Yale Quantum Institute

Office of Naval Research · ONR · Science & Technology

MAJORANA FERMIONS & BEYOND

An ONR Sponsored Workshop

October 26-28, 2017

ORGANIZED BY:
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Program at a glance

The three-day program will focus on the recent experimental and theoretical advances in mesoscopic physics of topological materials and devices.

THURSDAY

9:00 am - Registration & light breakfast

9:30 am - Welcome to the Yale Quantum Institute by Rob Schoelkopf

9:40 am - Welcome and opening remarks by Michel Devoret & Leonid Glazman

9:45 am - 12:30 pm - **Session 1 - Electron transport in proximitized nanostructures** (page 5)

12:30 pm - Lunch

2:00 pm - 4:45 pm - **Session 2 - Advanced semiconductor heterostructures** (page 6)

5:00 pm - Guided tour of the Becton laboratories (page 7)

7:00 pm - Workshop dinner at ROIA (page 7)

FRIDAY

9:00 am - 12:30 pm - **Session 3 - Josephson junctions spectroscopy and quasiparticles** (page 7)

12:30 pm - Lunch

2:00 pm - 4:45 pm - **Session 4 - Local probes of topological states** (page 8)

5:30 pm - Poster session (page 9)

7:00 pm - Dinner on your own (restaurants, bars and entertainment suggestions page 11)

SATURDAY

9:00 am - Light breakfast

9:30 am - 11:00 am - **Session 5 - New topological materials** (page 10)

