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Realizing symmetry-guaranteed pairs of bound states in the continuum in metasurfaces

Chloe F. Doiron, Igal Brener, and Alexander Cerjan

2022 CLEO

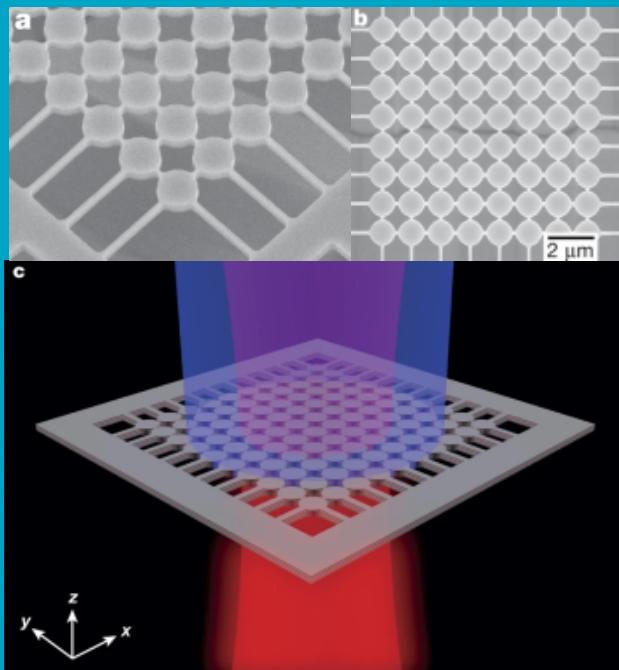


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High-Q states strongly enhance light-matter interactions

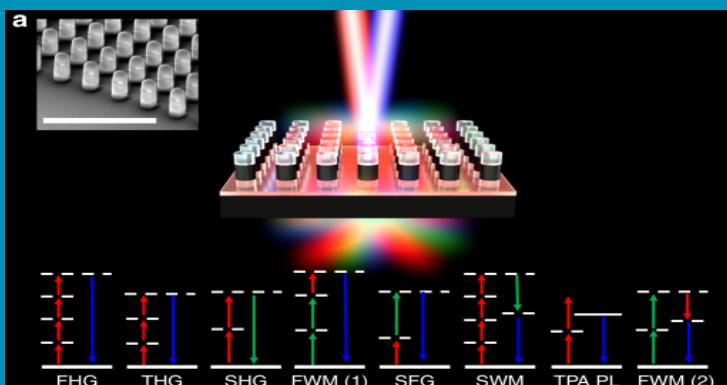


Lasing



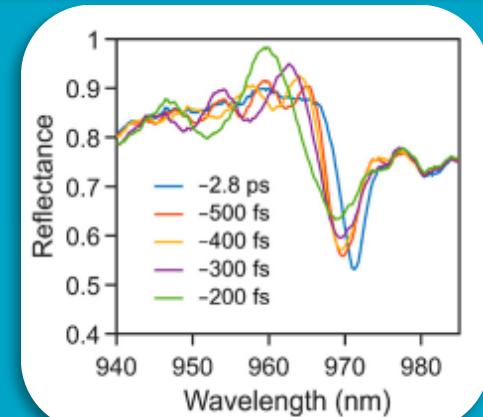
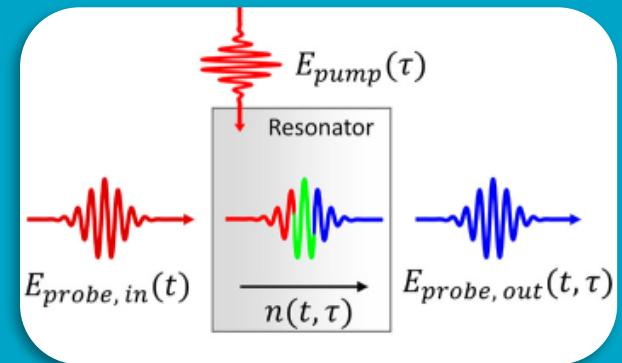
Kodigala et al., *Nature*, 2017,
doi: 10.1038/nature20799.

Frequency-Conversion



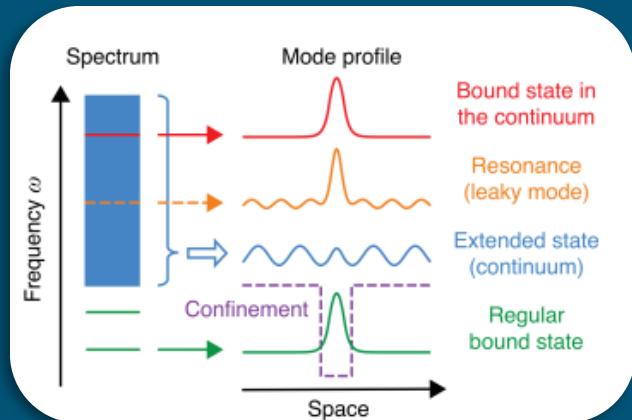
Liu et al., *Nat Commun.*, 2018,
doi: 10.1038/s41467-018-04944-9.

Actively Tunable Optics

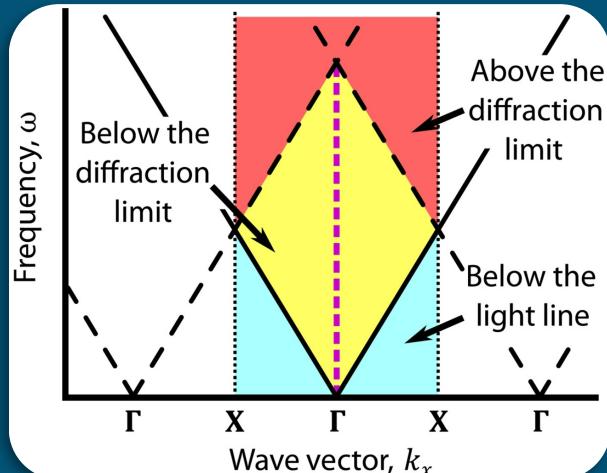


Karl et al., *Nano Lett.*, 2020,
doi: 10.1021/acs.nanolett.0c02113.

Bound states in the continuum (BICs) enable high- Q states

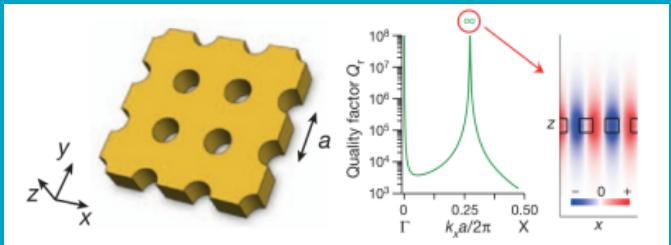


Hsu et al., Nat Rev Mater, 2016,
doi: 10.1038/natrevmats.2016.48.



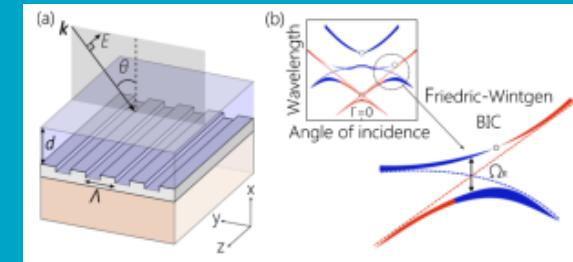
A. Cerjan et al., Science Advances, 2021,
doi: 10.1126/sciadv.abk1117.

Parameter Tuning: Single Resonance



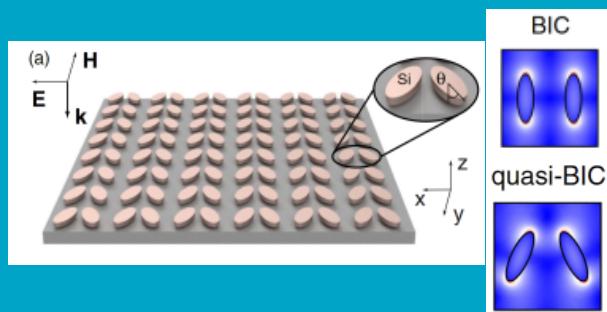
Hsu et al., 2013, doi: 10.1038/nature12289.

