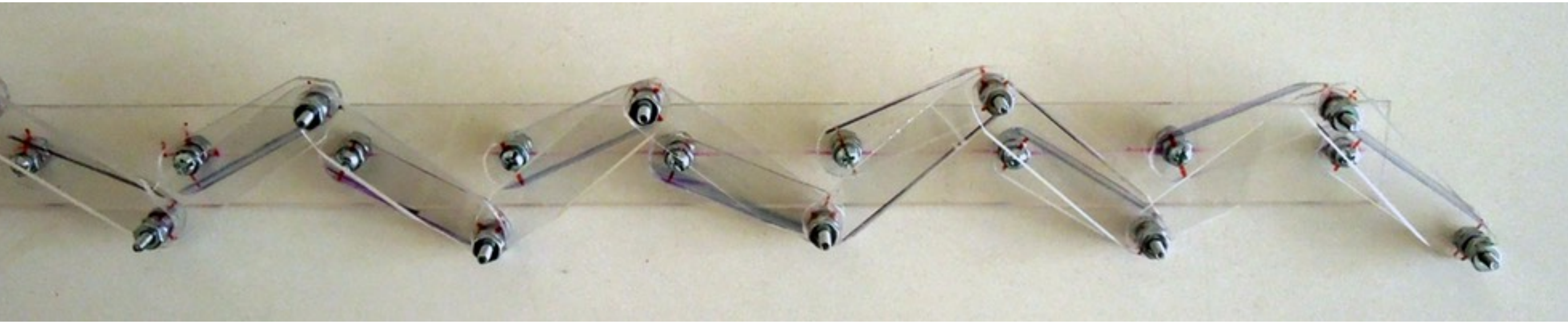
Mechanisms and nonlinear waves from topological modes



Bryan Gin-ge Chen

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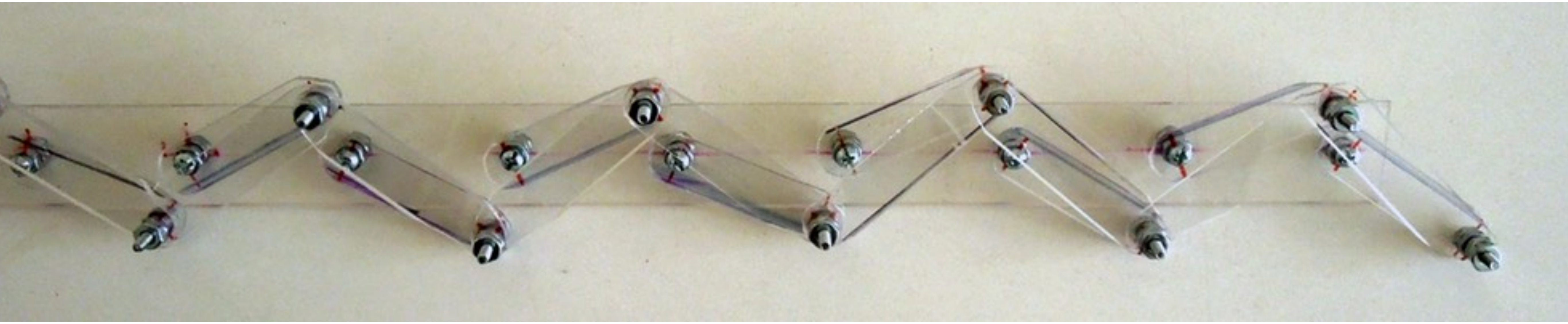
How I got my boss to buy me $600 of LEGO



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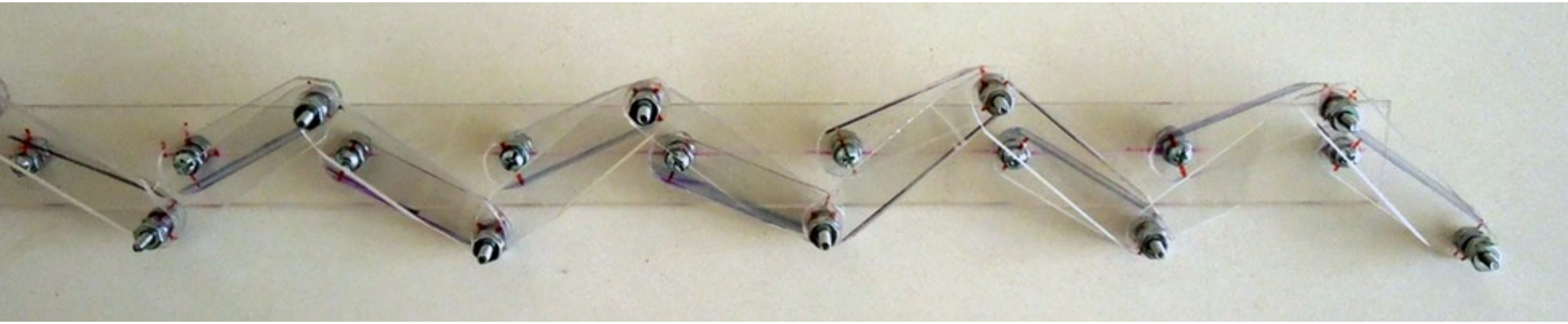

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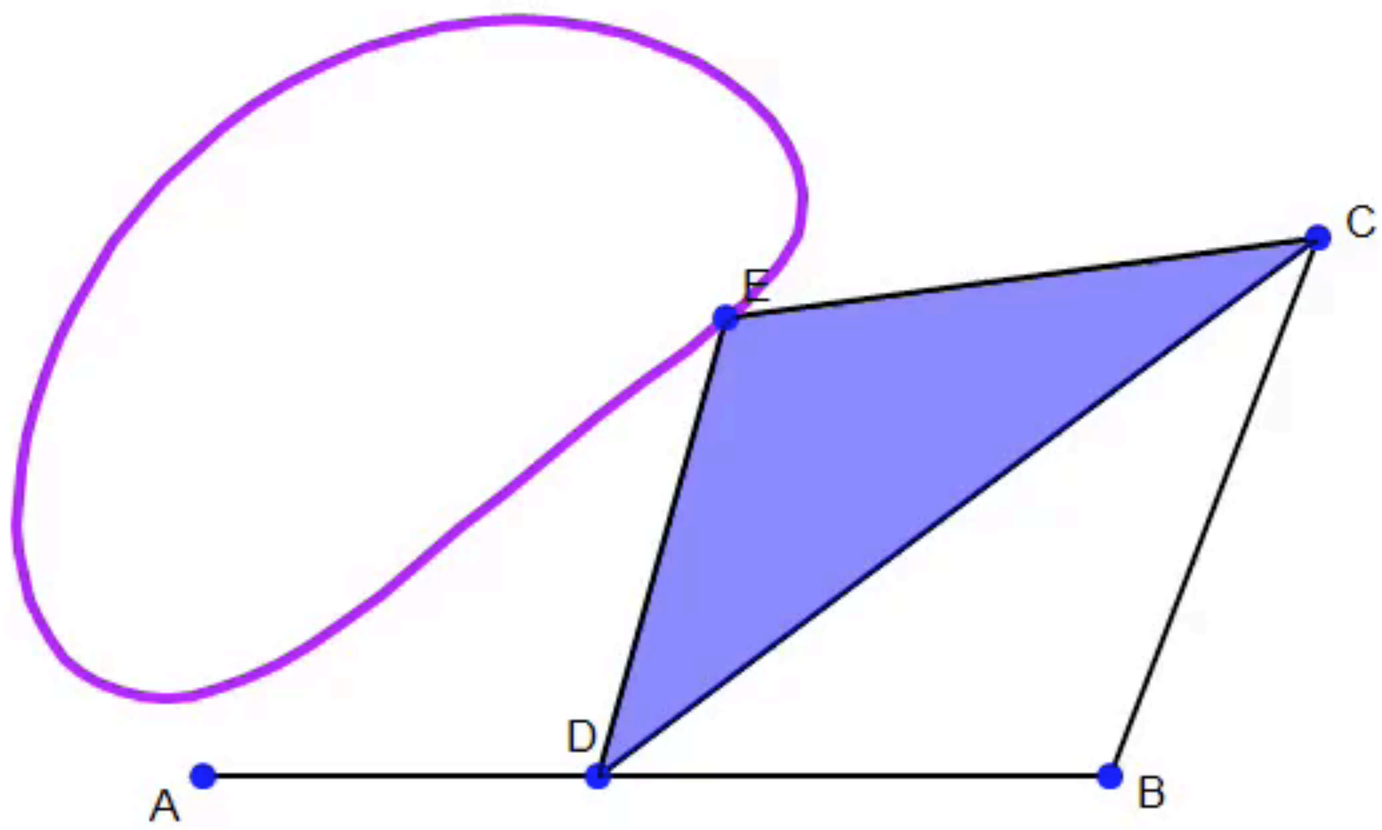
What is a linkage ?

Network of rigid bars connected by joints

http://en.wikipedia.org/wiki/File:4_bar_linkage_animated.gif

What is a linkage ?



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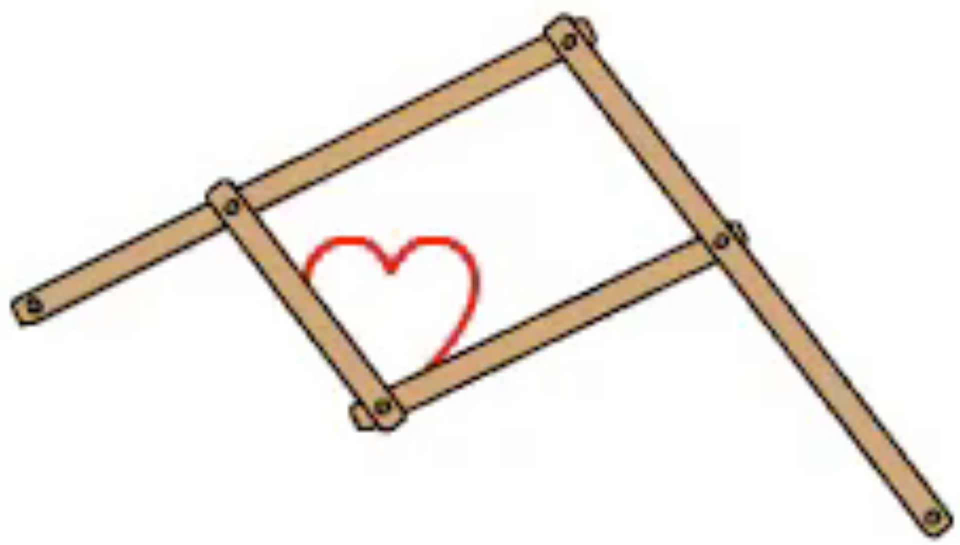

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Ron Resch, "The Paper and Stick Film" 1971

vimeo.com/36122966

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From mechanisms to **metamaterials** ...

Ron Resch, "The Paper and Stick Film" 1971

vimeo.com/36122966

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Can we understand these **materials** and design their **motions**?

Ron Resch, "The Paper and Stick Film" 1971

vimeo.com/36122966

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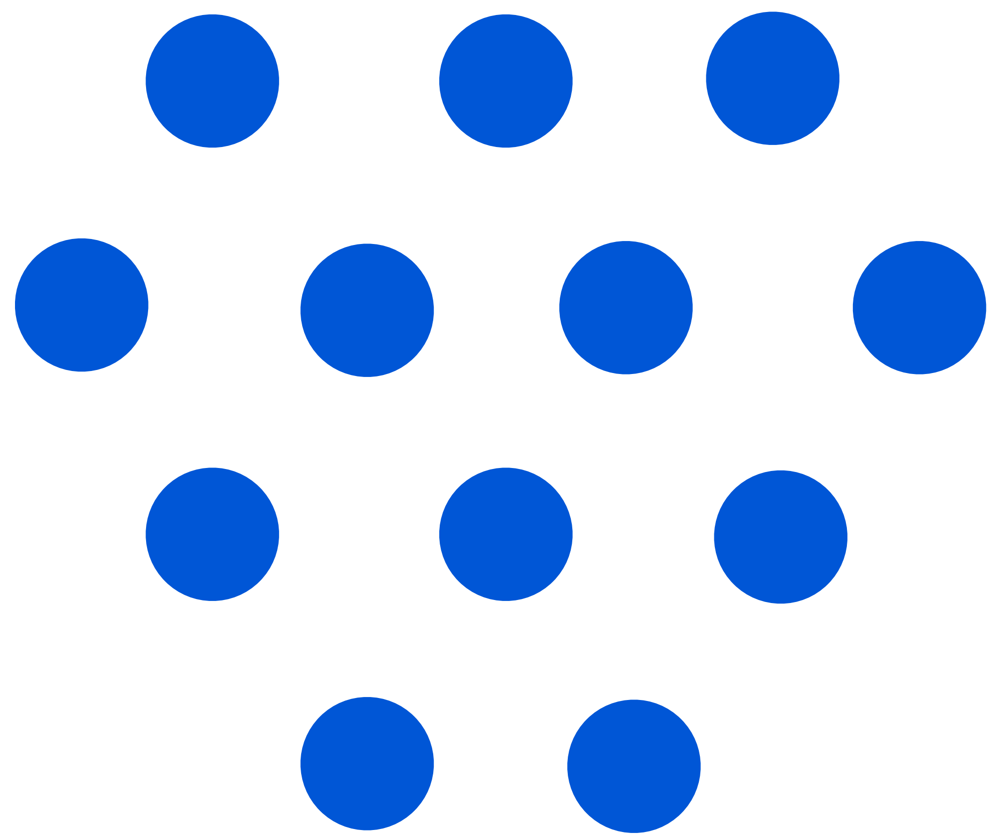
Marginal Rigidity

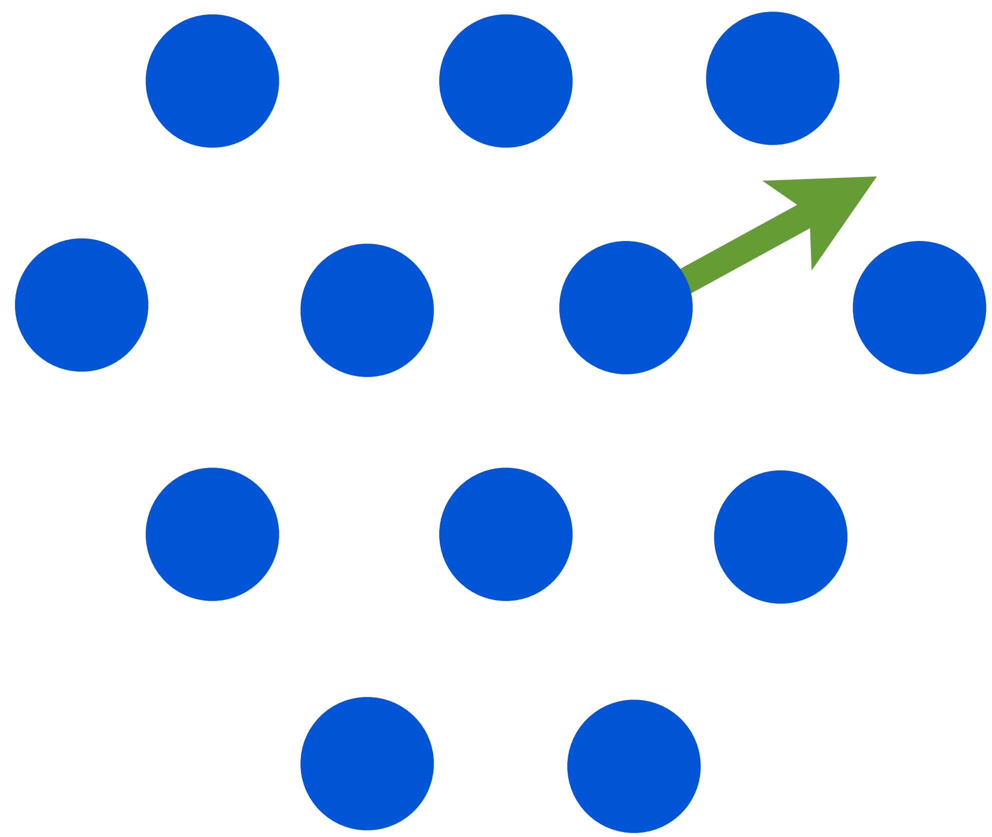


Degrees of freedom >> constraints

Under-coordinated

Maxwell 1864
Alexander 1998
O'Hern et al 2003
Wyart et al 2005

Marginal Rigidity



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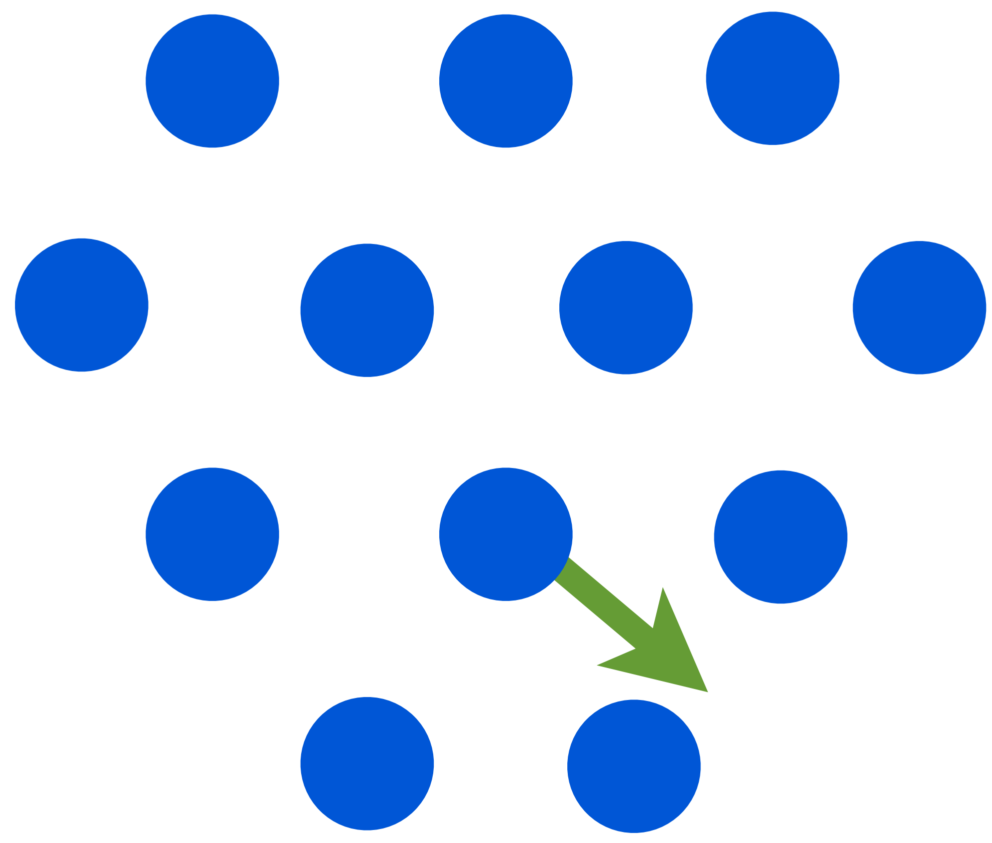

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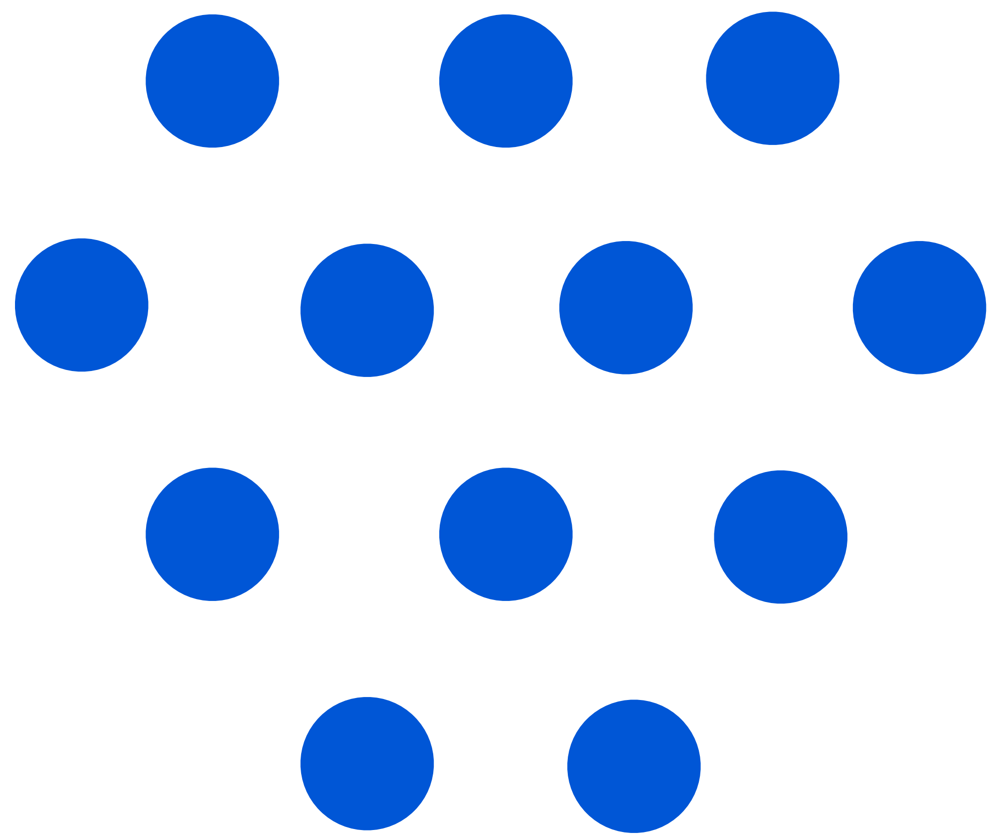

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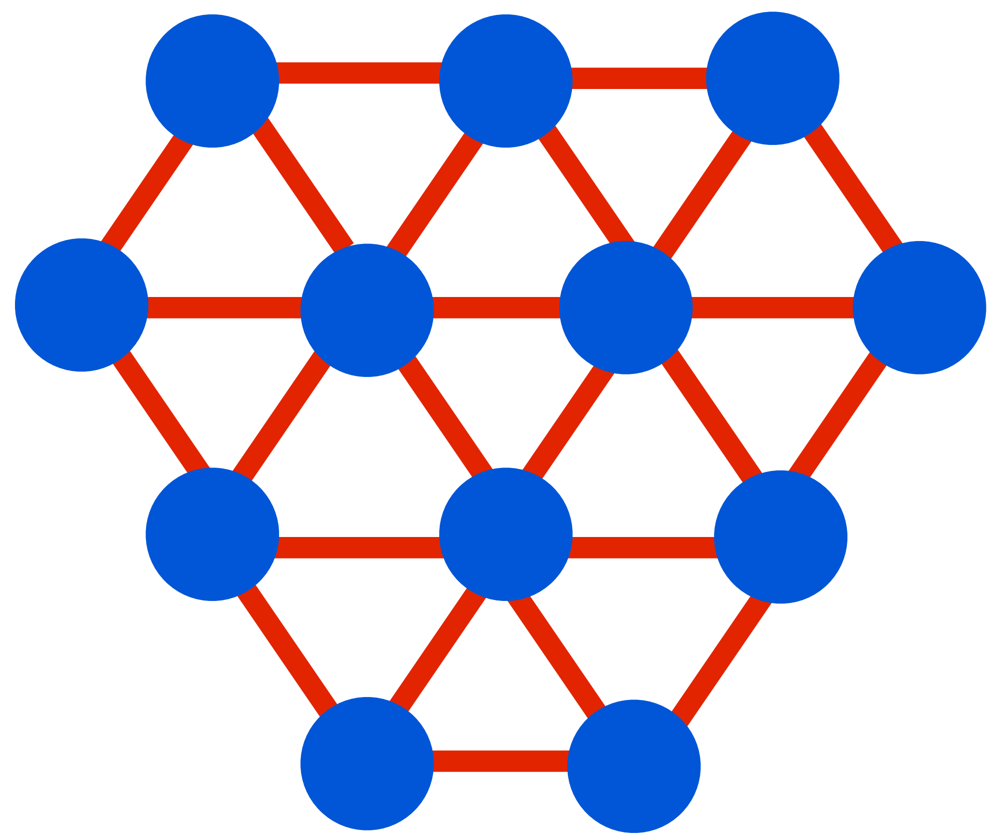

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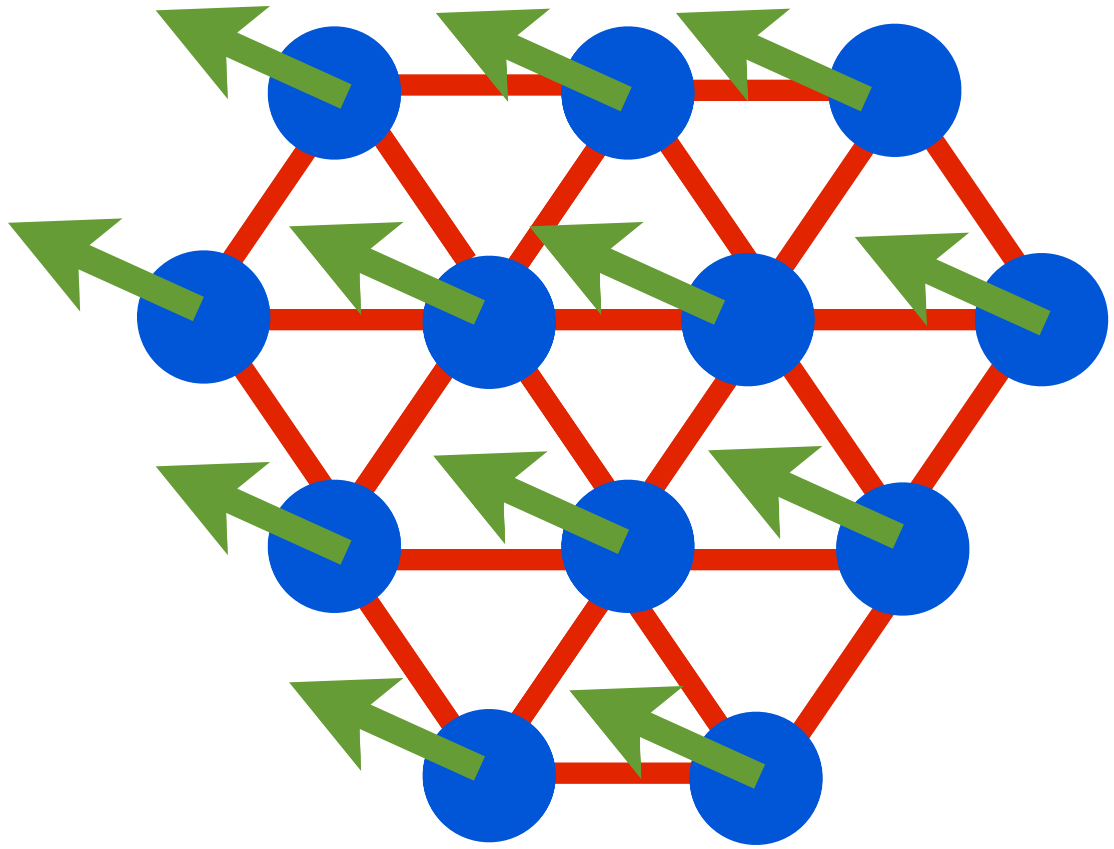

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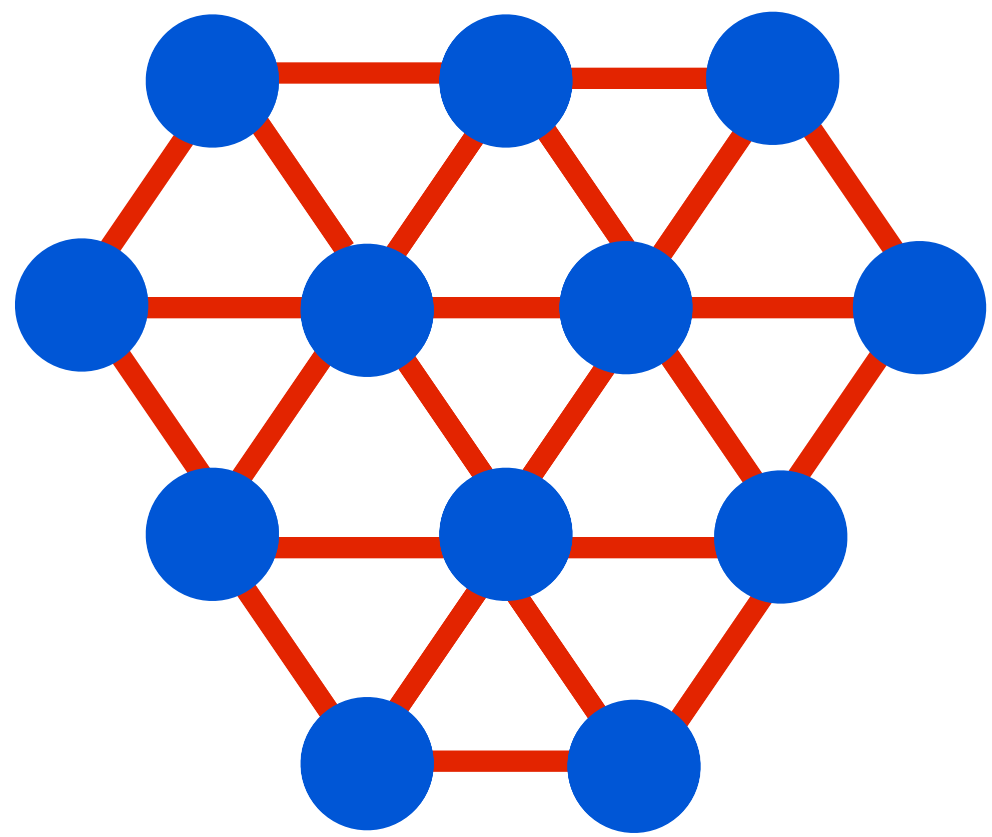

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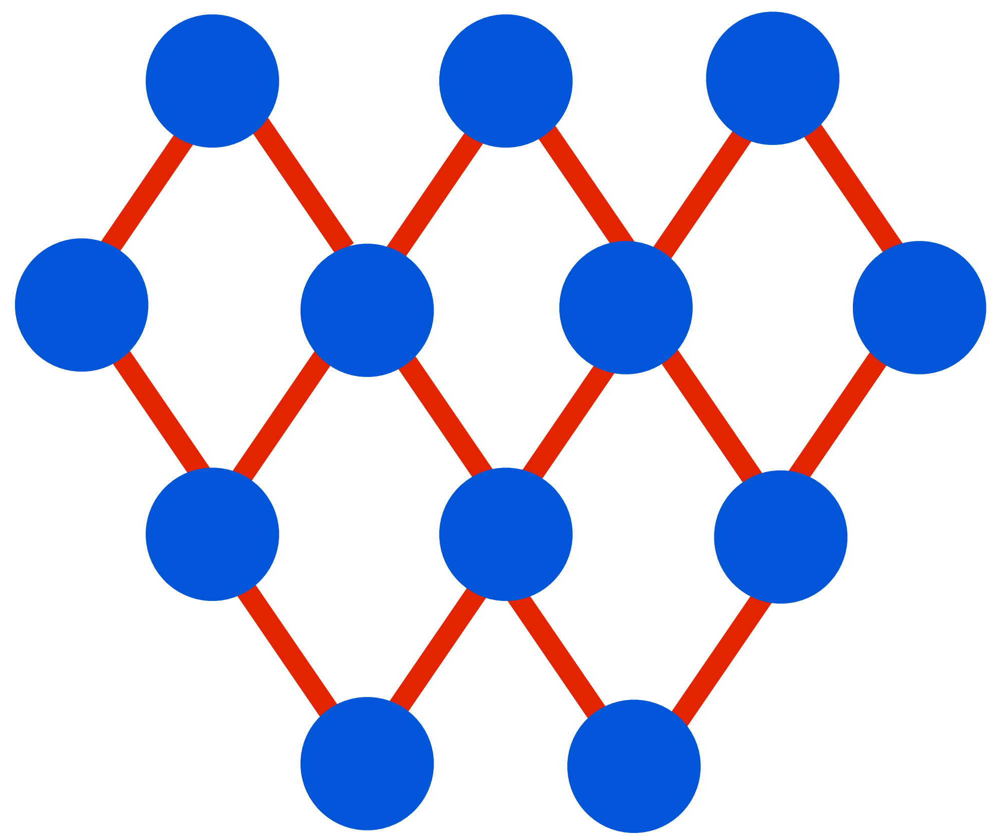

Degrees of freedom ≈ constraints

(bulk) **Isostatic**

Maxwell 1864
Alexander 1998
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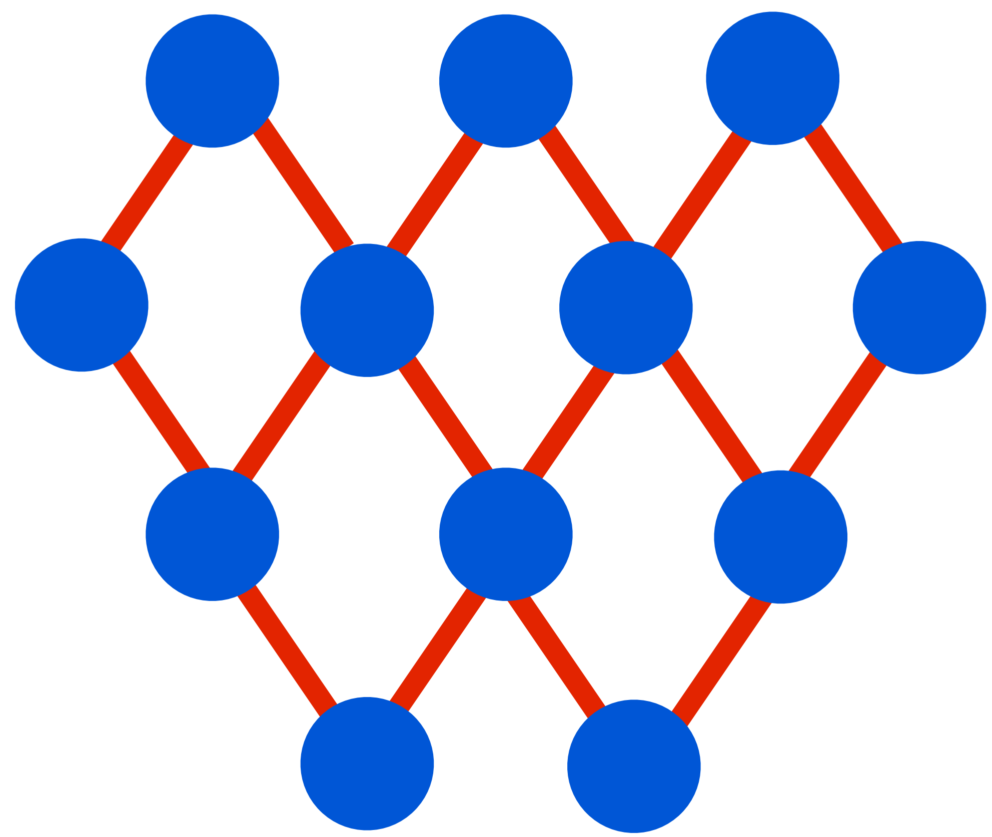
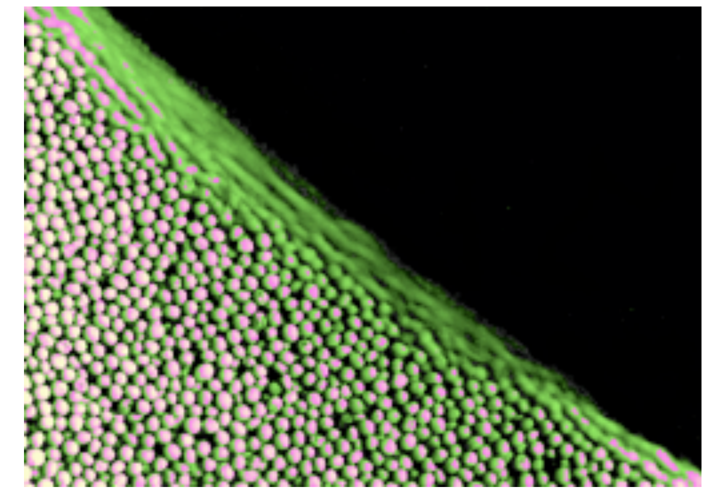
Marginal Rigidity





Jaeger and Nagel 1992

Degrees of freedom ≈ constraints

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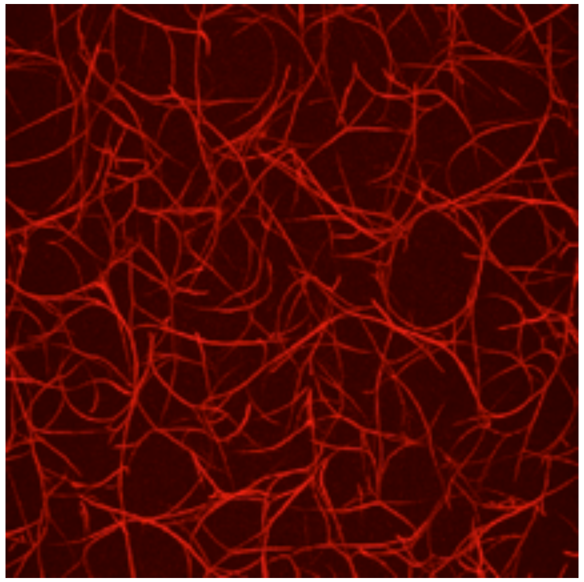
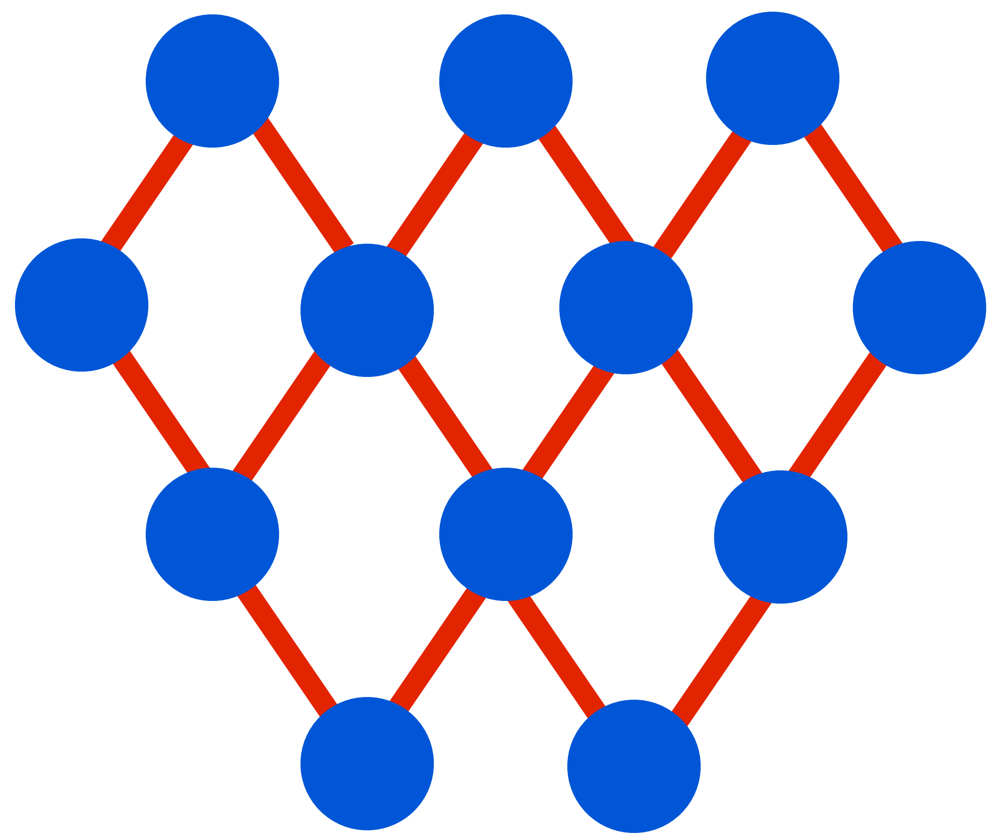
Marginal Rigidity



Andreas Bausch, TUM, http://bio.ph.tum.de/home/e27-prof-dr-bausch/bausch-home.html



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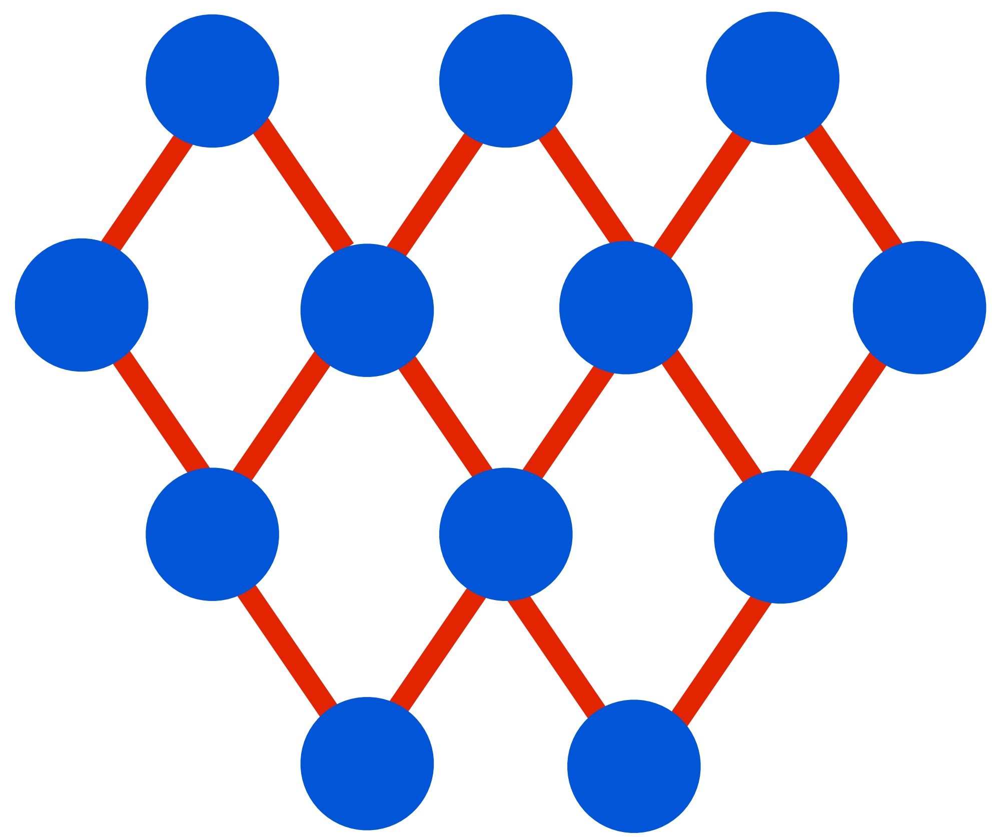

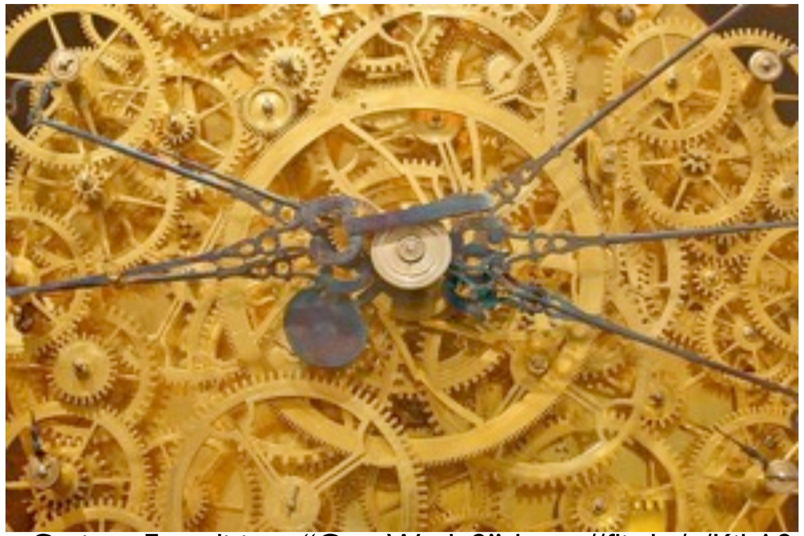

Curious Expeditions, "Gear Work 2", https://flic.kr/p/KikA9

Degrees of freedom ≈ constraints

(bulk) **Isostatic**

Maxwell 1864
Alexander 1998
O'Hern et al 2003
Wyart et al 2005

What can **theoretical physics** say about linkages?

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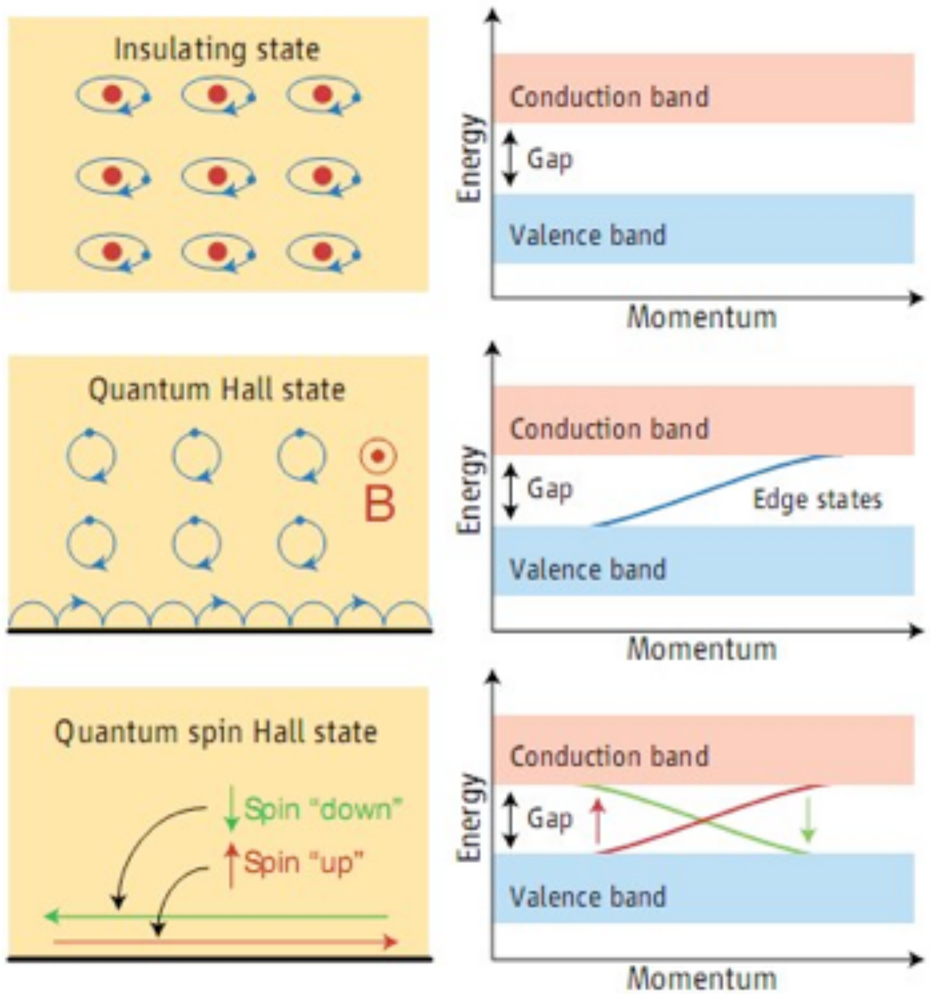
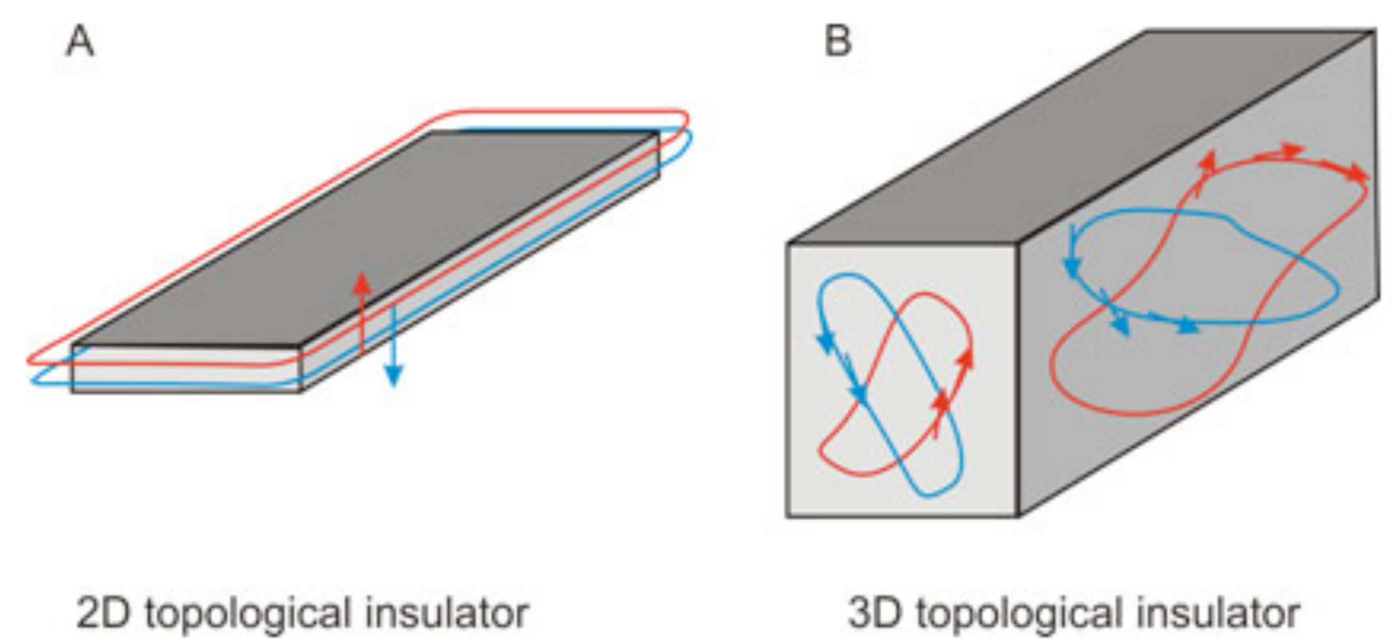
Topological Matter



Kane, Mele, Science 2006



https://www-ssrl.slac.stanford.edu/research/highlights_archive/topological_insulator.html

Electronic properties **insensitive to smooth changes** in material parameters

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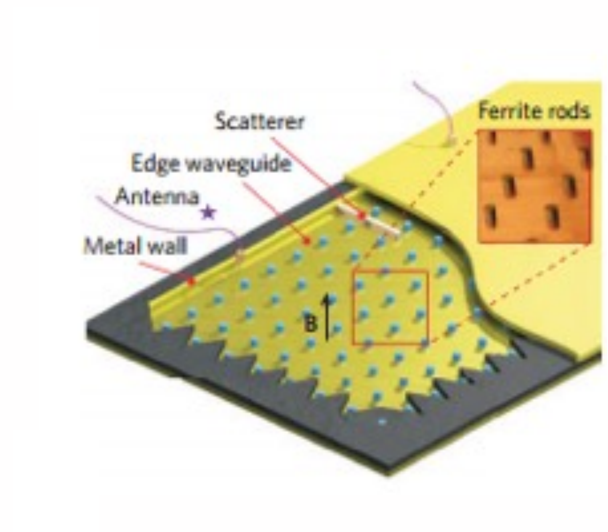
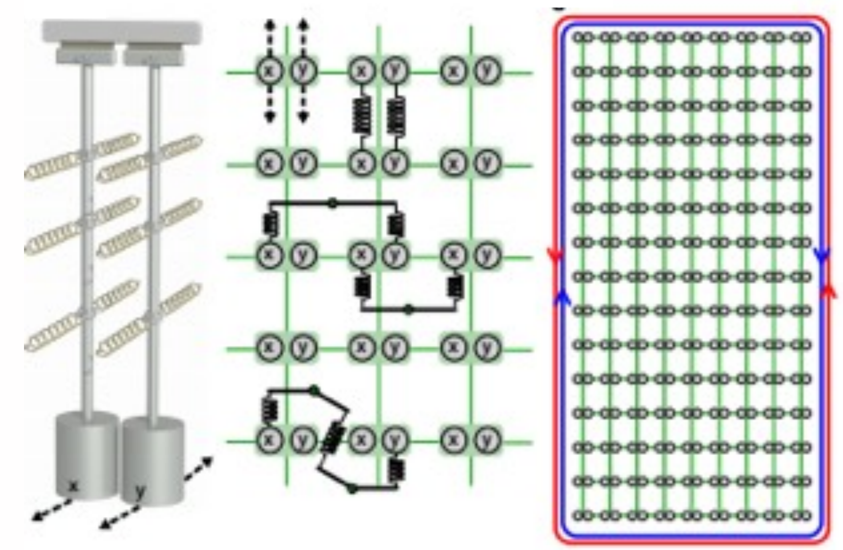
Topological matter without QM



Photonic crystals
Lu, Joannopoulos
and Soljačić (2014)

Gyroscopes
Nash et al. (2015)



Coupled pendula
Susstrunk and Huber
(2015)

Physical properties **insensitive to smooth changes** in material parameters

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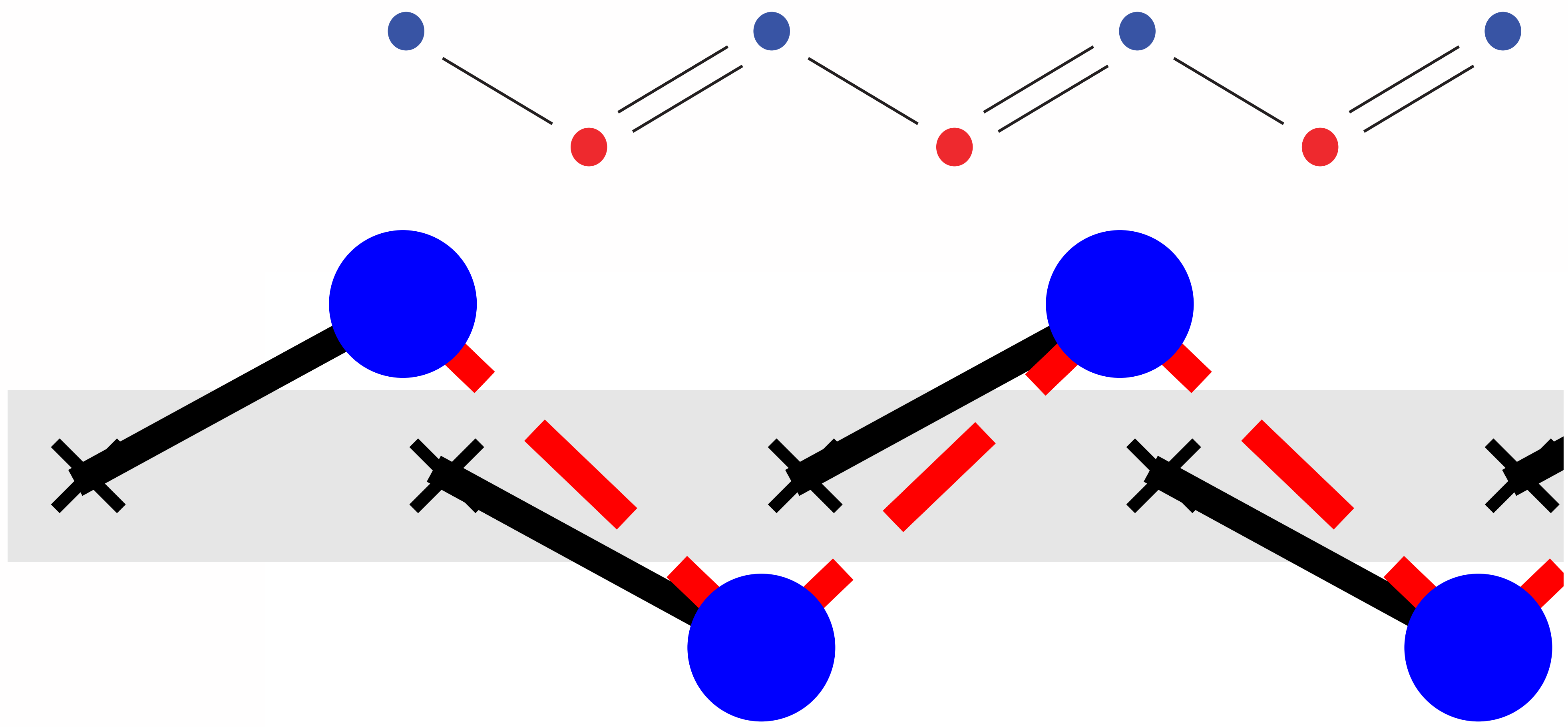
A simple topological mechanical system



Kane and Lubensky, Nature Physics 2014
Su, Schrieffer, Heeger PRL 1979

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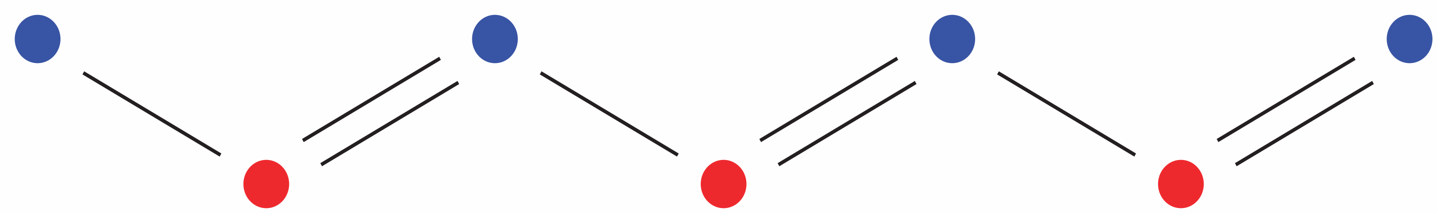

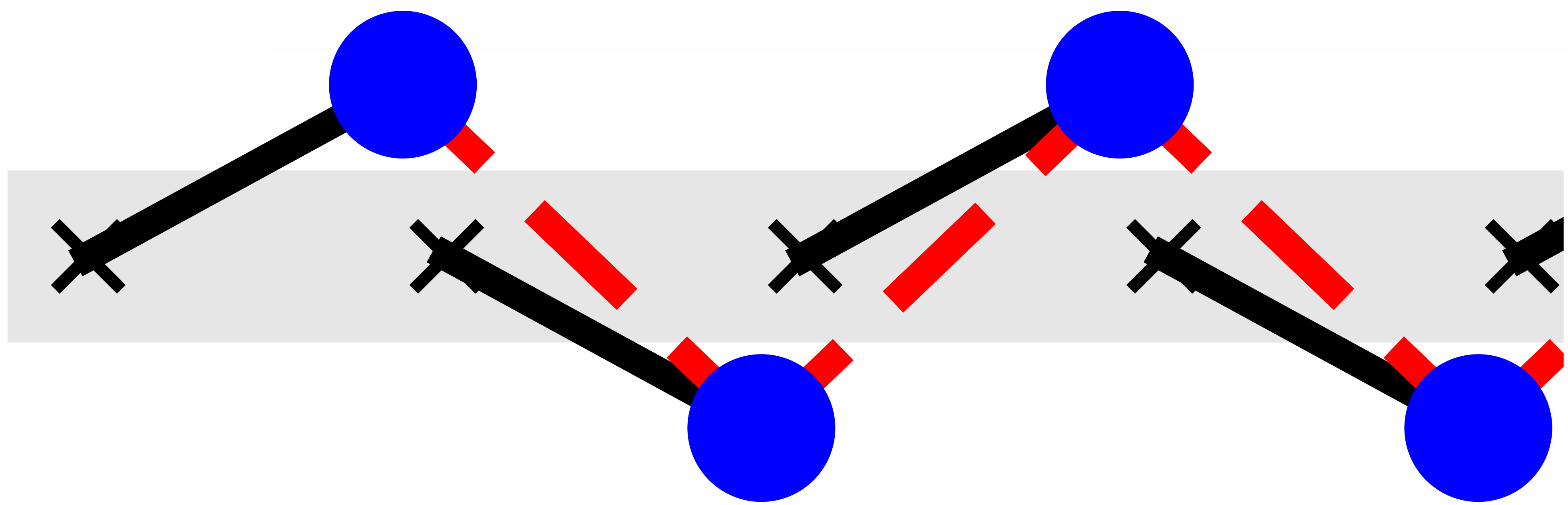

The vibrations of an isostatic mechanical system may be mapped to the electronic states in a topological superconductor

Kane and Lubensky, Nature Physics 2014
Su, Schrieffer, Heeger PRL 1979

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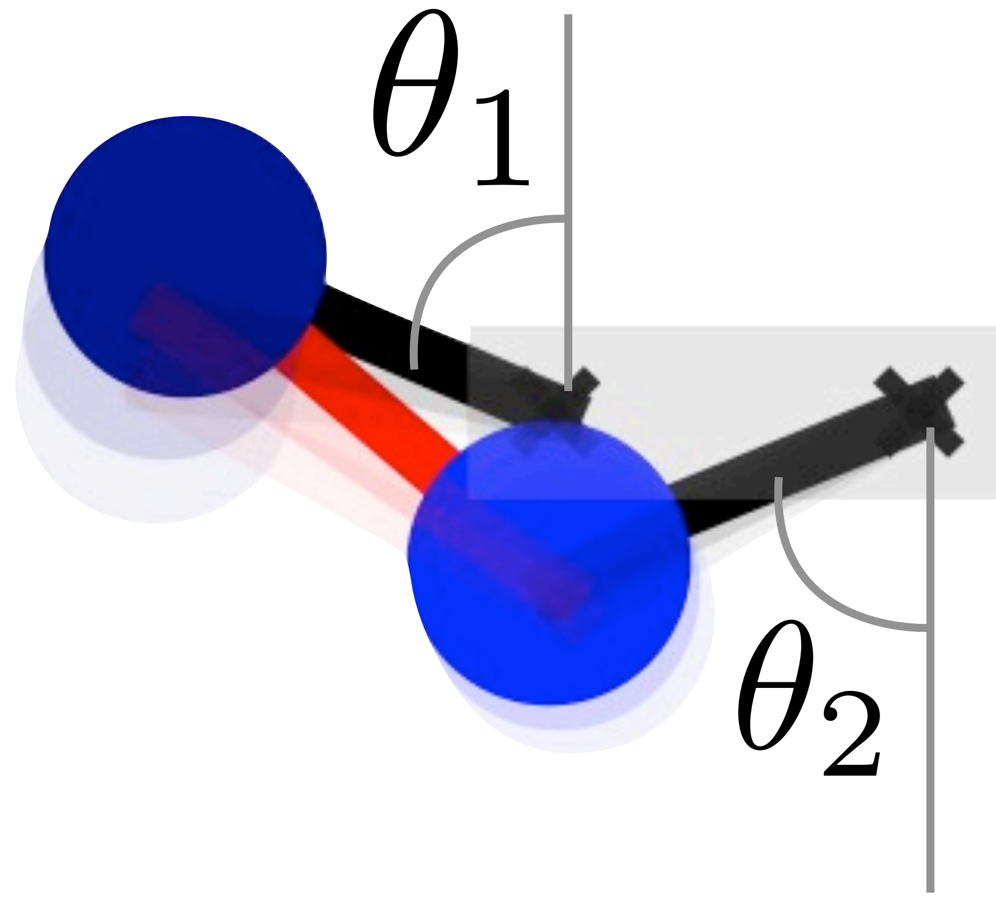
The humble four-bar linkage:



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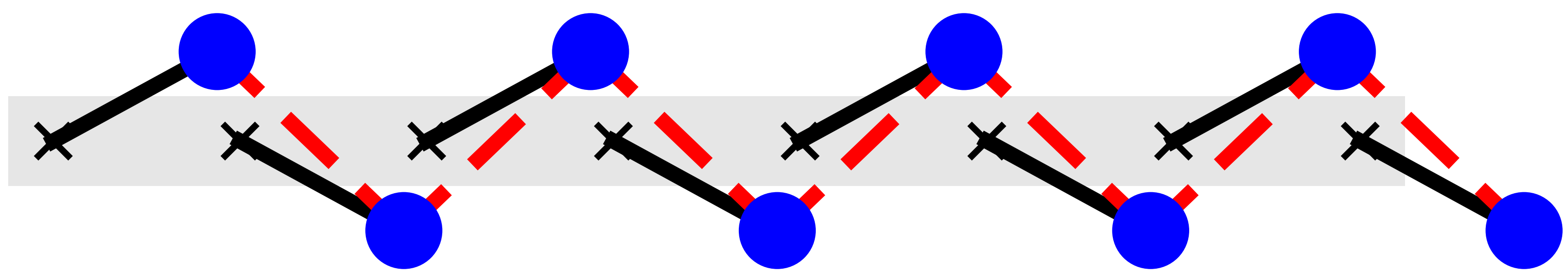
The toy chain

rotors



springs

Kane and Lubensky, Nature Physics 2014

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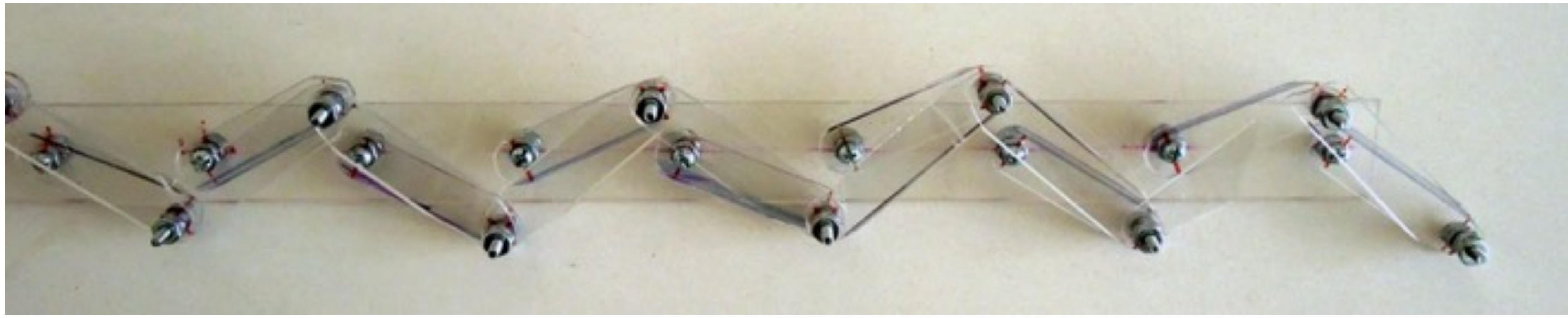

bars

Kane and Lubensky, Nature Physics 2014

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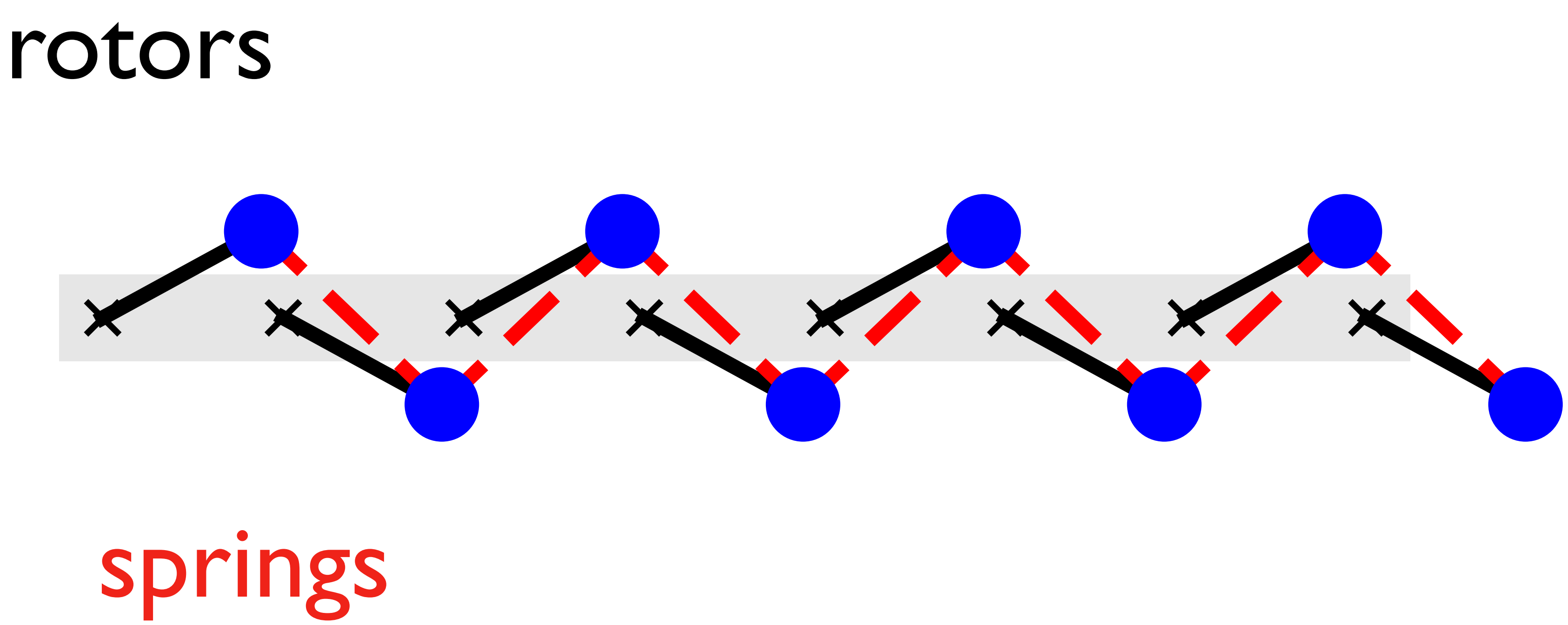

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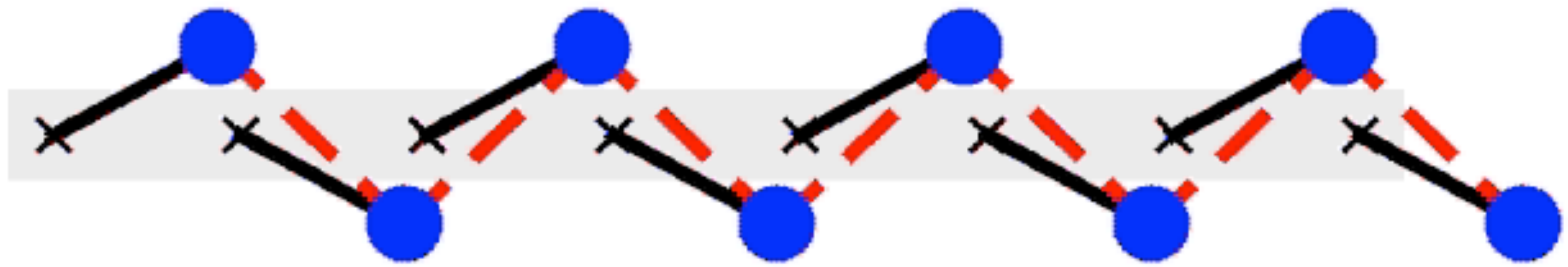

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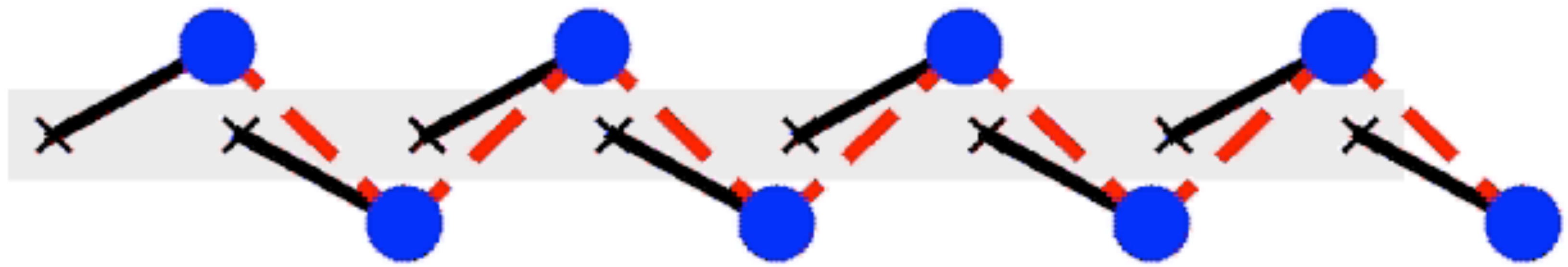

springs

2 uniform stable states!

