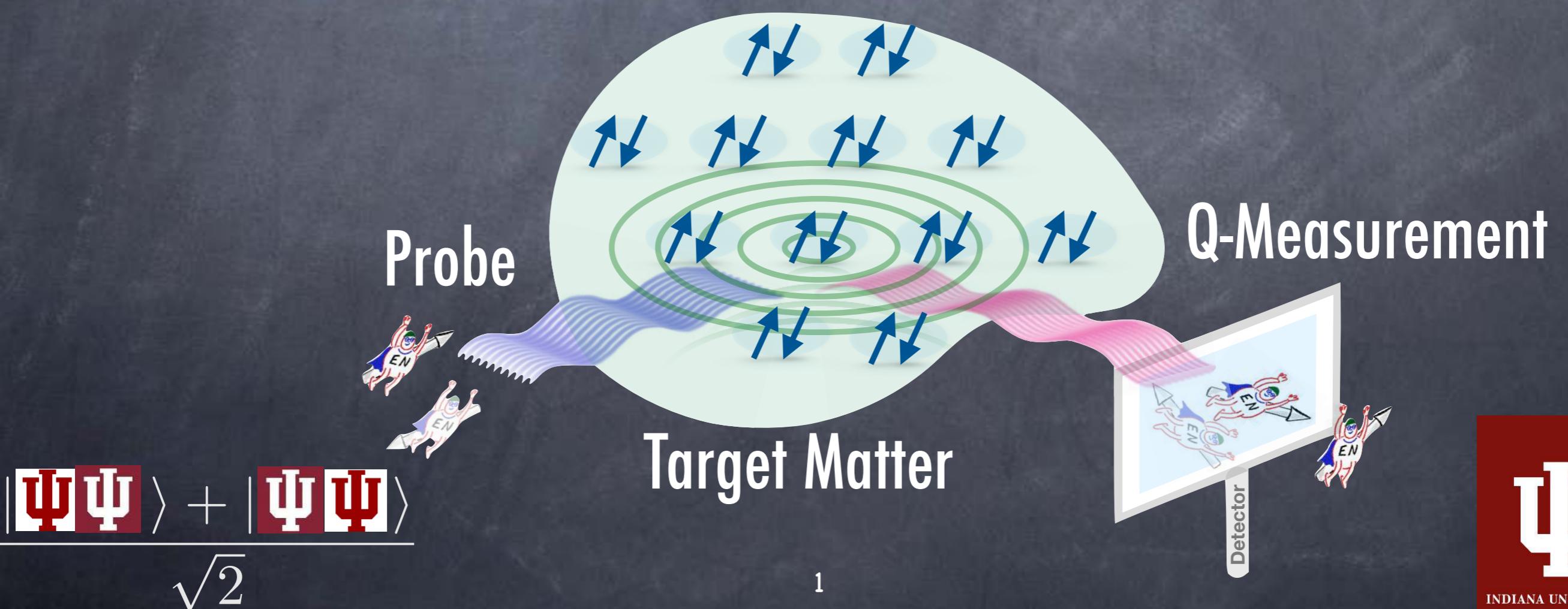


Fundamentals of Entangled Probes for Entangled Matter

Unveiling Correlations in Matter and Fundamental Physics Tests

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Indiana University Quantum Science and Engineering Center



Entangled Probes: What and Why?

We are interested in developing ways of learning about the intrinsic entanglement present in interesting states of matter, such as **frustrated magnets, unconventional superconductors, and topological matter**

Can we exploit entanglement in the **probe** to uncover entanglement in the **target** material?

What new information can one obtain?

Entangled Probes: What and Why?

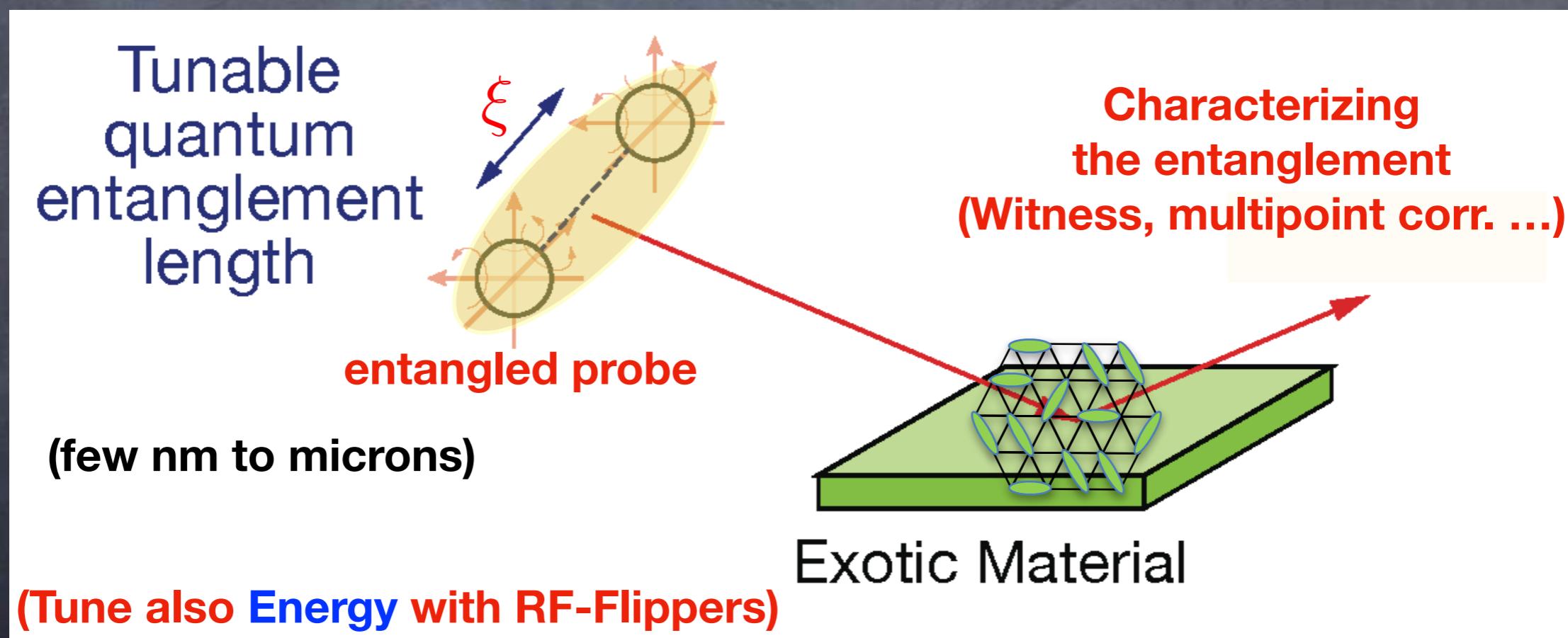
The quantum probe can be neutrons, photons, X-rays, electrons, atoms, quantum dots, and everything you are able to entangle

Control and manipulation of the probe's entanglement to unveil/sense hidden properties of matter and fundamental interactions:

Direct Probe of Multipartite Entanglement in Materials
Probe multipoint correlations in strongly coupled systems
Fundamental tests: Gravity-spin-couplings, time-reversal

Entangled Probes: What and Why?

The quantum probe can be neutrons, photons, X-rays, electrons, atoms, quantum dots, and everything you are able to entangle



Working Hypothesis

Coupling between matter and controlled probe's entanglement unveils “new correlation functions” or “hidden correlations”

For example:

“The ξ dependence of the cross section (correlation function) will exhibit enhancements for particular values of ξ .

These values of ξ correspond to spatial scales of entanglement in the sample of interest.”

Entangled Probes: Three modes of Op

- Interferometry and Development of Entanglement Witnesses
- Entangled-Probe Scattering (Weak measurement)
- Quantum-enhanced Metrology (Precision Measurement)

Relevant References:

Nature Commun. 11, 930 (2020)

Phys. Rev. A 101, 042318 (2020)

New J. Phys. 23, 083022 (2021)

Phys. Rev. Research 3, 023227 (2021)

Spin-textured neutron beams and OAM
arXiv:2207.12419 (2022)

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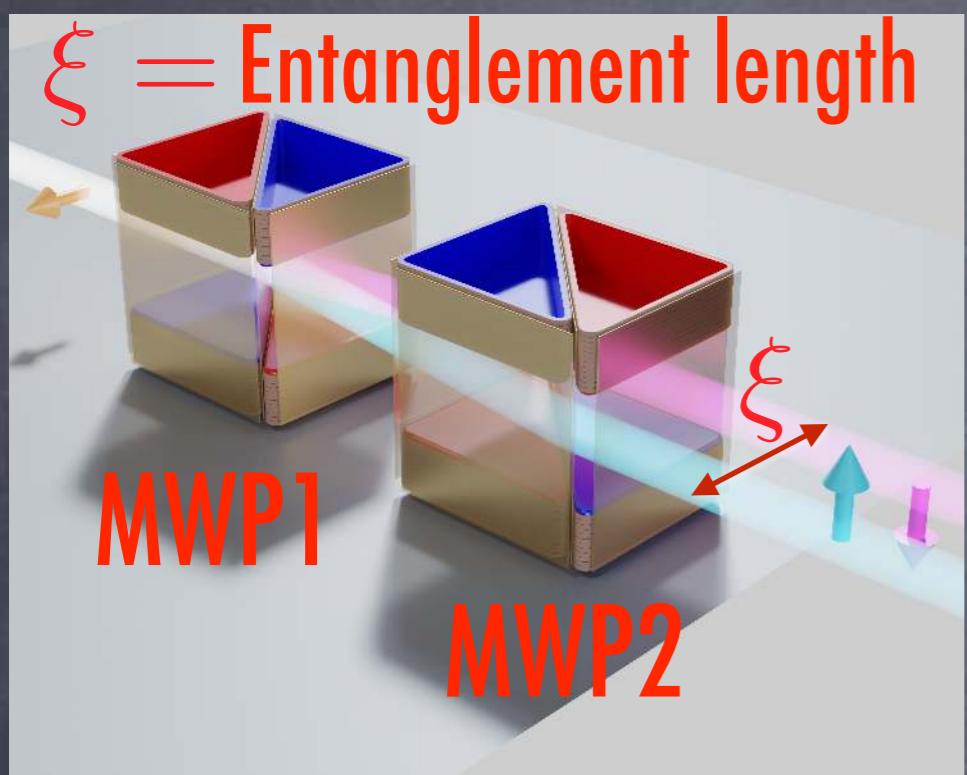


