Chiral modes in optics and electronics of 2D systems – Aussois, November 26-28, 2018

TOPOLOGICAL PHOTONICS WITH MICROWAVES

Fabrice Mortessagne

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Waves in Complex Systems team

- Flexible experimental platforms in microwaves or optics (and a hint of acoustics)
- Random Matrix Theory, effective Hamiltonian formalism, numerical simulations
- Complex geometries : multimode optical fibres, 2D or 3D microwave cavities
- (dis)ordered lattices : coupled µwave resonators, photo-induced/laser-written photonic structures
- Wave chaos – Anderson localization
- Artificial Dirac materials
- Quantum fluids of light
- Topological photonics

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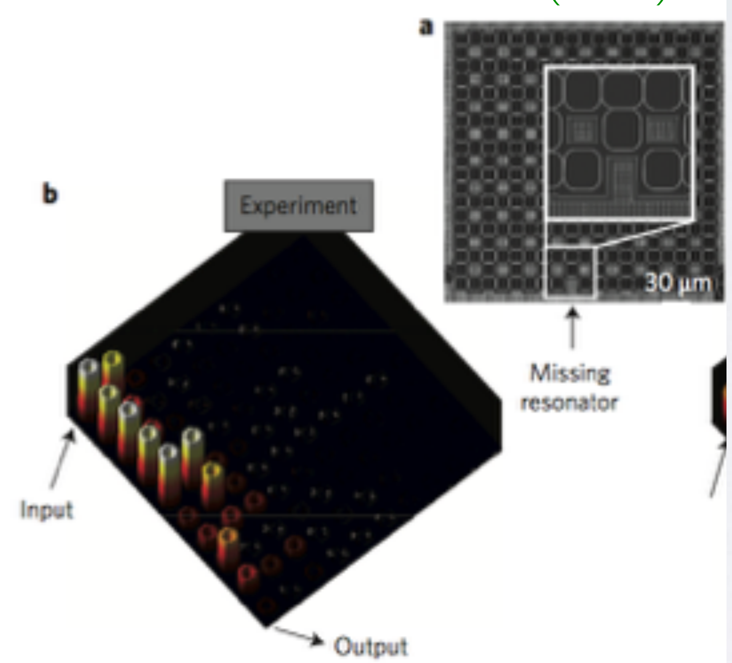
Recall Alberto 's lecture

Topological photonics

This field aims to explore the physics of topological phases of matter in a novel optical context. T. Ozawa *et al.* arXiv1802.04173

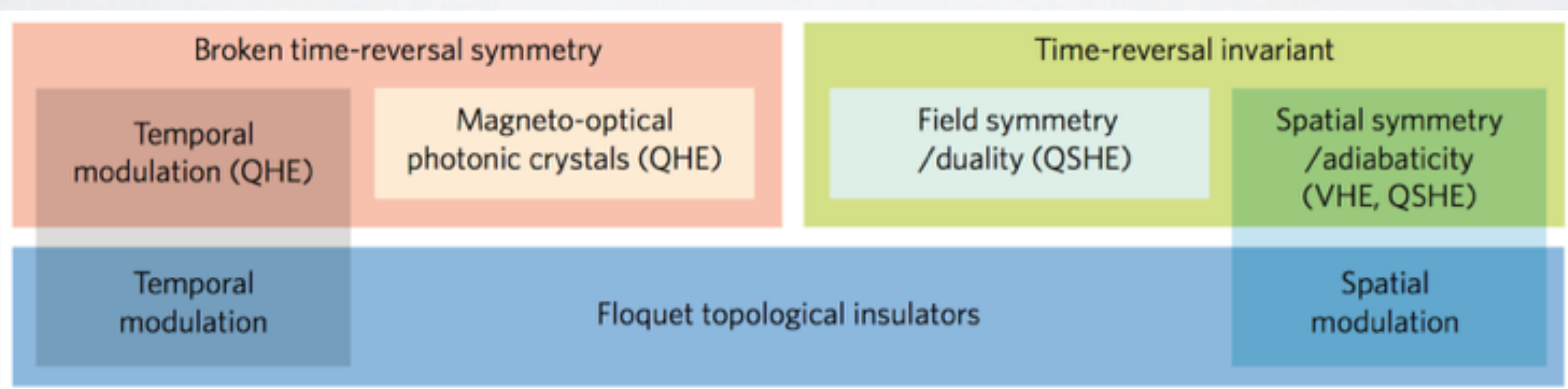
- 2008: First theoretical prediction (Haldane & Raghu)
- 2009: First experimental realization (Wang *et al.*, MIT)
- since there: Different strategies to emulate topological phases with photons

Hafezi *et al.*, Nat. Photon. 7 (2013)



Chiral edge state in a lattice of coupled ring resonators on a silicon chip.

Pseudospins given by clockwise and anticlockwise modes.



Recall yesterday's talks

Khanikaev & Shvets, Nat. Photon. 11, 763 (2017)

Outline

1. Microwave realization of tight-binding model

   dielectric resonators, TE mode, evanescent coupling, LDOS & eigenstates

2. SSH chain: Control of topological interface states

   zero-mode, selective enhancement, non-linear absorption, reflective limiter

3. 2D lattices : Lieb (and Penrose)

   partial symmetry breaking, (not so) flat band, zero-mode, gap labeling (naive picture)

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Experimental setup

- Vectorial Network Analyzer (@ 6~7 GHz): complex scattering matrix;
- dielectric resonators sandwiched between metallic plates;
- ‘kink’ and ‘loop’ antennas excite TE polarization:

$$\psi(\vec{r}) = B_z(\vec{r})$$

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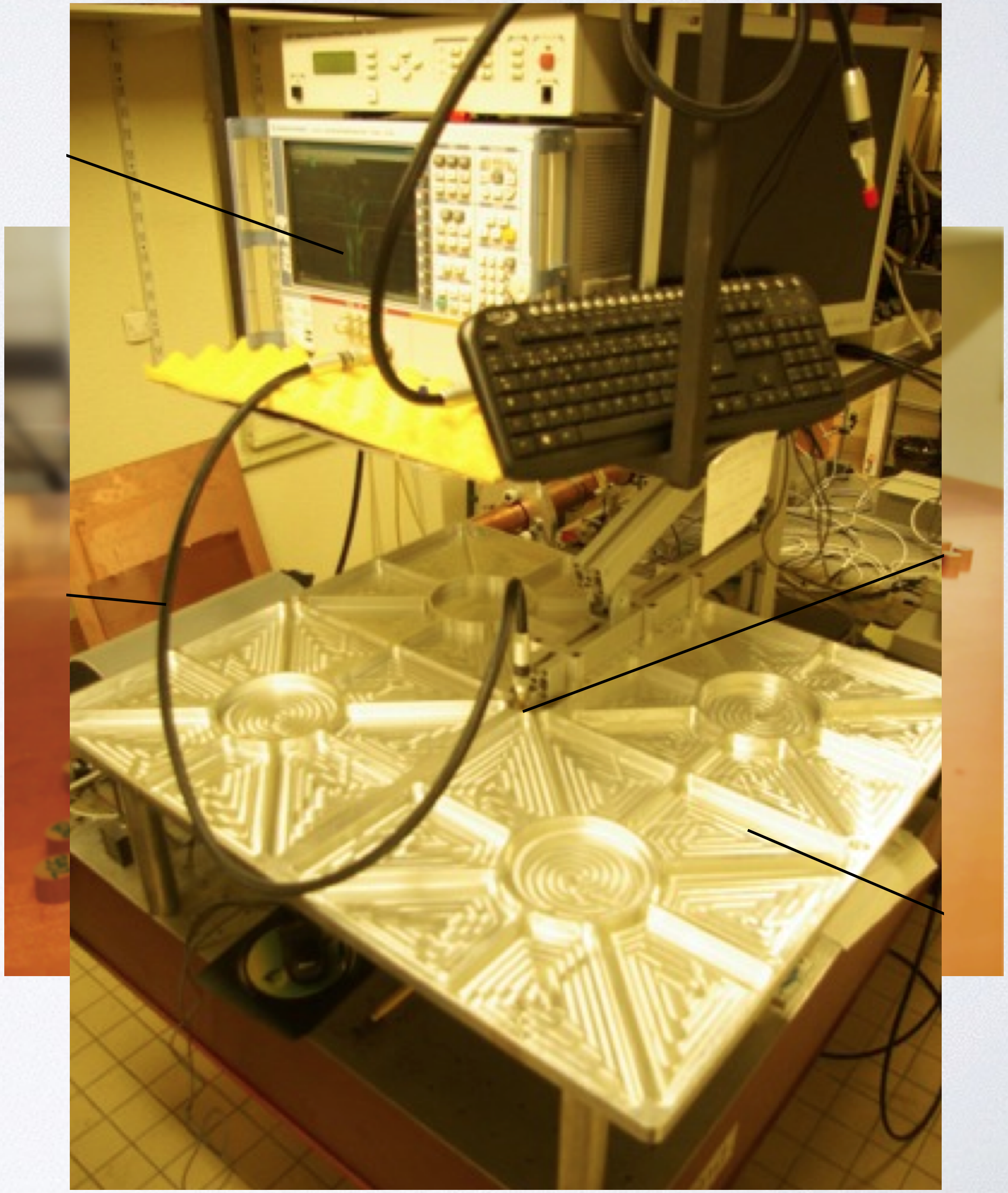

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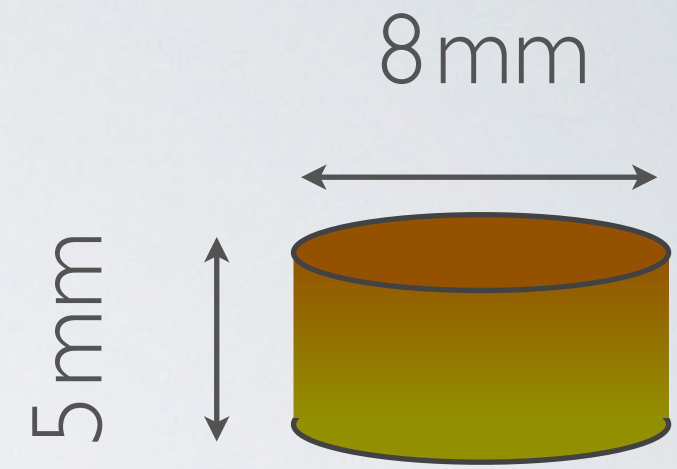
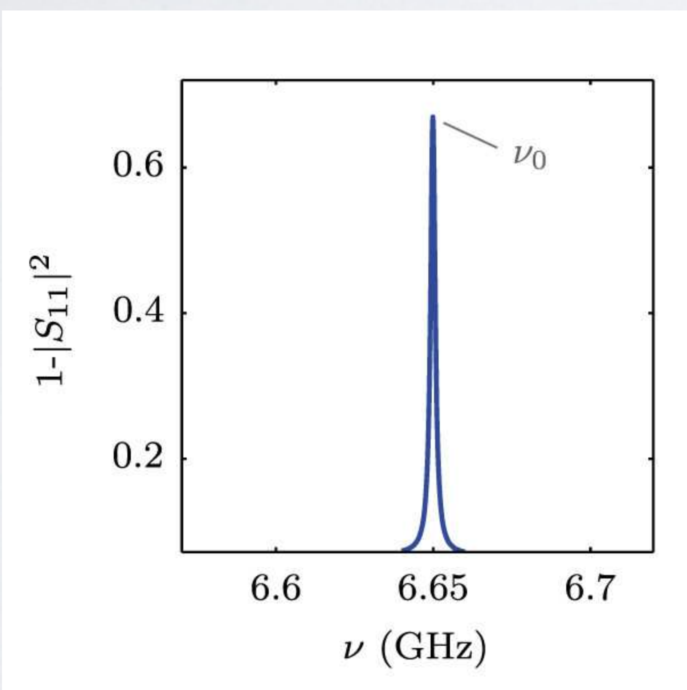
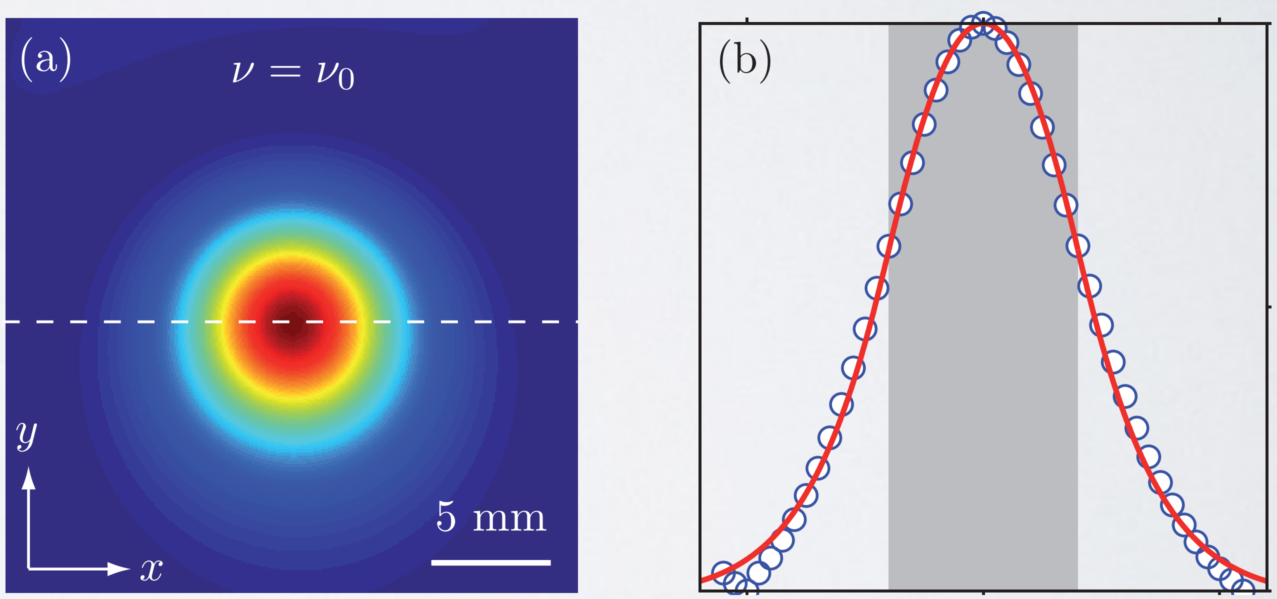
Microwave resonator

Dielectric ceramic (ZrSnTiO):

- high permittivity: $\varepsilon = 37$
- low loss: $Q \simeq 7000$







- TE$_1$ Mie resonance @ 6.65 GHz

- Energy essentially inside
- Evanescent field outside

Microwave resonator

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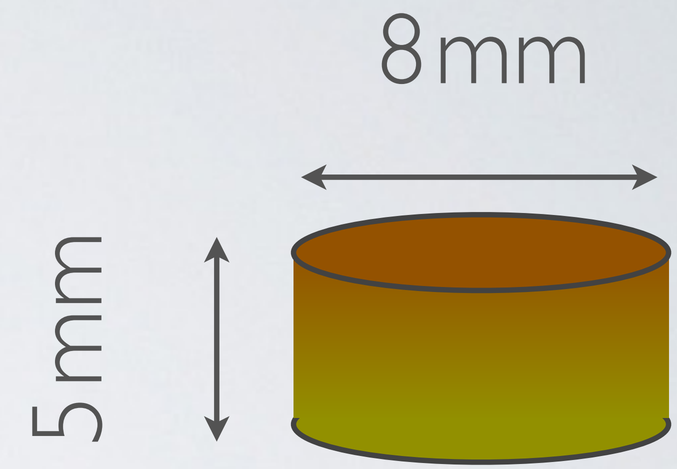

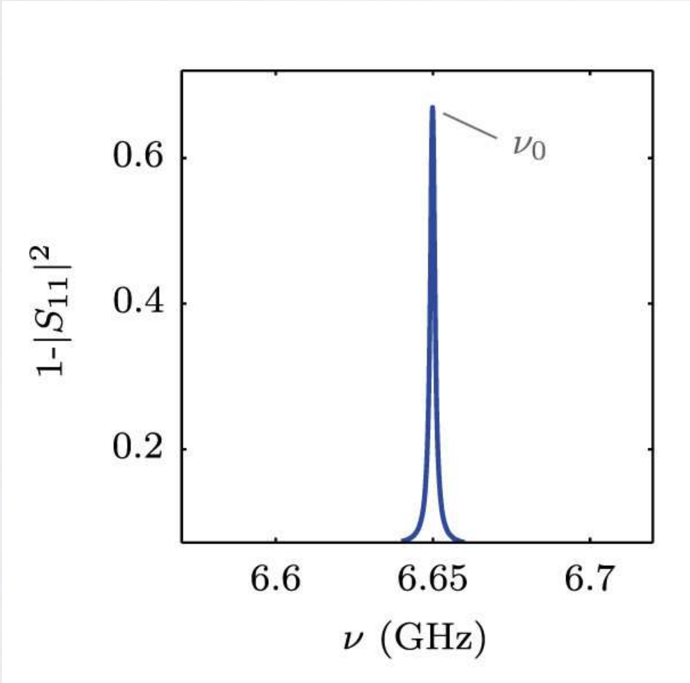

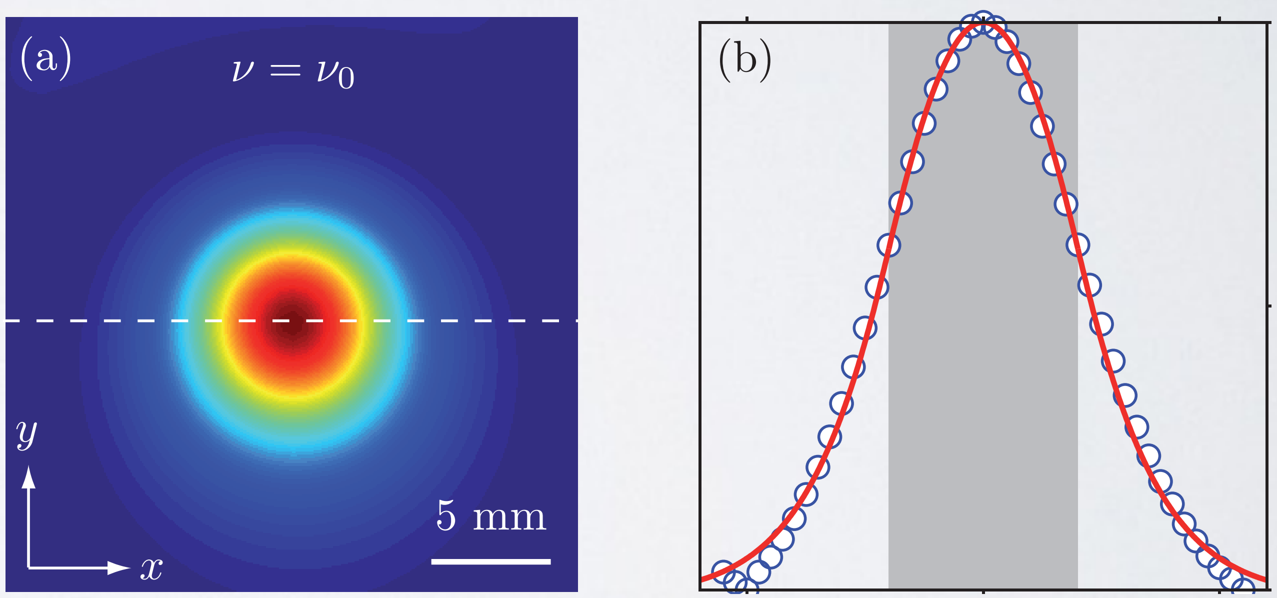

- TE₁ Mie resonance @ 6.65 GHz

$$B_z(\vec{r}, z) = B_0 \sin\left(\frac{\pi}{h} z\right) \times \begin{cases} J_0(\gamma_j \vec{r}) \\ \alpha K_0(\gamma_k \vec{r}) \end{cases}$$

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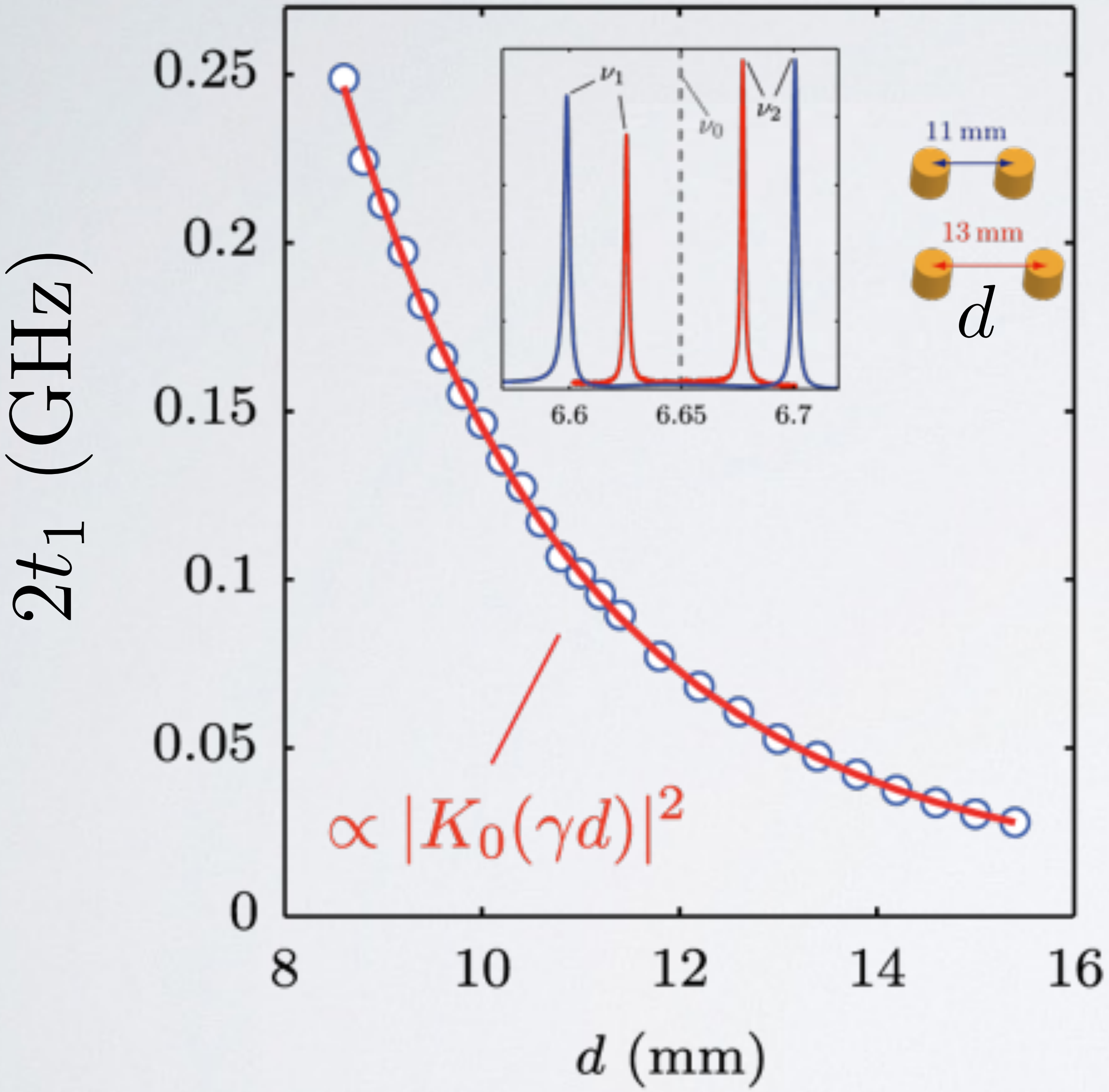
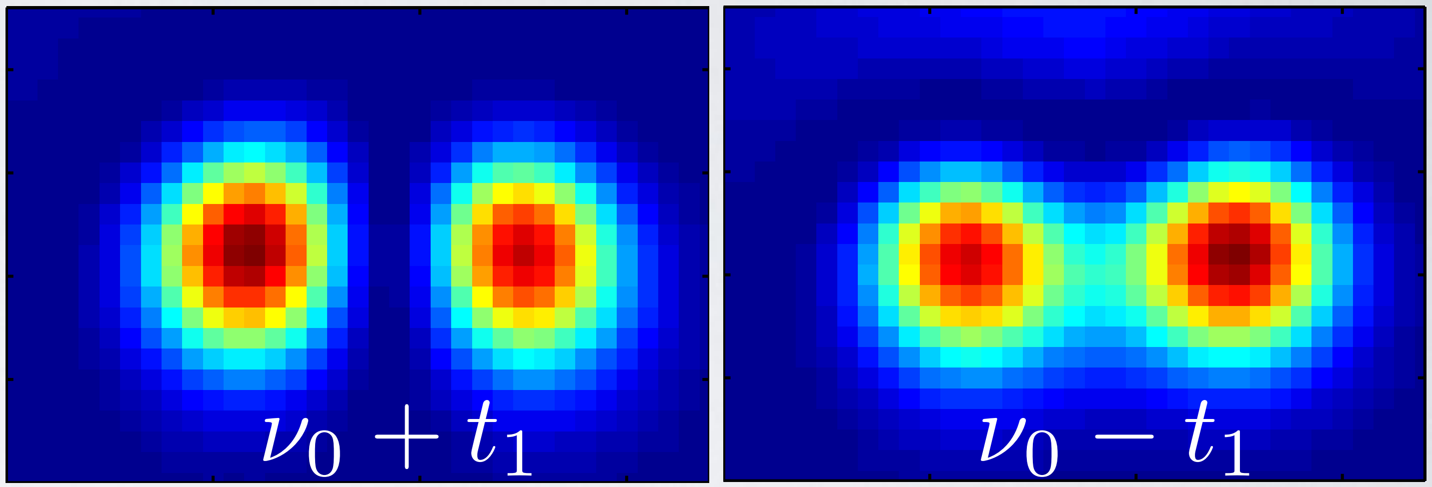
Tight-binding coupling





$$H(d) = \begin{pmatrix} \nu_0 & -t_1(d) \\ -t_1(d) & \nu_0 \end{pmatrix}$$

$$t_1(d) \propto -|K_0(d/2\ell)|^2$$

$$\ell \simeq 3\,\mathrm{mm}$$

Buildings blocks of artificial molecules, (quasi-)crystals, disordered lattices… (well controlled metamaterials)

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LDoS & eigenstates

A direct access to the density of states and intensity of the eigenstates through:

$$g(\mathbf{r}_1, \nu) = |S_{11}(\nu)|^2 \varphi'_{11}(\nu)$$

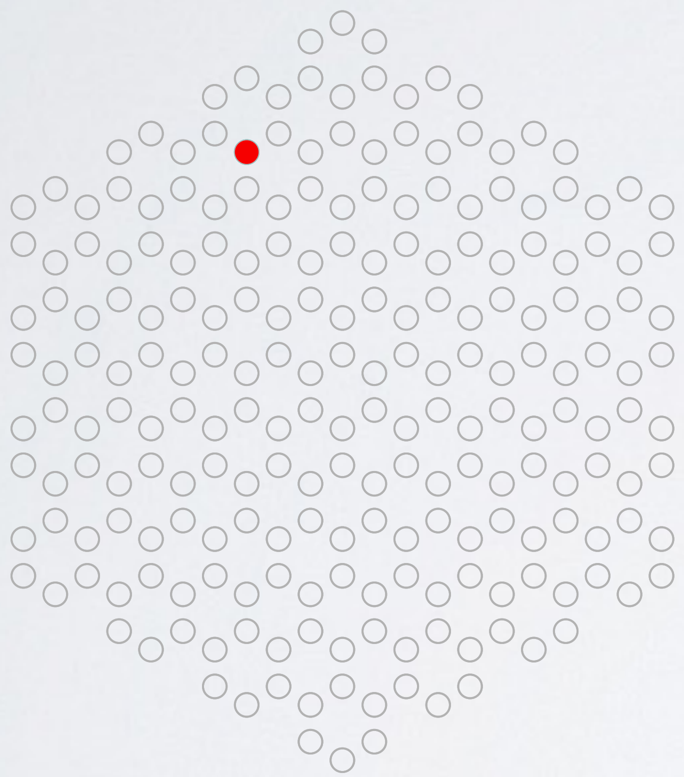
$$\arg\left[S_{11}(\nu)\right] = \varphi_{11}(\nu)$$

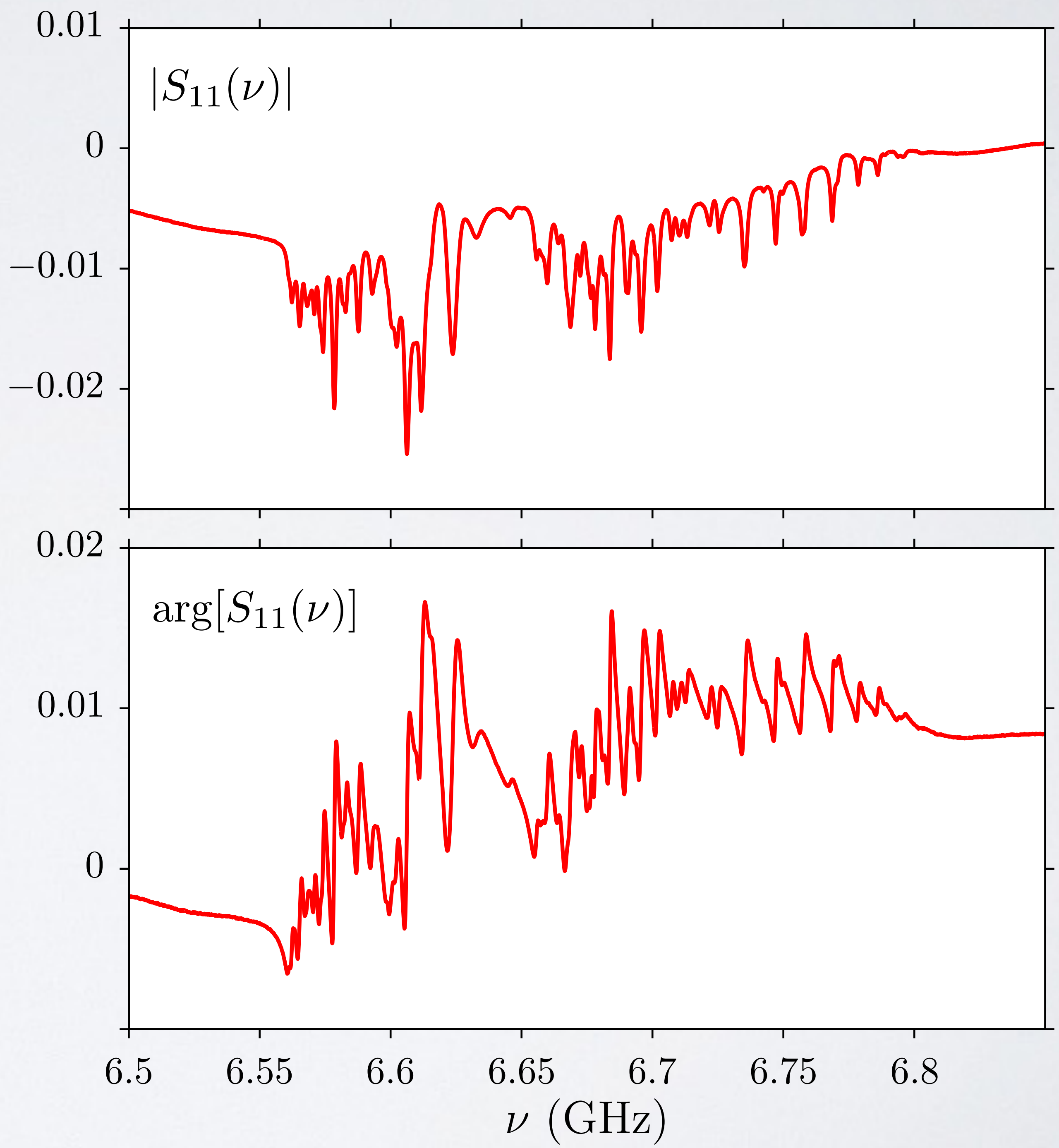
$$g(\mathbf{r}_1, \nu) \simeq \frac{\sigma}{\Gamma} \sum_n |\Psi_n(\mathbf{r}_1)|^2 \delta(\nu - \nu_n)$$

