TEL AVIV UNIVERSITY
Pursuing the Unknown

Synthetic Magnetism in Nonlinear Optics

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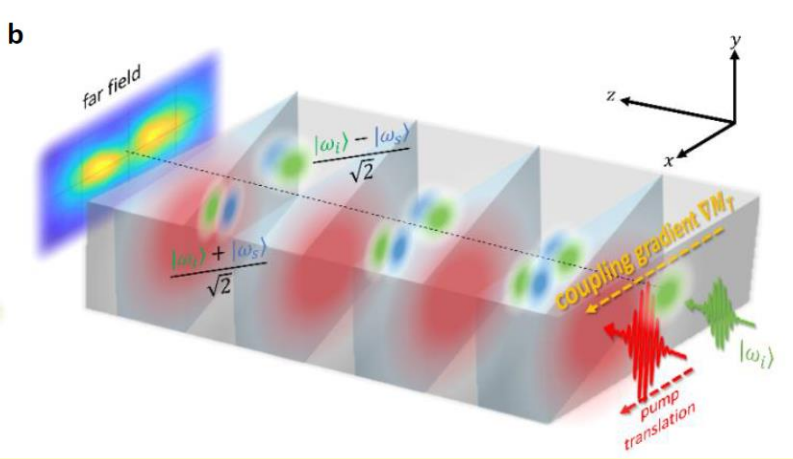
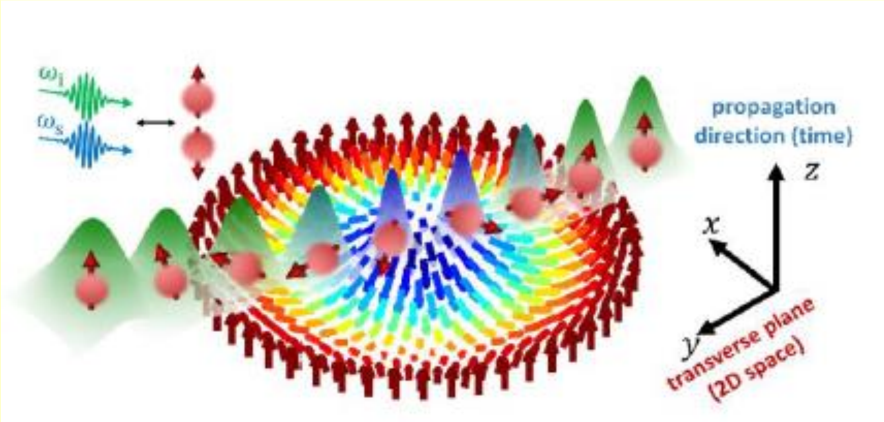




Spice workshop on Spin Textures: Magnetism meets Plasmonics
July 2024

Outline

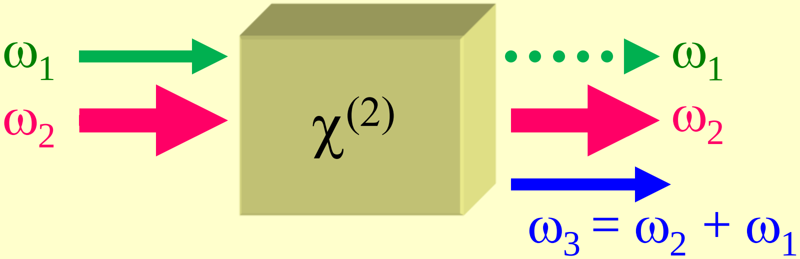
- Sum frequency generation as a two-level system
    - Rabi oscillations
    - Adiabatic frequency conversion
    - Adiabatic geometric phase

- Pauli equation for diffracting beams and the all-optical Stern-Gerlach effect in space.

- The all-optical Stern-Gerlach effect in the time domain.

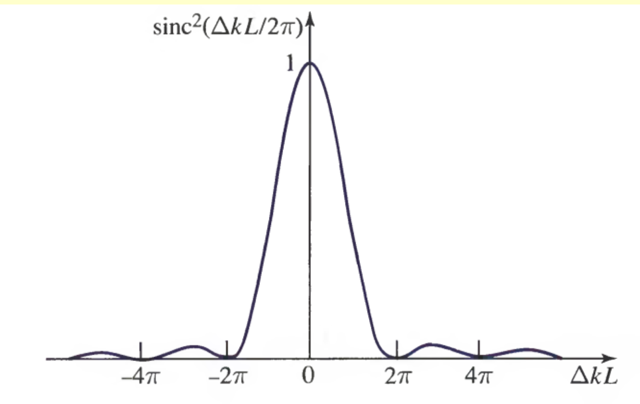
- Spintronic effects and devices in optics:
    - Anderson localization of the signal and idler in disordered nonlinear media
    - Spin valve – controlling the transmission and reflection of signal-idler in-phase beam with a pump beam
    - Spin waveguide – guiding of signal-idler in-phase beam
    - Skyrmionic nonlinear photonic crystals and the topological Hall effect for light

Sum Frequency Generation – textbook problem

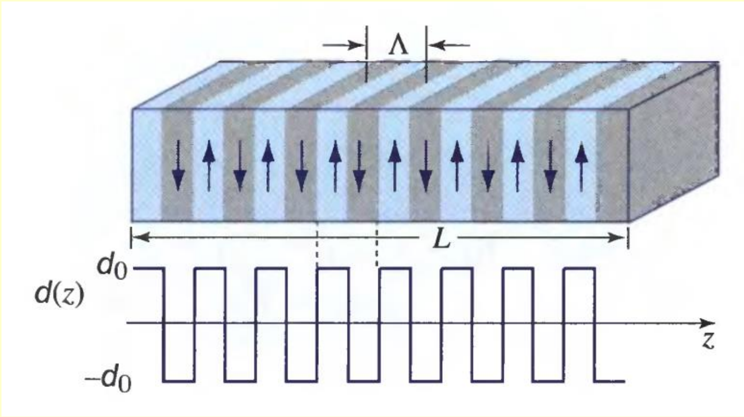


Energy conservation: $\omega_1+\omega_2=\omega_3$

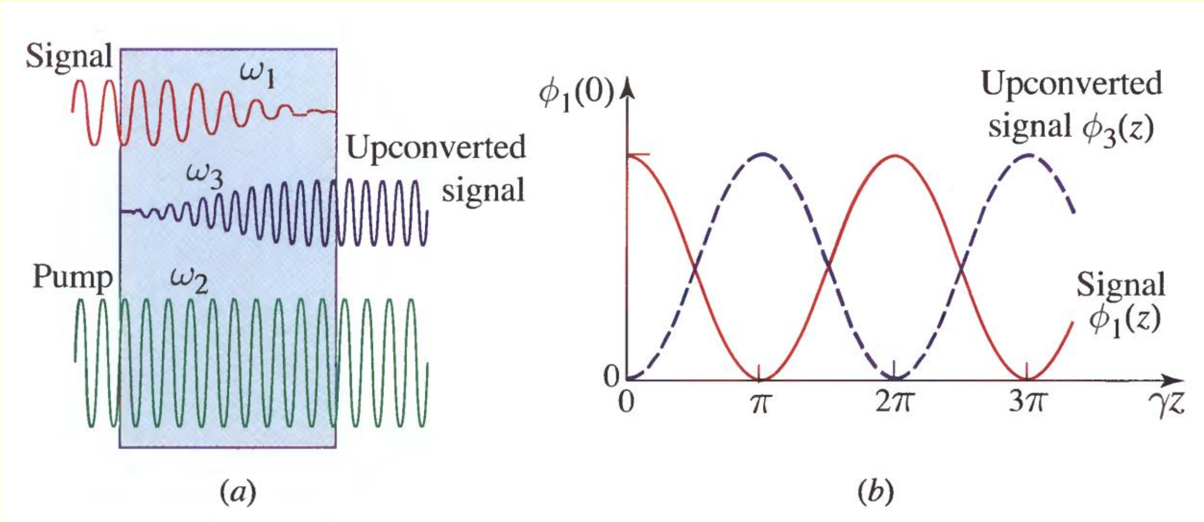
Momentum conservation: $k_1+k_2=k_3$



Quasi phase matching



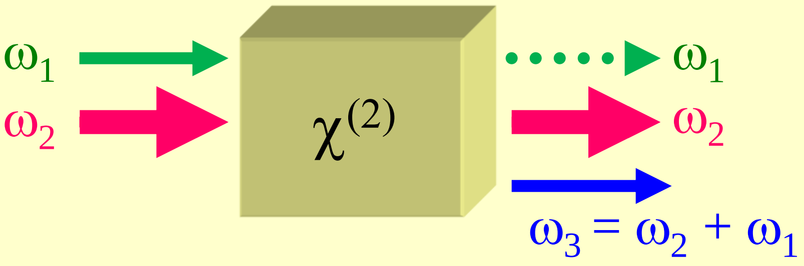
Signal and idler intensities vs. nonlinear coupling, for undepleted pump



Saleh and Teich, Fundamentals of Photonics

Sum Frequency Generation – a 2-mode system

Sum Frequency Generation with strong (un-depleted) pump



Assuming slowly varying amplitudes, we obtain a two-coupled-mode system:

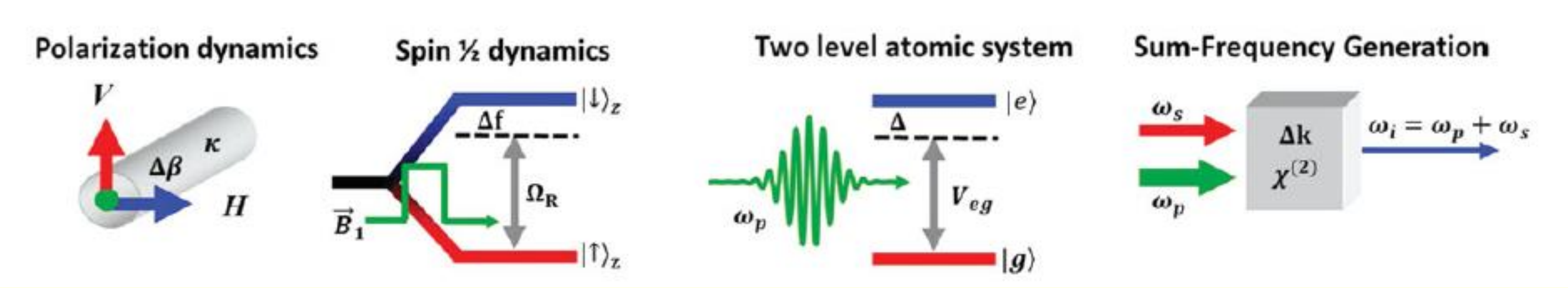
$$-i\frac{dA_1}{dz} = K_1 A_3 e^{-i\Delta kz}$$
$$-i\frac{dA_3}{dz} = K_3 A_1 e^{i\Delta kz}$$

$$\mathrm{A}_i \equiv \frac{A_i}{\sqrt{K_i}}$$

$$-i\frac{d\mathrm{A}_1}{dz} = \kappa \mathrm{A}_3 e^{-i\Delta kz}$$
$$-i\frac{d\mathrm{A}_3}{dz} = \kappa^* \mathrm{A}_1 e^{i\Delta kz}$$

R. W. Boyd, *Nonlinear Optics*, 2nd Edition (2003)

Examples of two-coupled-mode systems



Suchowski et al, *Lasers and Photonics Reviews* (2014)

One can utilize representation methods (e.g. Bloch sphere, eigenvalue diagram) and concepts (adiabatic following, geometric phase) developed in other disciplines for nonlinear optics.

Specifically, here we focus on **analogy with spin-1/2 in magnetic field.**

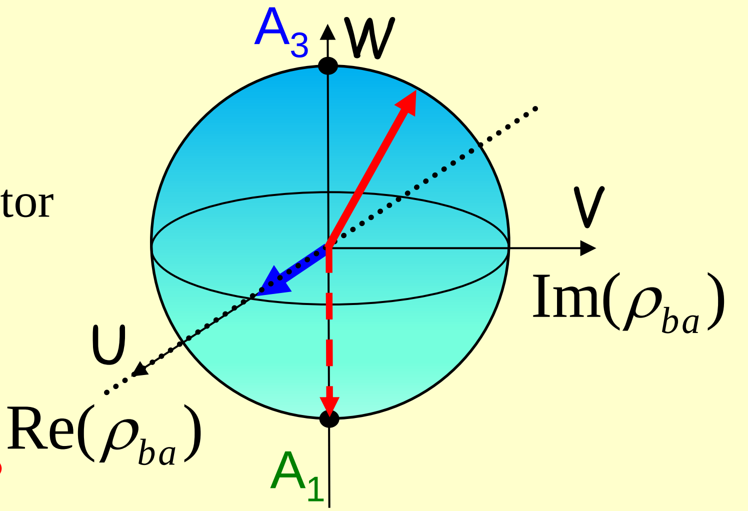
SFG representation with Bloch sphere

All the possible states can be represented using a sphere, whose coordinates are determined the complex amplitudes A_1 and A_3

$U_{SFG} = A_1^* A_3 + A_3^* A_1$ Real coherence operator

$V_{SFG} = i(A_1^* A_3 - A_3^* A_1)$ Imaginary coherence operator

$W_{SFG} = |A_3|^2 - |A_1|^2$ "Excitation" operator



Torque or "magnetic field" vector

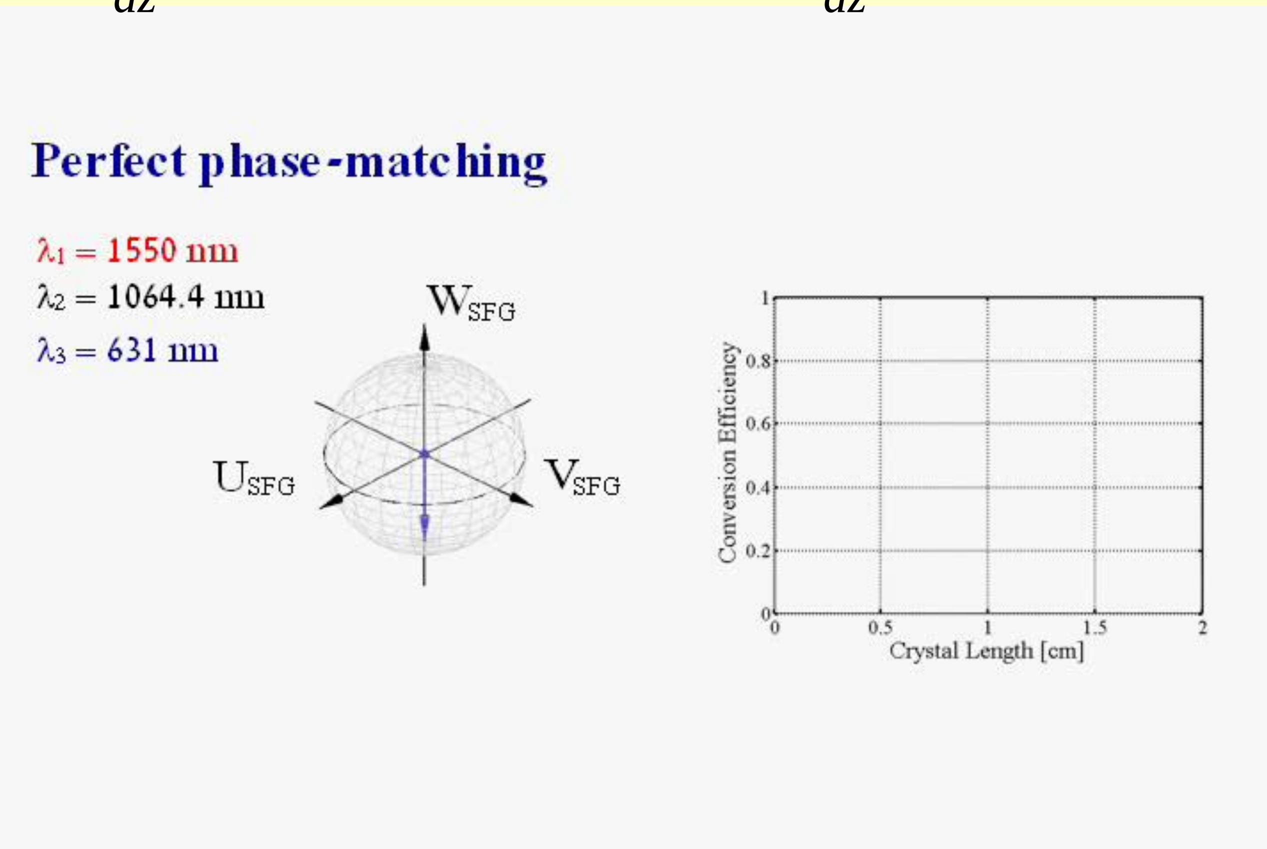
B= $\sqrt{\kappa^2 + \Delta k^2}$; $\vec{B} = [\mathrm{Re}(\kappa), \mathrm{Im}(\kappa), \Delta k]$

System dynamics:

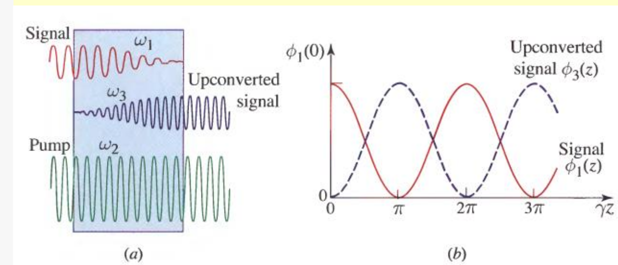
$$\frac{d\vec{\rho}_{SFG}}{dz} = \vec{B} \times \vec{\rho}_{SFG}$$

Constant phase mismatch (Δk=0)

$$-i\frac{dA_1}{dz} = \kappa A_3 e^{-i\Delta k z}, \quad -i\frac{dA_3}{dz} = \kappa^* A_1 e^{i\Delta k z} \xrightarrow{\Delta k = 0} -i\frac{dA_1}{dz} = \kappa A_3, \quad -i\frac{dA_3}{dz} = \kappa^* A_1 \xrightarrow{Solution} \left|A_3(z)\right|^2 = \cos^2(\kappa z), \quad \left|A_1(z)\right|^2 = \sin^2(\kappa z)$$



$$\vec{B} = [\mathrm{Re}(\kappa), \mathrm{Im}(\kappa), 0]$$



Manifestation of **Rabi Oscillations** in nonlinear optics

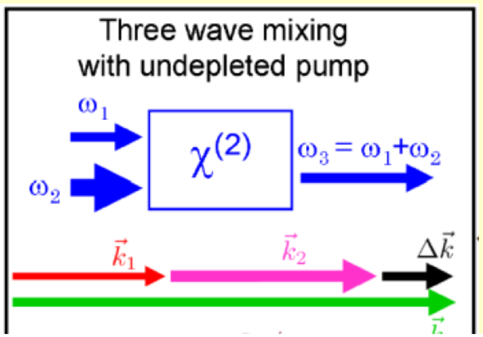
SFG analogy with atomic two-level system

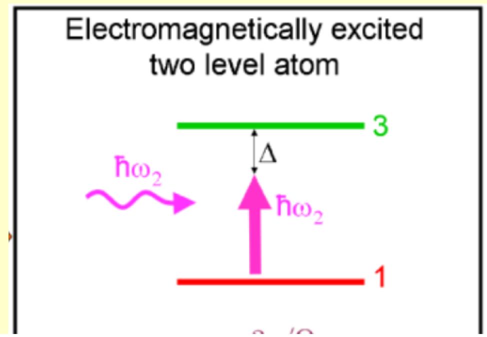
Dynamics of SFG Process

$$i\begin{pmatrix}\dot{A}_1(z)\\ \dot{A}_3(z)\end{pmatrix}=\frac{1}{2}\begin{pmatrix}0 & \kappa^* e^{i\Delta kz}\\ \kappa e^{-i\Delta kz} & 0\end{pmatrix}\begin{pmatrix}A_1(z)\\ A_3(z)\end{pmatrix}$$

Dynamics of atomic two level system

$$i\hbar\begin{pmatrix}\dot{c}_a(t)\\ \dot{c}_b(t)\end{pmatrix}=\frac{\hbar}{2}\begin{pmatrix}0 & \Omega_0^* e^{i\Delta t}\\ \Omega_0 e^{-i\Delta t} & 0\end{pmatrix}\begin{pmatrix}c_a(t)\\ c_b(t)\end{pmatrix}$$



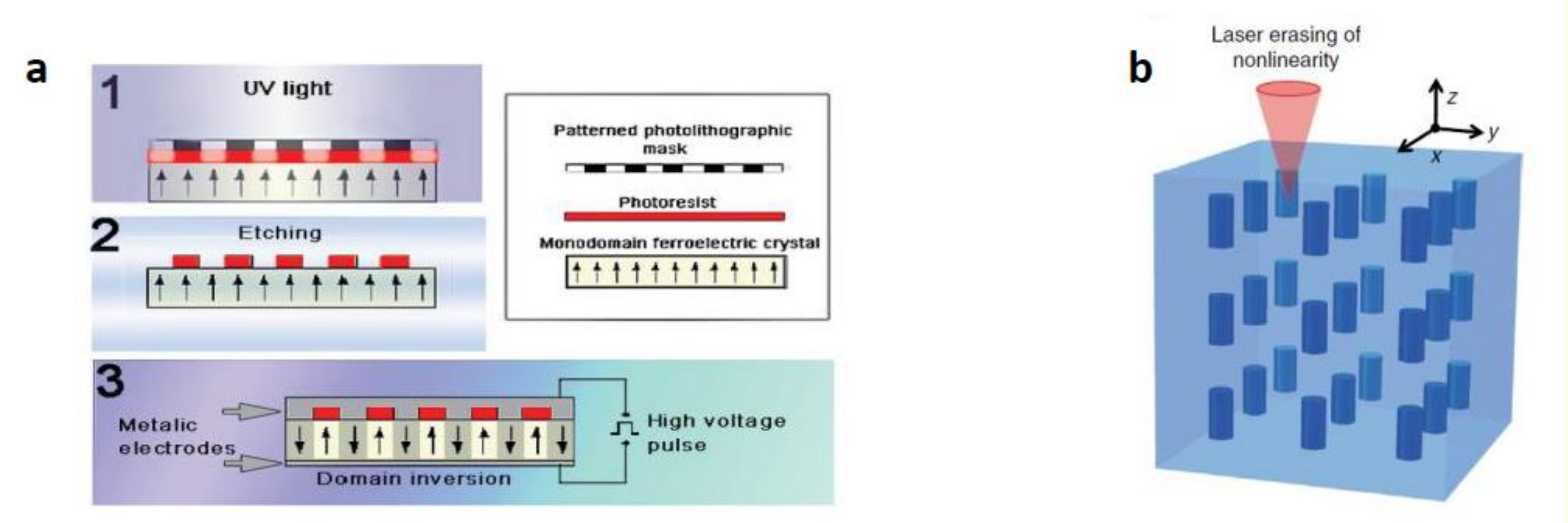


Parameter	Optical Bloch sphere	SFG sphere realization
Evolution parameter	time	z axis
Ground/excited state population	$\lvert a_g\rvert^2, \lvert a_e\rvert^2$	$\lvert A_1\rvert^2, \lvert A_3\rvert^2$
Energy difference	$\omega_0 = \omega_{fg}$	$n(\omega_2)\omega_2/c$
Detuning/phase mismatch	Δ	Δk
"Rabi" frequency	$\Omega_0 = \frac{1}{\hbar}\mu E_{in}$	$\kappa = \frac{4\pi w_1 w_3}{(k_1 k_3)^{1/2} c^2}\chi^{(2)} E_2$
Torque vector	$\Omega = (\mathrm{Re}\{\Omega_0\}, \mathrm{Im}\{\Omega_0\}, \Delta)$	$g = (\mathrm{Re}\{\kappa\}, \mathrm{Im}\{\kappa\}, \Delta k)$
State vector—ρ	$(\mathrm{Re}\{a_f^* a_g\}, \mathrm{Im}\{a_f^* a_g\}, \lvert a_f\rvert^2 - \lvert a_g\rvert^2)$	$(\mathrm{Re}\{A_3^* A_1\}, \mathrm{Im}\{A_3^* A_1\}, \lvert A_3\rvert^2 - \lvert A_1\rvert^2)$

How to structure nonlinear crystals?