Creating Entangled Beams of Neutrons

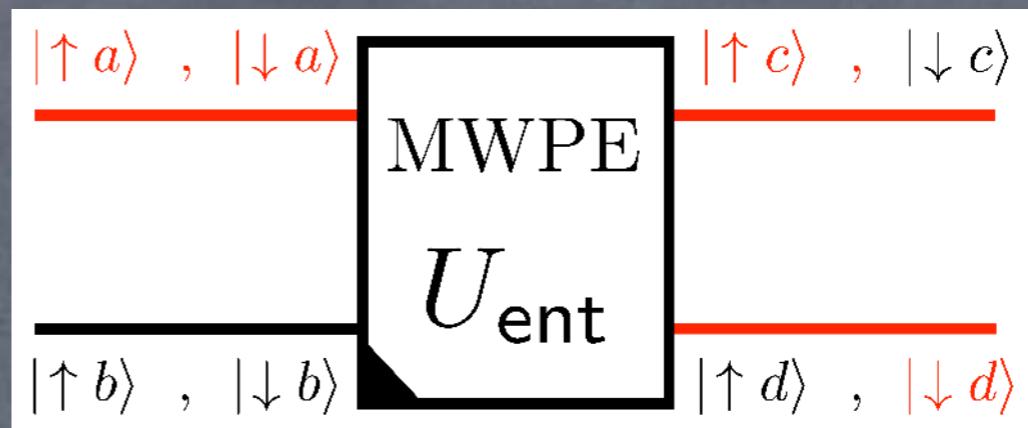
Neutron Entangler Devices

Magnetic Wollaston Prism (MWP): Polarizing Beam Splitter

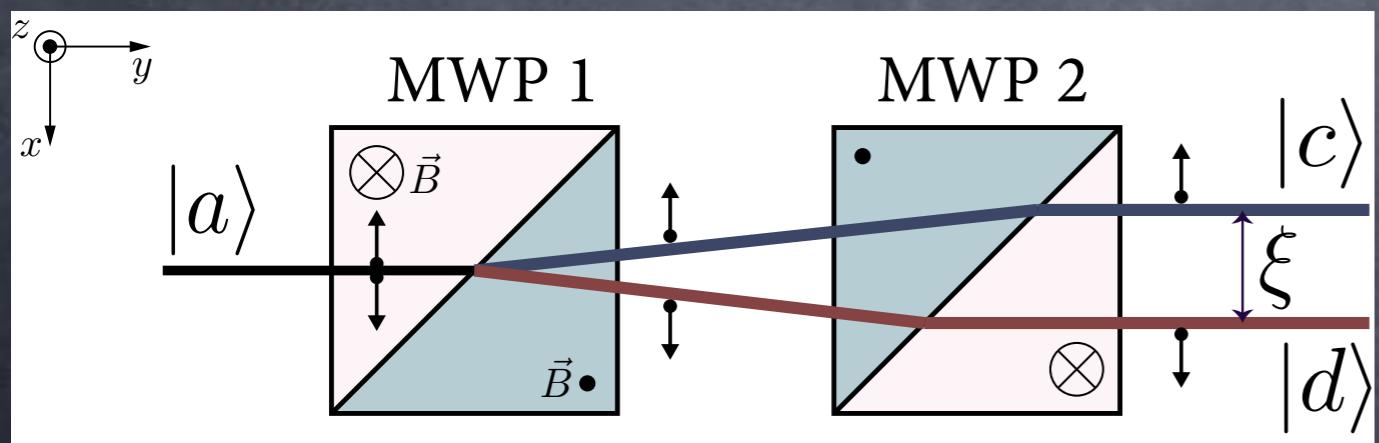
ξ = Entanglement length



Bi-Partite Mode-Entanglement



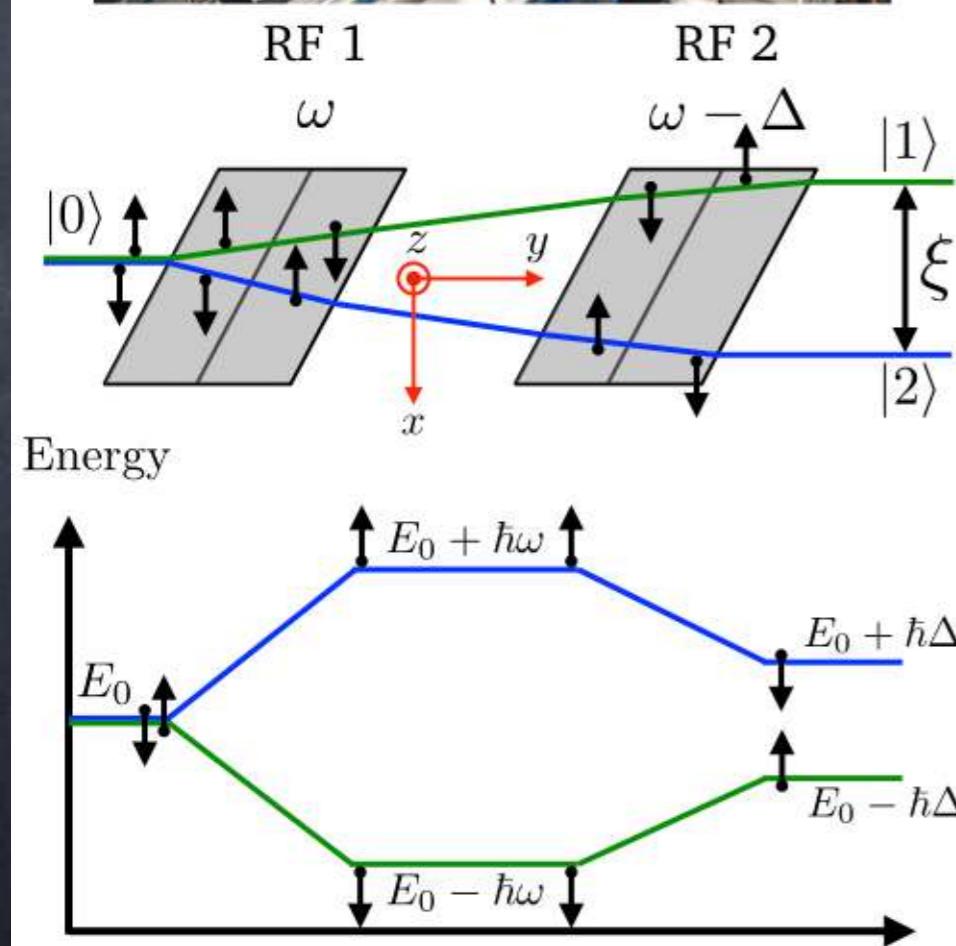
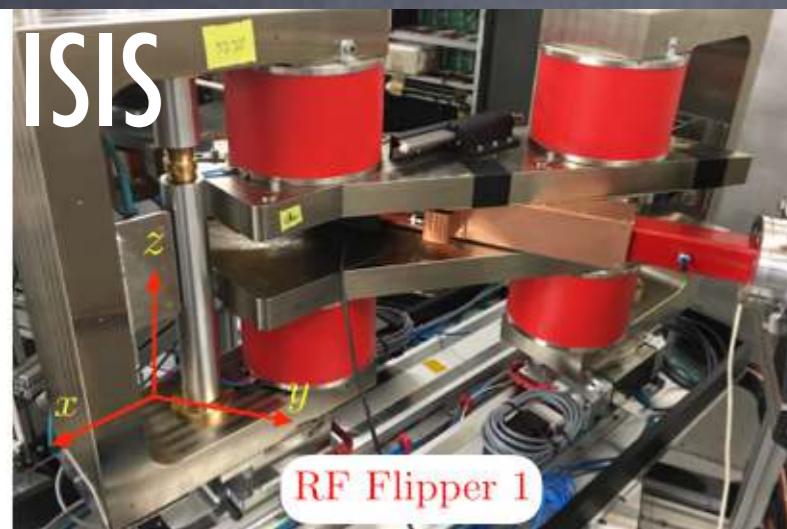
$$U_{\text{ent}} \frac{|\uparrow\rangle + |\downarrow\rangle}{\sqrt{2}} \otimes |a\rangle = e^{i\varphi} \frac{|\uparrow c\rangle + |\downarrow d\rangle}{\sqrt{2}} = |\psi_{\text{Bell}}\rangle$$



$$U_{\text{ent}} = \begin{pmatrix} e^{i\varphi} & 0 & 0 & 0 \\ 0 & e^{i\varphi} & 0 & 0 \\ 0 & 0 & 0 & -e^{-i3\varphi} \\ 0 & 0 & e^{i\varphi} & 0 \end{pmatrix}$$

