Topological Materials, Strongly Correlated Systems, and Quantum Information

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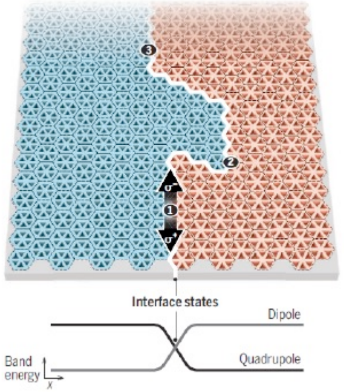
Texas Tech University

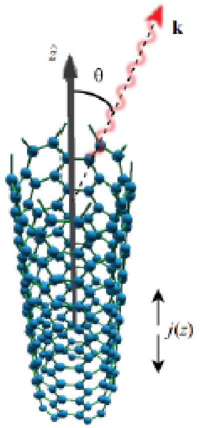
<u>Department Colloquium</u>

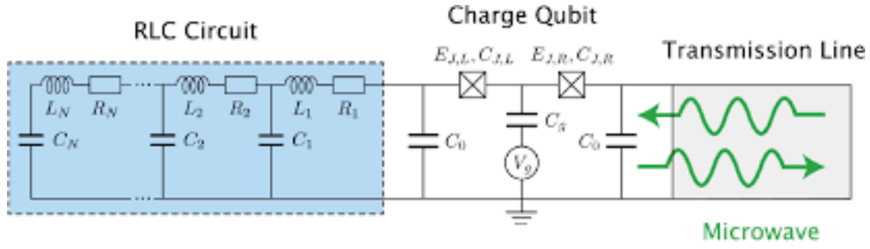
August 24, 2020

Outline

- Topological Phases of Matter
  - Majorana Fermions
  - Topological Quantum Computation
  - Engineered Topological Systems
- Quantum Liquids in Low-Dimensions
  - Luttinger Liquids
  - Hydrodynamics of 1D Liquids and Gases of Fermions
  - 1D Quantum Liquids Coupled to Light
- Superconducting Circuits
  - Brief discussion of examples of possible future work
  - Long-term Outlook
  - Conclusions







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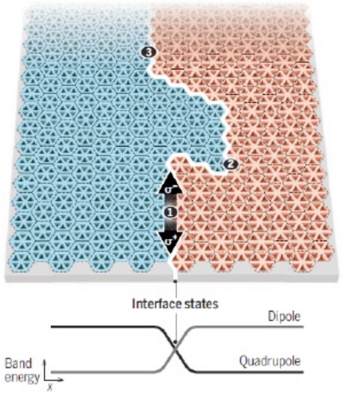
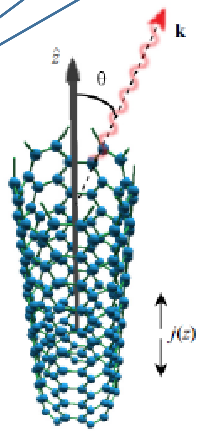
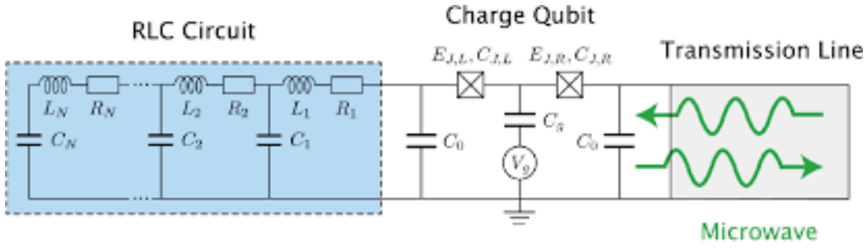


Three Areas of Research





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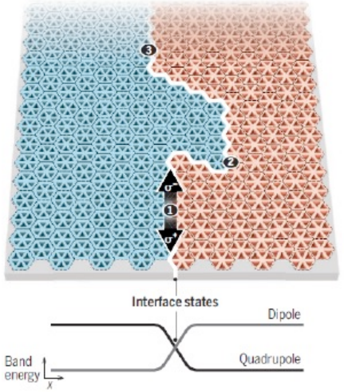
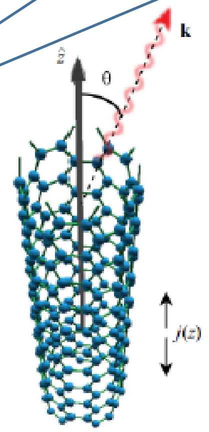
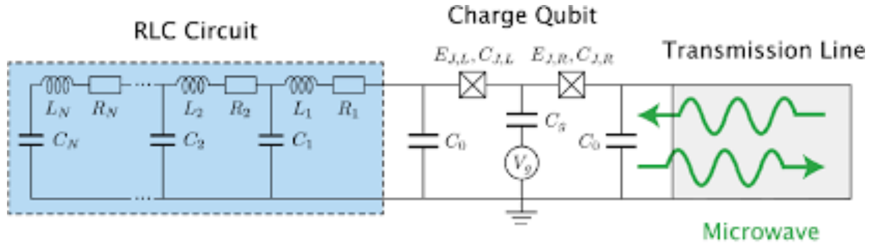


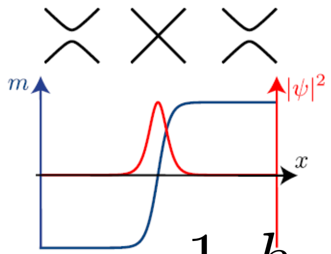
Major Themes: Quantum Information, Non-Fermi liquids, Engineered Systems, Topological Order, Exotic Quasiparticles





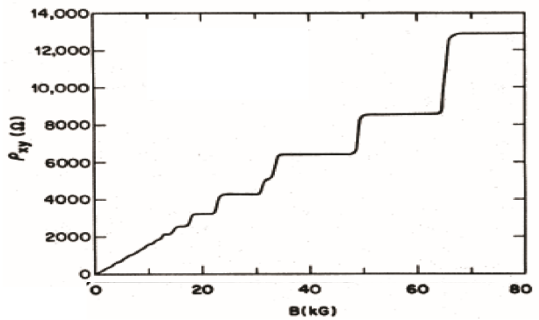
Topological Systems and **Protected Edge States**