Parameter Tuning: Friedrich-Wintgen



Azzam et al., 2018, doi:
10.1103/PhysRevLett.121.253901.

Symmetry Protection



Koshelev et al., 2018, doi:
10.1103/PhysRevLett.121.193903.

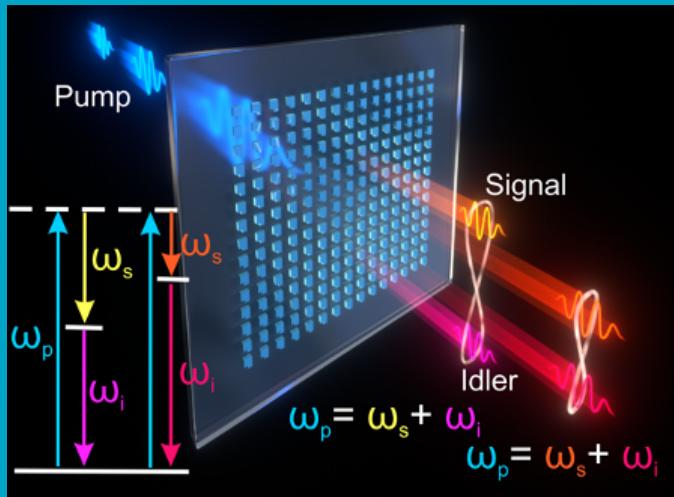
- Mode symmetry incompatible with free space
- Free space → Odd under 180° rotation (C_2)
- Symmetry-protected BIC → Even under 180° rotation (C_2)
- Robust to fabrication/material imperfections

To date, only produced spectrally isolated BICs
Degeneracies or near-degeneracies are “accidental”

Need for degenerate or nearly-degenerate BICs

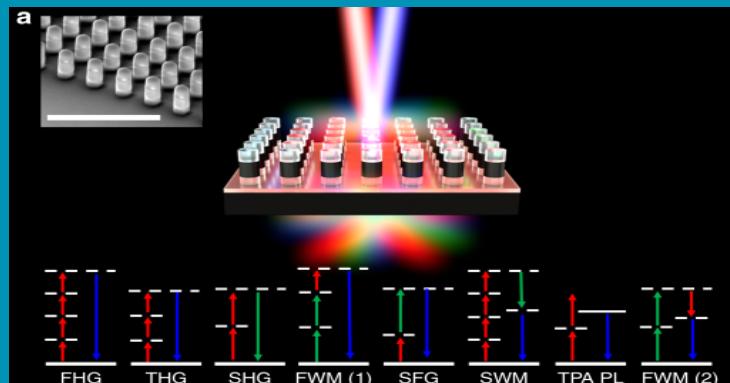


Single Photon Pair Generation via SPDC



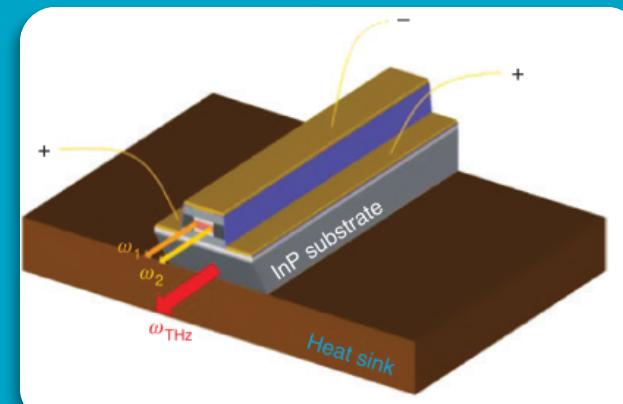
Santiago & Gennaro et al., In Preparation

Four-Wave Mixing



Liu et al., 2018,
doi: 10.1038/s41467-018-04944-9.

THz generation via Intra-Cavity difference-frequency generation



K. Fujita et al., 2018, doi: 10.1515/nanoph-2018-0093.

Can group theory provide a robust solution?

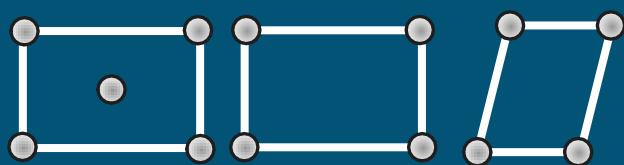
Group theory predicts symmetry-protected degenerate BICs



Lattice

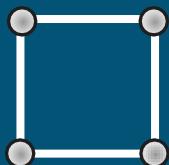
Properties from Representation Theory

C_2 - 180°
rotational symmetry



A_1, A_2
 180° rotation = Even
Dimensionality = 1
Non-degenerate symmetry-protected BICs

C_4 - 90°
rotational symmetry



A_1, A_2
 180° rotation = Even
Dimensionality = 1
Non-degenerate symmetry-protected BICs

E
 180° rotation = Odd
Dimensionality = 2
Degenerate non-BIC

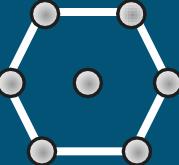
Nomenclature

Symmetry-protected \rightarrow BIC

Symmetry-guaranteed \rightarrow Degeneracy guaranteed by symmetry

Group theory predicts symmetry-protected degenerate BICs



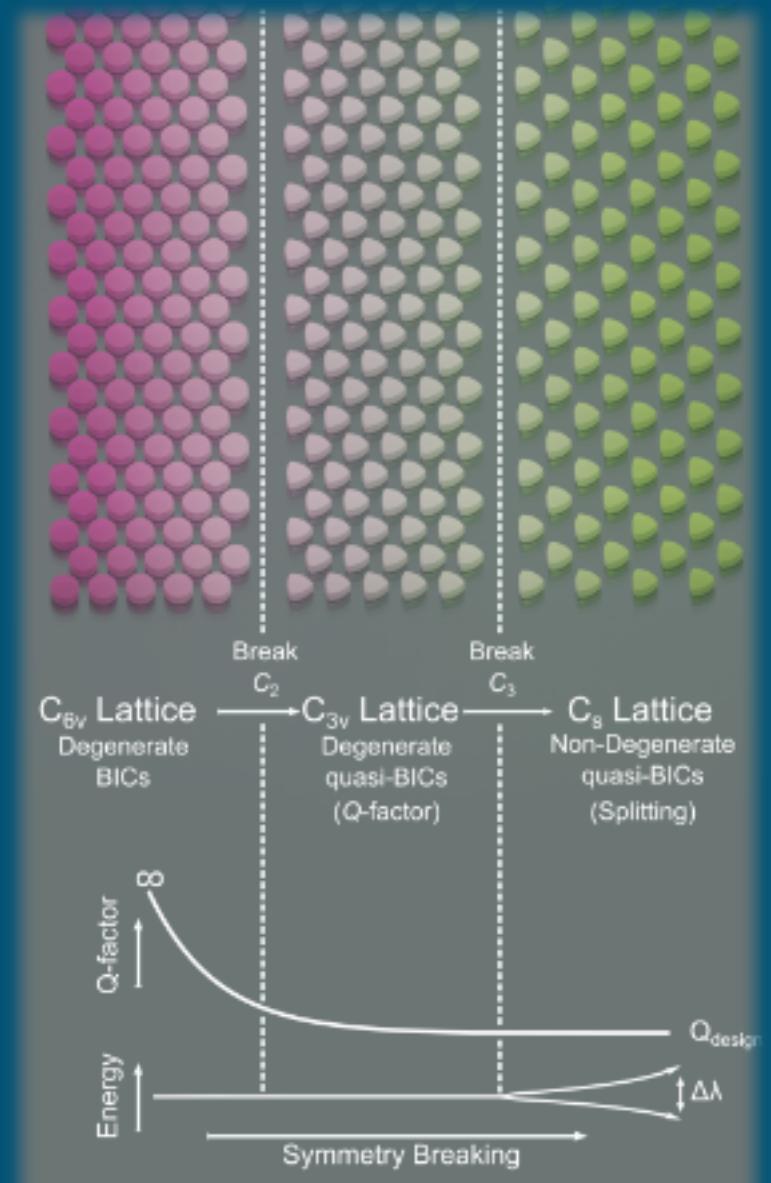
Lattice	Properties from Representation Theory
C_6 - 60° <i>rotational symmetry</i> 	E_2 180° rotation = Even Dimensionality = 2 Degenerate symmetry-protected BICs C_2 , 180° rotation → Symmetry-protected BIC C_3 , 120° rotation → Symmetry-guaranteed Degeneracy C_2 and C_3 are independent, non-trivial subgroups of C_6

