



**Institute of
Applied Physics**

Friedrich-Schiller-Universität Jena

Nanoprinted platforms for topological photonics

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- Galvo-dithered direct laser writing
- Nanoprinted 3D photonic crystals:
 - High-refractive index photonic crystals
 - Topological photonic systems
 - Overview of other applications
- Potential projects with 3D photonic crystals

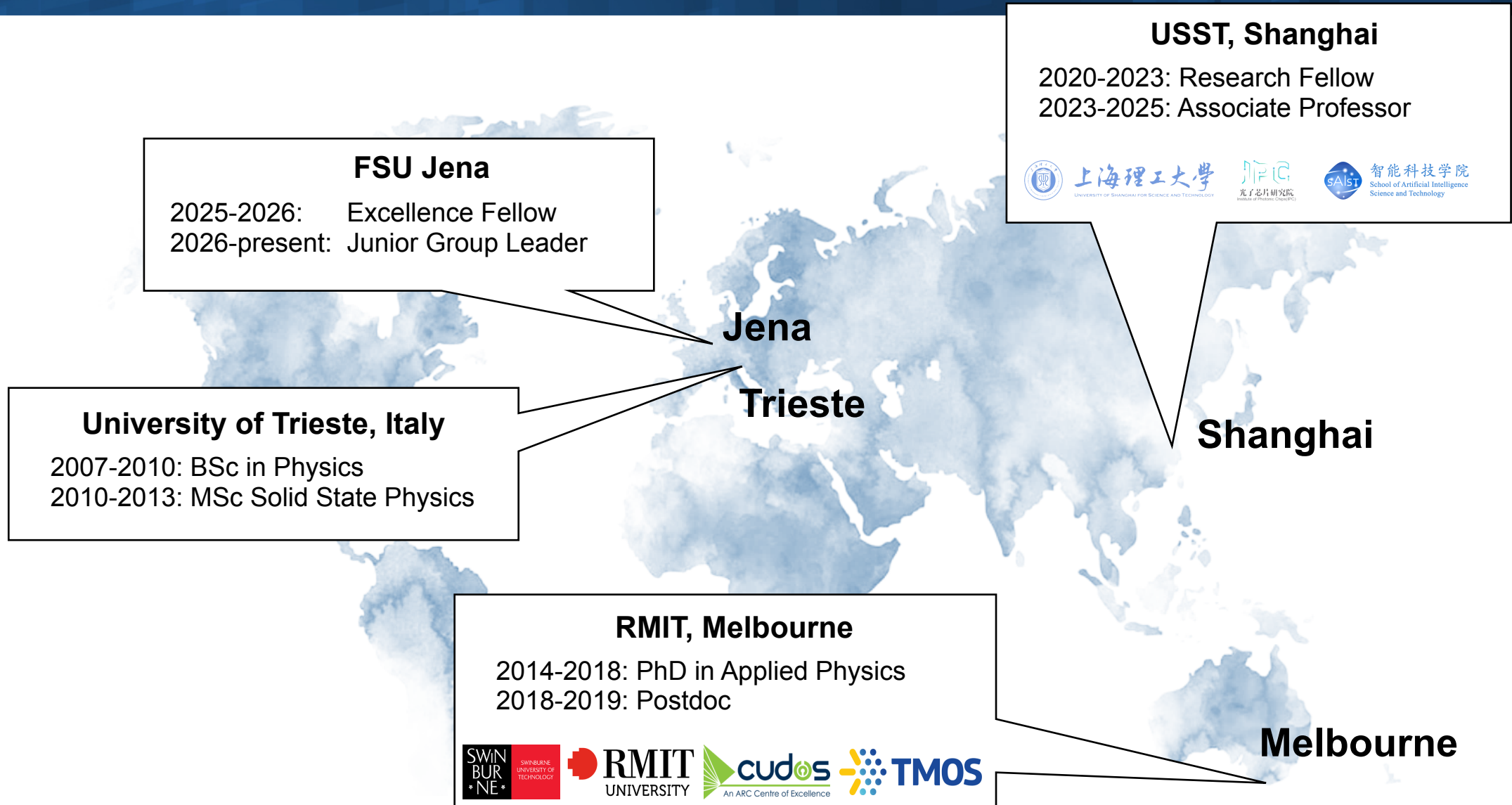
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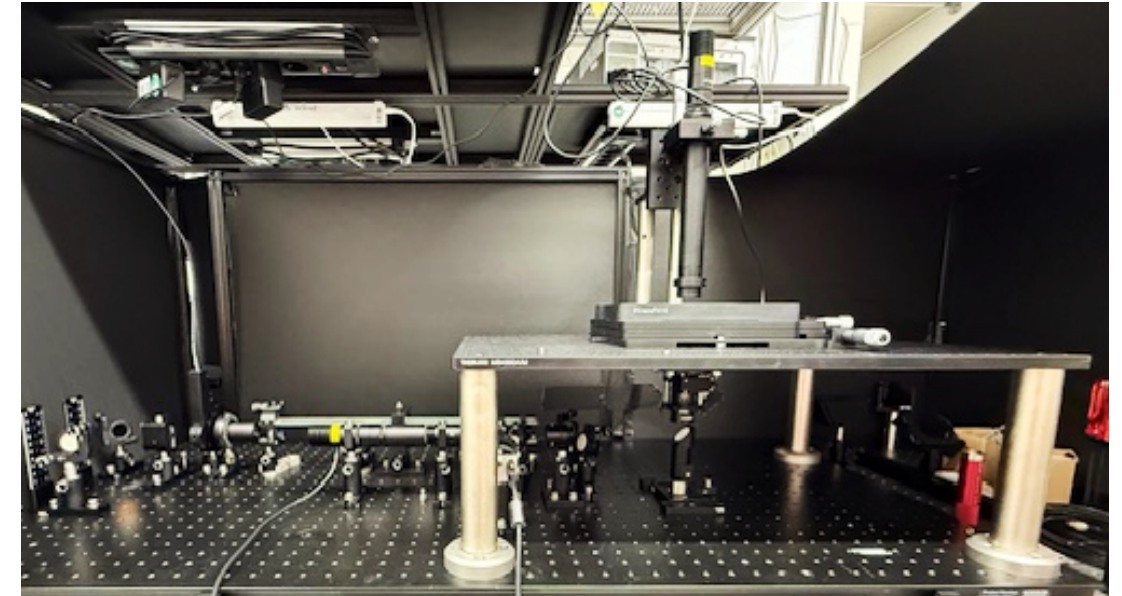
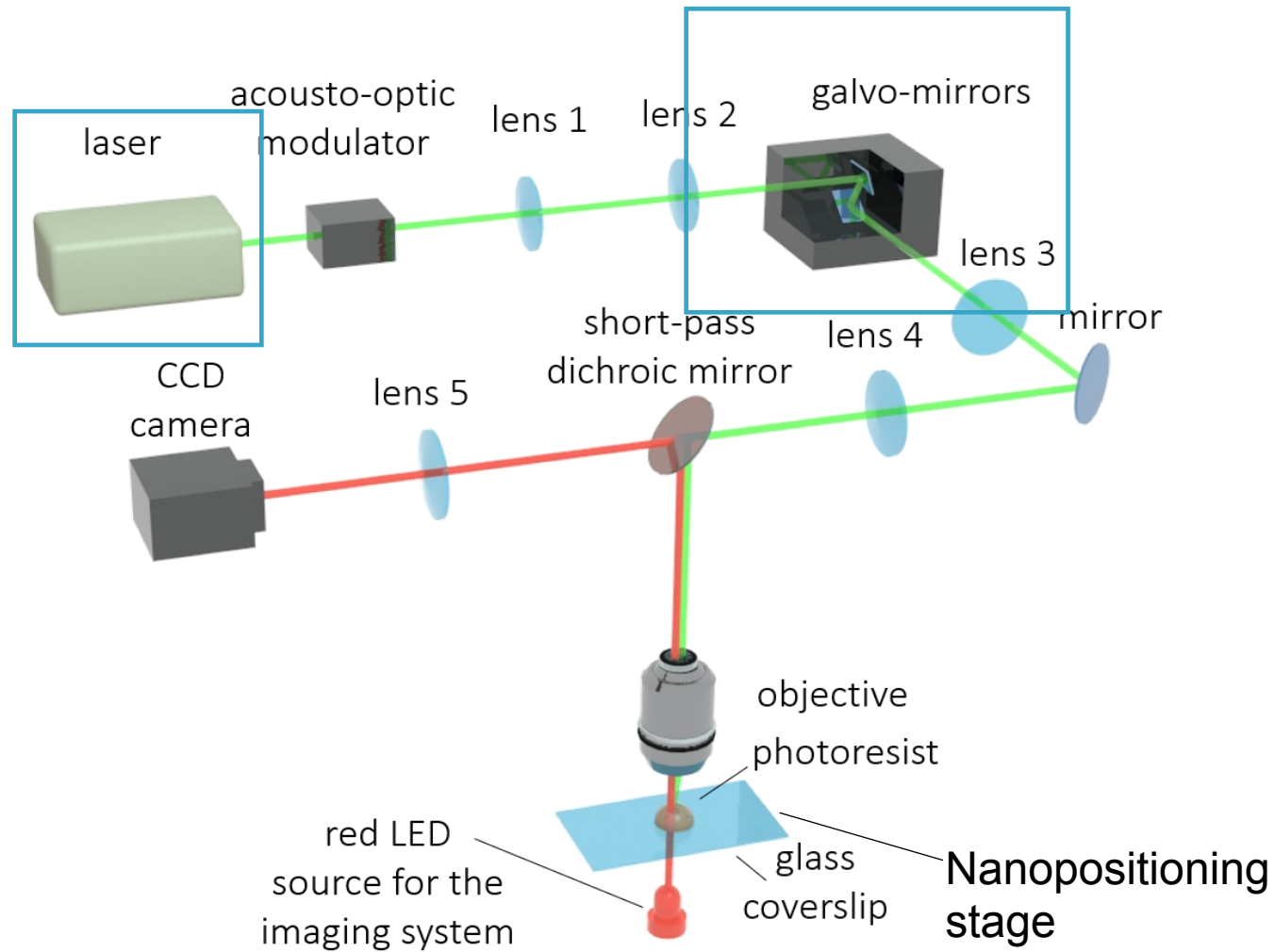
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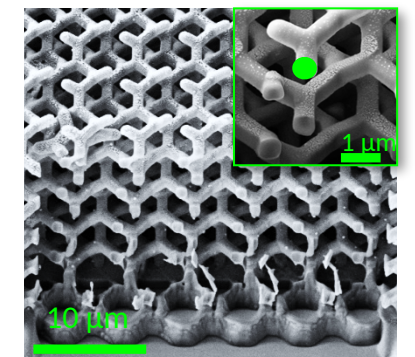
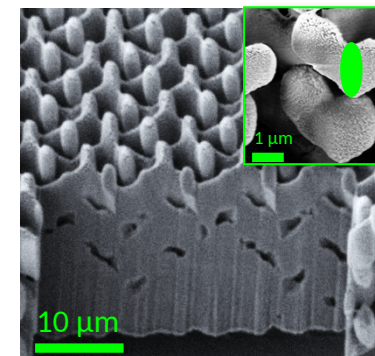
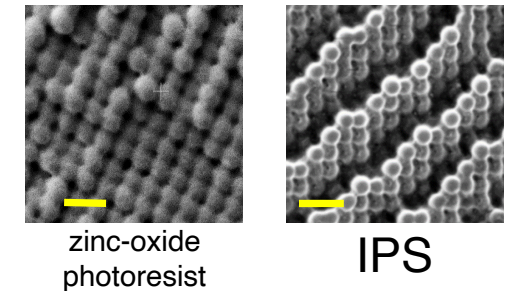
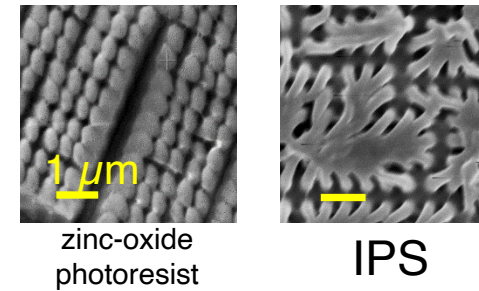
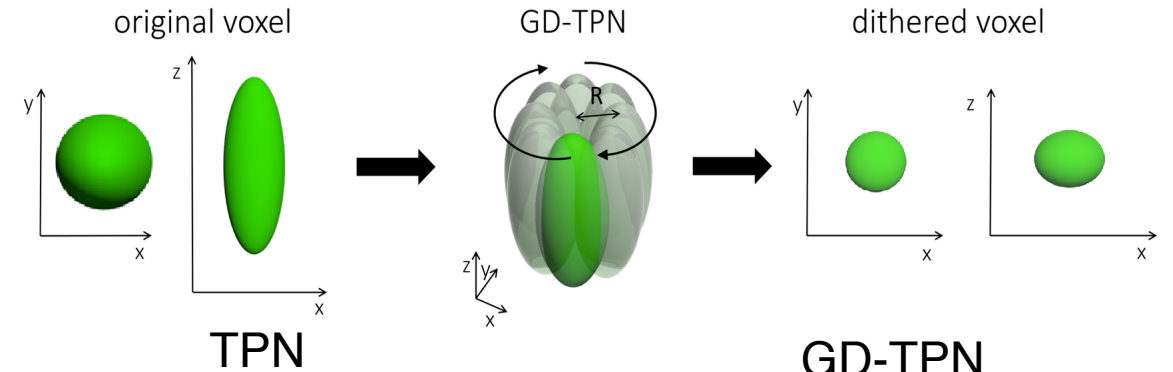
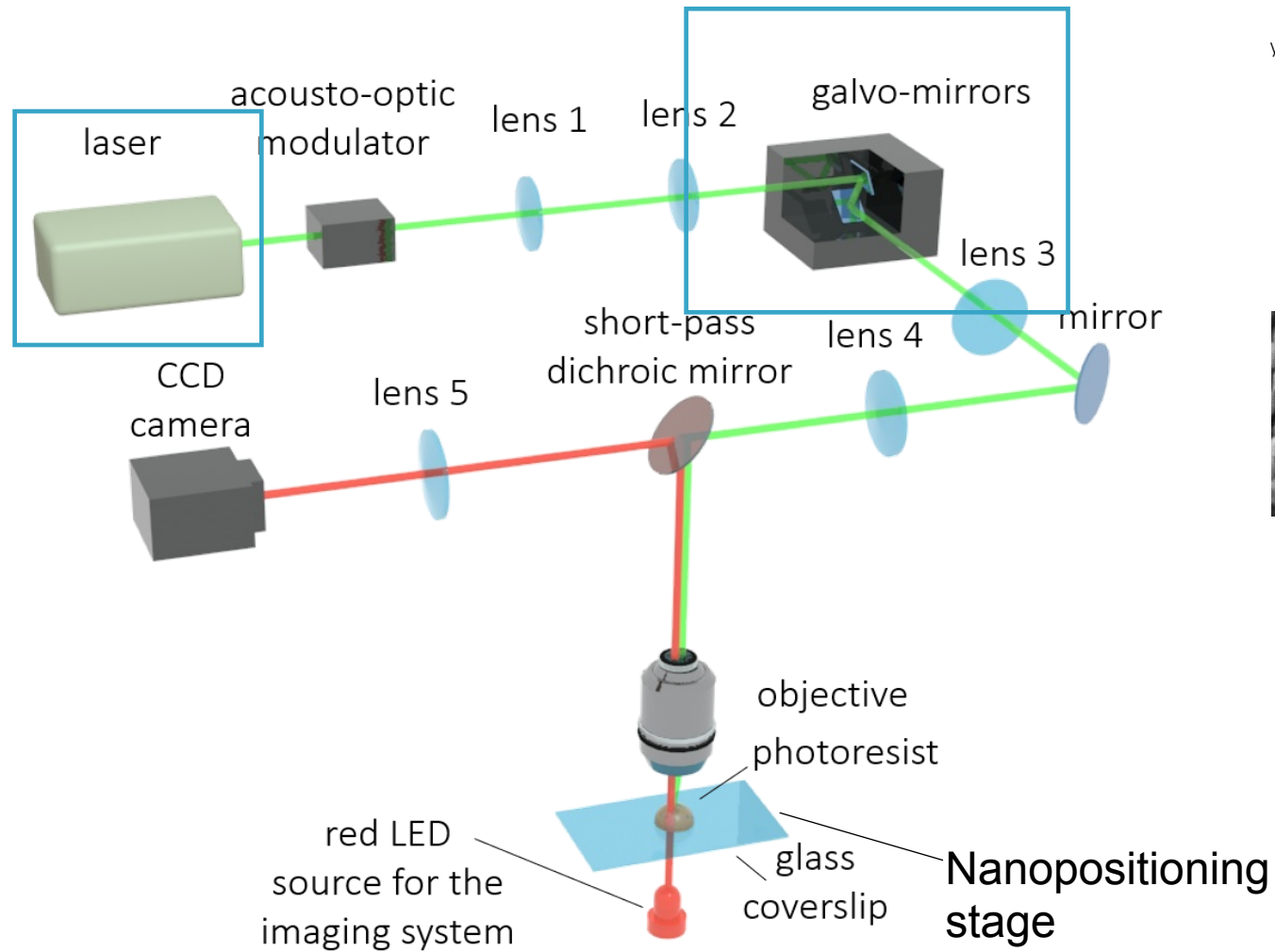