- Su-Schrieffer-Heeger Model

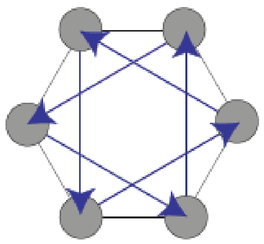


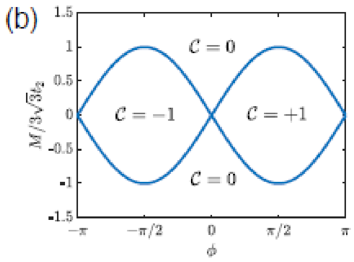
- Integer Quantum Hall Effect

$$\rho_H = \frac{1}{n}\frac{h}{e^2}$$

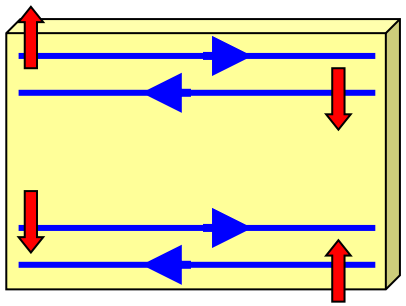


- Haldane Model





- Quantum Spin Hall



Klitzing et. al., *PRL*, 45, 1980
Tsui et. al., *APL*, 38, 1981
TKNN, PRL **49**, 405-408 (1982).
C. L. Kane and E. J. Mele
Phys. Rev. Lett. **95**, 226801 – Published 23 November 2005
F.D.M. Haldane Physical Review Letters, Volume 61, Number 18, Oct 31, 1988

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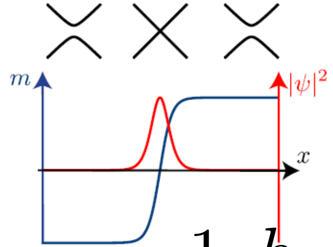

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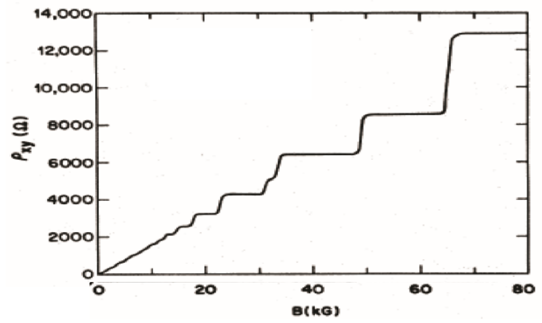

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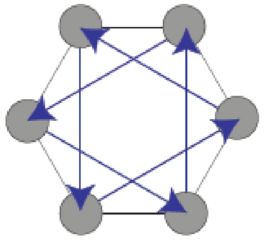

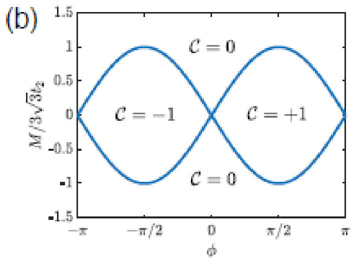

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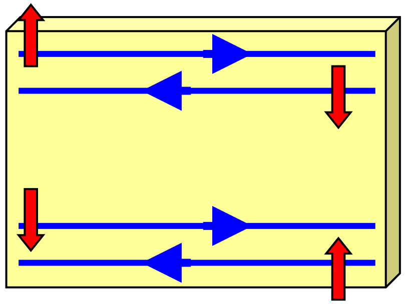

Area 1

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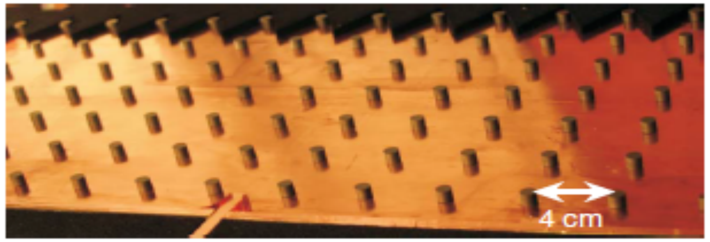
Challenges

- Examples of topological insulators in condensed matter are select. They must be *discovered.*

- Fermi level in topological insulators is very difficult to tune.

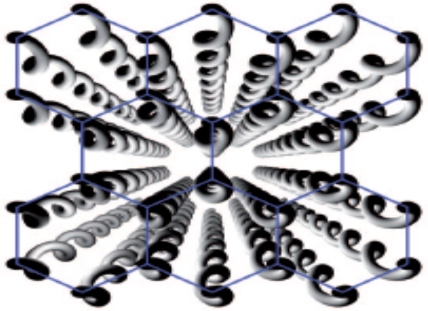
Engineered Topological Systems

Real magnetic field



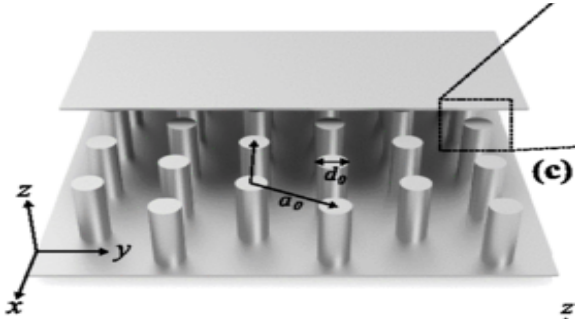
Wang et. al., *Nature*, (2009)

Floquet system

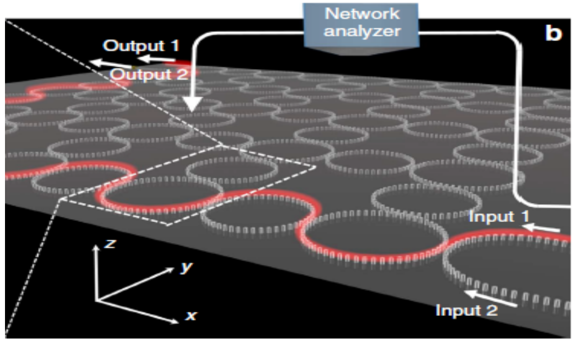


M.C. Rechtsman, et. al., Nature (2013)