Kane and Lubensky, Nature Physics 2014

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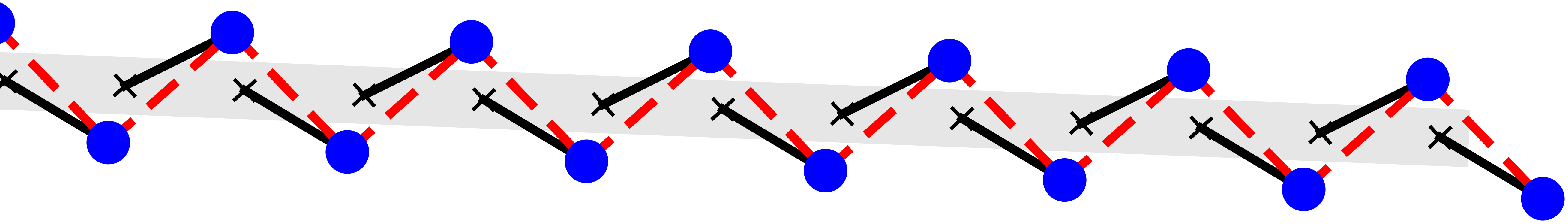
Rigid in the bulk



Chen, Upadhyaya, Vitelli PNAS 111, 13004 (2014)

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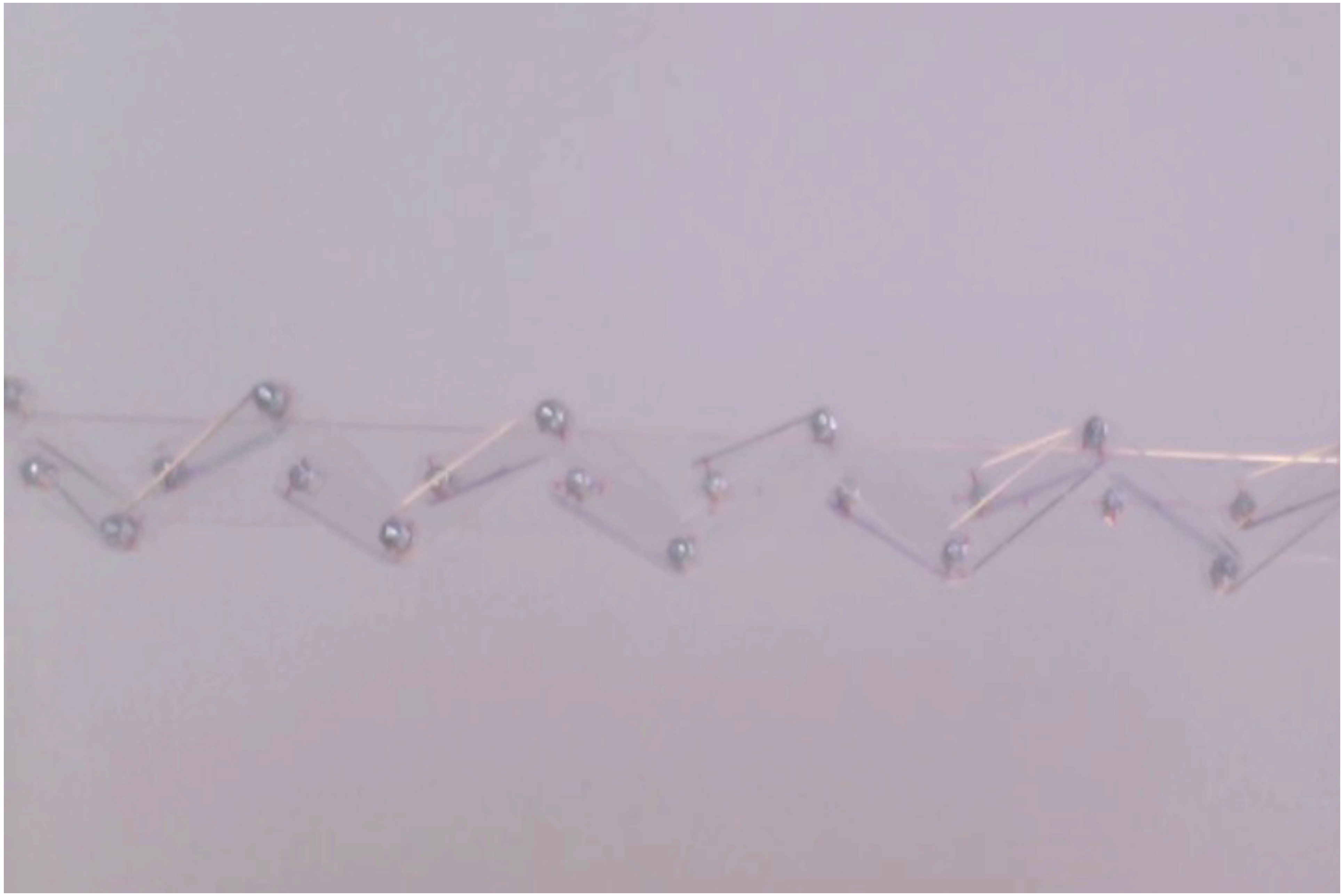
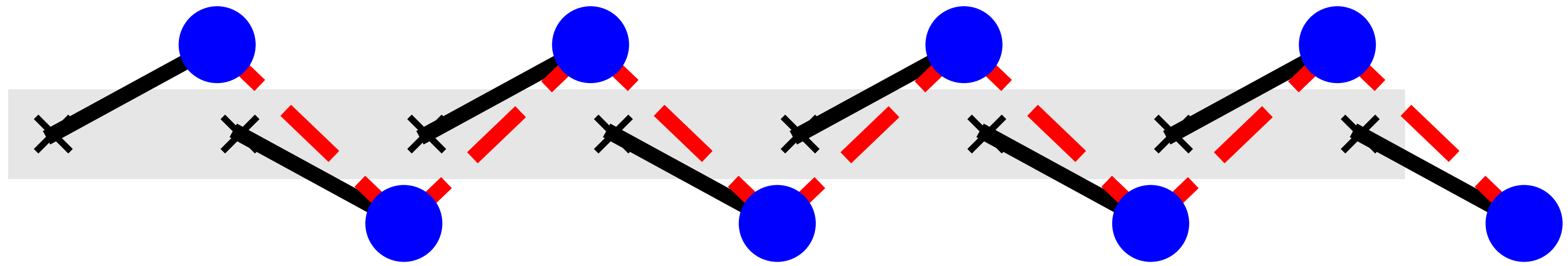


Chen, Upadhyaya, Vitelli PNAS 111, 13004 (2014)

Exponentially localized zero mode



This chain has 8 rotors and 7 springs;
8-7=1 unconstrained degree of freedom

Kane and Lubensky, Nature Physics 2014

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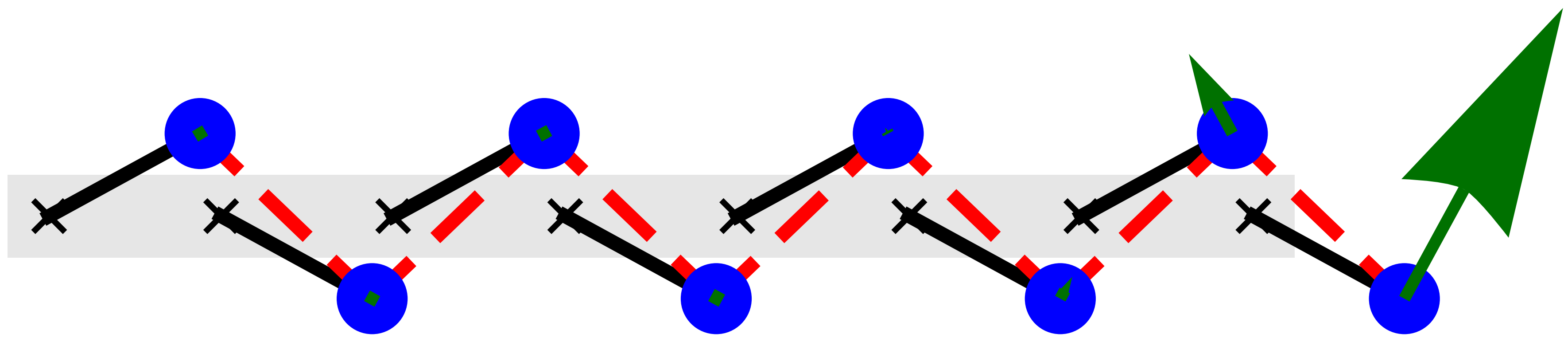
Exponentially localized zero mode



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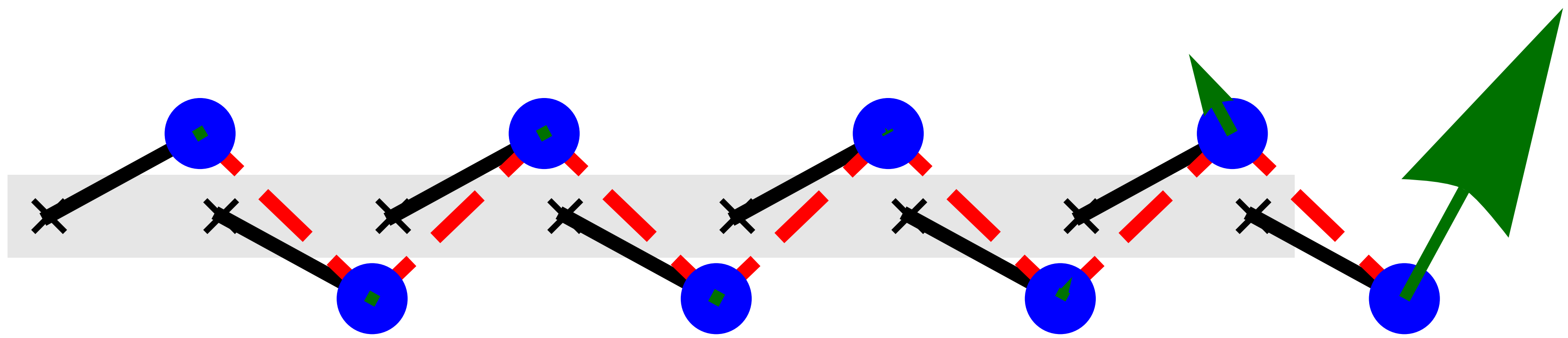

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The zero mode is exponentially **localized** at the end.

Kane and Lubensky, Nature Physics 2014

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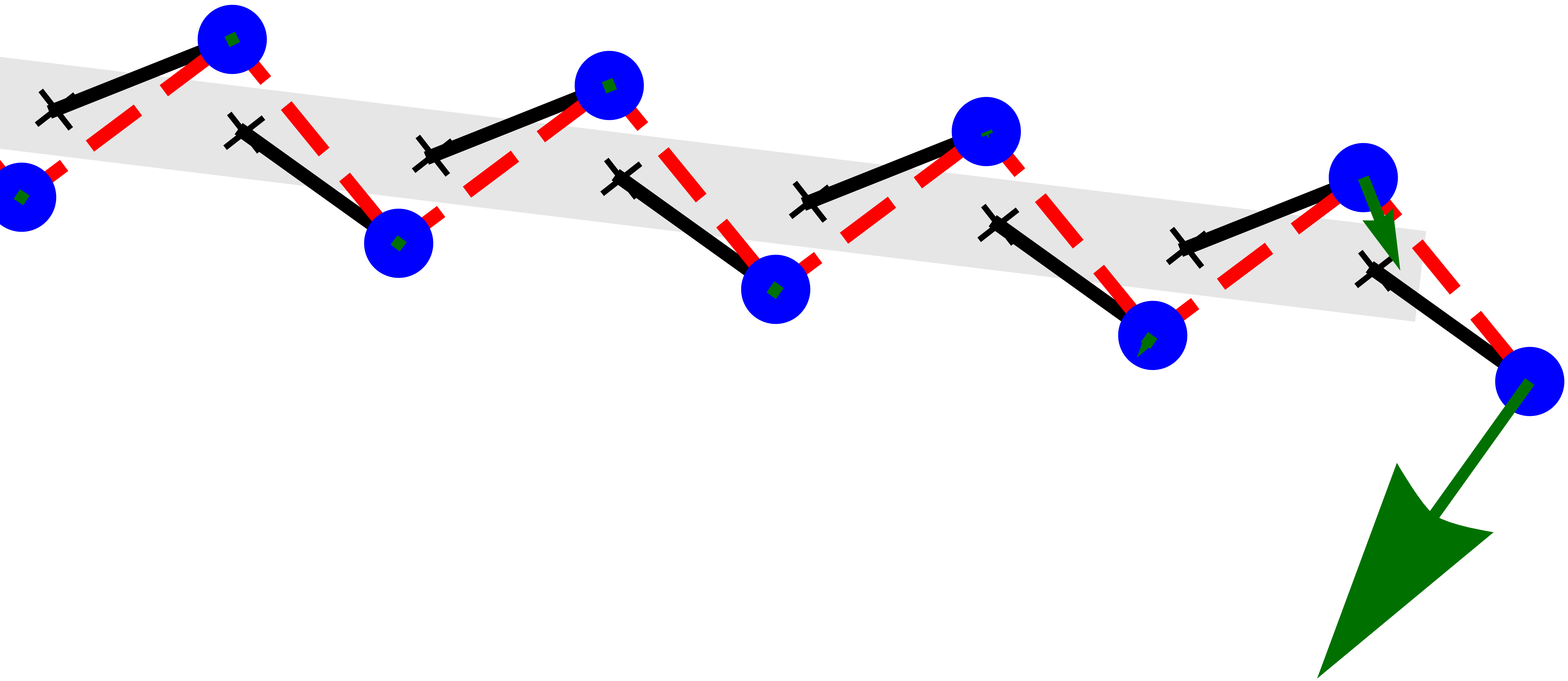

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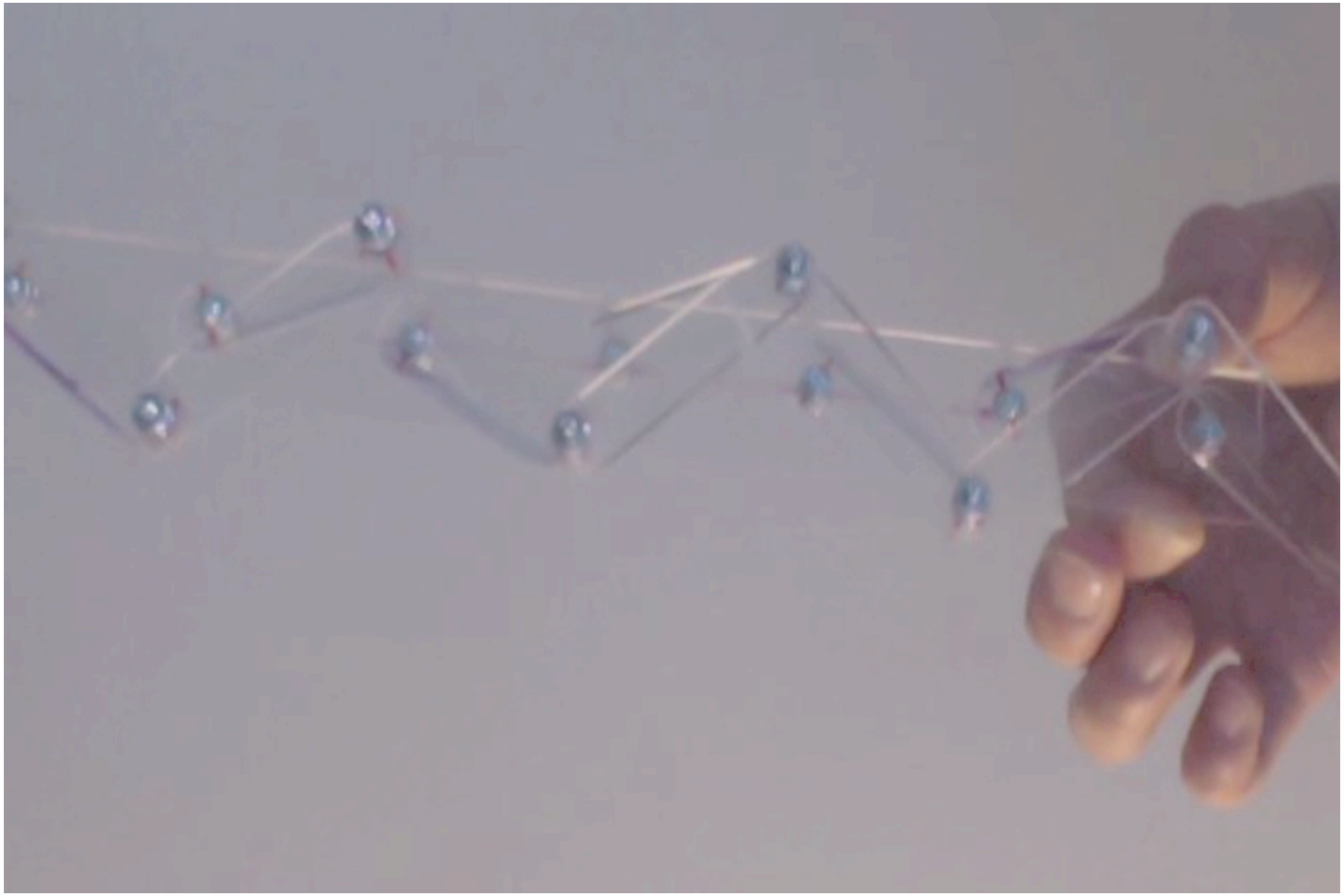

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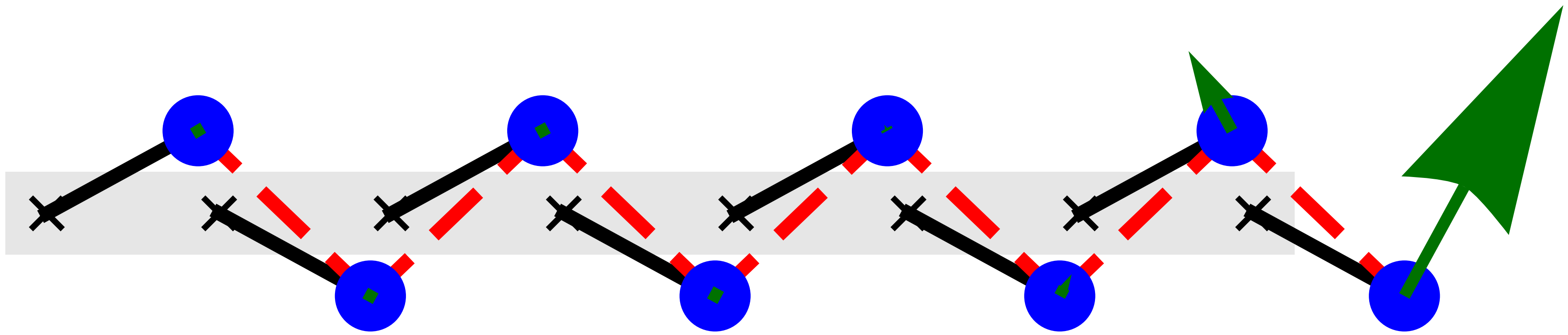
Two edges, two ground states



Kane and Lubensky, Nature Physics 2014

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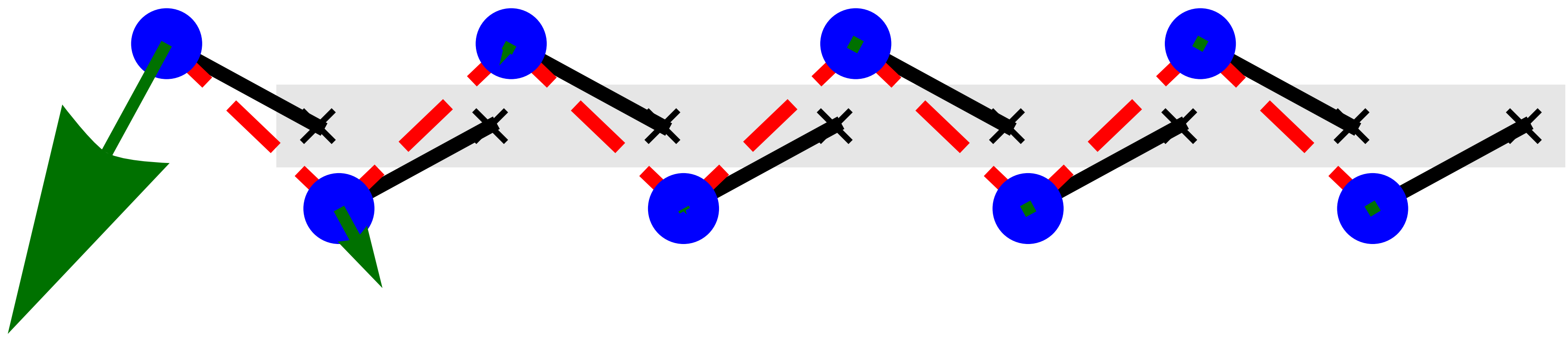

Kane and Lubensky, Nature Physics 2014

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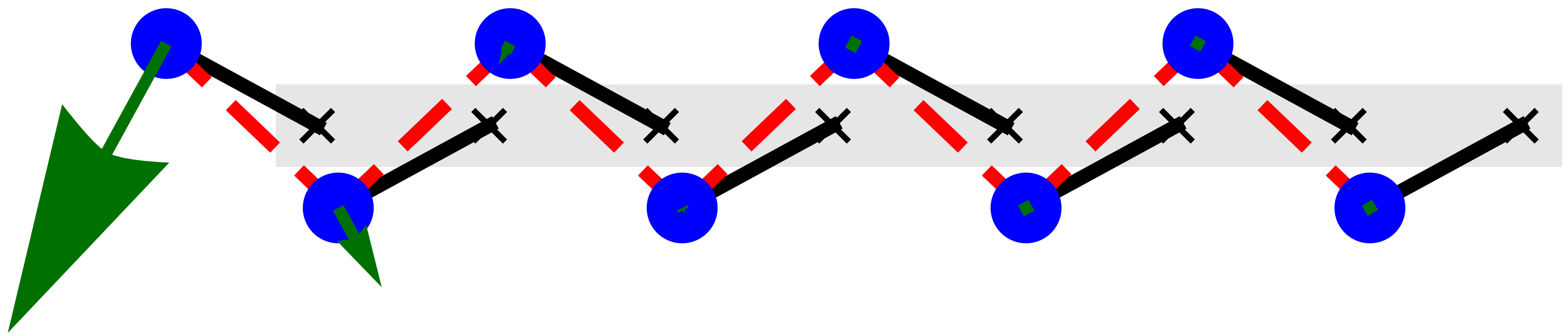

Left- and right-leaning states have modes localized at the left and right edges....

Kane and Lubensky, Nature Physics 2014

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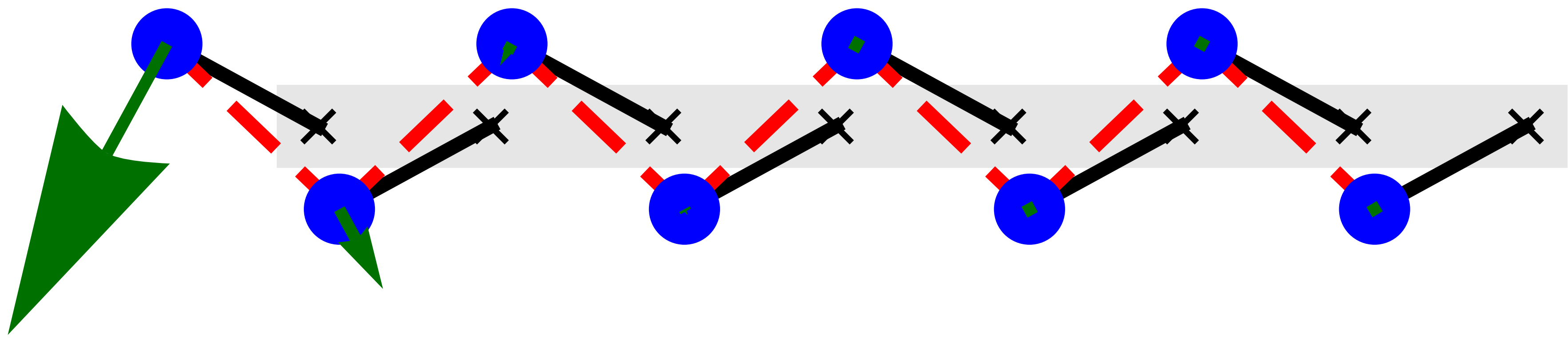

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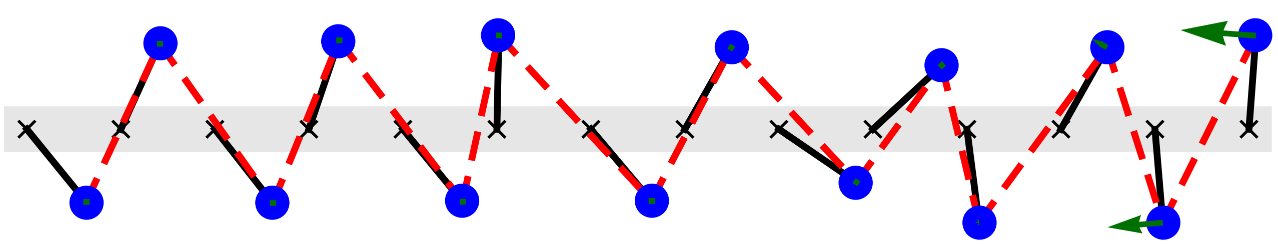

Kane and Lubensky, Nature Physics 2014

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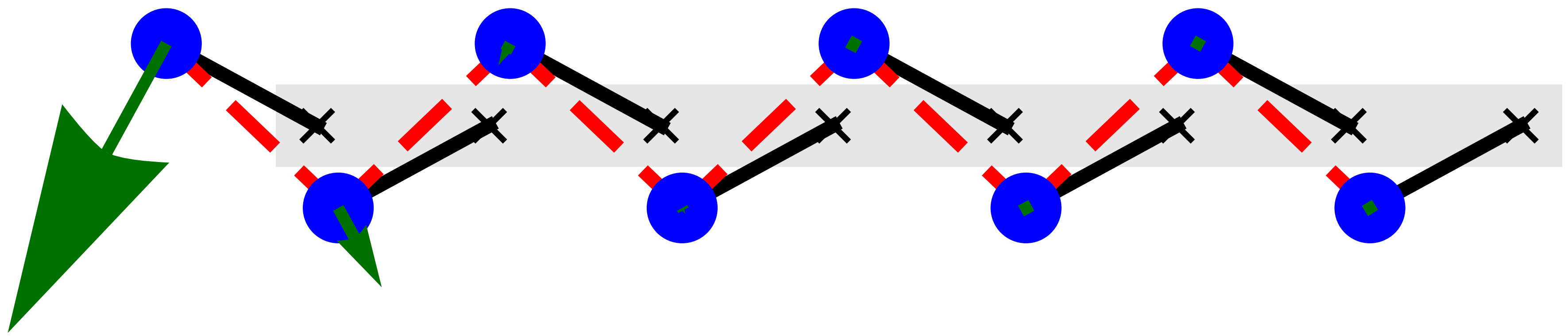

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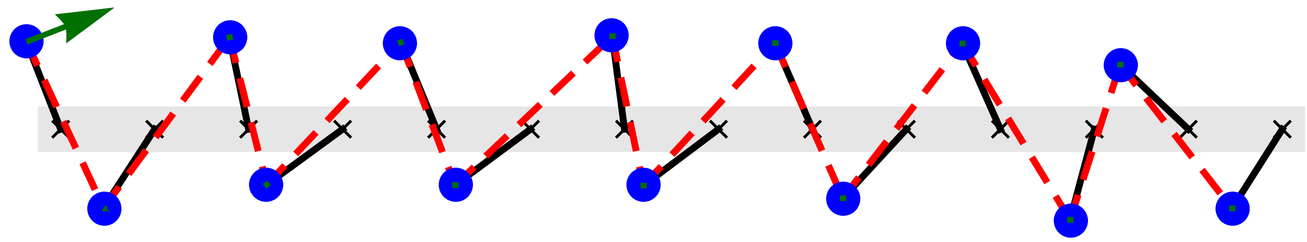

Kane and Lubensky, Nature Physics 2014

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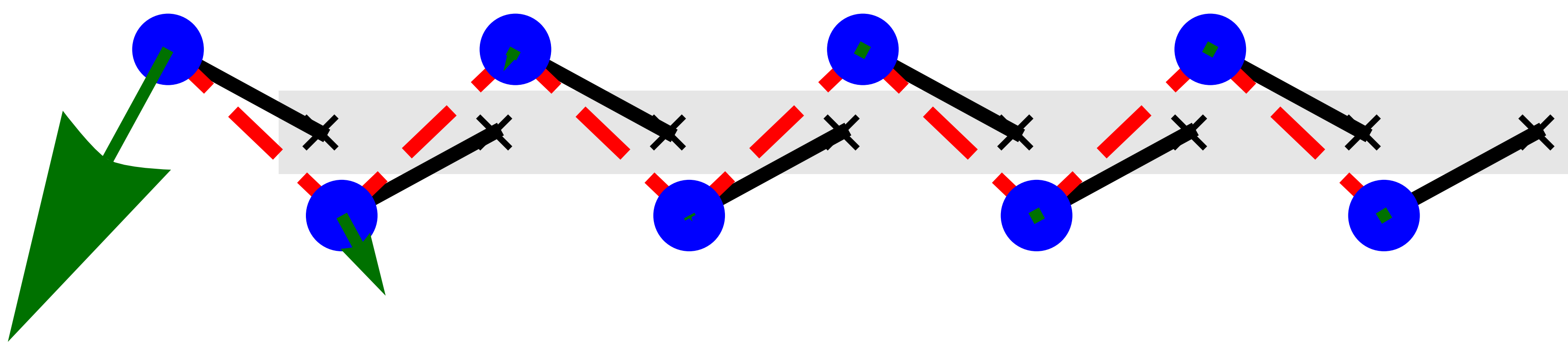

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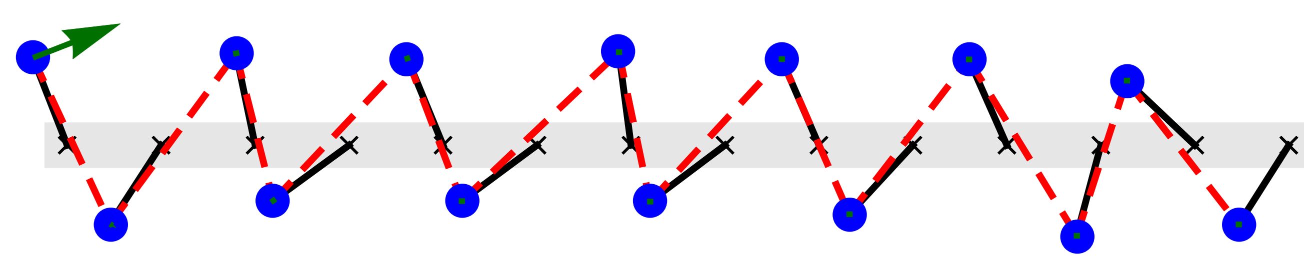

Topologically protected

Kane and Lubensky, Nature Physics 2014

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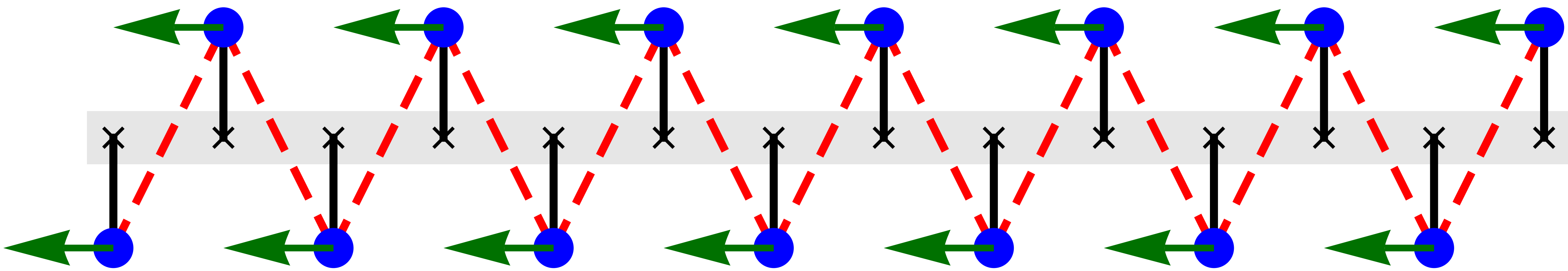

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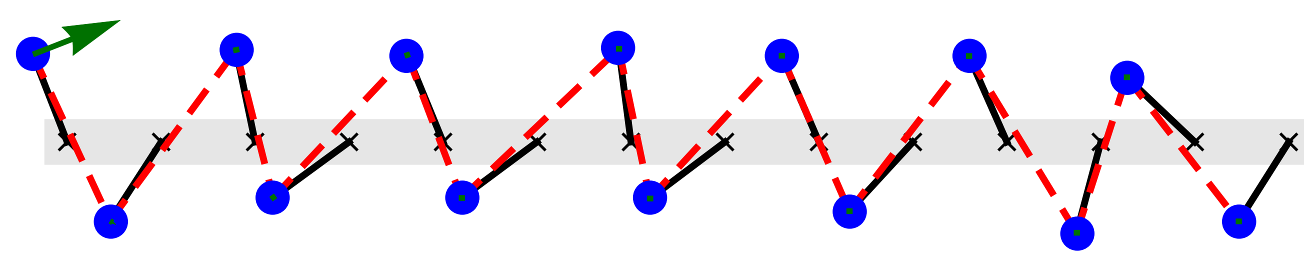

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Kane and Lubensky, Nature Physics 2014

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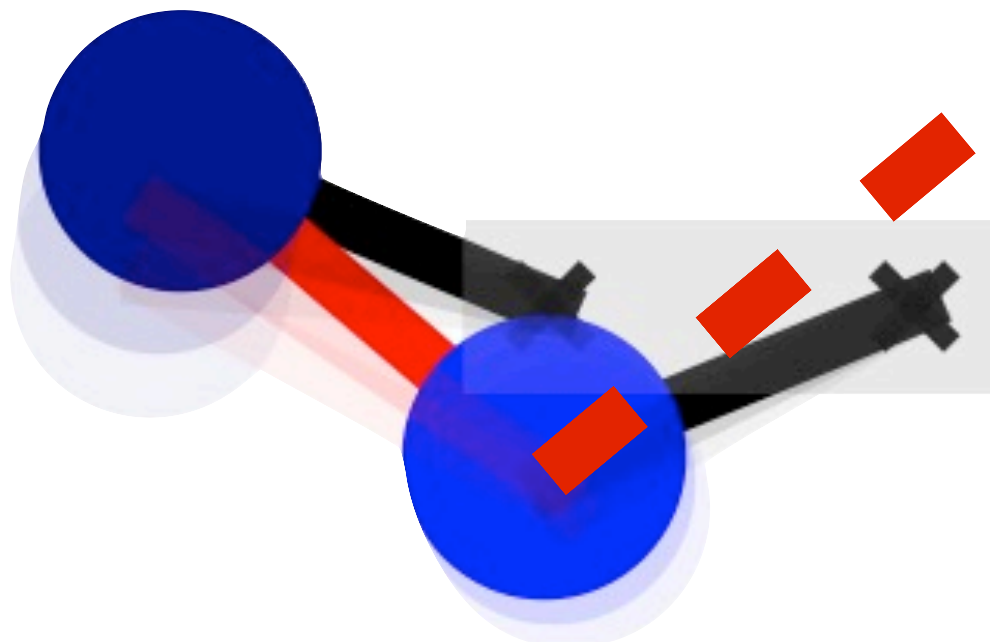
“Polarization”



Resta, Rev Mod Phys 1994
Kane and Lubensky, Nature Physics 2014

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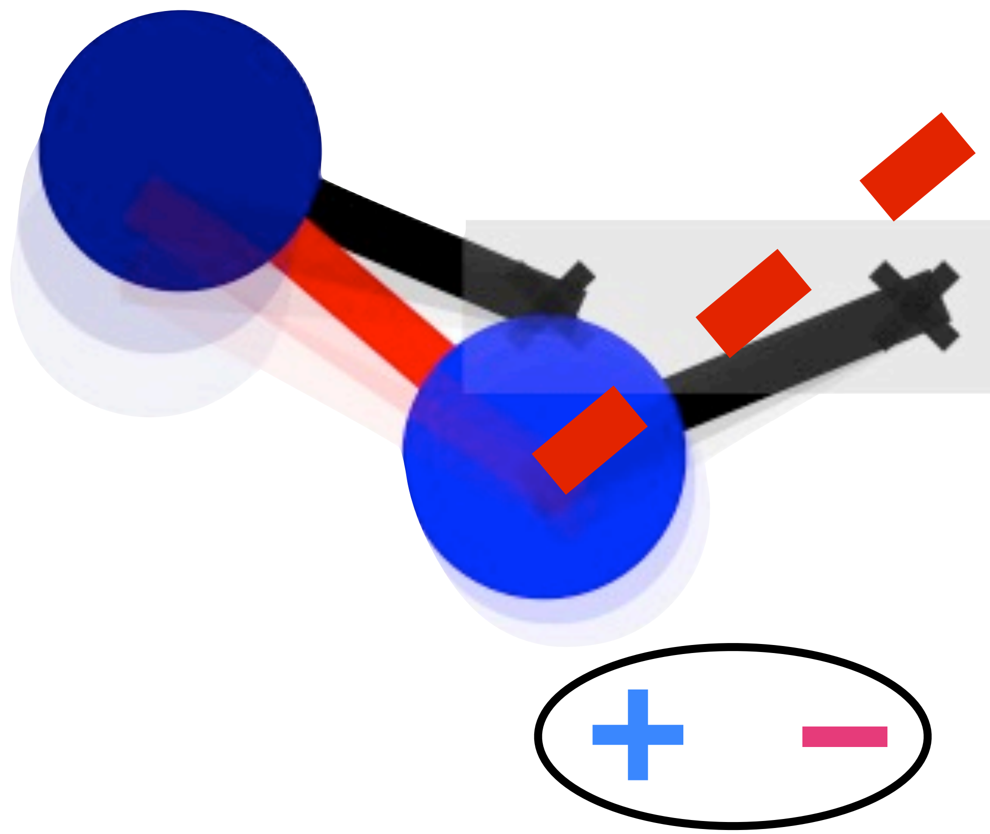

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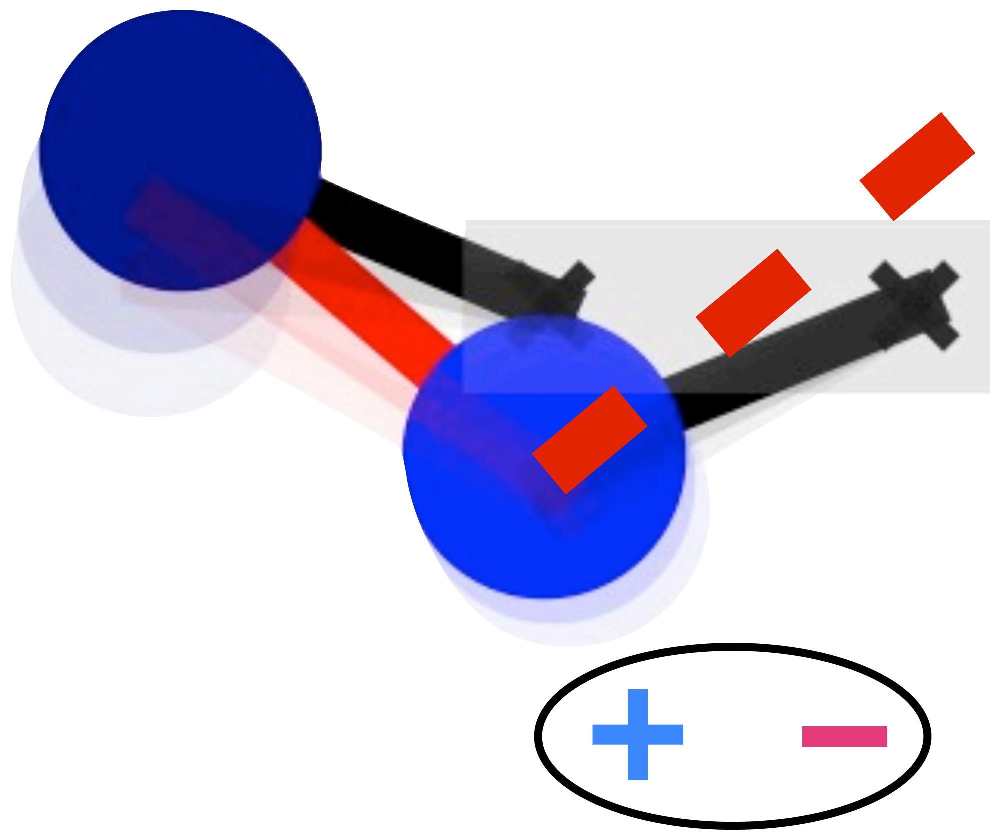

+ charges: degrees of freedom

− charges: constraints

Resta, Rev Mod Phys 1994
Kane and Lubensky, Nature Physics 2014

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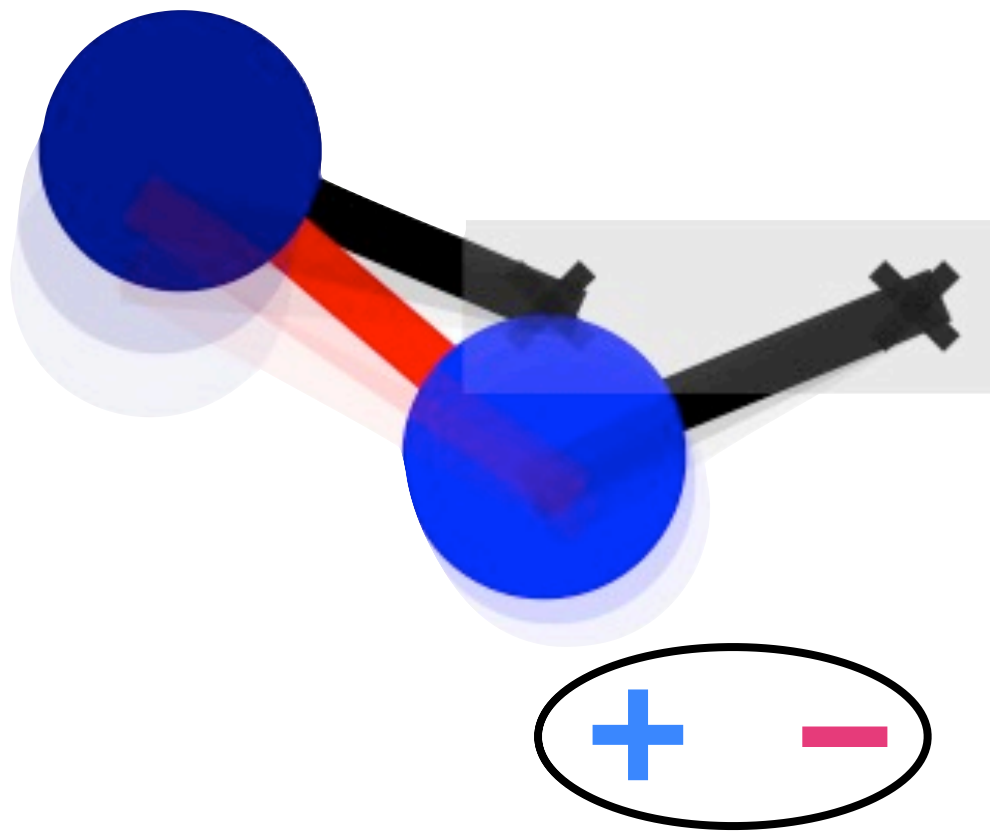

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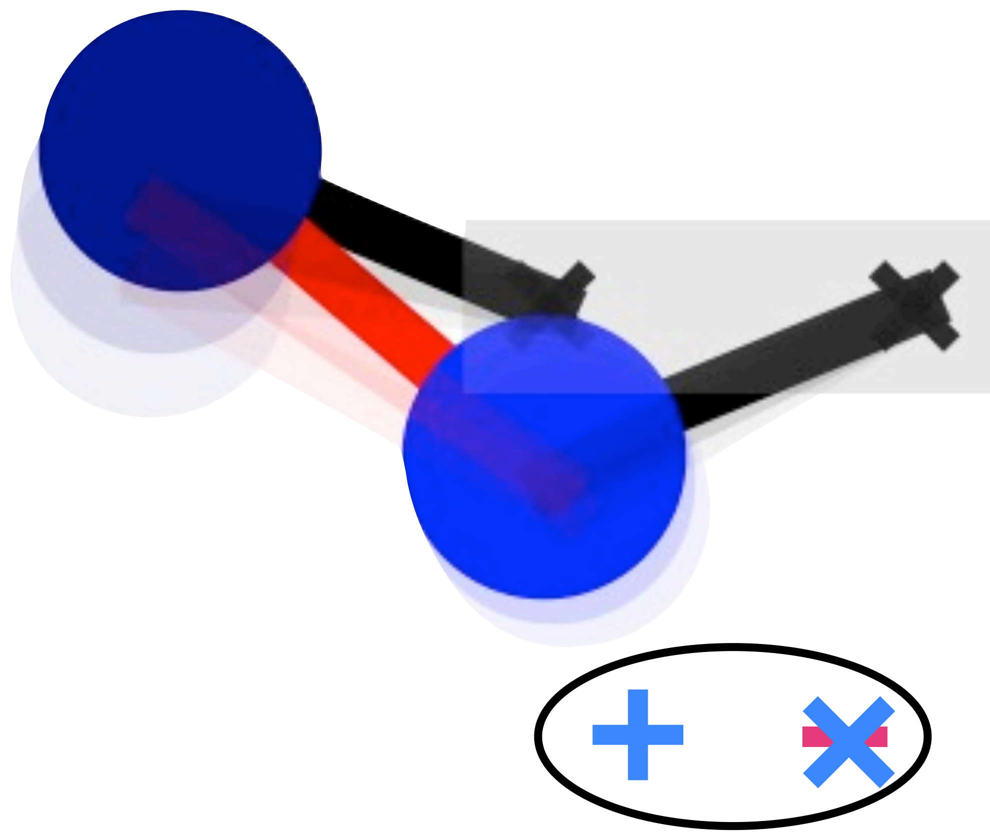

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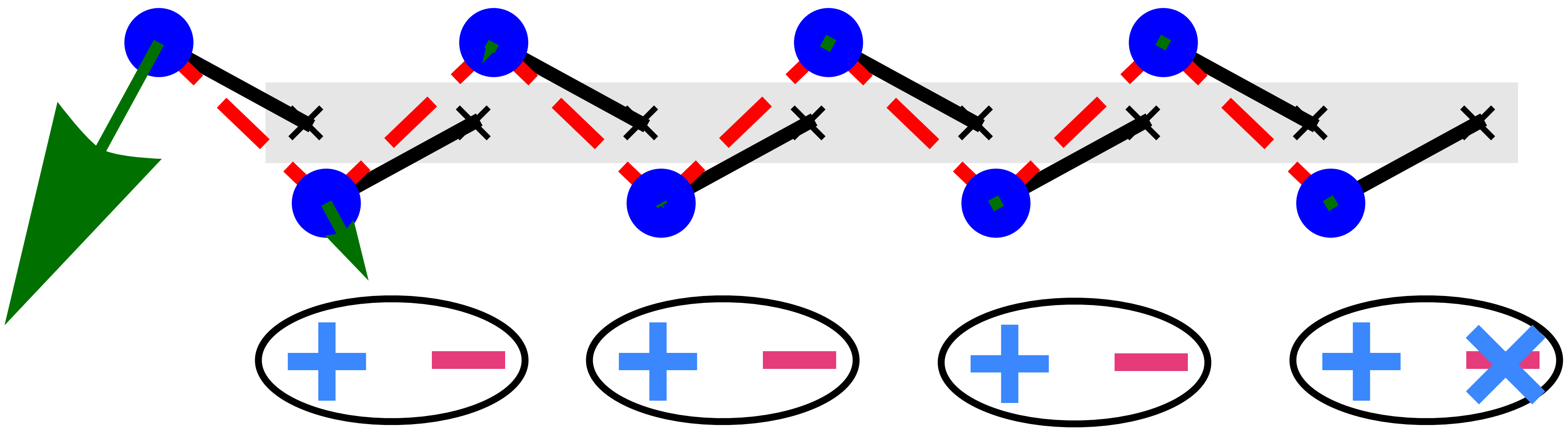
Bulk / Boundary



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Kane and Lubensky, Nature Physics 2014

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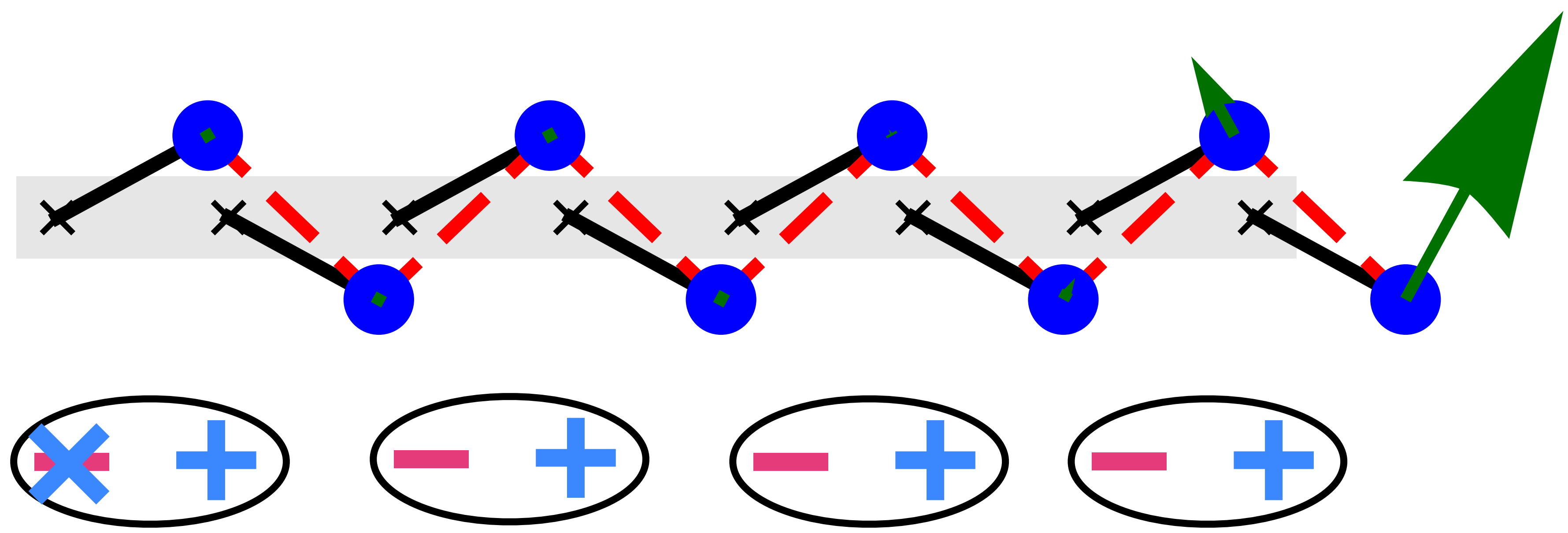
Bulk / Boundary



+ charges: degrees of freedom

– charges: constraints

Resta, Rev Mod Phys 1994

Kane and Lubensky, Nature Physics 2014

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Mechanical energy **cannot** be transmitted across the chain via **linear** vibrations!

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Mechanical energy **cannot** be transmitted across the chain via **linear** vibrations!

OUR QUESTION:
What happens when we excite the zero mode **beyond the linear regime**?

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Chen, Upadhyaya, Vitelli PNAS 111, 13004 (2014)

The chain **conducts** mechanical energy !

Chen, Upadhyaya, Vitelli PNAS 111, 13004 (2014)

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An insulator at harmonic level has become a conductor in non-linear theory

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The chain **conducts** mechanical energy !

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Aside: "Jacob's ladder" toy shares this mechanism

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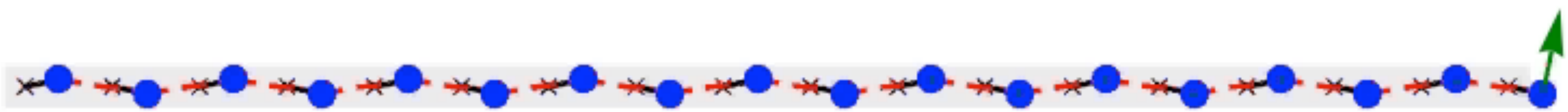

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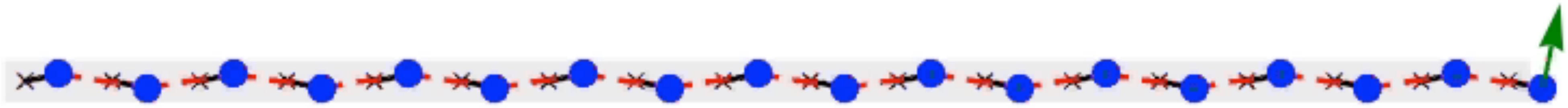
localized zero mode is transported from end to end (and back)!



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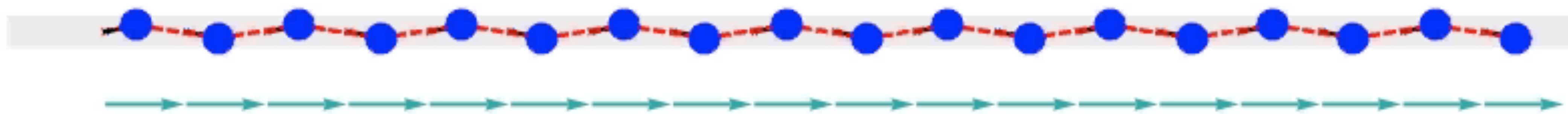

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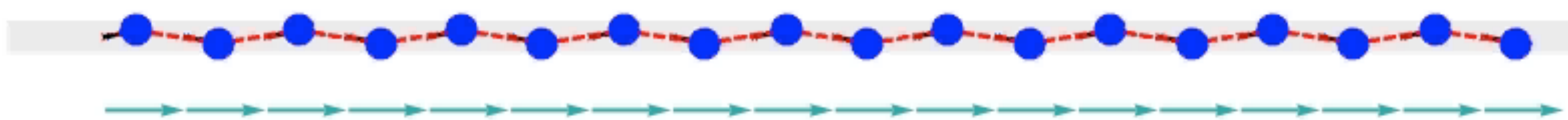
The Flipper



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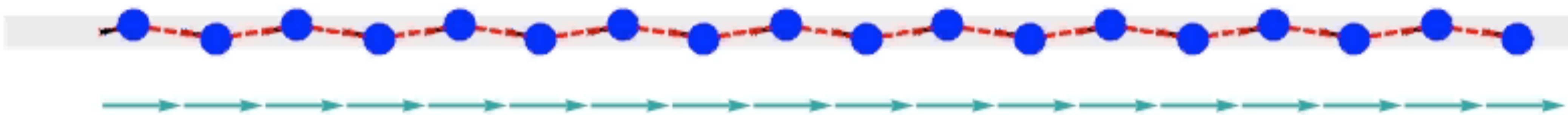
The Flipper



Beyond linear order, the zero mode becomes a moving **domain wall** converting left-leaning to right-leaning and vice versa!

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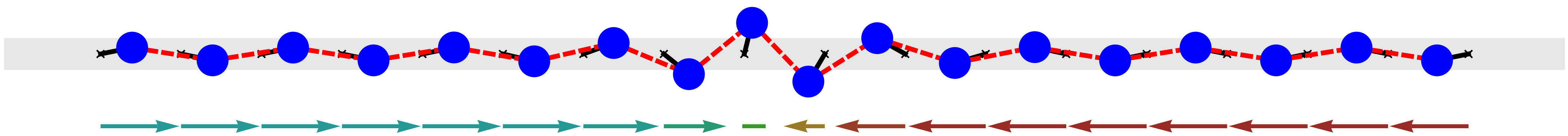
The Flipper



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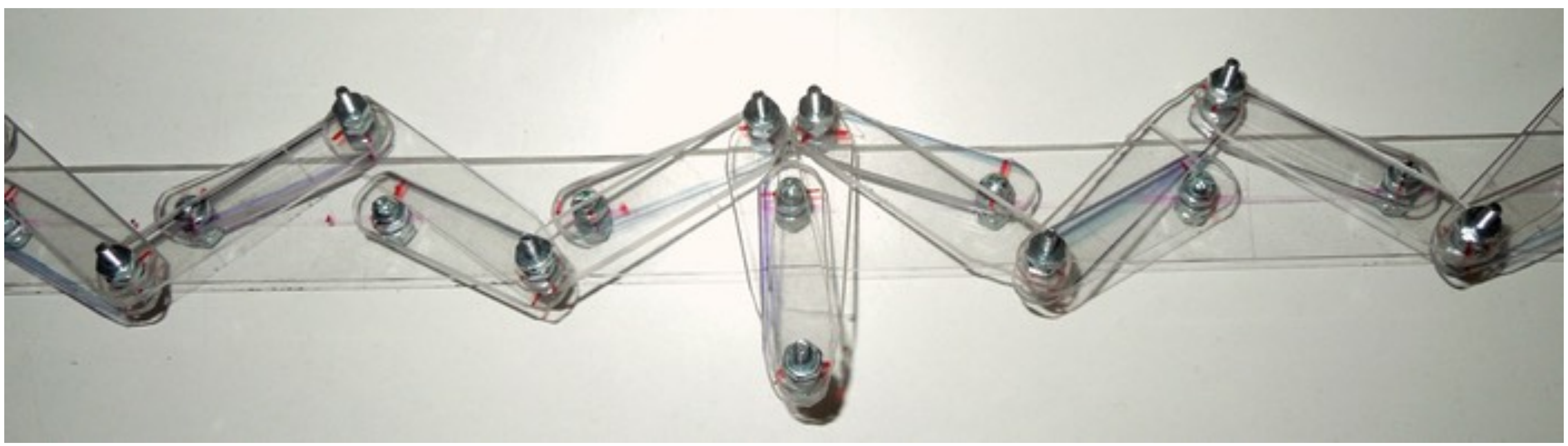
Energy propagates via a **topological soliton**



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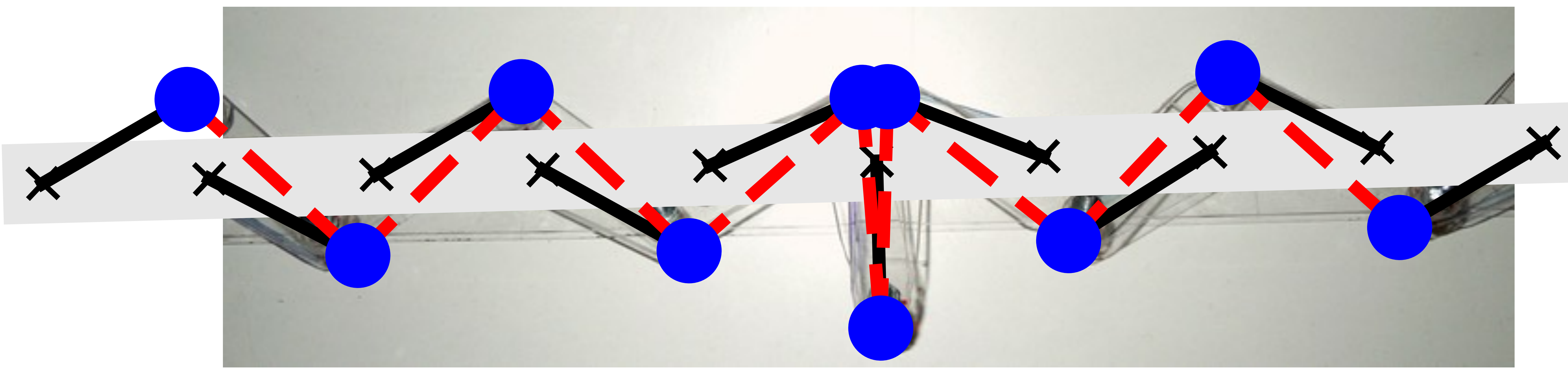

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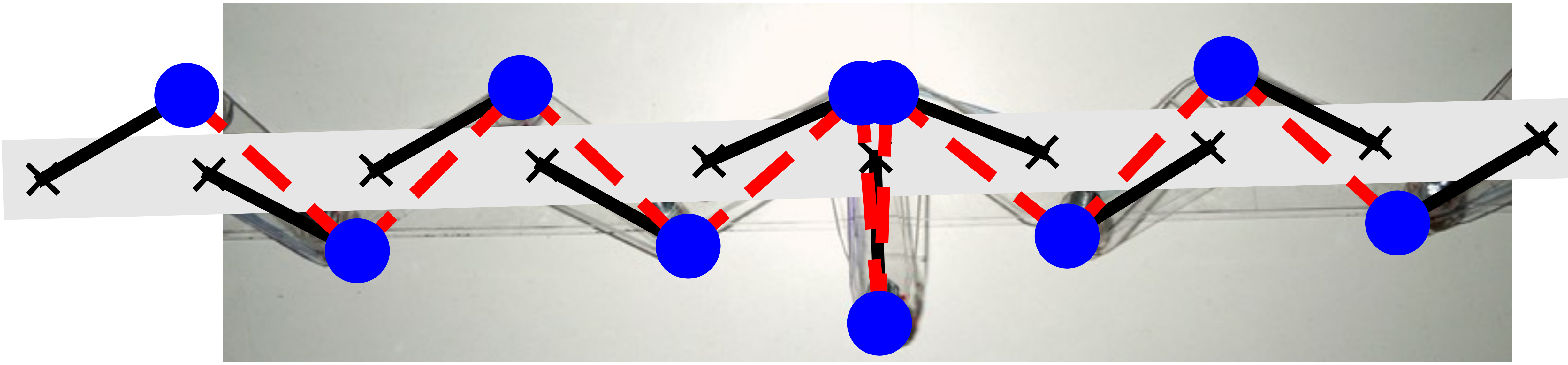

left-leaning

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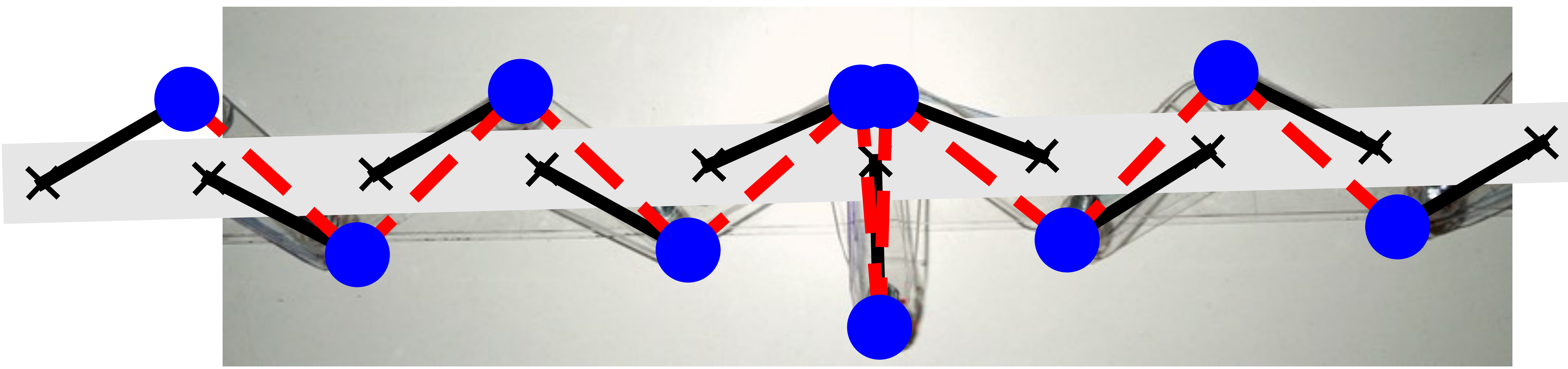

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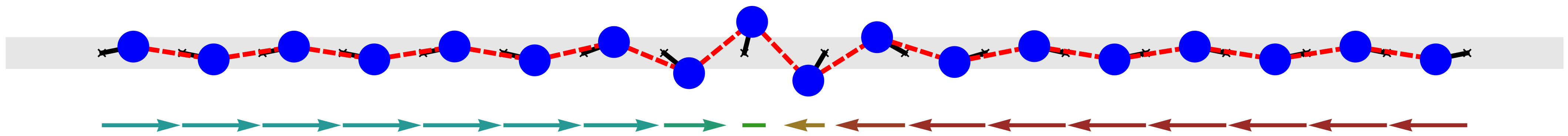
what soliton?