11:00 am - Final remarks and workshop closing

YQI

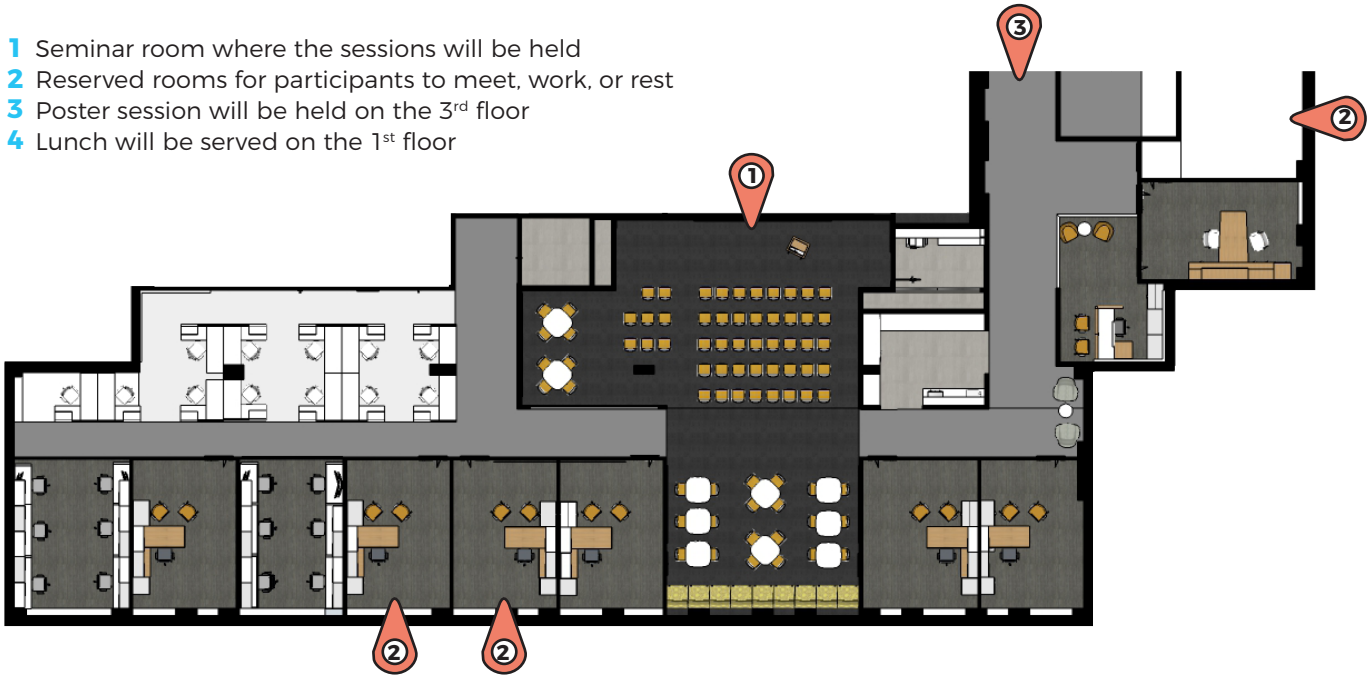
SOCIAL MEDIA

Follow @Yale_QI on Twitter and continue the conversation online with **#YQIMAJORANA**

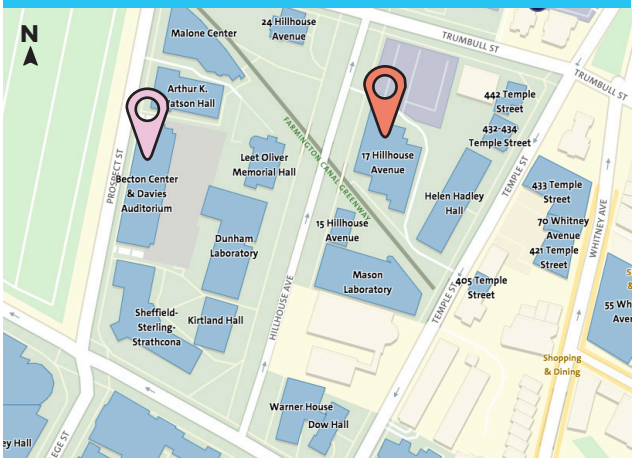
Workshop Area

The Majorana Fermions & Beyond is hosted at the Yale Quantum Institute, which facilitates research and teaching of quantum science on the Yale campus, and performs outreach in the form of seminars, workshops, and hosting of world leading scientists from around the world. Located on the 4th floor of 17 Hillhouse avenue, the institute is ideally located on Science Hill, at walking distance of Old Campus and Downtown.

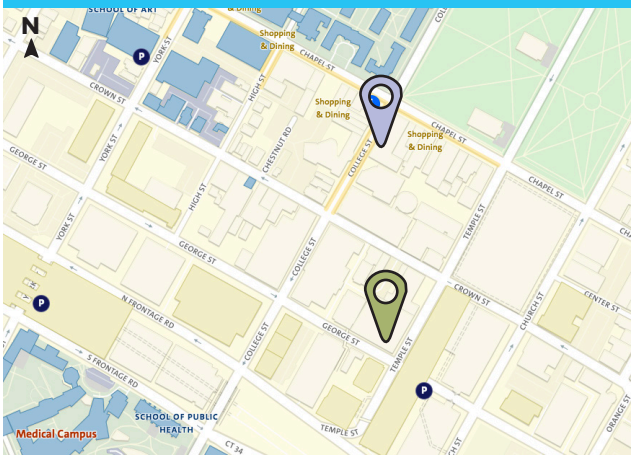
1 Seminar room where the sessions will be held
2 Reserved rooms for participants to meet, work, or rest
3 Poster session will be held on the 3rd floor
4 Lunch will be served on the 1st floor



SCIENCE HILL



DOWNTOWN



Yale Quantum Insitute
Becton Laboratories
New Haven Hotel
Roìa Restaurant

Sessions Schedule

26 **THURSDAY**
OCTOBER, 2017
9:45 am - 12:30 pm

YQI Seminar Room , 17 Hillhouse Ave.
4th Floor

NICHOLAS READ
Yale Quantum Institute

ELECTRON TRANSPORT IN PROXIMITIZED NANOSTRUCTURES

9:45 AM - KAM MOLER - STANFORD UNIVERSITY

Measurements of Current-Phase Relations

We use a scanning SQUID microscope to measure the current that flows around a ring in response to an applied magnetic flux. The strong agreement of theory and experiment in conventional metals and superconductors sets the stage to study the current-phase relation (CPR) in superconducting rings interrupted by a single Josephson junction. I will report on CPR measurements of gate-tuned InAs nanowires and other systems.