Local Density of States, DoS by averaging

for a given eigenfrequency: measure the local intensity

(Local) Density of States





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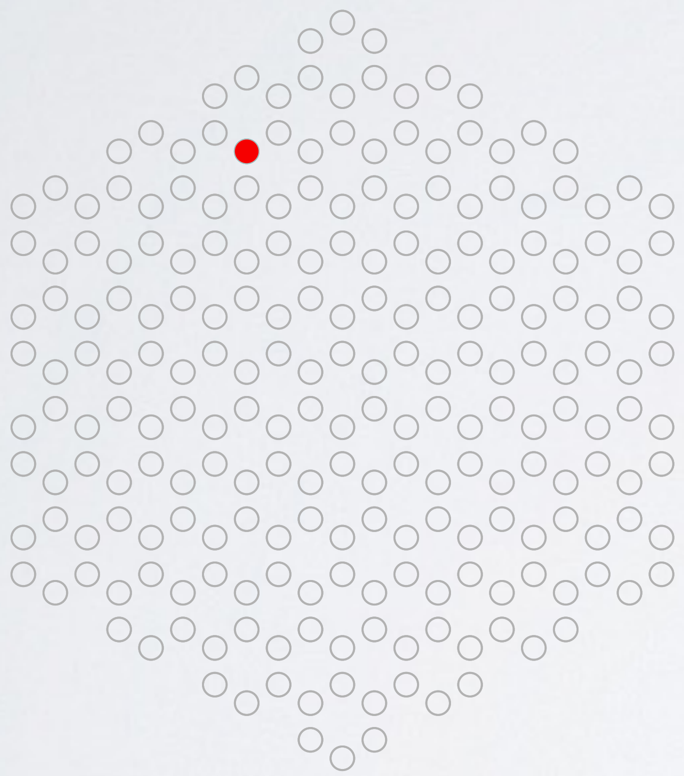

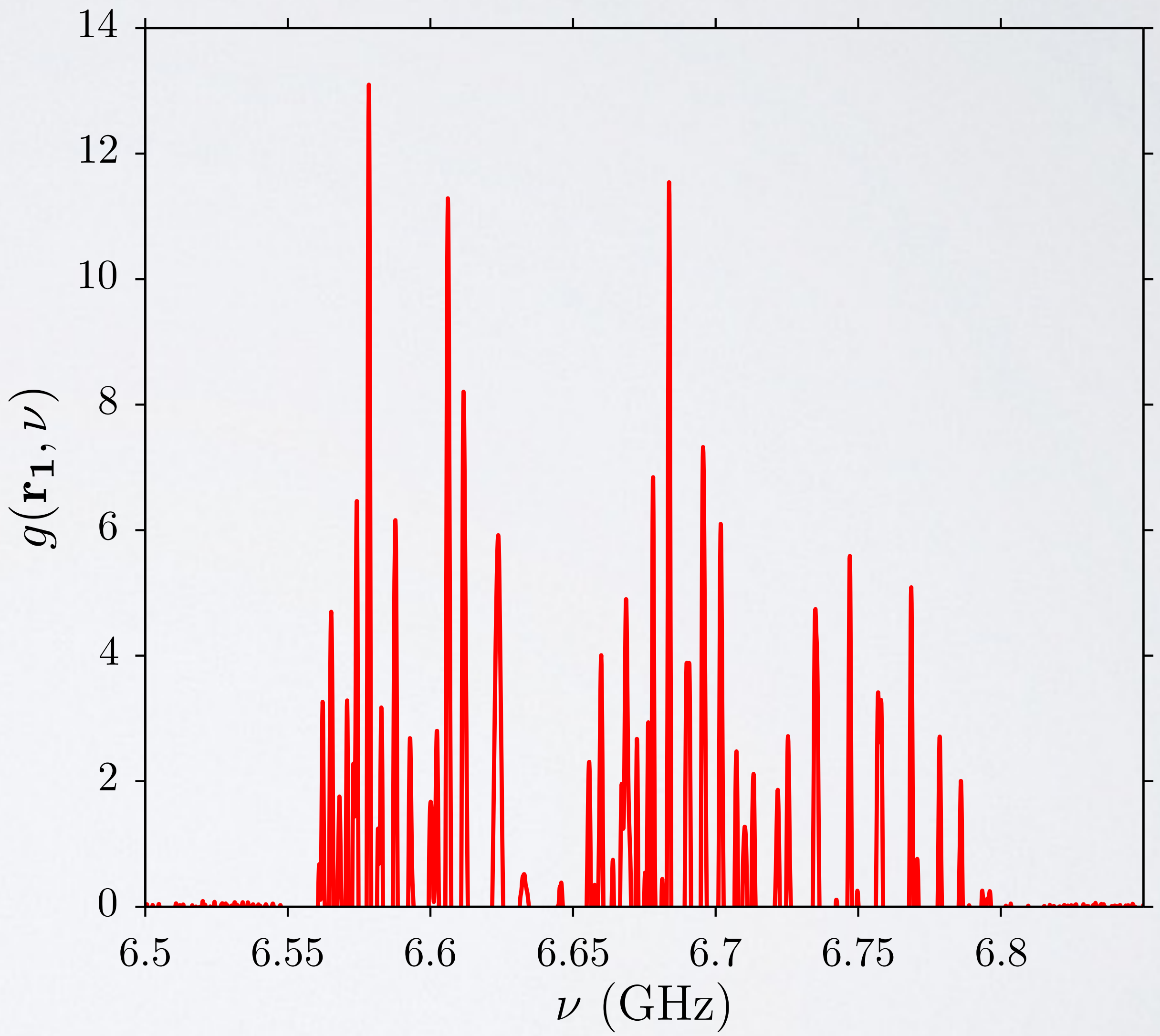

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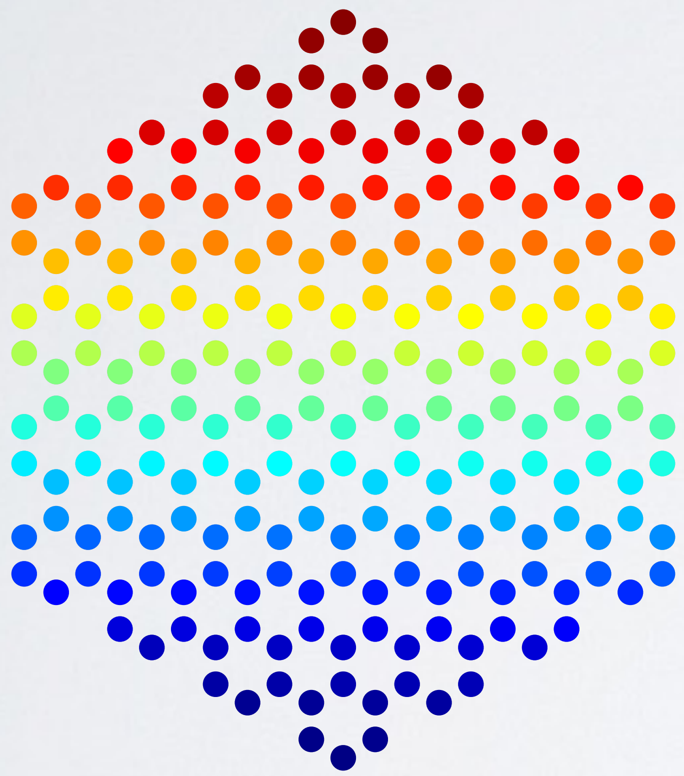

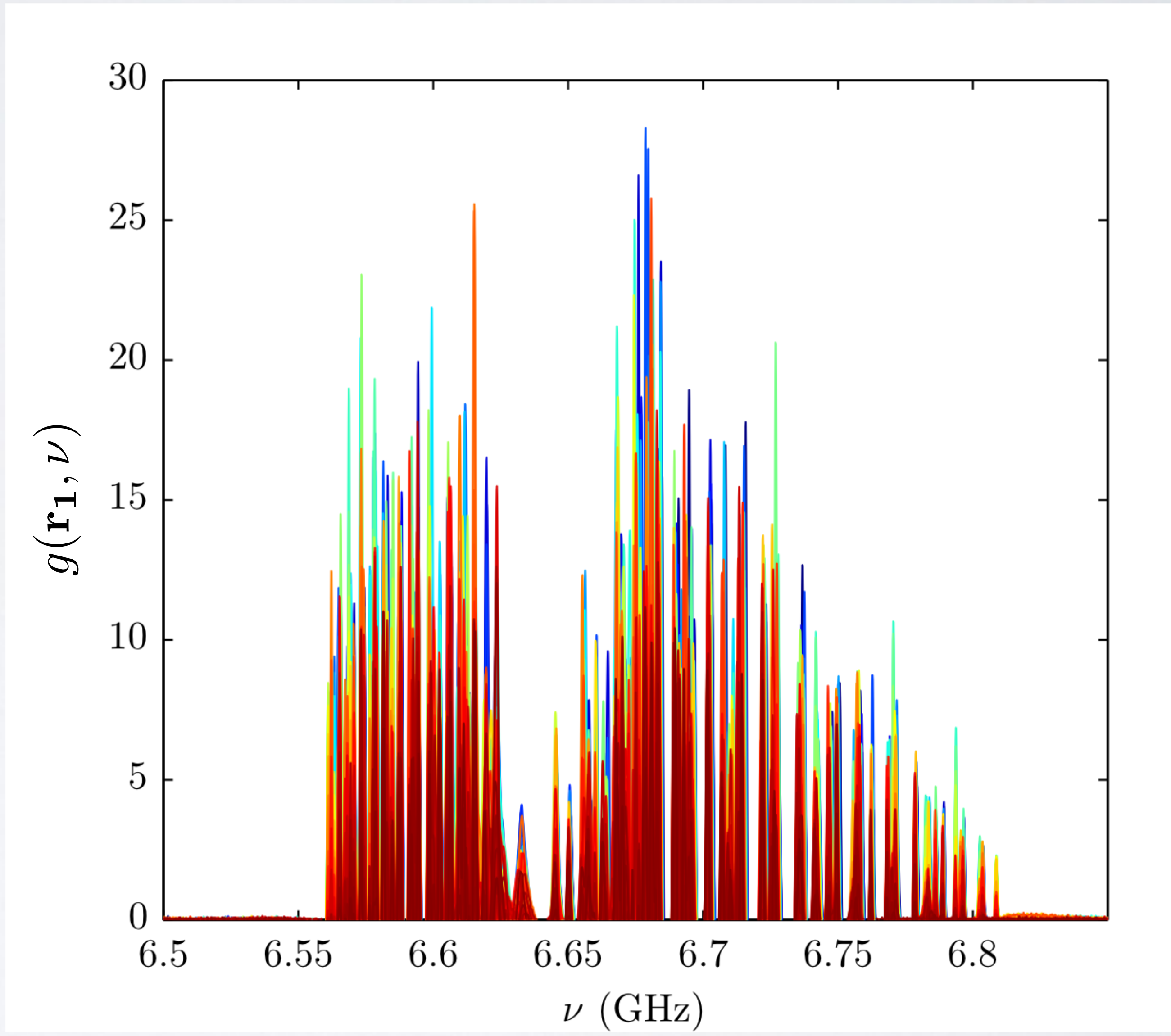

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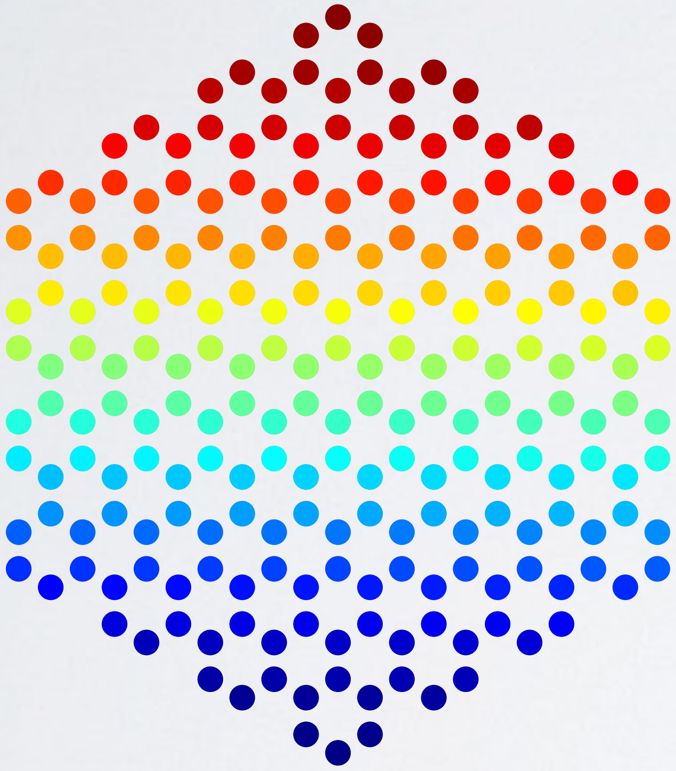

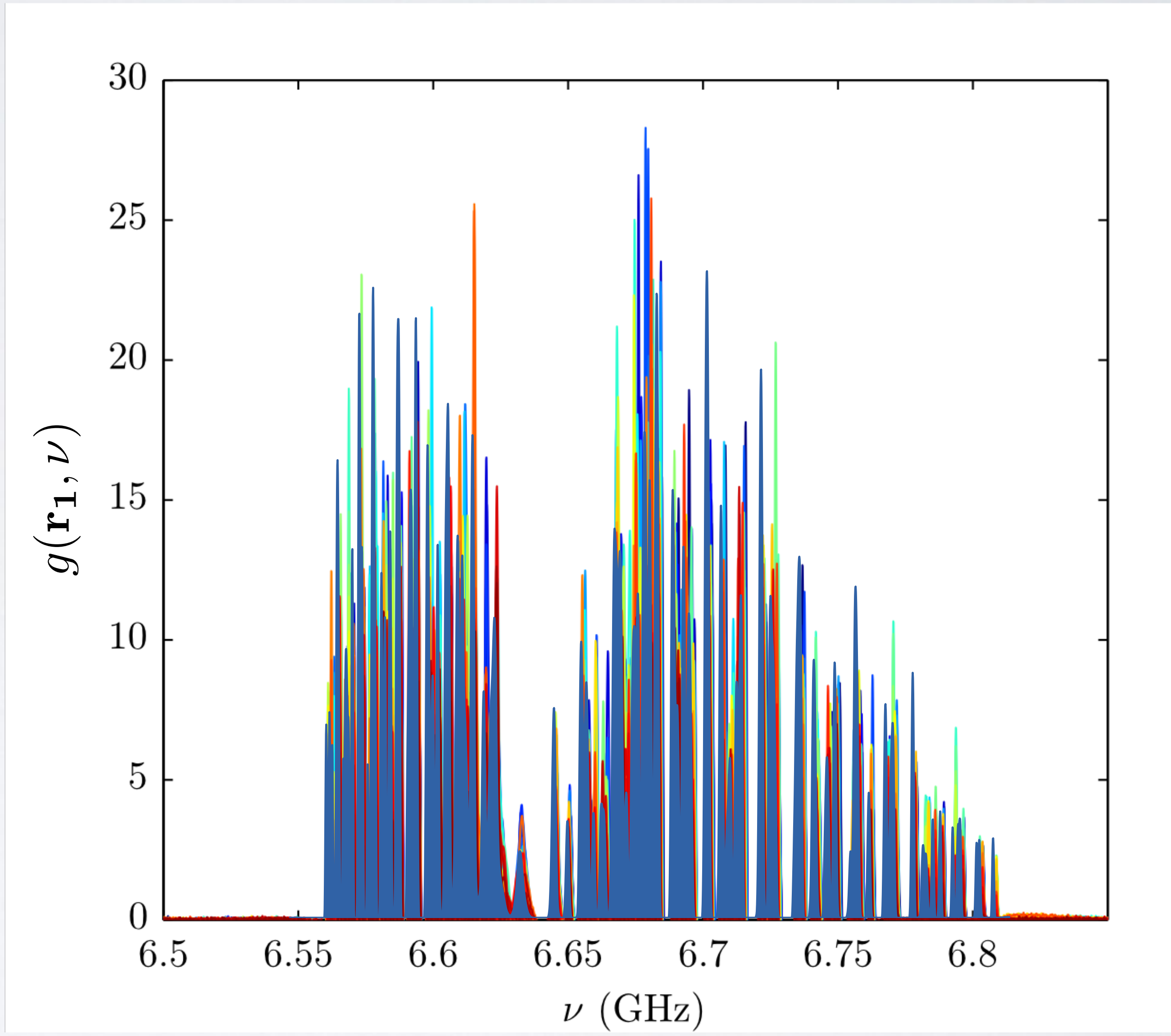

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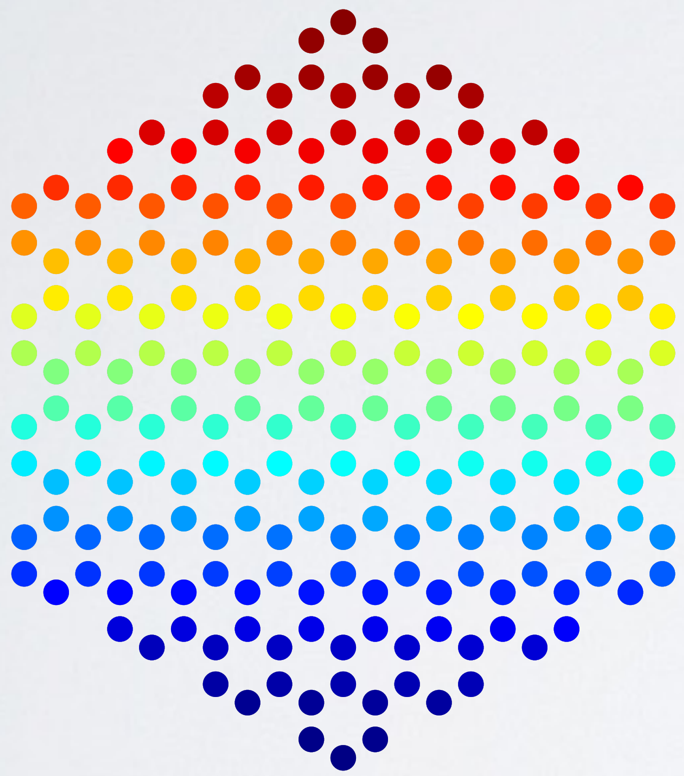
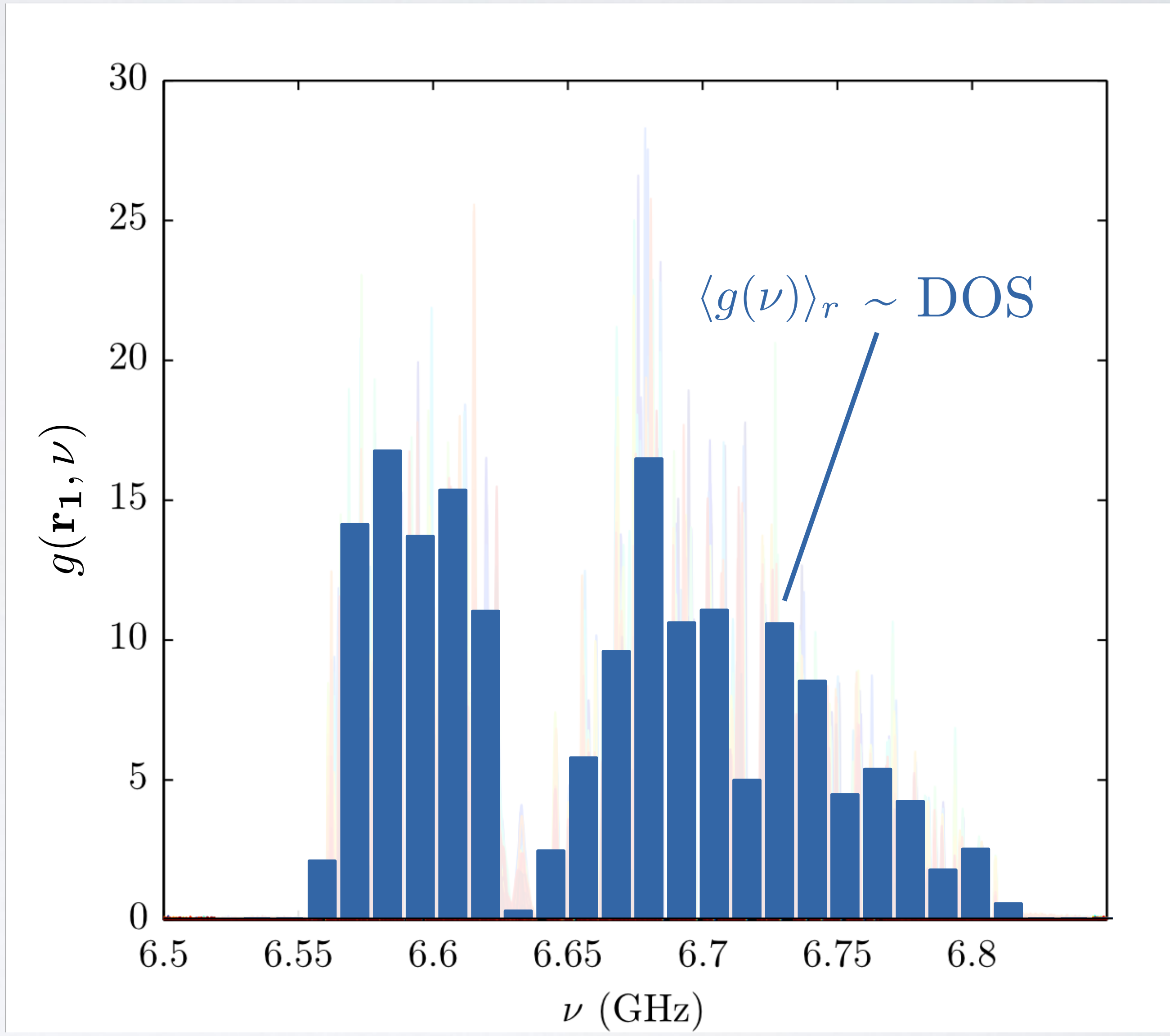
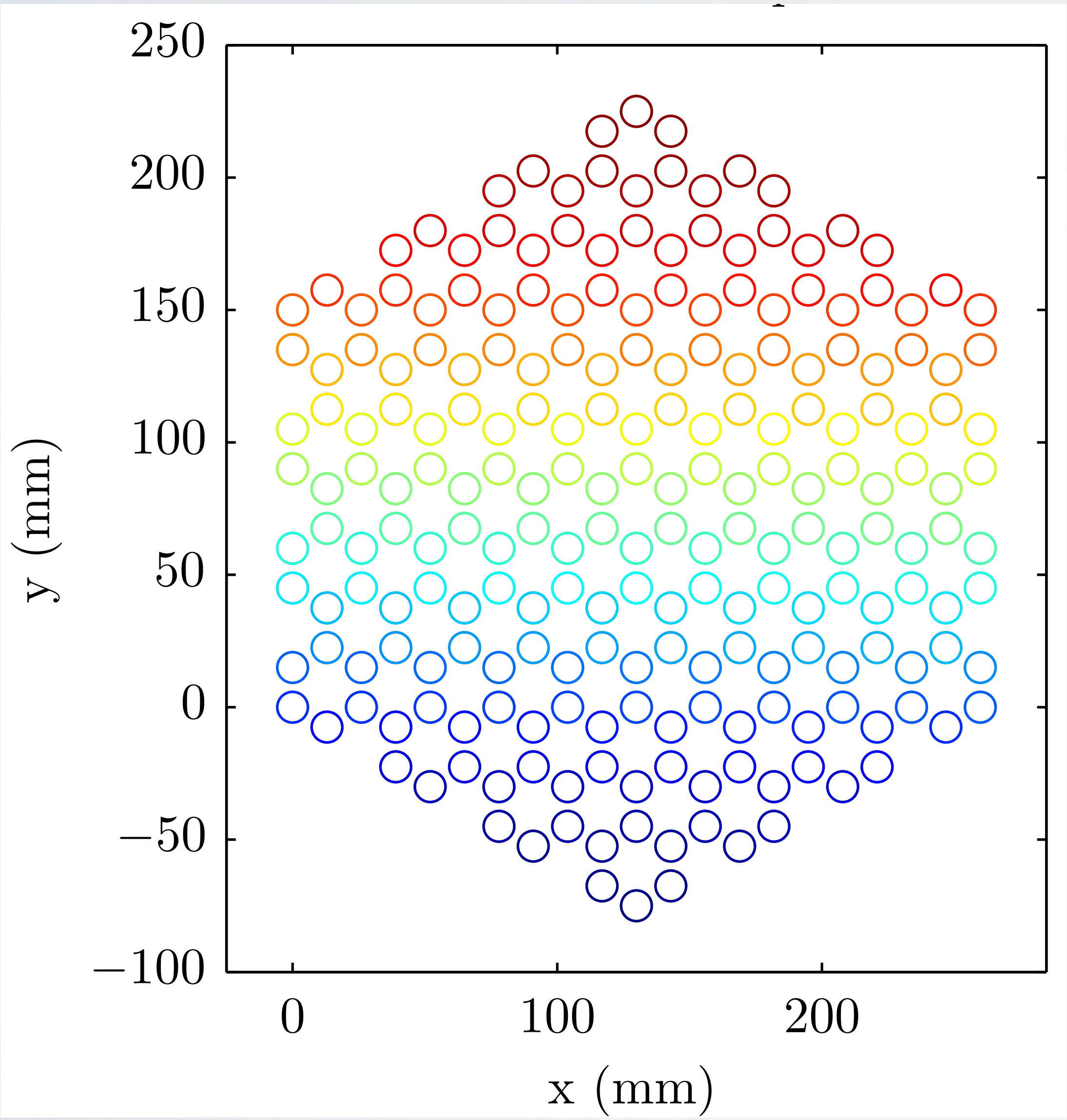
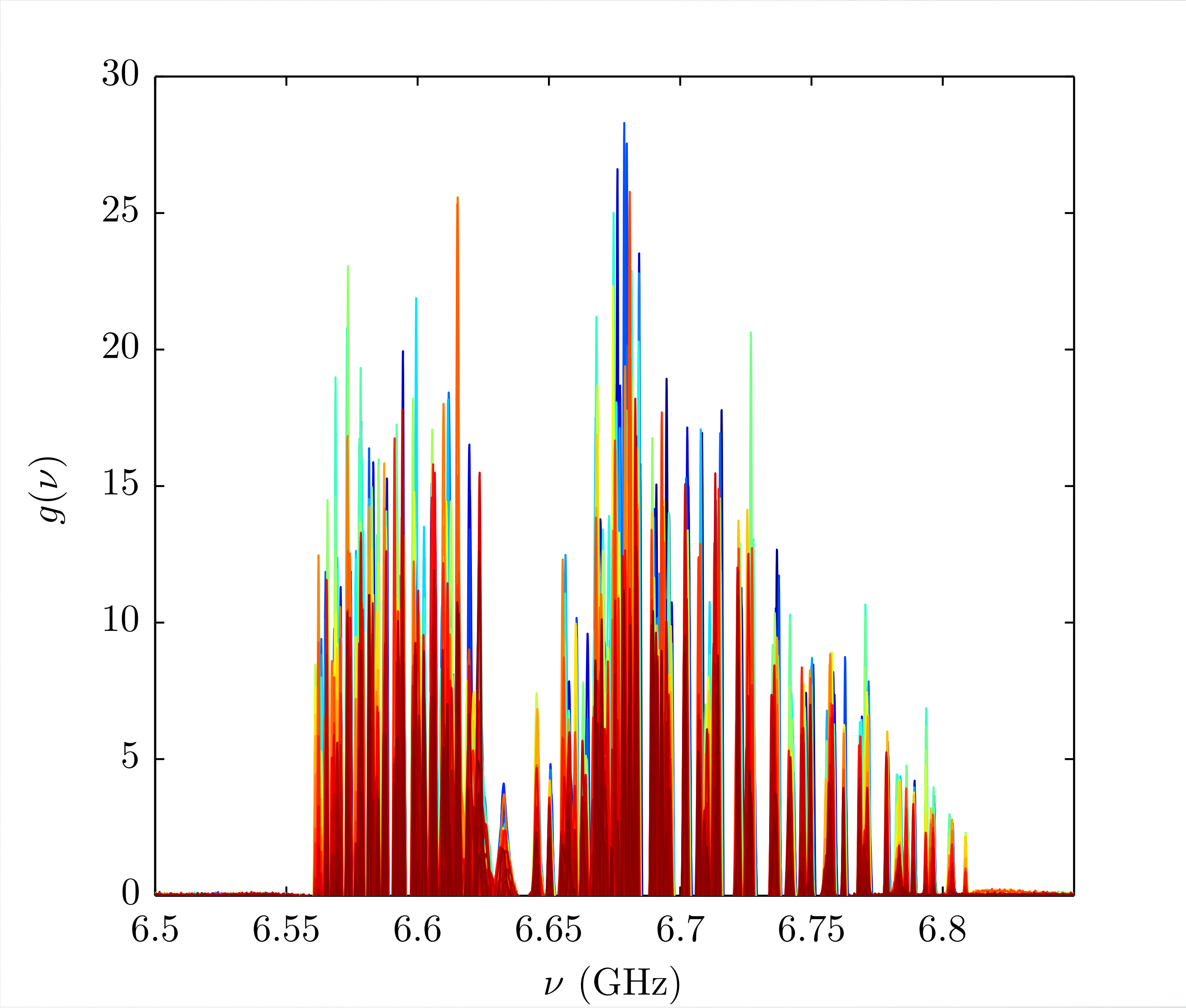




Eigenstates





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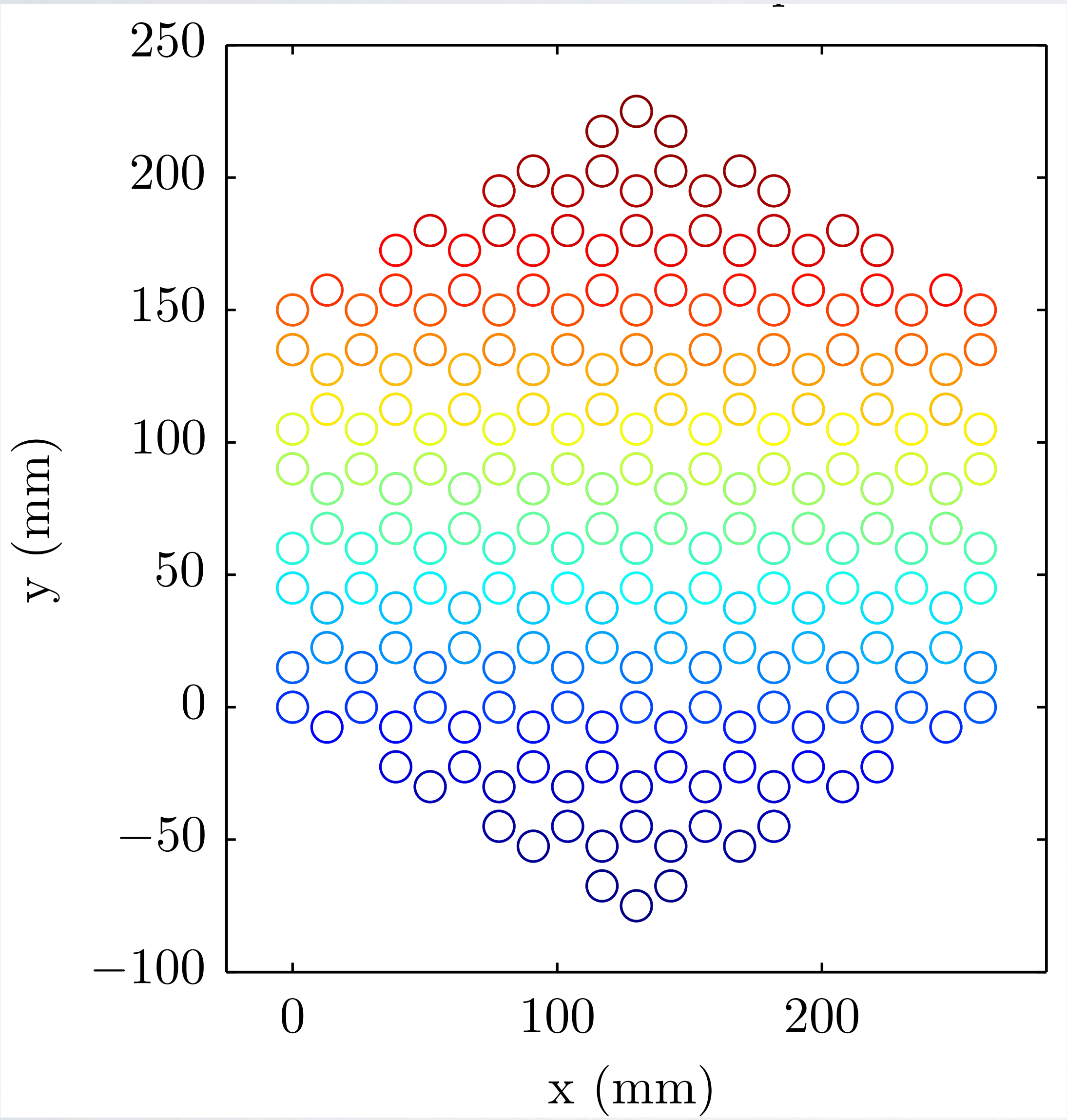