Metamaterials: SO Coupling



Plasmonics



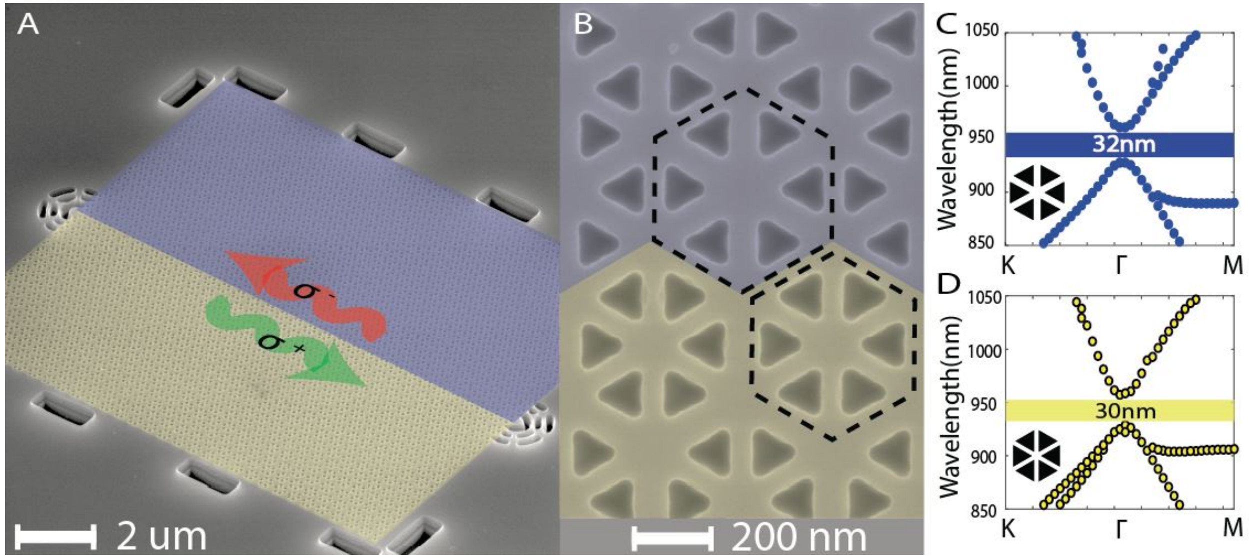
G. Jiang, Y. Chong, PRL (2013)

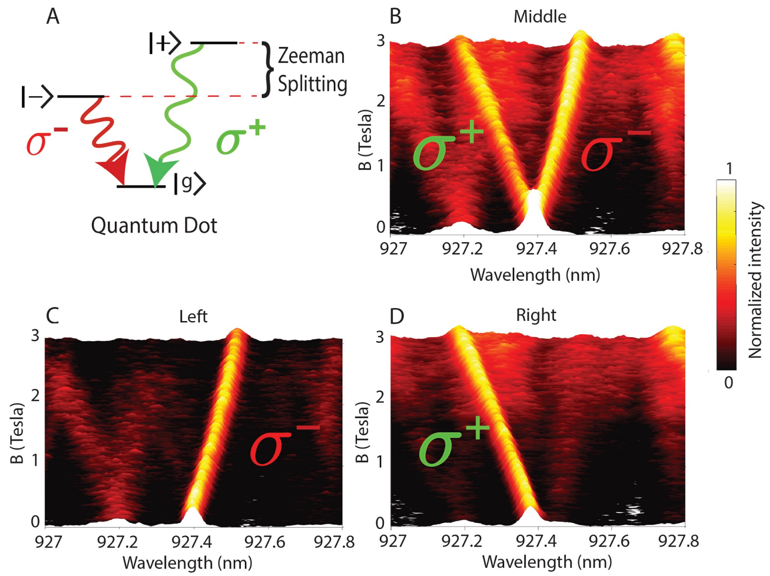
- Wang et. al., *Nature*, (2009)
- YE Kraus, et. al., Physical Review Letters, (2012)
- K Fang, Z Yu, S Fan, Nature Photonics (2012)
- A. Khanikaev, et. al., Nature Materials (2013)
- M.C. Rechtsman, et. al., Nature (2013)
- G. Jiang, Y. Chong, Physical Review Letters (2013)
- L. D. Tzuang, et. al., Nature Photonics (2014)
- L. Lu, et. al., Nature Photonics (2014)
- W. J. Chen, et. al., Nature Comm. (2014)
- Y. Plotnik, et. al., Nature Materials (2014)
- J. Ningyuan, et. al., Phys. Rev. X (2015)

A Topological Photonic Crystal

- Synthesizes spin-orbit interaction in photonic crystals

- Topological States are protected by a crystalline *rotational* symmetry.





L. Wu and X. Hu, PRL **114**, 223901 (2015).

S. Barik, H. Miyake, **WD**, E. Waks, M. Hafezi, NJP **18** 113013 (2016).

S. Barik, A. Karasahin, C. Flower, T. Cai, H. Miyake, **WD,** E. Waks, M. Hafezi, Science **359** 666-668 (2018).

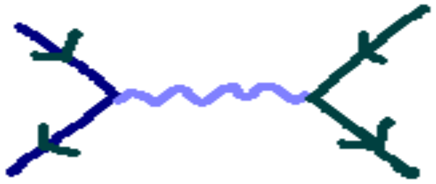
Landau's Fermi Liquid Theory

- Landau's Fermi liquid theory explains a deep mystery:

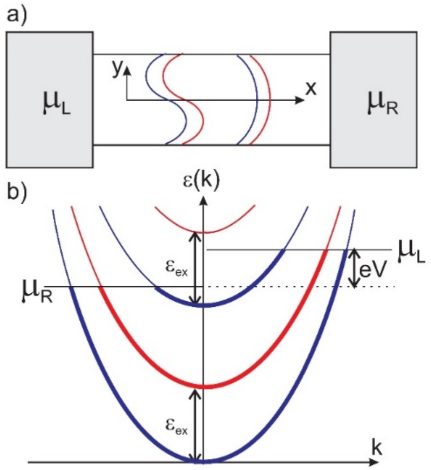
Why is the independent electron approximation so successful in describing metals?