11:00 AM - JAY SAU - UNIVERSITY OF MARYLAND

Regular and Coulomb blockaded transport signatures of Andreev versus Majorana states

Following the original observations of zero bias conductance peak associated with Majorana zero modes(MZMs) in semiconductor nanowires, phenomenal improvements have been made in the quality of Majorana nanowire devices. As a result of this progress high quality/stable superconducting gaps, zero-bias peaks with conductances approaching quantization have been seen. I will review some of the simulations from the Maryland group to understand how these recent experiments fit into the Majorana as well as to other non-topological (Andreev bound states - ABSs)frameworks. In particular, I will discuss the complexity of distinguishing the Majorana signature in the presence of quantum dots, multiple channels and dissipation. I will then discuss some analysis of the teleportation-like transport signatures through Coulomb blockaded structures with the goal of distinguishing ABSs from MZMs.

11:45 AM - CHARLIE MARCUS - NIELS BOHR INSTITUTE COPENHAGEN

Majorana wires and next steps toward topological quantum devices

This talk will briefly review the experimental status and evidence for Majorana modes in semiconductor-superconductor nanowire systems, then discuss extensions to future topological devices, and how we are assembling components for topological information processing. Along the way, new materials challenges arise, including moving from as-grown hybrid nanowires to top-down processed 1D systems fabricated from two-dimensional heterostructures. Many new problems, from fundamentals of how to identify Majorana zero modes, to how to process and store quantum information with topological protection, to how to design and extended hybrid superconductor-semiconductor materials will be touched on, though the most exciting developments are for the future. Research supported by the Danish National Research Foundation and Microsoft Corporation.

// Session Schedule

26 **THURSDAY**
OCTOBER, 2017
2:00 pm - 5:00 pm

YQI Seminar Room, 17 Hillhouse Ave.
4th Floor

VLAD PRIBIAG
University of Minnesota

ADVANCED SEMICONDUCTOR HETEROSTRUCTURES

2 PM - JAVAD SHABANI - NEW YORK UNIVERSITY

Two-dimensional epitaxial superconductor-semiconductor heterostructures: A platform for topological superconducting networks

Progress in the emergent field of topological superconductivity relies on synthesis of new material combining superconductivity, low density, and spin-orbit coupling. Recently, epitaxial growth of Al on InAs nanowires was shown to yield a high quality superconductor-semiconductor (S-Sm) system with uniformly transparent interfaces and a hard induced gap, indicted by strongly suppressed subgap tunneling conductance. Here we report the realization of a two-dimensional (2D) InAs/InGaAs heterostructure with epitaxial Al and Nb, yielding a planar S-Sm system with structural and transport characteristics as good as the epitaxial wires. The realization of 2D epitaxial S-Sm systems represent a significant advance over wires, allowing extended networks via top-down processing. We demonstrate high quality transport, density-controlled quantum well and Josephson junctions and a highly transparent 2D S-Sm interface. Among numerous potential applications, this new material system can serve as a platform for gate-able Josephson circuits and gate-based qubits (Gatemons).

2:45 PM - TINGXIN LI - RICE UNIVERSITY

Materials aspects: InAs/GaSb - based 2D topological insulator and beyond

It was proposed that InAs/GaSb bilayers can form a topological insulator when the bands are in the inverted regime. InAs/GaSb – based topological insulators have been the subject of research by many groups because of their potential to provide the platform for studies of interesting quantum phases such as helical edge modes, Luttinger liquids, and single-mode Majorana bound states. This talk will emphasize the materials aspects of this system. We first describe the characteristic transport properties of InAs/GaSb bilayers in three distinct regimes, namely, the semiconductor-, the shallowly inverted-, and the deeply inverted- regime. We note that quantum spin Hall effect can be clearly observed only in the shallowly-inverted regime, and discuss how to correctly identify this regime, in particular, by observation of the characteristic Rxx and Rxy behavior near the boundary of inverted to non-inverted transition. We comment on the recent theoretical proposals explaining the robust helical edge transport observed in this regime. We will then talk about the large-gap quantum spin Hall insulators in strained-layer InAs/GaInSb bilayers, in which the bulk gaps are enhanced by up to five folds as compared to the binary InAs/GaSb. With consequently increasing edge Fermi velocity, the edge conductance at zero and applied magnetic fields manifests time reversal symmetry- protected properties consistent with Z2 topological insulator. Finally, we will discuss perspectives for materials improvement and future research of InAs/GaSb – based topological insulators.

