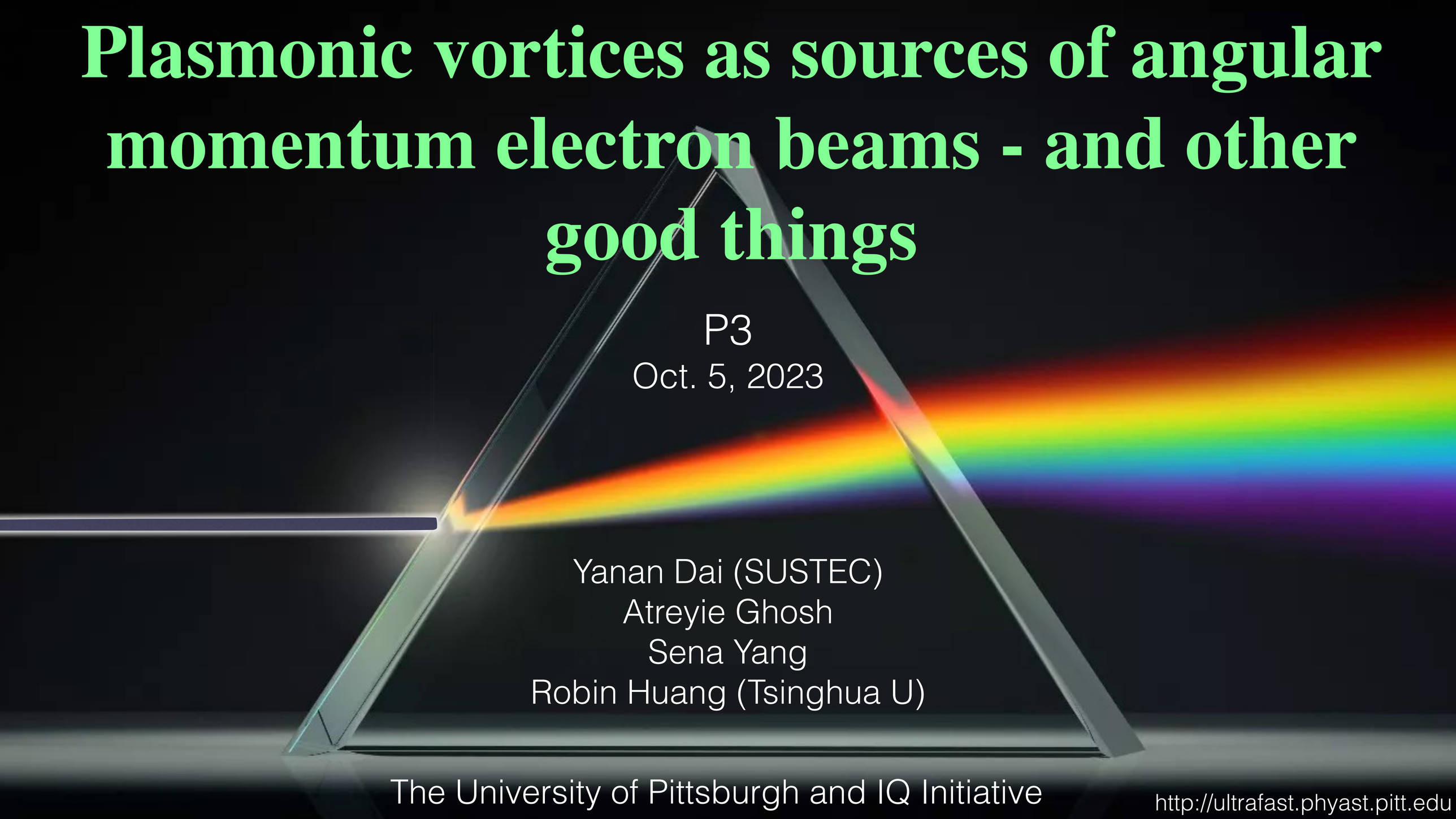
Plasmonic vortices as sources of angular momentum electron beams - and other good things

P3

Oct. 5, 2023



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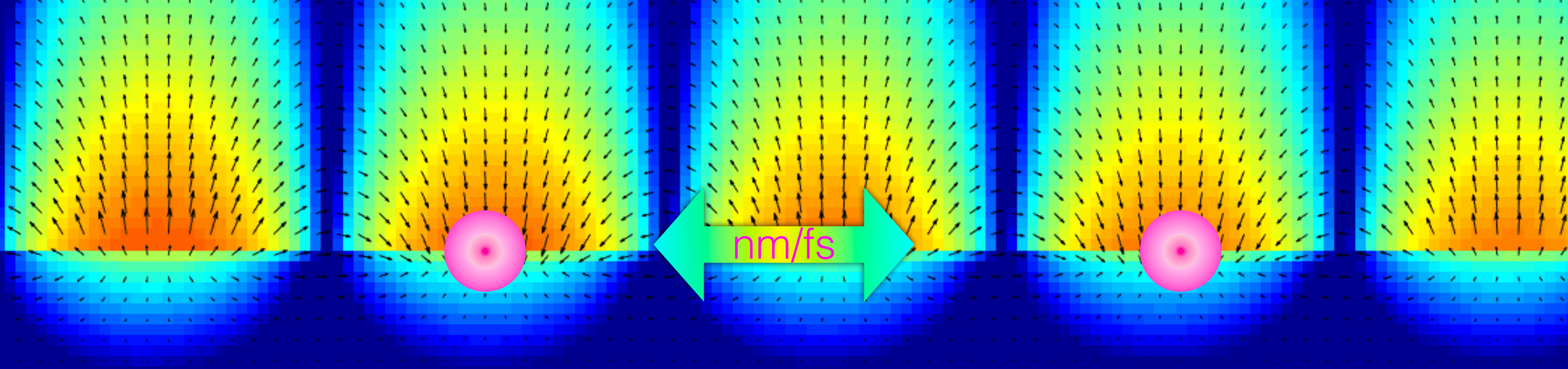


Floquet engineering of nonlinear photoemission fields.

Vectorial electromagnetic fields beyond Maxwell?

Ultrafast photoelectron emission microscopy - how to see light.

Nanofemto electron imaging the spin-orbit interaction of light.

Vortices - topology, parity-time symmetry, and arrays.

Magnetoelectric ($E \cdot B$) interaction.

Floquet engineering of metal surface states

$$\Psi_\alpha(x,t) = \exp\left(-\frac{i\epsilon_\alpha t}{\hbar}\right)\Phi_\alpha(x,t)$$
$$\text{where } \Phi_\alpha(x,t) = \Phi_\alpha(x,t+T)$$

$\hbar\omega_L = \epsilon_\alpha$

image potential states do not preexist

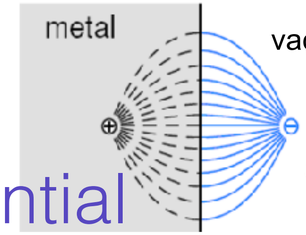
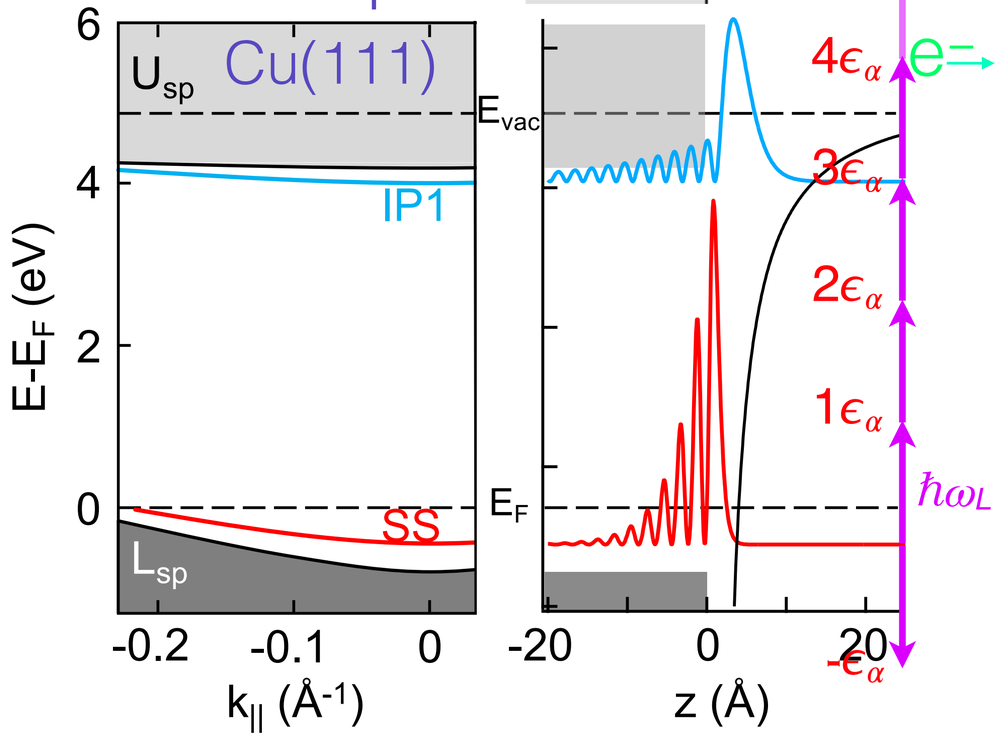
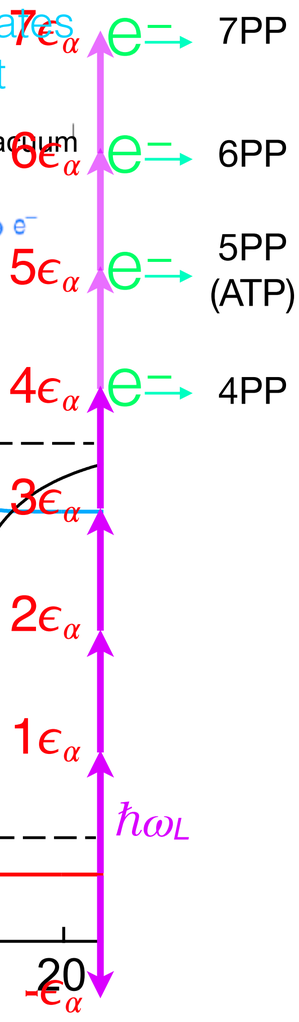


