Topological solitons and slow light

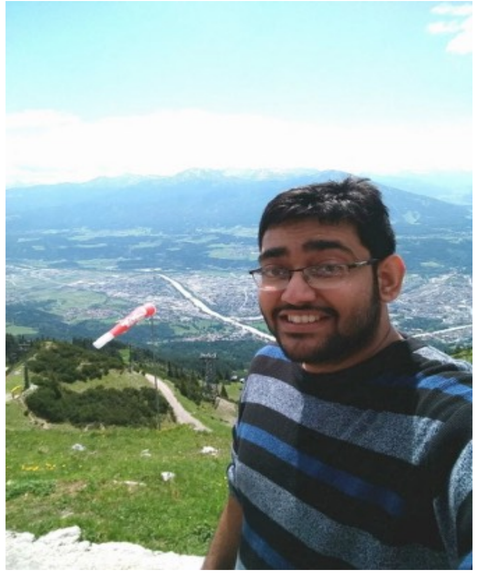
Mikael C. Rechtsman, Penn State

KITP, October 2019

My group


Jiho Noh


Jonathan Guglielmon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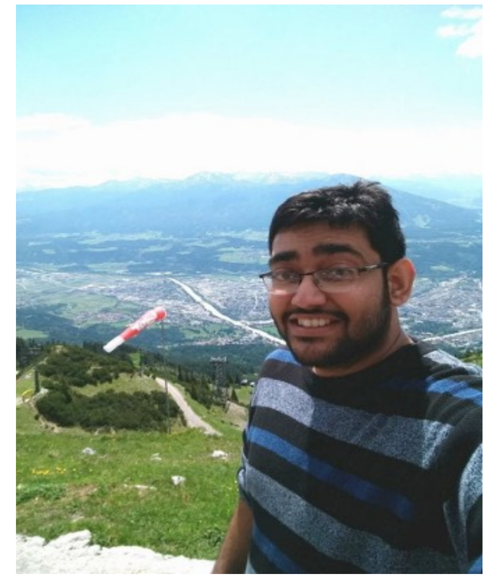

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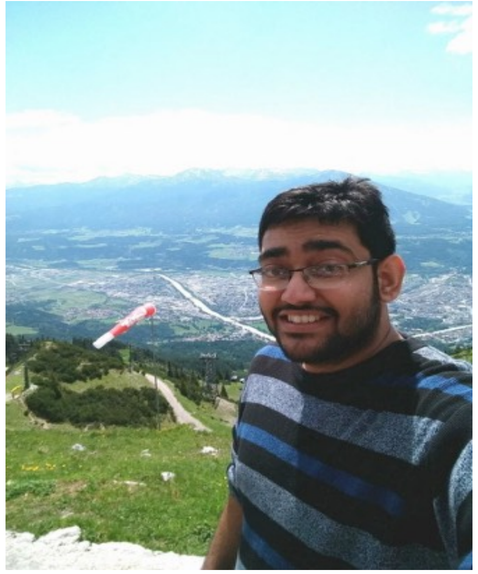
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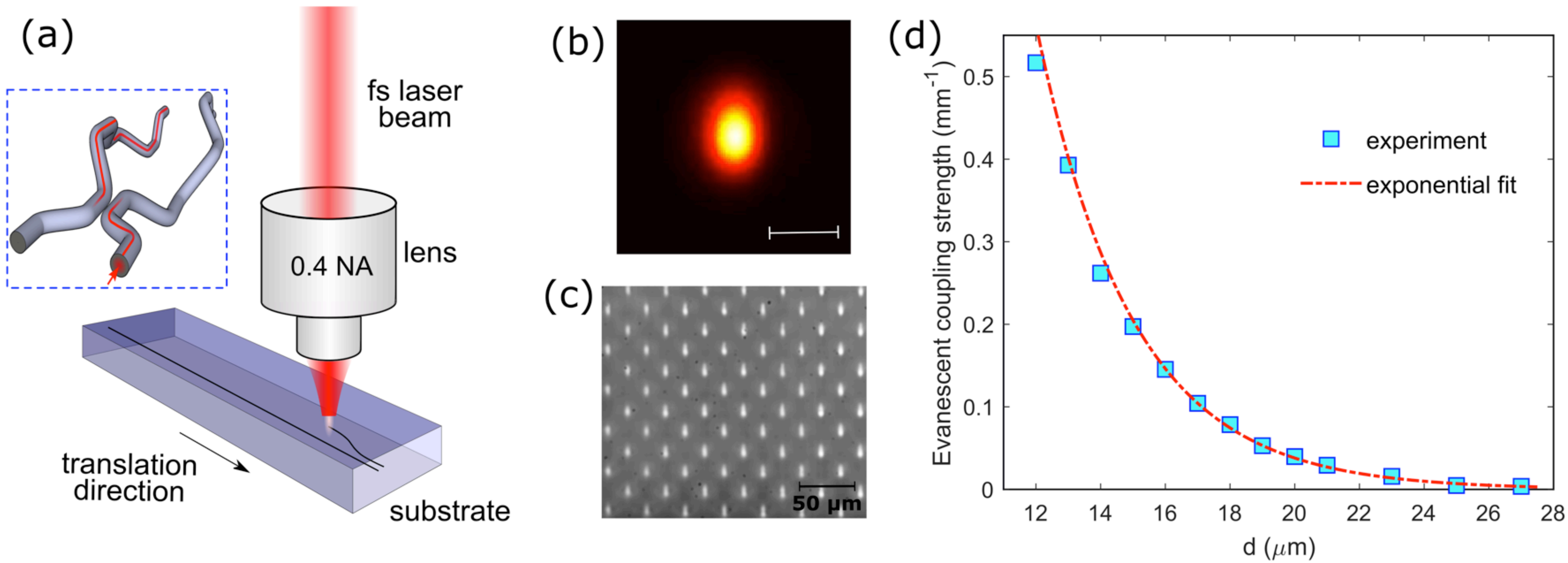
Outline

(0) Short background on topological photonics

(1) Observation of topological solitons

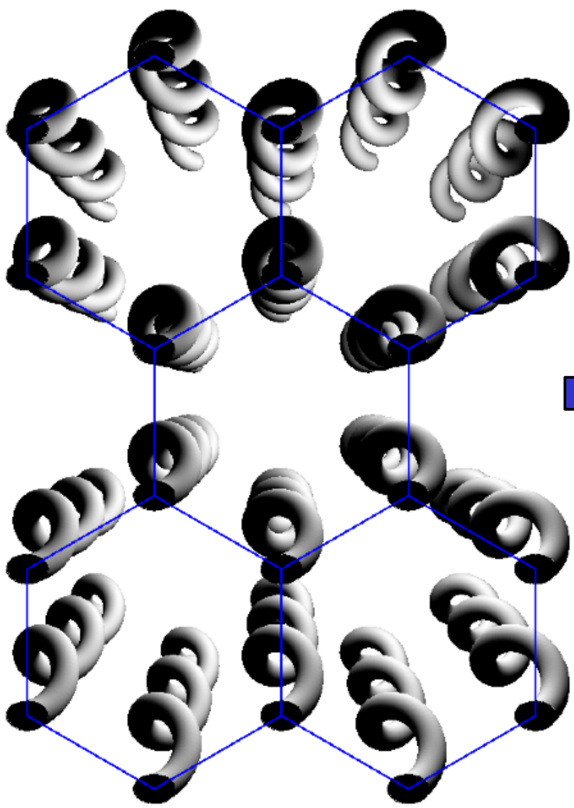
(2) Topological slow light

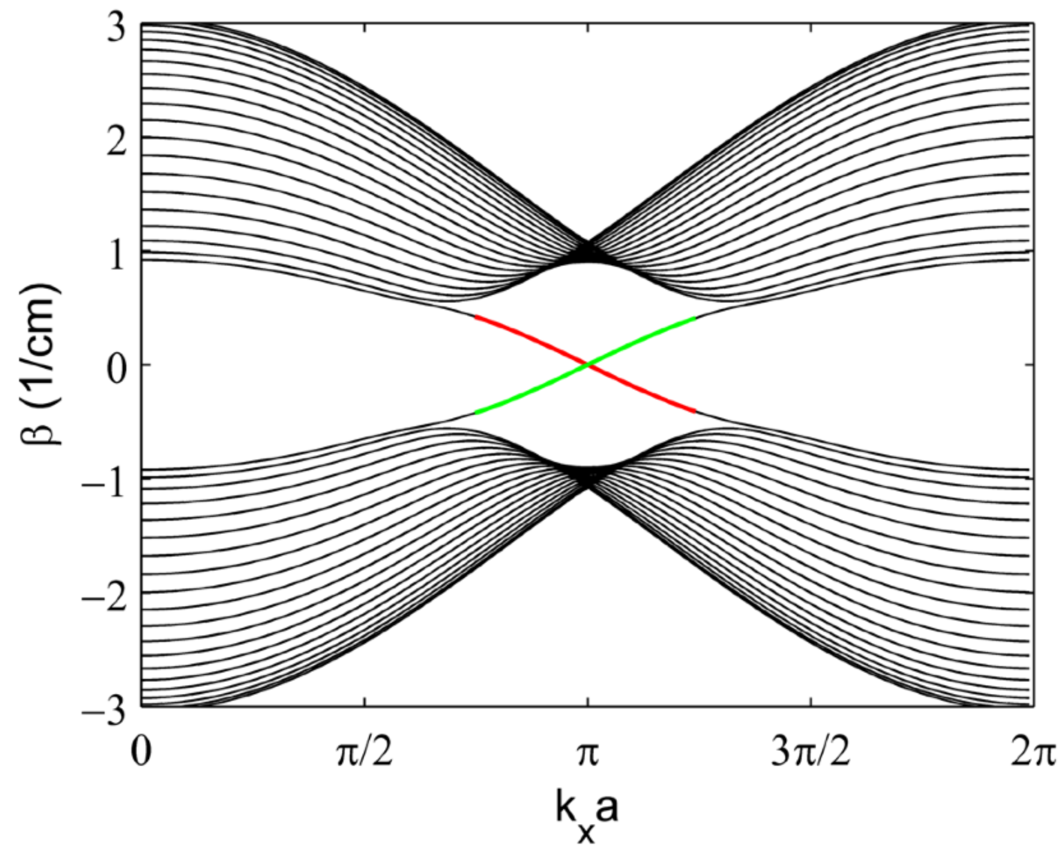
Laser-written waveguide arrays

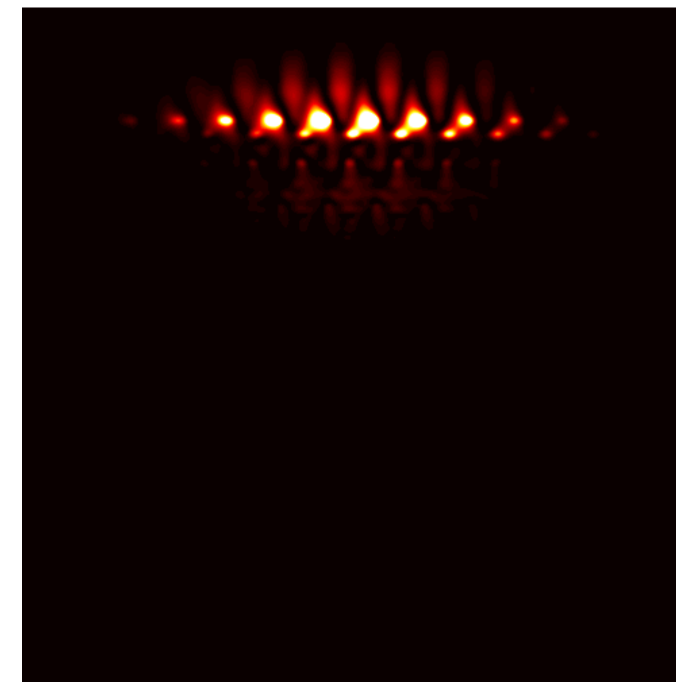


$$\nabla \times \nabla \times E = \epsilon \left(\frac{\omega}{c}\right)^2 E \longrightarrow i\partial_z \psi = H\psi$$

Background: photonic topological insulators







- Background material: Photonic topological insulator (PTI) realized in laser written waveguide arrays: Rechtsman et al., Nature 496, 196 (2013).

- Light propagates unidirectionally around structure without scattering due to any form of defect/disorder as long as the bulk gap stays open.

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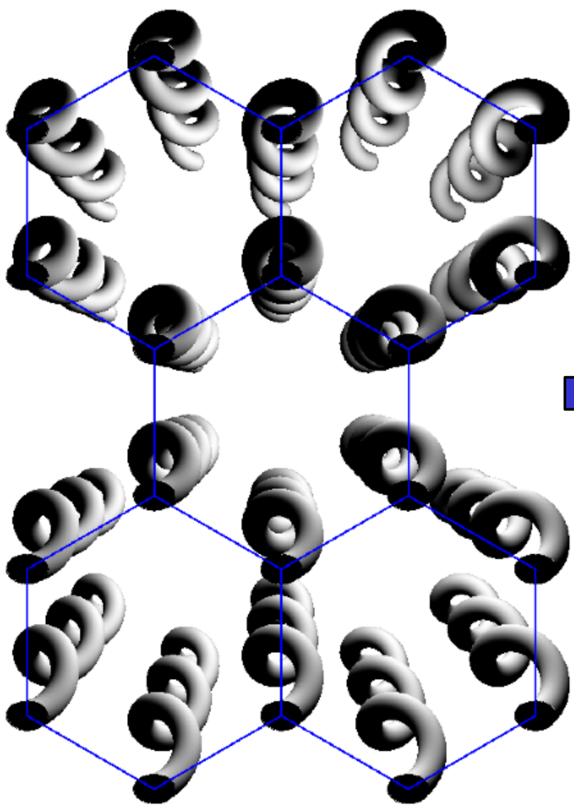

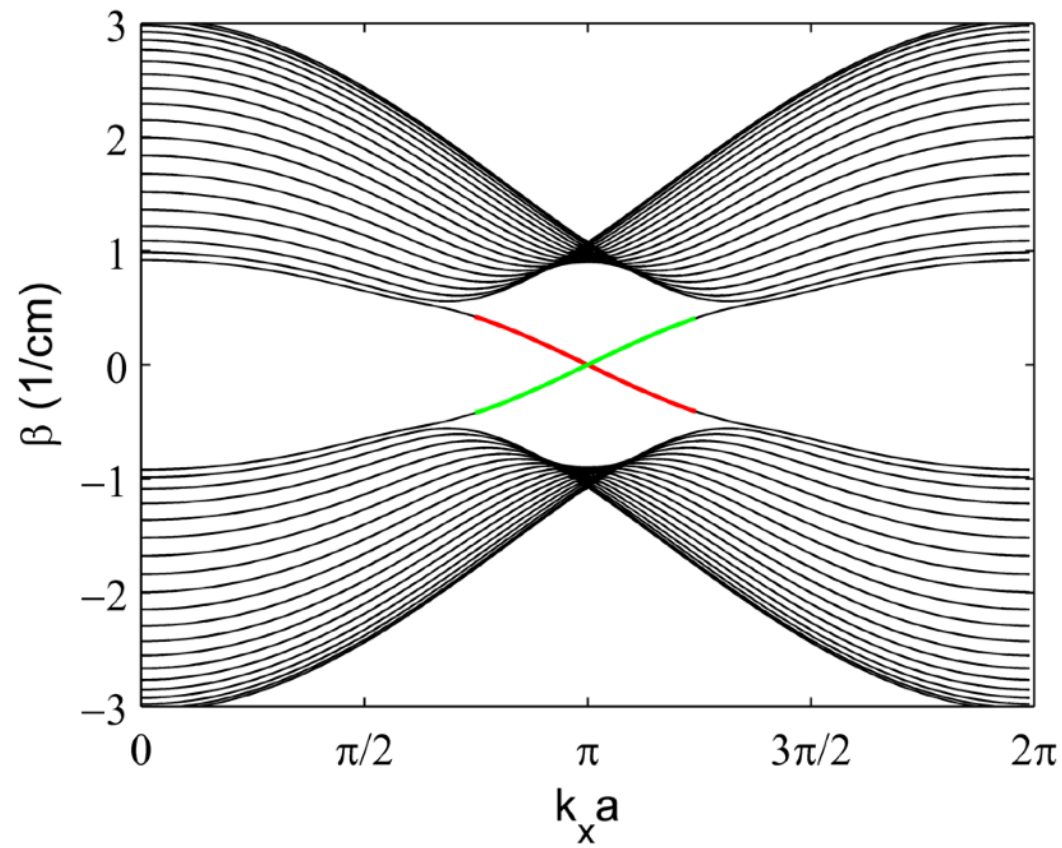

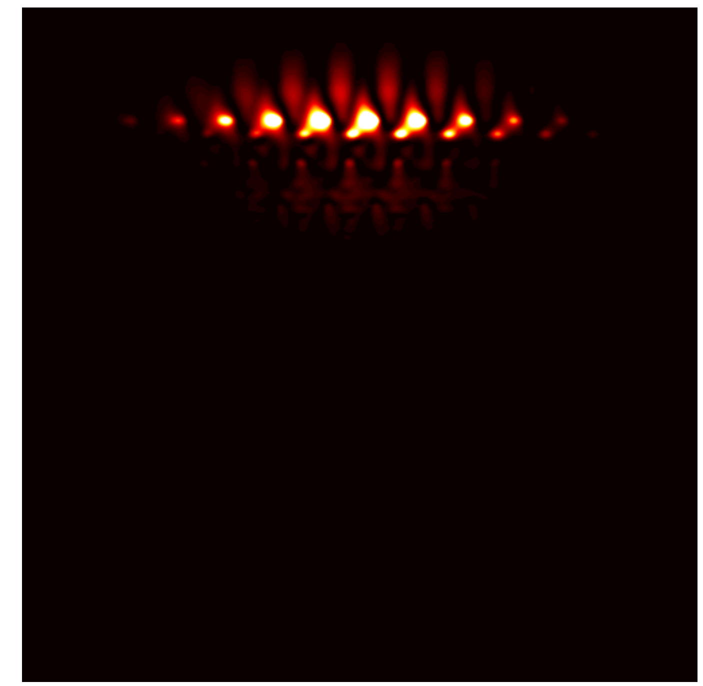

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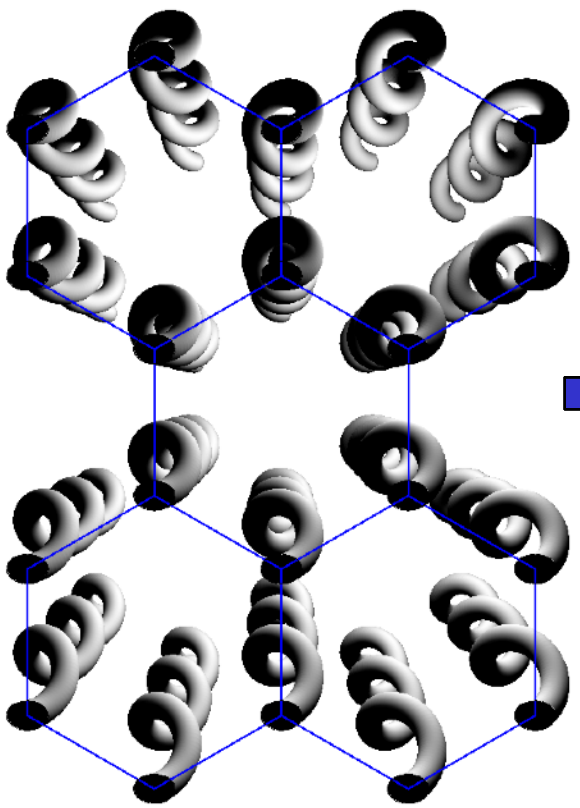

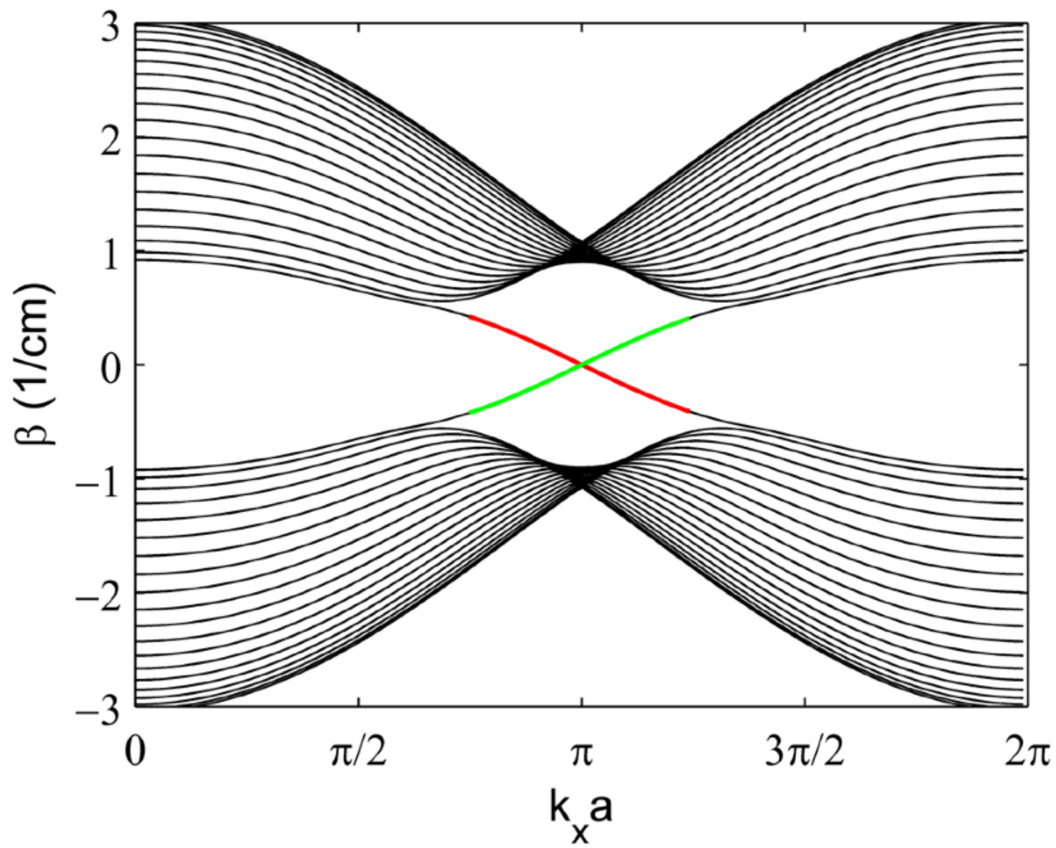

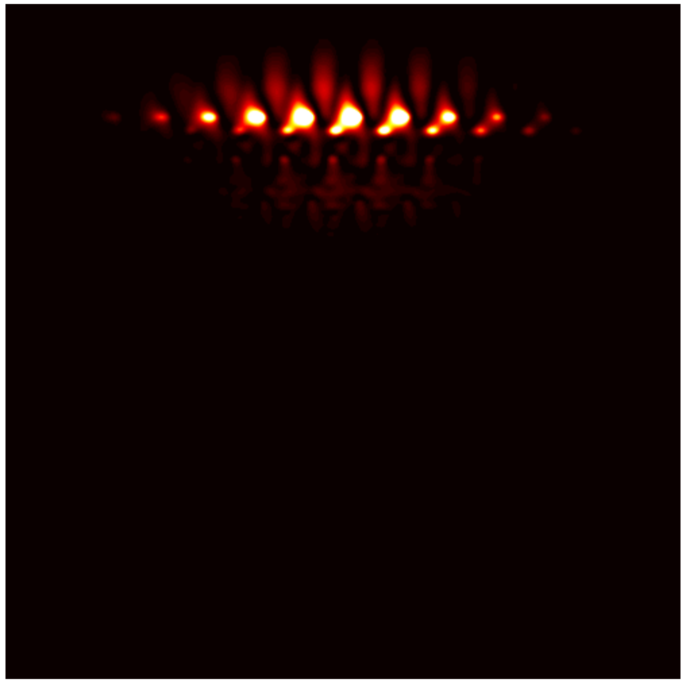

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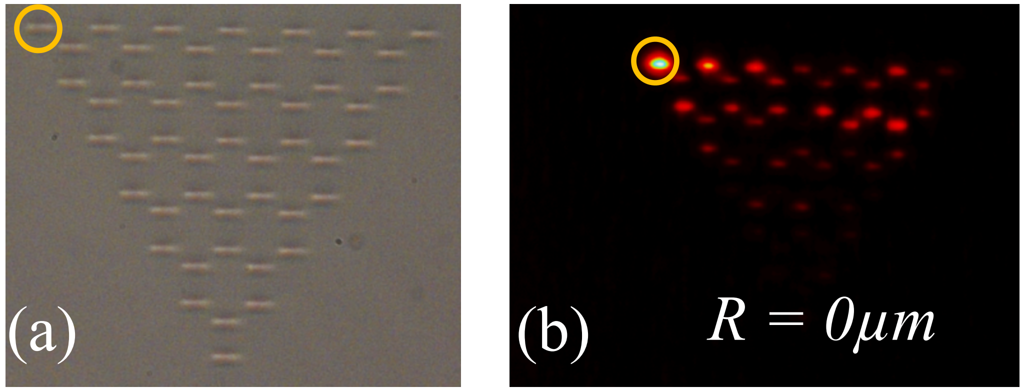

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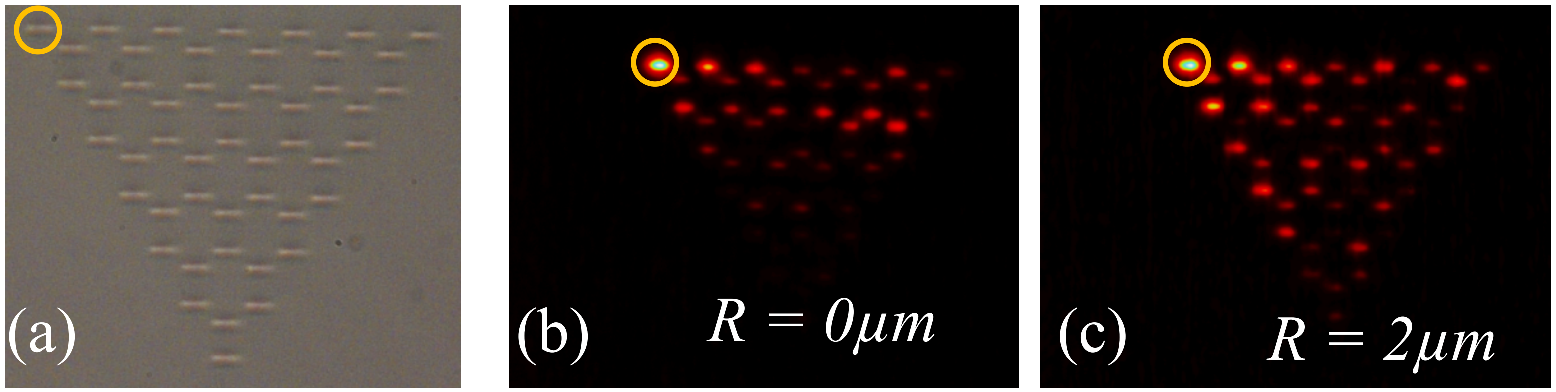

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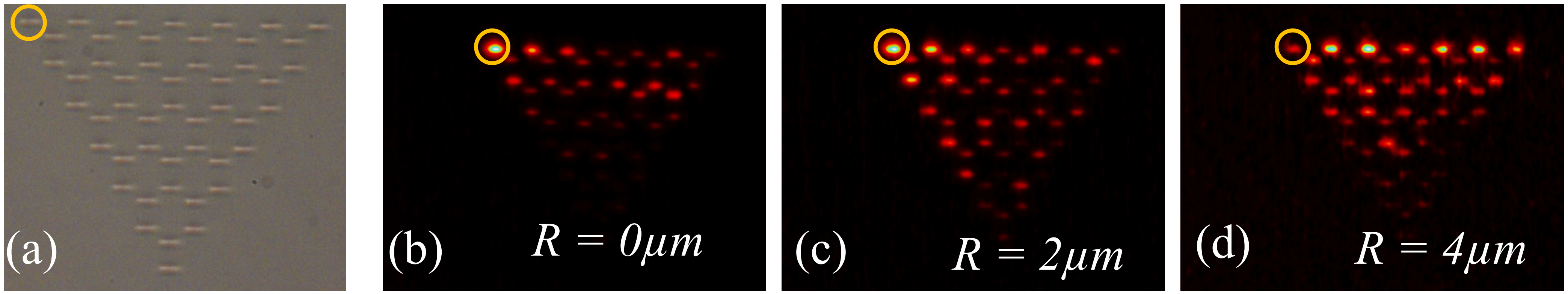

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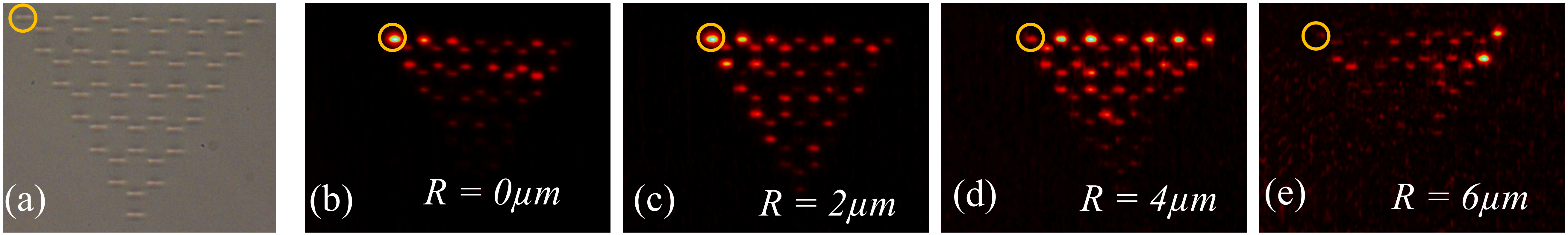

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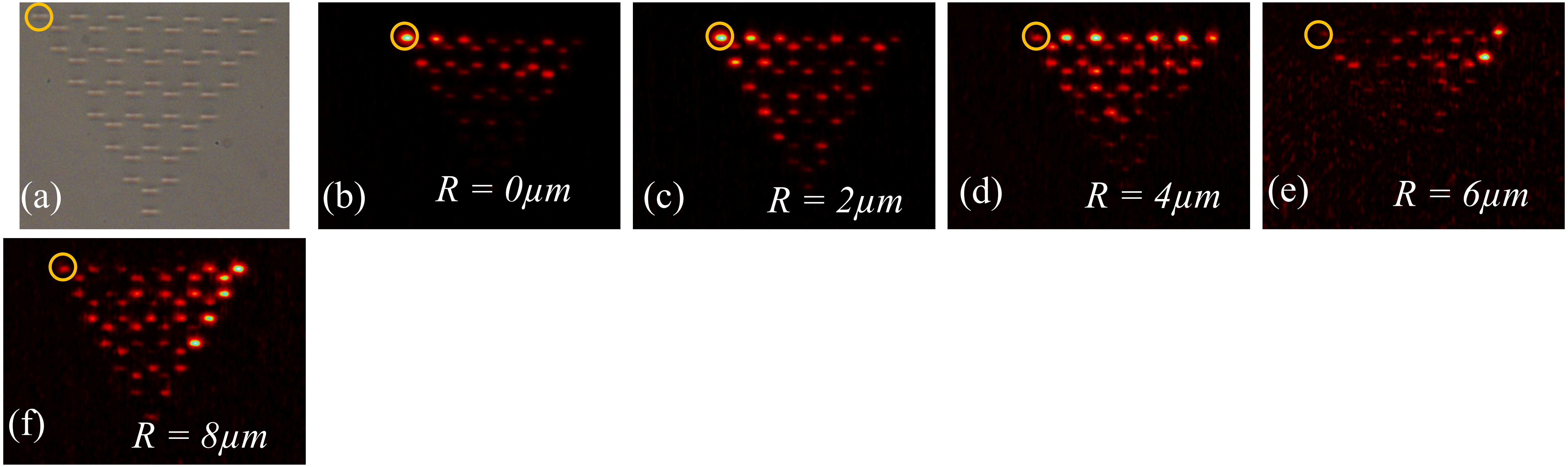

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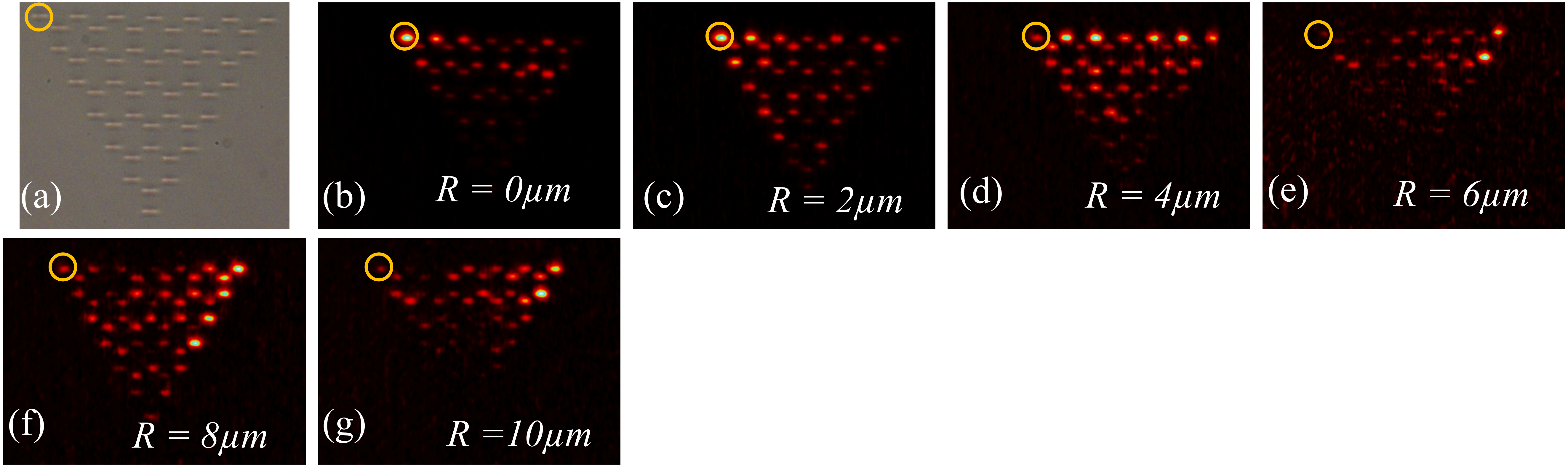