3:30 PM - COFFEE BREAK

4 PM - CHRIS PALMSTRØM - UNIVERSITY OF CALIFORNIA, SANTA BARBARA

A Materials Perspective on Low Dimensional Super-Semi Hybrid Systems for Majorana Fermions

26 **THURSDAY**
OCTOBER, 2017
5:00 pm

Becton Laboratories, 15 Prospect St
4th Floor

ROB SCHOELKOPF
Yale Quantum Institute

GUIDED TOUR OF THE BECTON LABORATORIES

Beginning with pioneering work on macroscopic quantum coherence in the 80's to the realization of today's quantum information processors, Yale professors are renowned for their leadership of the Quantum Revolution. In the past fifteen years, the Yale team of more than fifty researchers has been proud to demonstrate several milestones in quantum computing, including the development of the first solid state quantum information processors, based on superconducting electronics. YQI is now pursuing the collective goal of turning quantum physics into practical technologies and advancing our fundamental understanding of quantum science and engineering.
After spending the day at the Yale Quantum Institute which hosts our theoretician researchers, you will have the chance to visit the experimental side of YQI, where are located our 12 dilution fridges, on-site clean rooms and the machining facilities.
Groups will leave from YQI around 5 pm and walk to the Becton Center where the quantum laboratories are located.

26 **THURSDAY**
OCTOBER, 2017
7:00 pm

Roia Restaurant
261 College St

MICHEL DEVORET
LEONID GLAZMAN
Yale Quantum Institute

WORKSHOP DINNER AT ROÌA

Originally built as a restaurant for the Taft Hotel (now apartments), the 100-year-old space located next to the prestigious Shubert Theater now hosts Roia Restaurant. Named after a river that winds along the border of France and Italy as a metaphor for the menu, the food, rooted in both cuisines, is largely traditional, leavened with a bit of contemporary creativity and New England ingredients.

You can meet your colleagues directly at ROÌA, or walk together to the restaurant from the New Haven Hotel lobby where a group will leave around 6:45 pm.

27 **FRIDAY**
OCTOBER, 2017
9:00 am - 12:30 pm

YQI Seminar Room
17 Hillhouse Avenue
4th Floor

MICHEL DEVORET
Yale Quantum Institute

JOSEPHSON JUNCTIONS SPECTROSCOPY AND QUASIPARTICLES

9:00 AM - MAX HAYS - YALE UNIVERSITY

Quantum dynamics of Andreev levels in a semiconducting nanowire Josephson junction

9:45 AM - ATTILA GERESDI - DELFT UNIVERSITY OF TECHNOLOGY

On-chip microwave spectroscopy: the toolset to identify topological superconductivity

Narrow gap semiconductors, such as InAs and InSb have become the most studied platform of topological superconductivity and Majorana zero modes (MZMs) due to their strong spin-orbit coupling, large Landé g-factor and the possibility of inducing superconductivity with highly transparent Ohmic contacts to bulk superconductors.

// Session Schedule

We utilize a superconducting tunnel junction as an on-chip microwave generator to investigate the essential building blocks of prospective topological quantum bits. By exploiting the AC Josephson effect, we map the excitations of nanowire Josephson junctions up to 90 GHz bounded by the superconducting gap of the generator. With this technique, we show the presence of gate-tunable Andreev bound states in a ballistic semiconductor channel for the first time, and demonstrate how an external magnetic field influences the spectrum in the presence of strong spin-orbit coupling, relevant for the search of Majorana bound states. In addition, we demonstrate that the microwave generator has a profound influence on the poisoning dynamics of Cooper-pair transistors made of InAs nanowires, the atomic building blocks of braiding and fusion schemes.