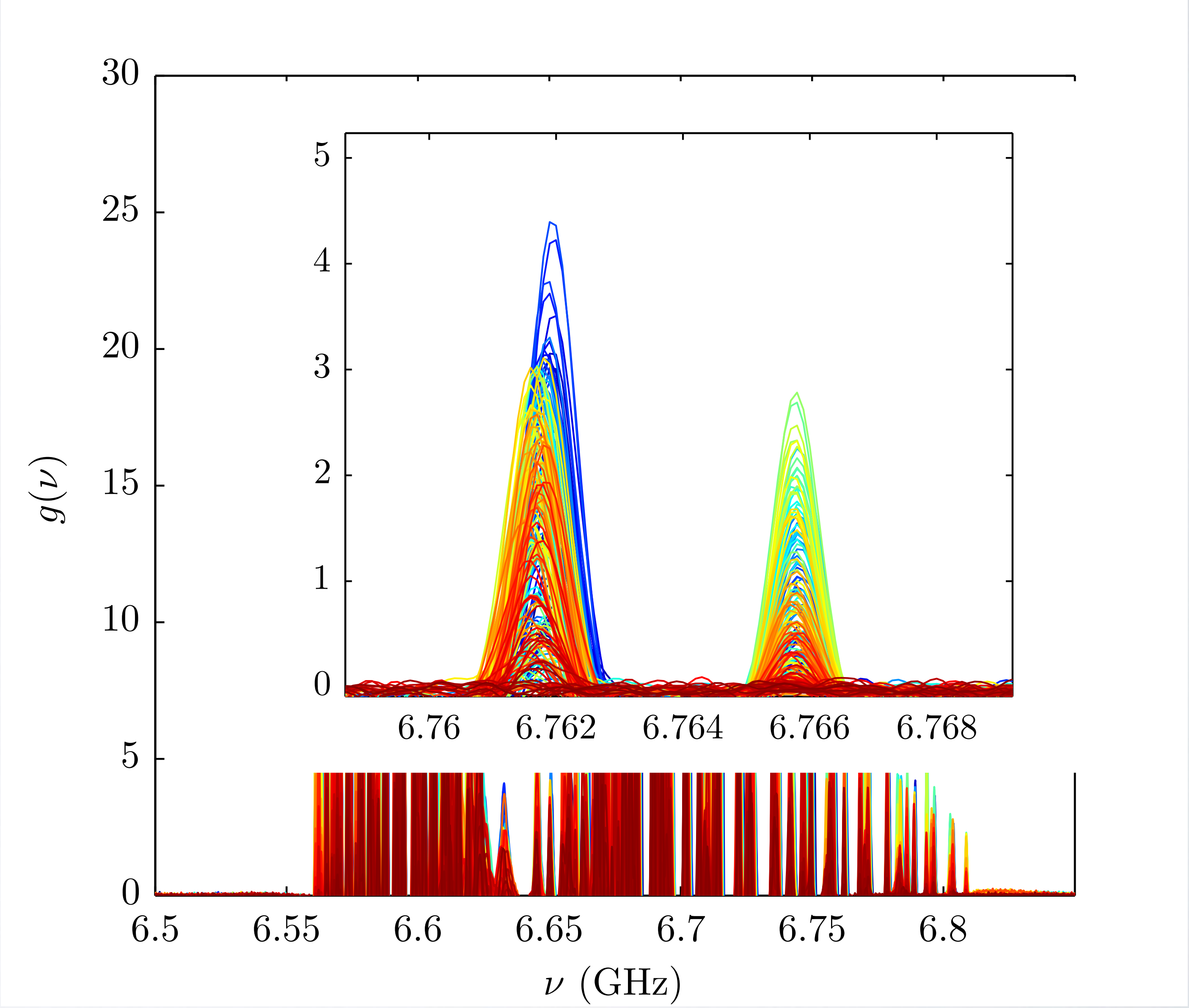

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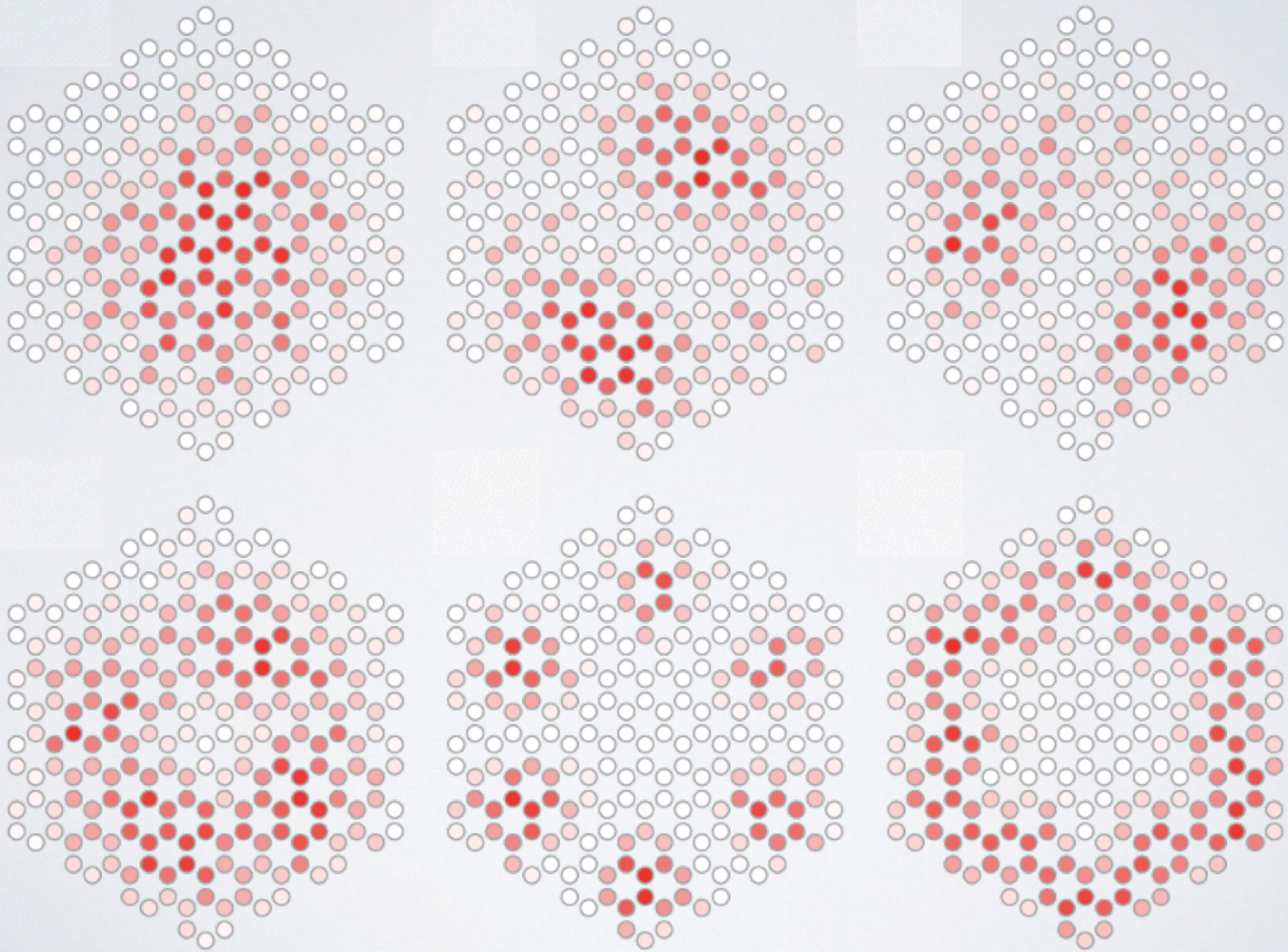

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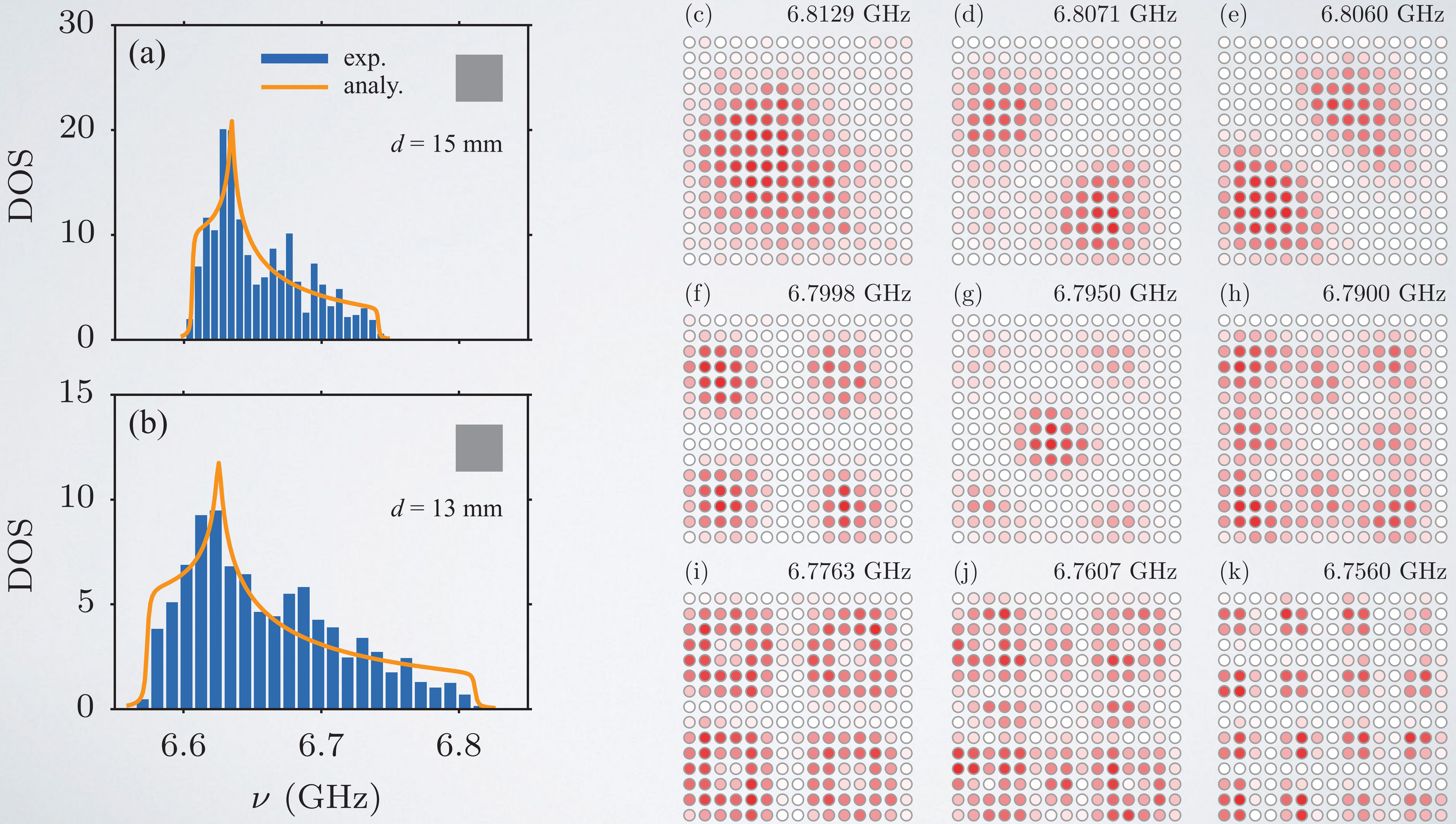
PRB **88**, 115437 (2013)

A flexible and versatile experimental platform



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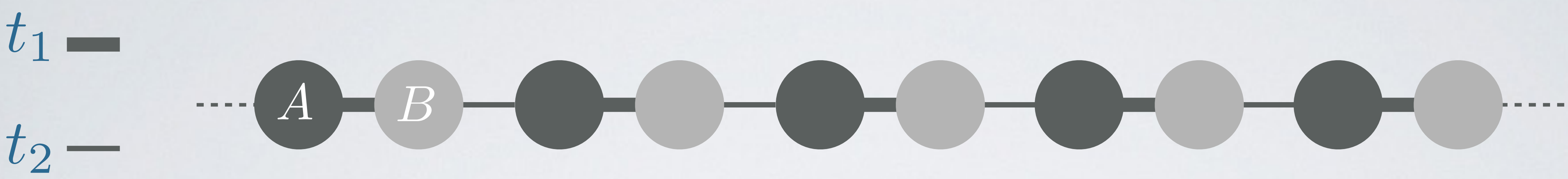
Recall Alberto 's lecture

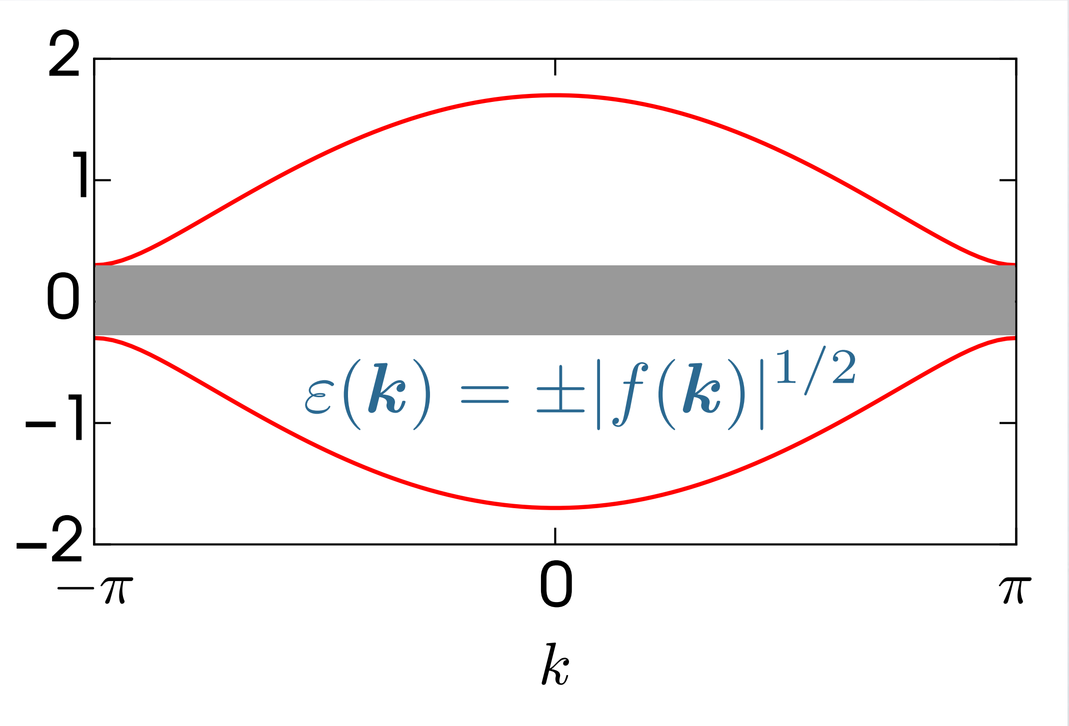
The simplest topological system



Bloch Hamiltonian: $\mathcal{H}_{\boldsymbol{k}} = \begin{pmatrix} 0 & f^*(\boldsymbol{k}) \\ f(\boldsymbol{k}) & 0 \end{pmatrix}$

Eigenstates: $\psi^{\pm}_{\boldsymbol{k}}(\boldsymbol{r}) = \frac{1}{\sqrt{2}} \begin{pmatrix} \pm 1 \\ e^{i\phi_{\boldsymbol{k}}} \end{pmatrix} e^{i\boldsymbol{k}\cdot\boldsymbol{r}}$

Topological quantity: $\phi_{\boldsymbol{k}} = \arg[f(\boldsymbol{k})]$



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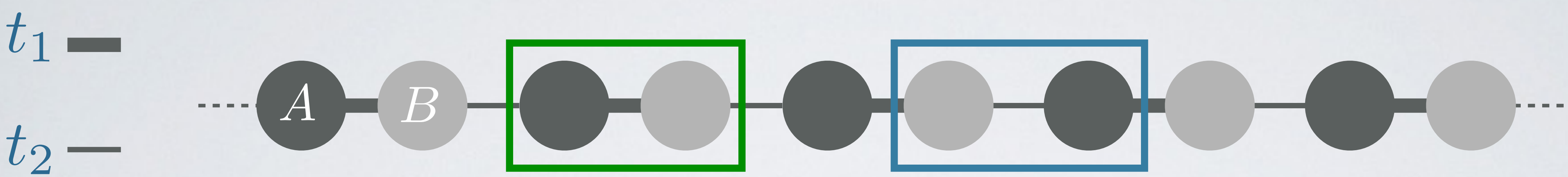

$f_\alpha(\boldsymbol{k}) = t_1 + t_2 e^{i\boldsymbol{k}}$

$f_\beta(\boldsymbol{k}) = t_2 + t_1 e^{i\boldsymbol{k}}$

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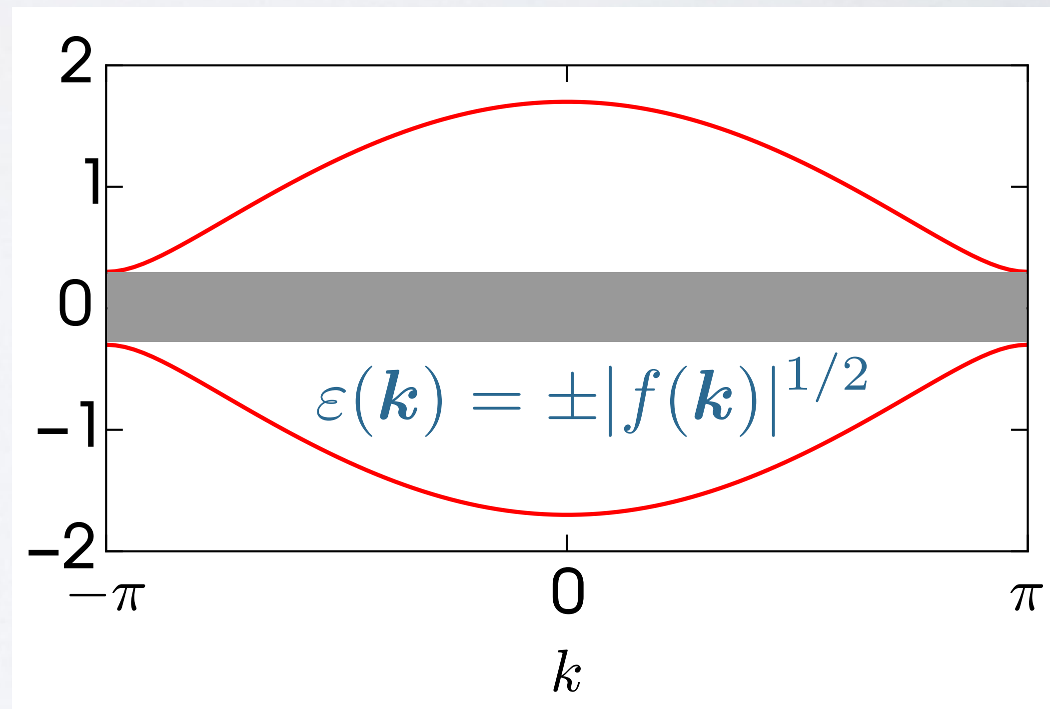

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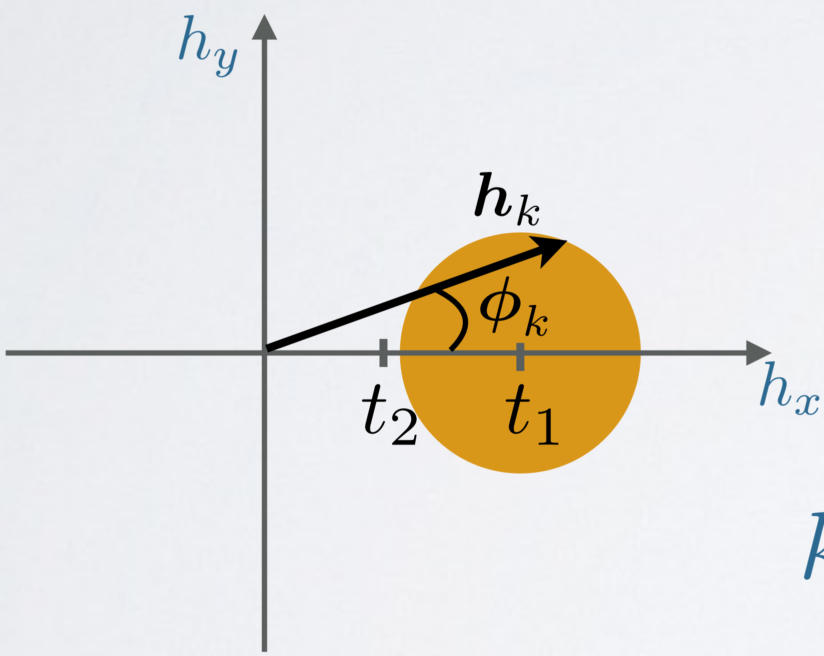
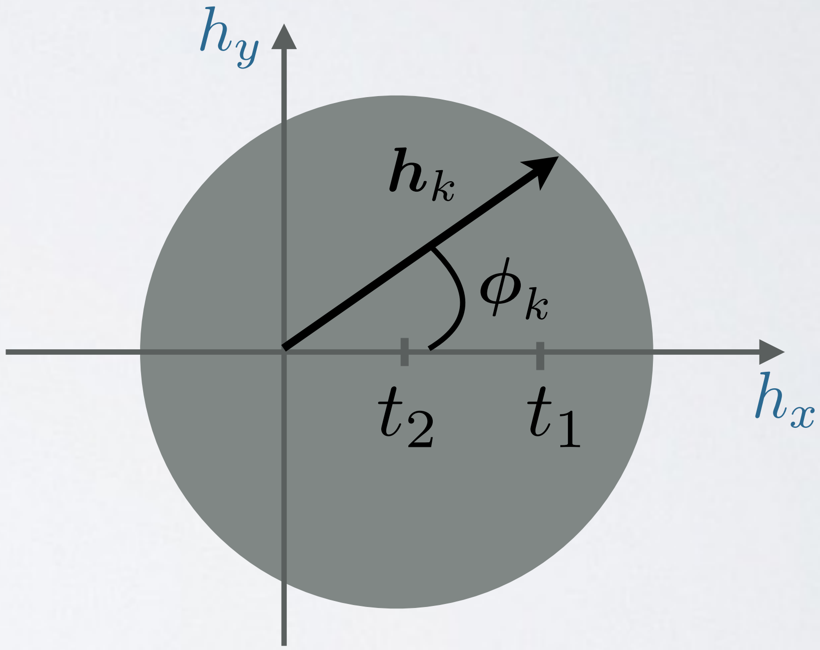
Two topological phases

$$\mathcal{H}_{\alpha,\beta;\boldsymbol{k}} = \boldsymbol{h}_{\alpha,\beta}\cdot\boldsymbol{\sigma} \quad \text{with} \quad \boldsymbol{h}_\alpha = \begin{pmatrix} t_1 + t_2\cos(k) \\ t_2\sin(k) \\ 0 \end{pmatrix} \quad \boldsymbol{h}_\beta = \begin{pmatrix} t_2 + t_1\cos(k) \\ t_1\sin(k) \\ 0 \end{pmatrix}$$

$(\alpha) : (h_x - t_1)^2 + h_y^2 = t_2^2$



$(\beta) : (h_x - t_2)^2 + h_y^2 = t_1^2$



$k \in [-\pi, \pi]$

winding number = 0, $\mathcal{Z} = 0$

winding number = 1, $\mathcal{Z} = \pi$

Zak phase corresponds to the Berry phase accumulated by the wave-function along a path exploring the Brillouin zone.

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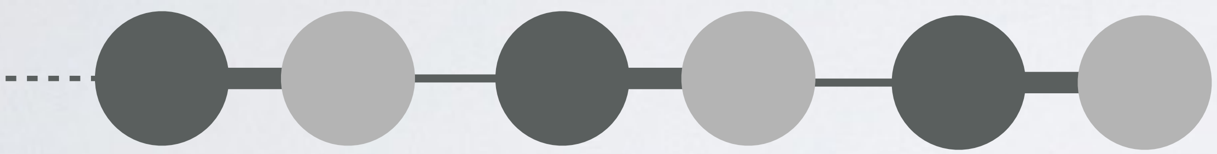
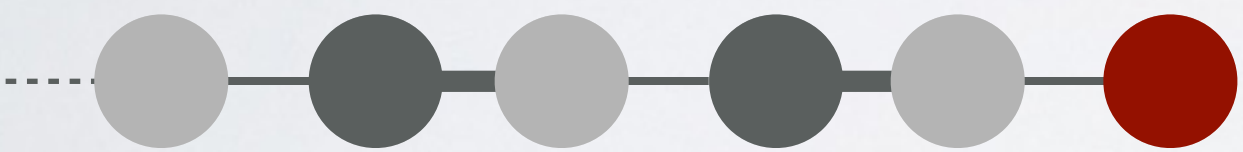
Recall Pascal's lecture

Topological interface state

In a semi-infinite system, the existence of **edge states** is determined by the topological property of the **bulk wavefunction**:



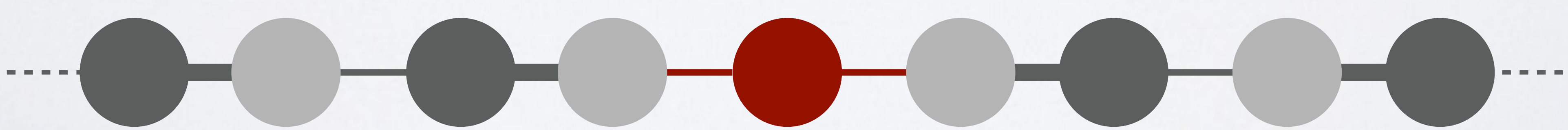
$\mathcal{Z}_\alpha = 0 \Rightarrow$ no edge state



$\mathcal{Z}_\beta = \pi \Rightarrow$ edge state

Interface between 2 distinct topological phases:

$\mathcal{Z}_\alpha = 0$ $\qquad$ $\mathcal{Z}_\beta = \pi$



mid-gap topological interface state (zero-mode)

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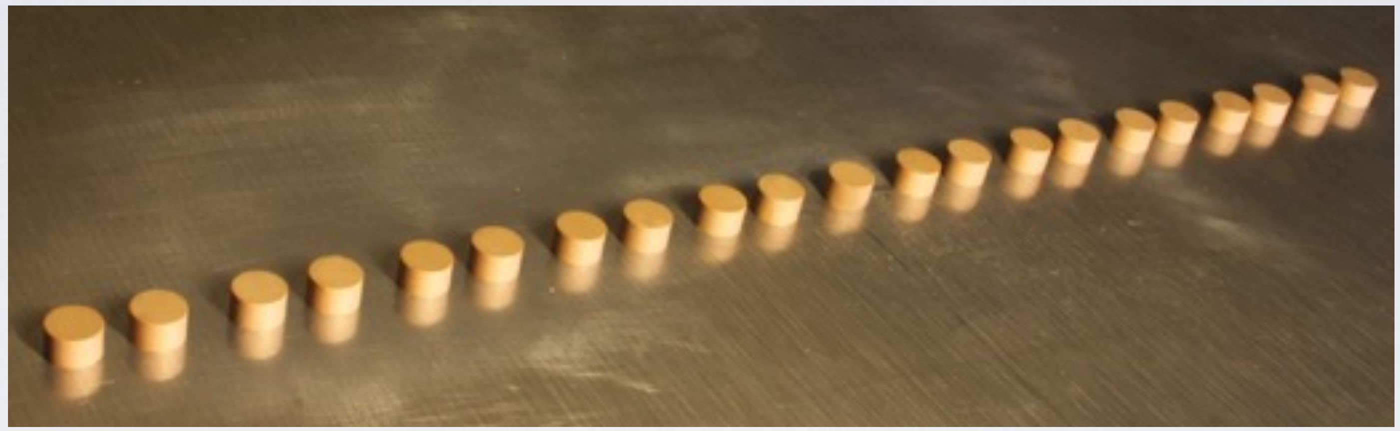
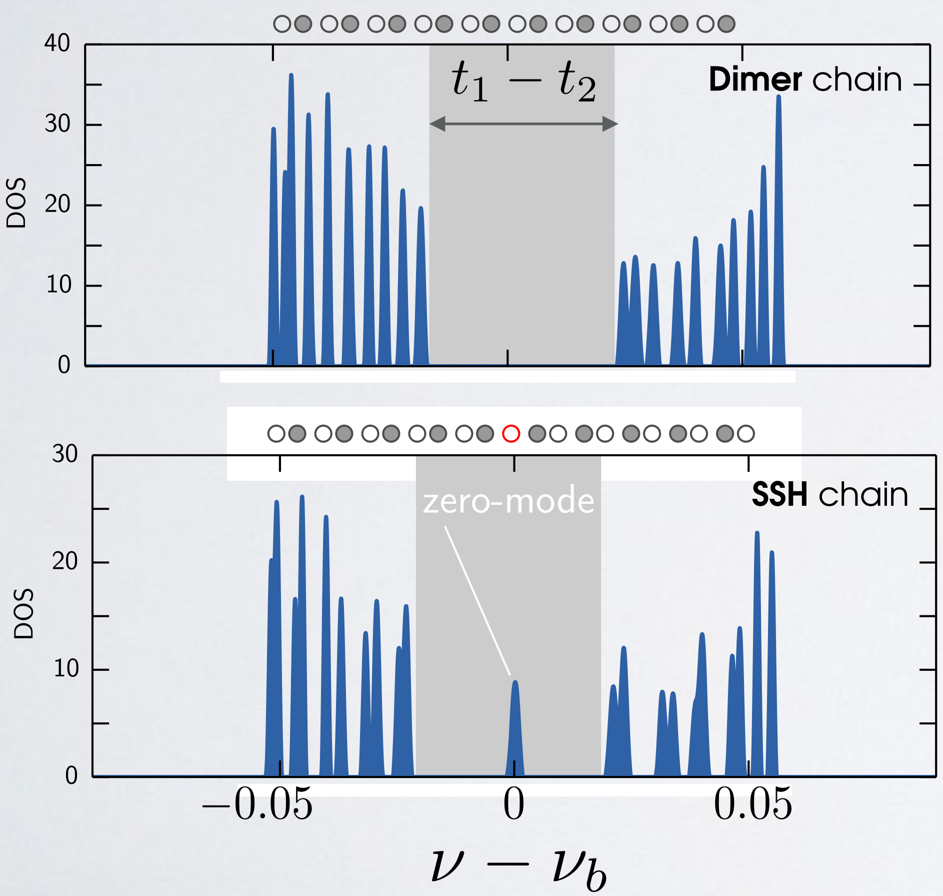
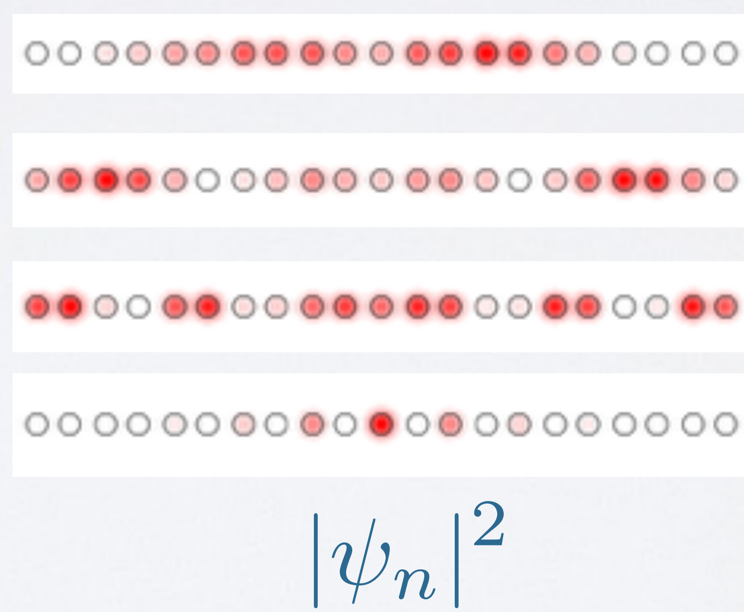
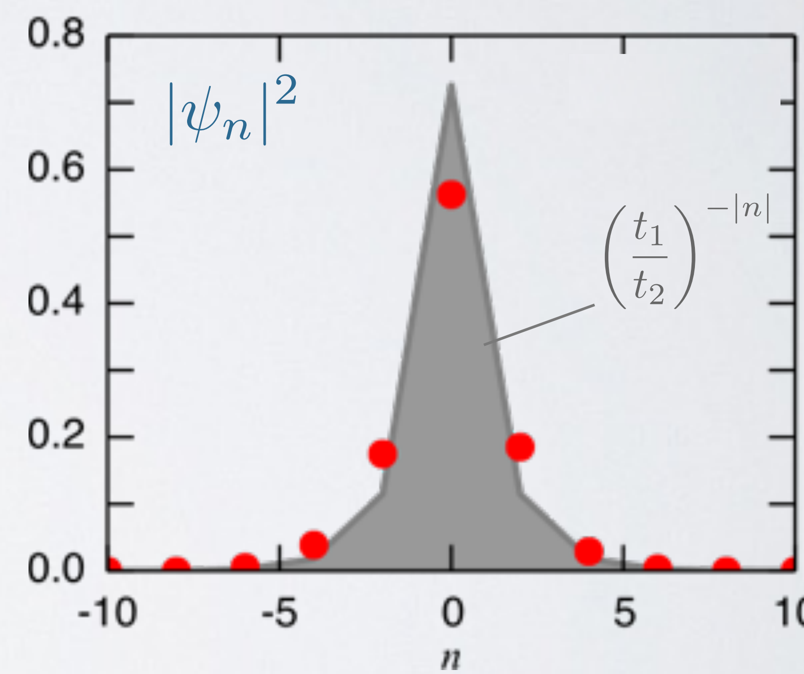
Microwaves realization