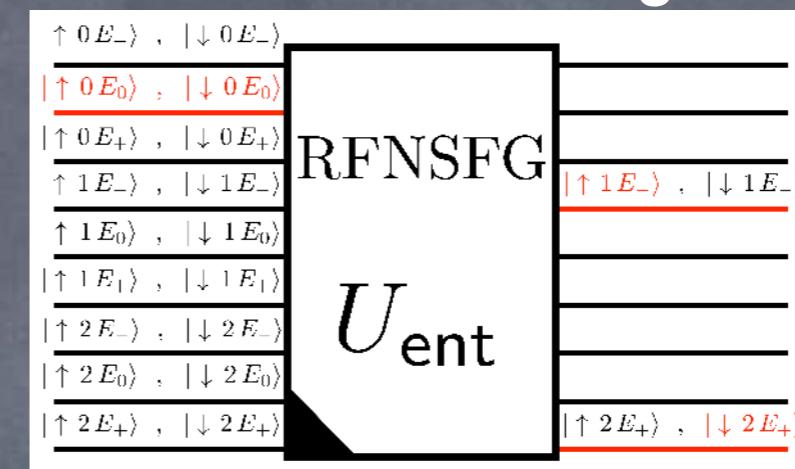
Neutron Entangler Devices

Radio Frequency (RF) Flipper



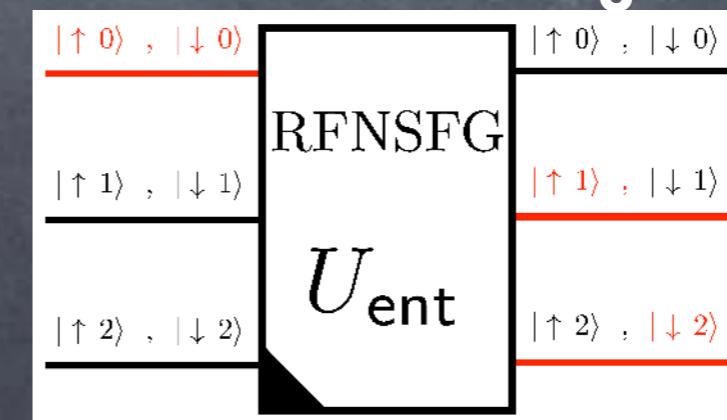
Quantum Information Language

Tri-Partite Mode-Entanglement



$$U_{\text{ent}} \frac{|\uparrow\rangle + |\downarrow\rangle}{\sqrt{2}} \otimes |0 E_0\rangle = \frac{|\uparrow 1 E_{-}\rangle + |\downarrow 2 E_{+}\rangle}{\sqrt{2}} = |\psi_{\text{GHZ}}\rangle$$

Bi-Partite Mode-Entanglement

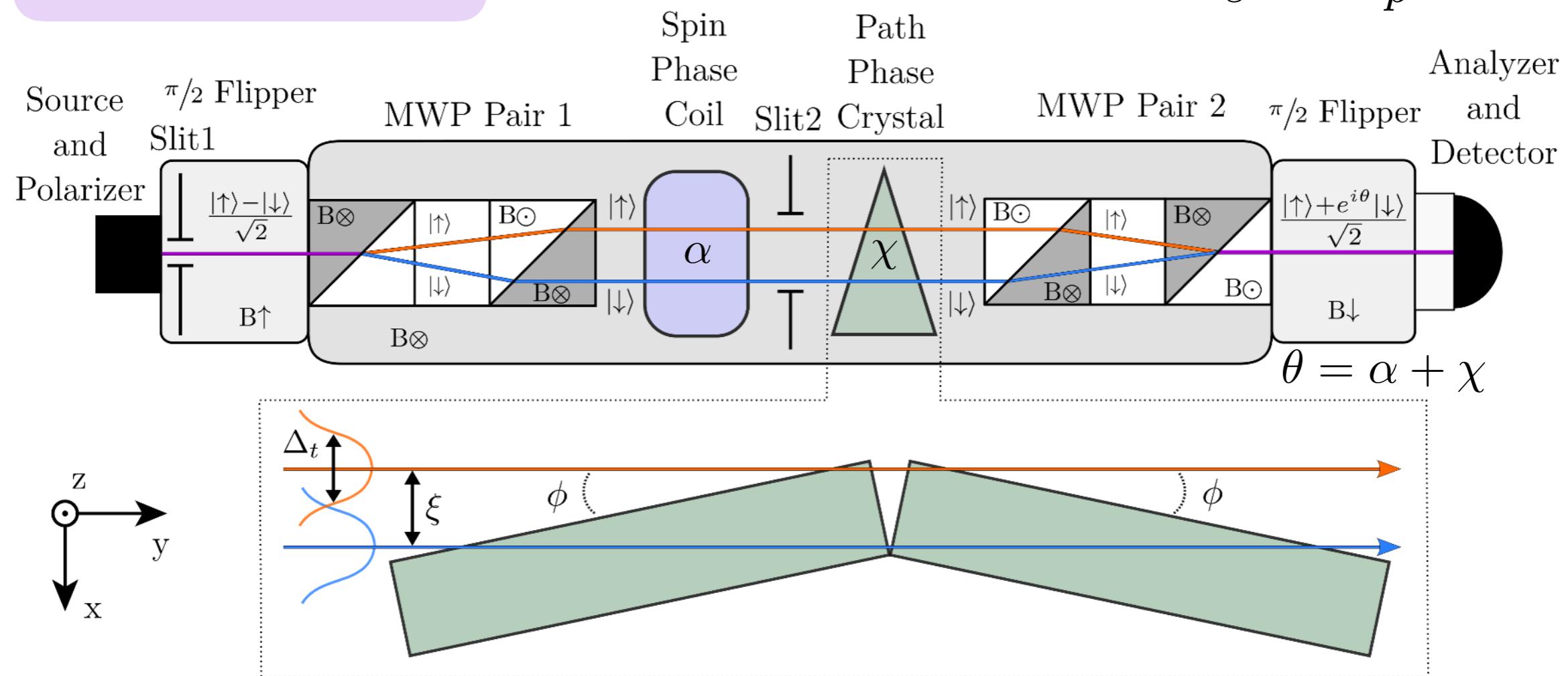


$$U_{\text{ent}} \frac{|\uparrow\rangle + |\downarrow\rangle}{\sqrt{2}} \otimes |0\rangle = \frac{|\uparrow 1\rangle + |\downarrow 2\rangle}{\sqrt{2}} = |\psi_{\text{Bell}}\rangle$$

Neutron Interferometers (NSE-type)

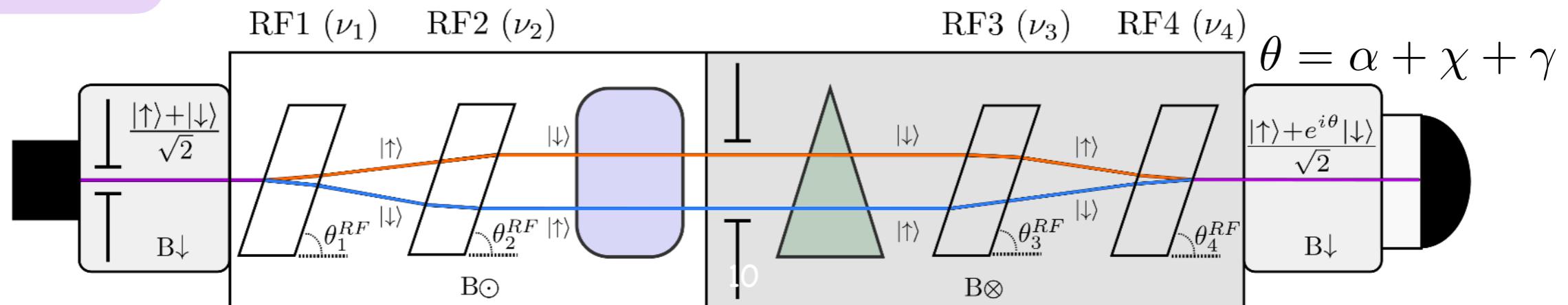
(a) Magnetic Wollaston Prism

$$\mathcal{H} = \mathcal{H}_s \otimes \mathcal{H}_p$$

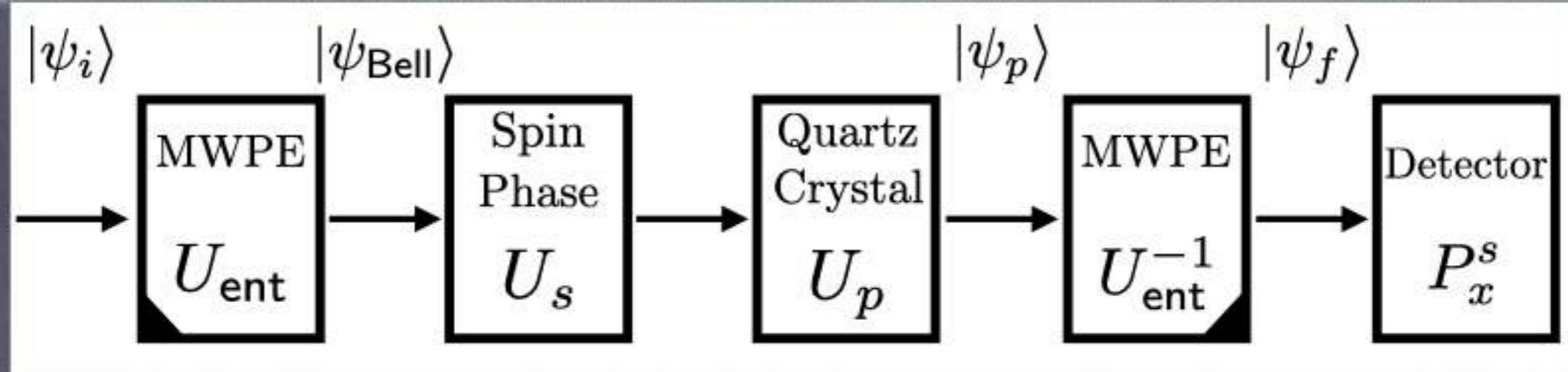


(b) RF Flipper

$$\mathcal{H} = \mathcal{H}_s \otimes \mathcal{H}_p \otimes \mathcal{H}_E$$



Neutron Quantum Optics



$$|\psi_i\rangle = \frac{|\uparrow\rangle + |\downarrow\rangle}{\sqrt{2}} \otimes |a\rangle$$

$$|\psi_{\text{Bell}}\rangle = U_{\text{ent}}|\psi_i\rangle = e^{i\varphi} \frac{|\uparrow c\rangle + |\downarrow d\rangle}{\sqrt{2}}$$

$$|\psi_p\rangle = U_p U_s |\psi_{\text{Bell}}\rangle = e^{i\varphi} \frac{|\uparrow c\rangle + e^{i(\alpha+\chi)} |\downarrow d\rangle}{\sqrt{2}}$$

$$|\psi_f\rangle = U_{\text{ent}}^{-1} |\psi_p\rangle = \frac{|\uparrow\rangle + e^{i(\alpha+\chi)} |\downarrow\rangle}{\sqrt{2}} \otimes |a\rangle$$