Only triangular lattices support symmetry-protected degenerate BICs

Nomenclature

Symmetry-protected → BIC

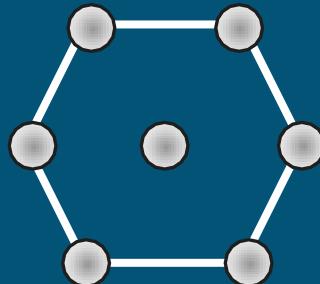
Symmetry-guaranteed → Degeneracy guaranteed by symmetry



Finding symmetry-protected degenerate BICs

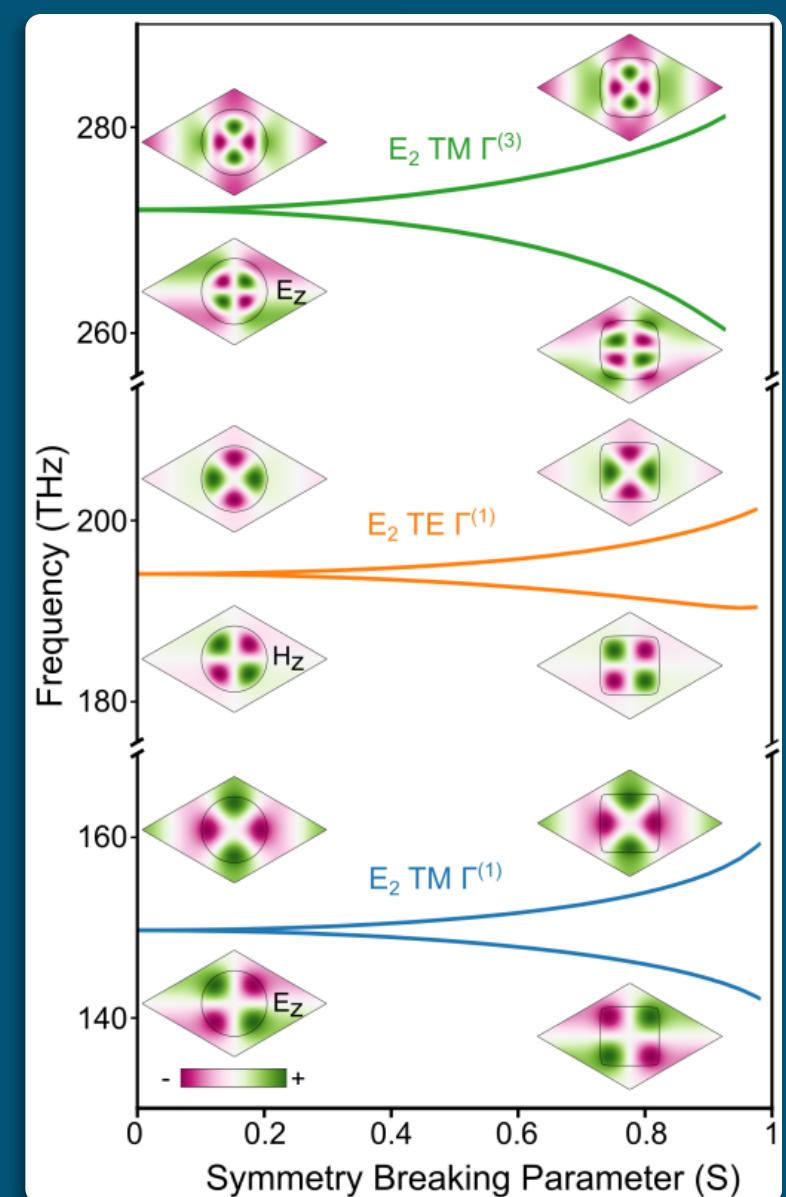
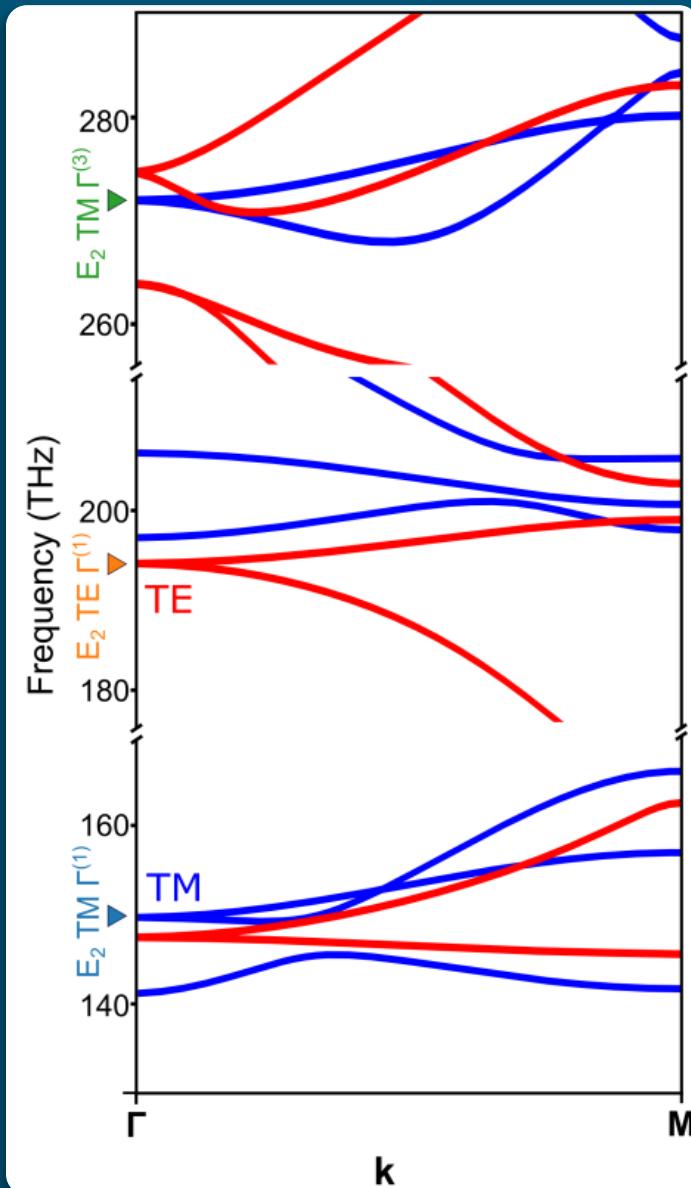


2D Triangular lattice of Si rods



For BICs state must be at center of Brillouin Zone ($K_{||} = \Gamma$)