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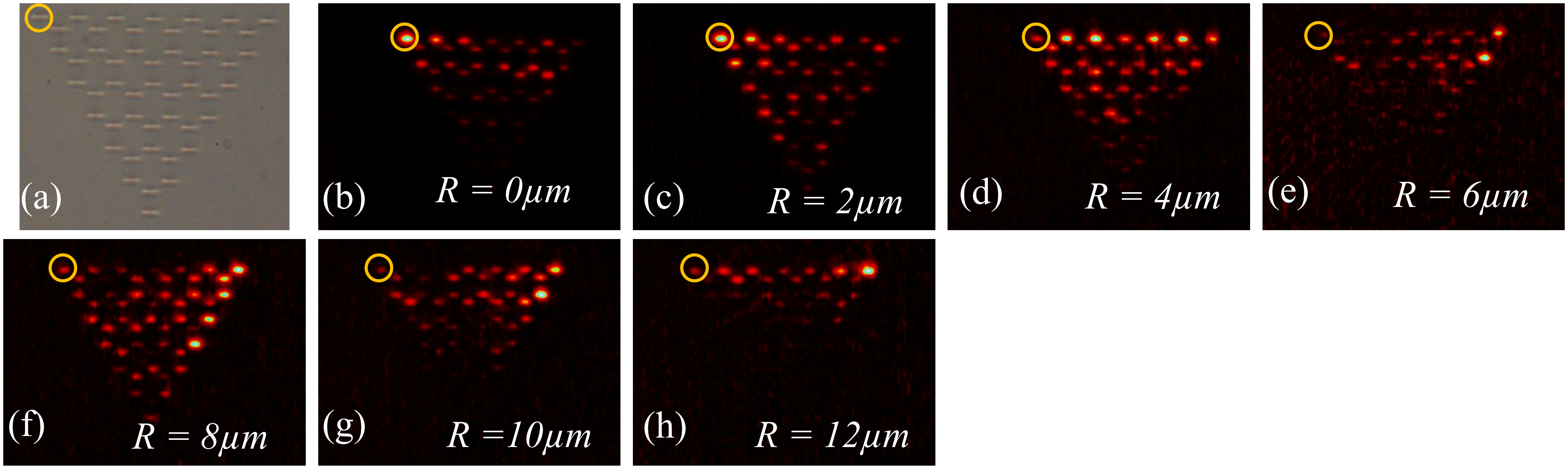

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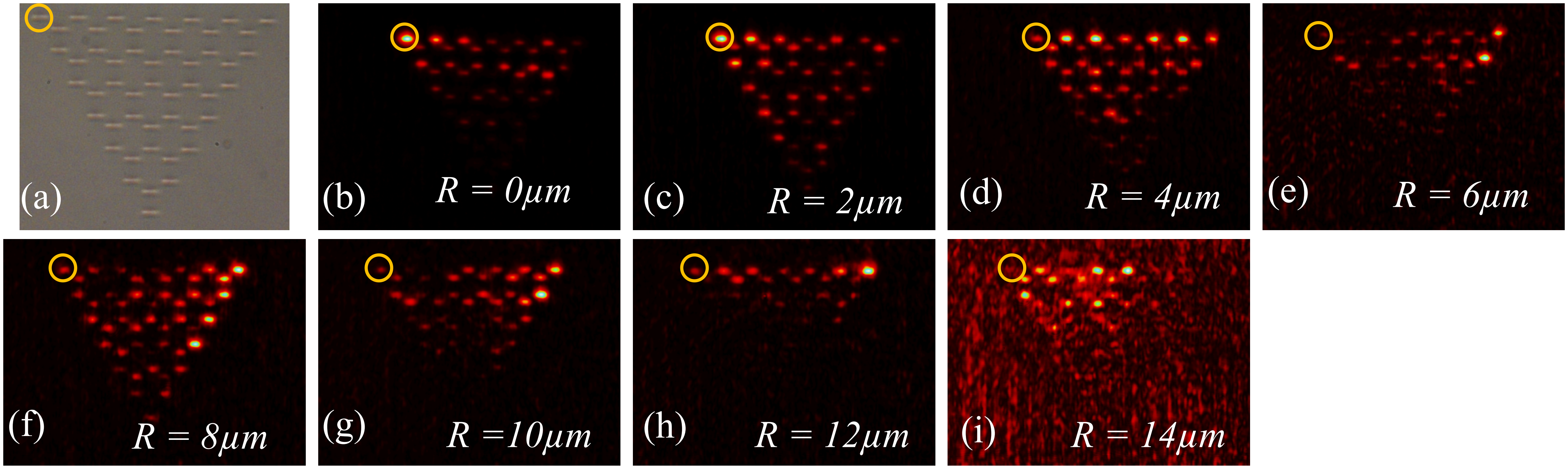

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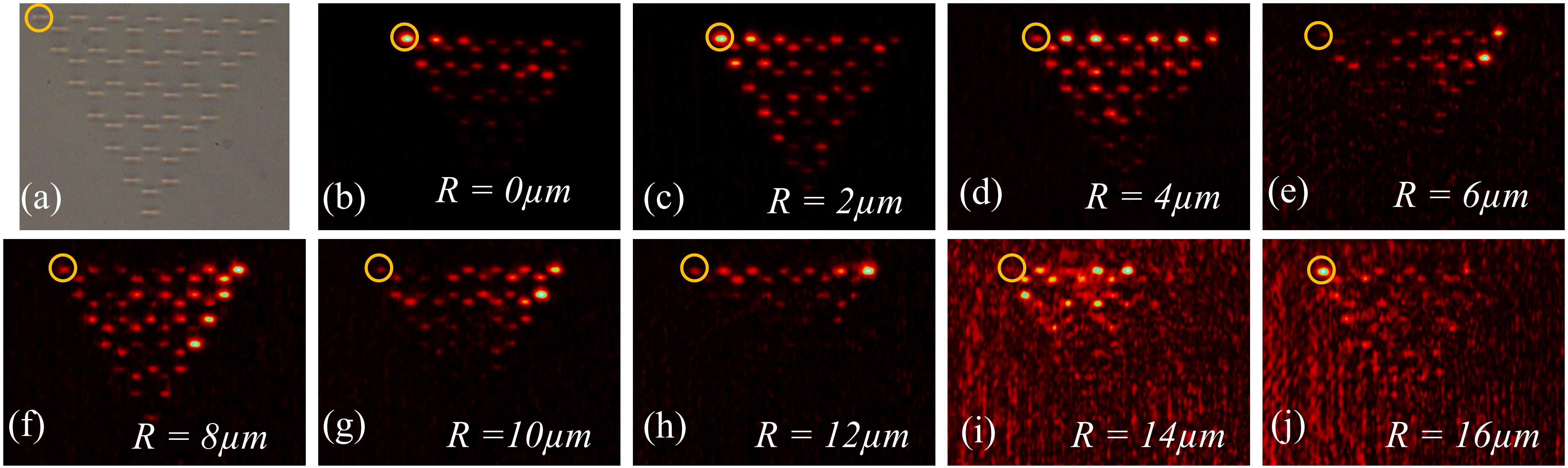

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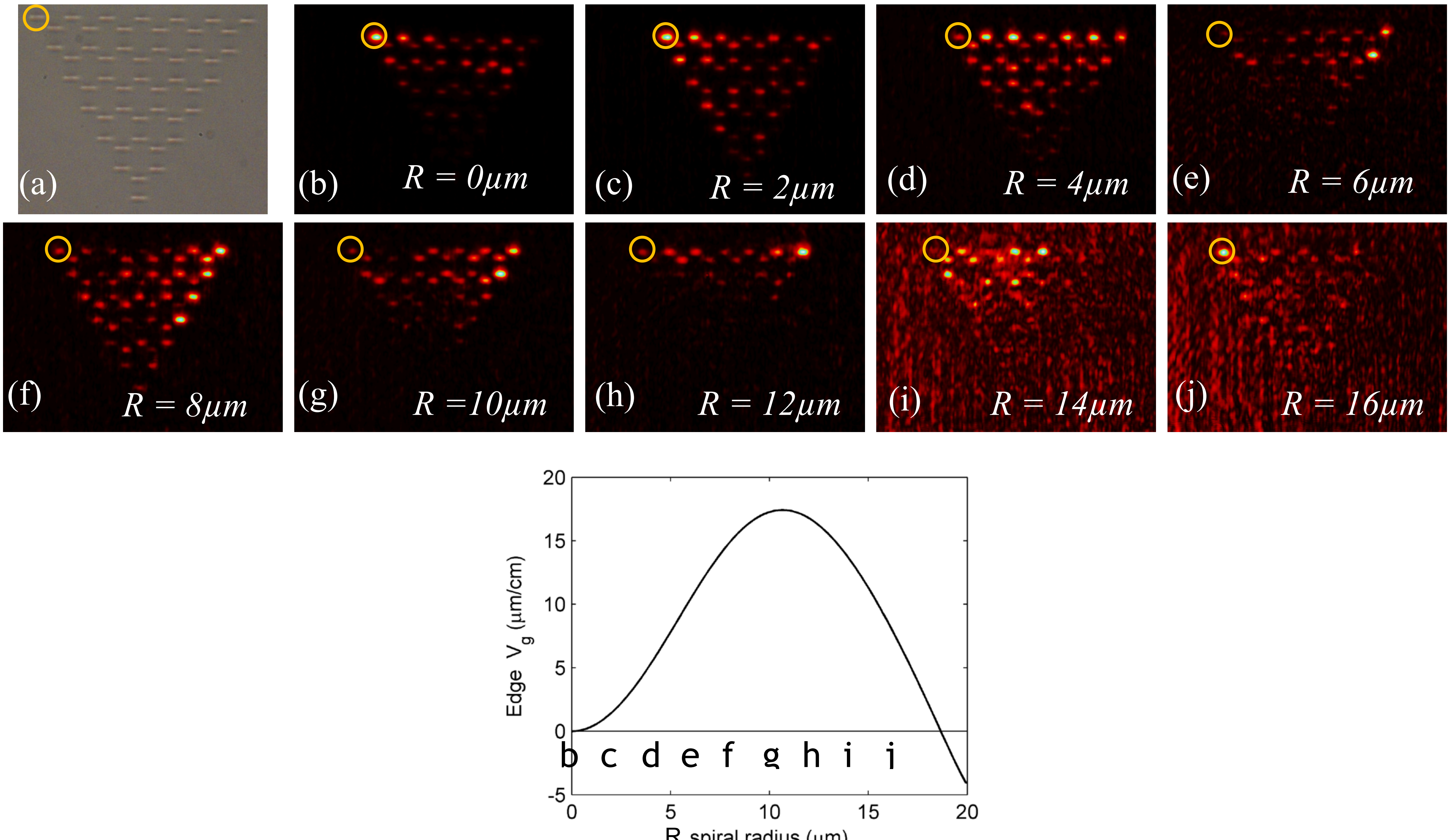

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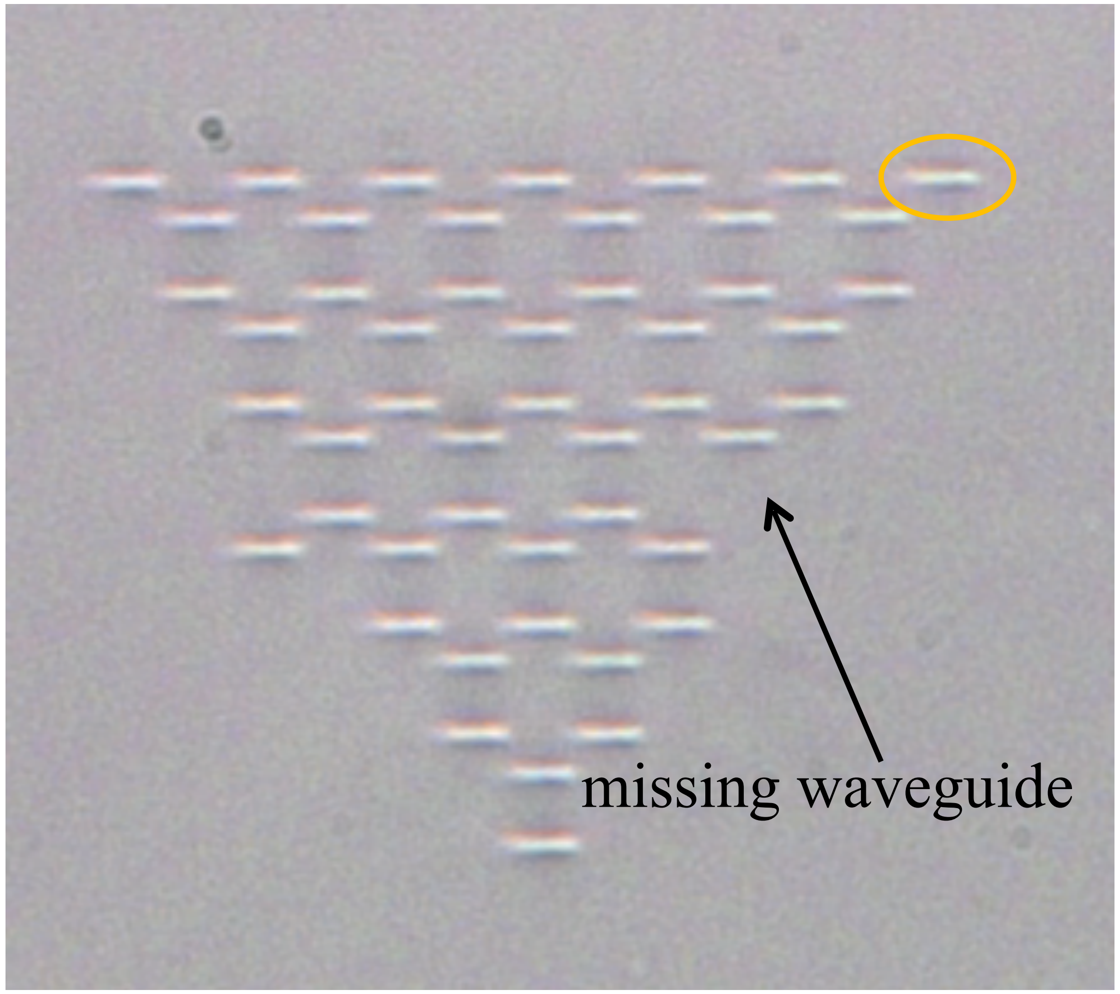
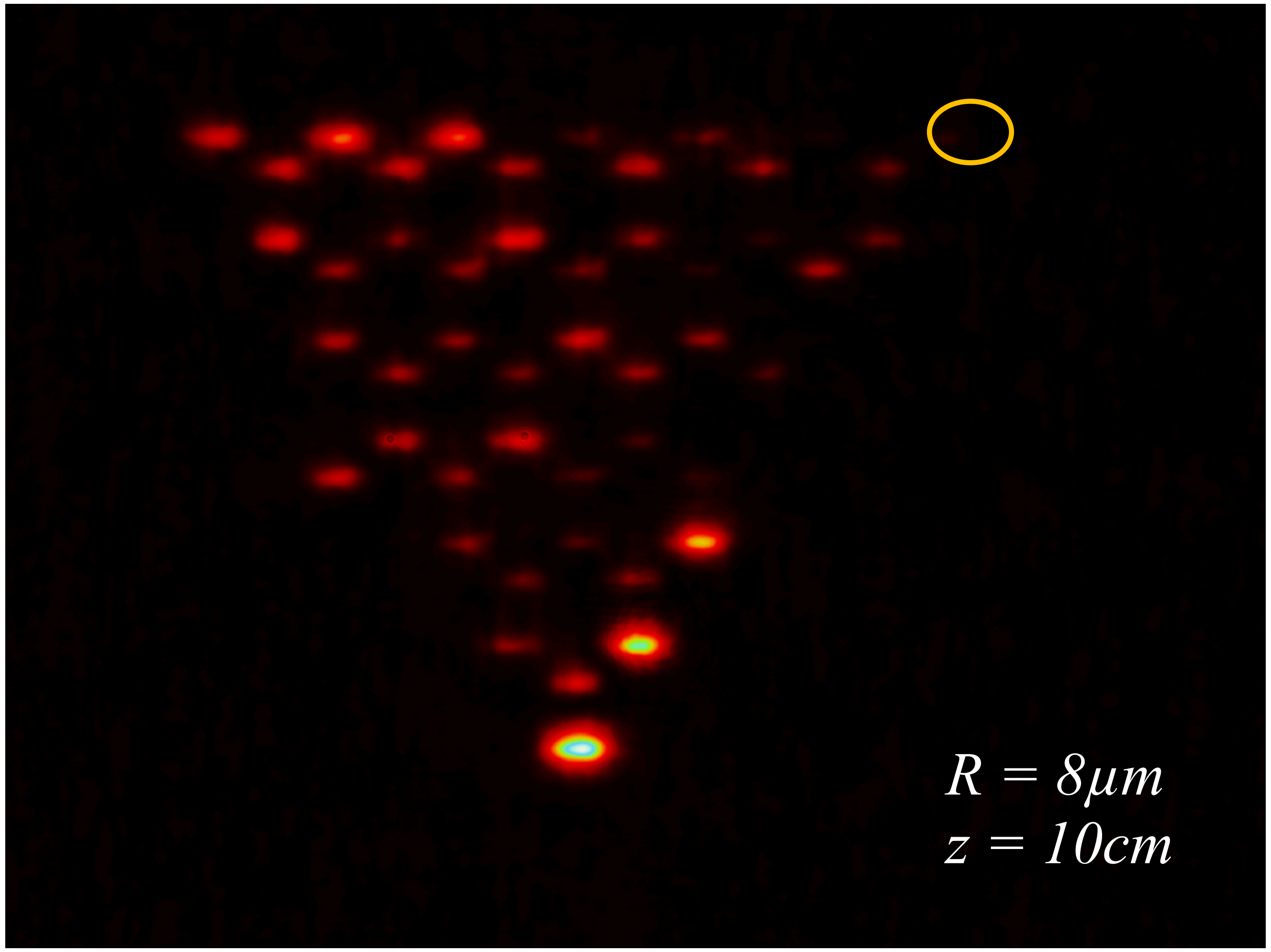
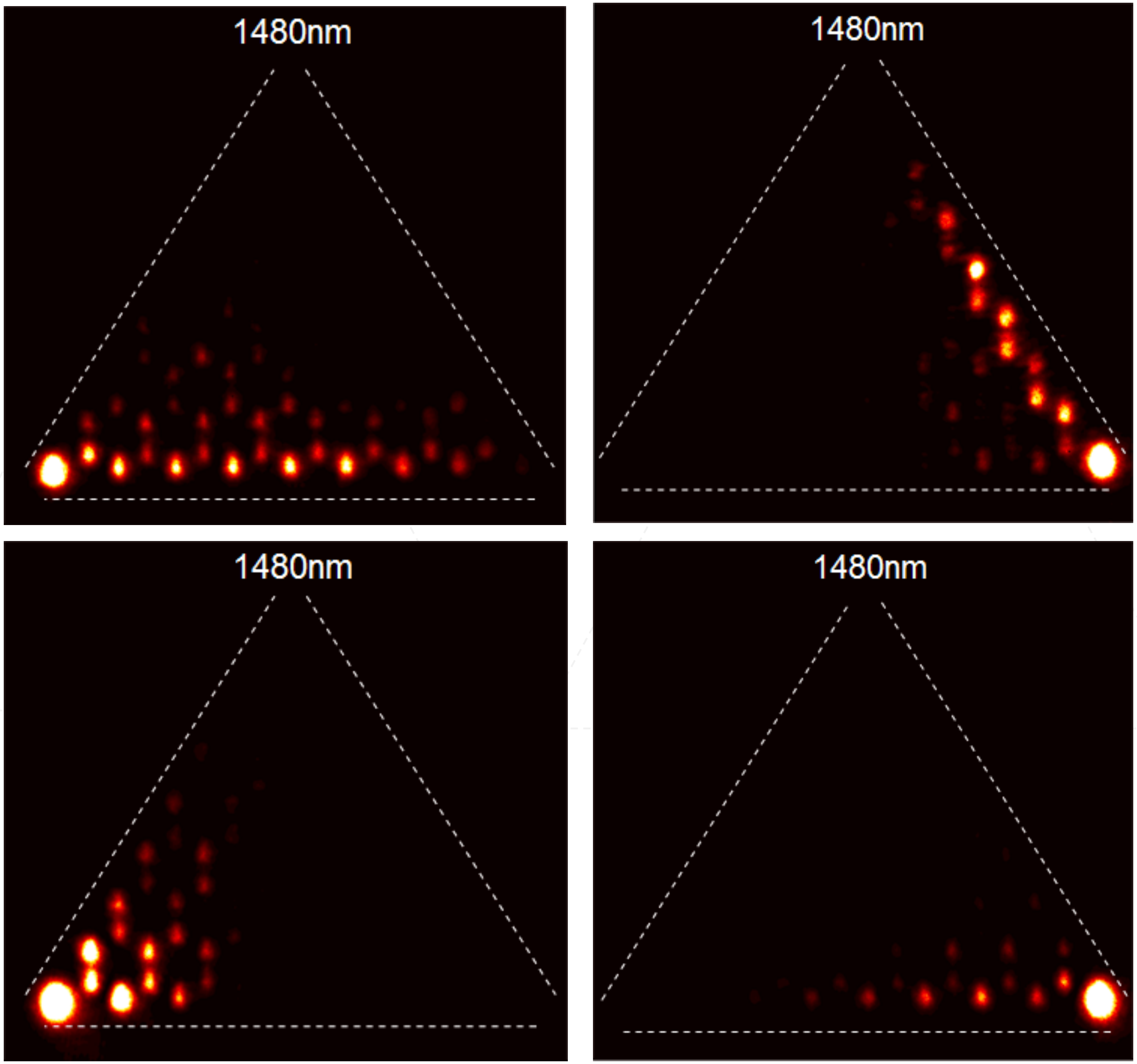




Observation of a topological transition

$(R,Z) = (20\mu m, 1.0cm)$

$(R,Z) = (106\mu m, 2.4cm)$



Guglielmon et al., Phys. Rev. A **97**, 031801 (2018)

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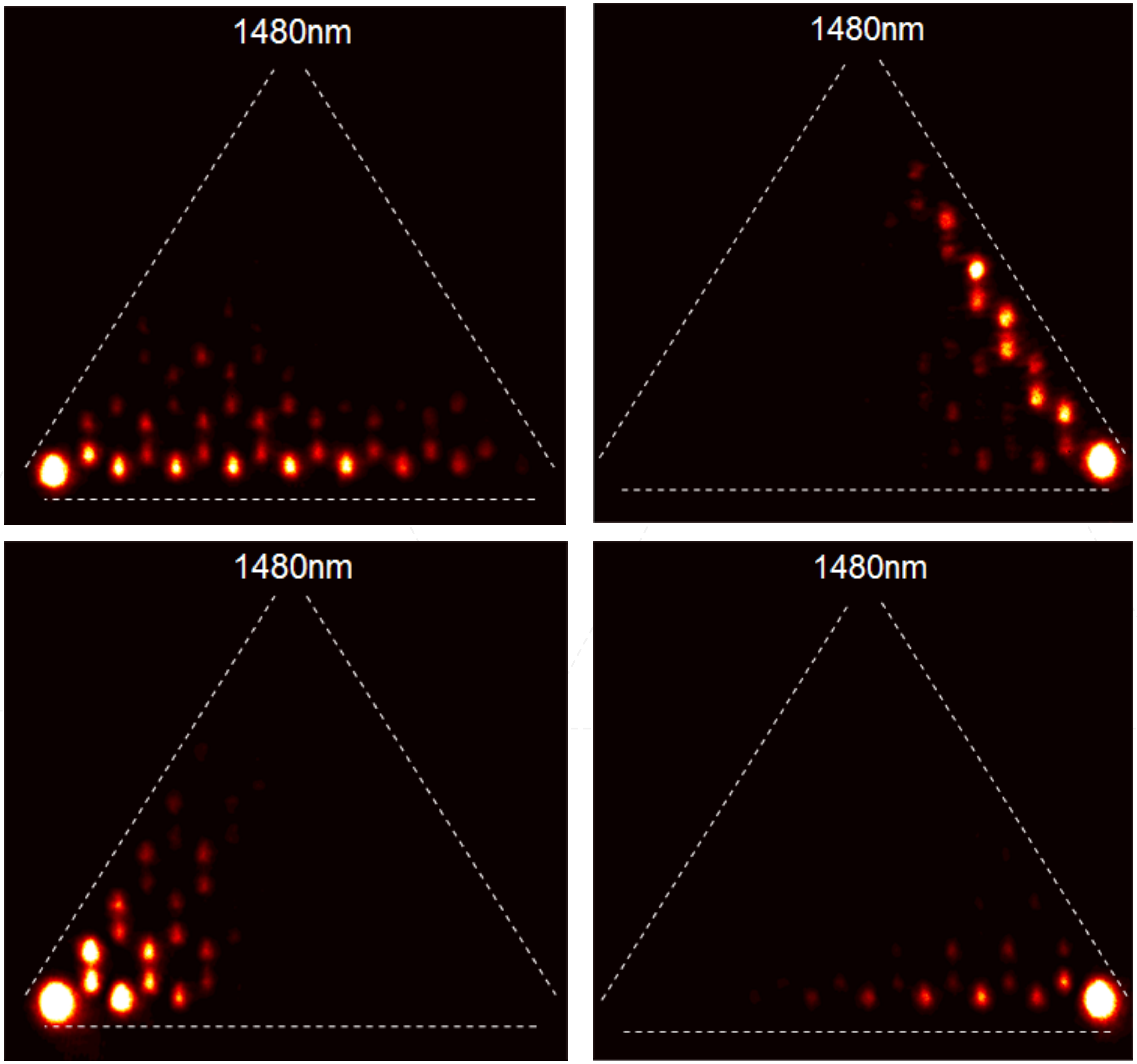

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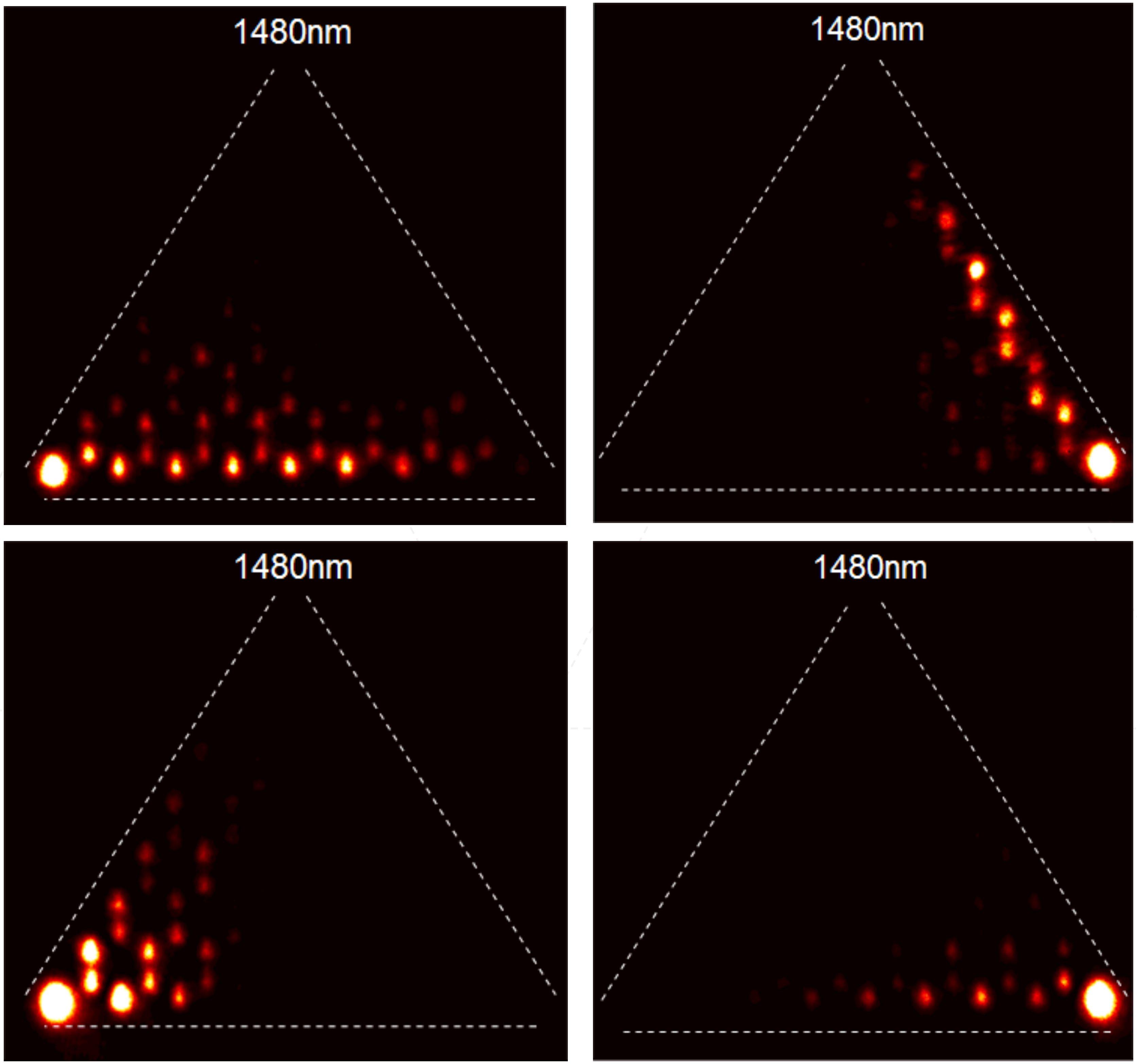

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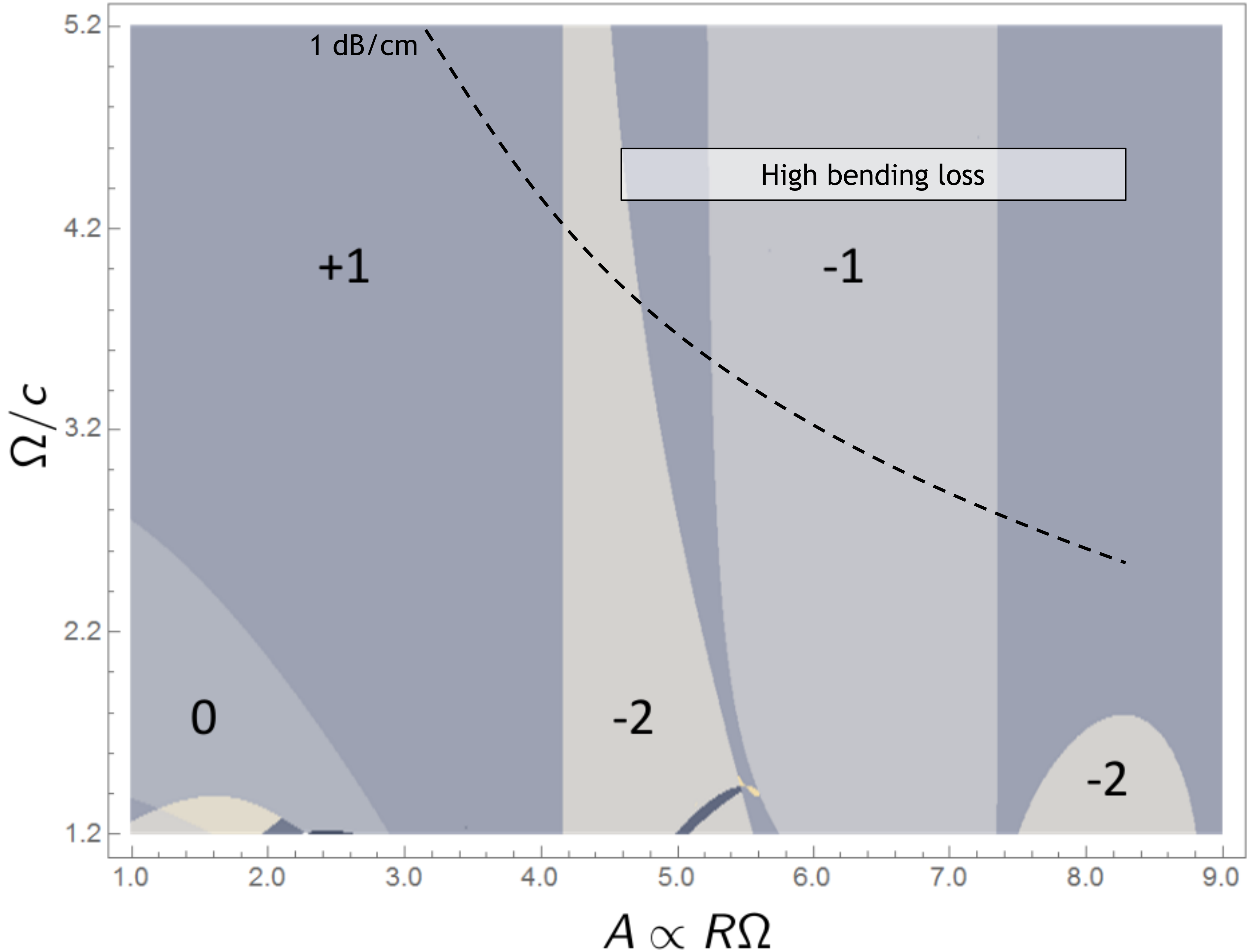


Guglielmon et al., Phys. Rev. A **97**, 031801 (2018)

What about interactions?

$$i\partial_z \psi = H\psi - |\psi|^2\psi$$

Gross-Pitaevskii equation on a topological lattice
(mean-field limit of Bose-Hubbard with attractive interactions)

a.k.a.