- Landau's theory is deep, but rests on the concepts of adiabaticity and *quasiparticles.*

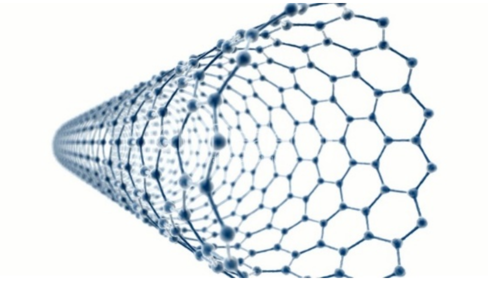
- Dimensionality plays a crucial role in Fermi liquid theory. A natural place to look for exotic behavior is in low-dimensional systems.

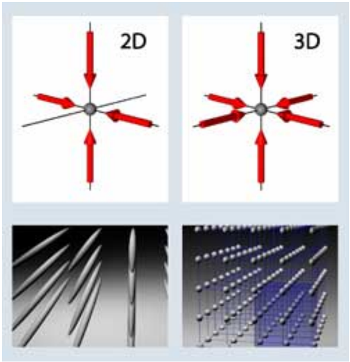


1D Quantum Systems



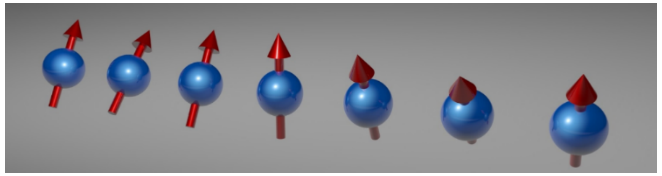
quantum wires


carbon nanotubes



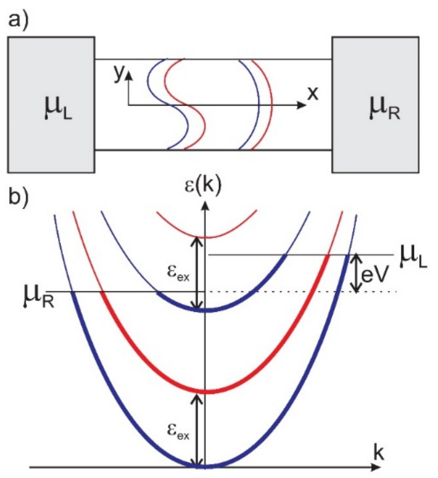
cold atomic systems


Neutron star crusts?

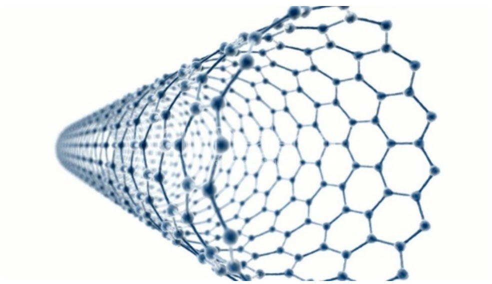

spin chains

Area 2

1D Quantum Systems



quantum wires



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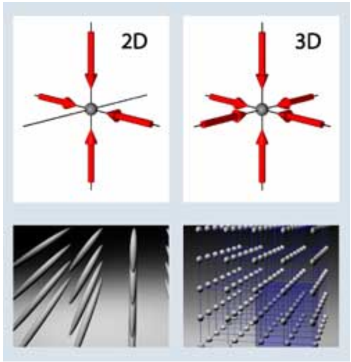

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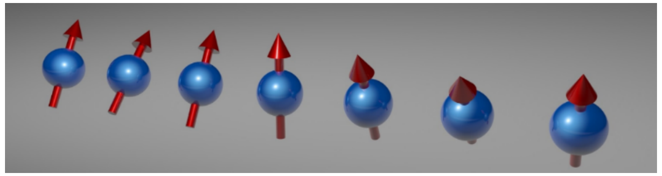
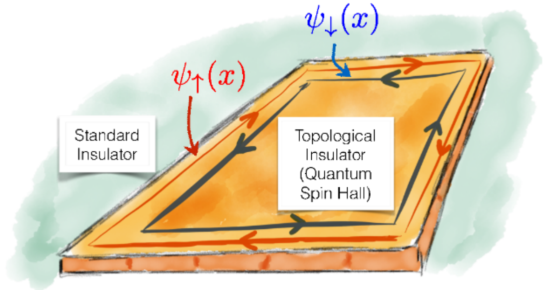
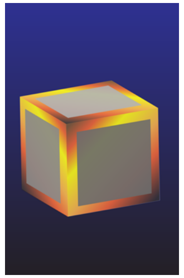