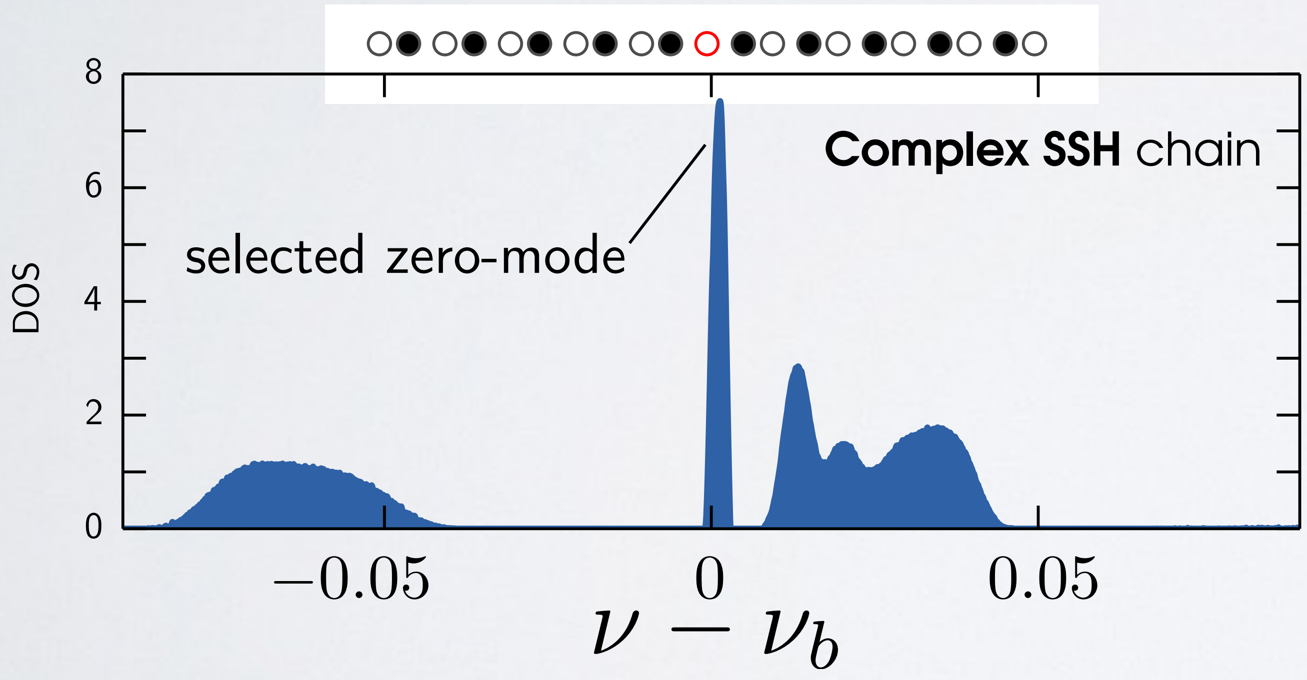


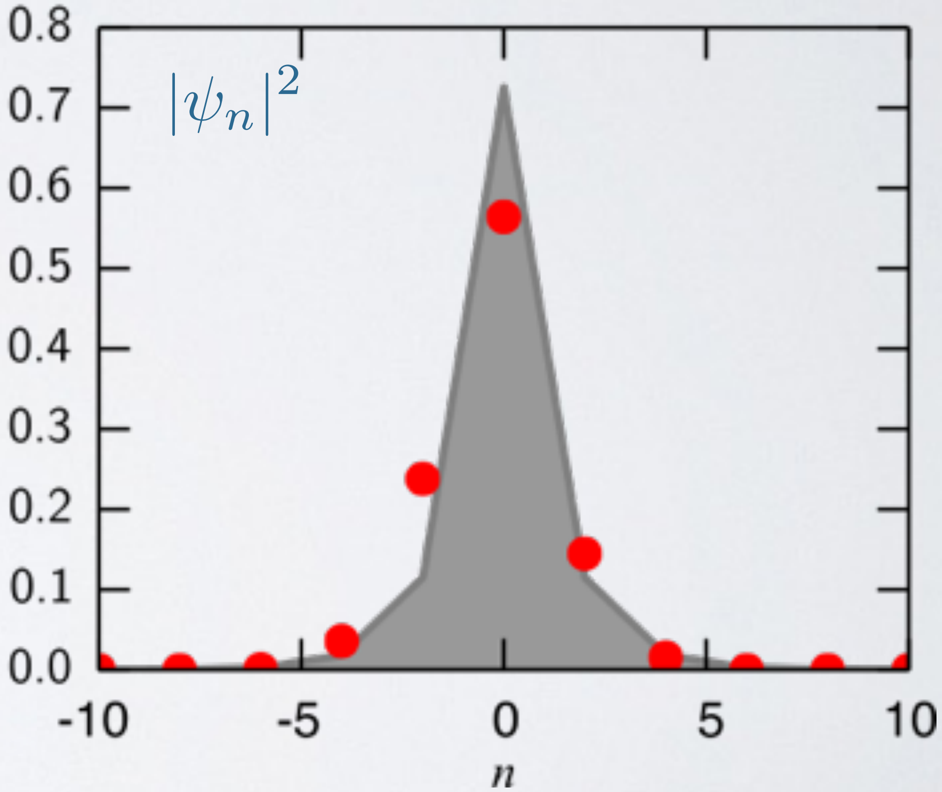




- the defect breaks the sublattice (chiral) symmetry
- the interface state is spectrally protected and spatially confined

Selective enhancement by losses





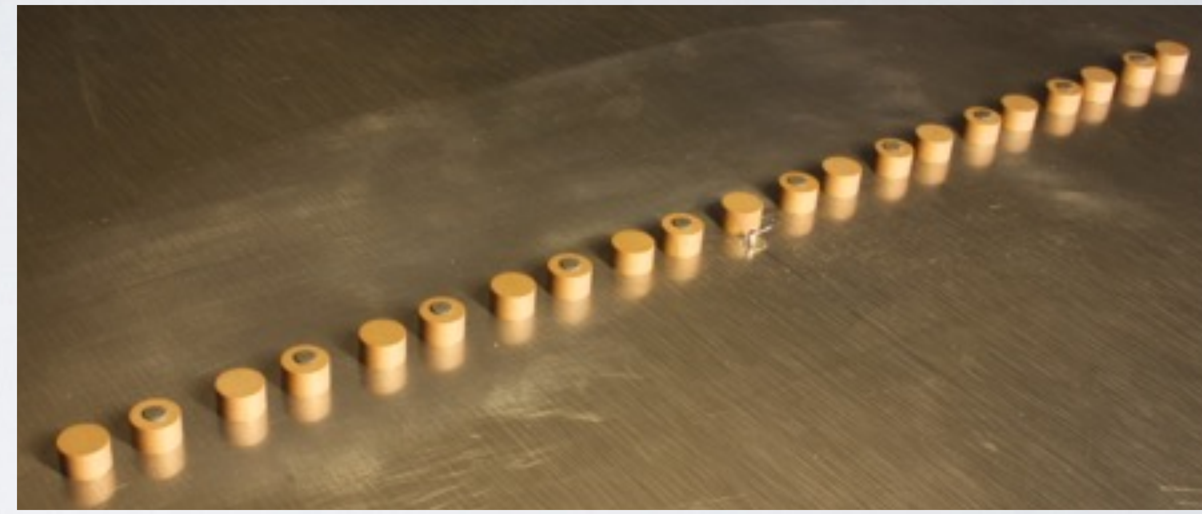
- losses on the B-sublattice through elastomer patches breaks T-symmetry
- the topological state is spectrally and spatially unaffected

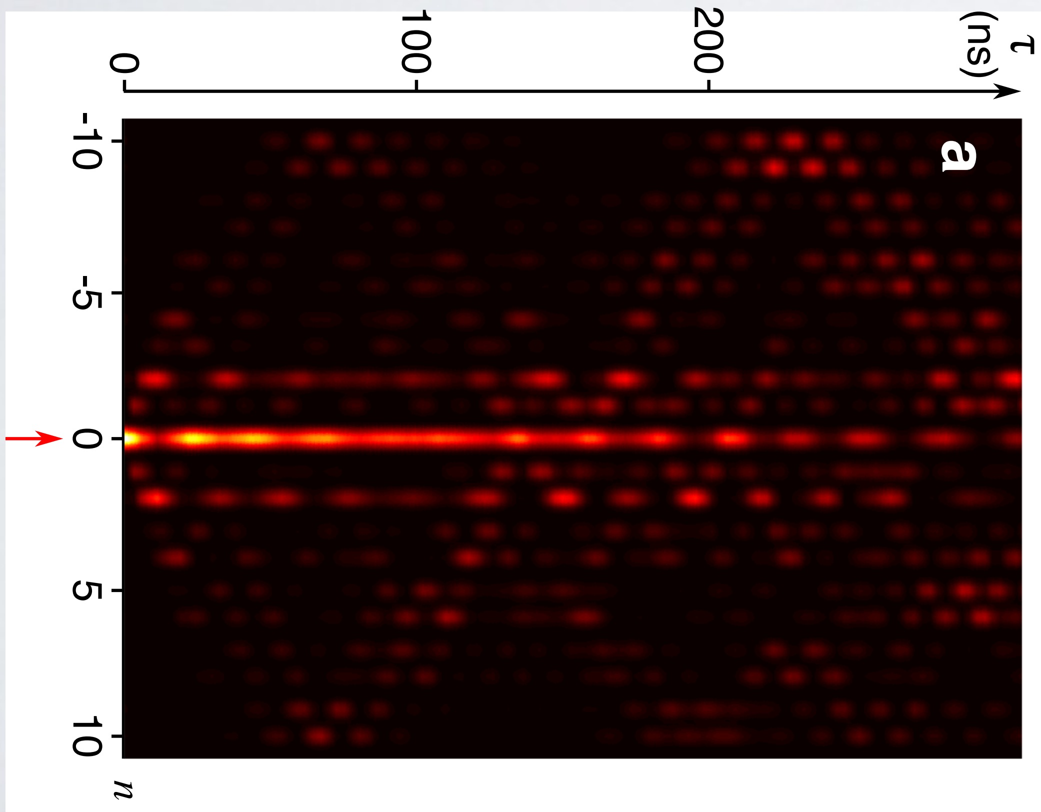
Nature Communications, 6:6710 (2015)

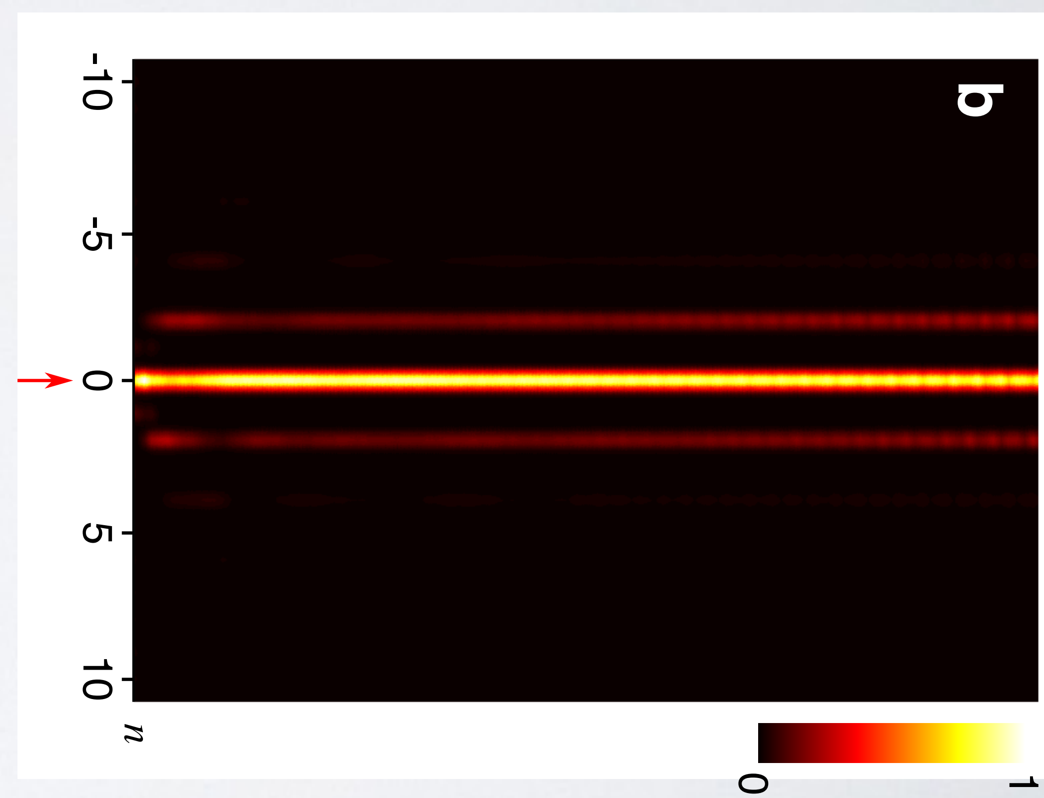
Loss-assisted propagation

transmissions between the defect resonator and all the others :

$$S_{12}(\vec{r}_i, \vec{r}_{\mathrm{d}}; \nu) \xrightarrow{FT} s_i(t)$$







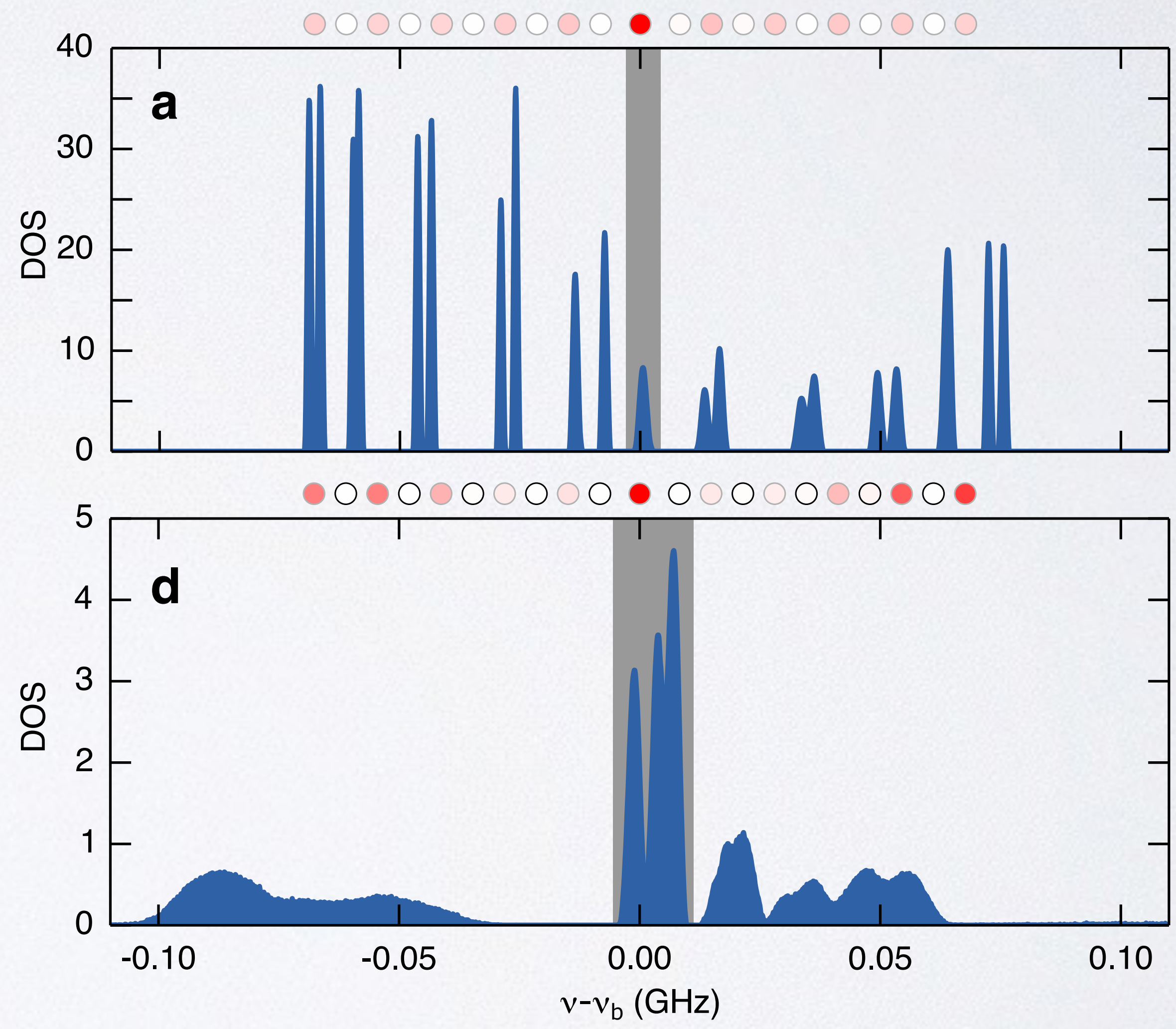
without absorption, diffraction and interferences spoil the propagation

with absorption, the enhanced defect mode dominates the propagation

Topology is crucial

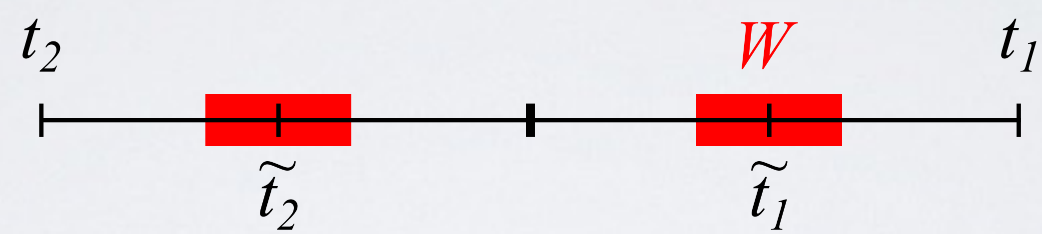
regular chain with central defect:

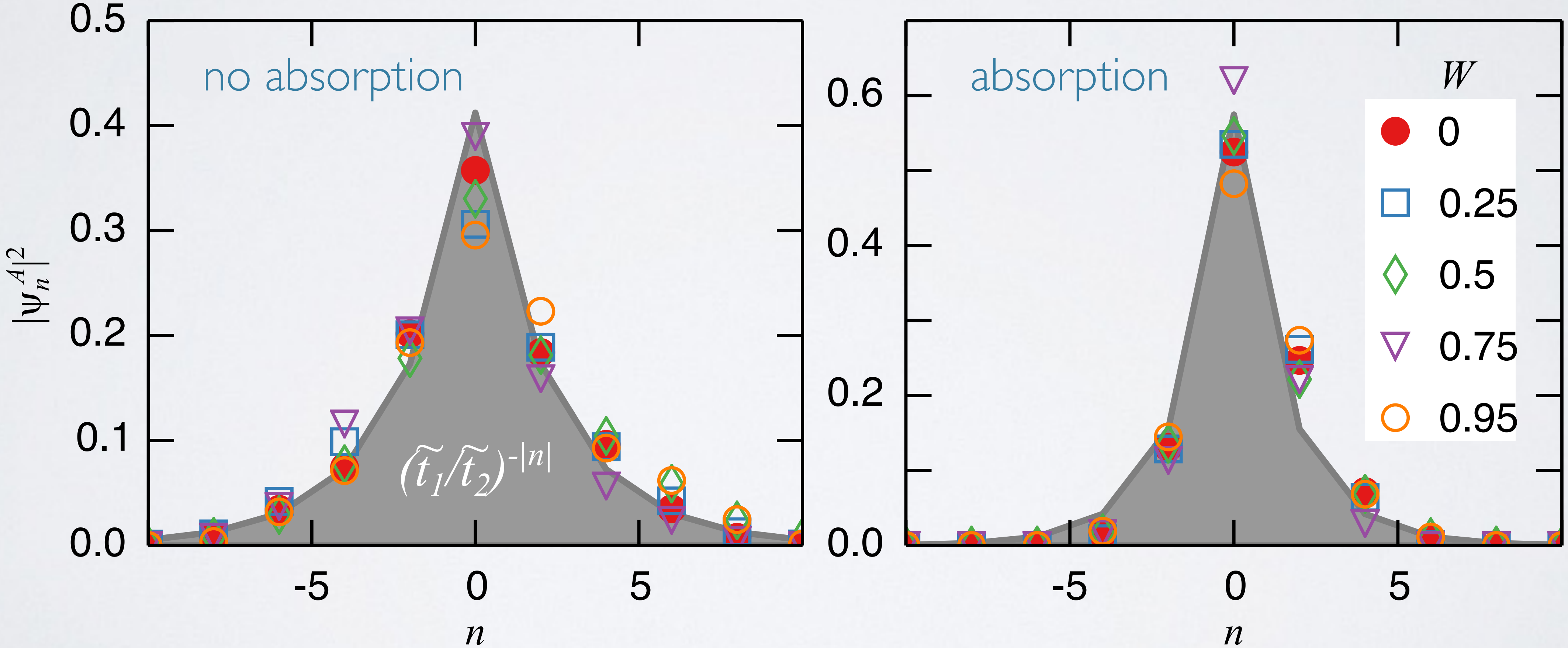
- localized absorption or disorder hybridizes defect and extended states
- no spectral and spatial topological protections



Robust to disorder

random couplings which preserve the dimer structure





with or without absorption, the topologically protected defect mode is insensitive to structural disorder

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Robust to disorder

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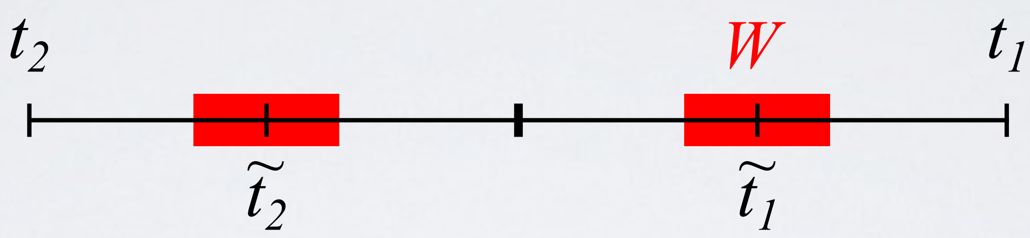

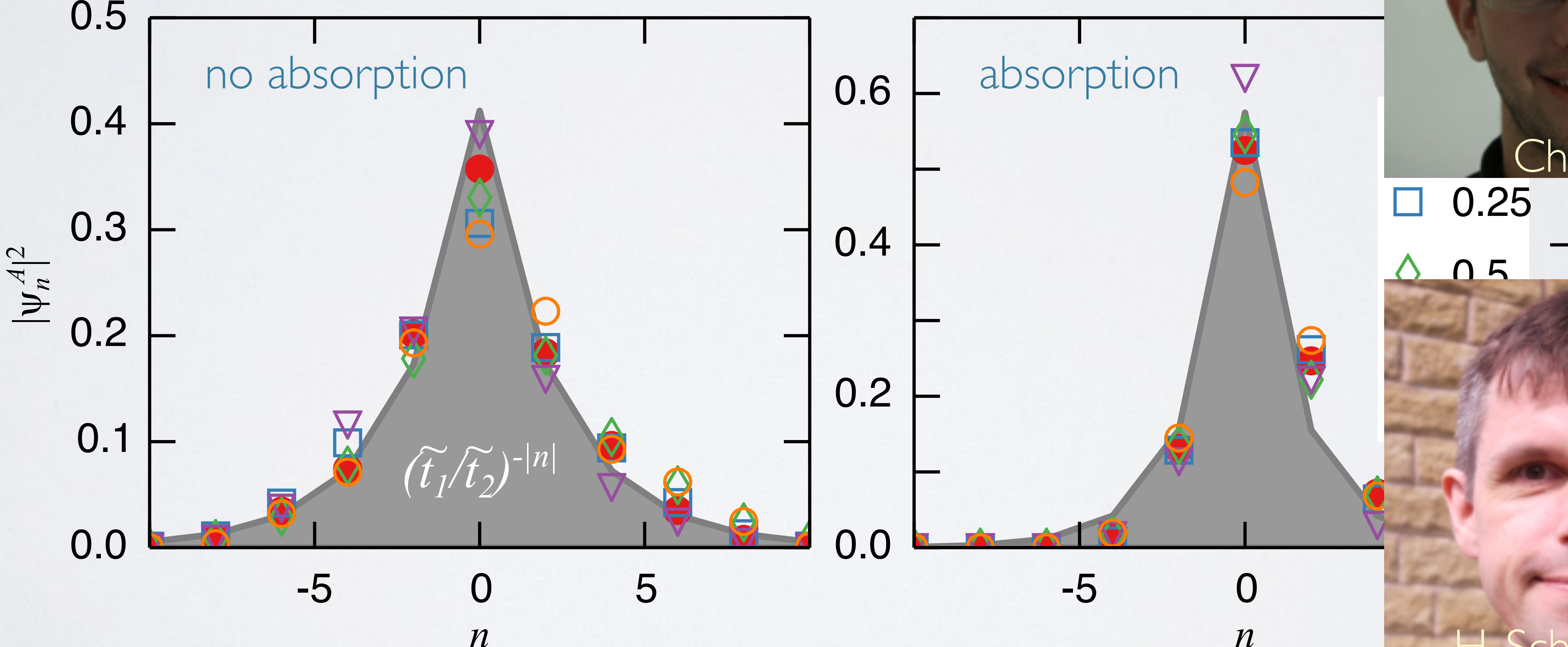

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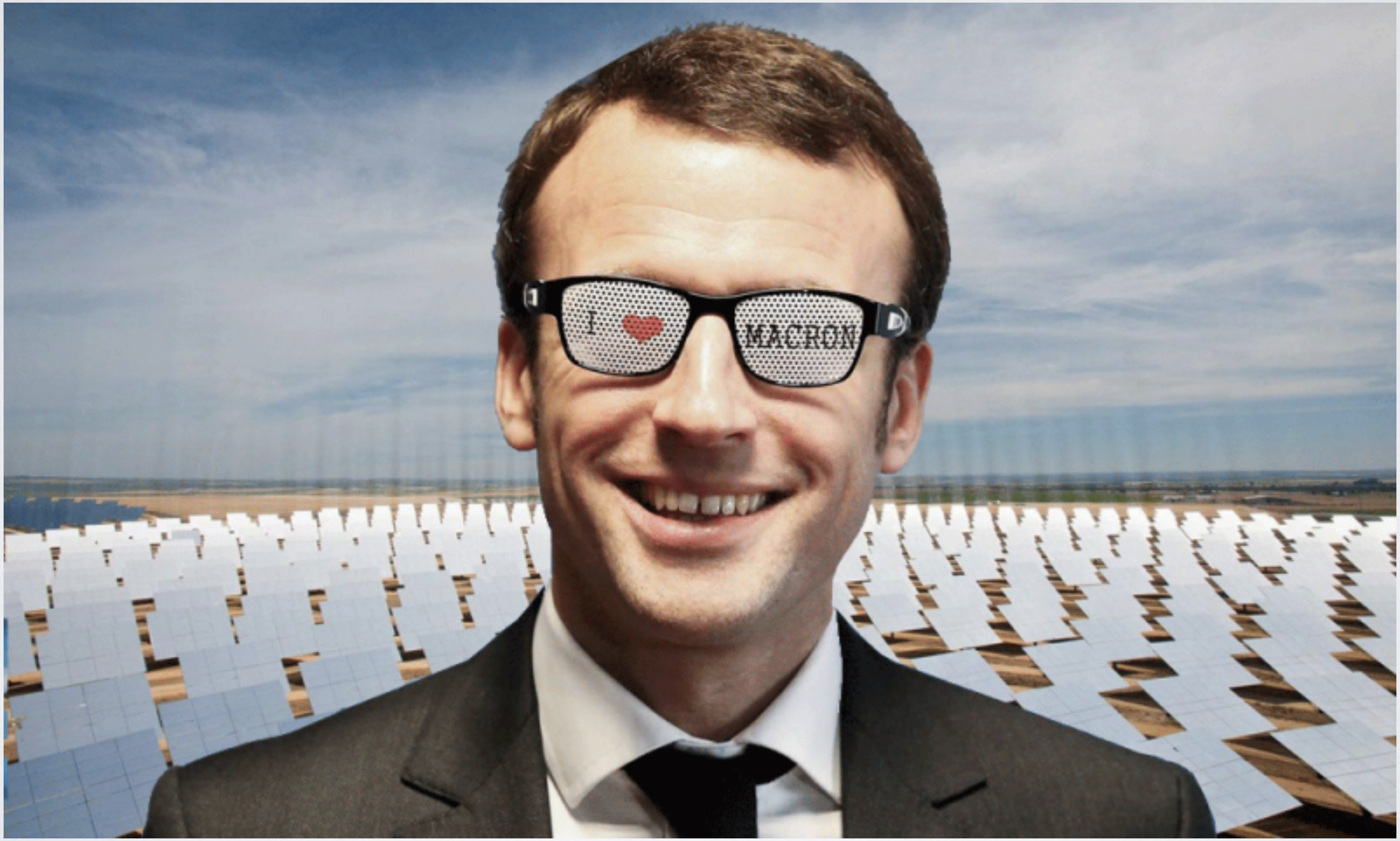
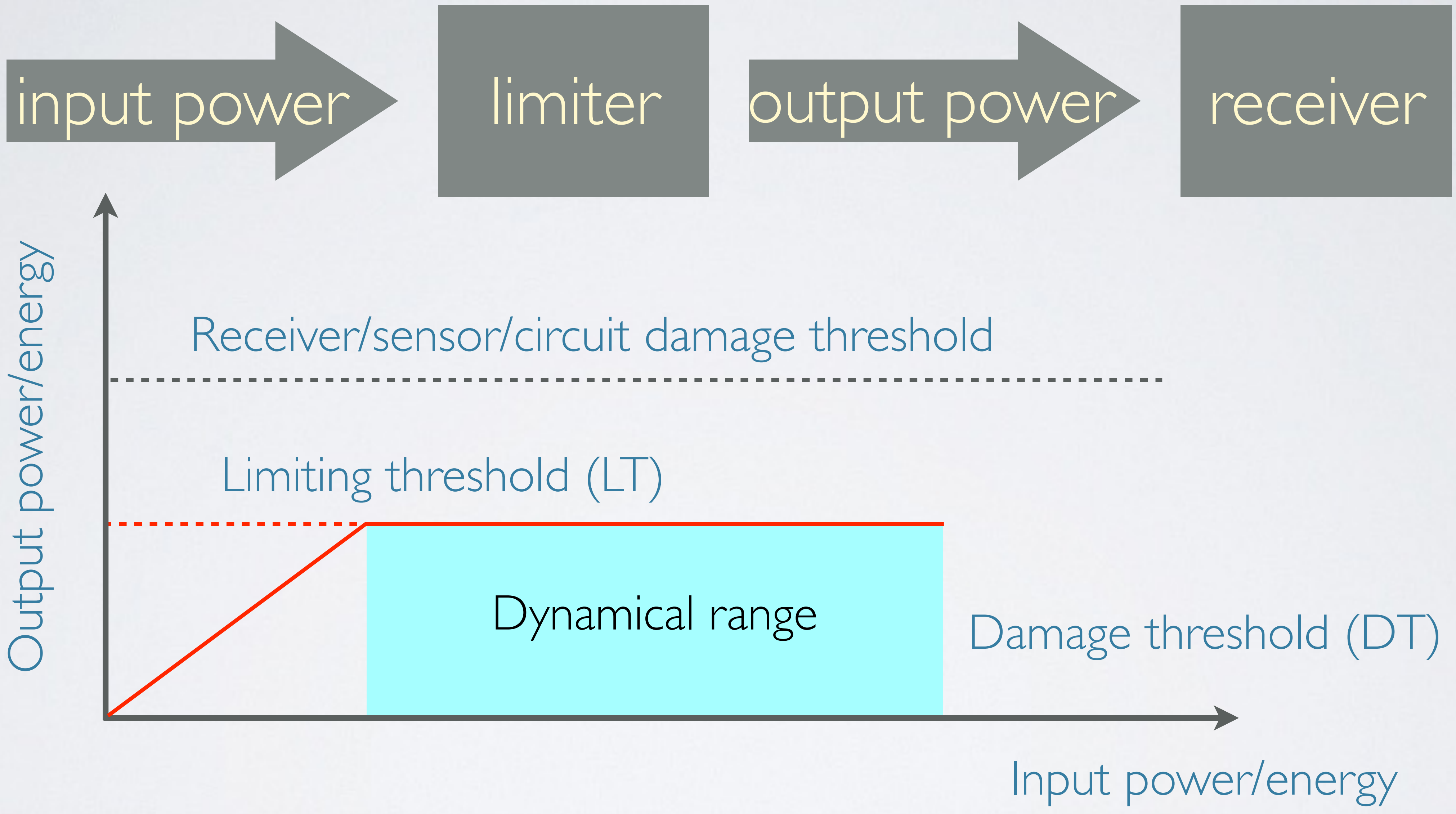
Optical limitation