Bell and Mermin-type Inequalities

Define the CHSH witness:

$$S = E(\alpha_1, \chi_1) + E(\alpha_1, \chi_2) + E(\alpha_2, \chi_1) - E(\alpha_2, \chi_2)$$

$$E(\alpha, \chi) = \langle \psi_{\text{Bell}} | \sigma_{u(\alpha)}^s \sigma_{v(\chi)}^p | \psi_{\text{Bell}} \rangle$$

$$E(\alpha, \chi) = \frac{\sum_{\mu_s, \mu_p=0,1} (-1)^{\mu_s + \mu_p} N(\alpha + \mu_s \pi, \chi + \mu_p \pi)}{\sum_{\mu_s, \mu_p=0,1} N(\alpha + \mu_s \pi, \chi + \mu_p \pi)}$$

$$|S| \leq 2$$

Classical expectation

$$S_{\text{Bell}} = 2\sqrt{2}$$

Tsirelson bound

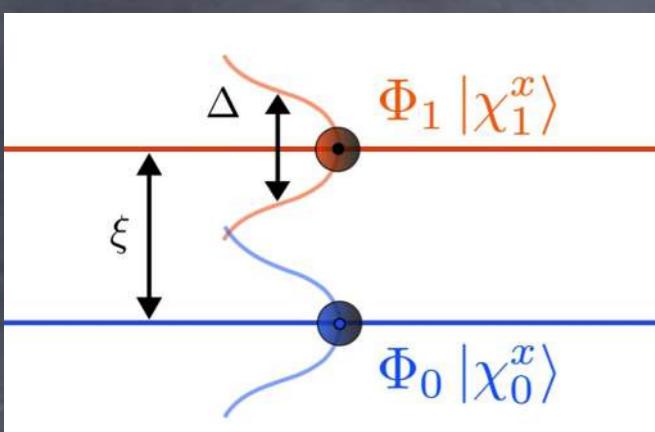
Bell and Mermin-type Inequalities

Define the Mermin witness:

$$M = E[\sigma_x^s \sigma_x^p \sigma_x^e] - E[\sigma_x^s \sigma_y^p \sigma_y^e] - E[\sigma_y^s \sigma_x^p \sigma_y^e] - E[\sigma_y^s \sigma_y^p \sigma_x^e]$$

$$|M| \leq 2$$

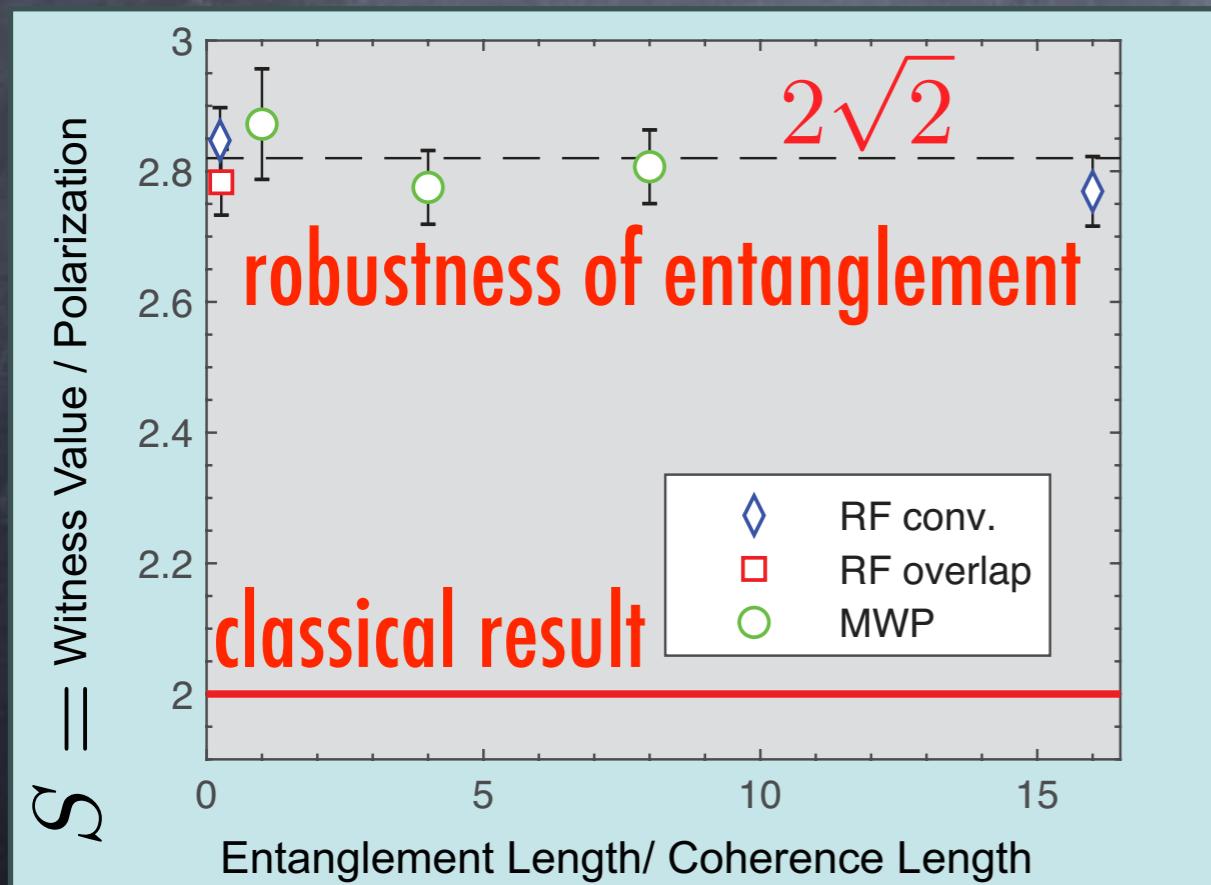
Experimental Results



Probe's Tunability:

$$\left\{ \begin{array}{l} \lambda_n \in \{3.5\text{\AA}, 7.5\text{\AA}\} \\ \Delta \in \{75\text{nm}, 600\text{nm}\} \\ \xi \in \{85\text{nm}, 1600\text{nm}\} \end{array} \right.$$