10:30 AM - COFFEE BREAK

11 AM - MANUEL HOUZET - COMMISSARIAT ENERGIE ATOMIQUE GRENOBLE

Signature of Majorana fermions in multi-terminal junctions

We analyze the Andreev spectrum in a four-terminal Josephson junction between topological superconductors. We find that a topologically protected crossing in the space of three superconducting phase differences can occur between the two lowest Andreev bound states. This crossing can be detected through the transconductance quantization, in units of $2e^{2/h}$, between two voltage-biased terminals. We discuss possible realizations of such a junction with semiconducting crossed nanowires and with quantum-spin Hall insulators. Our prediction provides an example of a topological Josephson junction protected by a Z_2 index, in contrast with recently investigated multi-terminal junctions between conventional superconductors, which are protected by a Z index.

11:45 AM - LEANDRO TOSI - COMMISSARIAT ENERGIE ATOMIQUE SACLAY

Quasiparticle dynamics in Andreev quantum dots

In contrast with a bulk superconductor, a single-channel phase-biased superconducting weak link hosts a discrete subgap quasiparticle state, called “Andreev state”. As such, it can be seen as a sort of quantum dot in which zero, one or two quasiparticles can be trapped, not due to electrostatic barriers, but to the phase drop. This “Andreev quantum dot” constitutes a very simple playground to explore the foundations of mesoscopic superconductivity. I will present experiments on Andreev quantum dots obtained at one-atom contacts between aluminum electrodes, in which we probe the dynamics of quasiparticles trapping and un-trapping using circuit-QED like techniques. I will focus in particular on the effect of the cavity on this dynamics.

27 **FRIDAY**
OCTOBER, 2017
2:00 pm - 5:30 pm

YQI Seminar Room
4th Floor

LIANG JIANG
Yale Quantum Institute

LOCAL PROBES OF TOPOLOGICAL STATES

2 PM - SERGEY FROLOV - UNIVERSITY OF PITTSBURG

Quantum dot chains as emulators of topological superconductors

Tunneling spectroscopy measurements on one-dimensional superconducting hybrid materials have revealed signatures of Majorana fermions which are the edge states of a bulk topological superconducting phase. We couple strong spin-orbit semiconductor InSb nanowires to conventional superconductors (NbTiN, Al) to obtain additional

signatures of Majorana fermions and to explore the magnetic-field driven topological phase transition. Specifically, we map out the phase diagram of the topological phase in the space of Zeeman energy and chemical potential, and investigate the apparent closing and re-opening of the superconducting gap. We investigate how the topological superconducting phase would manifest in finite size systems, by electrostatically splitting the wire into segments of varied length. By chaining up several segments of a nanowire, we are realizing a quantum simulator of the Kitaev chain with tunable on-site energies and couplings between the sites, a step towards quantum simulation with semiconductor nanostructures.

2:45 PM - LIANG FU - MASSACHUSETTS INSTITUTE OF TECHNOLOGY

From Majoranas to Fractons

3:30 PM - COFFEE BREAK

4 PM - ALI YAZDANI - PRINCETON UNIVERSITY

Majorana Spin Litmus Test and other results in 1D superconductors

4:45 PM - ZHI-XUN SHEN - STANFORD UNIVERSITY

Quantum Phase Transitions in QAHE States

I will present our recent work on the QSH state in 1T' WTe2 and quantum phase transitions in magnetic topological insulators.

27 **FRIDAY**
OCTOBER, 2017
5:30 pm

YINS Seminar Room
17 Hillhouse Ave
3rd Floor

FLORIAN CARLE
Yale Quantum Institute

POSTER SESSION

The workshop will include a poster session where researchers from various institutions and from the Yale Quantum Institute can present their current work. The poster session will be hosted by our friends at the Yale Institute for Network Science on the 3rd floor. Refreshments and snacks will be served through the session.