spin chains



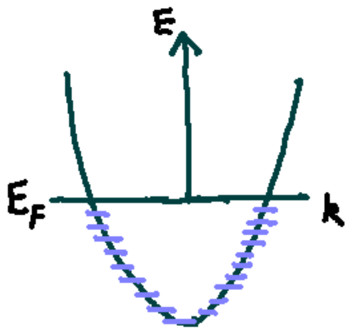
Topological edge states

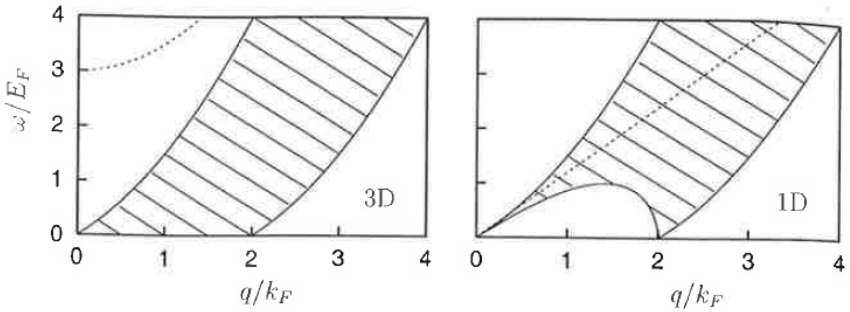


Higher order TI edge states

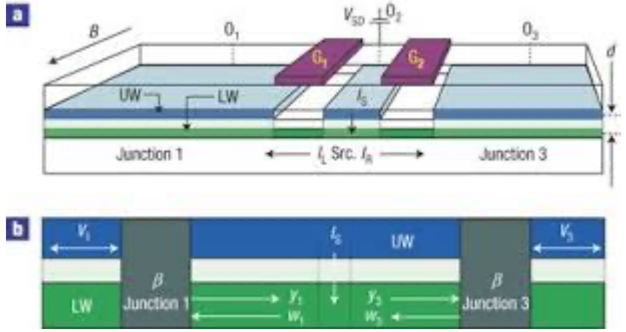
Non-Fermi Liquid Behavior in 1D

- All excitations in 1D are collective.



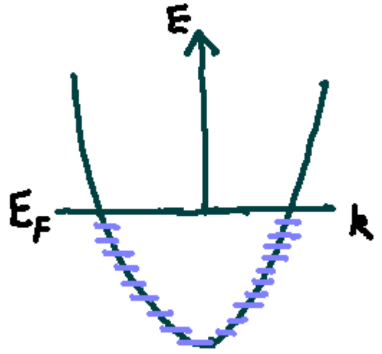


- This leads to dramatic phenomena, such as **charge fractionalization** and **spin-charge separation**.

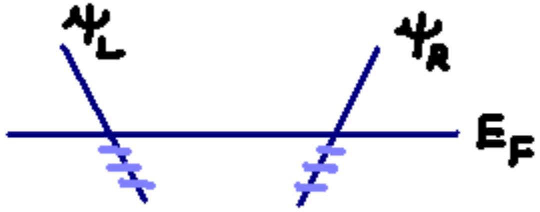


Steinberg, H., Barak, G., Yacoby, A. *et al.* Charge fractionalization in quantum wires. *Nature Phys* **4,** 116–119 (2008) doi:10.1038/nphys810

Tomonaga-Luttinger Liquid



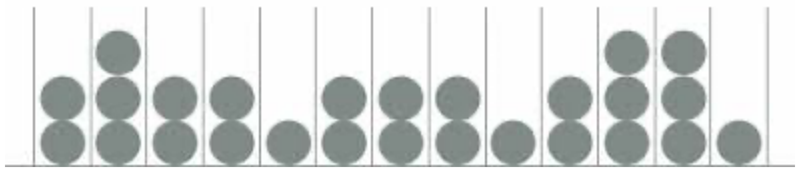
- The Tomonaga-Luttinger liquid is an exactly solvable model of 1D fermions with density-density interactions.



- Remarkably, this model can be mapped onto a system of free bosons.

$$H_0 = \frac{hv}{2\pi} \int dx \left[K \left(\nabla\theta\right)^2 + K^{-1} \left(\nabla\phi\right)^2 \right]$$

$$H = \sum_p \varepsilon_p b_p^\dagger b_p + \frac{\pi\hbar}{2L} \left[v_N \left(N - N_0\right)^2 + v_J J^2 \right]$$



T. Giamarchi, *Quantum Physics in One Dimension*, 2004.

Challenges

- Luttinger liquid behavior can be difficult to identify experimentally.
- For transport measurements, subtle effects can be swamped by Fermi liquid leads.
- New probes of these systems would greatly enhance our understanding of their properties.

see e.g., Maslov and Stone, PRB **52**, R55349(R) (1995)

Non-Linear Luttinger Liquids

- Non-linear Luttinger liquid behavior is actively studied.

- Understanding non-equilibrium behavior requires accounting for the finite lifetime of a system's quasiparticles.

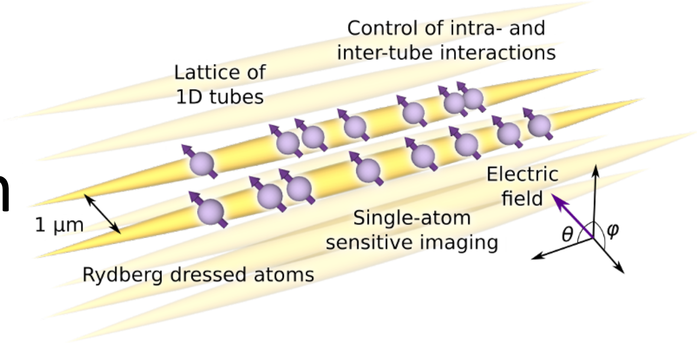
- Extended bosonization accounts for the density dependence of the Luttinger parameters *v* and *K.*

$$H_\alpha = \int dx \left[\alpha_\theta \left(\nabla\phi\right)\left(\nabla\theta\right)^2 + \alpha_\phi \left(\nabla\phi\right)^3\right] \qquad \alpha_\phi = \frac{\hbar}{6\pi^2}\partial_n\left(\frac{v}{K}\right) \qquad \alpha_\theta = \frac{\hbar}{2\pi^2}\partial_n\left(vK\right)$$

- These terms are *irrelevant* (in the RG sense), and thus describe small effects at low energies.

Imambekov, Schmidt, and Glazman Rev. Mod. Phys. (2012).

Hydrodynamics of 1D Quantum Liquids and Gases



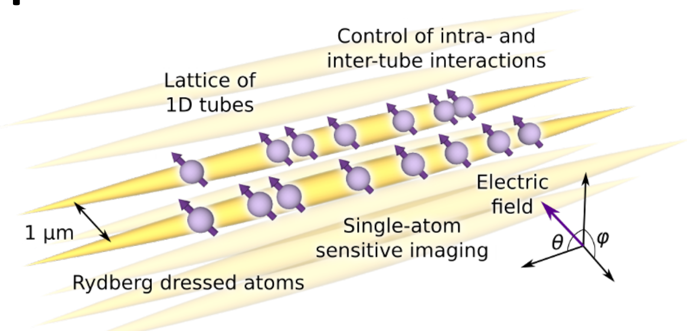
Exotic Quantum Matter Group, Heidelberg

- The application of hydrodynamics to degenerate quantum liquids and gases has been an active area of current research.