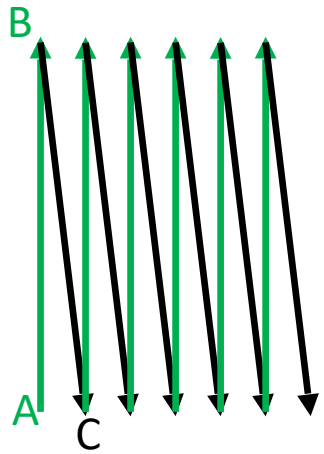
Galvo-Dithered Two-photon nanolithography



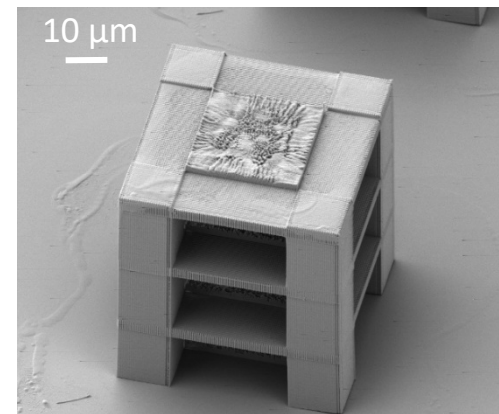
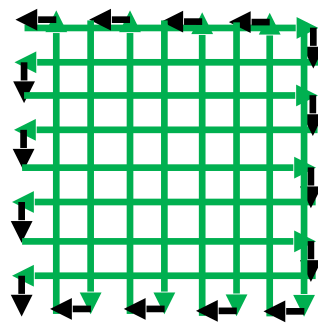
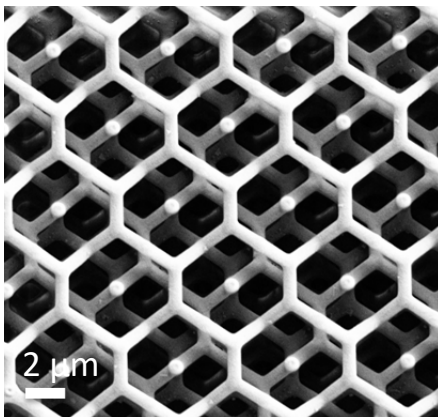
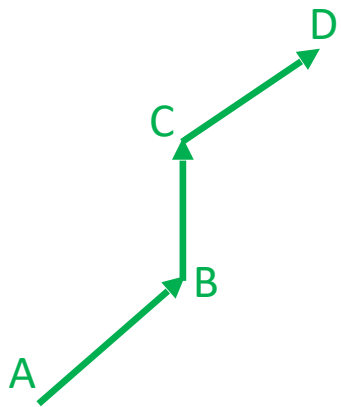
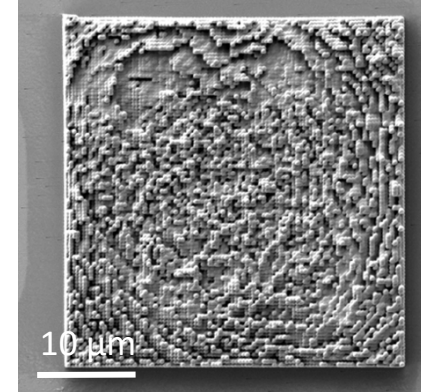
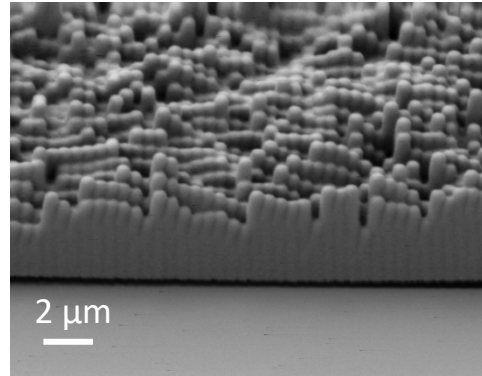
Setup in Lab E28, ACP, Jena.