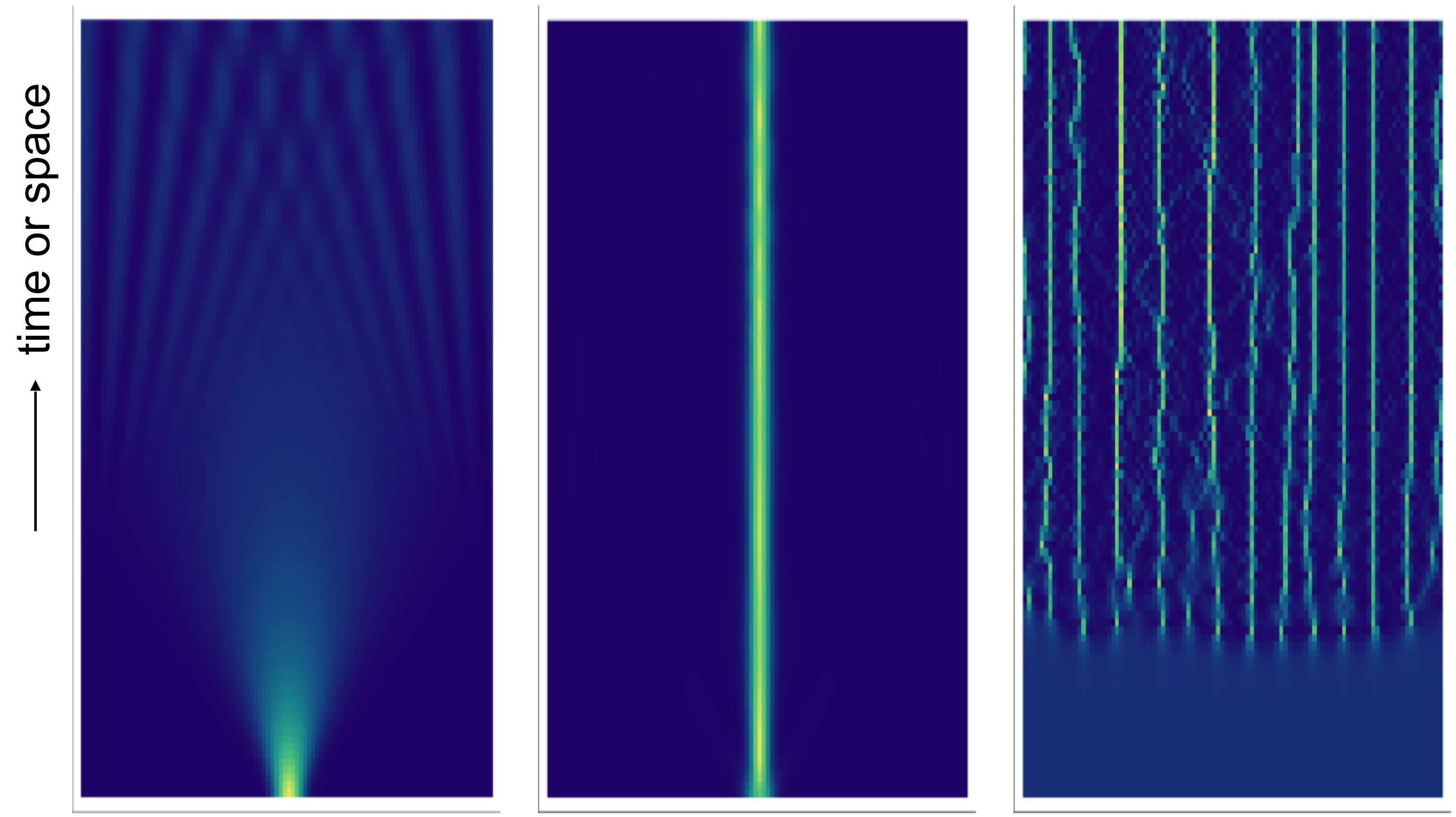
Topological nonlinear optics

Part 1: Observation of topological solitons

S. Mukherjee, M. C. Rechtsman, in preparation

What are solitons?

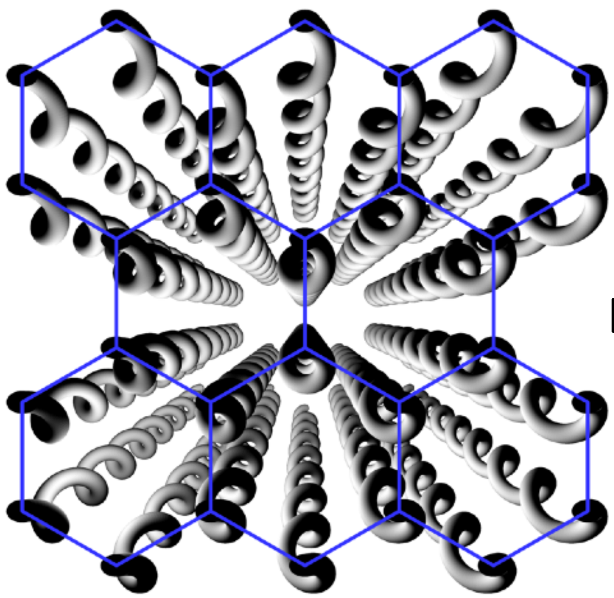
Credit: Hariot-Watt Mathematics Department
Discovery: John Scott Russell, Scottish Naval Engineer

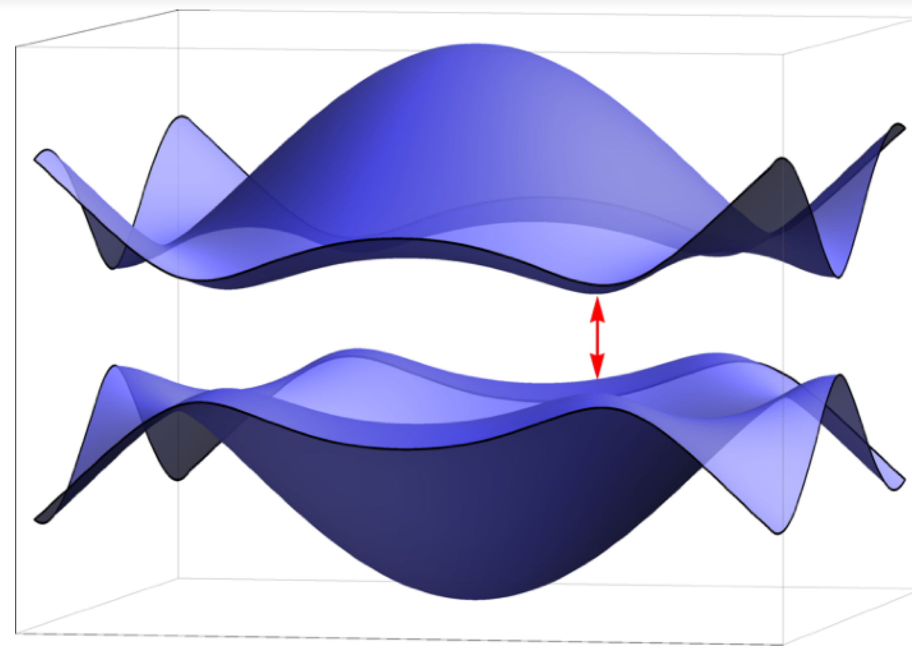


- Solitons are self-sustaining waves that balance spreading and nonlinearity.
- Fundamental “basis” for many nonlinear differential equations.
- Ubiquitous in wave physics: optics; ultracold bosons; polymer chains; MEMS/NEMS; Josephson junctions; plasmas; water waves; etc.
- Applications in optics: passive mode locking in lasers; on-chip frequency combs; telecommunications(?).

Original prediction for topological systems: Lumer et al., Phys. Rev. Lett. (2013).

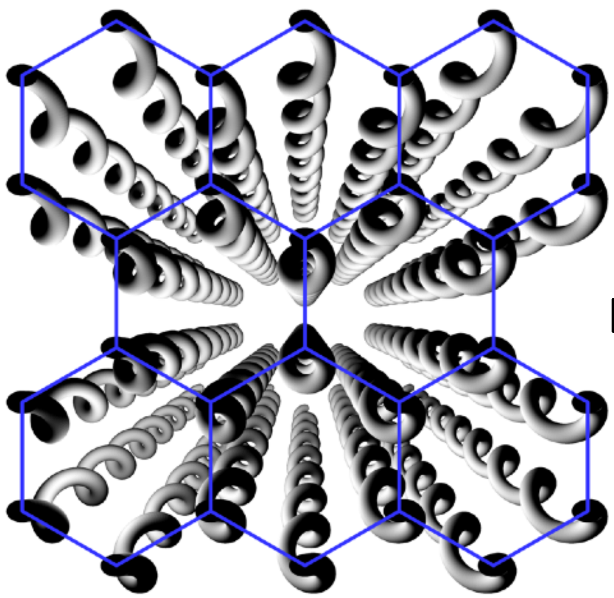
Lattice: anomalous Floquet topological insulator

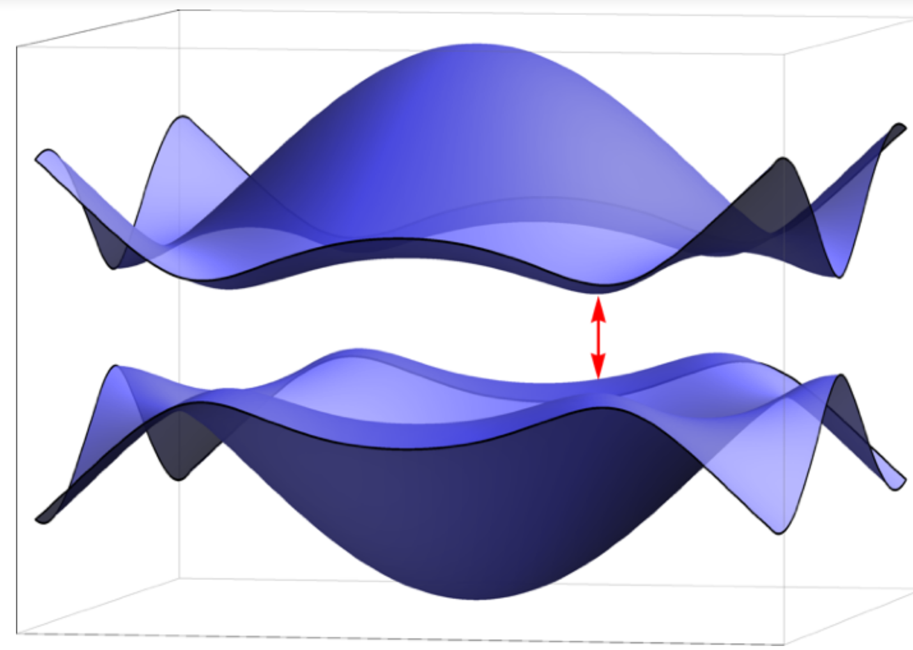




Floquet Chern insulators have trivial gaps

Lattice: anomalous Floquet topological insulator





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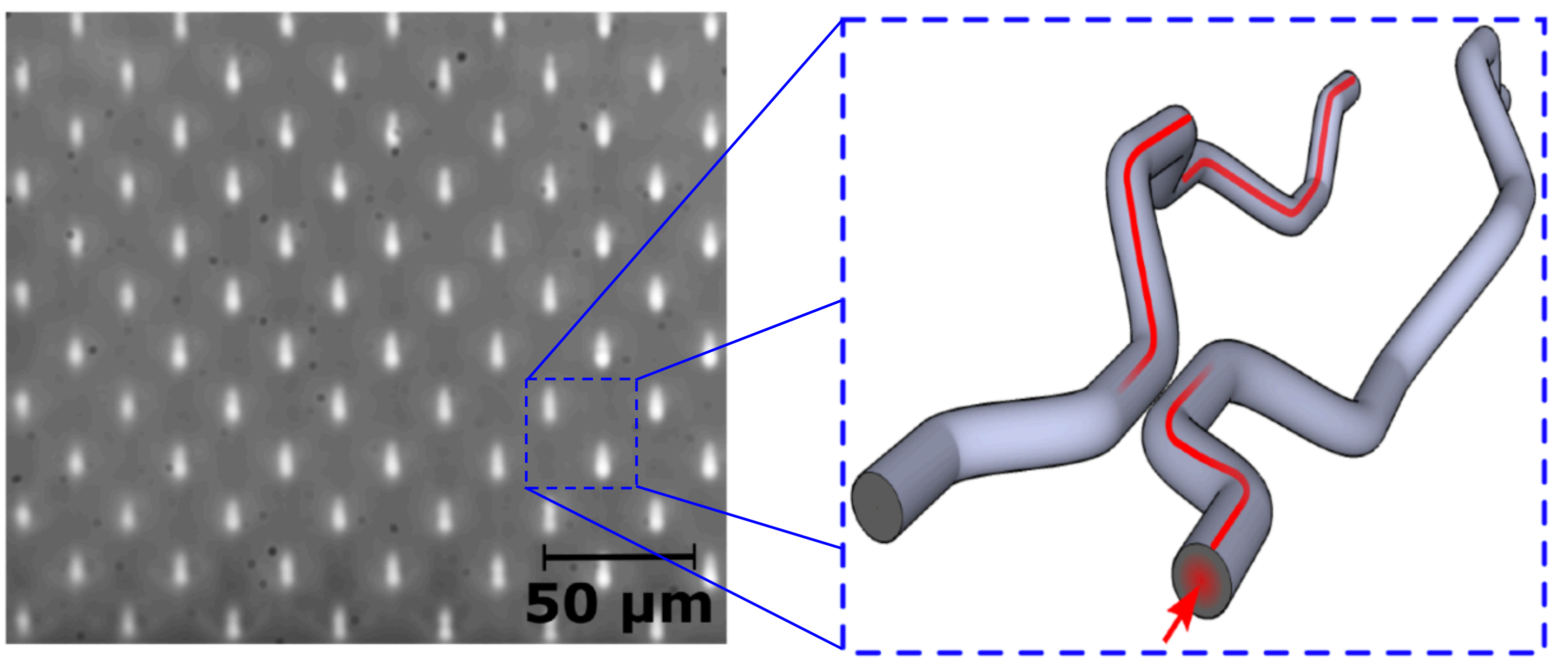
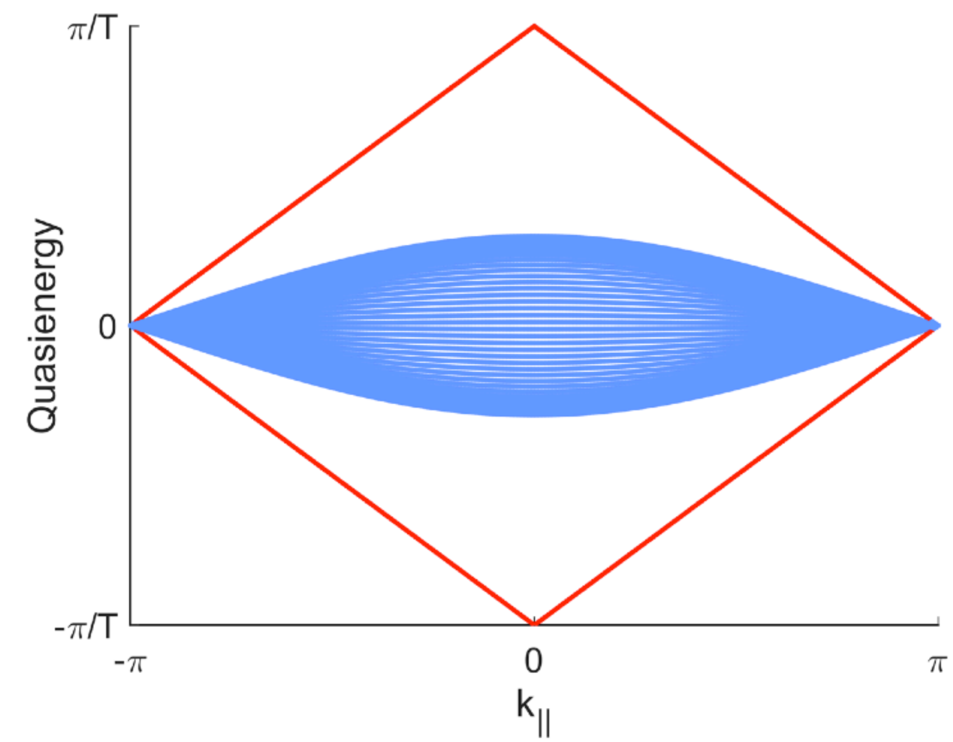




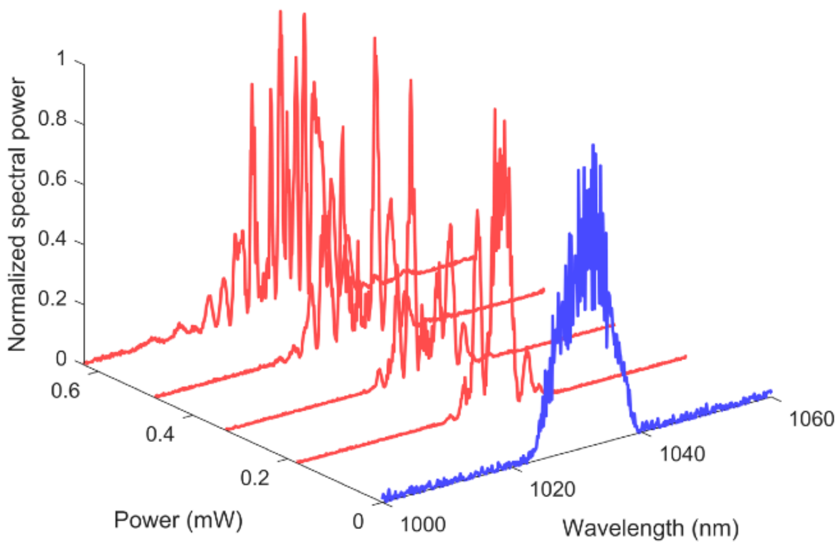
Microscope image of lattice

Unit cell

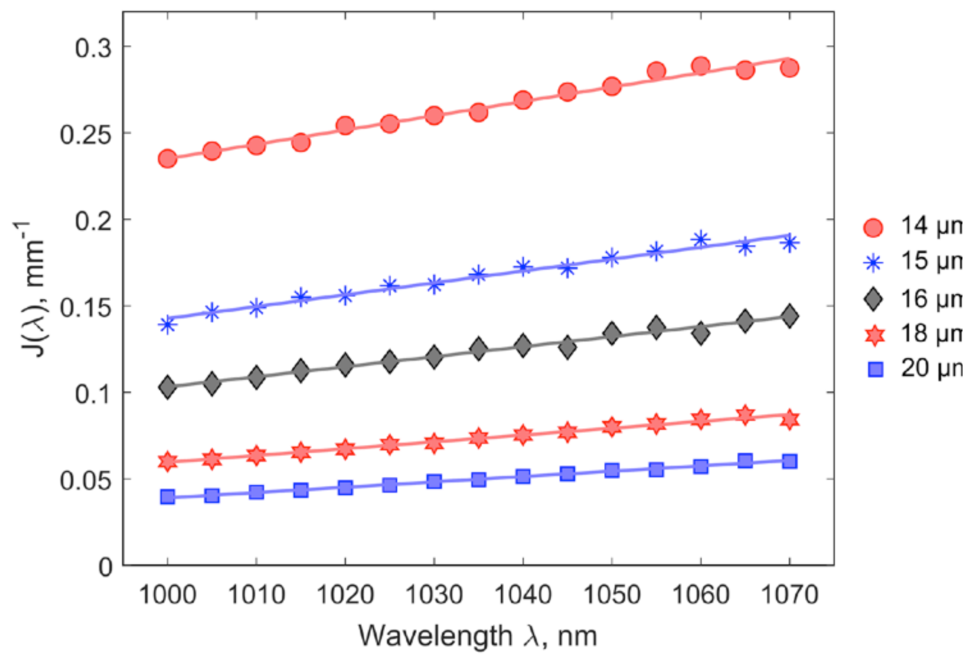
Floquet band structure

Lattice model inspired by: Rudner et al., Phys. Rev. X 3, 031005 (2013);
Solitons discussed in this model: Leykam and Chong, Phys. Rev. Lett. (2016)

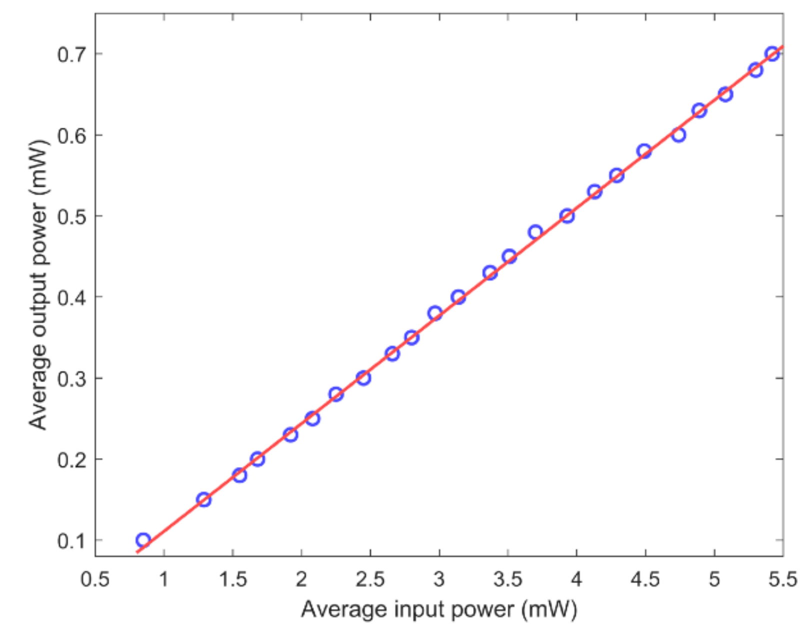
Experimental sanity checks



Sanity check #1: spectral width limited to ~20nm; self-phase modulation insignificant



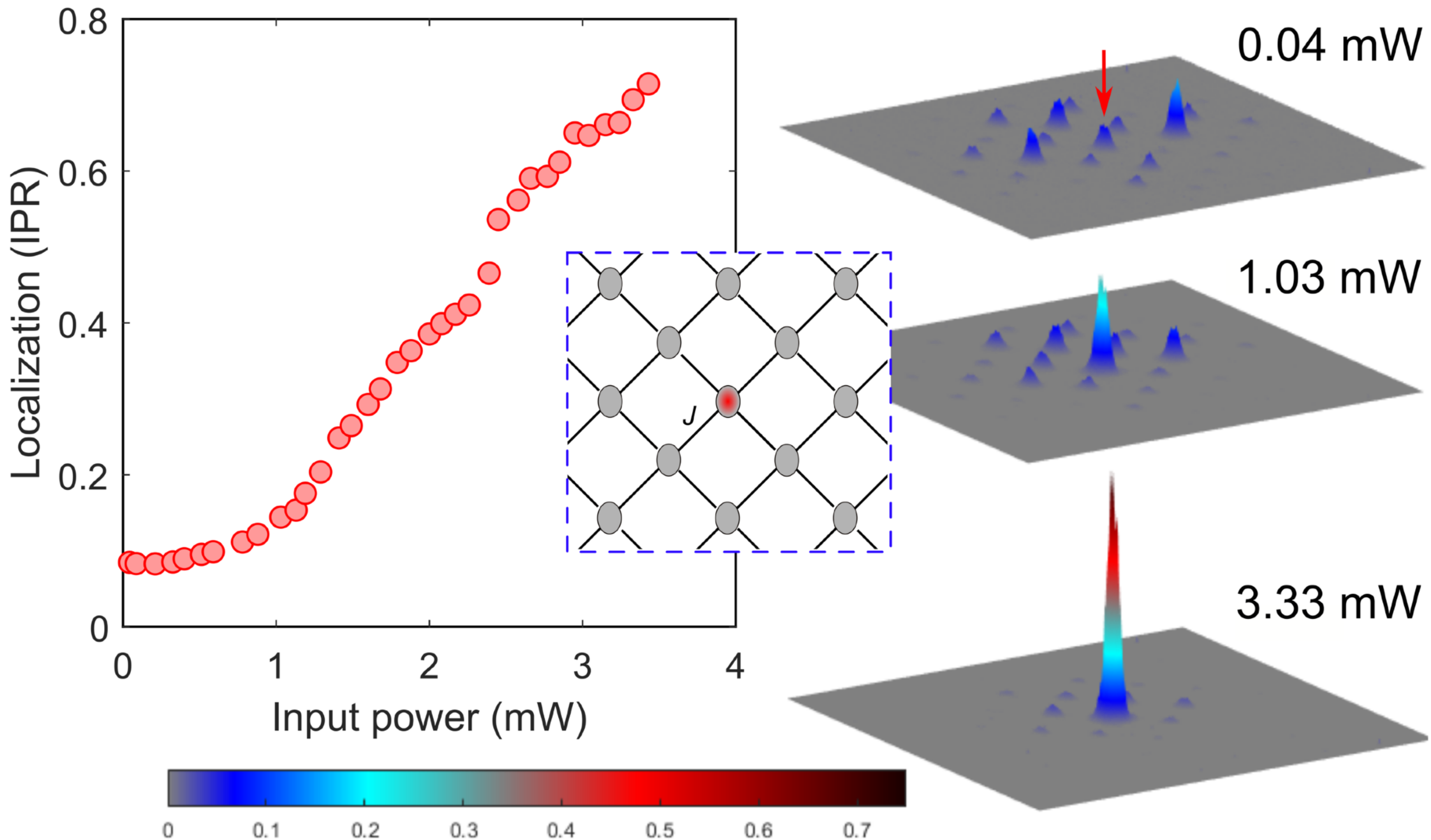
Sanity check #2: inter-waveguide hopping varies minimally over 20nm



Sanity check #3: input power varies linearly with output power: no nonlinear loss

Conclusion: our system is governed by the standard NLS / GP

Experimental sanity check: square lattice



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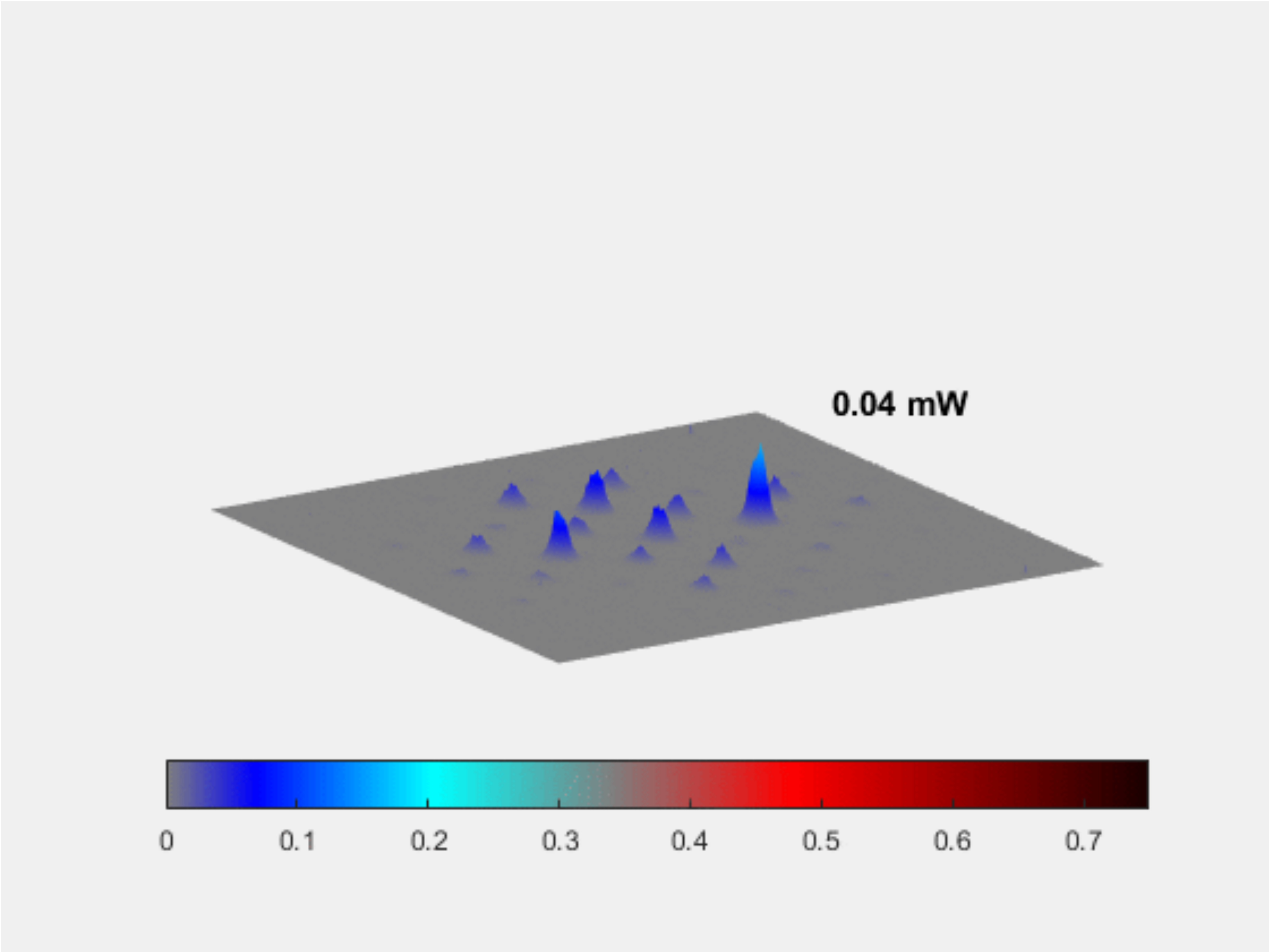