WD and Matveev, PRL **114**, 236405 (2015).
WD and Matveev, PRB **97**, 045135 (2018).
WD and Matveev, PRB **99**, 245121 (2019).
WD and Matveev, PRL **125**, 076601 (2020).

K. A. Matveev
Argonne

Hydrodynamics of 1D Quantum Liquids and Gases



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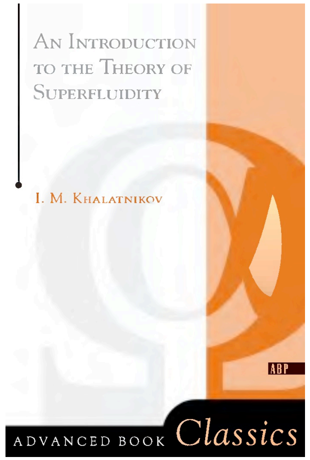
- The application of hydrodynamics to degenerate quantum liquids and gases has been an active area of current research.
- Recent work investigates the emergence of **two-fluid hydrodynamics** in such systems.

$$R = \zeta_2 (\mathrm{div}\, \mathbf{v}_n)^2 + \zeta_3 (\mathrm{div}(\mathbf{j} - \rho \mathbf{v}_n))^2 + 2\zeta_1\, \mathrm{div}\, \mathbf{v}_n\, \mathrm{div}(\mathbf{j} - \rho \mathbf{v}_n)$$
$$+ \frac{1}{2}\eta \left(\frac{\partial v_{ni}}{\partial r_k} + \frac{\partial v_{nk}}{\partial r_i} - \frac{2}{3}\delta_{ik} \frac{\partial v_{n\ell}}{\partial r_\ell} \right)^2 + \kappa \frac{(\nabla T)^2}{T} \qquad (9\text{-}17)$$



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WD and Matveev, PRB **97**, 045135 (2018).
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WD and Matveev, PRL 125, 076601 (2020).

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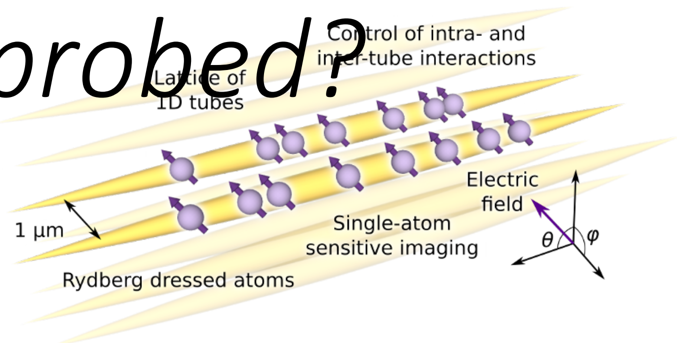
How can the (putative) two-fluid hydrodynamics of 1D systems be probed?



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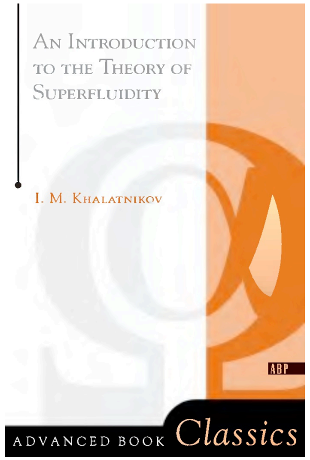

$$R = \zeta_2 (\mathrm{div}\, \mathbf{v}_n)^2 + \zeta_3 (\mathrm{div}(\mathbf{j} - \rho \mathbf{v}_n))^2 + 2\zeta_1\, \mathrm{div}\, \mathbf{v}_n\, \mathrm{div}(\mathbf{j} - \rho \mathbf{v}_n) + \frac{1}{2}\eta \left(\frac{\partial v_{ni}}{\partial r_k} + \frac{\partial v_{nk}}{\partial r_i} - \frac{2}{3}\delta_{ik} \frac{\partial v_{n\ell}}{\partial r_\ell} \right)^2 + \kappa \frac{(\nabla T)^2}{T} \qquad (9\text{-}17)$$

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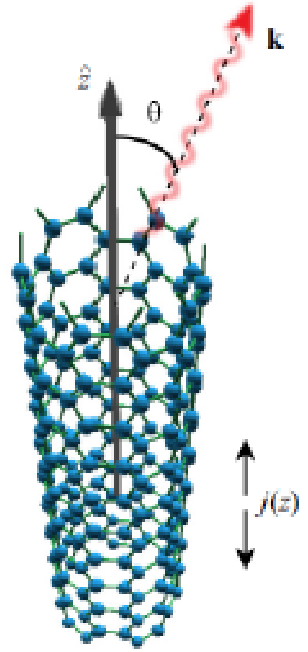
Thermal Radiation as a Probe of non-linear Luttinger Physics

$$H_{\rm int} = -\frac{e}{c}\int d\mathbf{r}\; \mathbf{j}(\mathbf{r}t)\cdot \mathbf{A}_{\rm rad}(\mathbf{r}t)$$

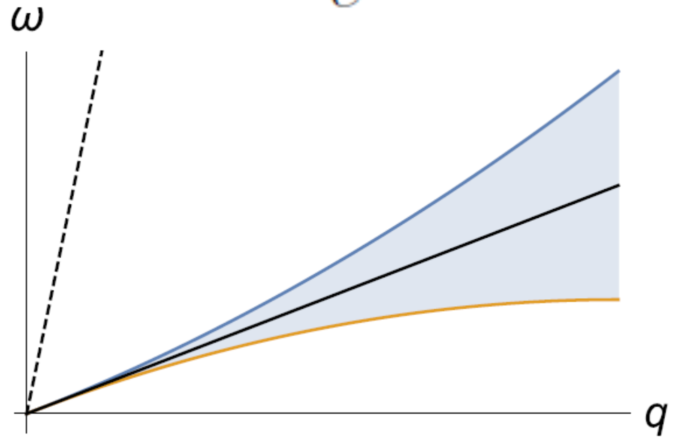


- The emission of a photon removes both energy and momentum from the system.