Galvo-Dithered Two-photon nanolithography





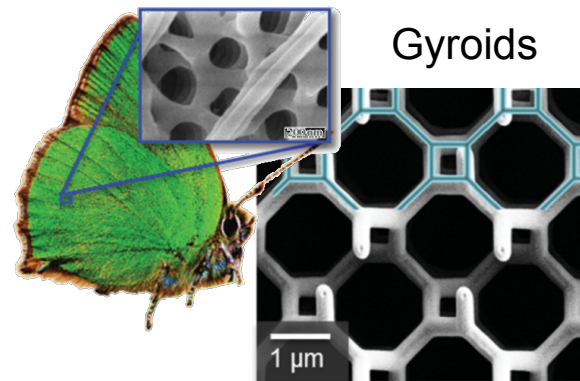
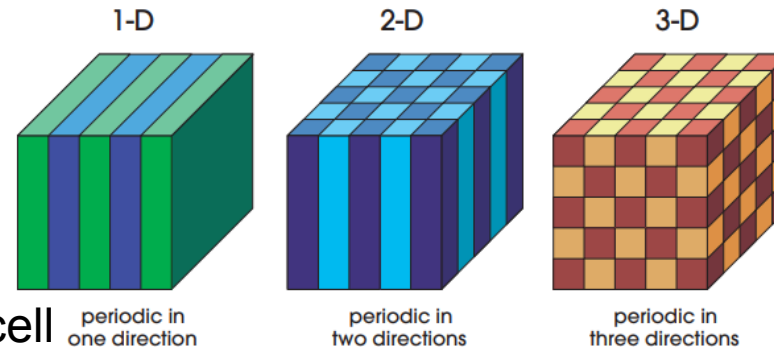
Laser on
Laser off



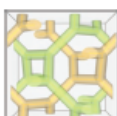
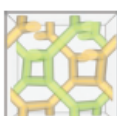
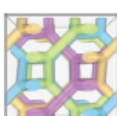
- 200X200X200 μm
- Lateral resolution: 200-250 nm
- Aspect ratio: 2-3 without corrections, 1 with corrections
- Commercial polymers and custom polymers
- Metal coating, ALD coating, LBL deposition
- Printing on arbitrary substrates, including no substrate
- Wavelengths: 532, 680-1090, 1064. Power 2-4 W.

3D Photonic crystals: micro- and nanostructures with a periodicity in dielectric constant. Maxwell's equations in a periodic medium give a band structure, capable of shaping and molding the flow of light in the three dimensions. Because they control light propagation volumetrically:

- Complete Photonic Bandgap (PBG)
- Full 3D light control through volumetric interaction:
 - Tailored photon density of states
 - Control of spontaneous emission (Purcell enhancement or suppression)
 - Isotropic optical properties
- Greater design freedom
- Higher device integration potential
- Characterization of nontrivial phenomena
- Challenges in fabrication



J. D. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, *Photonic Crystals: Molding the Flow of Light*, 2nd ed. Princeton, NJ, USA: Princeton University Press, 2008.

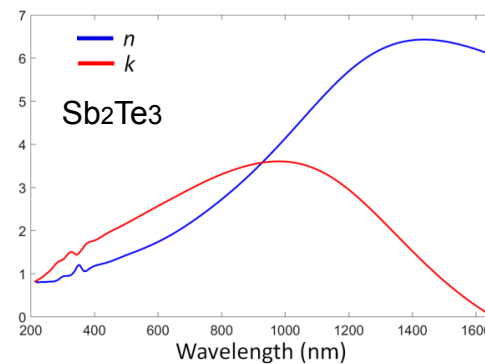
Srs composite		Group symmetry	Primitive unit cell	CD	OA
1-srs		$I4_132^{[17]}$	BCC	✓	✗
2-srs achiral		$Ia\bar{3}d^{[4]}$	BCC	✗	✗
2-srs chiral		$P4_222^{[17]}$	Tetragonal trapezohedral	✓	✗
4-srs		$P4_232^{[17]}$	SC	✓	✗
8-srs		$I432^{[17]}$	BCC	✗	✓

E.Goi, B. P.Cumming, M.Gu, *Advanced Optical Materials*, 6, 1800485 (2018)

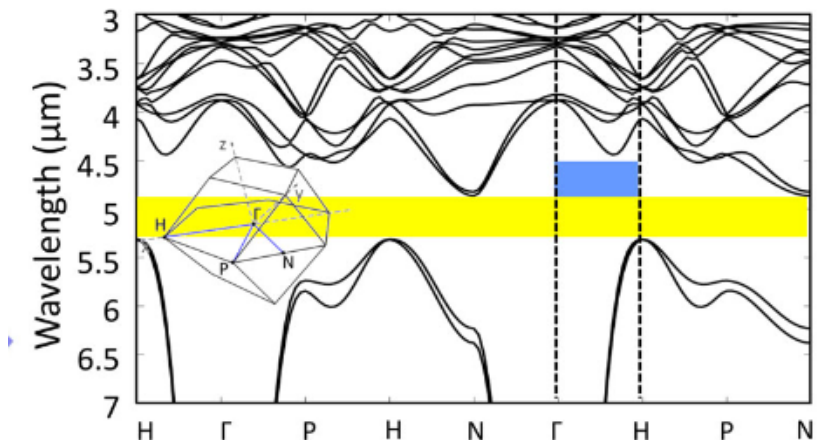
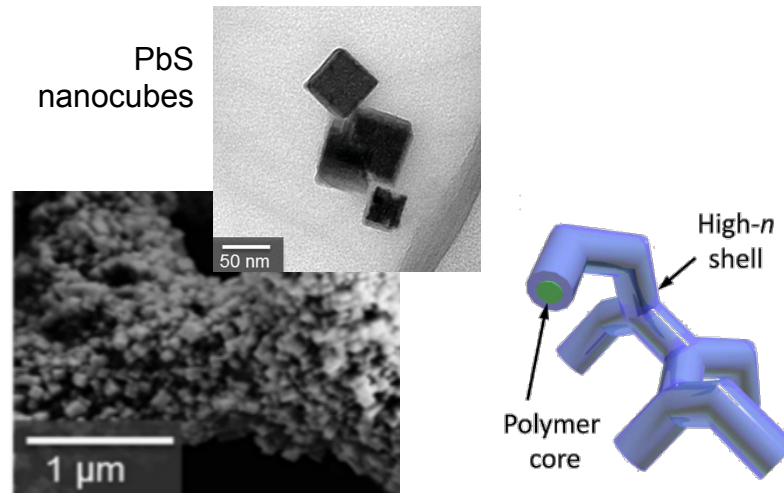
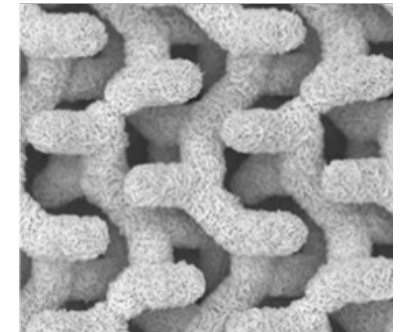
Gyroid PhCs are periodic dielectric structures based on the gyroid minimal surface, a chiral lattice with no mirror symmetry, that can support complete photonic bandgaps and enable strong, isotropic control of light propagation.

Advanced optical materials

- Design: srs networks
- Material synthesis
 - Photoresist
 - PbS nanocubes, PbSe quantum dots
- GD-TPN fabrication
- Layer-by-layer deposition protocol development
- Atomic Layer Deposition
 - Sb_2Te_3

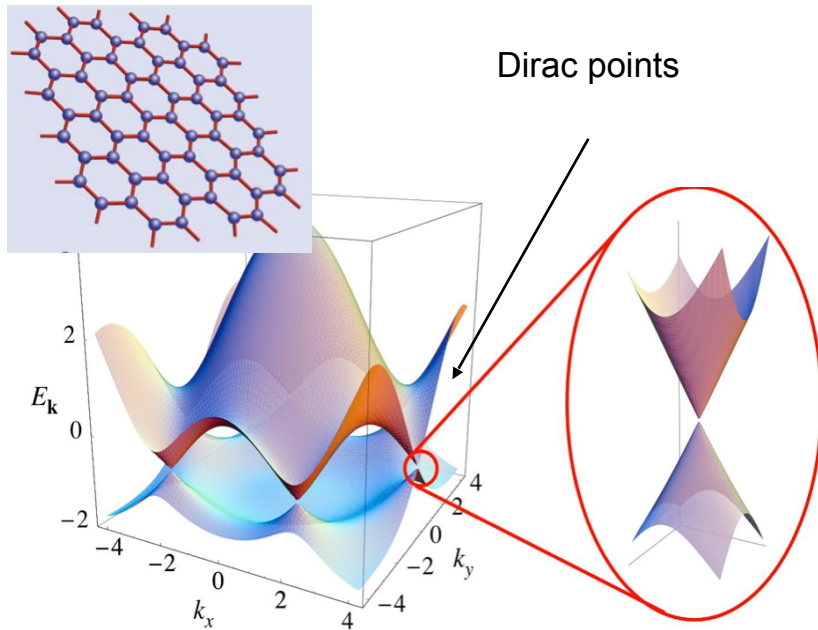


Precise
engineering
of 3D photonic
bandgap



In photonics, topology allows the realization of nontrivial optical effects and new phases of light.

