Jesse Thaler

Final Report — DOE Early Career Award

- DOE award #: **DE-SC0006389** (formerly DE-FG02-11ER-41741)
- Institution: **Massachusetts Institute of Technology**
- Project Title: **Interpreting New Data from the High Energy Frontier**
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1 Research Accomplishments

Thaler's research group made substantial contributions in three categories of research proposed and funded by the DOE Early Career Award: Supersymmetry Breaking, Novel Dark Matter Dynamics, and Jet Substructure. Highlights from the full five-year funding period are summarized below, with more details given about research carried out in the final year of funding. Present affiliations of Thaler's collaborators are provided in the research descriptions.

In addition to the work described here, Thaler performed research under Task C of grants DE-FG02-05ER-41360 and DE-SC0012567 (MIT Center for Theoretical Physics), including work on non-supersymmetric extensions of the Standard Model (SM) and non-perturbative aspects of jet physics. These projects have already been reported on and will not be mentioned here.

During the course of this DOE Early Career Award, Thaler received three prestigious awards: a Presidential Early Career Award for Scientists and Engineers (PECASE) from the White House in 2012, a Sloan Research Fellowship from the Alfred P. Sloan Foundation in 2013, and a Harold E. Edgerton Faculty Achievement Award from MIT in 2016.

1.1 Supersymmetry Breaking

Supersymmetry (SUSY) is a leading candidate for physics beyond the SM and a well-motivated target for new physics searches at the Large Hadron Collider (LHC). In order to be realized in nature, though, SUSY must be spontaneously broken. In his research, Thaler studies how the dynamics of this breaking can affect collider physics and cosmology. Research highlights from the first four years of the Early Career Award are as follows.

- **Flavor Mediation**: With Nathaniel Craig (U.C. Santa Barbara) and Matthew McCullough (former MIT postdoc, now CERN), Thaler showed how to connect SUSY breaking to a proposed "flavor force". This yields a novel spectrum of superpartners with inverted relations between SM flavor and SUSY flavor, motivating new kinds of searches at the LHC.

- **Theoretical Structure of Anomaly Mediation**: With Francesco D'Eramo (former MIT graduate student, now U.C. Santa Cruz) and Zachary Thomas (former MIT graduate student, now U. Minnesota), Thaler elucidated the mechanism behind "anomaly mediation", a ubiquitous source of (apparent) SUSY breaking that appears in all models of supergravity. This work showed that anomaly mediation is in fact a SUSY-preserving effect from the perspective of anti-de Sitter space, which persists even though our universe has de Sitter geometry.

- **Auxiliary Gauge Mediation**: With Yonatan Kahn (former MIT graduate student, now Princeton) and McCullough, Thaler extended his work on flavor mediation to propose an "auxiliary" force (a combination of flavor and Higgs forces). The resulting superpartner spectrum exhibits large hierarchies, allowing such models to be viable despite stringent bounds on SUSY from the LHC.

In the final year of the Early Career Award, Thaler made the following contribution.

- **Cosmology and Supergravity**: There is overwhelming cosmological evidence that the universe underwent a period of accelerated expansion called inflation, driven by a particle called the inflaton. Because inflation requires a large cosmological constant, SUSY (if realized in nature) must be spontaneously broken during the inflationary epoch, resulting in a Goldstone fermion called the goldstino. In previous work with Kahn and Daniel Roberts (former MIT graduate student, now IAS), Thaler presented the minimal effective field theory (EFT) to realize SUSY in the early universe, involving just the inflaton and the goldstino. This was a dramatic simplification compared to previous constructions, but it was only valid in the EFT approximation. With Sergio Ferrara (CERN) and Renata Kallosh (Stanford), Thaler extended this construction to include the full nonlinear structure of supergravity, providing a minimal, consistent, and flexible framework to study the cosmological implications of SUSY.

1.2 Novel Dark Matter Dynamics

The gravitational evidence for dark matter is overwhelming, but to date, there is no firm evidence for possible non-gravitational interactions between dark matter and ordinary matter. In his research, Thaler studies how novel dynamics can affect dark matter discovery prospects. Thaler also continues to play an advisory role for the DarkLight experiment, an MIT-led proposal to use the energy recovery linac at Jefferson Lab to search for "dark photons". Research highlights from the first four years of the Early Career Award are as follows.