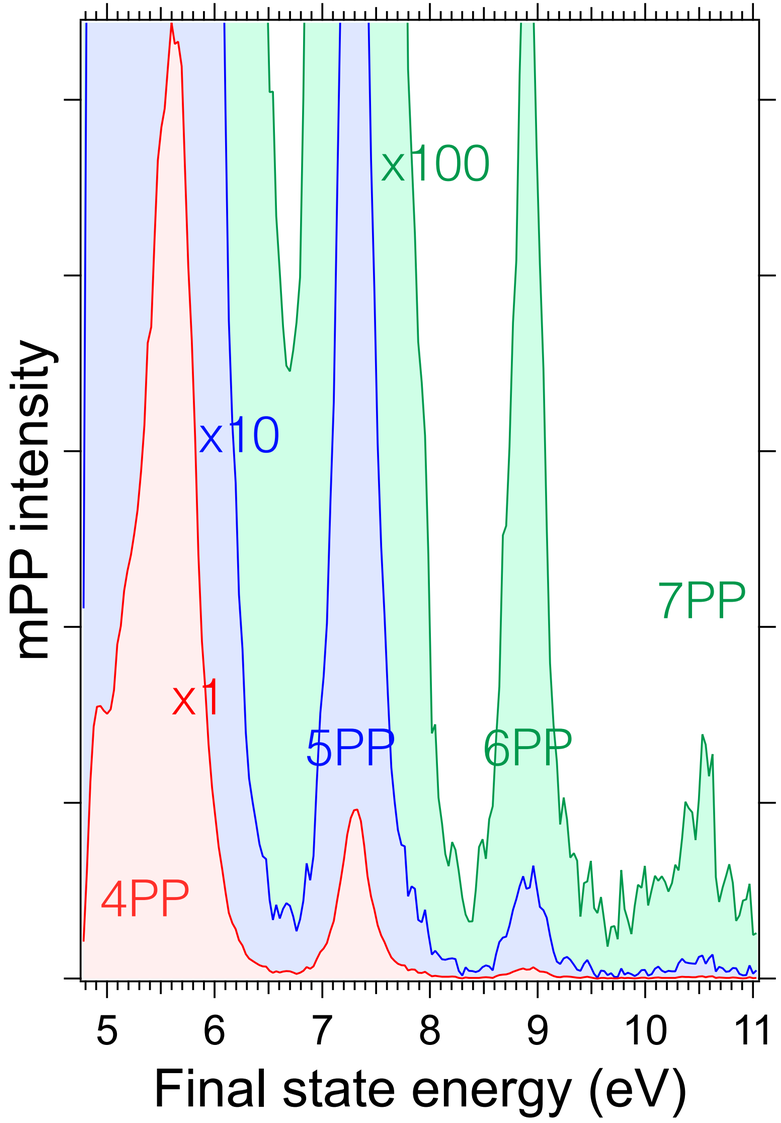
Image potential

lattice potential

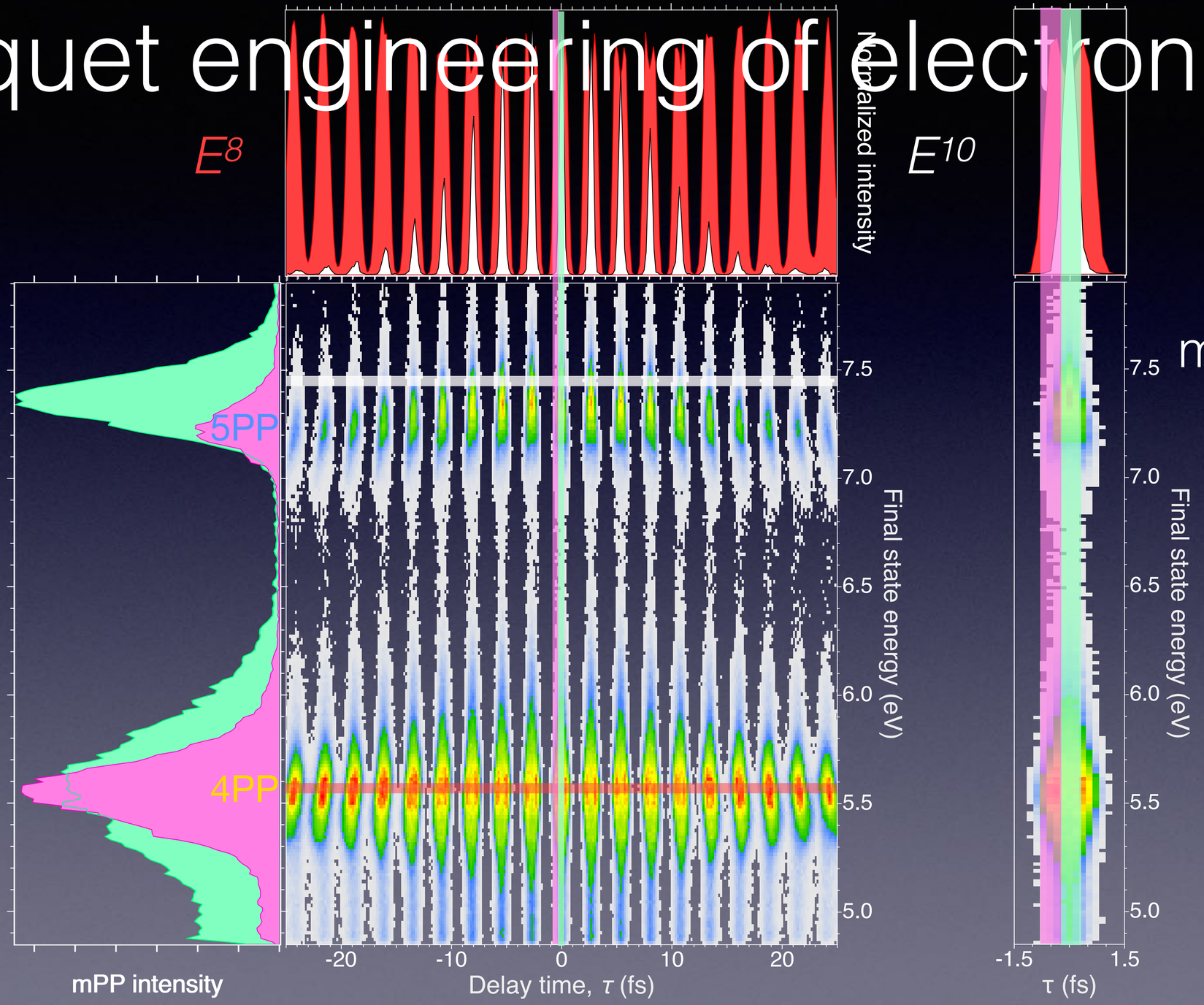


Floquet ladder





Floquet engineering of electronic bands



How fast does matter respond?

Magnetoelectric effect of pseudoscalar $E \cdot B$

- Topological field theory relates $E \cdot B \neq 0$ to magnetic monopoles and axion quasiparticles
- under this condition H induces polarization P, and D magnetization M
- $E \cdot B \neq 0$ is a material property when $\mathscr{P}$ and $\mathscr{T}$ are anti-symmetric, but $\mathscr{PT}$ symmetry is preserved

Maxwell's equations when $E \cdot B \neq 0$

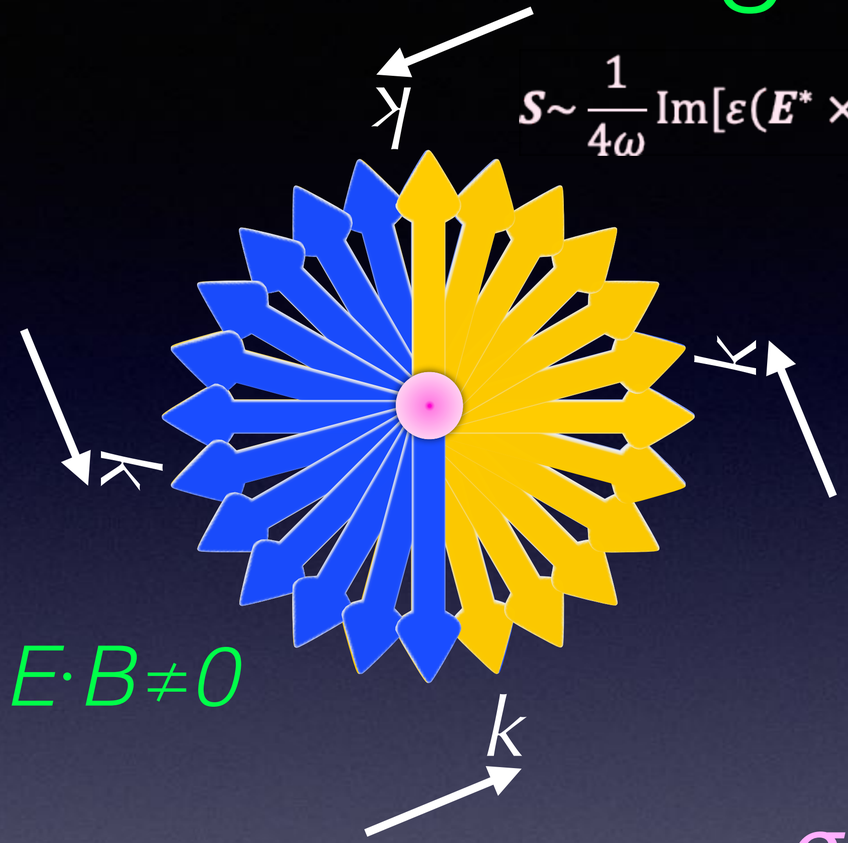
Name	Equations
Gauss's law	$\nabla \cdot (\mathbf{E} - \kappa\,\theta\,c\mathbf{B}) = \dfrac{\rho_e}{\varepsilon_0}$
Gauss's law for magnetism	$\nabla \cdot (c\mathbf{B} + \kappa\,\theta\,\mathbf{E}) = c\mu_0\rho_m$
Faraday's law	$\nabla \times (-\mathbf{E} + \kappa\,\theta\,c\mathbf{B}) = \partial_{ct}(c\mathbf{B} + \kappa\,\theta\,\mathbf{E}) + \mu_0\,\mathbf{J}_m$
Ampère–Maxwell law	$\nabla \times (c\mathbf{B} + \kappa\,\theta\,\mathbf{E}) = \partial_{ct}(\mathbf{E} - \kappa\,\theta\,c\mathbf{B}) + c\mu_0\,\mathbf{J}_e$
Axion law	$\left(\Box + m_{\mathrm{A}}^2\right)\,\theta = -\kappa\,\mathbf{E}\cdot\mathbf{B}$