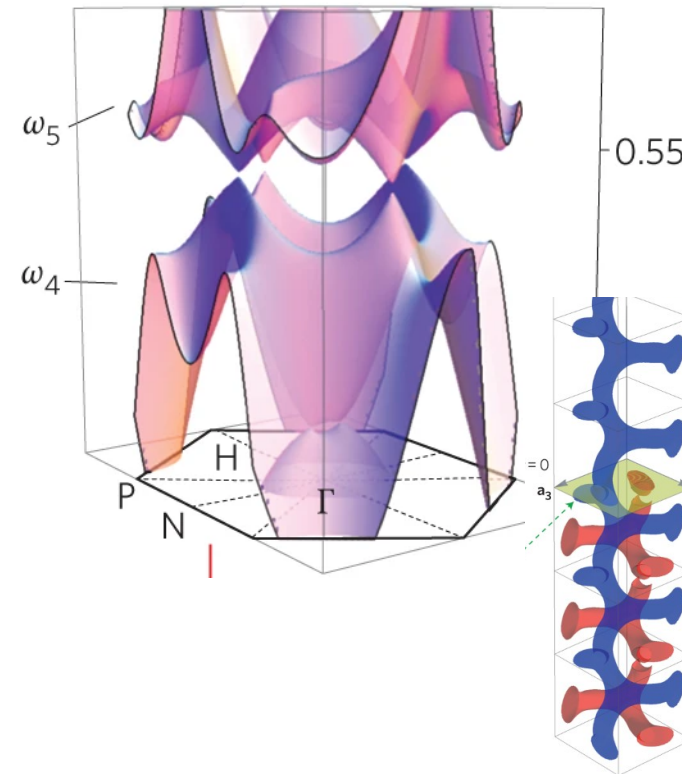
2D Dirac points, linear band crossings with conical dispersion.



Dirac cones in graphene.

A. H. Castro Neto et al., *Reviews of Modern Physics*, 81, 1, 109–162 (2009).

3D Weyl points



Lu, L., et al. Weyl points and line nodes in gyroid photonic crystals. *Nature Photon* 7, 294–299 (2013).

The Weyl equation is the massless limit of the Dirac equation.

$$i\partial_t\psi = \pm c \boldsymbol{\sigma} \cdot \mathbf{p} \psi$$

It describes chiral (handed) spin-1/2 particles, Weyl fermions, with linear Energy-momentum dispersion relation:

$$E(\mathbf{p}) = \pm c|\mathbf{p}|$$

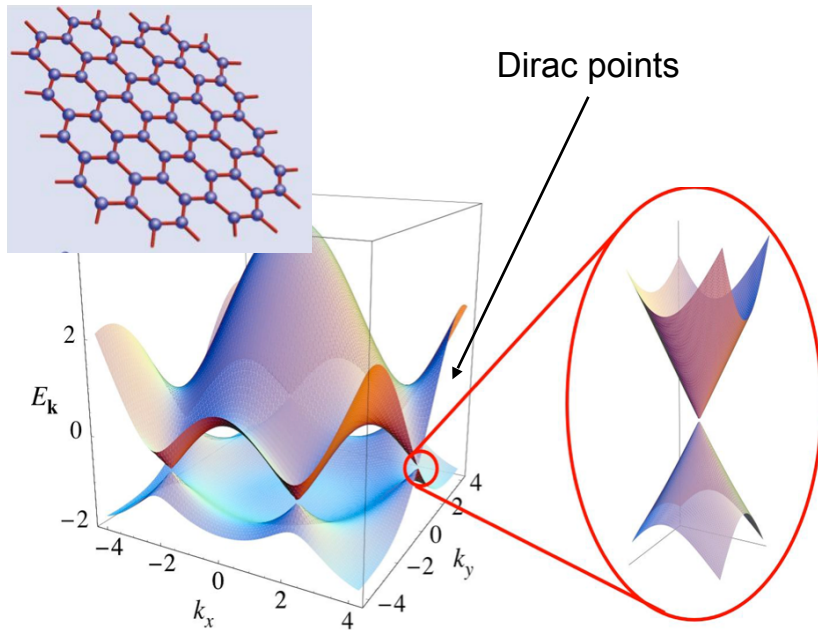
In condensed matter and photonics, quasiparticles near Weyl points ($\mathbf{k}_0$) obeying the an effective Weyl Hamiltonian:

$$H(\mathbf{k}) = \hbar v_F \boldsymbol{\sigma} \cdot (\mathbf{k} - \mathbf{k}_0)$$

$$E(\mathbf{k}) = \pm \hbar v_F |\mathbf{k} - \mathbf{k}_0|$$

In photonics, topology allows the realization of nontrivial optical effects and new phases of light.

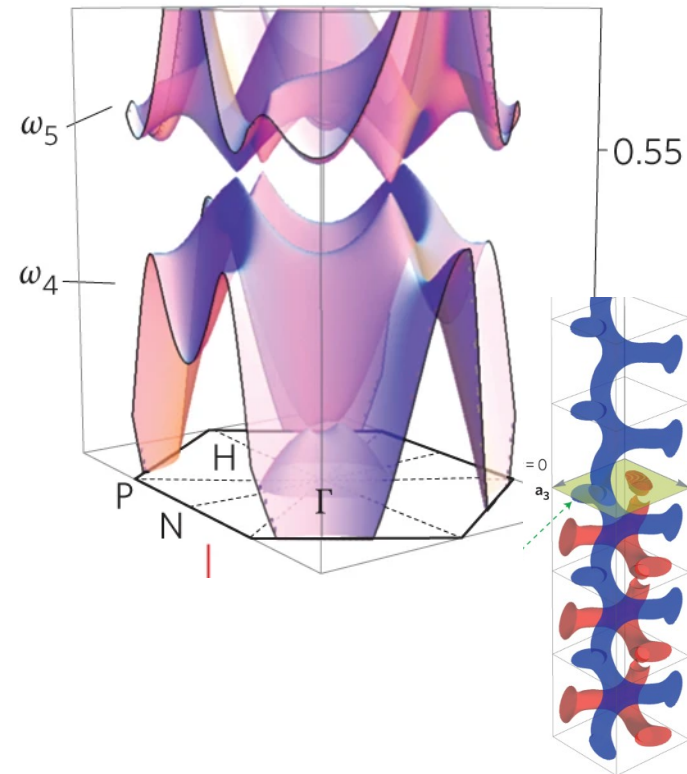
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3D Weyl points



Lu, L., et al. Weyl points and line nodes in gyroid photonic crystals. *Nature Photon* 7, 294–299 (2013).

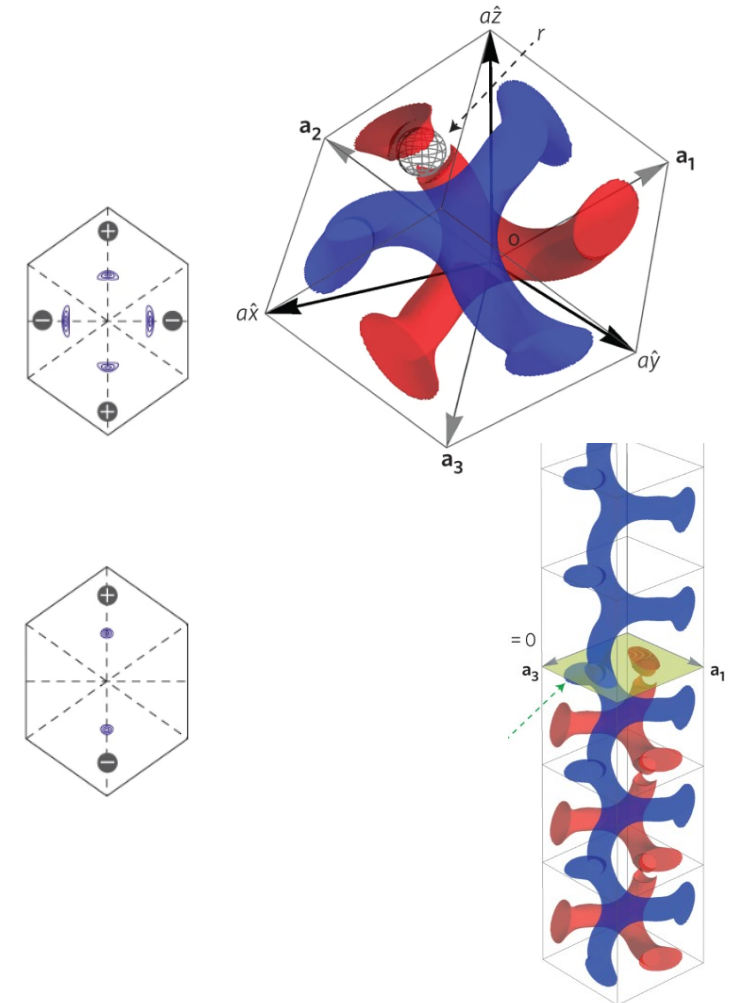
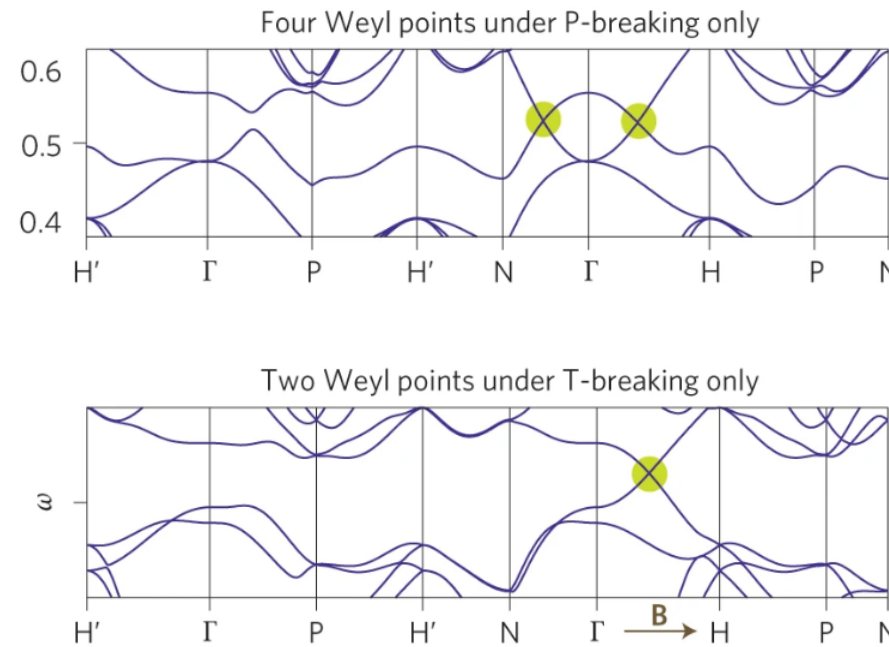
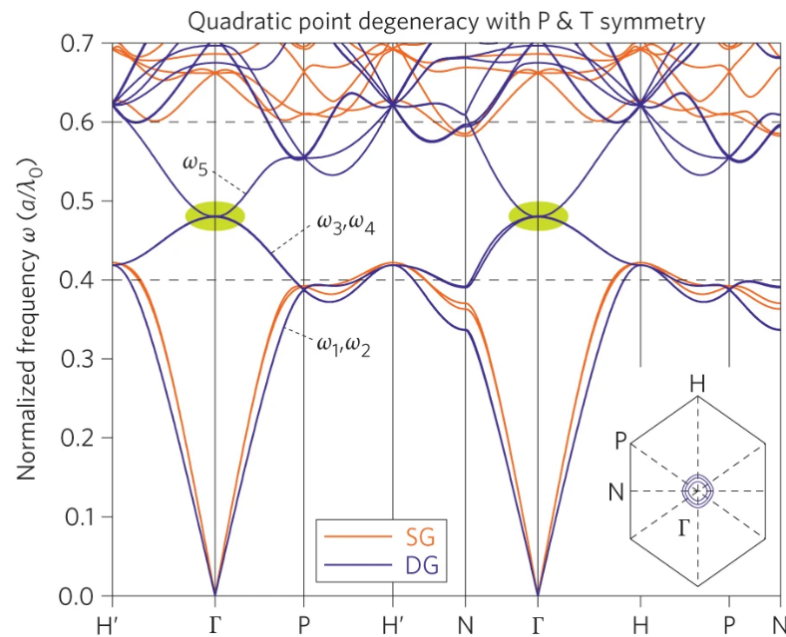
- 3D linear point degeneracies between two bands
- Sources or sinks of Berry curvature in momentum space
- Carry a quantized topological charge (Chern number)
- Topological protection against perturbations
- Lead to robust, directional surface states (Fermi arcs)