1D/2D E field poling

Laser induced poling (allows 3D modulation)



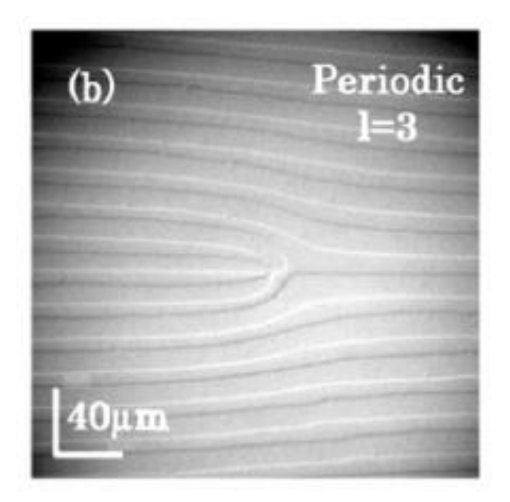
Poling periods: 3-40 μm (state of the art: 0.317 μm).

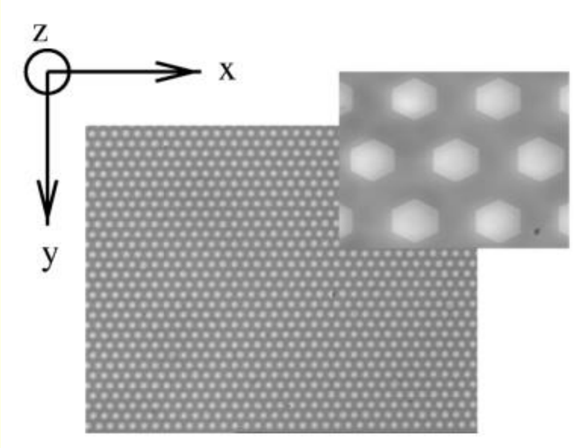
Crystal thickness: 1 mm (state of the art: 10 mm).

A. Arie and N. Voloch, Laser Photon. Rev. 4, 355 (2010)
Y. Zhang, Y. Sheng, S. Zhu, M. Xiao, and W. Krolikowski, Optica 8, 372 (2021).

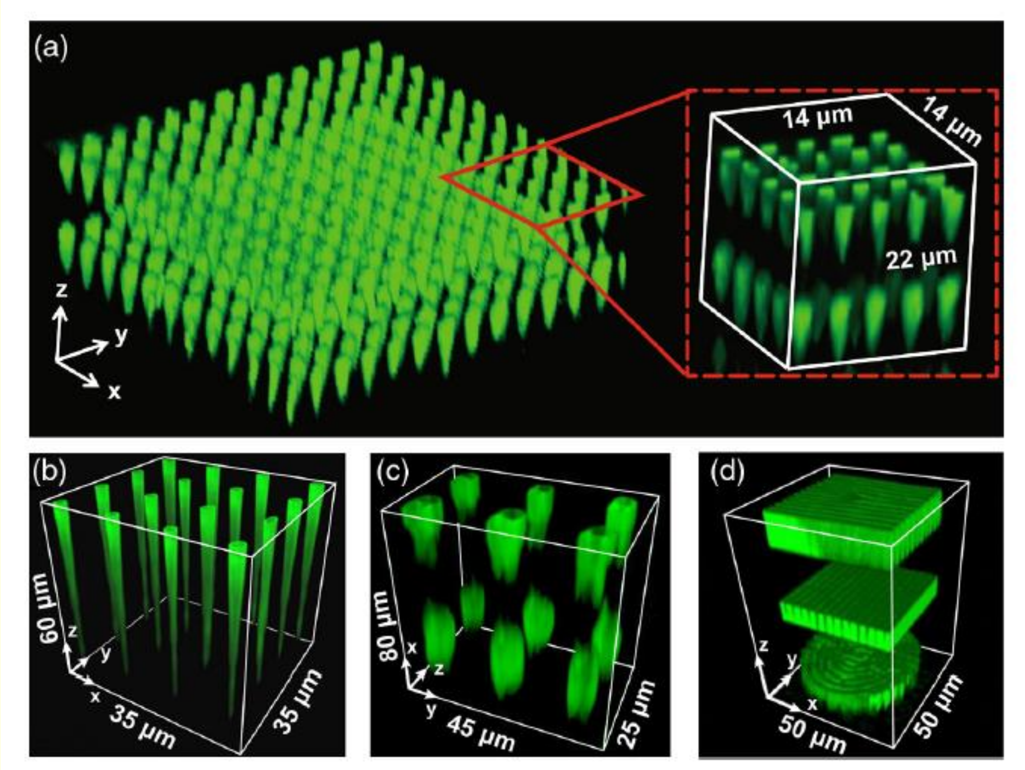
Examples of poled crystals by E-field poling (selective etching of the top surface)

Examples of 3D lasers-poled crystals (Cerenkov nonlinear microscopy)



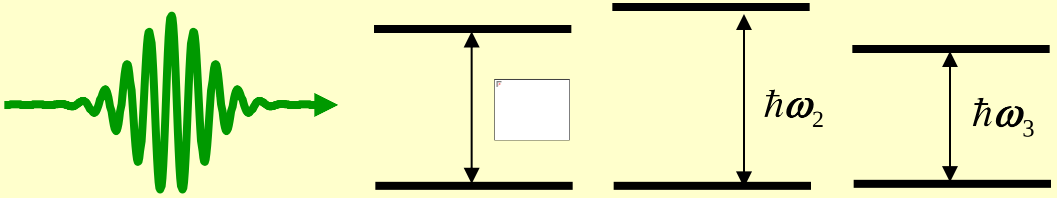


Sharabi,..AA, PRL (2014)
Broderick et al, PRL (2000)



Zhang et al, Optica (2021)

Adiabatic frequency conversion

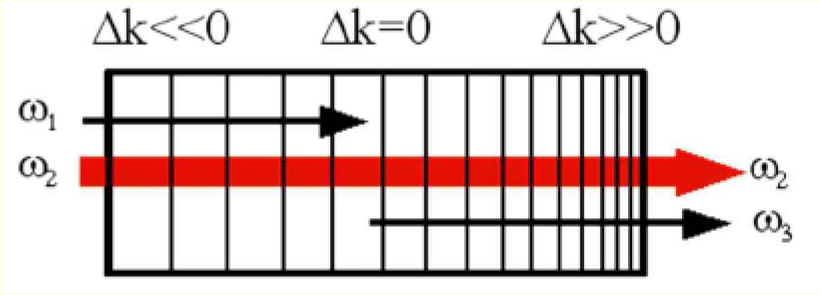


1. Far off Resonant $|\Delta| >> \Omega_0$
2. Adiabatic changing of $\Delta<0$ to $\Delta>0$

In nonlinear optics:

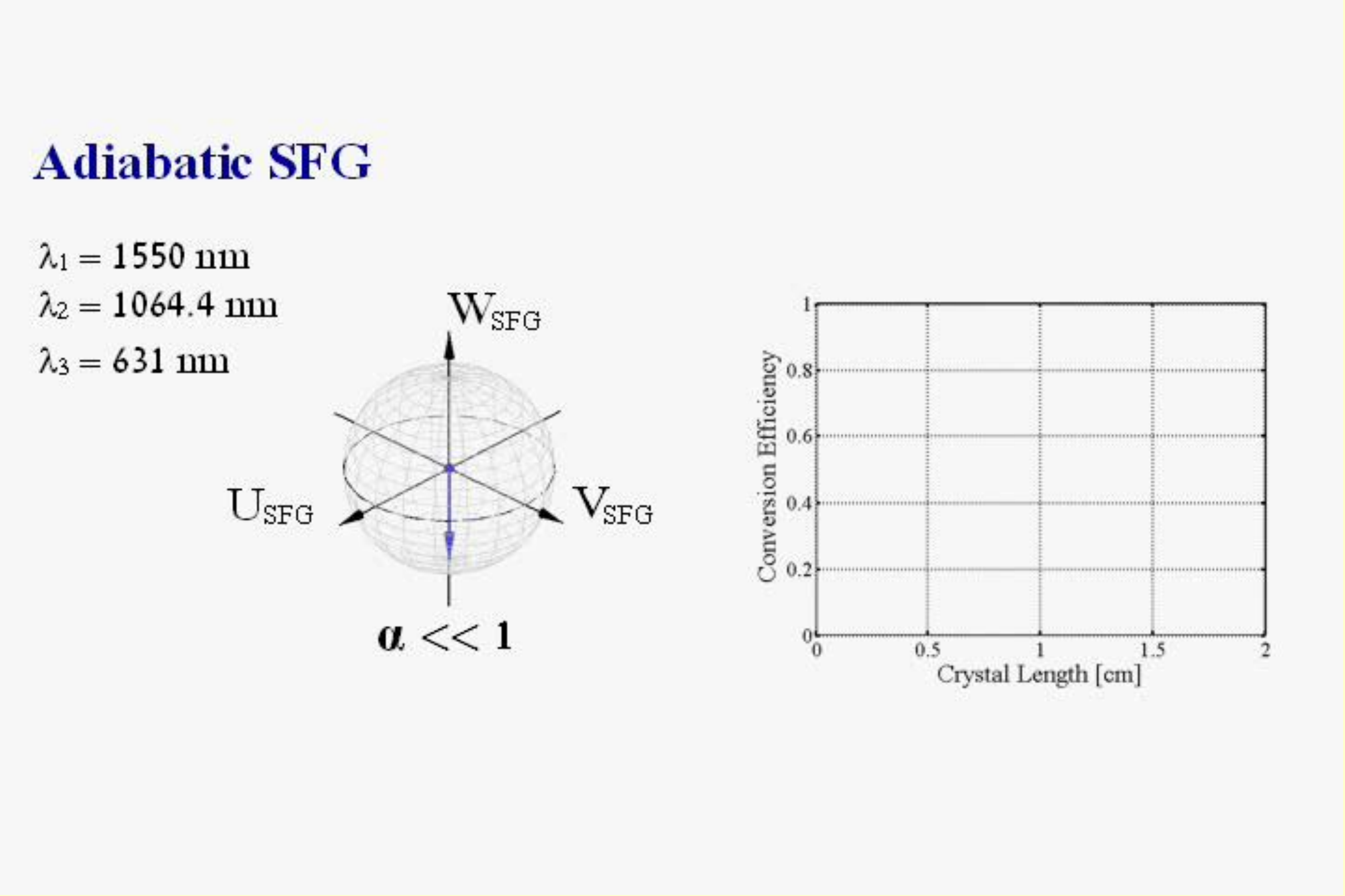
1. Large phase mismatch $|\Delta k| >> \kappa$
2. Adiabatic changing of $\Delta k<0$ to $\Delta k>0$ (or vice versa)

$$\left|\frac{d\Delta k}{dz}\right| << \frac{\left(\Delta k^2+\kappa^2\right)^{3/2}}{\kappa}$$



- Efficient Frequency conversion
- Robust for parameter variation

Adiabatic frequency conversion on Bloch Sphere

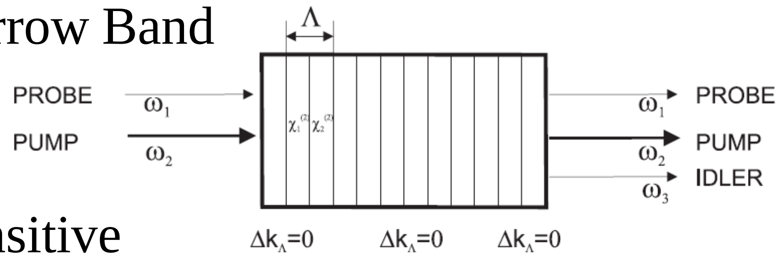


H. Suchowski, D. Oron, A. Arie and Y Silberberg, *PRA* **78**, 063821 (2008)

Adiabatic SFG: broad spectral acceptance

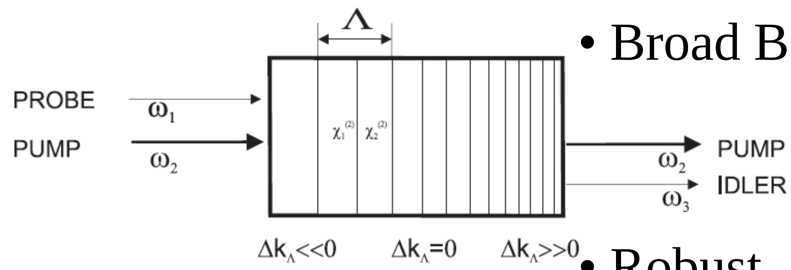
Periodically Poled

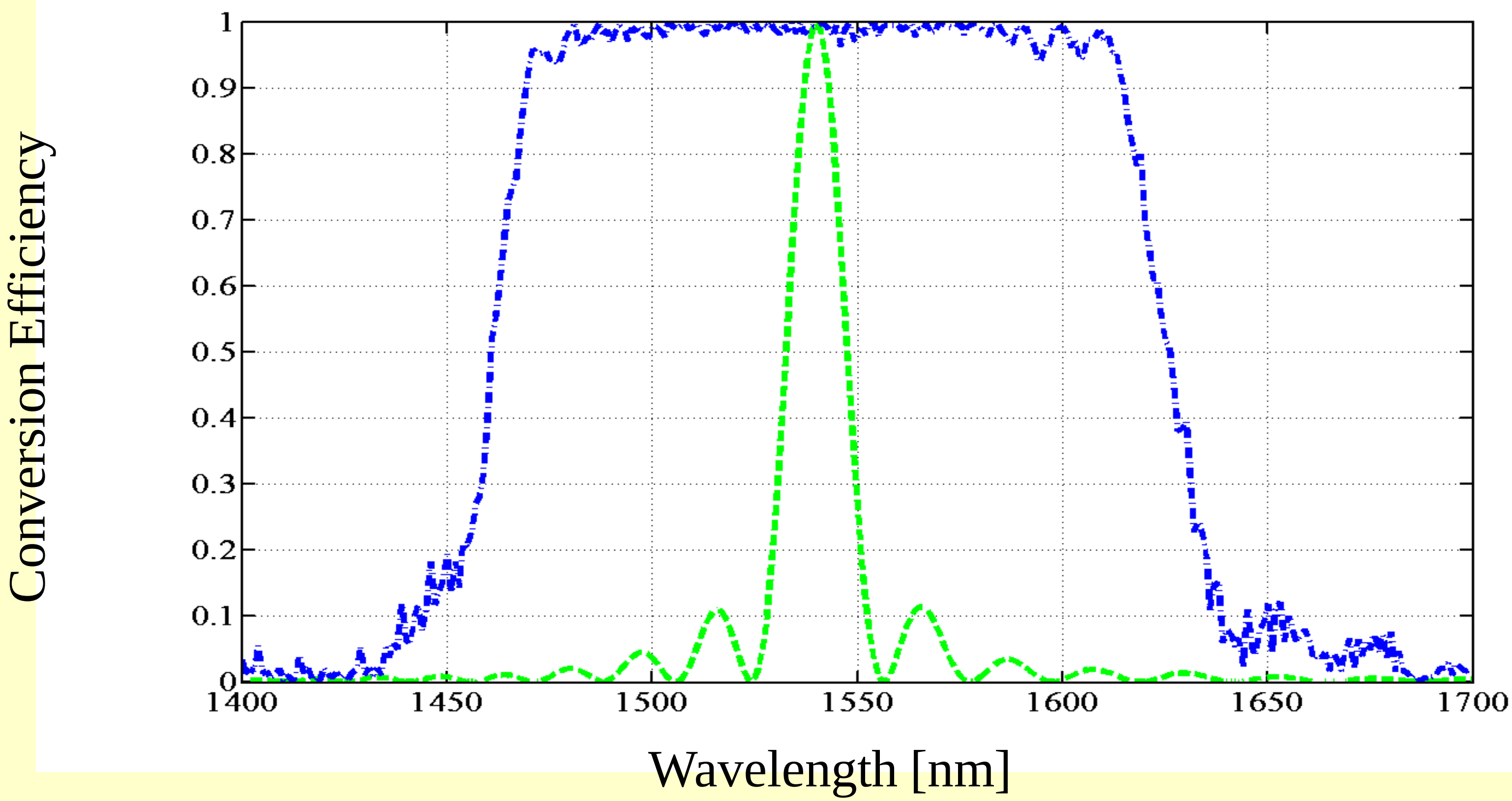
- Narrow Band
- Sensitive



Adiabatic aperiodically structure

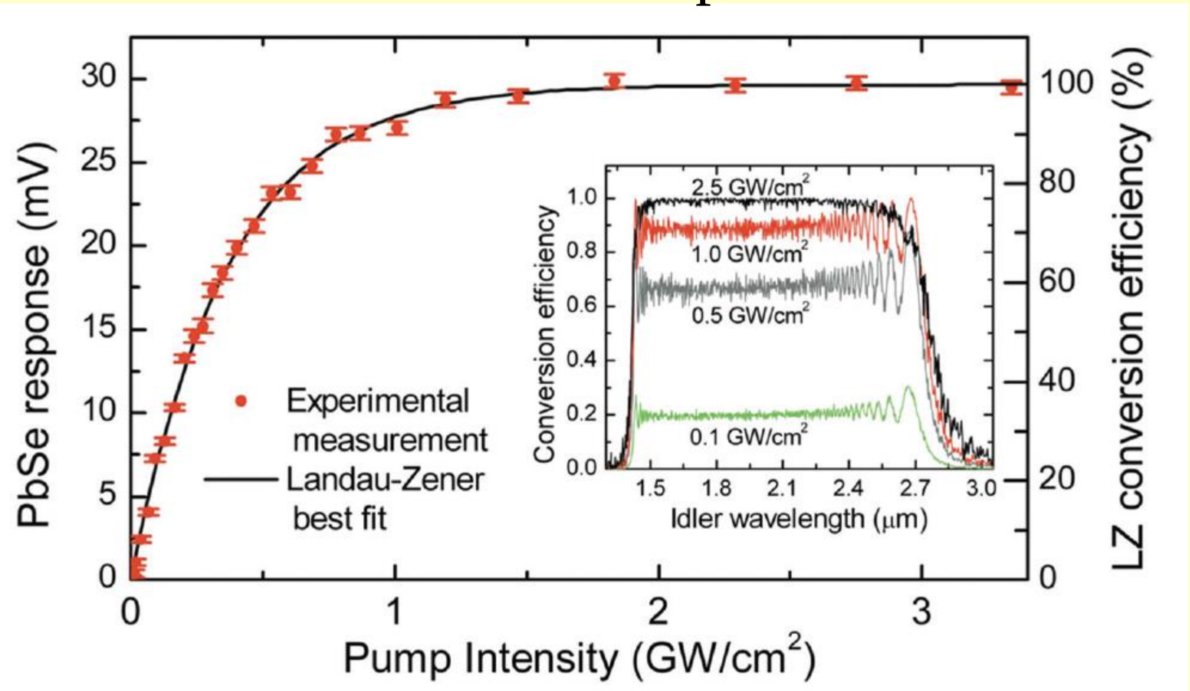
- Broad Band
- Robust





Conversion efficiency vs. pump intensity

Adiabatic frequency conversion is efficient, broadband and robust.
It is suitable for conversion of ultrafast pulses.