- **Searching for Invisible Dark Photons**: With Kahn, Thaler showed how the inclusion of calorimetry in the DarkLight experiment would allow it to be sensitive to dark photons with invisible decays. With the successful test run of DarkLight completed this summer, the final detector design is anticipated to include new calorimeter elements to enable this search.

- **Observational Implications of Semi-Annihilation**: With D'Eramo and McCullough, Thaler showed how a novel mechanism called semi-annihilation (introduced previously with D'Eramo) could lead to new signatures of dark matter in the Milky Way halo. These unique signatures were searched for with the *Fermi* gamma ray space telescope. In related work with Nayara Fonseca (visiting MIT student, now DESY) and Lina Necib (MIT graduate student), Thaler showed how semi-annihilation could be connected to the baryon asymmetry of the universe to yield similar signatures.

- **(In)direct Detection of Boosted Dark Matter**: With Kaustubh Agashe (U. Maryland), Yanou Cui (U.C. Riverside), and Necib, Thaler introduce a new paradigm for dark matter, where heavy dark matter in the Milky Way halo annihilates to light dark matter. This gives the light dark matter particles a large Lorentz boost, such that this "boosted dark matter" can be searched for in neutrino detectors like Super-K and the proposed DUNE experiment.

- **Dark Matter Beams from Cyclotrons**: With Kahn, Gordan Krnjaic (Fermilab), and Matthew Toups (MIT experimentalist), Thaler showed that the cyclotrons used in the proposed DAEδALUS experiment could also be used to produce dark photons. If the dark photons subsequently decay to dark matter, this creates a beam of dark matter that can be probed downstream in neutrino detectors.

In the final year of the Early Career Award, Thaler made the following contributions.

- **Searching for Dark Photons using LHCb**: There is a worldwide effort to search for dark photons, with ongoing and proposed experiments falling roughly into two categories: collider experiments to search for prompt decays, and fixed target experiments to search for displaced decays. In the dark photon parameter space, there is a perplexing gap in coverage between these two search strategies, so one needs experiments with both prompt and displaced sensitivity. With Philip Ilten (MIT experimentalist), Yotam Soreq (MIT postdoc), Mike Williams (MIT experimentalist), and Wei Xue (MIT postdoc), Thaler showed that the LHCb experiment is ideally suited to cover this gap. LHCb was originally designed to measure the properties of bottom and charm quarks, so it has both excellent mass resolution (for a prompt search) and excellent vertex resolution (for a displaced search). Crucially, LHCb will upgrade to triggerless detector readout and calibration, allowing it to perform real-time searches for dark photons. Using a combination of rare charm meson decays and inclusive dimuon searches, Thaler and collaborators have shown that by the end of 2023, LHCb will have sensitivity to a large portion of the viable dark photon parameter space.

- **New Experimental Design for Axion Dark Matter**: The axion is a hypothetical particle that could solve two mysteries left unanswered by the SM: the resolution of the strong CP problem and the nature of dark matter in the universe. When axion dark matter encounters a static magnetic field, it generates response electromagnetic fields that can detected in experiments like ADMX. With Kahn and Benjamin Safdi (MIT Pappalardo fellow), Thaler proposed a new kind of axion dark matter experiment that probes a complementary region of axion parameter space compared to ADMX. Whereas ADMX is based on measuring axion-induced excitations of a cavity resonance mode, Thaler's proposal is based on measuring

oscillating magnetic fluxes. Whereas ADMX uses resonance readout of the axion-induced signal, Thaler's proposal can use either broadband or resonant readout. Intriguingly, this new design is potentially sensitive to axions whose properties are connected to grand unification. There is currently an effort at MIT to build a prototype of this new axion dark matter detector under the name ABRACADABRA-10cm.

1.3 Jet Substructure

Jets are collimated sprays of particles that are produced from the fragmentation of high energy quarks and gluons. Jets can also occur, though, if heavier particles such as Higgs bosons and top quarks are produced with such a large Lorentz boost factor that their decay products are "accidentally" collimated. In his research, Thaler develops new jet substructure techniques to disentangle these two mechanisms for jet production, as well as new calculational techniques to gain an analytic understanding of jet substructure methods. Research highlights from the first four years of the Early Career Award are as follows.