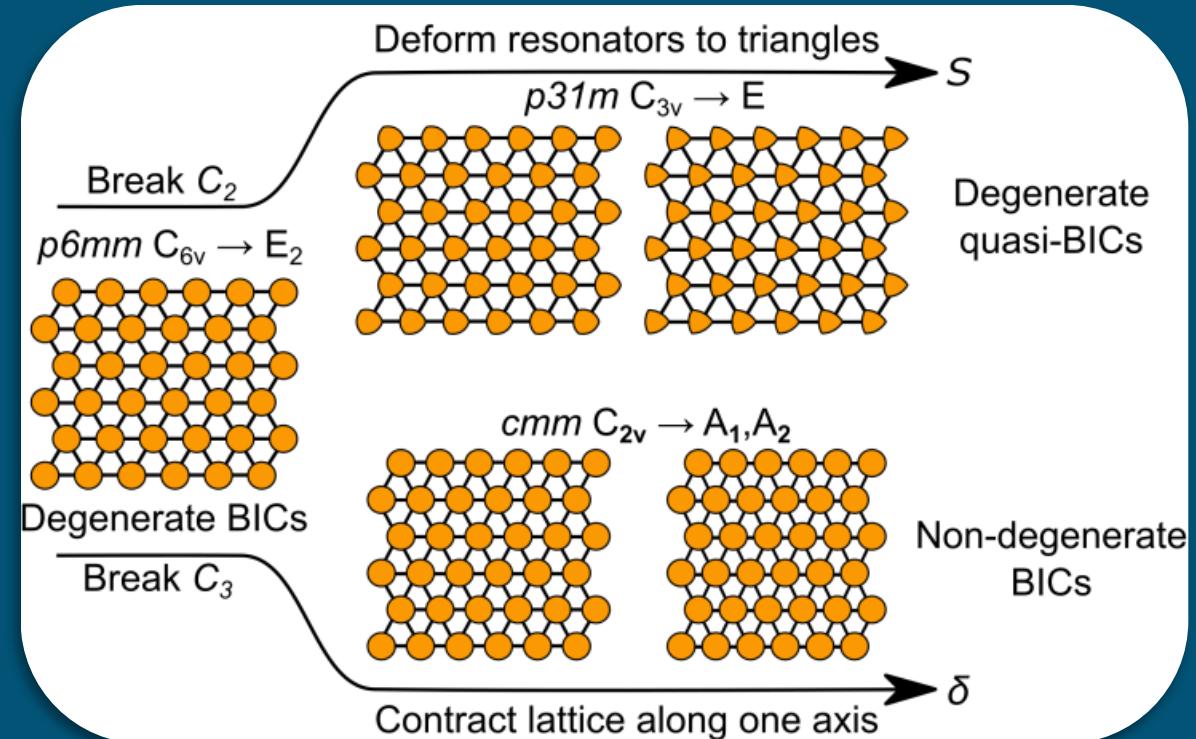
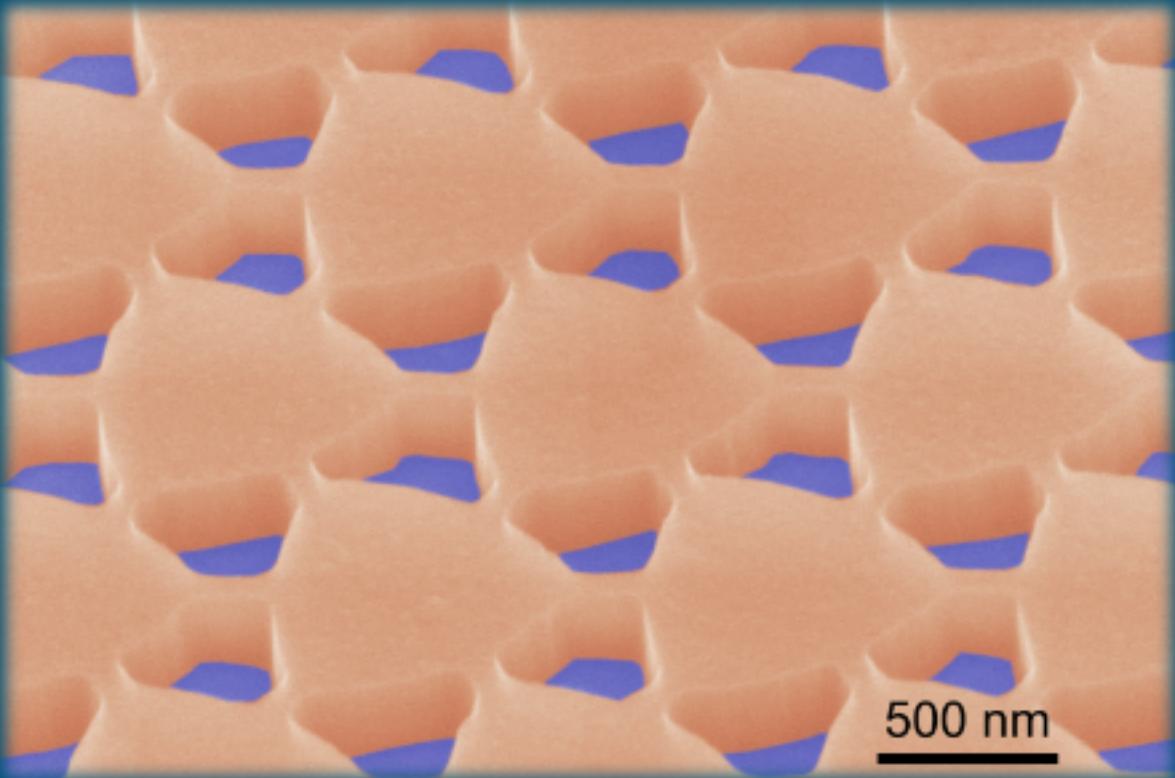
- Away from $K_{||} = \Gamma$ degeneracy is lifted and $Q < \infty$
- Use resonator and lattice deformations to break symmetry at $K_{||} = \Gamma$