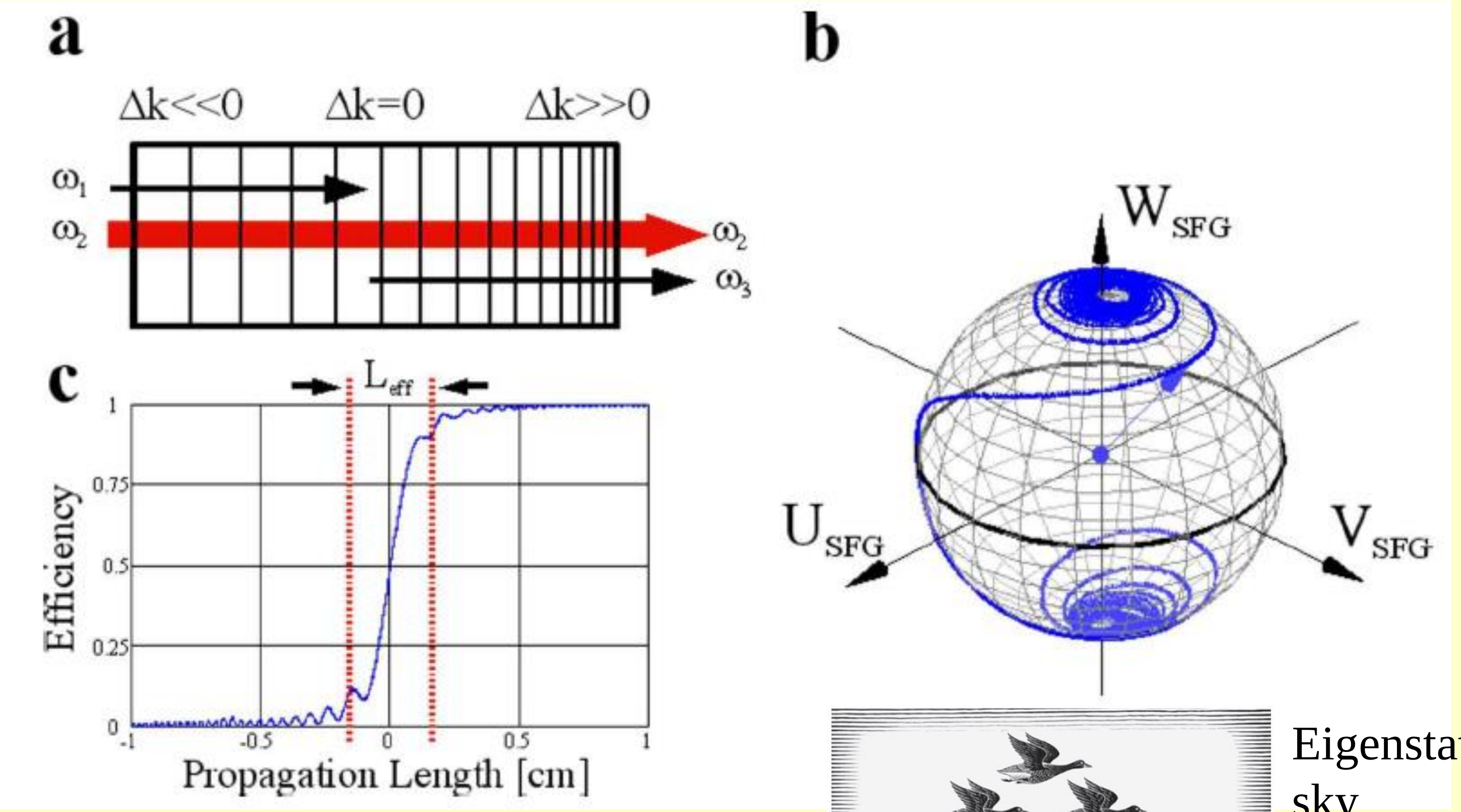


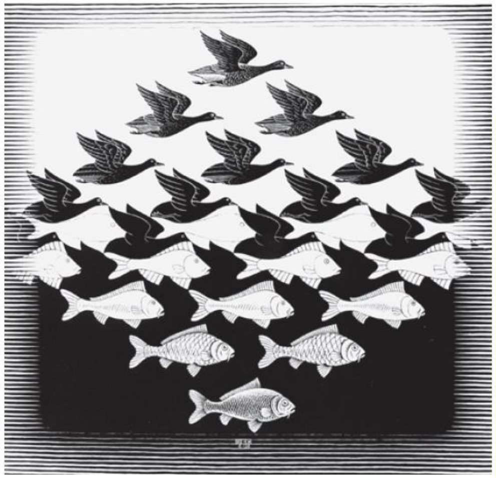
Conversion efficiency ~100%

Landau-Zener limit: $\eta_{LZ}(z \to \infty) = 1 - \exp\left(-2\pi \frac{\kappa^2}{d\Delta k / dz} \right)$

J. Moses, H. Suchowski, F. Kartner, Opt. Lett. (2012)

Adiabatic following and M.C. Escher





Eigenstate in sky

Eigenstate in water

Sky and Water I (1938)

Generalize coupled wave equation

So far we considered only variations in Δk, which correspond to changes in the torque vector from the north pole to the south pole. A general coupled wave equation:

$$i\frac{d}{d\tau}\begin{pmatrix}\tilde{A}_i\\ \tilde{A}_s\end{pmatrix} = -\boldsymbol{\sigma}\cdot\boldsymbol{B}\begin{pmatrix}\tilde{A}_i\\ \tilde{A}_s\end{pmatrix}$$

where $\boldsymbol{\sigma}$ represents the Pauli matrices

$$\sigma_x = \begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}, \qquad \sigma_y = \begin{pmatrix}0 & -i\\ i & 0\end{pmatrix}, \qquad \sigma_z = \begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}$$

and the Magnetization, or torque vector, is given by

$$\boldsymbol{B} = \frac{1}{2}\kappa \sin \pi D\,(\hat{x}\cos\phi + \hat{y}\sin\phi) + \frac{\Delta k}{2}\hat{z}$$

D – duty cycle, $\boldsymbol{\phi}$ - pump phase – poling phase, $\boldsymbol{\Delta k}$ – phase mismatch

<u>Details:</u>

Move to the *rotating frame* and define amplitudes:

$$A_i = \sqrt{k_s}\omega_i e^{-\frac{i}{2}(\Delta k_0 z - \int q(z')dz')}\tilde{A}_i \qquad A_s = \sqrt{k_i}\omega_s e^{+\frac{i}{2}(\Delta k_0 z - \int q(z')dz')}\tilde{A}_s$$

Dimensionless propagation coordinate: $\tau = \sqrt{k_i k_s} z$

Phase mismatch: $\Delta k(\tau) = \Delta k_0 - q(\tau)$; Nonlinear coupling: $\kappa(z) = \frac{4\sqrt{k_i k_s}}{n_i n_s}\left|d(z)A_p\right|$

Controlling the torque vector on the Bloch sphere

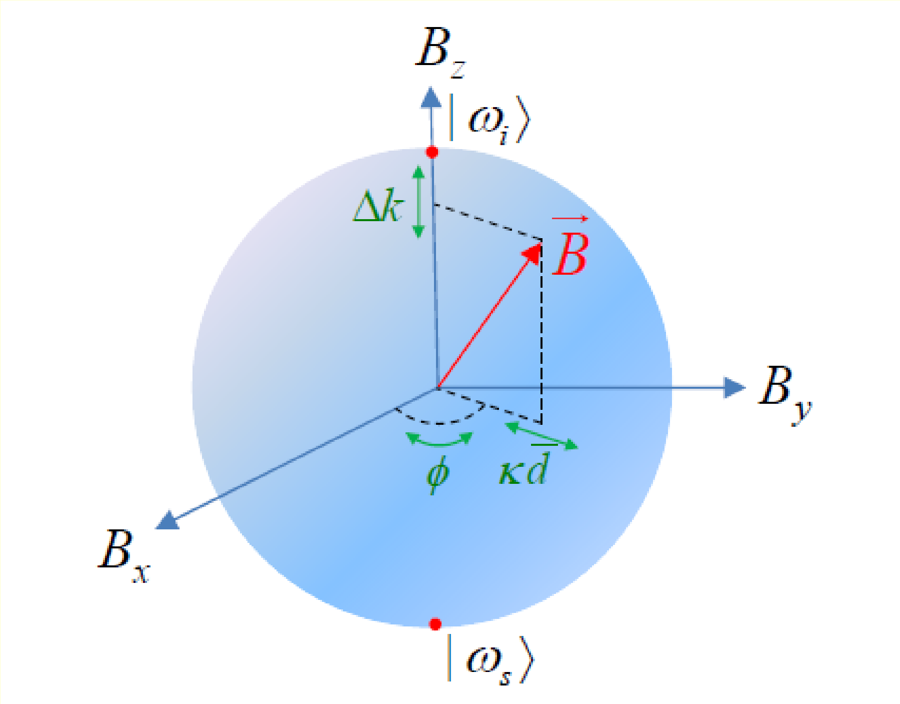
The torque vector, or magnetic-field equivalent vector:

$$\mathbf{B}(\tau) = B_0(\tau)\hat{\mathbf{B}}[\theta(\tau), \phi(\tau)],$$

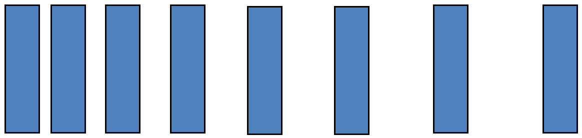
$$B_0(\tau) = \frac{1}{2\sqrt{k_i k_s}}\sqrt{\kappa^2 \bar{d}^2(\tau) + \Delta k^2(\tau)},$$

$$\cos\theta(\tau) = \frac{\Delta k(\tau)}{\sqrt{\kappa^2 \bar{d}^2(\tau) + \Delta k^2(\tau)}},$$

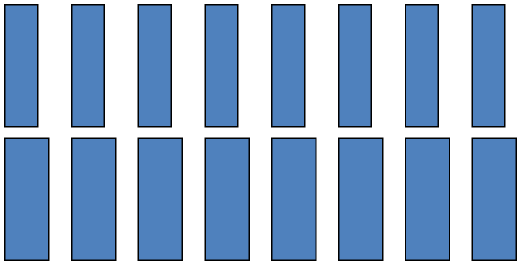
$$\phi(\tau) = \phi_p - \phi_d(\tau).$$



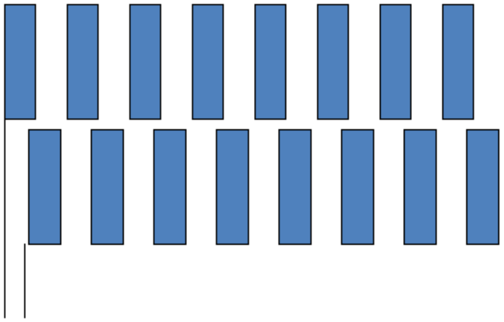
QPM Period – controls phase mismatch Δk => Z axis



Duty cycle d (together with Δk) control vector size,



Phase offset control ϕ



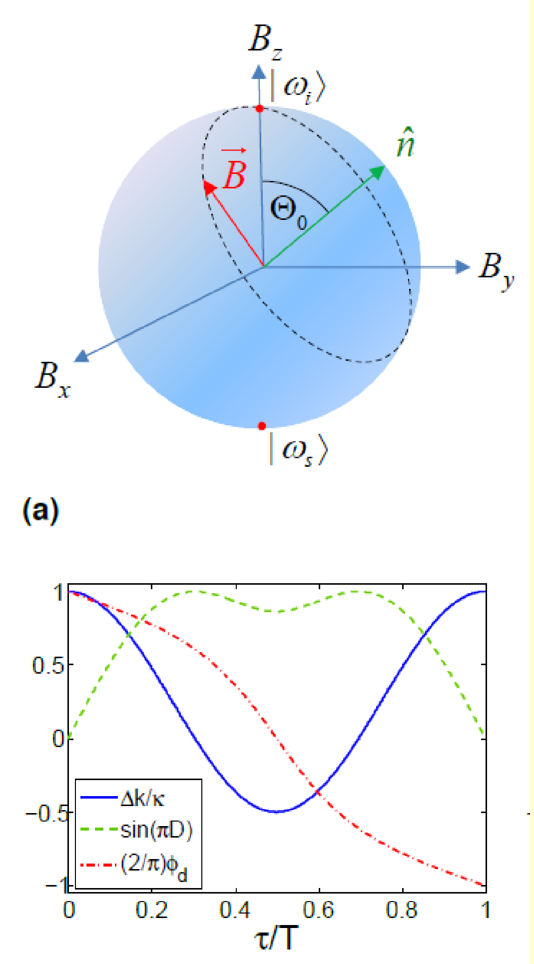
Circular adiabatic rotation in SFG

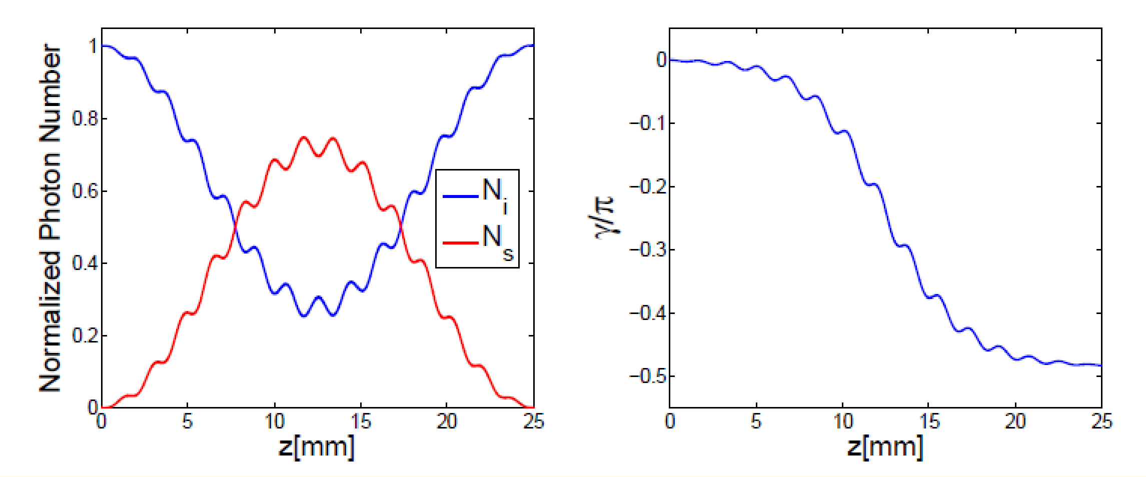
Starting with eigenstate in the north pole, we can utilize the nonlinear modulation degrees of freedom to realize a closed rotation on the Bloch sphere

Circular Rotation

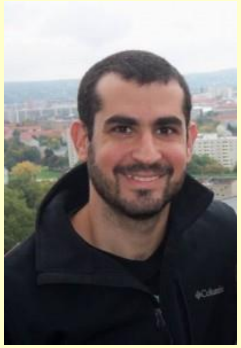
$\gamma = -\pi(1 - \cos\Theta_0)$

Simulation results for $LiNbO_3$, $L = 2.5\ cm$ and $I_p = 100\ MW/cm^2$ with $\gamma = -\frac{\pi}{2}$



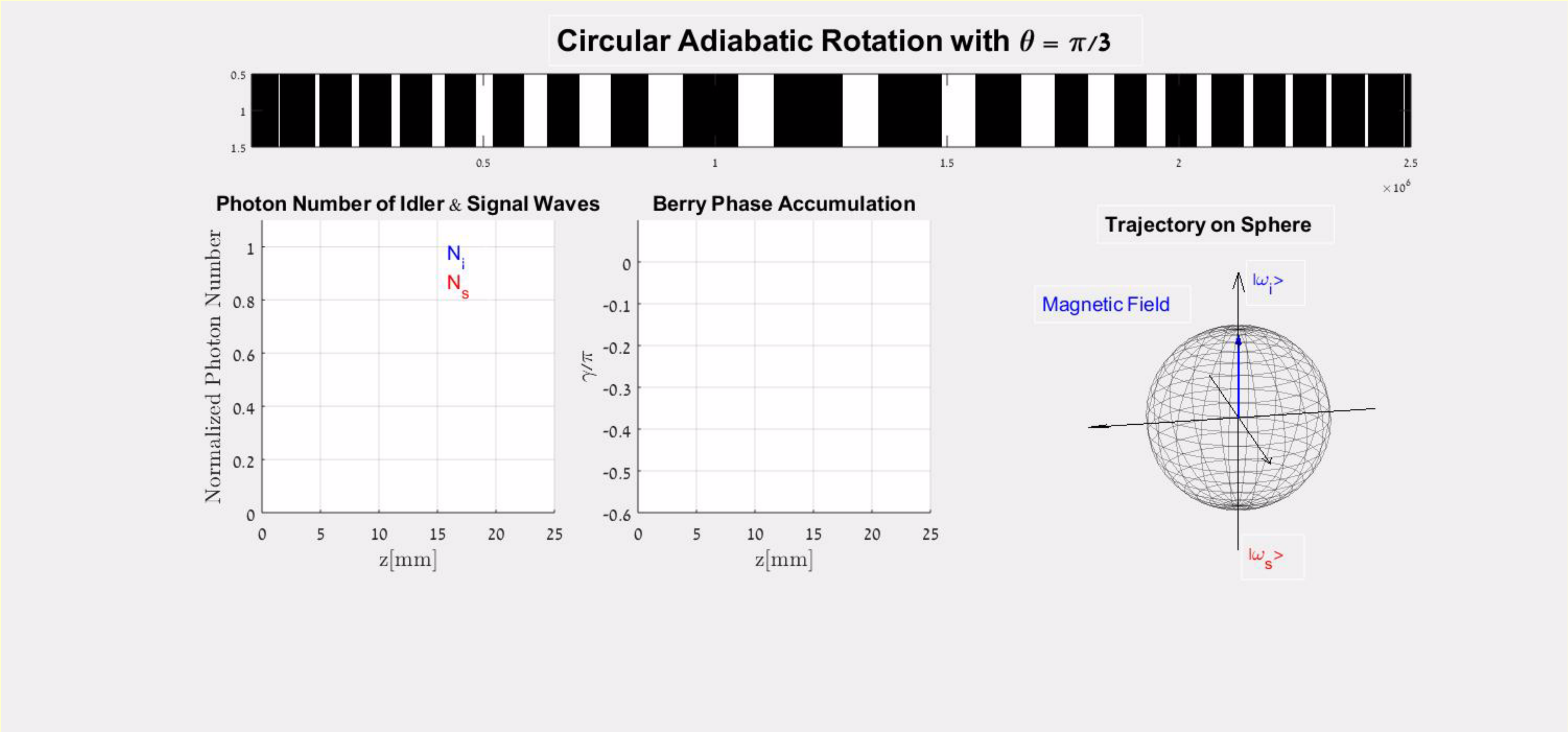


Aviv Karnieli



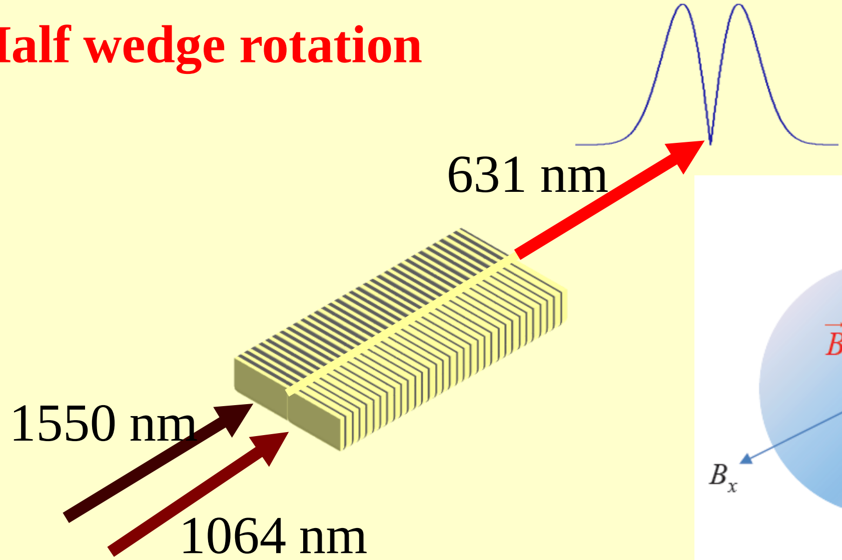
Karnieli and Arie, *Opt. Exp.* **26**, 4920(2018)

