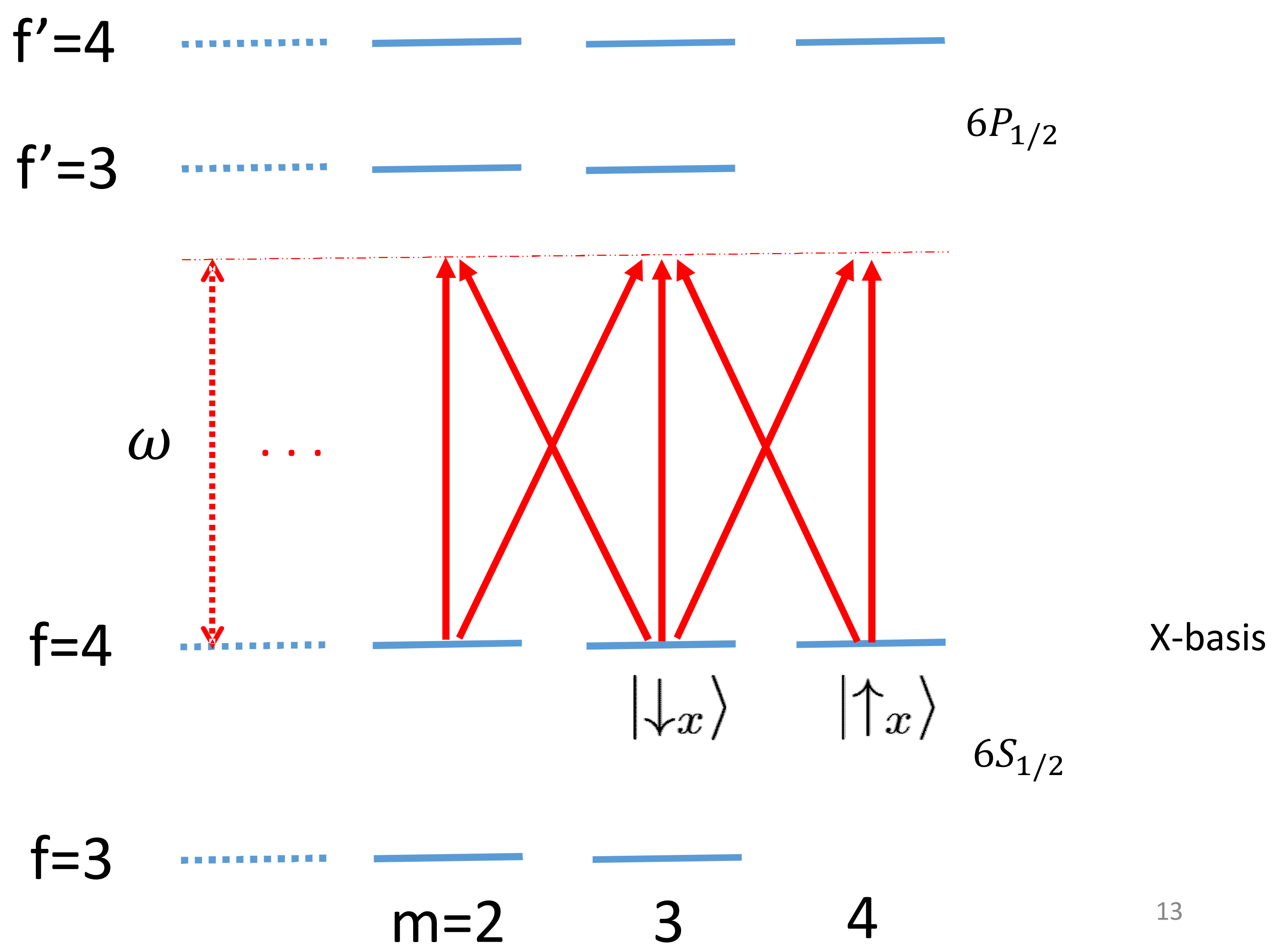
where $s = \mathrm{sign}(\chi_{33})$ and $\hat{\rho}$ is the collective atomic state.