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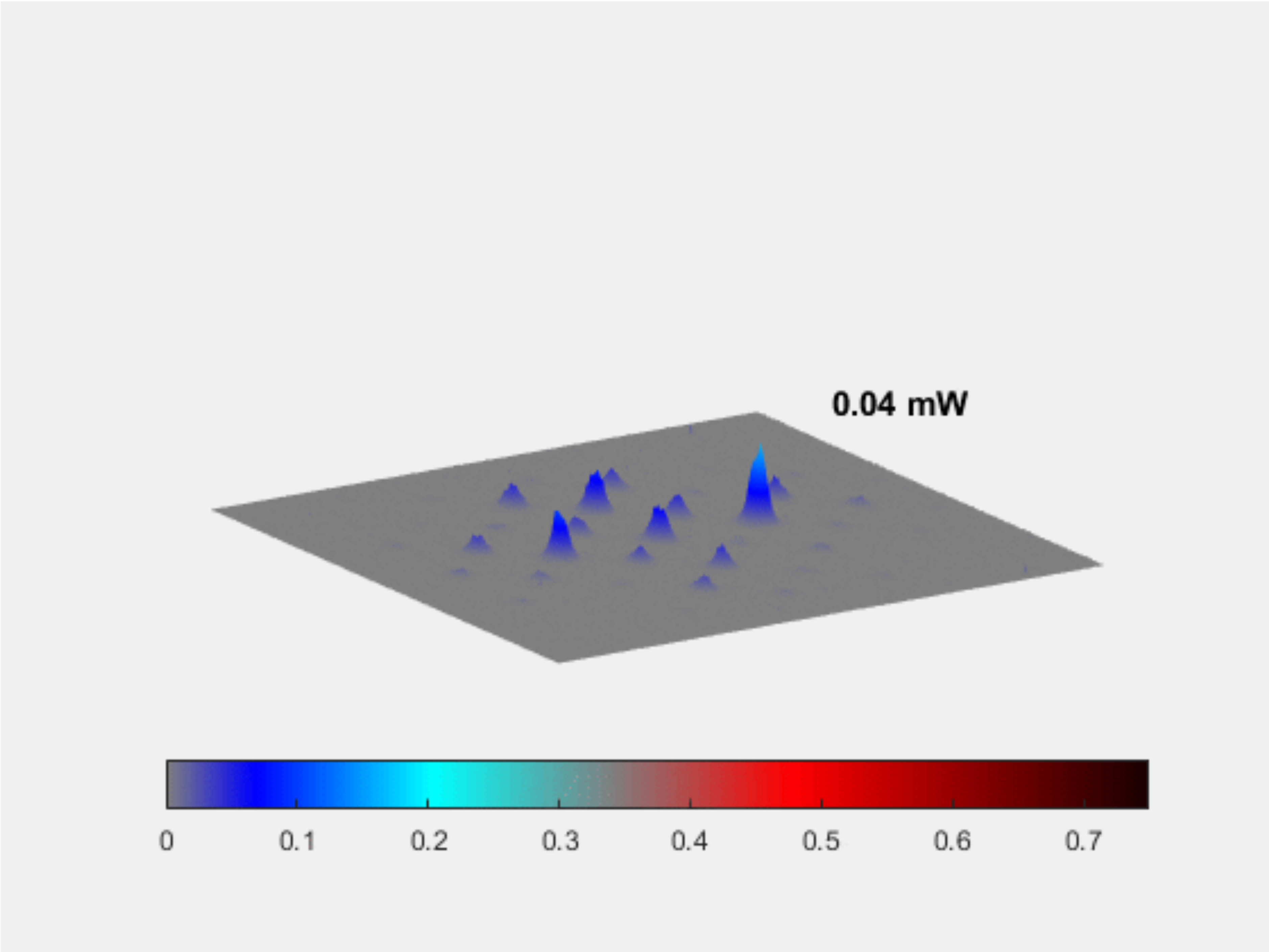
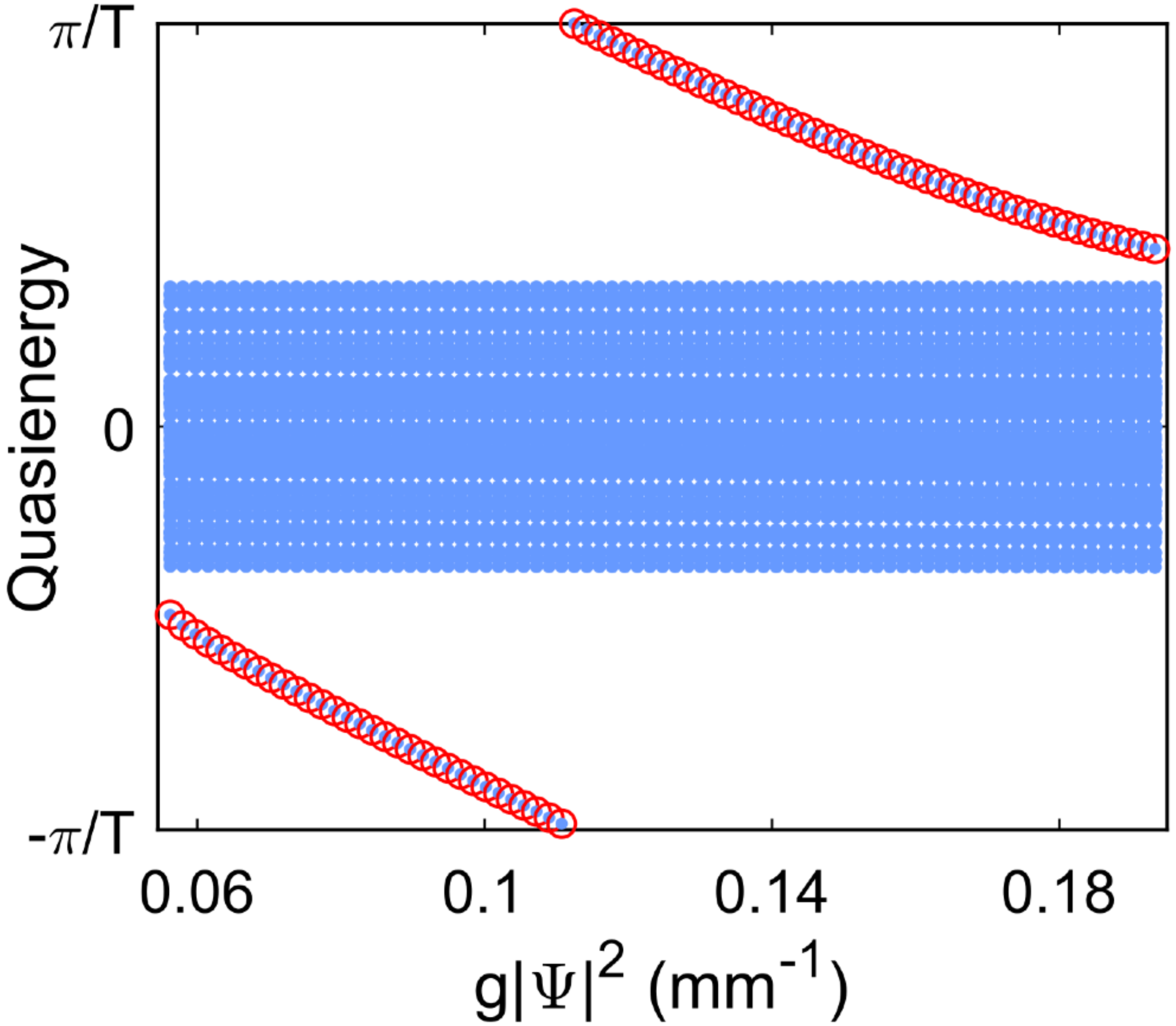
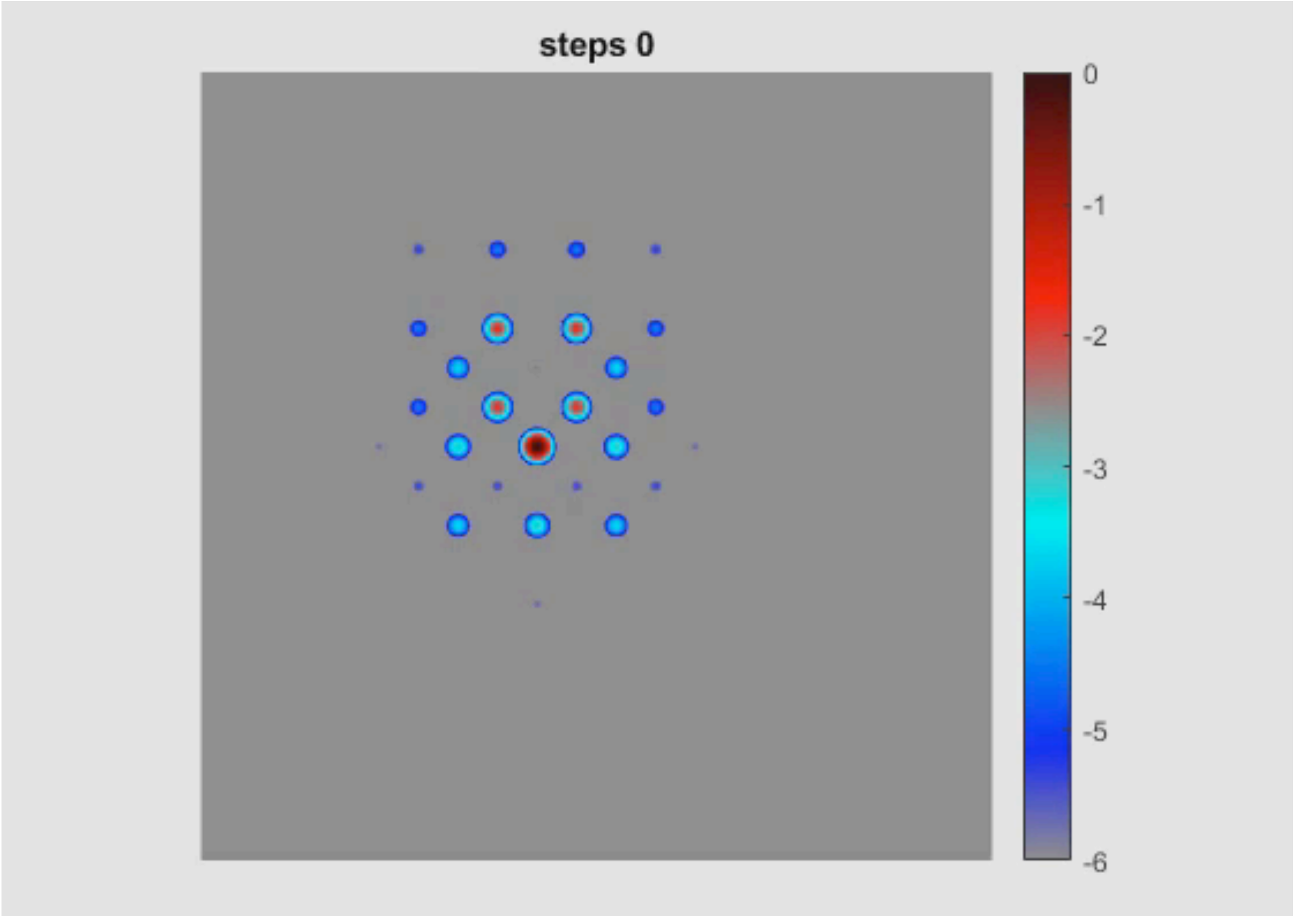


Theory: Floquet soliton resides in the topological gap





Solitons start large, shrink at mid-gap and then expand

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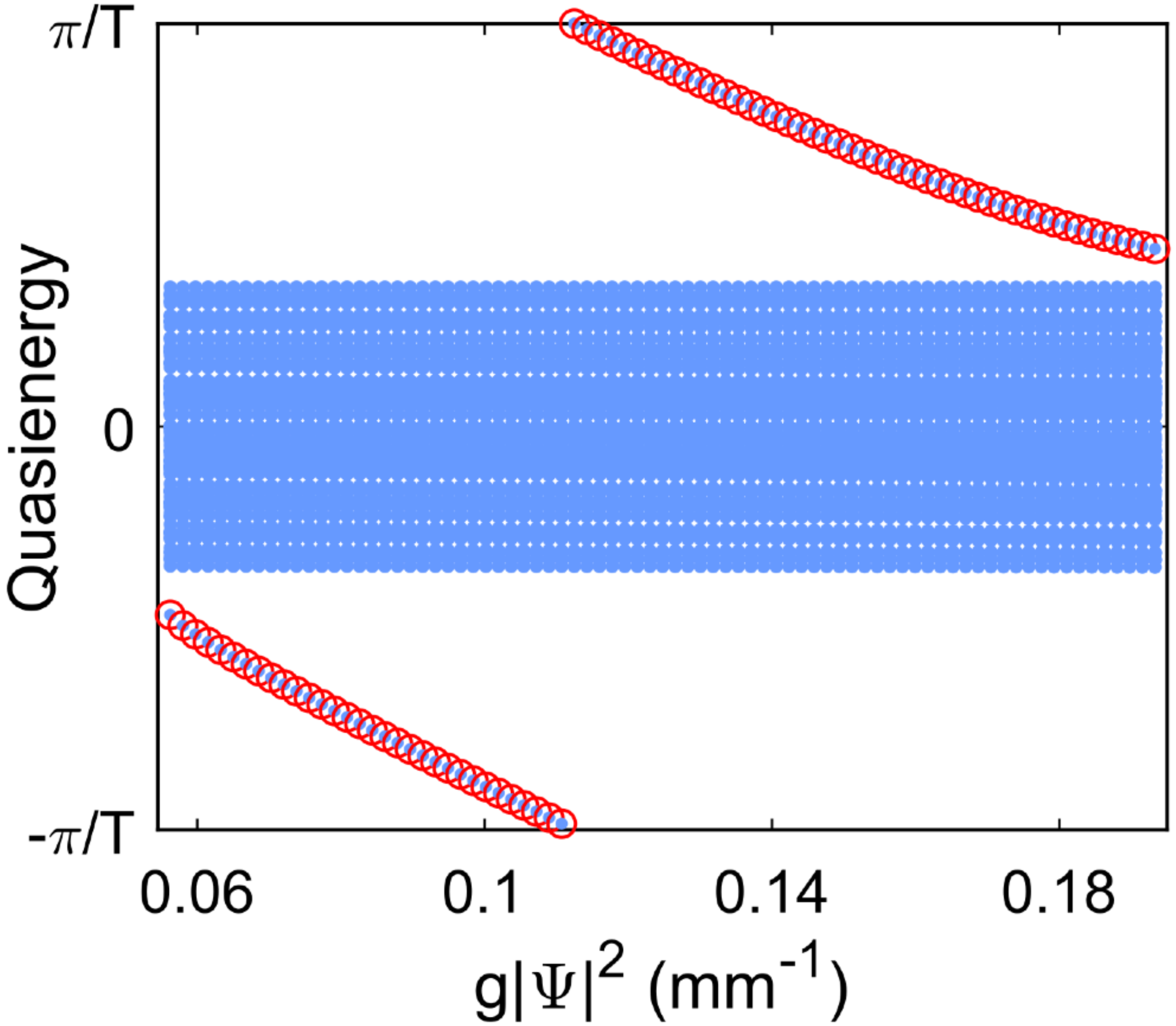
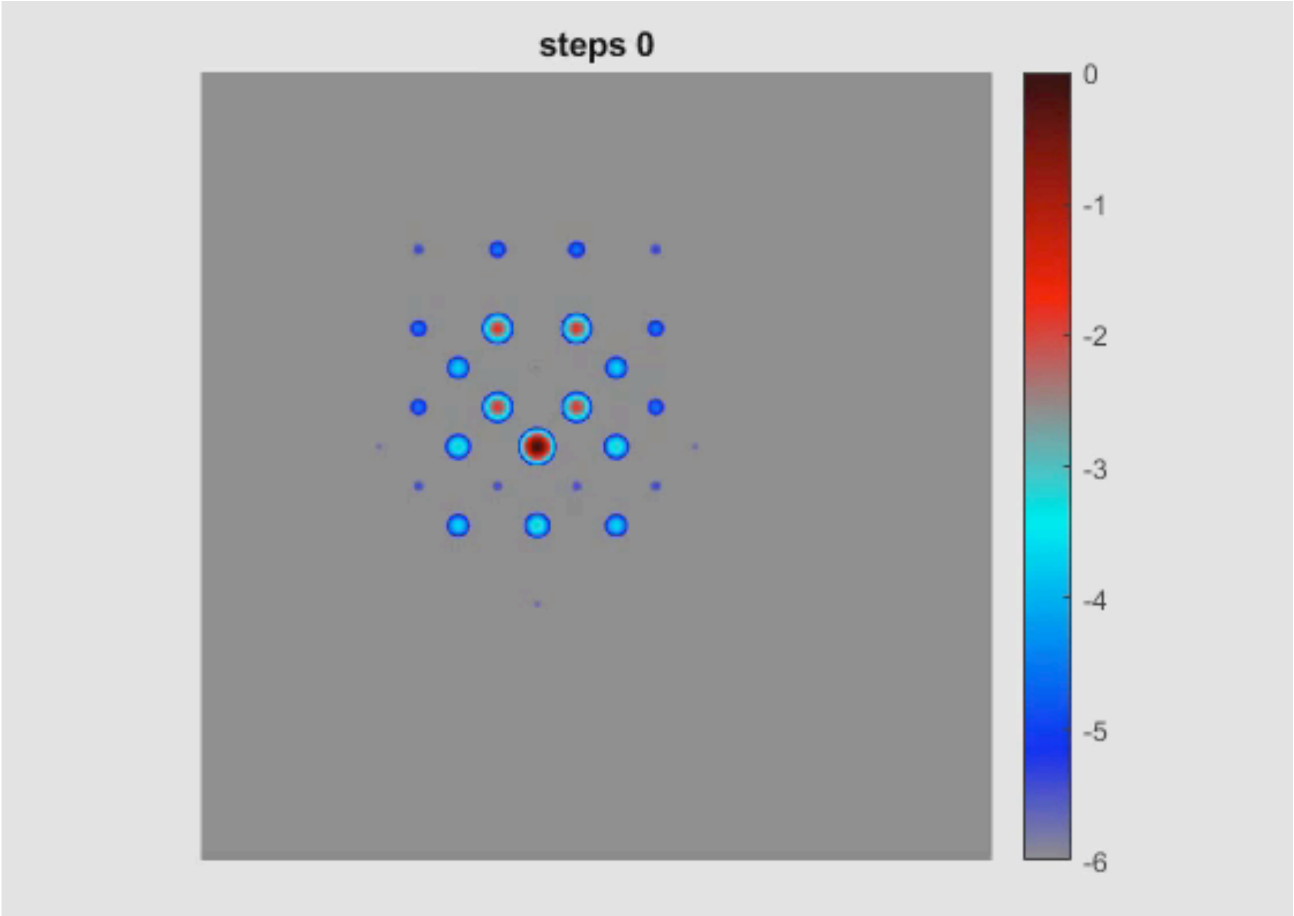
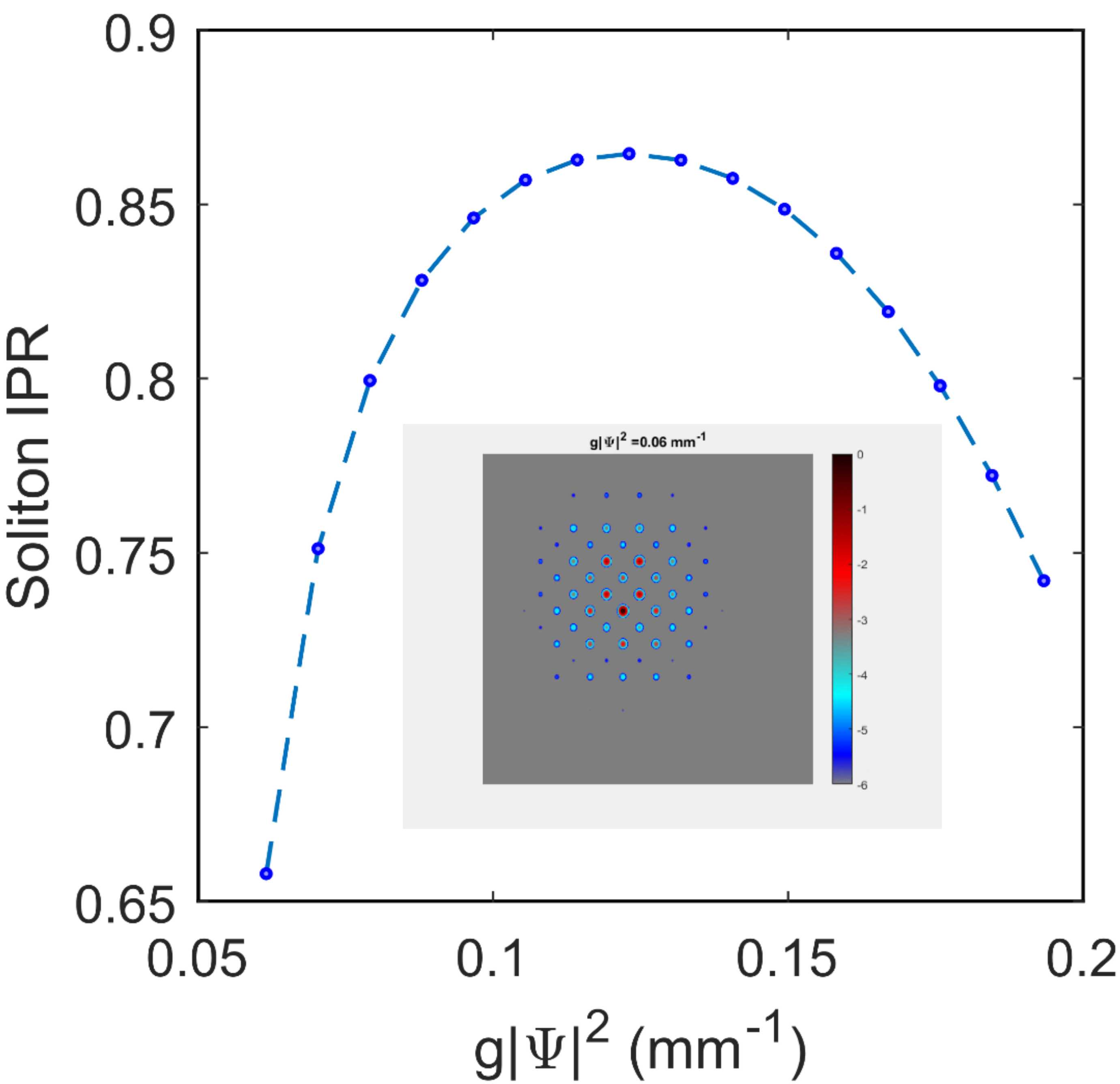
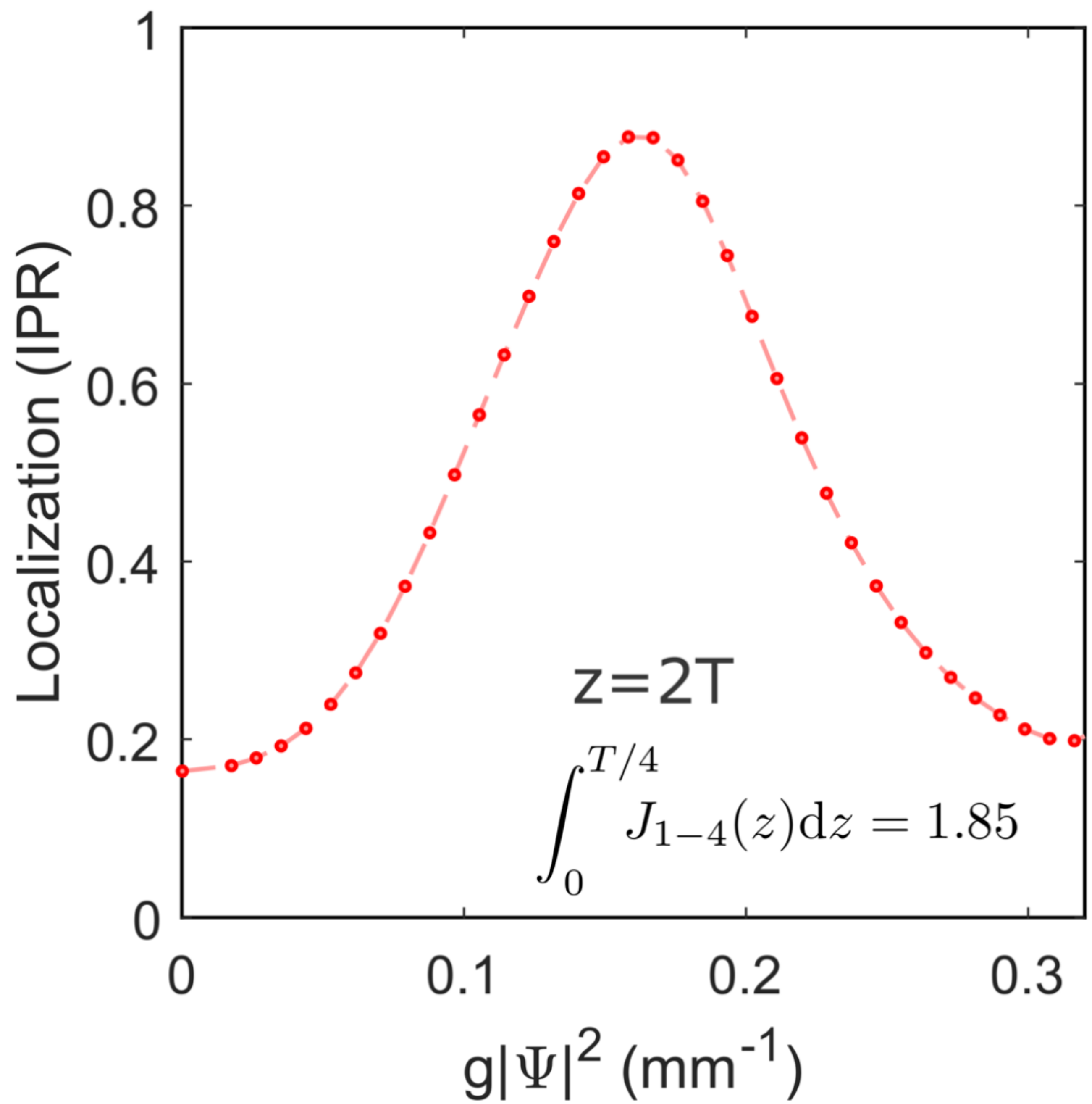




Solitons start large, shrink at mid-gap and then expand

Theory: soliton is most localized at mid-gap





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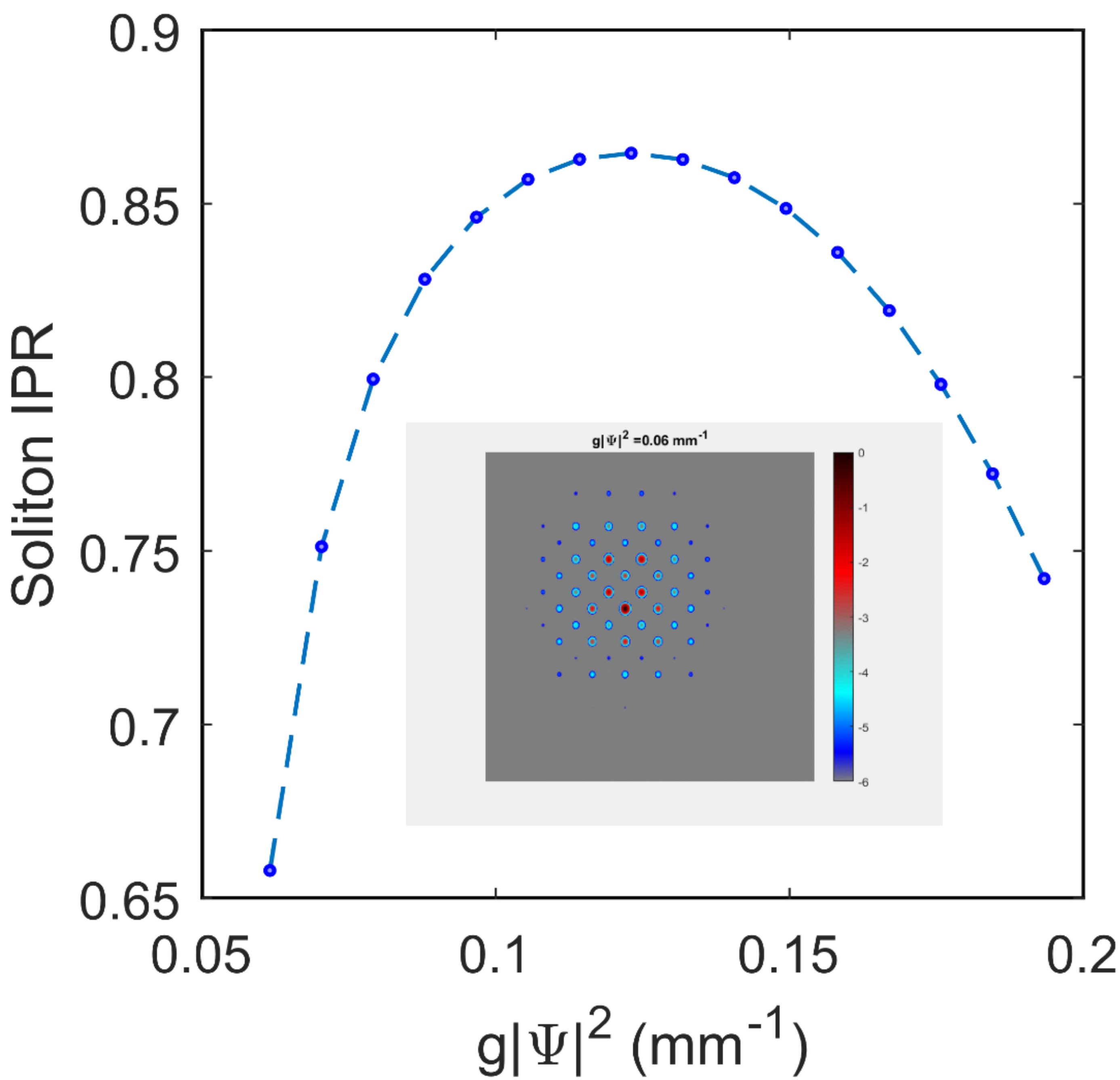
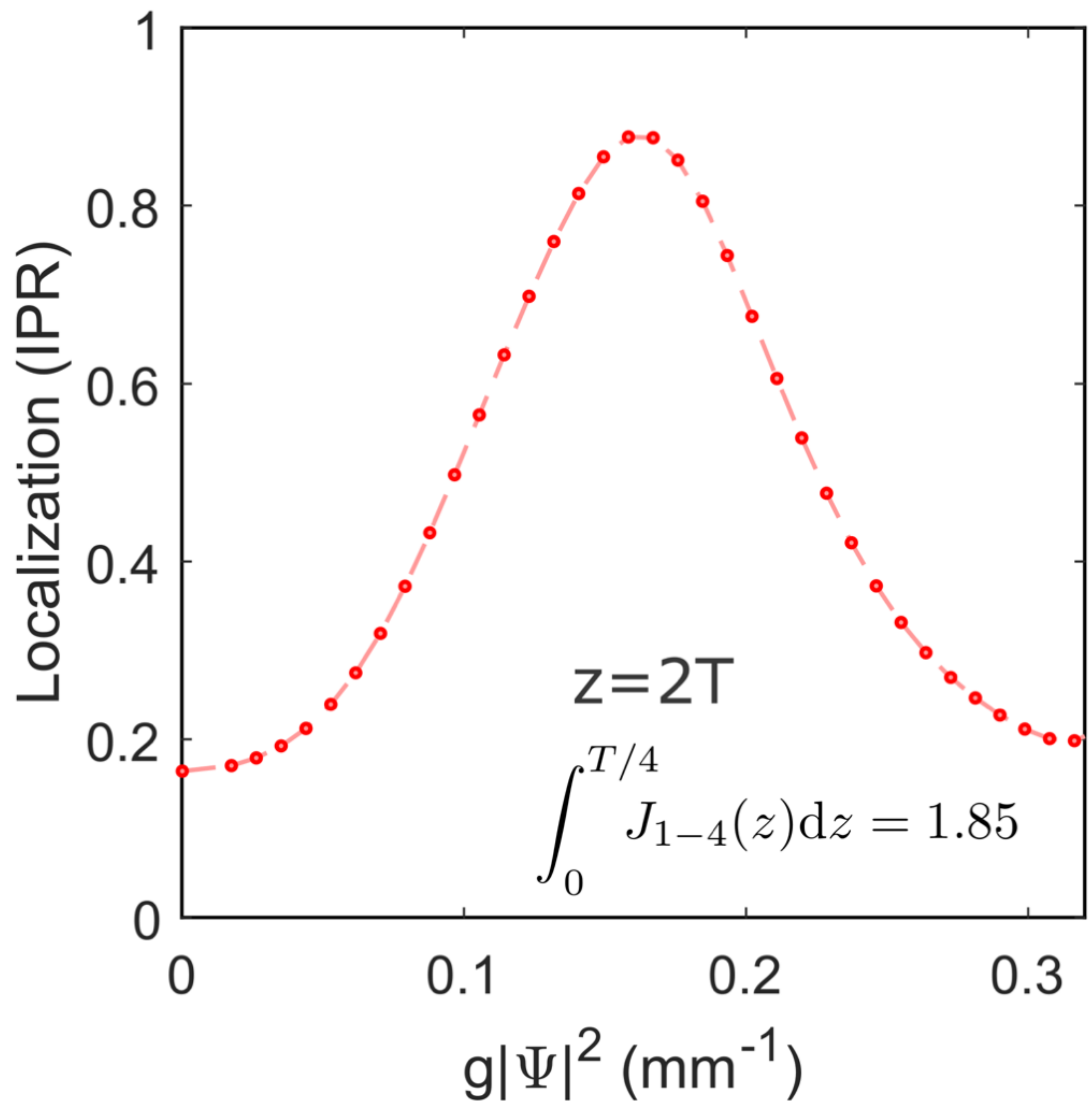
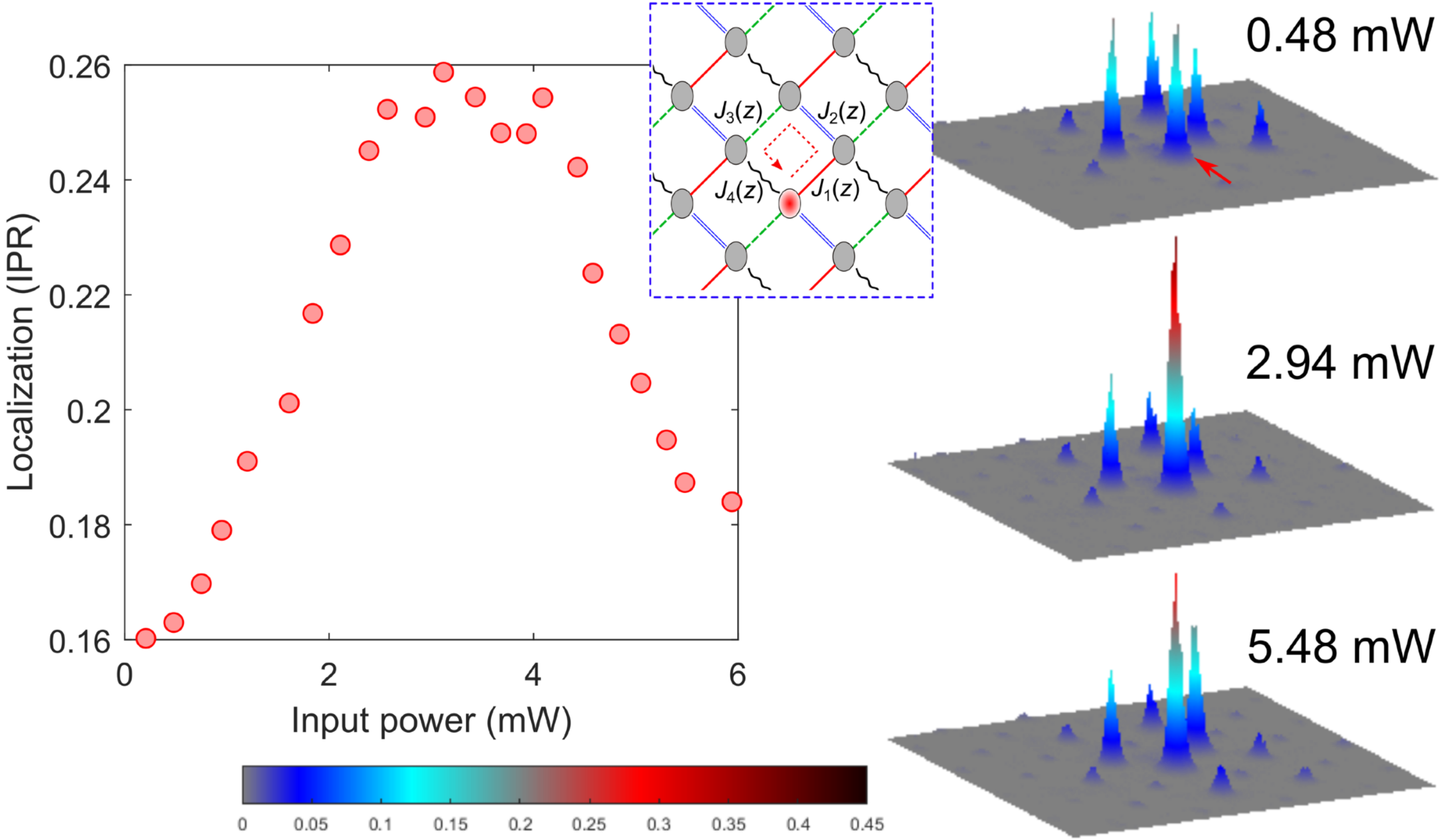