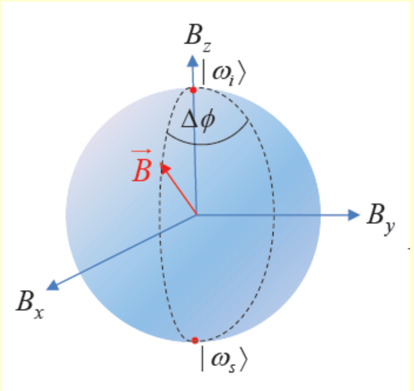
Circular adiabatic rotation in SFG



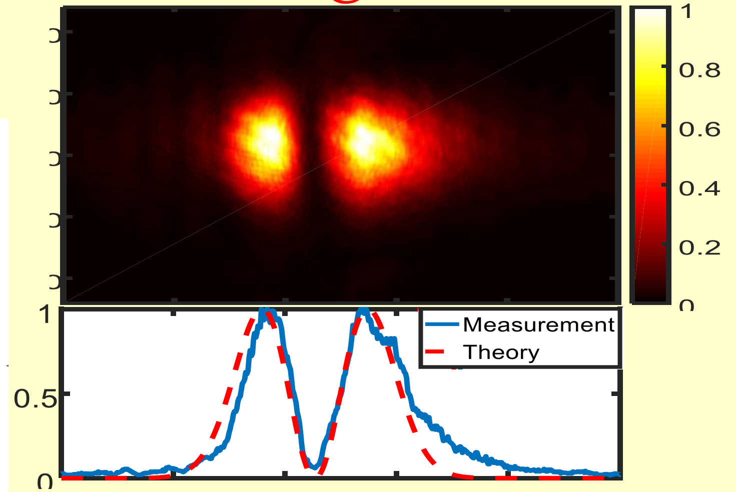
Broadband mode converter: HG00->HG01

Half wedge rotation

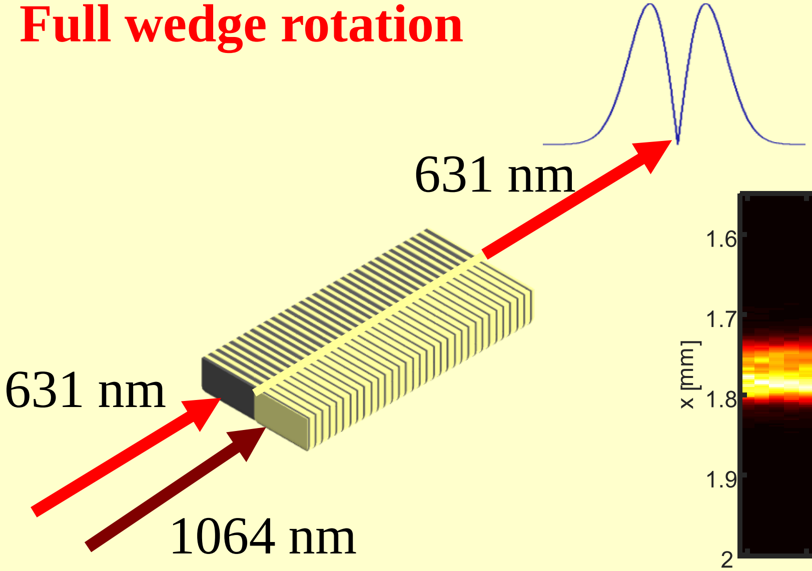




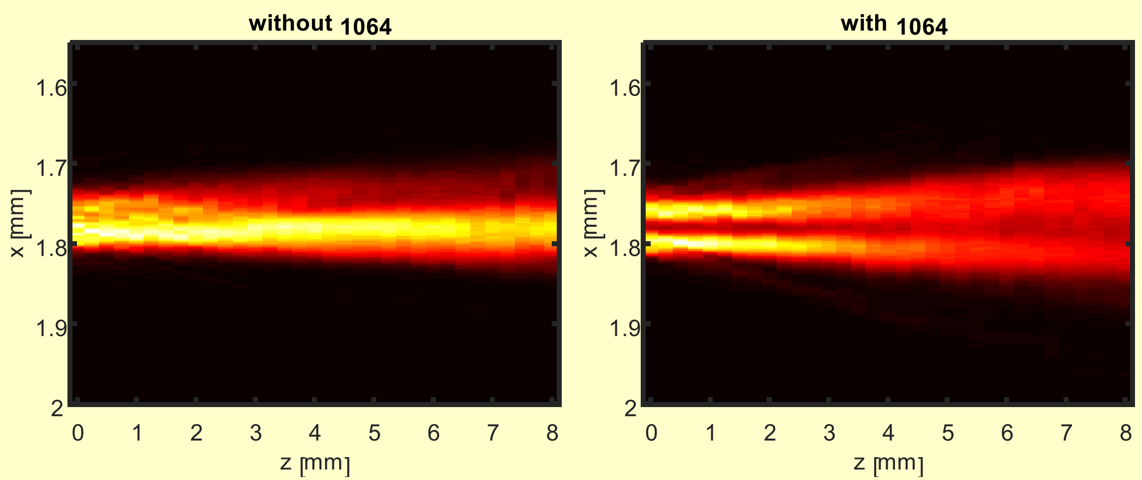
Far Field @ 631 nm



Full wedge rotation



Propagation dynamics @ 631 nm



Paraxial SFG and the Pauli equation

So far we assumed that the interacting waves act as ***plane waves***, with negligible diffraction.

Let's consider now the case of ***paraxial diffraction***. The wave equation can be written as:

$$\nabla_T^2 A_i + 2ik_i \frac{\partial A_i}{\partial z} = -\frac{4d_{eff}\omega_i^2}{c^2} A_p^* A_s e^{-i\Delta k(\mathbf{r})z}$$

$$\nabla_T^2 A_s + 2ik_s \frac{\partial A_s}{\partial z} = -\frac{4d_{eff}\omega_s^2}{c^2} A_p A_i e^{i\Delta k(\mathbf{r})z}$$

$$i\frac{d}{d\tau}\begin{pmatrix}\tilde{A}_i \\ \tilde{A}_s\end{pmatrix} = \left(\frac{1}{2}\mathbf{M}^{-1}\tilde{\boldsymbol{p}}_T^2 - \boldsymbol{\sigma}\cdot\boldsymbol{B}\right)\begin{pmatrix}\tilde{A}_i \\ \tilde{A}_s\end{pmatrix}$$

"Mass" matrix $\qquad -\nabla_T^2$

Assuming the *long-wavelength pump approximation* $k_p \ll k_i, k_s$: $\quad \mathbf{M}^{-1} \to \frac{1}{m},\ m = \frac{2\sqrt{k_i k_s}}{k_i + k_s} \cong 1$

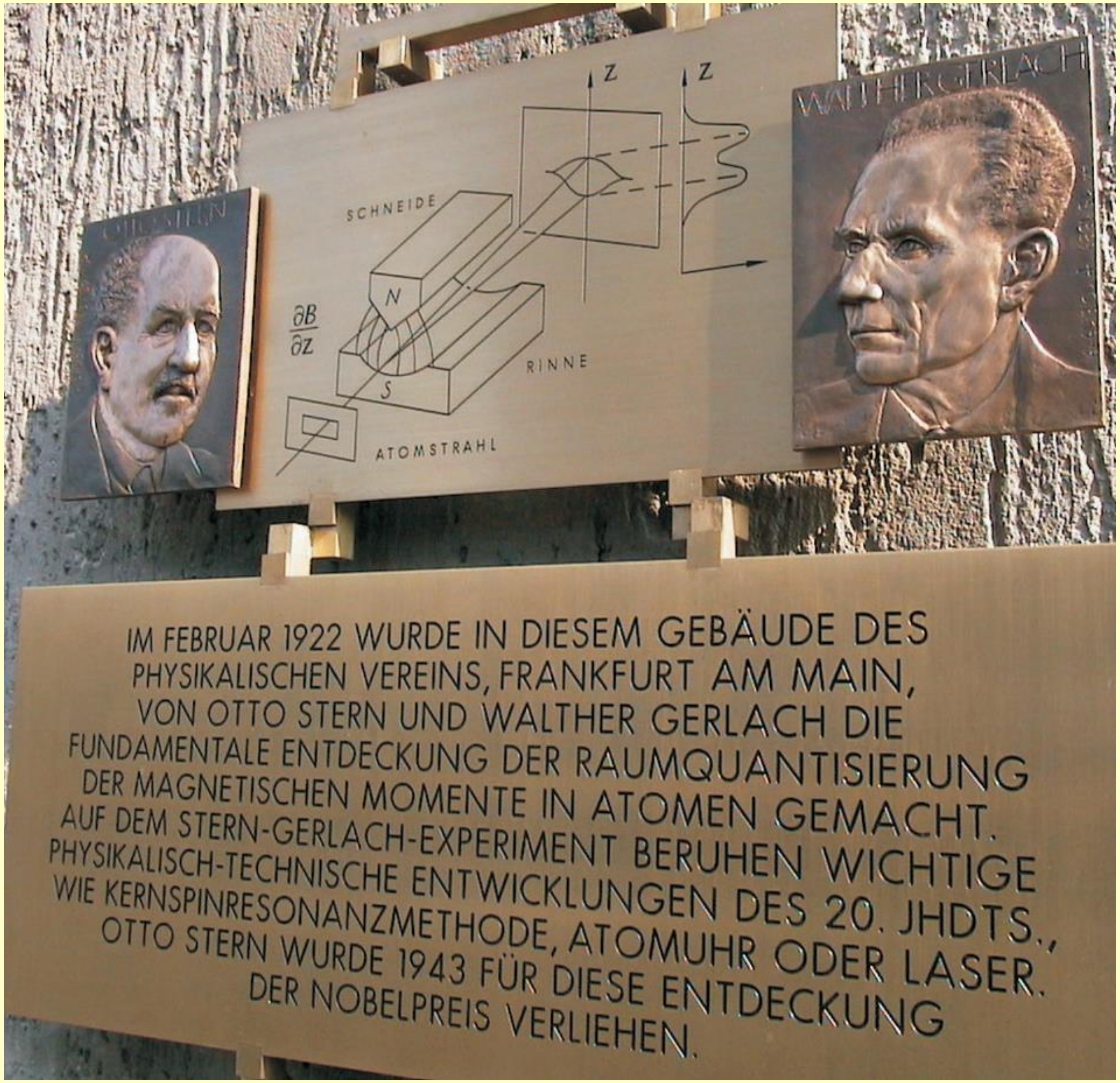
This equation has a similar form to the Pauli equation, describing a spin ½ particle in a weak transverse magnetic field

$$i\hbar\frac{\partial}{\partial t}|\psi\rangle = \left(\frac{\boldsymbol{p}_T^2}{2m} - \mu\boldsymbol{\sigma}\cdot\boldsymbol{B}_T\right)|\psi\rangle$$

μ is the magnetic moment and $\boldsymbol{\sigma}$ the Pauli matrix

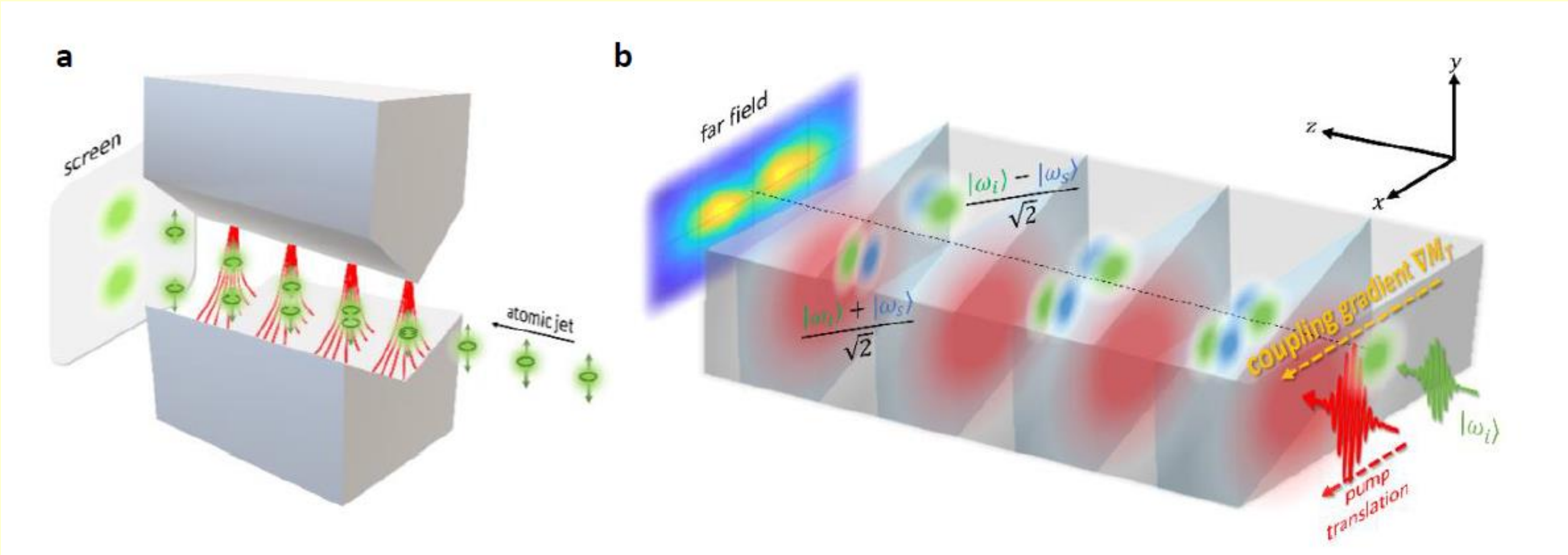
The Stern-Gerlach experiment

Memorial Plaque in Frankfurt



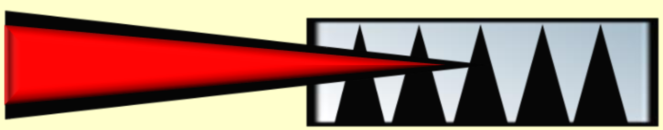
For more details: B. Friedrich and D. Hershbach, Phys. Today 53-59, Dec. 2003.

The Stern-Gerlach effect in NLO

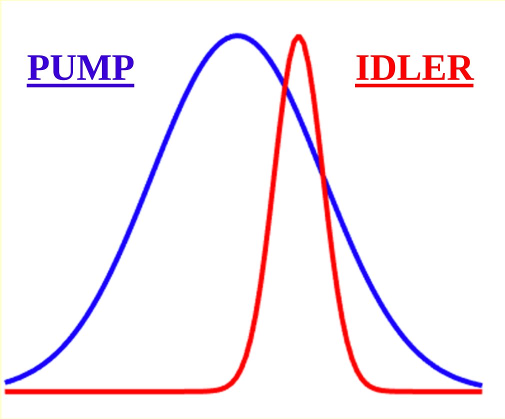


Transverse magnetization gradient:

Structured crystal

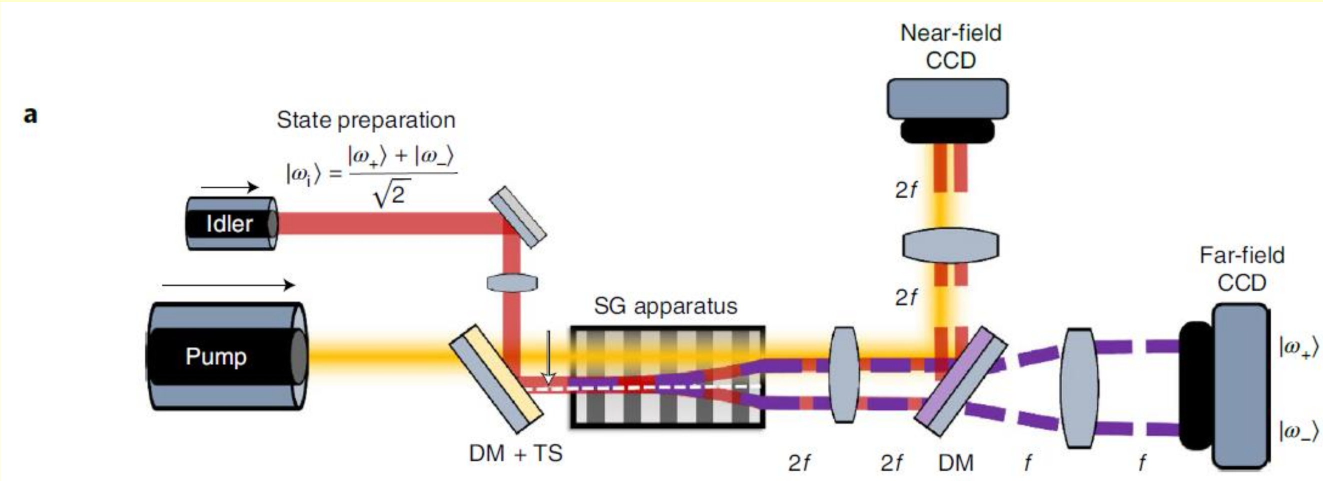


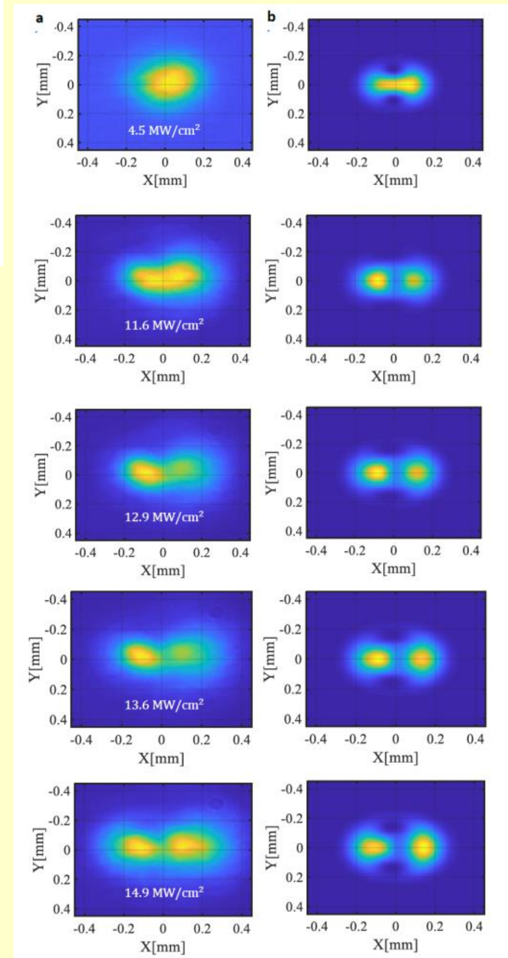
Shaped pump

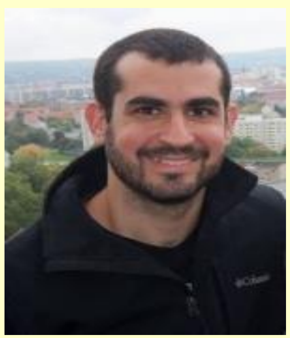


Karnieli and Arie, *Phys. Rev. Lett.* **120**, 053901 (2018)
O. Yesharim,…A. Arie, *Nature Photonics* **16**, 582 (2022)

The all-optical Stern-Gerlach effect - experiment







Ofir Yesharim Aviv Karnieli

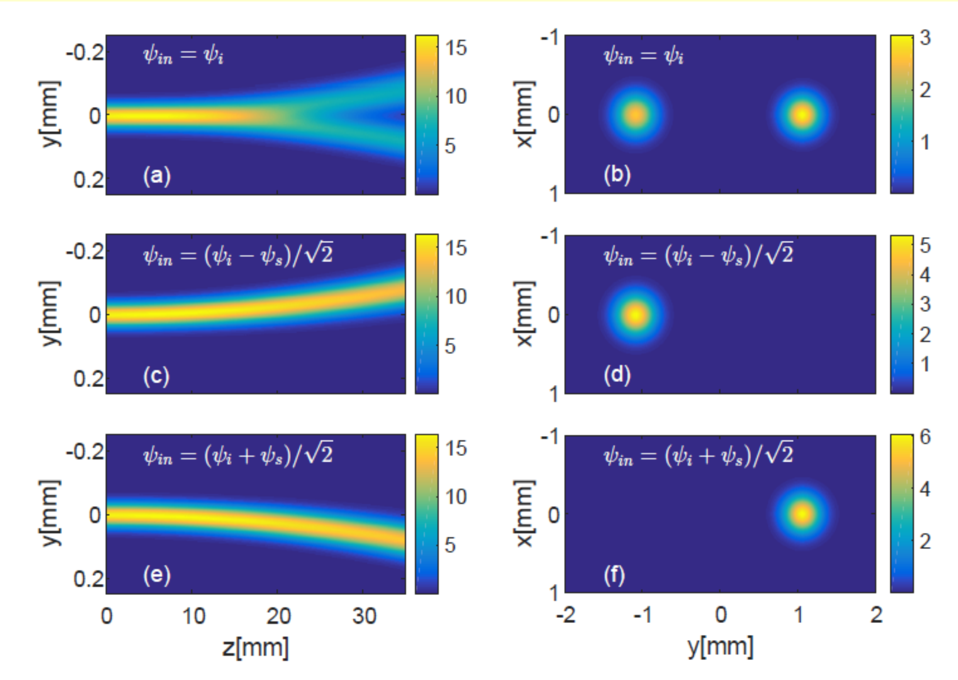
O. Yesharim,…A. Arie, *Nature Photonics* **16**, 582 (2022)

Stern-Gerlach effect for eigenstates

Input: idler only $\begin{pmatrix}1\\0\end{pmatrix}$

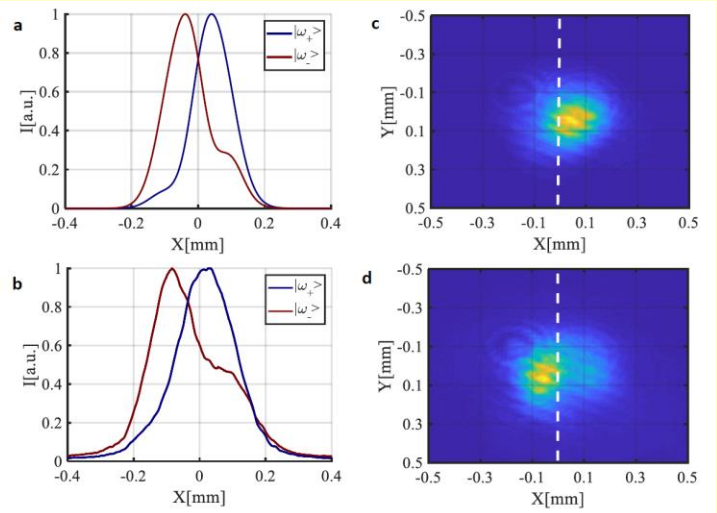
Input: idler – signal, $\frac{1}{\sqrt{2}}\begin{pmatrix}1\\-1\end{pmatrix}$

Input: idler + signal, $\frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix}$



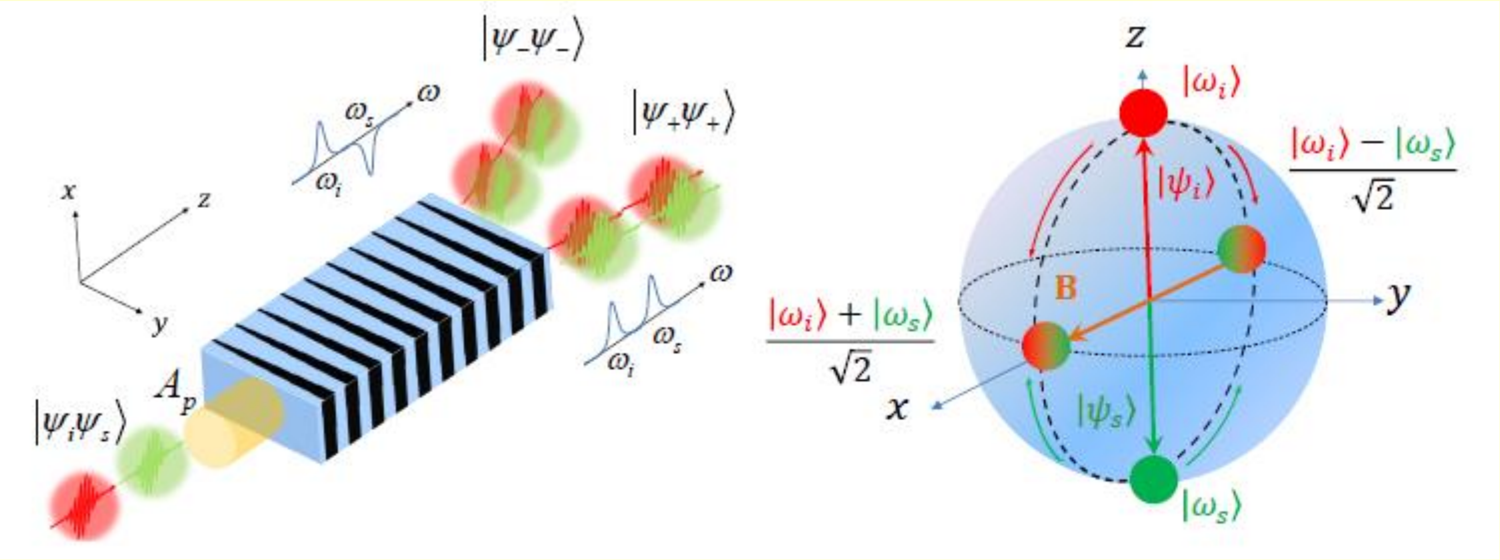
Controlling the signal-idler relative phase

Measurement of the two eigenstates



Quantum optical Stern-Gerlach effect: two-photon input

Two different photons in idler and signal frequency: never detected at two outputs simultaneously and transformed into superposition!