$$\langle\hat{O}\rangle = \mathrm{tr}\left[\hat{\rho}\hat{O}\right].$$

Coherent coupling and optical pumping



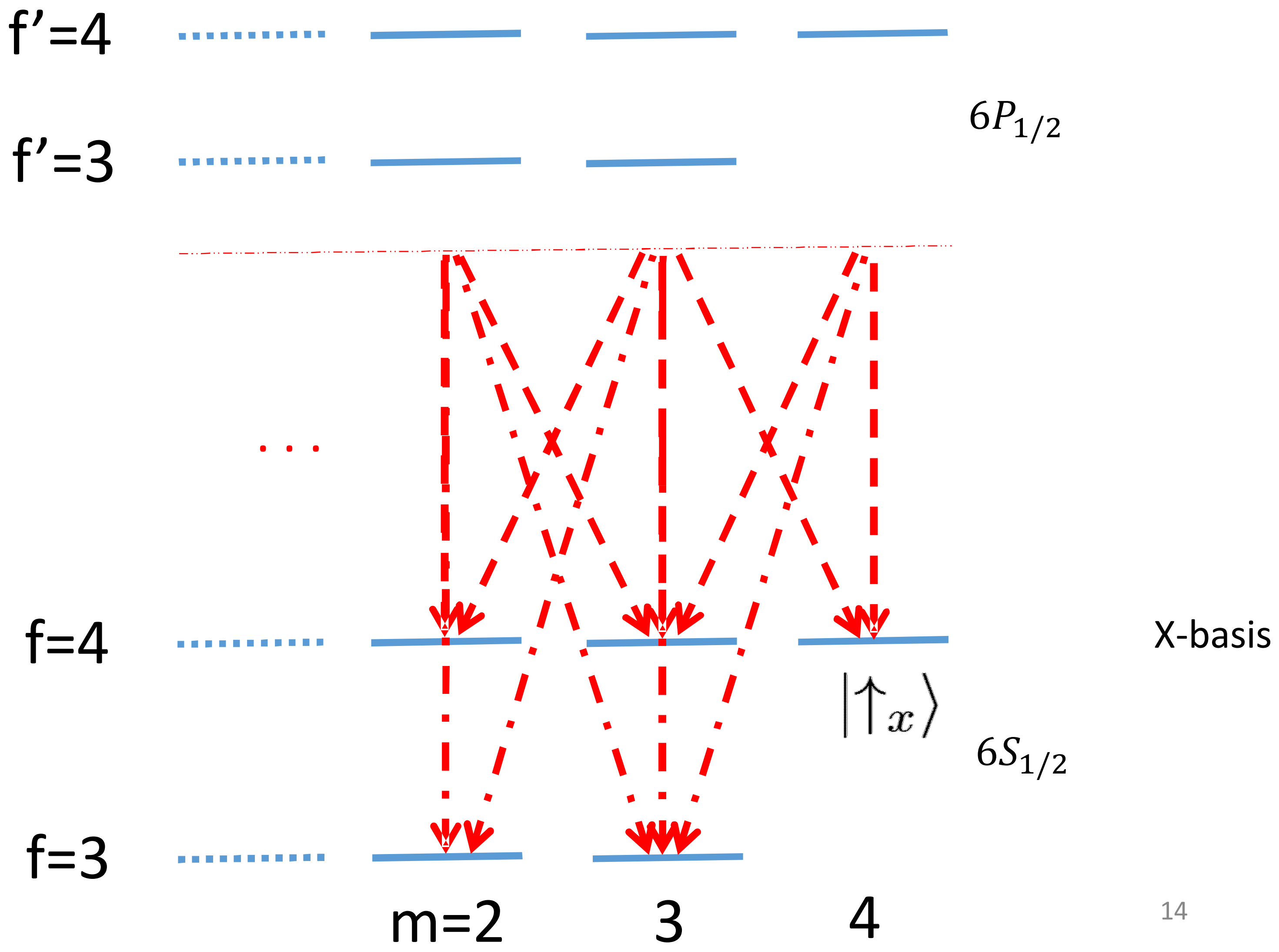
Coherent coupling and optical pumping



Coherent coupling and optical pumping

$$\gamma_s \mathcal{D}[\rho] = -\frac{i}{\hbar}\left[\hat{H}_{\text{eff}}\hat{\rho} - \hat{\rho}\hat{H}_{\text{eff}}^{\dagger}\right] + \sum_{f_b, f_a, q} \hat{W}_q^{f_b f_a}\hat{\rho}\hat{W}_q^{f_b f_a \dagger} = \sum_{a,b}\gamma_{ba}|b\rangle\langle a|.$$

$$\gamma_s \equiv \frac{\Gamma\Omega^2}{4\Delta_{\text{eff}}^2} = \frac{\sigma_0}{A_0}\frac{\Gamma^2}{4\Delta_{\text{eff}}^2}\dot{N}_L$$



Modeling Spin Squeezing Dynamics

- Equations of spin dynamics (Gaussian approximation)

$$d\langle\hat{\sigma}_{ba}\rangle = d\langle\hat{\sigma}_{ba}\rangle\big|_{op} + d\langle\hat{\sigma}_{ba}\rangle\big|_{\mathcal{H}} + d\langle\hat{\sigma}_{ba}\rangle\big|_{\mathcal{L}} \tag{1}$$

$$\begin{aligned} d\langle\Delta\sigma_{ba}^{(1)}\Delta\sigma_{dc}^{(2)}\rangle_s &= d\langle\Delta\sigma_{ba}^{(1)}\Delta\sigma_{dc}^{(2)}\rangle_s\Big|_{op} \\ &+ d\langle\Delta\sigma_{ba}^{(1)}\Delta\sigma_{dc}^{(2)}\rangle_s\Big|_{\mathcal{H}} + d\langle\Delta\sigma_{ba}^{(1)}\Delta\sigma_{dc}^{(2)}\rangle_s\Big|_{\mathcal{L}}. \end{aligned} \tag{2}$$

where $\hat{\sigma}_{ba} = |b\rangle\langle a|.$

$$\hat{f} = \sum_{b,a}\langle b|\hat{f}|a\rangle\hat{\sigma}_{ba}.$$

Physical Essence of Spin Squeezing with Faraday interaction

- Measurement strength

$$\kappa \sim |\chi_{33}|^2 \sim \mathrm{Re}\left[\left(\mathbf{u}_H^*(\mathbf{r}') \times \mathbf{u}_V(\mathbf{r}')\right) \cdot \mathbf{e}_{\tilde{z}}\right] \sim \frac{1}{A_{\mathrm{int}}^2}$$

$$A_{\mathrm{int}}^2 \propto \frac{1}{n_g \mathrm{Re}\left[\mathbf{u}_H^* \times \mathbf{u}_V\right] \cdot \hat{e}_{\tilde{z}}} = \frac{1}{n_g \mathrm{Re}\left[\mathbf{u}_D^* \times \mathbf{u}_{\bar{D}}\right] \cdot \hat{e}_{\tilde{z}}}$$