Experimental results: end of full period



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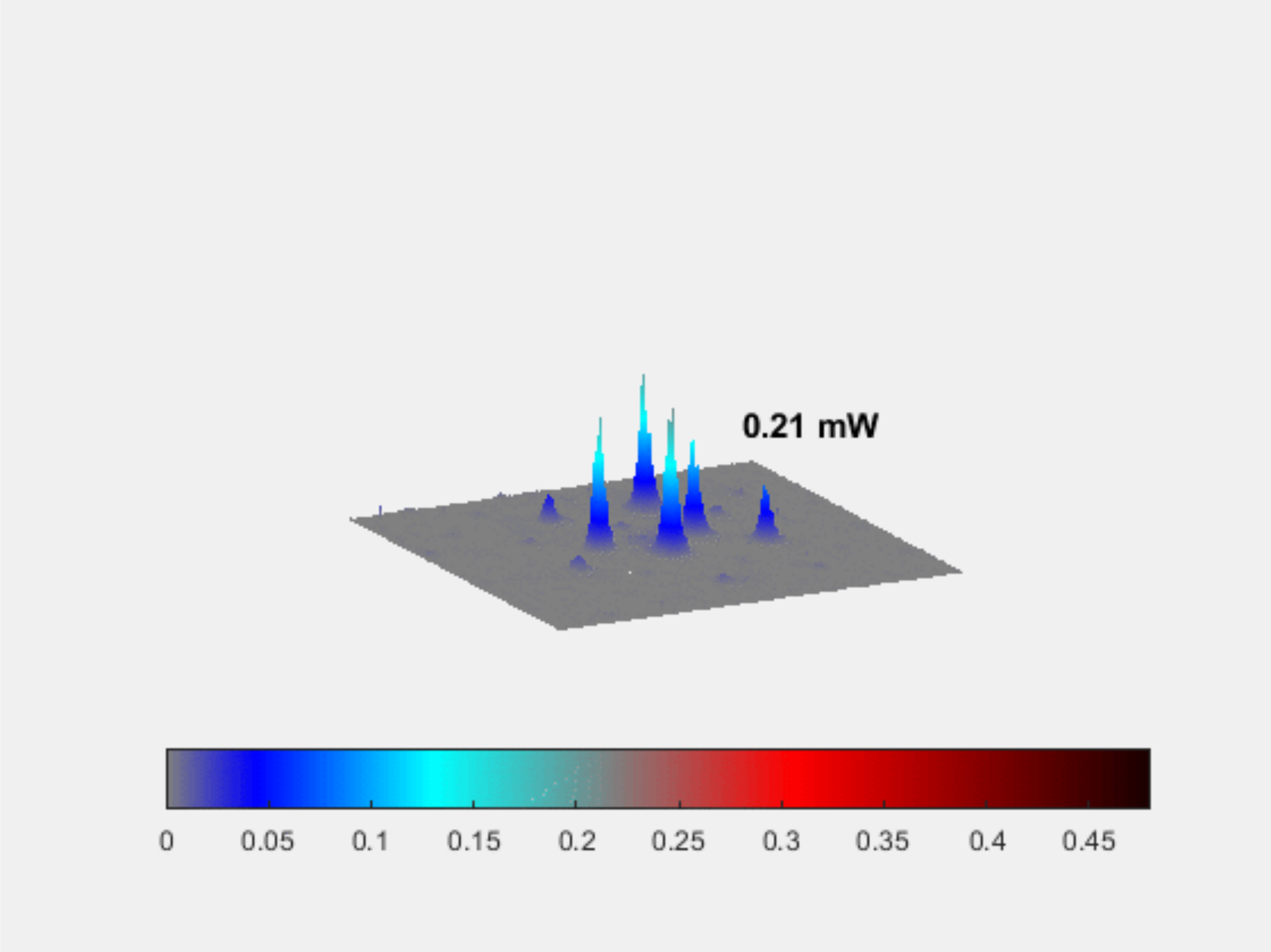

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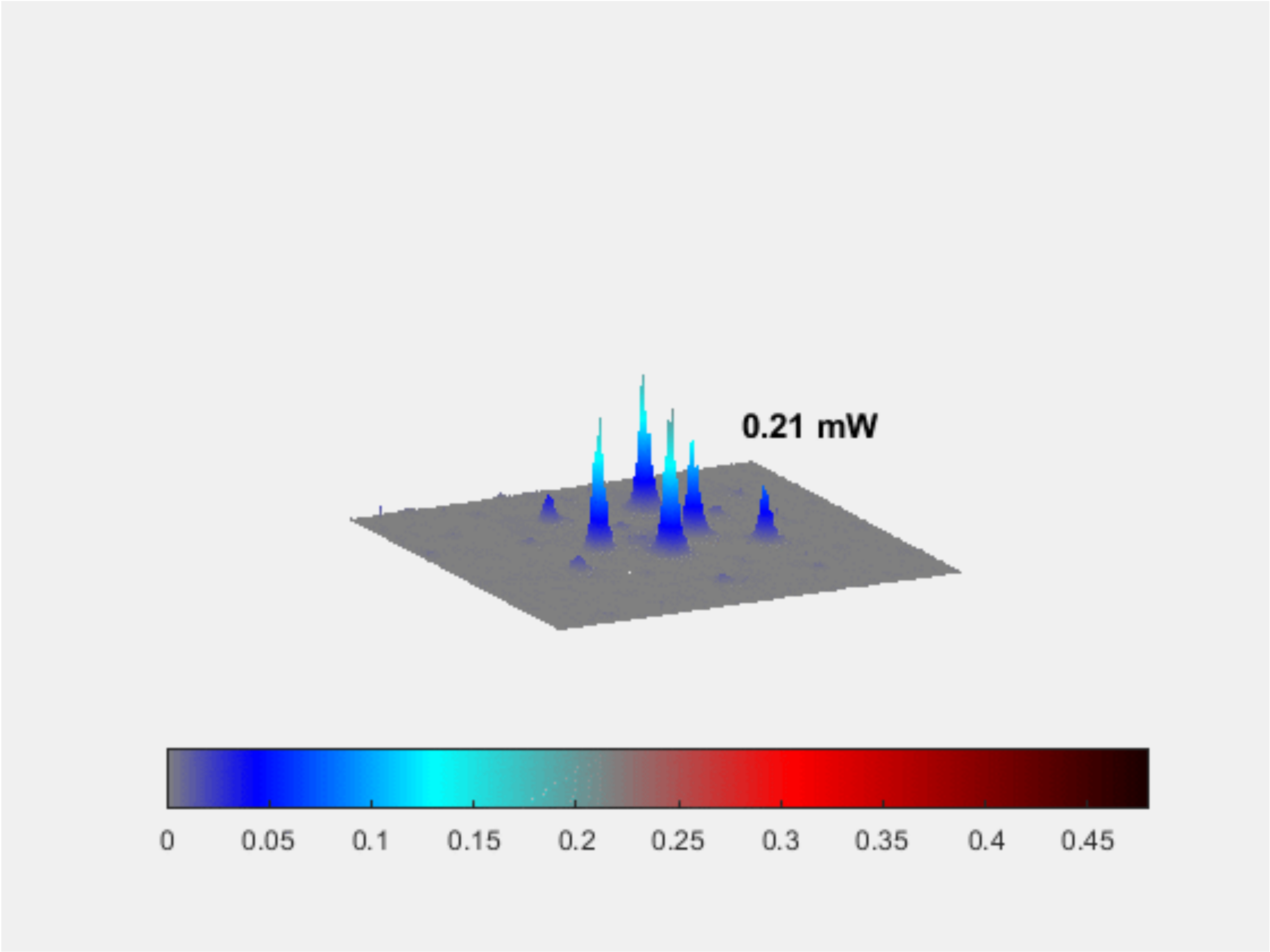
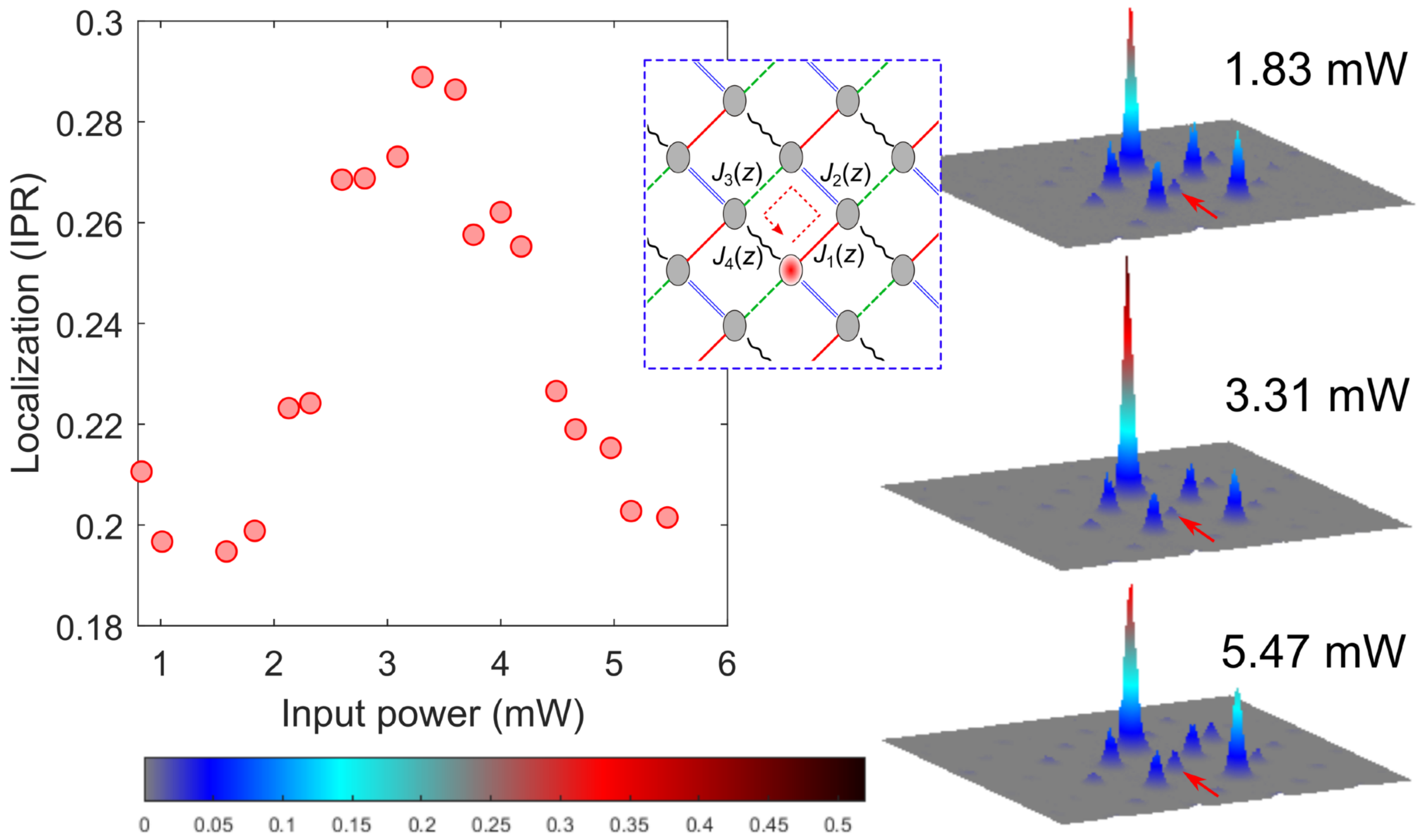


Experimental results: mid-period



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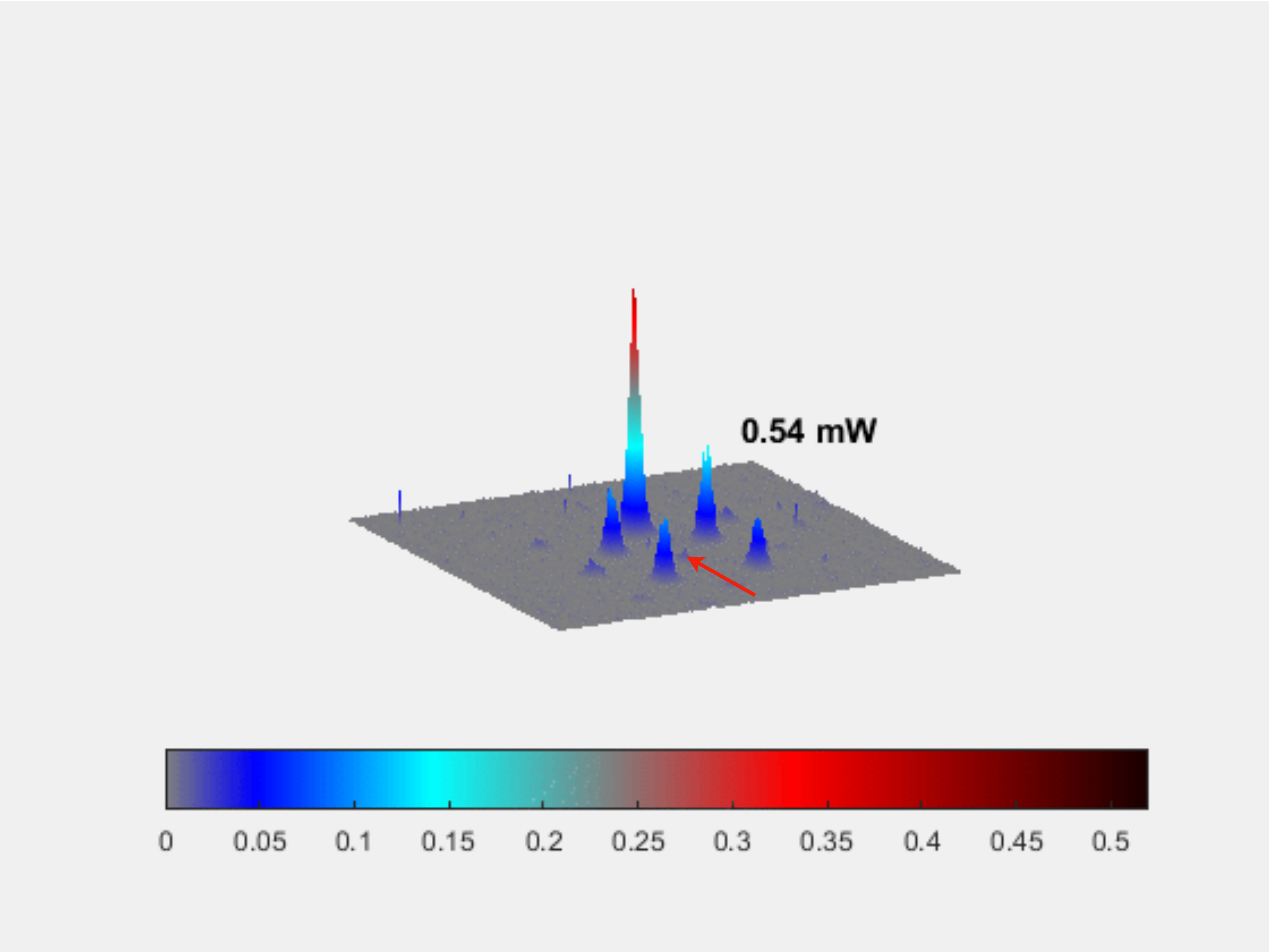

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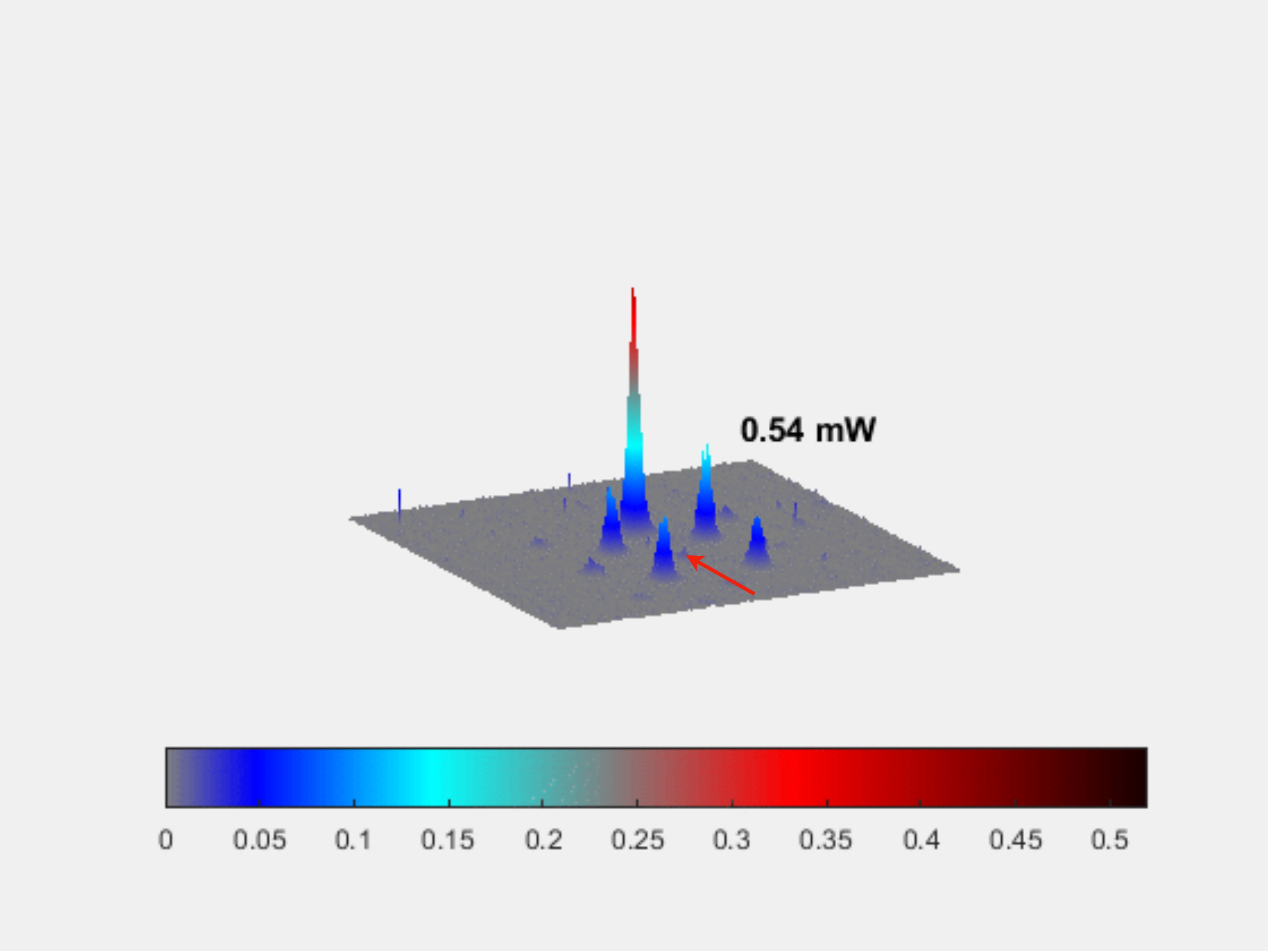
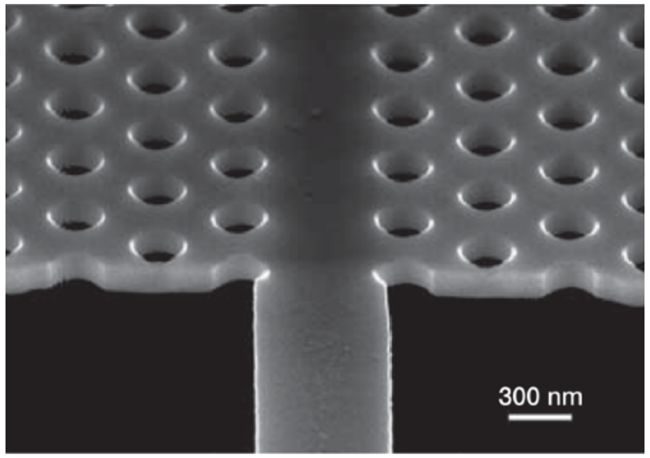
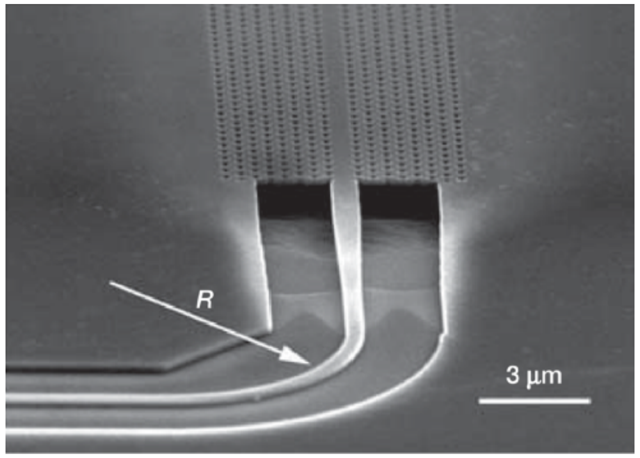


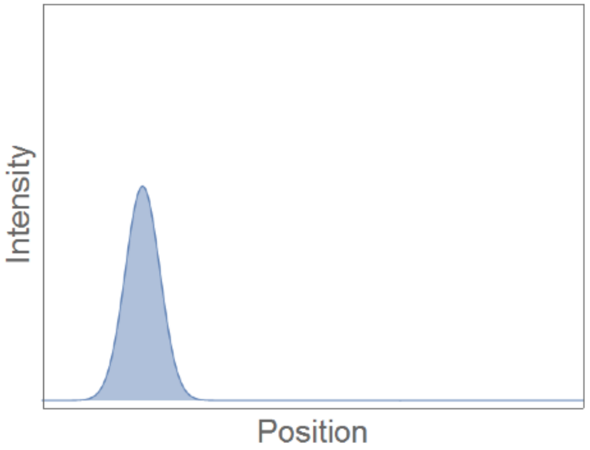
Part 2: Topological slow light

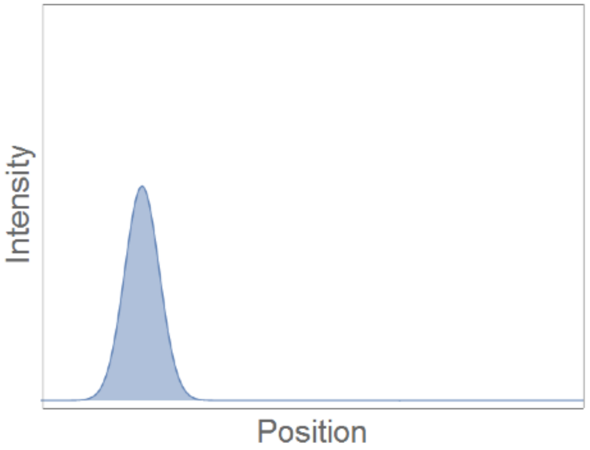
J. Guglielmon and M. C. Rechtsman, Phys. Rev. Lett. **122**, 153904 (2019).

Idea: topological slow light

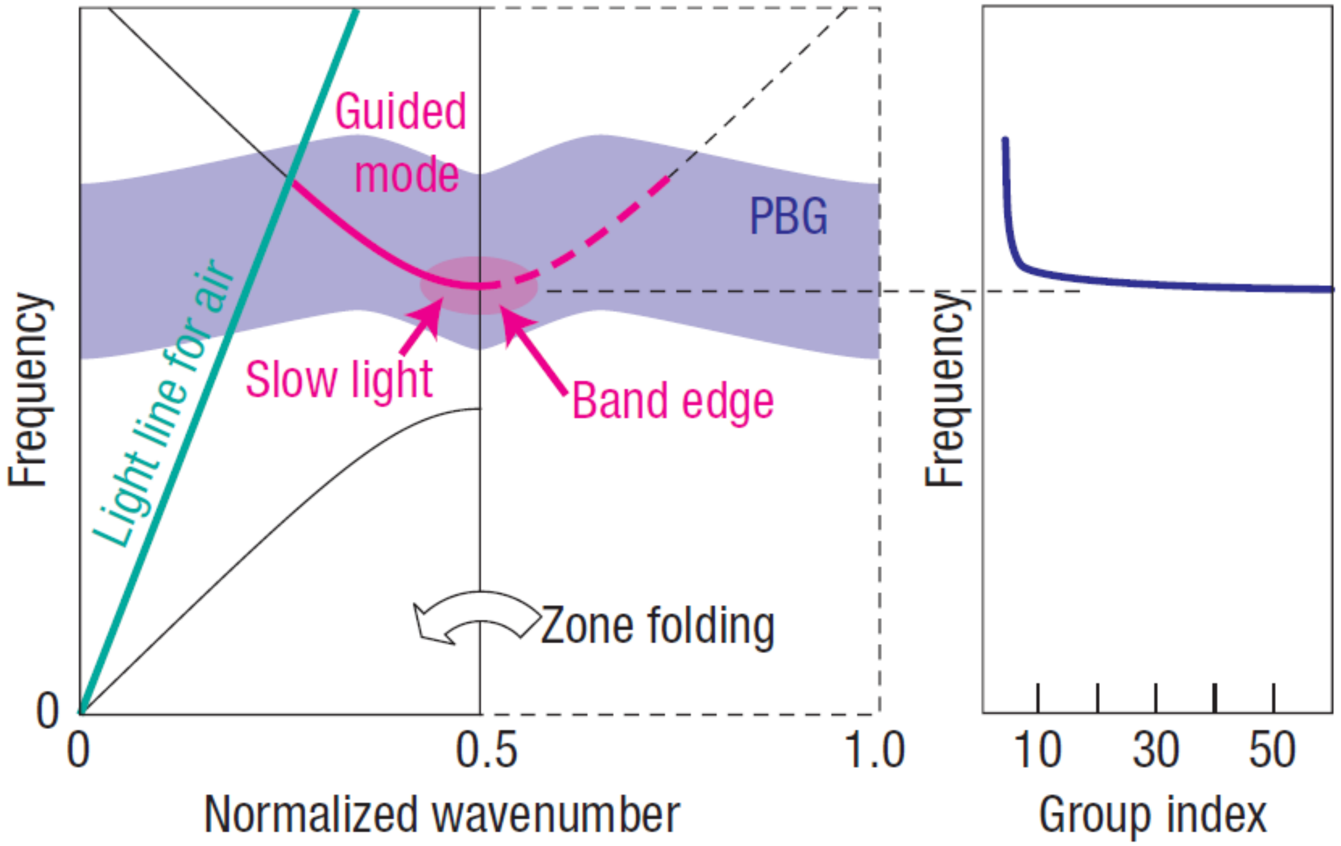








Vlasov, Yurii A. et al., Nature 438, 7064 (2005).



M. Notomi et al. (2001); T. Baba (2008)

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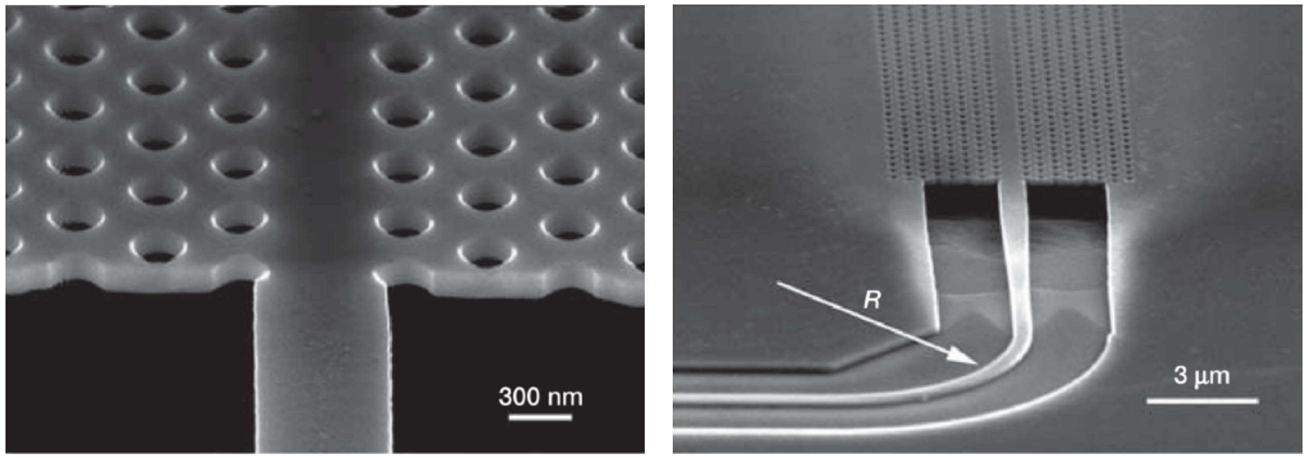

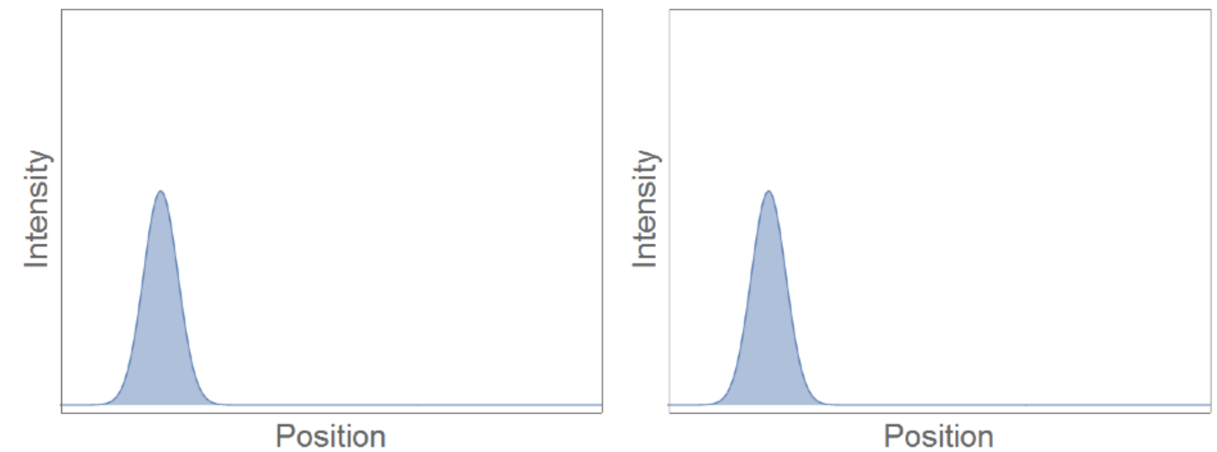

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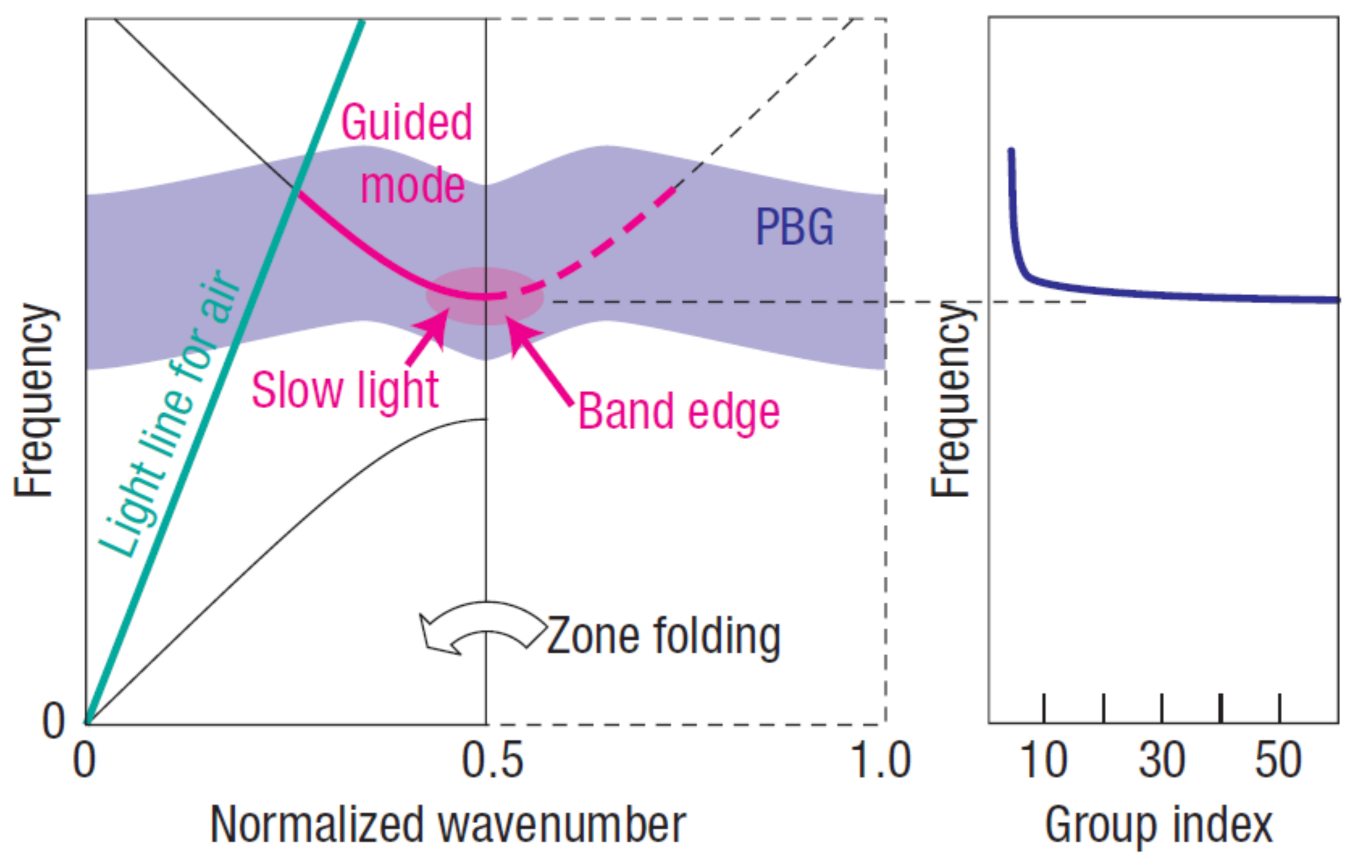
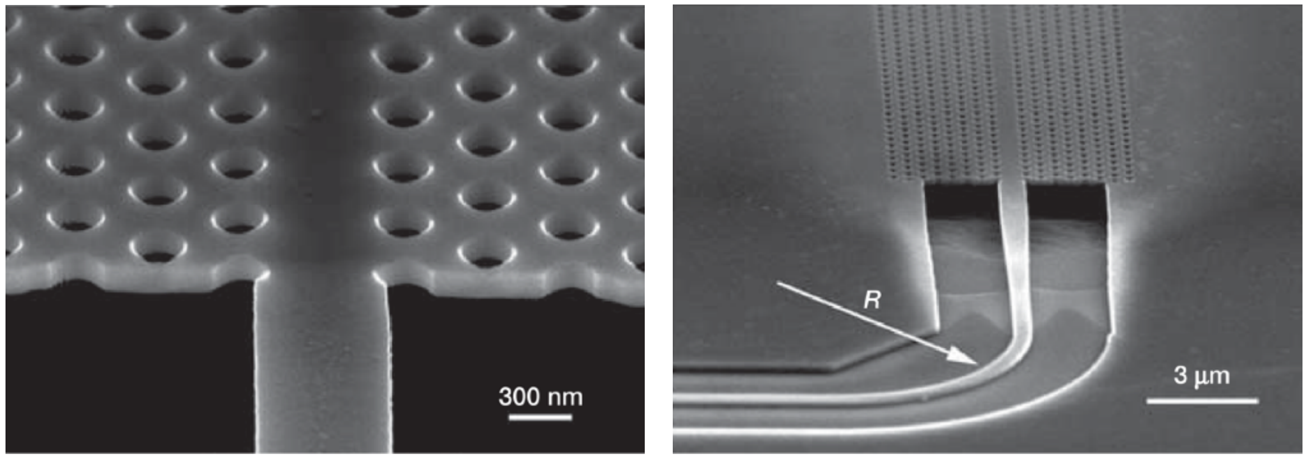
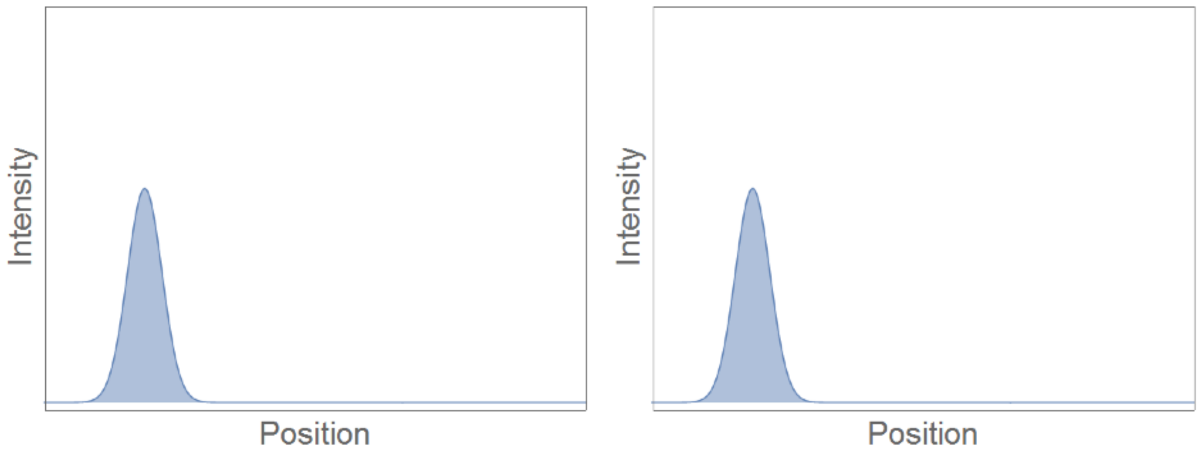