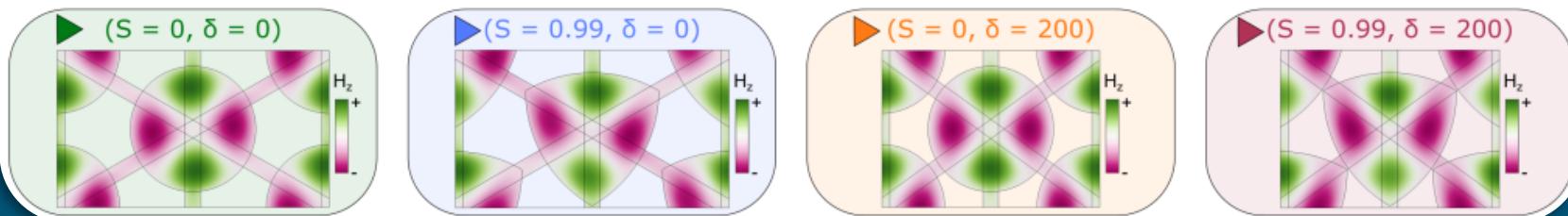
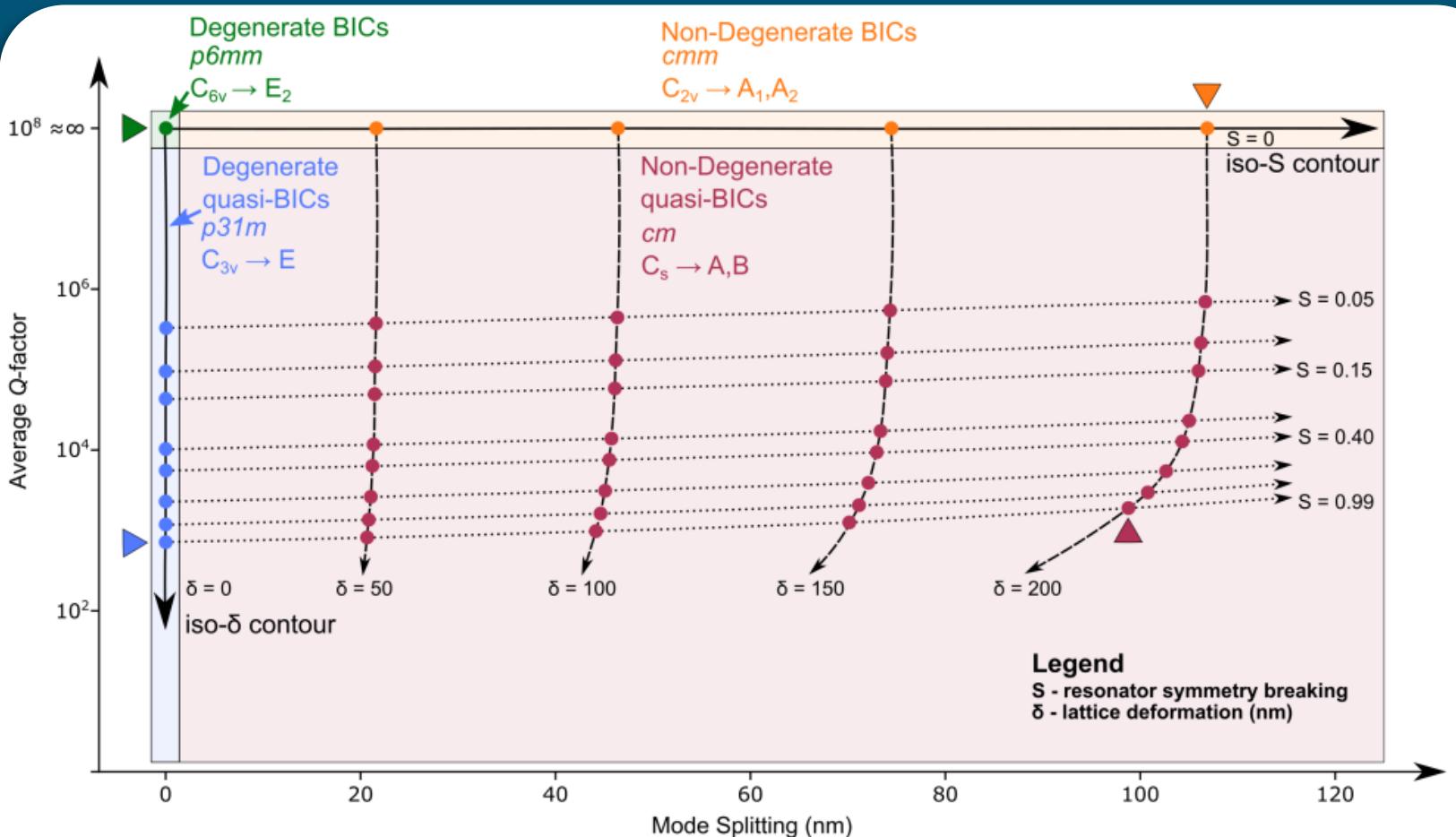
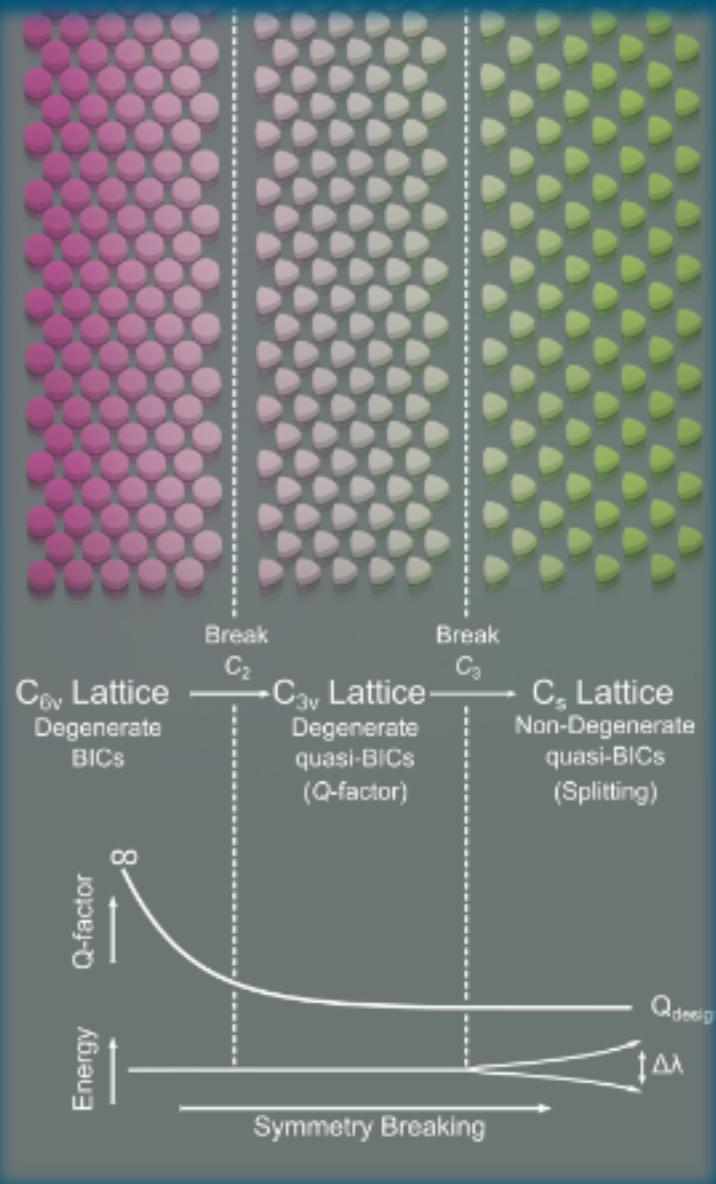
Two classes of deformations → Control over Q-factor and splitting



Fabricated silicon metasurface on fused silica



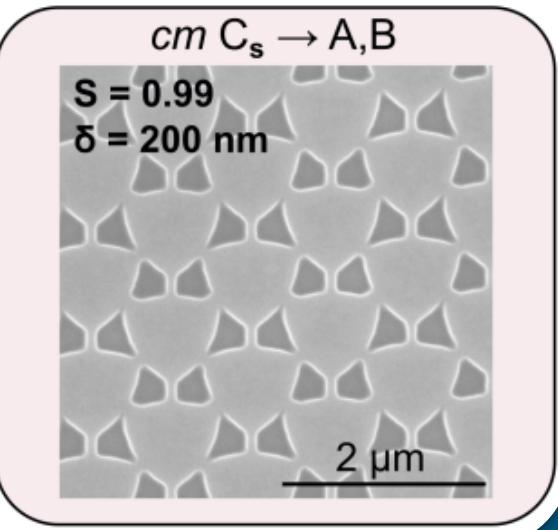
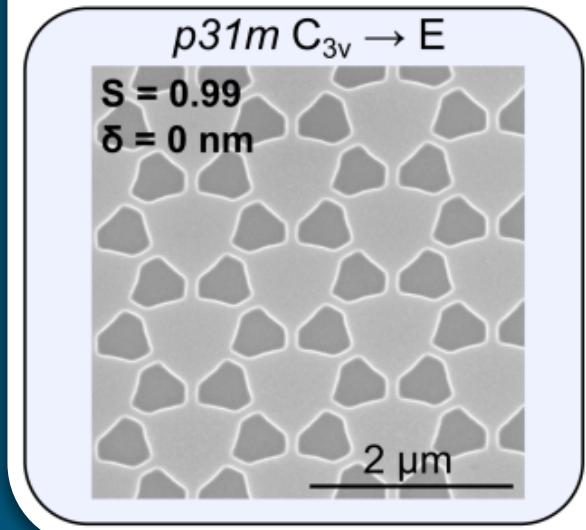
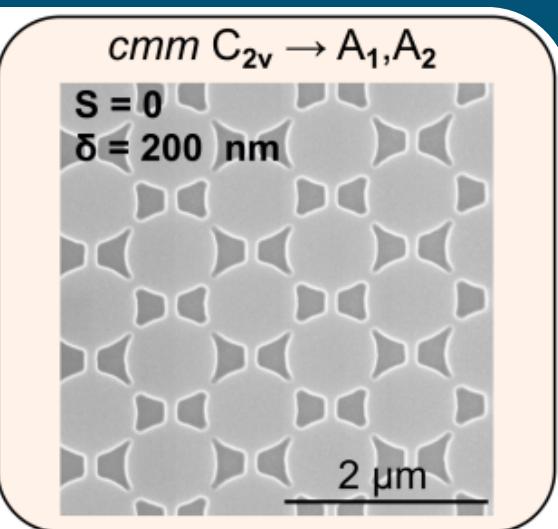
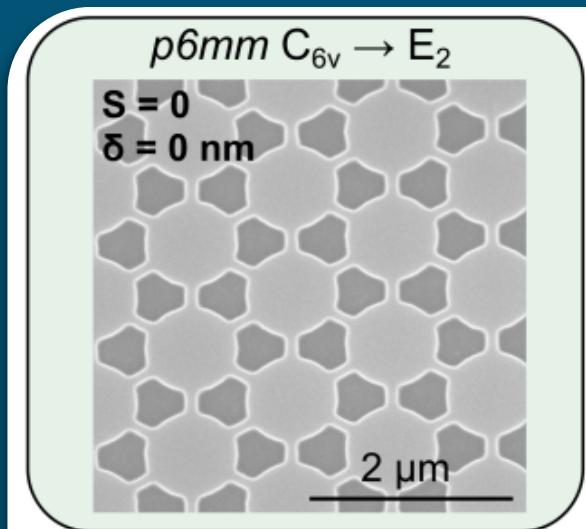
Two classes of deformations → Control over Q-factor and splitting