CHSH Bi-partite Entanglement

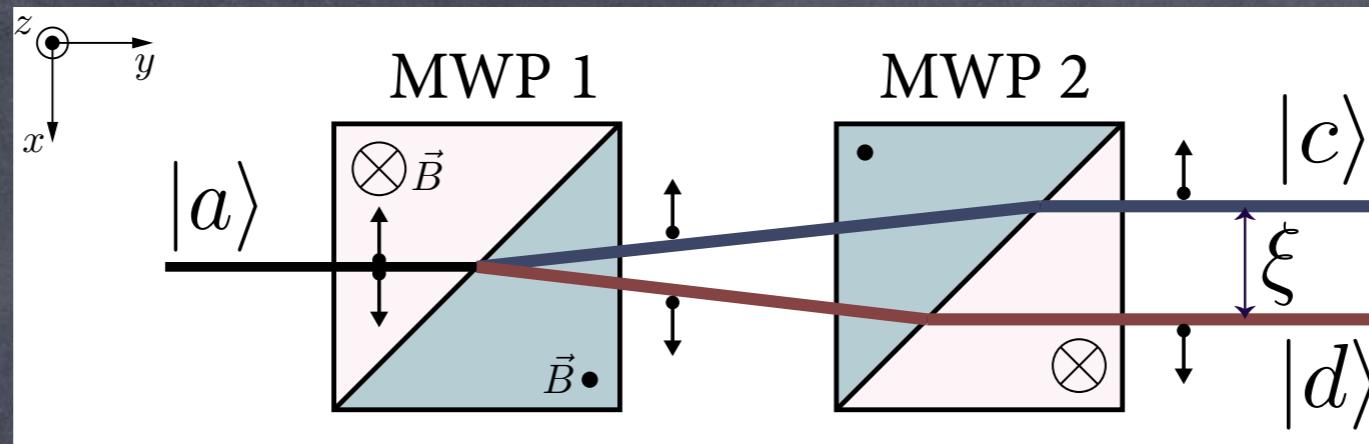


Mermin Tri-partite Entanglement

$$M/\text{Polarization} = 3.92 \pm 0.03$$

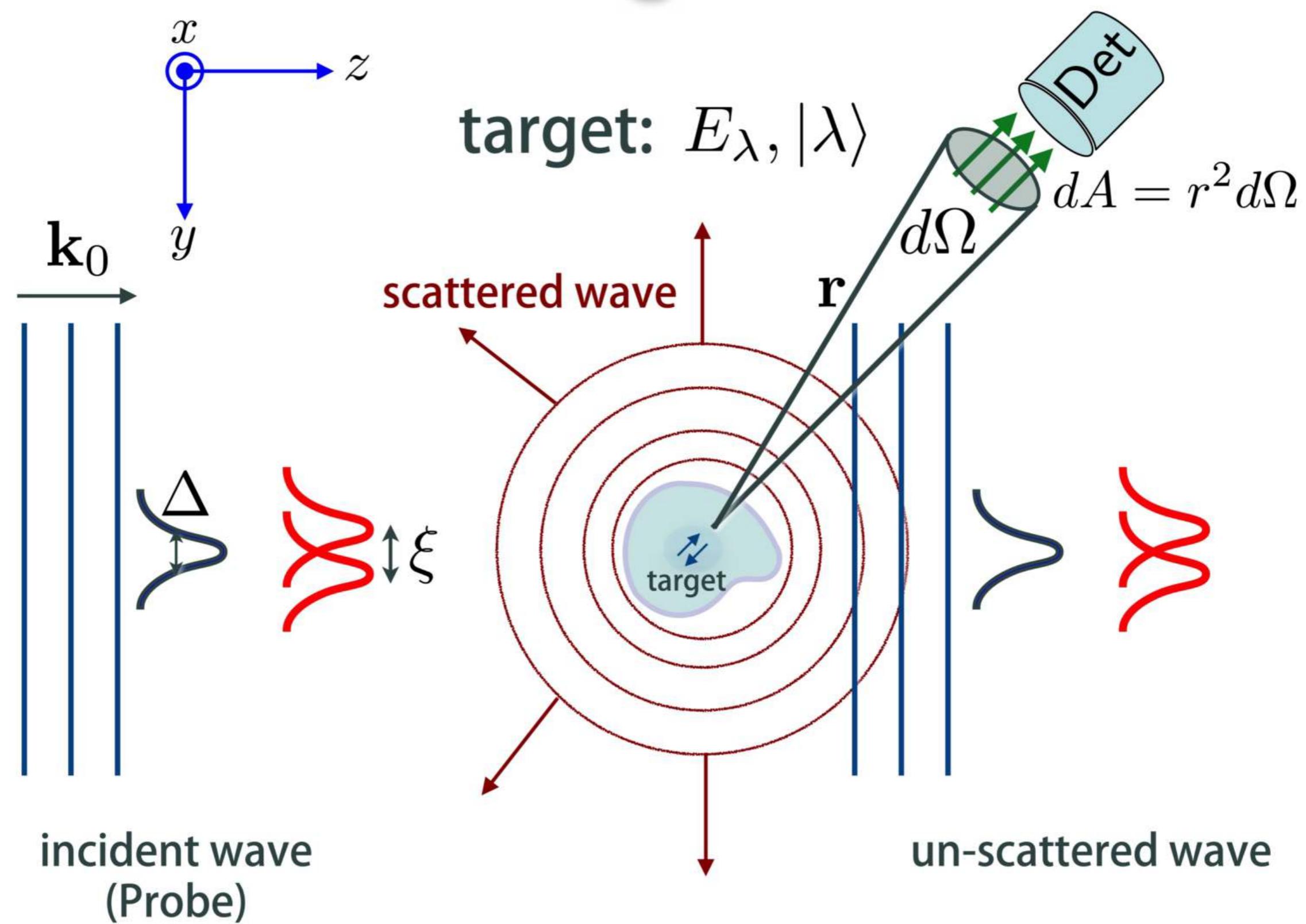
$$M_{\text{GHz}} = 4$$

Universal Probe for Q Materials!



What is it useful for?
Entangled-Probe Scattering
Extension of the Textbook theory of Scattering

Entangled-Probe Scattering Theory



T-Matrix Formalism: Magnetic Scattering

Hamiltonian of the probe-target system:

$$H = \hat{H}_p + \hat{H}_{\text{target}} + \hat{V}$$

$$\hat{V} = \gamma \mu_N \mu_B \sum_j \left[2 \hat{\sigma} \cdot \nabla \times \left(\frac{\hat{s}_j \times R_j}{|R_j|^3} \right) - \left(\hat{p}_j \cdot \frac{\hat{\sigma} \times R_j}{\hbar |R_j|^3} + \frac{\hat{\sigma} \times R_j}{\hbar |R_j|^3} \cdot \hat{p}_j \right) \right],$$

spin neutron
spin electron
momentum electron
position electron

↓
↓
↓
↓

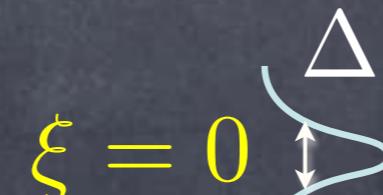
-1.913

Standard Unentangled-Probe Scattering: Van Hove theory

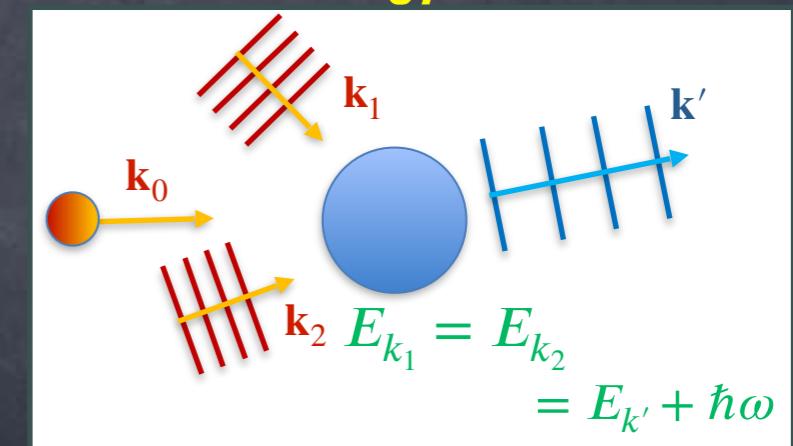
Probe's initial state: $\xi = 0$ $k \rightarrow$ $\frac{d^2\sigma}{d\Omega dE_{k'}} = r_0^2 \frac{k'}{k} S(k - k', \omega)$; $r_0 = \frac{\gamma e^2}{m_e c^2}$

↑ Magnetic structure factor
↓ Momentum transfer
↓ Energy transfer

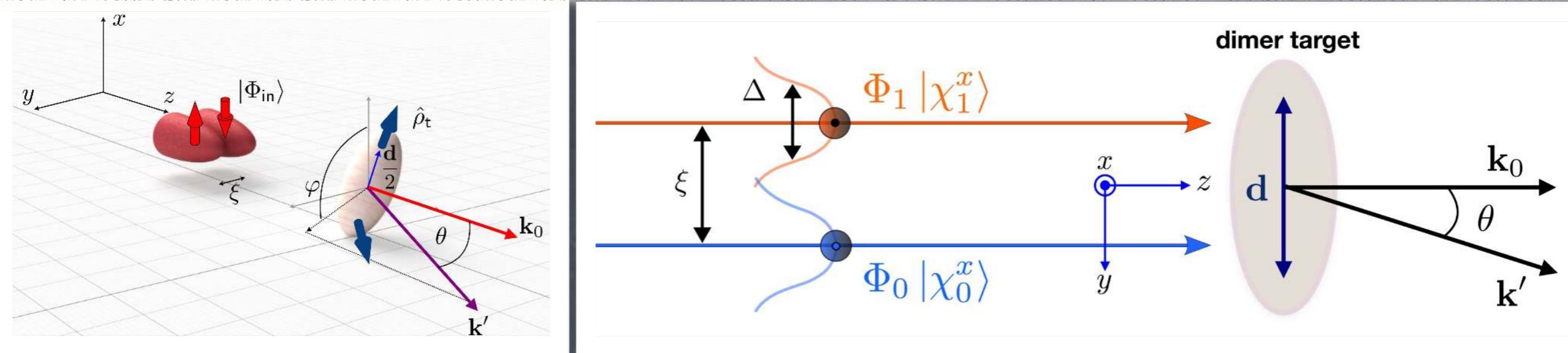
Had we used wave packet initial state:

$$\xi = 0$$


$$\frac{d^2\sigma}{d\Omega dE_{k'}} \sim \int dk_1 dk_2 S(k_1 - k', k_2 - k', \omega)$$



(Mode) Entangled Magnetic Scattering



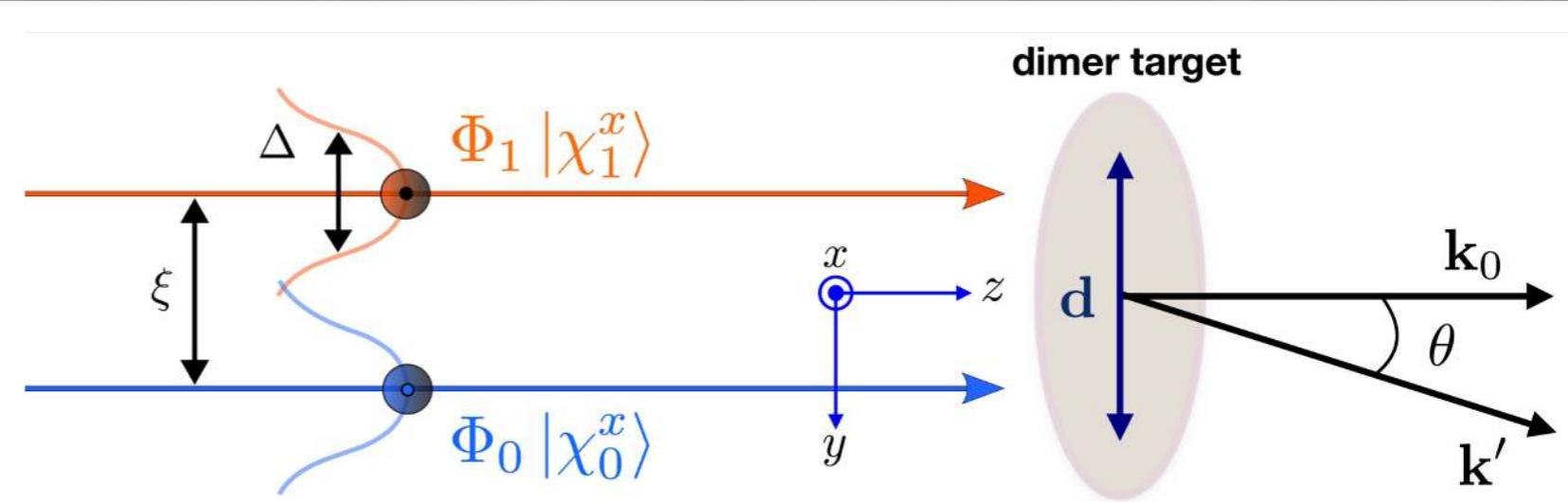
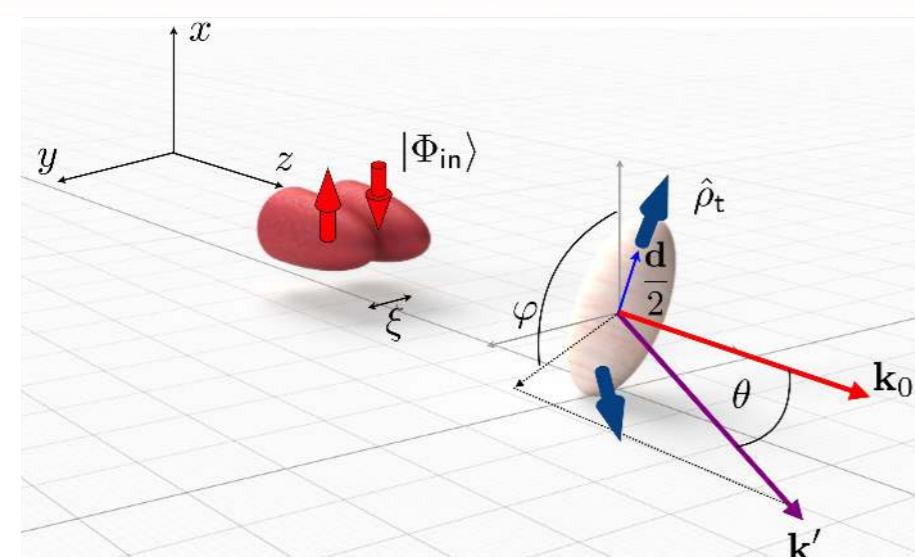
(Probe) Initial State: We use (spin-path) entangled wave packets

$$\Phi_{in}(\mathbf{r}, t_0) = \frac{\Phi_0(\mathbf{r}, t_0)|\chi_0^\alpha\rangle + \Phi_1(\mathbf{r}, t_0)|\chi_1^\alpha\rangle}{\sqrt{2}}, \quad (\text{Spin quantization}) \quad \alpha = x, y, z$$

spin states

$$\Phi_{in}(\mathbf{r}, t_0) = \int d\mathbf{k} \ g_\Delta(\mathbf{k}) e^{i\mathbf{k}\cdot\mathbf{r} - i\omega t} \frac{e^{-i\mathbf{k}\cdot\frac{\xi}{2}}|\chi_0^\alpha\rangle + e^{i\mathbf{k}\cdot\frac{\xi}{2}}|\chi_1^\alpha\rangle}{\sqrt{2}}$$