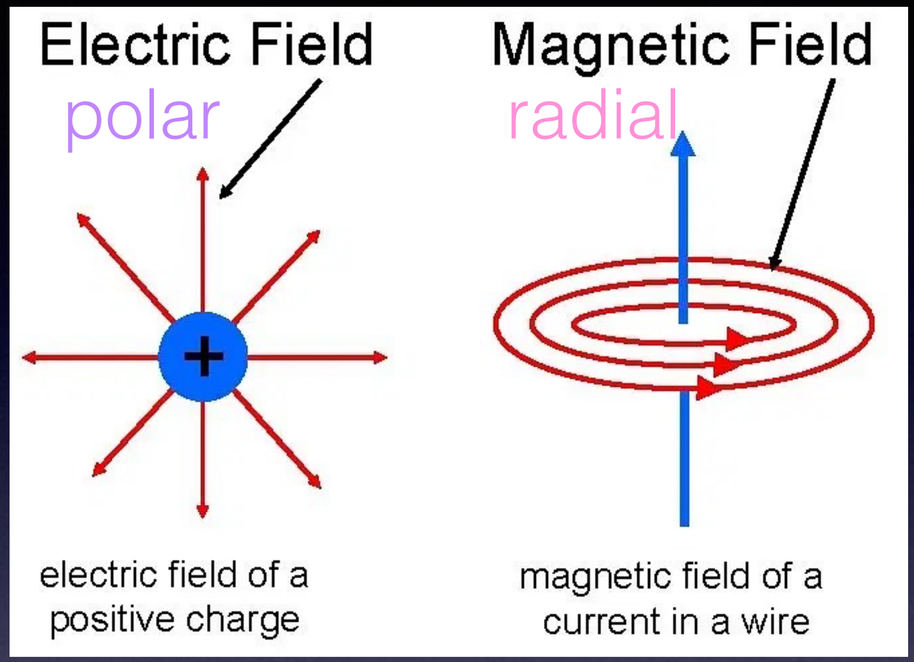
Magnetoelectric effect

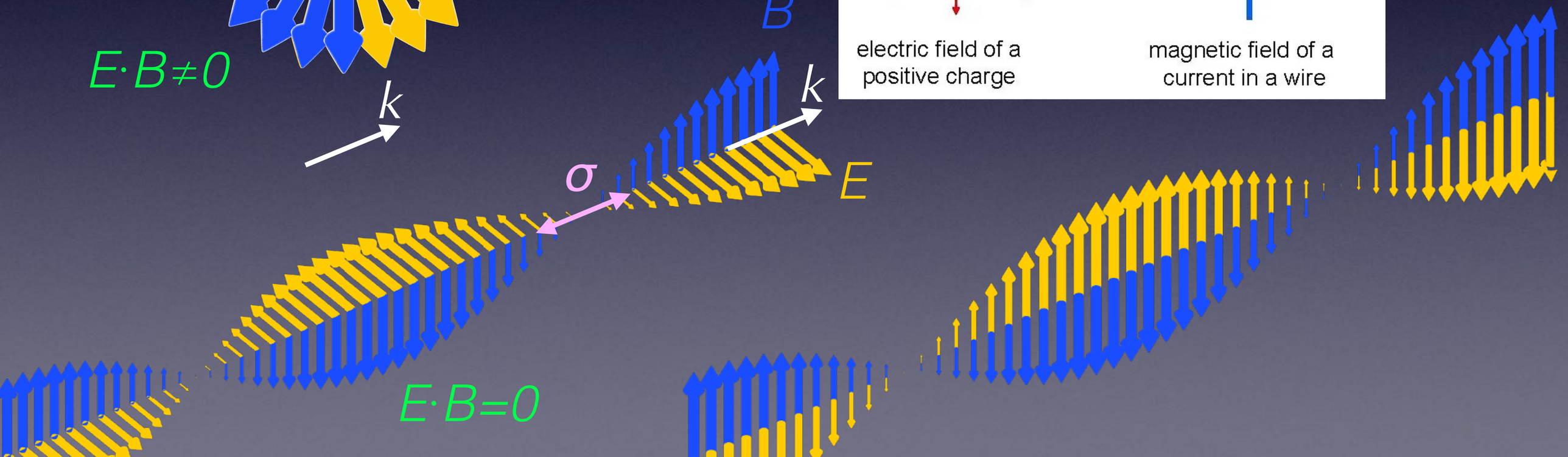
$$\begin{bmatrix} \mathbf{E}' \\ c\mathbf{B}' \end{bmatrix} = \begin{bmatrix} \mathbf{E} - \kappa\,\theta\,c\mathbf{B} \\ \kappa\,\theta\,\mathbf{E} + c\mathbf{B} \end{bmatrix} = \frac{1}{\cos\xi} \begin{bmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{bmatrix} \begin{bmatrix} \mathbf{E} \\ c\mathbf{B} \end{bmatrix}$$

Coherent magnetoelectric *E·B* interaction

$$S \sim \frac{1}{4\omega} \mathrm{Im}[\varepsilon(E^* \times E) + \mu(H^* \times H)]$$







Vectorial properties of optical vortex light

Spin angular momentum (SAM)
rotating polarization

Orbital angular momentum (OAM)
rotating wavefront

Maxwell's equations very versatile, but ..

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

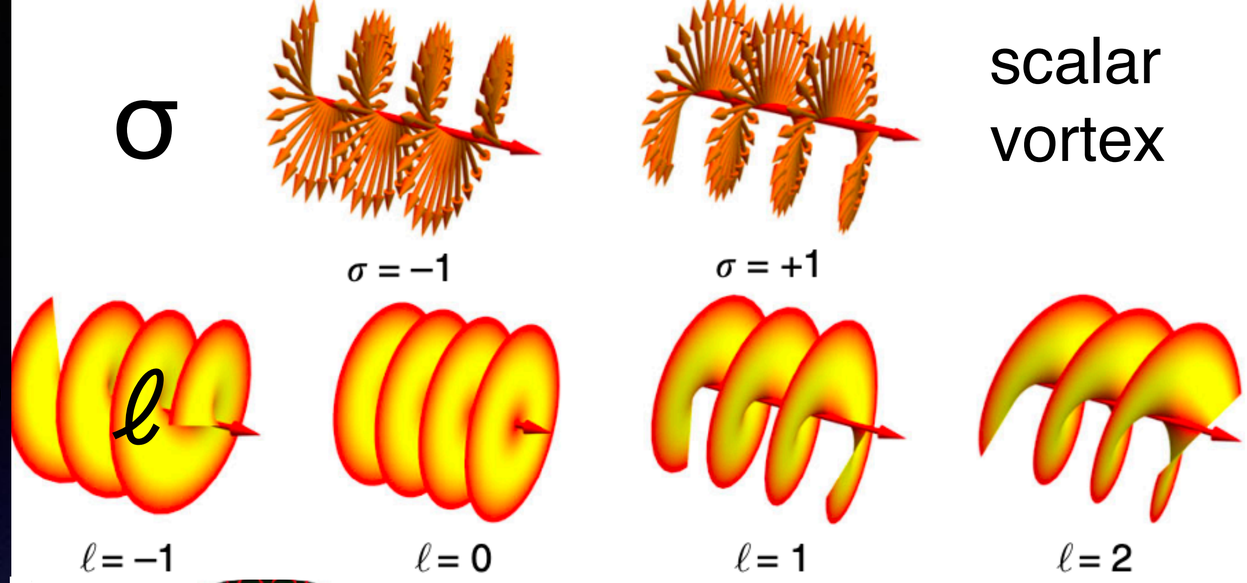
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$$