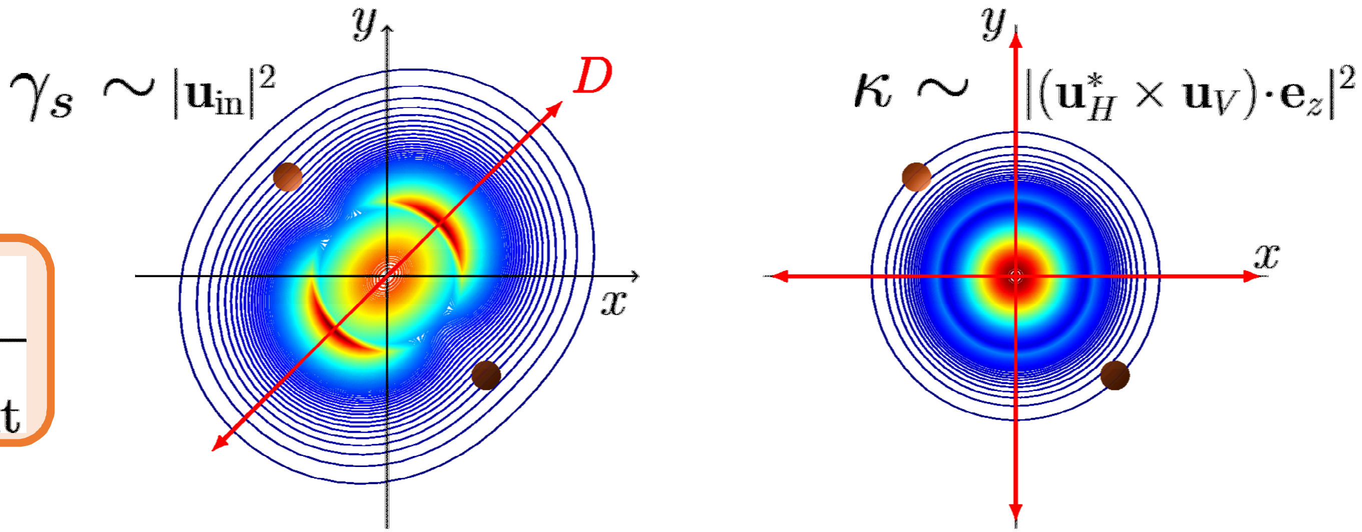
Characteristic photo scattering rate

$$\gamma_s \sim |\mathbf{u}_D(\mathbf{r}')|^2 \sim \frac{1}{A_0}$$

Optimal Geometry

- Figure of merit--Optical Depth per atom:

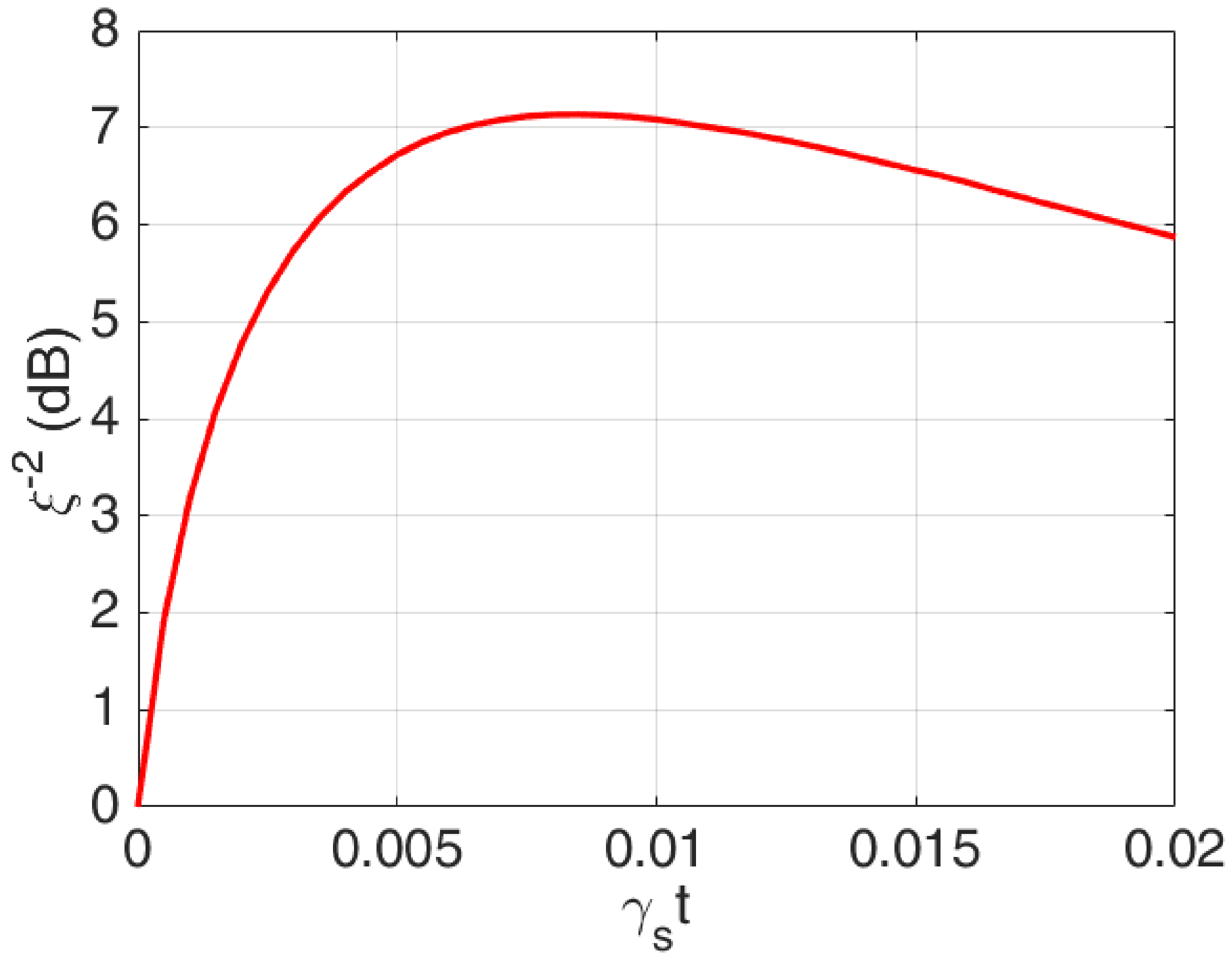
$$\frac{\mathrm{OD}_{\mathrm{eff}}}{N_A} = \frac{\quad}{\quad} = \frac{\kappa}{\gamma_s} = \sigma_0 \frac{A_0}{A_{\mathrm{int}}^2}$$