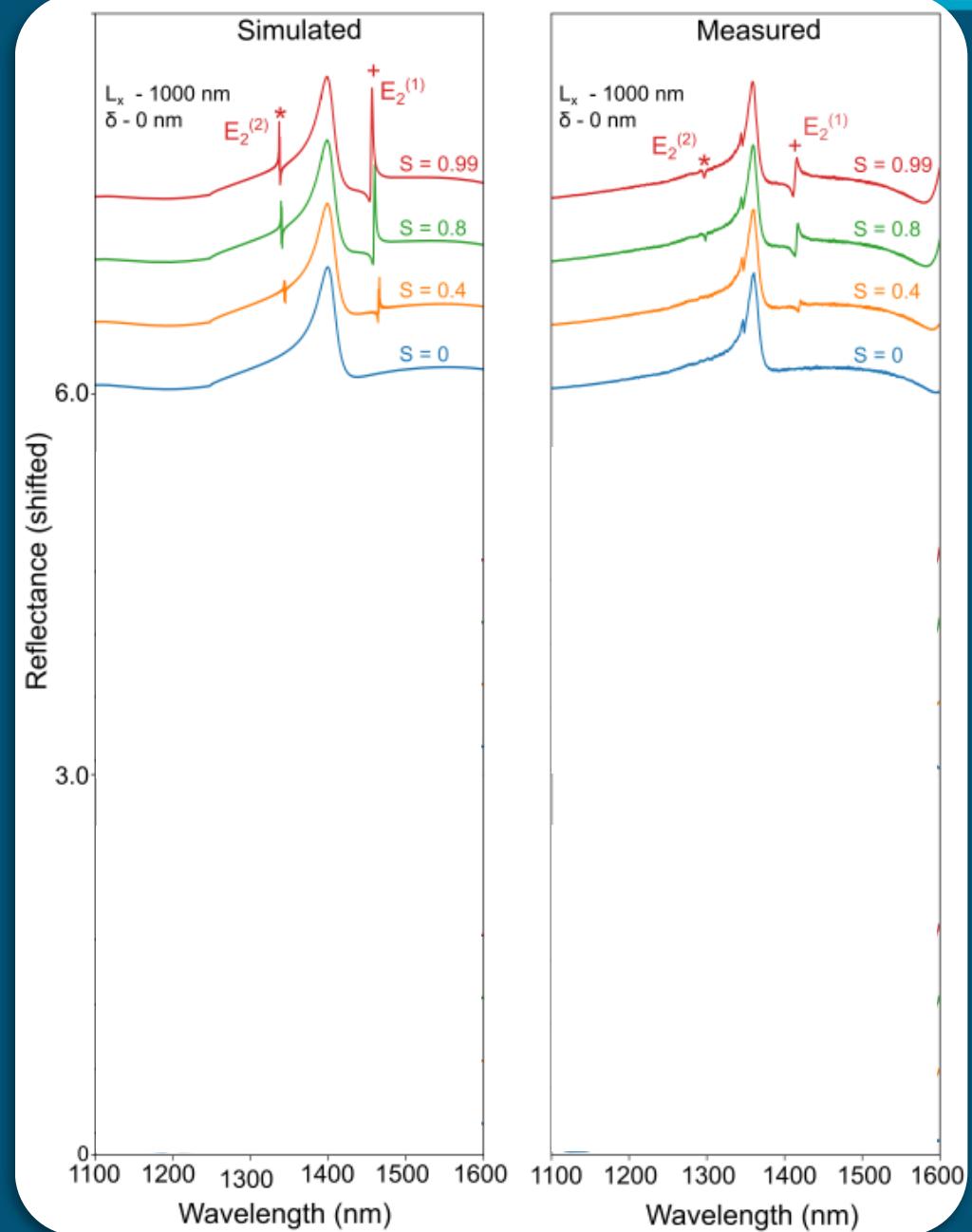
Observe independent tuning experimentally