PhCs provide a deterministic, tunable platform to study Weyl physics. Under suitable symmetry, the photonic band structure develops points where:

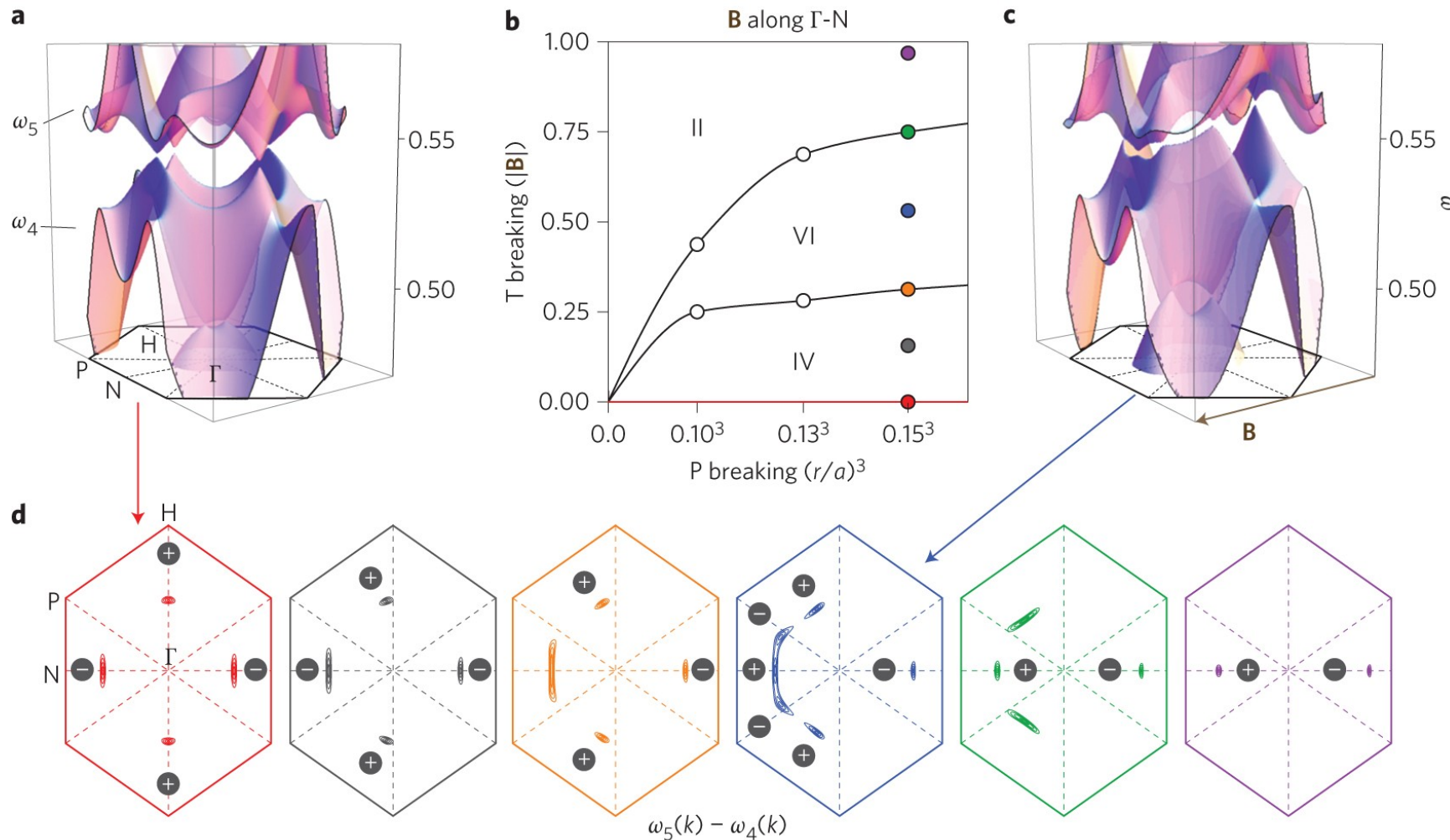
$$\omega(\mathbf{k}) \approx \omega_0 \pm v|\mathbf{k} - \mathbf{k}_0|$$

One possible starting point for obtaining Weyl points is a DG photonic crystal with a quadratic band degeneracy at the Brillouin zone centre (Γ) in an otherwise complete bandgap.

- High refractive index for the complete bandgap (4 or higher)
- Applying perturbations breaking either P or T
- T-breaking can be realized with chiral magnetic materials