Geometry of the Faraday protocol

Spin Squeezing Using Faraday Interaction

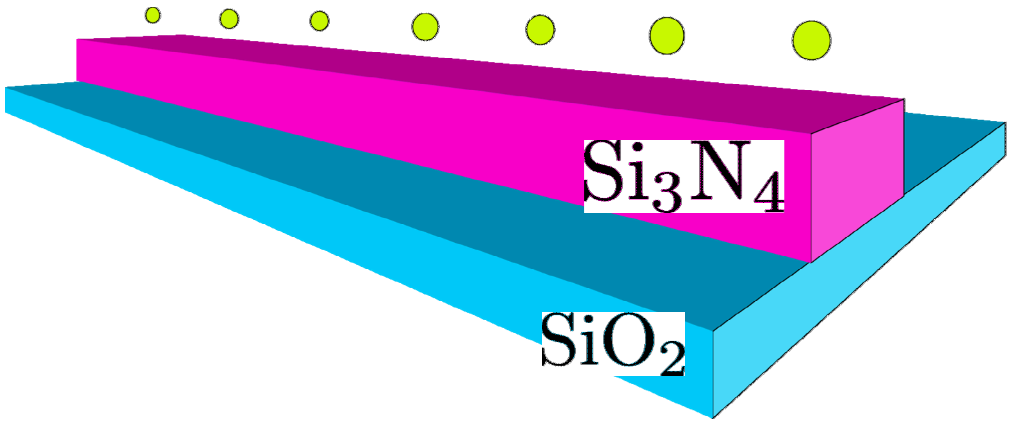
$$N_A = 2500$$
$$a = 225nm$$
$$\lambda = 895nm$$

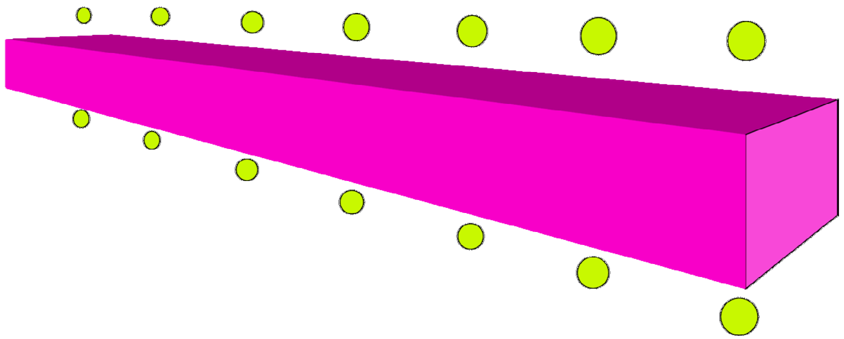


Radial position of atoms: $r'_\perp = 1.8a$ (180nm from the surface)

Spin Squeezing with Nanophotonic Waveguides

- Geometry





Current focus: square waveguides
a → 300nm

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Yuan-Yu Jau

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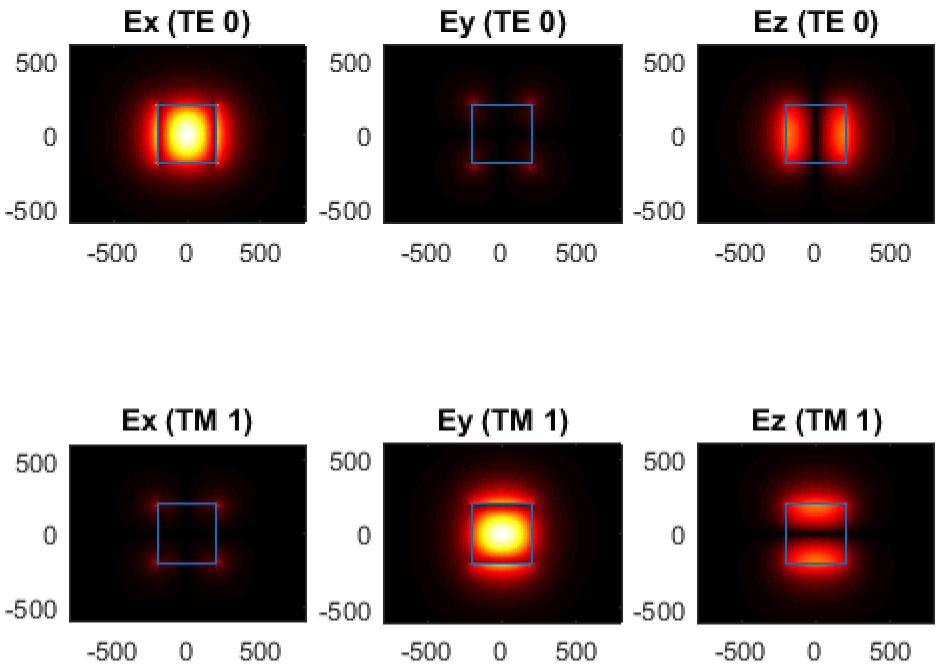
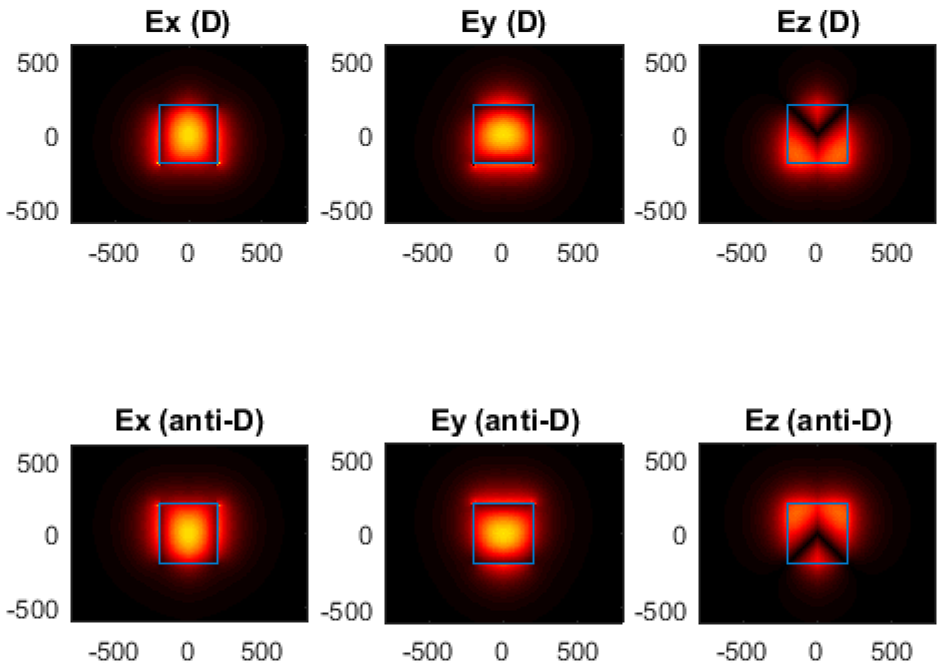
Spin Squeezing on a Square Nano-waveguide