- **N-subjettiness**: With Ken Van Tilburg (former MIT undergraduate student, now IAS), Thaler introduced a powerful jet substructure technique called N-subjettiness (denoted τ_N), which tests a jet for N-prong substructure. This method is widely used by the ATLAS and CMS experiments at the LHC to search for boosted top quarks (using τ_3/τ_2) and boosted W/Z/Higgs bosons (using τ_2/τ_1). The original definition of N-subjettiness was proposed prior to Thaler's Early Career Award, but the versions in current use at the LHC are based on improvements implemented using this grant.

- **Energy Correlation Functions**: With Andrew Larkoski (former MIT postdoc, now Reed College) and Gavin Salam (CERN), Thaler introduced a class of jet substructure discriminants based on correlations between N particles within a jet. These energy correlation functions are now used by ATLAS at part of the D_2 discriminant (developed subsequently by Larkoski and collaborators).

- **Sudakov Safe Observables**: With Larkoski, Thaler showed that a wide variety of jet substructure observables cannot be calculated using standard methods in perturbative QCD, but can be calculated using resummation techniques that yield Sudakov form factors. Instead of having a series expansion in the strong coupling constant α_s, Sudakov safe distributions typically have a novel expansion in $\sqrt{\alpha_s}$.

- **Jets Without Jets**: With Daniele Bertolini (former MIT graduate student, now U.C. Berkeley) and Tucker Chan (former MIT undergraduate student, now deceased), Thaler introduced a new way to count a fractional number of jets without using a jet algorithm. Precision calculations of fractional jets were subsequently performed by Thaler with Bertolini and Jonathan Walsh (Leap Motion), and this technique is currently being pursued by the ATLAS experiment for use in its low-level trigger.

- **Soft Drop Declustering**: With Larkoski, Simone Marzani (former MIT postdoc, now SUNY Buffalo), and Gregory Soyez (Saclay), Thaler introduced a powerful method to remove contamination from a jet by systematically dropping soft radiation. Soft drop has a novel analytic

structure which facilitates precision jet substructure calculations, and it is now the default jet grooming procedure used by CMS.

- **A Standard Candle for Jets**: With Larkoski and Marzani, Thaler showed that a particular observable derived from soft drop declustering was not only Sudakov safe, but also independent of α_s at lowest order. This observable is nearly identical for quark-initiated and gluon-initiated jets, making it a standard candle for jet calibration. This new observable has now been used by CMS to test for modifications of jet properties in heavy ion collisions.

In the final year of the Early Career Award, Thaler made the following contributions.

- **The XCone Jet Algorithm**: Most jet analyses at the LHC are based on first finding a collection of jets using a jet algorithm and then studying the substructure of those jets using techniques like those described above. With Iain Stewart (MIT faculty), Frank Tackmann (DESY), Christopher Vermilion (Roobiq), and Thomas Wilkason (former MIT undergraduate student, now Stanford), Thaler introduced a new kind of jet algorithm that effectively finds jets and jet substructure at the same time. This algorithm, called XCone, always identifies N jets within an event, regardless of whether those jets are isolated or overlapping. For widely-separated jets, XCone behaves nearly identically to the popular anti-k_t algorithm. As jets start to overlap, however, XCone dynamically adjusts to maintain excellent performance without undesirable jet merging; this allows standard analysis techniques to be applied over a wide kinematic range without needing to perform dedicated jet substructure studies. XCone uses insights gained from Thaler's work on N-subjettiness and precursor work by Stewart and Tackmann on N-jettiness, and it was designed not only to have excellent performance but also to facilitate precision jet calculations.

- **Exposing the Dead Cone Effect**: The dead cone is a well-known effect in gauge theories where charged particles with mass m and energy E exhibit suppressed radiation patterns within an angle $\theta < m/E$. While the dead cone effect is widely accepted, no direct measurement of the dead cone radiation pattern has ever been performed at a collider, though there are a number of indirect tests available. With Fabio Maltoni (Louvain) and Michele Selvaggi (CERN), Thaler showed how to definitively test the dead cone effect for top quarks at the LHC by using advanced jet substructure techniques. As part of this research, Thaler identified a bug in a widely-used LHC simulation tool, showing the important of stress-testing all aspects of SM theoretical predictions. Beyond its importance for precision top properties, this work emphasizes the value of jet substructure for precision SM measurements.