Presenter list (by order of registration)

1 - Hao Wu - University of Pittsburgh - Kitaev model with quantum dot chains in InSb nanowires

2 - Jen-Feng Hsu - University of Pittsburgh - Superconducting Microwave Circuits with Semiconductor Nanowires in High Magnetic Fields

3 - Michal Papaj - MIT - Conductance through a superconductor island via multiple zero-energy localized states

4 - Stephen Gill - University of Illinois - Selective Area Epitaxy of Semiconductor-Superconductor Nanowires

5 - Peter Morgan - Yale University - Quantized Dirac spinor fields as random fields

6 - Joshuah T. Heath - Boston College - Exotic quantum statistics from a many-body theory of Majorana fermions

7 - Kyle Serniak - Yale Quantum Institute - Proximitized-superconducting quasiparticle traps for circuit QED devices

8 - Azarin Zarassi - University of Pittsburgh - Replicas of Andreev spectra in InSb nanowires

// Session Schedule

28 **SATURDAY**
OCTOBER, 2017
9:00 am - 12:30 pm

YQI Seminar Room
4th Floor

LEONID GLAZMAN
Yale Quantum Institute

NEW TOPOLOGICAL MATERIALS

9 AM - LIGHT BREAKFAST

9:30 AM - QING LIN HE - UNIVERSITY OF CALIFORNIA, LOS ANGELES

Quantized signature of chiral Majorana fermions

In a topological insulator coupled to an s-wave superconductor, the surface Dirac fermion at the interface forms a px+ipy type of superconductor, which can accommodate one-dimensional chiral Majorana fermion modes propagating along the edges when the topological order is carefully controlled. Experimental signatures of this mode is captured by the magneto-electric transport measurements in a hybrid system of a quantum anomalous Hall insulator [Cr-doped (Bi,Sb)2Te3] thin film partially capped by a superconductor layer (Nb). The external magnetic field serves as a "knob" to tune the system into different topological regimes that allow the degenerate and non-degenerate propagation of Majorana edge modes. This tuning was signified as quantized conductance transitions among e2/h, 0.5e2/h, and 0 as the external magnetic field was swept, in which the conductance quantized at 0.5e2/h is the hallmark of the single chiral Majorana fermion phase. This transport signature is reproducible over many magnetic field sweeps and appears at different temperatures, providing a solid signature of the chiral Majorana fermion modes.

10:15 AM - DAVID COBDEN - UNIVERSITY OF WASHINGTON

Electronic phenomena in the two-dimensional topological semimetal WTe2

The van der Waals layered material WTe2 has recently attracted interest for being a semimetal that exhibits very large magnetoresistance at low temperatures, and is expected to have topological features its single-particle band structure. Studying WTe2 down to the monolayer limit by exfoliation and encapsulation, we find that it exhibits a diverse range of phenomena, some of them quite mysterious. A monolayer exhibits edge conduction with properties generally consistent with those expected for the helical boundary modes of a quantum spin Hall insulator, albeit with finite backscattering that increases at the lowest temperatures. While the edge conduction appears otherwise quite robust, at the same time the 2D bulk of a monolayer varies between insulating, metallic and superconducting states as a function of temperature and gate voltage. These properties show signs of being linked to strong electron-hole correlations. Finally, whereas the monolayer is centrosymmetric, in two or more layers WTe2 is polar and we find that it is ferroelectric, that is, it is a switchable polar metal.

Enjoying New Haven

While a small city, New Haven has an intense multicultural food scene, a vibrant culture and a dynamique night life. From the birthplace of the Hamburger, to its famous Apizza, the multitude of ethnic food, the increasing number of breweries, you will discover the charm of this New England city! Here is a selection of our favorites places.