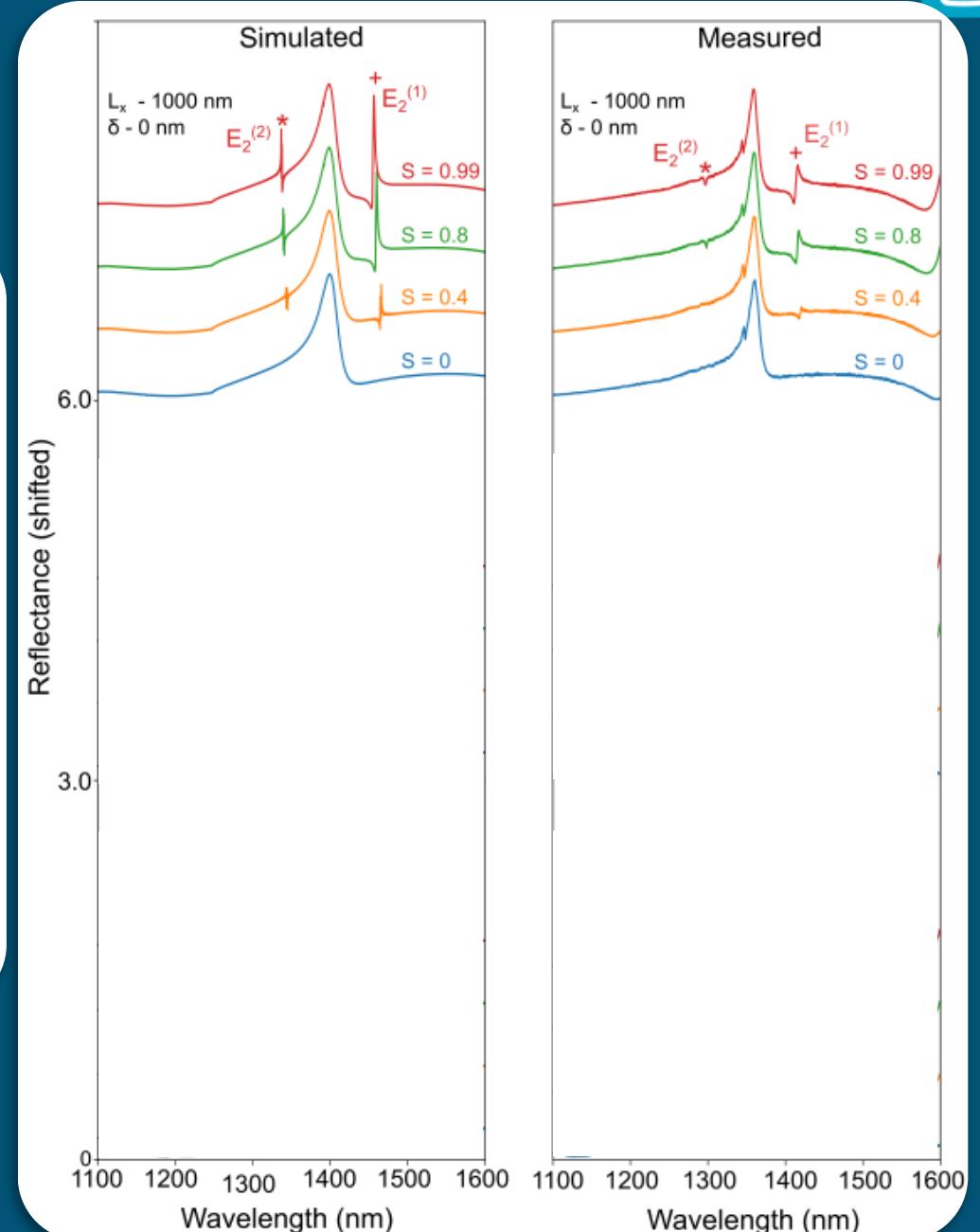
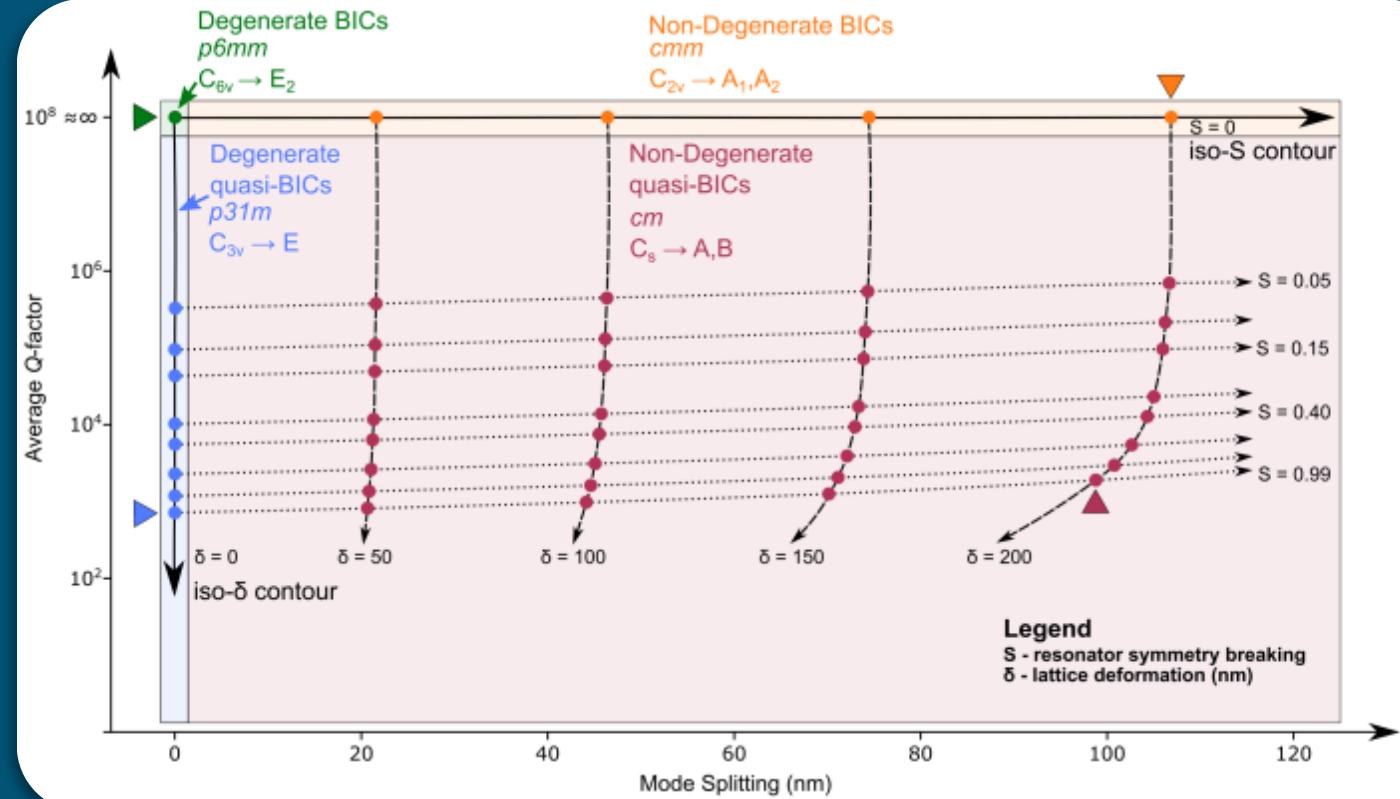
Silicon metasurfaces on fused silica