1.4 Summary

Thaler's work during his Early Career Award combines imaginative beyond-the-standard-model hypotheses, innovative experimental designs, novel data analysis methods, and compelling calculational techniques. By pushing the boundaries of theoretical knowledge, his research has already had an impact on experiments at the energy, intensity, and cosmic frontiers.

Thaler is continuing his successful DOE-supported research under the grant "Boosting the Search for New Physics at the Frontiers" (DE-SC0015476, July 15, 2016–March 31, 2017). Thaler looks forward to a continued fruitful relationship with the DOE in the years ahead.

2 Papers

The following list only includes papers that were completed using the DOE Early Career Award. It therefore omits papers submitted/published before July 15, 2011 and works covered entirely under Task C of grants DE-FG02-05ER-41360 and DE-SC0012567 (MIT Center for Theoretical Physics). All papers have equal division of effort among the authors.

2.1 Exclusive DOE HEP support

[E1] Francesco D'Eramo, Lin Fei, and Jesse Thaler, *Dark Matter Assimilation into the Baryon Asymmetry*, JCAP **1203**, 010 (2012) [arXiv:1111.5615 [hep-ph]].

[E2] Francesco D'Eramo, Jesse Thaler, and Zachary Thomas, *The Two Faces of Anomaly Mediation*, JHEP **1206**, 151 (2012) [arXiv:1202.1280 [hep-ph]].

[E3] Andrew J. Larkoski and Jesse Thaler, *Unsafe but Calculable: Ratios of Angularities in Perturbative QCD*, JHEP **1309**, 137 (2013) [arXiv:1307.1699].

2.2 Joint support of DOE HEP and other agencies

[J1] Jesse Thaler and Ken Van Tilburg, *Maximizing Boosted Top Identification by Minimizing N-subjettiness*, JHEP **1202**, 093 (2012) [arXiv:1108.2701 [hep-ph]].
Thaler partially supported by Aspen Center for Physics (NSF).

[J2] Daniele Bertolini, Keith Rehermann, and Jesse Thaler, *Visible Supersymmetry Breaking and an Invisible Higgs*, JHEP **1204**, 130 (2012) [arXiv:1111.0628 [hep-ph]].
Bertolini partially supported by INFN Bruno Rossi Fellowship.

[J3] Nathaniel Craig, Matthew McCullough, and Jesse Thaler, *The New Flavor of Higgsed Gauge Mediation*, JHEP **1203**, 049 (2012) [arXiv:1201.2179 [hep-ph]].
Craig supported by NSF, McCullough supported by Simons Foundation.

[J4] Nathaniel Craig, Matthew McCullough and Jesse Thaler, *Flavor Mediation Delivers Natural SUSY*, JHEP **1206**, 046 (2012) [arXiv:1203.1622 [hep-ph]].
Craig supported by NSF, McCullough supported by Simons Foundation.

[J5] Ilya Feige, Matthew D. Schwartz, Iain W. Stewart, and Jesse Thaler, *Precision Jet Substructure from Boosted Event Shapes*, Phys. Rev. Lett. **109**, 092001 (2012) [arXiv:1204.3898 [hep-ph]].
Stewart supported by DOE NP, Feige supported by NSERC of Canada.

[J6] Yonatan Kahn and Jesse Thaler, *Searching for an Invisible A' Vector Boson at DarkLight*, Phys. Rev. D **86**, 115012 (2012) [arXiv:1209.0777 [hep-ph]].
Kahn supported by NSF Graduate Fellowship, Thaler partially supported by Aspen Center for Physics (NSF).

[J7] Francesco D'Eramo, Matthew McCullough and Jesse Thaler, *Multiple Gamma Lines from Semi-Annihilation*, JCAP **1304**, 030 (2013) [arXiv:1210.7817 [hep-ph]].
D'Eramo supported by Miller Institute, McCullough supported by Simons Foundation.

[J8] Daniele Bertolini, Jesse Thaler and Zachary Thomas, *TASI 2012: Super-Tricks for Superspace*, arXiv:1302.6229 [hep-ph]. (Published in TASI 2012 Proceedings)
Bertolini partially supported by INFN Bruno Rossi Fellowship.

[J9] Andrew J. Larkoski, Gavin P. Salam, and Jesse Thaler, *Energy Correlation Functions for Jet Substructure*, JHEP **1306**, 108 (2013) [arXiv:1305.0007].
Salam supported by French Agence Nationale de la Recherche and by EU Initial Training Network, collaboration as a whole partially supported by MIT International Science and Technology Initiatives.