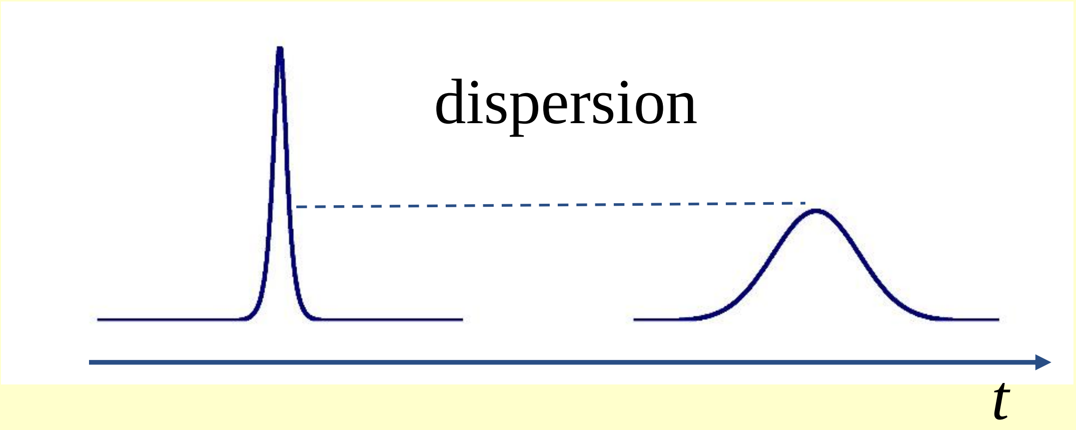
Stern-Gerlach-HOM effect with *distinguishable* photons

Karnieli and Arie, *Optica* **5**, 1297 (2018)
Also see: Kobayashi et al, *Nature Photonics* **10**, 441 (2016);
Imani et al, *Opt. Lett.* **43**, 2760 (2018).

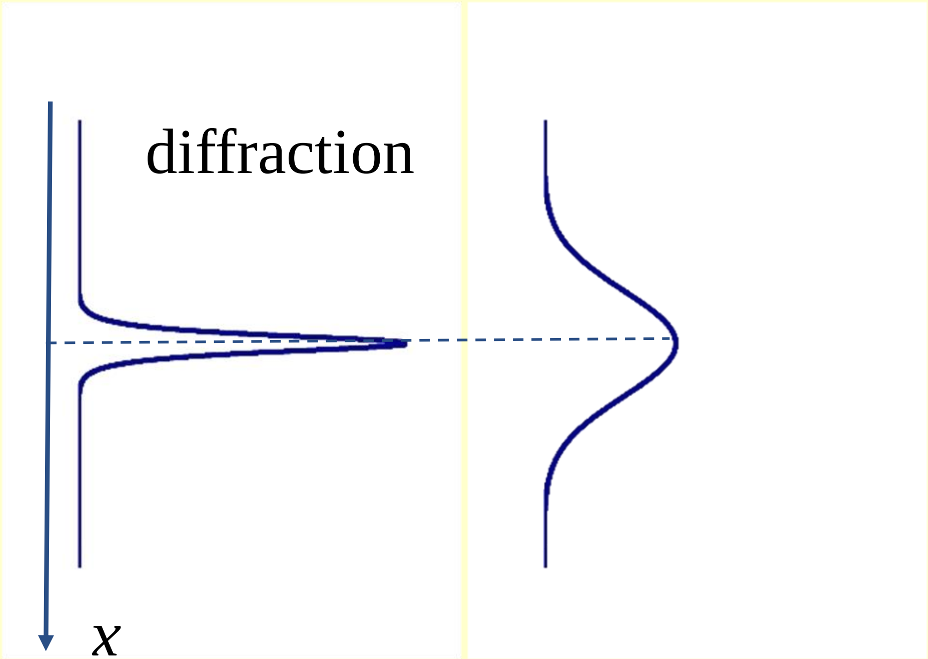
Dispersion-Diffraction analogy

$$\frac{\partial A(z,\eta)}{\partial z} - \frac{i}{2}\beta_2 \frac{\partial^2 A(z,\eta)}{\partial \eta^2} = 0$$

$$\eta = t - z/v_g$$



$$\frac{\partial U(z,x)}{\partial z} - \frac{i}{2k}\frac{\partial^2 U(z,x)}{\partial x^2} = 0$$



$$x \leftrightarrow \eta,\ 1/k \leftrightarrow -\beta_2,\ U(z,x) \leftrightarrow A(z,\eta)$$

Sum Frequency Generation: $\chi^{(2)}$ vs. $\chi^{(3)}$

Coupled wave equation for ***quadratic*** nonlinear material with undepleted pump:

$$\nabla_T^2 A_i + 2ik_i \frac{\partial A_i}{\partial z} = -\frac{4d_{eff}\omega_i^2}{c^2} A_p^* A_s e^{-i\Delta k(\mathbf{r})z}$$

$$\nabla_T^2 A_s + 2ik_s \frac{\partial A_s}{\partial z} = -\frac{4d_{eff}\omega_s^2}{c^2} A_p A_i e^{i\Delta k(\mathbf{r})z}$$

Coupled wave equation for ***qubic*** nonlinear material with two undepleted pump:

$$\frac{\partial^2}{\partial \tau^2} A_i - \frac{i2}{\beta_2}\frac{\partial A_i}{\partial z} = \frac{4}{\beta_2}\gamma A_{p1} A_{p2}^* A_s e^{-i\Delta kz}$$

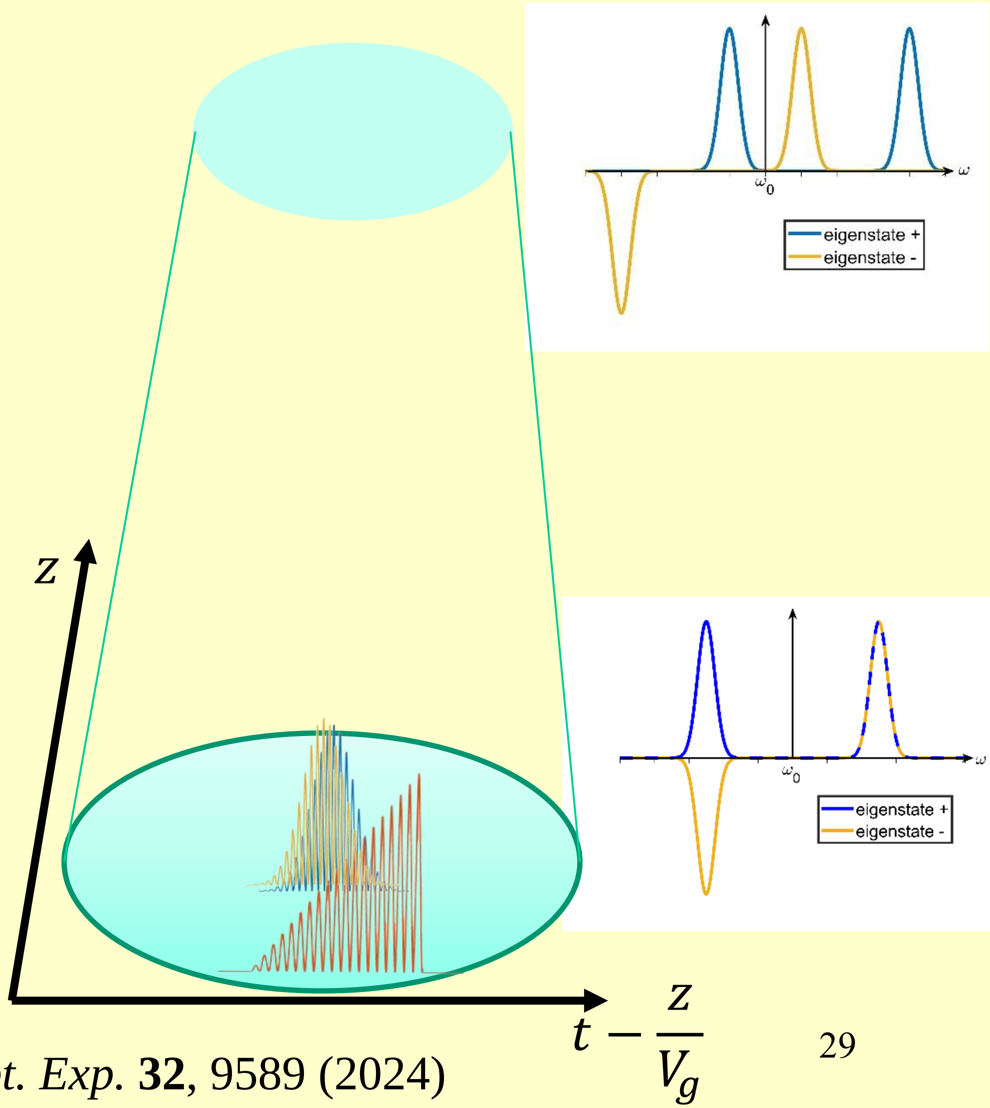
$$\frac{\partial^2}{\partial \tau^2} A_s - \frac{i2}{\beta_2}\frac{\partial A_s}{\partial z} = \frac{4}{\beta_2}\gamma A_{p2} A_{p1}^* A_i e^{i\Delta kz}$$

Stern-Gerlach effect in the time domain

Using four-wave mixing in an optical fiber. *Two* undepeted pumps + signal and idler

- Two pump tones in a ramp envelope
- Couple light between signal and idler pulses
- Creates two eigenstates that different in the optical phase
- The eigenstates have different speeds
- The spectrum of the eigenstates shifts in frequency domain to opposite directions

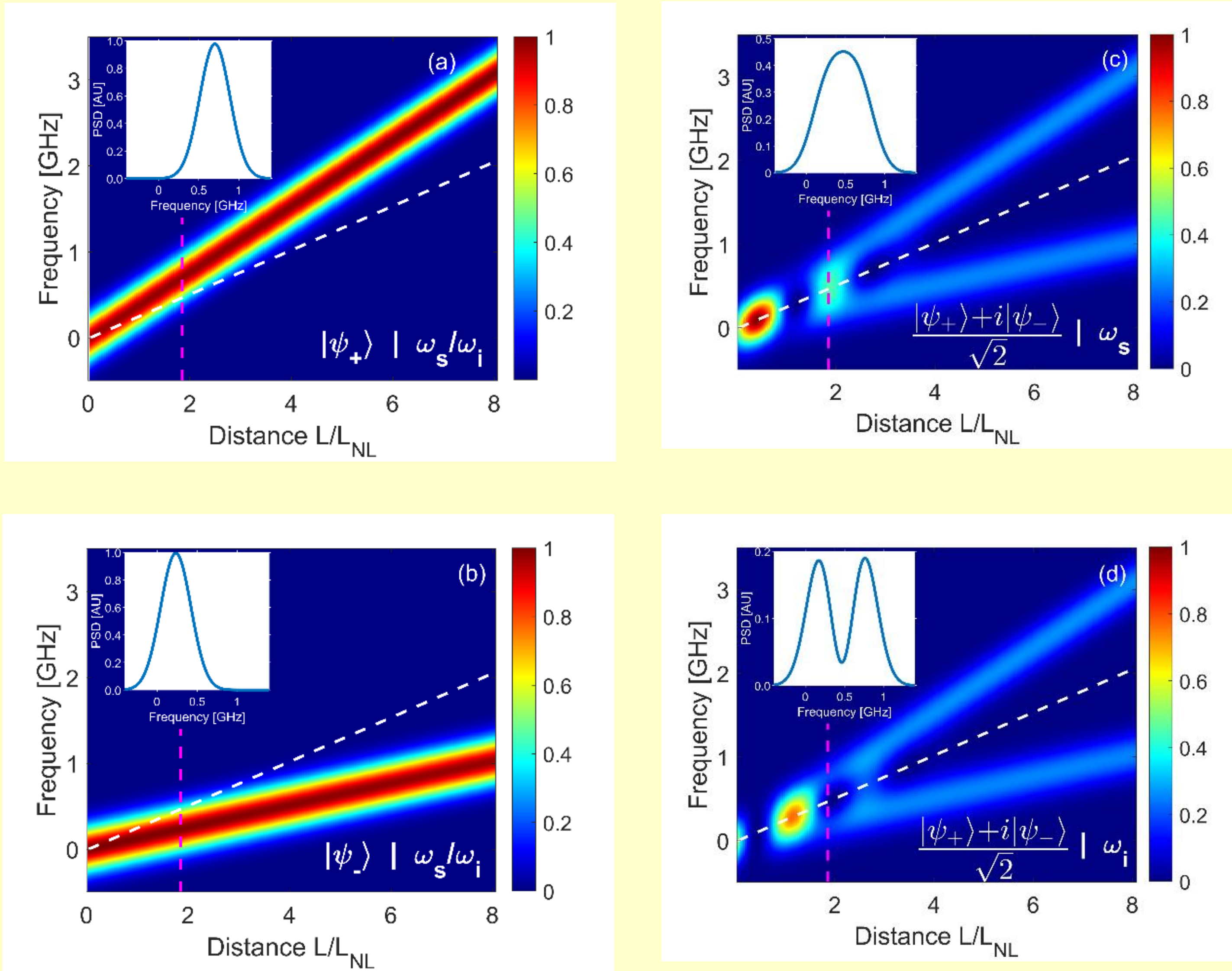
Gil Bashan



Bashan,..AA, *Opt. Exp.* **32**, 9589 (2024)

Eigenstates and mixed states

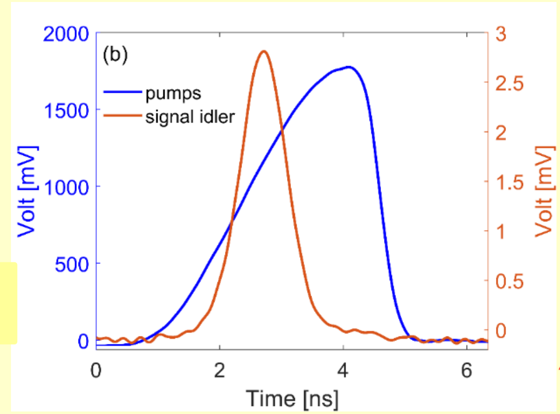
Eigenstates | Mixed states

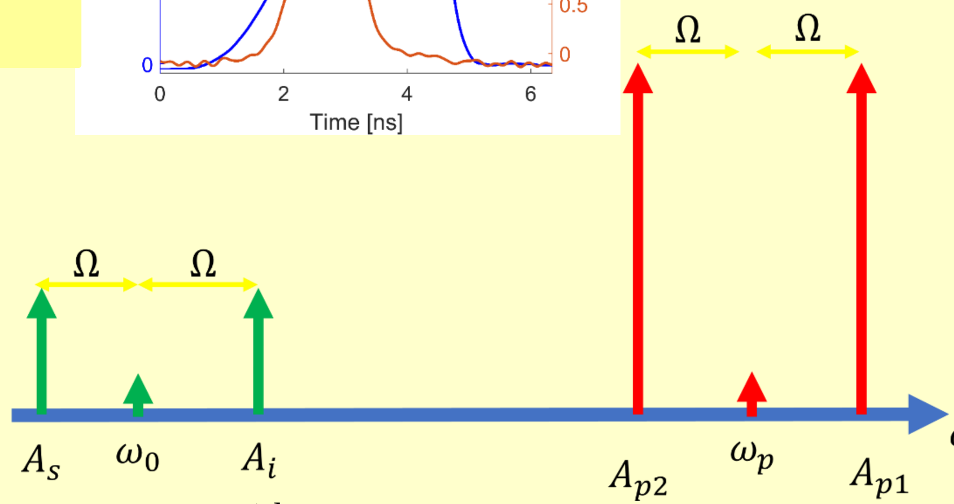


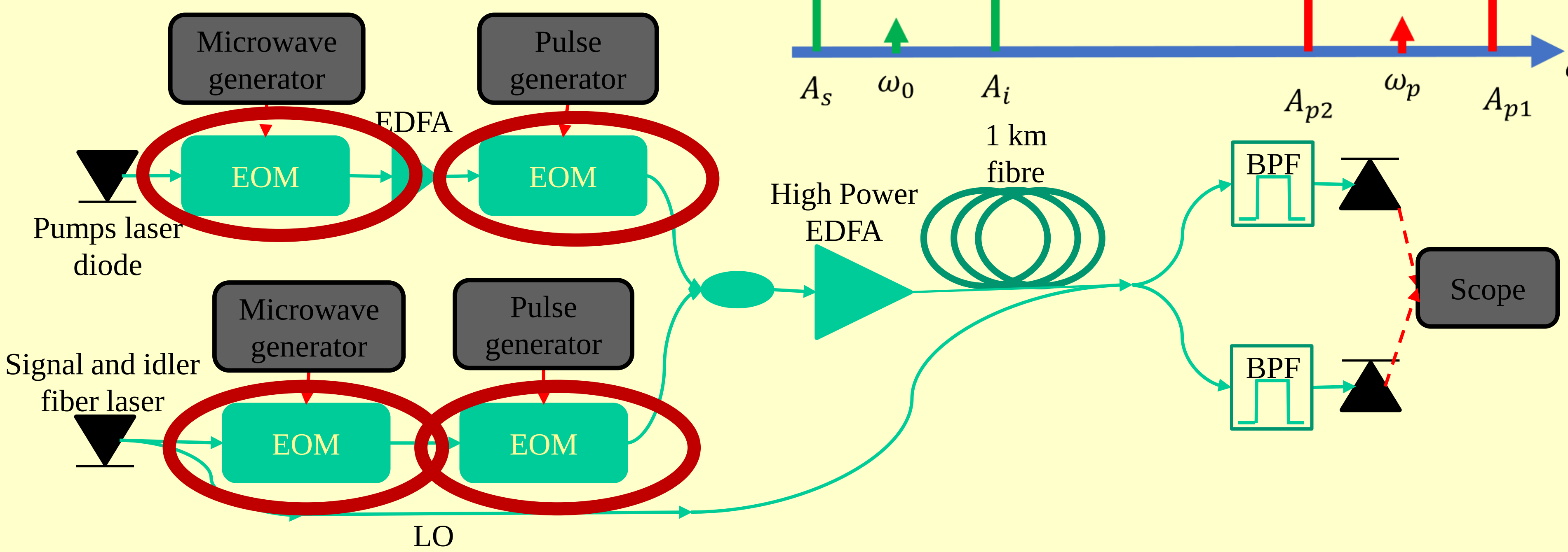
Dashed white line – frequency shift owing to cross-phase modulation.