M. Notomi et al. (2001); T. Baba (2008)

Idea: topological slow light





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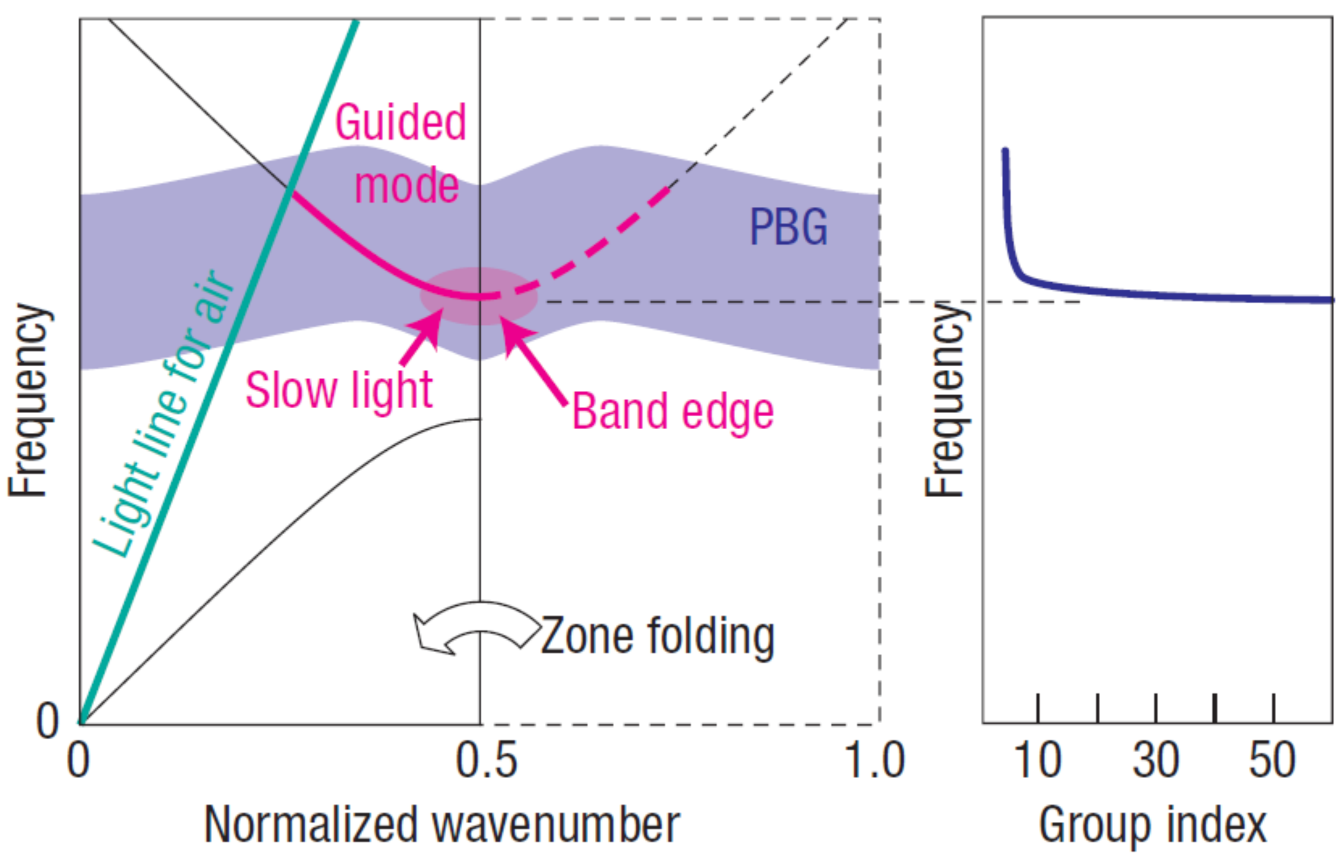
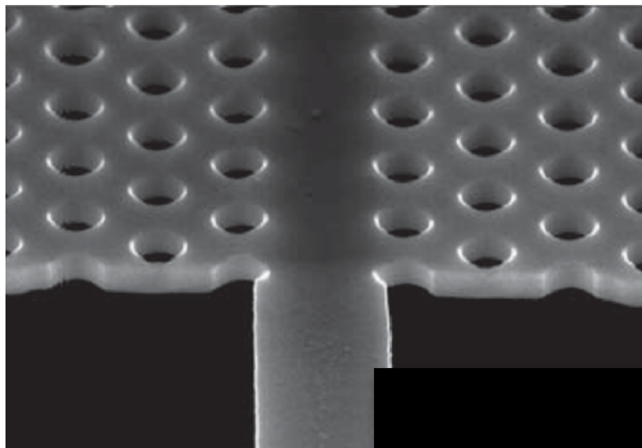


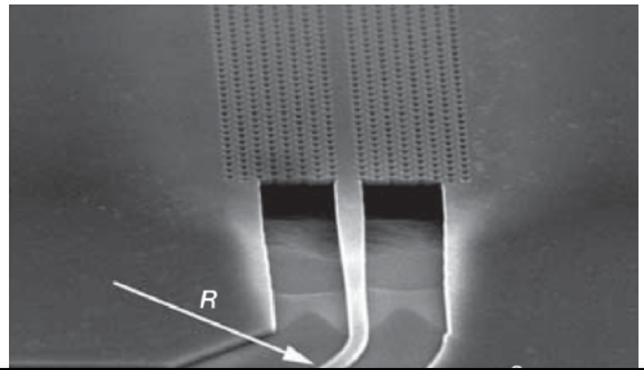
M. Notomi et al. (2001); T. Baba (2008)

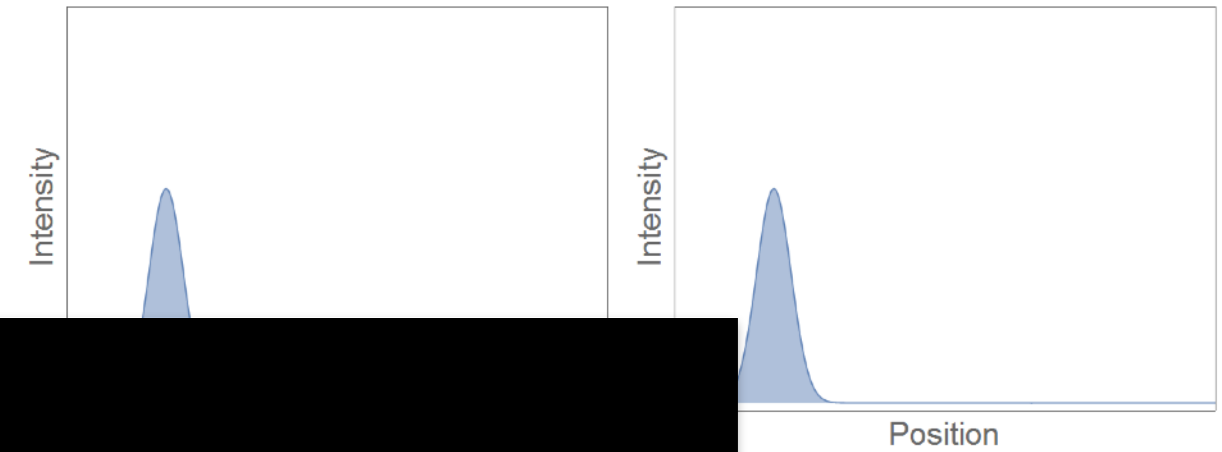
Obstacles:

- In-coupling
- Bandwidth
- Backscattering

Idea: topological slow light

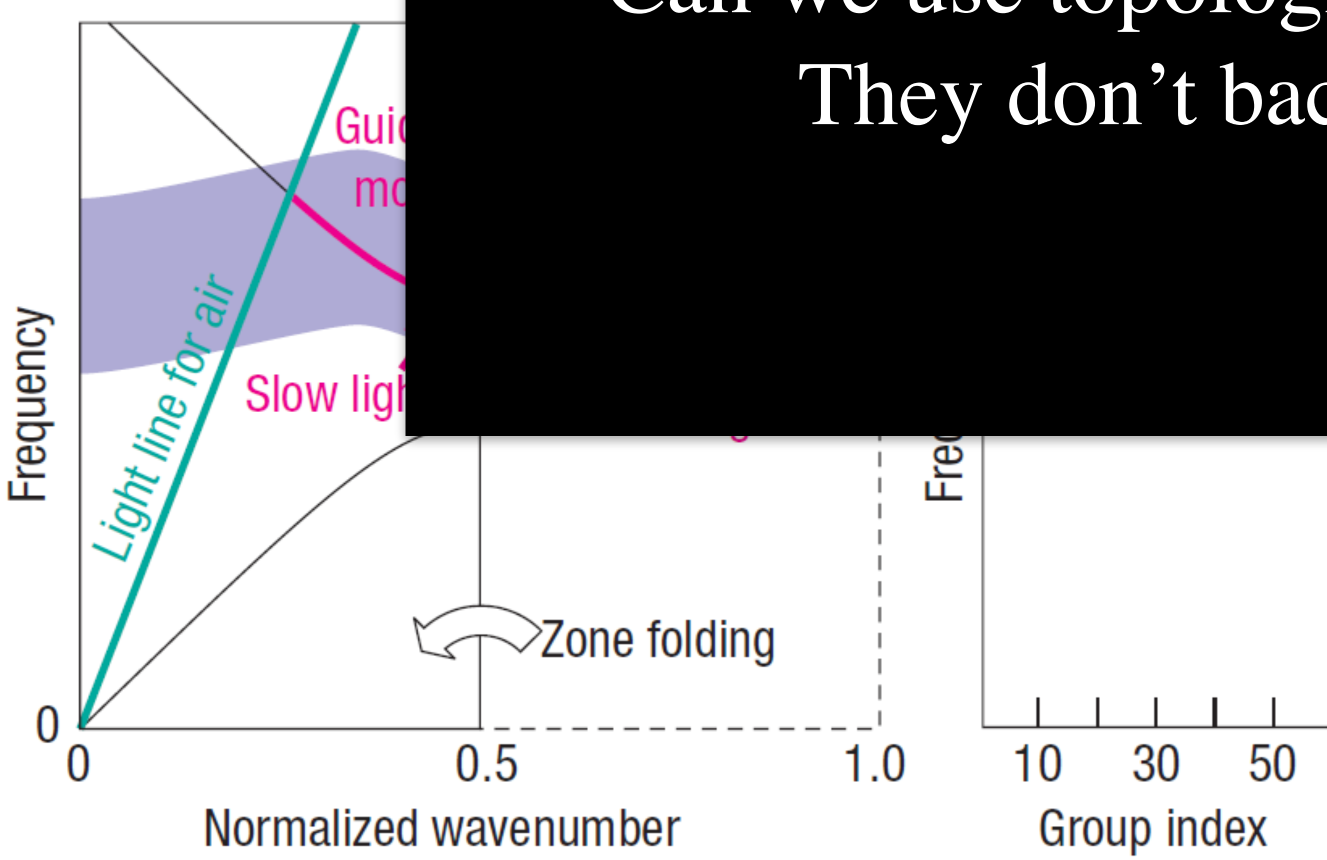






Vlasov, Yurii A

Can we use topological edge states?
They don't backscatter…

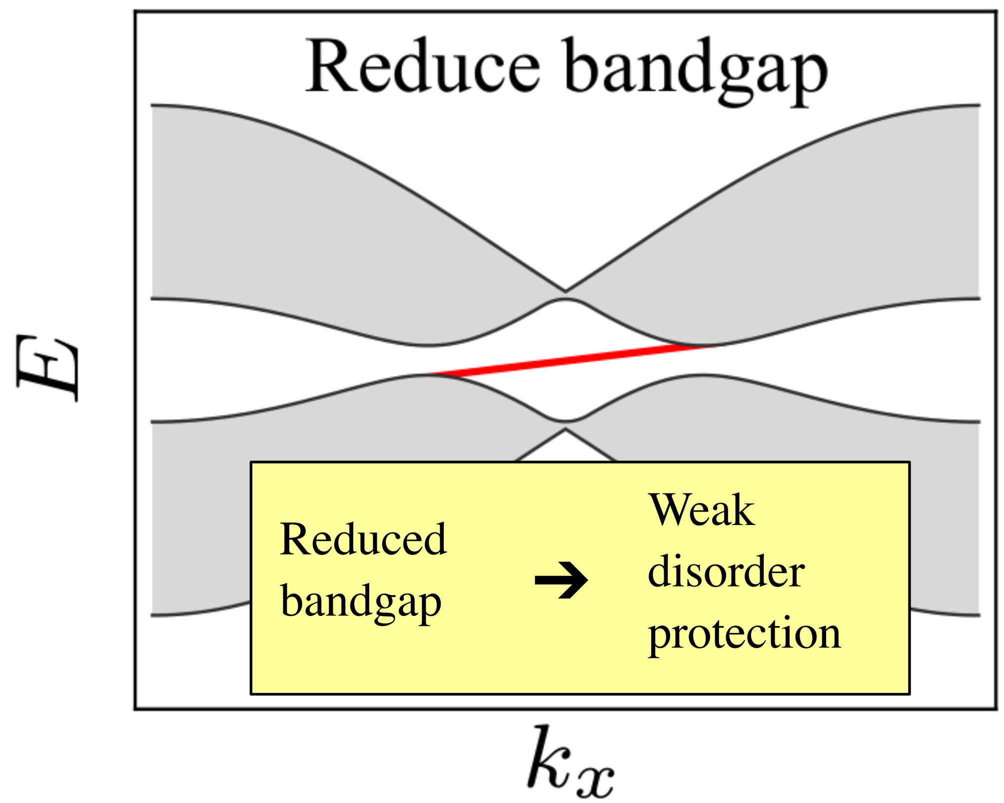


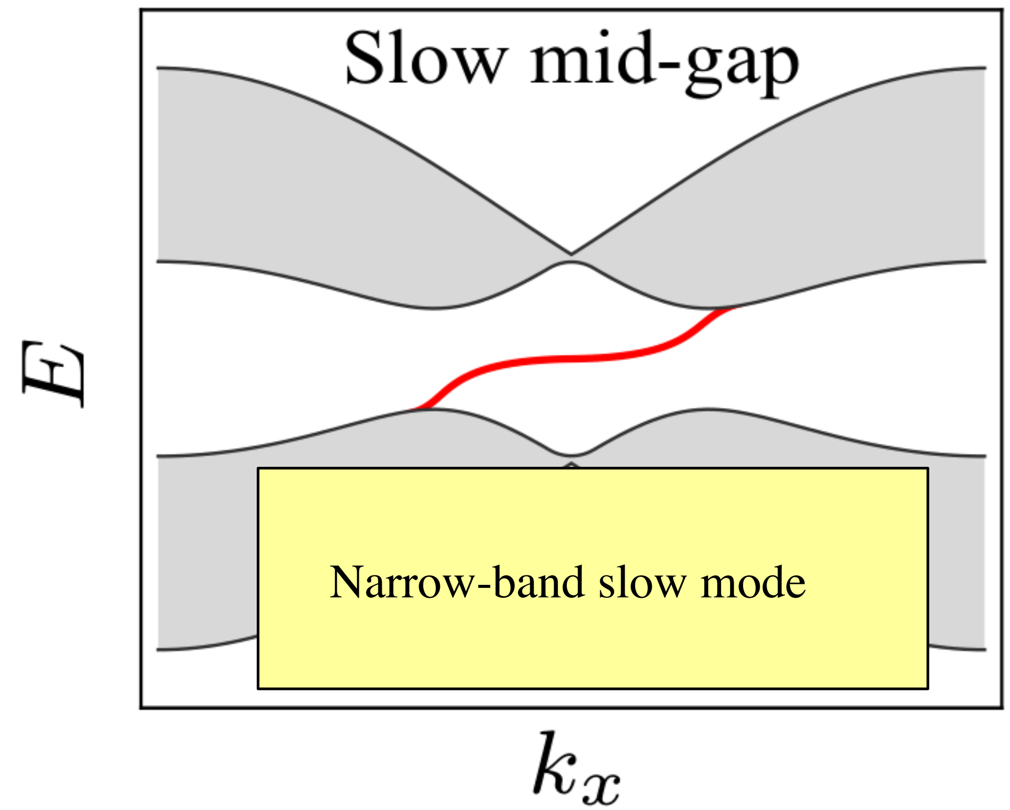
M. Notomi et al. (2001); T. Baba (2008)

ing

- Bandwidth
- Backscattering

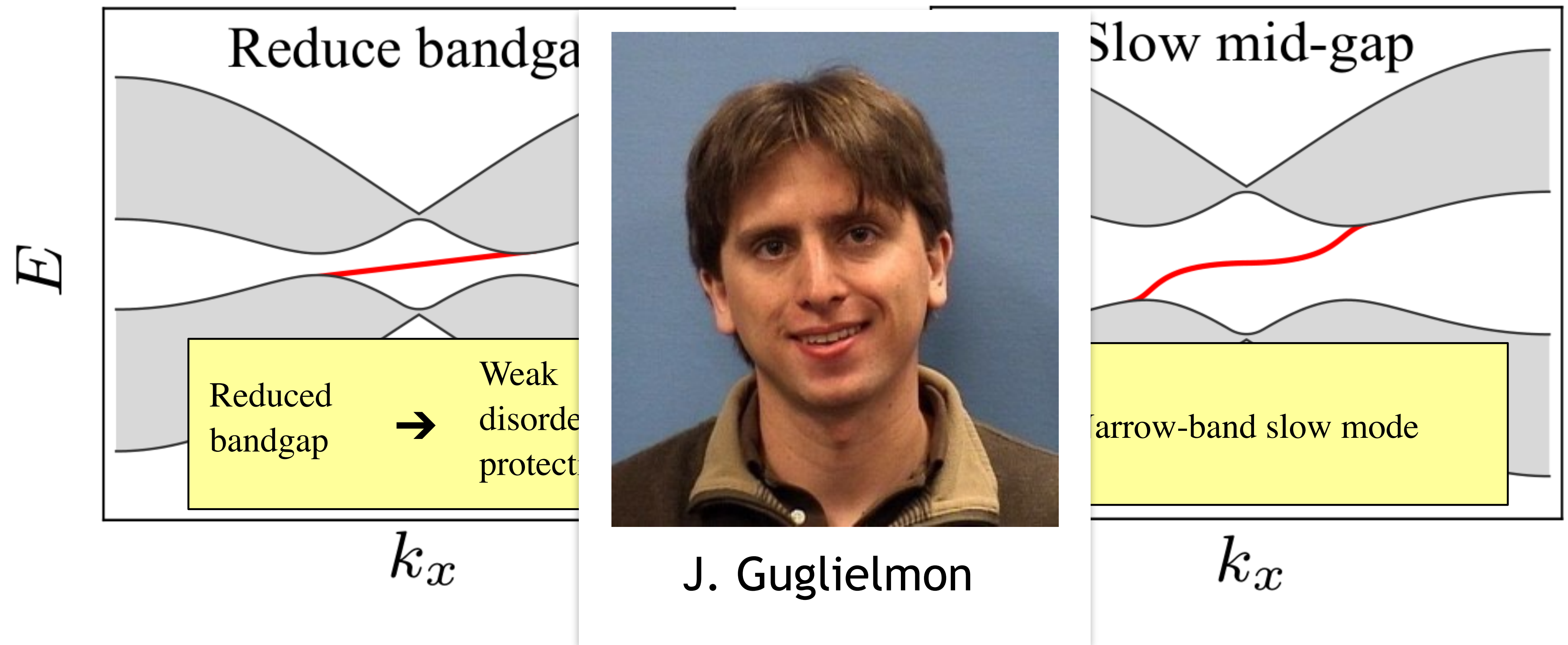
Obvious ideas





Note that both methods sacrifice bandwidth

Obvious ideas



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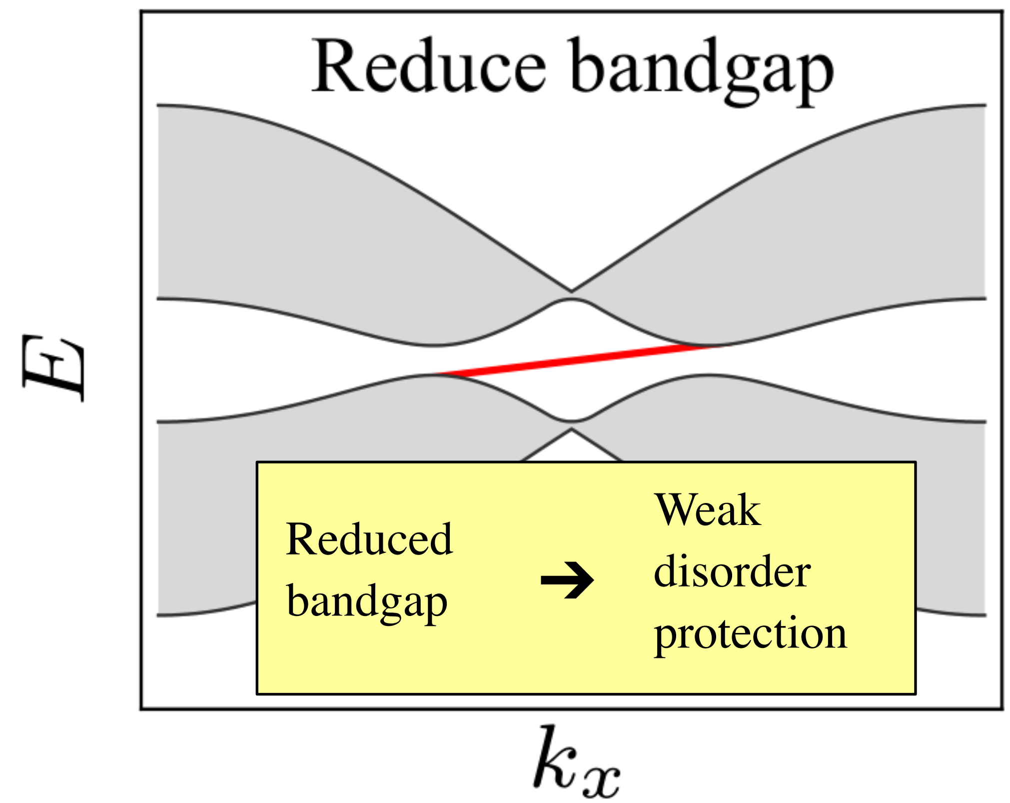
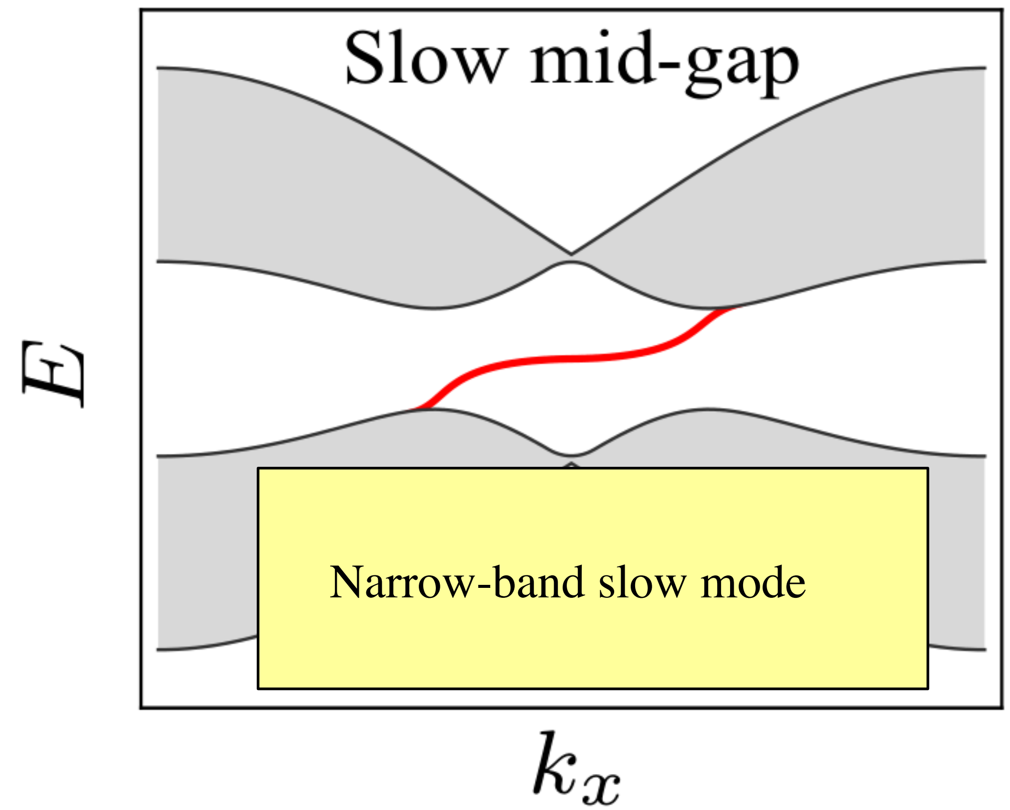
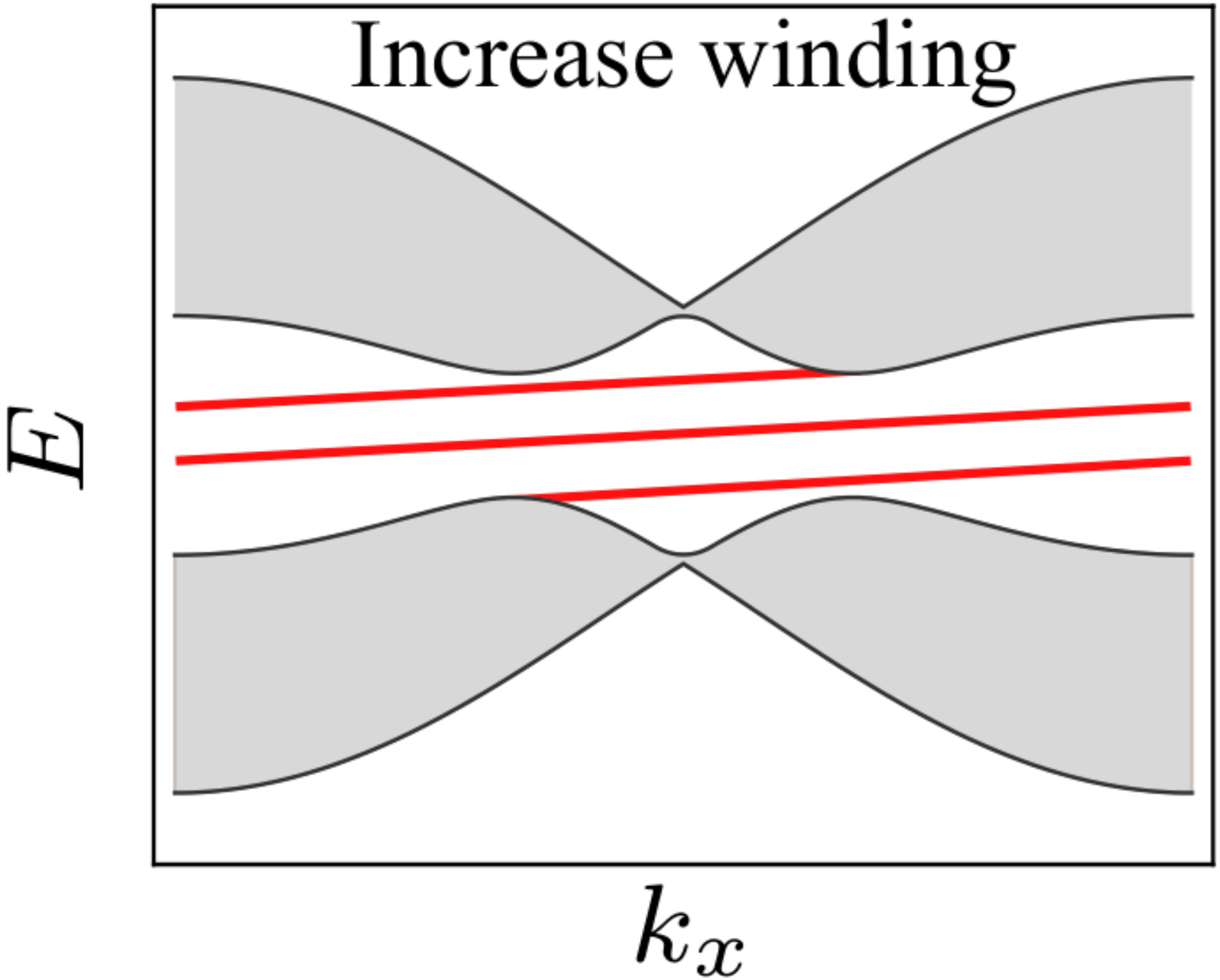
Obvious ideas





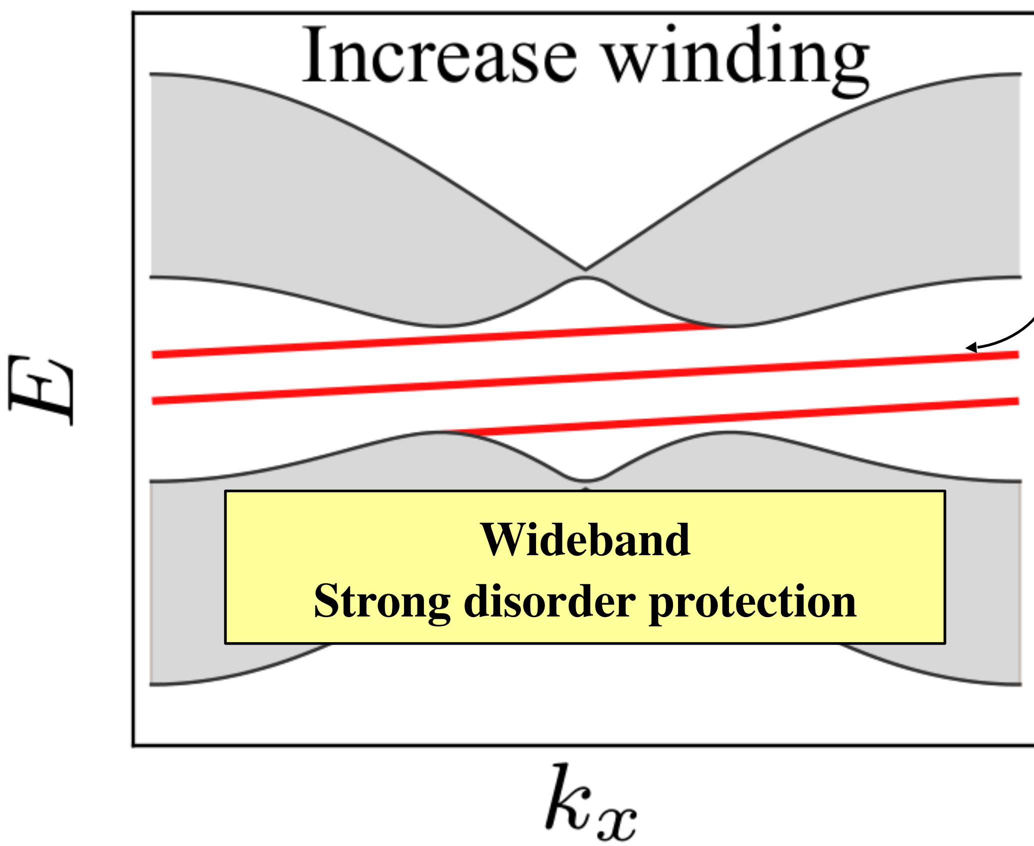
Note that both methods sacrifice bandwidth

Increase winding



Increase winding

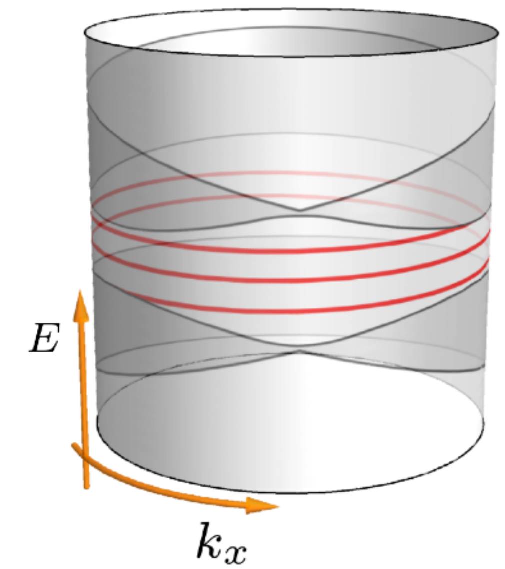
Topology forces edge mode to fully cross the gap → Increased winding around BZ



One mode which wraps multiple times around Brillouin zone as it crosses the gap

- ➢ Perfect in-coupling
- ➢ No backscattering
- ➢ High bandwidth (whole gap)

Periodic Brillouin Zone

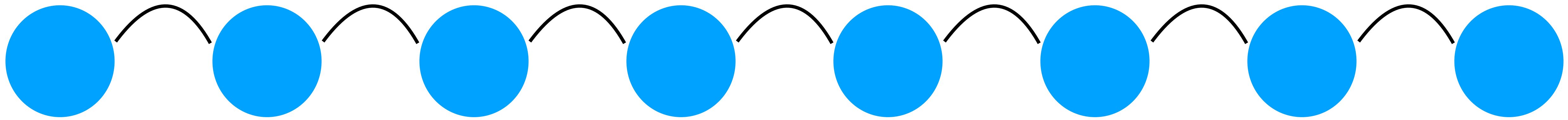


Extra notes:

- ➢ Not simply band folding
- ➢ Single-mode, even with large winding
- ➢ Won't work if it's not topological

J. Guglielmon and M. C. Rechtsman. Phys. Rev. Lett. **122**, 153904 (2019).

How do we do it?