[J10] Francesco D'Eramo, Jesse Thaler, and Zachary Thomas, *Anomaly Mediation from Unbroken Supergravity*, JHEP **1309**, 125 (2013) [arXiv:1307.3251].
D'Eramo supported by Miller Institute.

[J11] Yonatan Kahn, Matthew McCullough, and Jesse Thaler, *Auxiliary Gauge Mediation: A New Route to Mini-Split Supersymmetry*, JHEP **1311**, 161 (2013) [arXiv:1308.3490].
Kahn supported by NSF Graduate Fellowship, McCullough supported by Simons Foundation.

[J12] Daniele Bertolini, Tucker Chan, and Jesse Thaler, *Jet Observables Without Jet Algorithms*, JHEP **1404**, 013 (2014) [arXiv:1310.7584 [hep-ph]].
Bertolini supported by NSF LHC Theory Initiative Fellowship, Thaler partially supported by Sloan Foundation.

[J13] Andrew J. Larkoski, Duff Neill, and Jesse Thaler, *Jet Shapes with the Broadening Axis*, JHEP **1404**, 017 (2014) [arXiv:1401.2158 [hep-ph]].
Neill supported by MIT Pappalardo Fellowship, Thaler partially supported by Sloan Foundation.

[J14] Andrew J. Larkoski, Simone Marzani, Gregory Soyez, and Jesse Thaler, *Soft Drop*, JHEP **1405**, 146 (2014) [arXiv:1402.2657 [hep-ph]].
Marzani supported by UK Science and Technology Facilities Council, Soyez supported by French Agence Nationale de la Recherche and by EU Initial Training Network, Thaler partially supported by Sloan Foundation.

[J15] Kaustubh Agashe, Yanou Cui, Lina Necib, and Jesse Thaler, *(In)direct Detection of Boosted Dark Matter*, JCAP **1410**, 062 (2014) [arXiv:1405.7370 [hep-ph]].
Agashe and Cui supported by NSF and Maryland Center for Fundamental Physics, Thaler partially supported by Sloan Foundation.

[J16] Andrew J. Larkoski and Jesse Thaler, *Aspects of Jets at 100 TeV*, Phys. Rev. D **90**, 034010 (2014) [arXiv:1406.7011 [hep-ph]].
Thaler partially supported by Sloan Foundation.

[J17] Andrew J. Larkoski, Jesse Thaler, and Wouter J. Waalewijn, *Gaining (Mutual) Information about Quark/Gluon Discrimination*, JHEP **1411**, 129 (2014) [arXiv:1408.3122 [hep-ph]].
Waalewijn supported by Marie Curie International Fellowship, Thaler partially supported by Sloan Foundation.

[J18] Yonathan Kahn, Gordan Krnjaic, Jesse Thaler, and Matthew Toups, *DAEδALUS and Dark Matter Detection*, Phys. Rev. D **91**, 055006 (2015) [arXiv:1411.1055 [hep-ph]].
Kahn supported by NSF Graduate Fellowship, Krnjaic supported by NSF and Industry Canada, Toups supported by NSF, Thaler partially supported by Sloan Foundation.

[J19] Daniele Bertolini, Jesse Thaler, and Jonathan R. Walsh, *The First Calculation of Fractional Jets*, JHEP **1505**, 008 (2015) [arXiv:1501.01965 [hep-ph]].
Thaler partially supported by Sloan Foundation.

[J20] Andrew J. Larkoski, Simone Marzani, and Jesse Thaler, *Sudakov Safety in Perturbative QCD*, Phys. Rev. D **91**, 111501 (2015) [arXiv:1502.01719 [hep-ph]].
Marzani supported by NSF LHC Theory Initiative, Thaler partially supported by Sloan Foundation.

[J21] Yonatan Kahn, Daniel A. Roberts, and Jesse Thaler, *The Goldstone and Goldstino of Supersymmetric Inflation*, JHEP **1510**, 001 (2015), [arXiv:1504.05958 [hep-th]].
Kahn supported by NSF Graduate Fellowship, Roberts supported by the Fannie and John Hertz Foundation, Thaler partially supported by Sloan Foundation.