Experimental setup

- First EOMs modulate the pulses
- Second EOMs split the frequencies
- Self-heterodyne detection

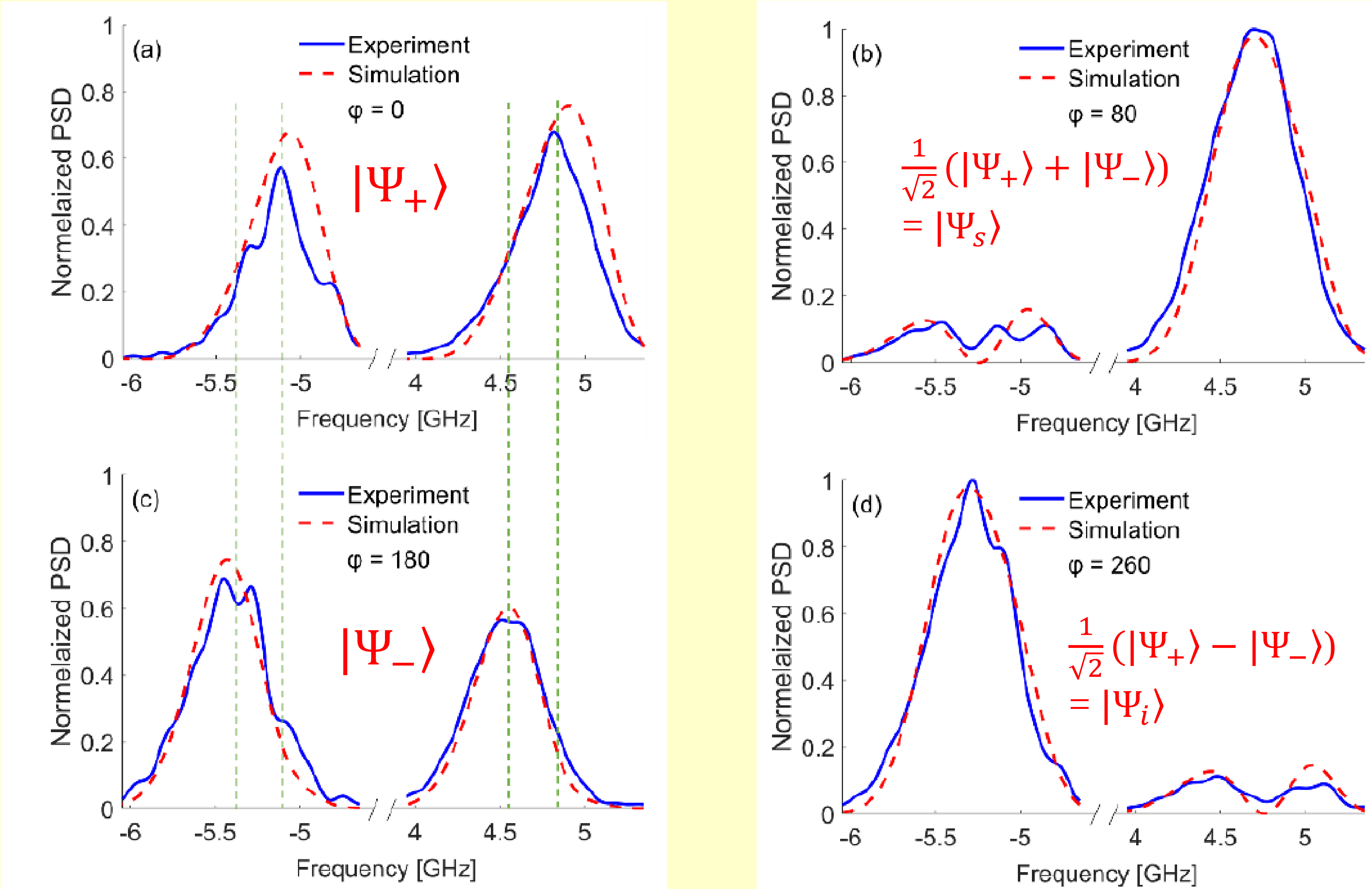






Output spectra: Eigenstates and mixed states

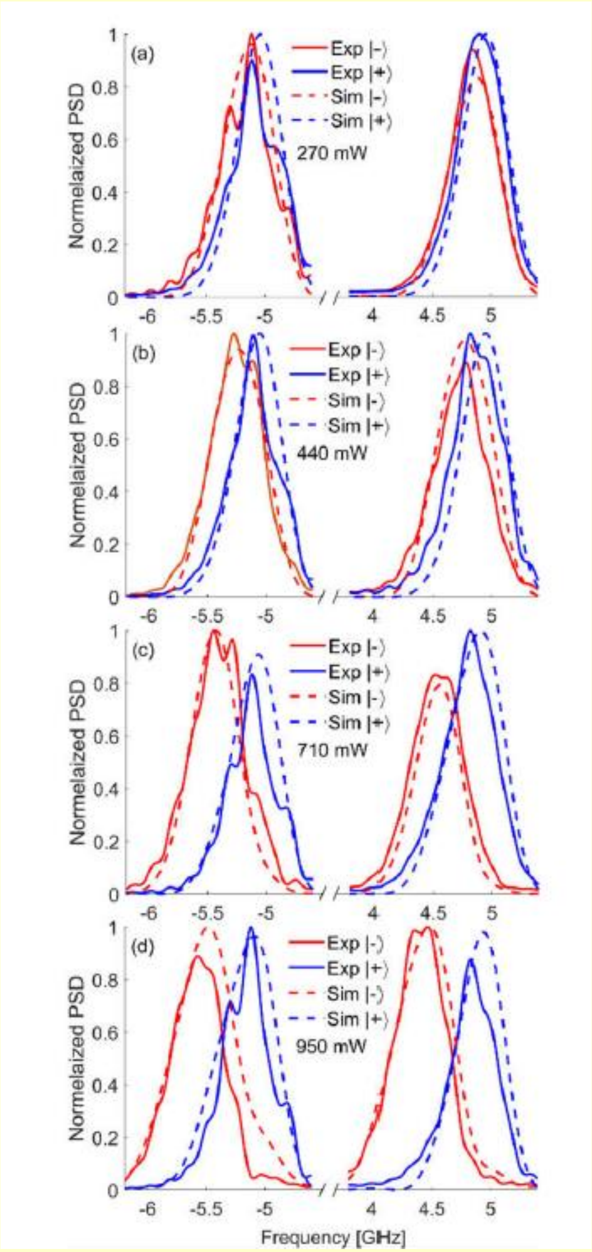
Eigenstates | Mixed states

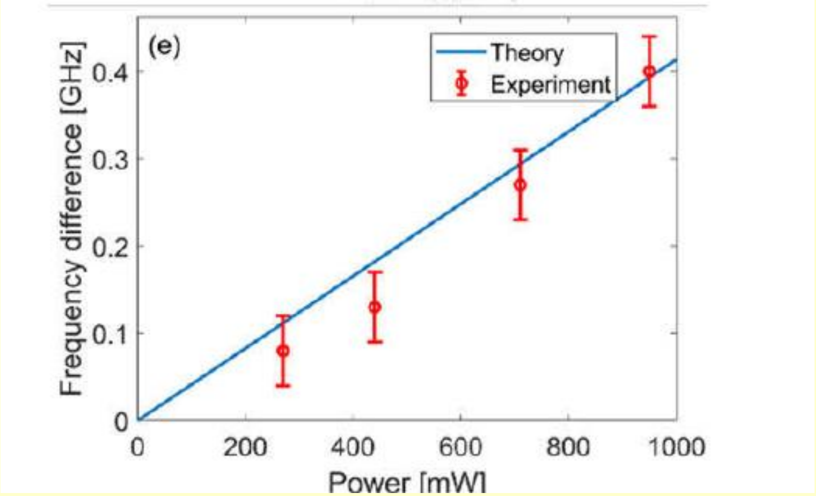


Bashan,..AA, *Opt. Exp.* **32**, 9589 (2024)

Frequency splitting of the eigenstates vs pump power

Low pump power, small splitting



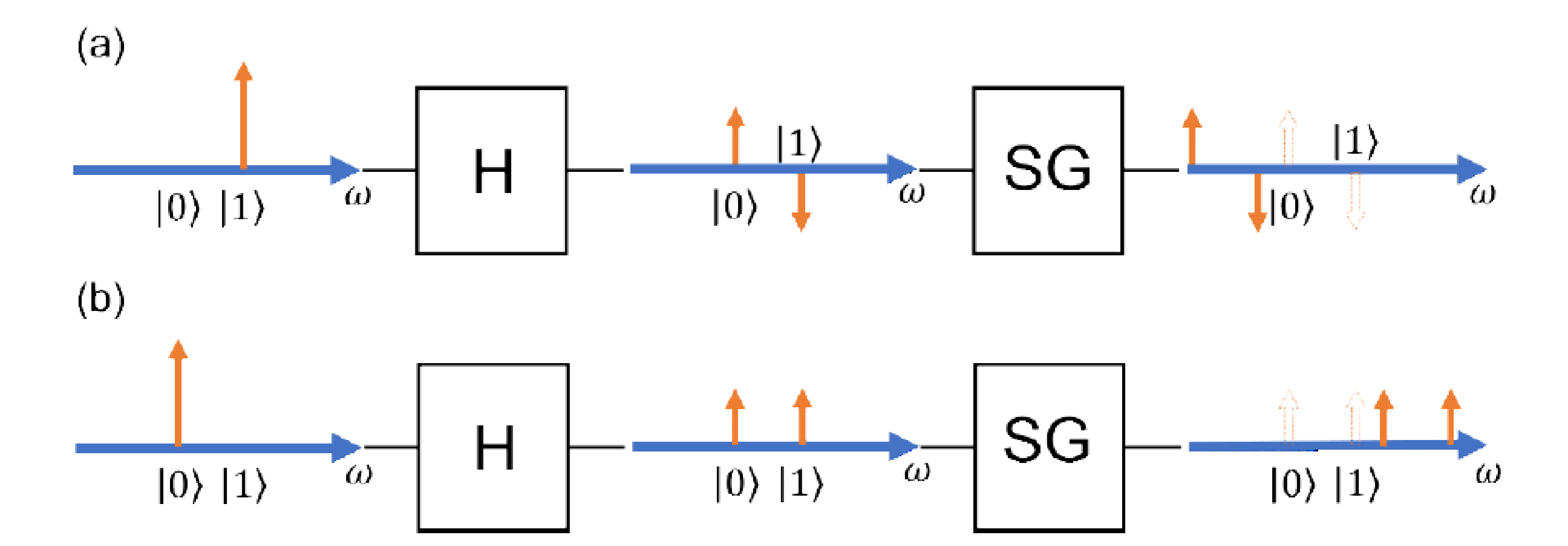


High pump power, large splitting

Bashan,..AA, *Opt. Exp.* **32**, 9589 (2024)

Application in classical and quantum communication

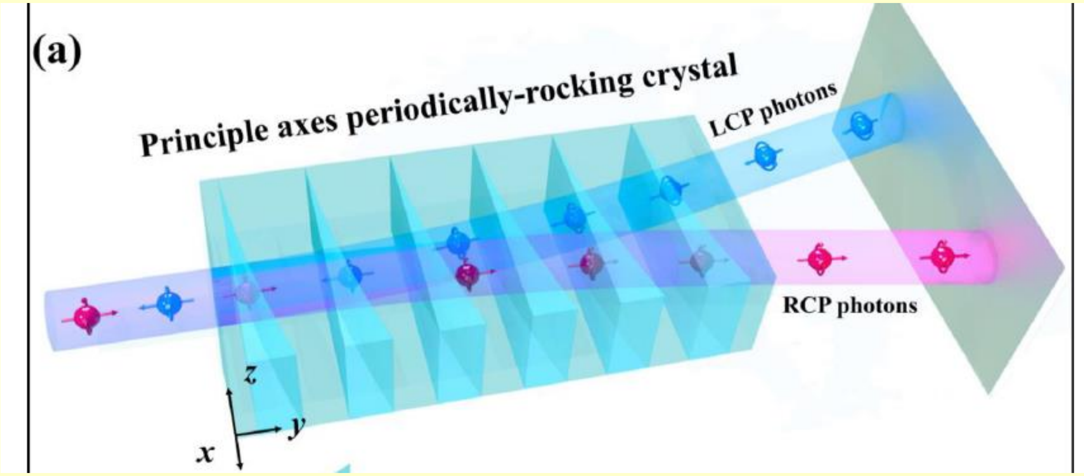
(Temporal) splitting of frequency-bin eigenstates in the Hadamard basis



Bashan,..AA, *Opt. Exp.* **32**, 9589 (2024)

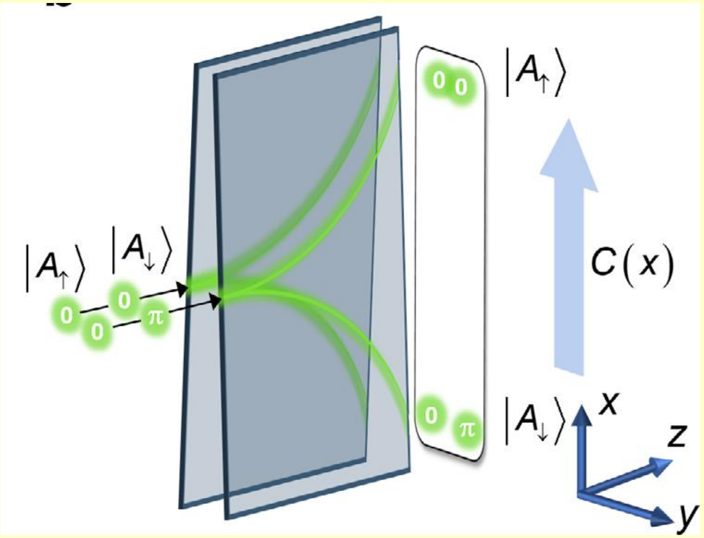
Optical Stern Gerlach – beyond nonlinear SFG

Splitting of polarization eigenstates using the electro-optic effect



Zhu et al, *Laser Photonics Rev.* **2024**, 2301030

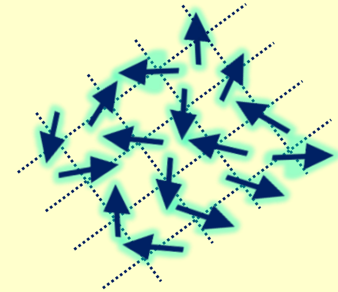
Splitting of spatial modes using tilted planar waveguides



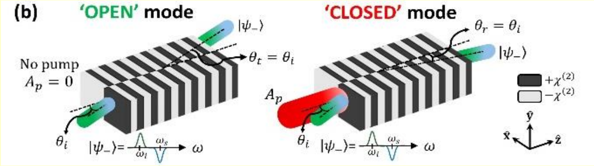
Li et al, *Laser Photonics Rev.* **2024**, 2301055

Spintronic effects and devices

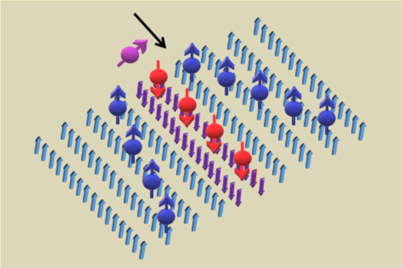
• **Anderson localization** of the signal and idler in disordered nonlinear media (spin glass)



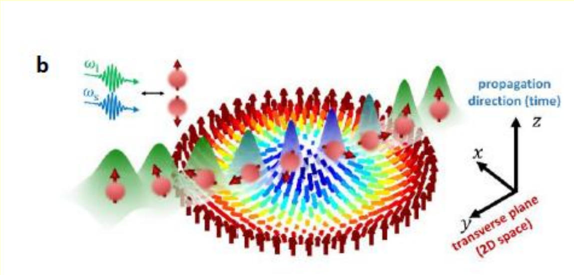
• **Spin valve** – controlling the transmission and reflection of signal-idler in-phase beam with a pump beam



• **Spin waveguide** – guiding of signal-idler in-phase beam

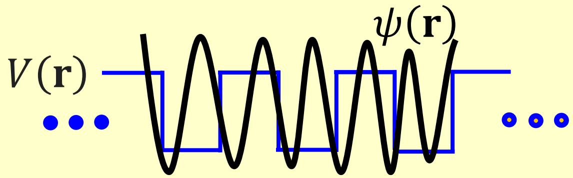


• **Skyrmionic nonlinear photonic crystals** and the topological Hall effect for light

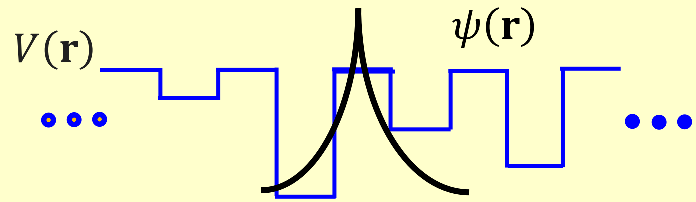


Anderson localization

Bloch state



Localized state



Conditions for Anderson Localization:

1. Time-invariant potential: $V(\mathbf{r},\mathrm{t}) = V(\mathbf{r})$
2. No interactions between the electrons – (true for photos as bosons)
3. Strong disorder

- Wave phenomenon: can be observed in many waves systems e.g., optical waves.
- Most works so far studied Anderson localization of a *single* wave.
- Here we focus on **transverse Anderson localization of *pseudo-spin*** (two color light waves $\begin{pmatrix} A_i \\ A_s \end{pmatrix}$ coupled by nonlinearity).

P. W. Anderson, *Phys. Rev.* **109**, 1492–1505 (1958).
T. Schwartz et al, *Nature* **446**, 52 (2007).

Spin glass in nonlinear media

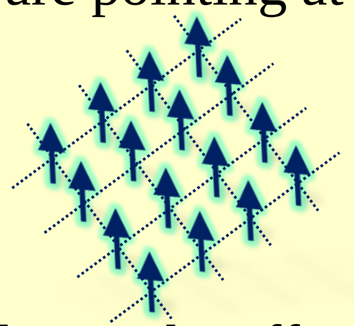
Shani Izhak

The effective magnetization for phase matched process ($\Delta k = 0$) is

$$\mathbf{M}(\mathbf{r}) = \mathbf{M}_{\mathrm{T}}(\mathbf{r}) = \mathrm{Re}\,\kappa\,\hat{\mathbf{x}} + \mathrm{Im}\,\kappa\,\hat{\mathbf{y}}$$
$$= |\kappa(\mathbf{r})|\cos\varphi(\mathbf{r})\,\hat{\mathbf{x}} + |\kappa(\mathbf{r})|\sin\varphi(\mathbf{r})\,\hat{\mathbf{y}}$$

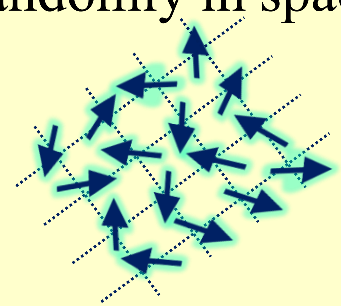
If the **nonlinear coupling $\boldsymbol{\kappa}(\mathbf{r})$** $\propto \boldsymbol{\chi}^{(2)}\boldsymbol{A}_{\boldsymbol{p}}$ is constant we get an **ordered ferromagnet**, where all the spins are pointing at the same direction:

Ferromagnet



But if the nonlinear coupling (and hence the effective magnetization) is random, we get **spin glass** - a disordered magnetic state in which the magnetic moments are aligned randomly in space

Spin - Glass



spin orientation

Psuedo-spin localization

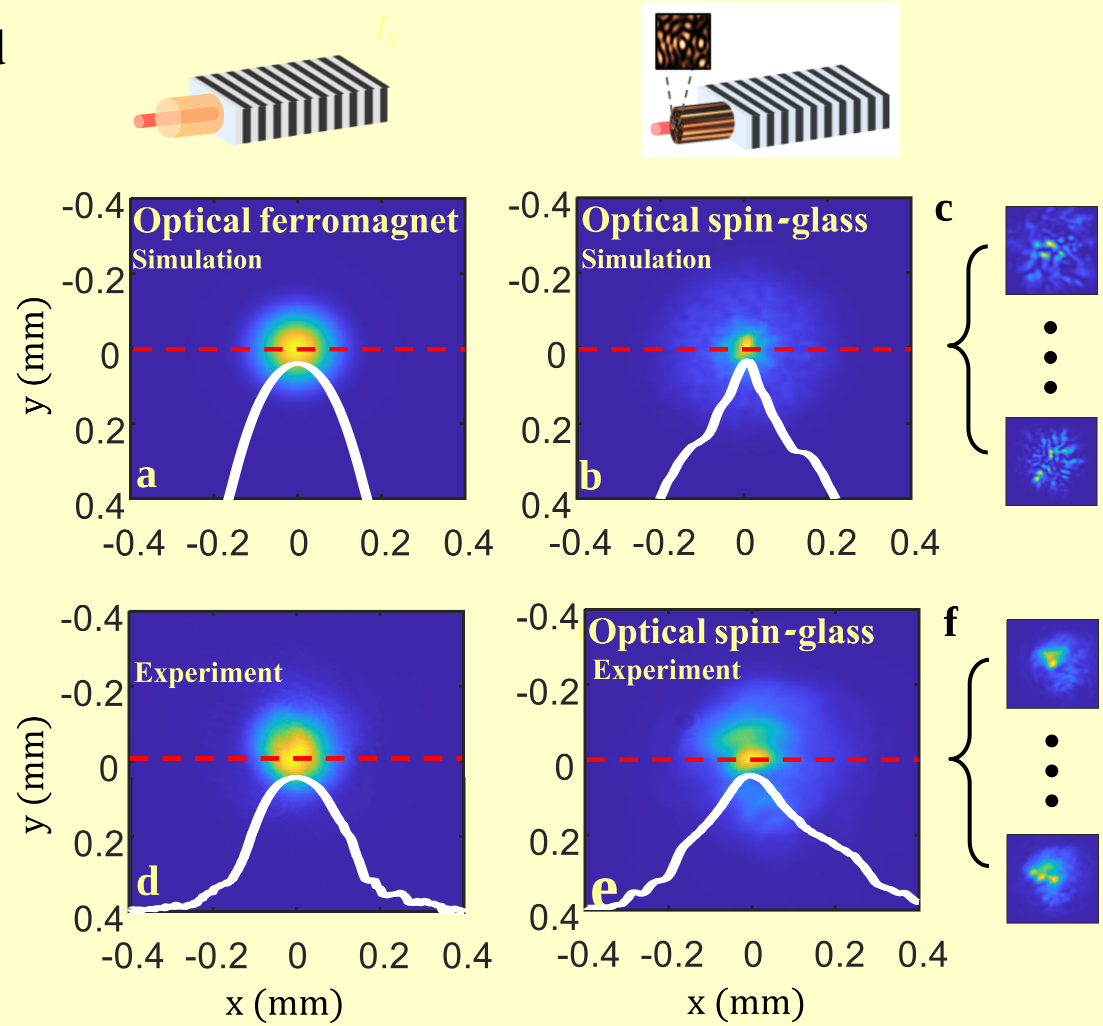
Results for shaping the pump field

- **Ordered** synthetic magnetization:
- **optical ferromagnet**

$$I_s \propto \exp\left(-2\frac{\mathbf{r}_T^2}{\sigma^2}\right) \rightarrow \log(I_s) \propto -\mathbf{r}_T^2$$

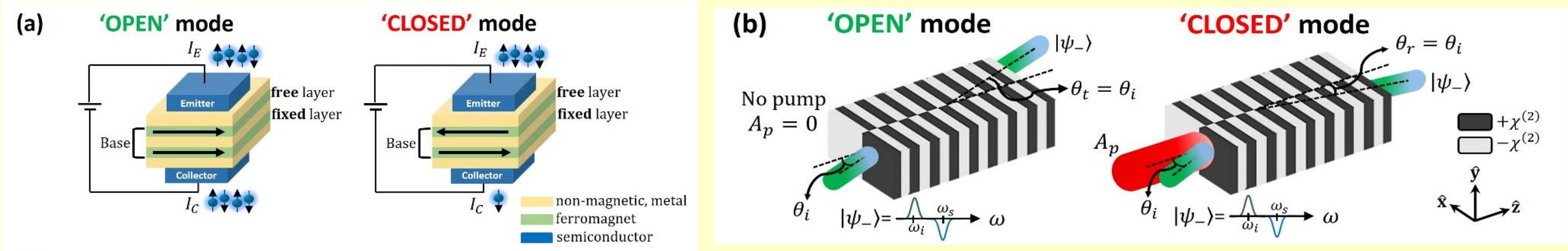
- **Disordered** synthetic magnetization:
- **optical spin-glass**

$$\overline{I_s} \propto \exp\left(-2\frac{|\mathbf{r}_T|}{\xi_{loc}}\right) \rightarrow \log(\overline{I_s}) \propto -|\mathbf{r}_T|$$



Spintronic spin valve and its optical analogue

<u>Our goal</u>: To mimic the functionality of a spintronic spin valve device.