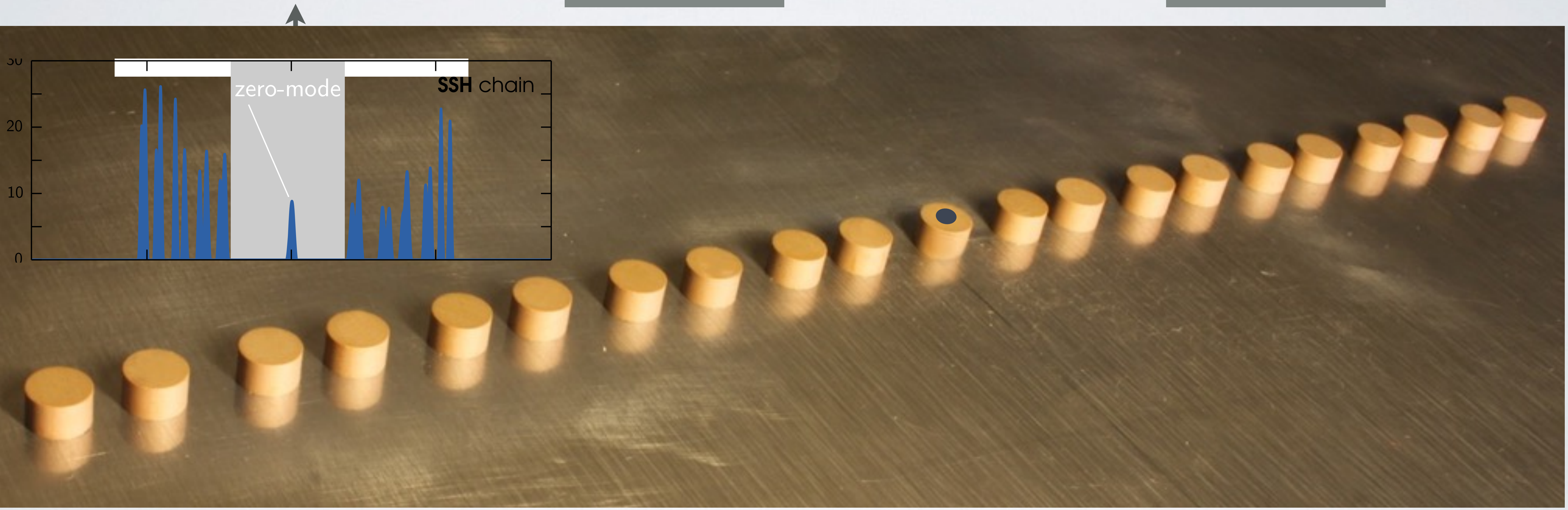


Ideal optical limiter



The larger the dynamical range, the better the limitation.

Ideal optical limiter



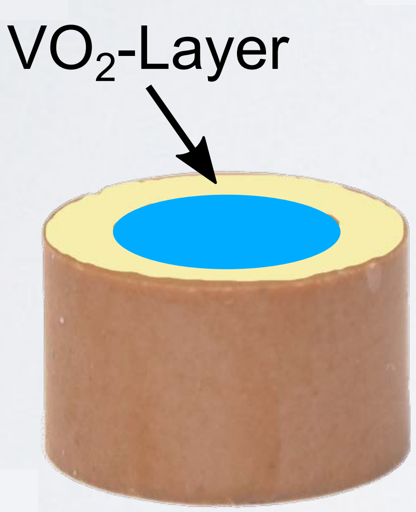
The larger the dynamical range, the better the limitation.

New concept: Topological reflective limiter

Non linear absorption

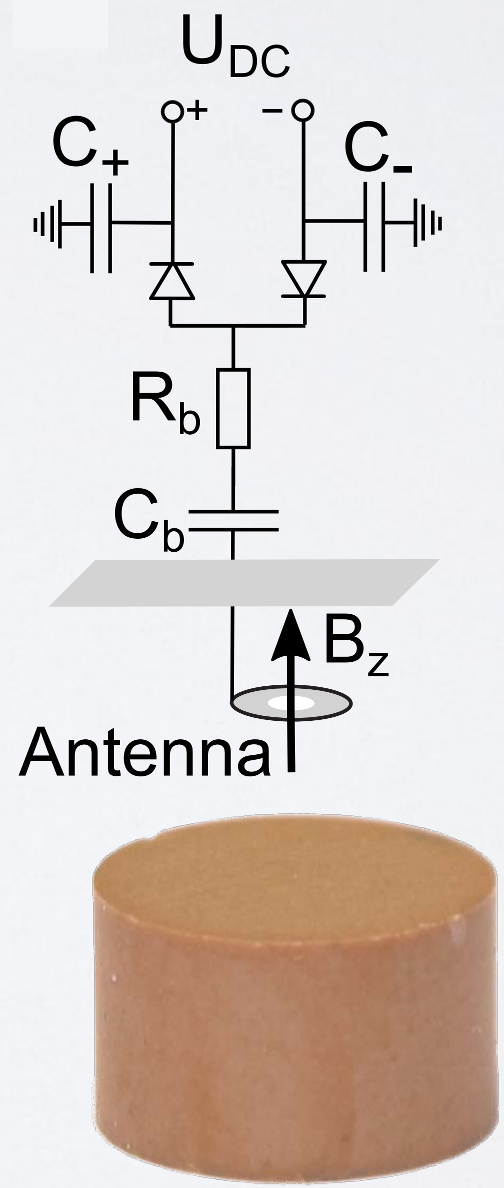
Losses depend on the strength of the incident radiation

Self-regulated losses



Material with a dielectric to metallic phase transition at some critical temperature.

Reconfigurable losses



Fast diode providing reconfigurability of the limiting threshold via an externally tuned DC voltage.

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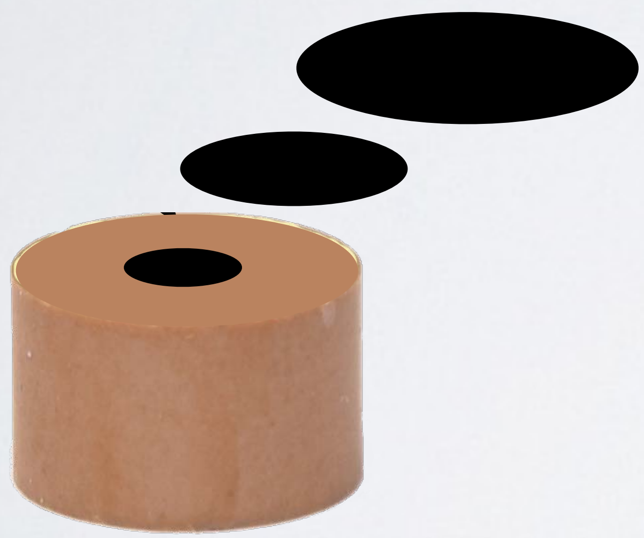
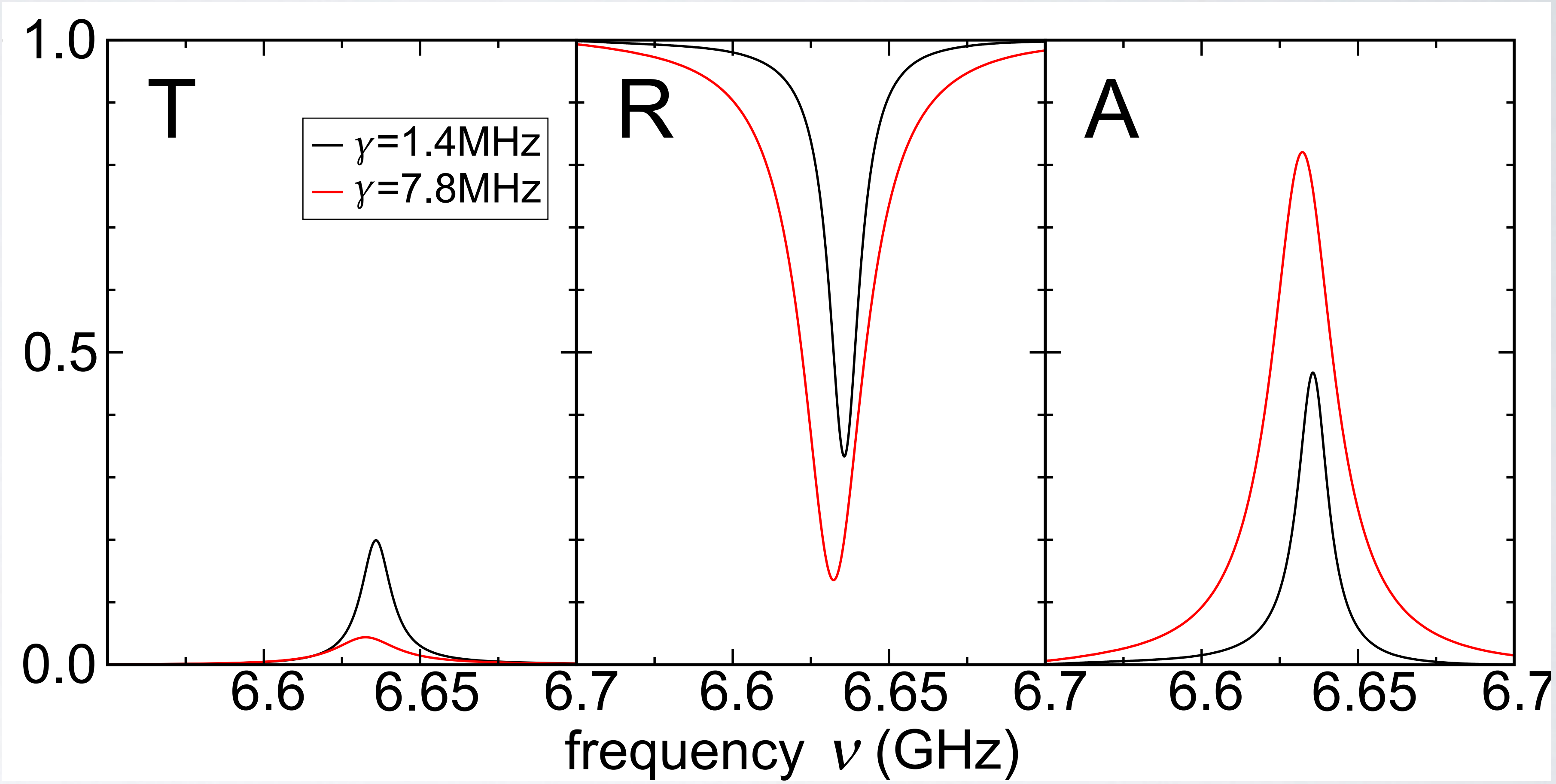
Lossy resonator

Varying the size of the absorbing patch:





Focus on demonstrating the effect of losses at the defect resonator on the transport properties.

Standalone lossy resonator acts as a sacrificial limiter.

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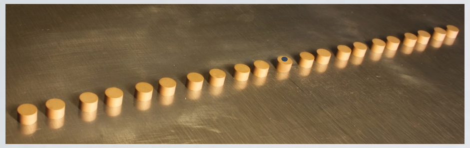
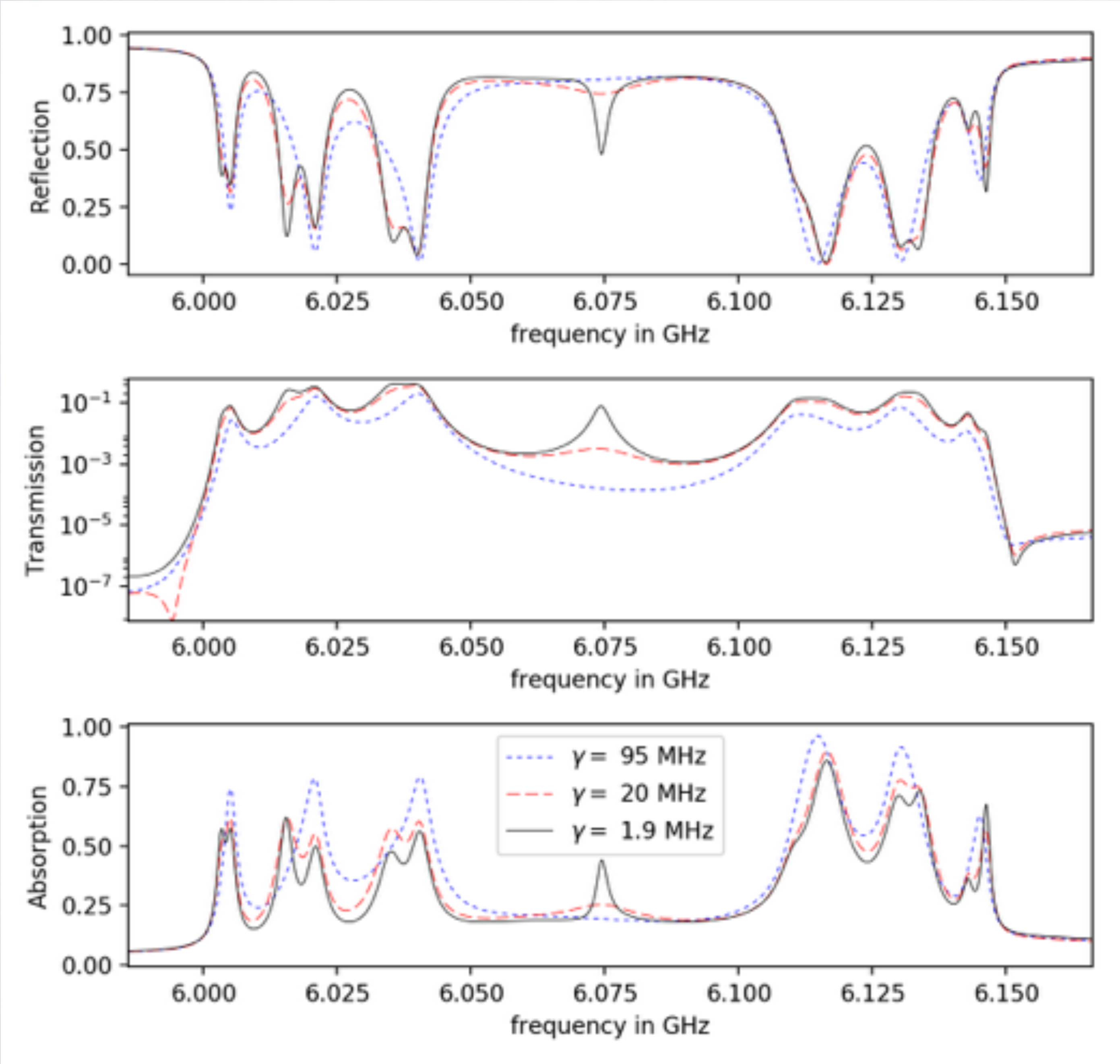
Topology-assisted reflective limiter





- As losses increase the transmission goes down and absorption goes down, meaning that the reflection goes up.

- The topological structure does not overheat because it ‘protects’ the lossy defect by decreasing the value of the field intensity as losses are increasing.

Phys. Rev. B, **95**, 121409(R) (2017)

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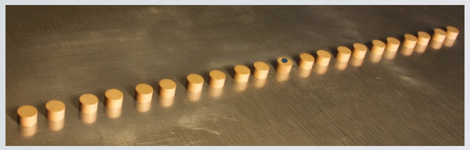
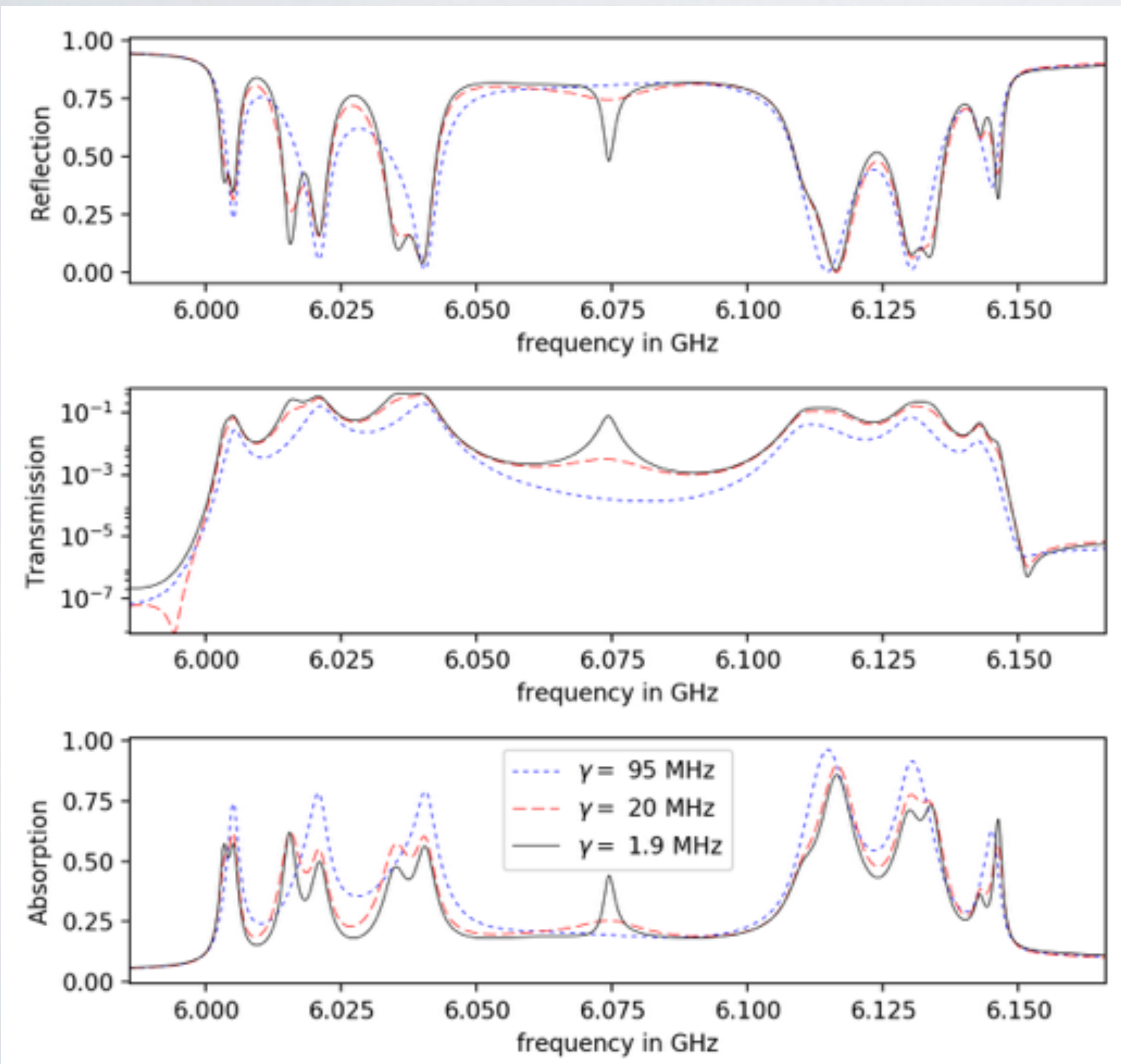
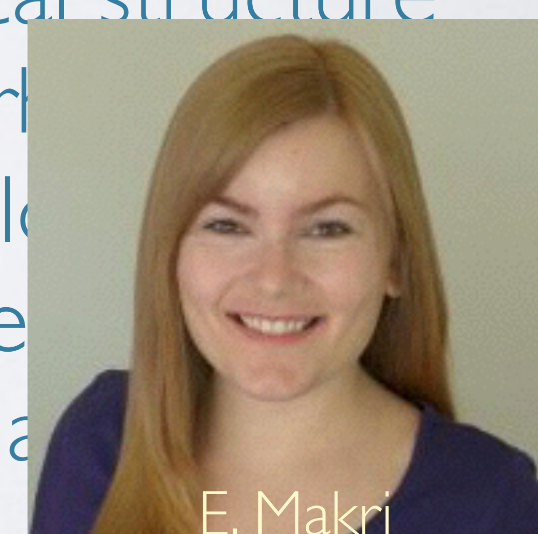
Topology-assisted reflective limiter





- As losses incre… transmission g… absorption goe… meaning that t… goes up.

- The topological structure does not overl… …t 'protects' the l… decreasing the… field intensity a… increasing.

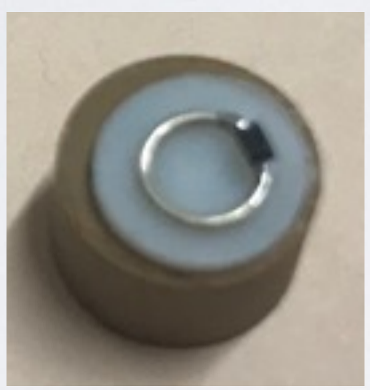


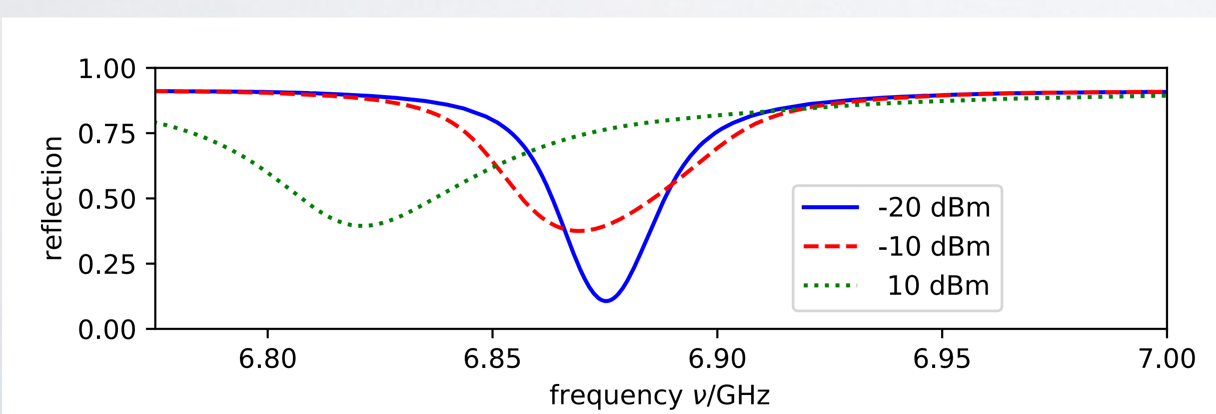
Phys. Rev. B, **95**, 121409(R) (2017)

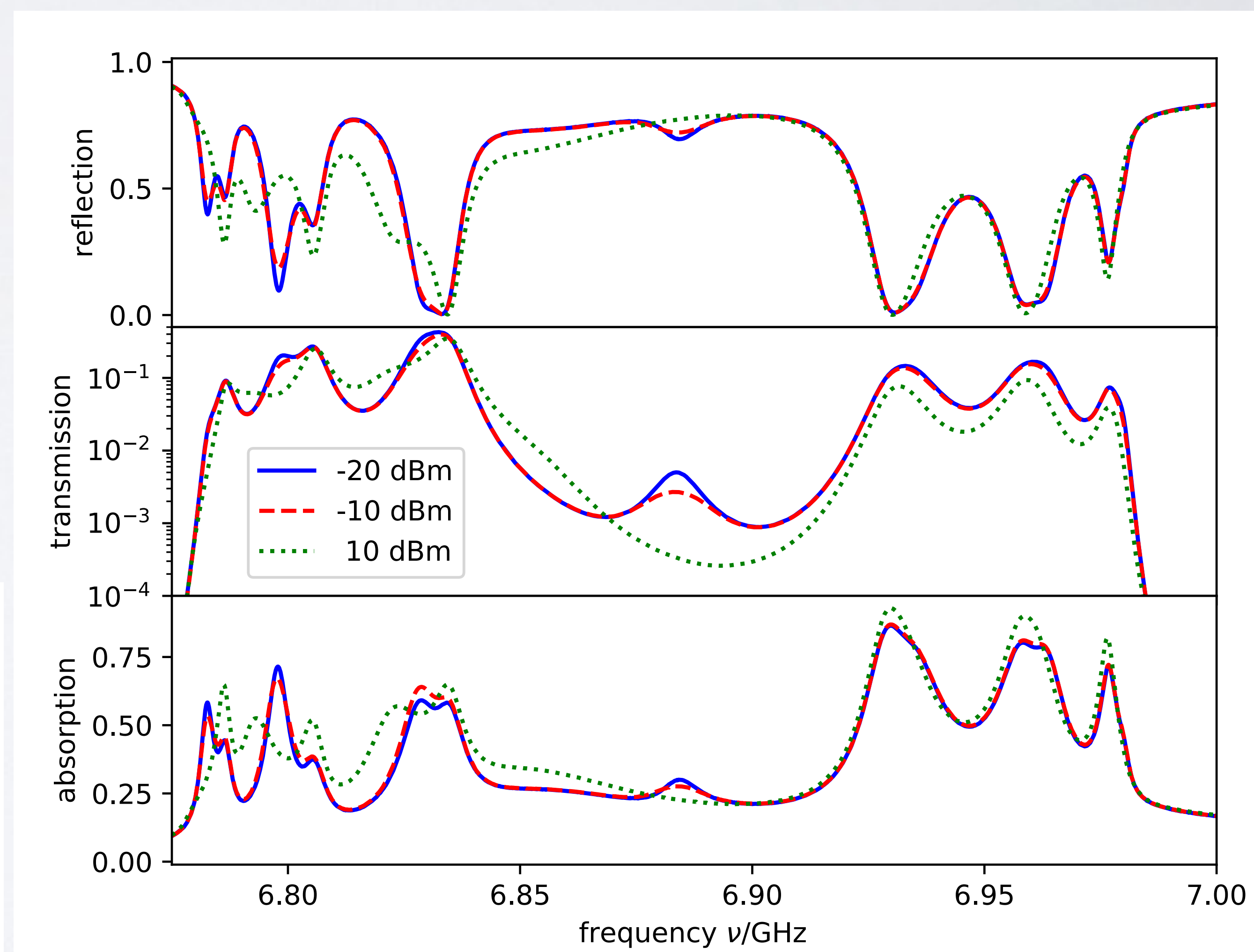
Genuine non-linear losses

Silicon Schottky diode
(Skyworks SMS7630)

Preliminary results: It works !