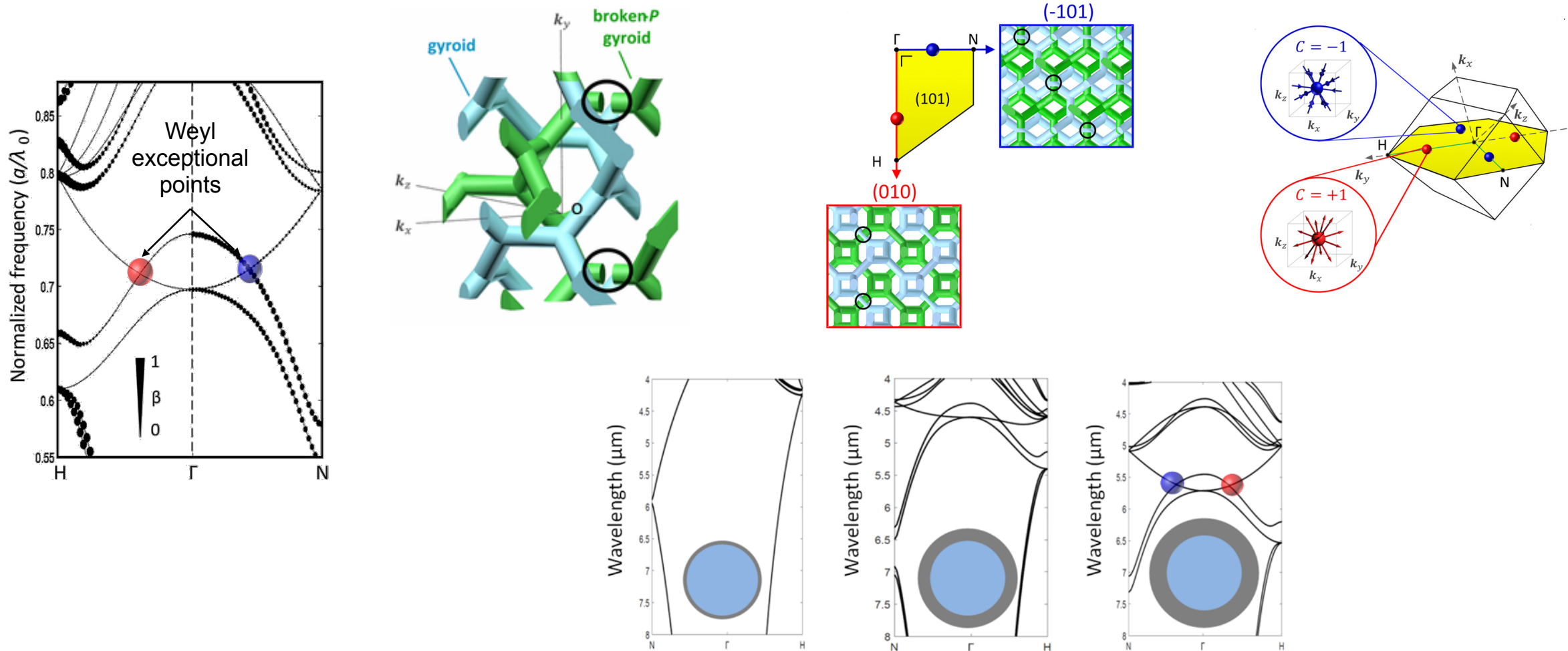
Weyl points in PhCs



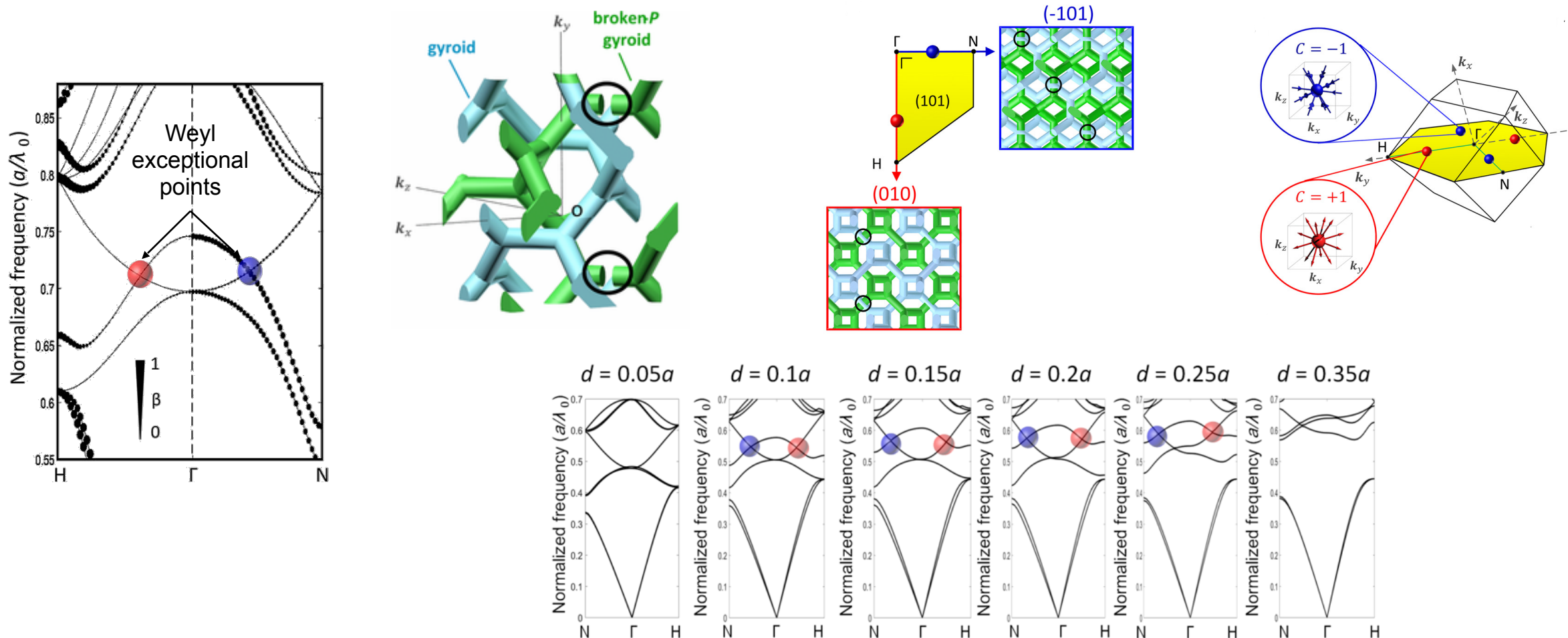
Lu, L., *et al.* Weyl points and line nodes in gyroid photonic crystals. *Nature Photon* **7**, 294–299 (2013).

E. Goi - Nanoprinted systems for topological and neuromorphic photonics

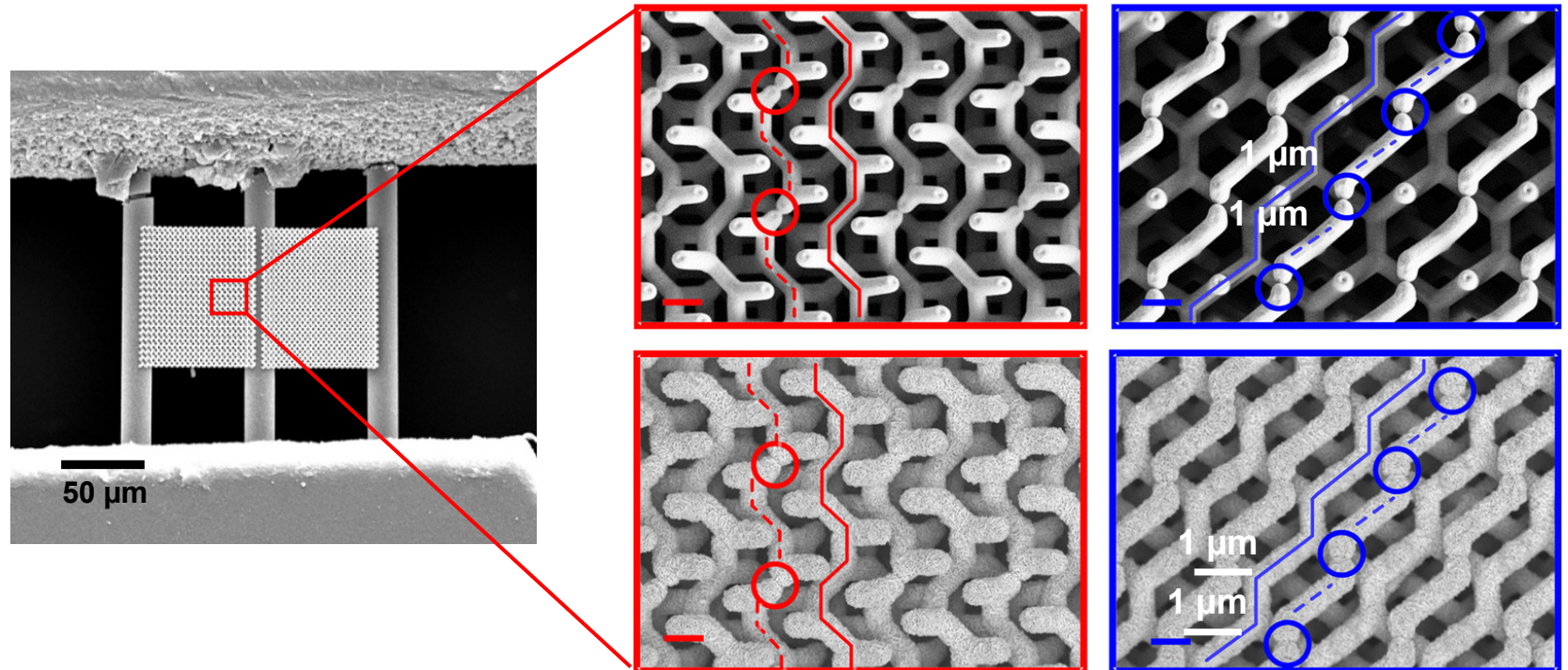
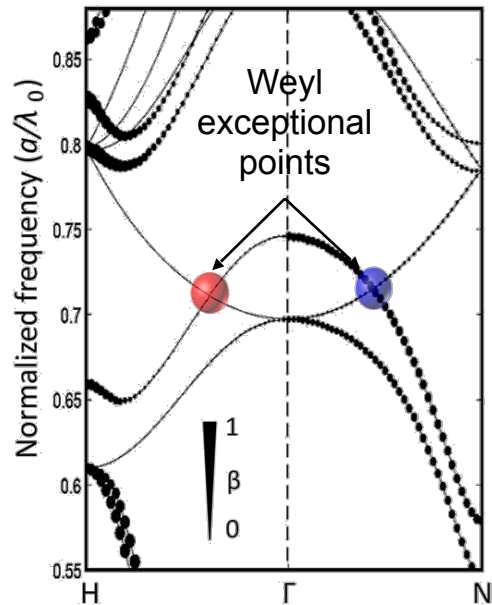
Weyl points in microscopic high-refractive index 3D photonic crystals: 2-srs networks with broken P-symmetry.



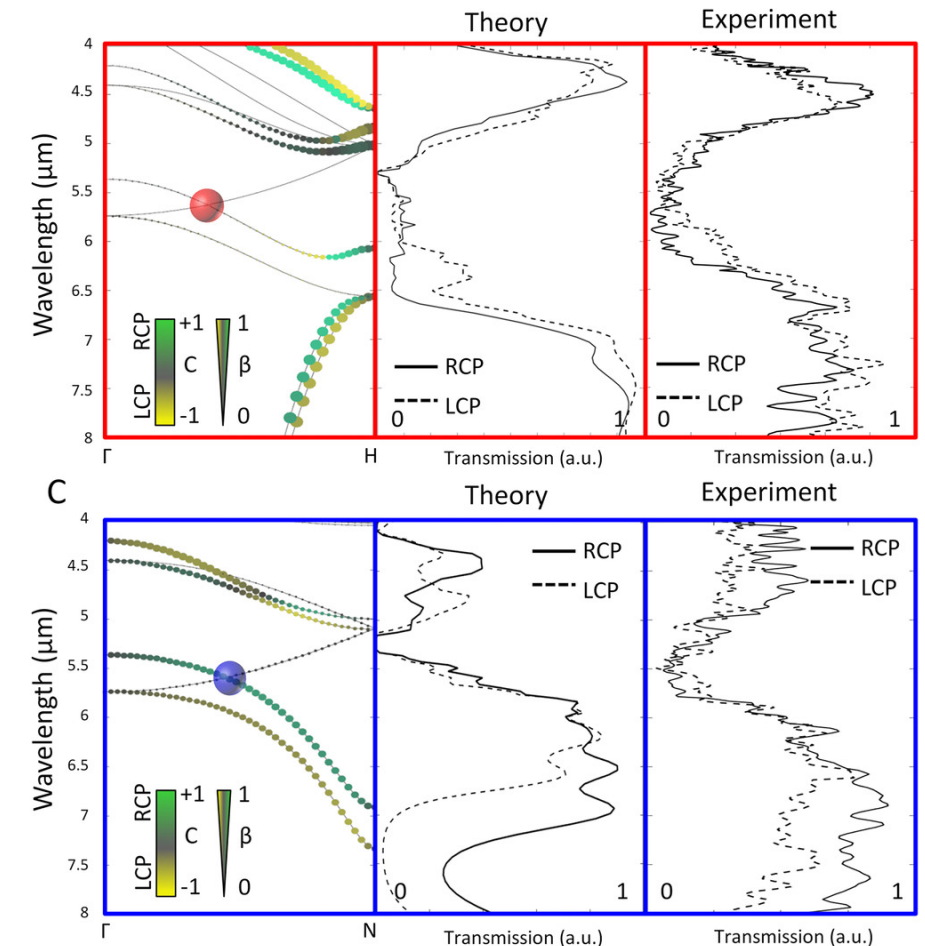
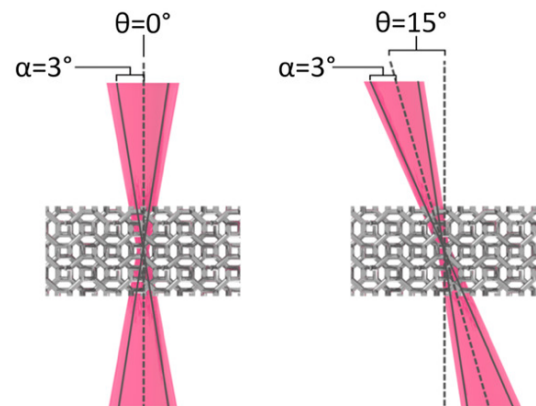
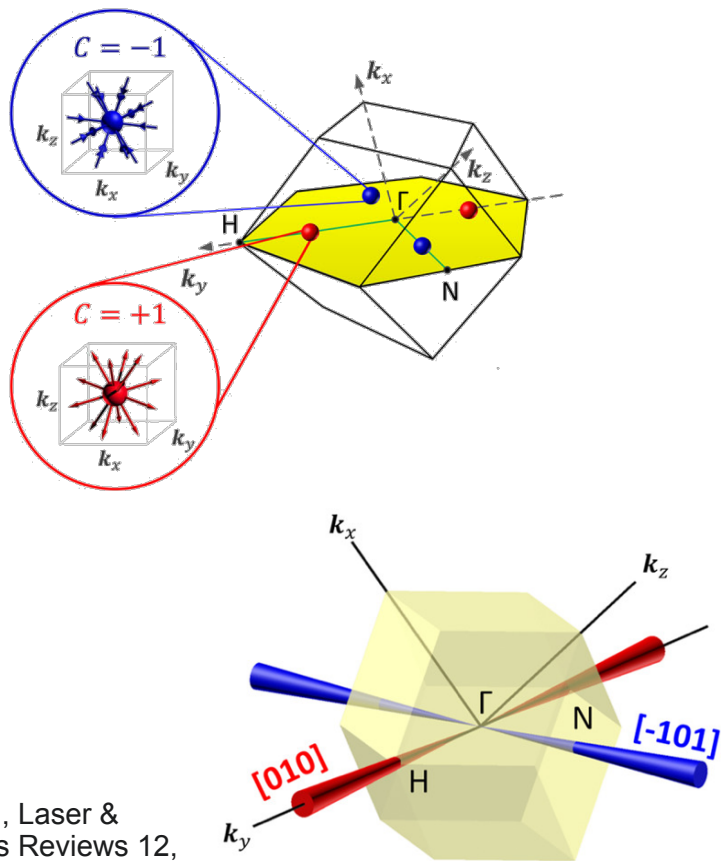
Weyl points in microscopic high-refractive index 3D photonic crystals: 2-srs networks with broken P-symmetry.