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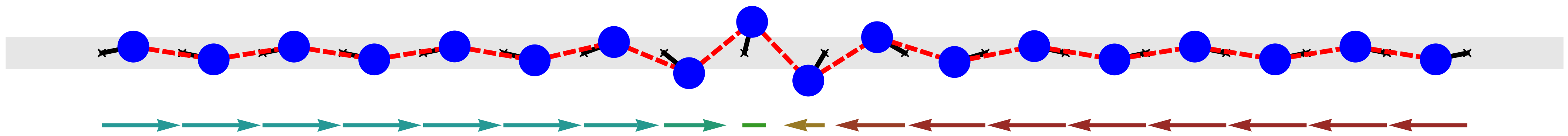

u(x) = **x-projection** of rotor at x

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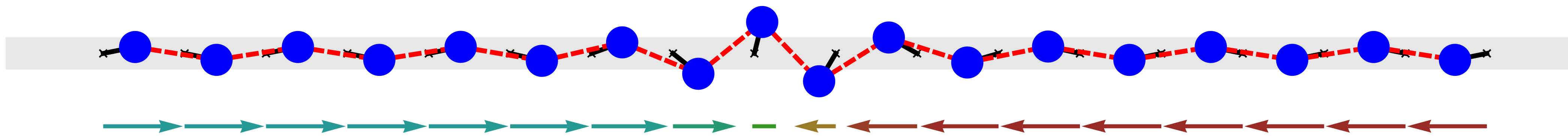

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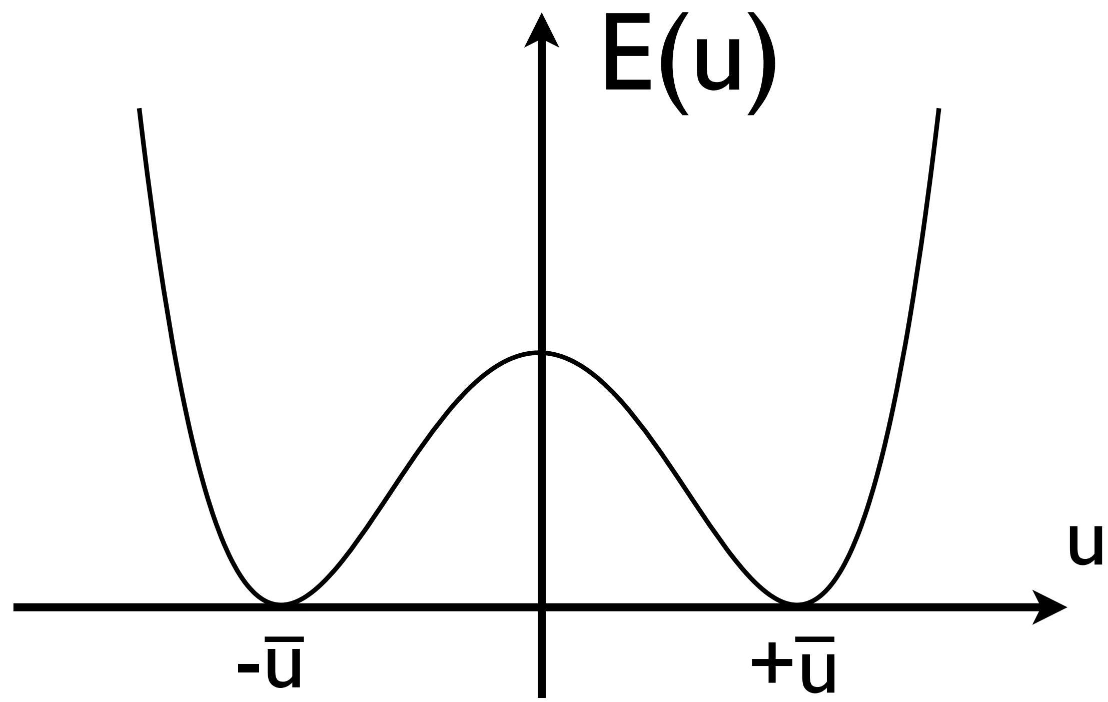

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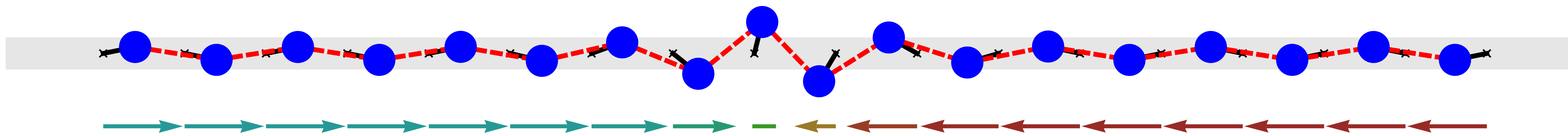
discretization of φ^4 **theory kink**



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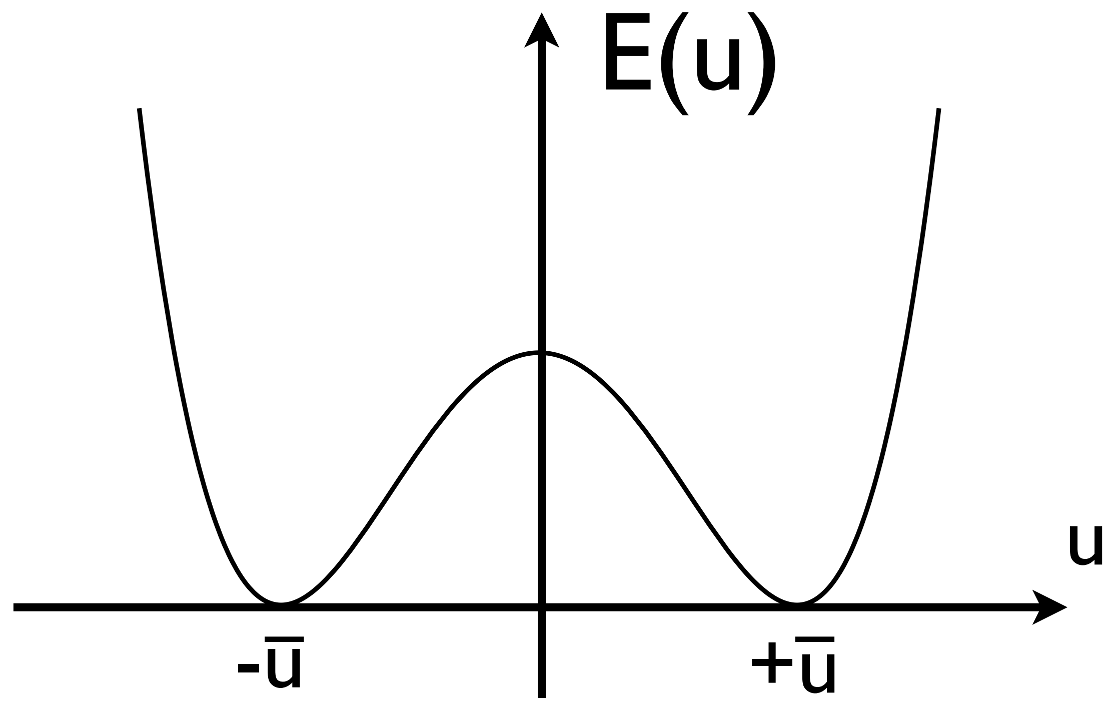

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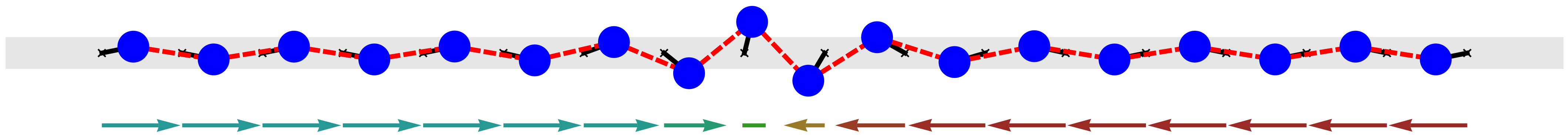
discretization of φ⁴ theory kink



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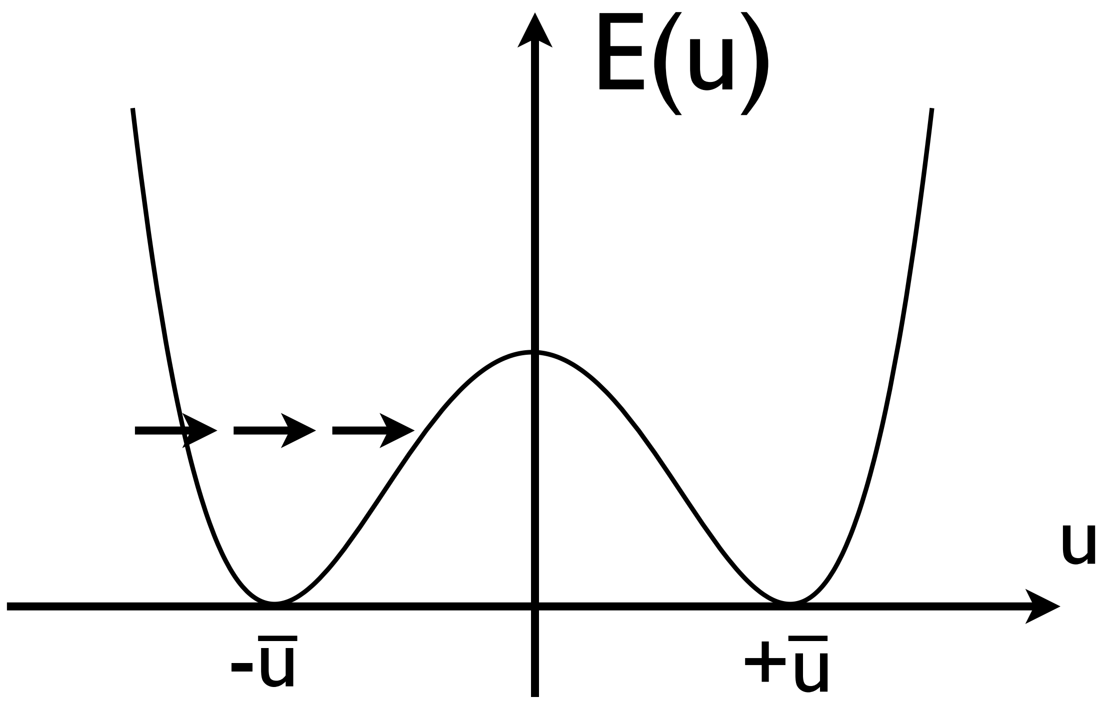

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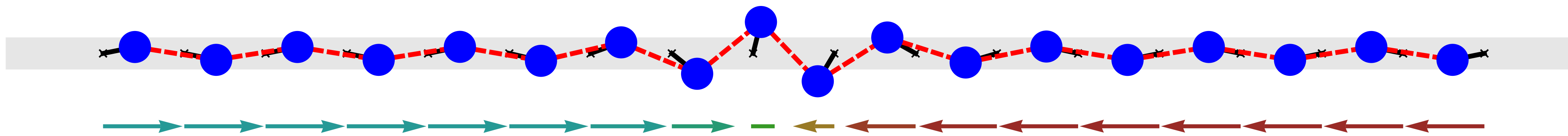

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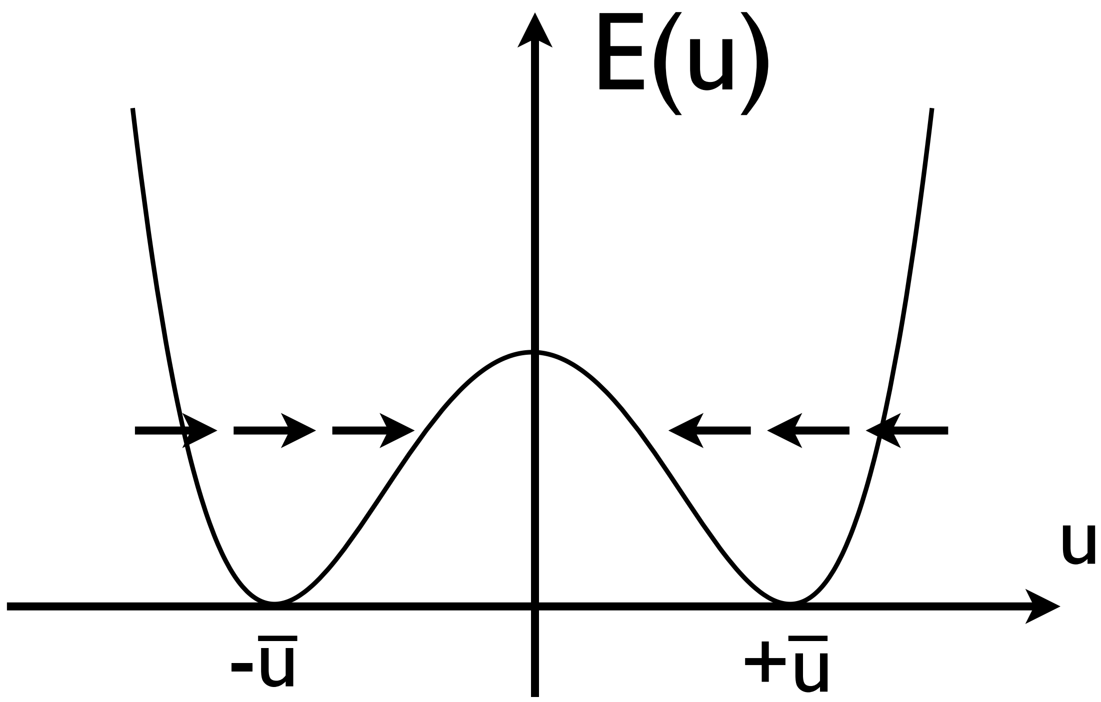

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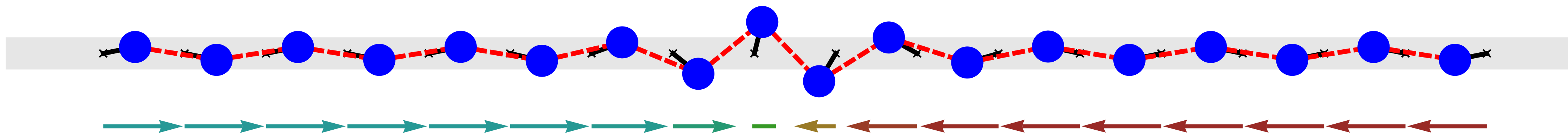

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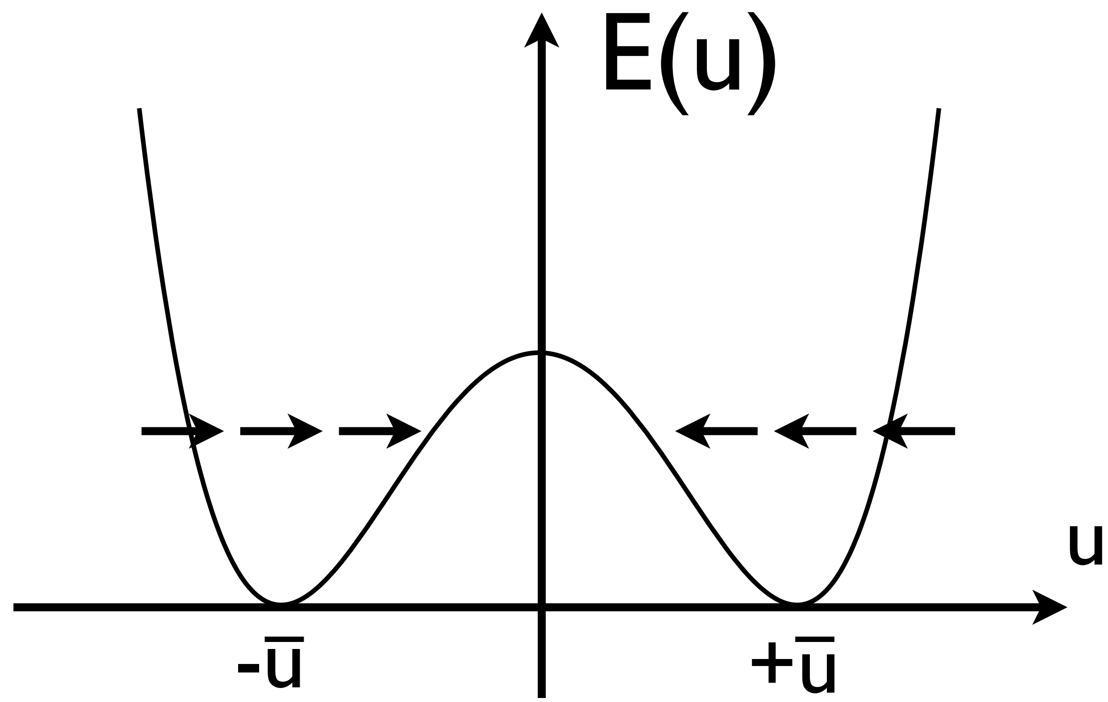

→→→ ←←← “kink” = domain wall profile

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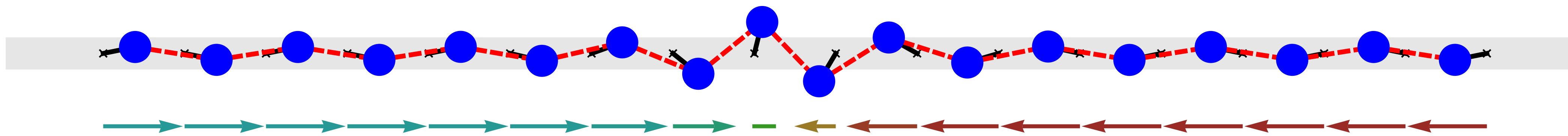
static profile : discretization of
φ⁴ theory kink



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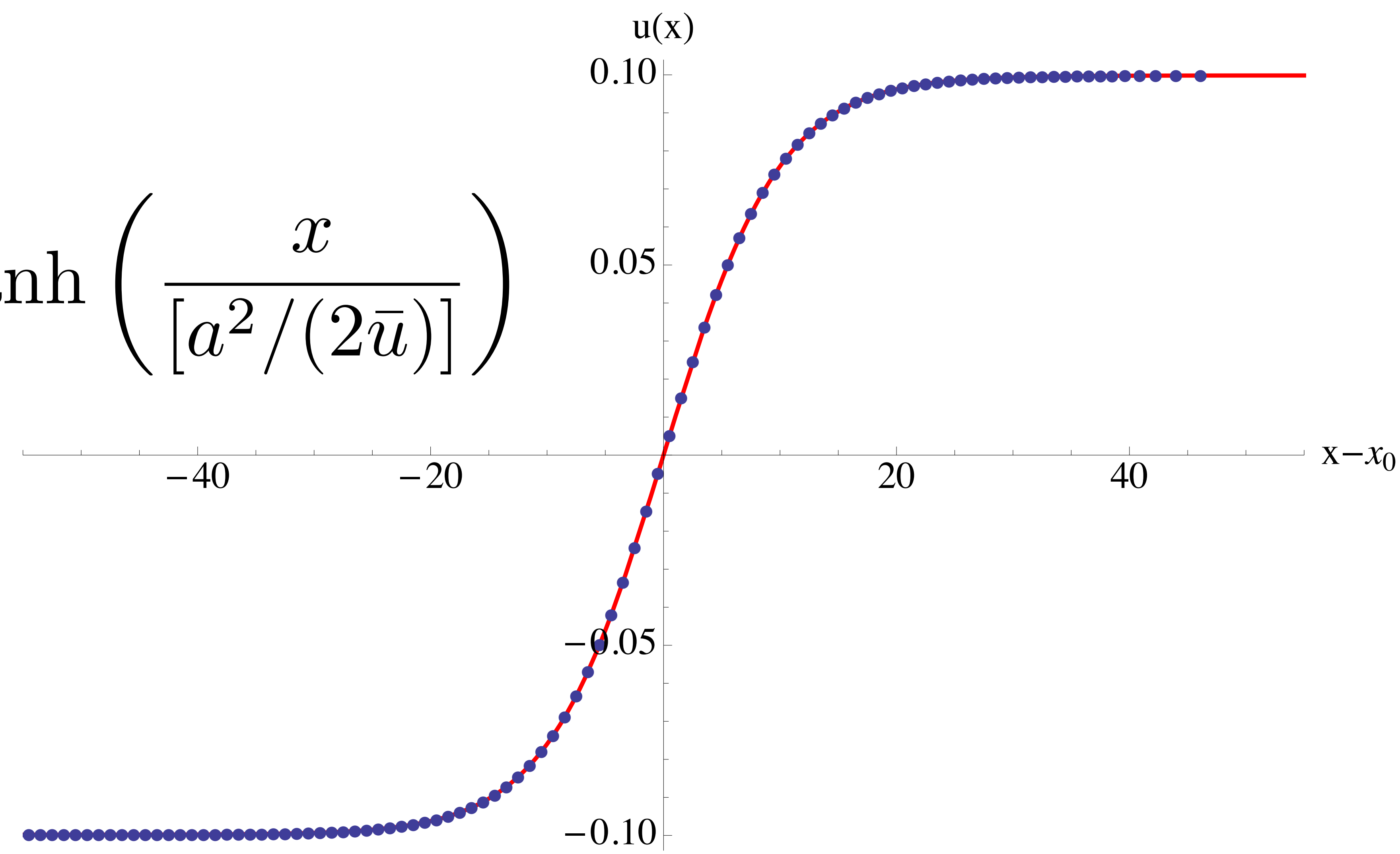
$$u(x) = \bar{u}\tanh\left(\frac{x}{[a^2/(2\bar{u})]}\right)$$



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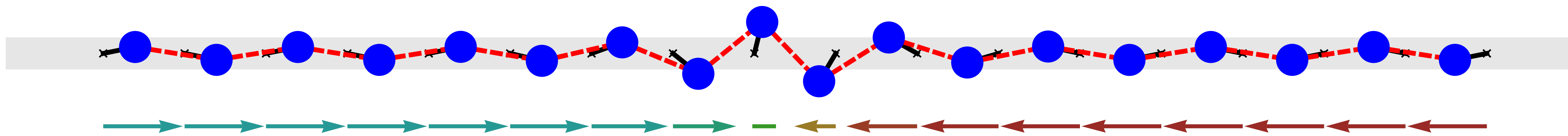

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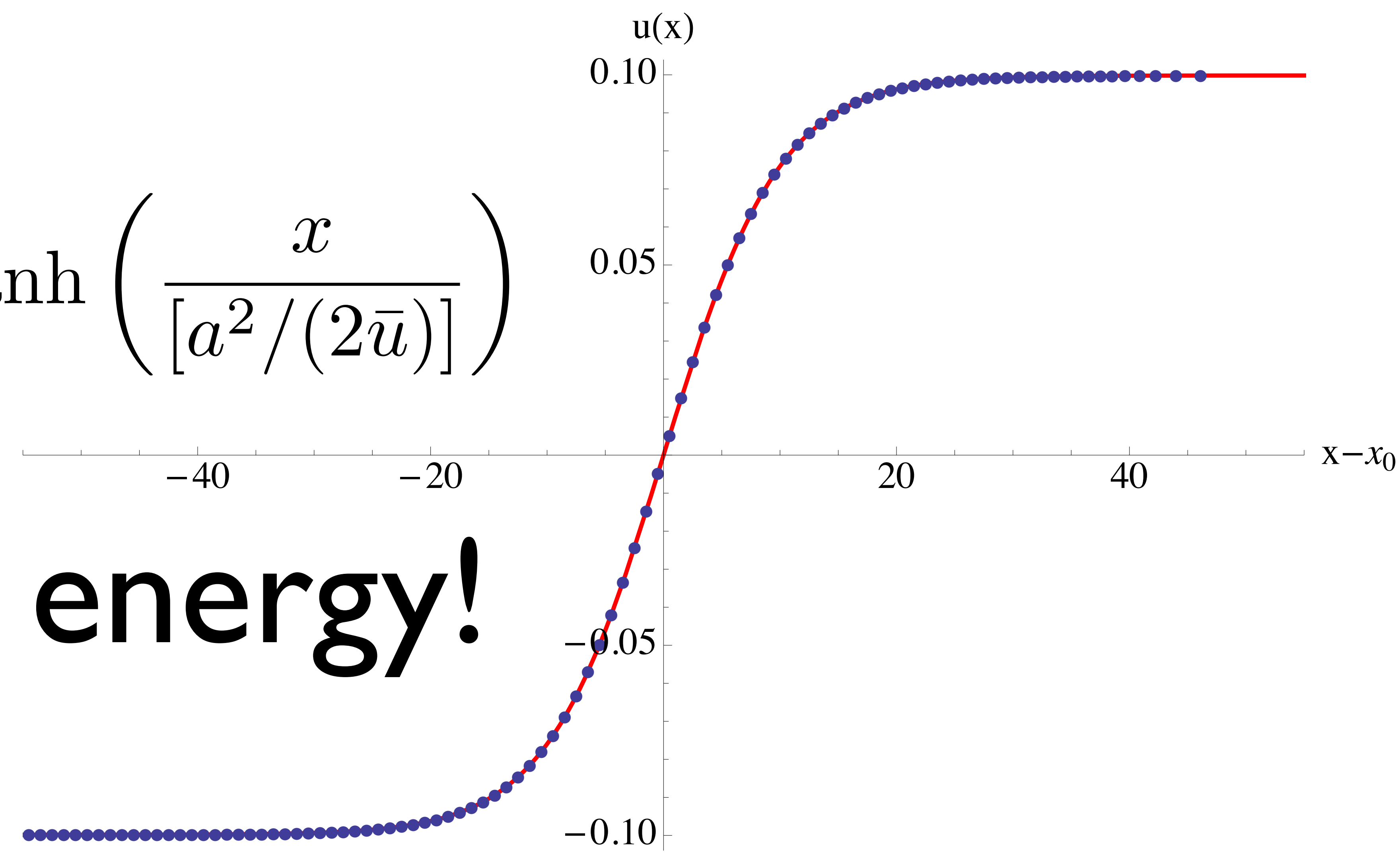

Zero energy!

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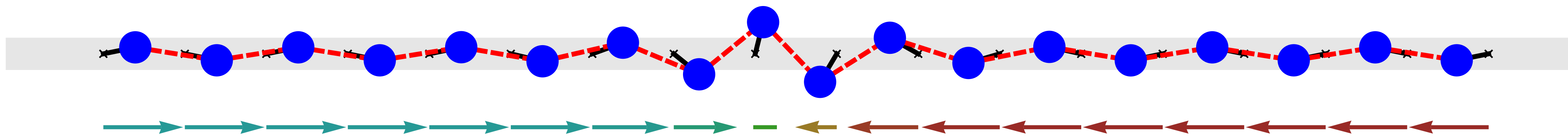

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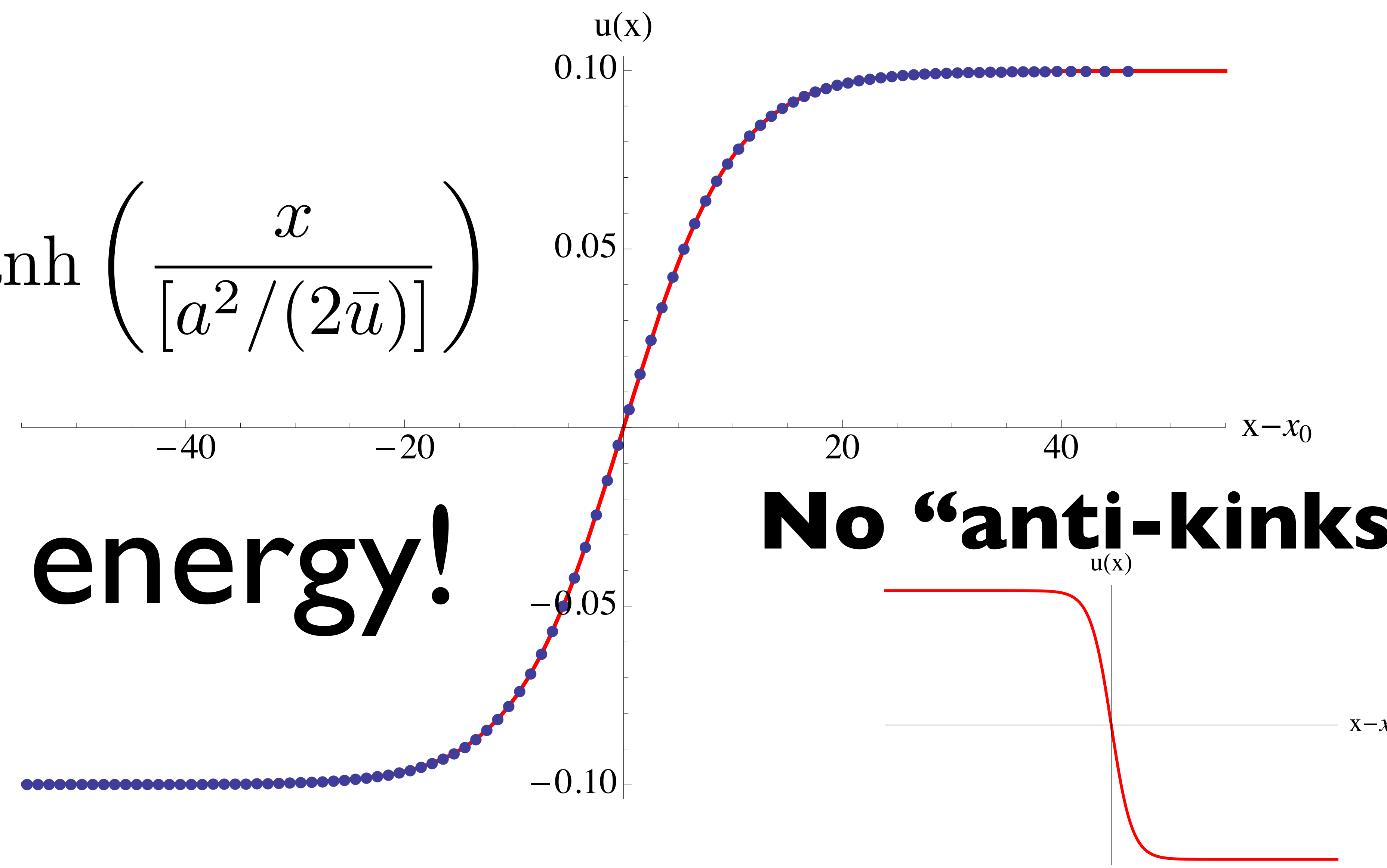

Zero energy!

No "anti-kinks"!

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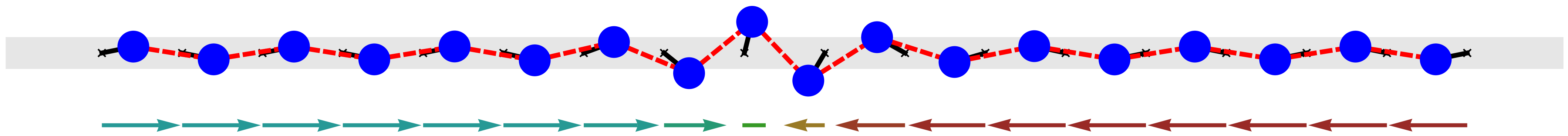

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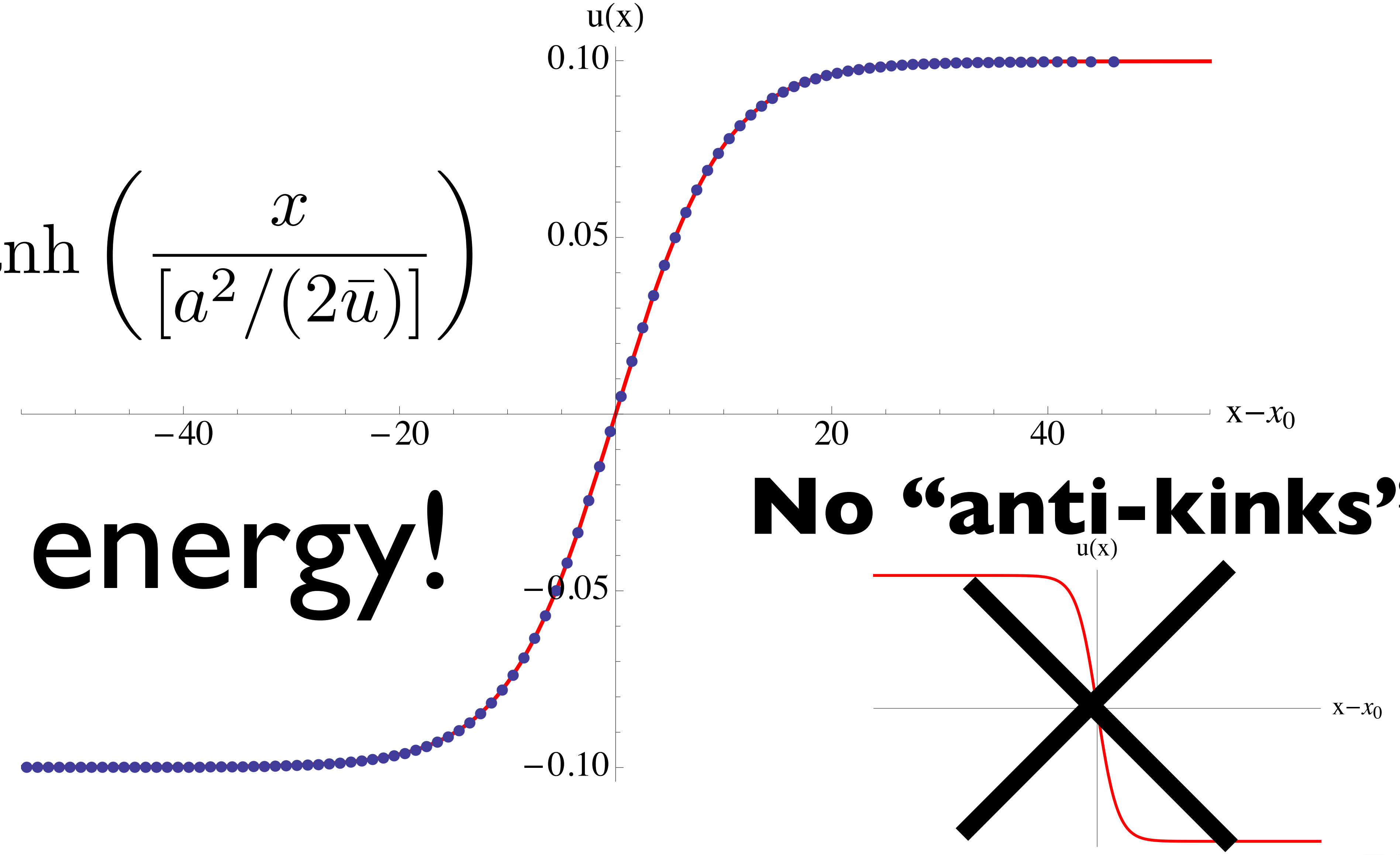

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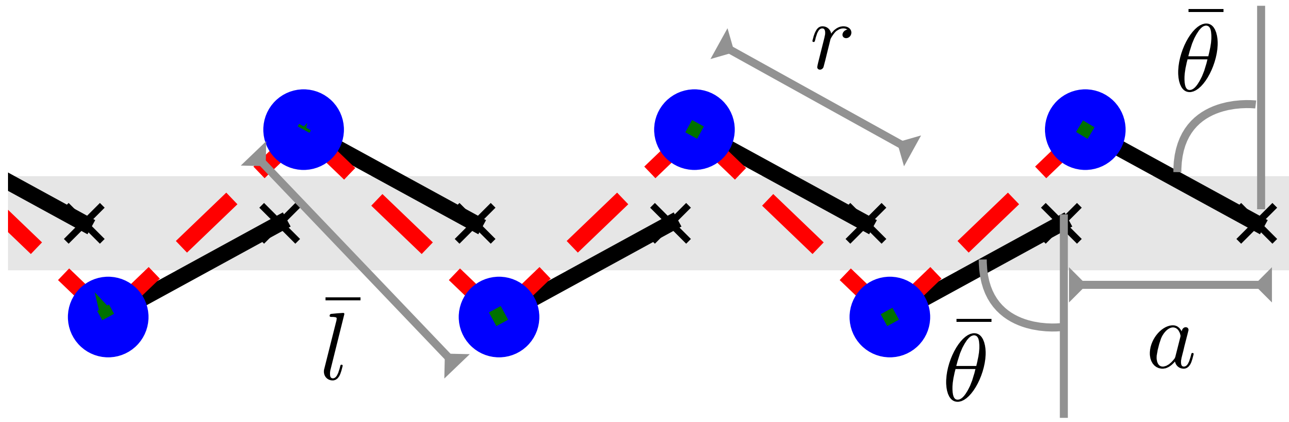
Continuum limit for flipper energy



$$V[u(x)] = \frac{4k_e}{\bar{l}^2}\left[(\bar{u}^2 - u^2) + \frac{a^2}{2}\frac{du}{dx}\right]^2$$

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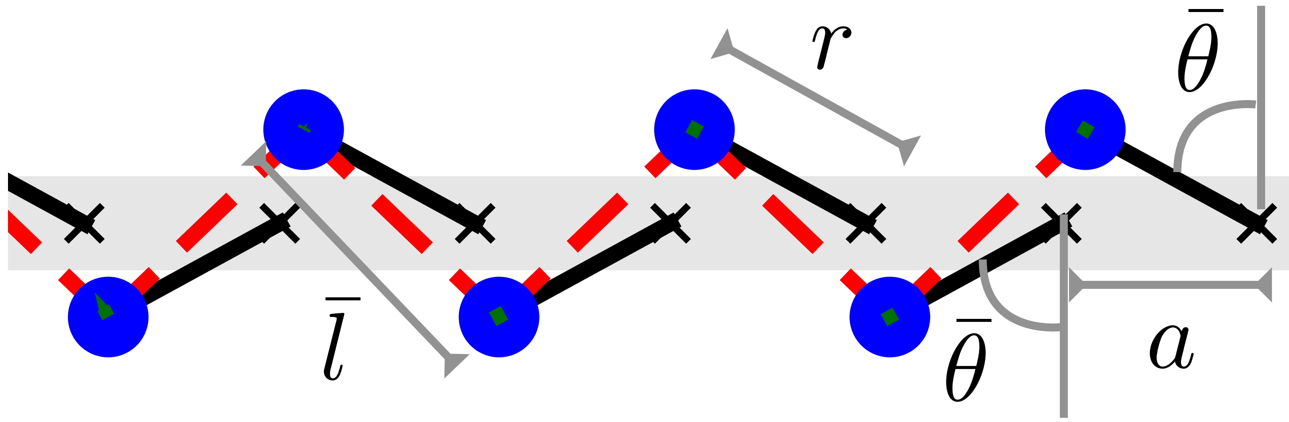
Continuum limit for flipper energy



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Expand the **perfect square**

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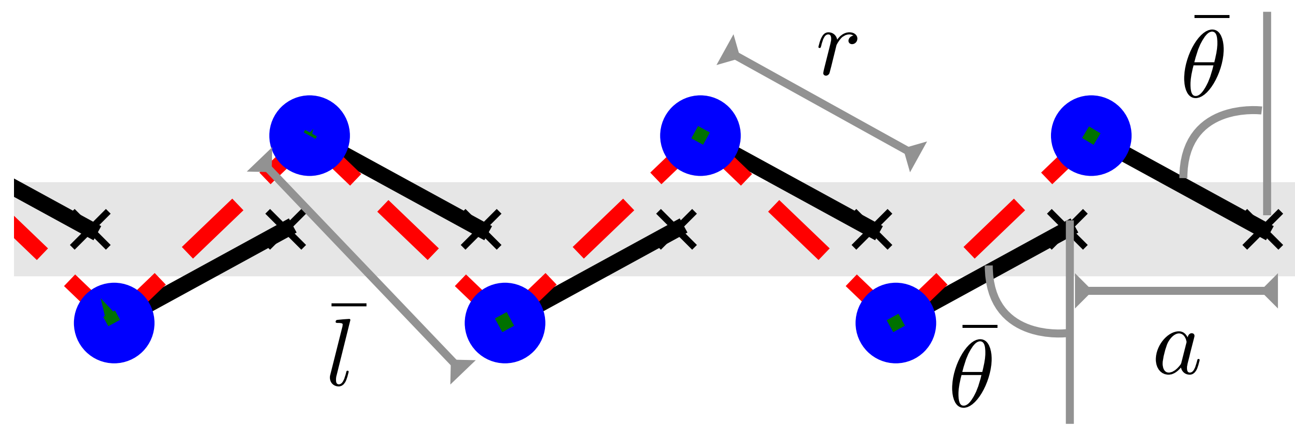
Continuum limit for flipper energy



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Expand the **perfect square**

$$V[u(x)] = \frac{4k_e}{\bar{l}^2}\left[\frac{a^4}{4}\left(\frac{du}{dx}\right)^2 + (\bar{u}^2 - u^2)^2 + \frac{a^2}{2}\frac{du}{dx}(\bar{u}^2 - u^2)\right]$$

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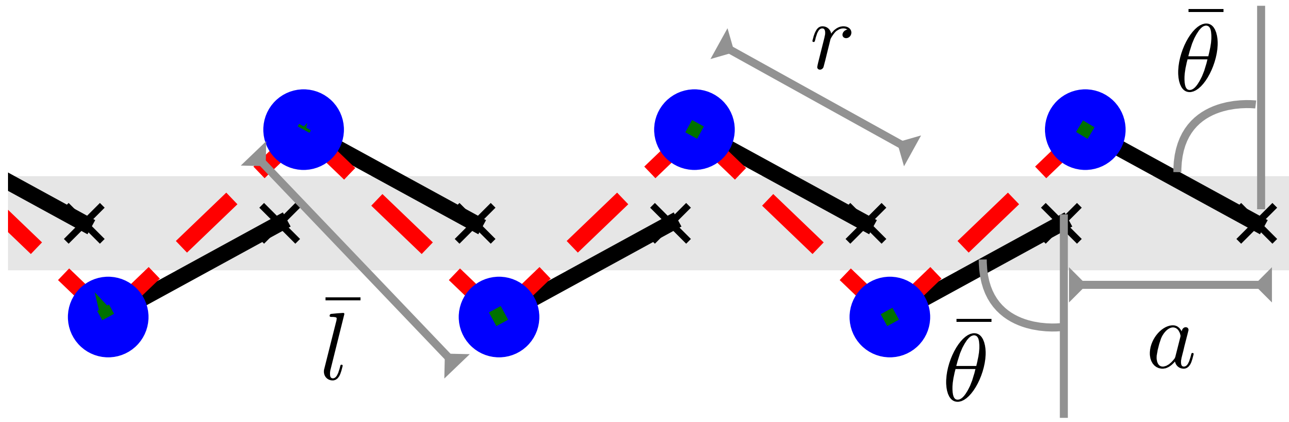
Continuum limit for flipper energy



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φ^4 theory

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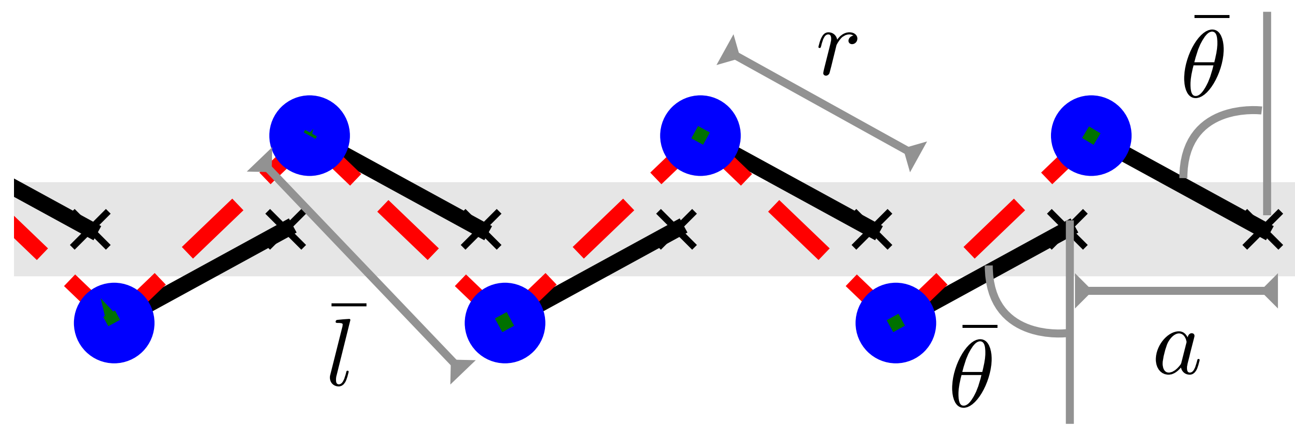

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φ^4 theory + *topological* term!

$$V[u(x)] = \frac{4k_e}{\bar{l}^2}\left[\frac{a^4}{4}\left(\frac{du}{dx}\right)^2 + (\bar{u}^2 - u^2)^2 + \frac{a^2}{2}\frac{du}{dx}(\bar{u}^2 - u^2)\right]$$

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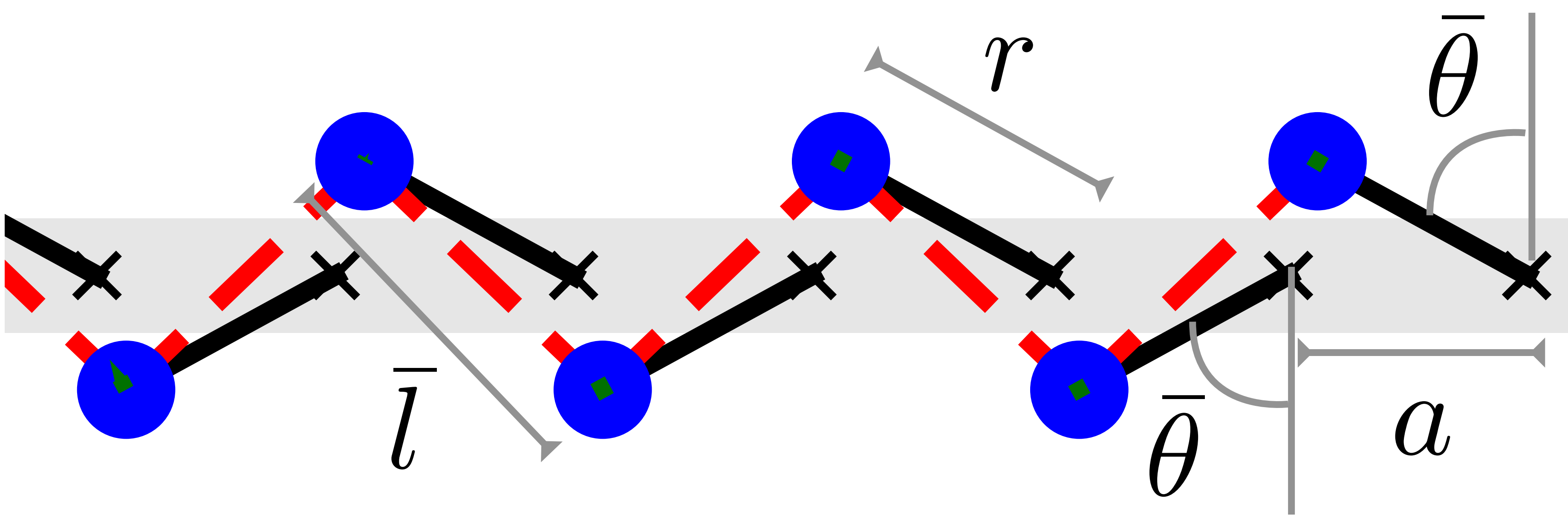
What properties are **robust**? What can be **tuned**?



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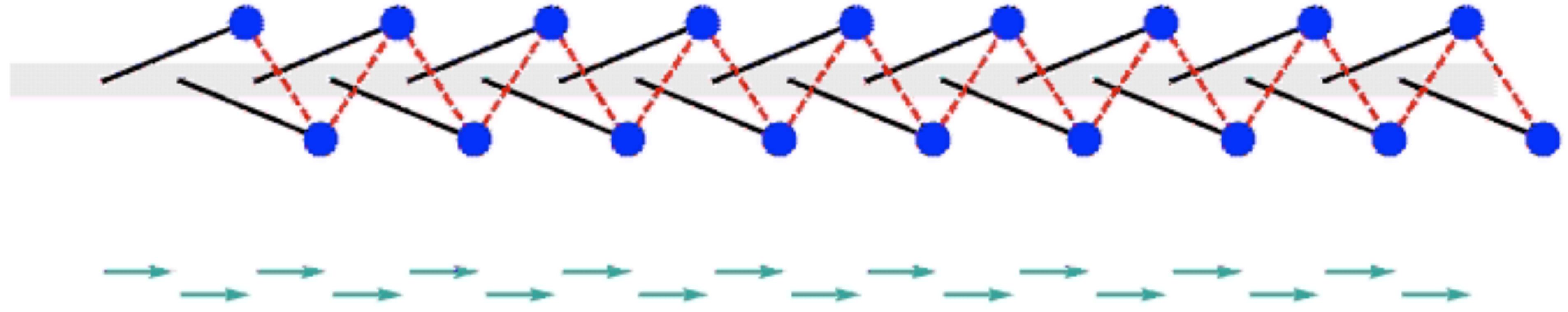
The Spinner



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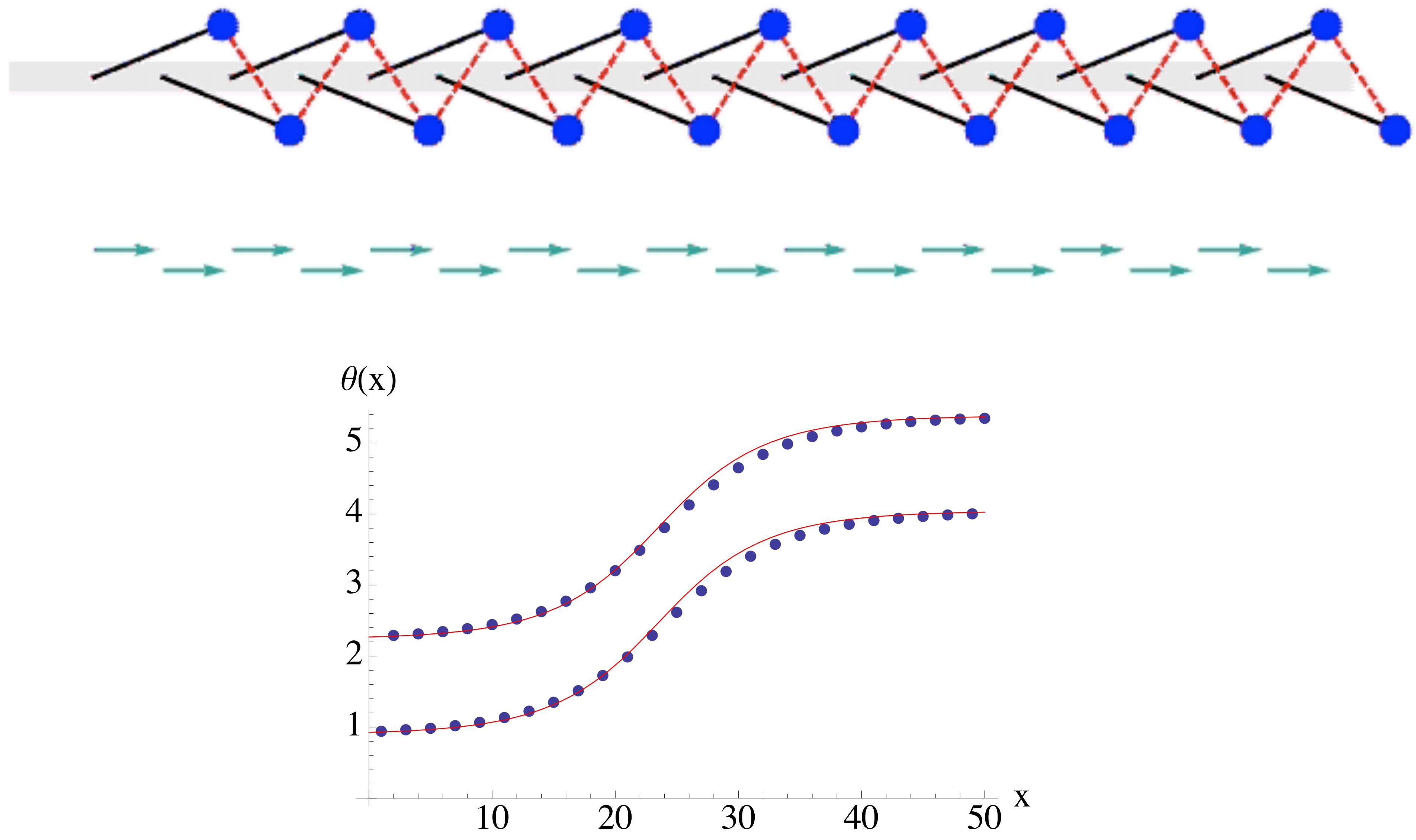

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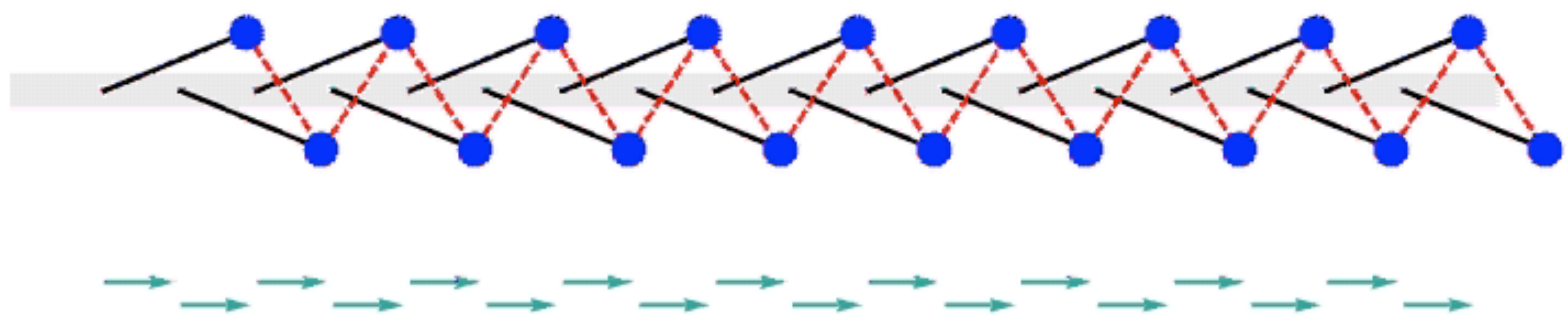

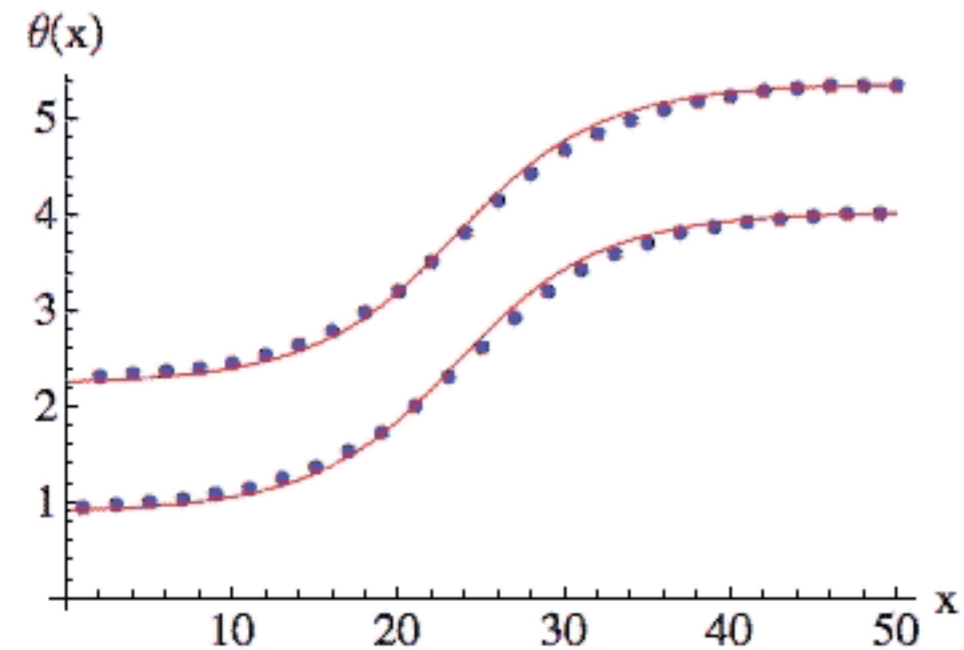

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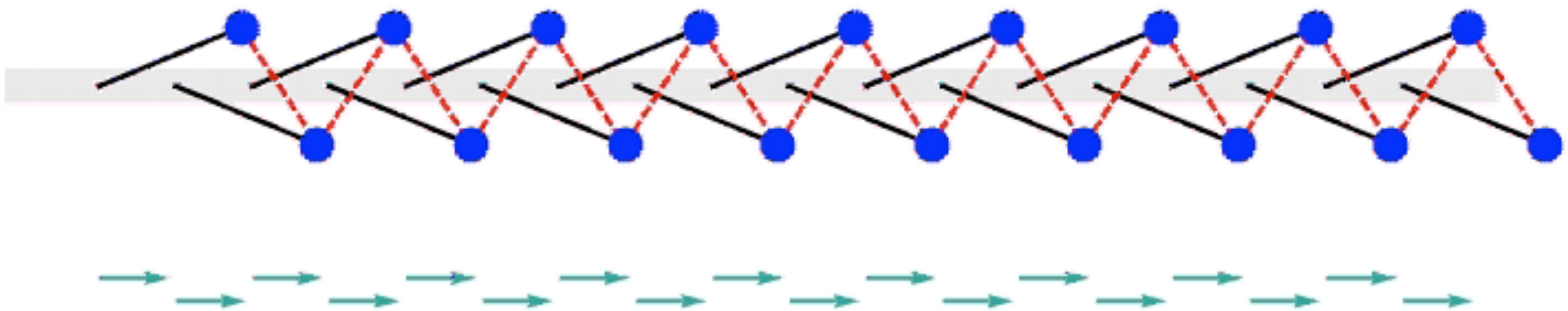

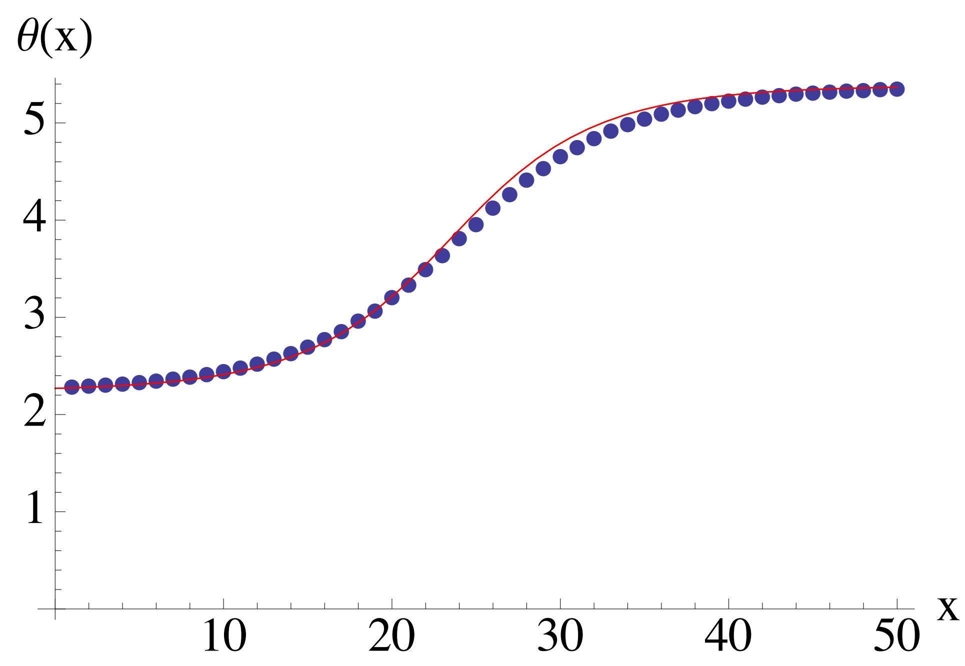

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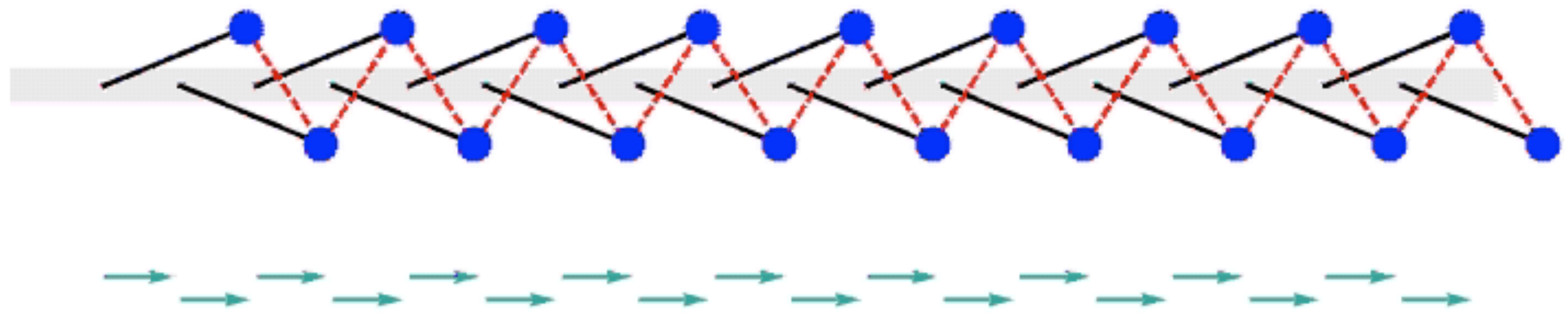

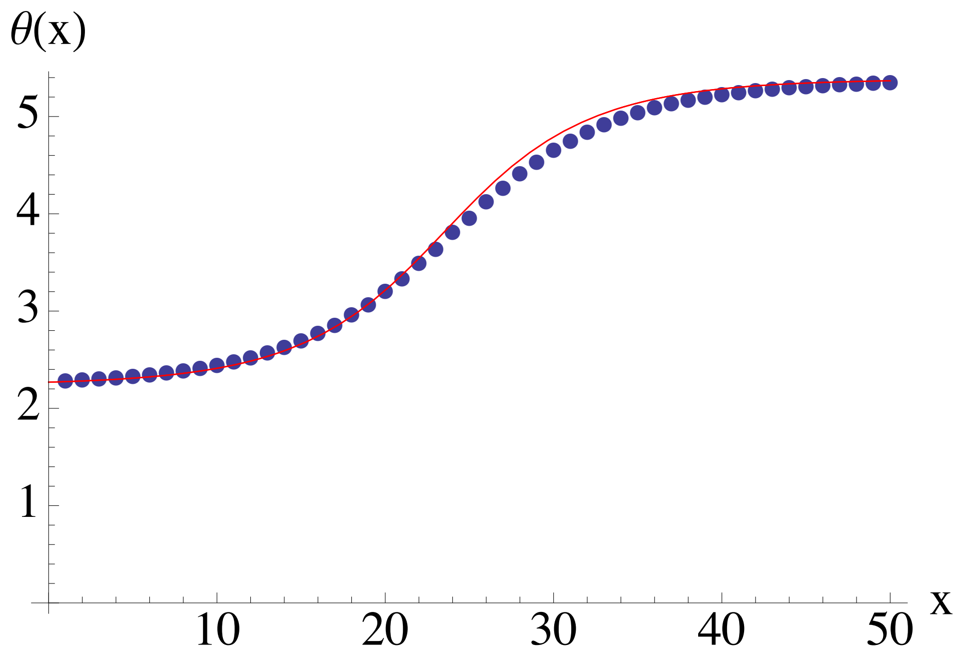

continuum limit: **2 coupled copies** of **sine-Gordon** kink!