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Outline

1. Microwave realization of tight-binding model

   dielectric resonators, TE mode, evanescent coupling, LDOS & eigenstates

2. SSH chain: Control of topological interface states

   zero-mode, selective enhancement, non-linear absorption, reflective limiter

3. 2D lattices : Lieb (and Penrose)

   partial symmetry breaking, (not so) flat band, zero-mode, gap labeling (naive picture)

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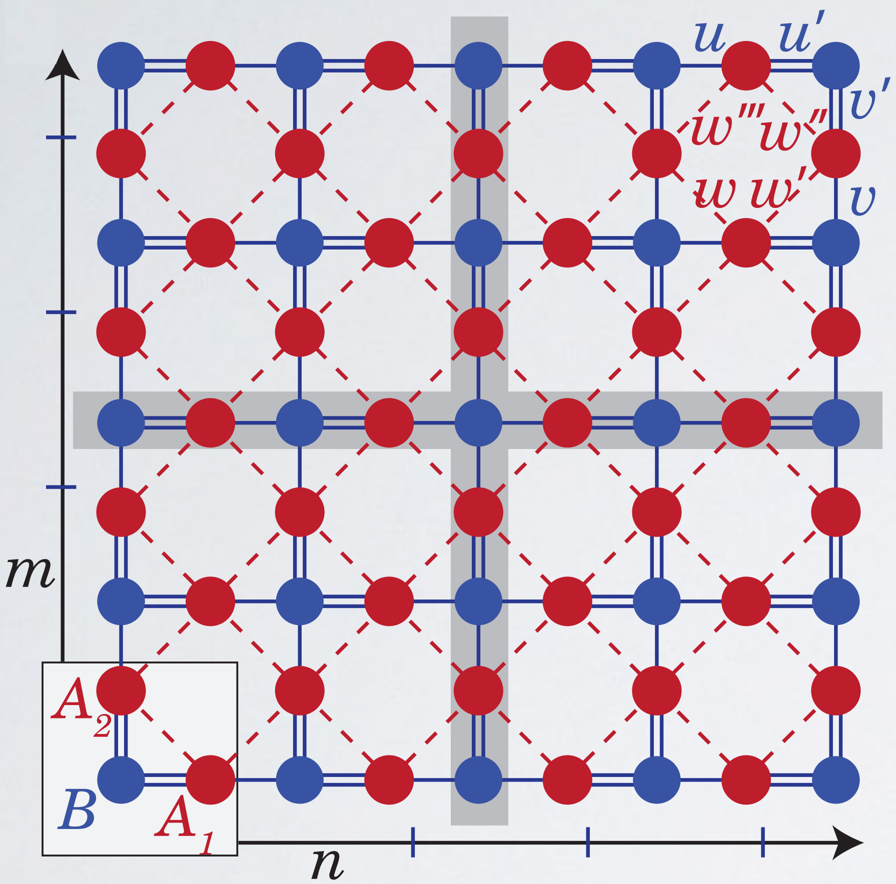
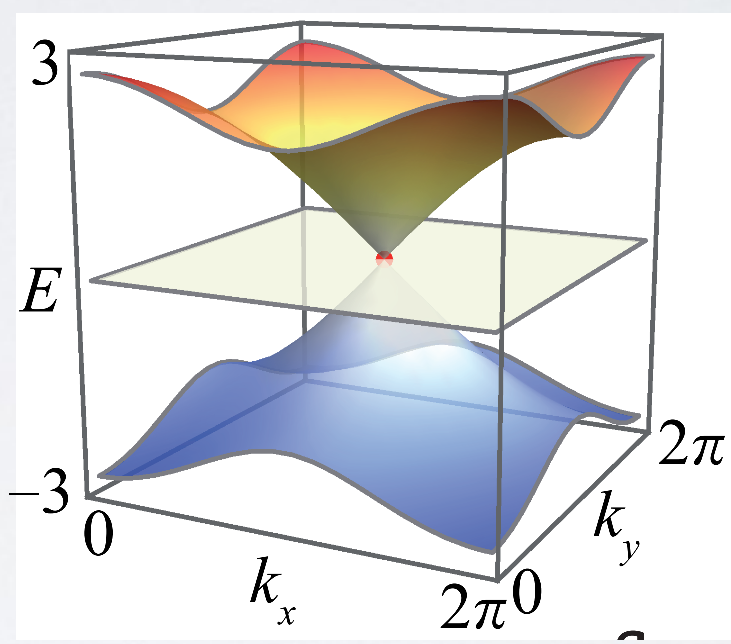
Lieb lattice

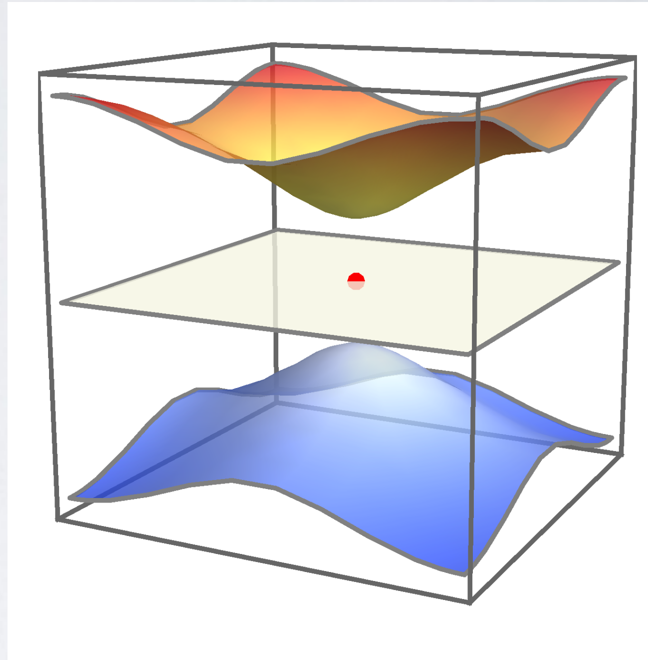


uniform couplings: topologically boring…



$u = u' = v = v' \quad w^{(i)} = 0$

more interesting when dimerized:



$2u = 2v = u' = v' \quad w^{(i)} = 0$

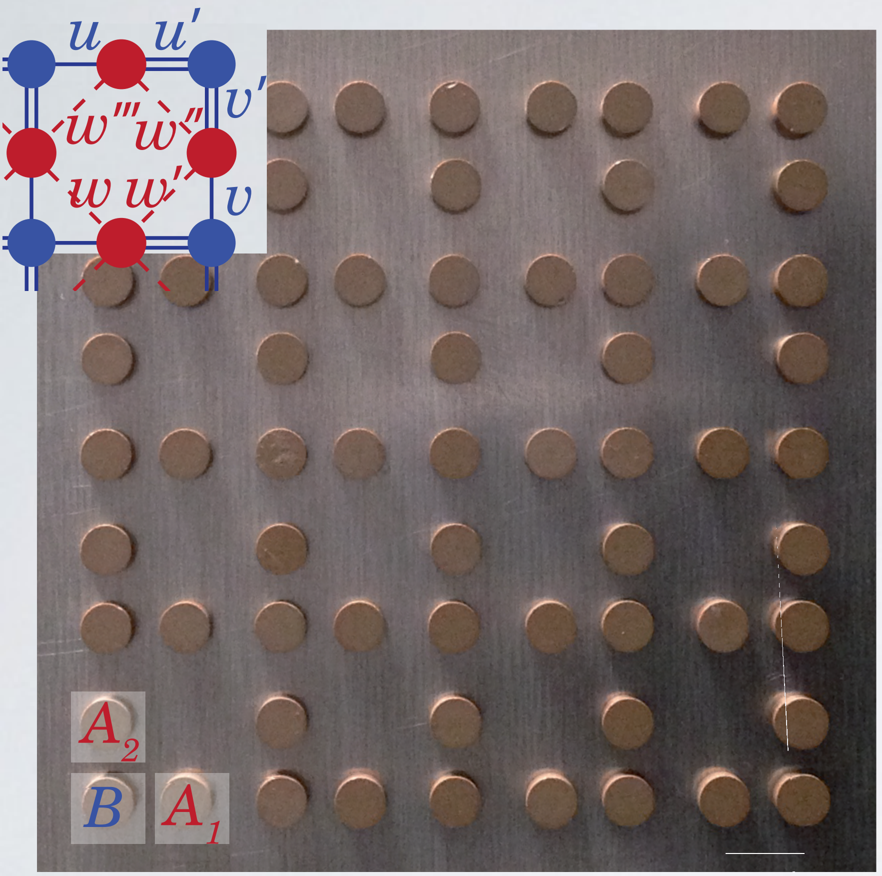
Global chiral symmetry:

$$H_{\mathrm{TB}}(\vec{k}) = \begin{pmatrix} 0 & t_{AB}(\vec{k}) \\ t_{BA}(\vec{k}) & 0 \end{pmatrix}$$

$$\sigma_z H_{\mathrm{TB}}(\vec{k}) \sigma_z = -H_{\mathrm{TB}}(\vec{k})$$

- flat band on the majority sublattice
- with an appropriate choice of boundary conditions: one extra zero-mode on the minority sublattice (B sites)… but still degenerated with the flat band.

Partial chiral symmetry

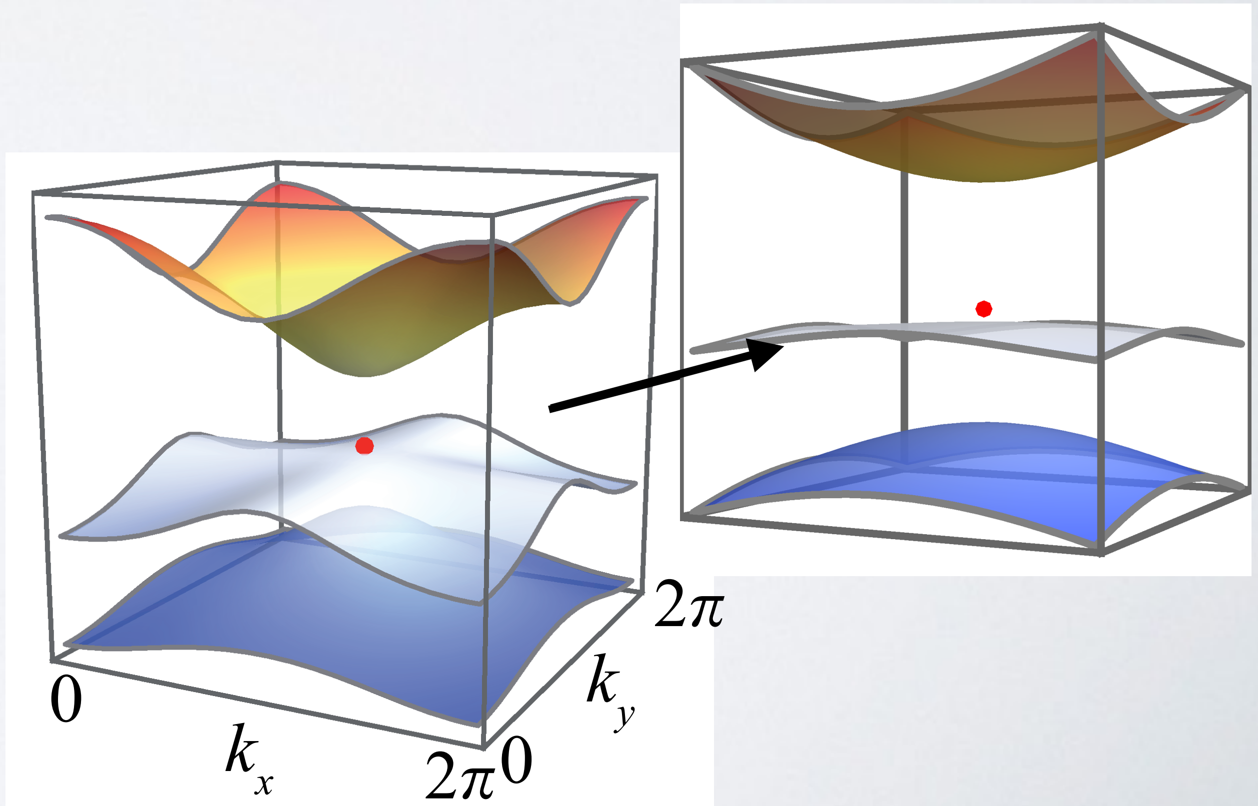


In the experiment, next-nearest neighbor couplings are effective: $w'' > w' = w''' > w$

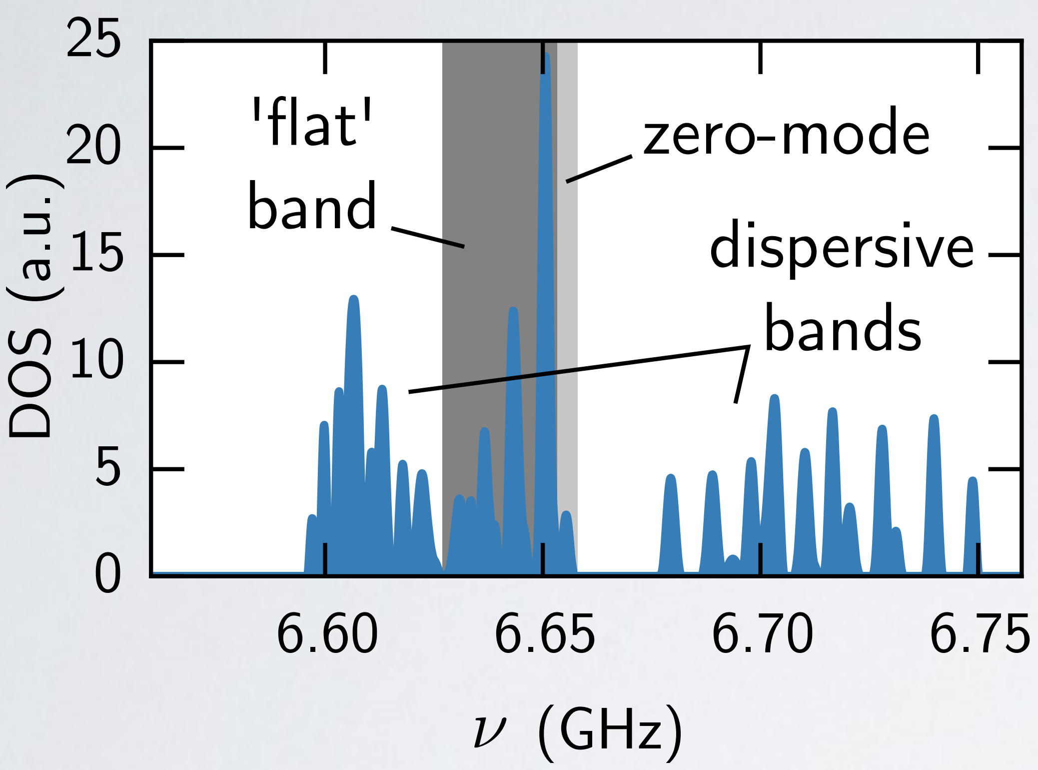
$$H_{\mathrm{TB}}(\vec{k}) = \begin{pmatrix} t_{AA}(\vec{k}) & t_{AB}(\vec{k}) \\ t_{BA}(\vec{k}) & 0 \end{pmatrix}$$

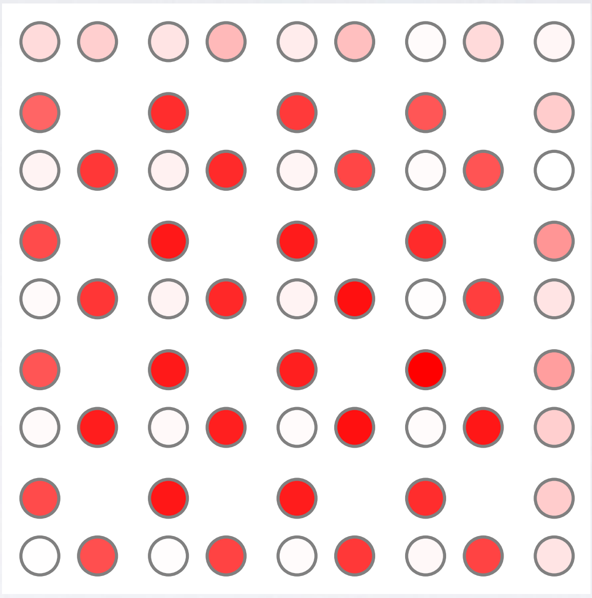
$$\left[\sigma_z H_{\mathrm{TB}}(\vec{k})\sigma_z\right]_{BB} = \left[-H_{\mathrm{TB}}(\vec{k})\right]_{BB}$$

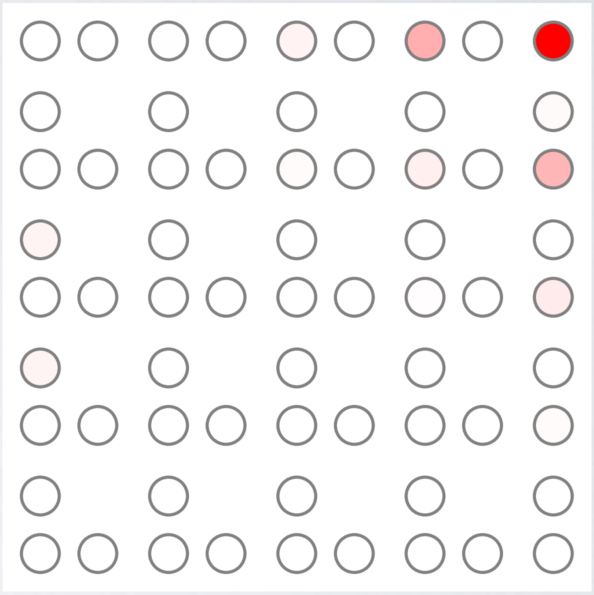
- the chiral symmetry of the majority sublattice is broken
- the flat band becomes dispersive
- the zero-mode is lifted away

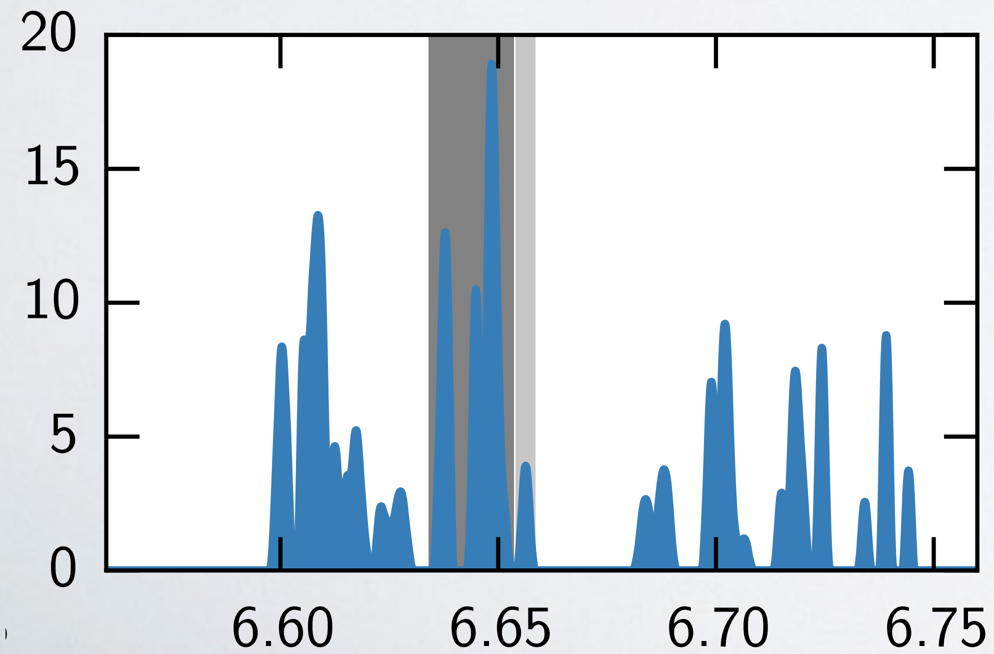


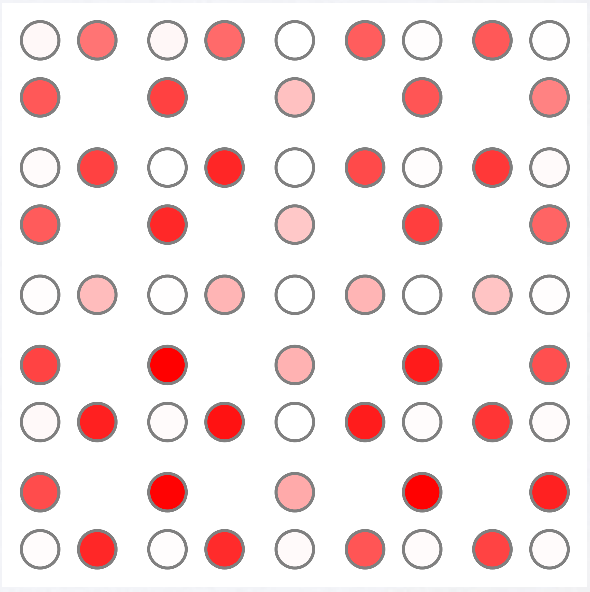
Engineering of defect states

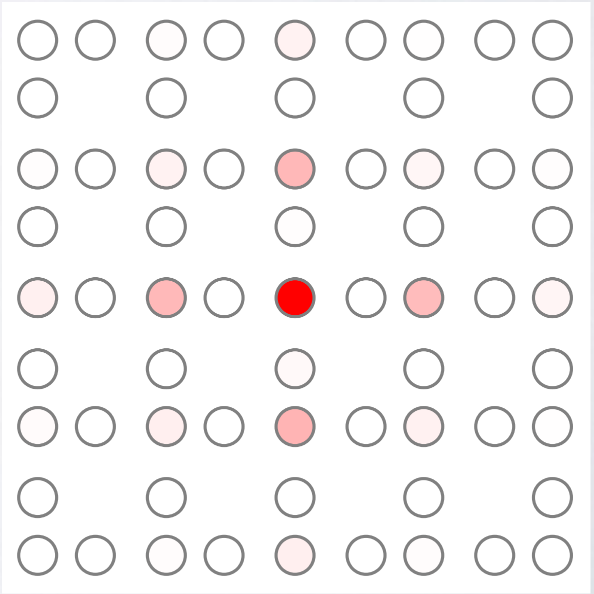








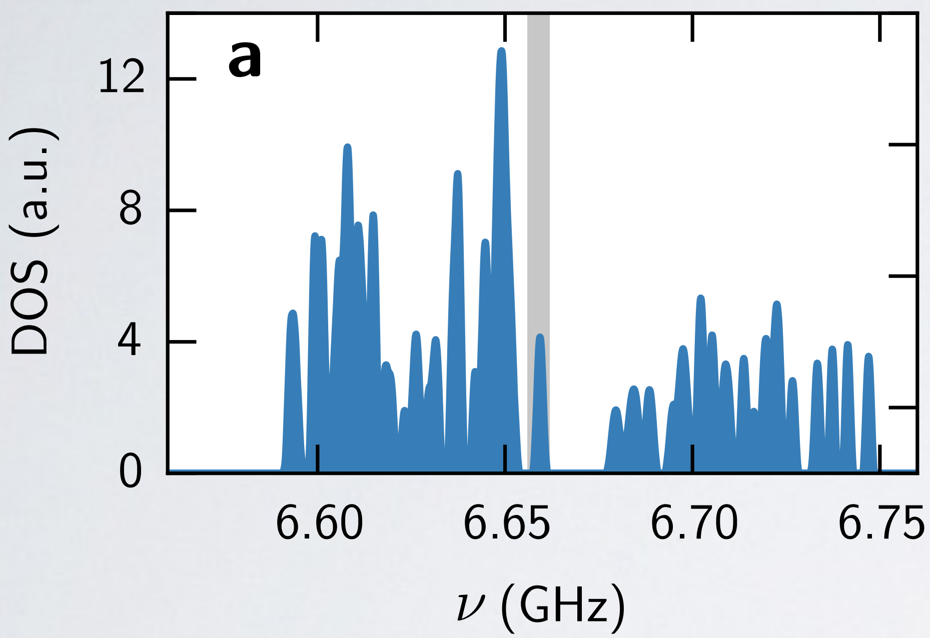


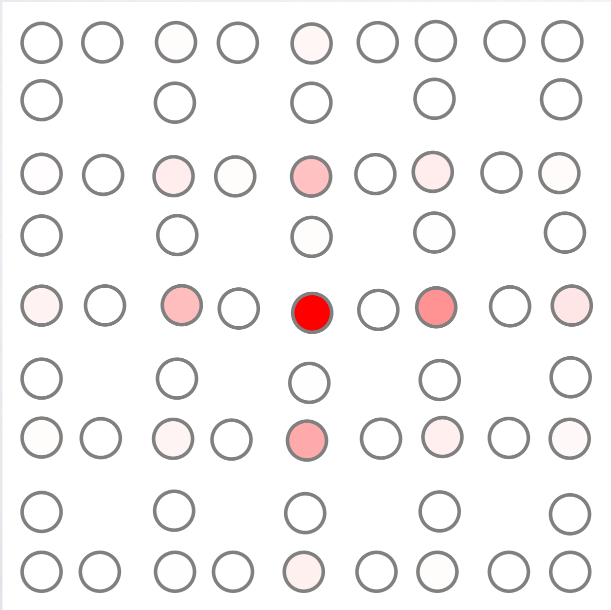


2D Materials 4, 025008 (2017)

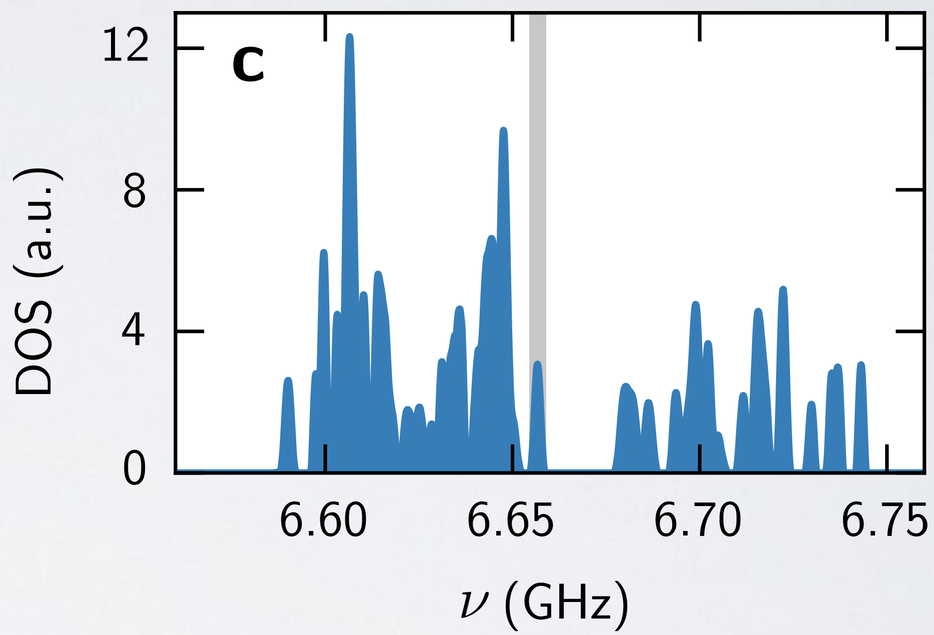
Topological protection

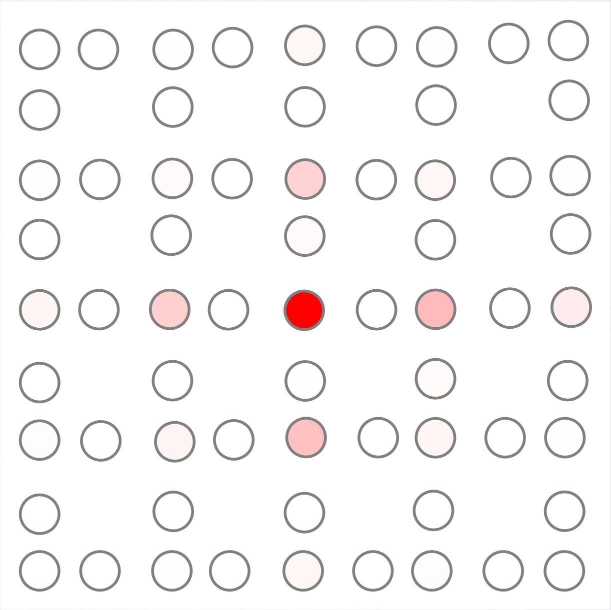
constrained disorder





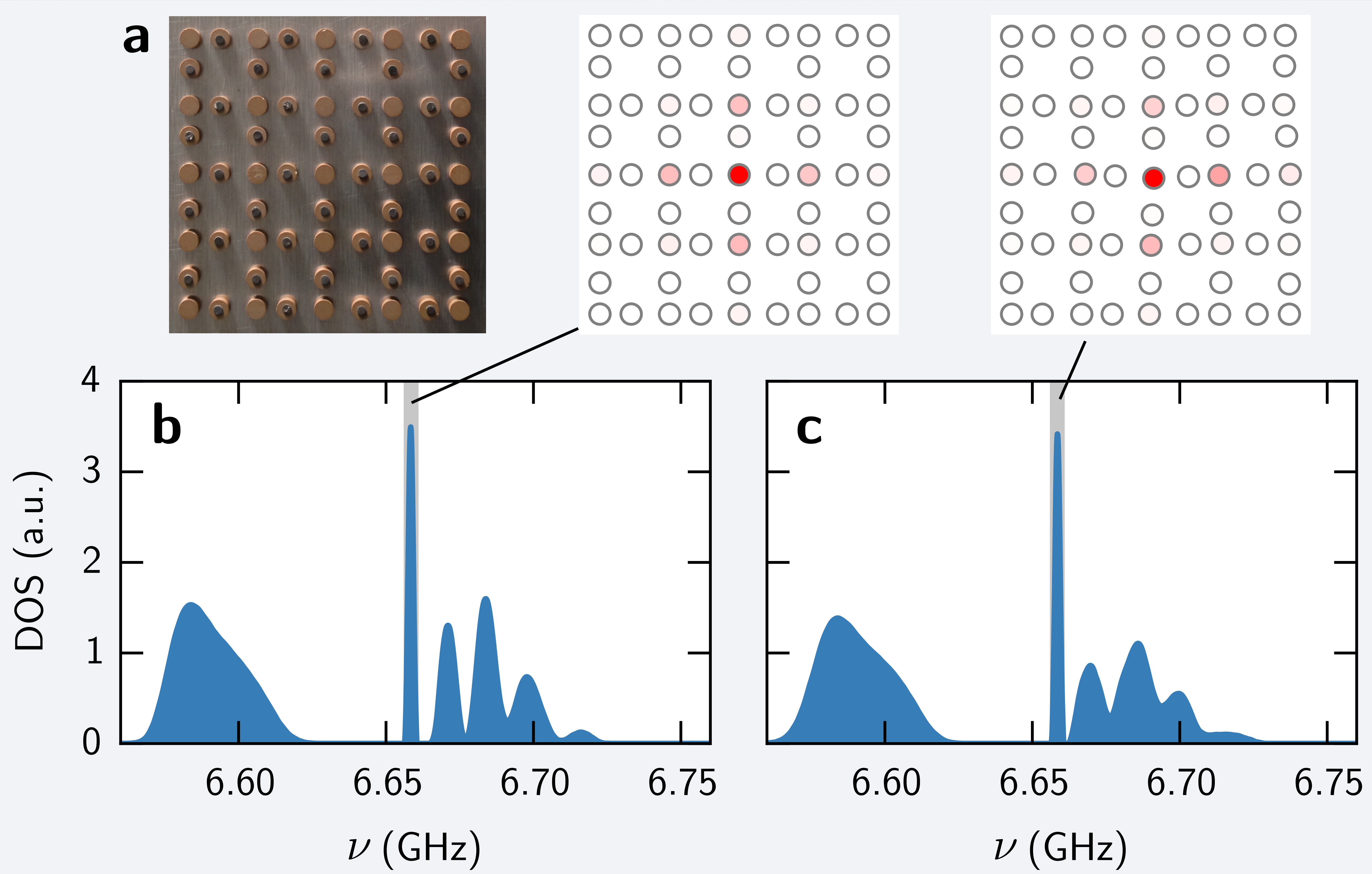
generic disorder





2D Materials 4, 025008 (2017)

Selective enhancement



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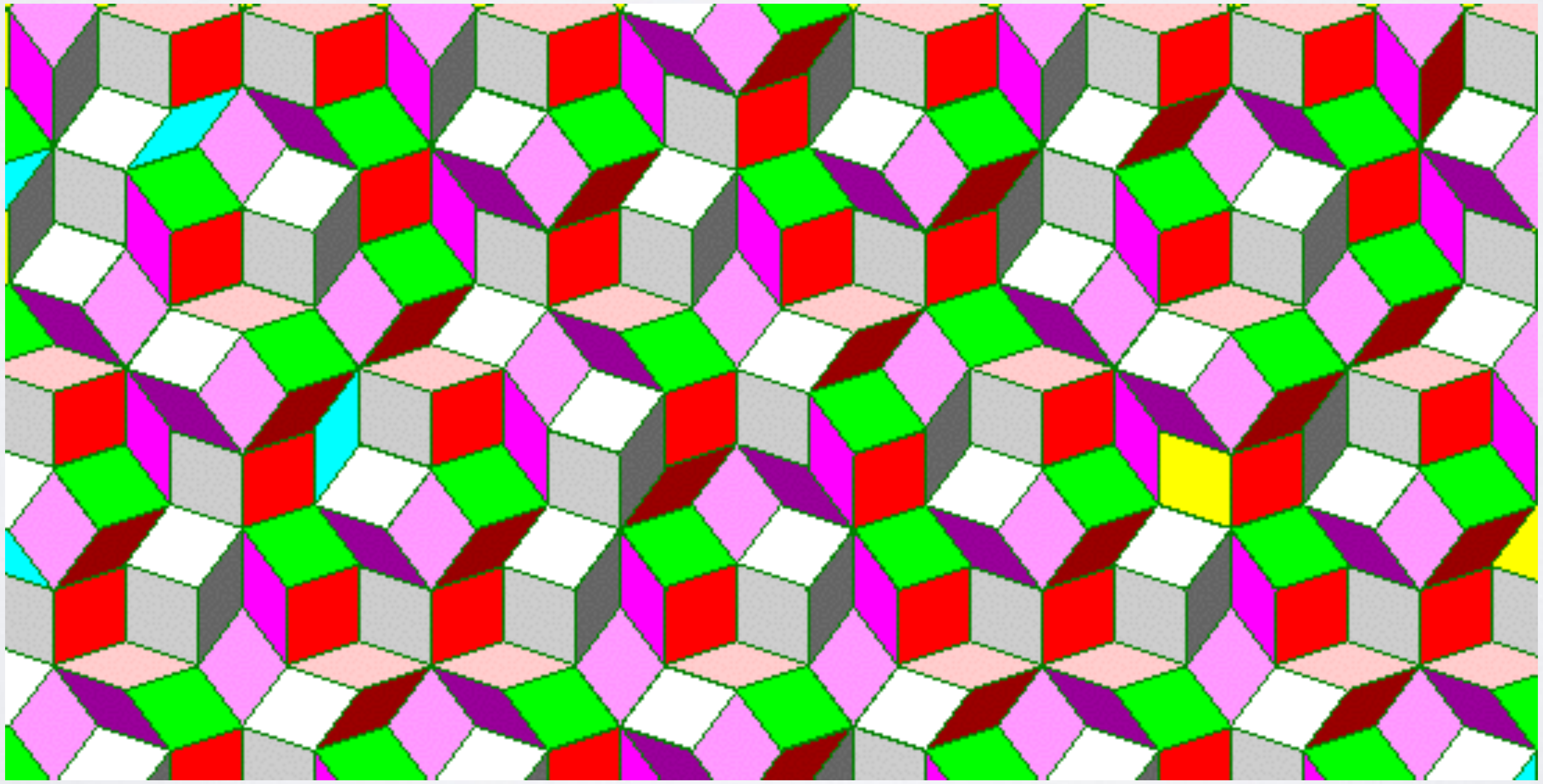
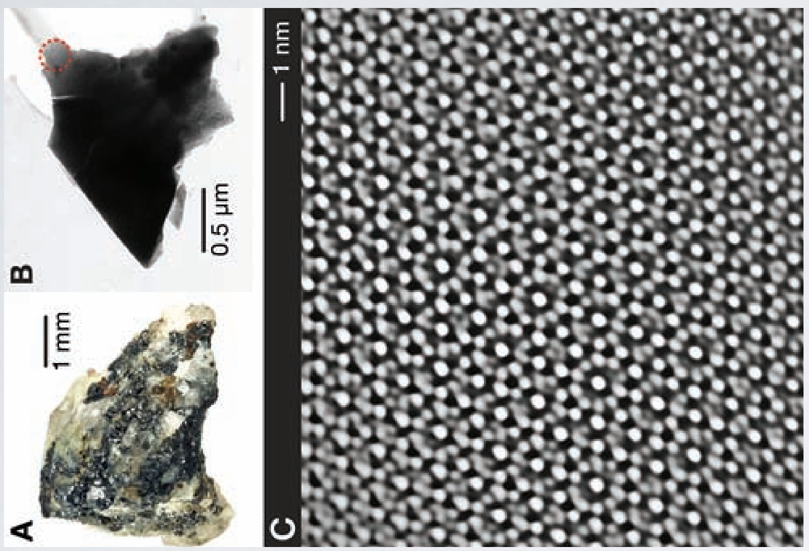
Intriguing quasicrystal