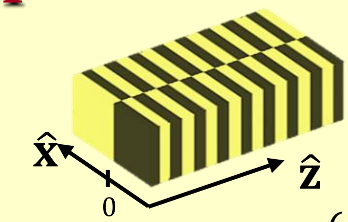


Characteristic	Spintronic Spin Valve	All-optical Spin Valve
Structure	Two ferromagnetic layers	Two synthetic magnetization layers
Operation modes	**Parallel (“P”), open** – high electric current, **Anti-parallel (“AP”), closed** – no current	**“P”, open** – full light **transmission**, **“AP”, closed** – full light **reflection**
How to switch?	An external magnetic field Based on the Giant Magnetoresistance (GMR) effect	An external optical pump field

S. Izhak, .. AA**,** *Opt. Lett.* **49**, 1025 (2024)

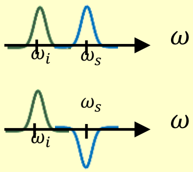
How the spin valve works?

The effective magnetization:

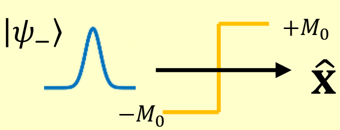


$$\phi_{NLPC}(\mathbf{r}) = \begin{cases}\pi, & x<0\\ 0, & x>0\end{cases}, \qquad \phi_p(\mathbf{r}_T) = const \to \mathbf{M_T}(\mathbf{r}) = \begin{cases}-M_0\,\hat{\mathbf{x}}, & x<0\\ +M_0\,\hat{\mathbf{x}}, & x>0\end{cases}, \qquad M_0 \propto \left|\chi^{(2)}A_p\right|$$

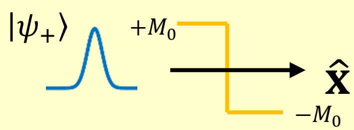
The eigenstates: $\Psi_\pm(\mathbf{r}) = \langle \mathbf{r}|\Psi_\pm\rangle,\ |\Psi_\pm\rangle = |\psi(\mathbf{r})_\pm\rangle \otimes \frac{|\omega_i\rangle \pm |\omega_s\rangle}{\sqrt{2}}$



For $|\Psi_-\rangle$ we get ***potential step***, whereas for $|\Psi_+\rangle$ we get ***potential drop***



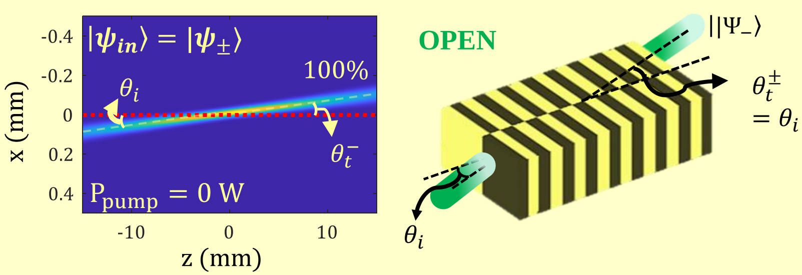
1D step potential



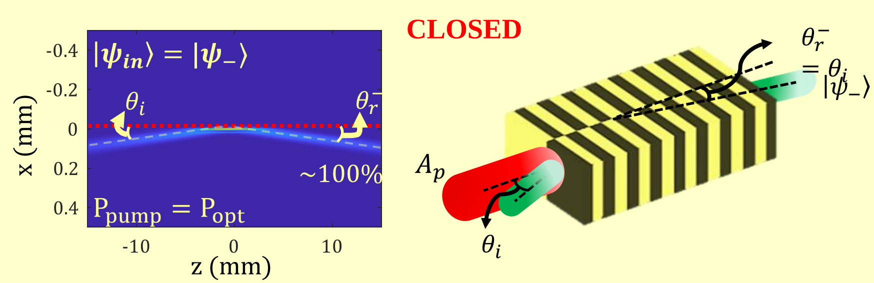
1D potential drop

Therefore, by turning on the pump, we can get ***total internal reflection for $|\Psi_-\rangle$***

No pump, $P_{pump} = 0\ W$



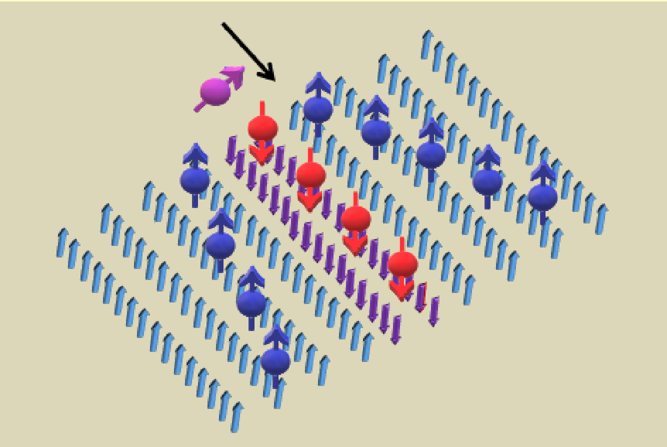
With pump power, $P_{pump} = P_{opt}$



Spin waveguide

A waveguide only for spin-up,
i.e. the in-phase superposition state,

$$|\Psi_+\rangle = \frac{|\omega_i\rangle + |\omega_s\rangle}{\sqrt{2}}$$

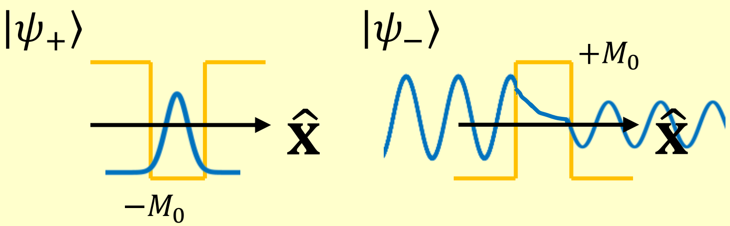


The nonlinear pattern:

$$d(x,z) = \begin{cases} 0.5, & |x| \le a, \\ 0, & else \end{cases}, \qquad \phi_{NLPC}(x) = 0 \ \forall x$$

Potential well for $|\Psi_+\rangle$

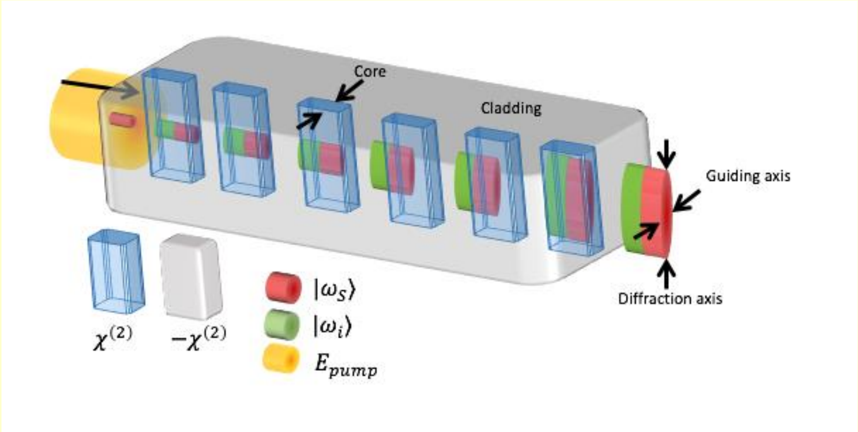
Potential barrier for $|\Psi_-\rangle$



1D finite potential well

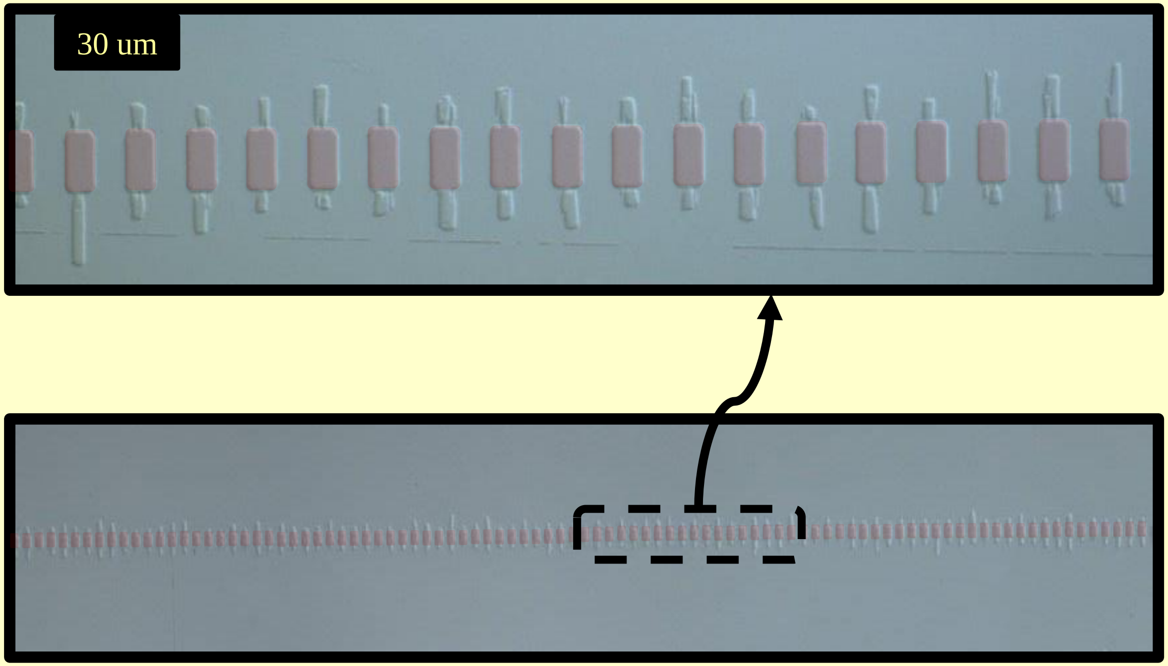
1D potential barrier

Nonlinear crystal for guiding the spin-up superposition beam

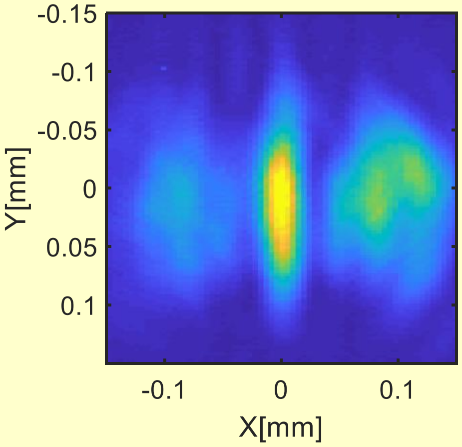


Spin waveguide – experimental results

Microscope image of poled KTP crystal



Measured output intensity for $|\Psi_+\rangle$



Ofir Yesharim

Magnetic skyrmions and the topological Hall effect

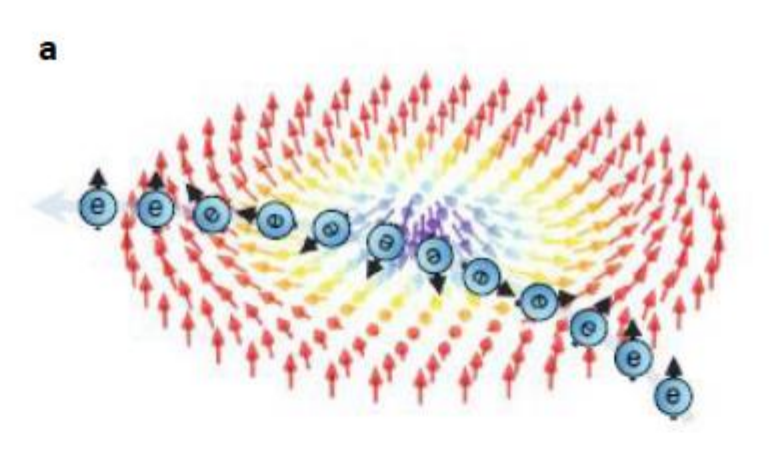
Skyrmions – topologically robust chiral magnetic structures.
The circular symmetric magnetization on a region of radius *R* is :

$$\hat{\mathbf{M}}(\rho,\phi) = \sqrt{1-m^2(\rho)}\left[\cos(n\phi+\eta)\,\hat{\mathbf{x}} + \sin(n\phi+\eta)\,\hat{\mathbf{y}}\right] + m(\rho)\hat{\mathbf{z}}$$

Where *n* determines the ***skyrmion number***:

$$S = [m(R) - m(0)] \times (n/2),$$

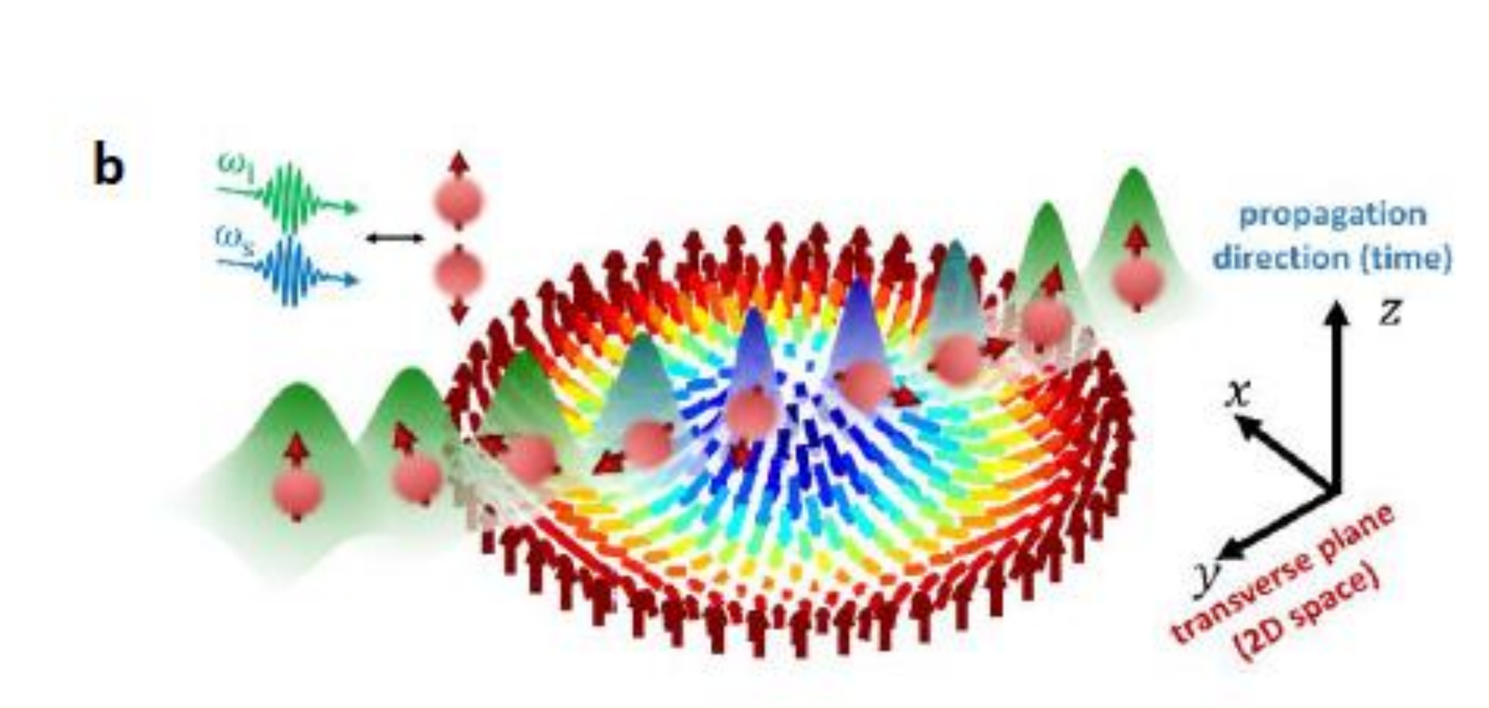
Skyrmions can be used to route spin currents via the ***topological Hall effect***.



Tsymbal and Panagopoulos, *Nature Materials* **17**, 1054 (2018).

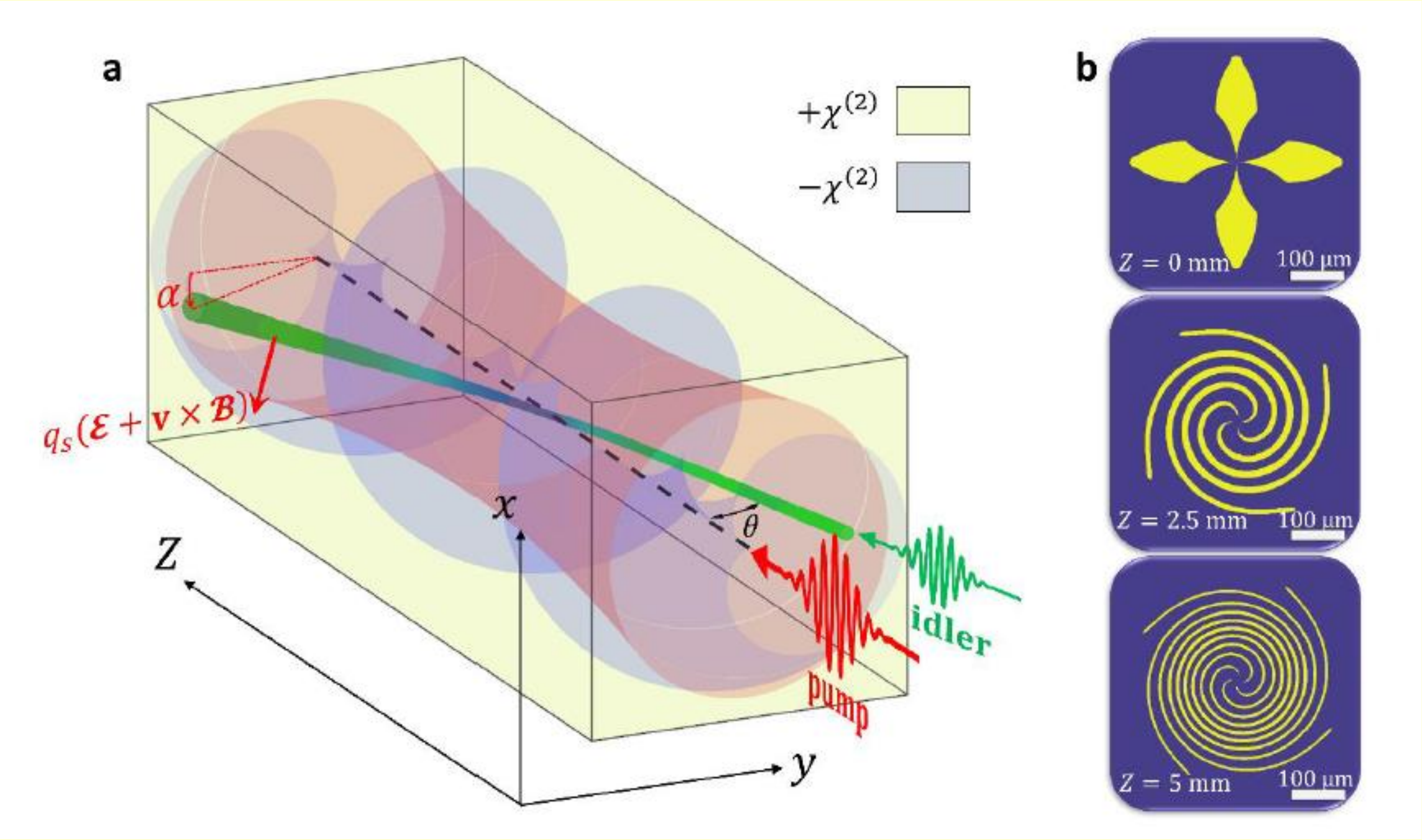
Nonlinear skyrmions & the topological Hall effect for light

Design the nonlinear structure and/or shape of pump beam to form synthetic magnetism in the form of a skyrmion.