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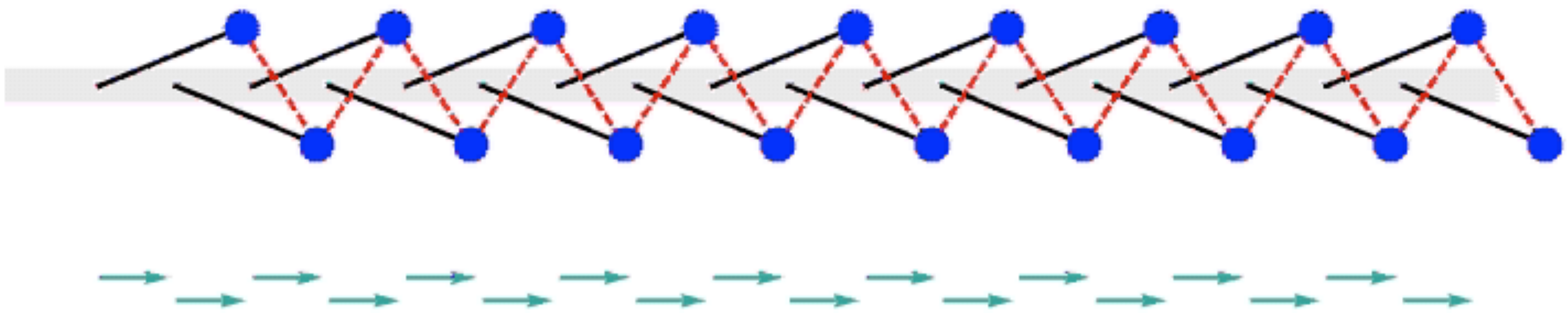
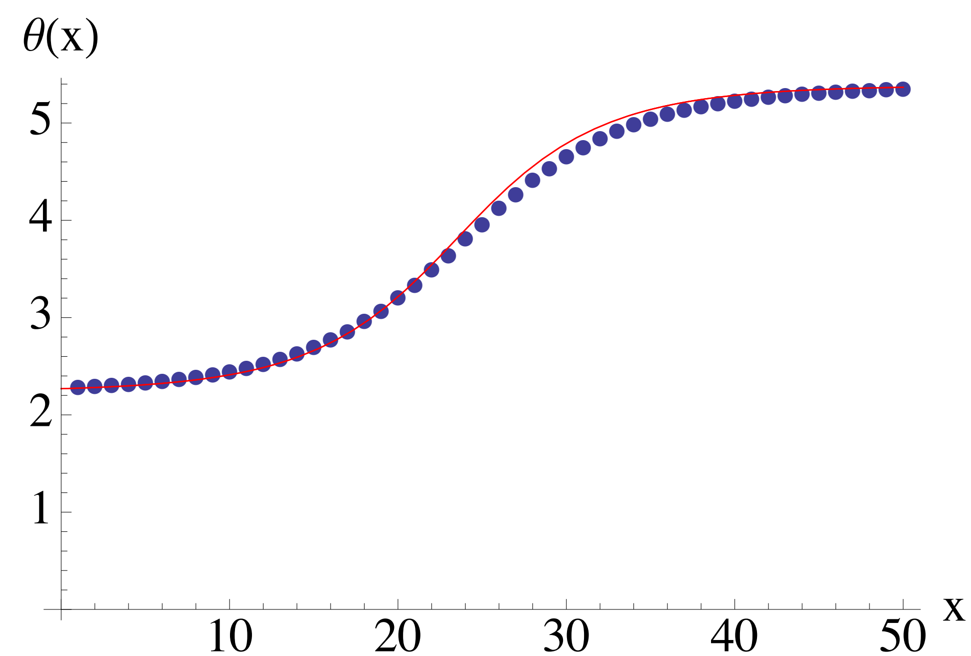
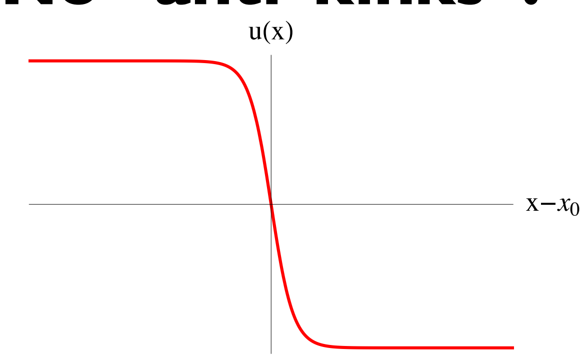




No “anti-kinks”!



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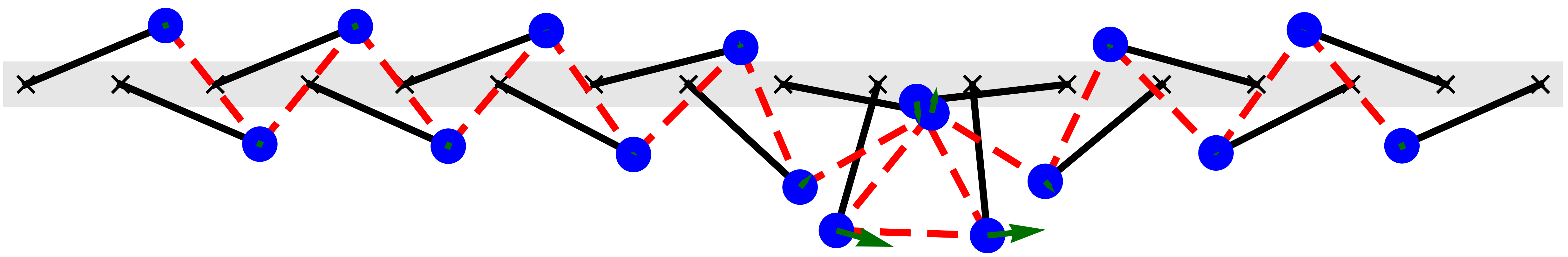

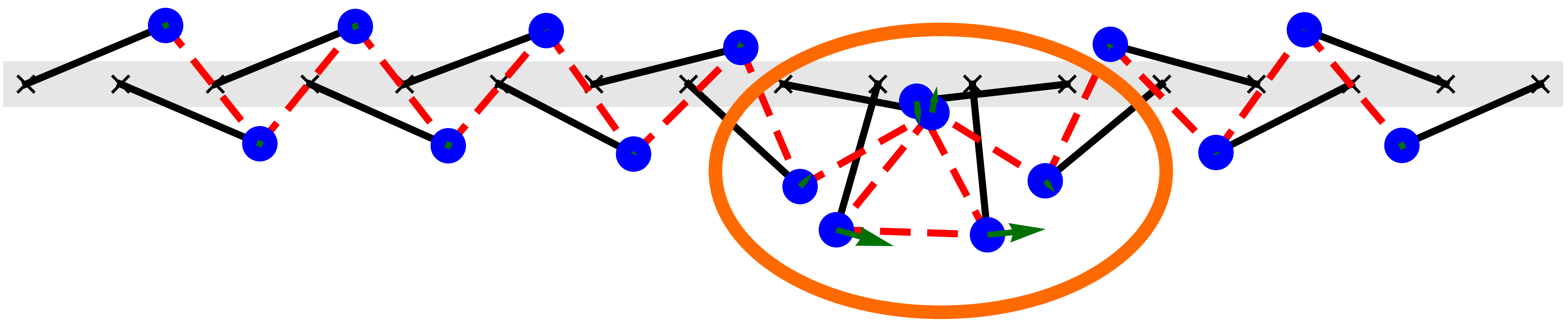

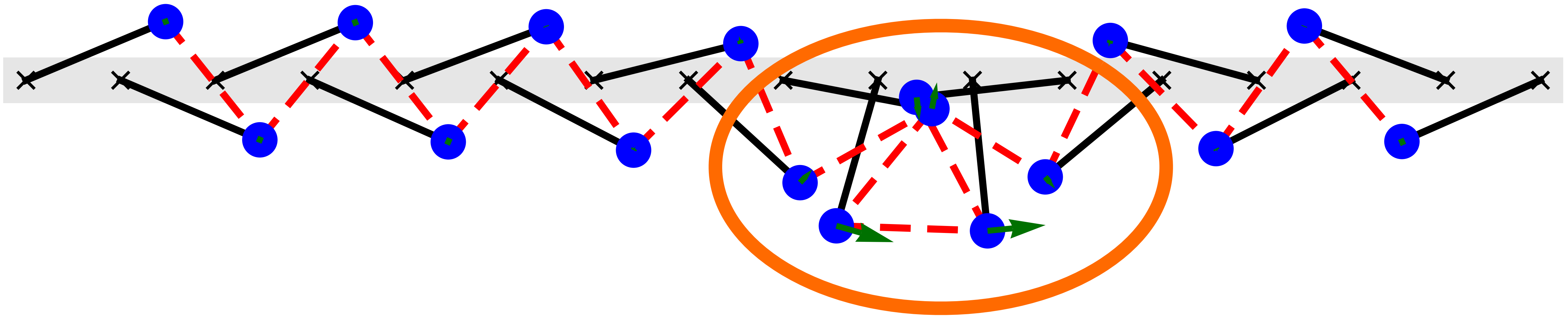

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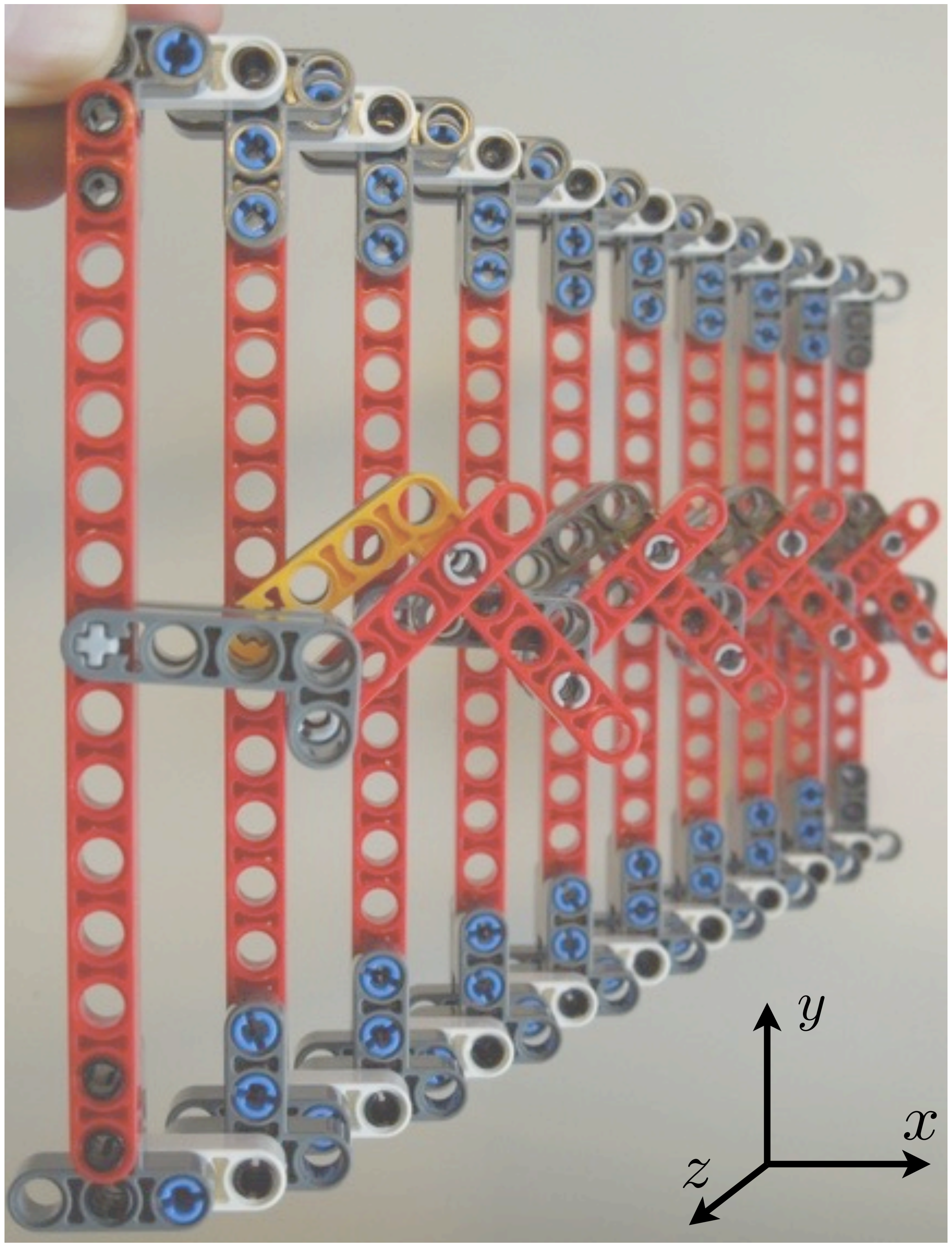

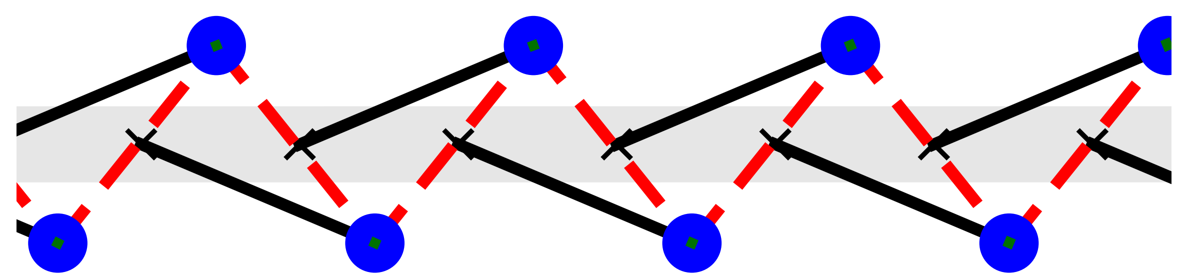

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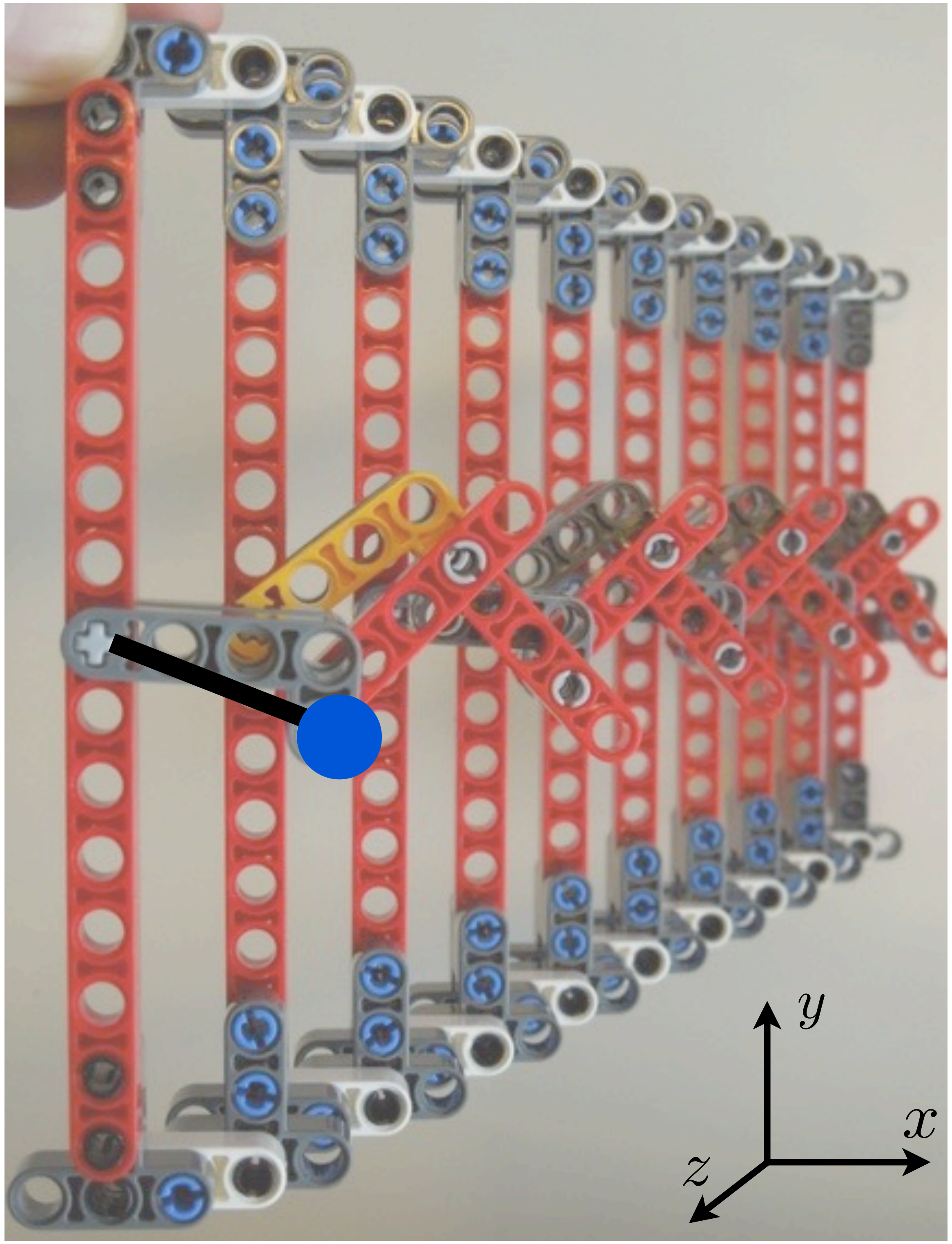

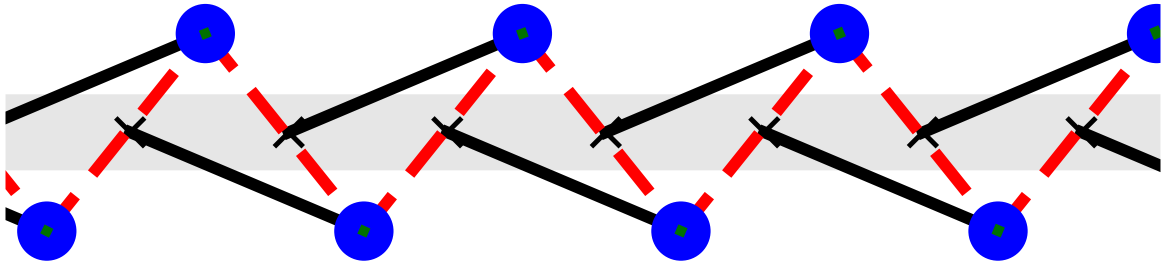

Chen, Upadhyaya, Vitelli PNAS 111, 13004 (2014)

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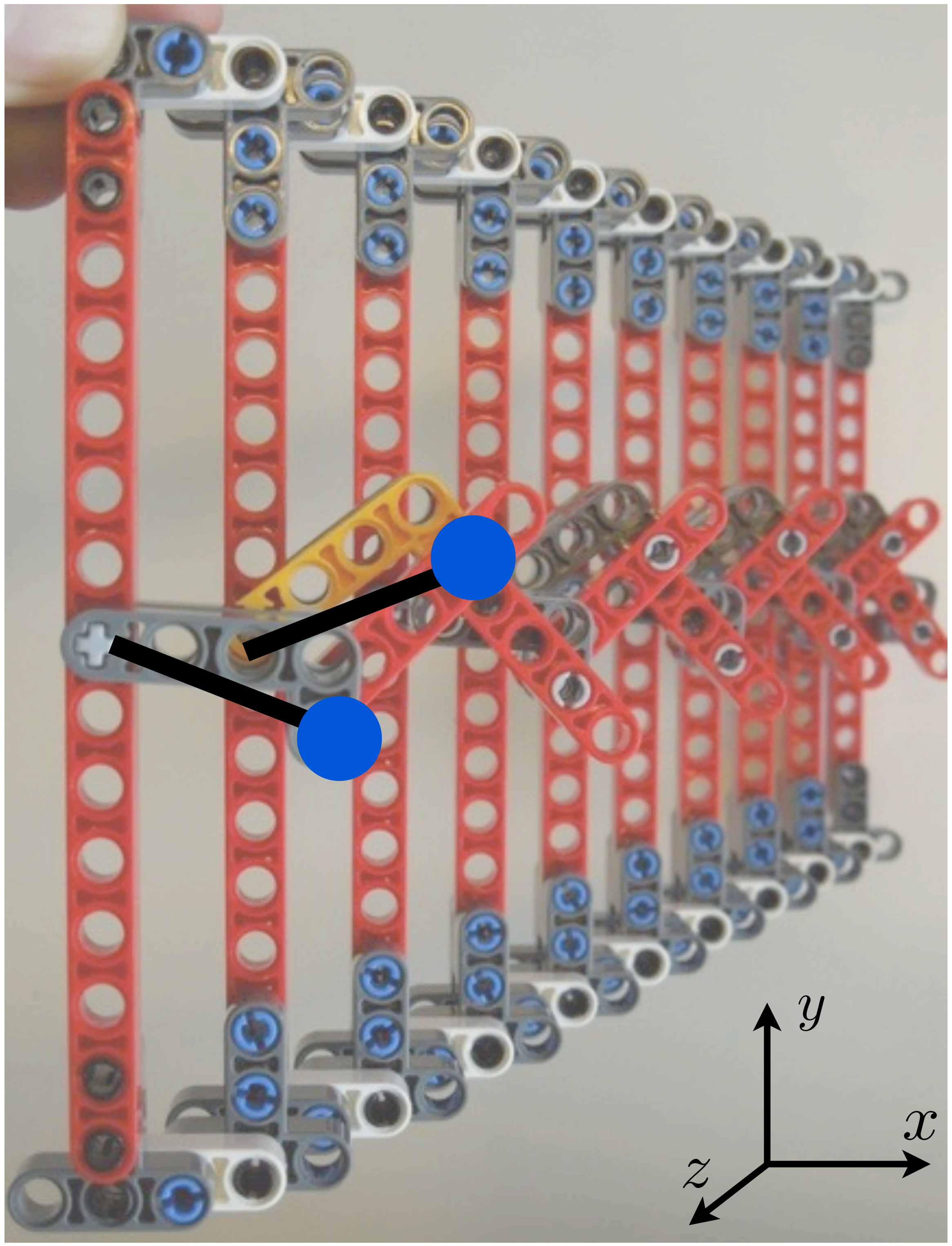

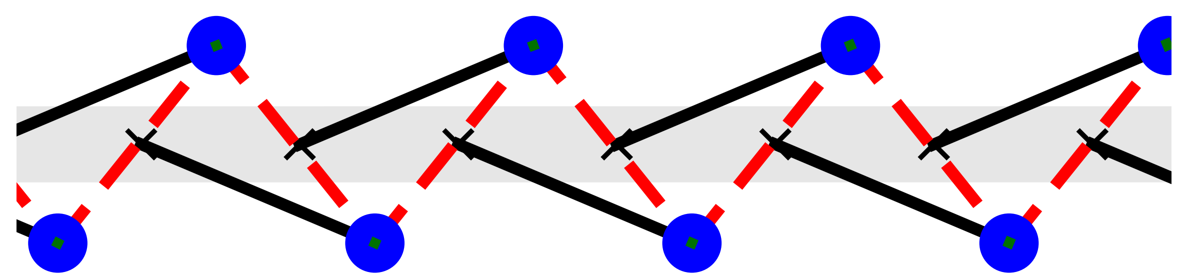

Chen, Upadhyaya, Vitelli PNAS 111, 13004 (2014)

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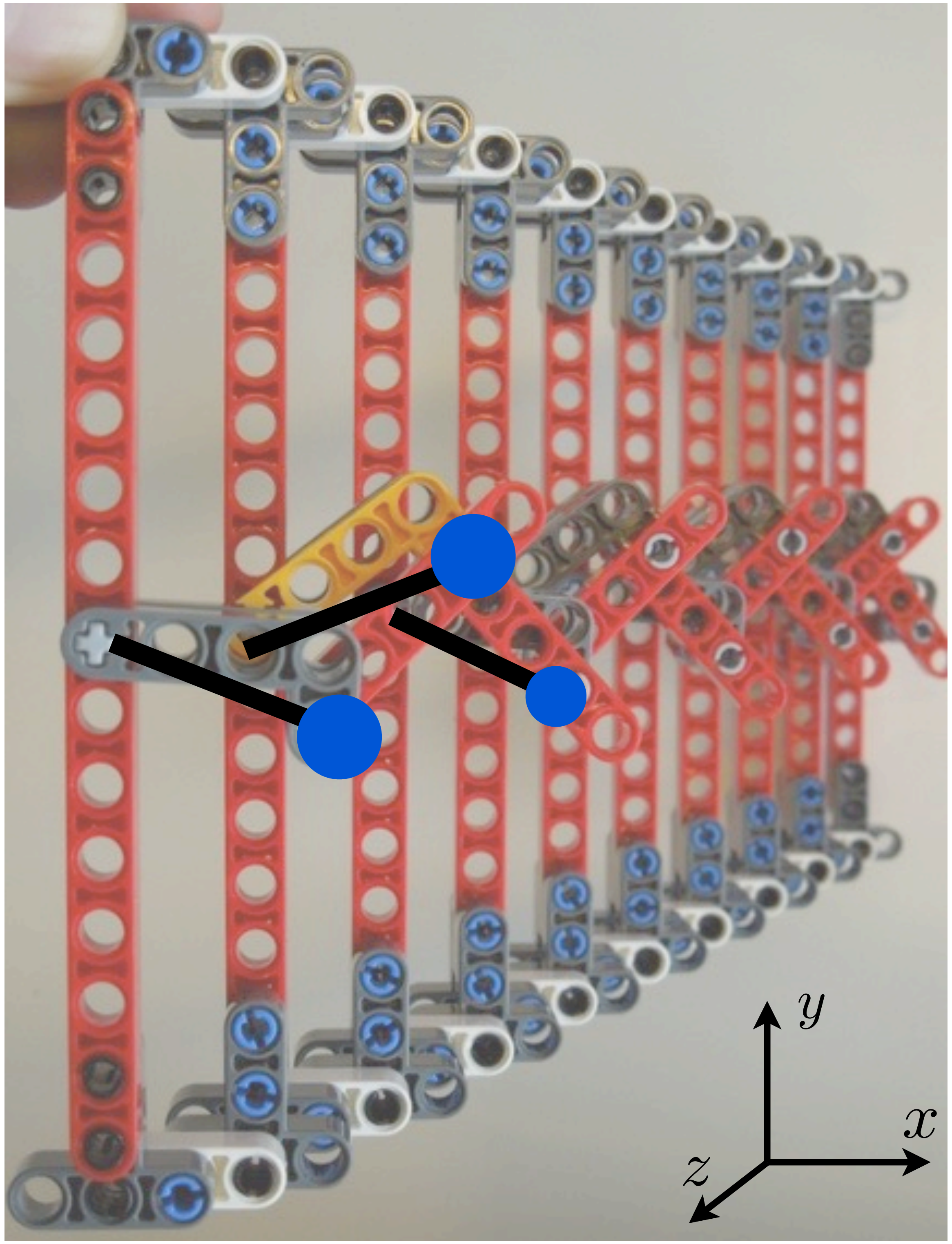

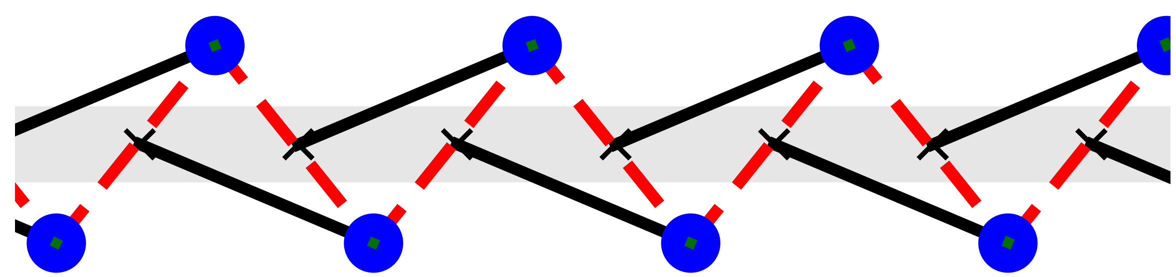

Chen, Upadhyaya, Vitelli PNAS 111, 13004 (2014)

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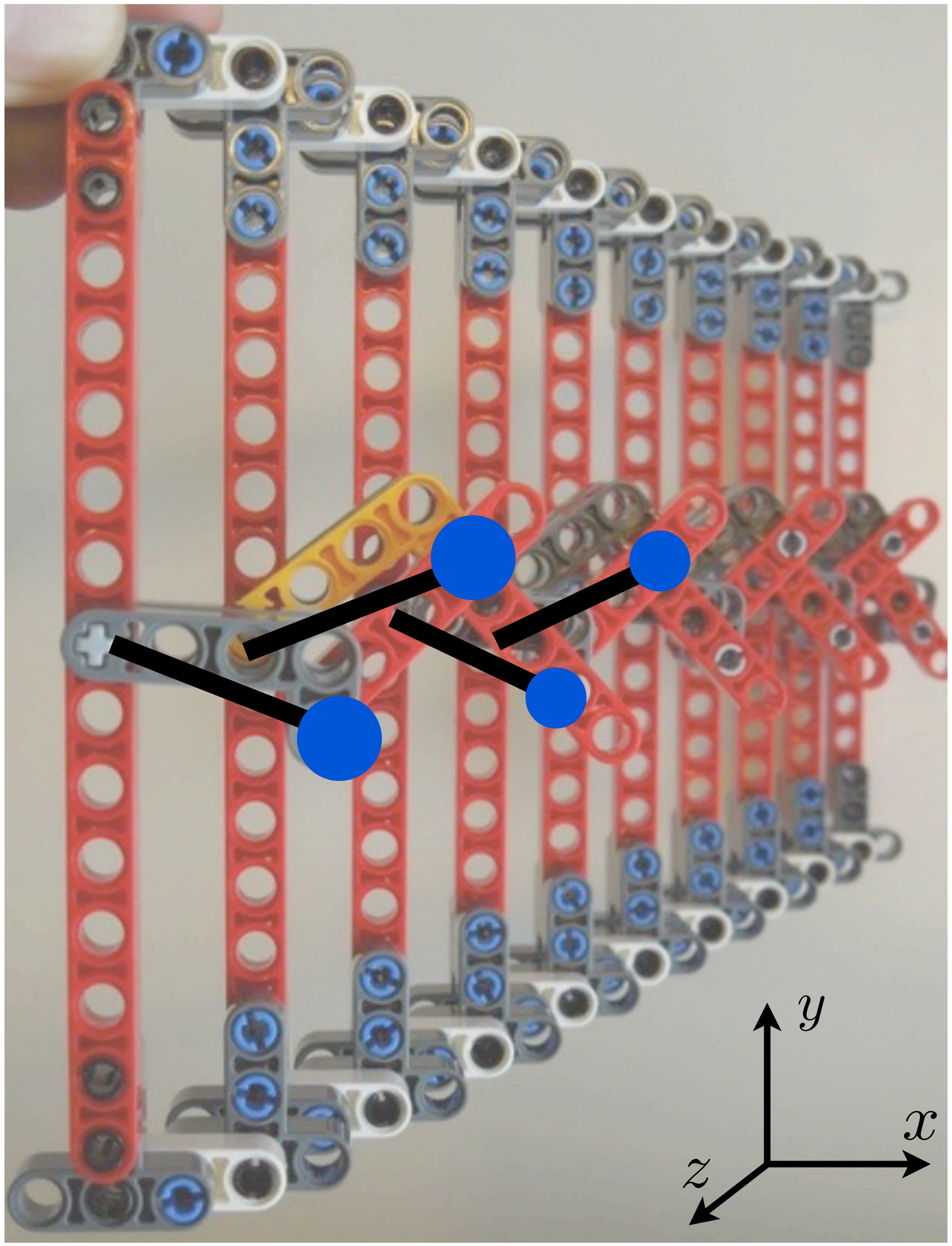

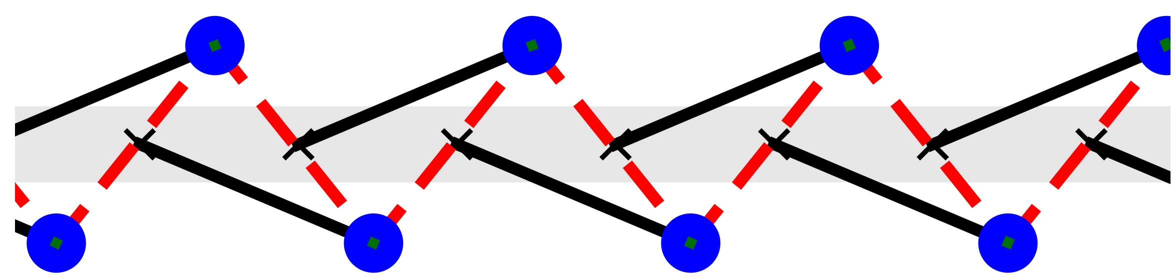

Chen, Upadhyaya, Vitelli PNAS 111, 13004 (2014)

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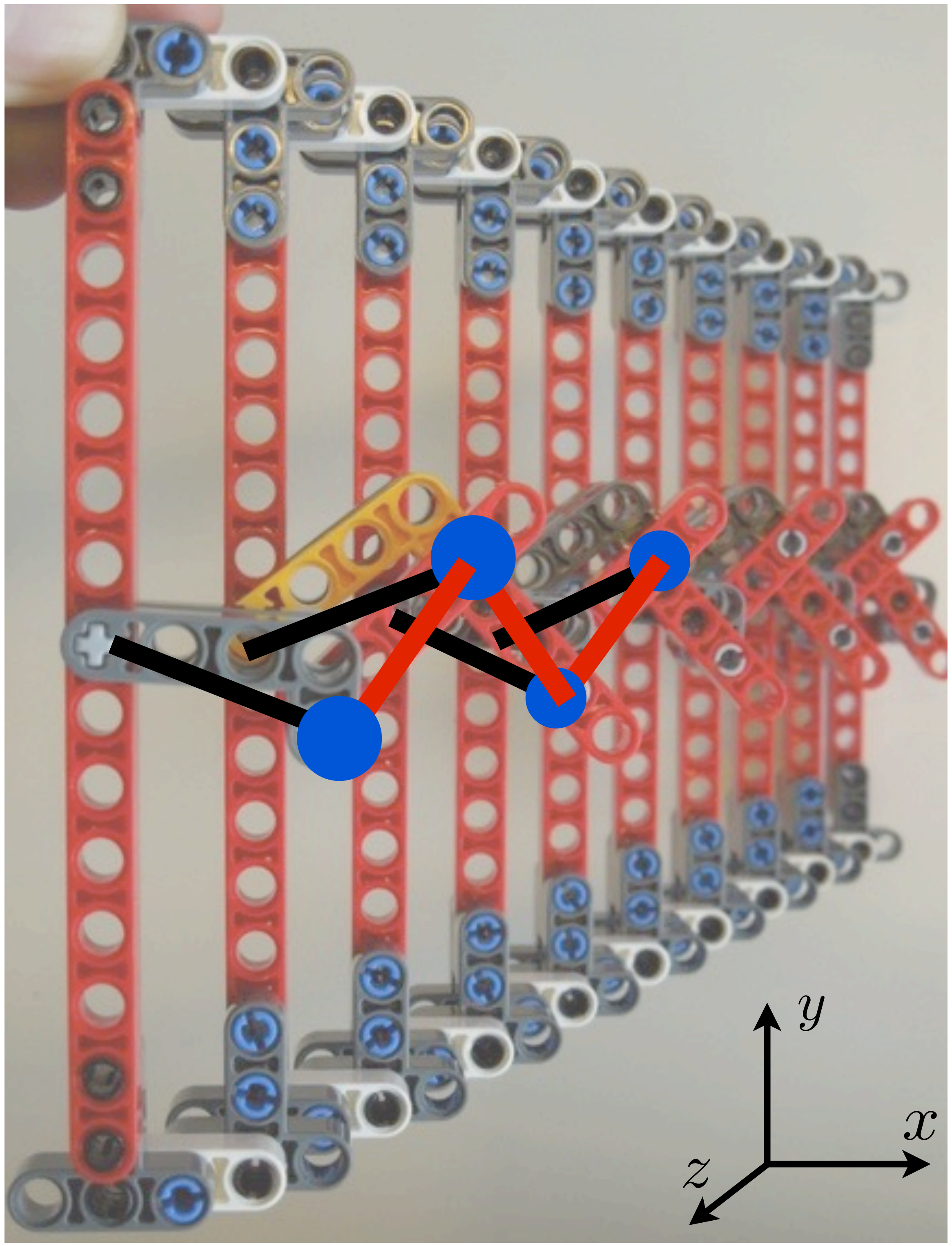
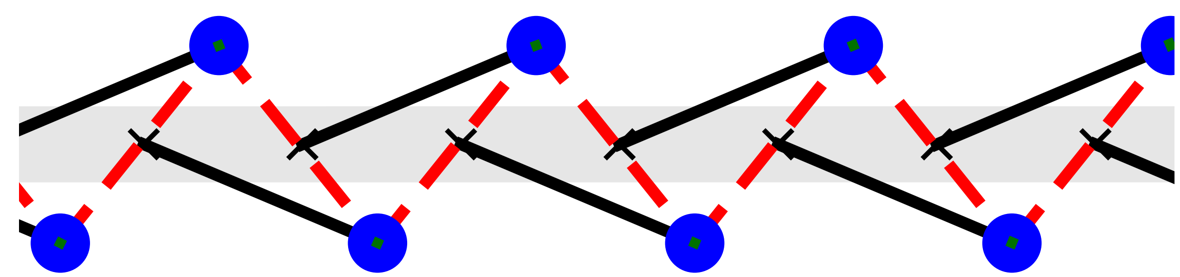


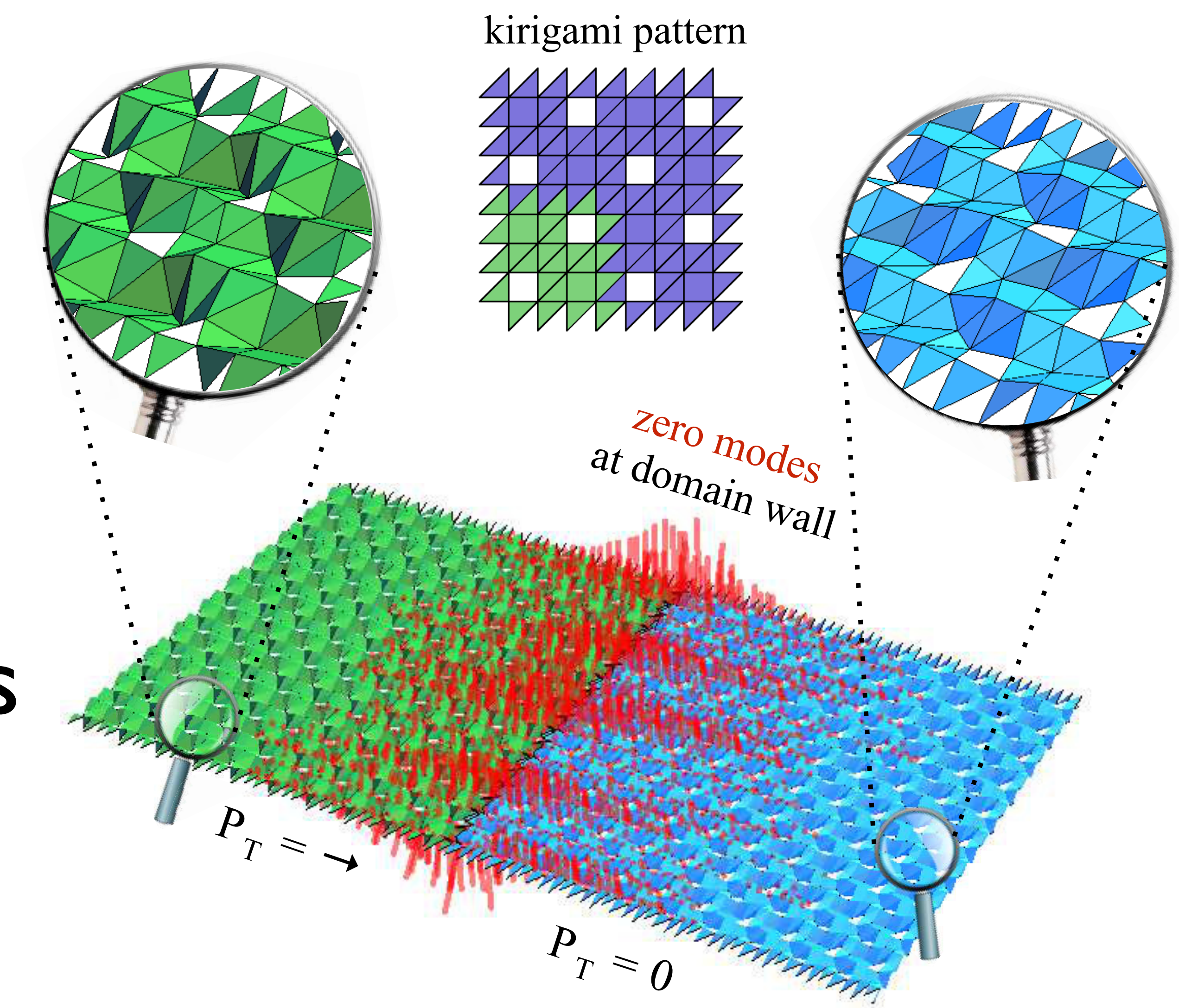


Chen, Upadhyaya, Vitelli PNAS 111, 13004 (2014)

Beyond beads and springs

Topologically polarized
origami and **kirigami**

Conjecture:
origami (without holes) always has zero polarization*



BGC, Liu, Evans, Paulose, Cohen, Vitelli, Santangelo. arXiv:1508.00795

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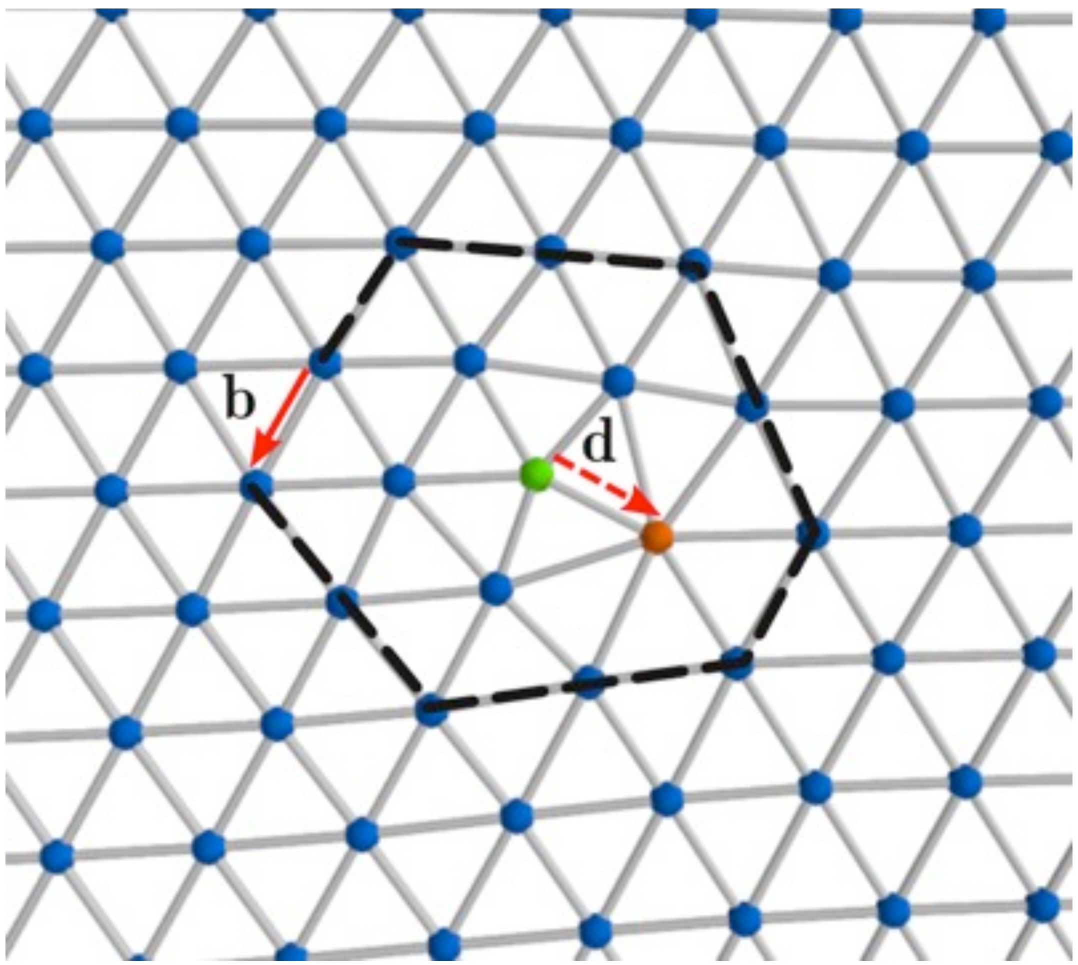

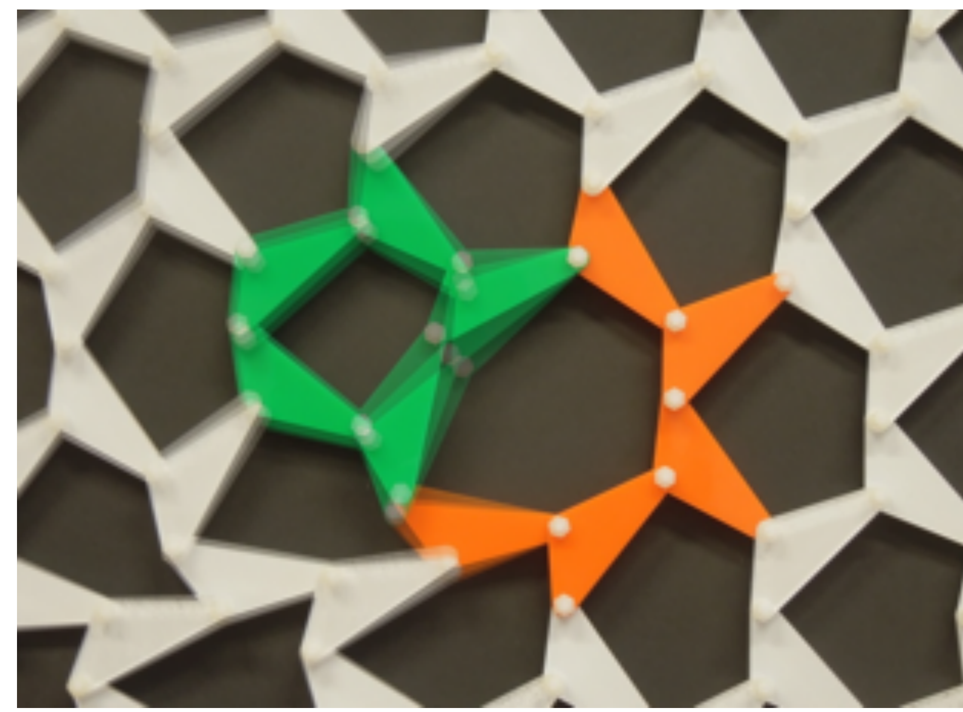

Paulose, BGC, Vitelli, Nature Physics 11, 153-156 (2015)

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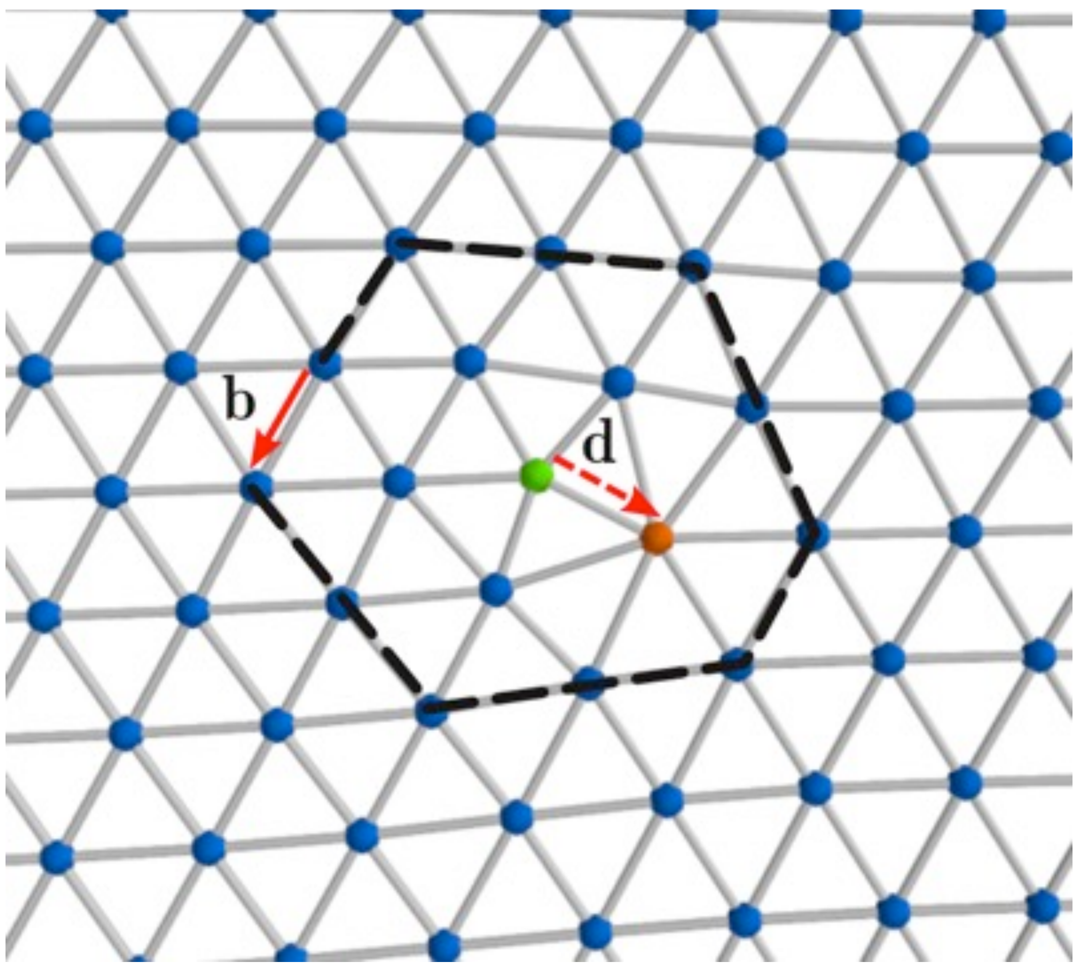
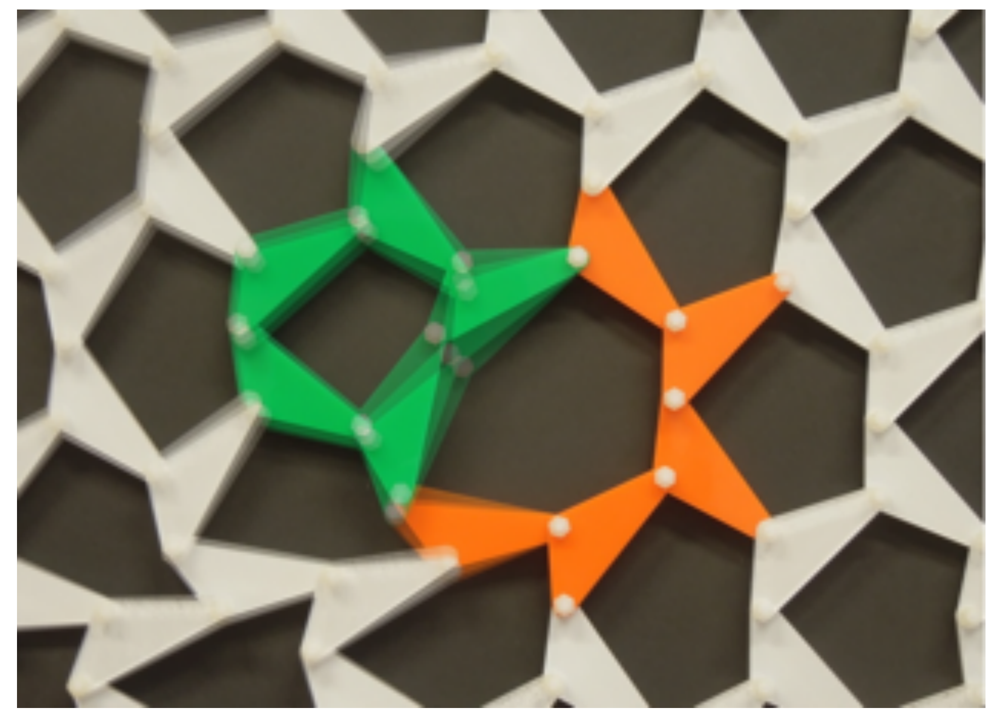
Topological modes at **point**-like defects called **dislocations**





Paulose, BGC, Vitelli, Nature Physics 11, 153-156 (2015)

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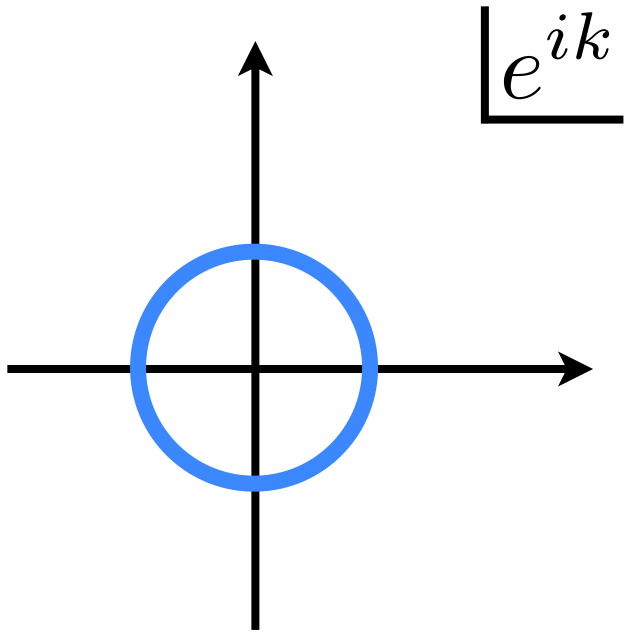
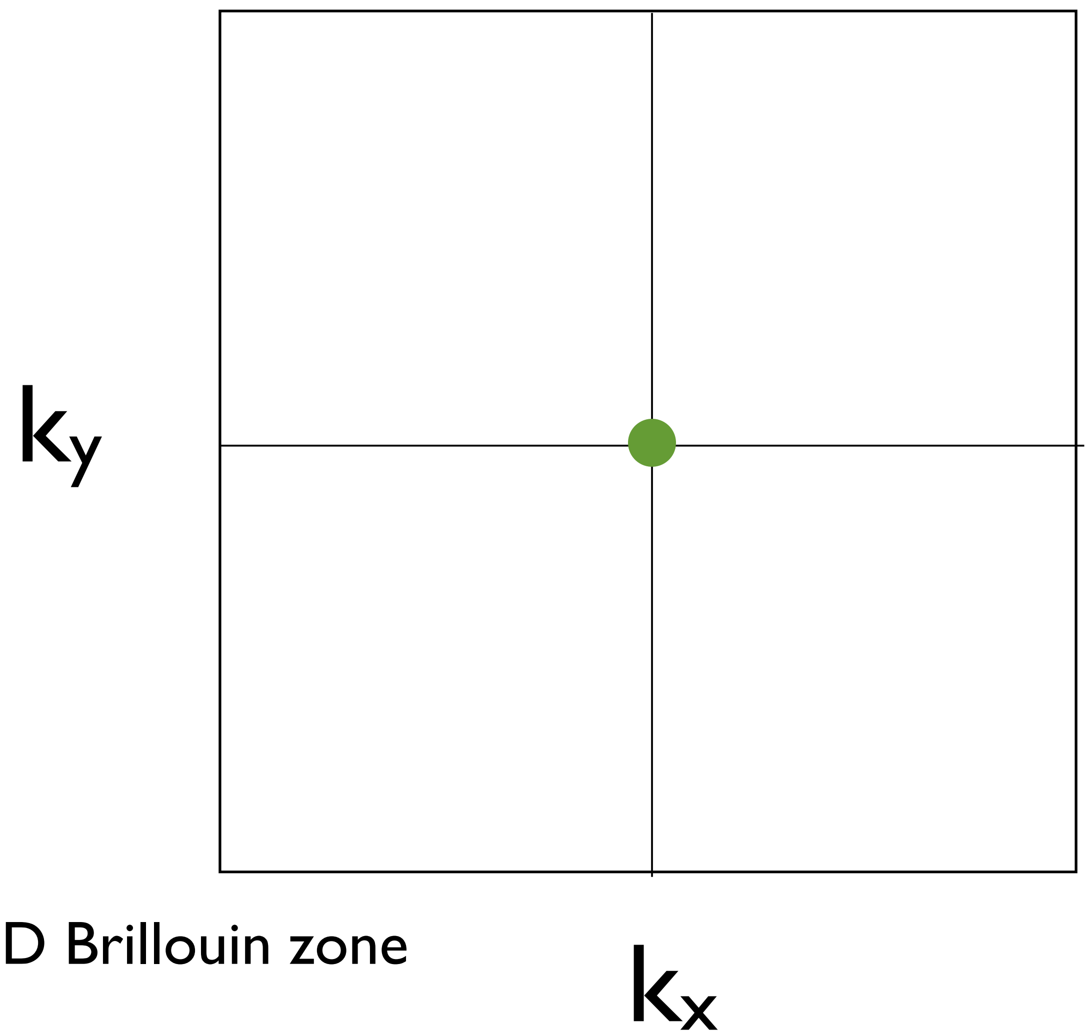
What about modes localized in **reciprocal space**?

Go to 2D!

winding of Arg det C



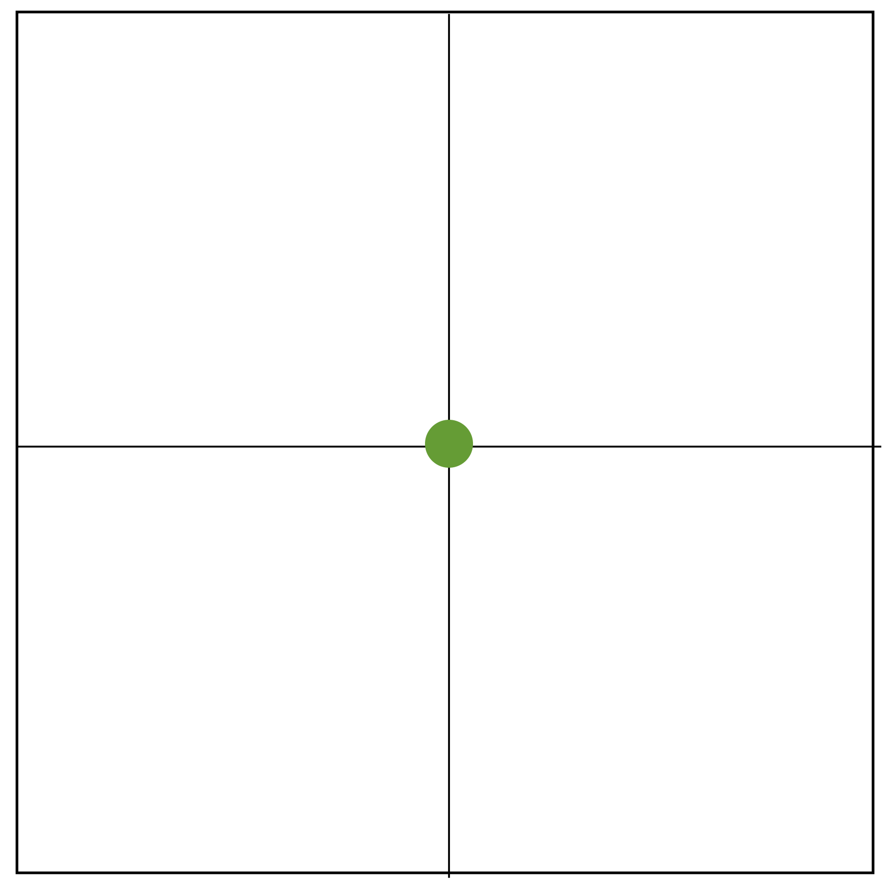


2D Brillouin zone

Kane and Lubensky, Nature Physics 2014

Go to 2D!

k_y

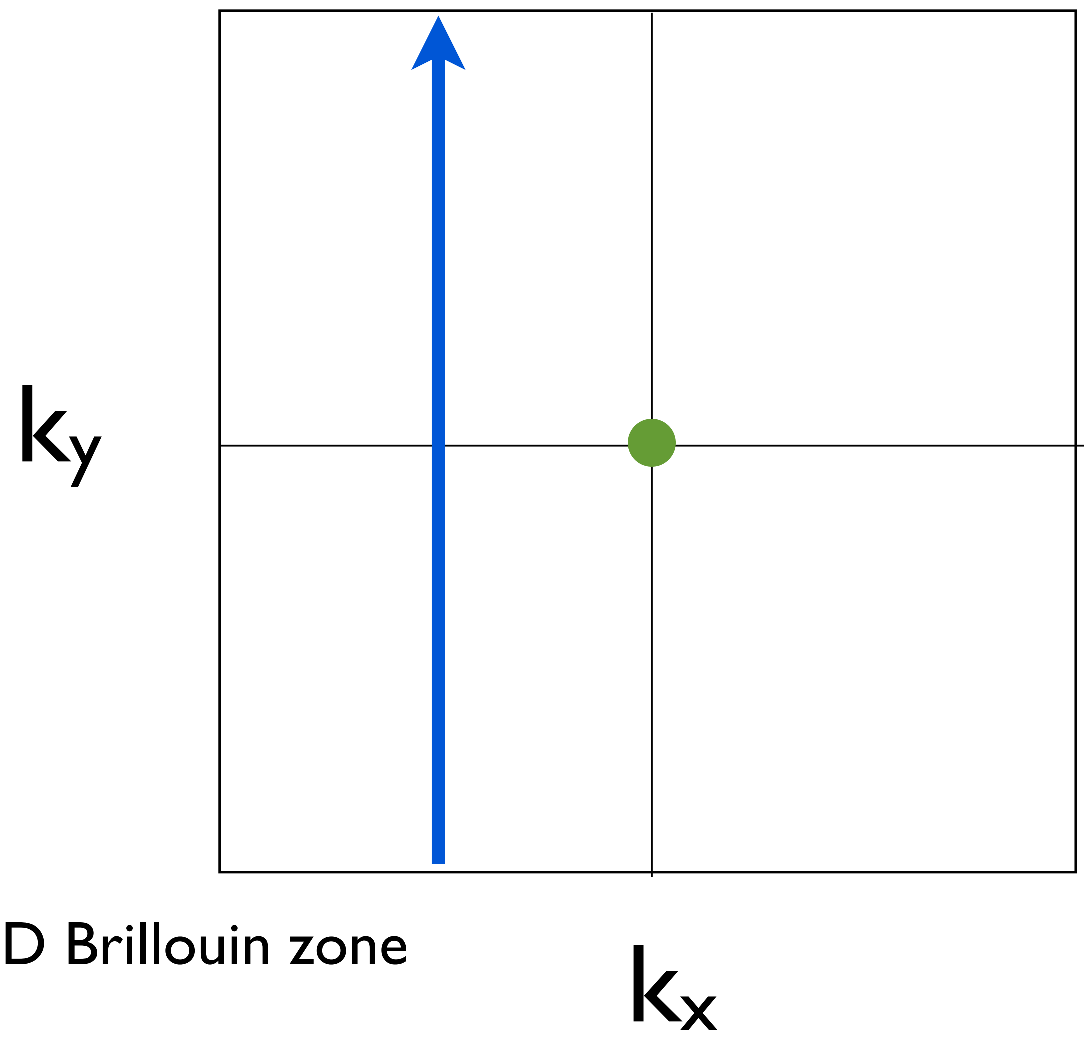


2D Brillouin zone

k_x

Kane and Lubensky, Nature Physics 2014

Go to 2D!