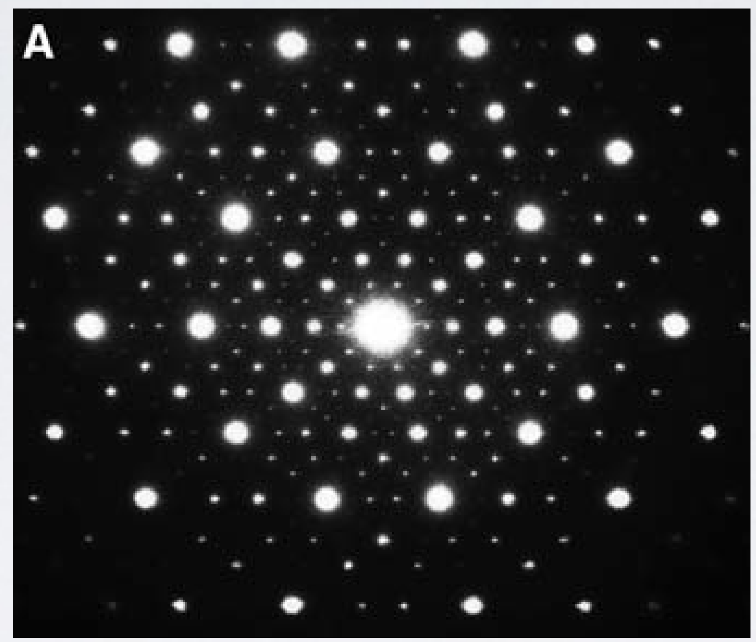
In a quasiperiodic cristal, the atomic positions along each symmetry axis are described by a sum of two or more periodic functions whose wavelengths have an irrational ratio (Bindi *et al.*)



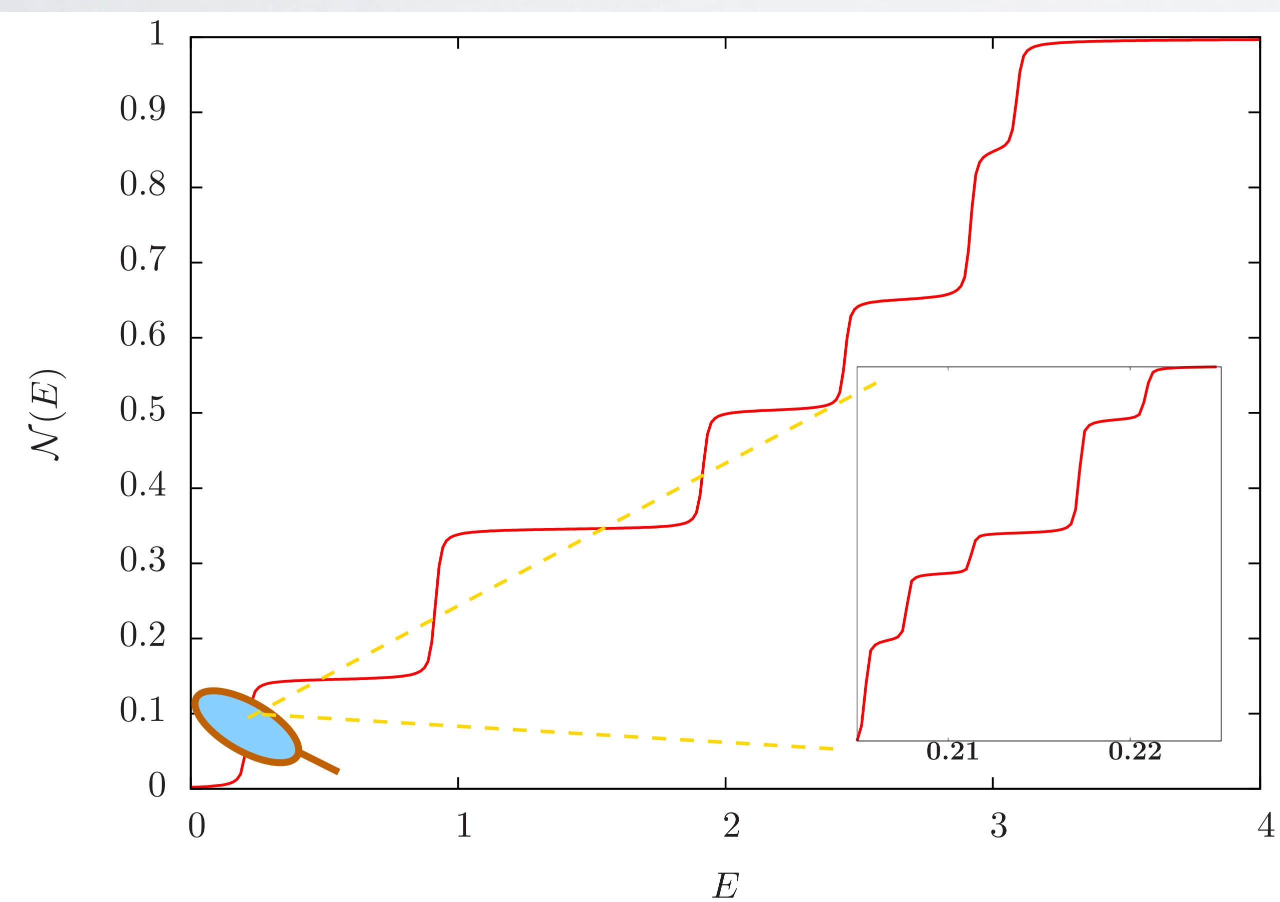
Bindi *et al.*, ***Science* 324** (2009)

Intriguing quasicrystal





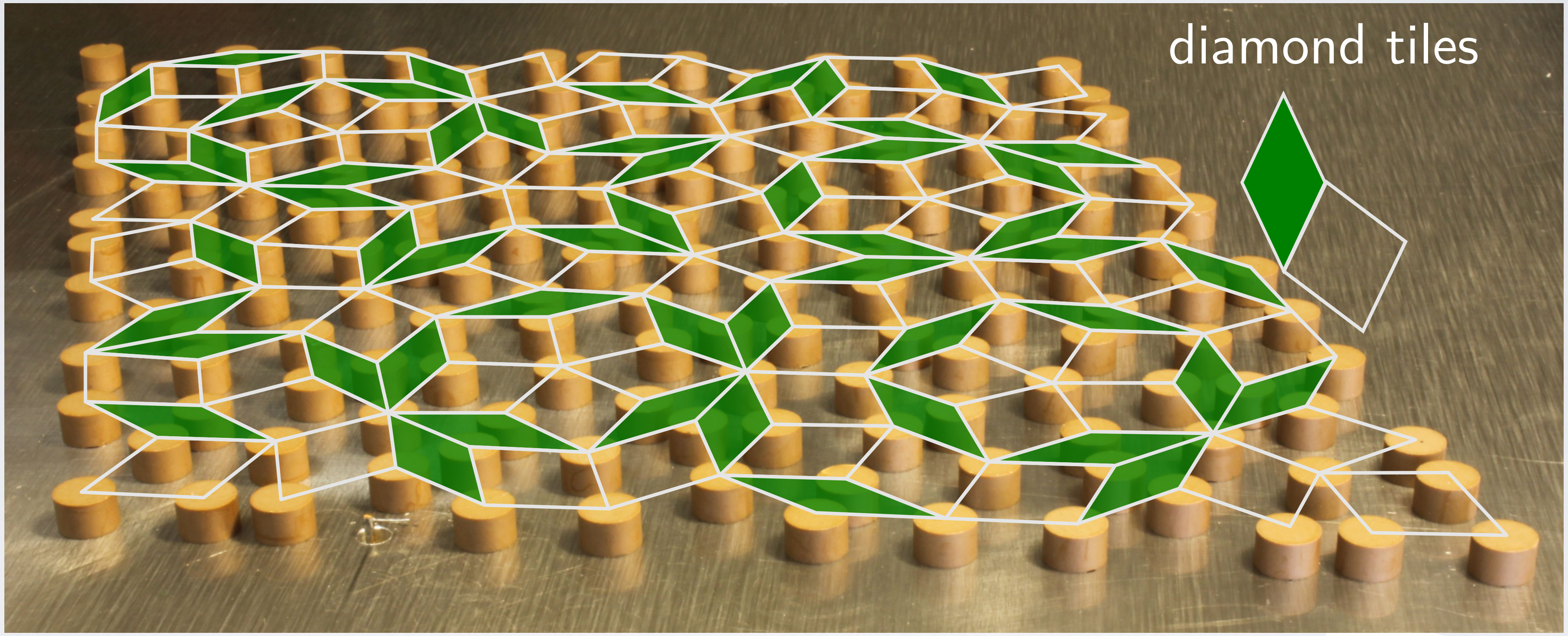
Diffraction pattern
with 5-fold symmetry !



Integrated density of states
with a staircase structure:

- irregular step heights
- smaller steps at higher energy resolution
- footsteps labeled by Chern numbers

Microwave Penrose tiling



- Penrose lattice with rhombic tiles
- 164 resonators placed at each rhombus vertex

$$H = E_b \sum_i |i\rangle\langle i| + \sum_{i,j,i\neq j} t_{ij} |i\rangle\langle j|$$

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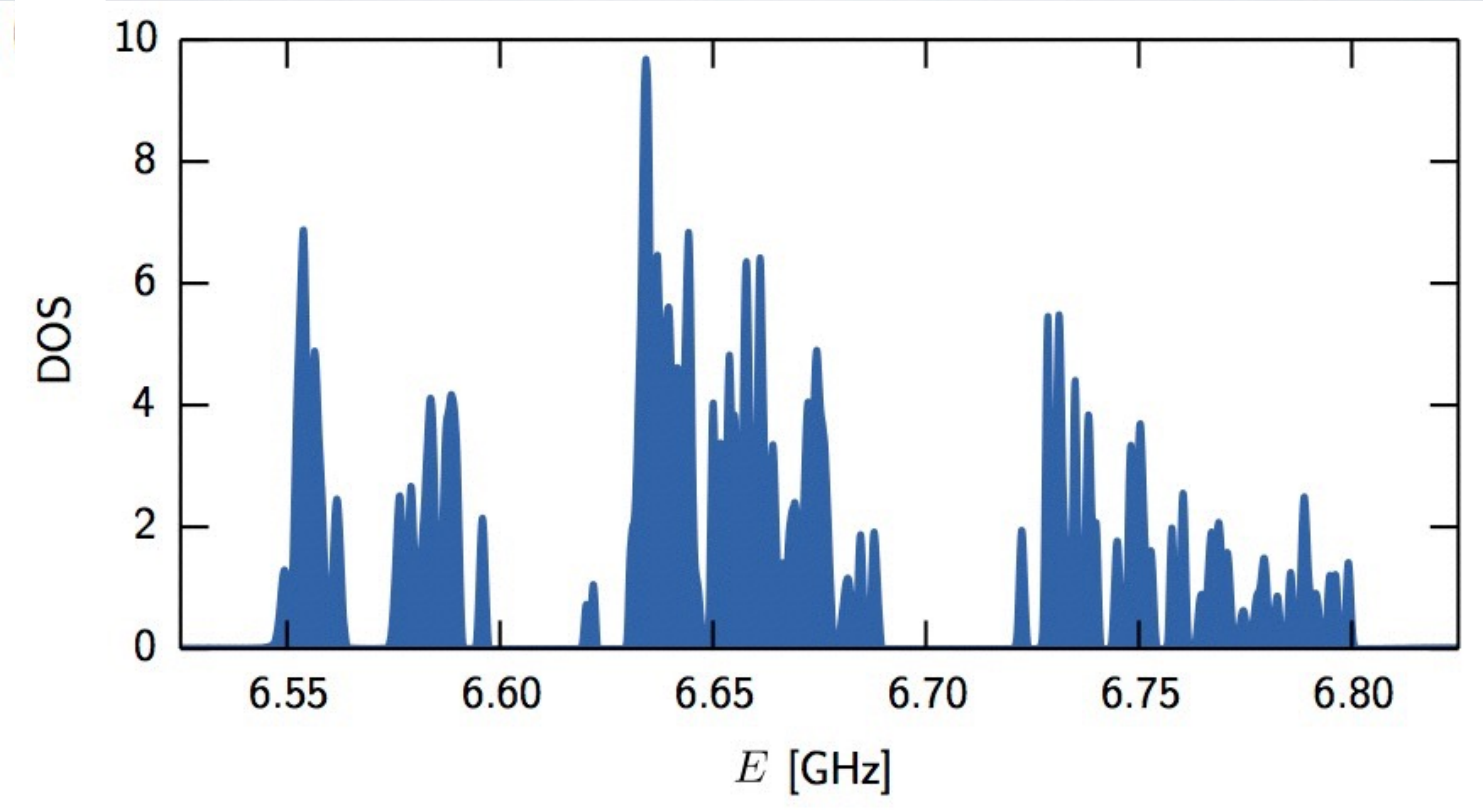
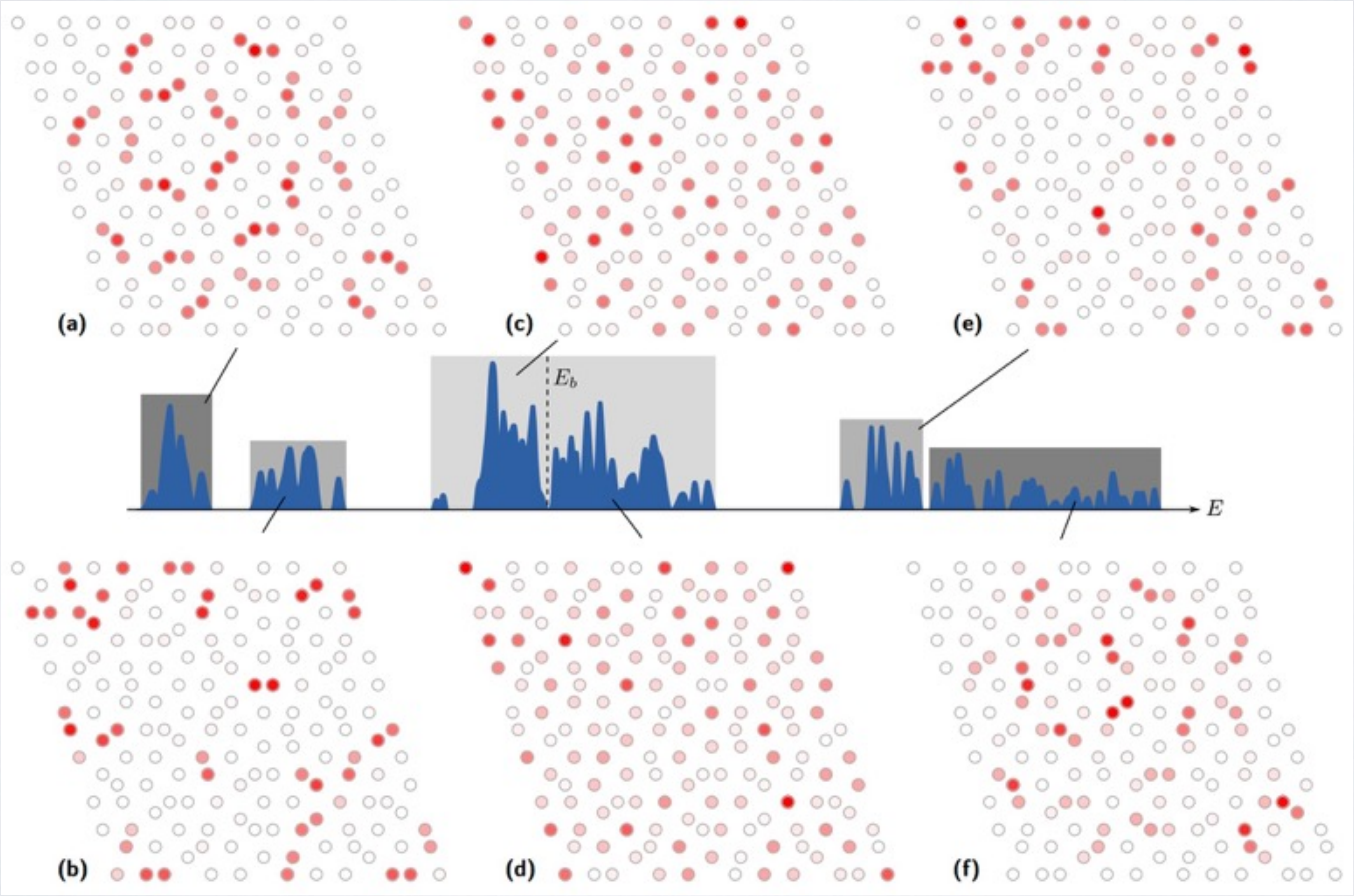
Density of states



Band wavefunctions



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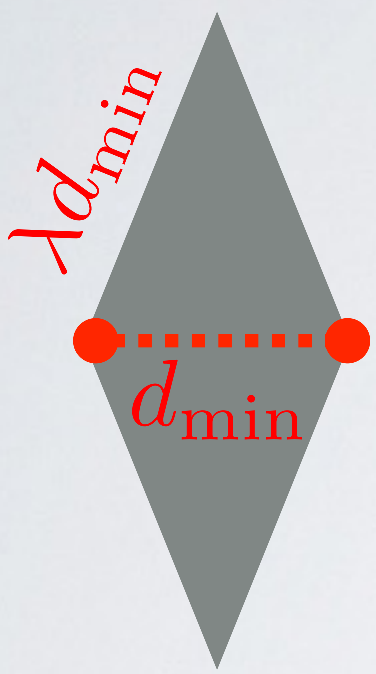
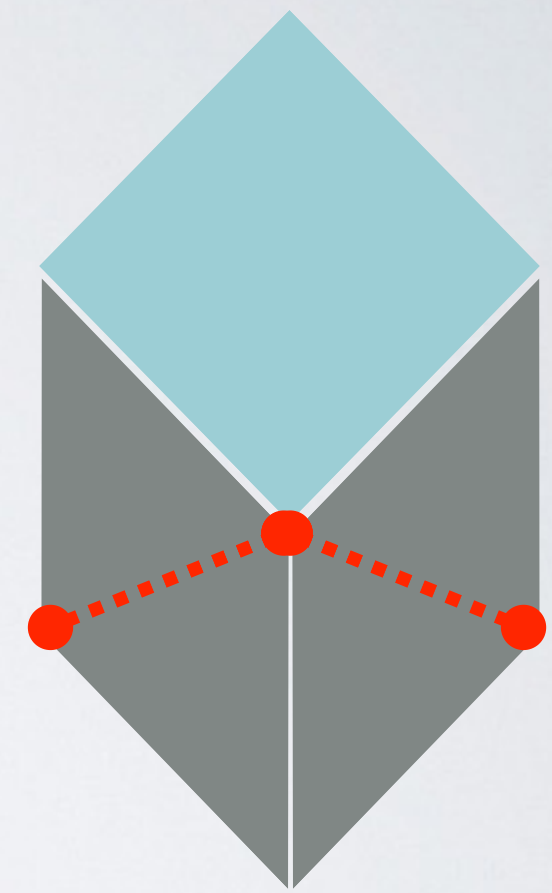
Dominant couplings



dimer

$$d_{\min} = 10\,\mathrm{mm} \Rightarrow t_{\max} \simeq 73\,\mathrm{MHz}$$

$$\lambda d_{\min} \simeq 16\,\mathrm{mm} \Rightarrow t \simeq 8\,\mathrm{MHz}$$



trimer

dominant coupling along the diagonal of the thin rhombus

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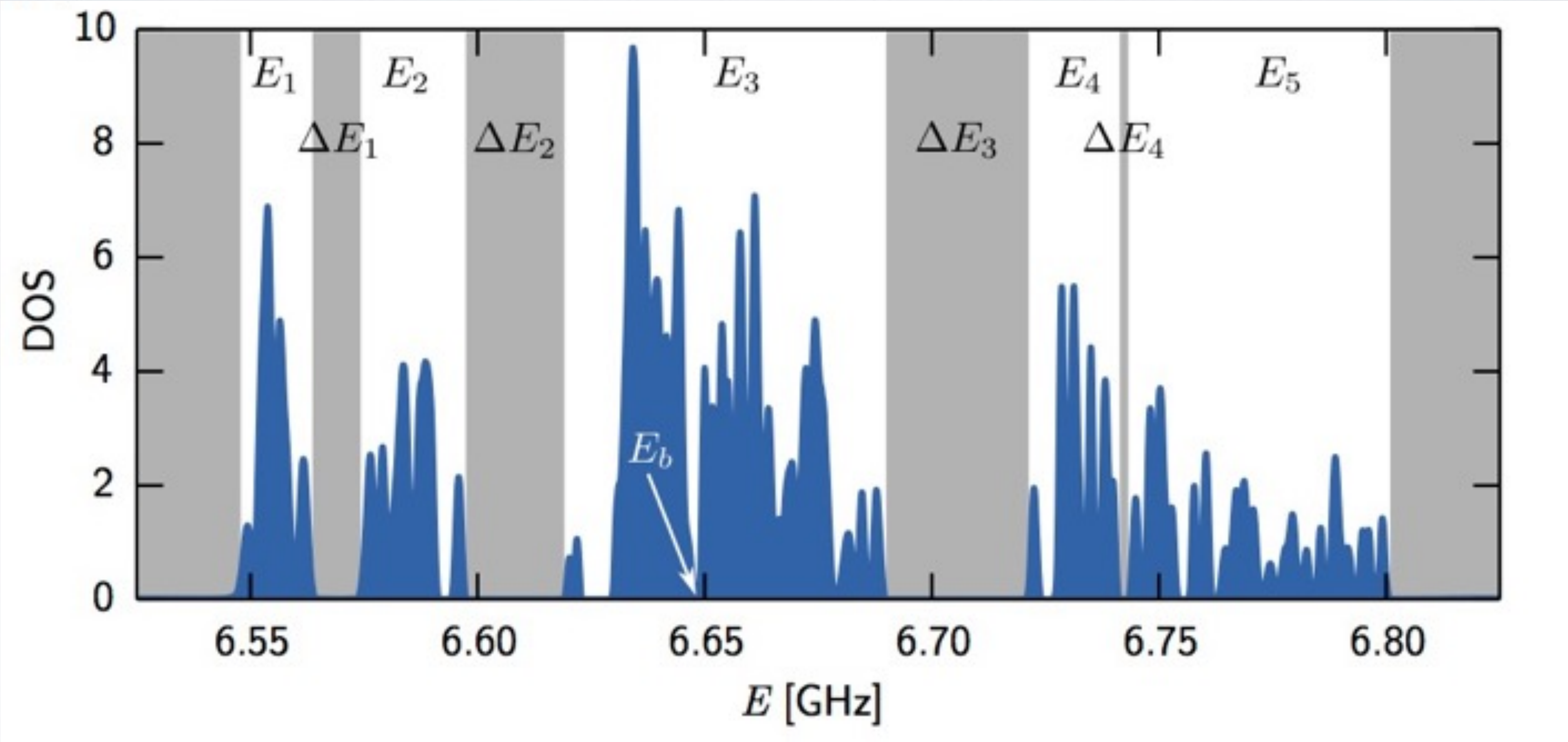
Band structure



$$E_1 = E_b - \sqrt{2}t_{\max} \simeq 6.55\,\mathrm{GHz}$$

$$E_5 = E_b + \sqrt{2}t_{\max} \simeq 6.75\mathrm{GHz}$$

$$E_2 = E_b - t_{\max} \simeq 6.58\,\mathrm{GHz}$$

$$E_4 = E_b + t_{\max} \simeq 6.73\,\mathrm{GHz}$$

$$E_3 = E_b = 6.65\,\mathrm{GHz}$$

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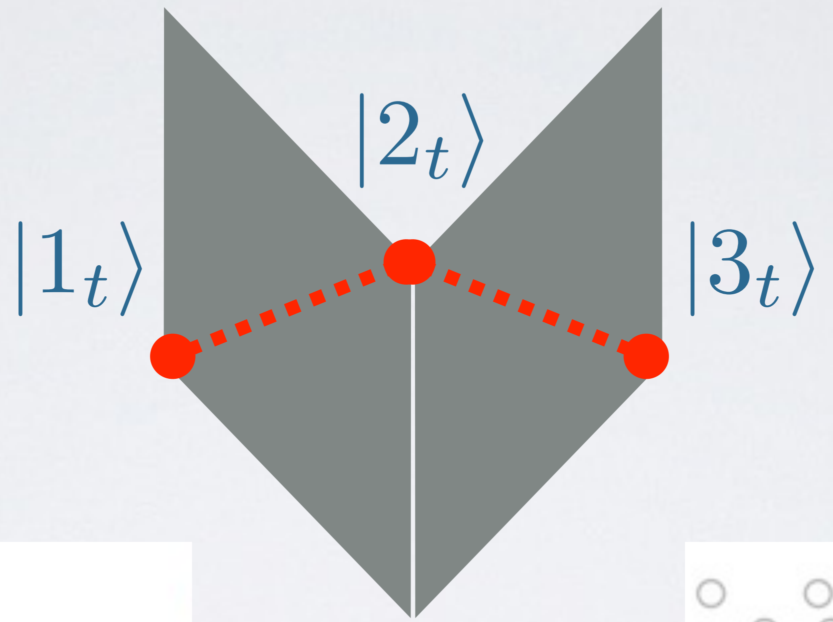
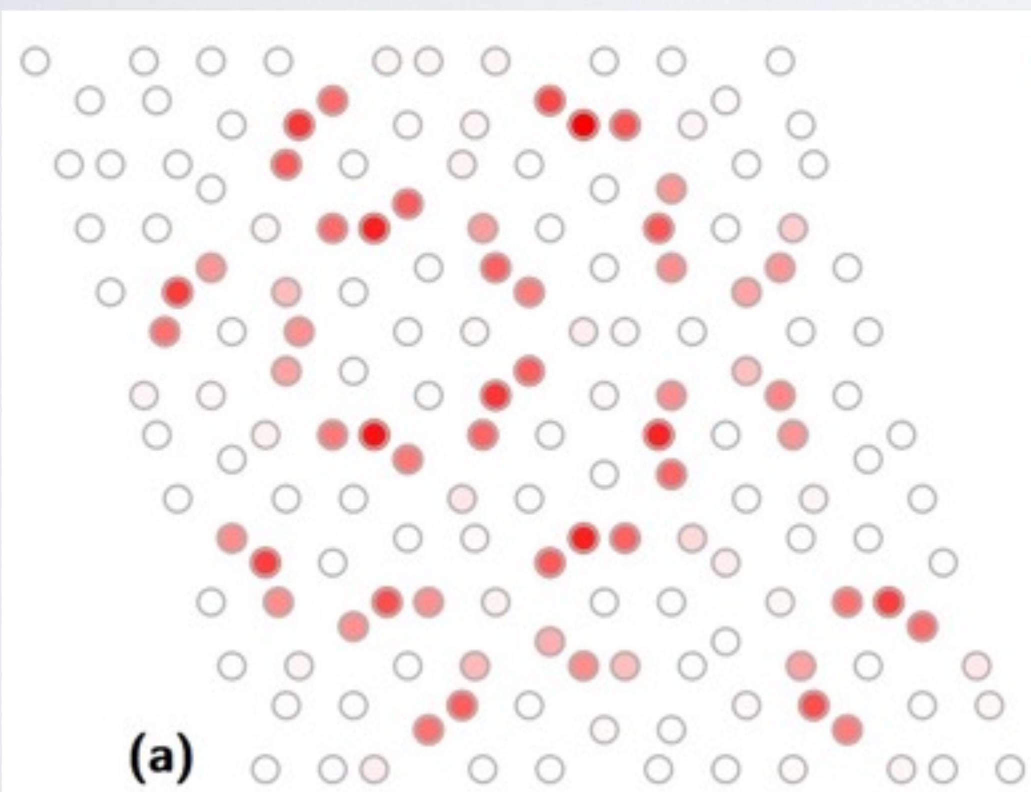
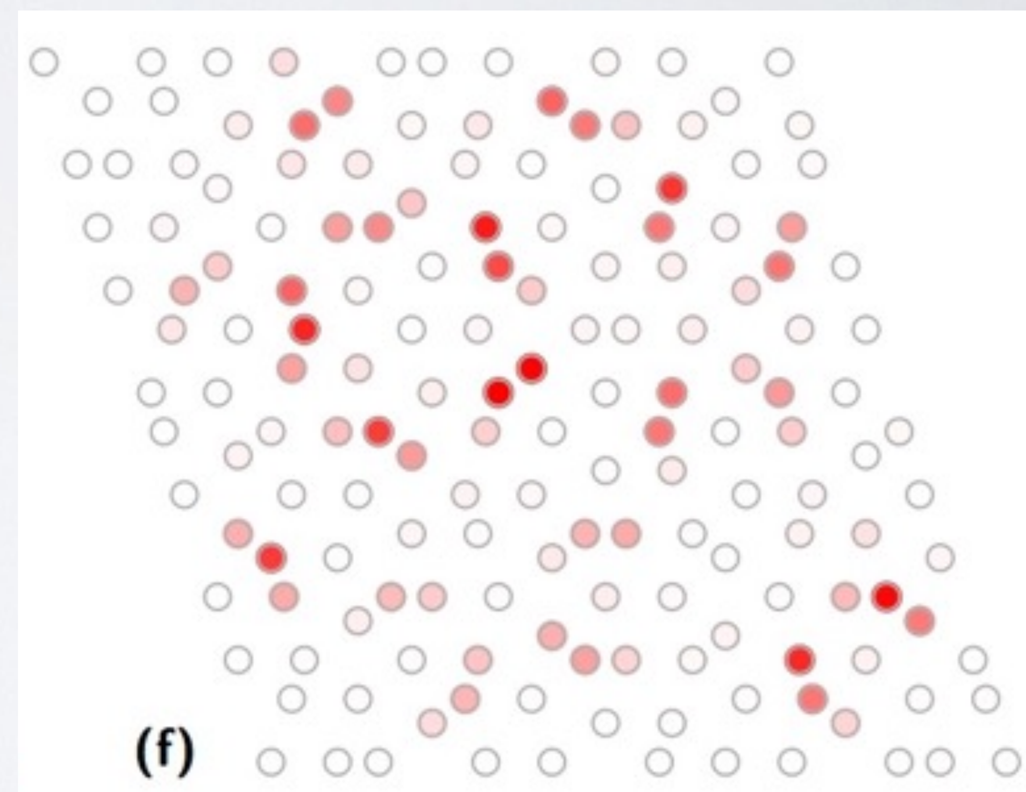
Trimer motif