- Thermal spectrum depends on the imaginary part of the (current) spectral function.

$$k_\omega = \frac{\omega}{c}\cos\theta$$

$$\frac{1}{L}\frac{d^2P}{d\omega\, d\Omega} = \frac{\alpha\hbar\omega^2}{2\pi^2c^2}\frac{\chi''(k_\omega,\omega)}{e^{\beta\hbar\omega}-1}\sin^2\theta$$



WD, Gullans, Hegde, Vishveshwara, Hafezi PRB **99**, 235124 (2019)
Kim, Yan, Suess, Murphy, Furhrer, and Drew, PRL **110**, 247402 (2013)

Thermal Radiation from a 1D Quantum Liquid

- Dimensionality plays a crucial role in the form of black-body radiation.
- Reduced phase space and strong interactions play a crucial role in the physics of 1D systems.
- Could this radiation serve as a probe of 1D quantum liquids?
  - carbon nanotubes
  - matter in neutron stars

Smitha Vishveshwara
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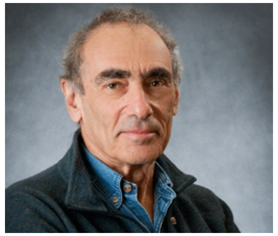

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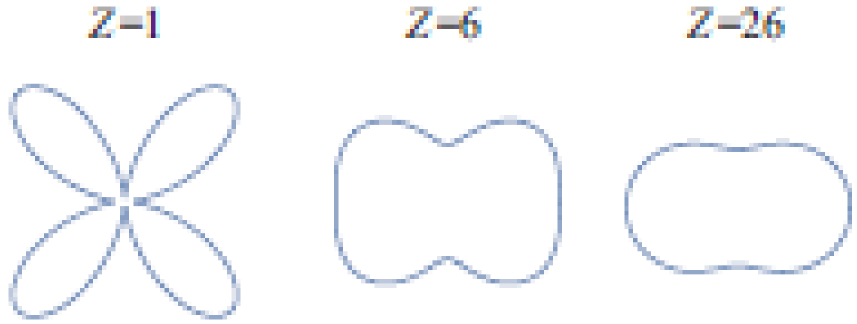
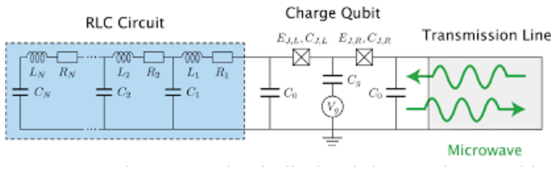
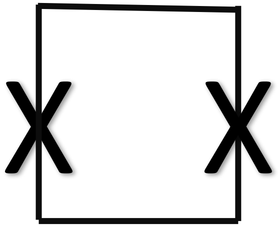


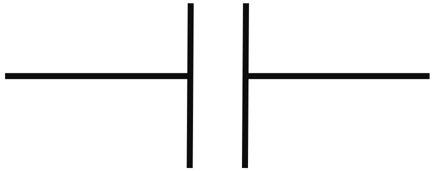
Intermediate *N* regime

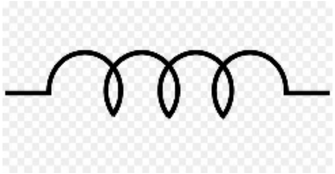
Number of circuit nodes



- Scalability of quantum architectures from 1 and a few capable qubits is a key step in realizing the next generation quantum computer.
- Unfortunately, the intermediate *N* regime is a no-man's land
  - Large Hilbert space size makes exact diagonalization impossible
  - No key principles for design and study of circuits

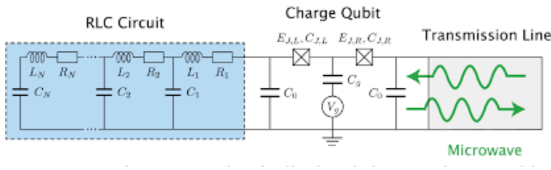






Intermediate *N* regime

Number of circuit nodes



- Scalability of quantum architectures from 1 and a few capable qubits is a key step in realizing the next generation quantum computer.
- Unfortunately, the intermediate *N* regime is a no-man's land
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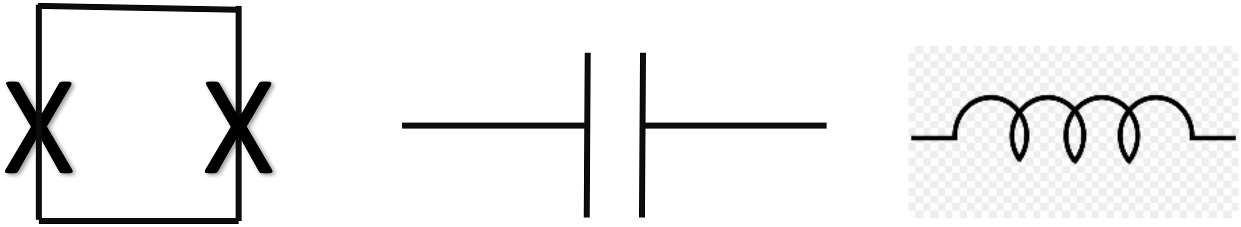
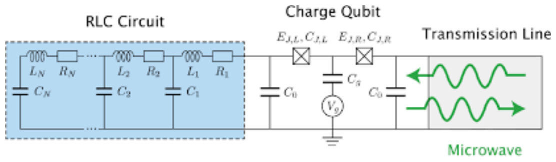
Area 3