2D Brillouin zone

Kane and Lubensky, Nature Physics 2014

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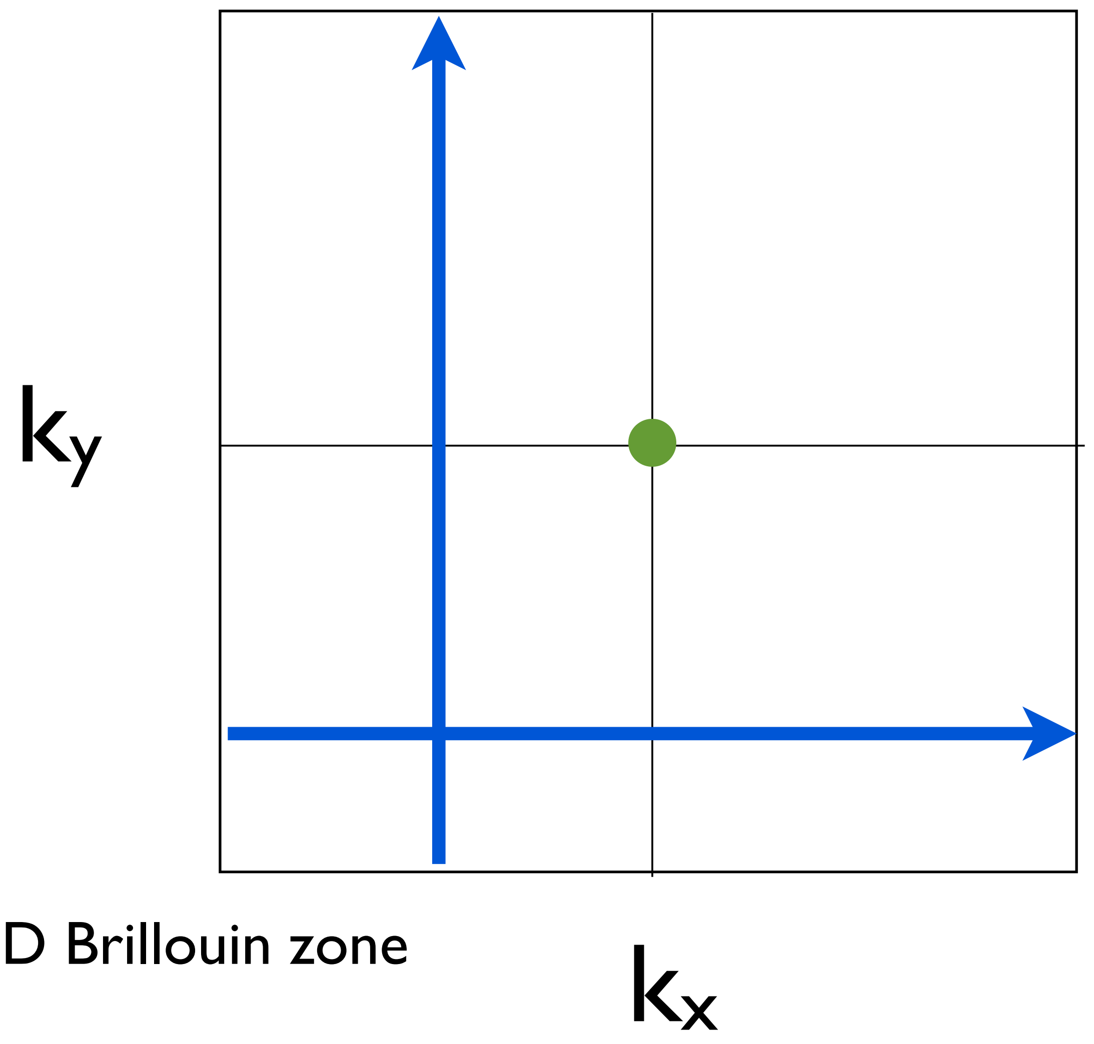

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Kane and Lubensky, Nature Physics 2014

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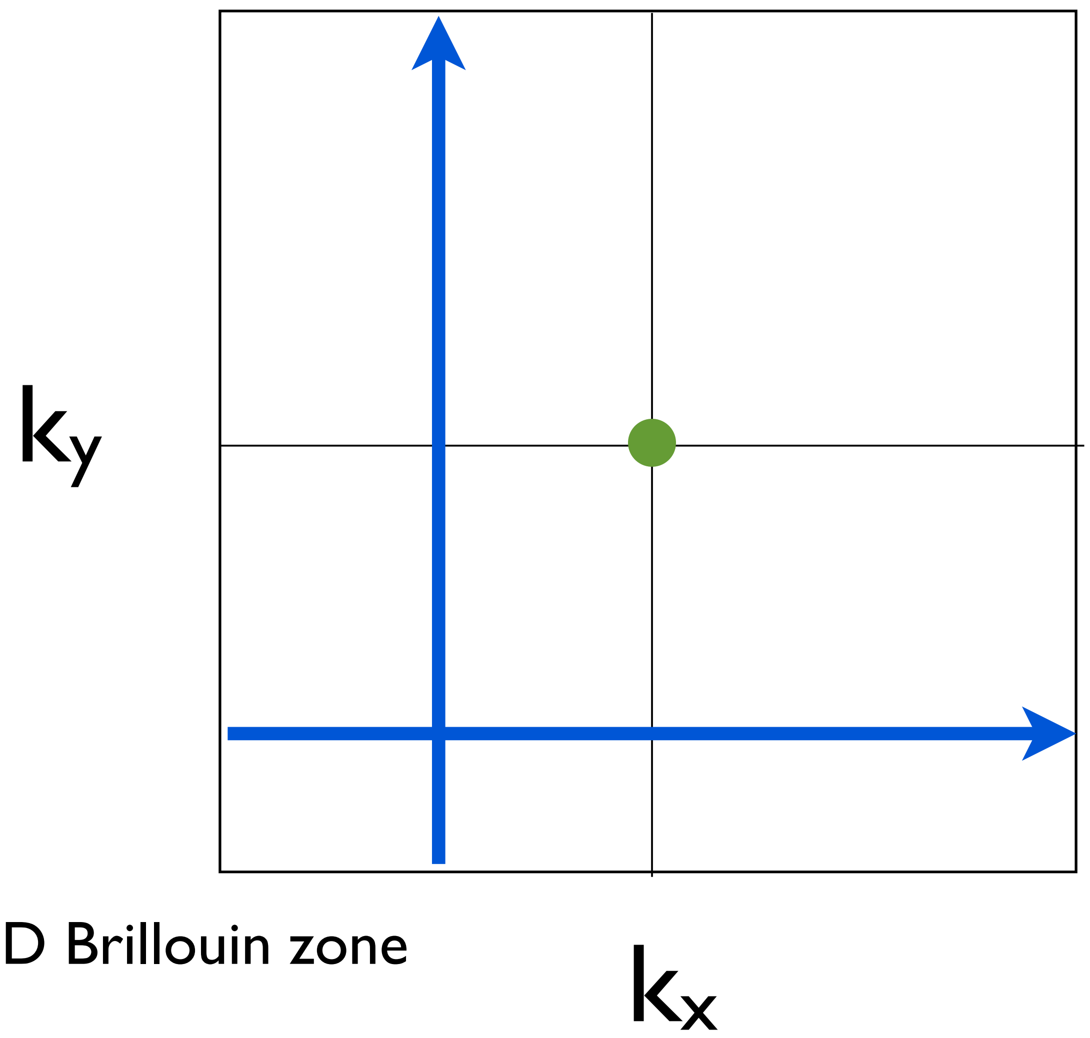

2D Brillouin zone

A pair of winding numbers gives a "topological polarization" **vector** that points towards floppy edge

Kane and Lubensky, Nature Physics 2014

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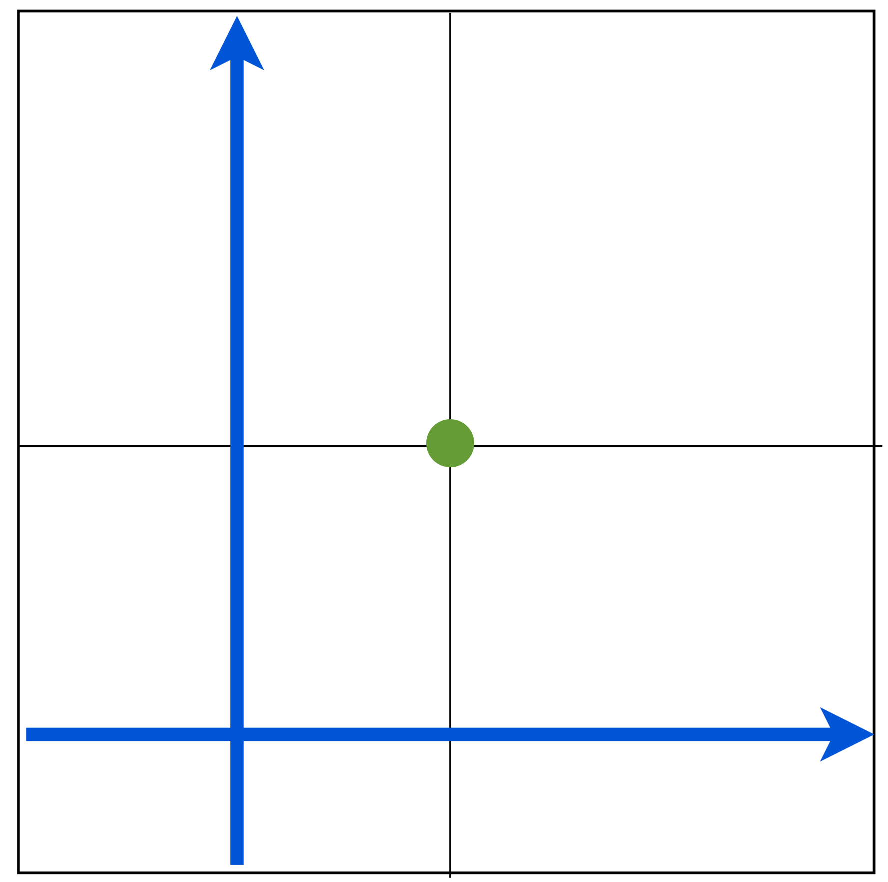
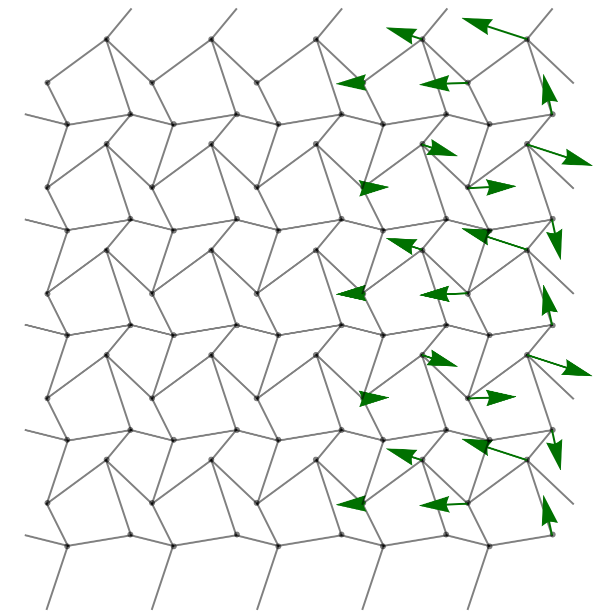
Go to 2D!

k_y



2D Brillouin zone

k_x



$P_T=(1,0)$

A pair of winding numbers gives a "topological polarization" **vector** that points towards floppy edge

Kane and Lubensky, Nature Physics 2014

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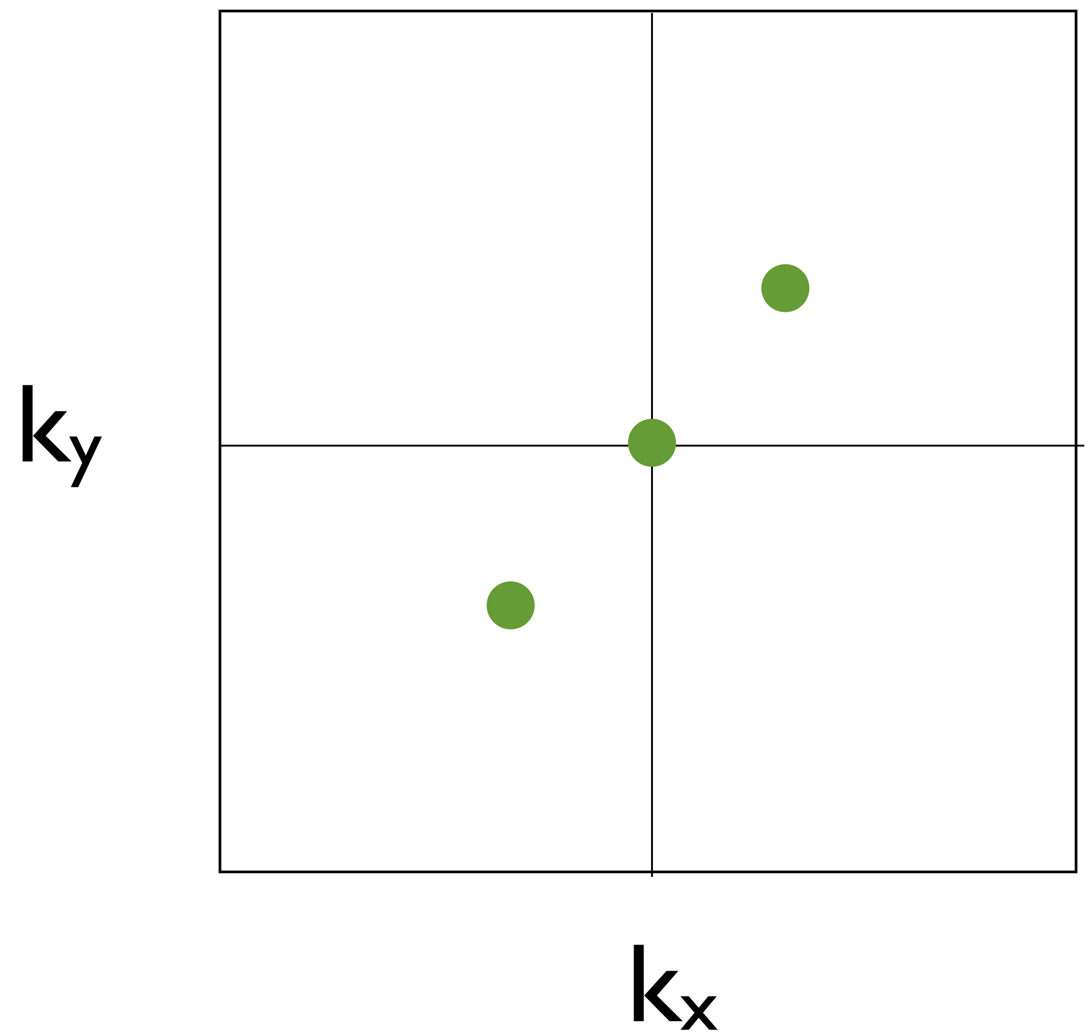
Go to 2D!

If we have **bulk** zero modes...



Rocklin, Chen, Falk, Vitelli, Lubensky. arXiv:1510.04970

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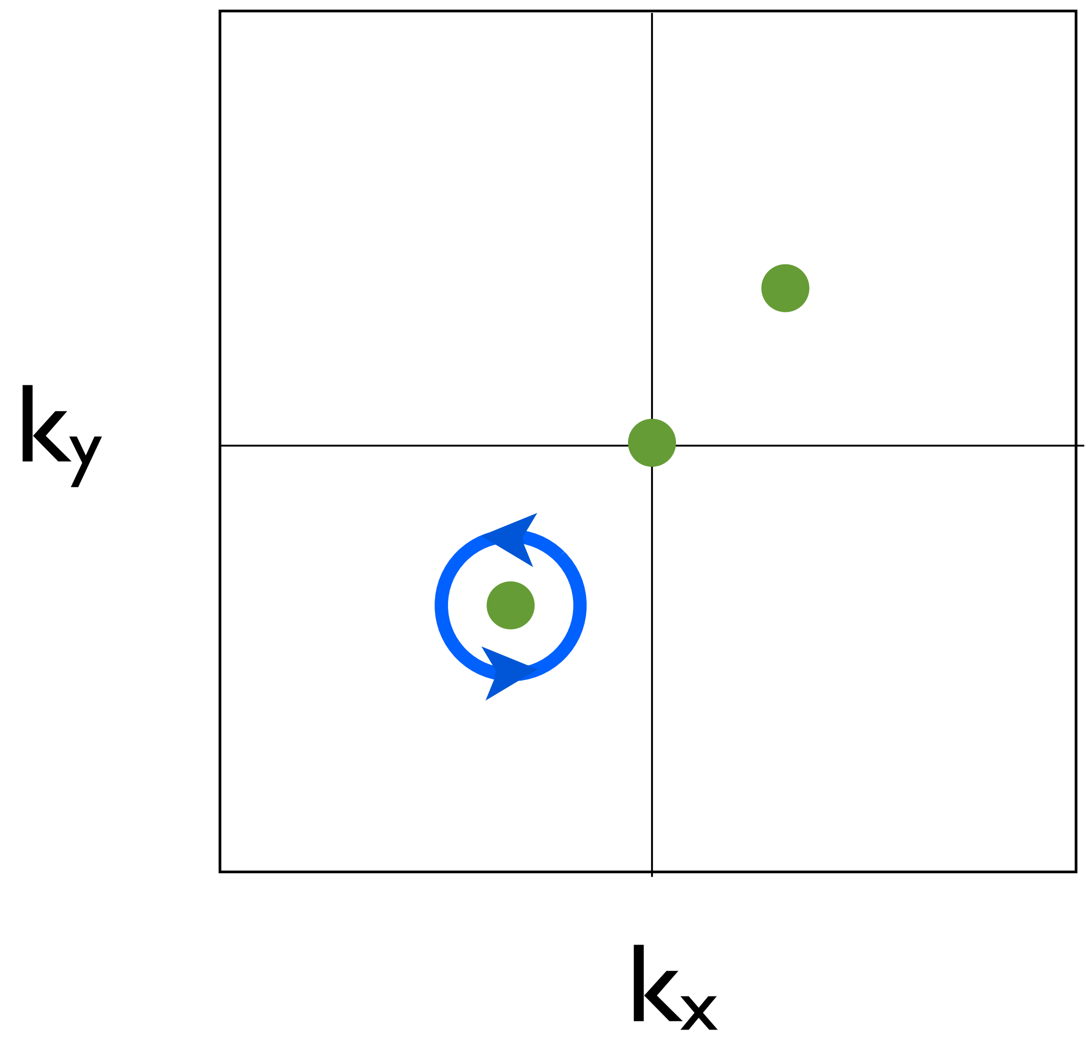

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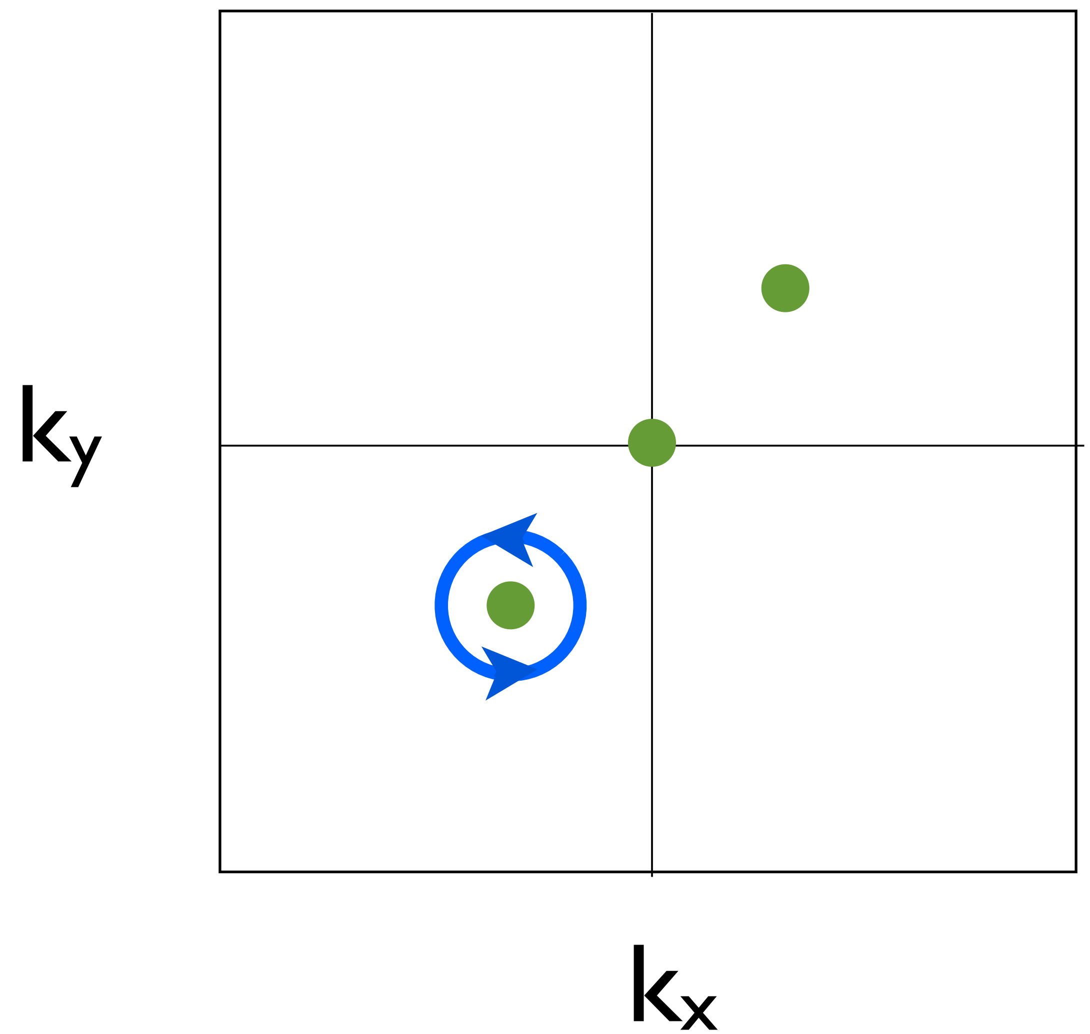

Winding in the phase of det R around the bulk mode protects it!

Rocklin, Chen, Falk, Vitelli, Lubensky. arXiv:1510.04970

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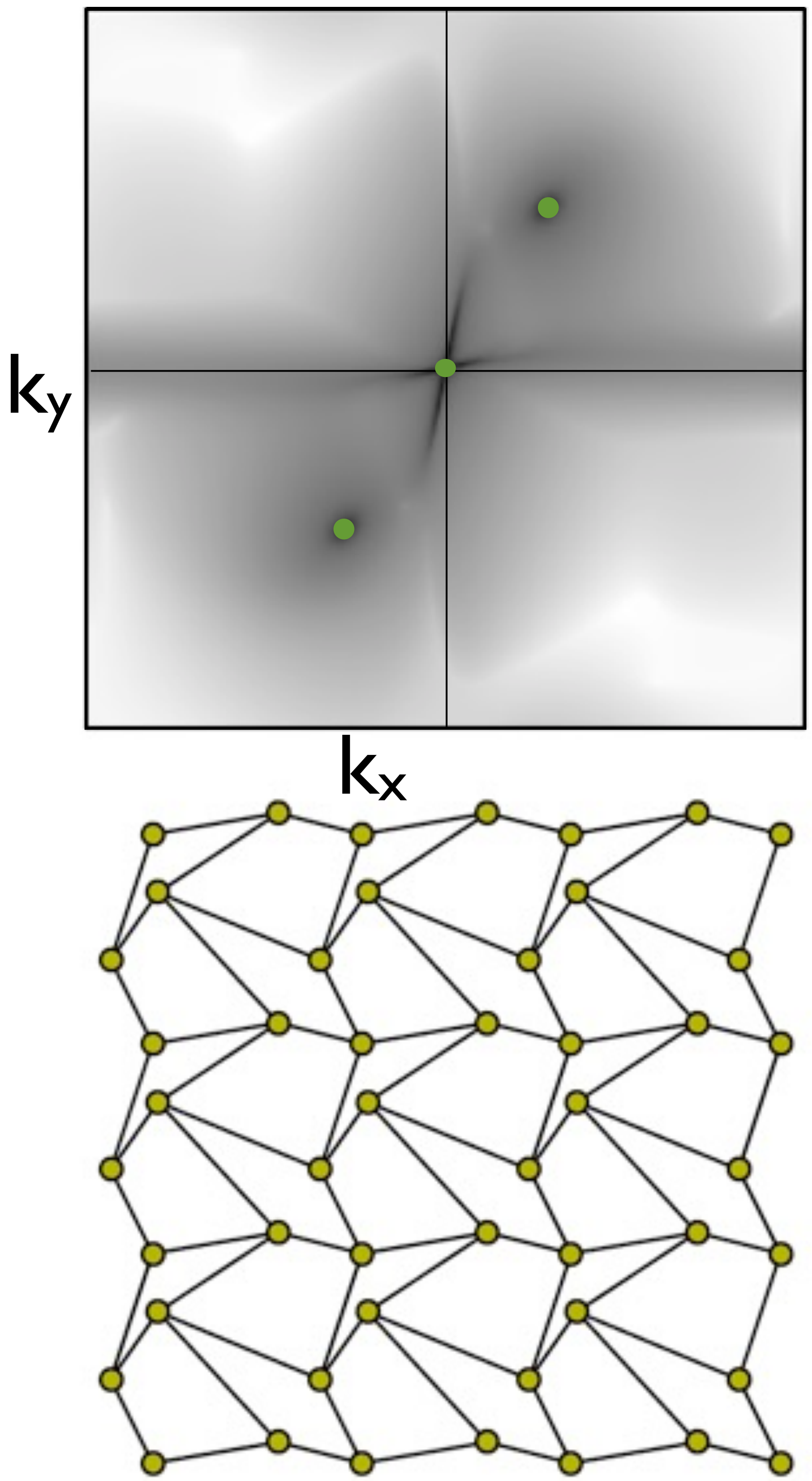
Weyl modes in **deformed square lattices**



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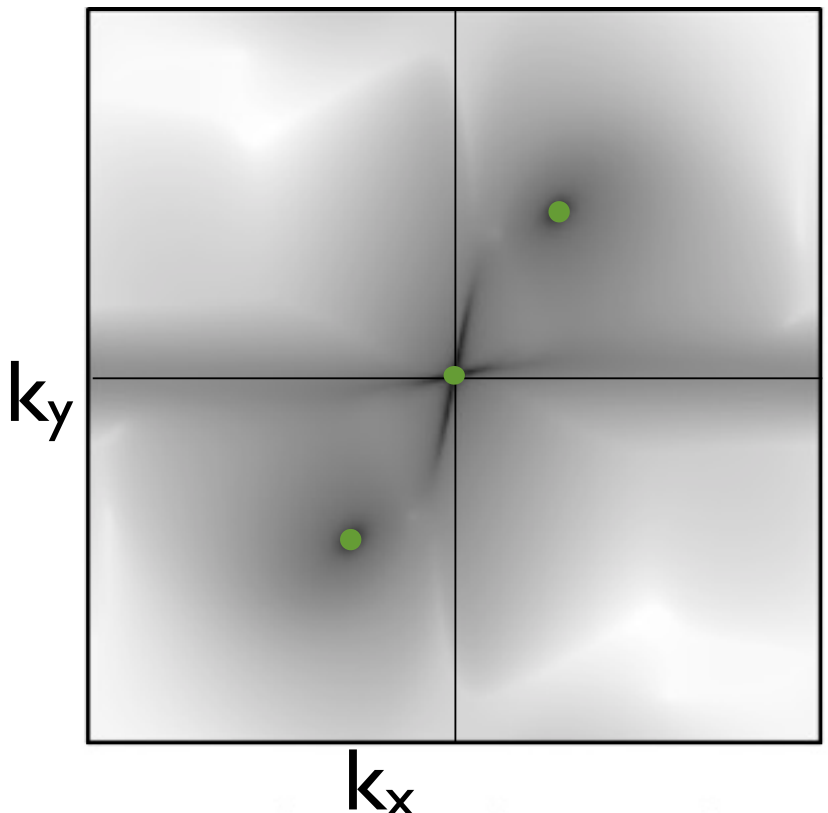

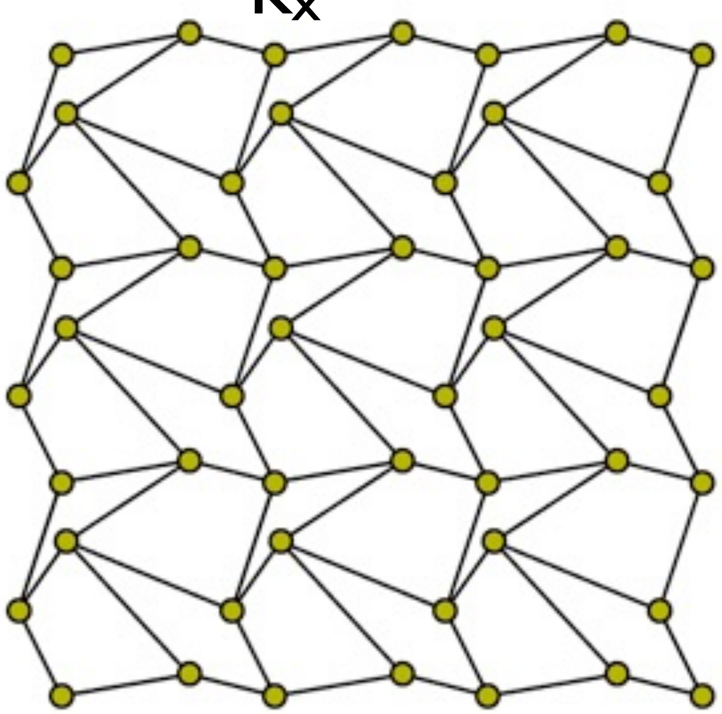

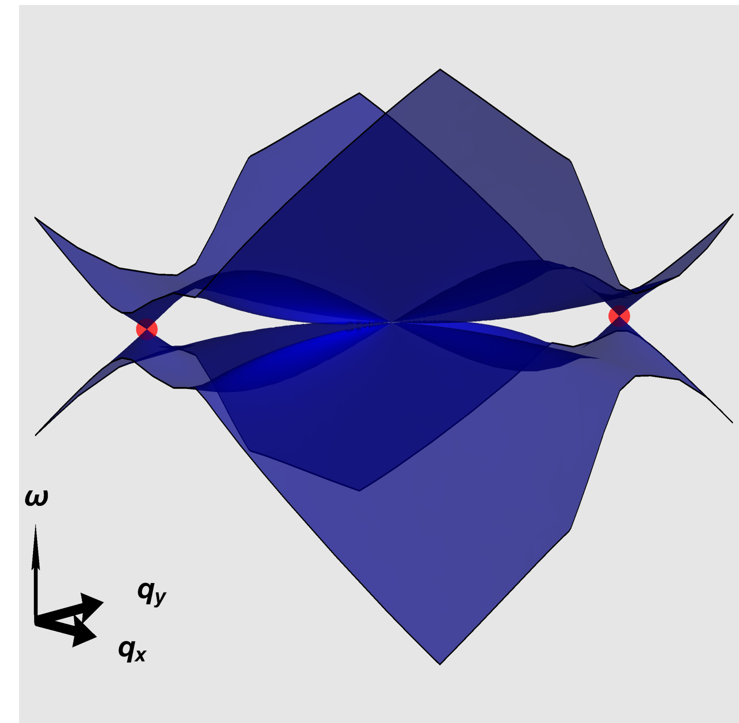

Rocklin, Chen, Falk, Vitelli, Lubensky. arXiv:1510.04970

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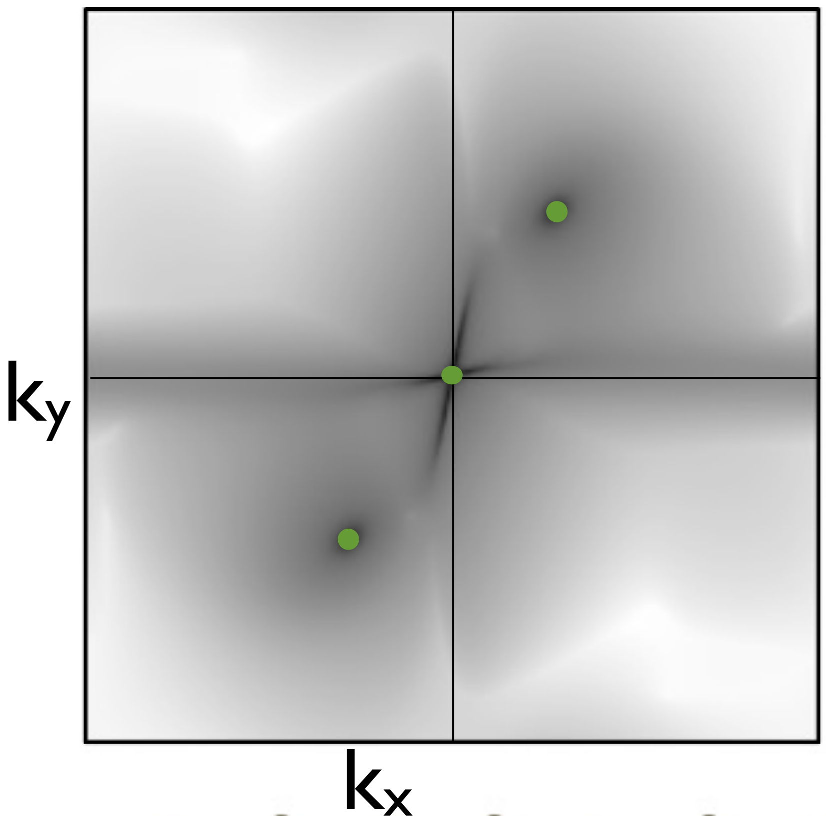

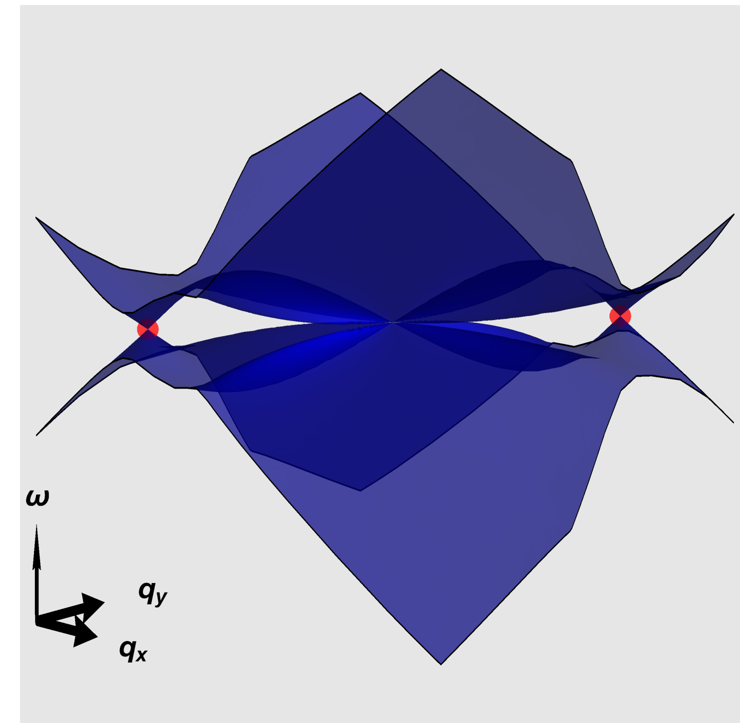

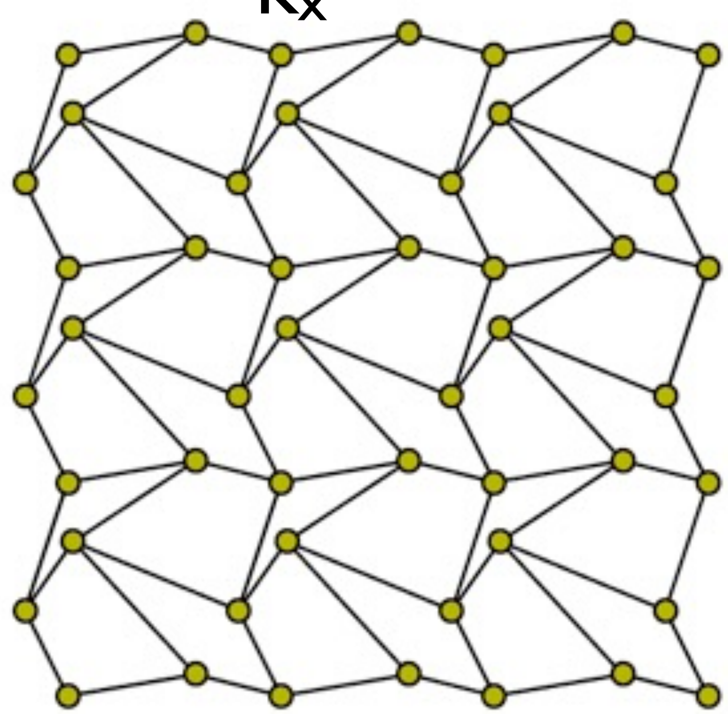

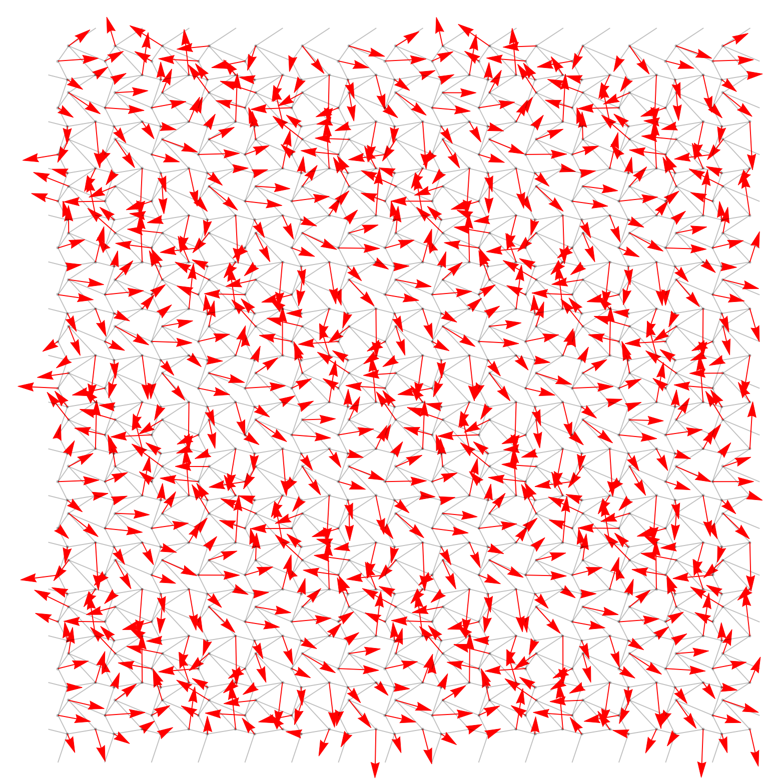

Rocklin, Chen, Falk, Vitelli, Lubensky. arXiv:1510.04970

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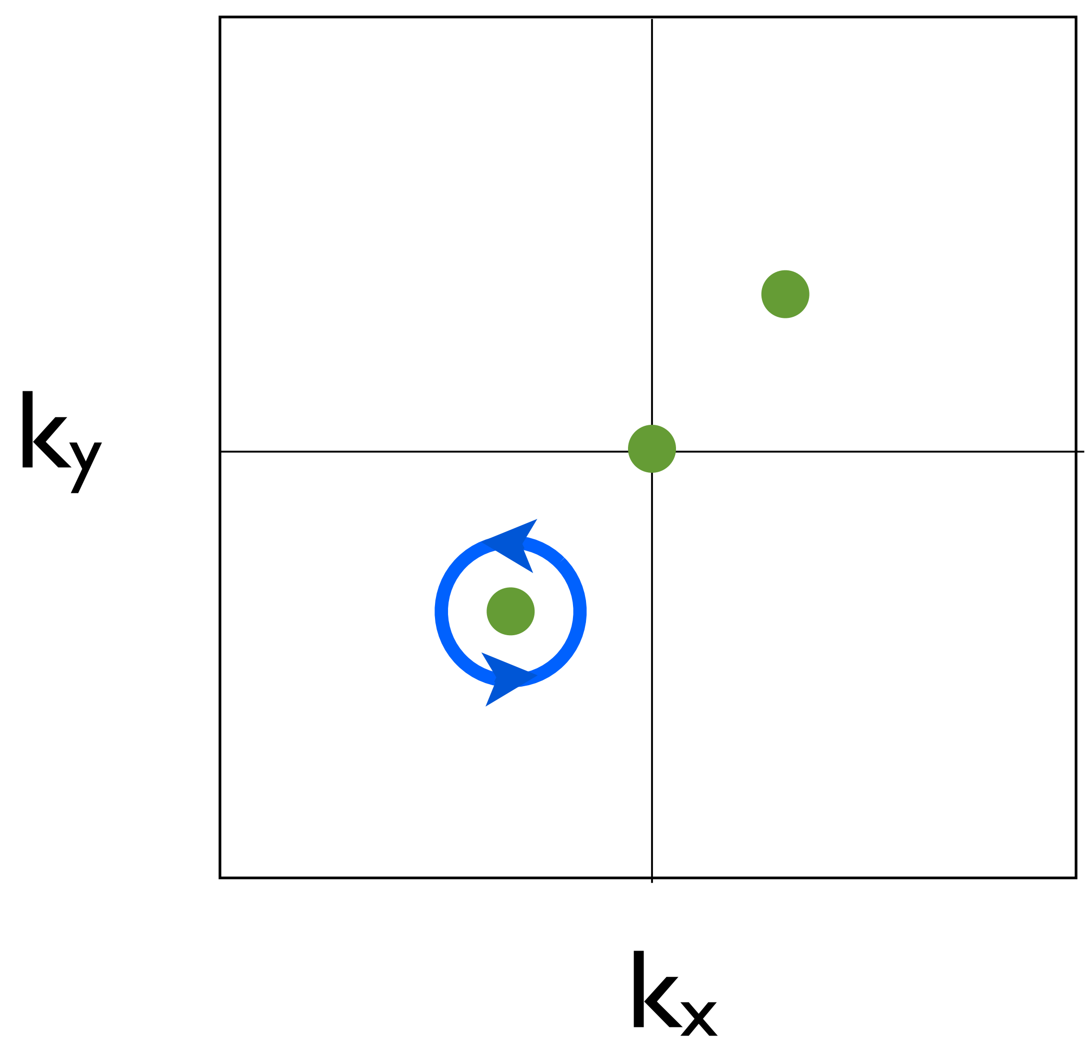
Where do the Weyl modes come from?



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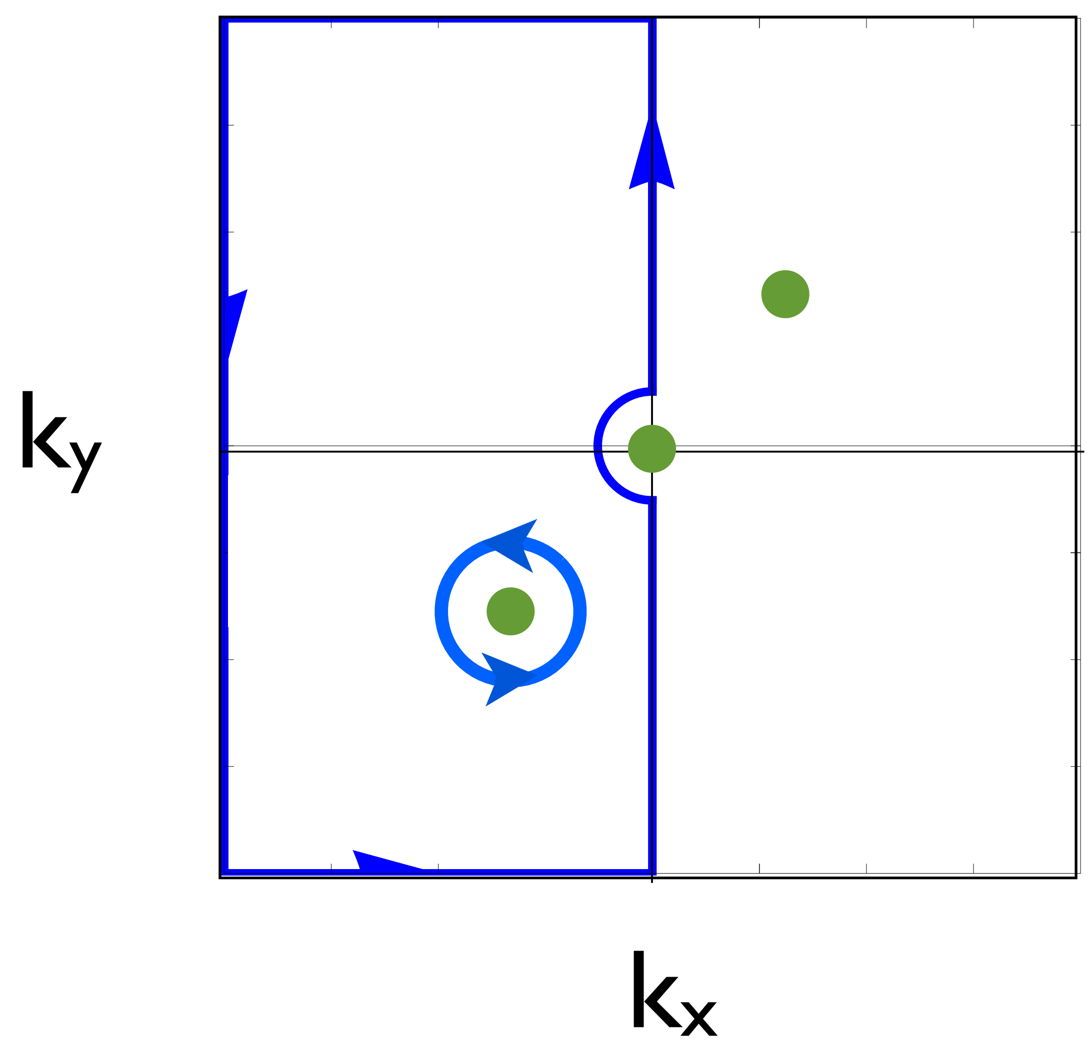

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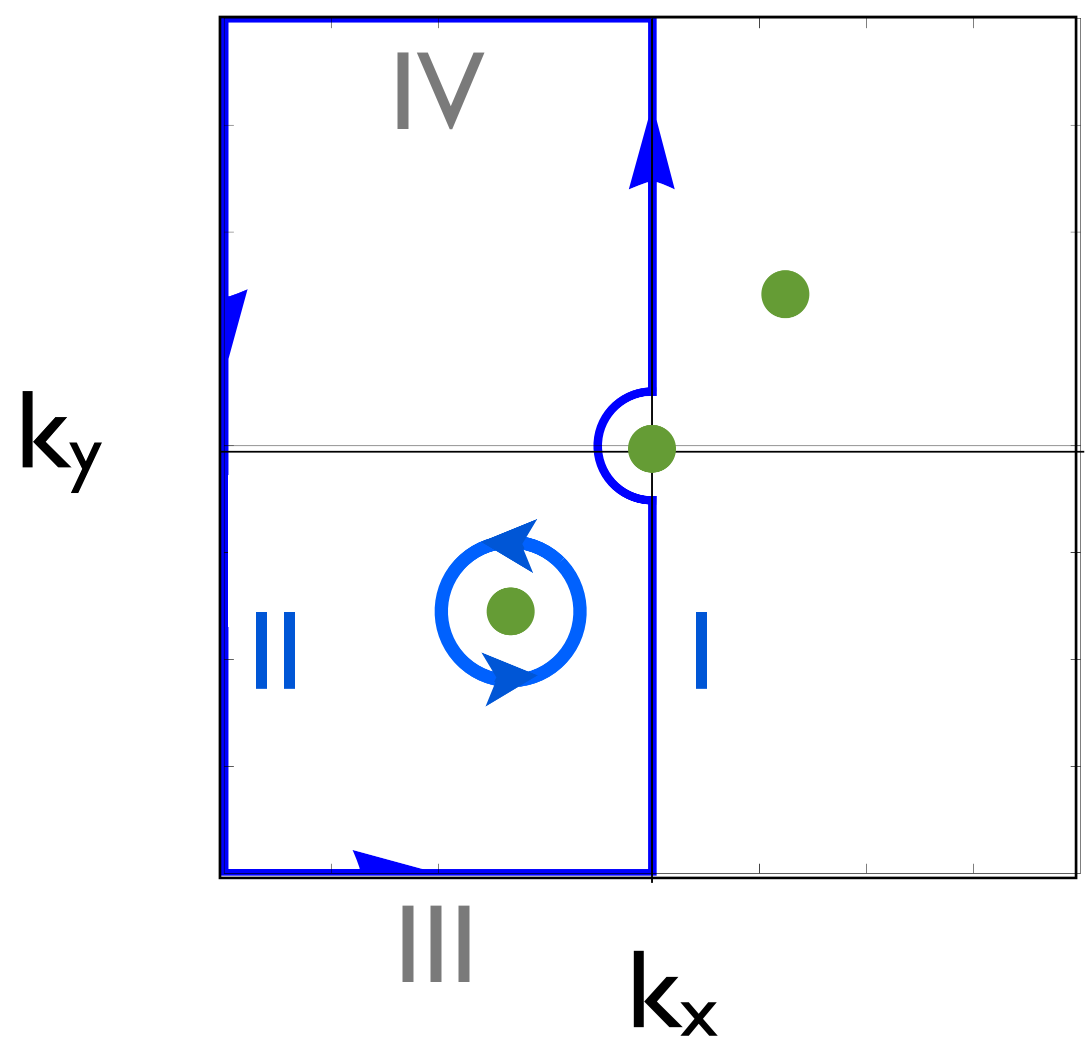

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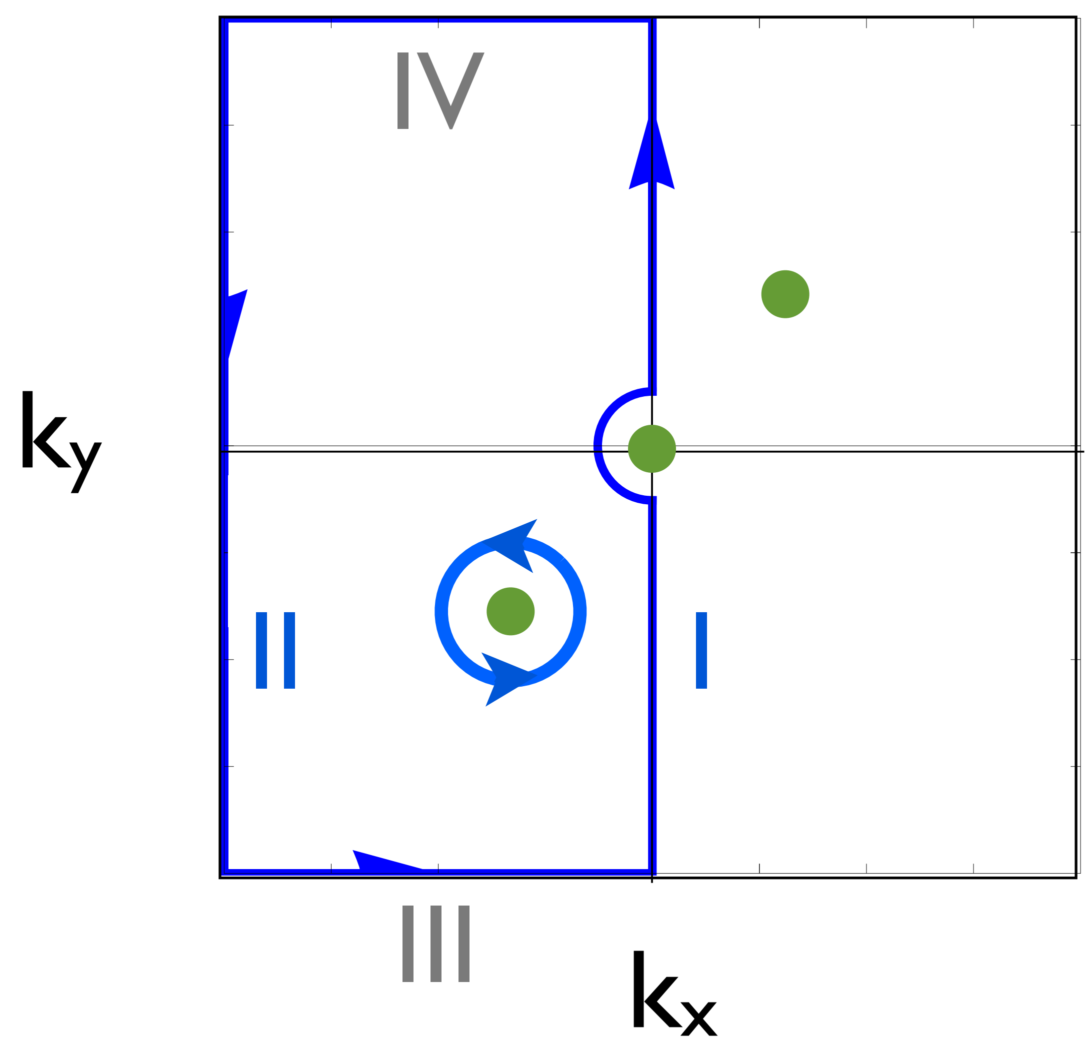

The winding around the bulk mode is the difference between contour I and contour II

Rocklin, Chen, Falk, Vitelli, Lubensky. arXiv:1510.04970

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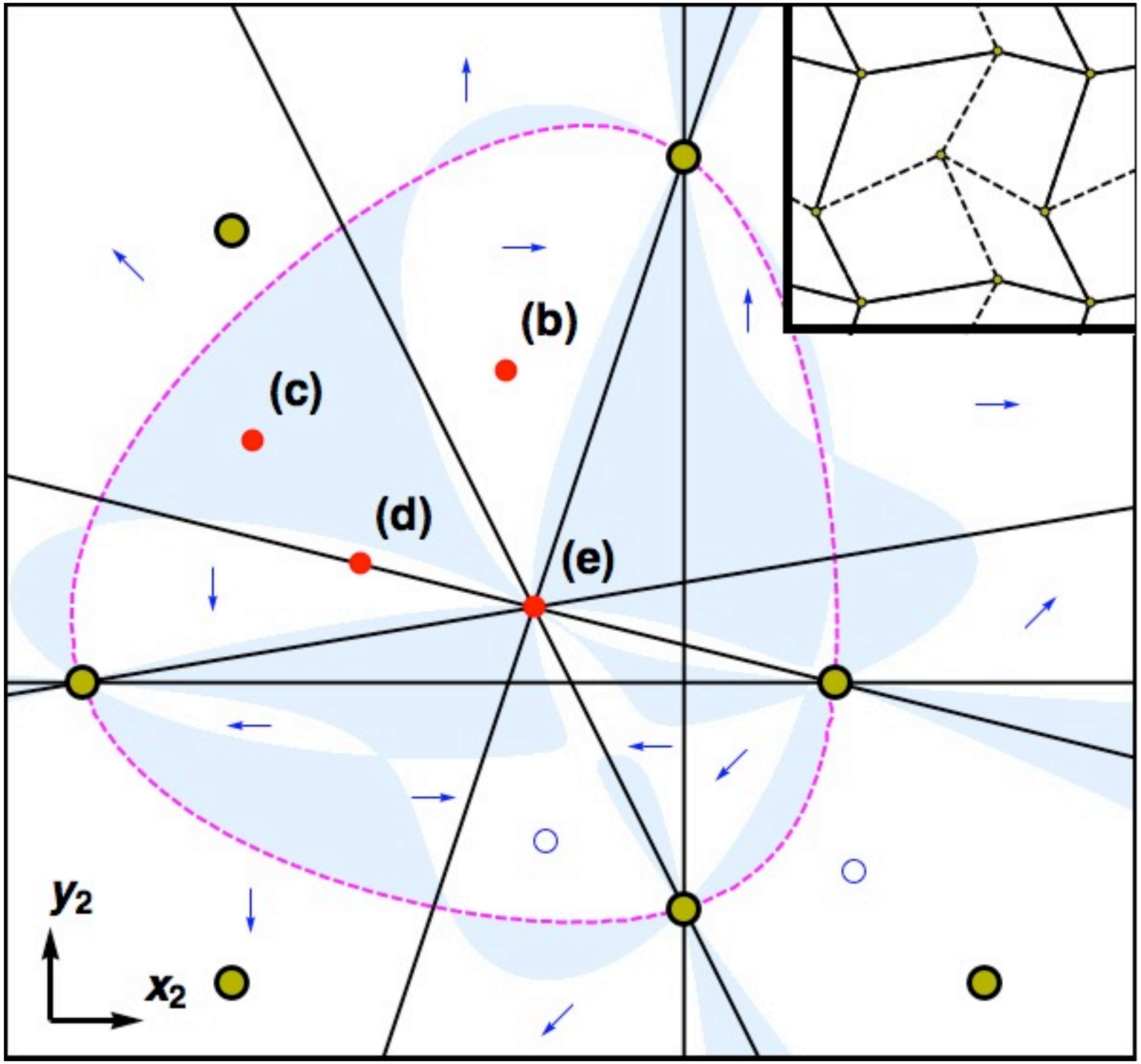

Rocklin, Chen, Falk, Vitelli, Lubensky. arXiv:1510.04970

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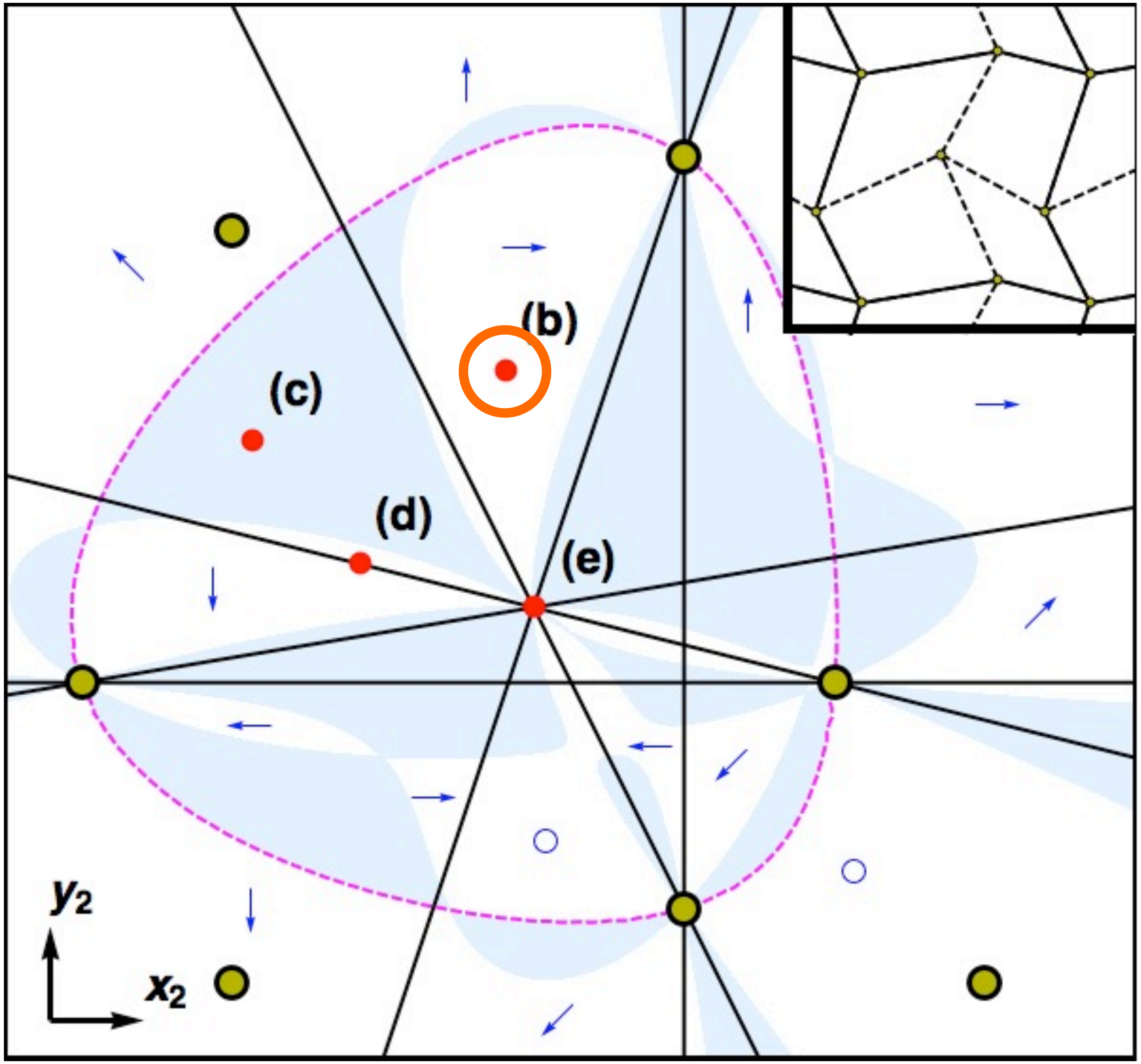