(Mode) Entangled Magnetic Scattering



(Probe) Initial State: We use (spin-path) entangled wave packets

$$\Phi_{\text{in}}(\mathbf{r}, t_0) = \frac{\Phi_0(\mathbf{r}, t_0)|\chi_0^\alpha\rangle + \Phi_1(\mathbf{r}, t_0)|\chi_1^\alpha\rangle}{\sqrt{2}}, \quad (\text{Spin quantization}) \quad \alpha = x, y, z$$

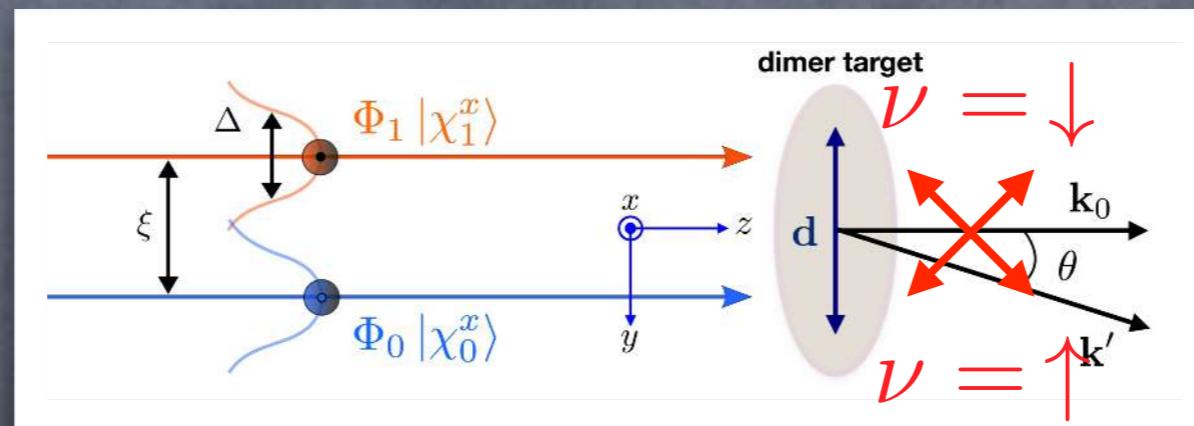
$$\Phi_{\text{in}}(\mathbf{r}, t_0) = \int d\mathbf{k} \ g_\Delta(\mathbf{k}) e^{i\mathbf{k}\cdot\mathbf{r} - i\omega t} \frac{e^{-i\mathbf{k}\cdot\frac{\xi}{2}}|\chi_0^\alpha\rangle + e^{i\mathbf{k}\cdot\frac{\xi}{2}}|\chi_1^\alpha\rangle}{\sqrt{2}}$$

$$|\chi_{\mathbf{k}\cdot\xi}\rangle = \frac{e^{-i\mathbf{k}\cdot\frac{\xi}{2}}|\chi_0^\alpha\rangle + e^{i\mathbf{k}\cdot\frac{\xi}{2}}|\chi_1^\alpha\rangle}{\sqrt{2}}$$

Entangled Magnetic Scattering

$$S(\kappa_1, \kappa_2, \omega) = \frac{1}{2} \sum_{\nu, \nu' = 0, 1} e^{i \frac{(-1)^\nu \mathbf{k}_1 \cdot \boldsymbol{\xi} - (-1)^{\nu'} \mathbf{k}_2 \cdot \boldsymbol{\xi}}{2}} S_{\nu\nu'}(\kappa_1, \kappa_2, \omega),$$

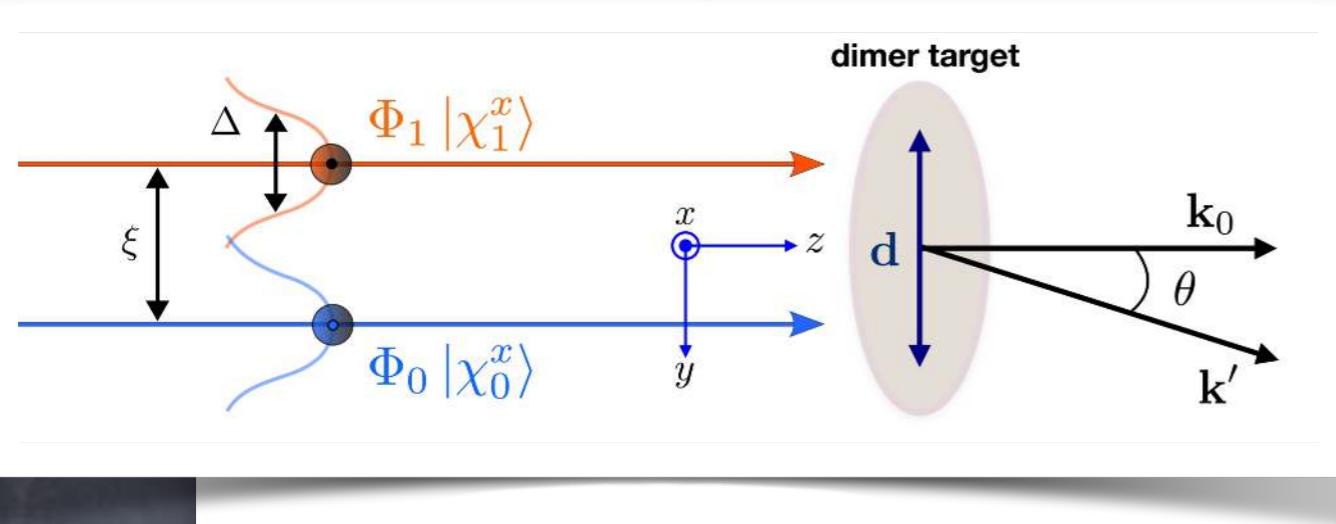
\downarrow \downarrow \downarrow
 $\kappa_{1,2} = \mathbf{k}_{1,2} - \mathbf{k}'$ spin entanglement length spin-components of neutron



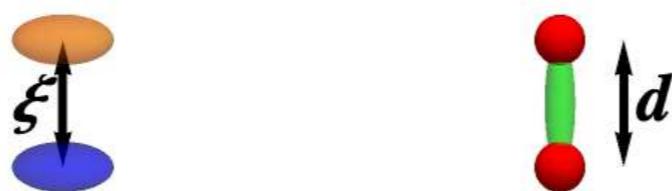
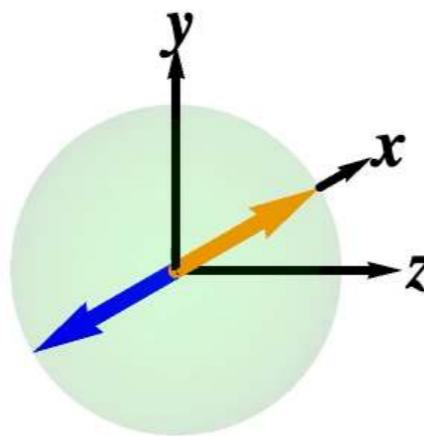
$$S_{\nu\nu'}(\kappa_1, \kappa_2, \omega) \quad \nu \neq \nu'$$