Proposed Work: Applying Many-Body Techniques intermediate size circuits

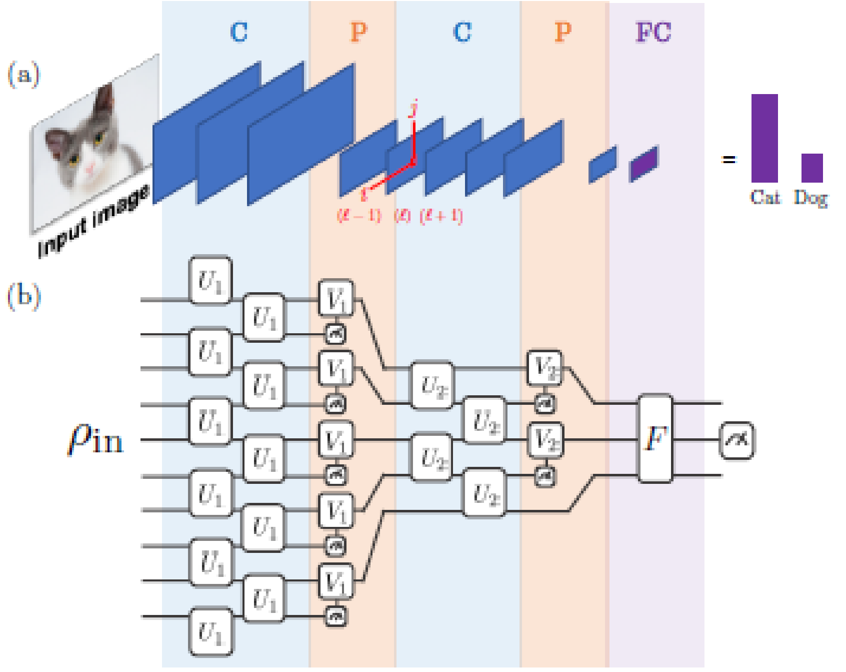


- Previous work investigated leveraging tight-binding “technology” to the study of circuits with Josephson junctions.
- Can many-body techniques, such as the real-space renormalization group methods be used to make the study of circuits tractable?
- What are the lessons to be learned from error-correcting codes and other topological systems?
- Circuits can be mapped to Bose-Hubbard model. Are there techniques used for the study of this model that can be leveraged to circuits?

How Can Machine Learning Be Used to Identify Quantum Phases of Matter?

- *Quantum* Machine Learning protocols may be particularly well-suited to identify quantum phases of matter.
- One application we are investigating is applying these protocols to identify topological phases of matter.
- Applying this to real data from a quantum

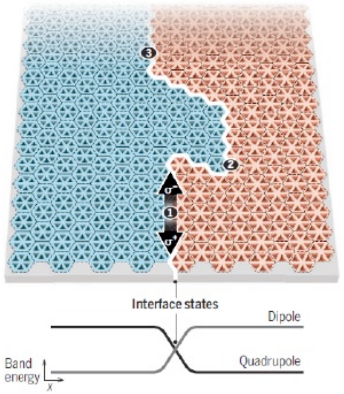
system is a goal.

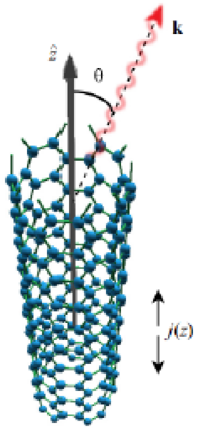


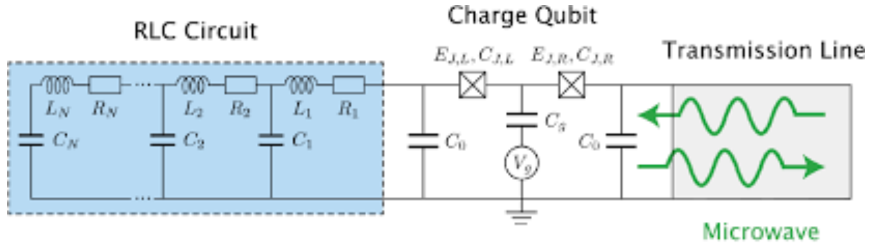
Cong, Choi, and Lukin, *Nat. Phys.* **15**, 1273-1278 (2019)

Outline

- Topological Phases of Matter
  - Majorana Fermions
  - Topological Quantum Computation
  - Engineered Topological Systems
- Quantum Liquids in Low-Dimensions
  - Luttinger Liquids
  - Hydrodynamics of 1D Liquids and Gases of Fermions
  - 1D Quantum Liquids Coupled to Light
- Superconducting Circuits
  - Brief discussion of examples of possible future work
  - Long-term Outlook
  - Conclusions







Overview of Research Efforts

Research Areas

- Area 1: Topological Systems
  - Topological Insulators
  - Topological Superconductors
  - Quantum (spin) Hall Liquids
  - Chiral Majorana Liquids
- Area 2: Quantum Liquids in (primarily) 1D
  - Tomonaga-Luttinger liquid phenomenology
  - Non-Linear Luttinger liquids
  - Out-of-Equilibrium Behavior
- Area 3: Superconducting Circuits
  - Needed: Protected Qubits
  - New Metrics
  - New Tools

Key Skills

- Topological Systems
  - Majorana Fermions
  - Conformal Field Theory
  - Topological Field Theory
- Quantum Liquids
  - Quantum Field Theory
  - Fermi Liquid Theory
  - Luttinger Liquid Theory
- Quantum Information
  - Superconducting Circuit Design
  - Quantum Information and Computation
  - *QuTip*

Collaborators

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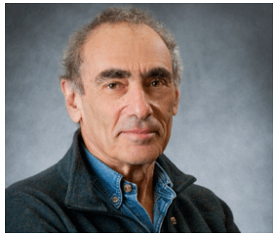

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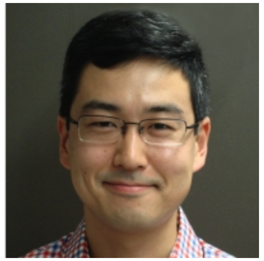

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Thank you!

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