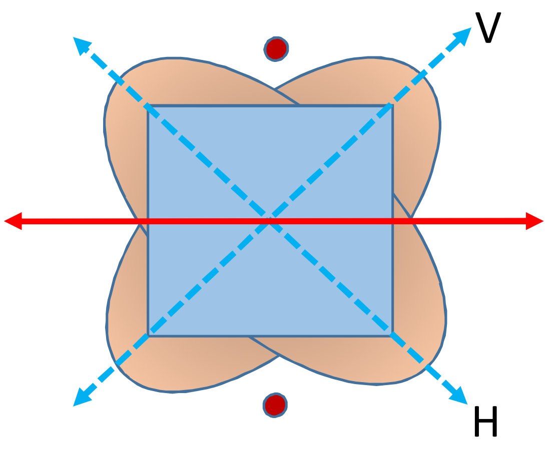
Fundamental TE and TM modes

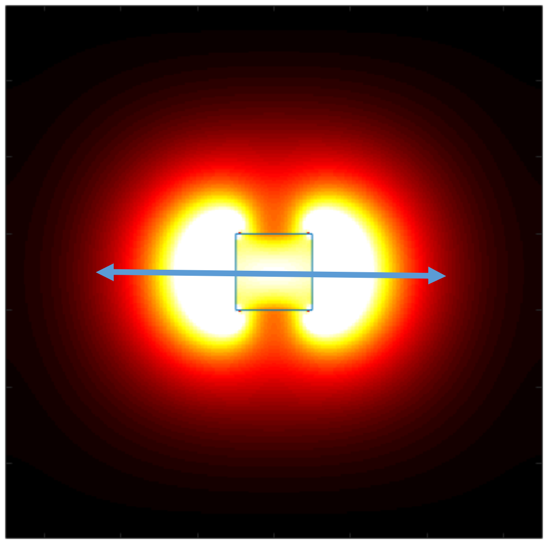


D and anti-D modes

Spin Squeezing on a SWG Platform Using Faraday Interactions

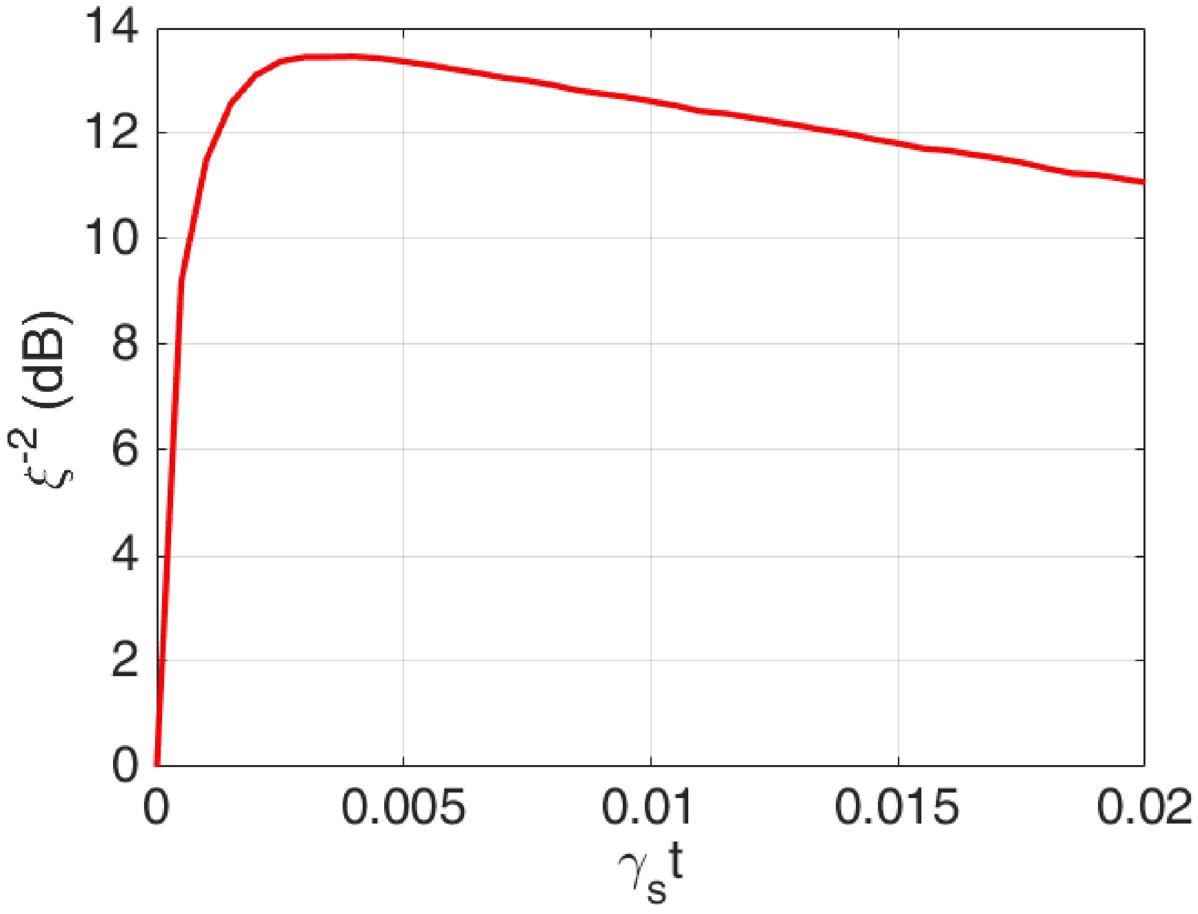
- Protocol geometry:





d=300nm, atoms are 150nm to the surface.

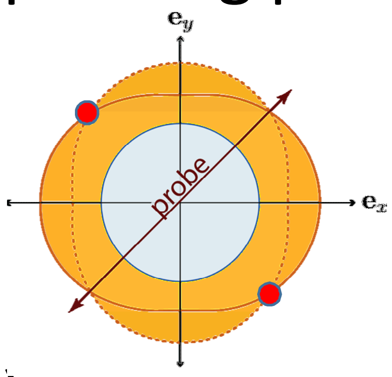
Spin squeezing dynamics (preliminary result)

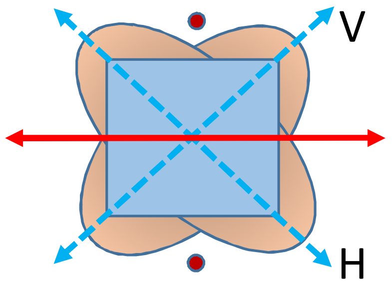


Summary

- Birefringence and Faraday spin squeezing protocols

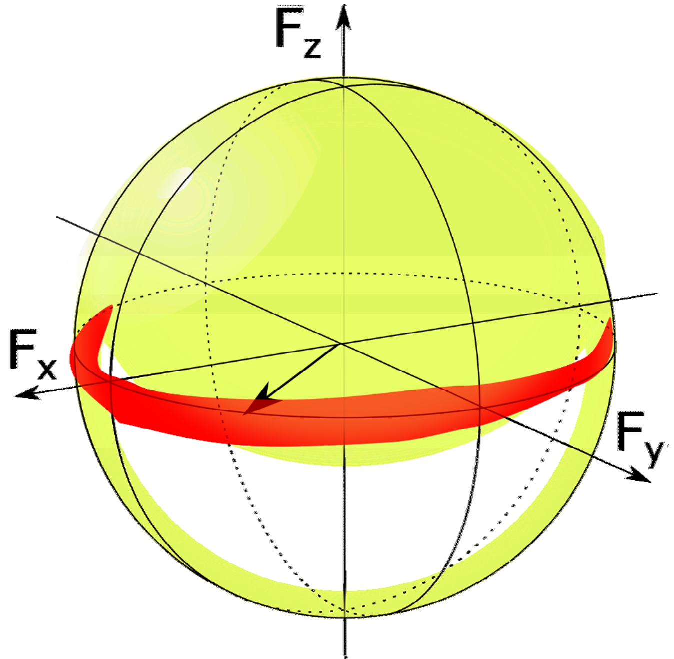
$$\frac{\mathrm{OD_{eff}}}{N_A} = \sigma_0 \frac{A_0}{A_{\mathrm{int}}^2}$$





- Typical peak squeezing (NA=2500)