$$E_1 = E_b - \sqrt{2}t_{\max}$$

$$E_5 = E_b + \sqrt{2}t_{\max}$$





$$|\phi_1\rangle = |1_t\rangle - \sqrt{2}|2_t\rangle + |3_t\rangle$$

$$|\phi_5\rangle = |1_t\rangle + \sqrt{2}|2_t\rangle + |3_t\rangle$$

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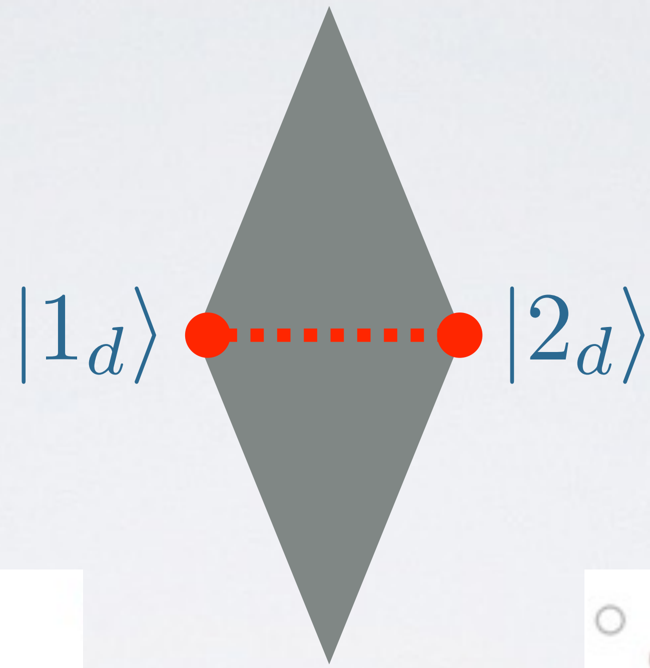
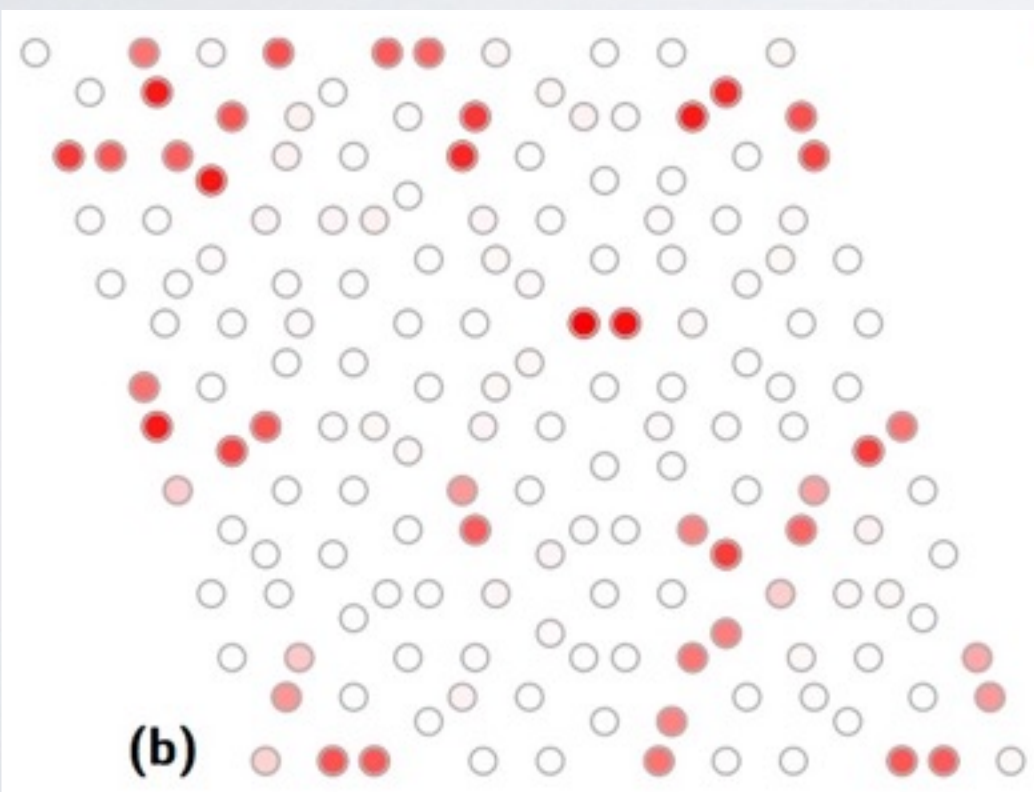
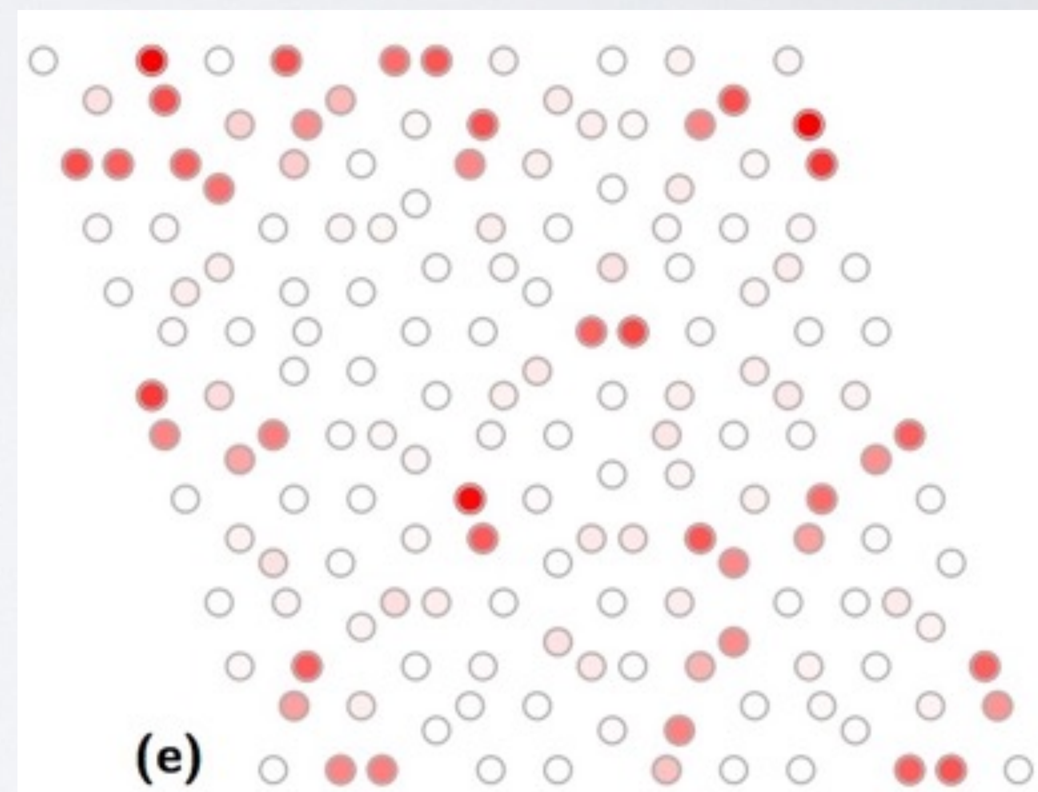
Dimer motif



$E_2 = E_b - t_{\max}$

$E_4 = E_b + t_{\max}$

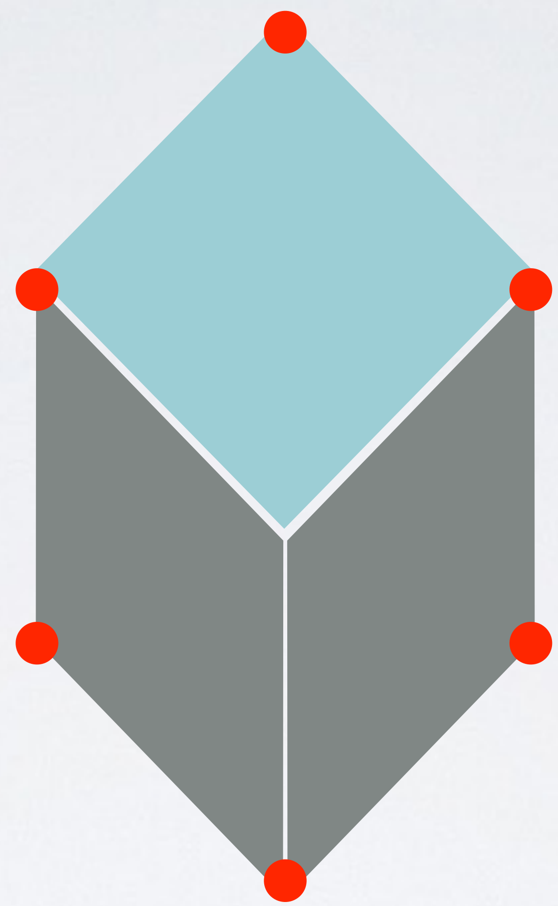


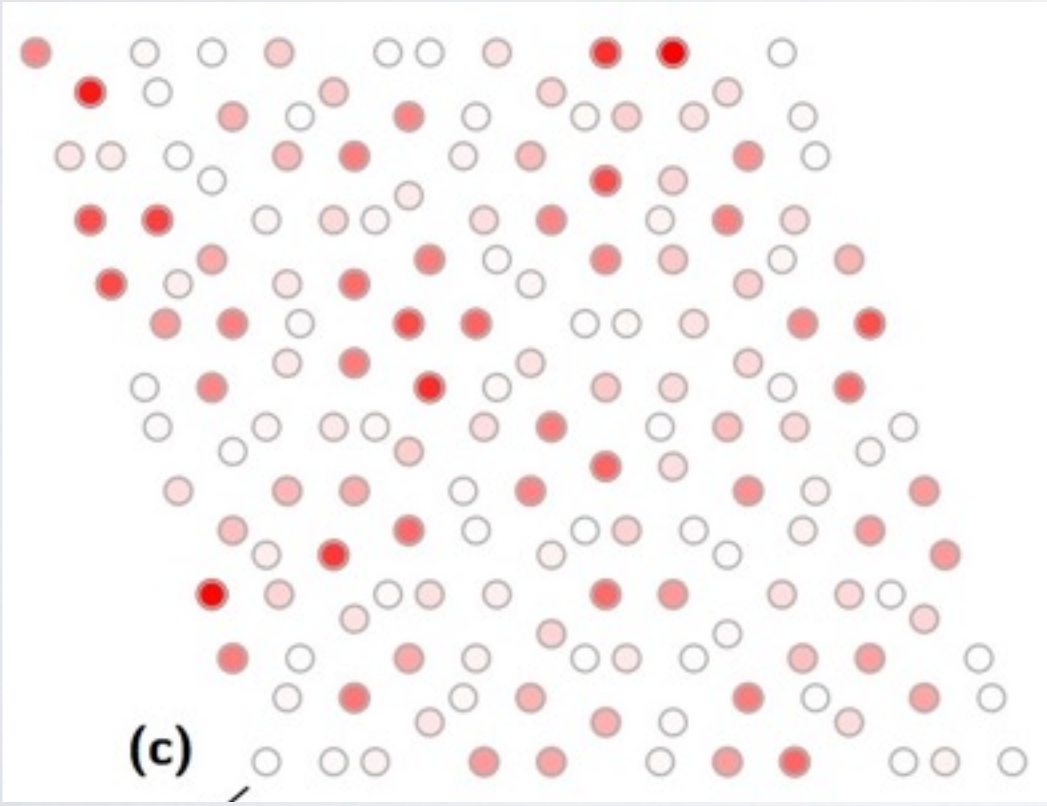


$|\phi_2\rangle = |1_d\rangle - |2_d\rangle$

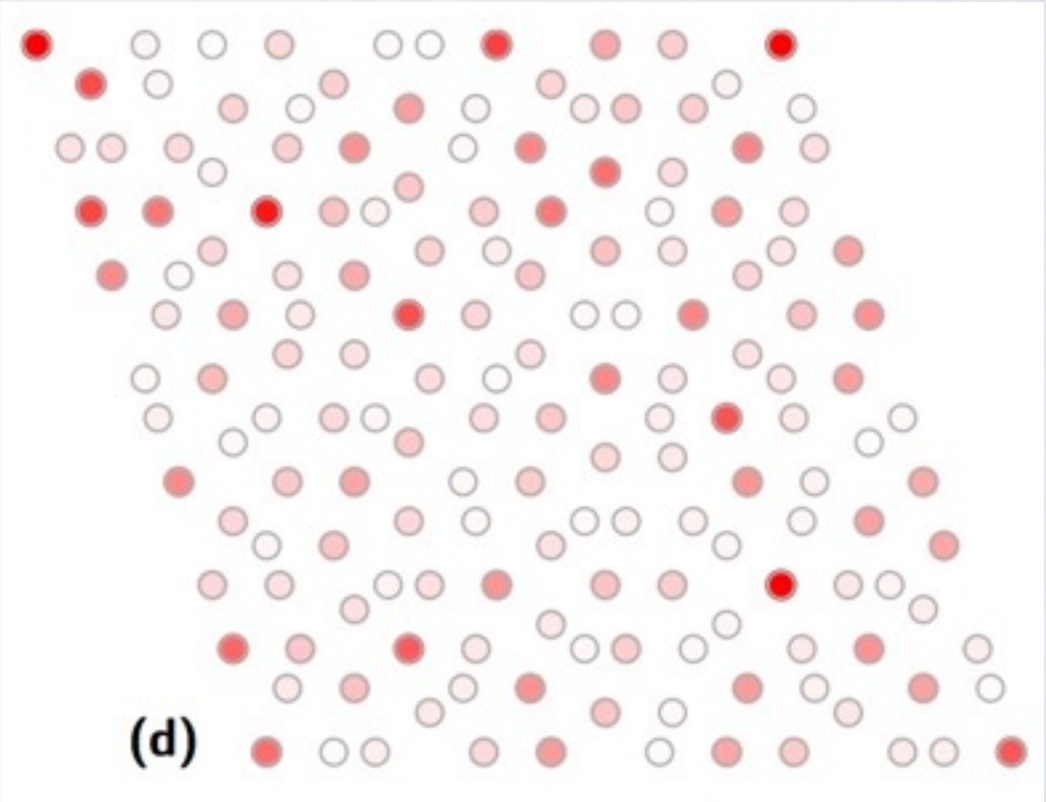
$|\phi_4\rangle = |1_d\rangle + |2_d\rangle$

Isolated sites



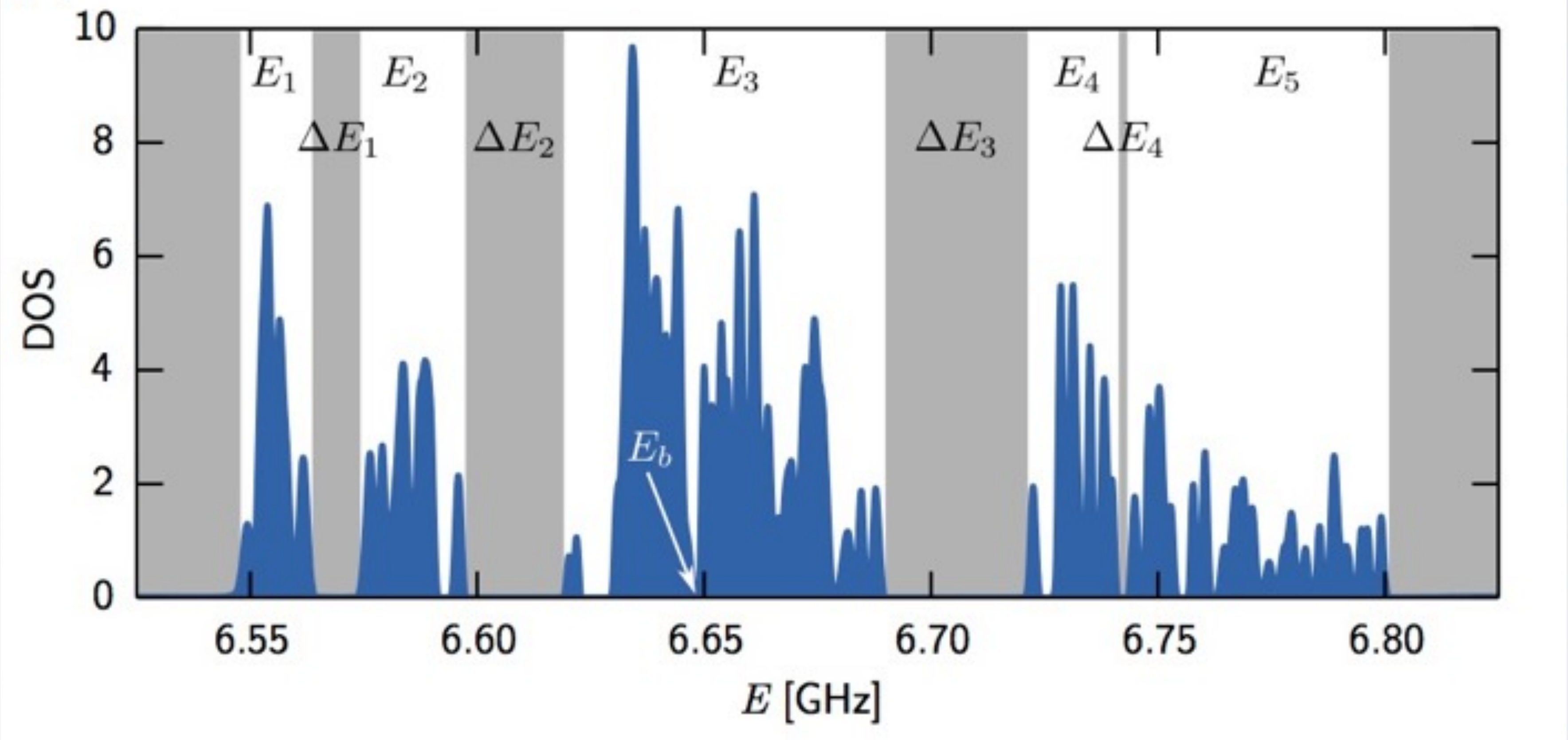


$$E_3 = E_b$$



$$|\phi_{3,a}\rangle = |1_t\rangle - |3_t\rangle \qquad |\phi_{3,b}\rangle = |1_s\rangle$$

Band populations



# of dimers: $\beta_1 = \beta_5 = 5 - 3\lambda$

# of trimers: $\beta_2 = \beta_4 = 5\lambda - 8$

# of others: $\beta_3 = 1 - 2\beta_1 - 2\beta_2 = 7 - 4\lambda$

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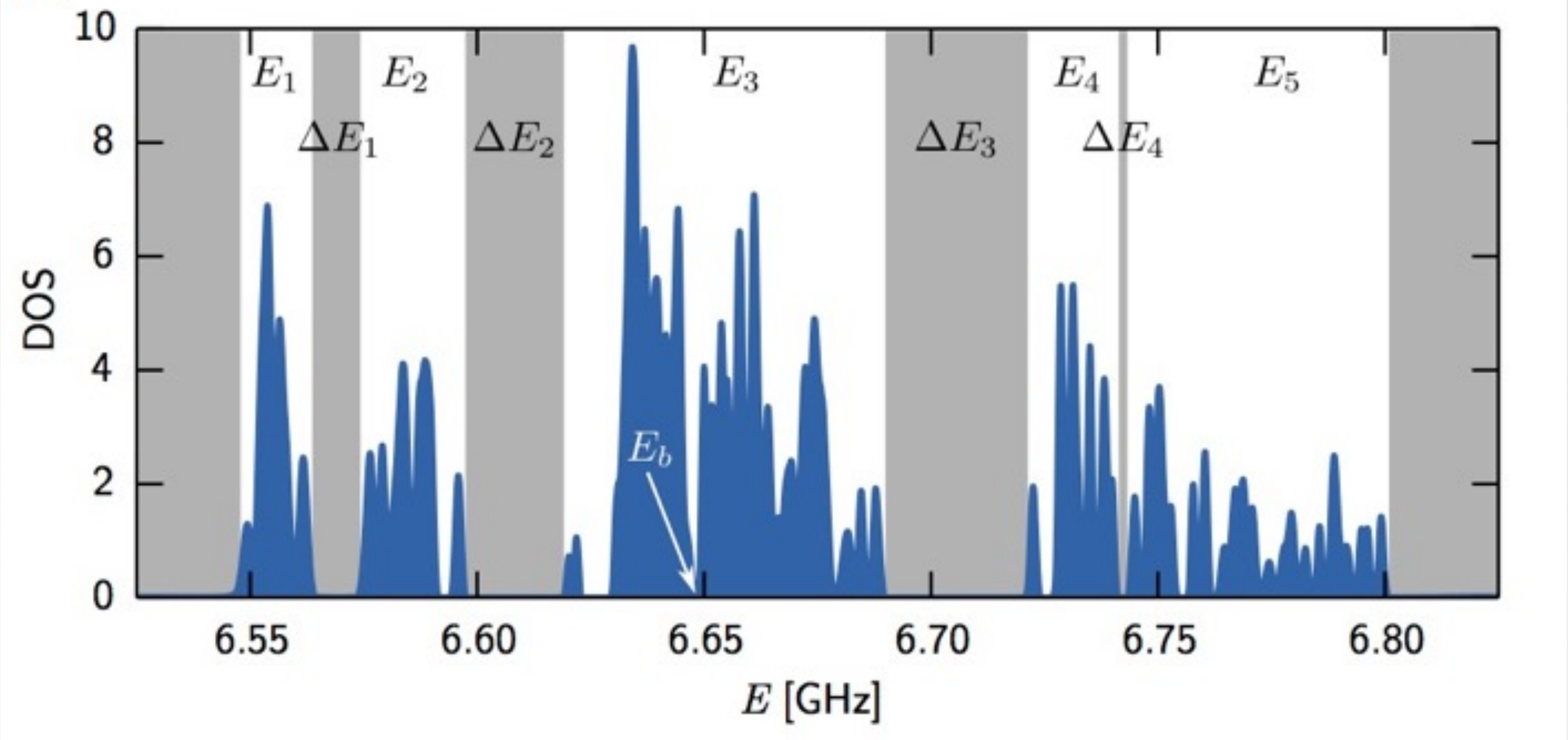
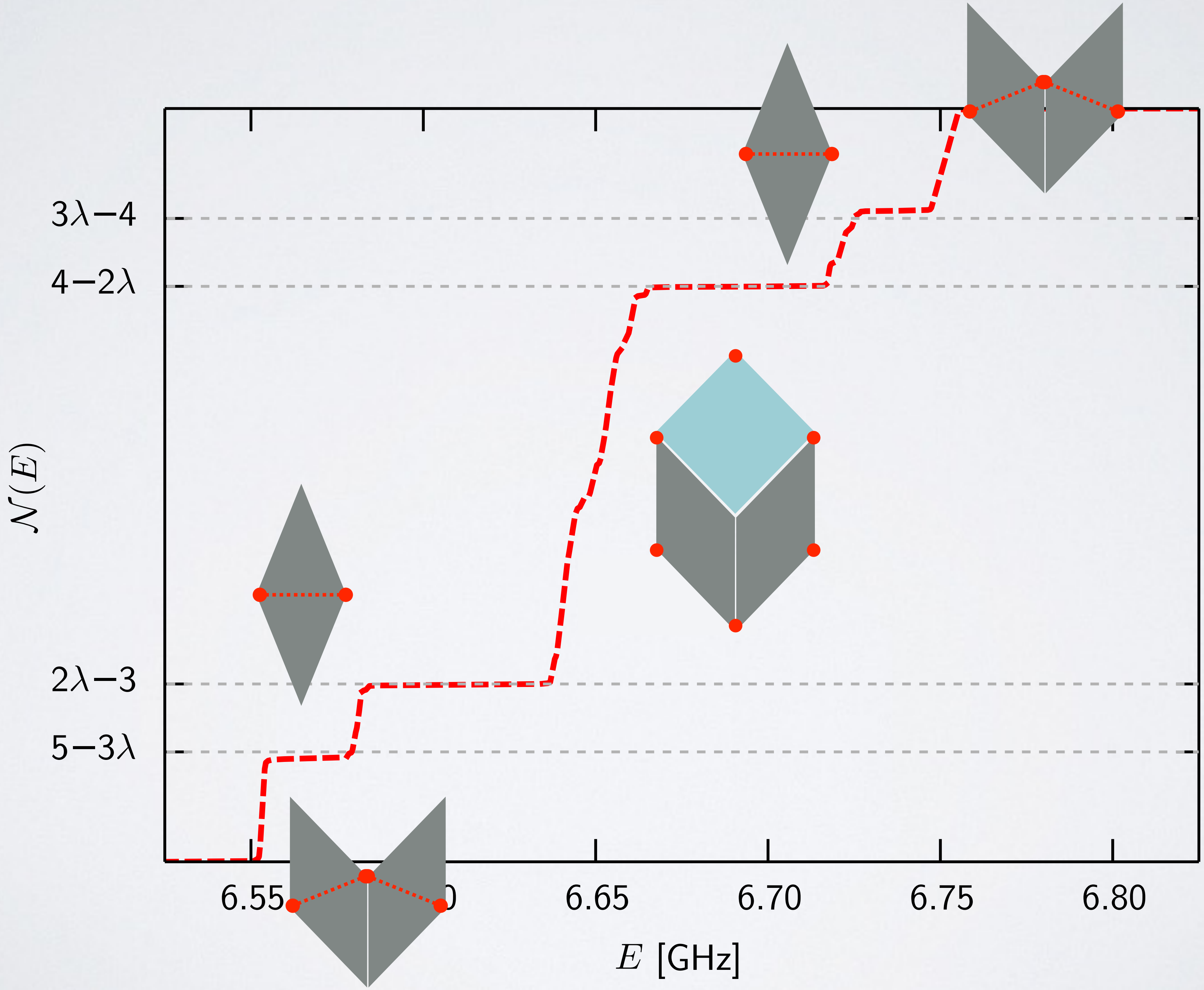
Band populations



$$\mathcal{N}(E) = \begin{cases} \beta_1 = 5 - 3\lambda, & E \in \Delta E_1 \\ \beta_1 + \beta_2 = 2\lambda - 3, & E \in \Delta E_2 \\ \beta_1 + \beta_2 + \beta_3 = 4 - 2\lambda, & E \in \Delta E_3 \\ \beta_1 + \beta_2 + \beta_3 + \beta_4 = 3\lambda - 4, & E \in \Delta E_4, \end{cases}$$

Vignolo *et al.*, Phys. Rev. B (2016)

Physical picture of the gap labeling



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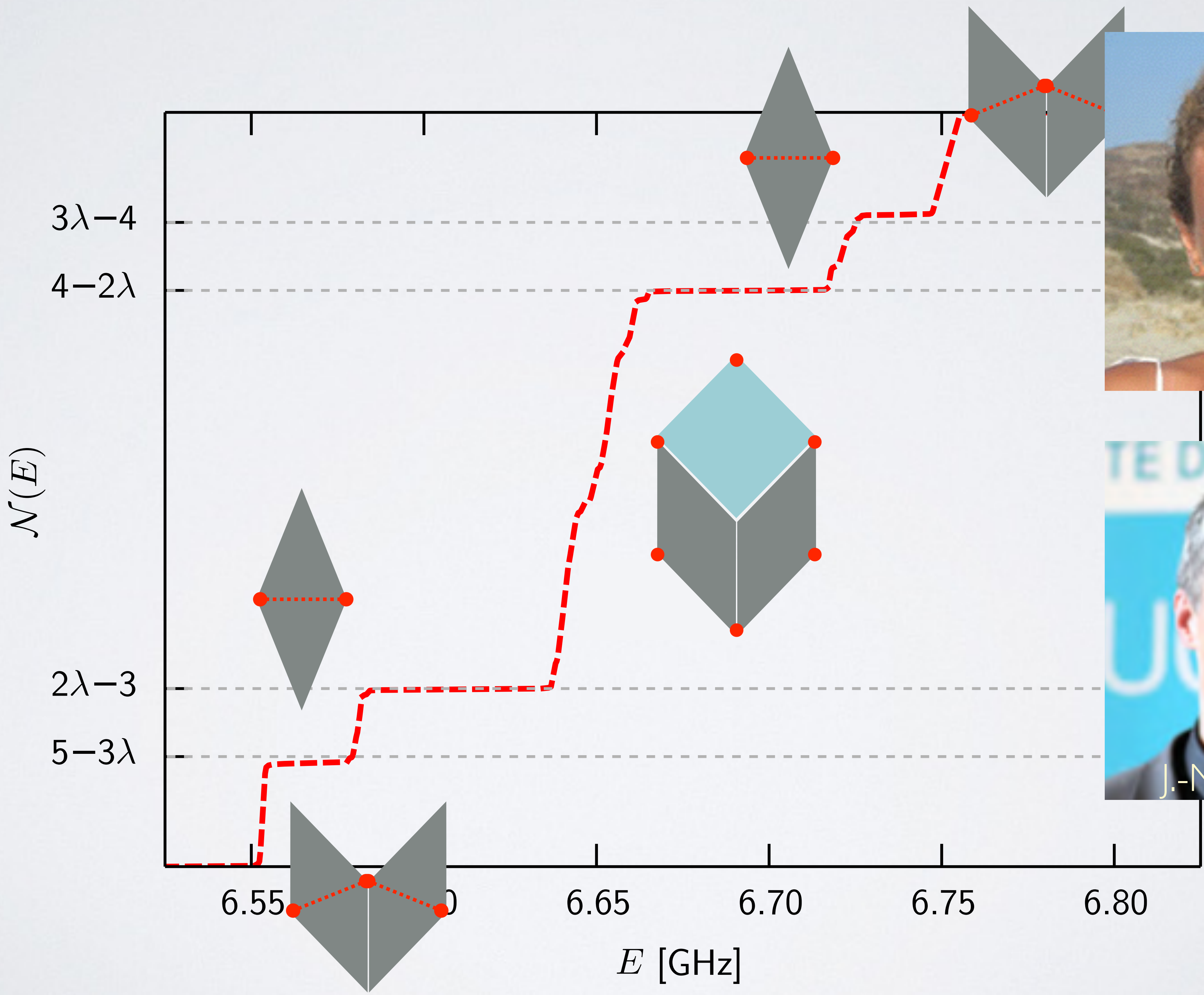
Vignolo *et al.*, Phys. Rev. B (2016)

Physical picture of the gap labeling



Nice physics 😊

2D Materials

2D Mater. **4** (2017) 025008

PAPER

Partial chiral symmetry-breaking as a route to spectrally isolated topological defect states in two-dimensional artificial materials

Charles Poli[1], Henning Schomerus[1], Matthieu Bellec[2], Ulrich Kuhl[2] and Fabrice Mortessagne[2]

Microwave emulations and tight-binding calculations of transport in polyacetylene

Thomas Stegmann[a], John A. Franco-Villafañe[b,a], Yenni P. Ortiz[a], Ulrich Kuhl[c], Fabrice Mortessagne[c], Thomas H. Seligman[a,d]

PHYSICAL REVIEW B **95**, 035413 (2017)

Transport gap engineering by contact geometry in graphene nanoribbons: Experimental and theoretical studies on artificial materials

Thomas Stegmann,[1,*] John A. Franco-Villafañe,[1,2,†] Ulrich Kuhl,[3] Fabrice Mortessagne,[3] and Thomas H. Seligman[1,4]

RAPID COMI

PHYSICAL REVIEW B **95**, 121409(R) (2017)

Waveguide photonic limiters based on topologically protected resonant modes

U. Kuhl,[1] F. Mortessagne,[1] E. Makri,[2] I. Vitebskiy,[3] and T. Kottos[2]

ARTICLE

Received 29 Jul 2014 | Accepted 19 Feb 2015 | Published 2 Apr 2015 DOI: 10.1038/ncomms7710 OPEN

Selective enhancement of topologically induced interface states in a dielectric resonator chain

Charles Poli[1], Matthieu Bellec[2], Ulrich Kuhl[2], Fabrice Mortessagne[2] & Henning Schomerus[1]

PRL **110,** 033902 (2013) PHYSICAL REVIEW LETTERS week ending 18 JANUARY 2013

Topological Transition of Dirac Points in a Microwave Experiment

Matthieu Bellec,[1] Ulrich Kuhl,[1] Gilles Montambaux,[2] and Fabrice Mortessagne[1,*]

PHYSICAL REVIEW B **93**, 075141 (2016)

Energy landscape in a Penrose tiling

Patrizia Vignolo,[1,*] Matthieu Bellec,[2] Julian Böhm,[2] Abdoulaye Camara,[1] Jean-Marc Gambaudo,[1] Ulrich Kuhl,[2] and Fabrice Mortessagne[2,†]

PRL **111,** 170405 (2013) PHYSICAL REVIEW LETTERS week ending 25 OCTOBER 2013

First Experimental Realization of the Dirac Oscillator

J. A. Franco-Villafañe,[1] E. Sadurní,[2] S. Barkhofen,[3] U. Kuhl,[4] F. Mortessagne,[4] and T. H. Seligman[1,5]

Manipulation of edge states in microwave artificial graphene

Matthieu Bellec[1], Ulrich Kuhl[1], Gilles Montambaux[2] and Fabrice Mortessagne[1]