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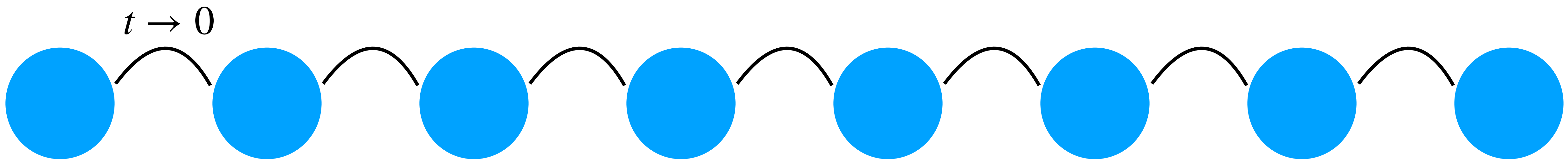

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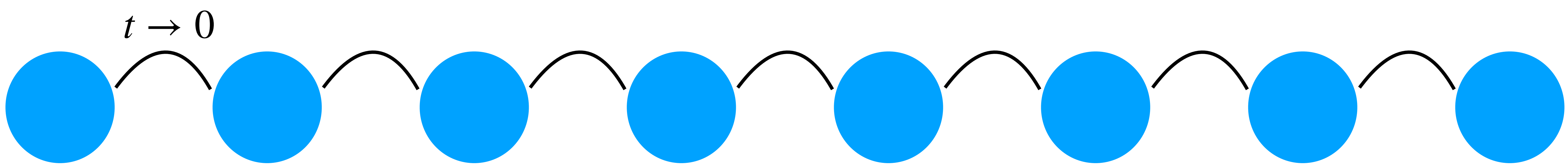
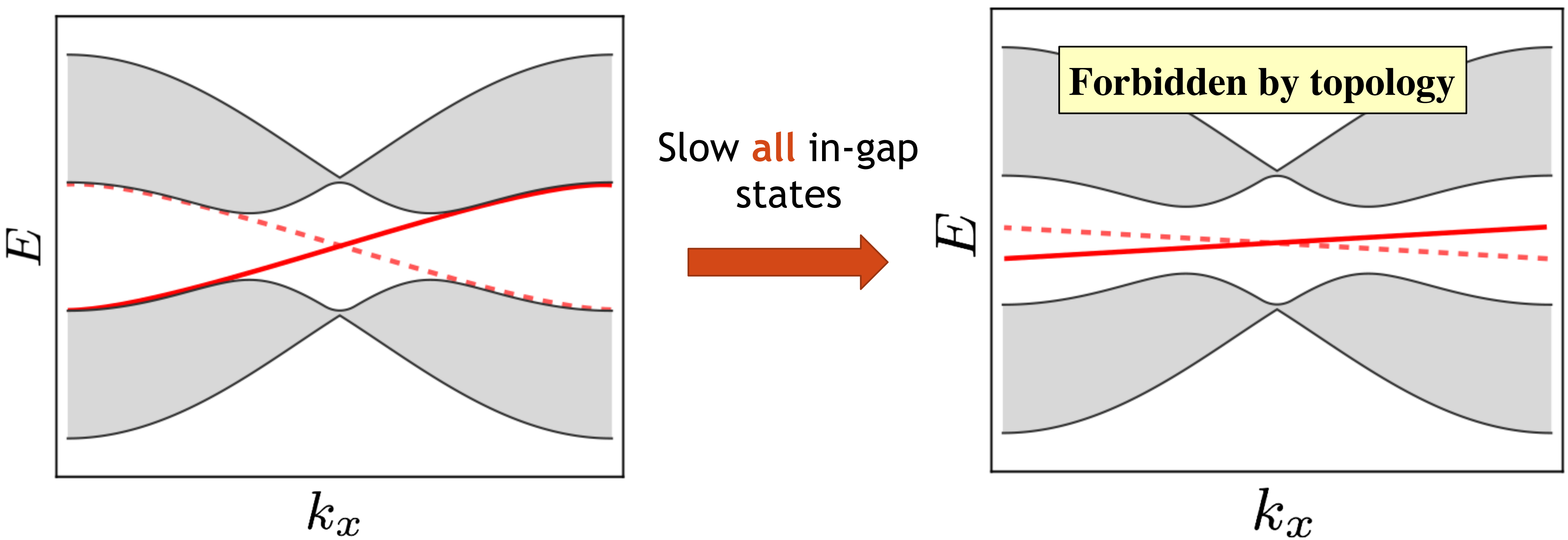
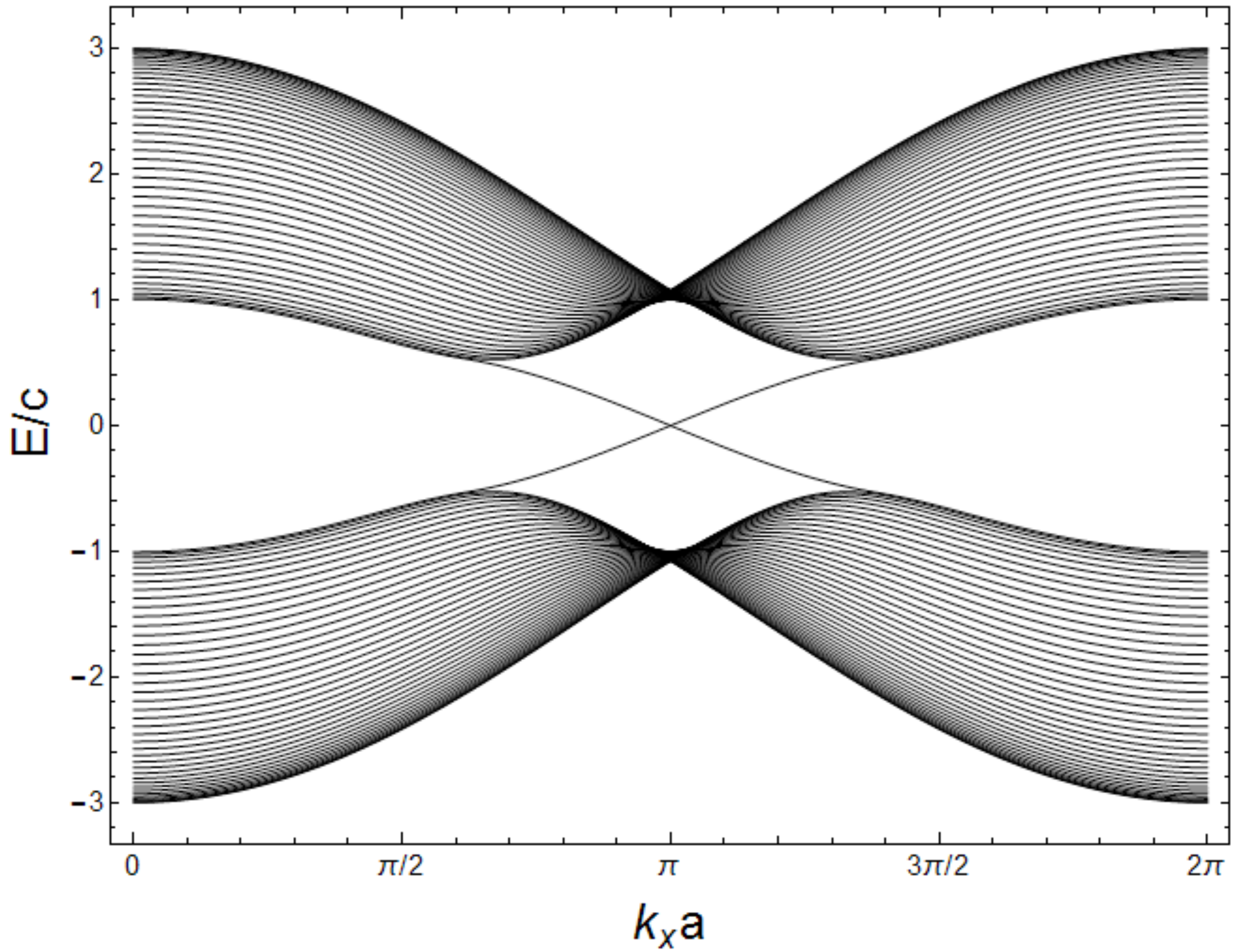
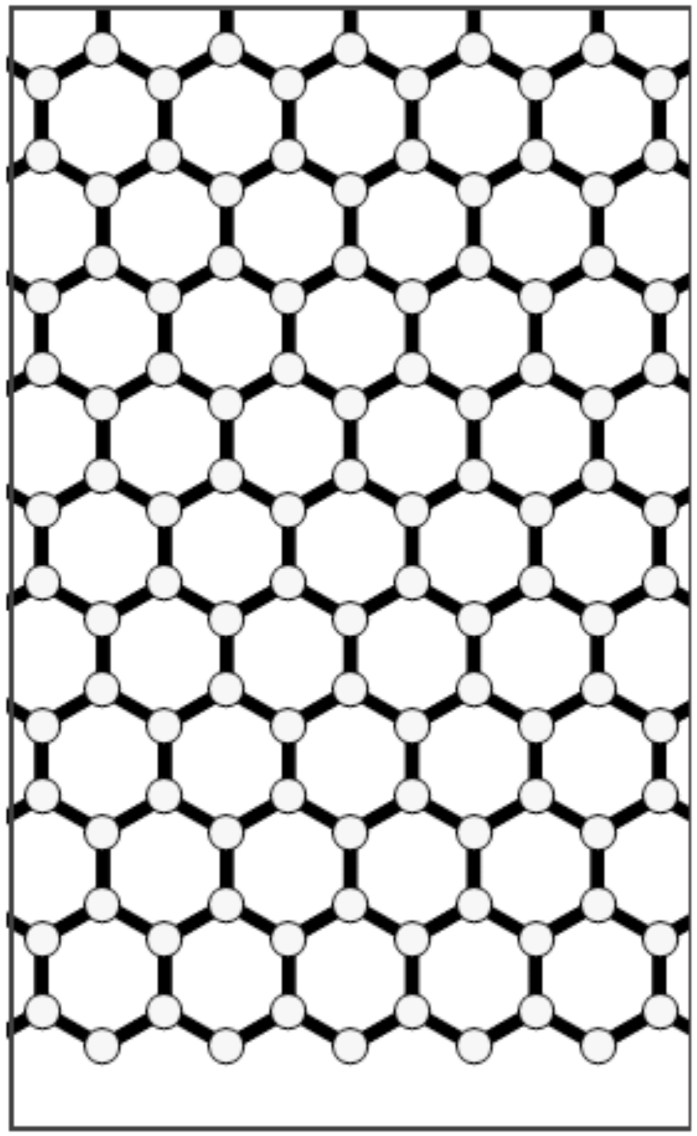




Engineering the edge…





J. Guglielmon and M. C. Rechtsman. Phys. Rev. Lett. **122**, 153904 (2019).

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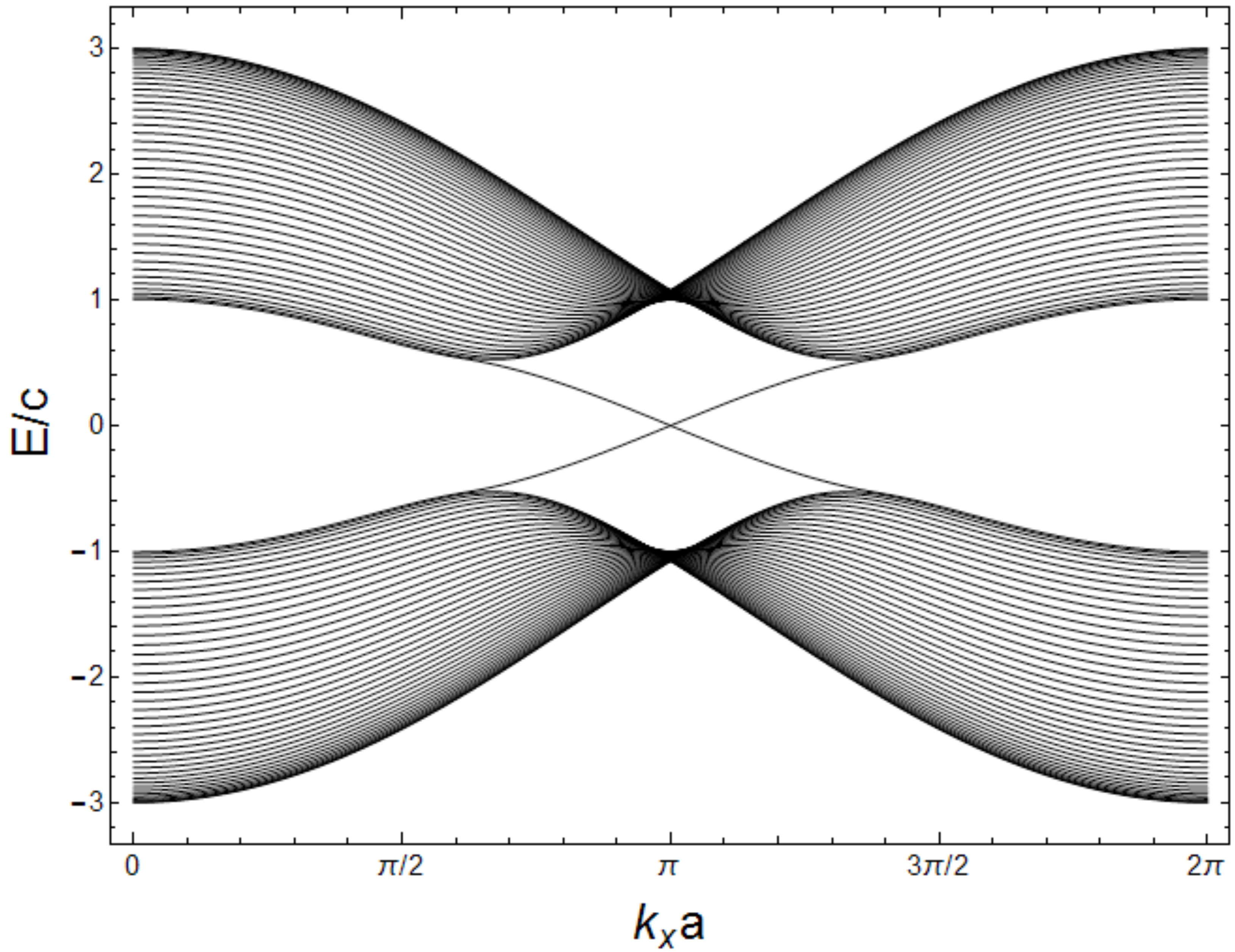
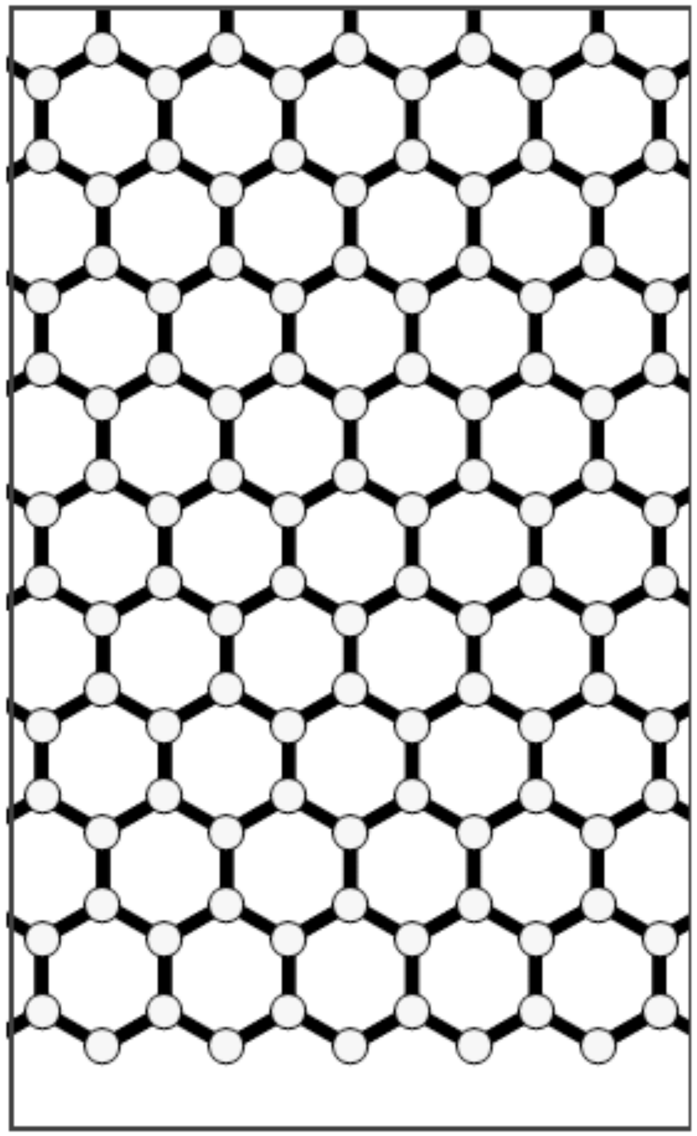
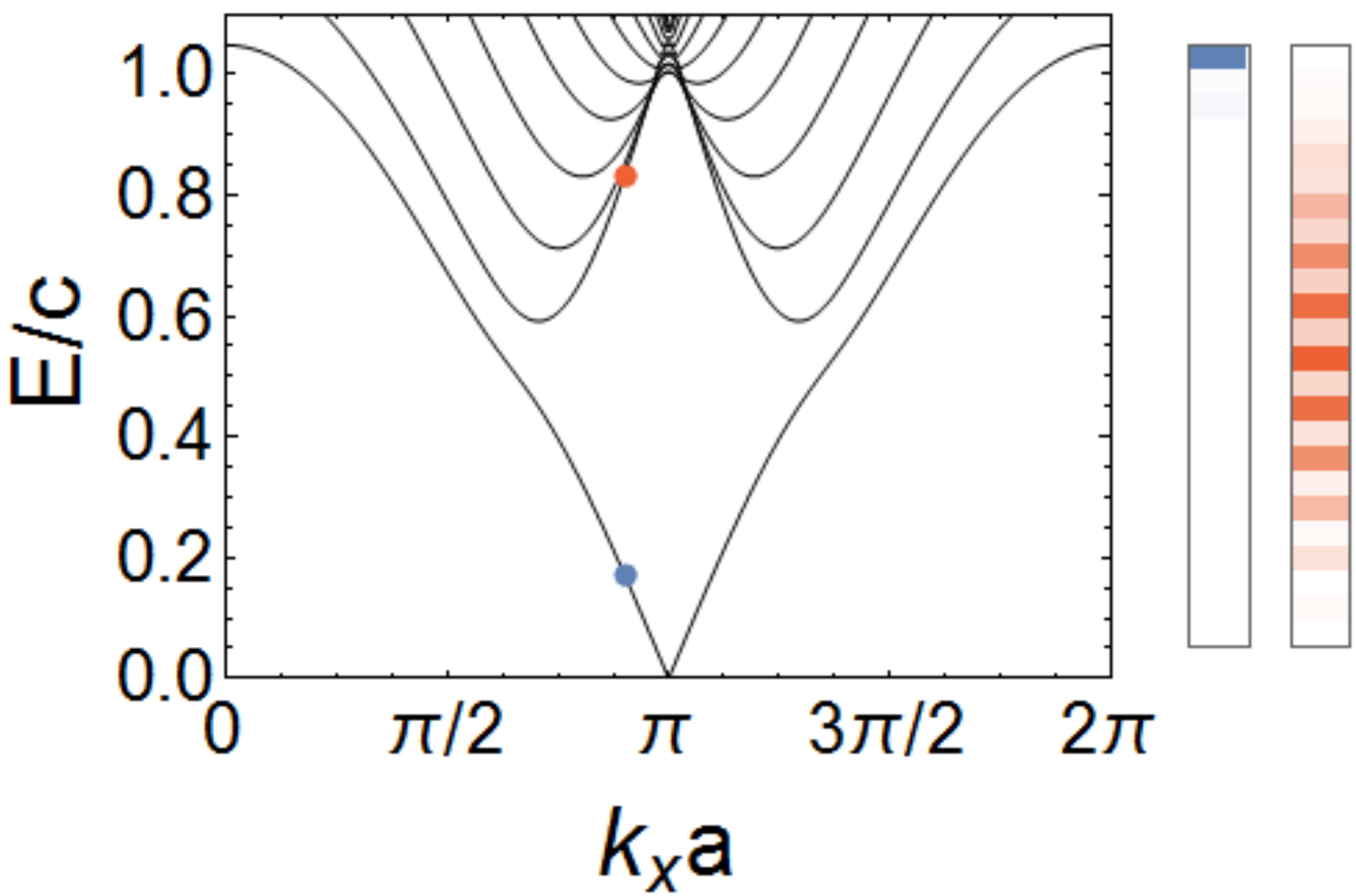




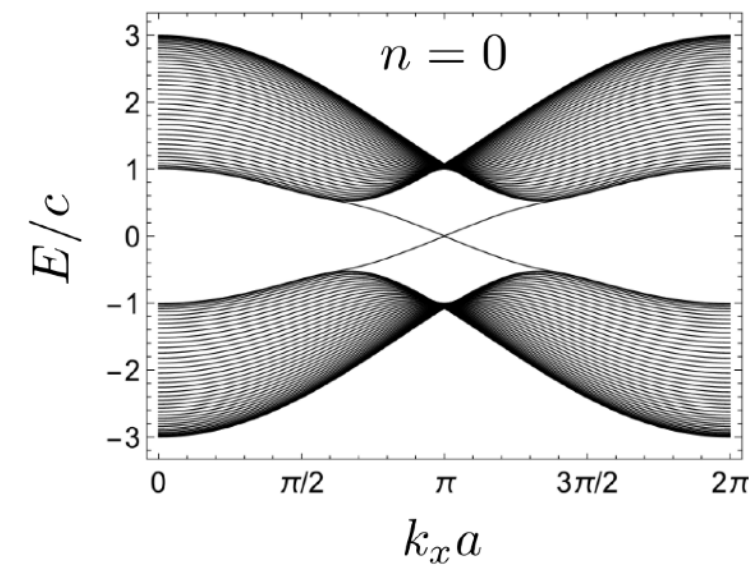
J. Guglielmon and M. C. Rechtsman. Phys. Rev. Lett. **122**, 153904 (2019).

Where do the new edge states come from?

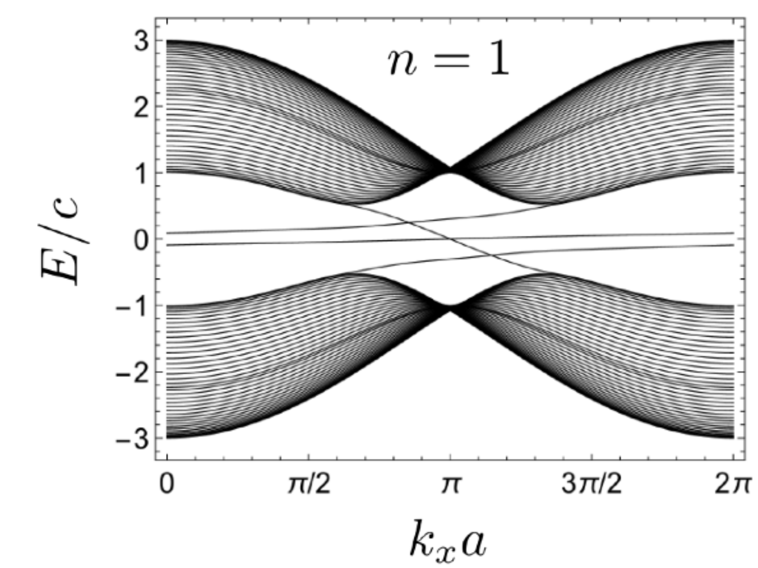
$$H_\lambda(k_x) = (1-\lambda)H_0(k_x) + \lambda H_1(k_x)$$



Initial band structure



Final band structure



… this defines an invariant

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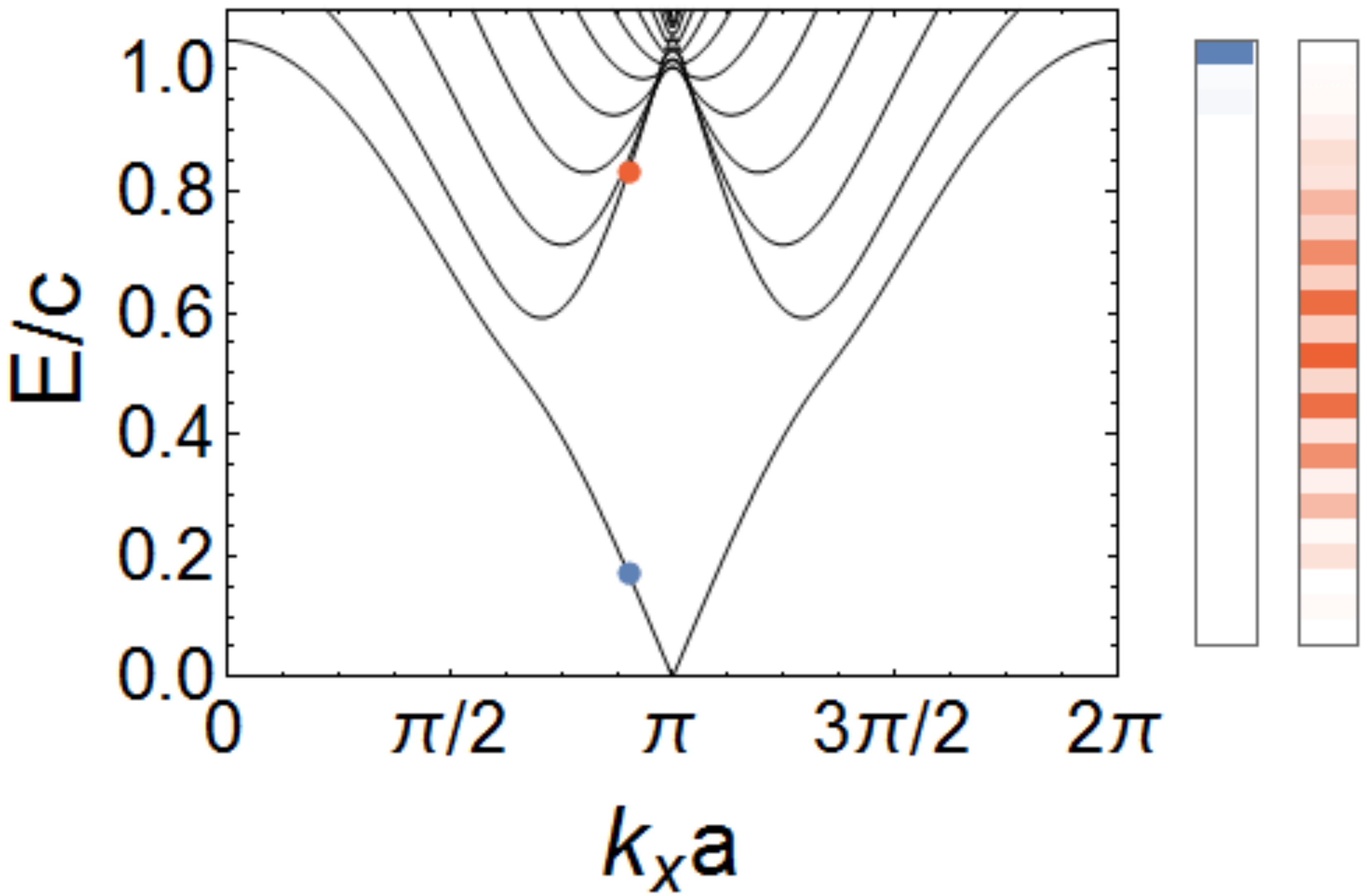

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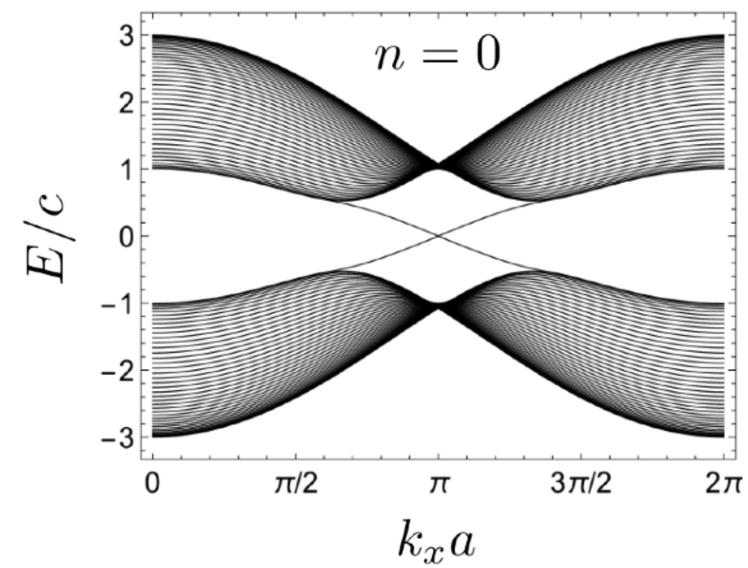
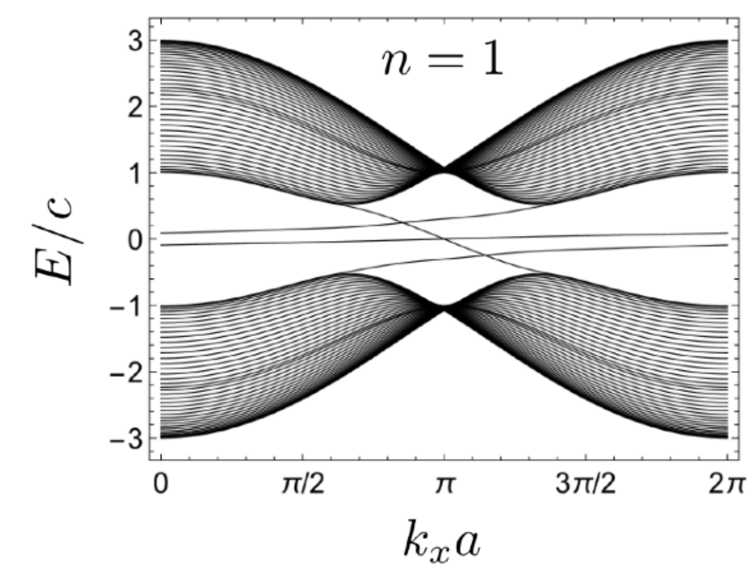