MODERN CHIC

- **Zinc New Haven** (American),
  964 Chapel Street $$$
- **Olea** (Mediterranean)
  39 High Street $$$
- **Union League Cafe** (French)
  1032 Chapel Street $$$$
- **116 Crown** (American)
  116 Crown Street $$$
- **Taste of China** (Chinese)
  954 Chapel Street $$$

CHEAPER

- **Kitchen Zinc** (Unusual pizza)
  966 Chapel Street $
- **Rudy's Bar** (Burger)
  1227 Chapel Street $
- **Mamoun's** (Middle Eastern)
  85 Howe Street $
- **Pho & Spice** (Vietnamese)
  76 Orange Street $
- **Mecha Noodle** (Japanese)
  201 Crown Street $

DRINKS

- **Ordinary**
  990 Chapel Street $$
- **Firehouse 12**
  45 Crown Street $
- **Elm City Social** (order the "Rubber Ducky")
  266 College Street $

FAMOUS/INFAMOUS PLACES

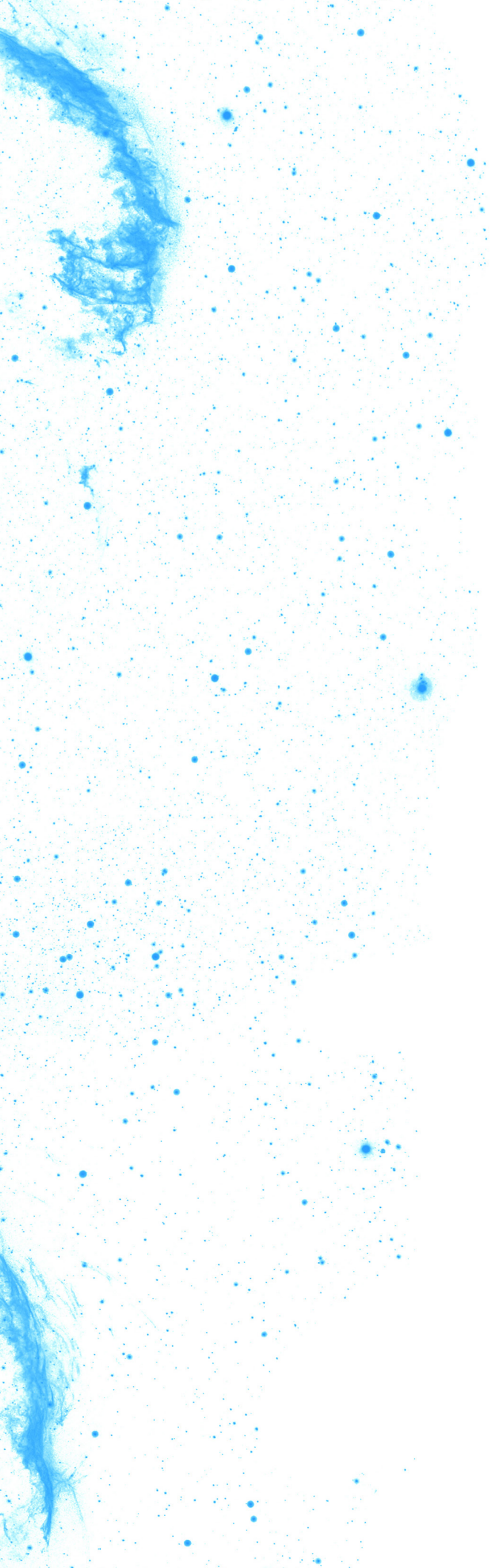
- **Louis' Lunch** (birthplace of the hamburger, do not ask for Ketchup!)
  263 Crown Street $
- **Franke Pepe Pizzeria Napoletana** ("Best pizza in America", try the Clam Casino apizza)
  157 Wooster Street $$
- **Anchor Spa** (storied dive bar open right after prohibition, try the "Yale Beets Harvard" cocktail)
  272 College Street $$

SUPRISE ME

- **Miya's** (Unexpected maki)
  68 Howe Street $$$
- **Bull & Swine** (BBQ)
  969 State Street $$
- **Lalibela Restaurant** (Ethiopian)
  176 Temple Street $$
- **Choupette Creperie**
  24 Whitney Avenue $
- **Jeera Thai**, (only 4 tables)
  216 Crown Street $

ENTERTAINMENT

- **Barcade** (Arcade games)
  966 Chapel Street
- **Karaoke Heroes**
  212 Crown Street
- **The Owl Shop** (Cigar lounge)
  268 College Street
- **BAR** (Brewery and dance club)
  254 Crown Street



MAJORANA FERMION & BEYOND

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