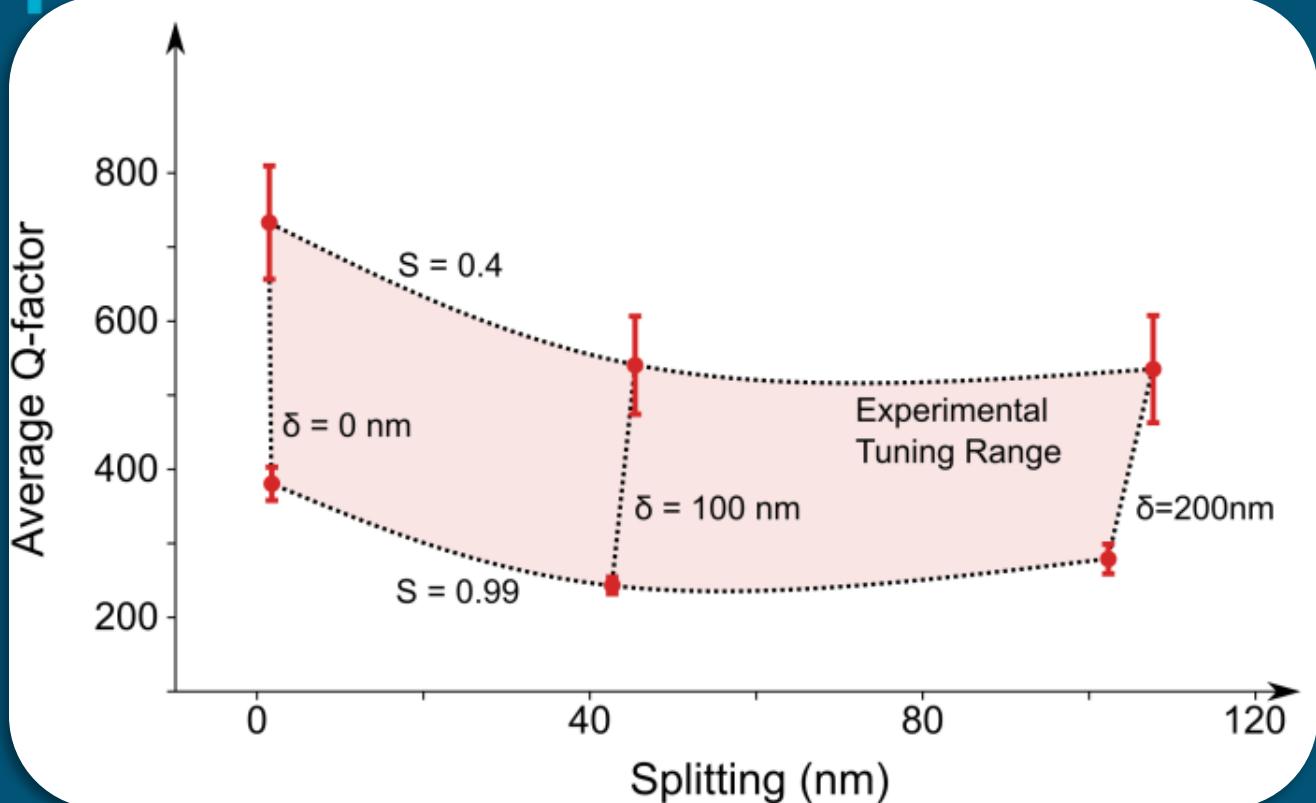
Si thickness – 200 nm
 Period – 1000 nm



Observe independent tuning experimentally



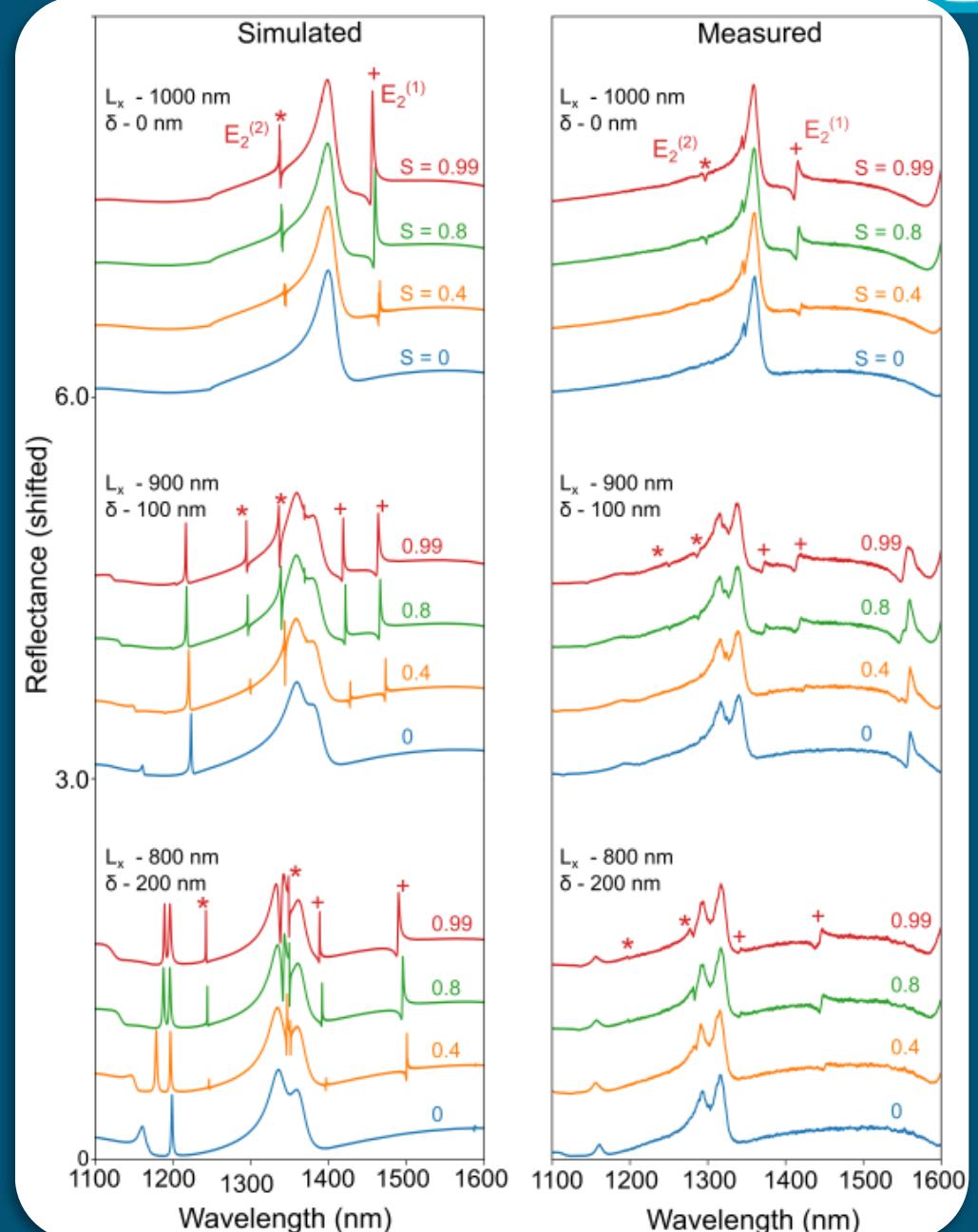
Observe independent tuning experimentally



Average mode wavelength differed by 47 nm

Mode splitting differed by 2 nm

Robust to fabrication and material imperfections



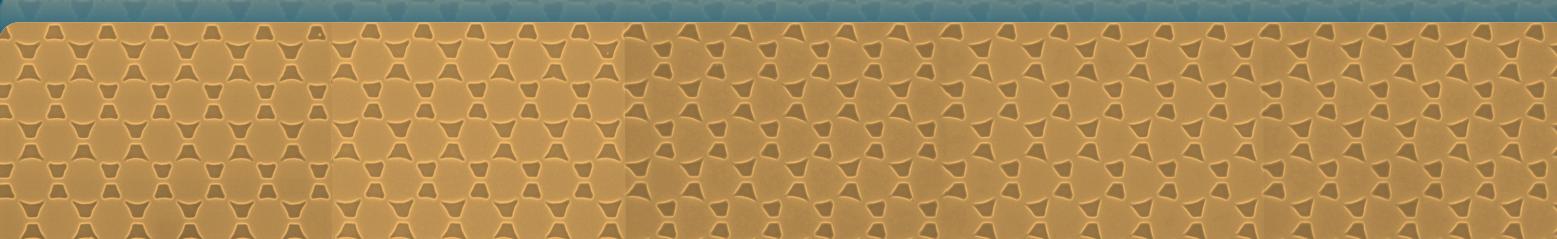
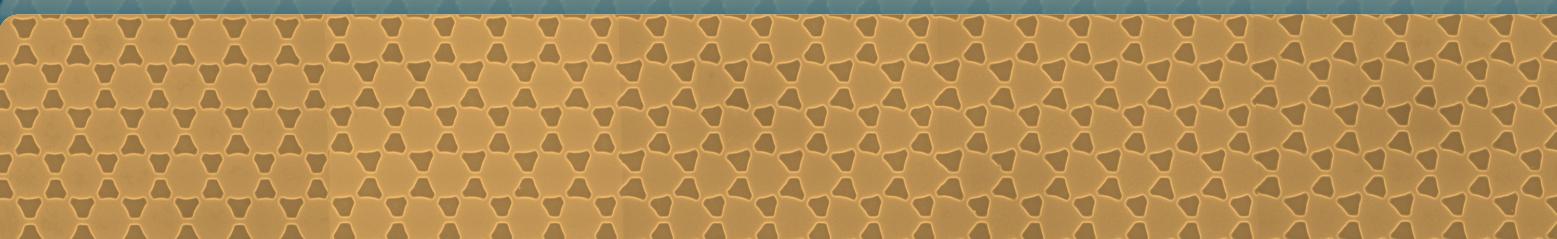
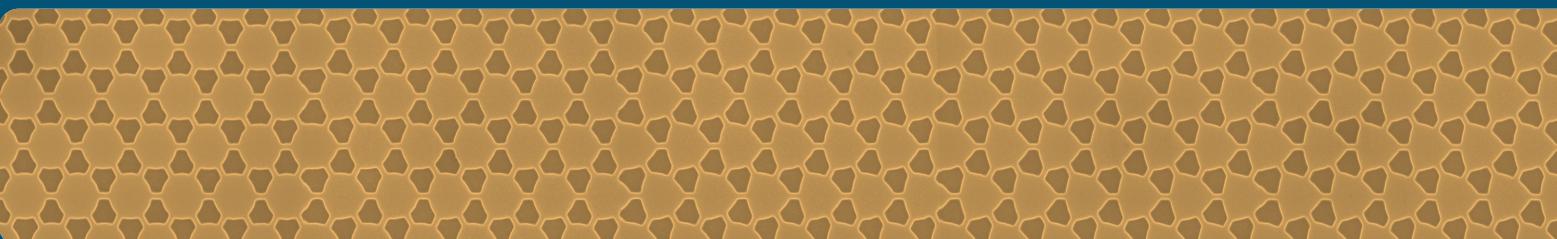
Conclusion & Acknowledgements



Only triangular lattices (C_6) support symmetry-protected degenerate BICs

Independent symmetry breaking operations control Q-factor (C_2) and splitting (C_3)

Experimentally demonstrated in silicon metasurfaces



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