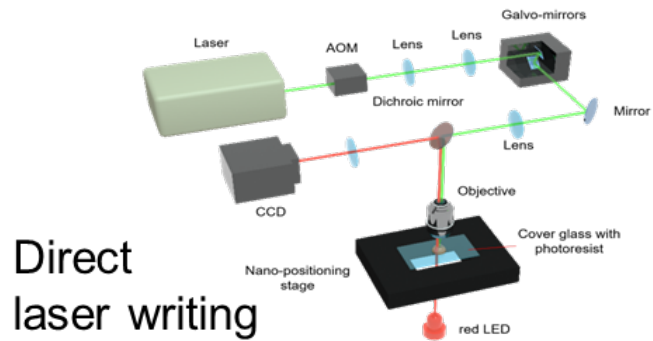
Weyl points in microscopic high-refractive index 3D photonic crystals.



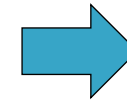
Weyl points act as monopoles Berry curvature in momentum space, and carry chirality defined by quantized topological charges (Chern number ± 1). This chirality leads to polarization-dependent effects, such as reversed circular dichroism near Weyl points.



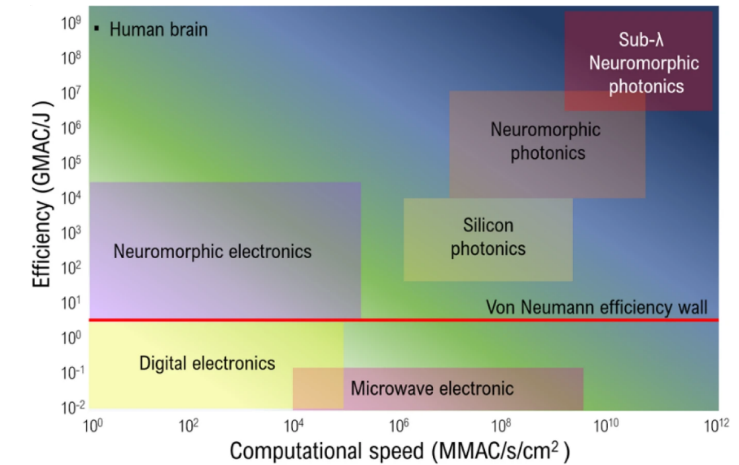
Overview of other applications



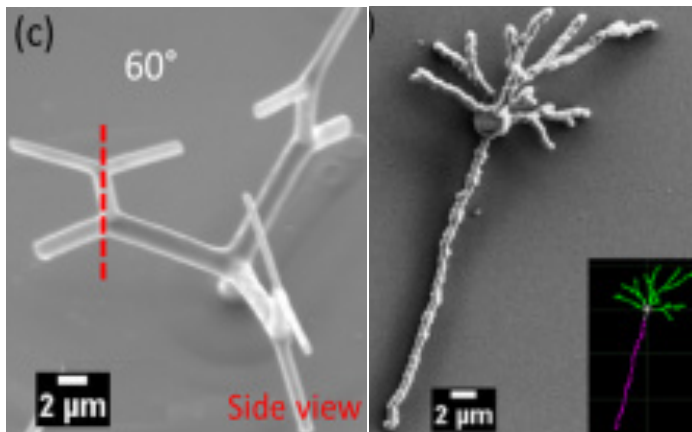
- Structures of great complexity in a single fabrication step
- Sub-micron feature size
- Compatible with fabrication on arbitrary substrates
- Static polymer structures



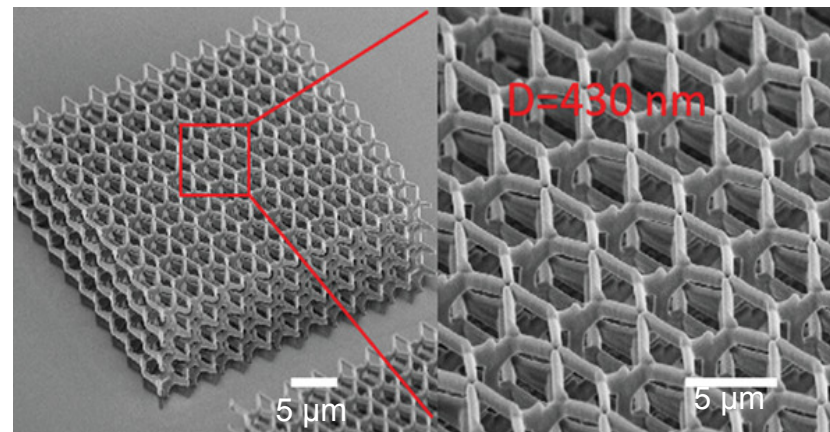
Neuromorphic photonic hardware



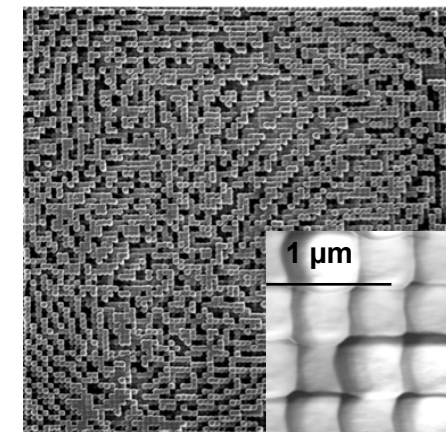
Goi et al.,
Photonix 1, 3
(2020).



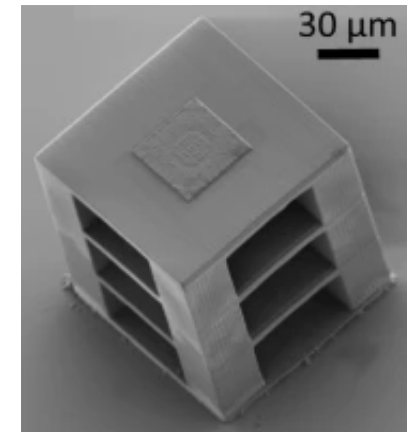
Bioinspired structures



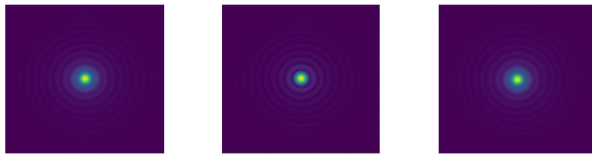
3D waveguide based
neural networks



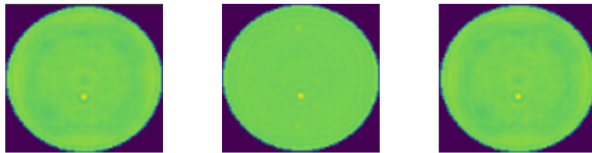
Nanoprinted holographic neural
networks



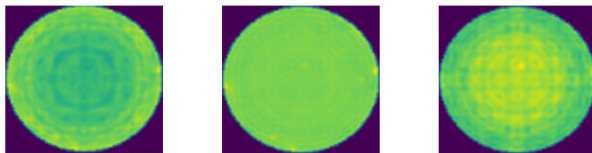
Reconstruction of symmetric aberrations



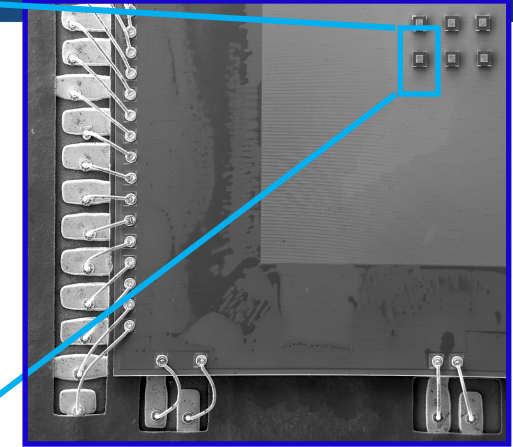
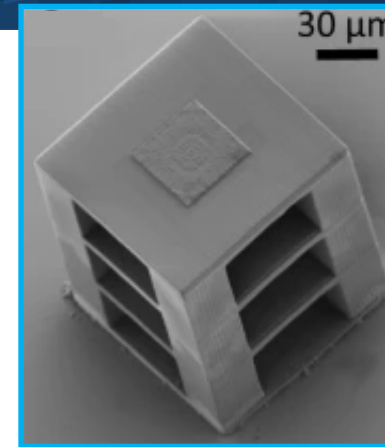
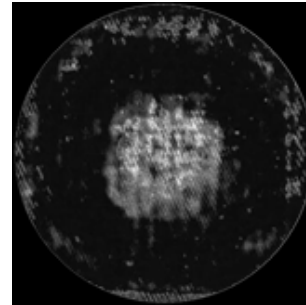
Trained with intensity input