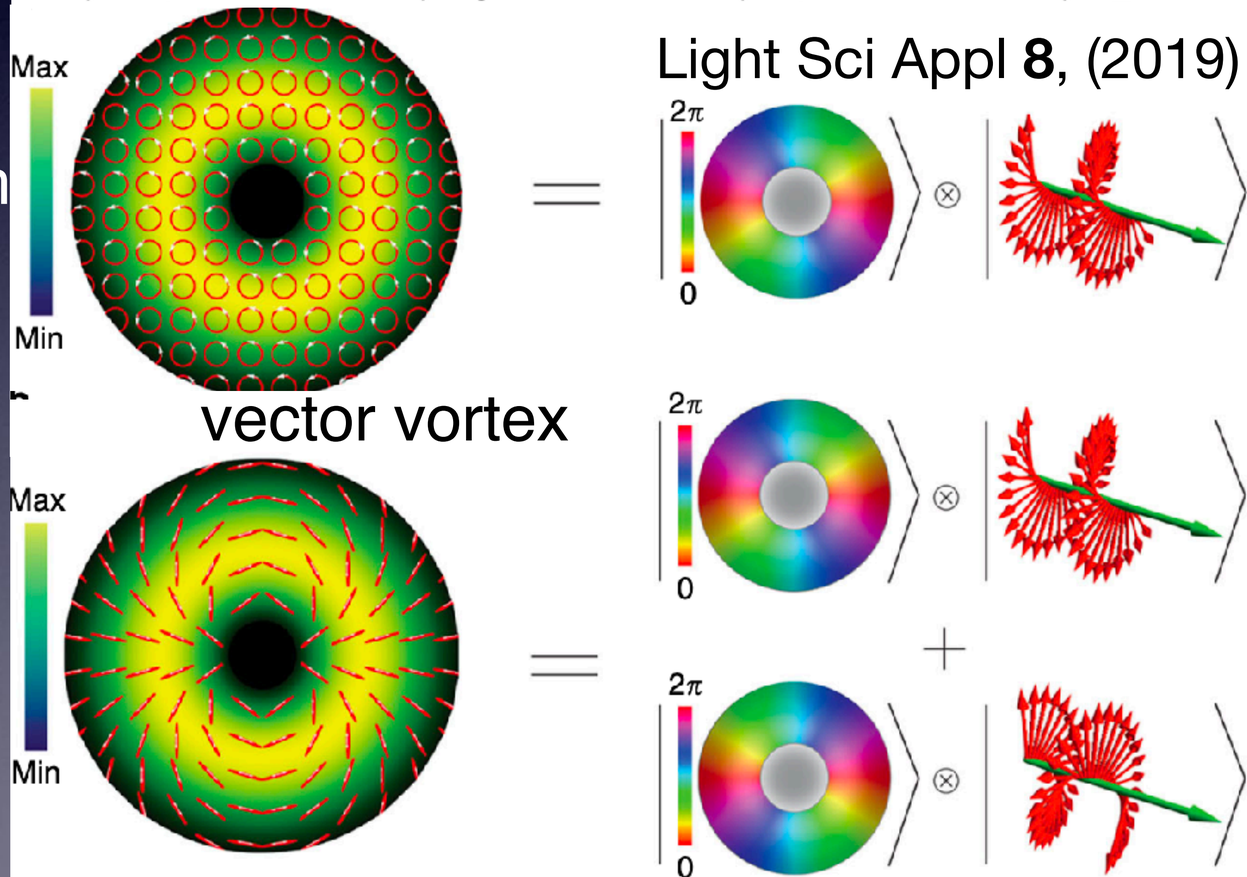
Conservation of angular momentum
J=L+S

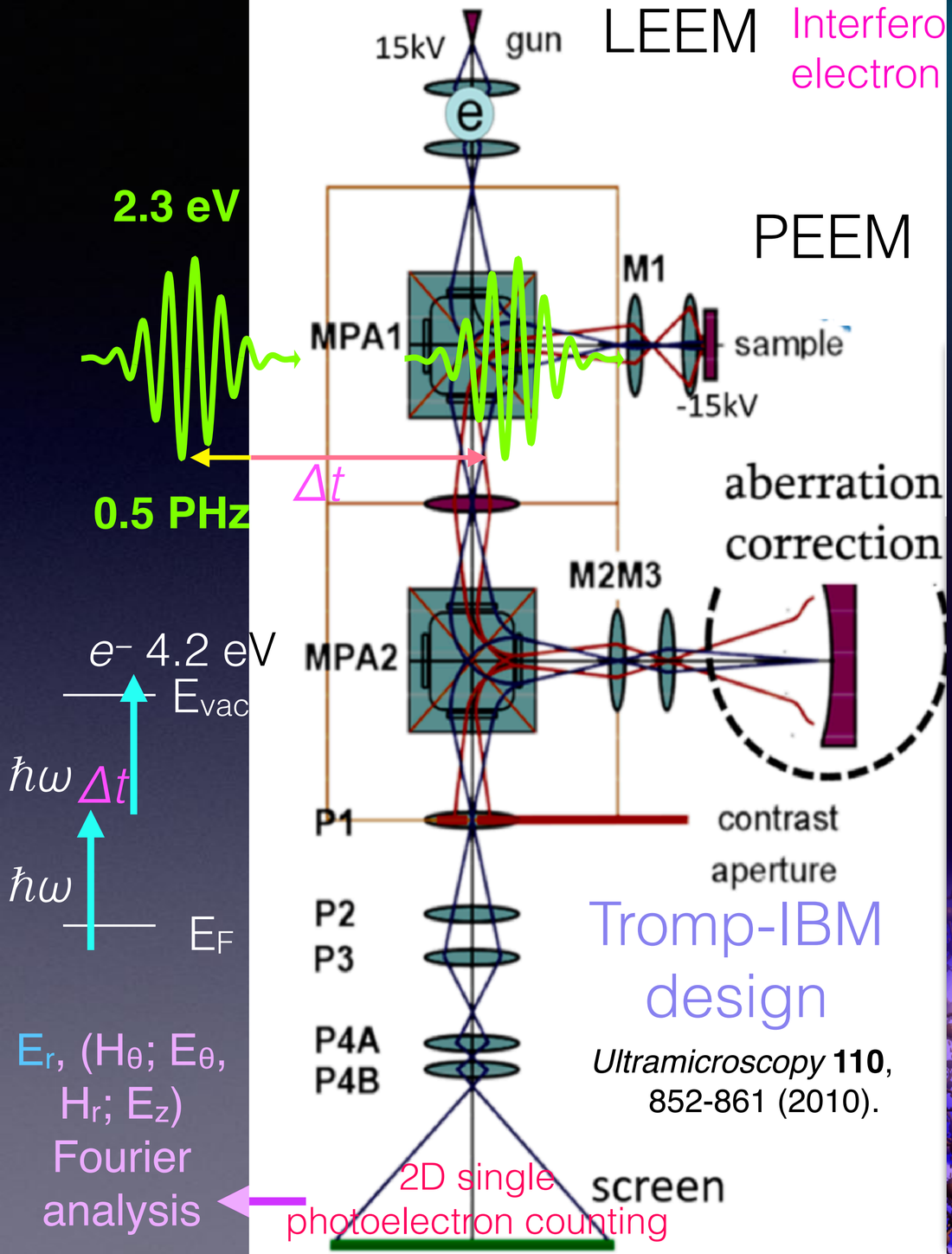
Spin-orbit interaction of light

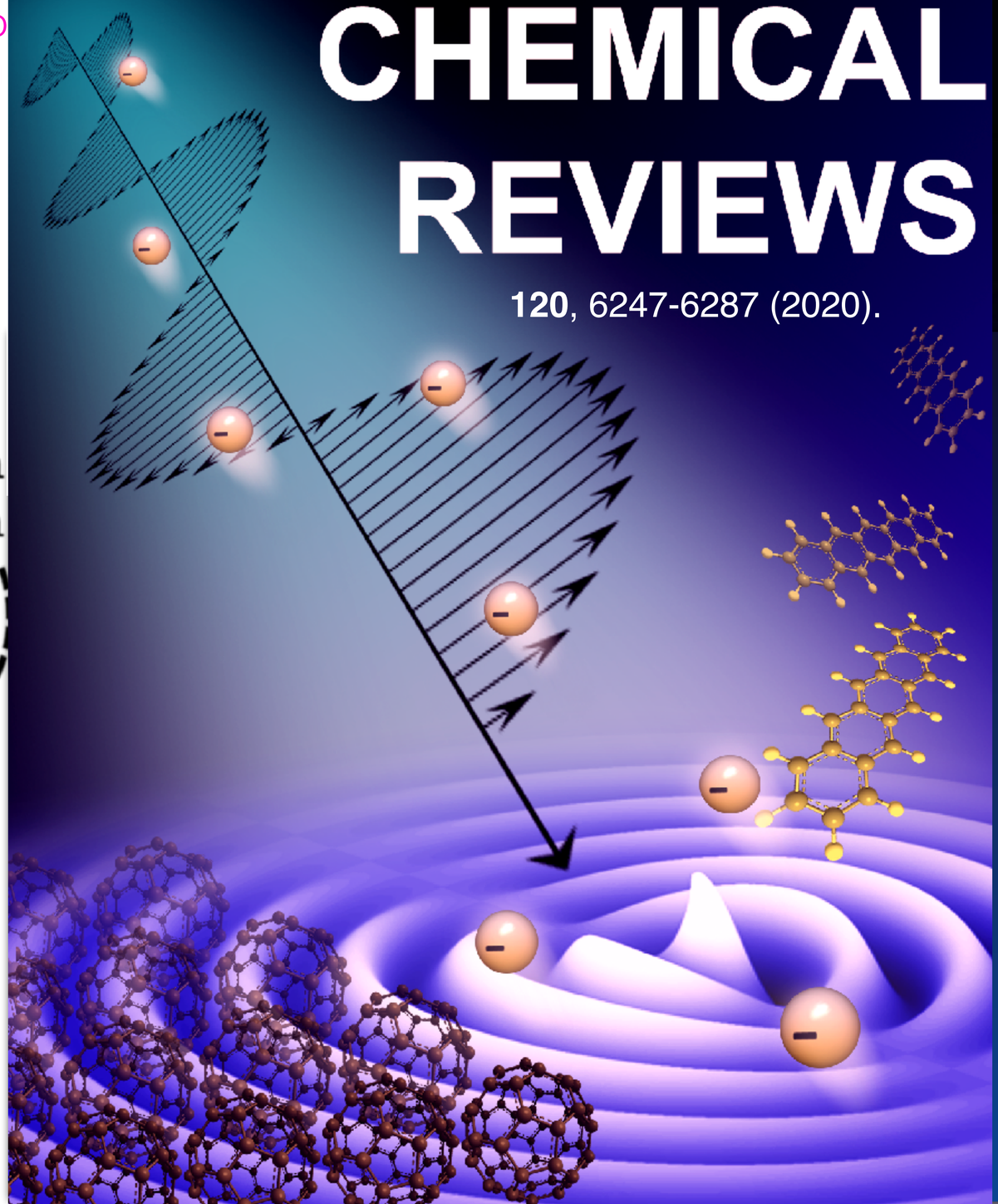
Degrees of freedom of light:
Amplitude, phase, polarization, spin and orbital angular momentum with nonseparable phase and polarization wavefronts.



Light Sci Appl **8**, (2019)

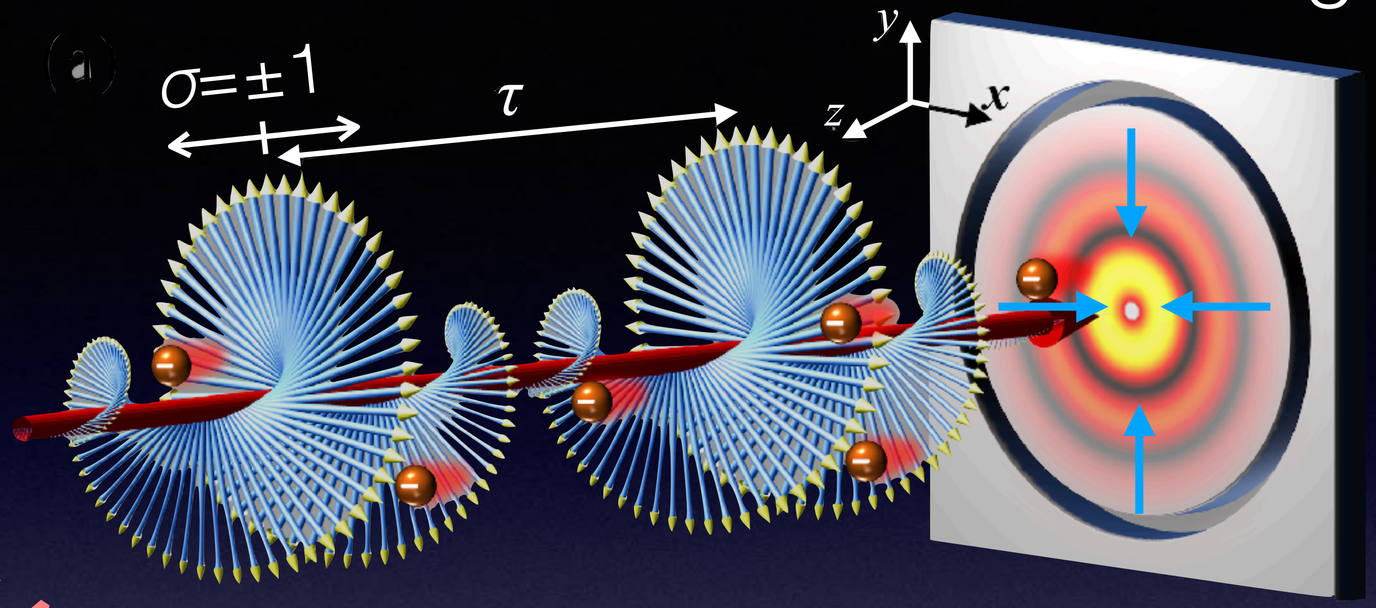



2.3 eV
0.5 PHz
Δt
e⁻ 4.2 eV
Evac
ħω
Δt
ħω
EF
15kV
gun
LEEM
Interfero
electron
e
PEEM
M1
MPA1
sample
-15kV
aberration
correction
M2M3
MPA2
P1
contrast
aperture
P2
P3
P4A
P4B
screen
2D single
photoelectron counting
Er, (Hθ; Eθ,
Hr; Ez)
Fourier
analysis
Tromp-IBM
design
Ultramicroscopy 110,
852-861 (2010).