Interference Terms Between Wave Packets

Dimer Scattering and Q-Erasure

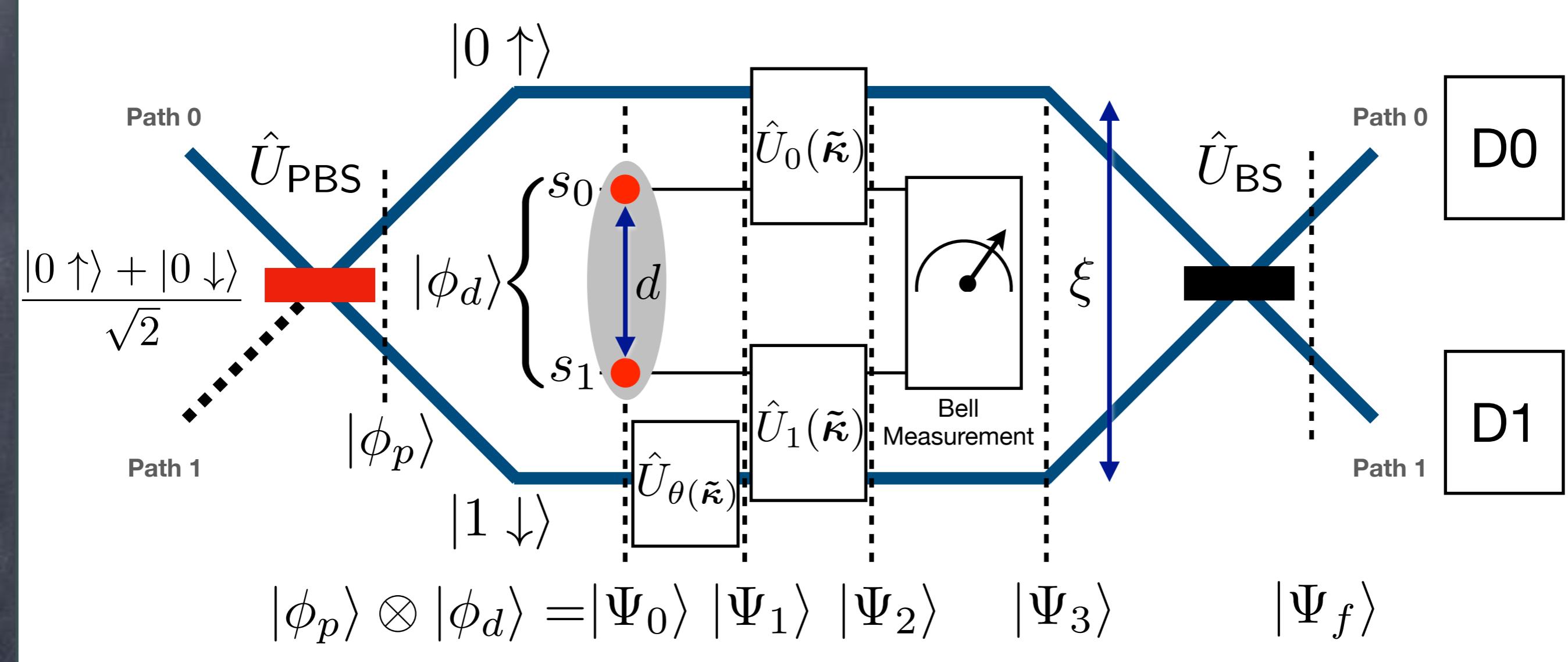


$$|d_{\perp}| \approx \xi$$

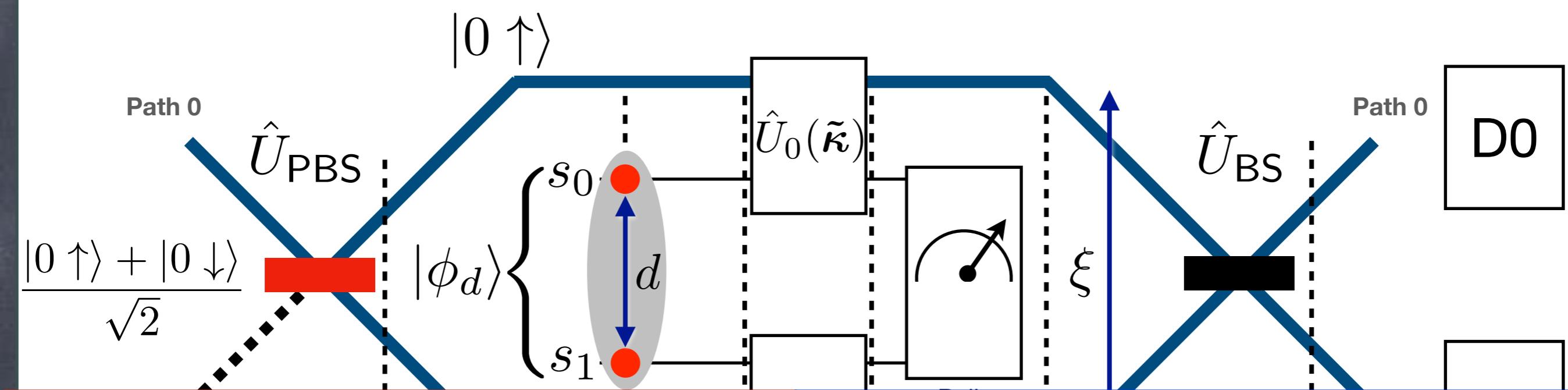


$|\uparrow\uparrow\rangle$

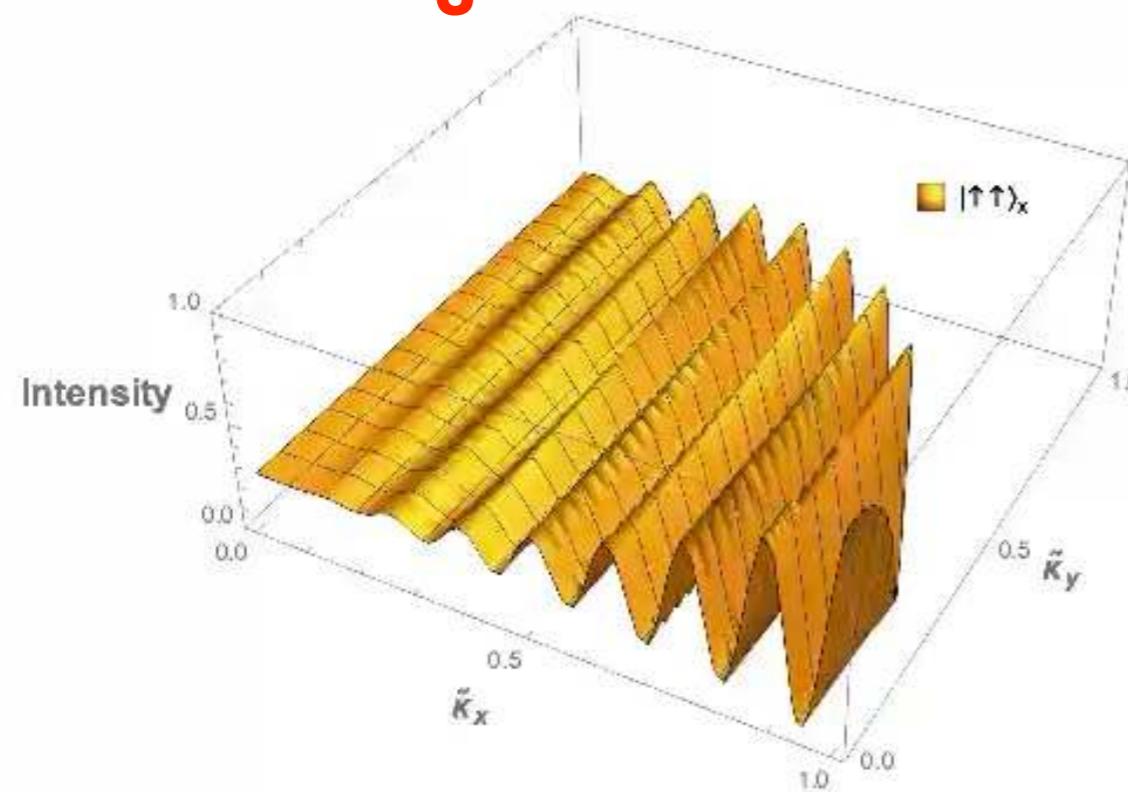
Interferometric Analogue of Entangled Scattering



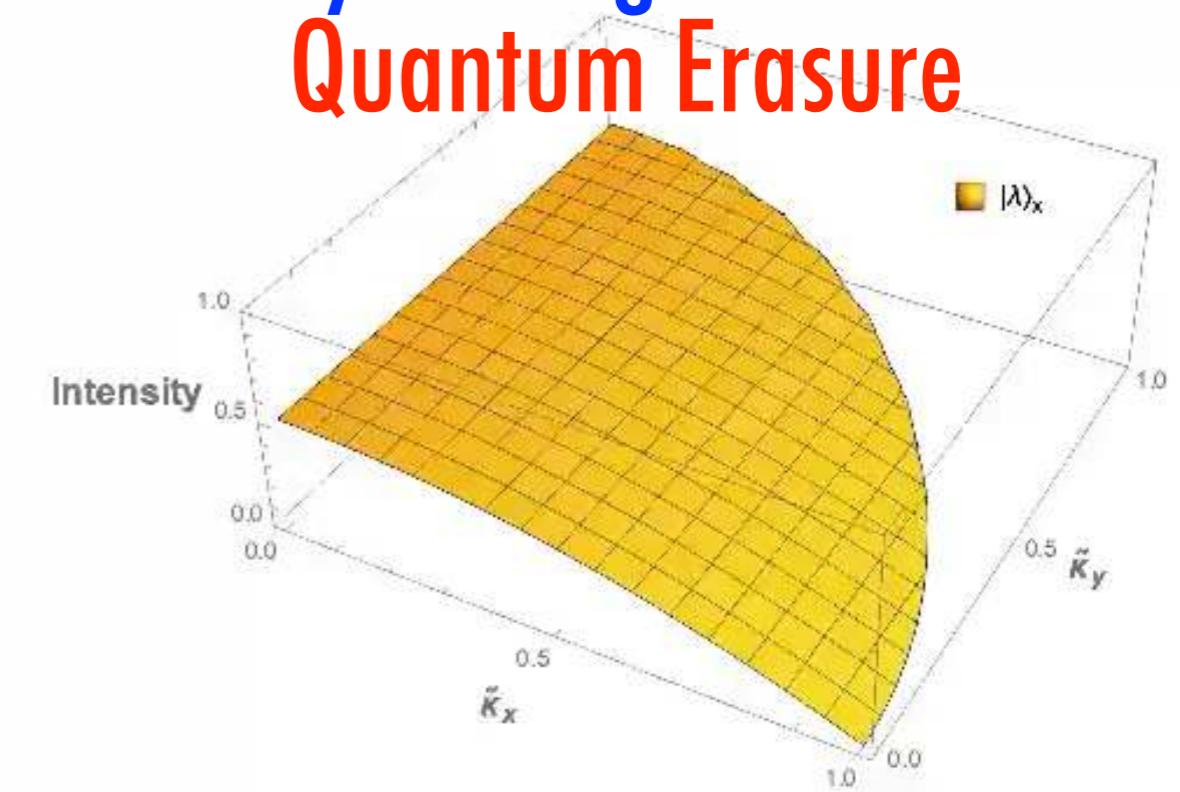
Interferometric Analogue of Entangled Scattering