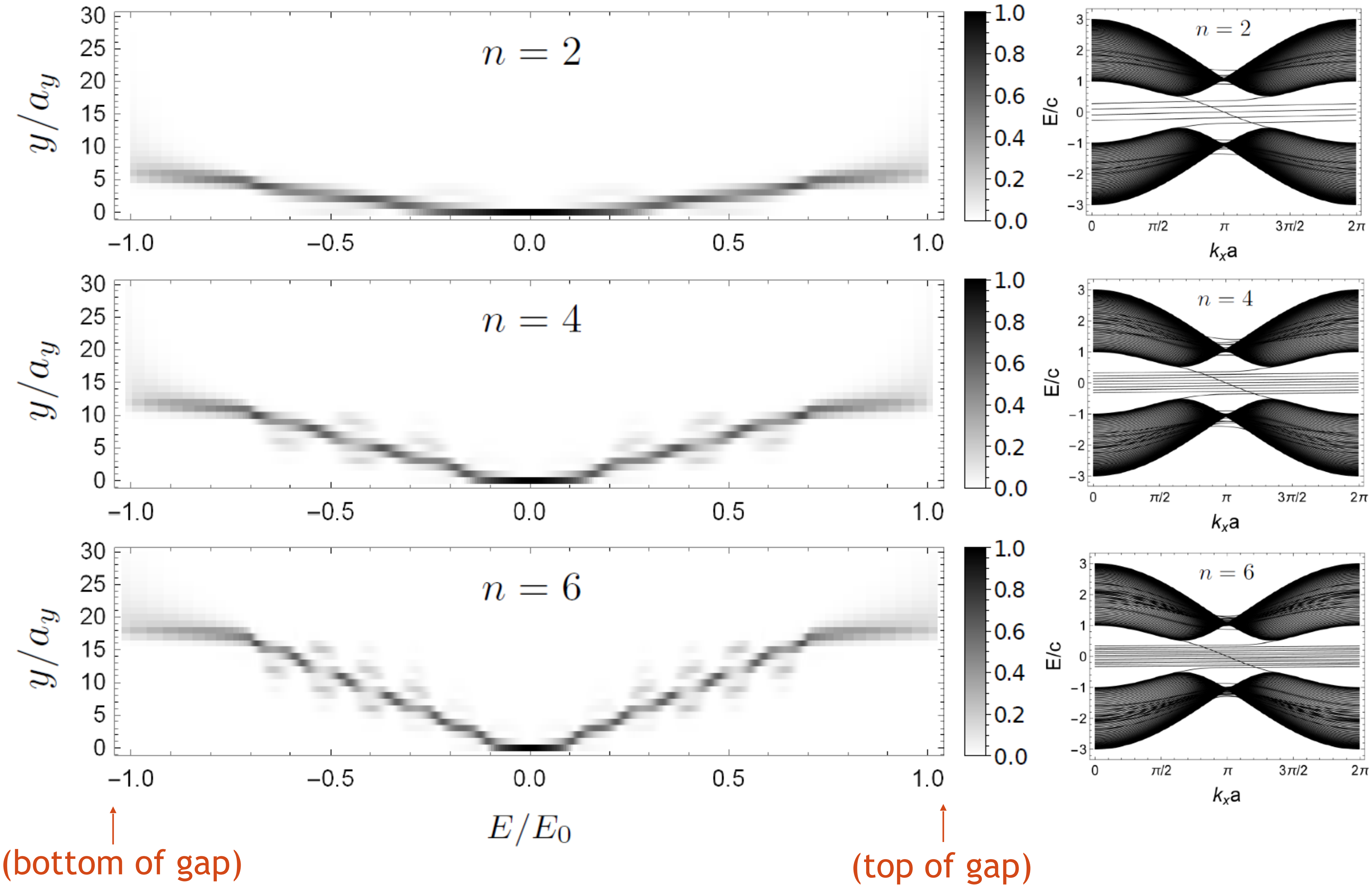
Final band structure



… this defines an invariant

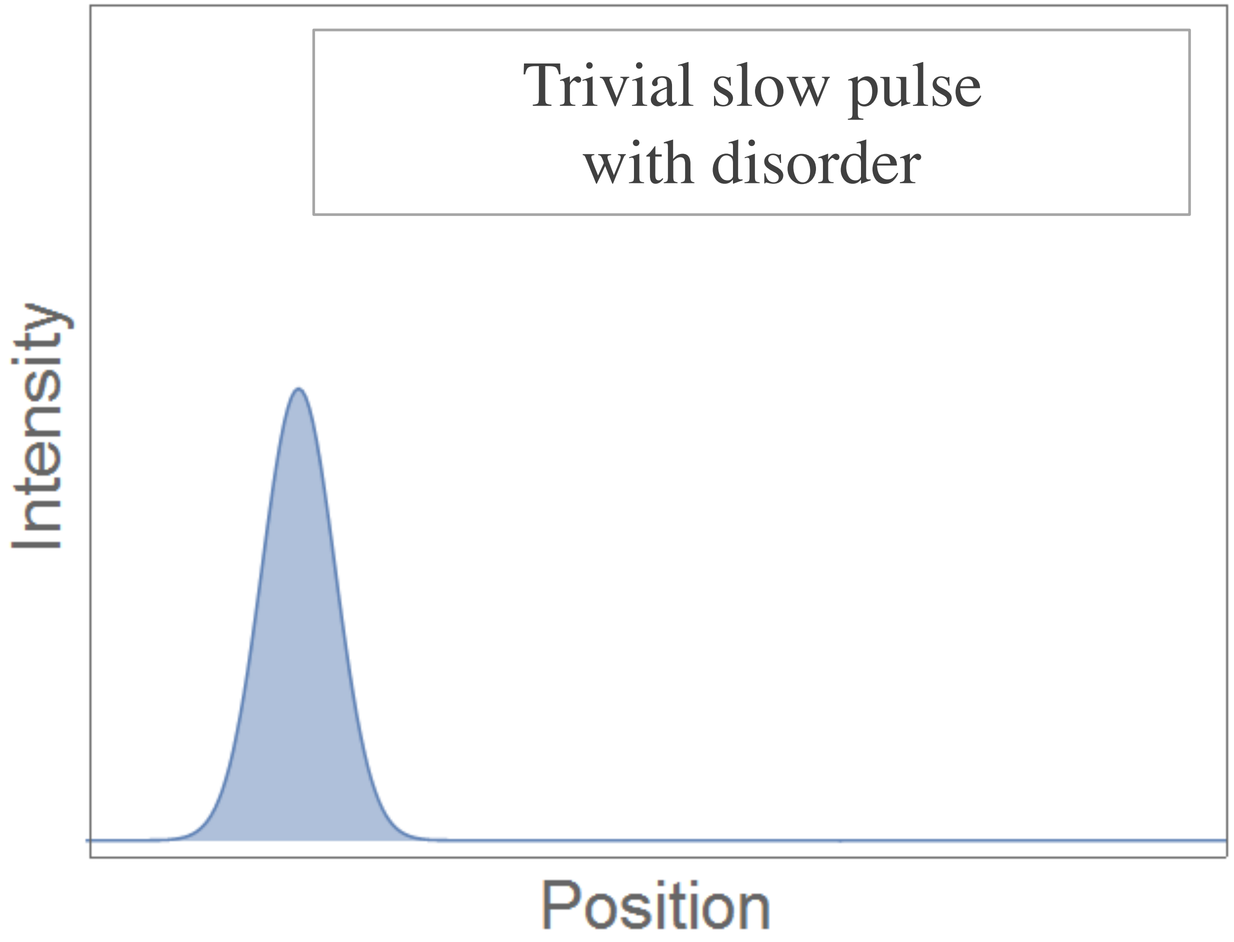
Confinement of slow light edge modes

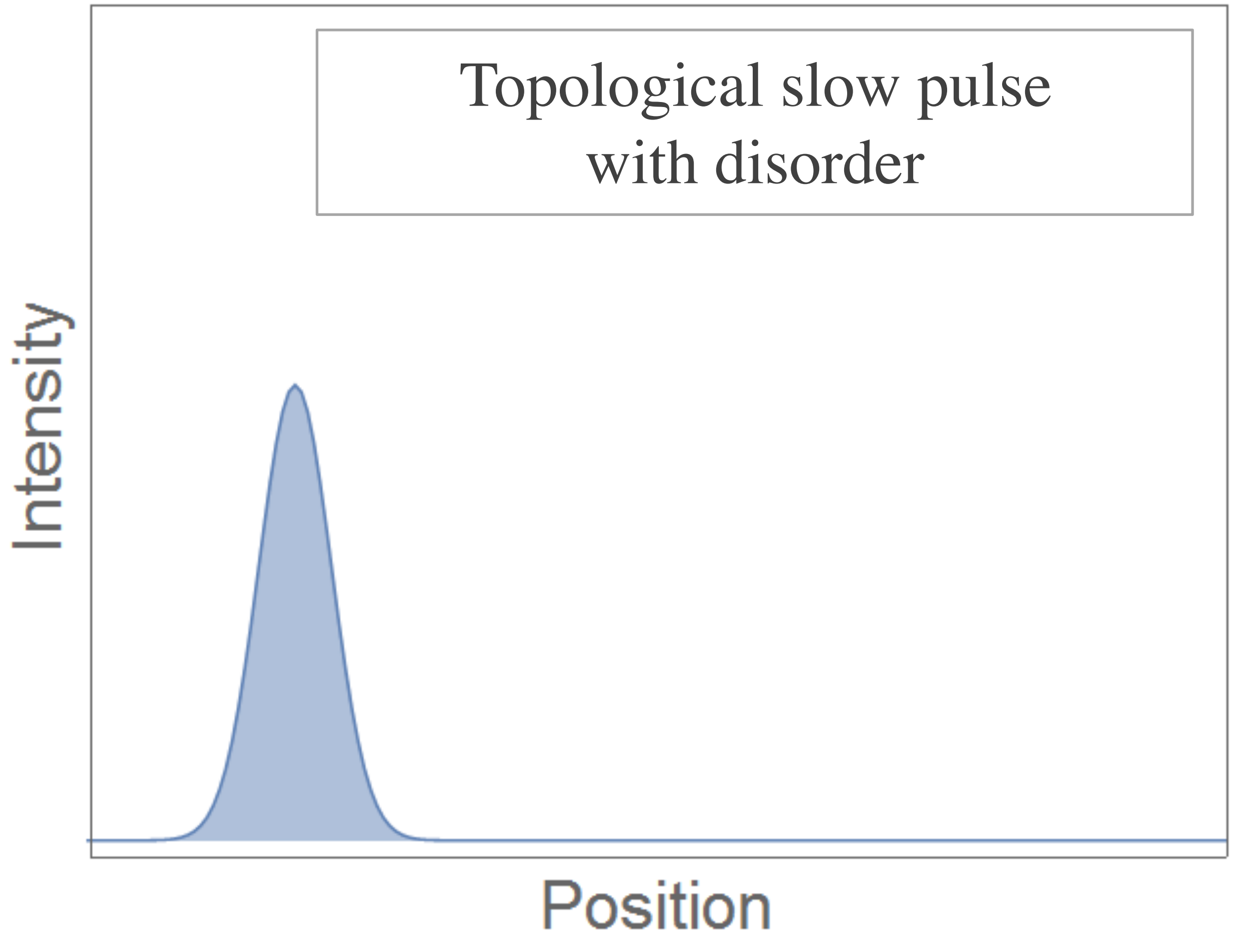
As winding increases, the edge modes utilizes more bulk sites



Robust slow light

These slow chiral edge states resist the severe backscattering associated with a reduced group velocity:





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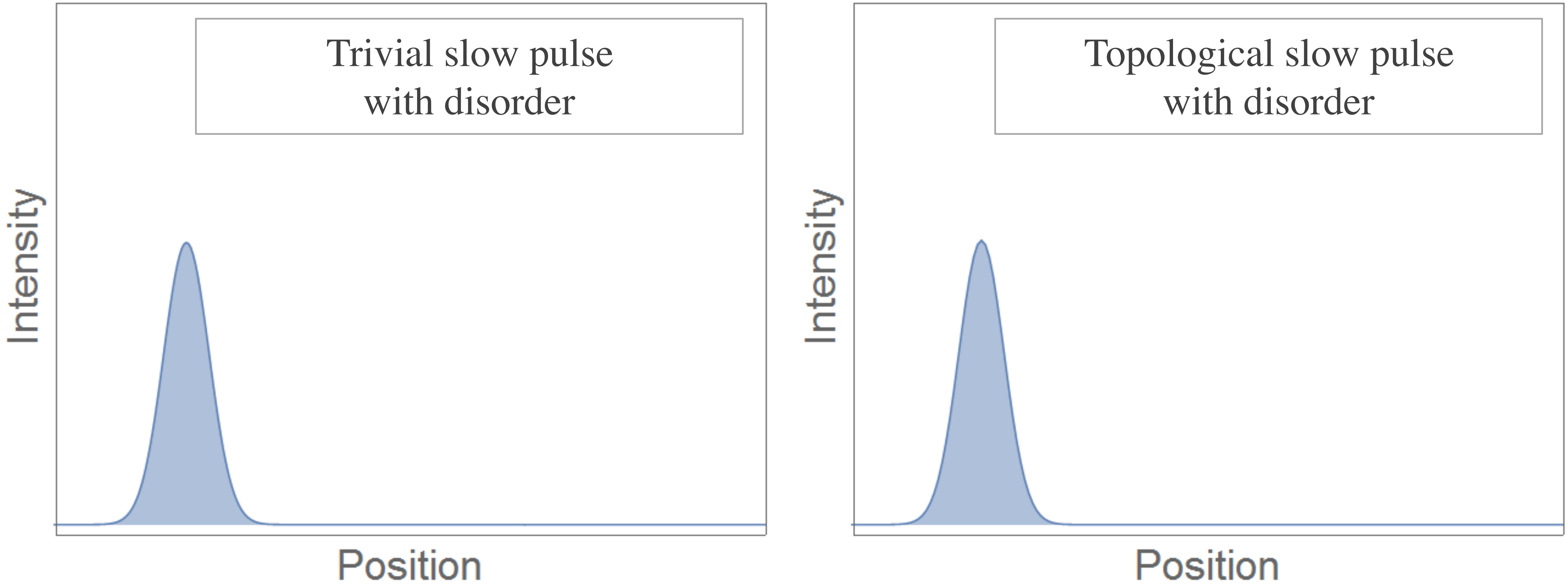
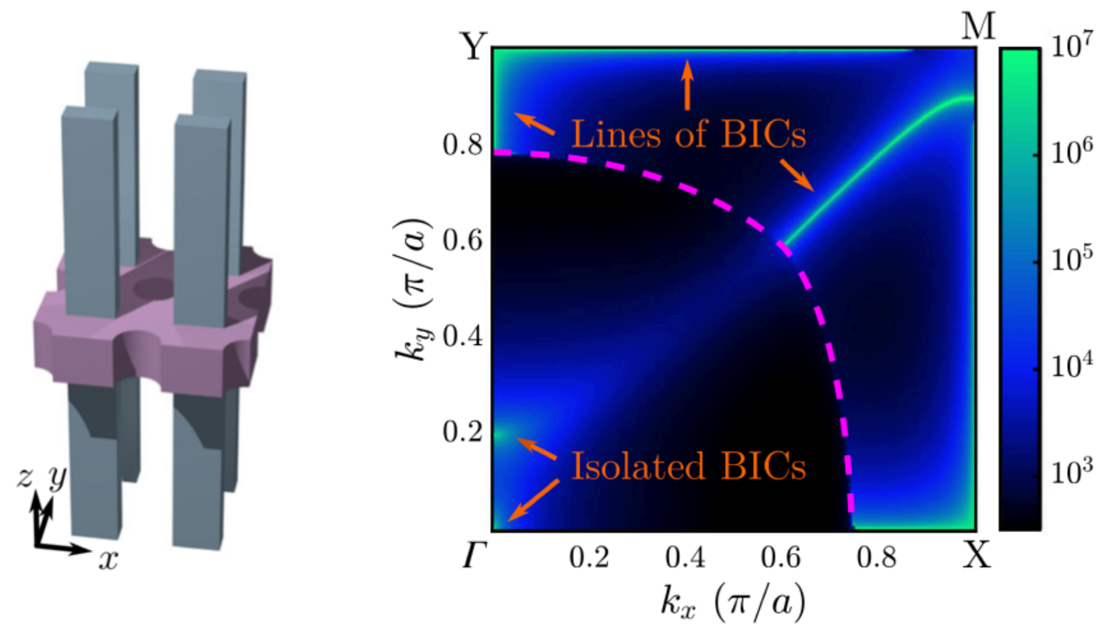
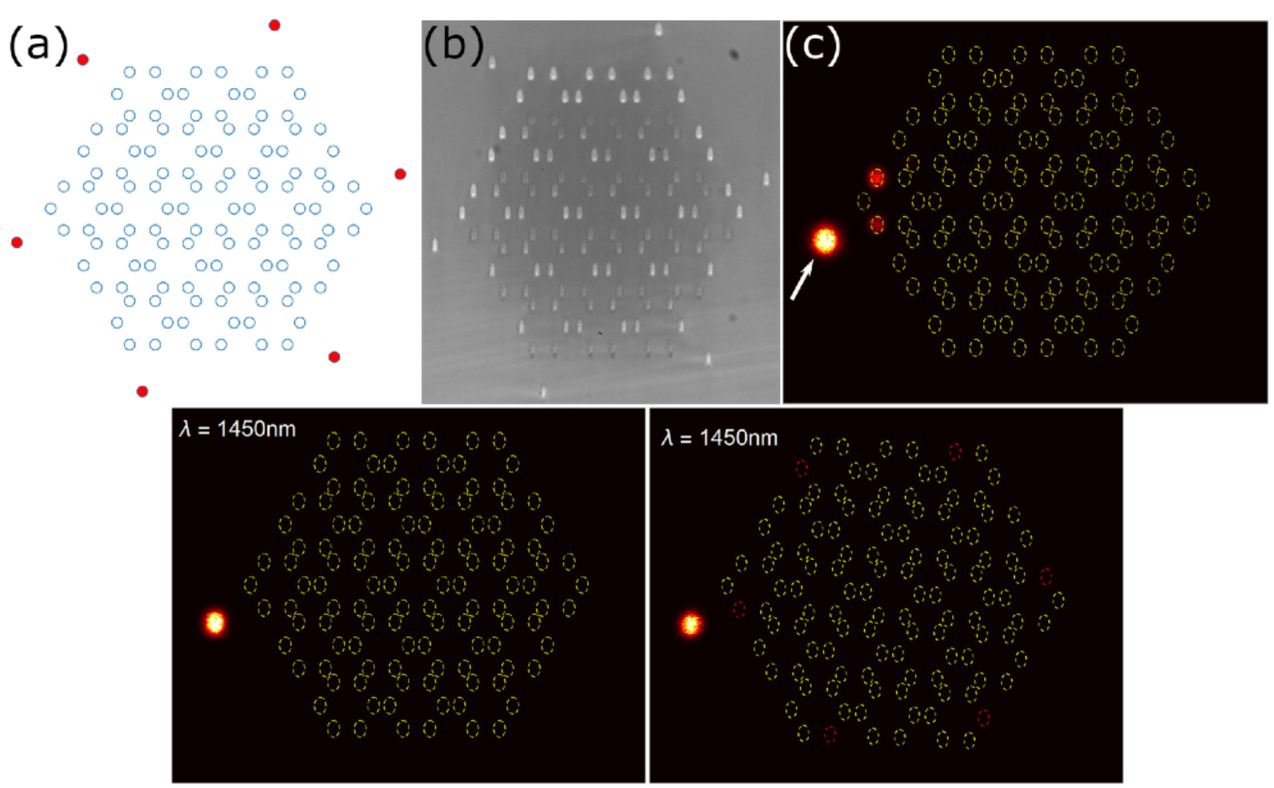


Brief summary of some other recent results…



Cerjan et al., Phys. Rev. Lett. 123, 023902 (2019)

Noh et al., Nature Physics 13, 611 (2017)



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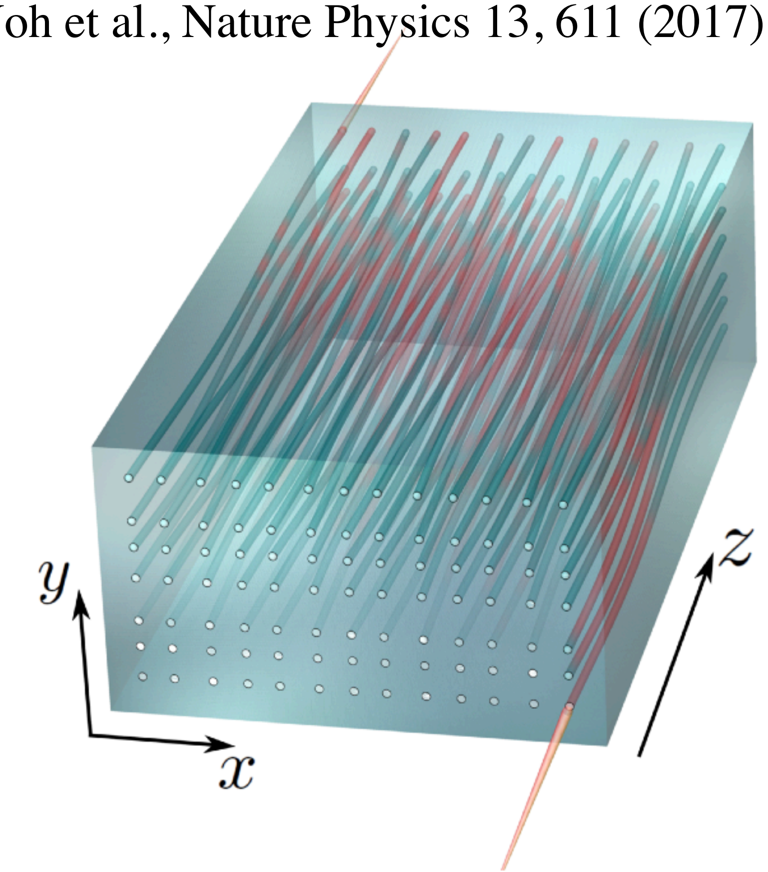

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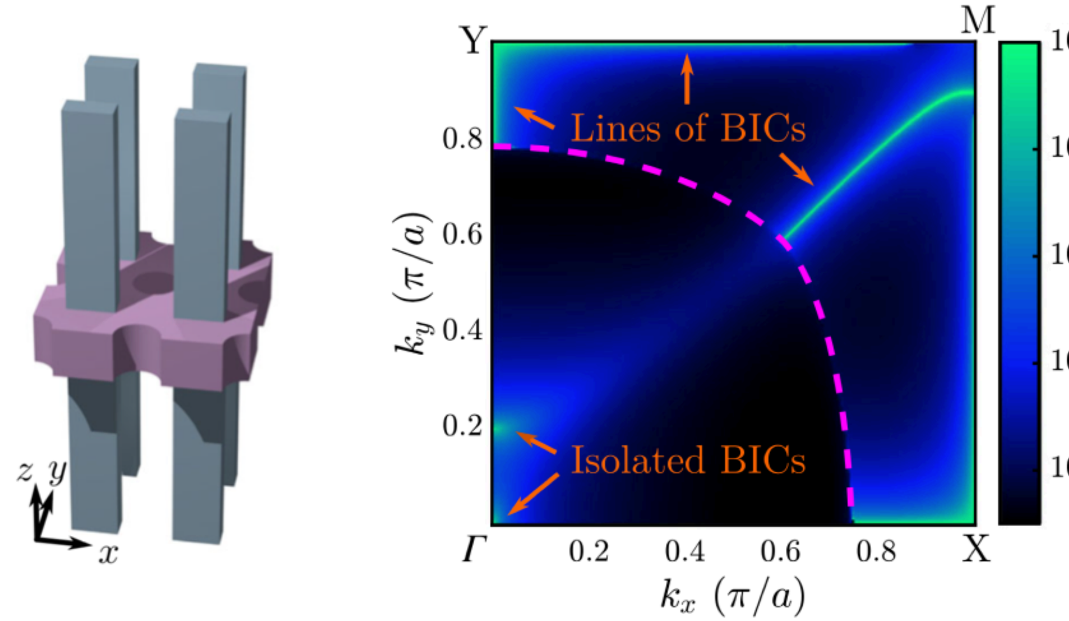

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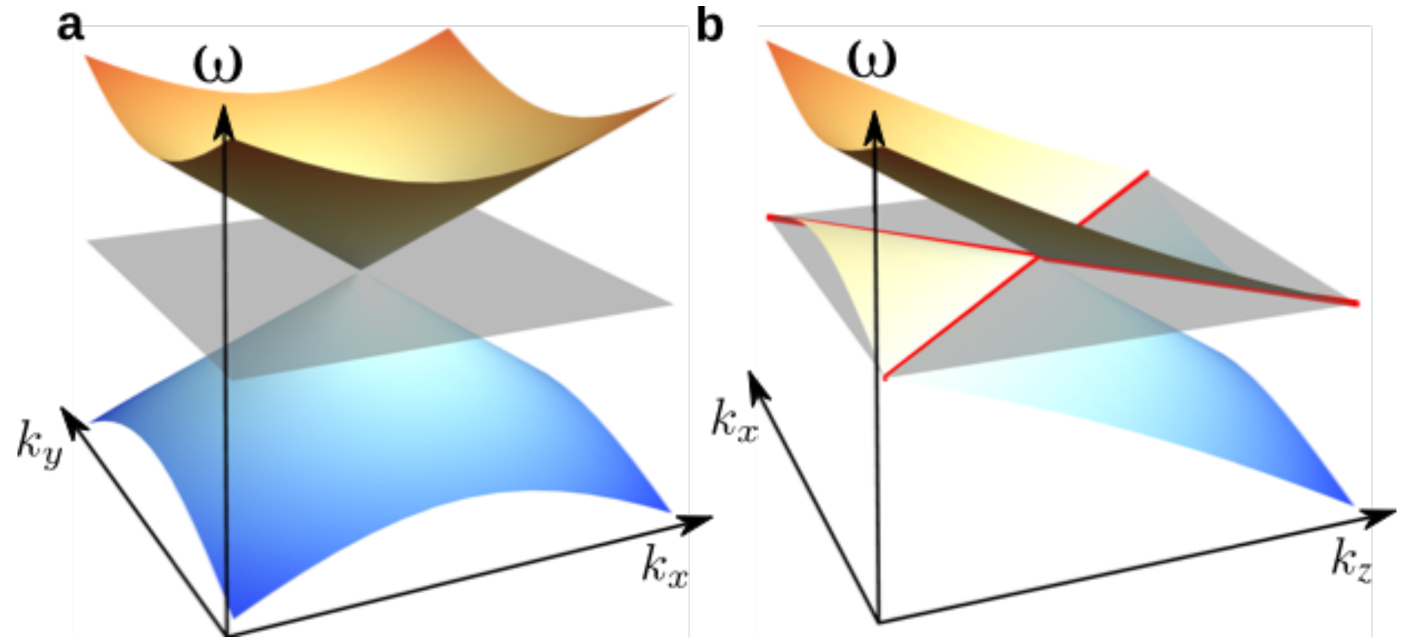

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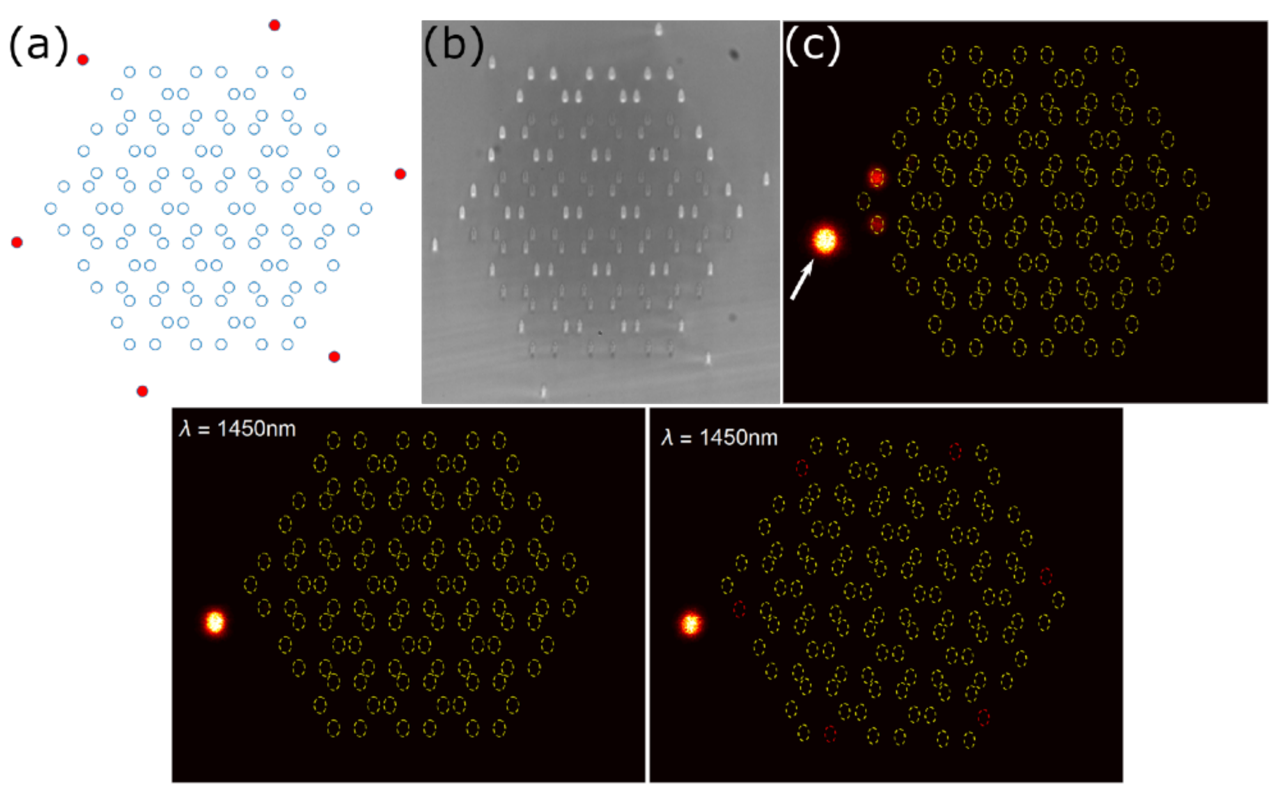

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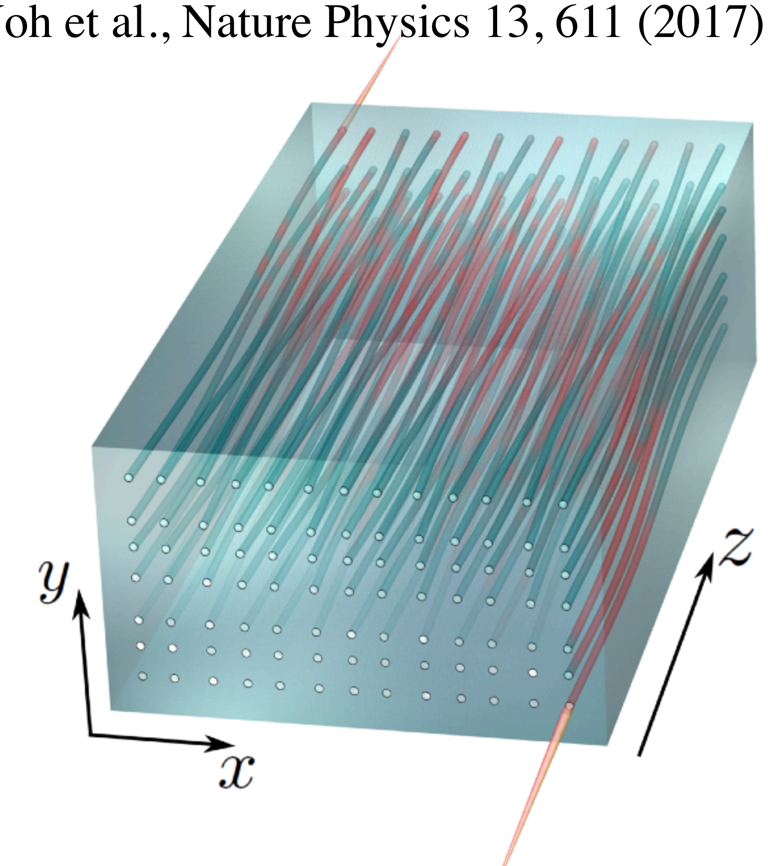
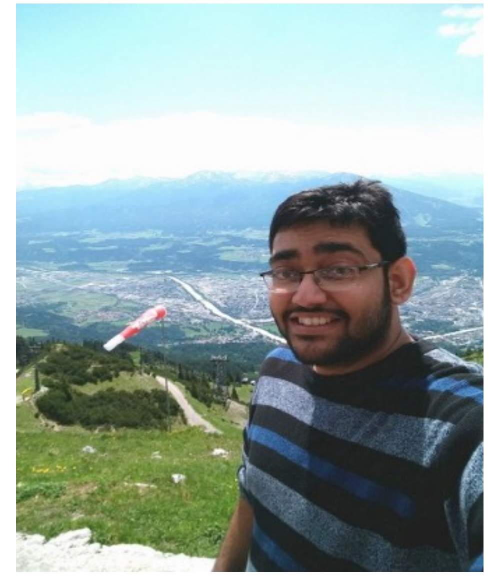


Zilberberg et al., Nature 553, 59 (2018)

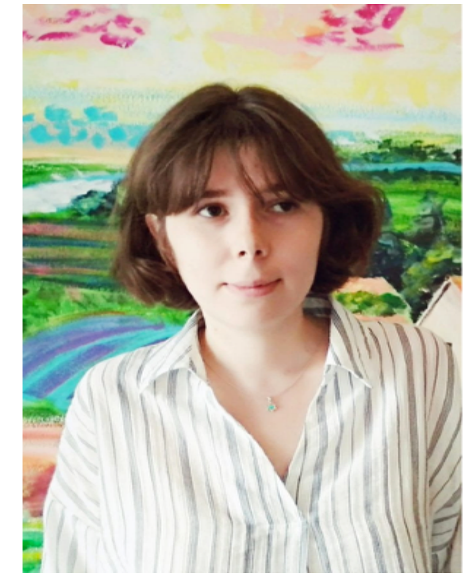
The group

Jiho Noh

Jonathan Guglielmon



Sachin Vaidya



Maria Barsukova

Dr. Alex Cerjan

Dr. Wladimir Benalcazar

Dr. Sebabrata Mukherjee

Kanchita Klangboonkrong

and Marius Juergensen (photo to come)

THE PENNSYLVANIA STATE UNIVERSITY · 1855 ·
ALFRED P. SLOAN FOUNDATION 1934
the David & Lucile Packard FOUNDATION
NSF
Office of Naval Research USN ONR Science & Technology
Charles E. Kaufman Foundation
A SUPPORTING ORGANIZATION OF THE PITTSBURGH FOUNDATION

How much nonlinearity do we have?

Pulses: $1\mu J$ over $2ps$ gives: $5 \cdot 10^5 W$ peak power

Mode area: $50\mu m^2$ Kerr coefficient, $n_2 \sim 2 \cdot 10^{-19} m^2/W$

Nonlinear index change, $\Delta n = n_2 I \sim 2 \cdot 10^{-3}$