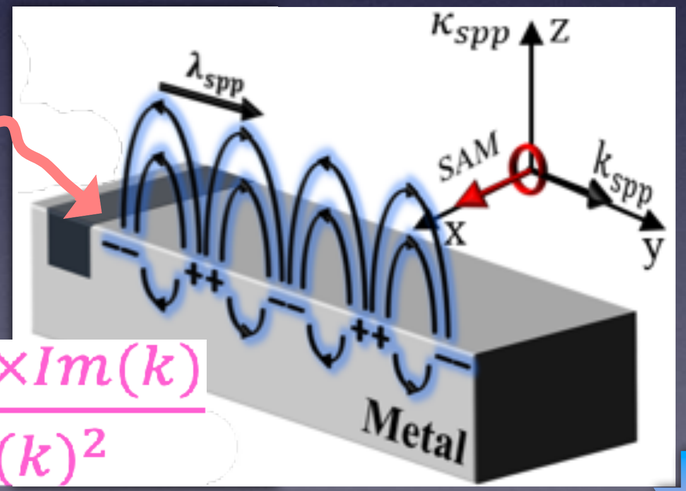

CHEMICAL
REVIEWS
120, 6247-6287 (2020).

Plasmonic vortices-SO interaction of light

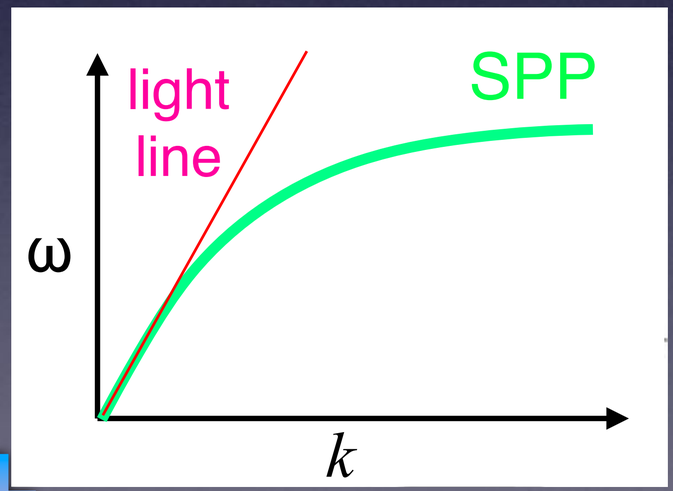
orbital angular momentum



plasmonic spin Hall effect

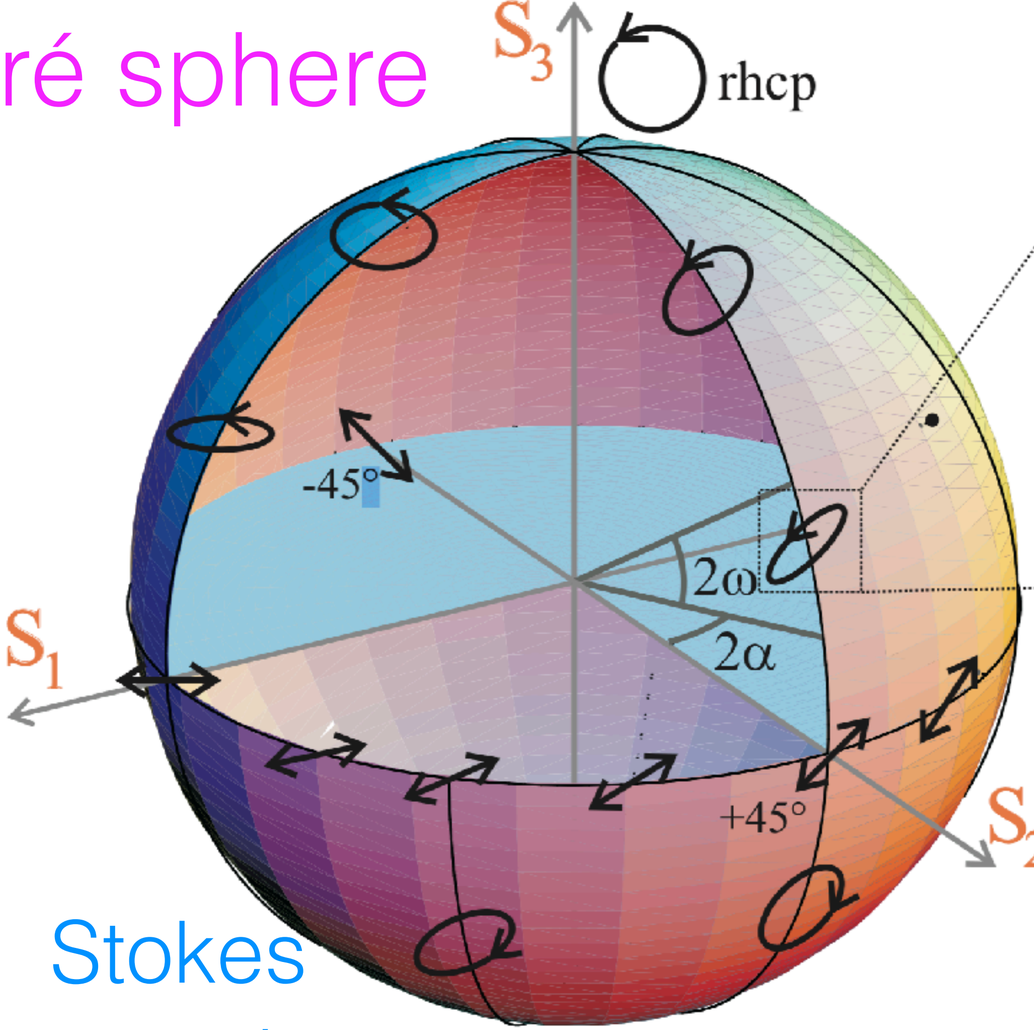


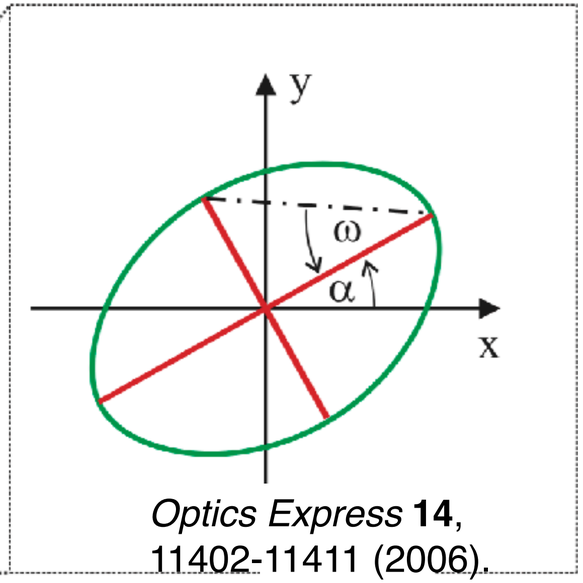
$$S \propto \frac{Re(k)\times Im(k)}{Re(k)^2}$$



spin-momentum locking

Poincaré sphere





Optics Express **14**, 11402-11411 (2006).

$$Q = \frac{1}{4\pi}\iint d^2r\vec{\vec{S}}\cdot\left(\frac{\partial\vec{\vec{S}}}{\partial x}\times\frac{\partial\vec{\vec{S}}}{\partial y}\right)$$

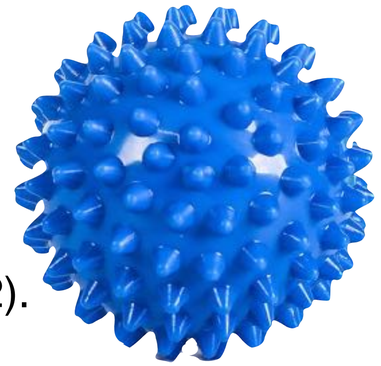
Topological spin textures

Equator - L-line- S-in-plane

skyrmion

Q=1

Appl. Phys. Rev. **9**, 011420 (2022).