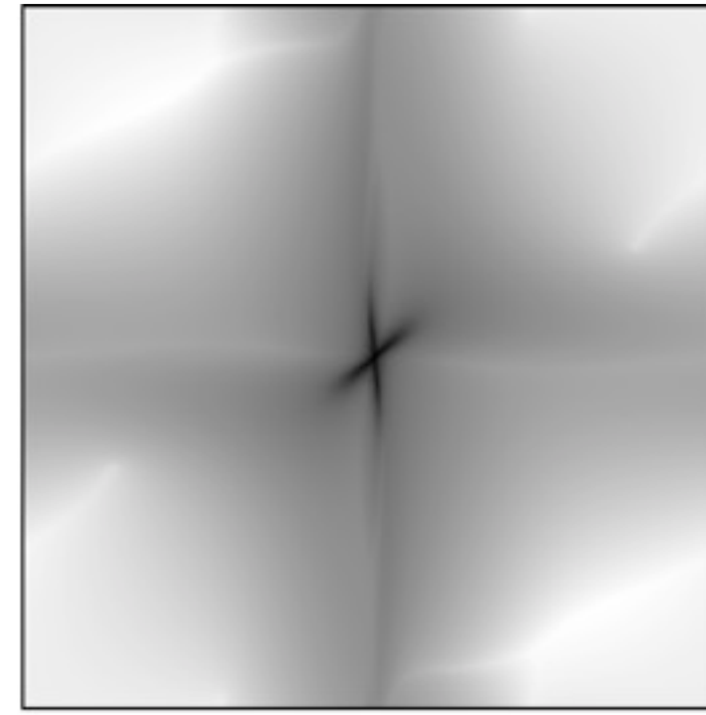

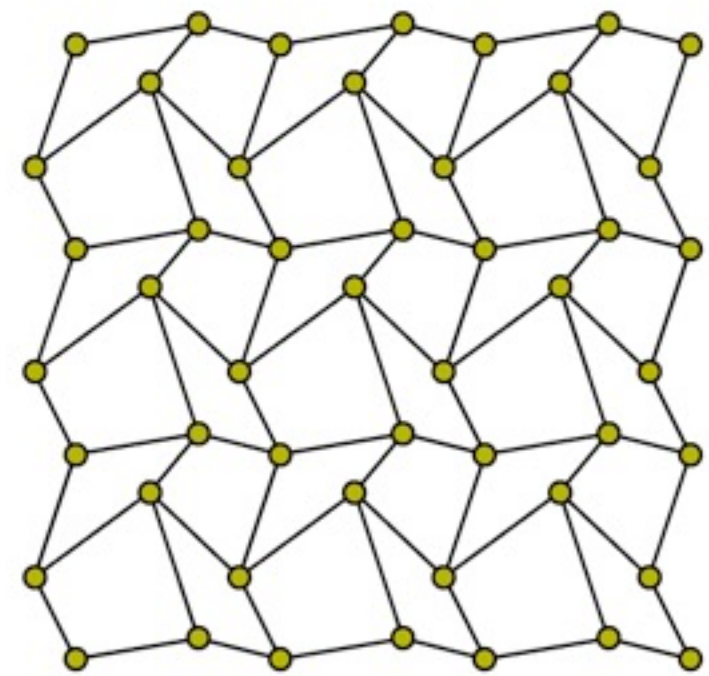

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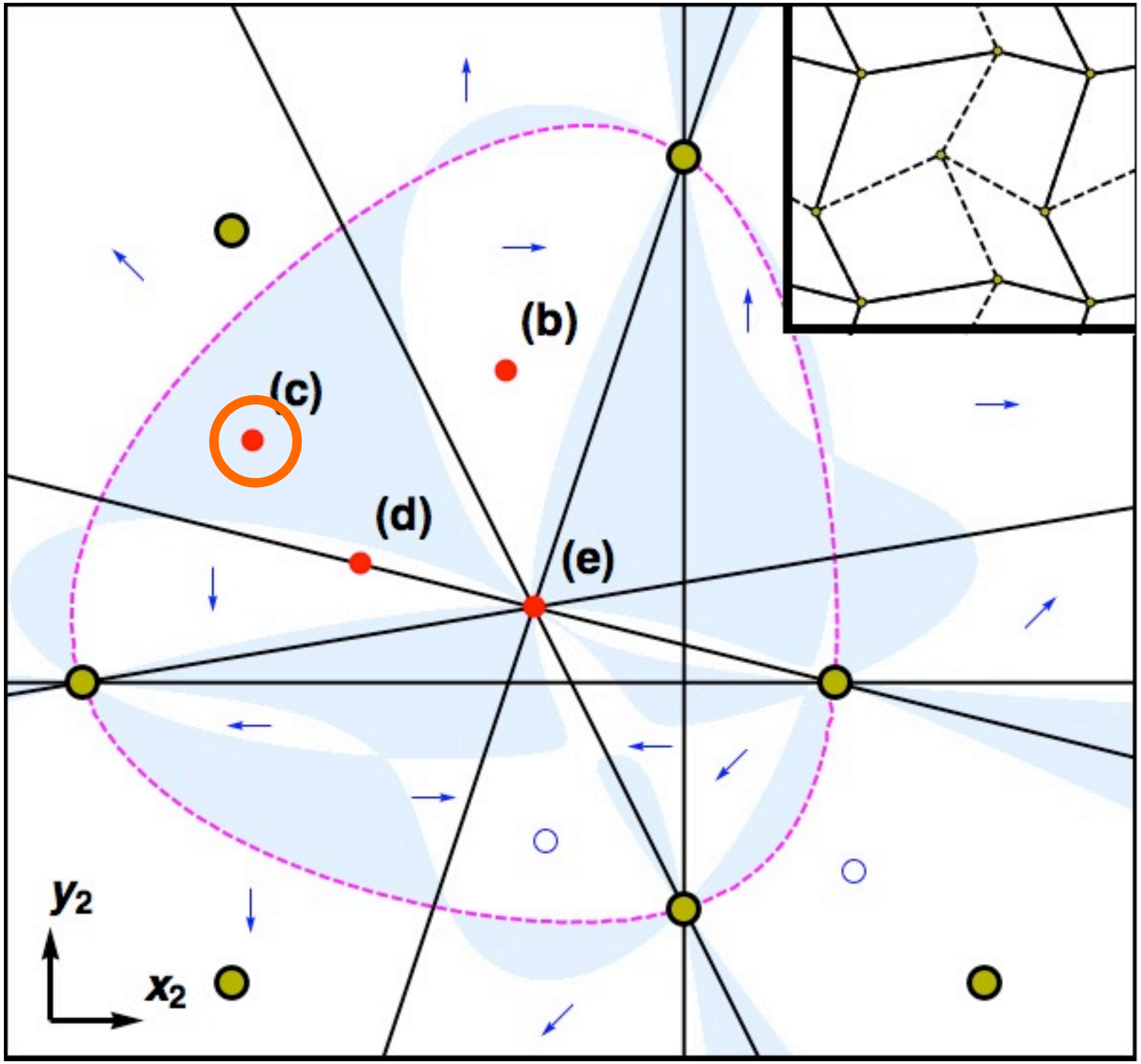
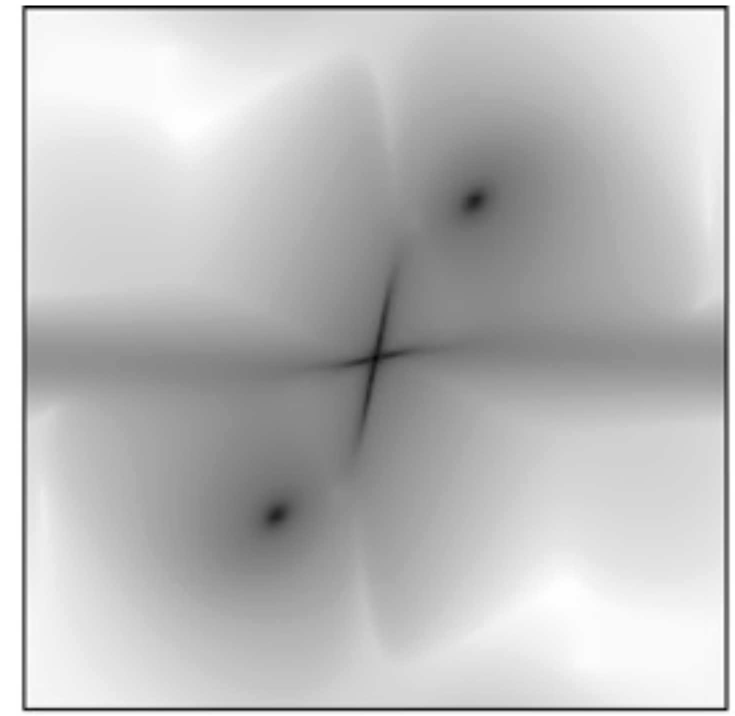
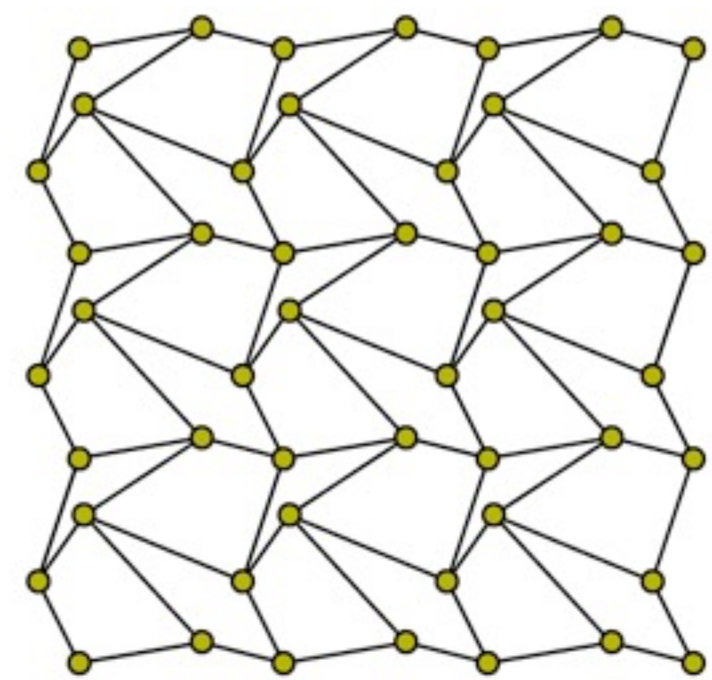
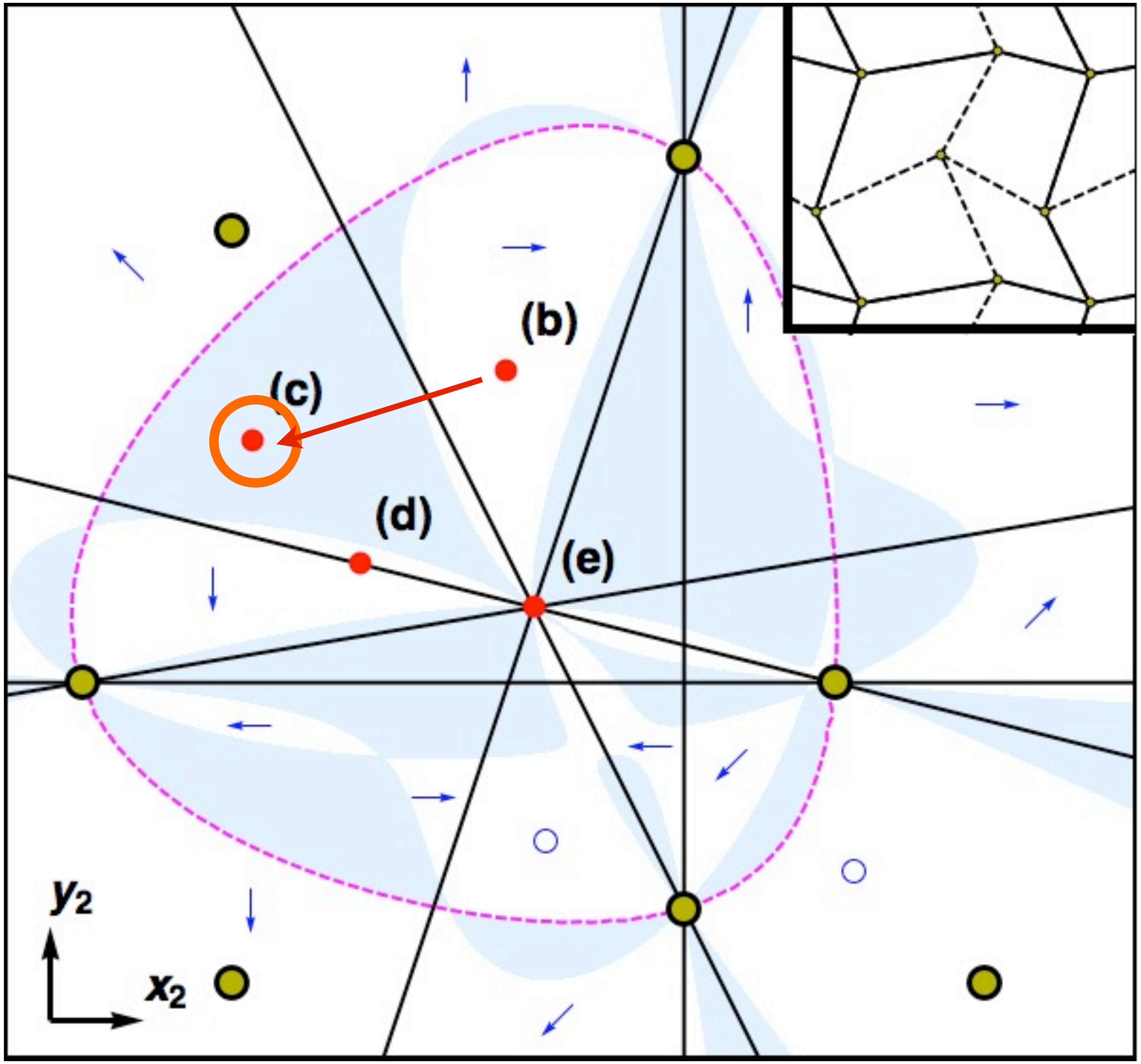
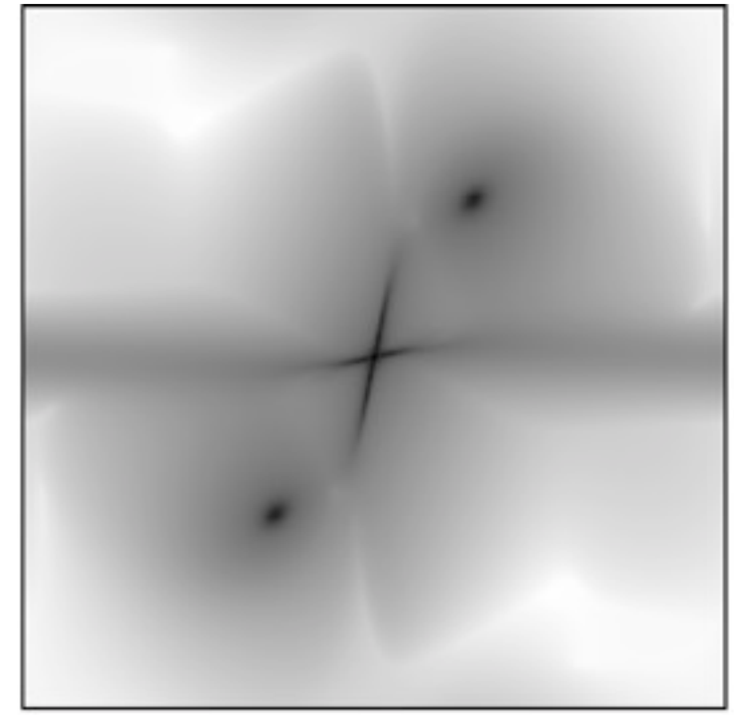


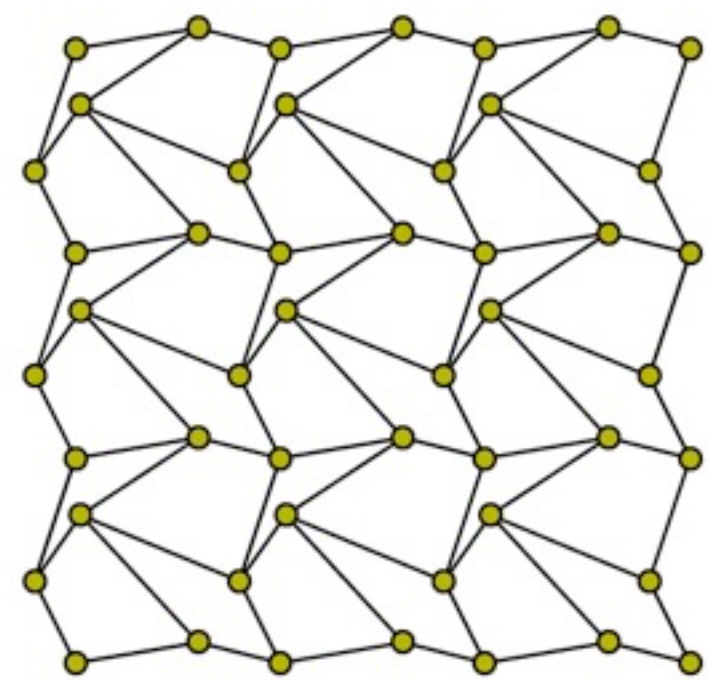




Rocklin, Chen, Falk, Vitelli, Lubensky. arXiv:1510.04970







Rocklin, Chen, Falk, Vitelli, Lubensky. arXiv:1510.04970

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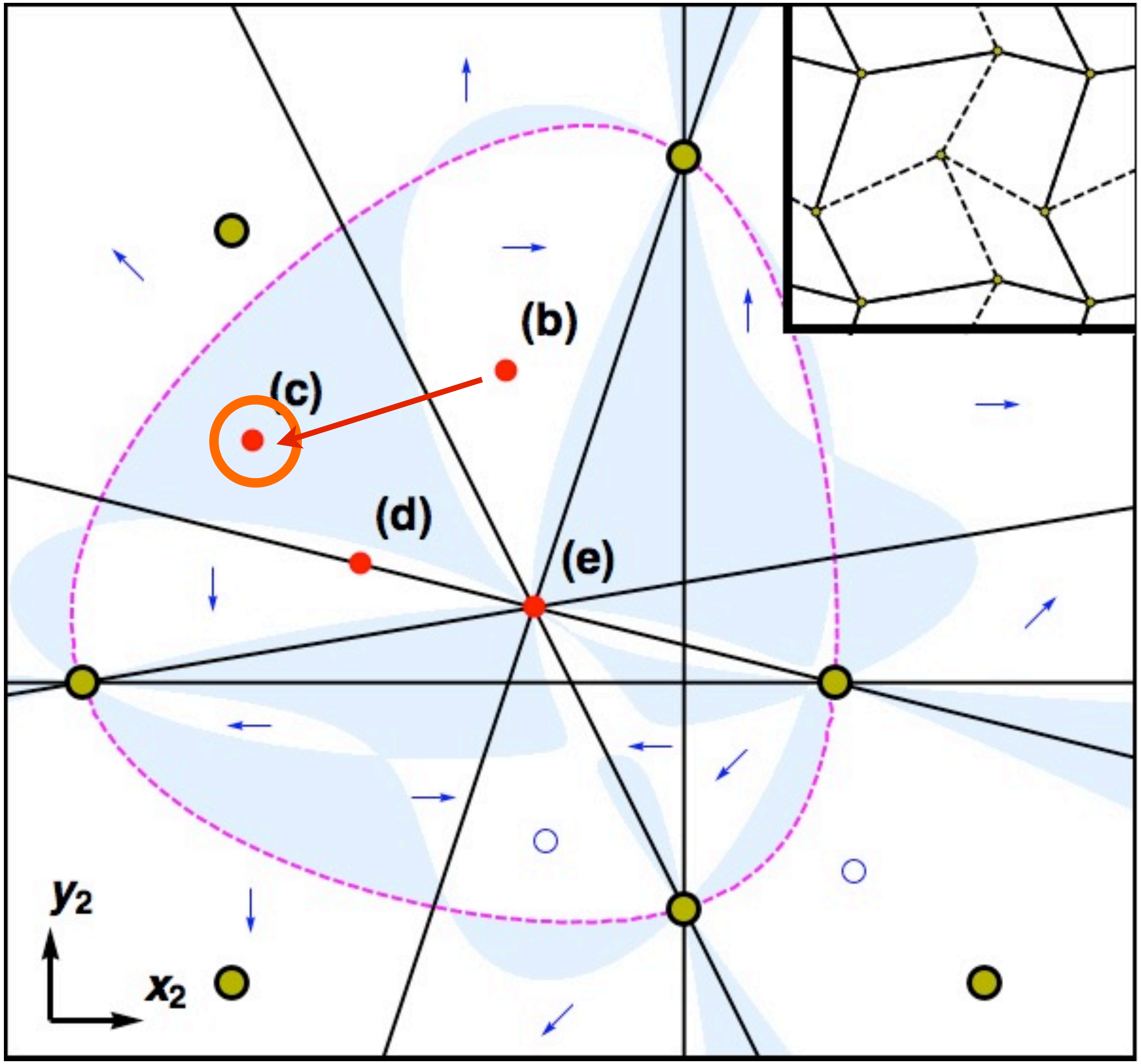
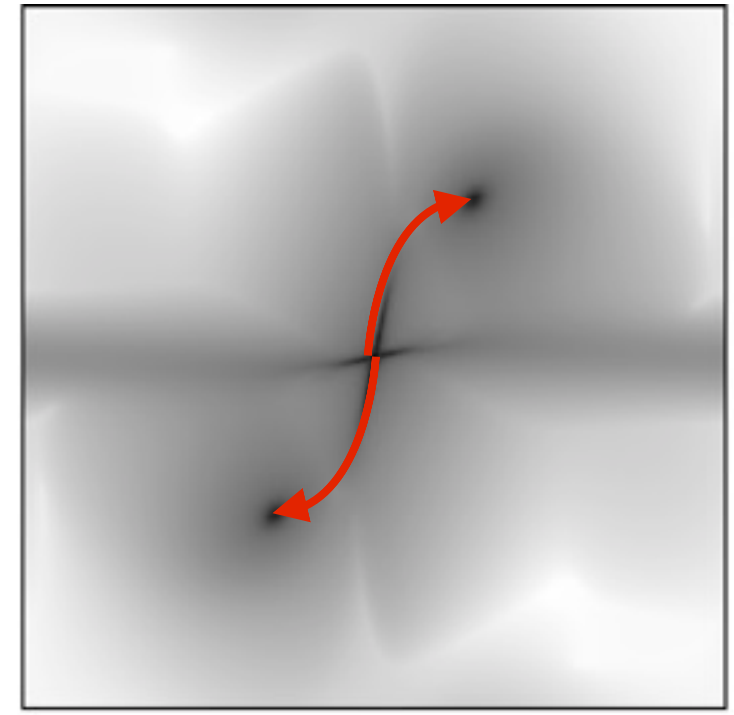
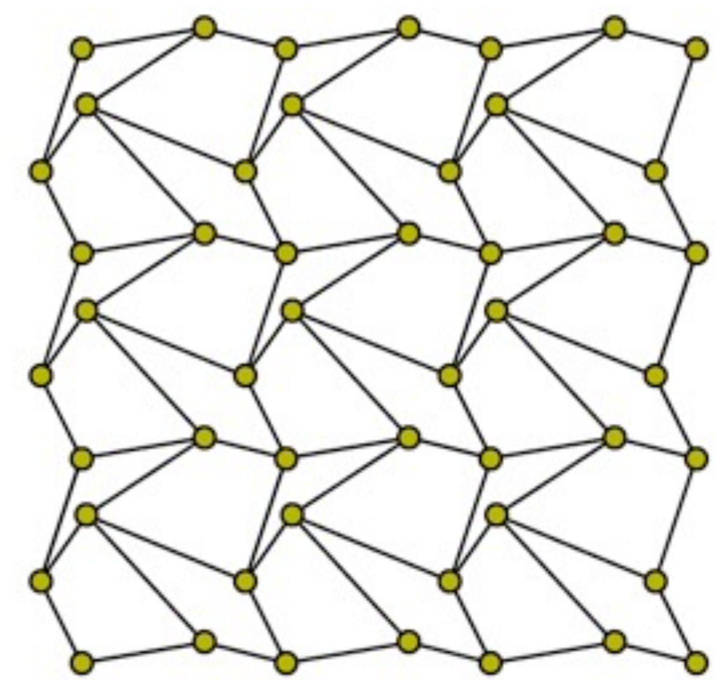
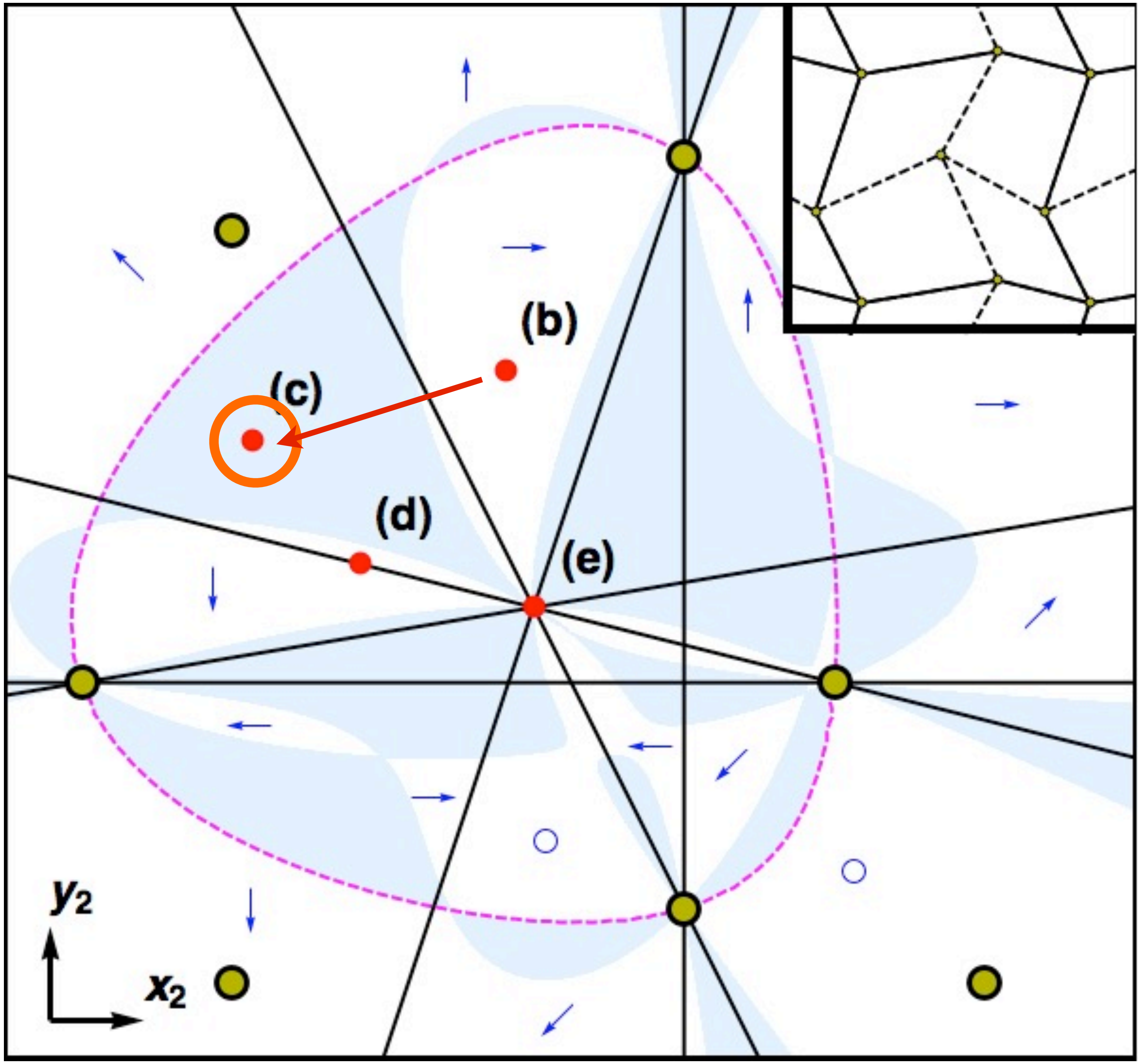
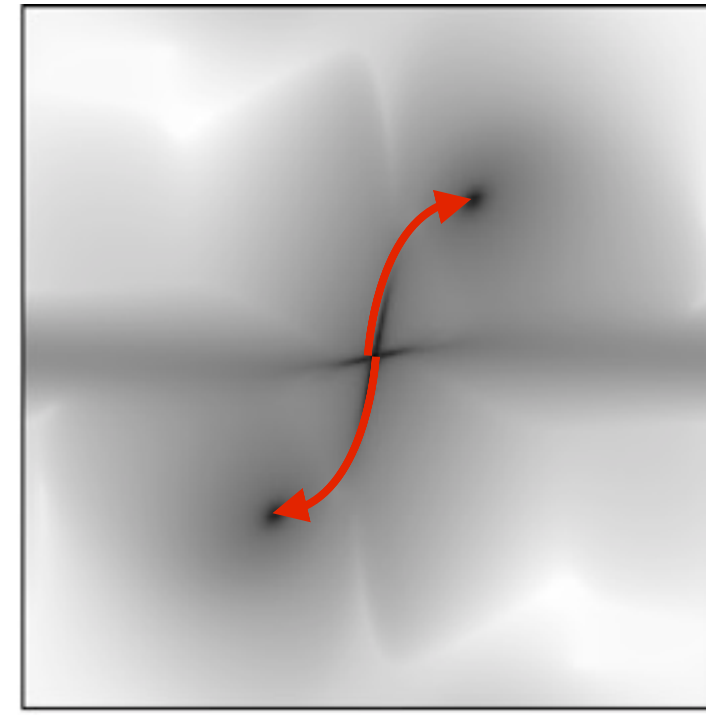


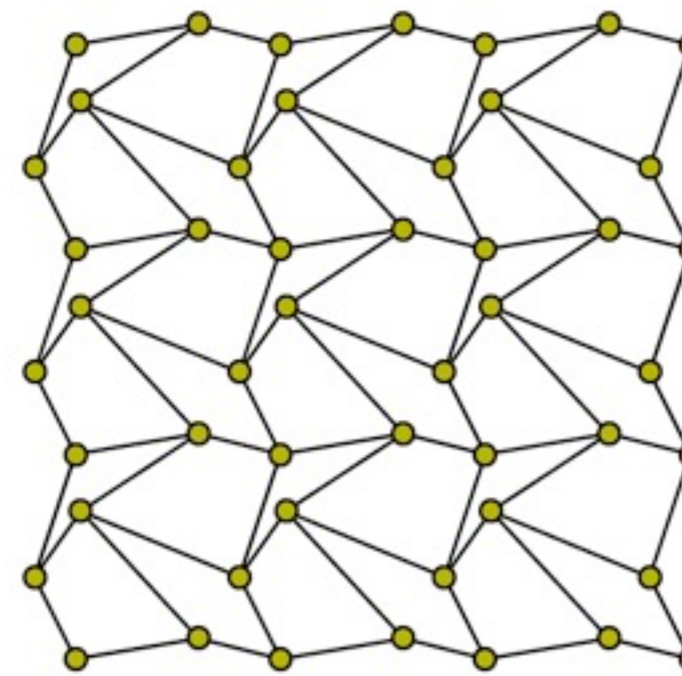




Rocklin, Chen, Falk, Vitelli, Lubensky. arXiv:1510.04970







Weyl “phases” are generic in isostatic lattices

Rocklin, Chen, Falk, Vitelli, Lubensky. arXiv:1510.04970

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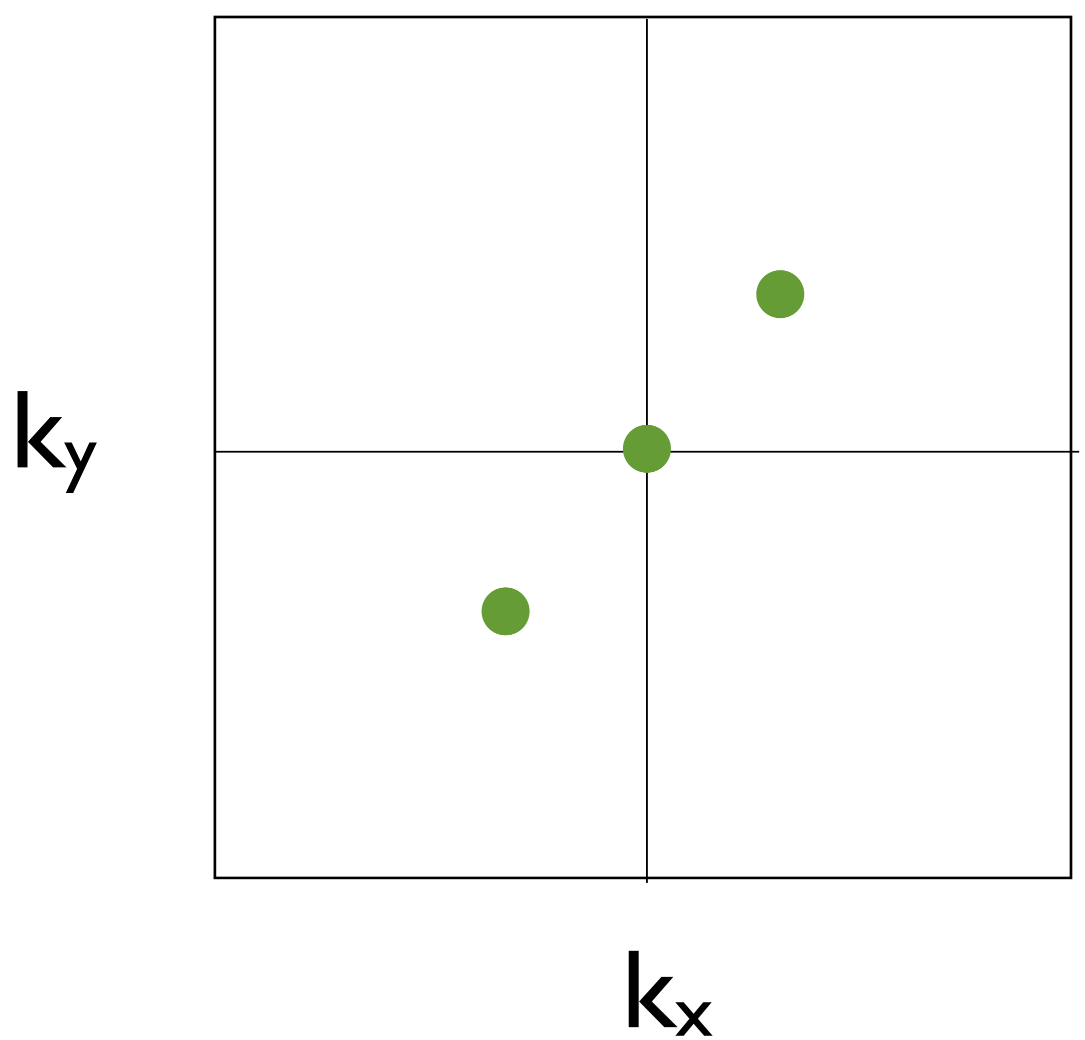
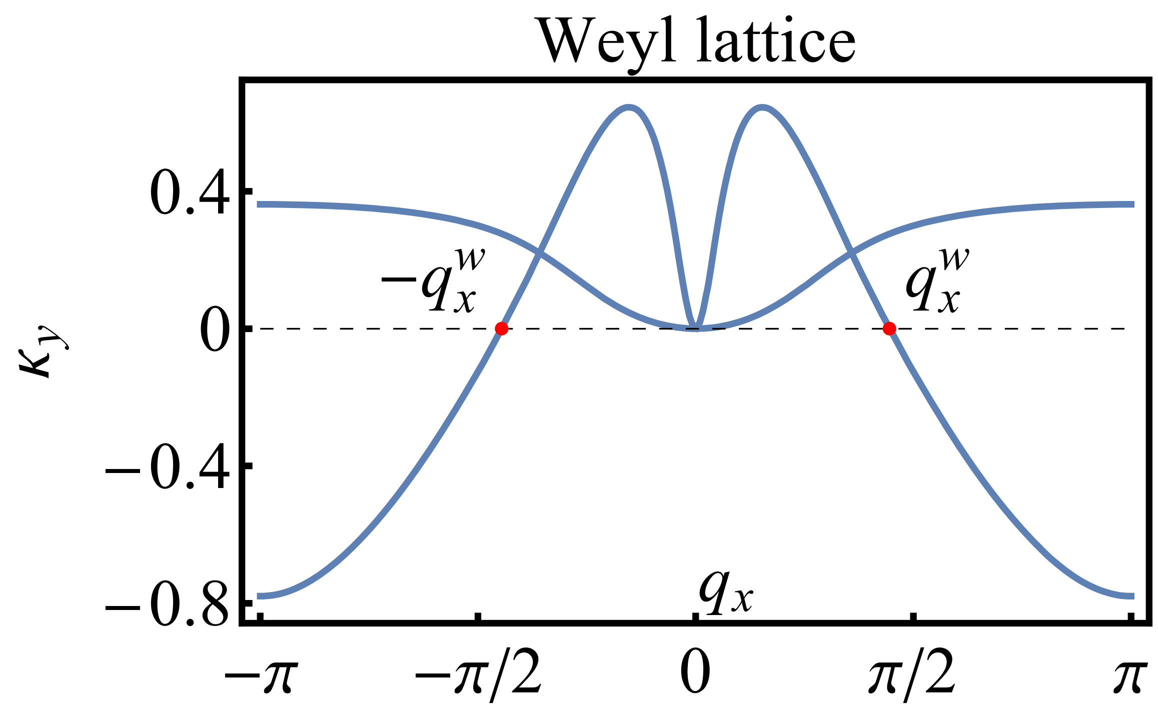
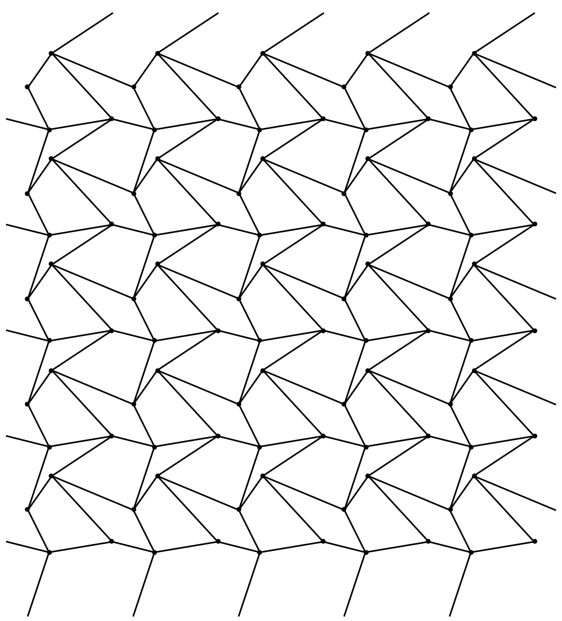
What do the Weyl modes do?







Different parts of the BZ have differing winding numbers

Rocklin, Chen, Falk, Vitelli, Lubensky. arXiv:1510.04970

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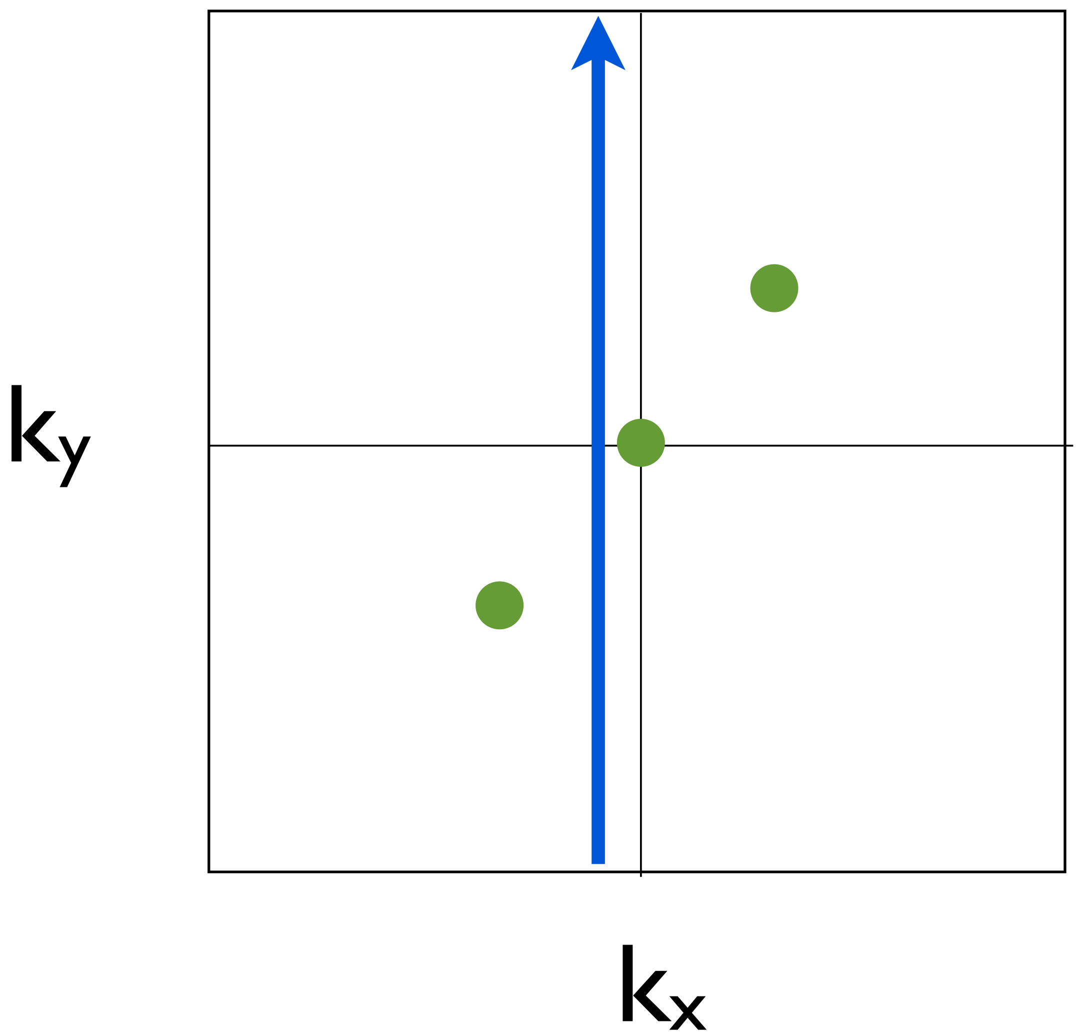

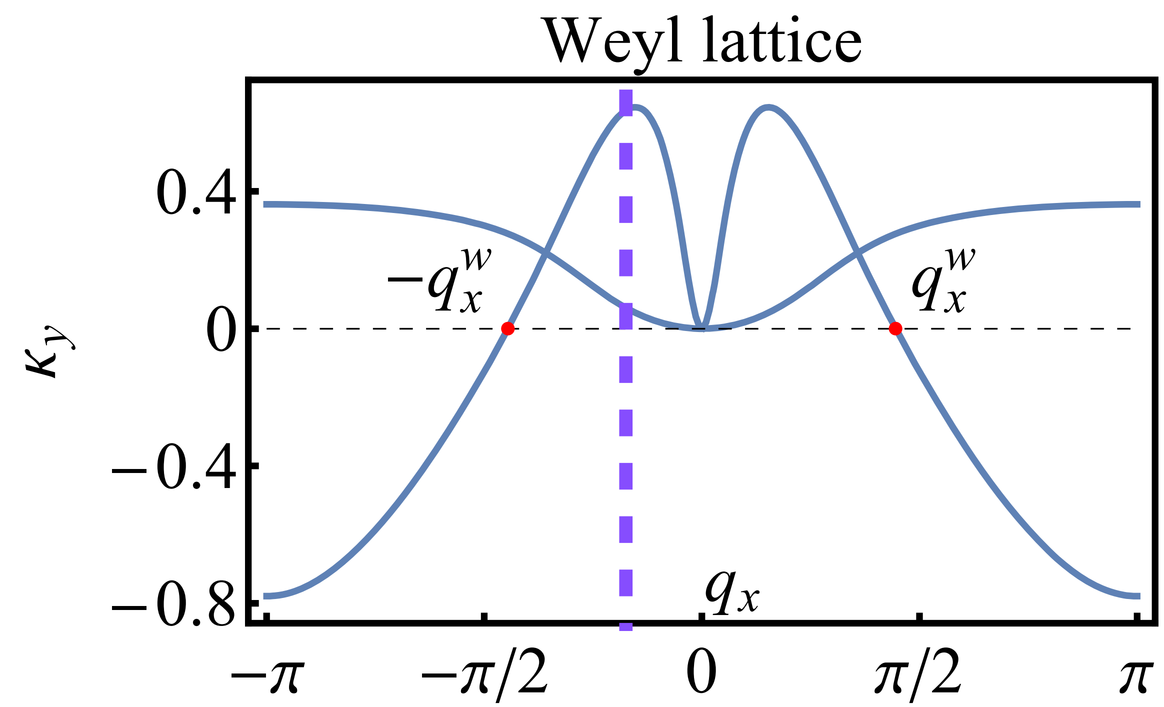

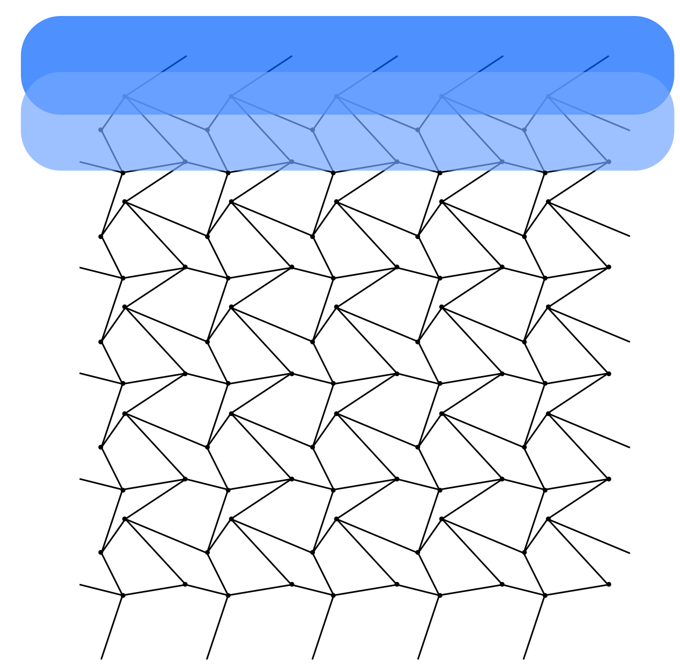

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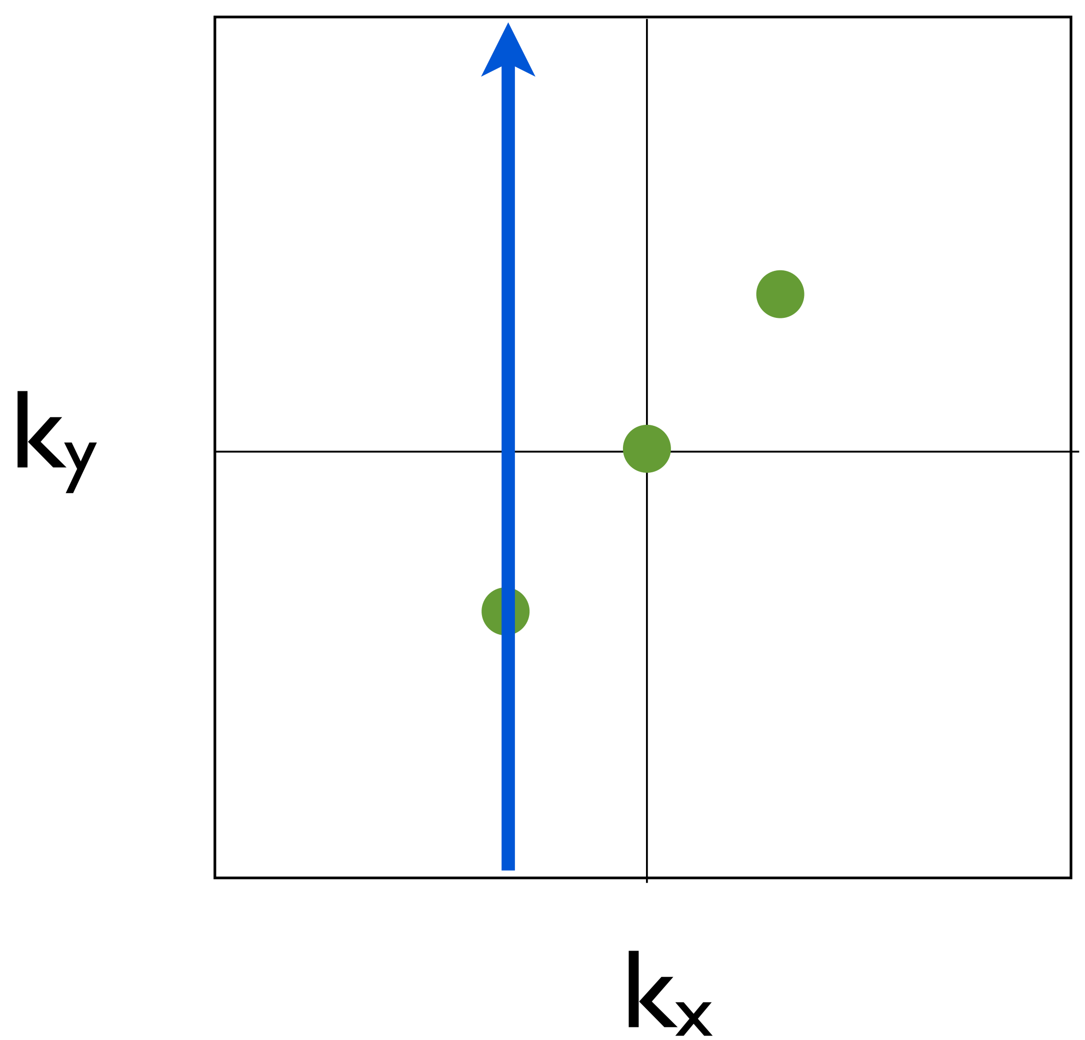

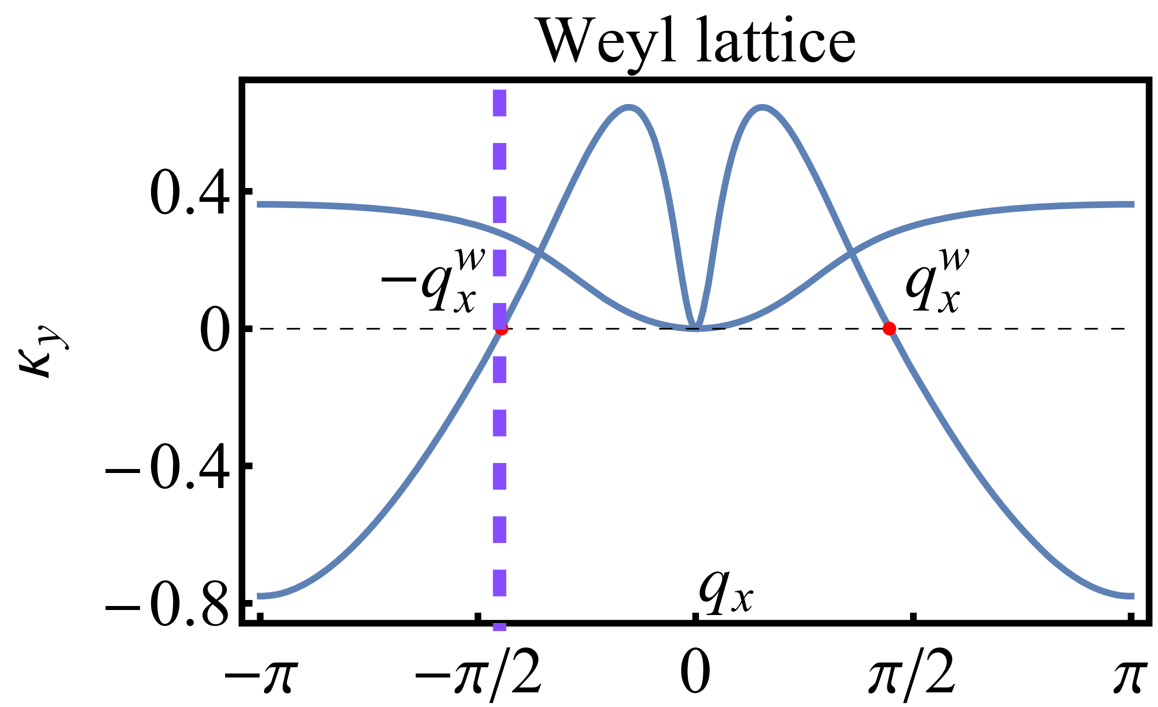

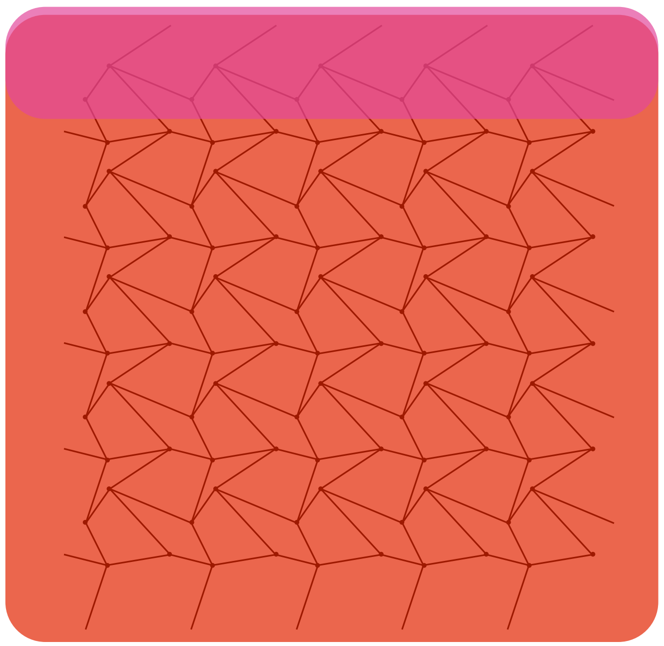

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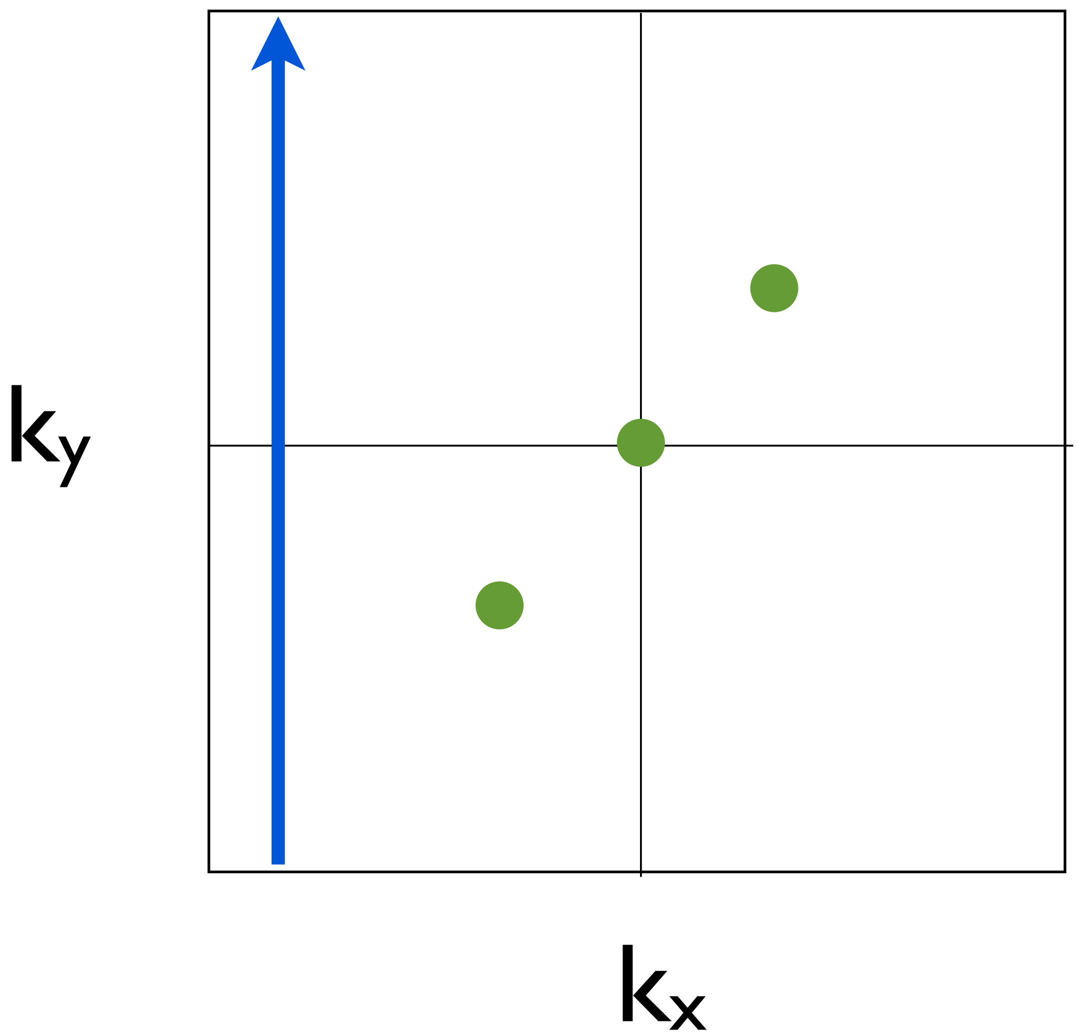

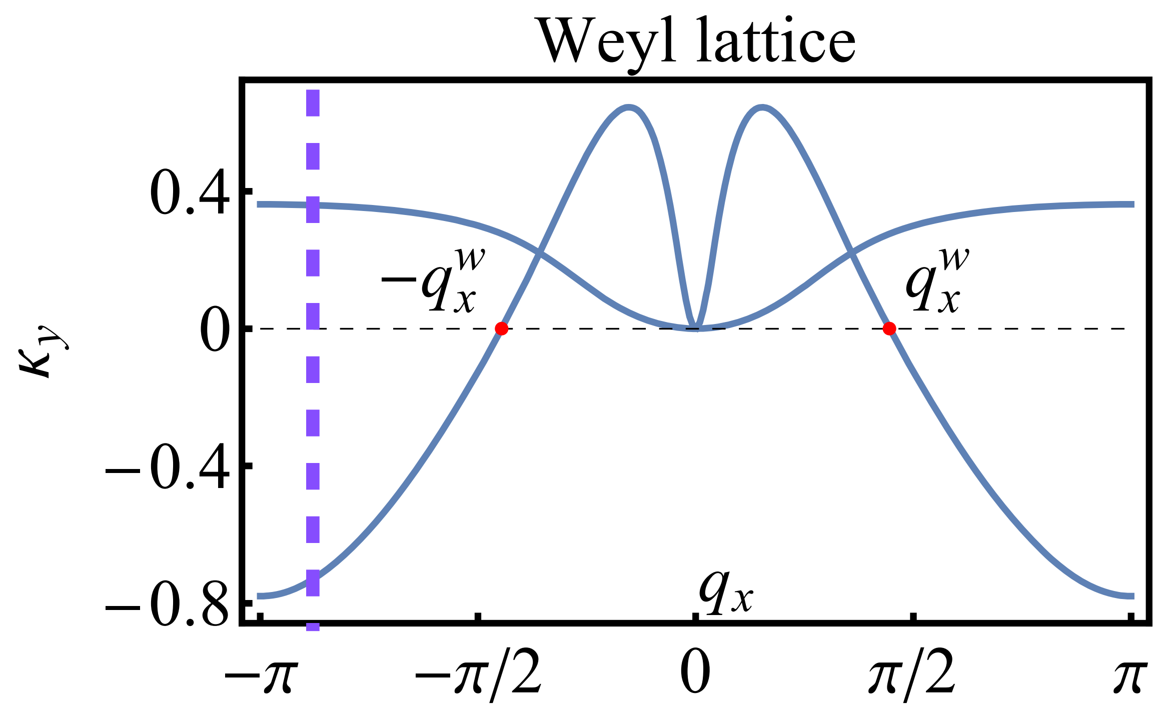

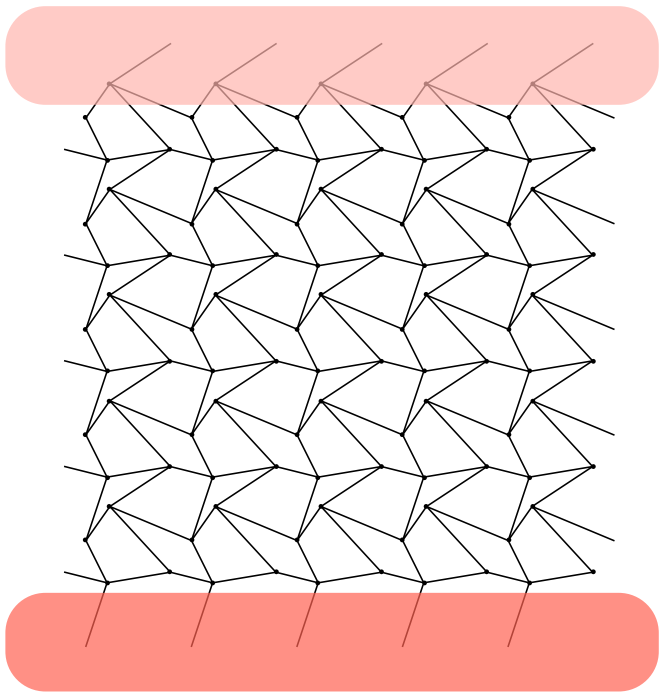

Different parts of the BZ have differing winding numbers

Rocklin, Chen, Falk, Vitelli, Lubensky. arXiv:1510.04970

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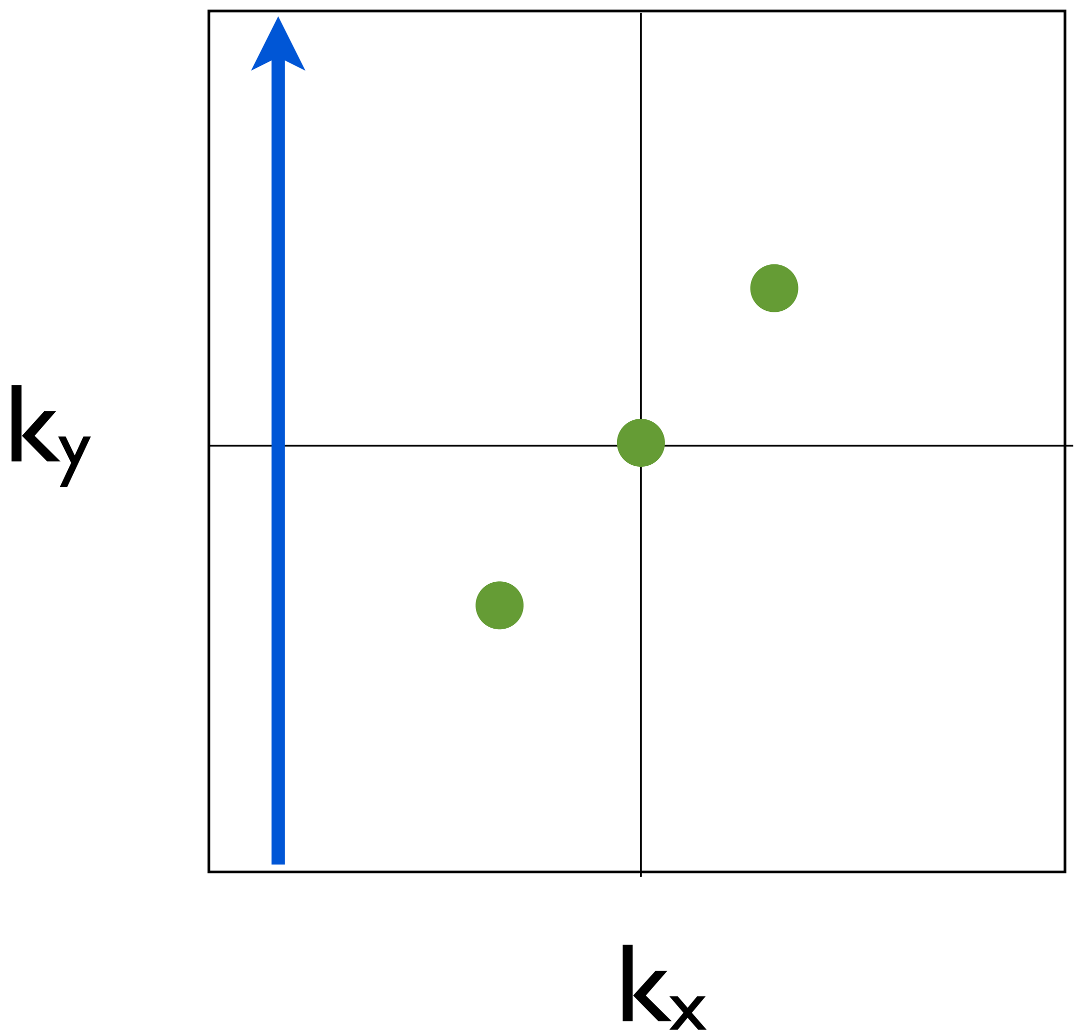
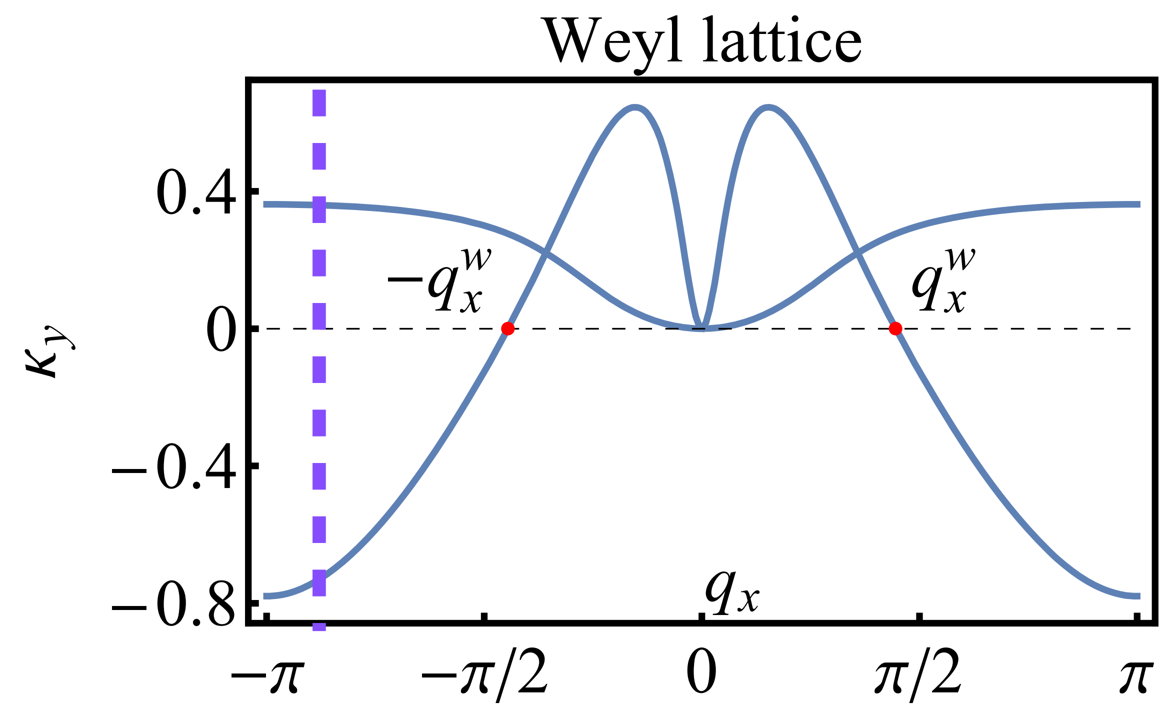
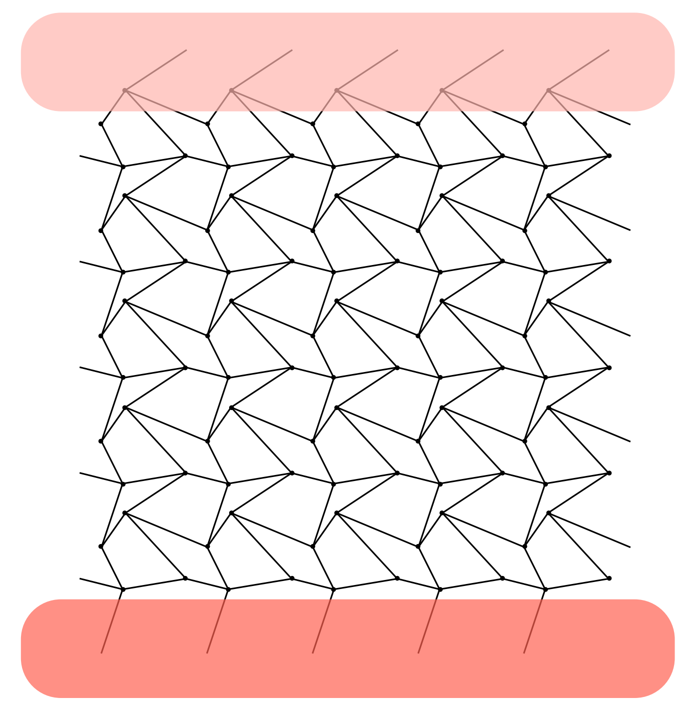
What do the Weyl modes do?







So the localization of surface modes becomes **k dependent**!

Rocklin, Chen, Falk, Vitelli, Lubensky. arXiv:1510.04970

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nonlinear Weyl modes lead to *tunable* structural transitions

Key idea: when Weyl wavenumber is commensurate, look at deformations of a "**supercell**"

BGC, Rocklin, Falk, Vitelli, Lubensky. In preparation.