Trained with complex field input



Reconstructed aberration



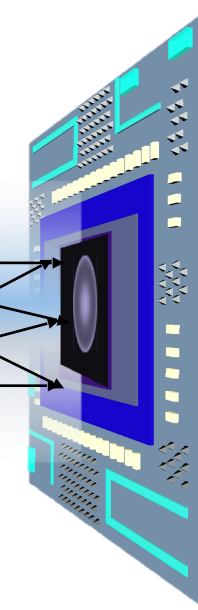
field input

Imaginary

Real



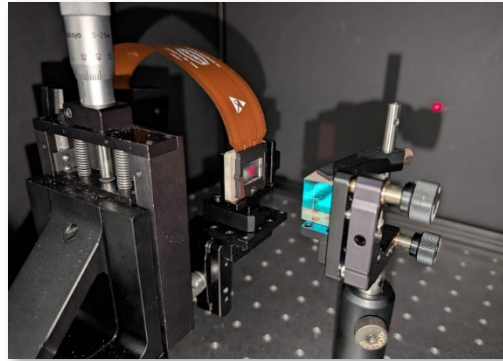
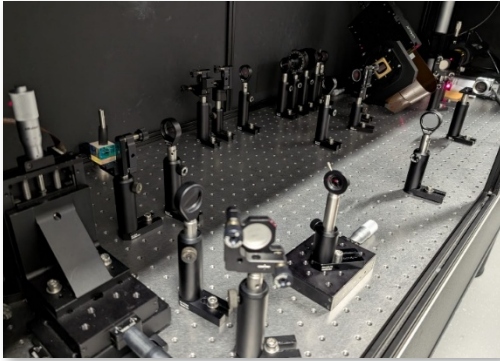
Diffractive elements
performing optical
computation



CMOS sensor

SEM image of diffractive
neural networks printed
directly on CMOS sensor

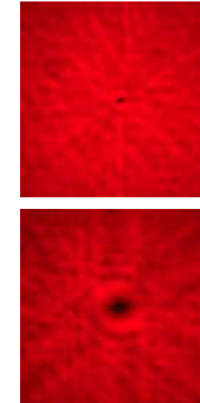
With DMD and SLMs



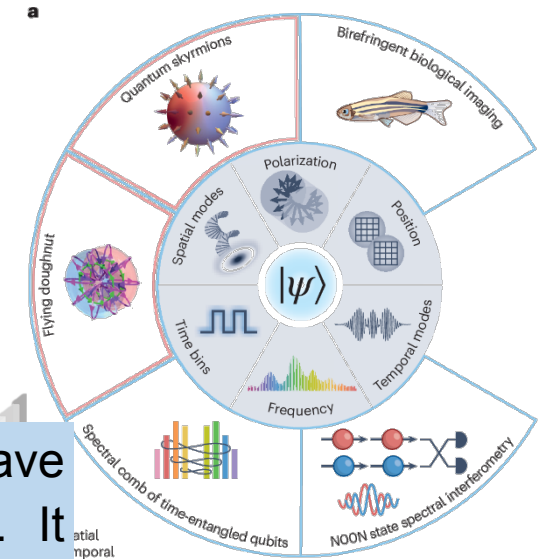
Intensity



OAM



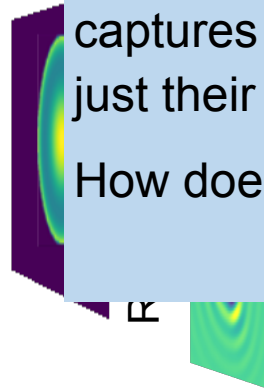
Structured light



Complete Berry curvature describes how the phase of a wave evolves when we move through the band structure. It captures the geometric properties of the eigenmodes, not just their energy.

How does it interact with structured light?

Aberrated PSF



Diffractive elements
performing optical
computation

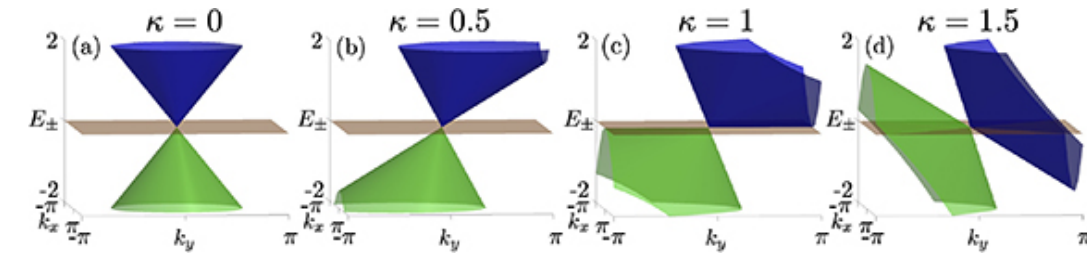
CMOS sensor

Potential projects with 3D photonic crystals

From type I to type II Weyl points



- Double-gyroid PhCs host type I Weyl points via symmetry breaking
 - **Type-I:** upright conical dispersion $\rightarrow$ point-like Fermi surface
 - **Type-II:** strongly tilted cones $\rightarrow$ open Fermi surface
- Geometry (unit cell deformation, symmetry, chirality) and refractive index tuning allow control of band dispersion
- Transition **in space** from Type-I to Type-II Weyl points via band tilting (geometry / anisotropy tuning)

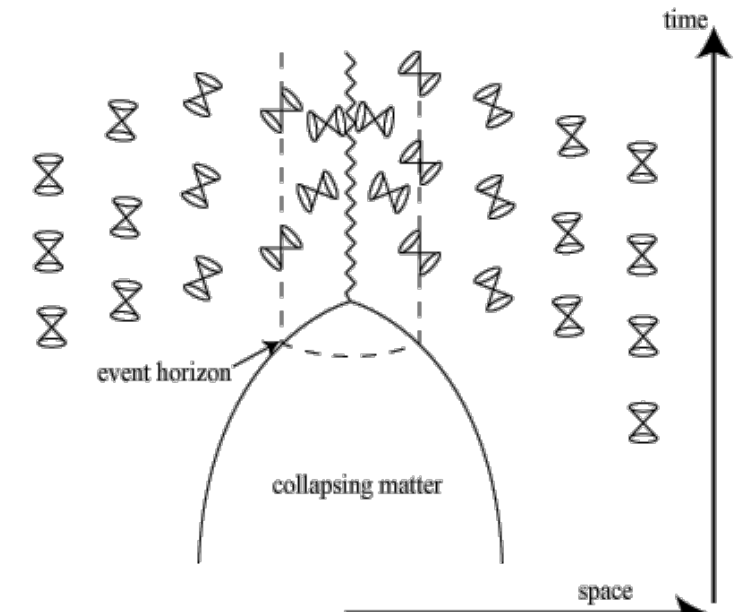


Marcus Stålhammar *et al.*, PT symmetry-protected exceptional cones and analogue Hawking radiation, 2023 *New J. Phys.* **25** 043012

PHYSICAL REVIEW LETTERS 124, 206802 (2020)

Analogue Gravity & Quantum Effects

- Type-II Weyl points mimic tilted light cones $\rightarrow$ analogue curved spacetime
- Transition WPI-WPII corresponds to emergence of effective horizons
- Enables study of:
 - Curved spacetime geometries in photonics (tilt or distortions of the cones)
 - Black hole analogues (event horizons with mode conversion)
 - Quantum-field-like effects in classical wave systems



<https://plato.stanford.edu/entries/spacetime-singularities/lightcone.html>

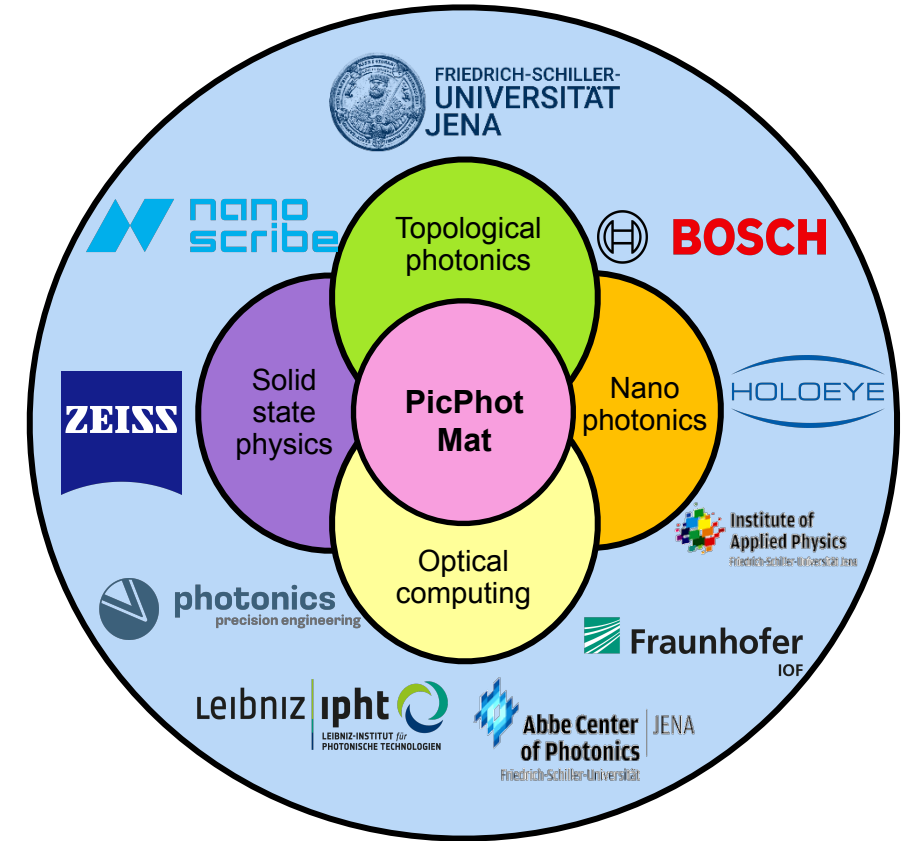
- GD-DLW
- Advanced optical material processing (layer-by-layer, ALD)

Photonic Crystals

- Fully deterministic and tunable platform
- Access to band structure engineering in 3D
- Direct measurement of dispersion, topological properties and, eventually, surface states
- WP position in momentum space is tunable by changing parameters of the photonic crystal in real space
- Provide a tailored spacetime for light: By carefully engineering Dirac or Weyl points, we can make photons behave as if they are in electromagnetic fields or in curved spacetime without any real charges or gravity

Volovik, G. *The Universe in a Helium Droplet* (Clarendon, 2003).

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Bundesministerium
für Forschung, Technologie
und Raumfahrt