Stokes parameters

Pole - C-point - S-normal

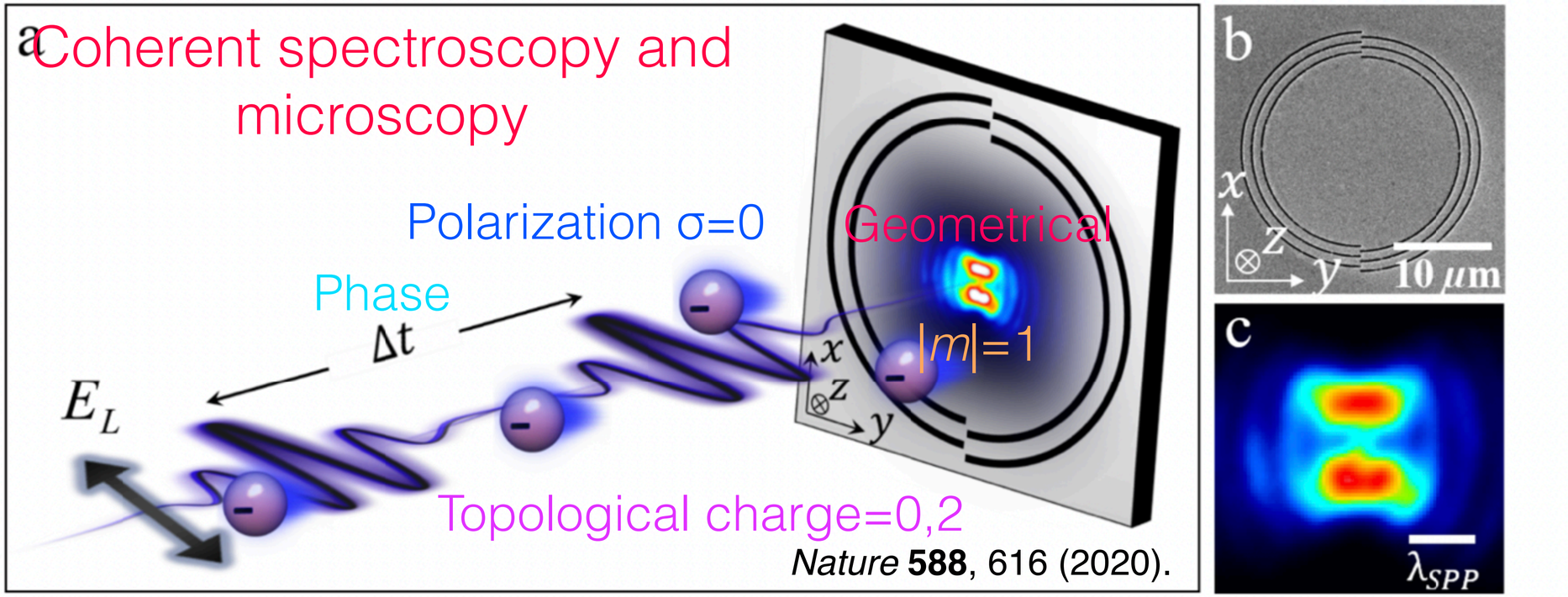
meron

½ skyrmion

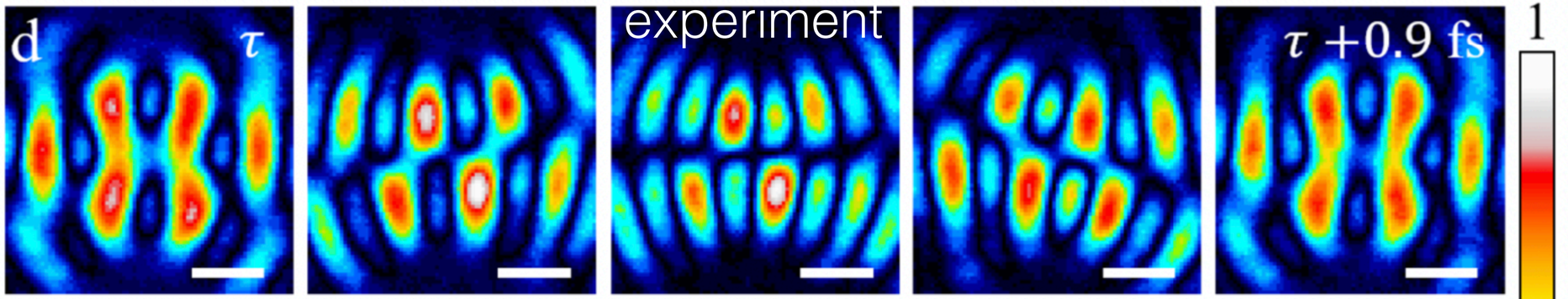
Q=½

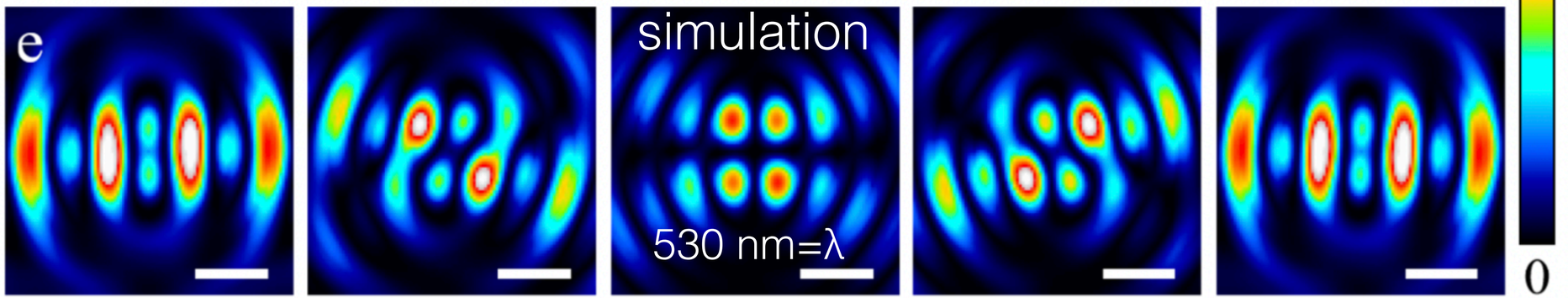
Nature **588**, 616 (2020).

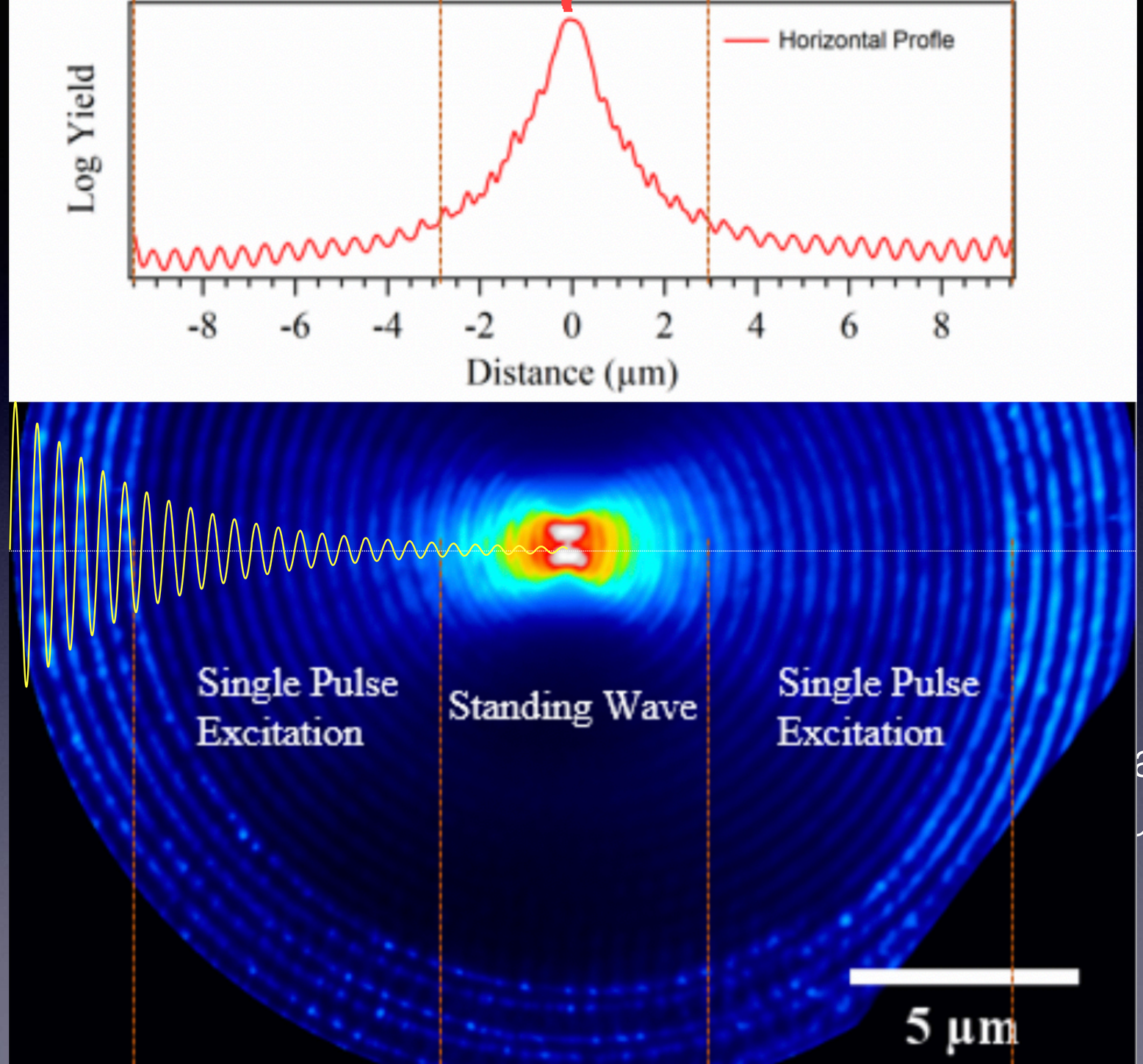
$$\begin{aligned}
S_0 &= |E_x|^2 + |E_y|^2, &&= I,\\
S_1 &= |E_x|^2 - |E_y|^2 &&= I_{0^\circ} - I_{90^\circ}\\
S_2 &= E_x^* E_y + E_x E_y^* &&= I_{45^\circ} - I_{135^\circ}\\
S_3 &= -i(E_x^* E_y - E_x E_y^*) &&= I_{\mathrm{rhcp}} - I_{\mathrm{lhcp}}
\end{aligned}$$



Nature **588**, 616 (2020).