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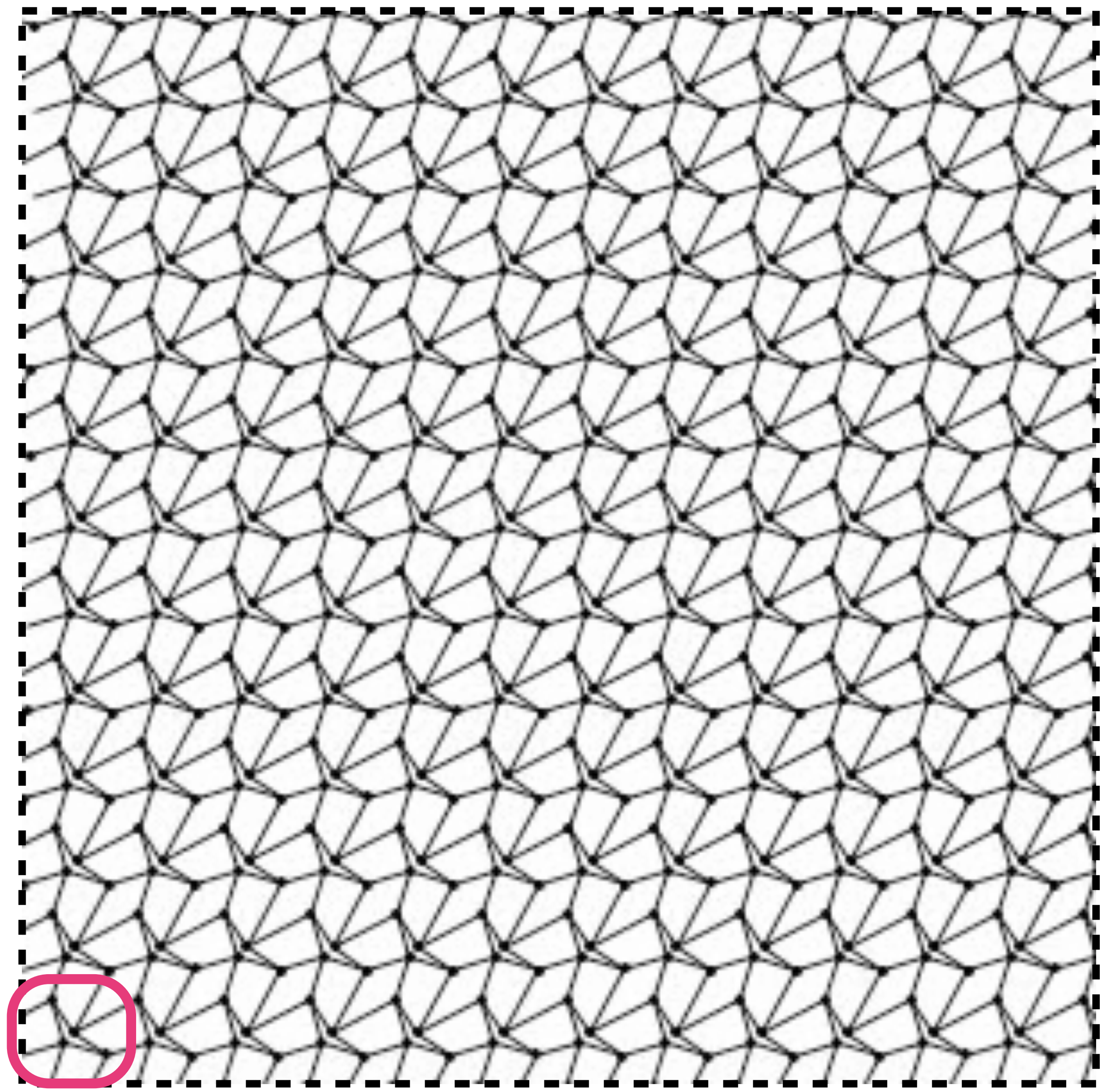

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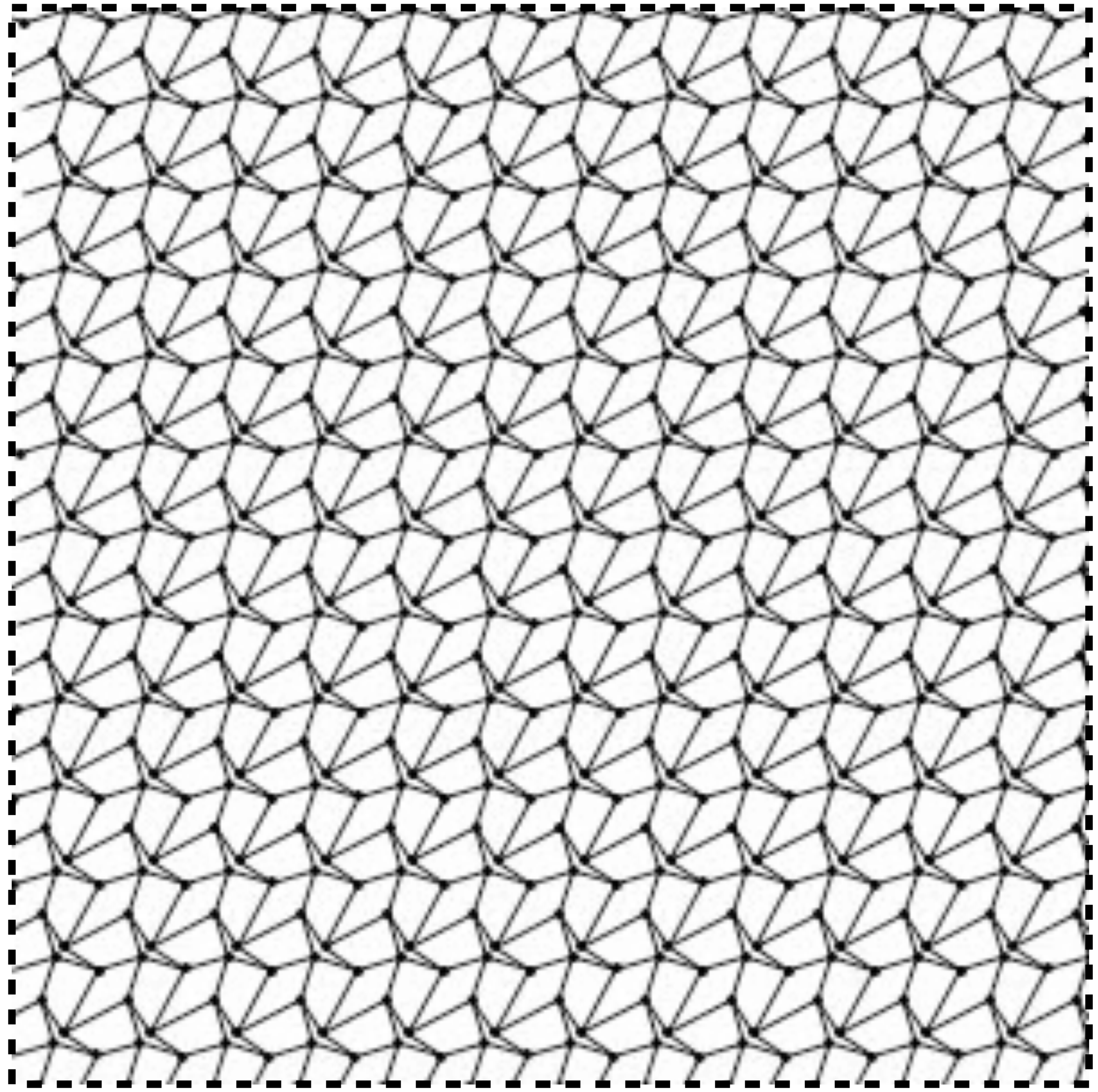

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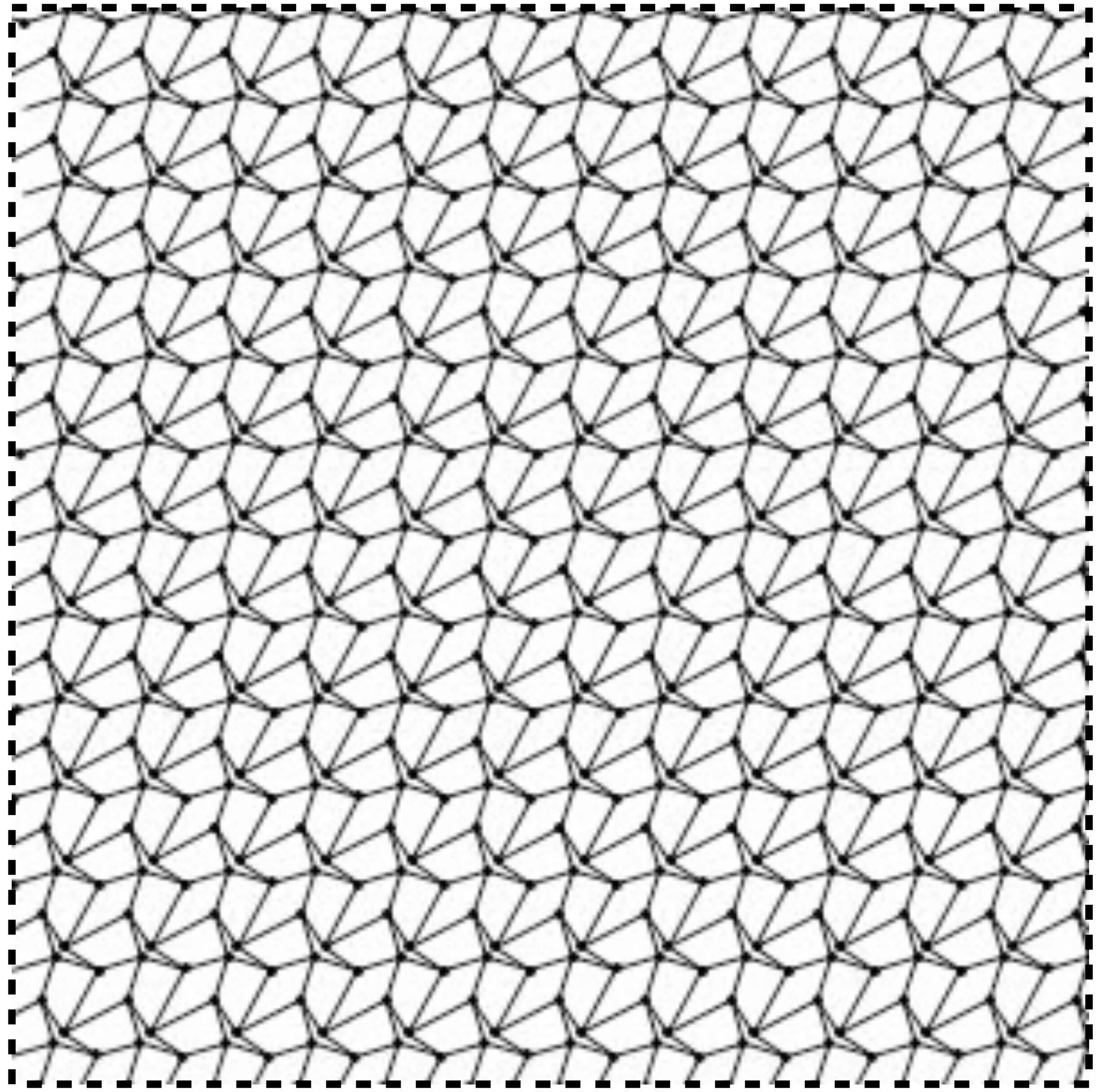

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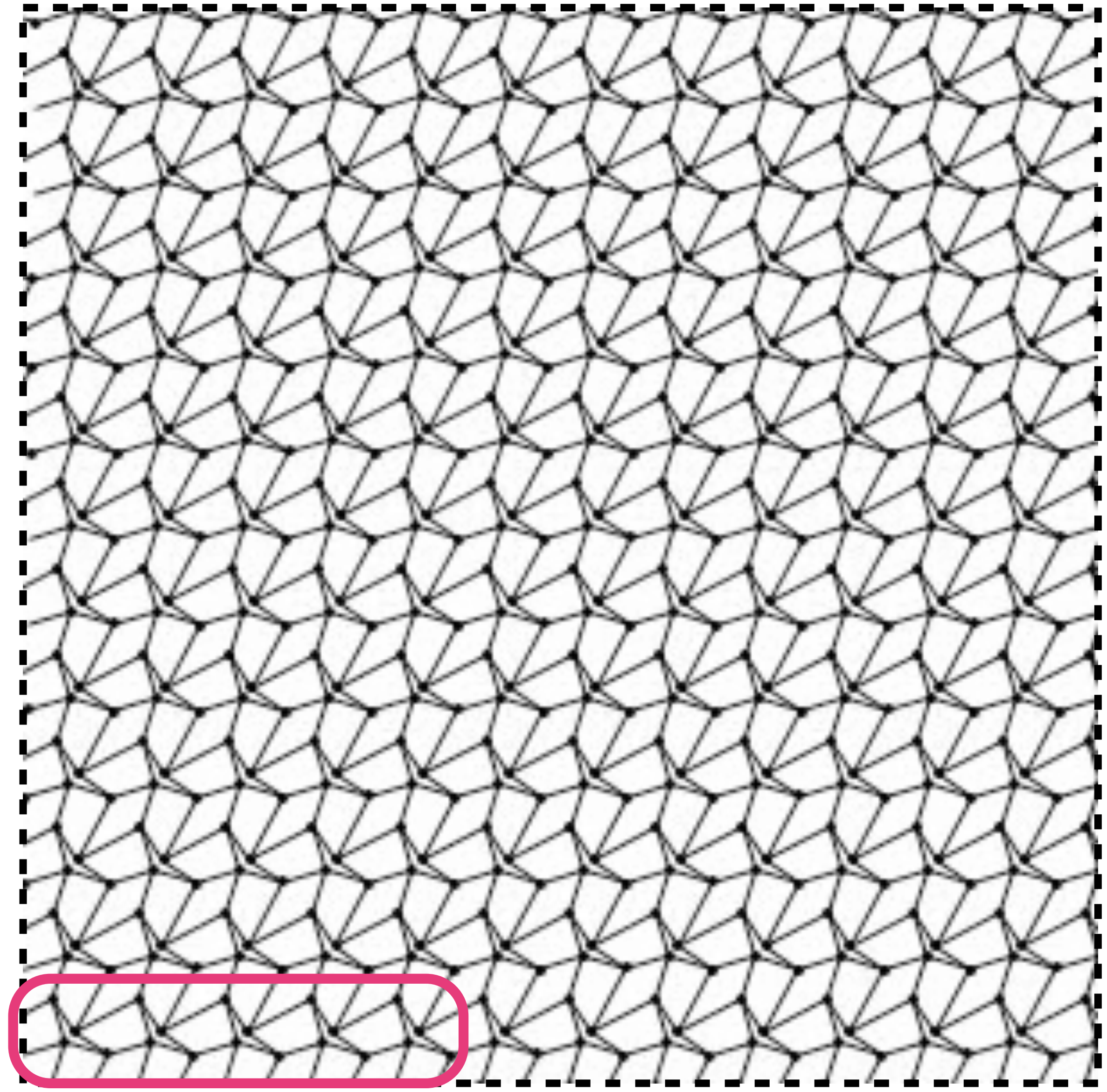

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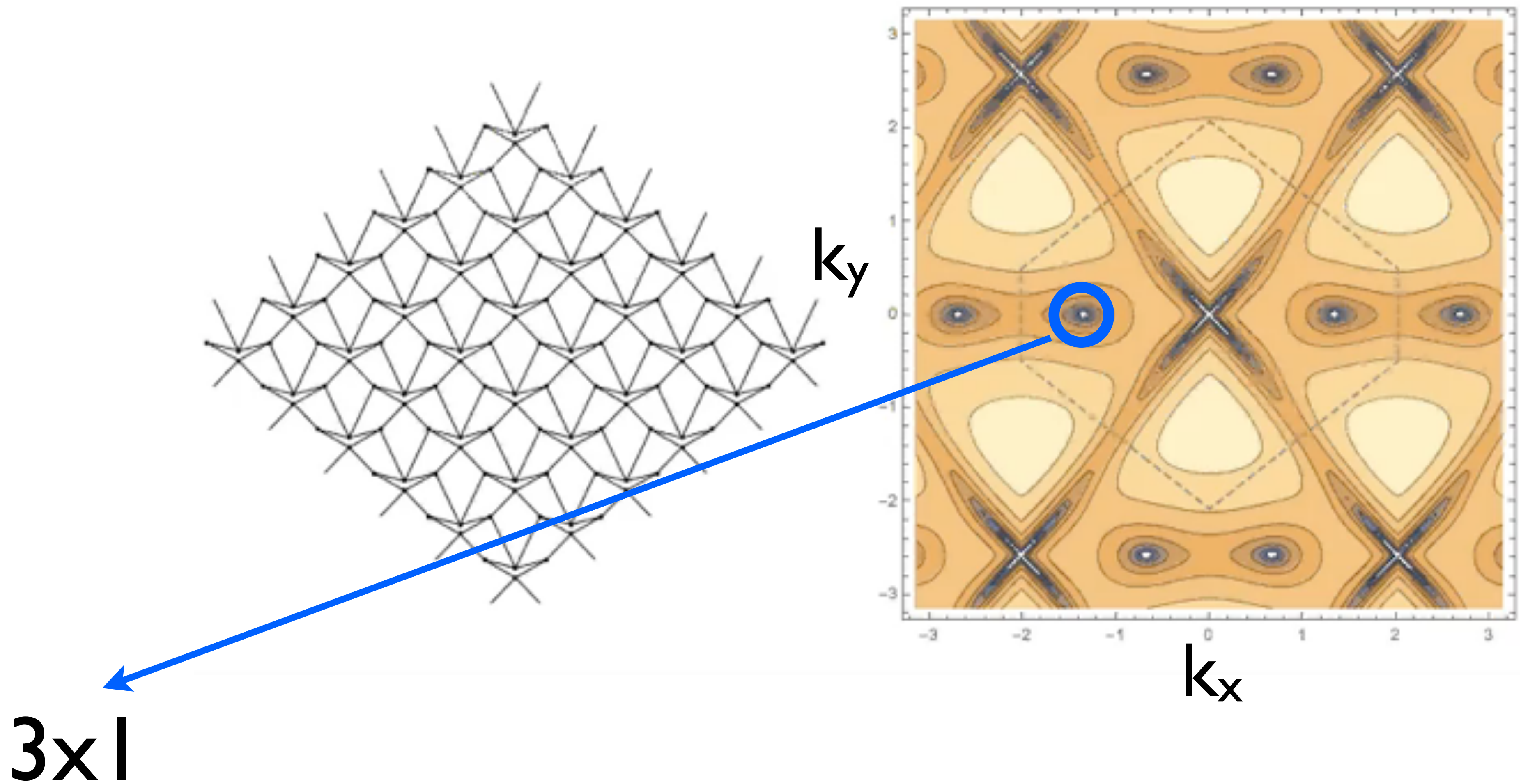
k_y

k_x

BGC, Rocklin, Falk, Vitelli, Lubensky. In preparation.



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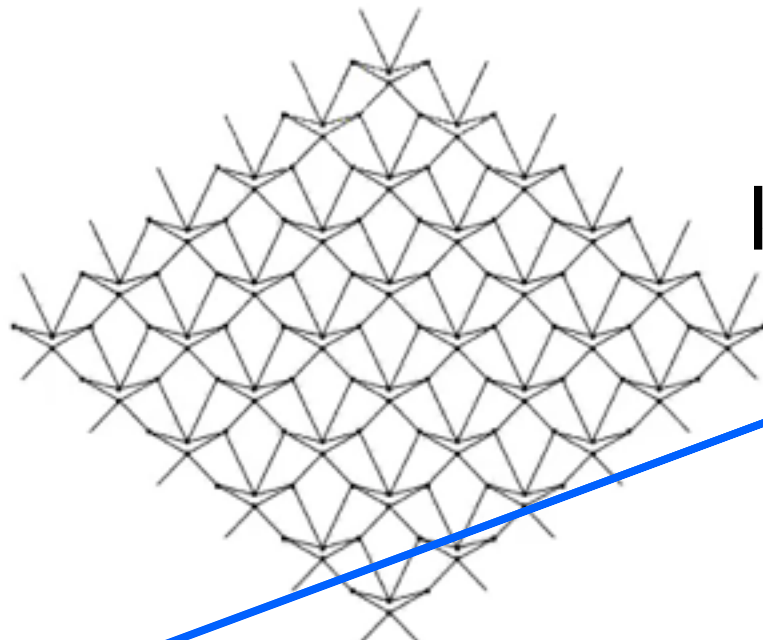

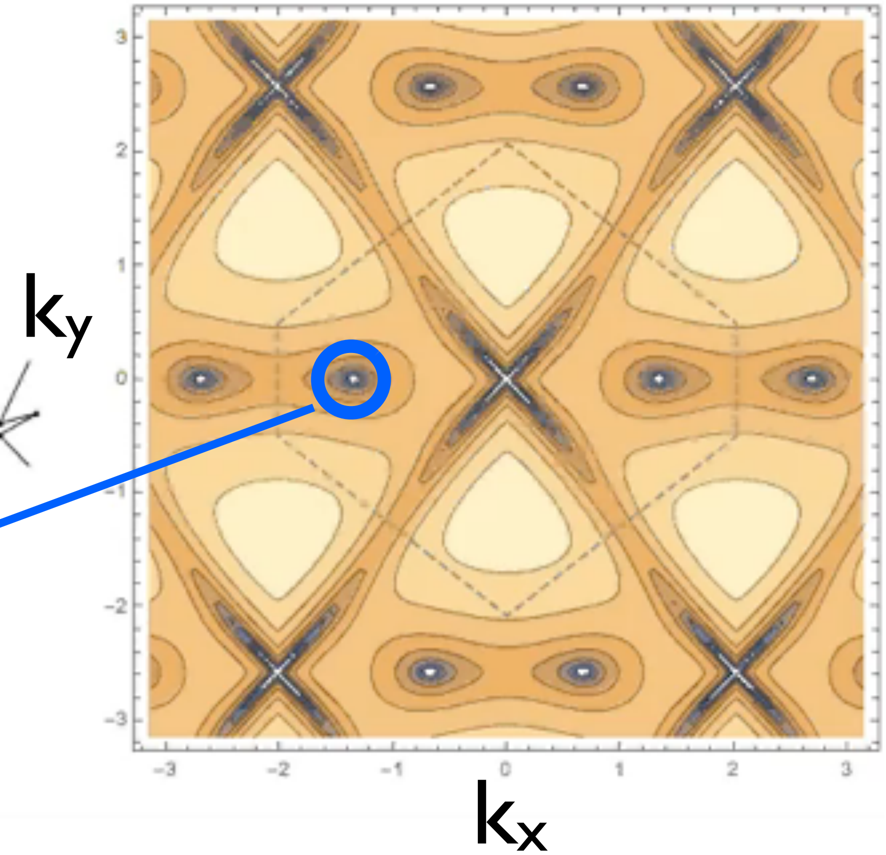

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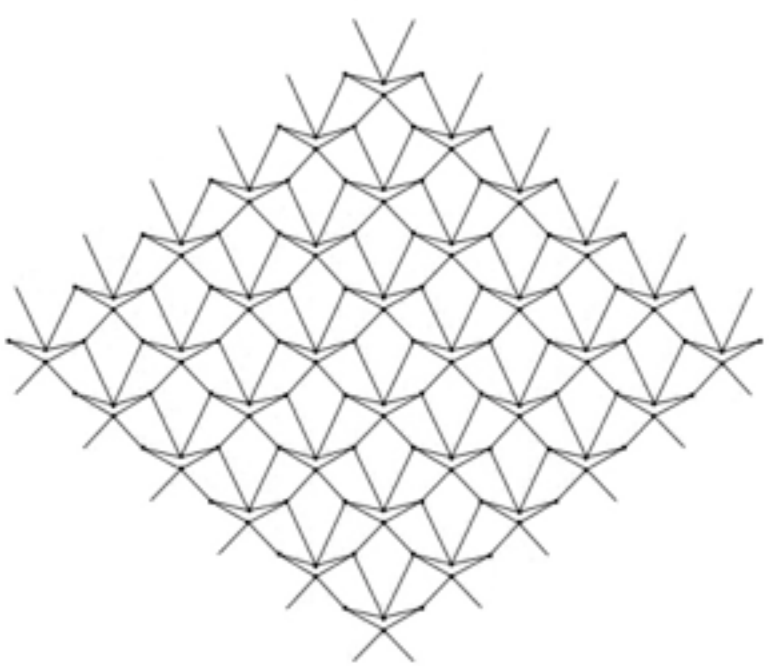

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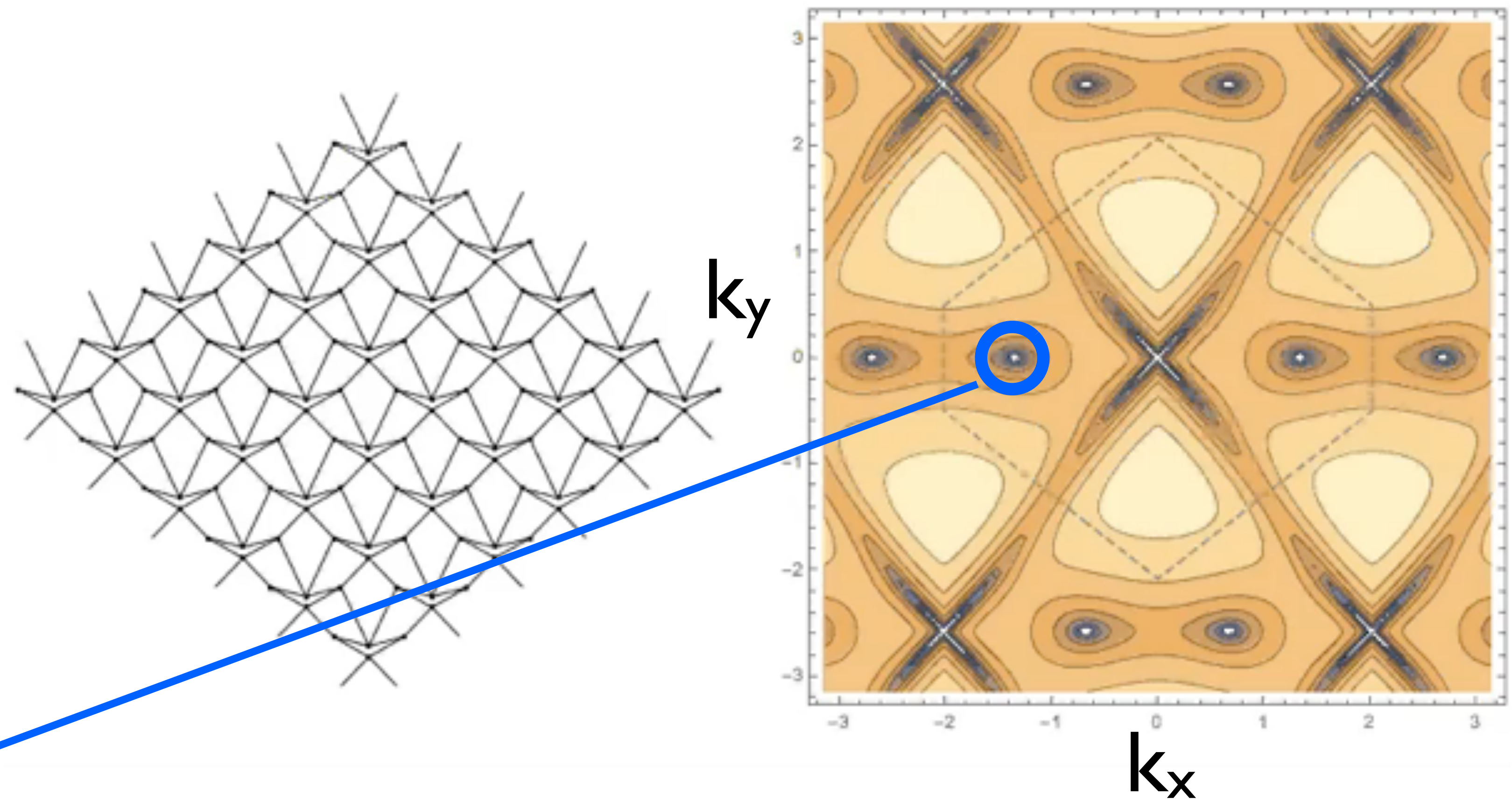

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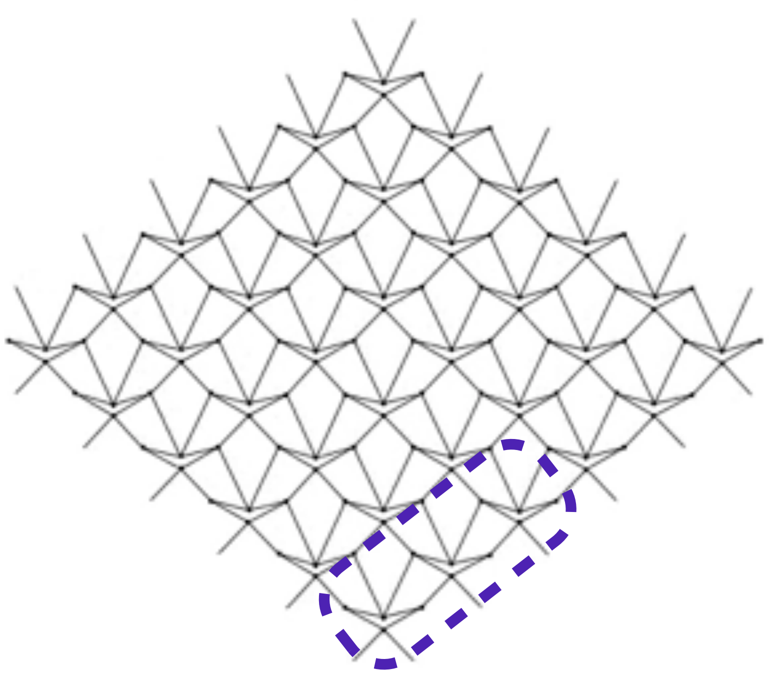

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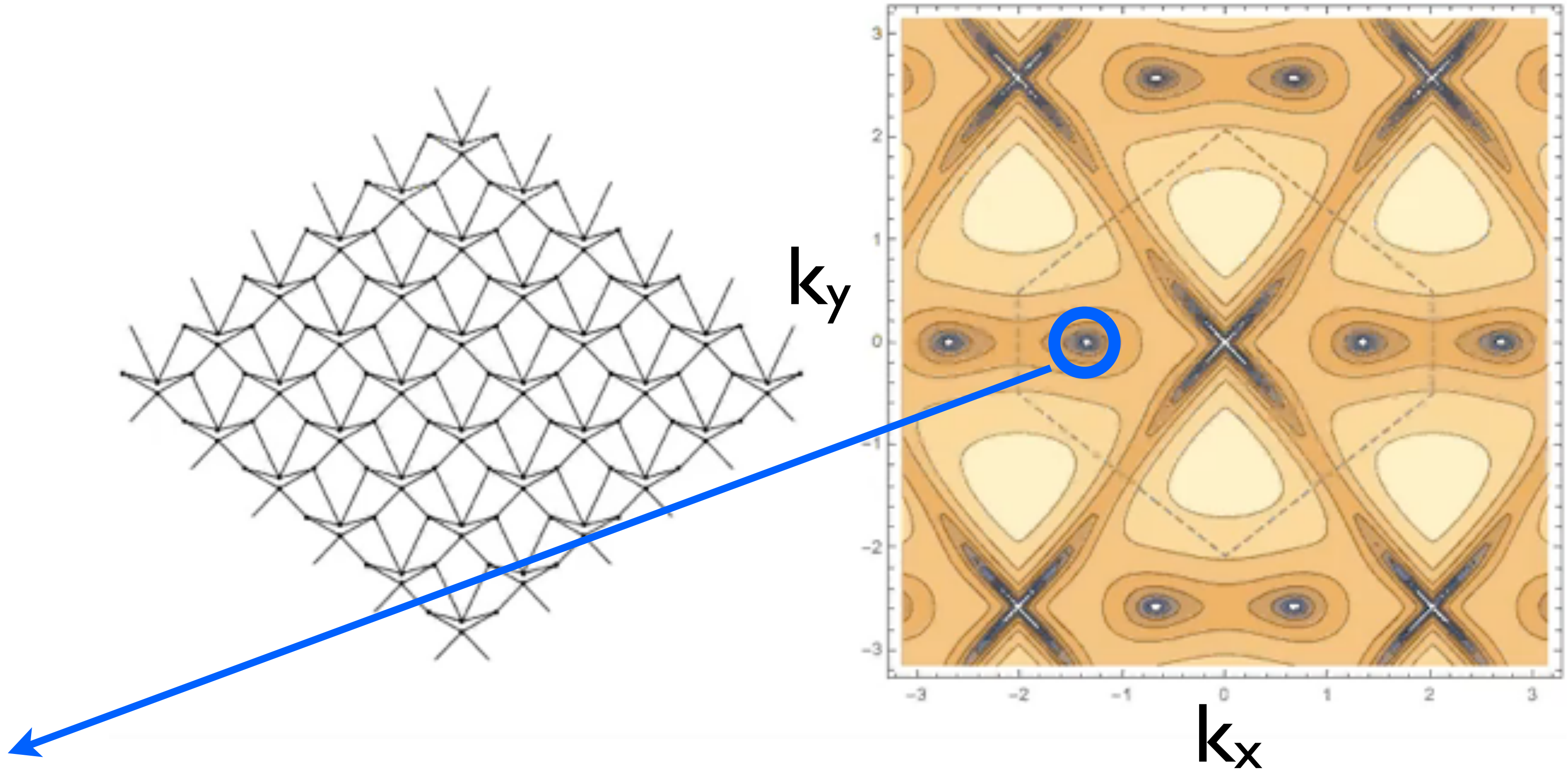

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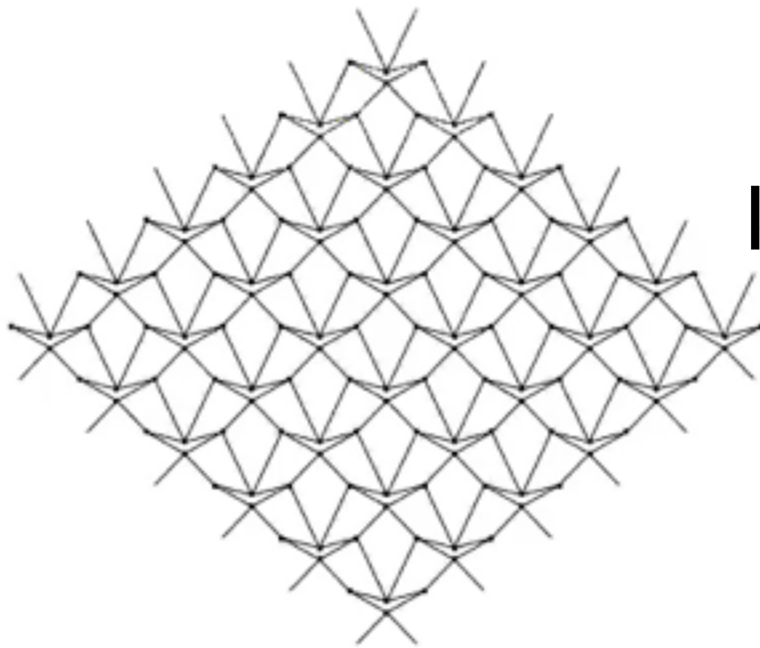

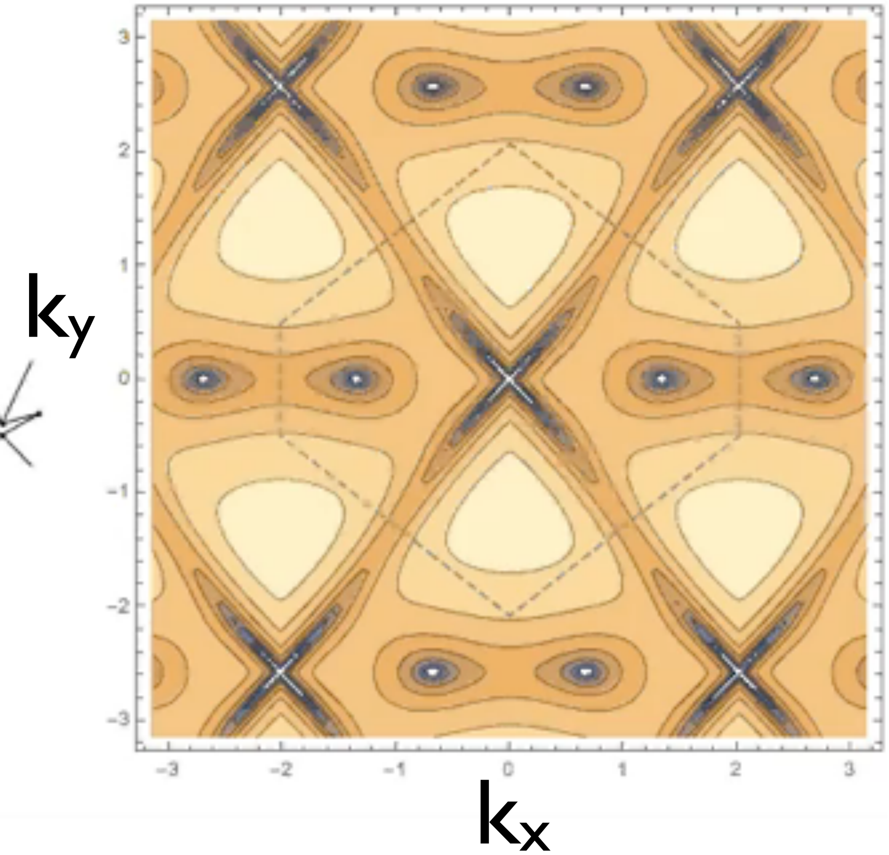

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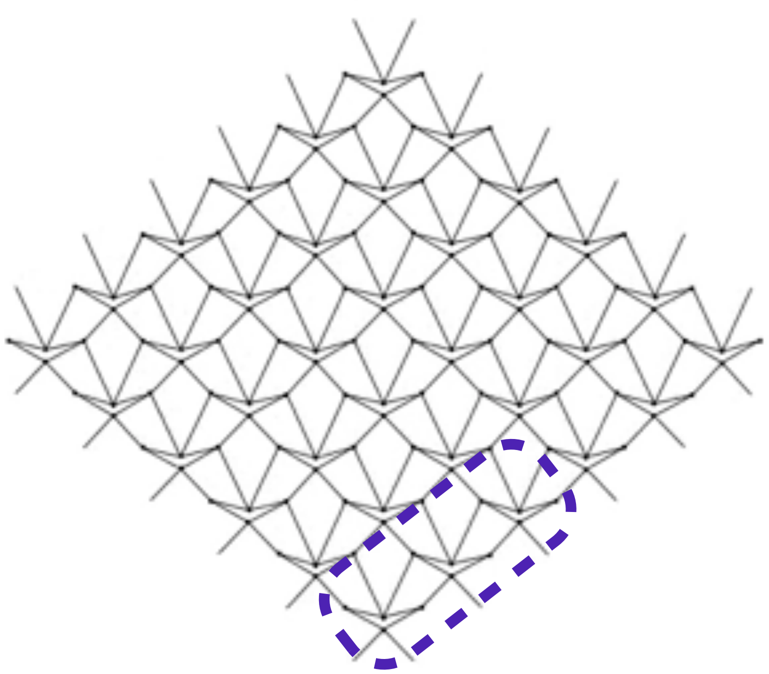

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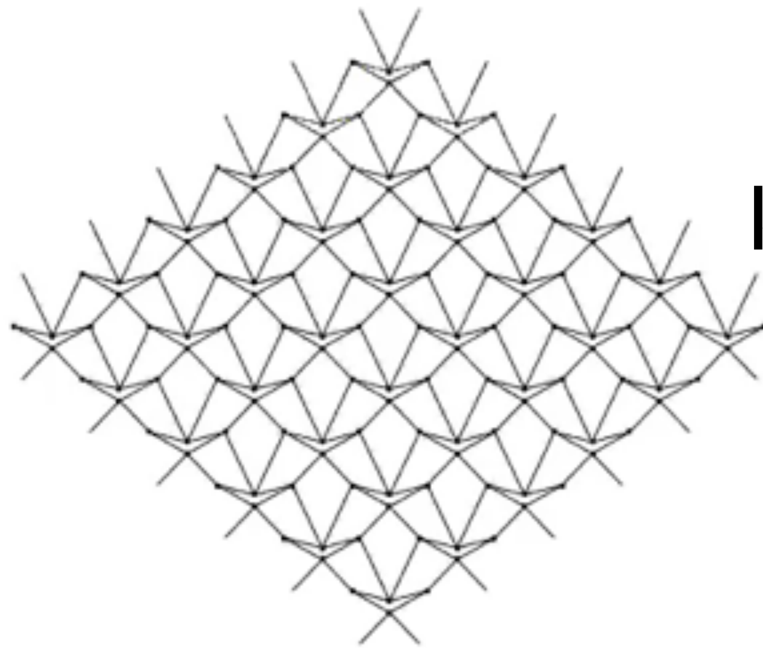
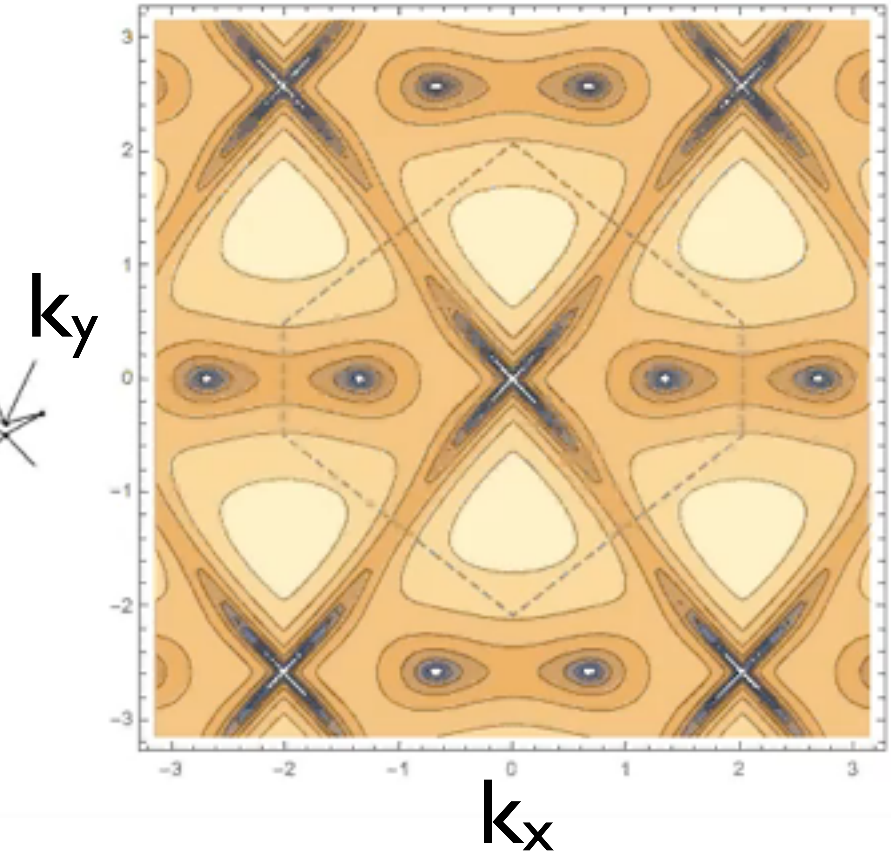
Tuning supercell size by flexing





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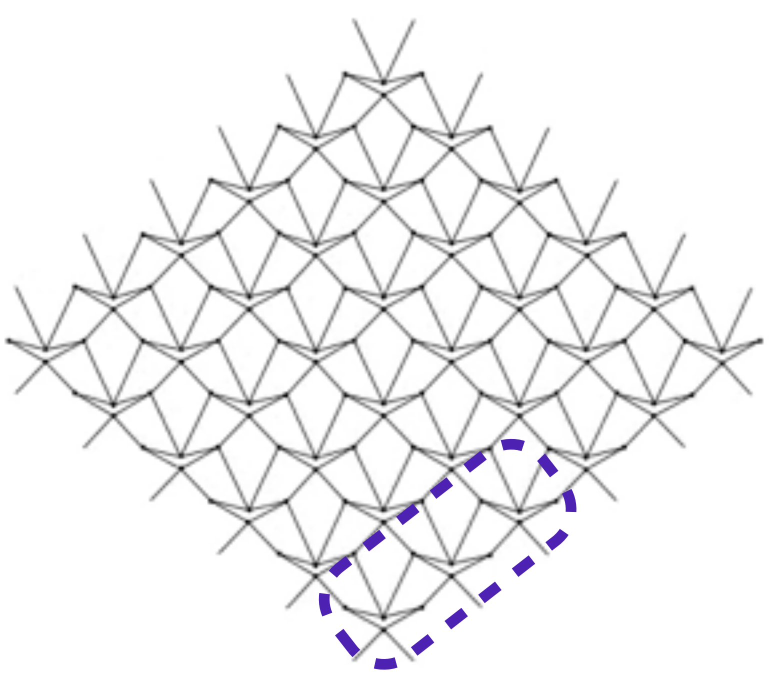

Rocklin, Zhou, Sun, Mao. arXiv:1510.06389

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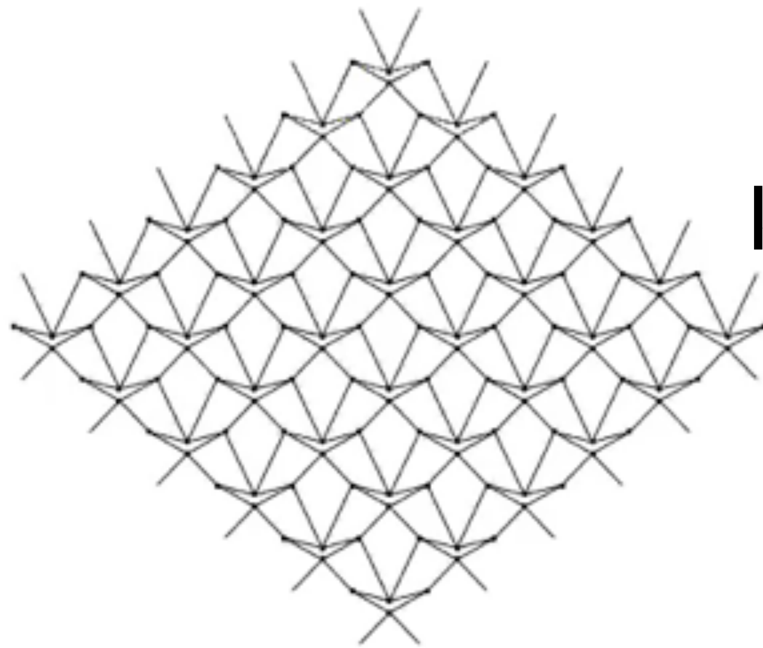

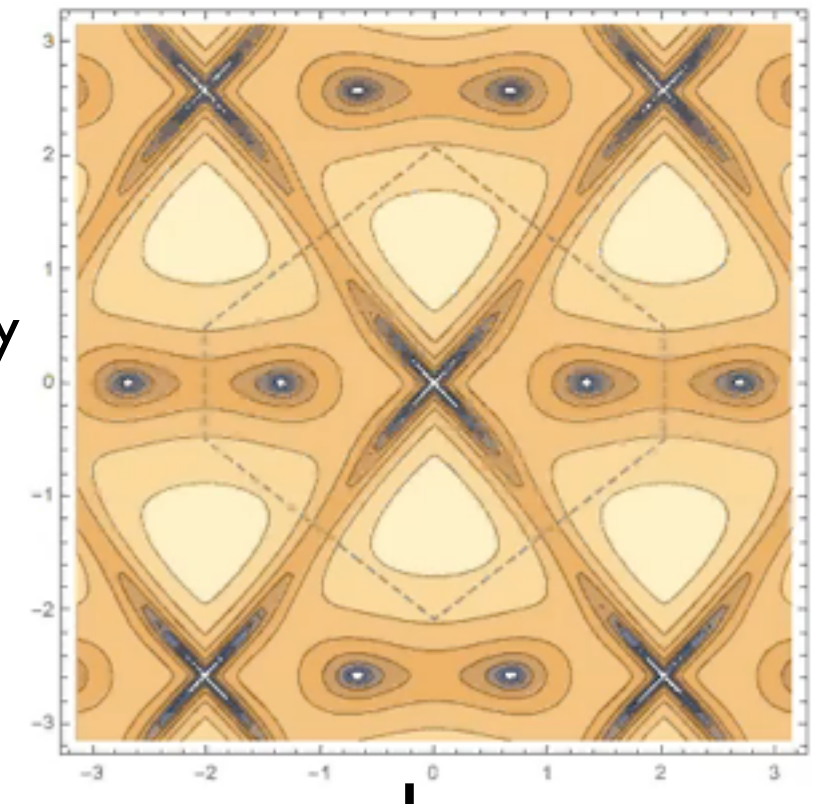

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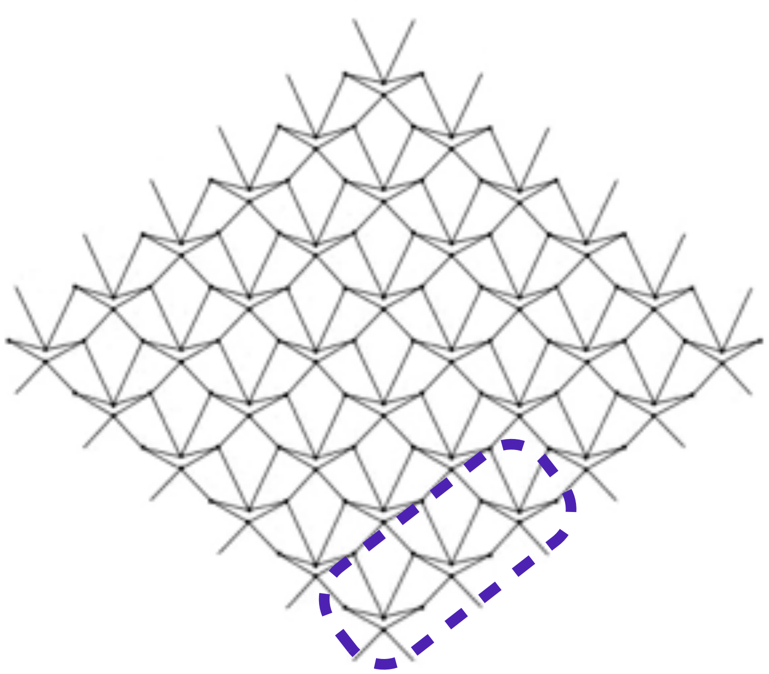

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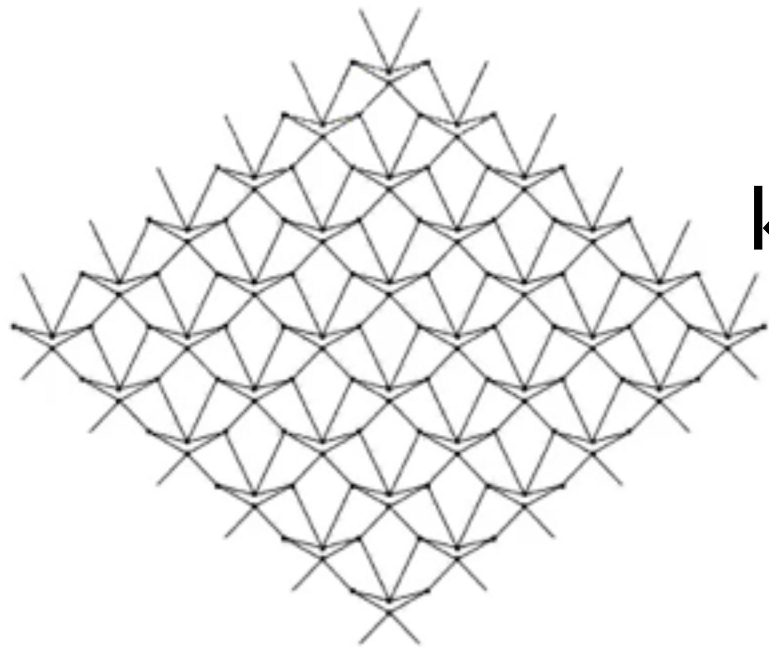

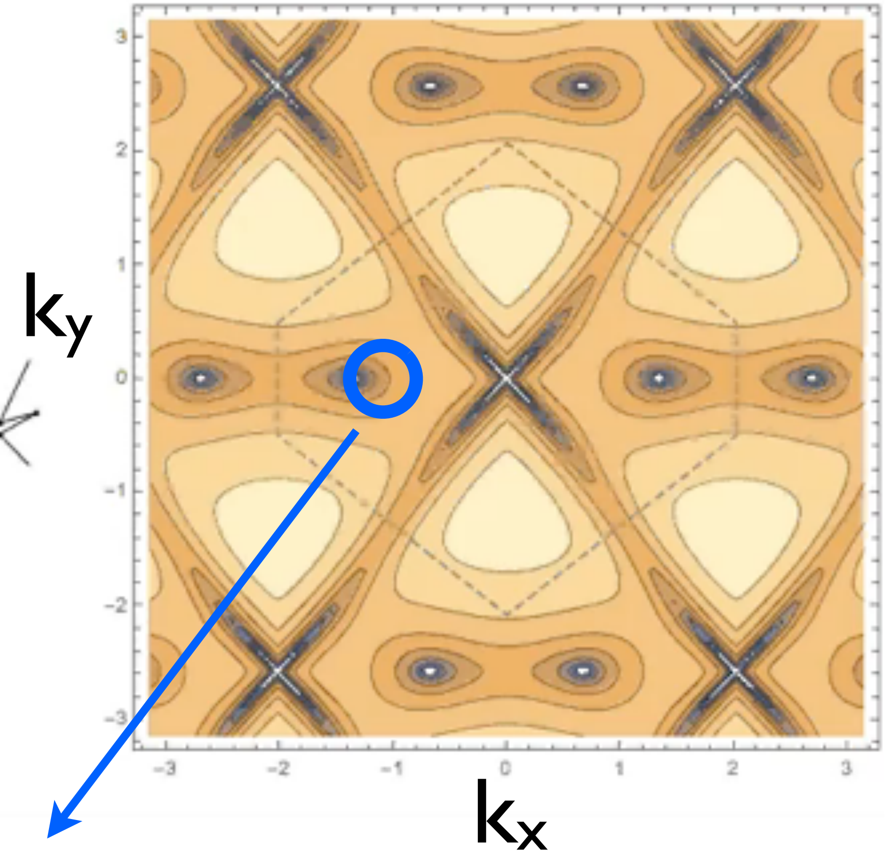

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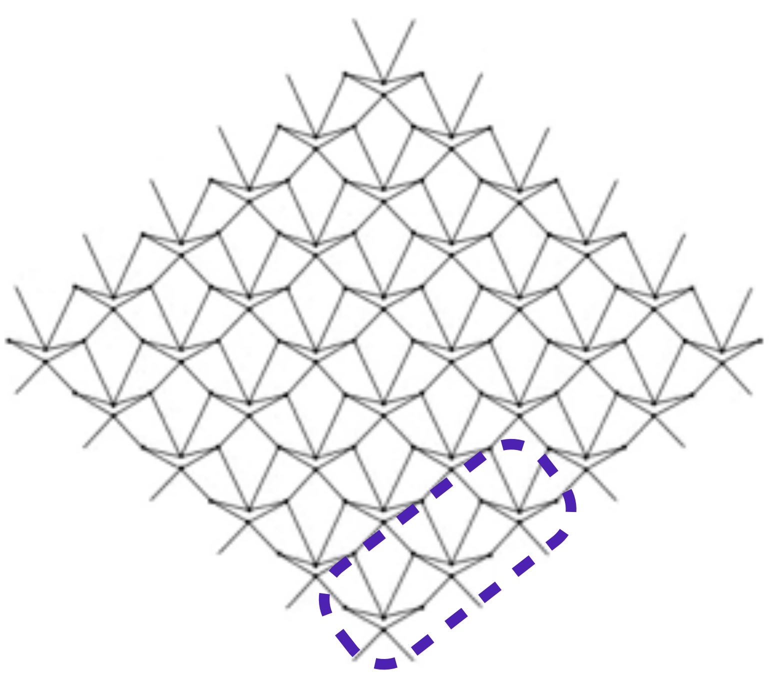

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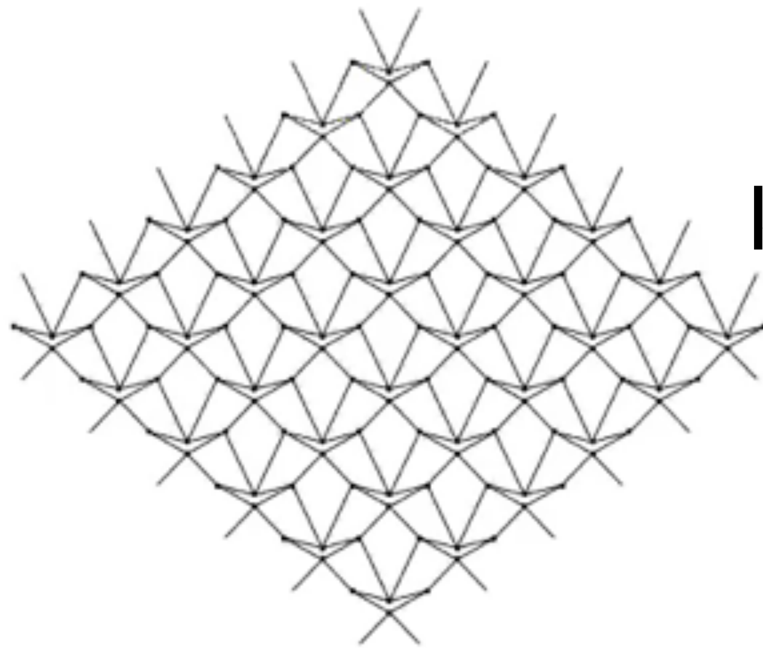

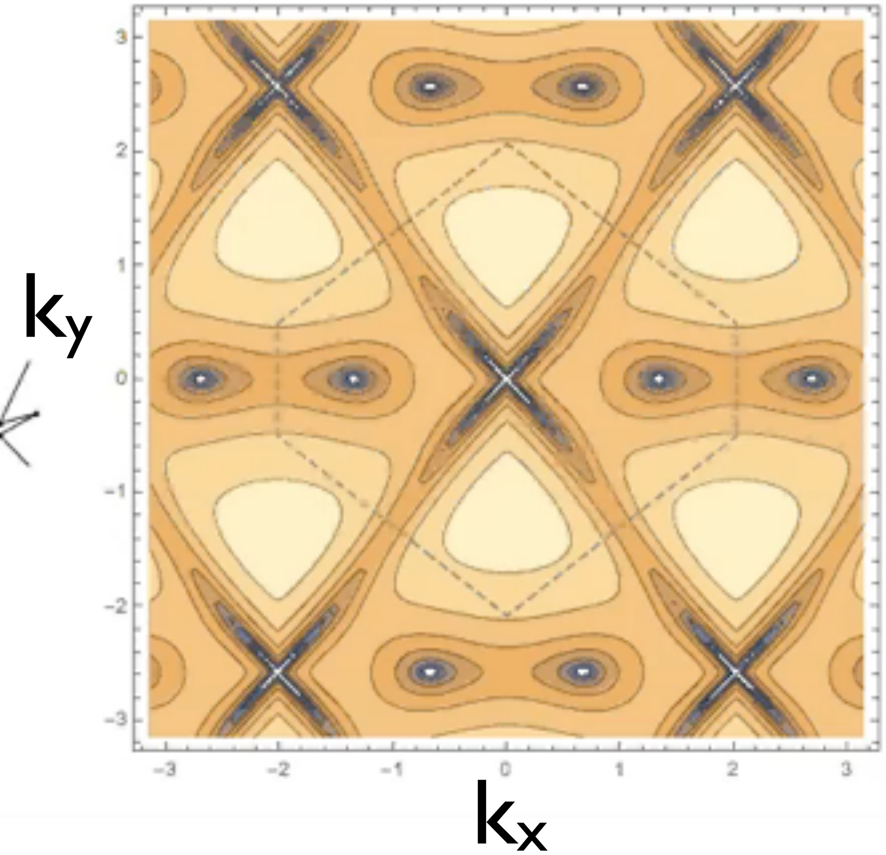

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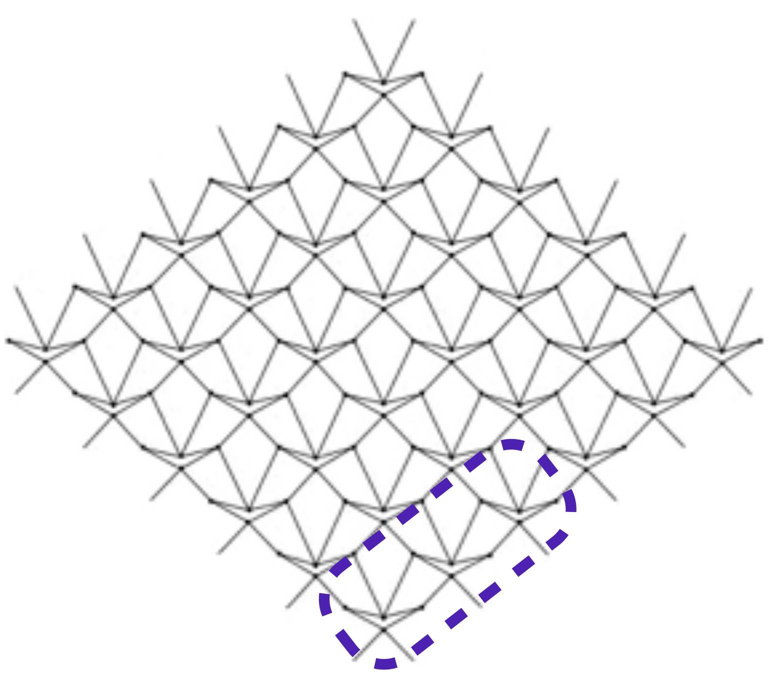

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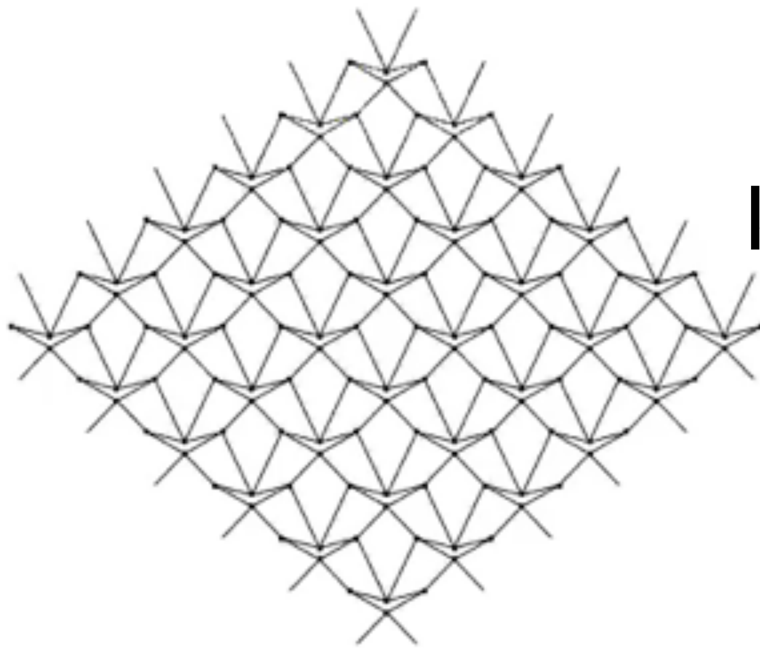

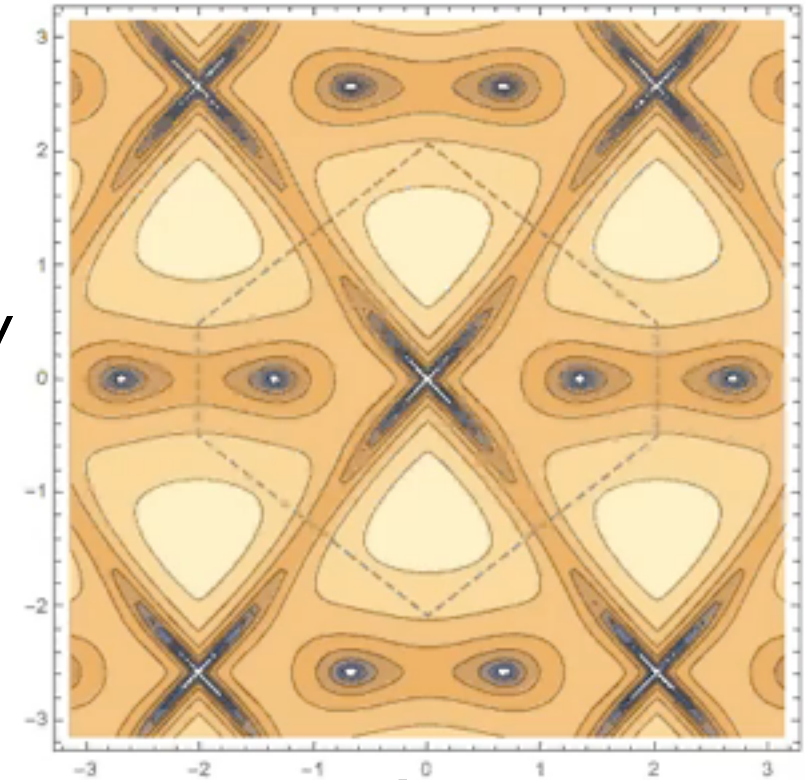

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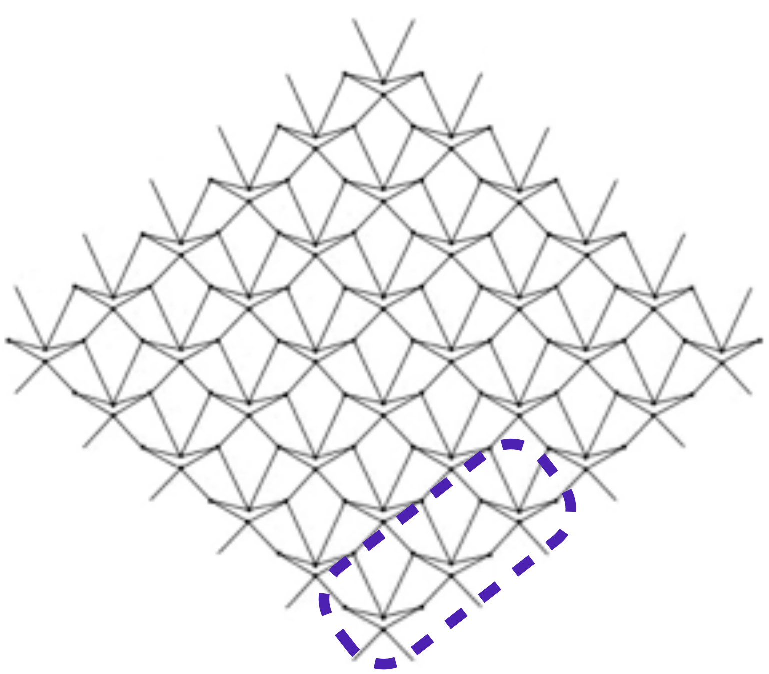

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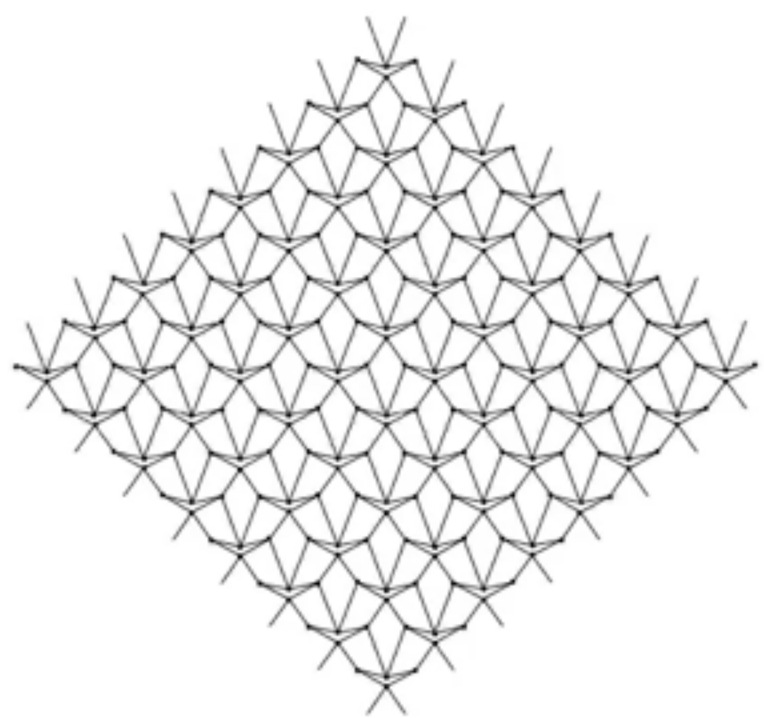