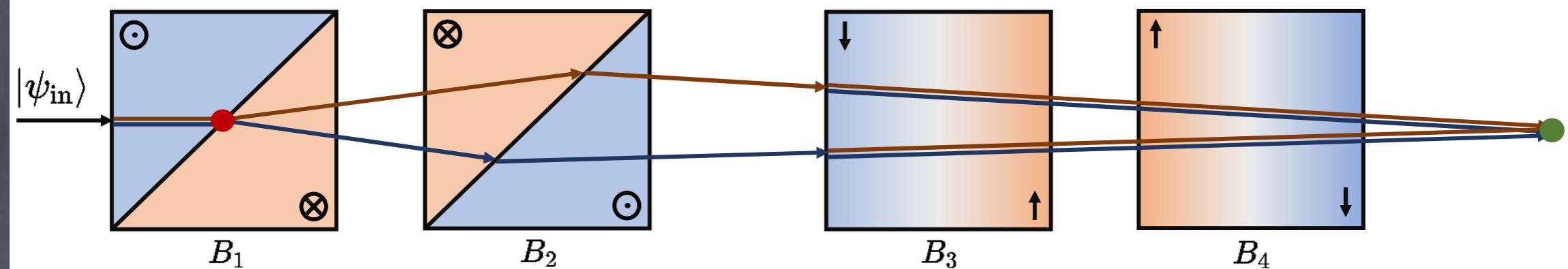
Un-Entangled Dimer States



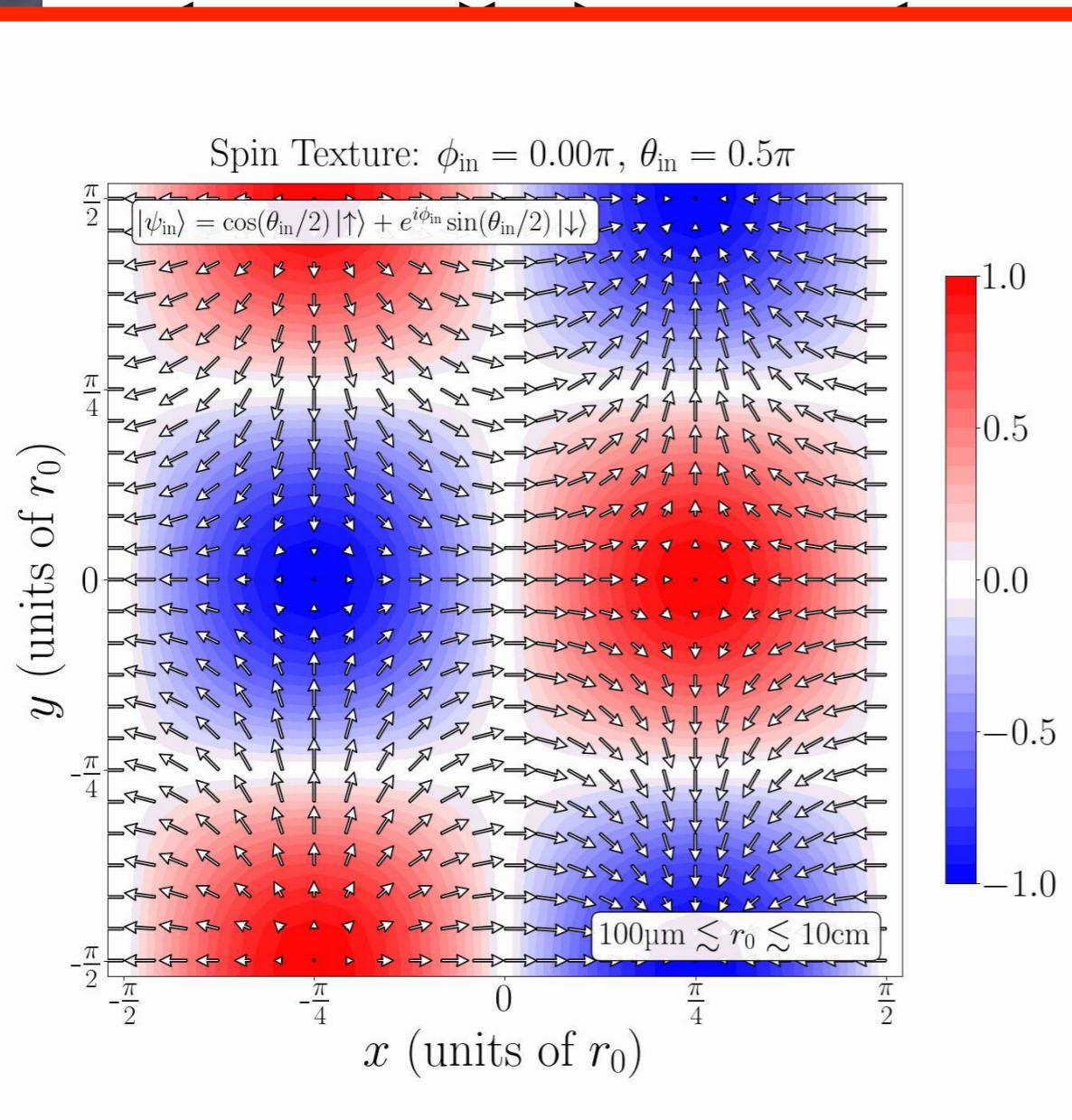
Maximally Entangled Dimer States
Quantum Erasure



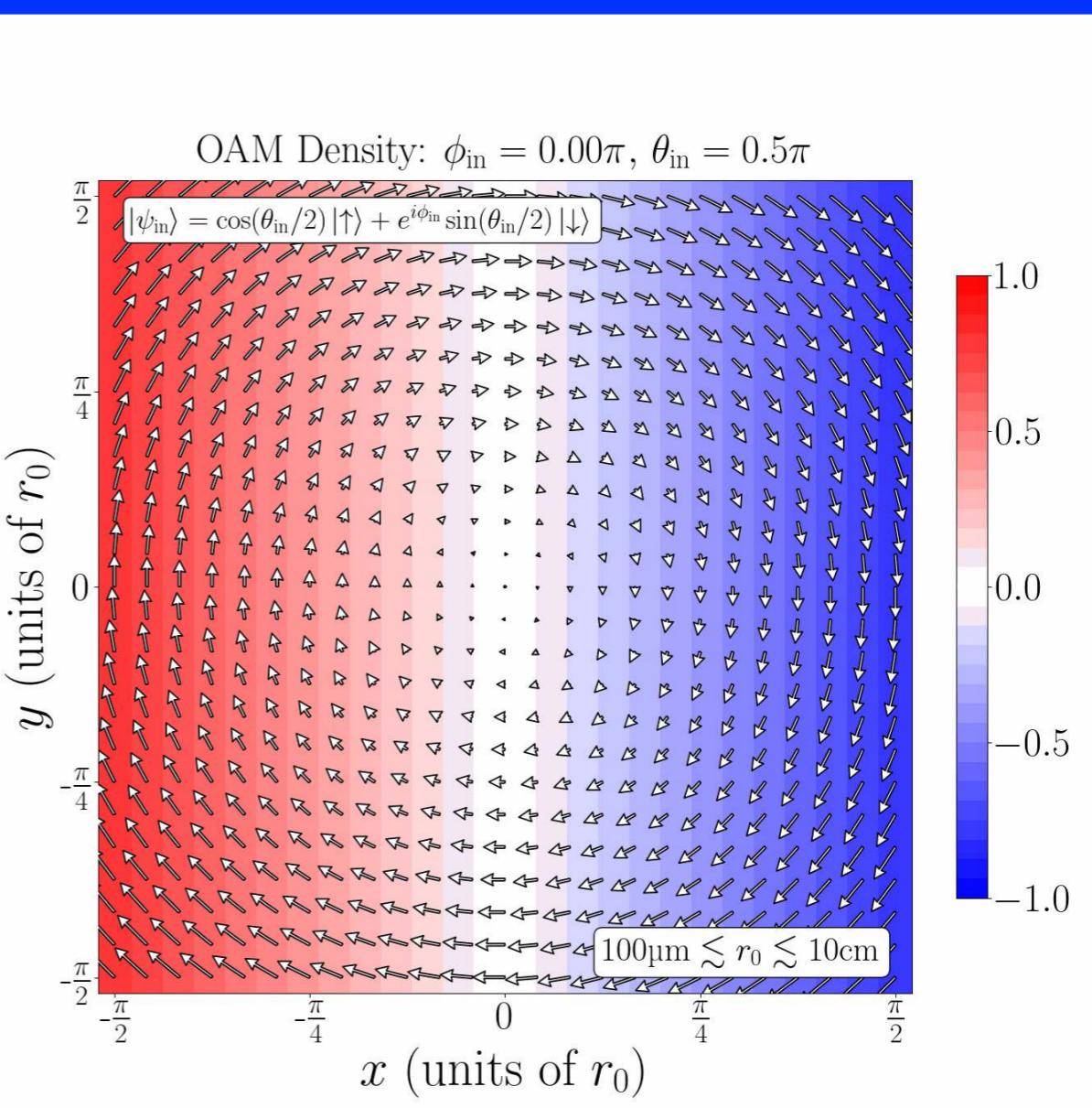
Spin-Textured Neutron Beams (OAM)



Spin Texture: $\phi_{\text{in}} = 0.00\pi, \theta_{\text{in}} = 0.5\pi$



OAM Density: $\phi_{\text{in}} = 0.00\pi, \theta_{\text{in}} = 0.5\pi$



Take-Home Messages

- Habemus universal quantum-entangled neutron probe
- Habemus a scattering theory for entangled beams

Quantum Erasure is a general phenomenon
for Maximally-Entangled N-spin systems

Immediate Future

- ⦿ OAM Experiment (November, ORNL)
- ⦿ Scattering/Interfer. theory for Spin textured-beams
- ⦿ Theory of the Entangled-Goos-Hanschen effect (reflectometry)
- ⦿ Measuring the coherence length of a single neutron
- ⦿ Frustrated quantum magnets with quantum spin-liquid ($D=2$ **NiGa₂S₄**, $D=3$ NaCa**Ni₂F₇**, Herbert Smithite), chiral, VBC, and RVB phases. Unconventional superconductors, Flat-band, and Topological quantum matter



THANK YOU