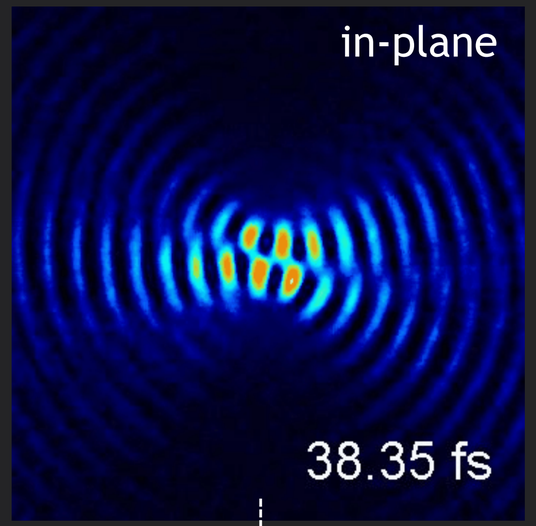




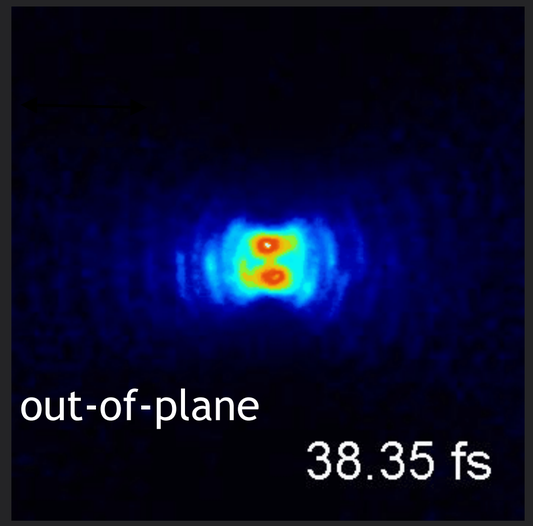
E_{SPP}

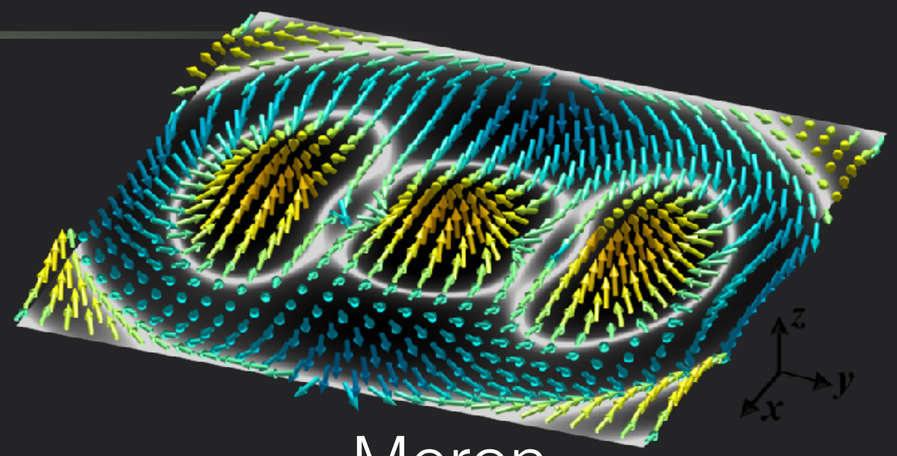
ase
ularity

Locating Meron (half-skyrmion) with PEEM



Fourier Filtering

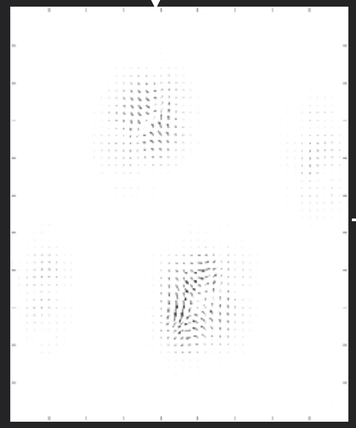




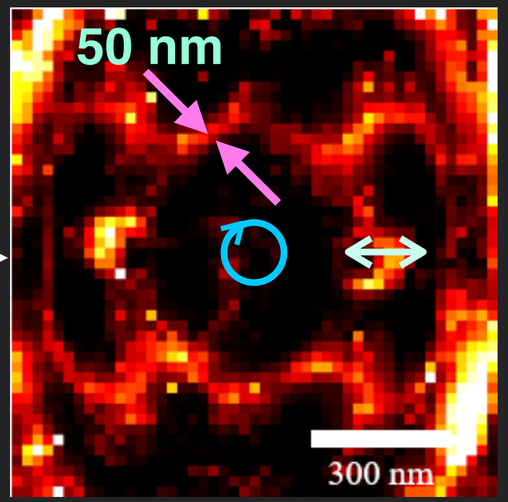
Meron

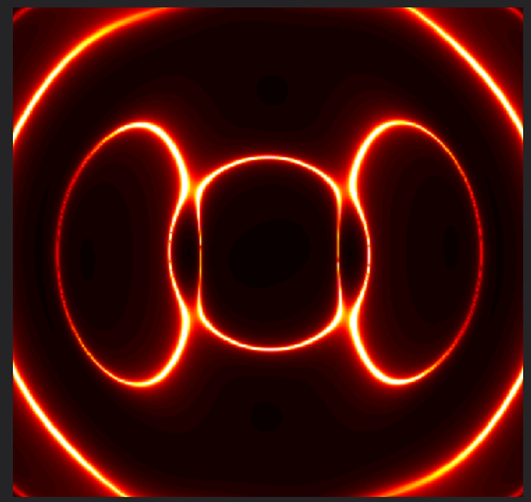
Nature **588**, 616 (2020)
Nature Reviews Physics **4**, 562 (2022)

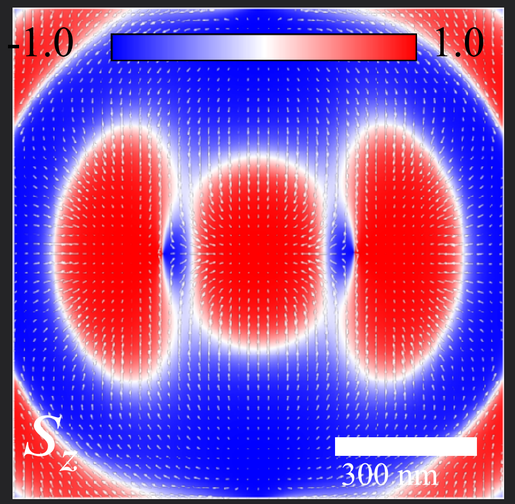
Horn Schunck Method



Optical flow







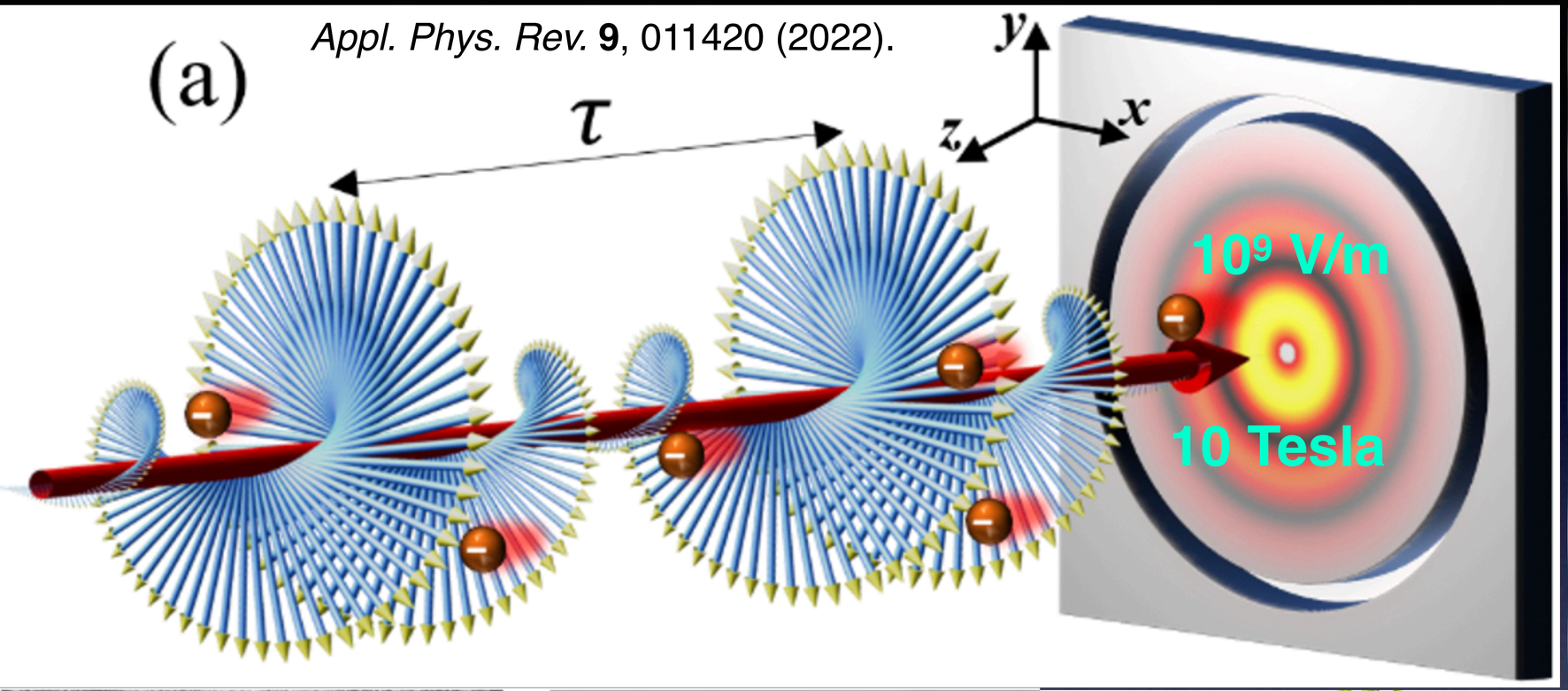
Artif. Intell. ***17****, 185 (1981).*

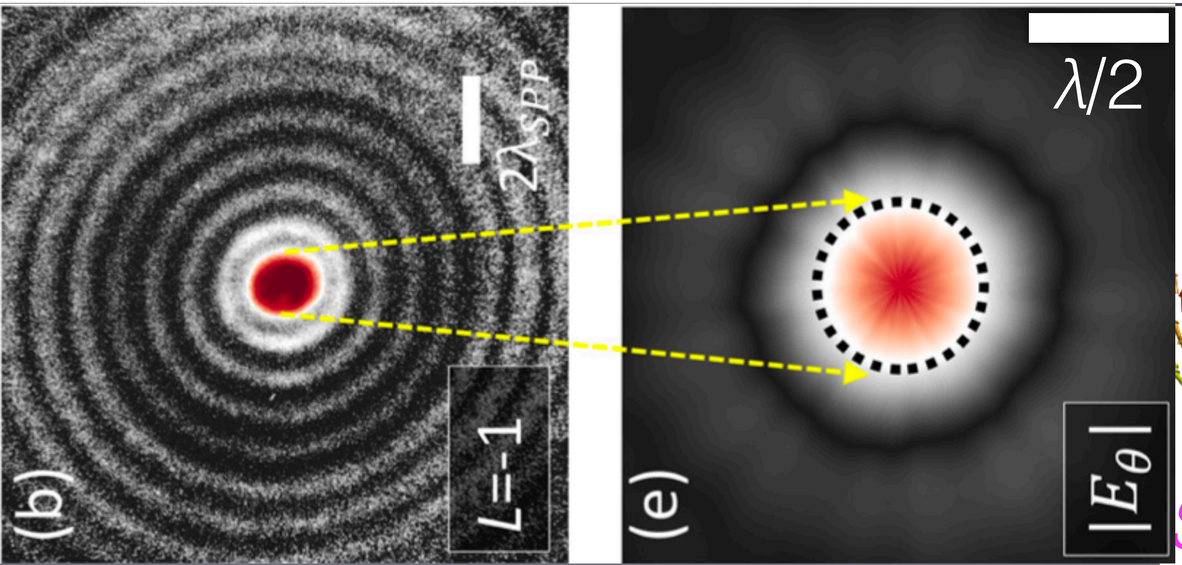
$$F_{HS} \sim \iint \left(I_x v_x + I_y v_y + I_t \right) dxdy$$