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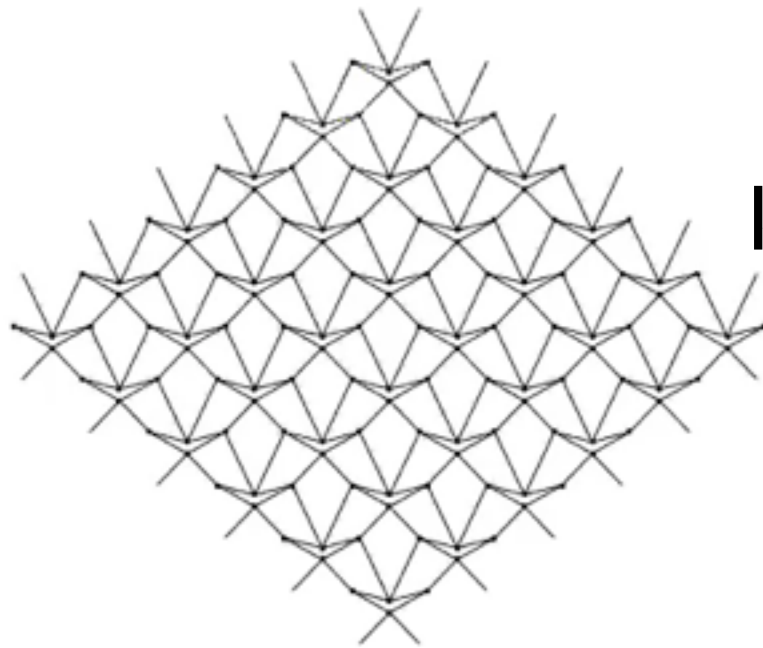

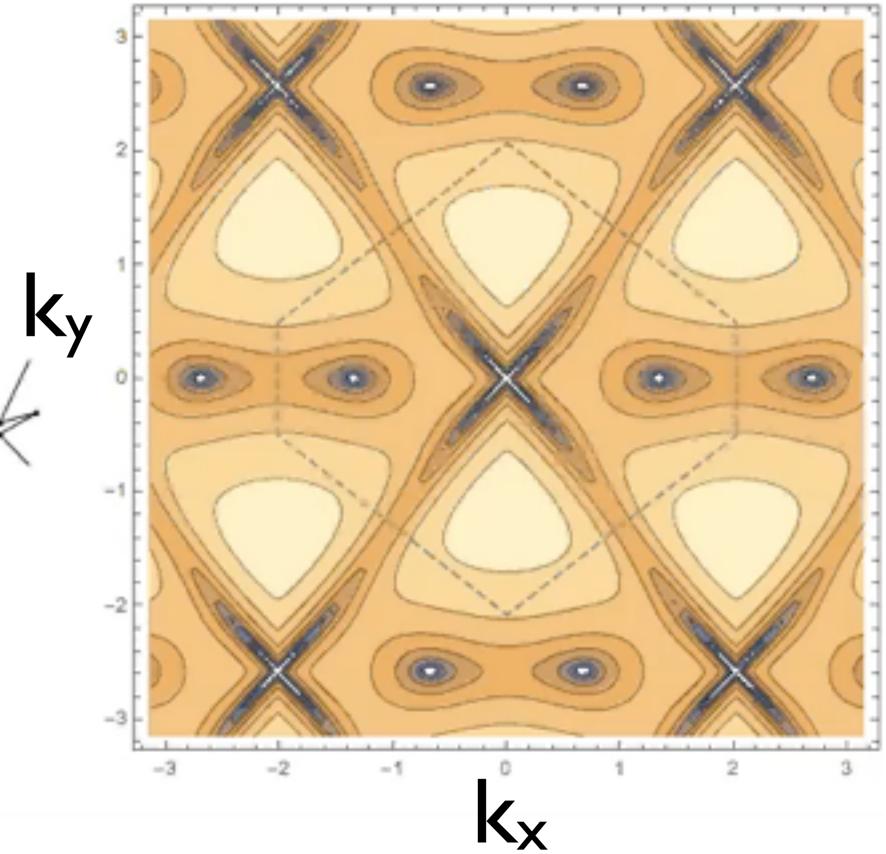

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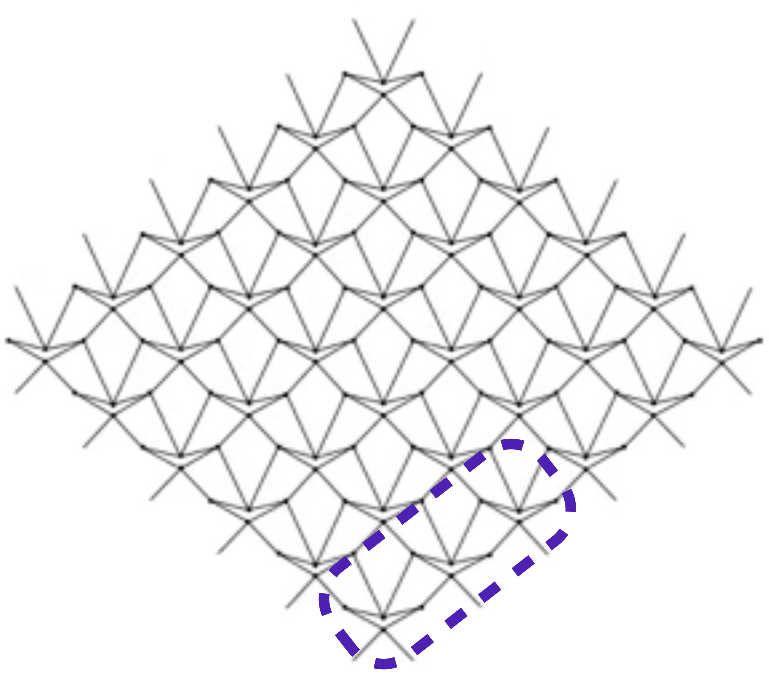

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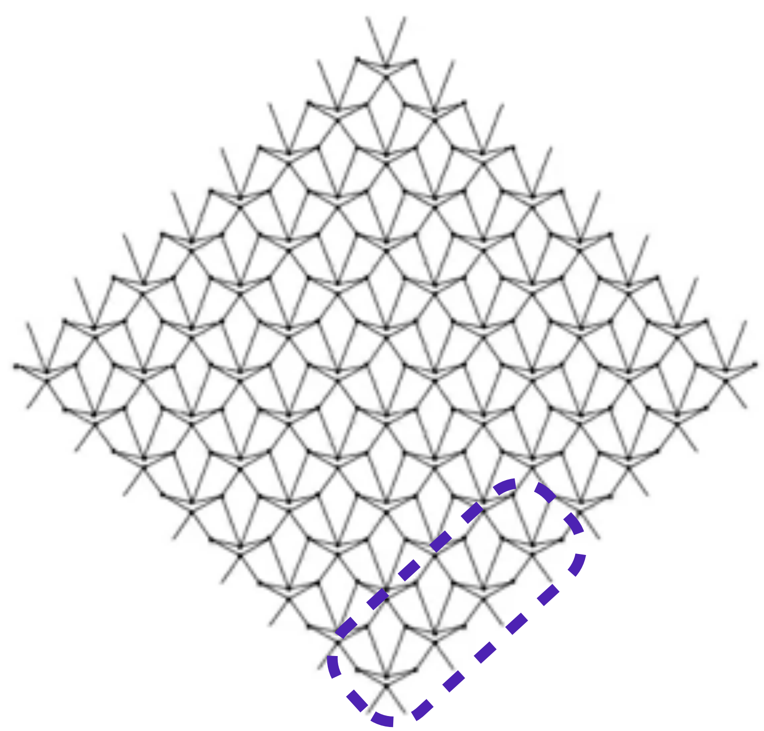

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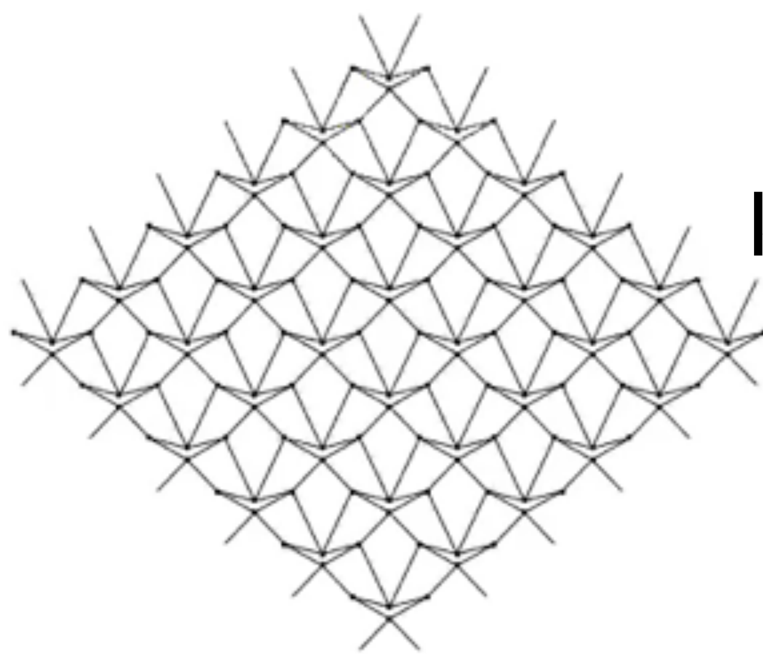

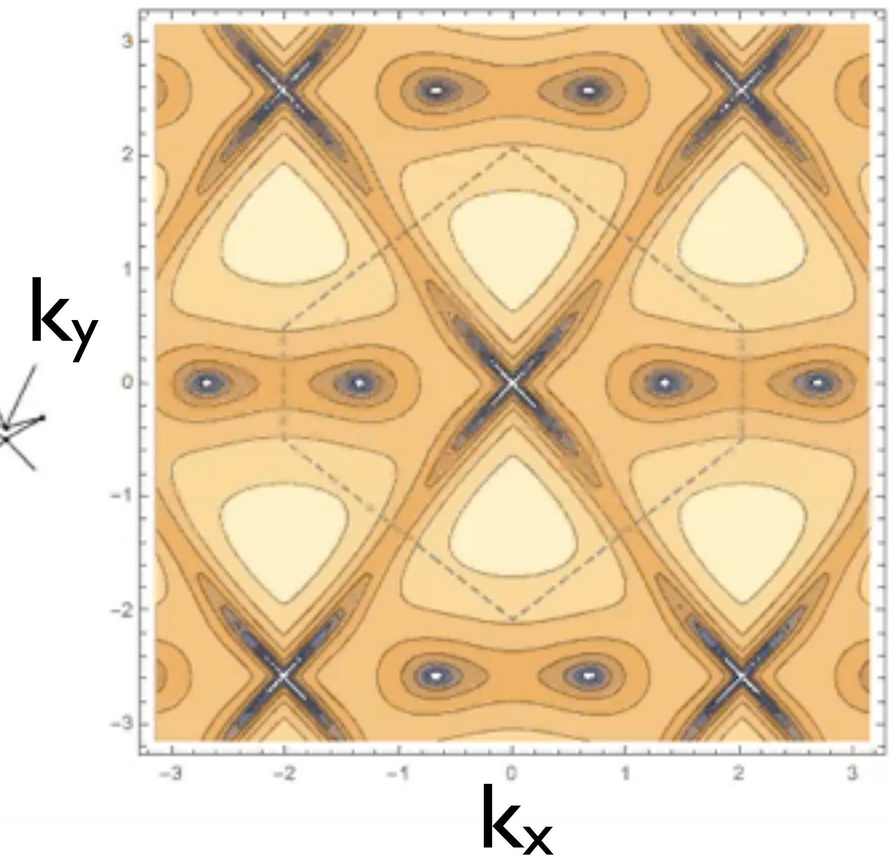

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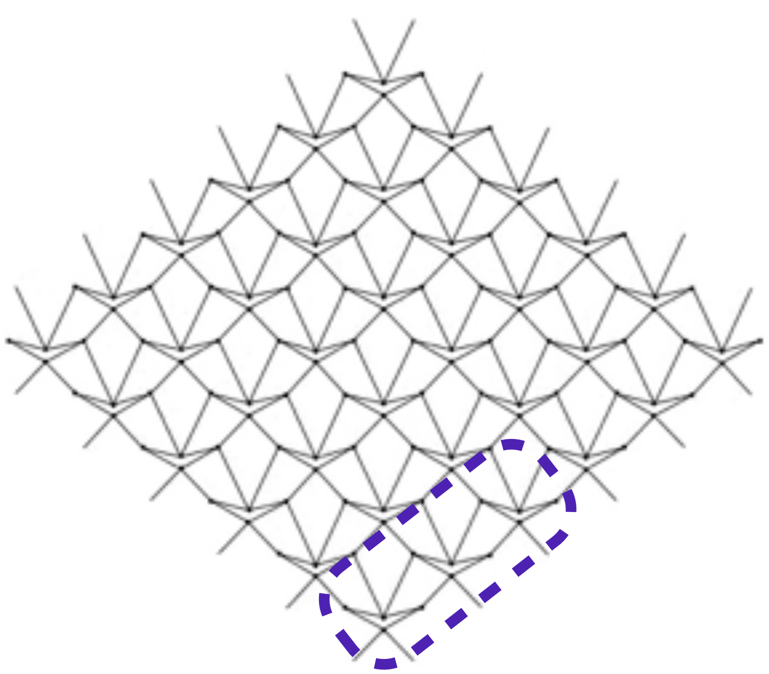

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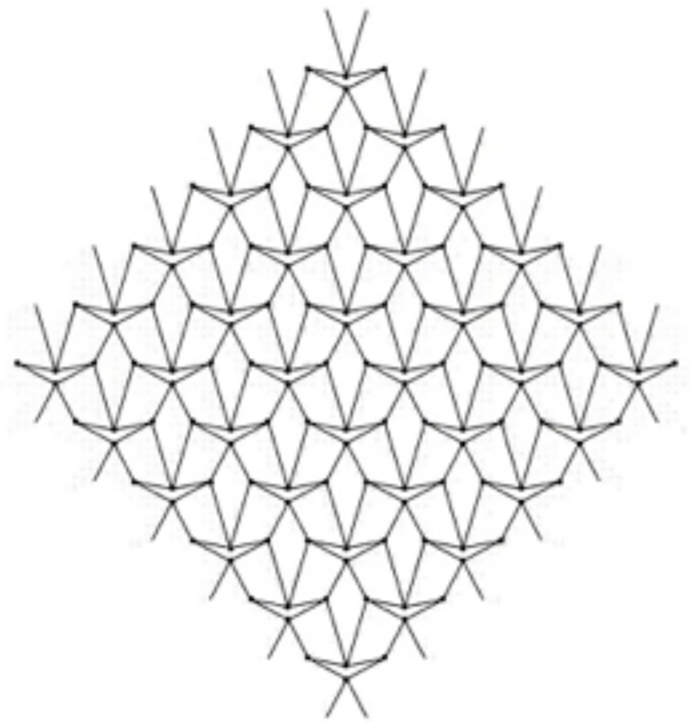

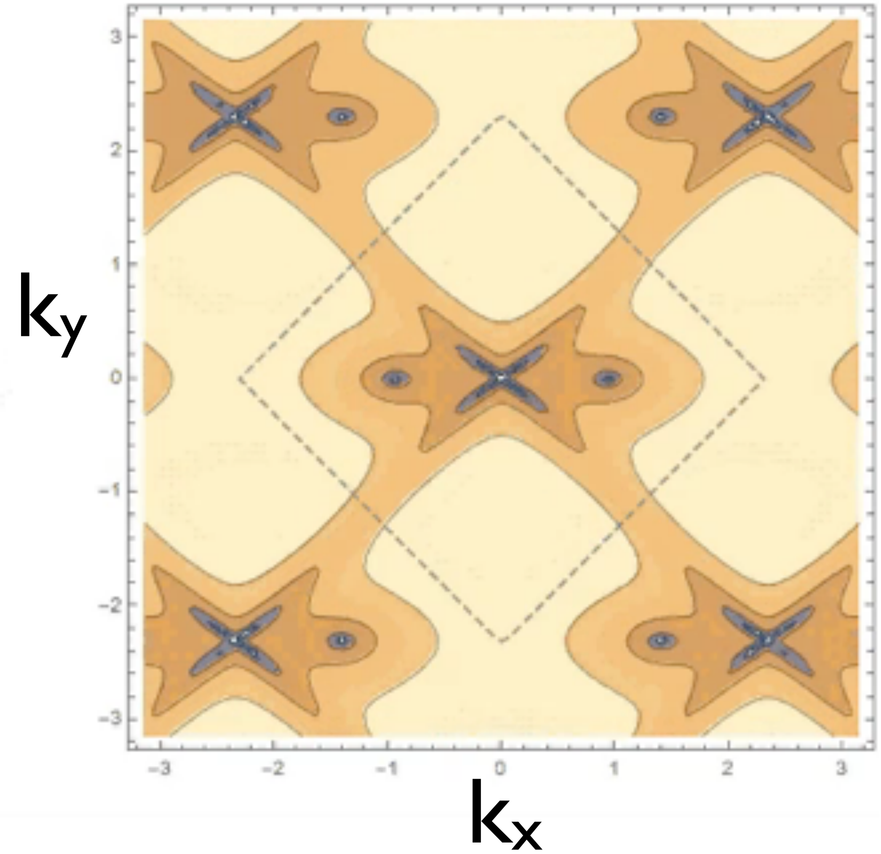

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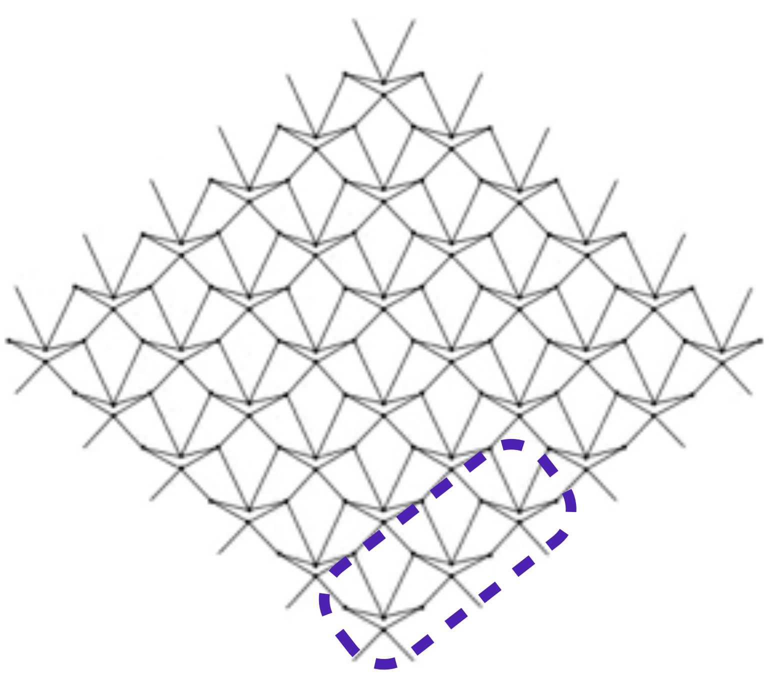

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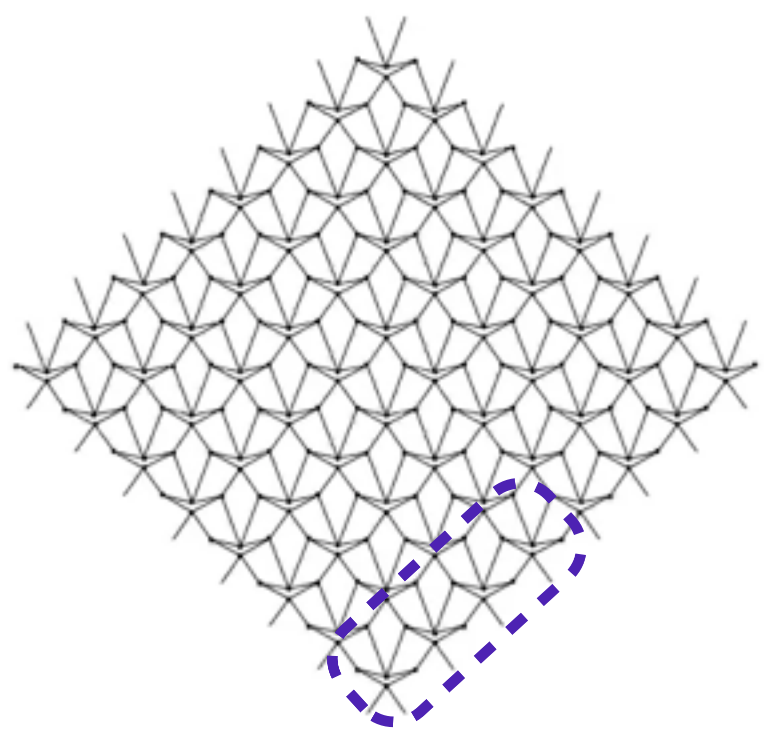

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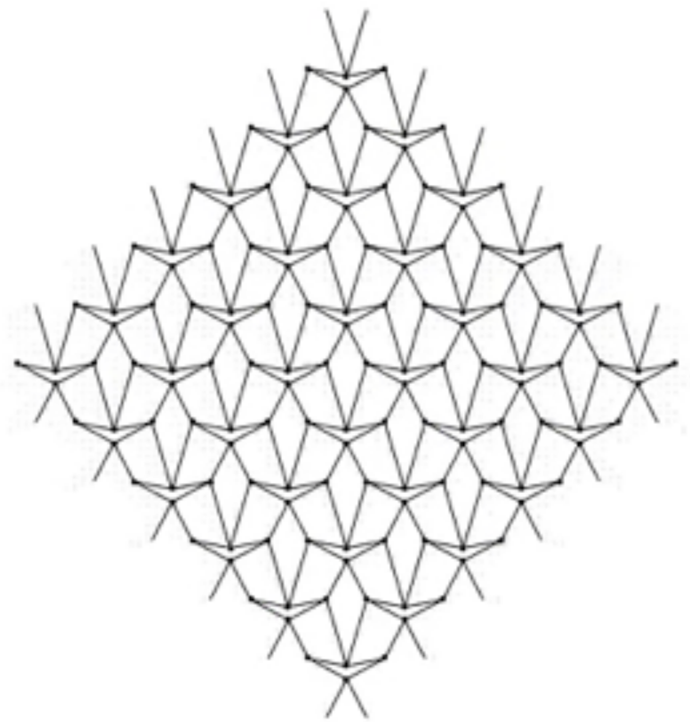

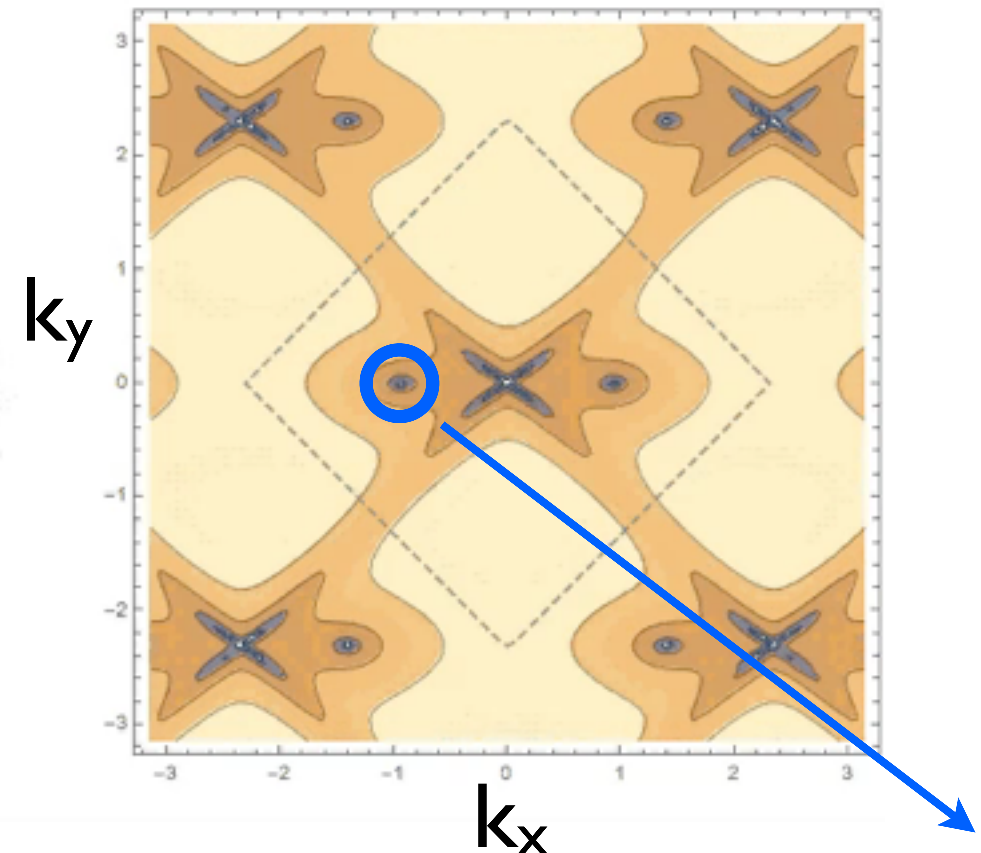

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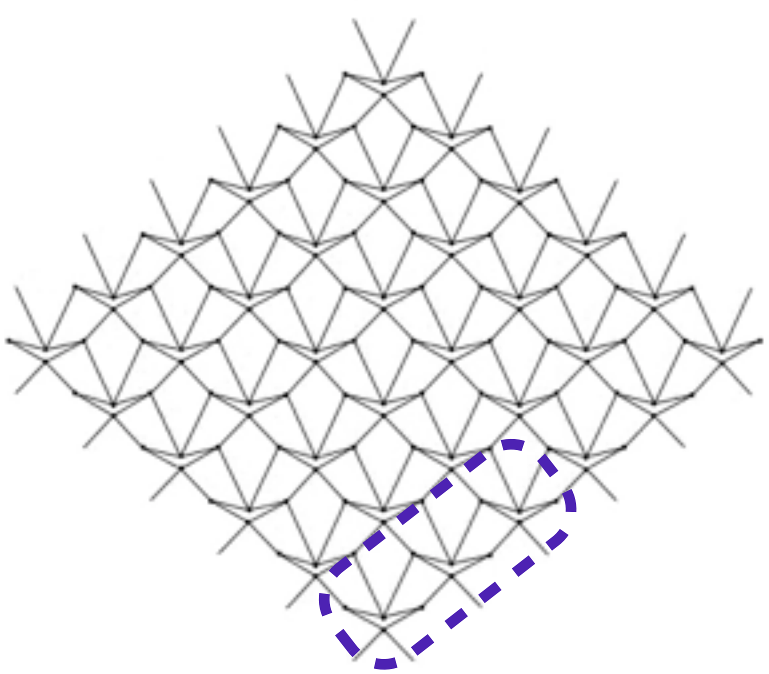

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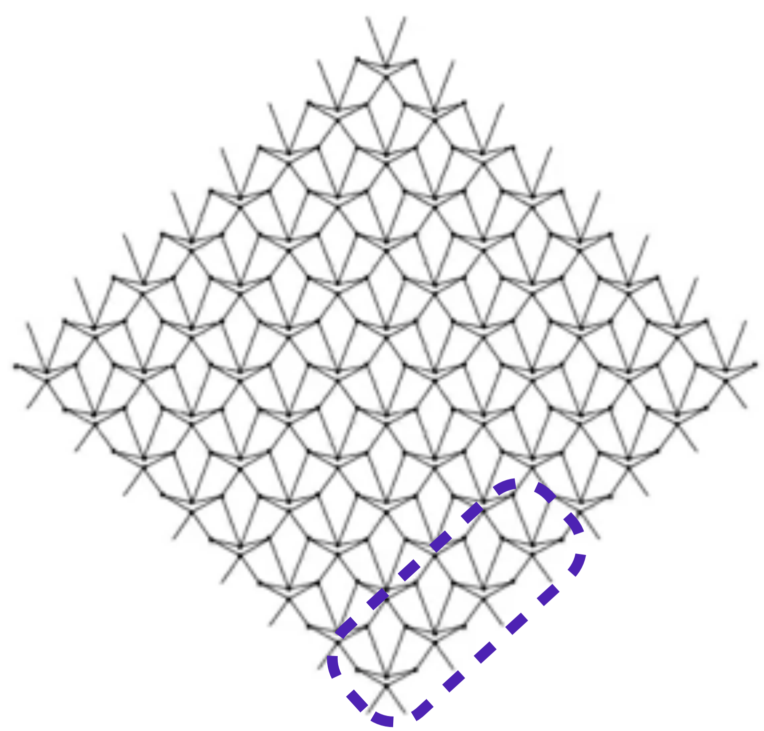

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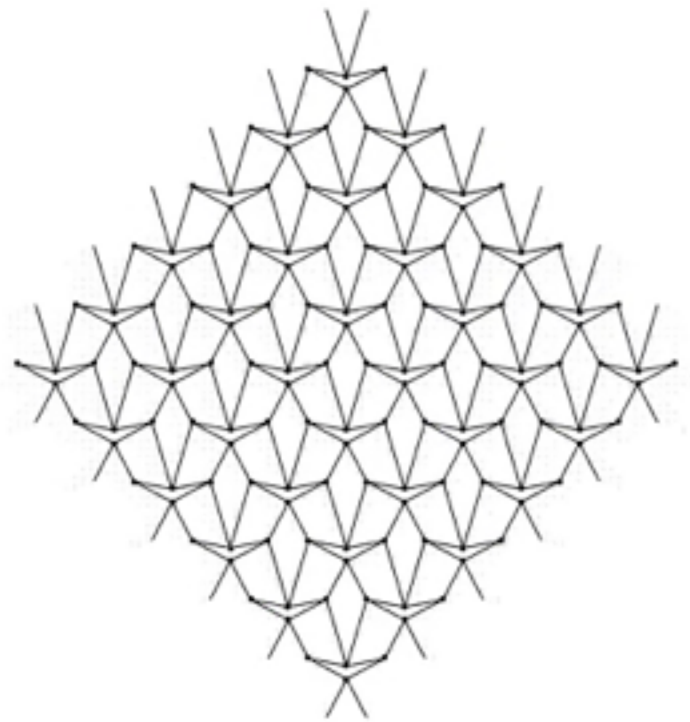

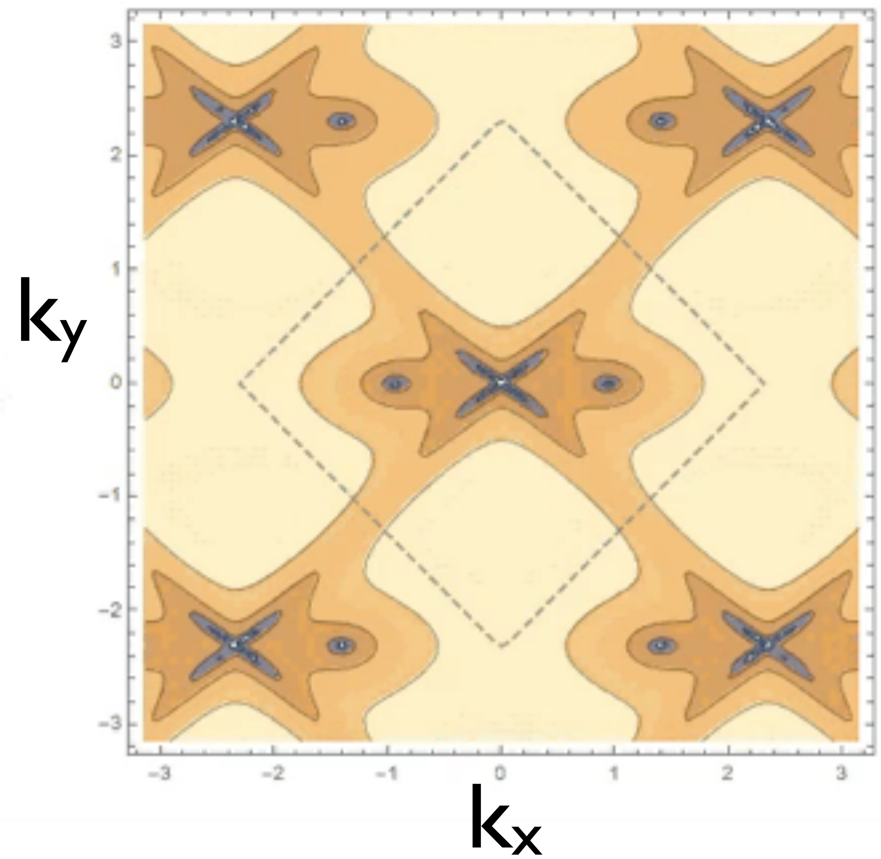

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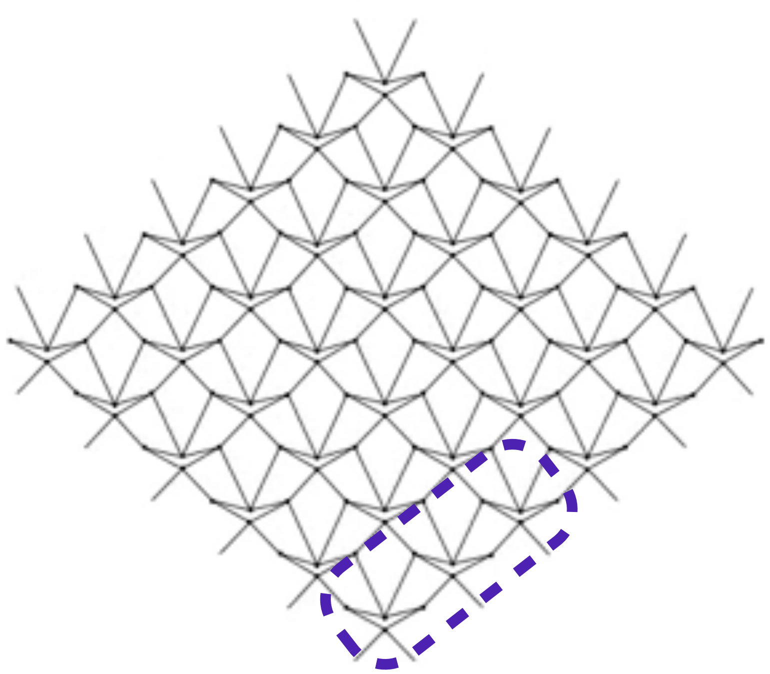

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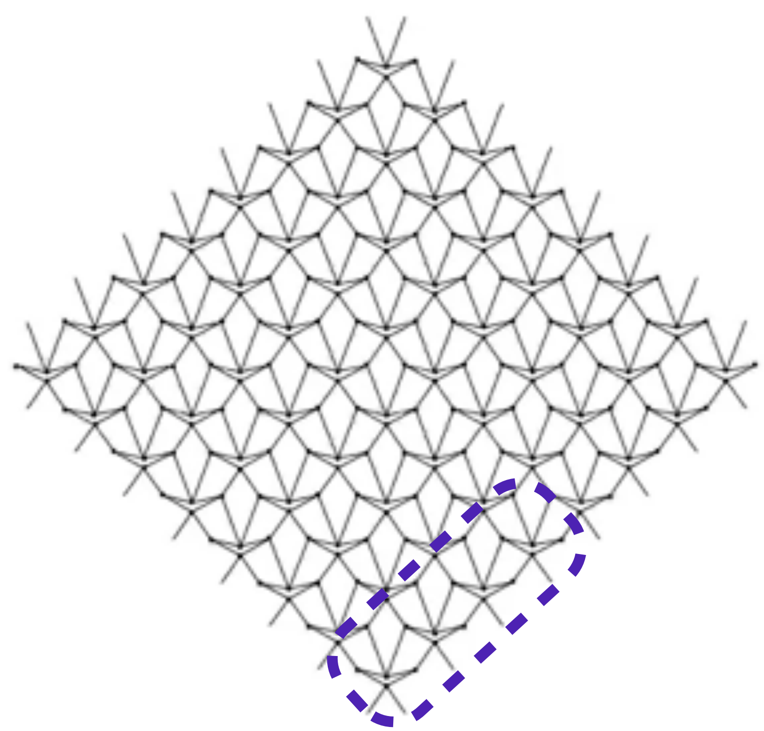

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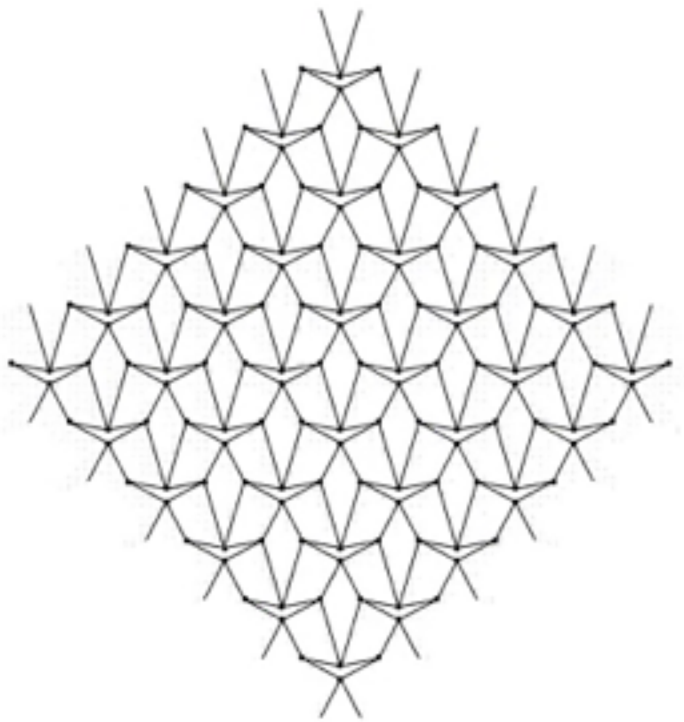

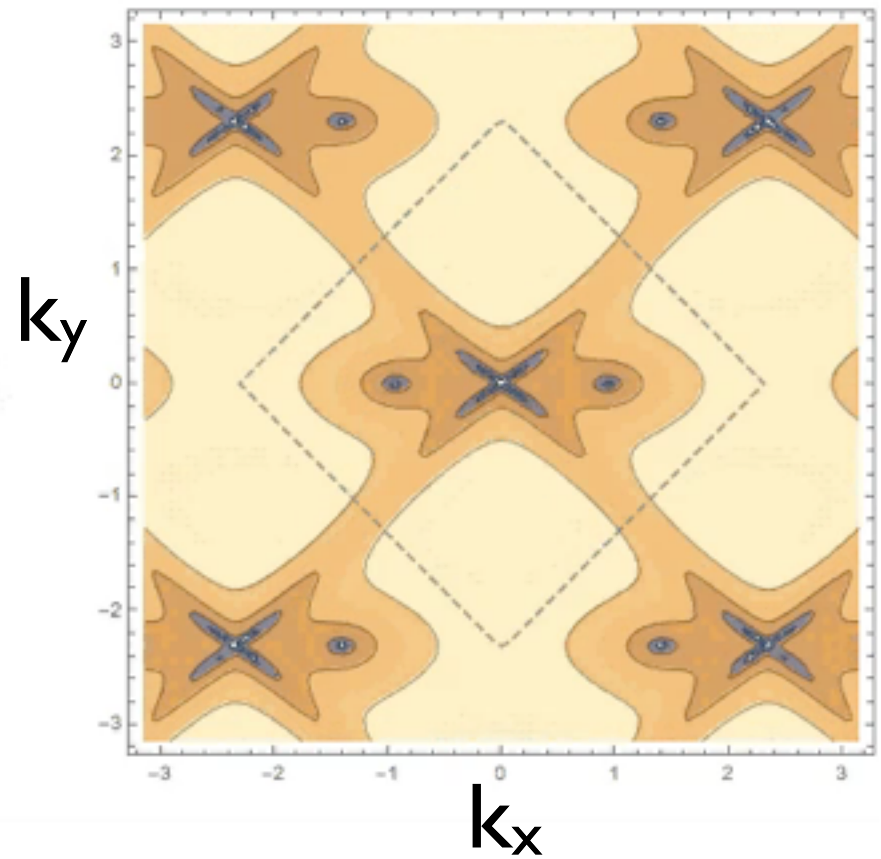

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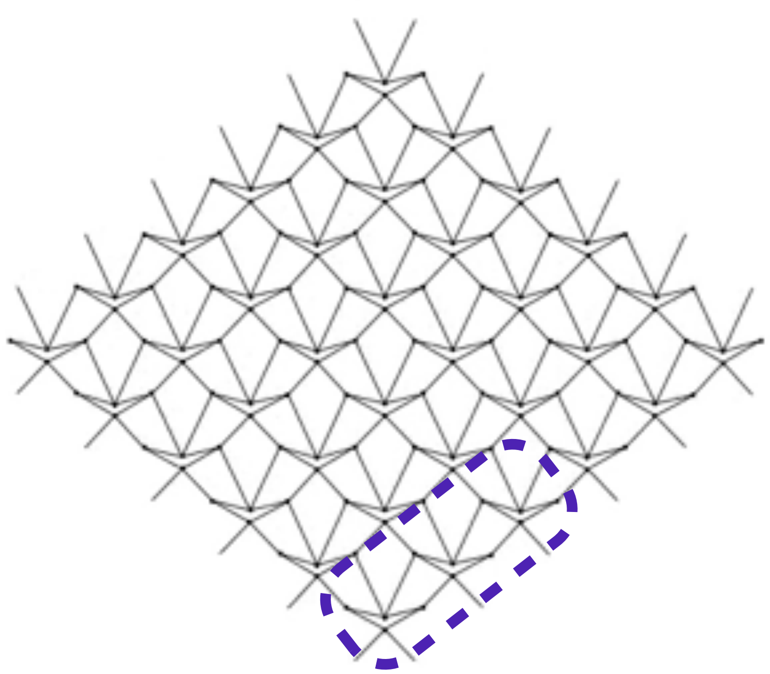

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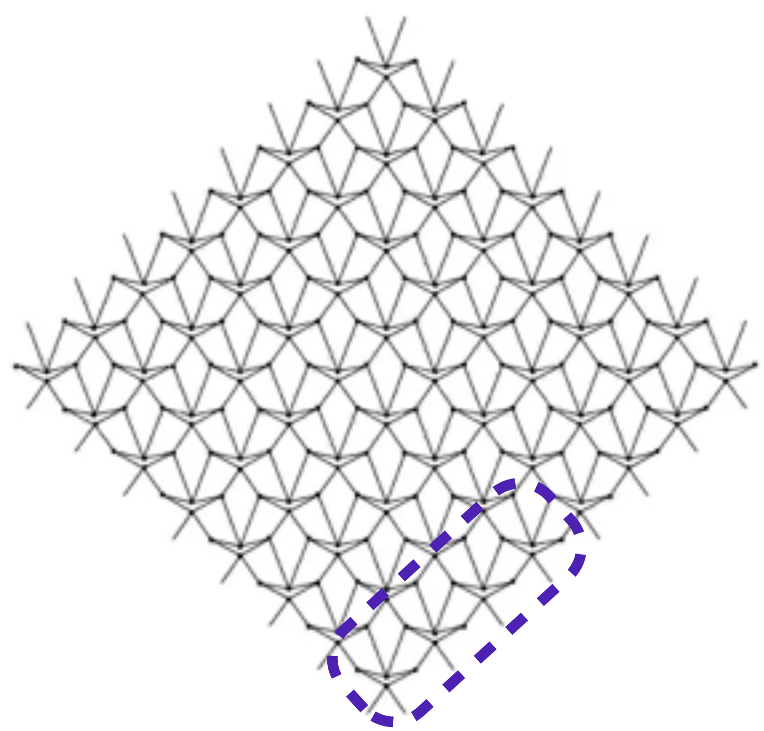

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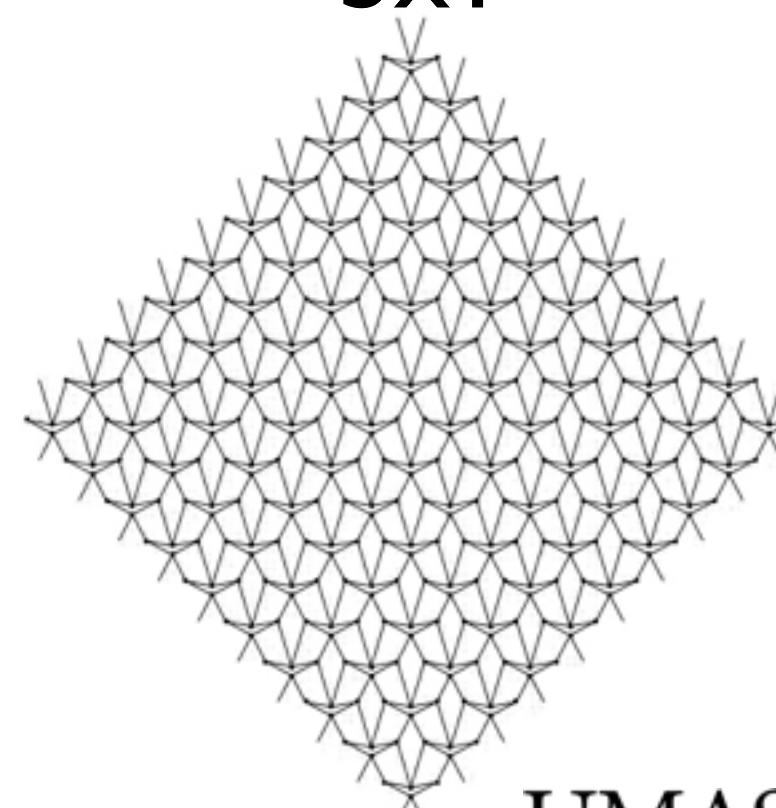

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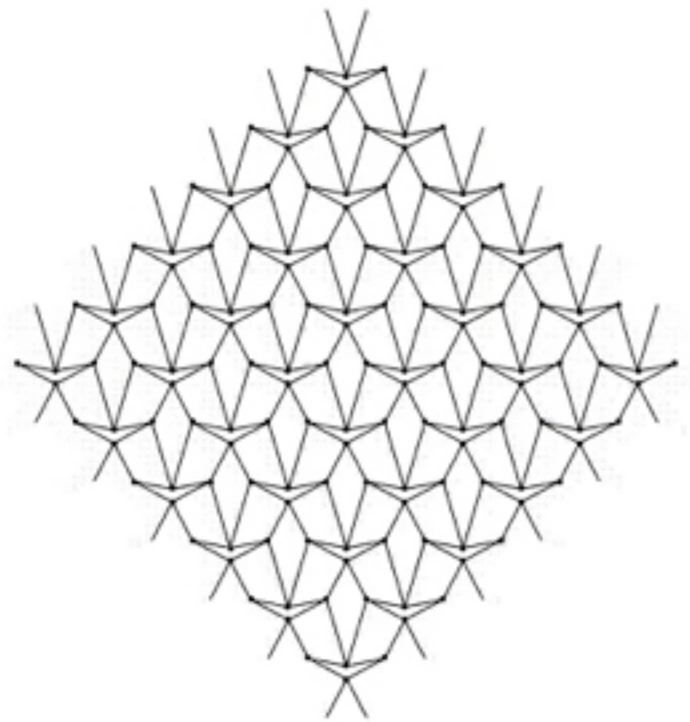

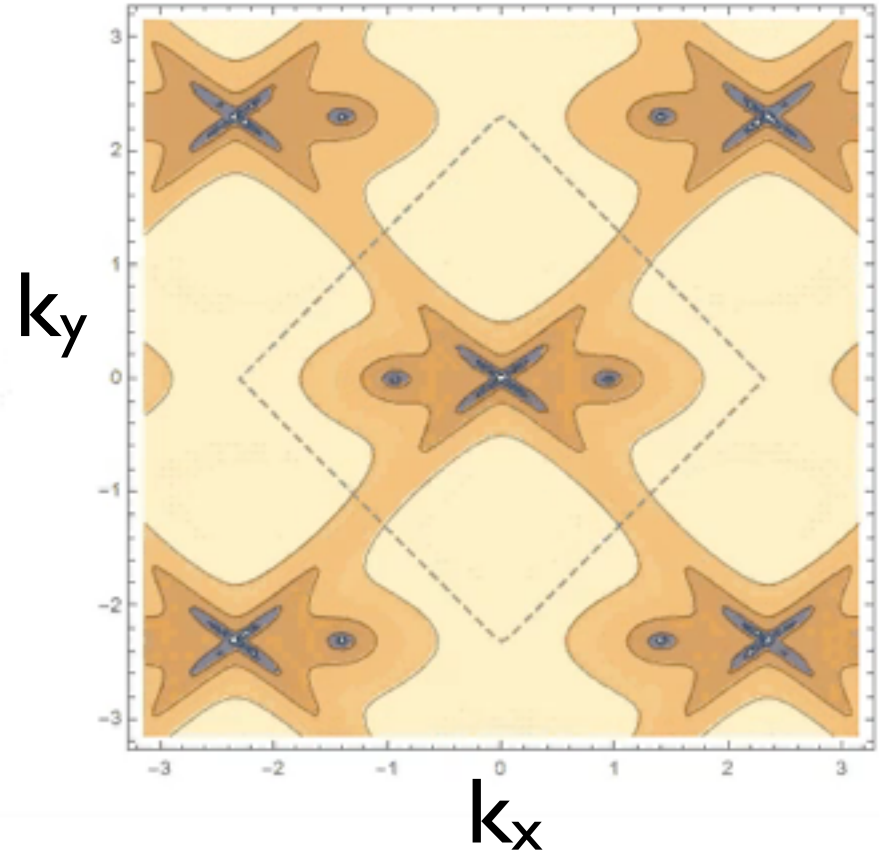

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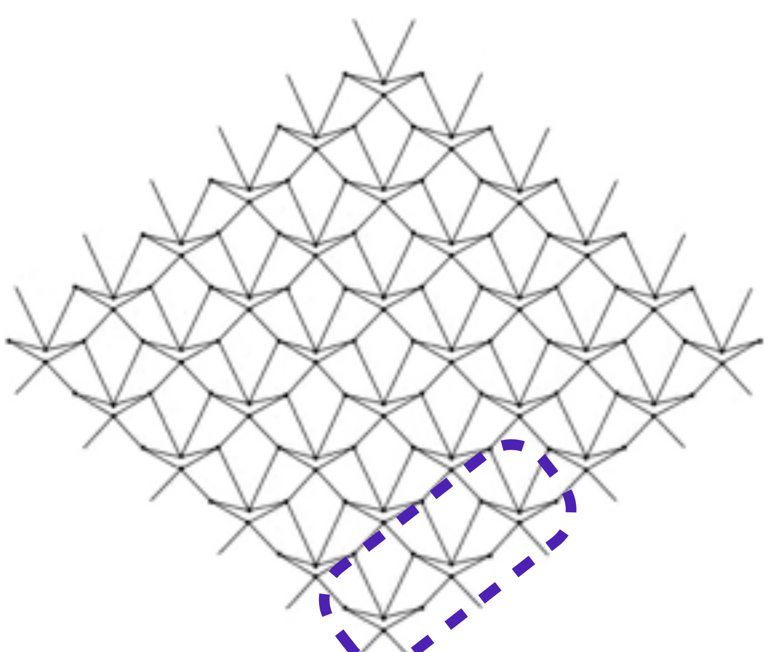

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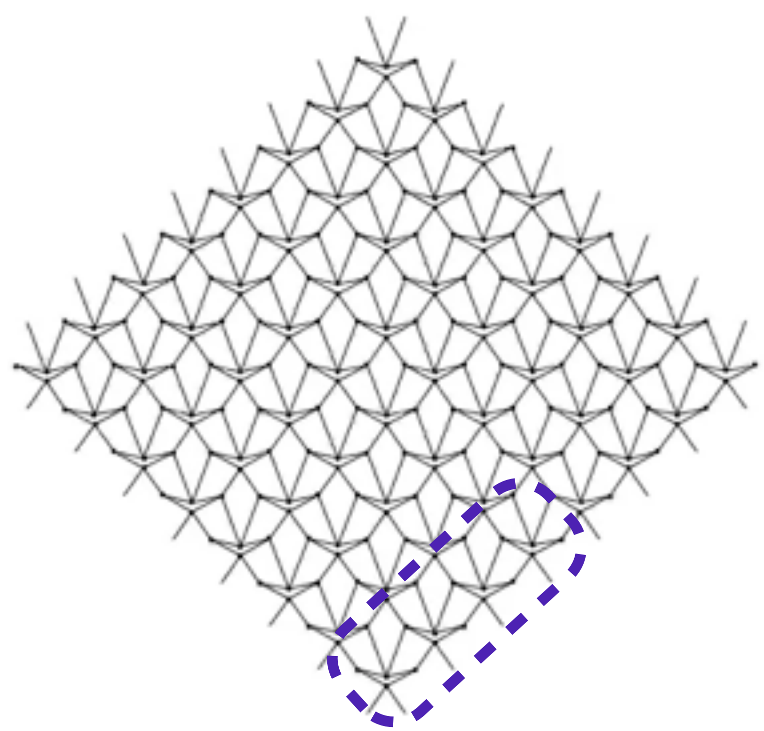

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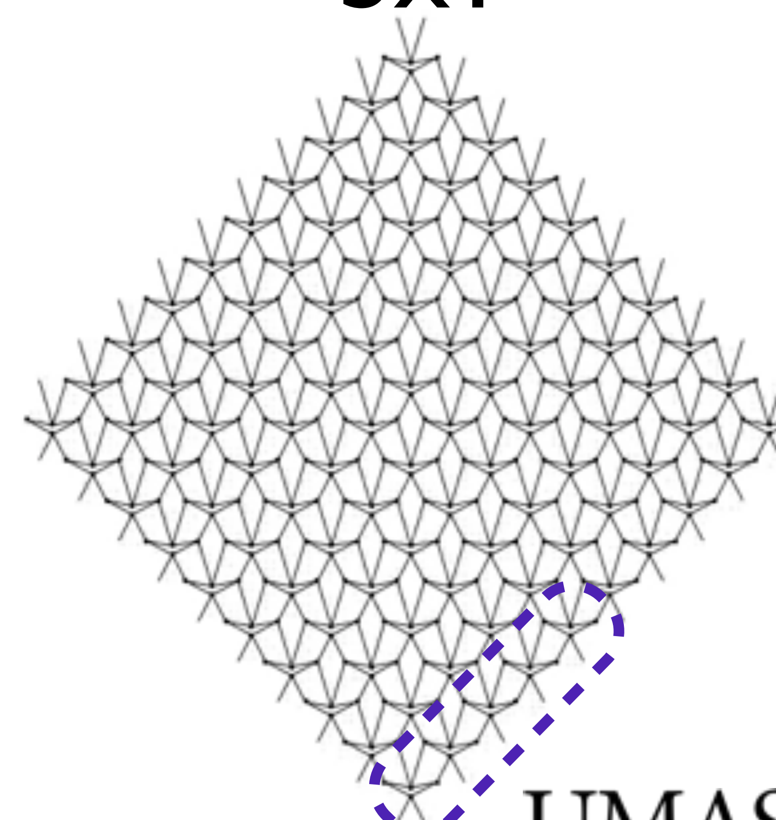

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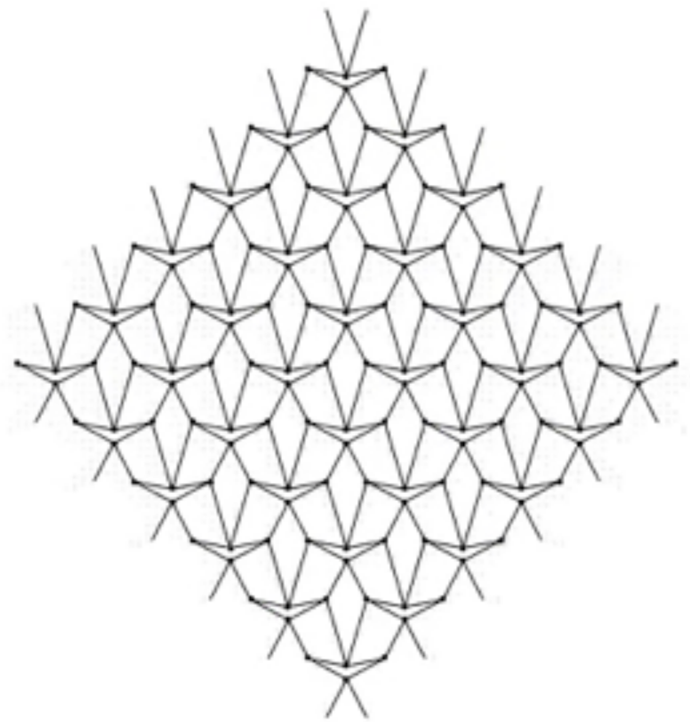
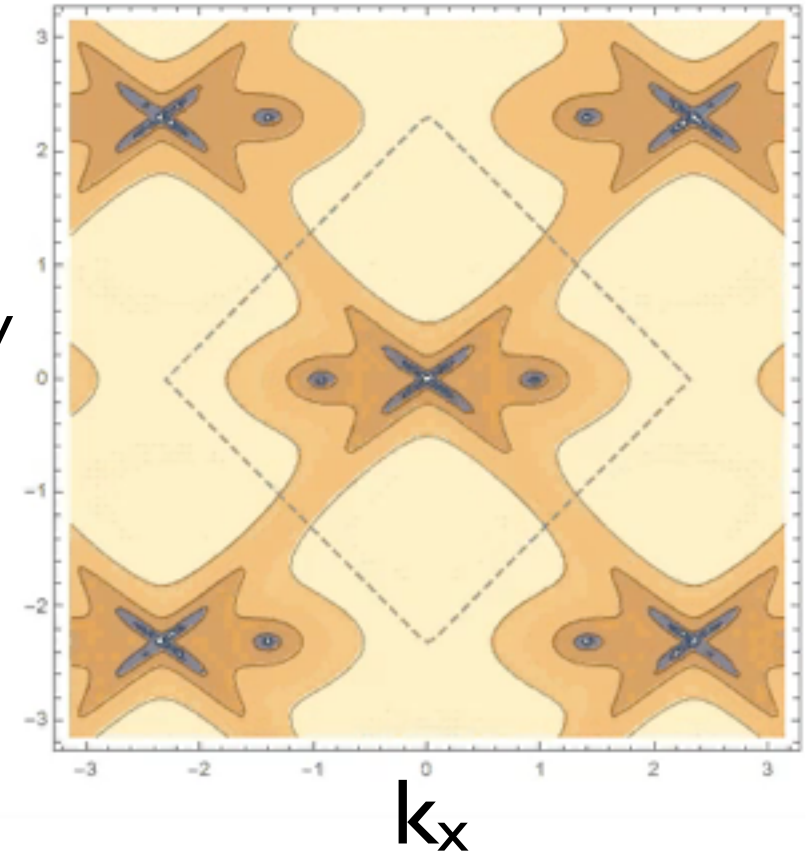
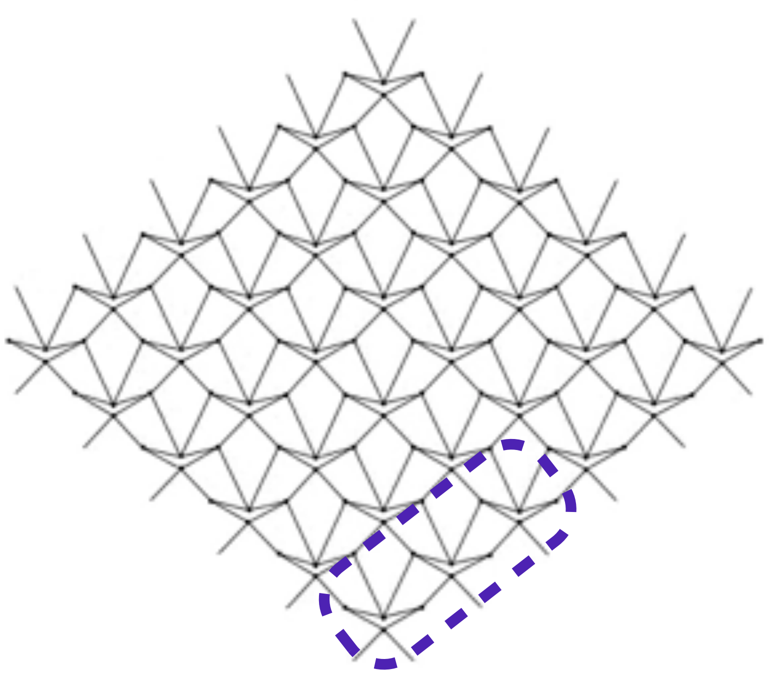
Tuning supercell size by flexing

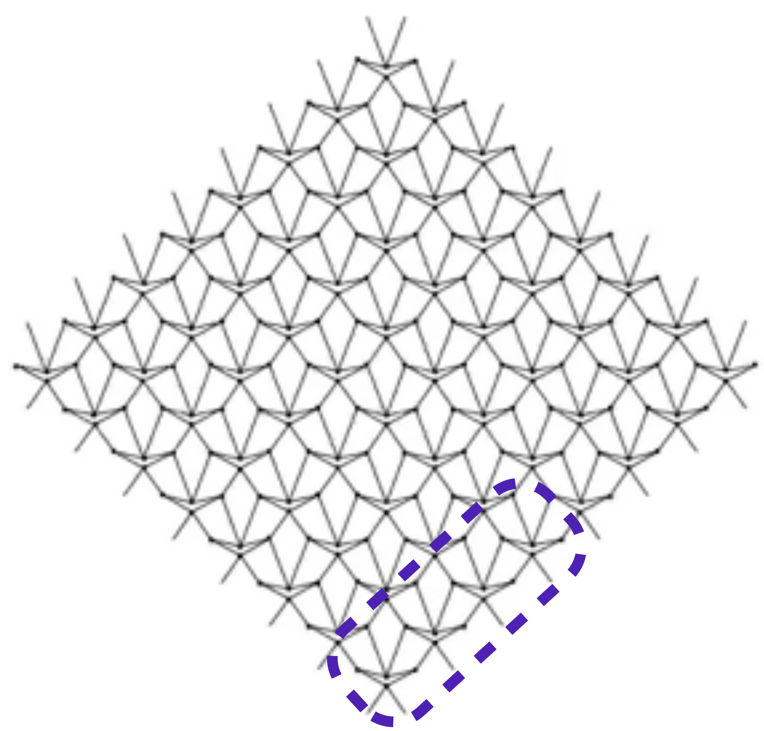




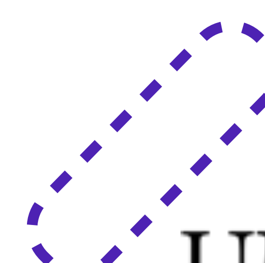
3x1



4x1



5x1



Rocklin, Zhou, Sun, Mao. arXiv:1510.06389

BGC, Rocklin, Falk, Vitelli, Lubensky. In preparation.

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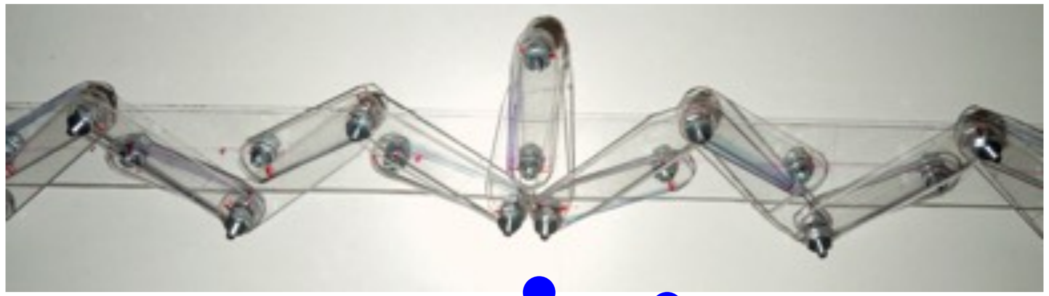
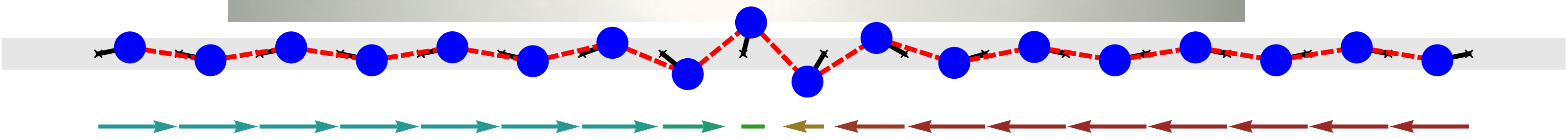
In a **topological mechanical insulator,**

energy may be transported by a **soliton**:

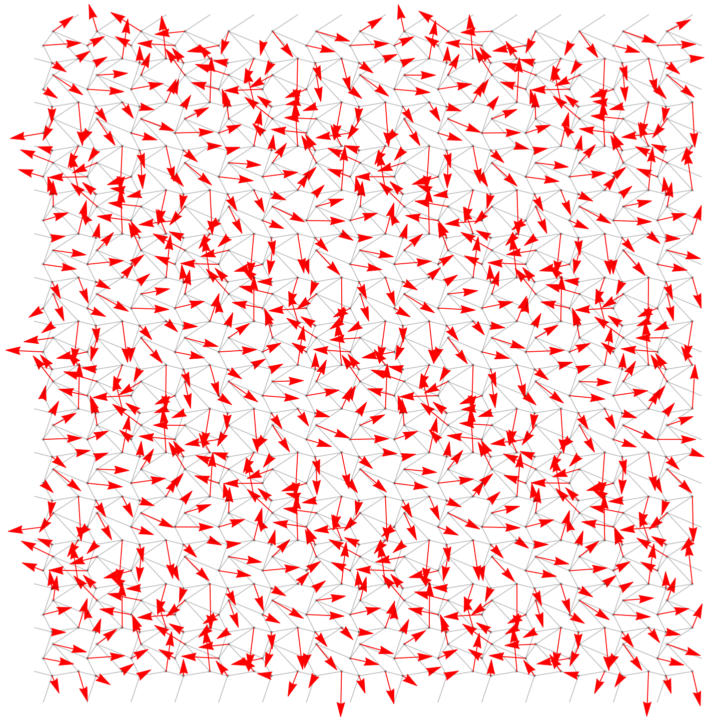




Thanks!

Tien-syh Chen
Jayson Paulose
Jeffrey Teo
Ari Turner
Yujie Zhou

There are **topologically protected** bulk zero modes in generic isostatic lattices:



Chen, Upadhyaya, Vitelli, PNAS 111, 13004 (2014)

Rocklin, Chen, Falk, Vitelli, Lubensky, arXiv:1510.04970

"Vitelli Lab" youtube

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