	$\xi_{\max}^{-2}$ (dB)
Nanofiber (r’-a=180nm)	7
SWG (r’ $-\frac{d}{2}$=150nm)	14

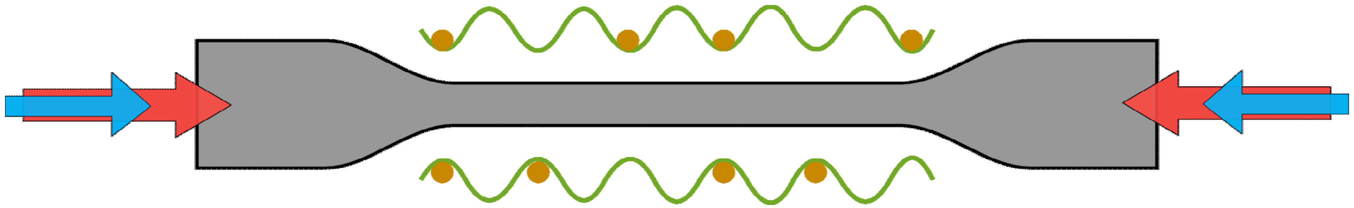


- Toward non-Gaussian states

If $N_A = 2500$, Gaussian limit: $\Delta F_z^2 \leq \langle F_x \rangle$

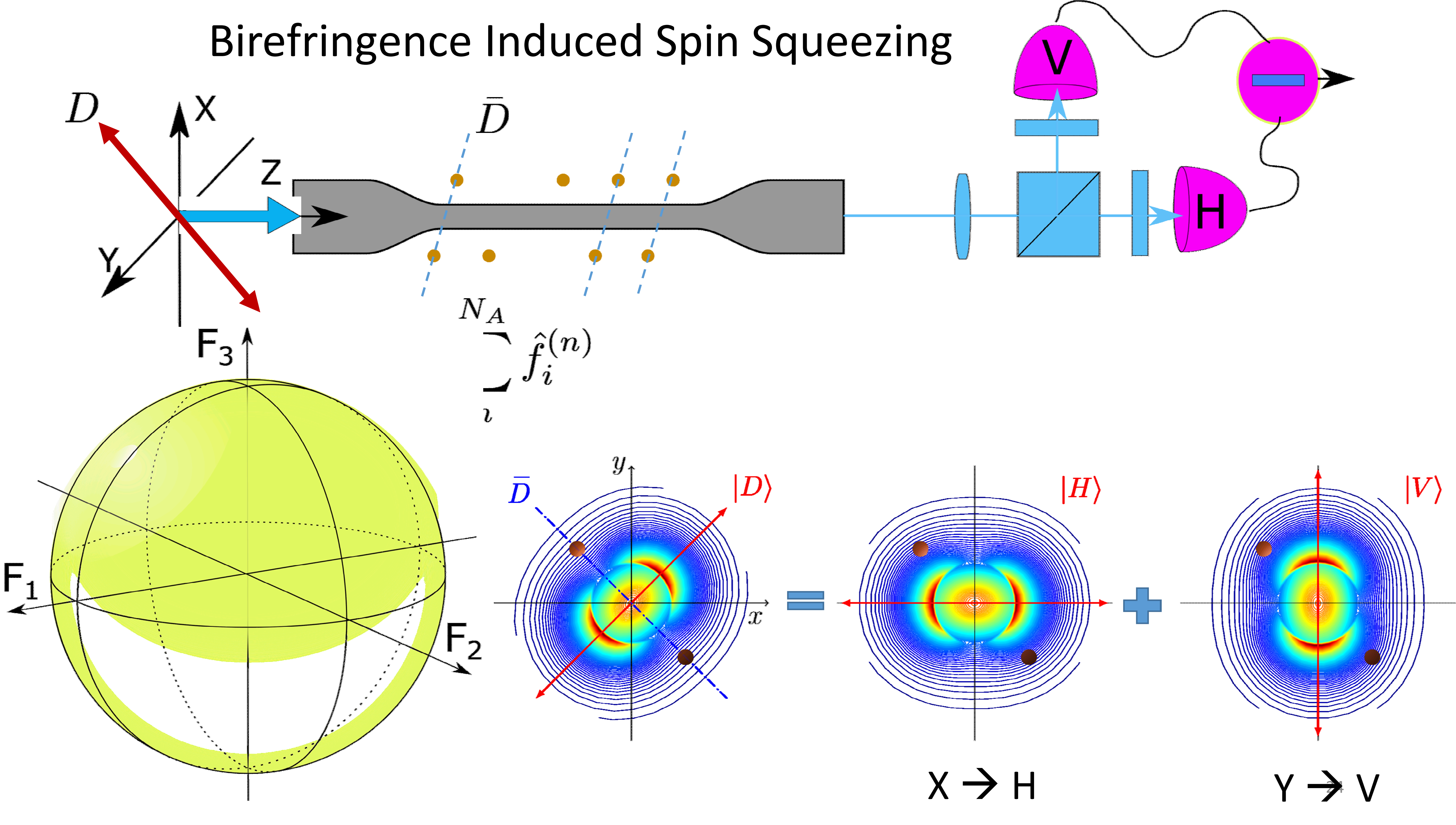
$$\Rightarrow \quad \xi^{-2} \leq \sqrt{2Nf} \approx 20dB$$

THANK YOU!



Email: qxd@unm.edu

Birefringence Induced Spin Squeezing



OD per atom (theory and comparison)

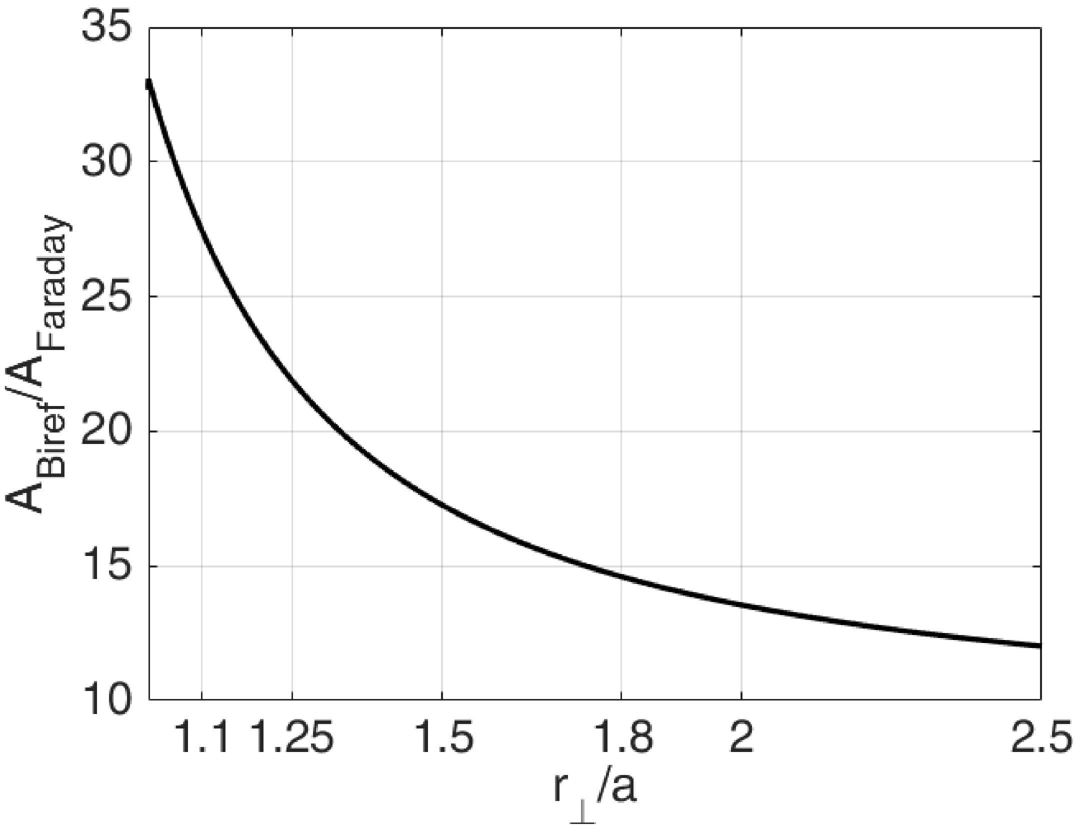
Enhancement of the Faraday protocol over the birefringence protocol:

$$\frac{\mathrm{OD}_{biref}}{N_A} = \sigma_0 \frac{A_0}{A_{\text{int}}^2} = \frac{\sigma_0}{A_{biref}}$$

$$\frac{\mathrm{OD}_{Faraday}}{N_A} = \sigma_0 \frac{A_0}{A_{\text{int}}^2} = \frac{\sigma_0}{A_{Faraday}}$$

$$A_{biref} = \frac{A_{\text{int}}^2}{A_0}$$

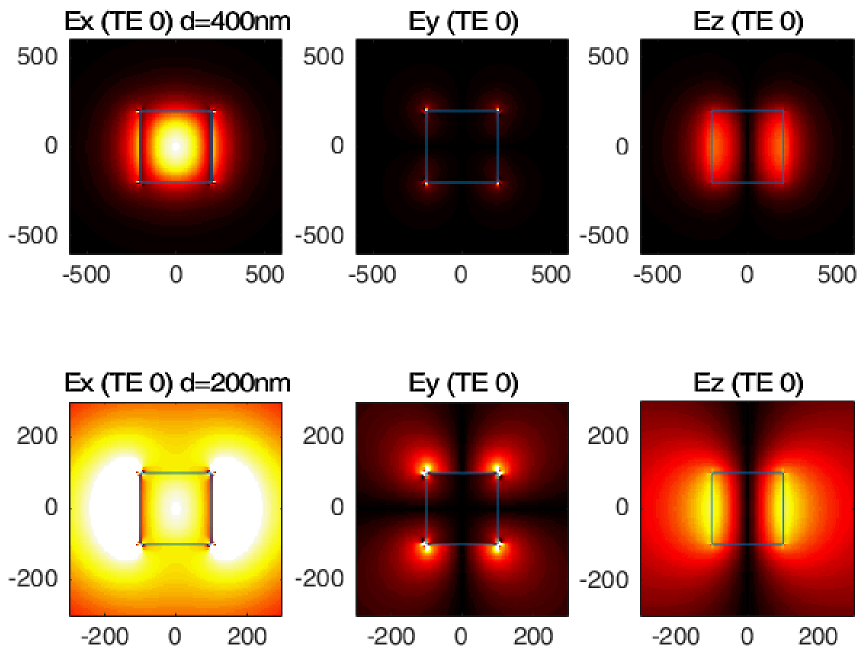
$$A_{Faraday} = \frac{A_{\text{int}}^2}{A_0}$$



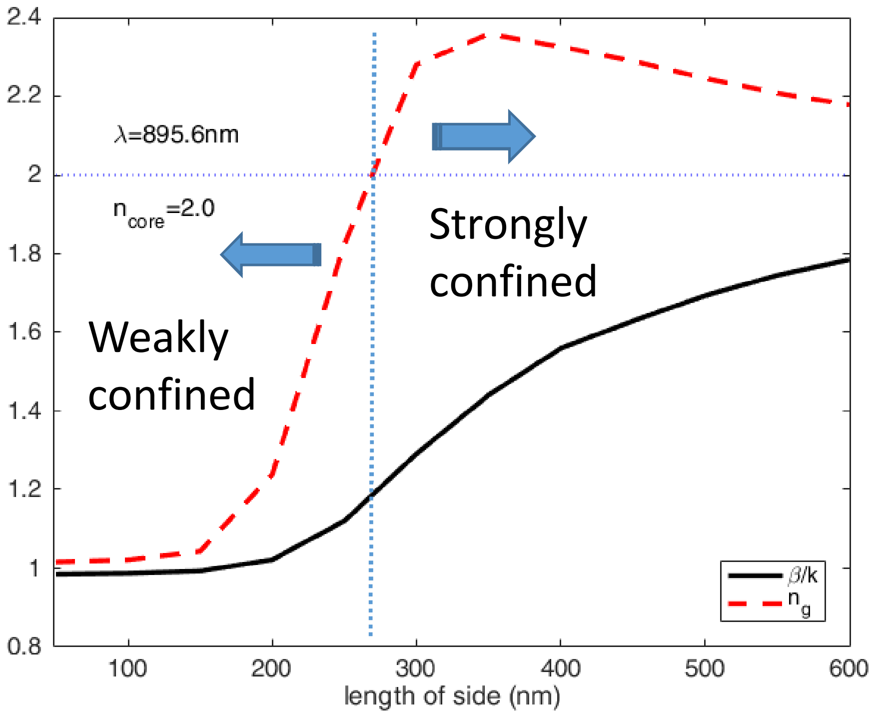
a=225nm

Spin squeezing on a square nano waveguide platform using Faraday interaction

- Square waveguides and their group index of refraction



TE mode components for d=400nm and 200nm



n_g of fundamental TE and TM modes