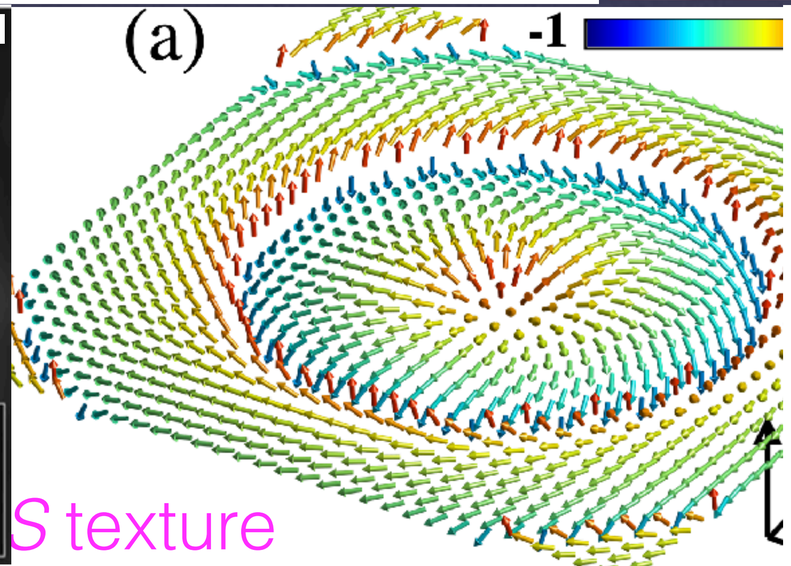
L-line map

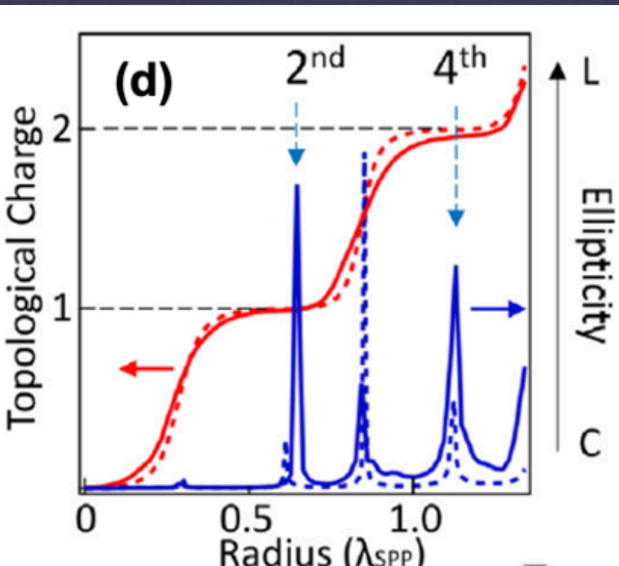
S_z

Spin-angular momentum (σ=±1)+geometric charge (*m*=0)





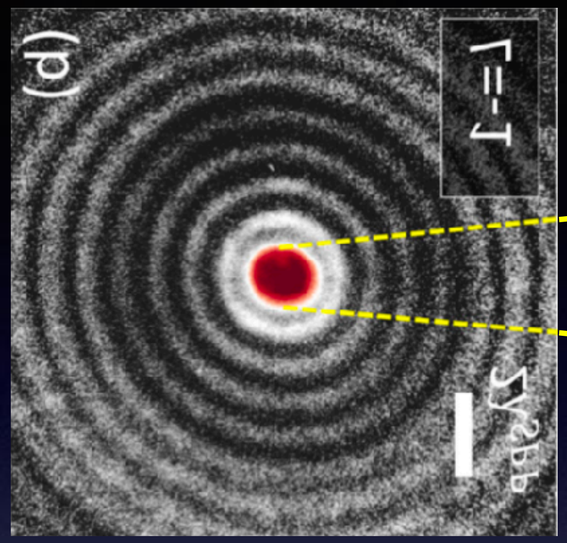


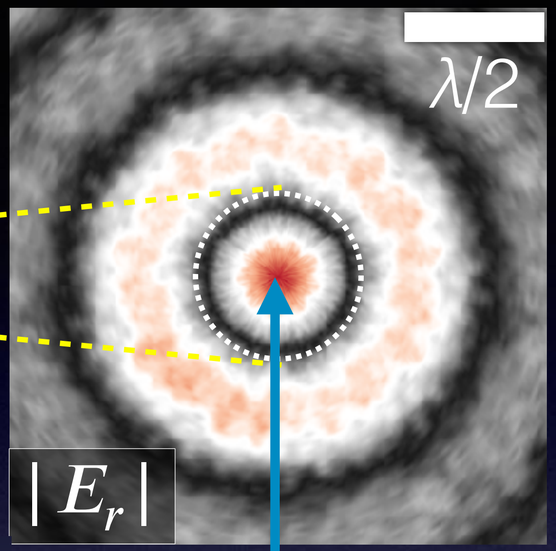


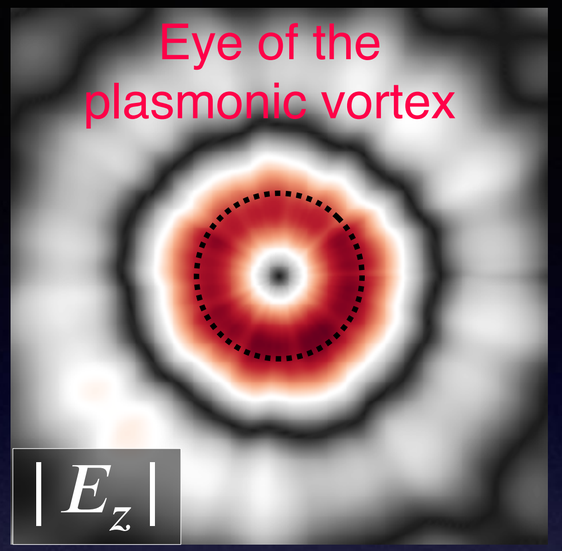
PEEM Image

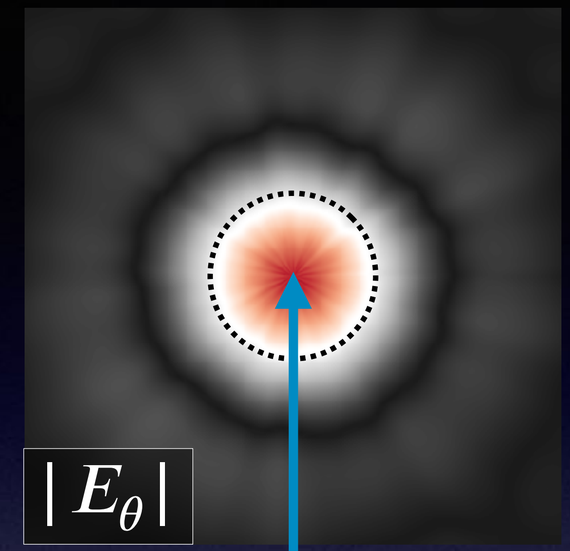
FT analysis

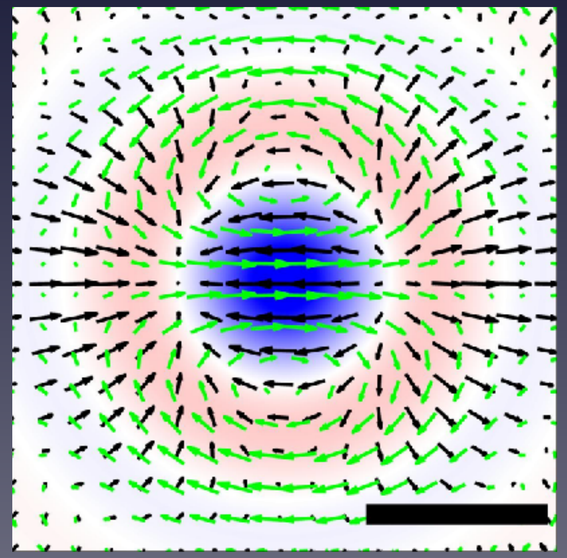
Maxwell

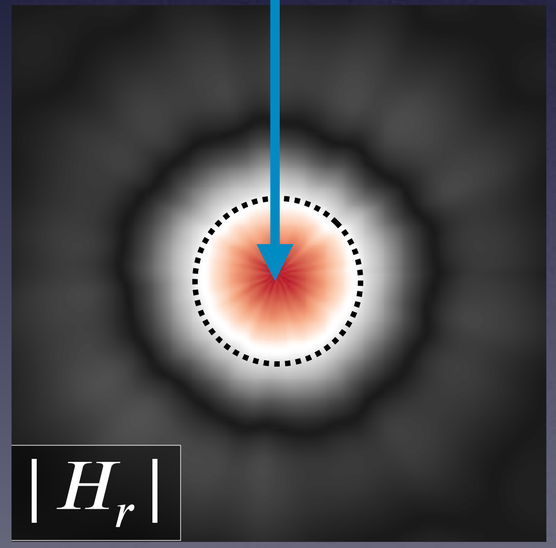




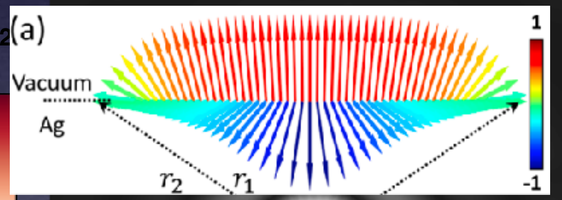


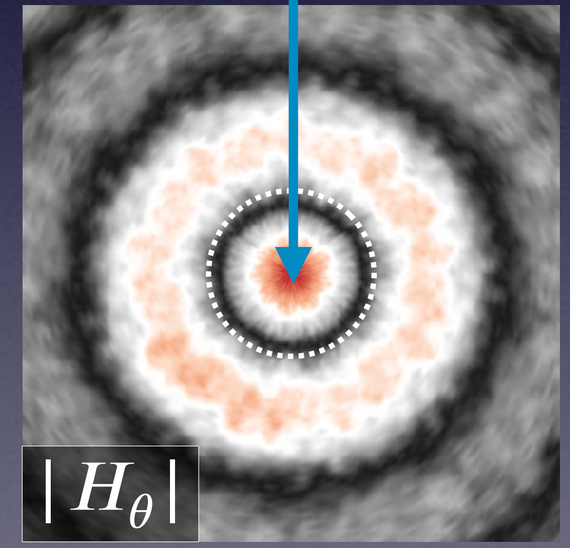






magnetic monopole





2λ SPP

Magnetoelectric field

Conclusions

- We have demonstrated imaging of vectorial plasmonic fields on $<\lambda/2$ length scale with attosecond precision
- This enables study of topological spin texturing by spin-orbit interaction of light. The textures are stable on second to attosecond pulse duration time.
- we can study spin-charge entanglement, $\mathscr{PT}$ symmetry breaking, non-reciprocal and non-Hermitian physics, in trivial and bianisotropeic condensed matter
- The structured fields can induce Poincaré dressing of topologically trivial matter (*Nature Reviews Physics* **4**, 562 (2022)
- Where did the angular momentum go?
- Can we use structured light to probe axion physics in topological matter or even cosmos?