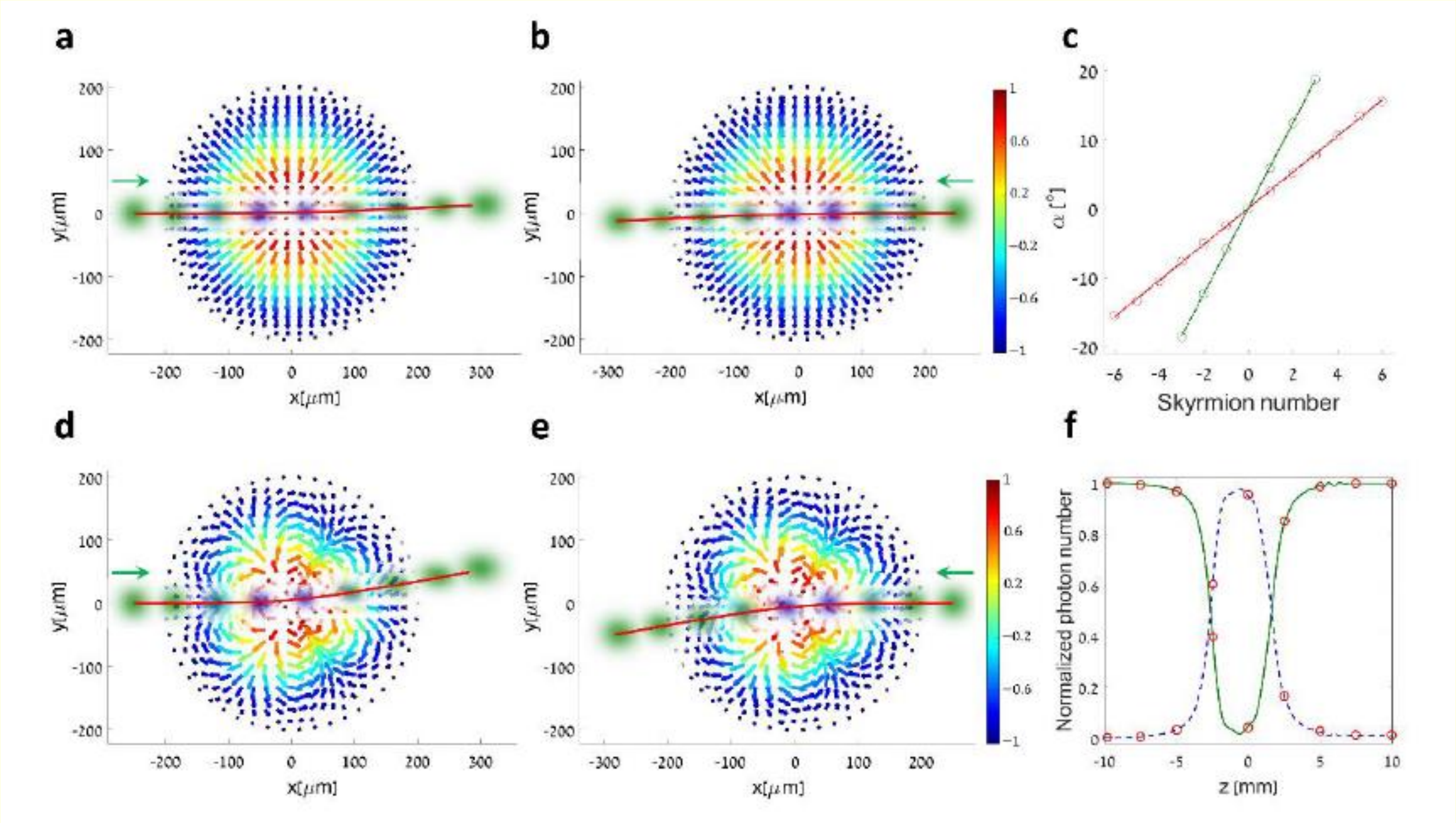
A. Karnieli .. A. Arie, *Nature Communications* **12**,1092 (2021)

Topological Hall Effect for Light Beams



A. Karnieli .. A. Arie, *Nature Communications* **12**,1092 (2021)

Topological Hall Effect for different skyrmion numbers



a, b skyrmion and anti-skyrmion for n=1

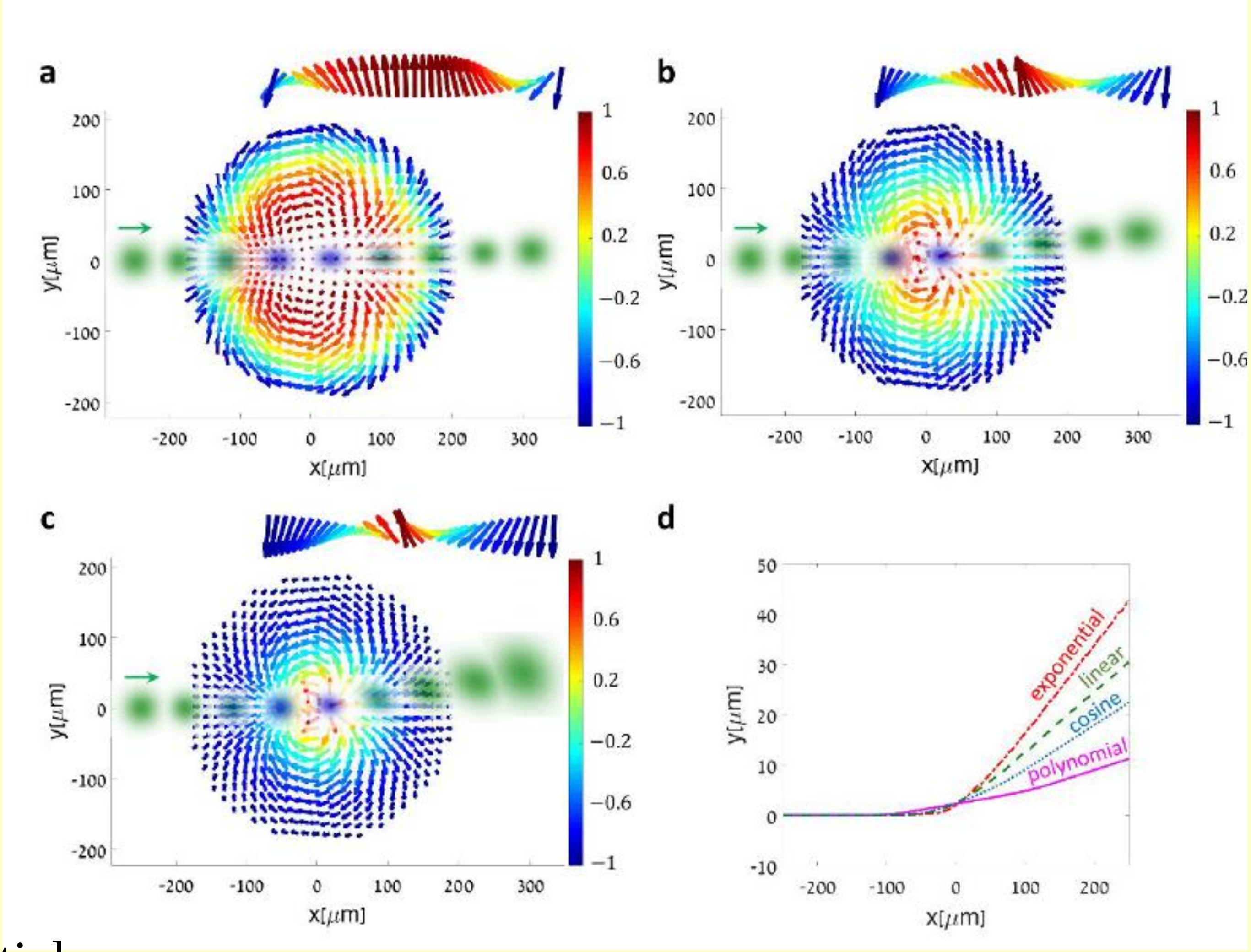
d, e skyrmion and anti-skyrmion for n=4 (considered *unstable* in 'real' magnetic structures).

c- deflection vs. skyrmion number

f- idler and signal dependence on propagation.

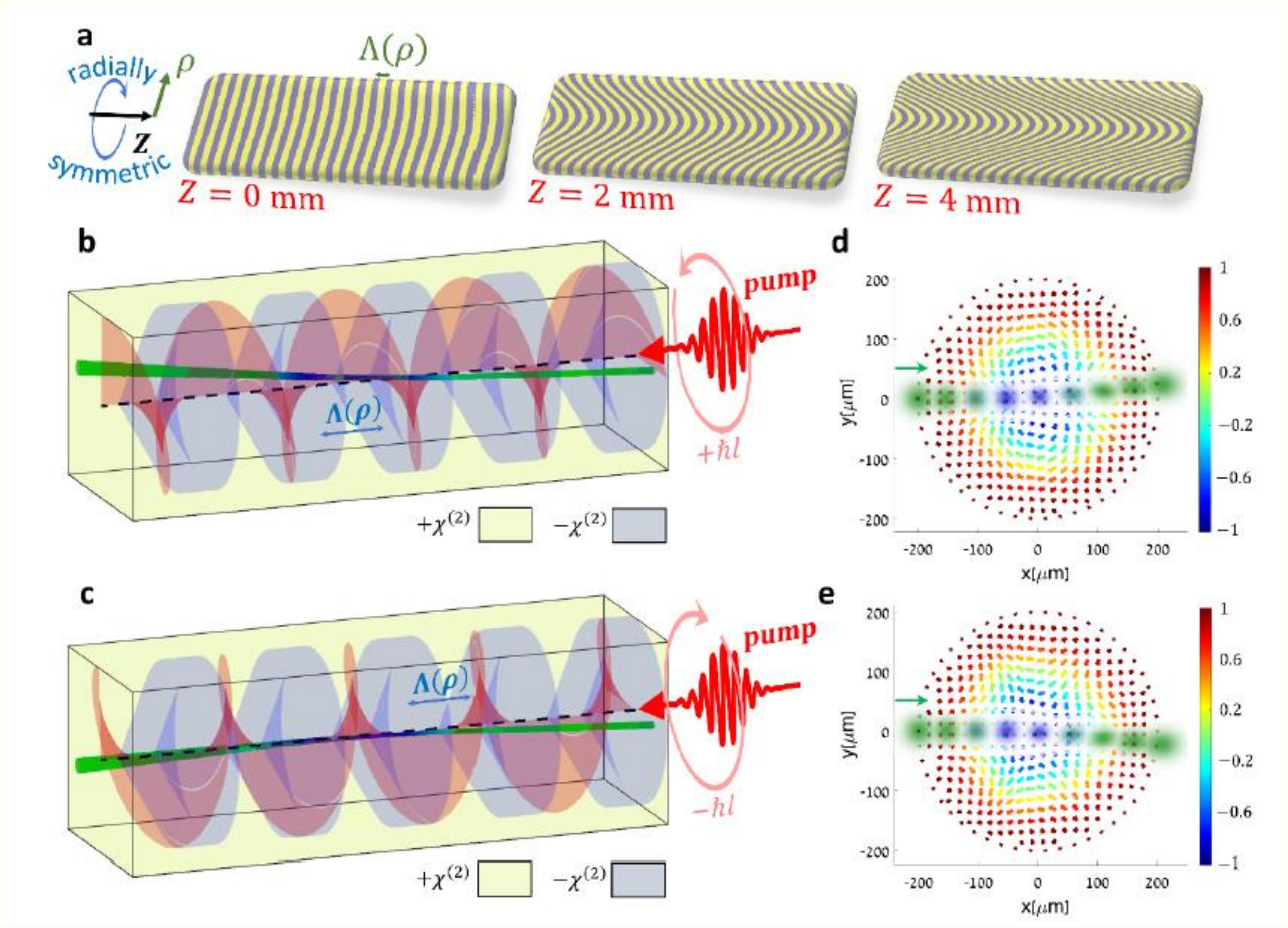
Effects of domain shapes on deflection

Cubic: $m(\rho) = 1 - 2(\rho/R)^3$ Linear: $m(\rho) = 1 - 2\rho/R$



Exponential:
$m(\rho) = exp(-\rho/R)[1 - (\rho/R)(1 + e)]$

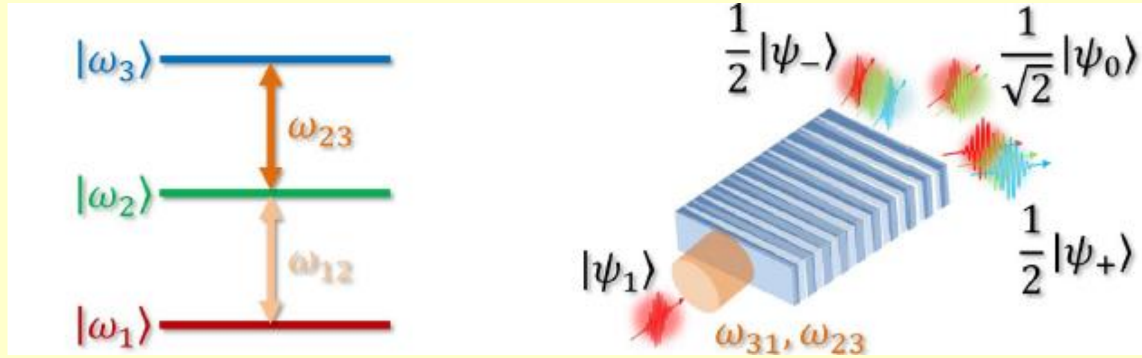
All-optical angular-momentum control of the topological Hall effect for light

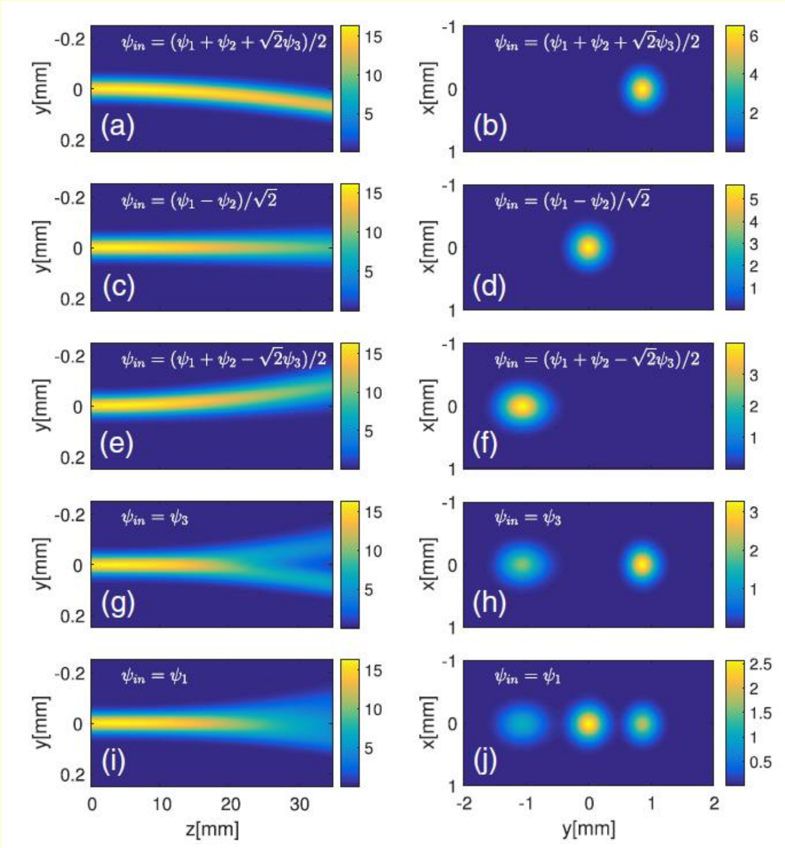


A. Karnieli .. A. Arie, *Nature Communications* **12**,1092 (2021)

Future directions (1)

Spin-1 dynamics using quasiperiodic crystal and two pumps



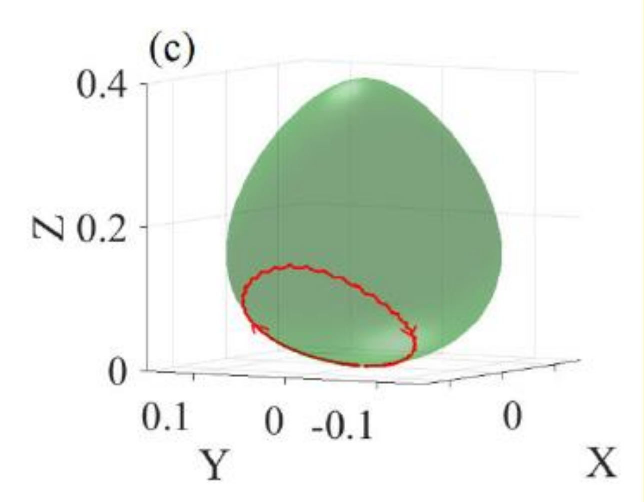


Karnieli and Arie, *Optica* **5**, 1297 (2018)

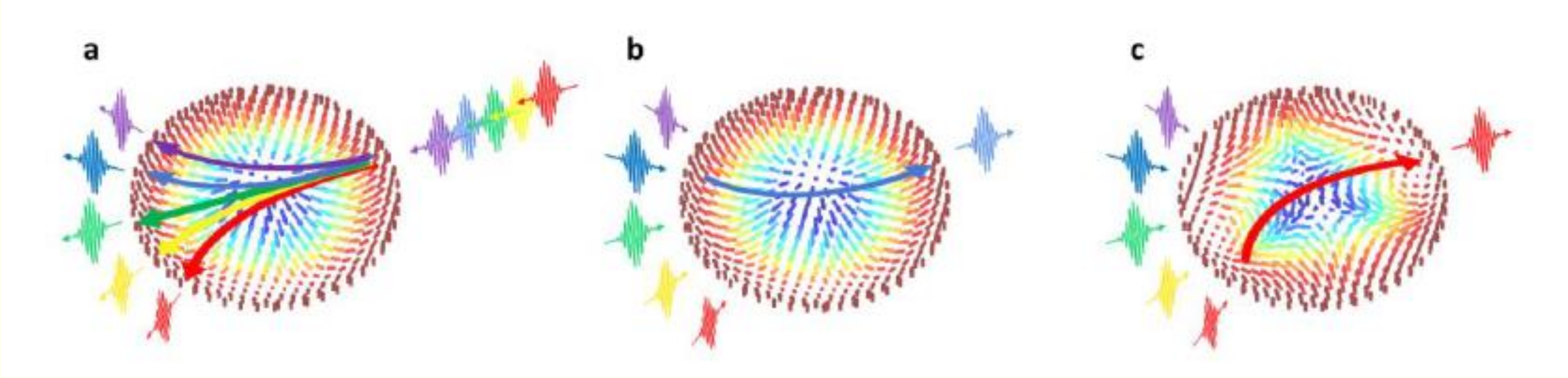
Future directions (2)

Fully nonlinear interaction (pump can also be depleted): magnetization is perturbed by the pseudospin, emulating spin-transfer torque.

Porat and Arie, *JOSAB* (2013)
Li,..AA, *PRA* (2020)



Ultrafast all-optical controlled multiplexers, de-multiplexers and routers.



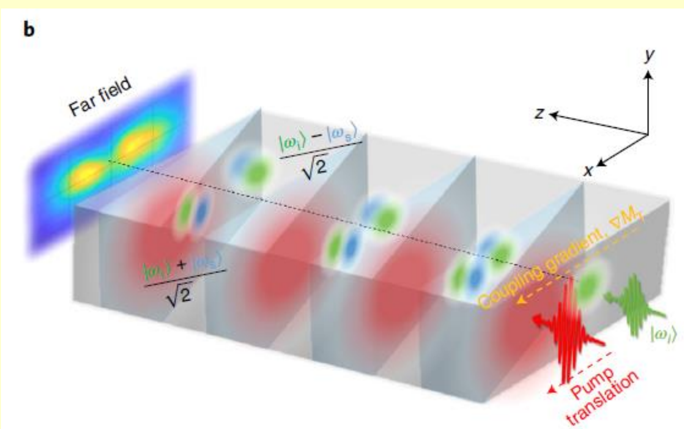
Summary

- SFG with undepleted pump can be modeled as a **two-level system**.

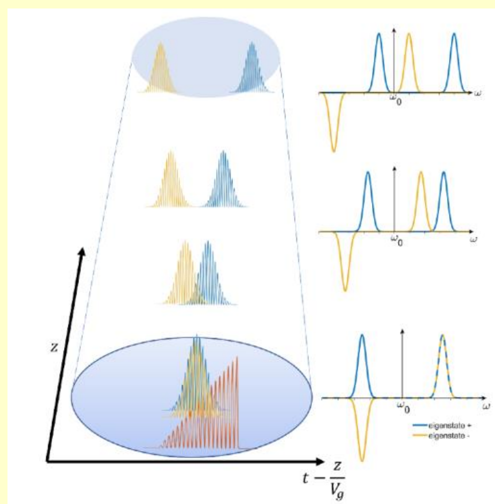
- The nonlinear dynamics is analogous to that of **spin-1/2 in magnetic field**, where the signal-idler vector is the pseudo-spin and the nonlinear coupling emulates the magnetization.

- Enables realization of **new devices and effects that split, switch or guide signal-idler waves according to their relative phase**.

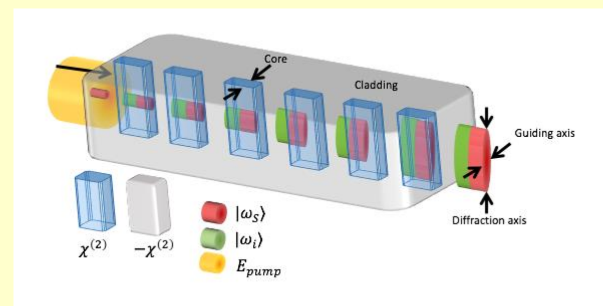
Stern-Gerlach in space

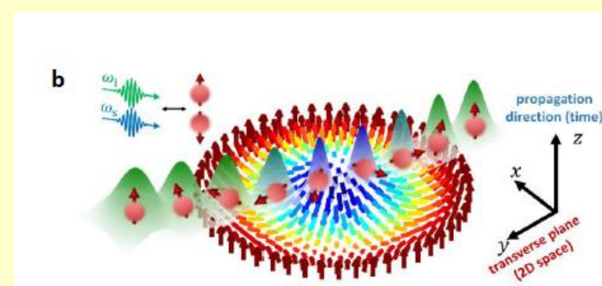


Stern-Gerlach in time



Spintronic devices





Thank You

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