[J22] Jesse Thaler, *Separated at Birth: Jet Maximization, Axis Minimization, and Stable Cone Finding*, Phys. Rev. D **92**, 074001 (2015) [arXiv:1506.07876 [hep-ph]].
Thaler partially supported by Sloan Foundation.

[J23] Nayara Fonseca, Lina Necib, and Jesse Thaler, *Dark Matter, Shared Asymmetries, and Galactic Gamma Ray Signals*, JCAP **1602**, 052 (2016) [arXiv:1507.08295 [hep-ph]].
Fonseca supported by FAPESP and CNPq, Thaler partially supported by Sloan Foundation.

[J24] Iain W. Stewart, Frank J. Tackmann, Jesse Thaler, Christopher K. Vermilion, and Thomas F. Wilkason, *XCone: N-jettiness as an Exclusive Cone Jet Algorithm*, JHEP **1511**, 072 (2015) [arXiv:1508.01516 [hep-ph]].
Stewart supported by DOE NP and the Simons Foundation, Tackmann supported by Deutsche Forschungsgemeinschaft, Vermilion supported by NSF LHC Theory Initiative, Thaler partially supported by Sloan Foundation.

[J25] Jesse Thaler and Thomas F. Wilkason, *Resolving Boosted Jets with XCone*, JHEP **1512**, 051 (2015) [arXiv:1508.01518 [hep-ph]].
Thaler partially supported by Sloan Foundation.

[J26] Philip Ilten, Jesse Thaler, Mike Williams, and Wei Xue, *Dark Photons from Charm Mesons at LHCb*, Phys. Rev. D **92**, 115017 (2015) [arXiv:1509.06765 [hep-ph]].
Ilten and Williams supported by NSF, Thaler partially supported by Sloan Foundation and INFN.

[J27] Sergio Ferrara, Renata Kallosh, and Jesse Thaler, *Cosmology with Orthogonal Nilpotent Superfields*, Phys. Rev. D **93**, 043516 (2016) [arXiv:1512.00545 [hep-th]].
Ferrara supported by INFN, Kallosh supported by NSF, Thaler partially supported by Sloan Foundation.

[J28] Yonatan Kahn, Benjamin R. Safdi, and Jesse Thaler, *Broadband and Resonant Approaches to Axion Dark Matter Detection*, arXiv:1602.01086 [hep-ph]. (Accepted to PRL).
Safdi supported by MIT Pappalardo Fellowship, Thaler partially supported by Sloan Foundation.

[J29] Philip Ilten, Yotam Soreq, Jesse Thaler, Mike Williams, and Wei Xue, *Proposed Inclusive Dark Photon Search at LHCb*, Phys. Rev. Lett. **116**, 251803 (2016) [arXiv:1603.08926 [hep-ph]].
Ilten and Williams supported by NSF, Thaler partially supported by Sloan Foundation.

[J30] Fabio Maltoni, Michele Selvaggi, and Jesse Thaler, *Exposing the Dead Cone Effect with Jet Substructure Techniques*, Phys. Rev. D **94**, 054015 (2016) [arXiv:1606.03449 [hep-ph]].
Maltoni and Selvaggi supported by EU Initial Training Network, Belgian Federal Science Policy Office, and Fonds de la Recherche Scientifique, Thaler partially supported by Sloan Foundation, collaboration as a whole partially supported by MIT International Science and Technology Initiatives.

3 Participants

For completeness, the following includes all researchers at the MIT Center for Theoretical Physics who were mentored by Thaler during the course of the Early Career Award, both those partially supported by this grant and those funded externally.

3.1 Partially Supported by this Grant

- PI—**Jesse Thaler**.
- Postdoctoral Researcher—**Keith Rehermann**. After MIT: Internal Consultant at Ab Initio Software Corporation.
- Postdoctoral Researcher—**Andrew Larkoski**. After MIT: NSF LHC Theory Initiative Fellowship at Harvard. Currently: Visiting Assistant Professor at Reed College.
- Postdoctoral Researcher—**Yotam Soreq**. Continuing at MIT.
- Graduate Student—**Daniele Bertolini**. PhD awarded June 2014. After MIT: Postdoctoral Reseacher at U.C. Berkeley.
- Graduate Student—**Lina Necib**. Anticipated PhD June 2017.

3.2 Funded Externally

- Postdoctoral Researcher—**Matthew McCullough**. After MIT: COFUND Fellowship at CERN. Currently: Staff Scientist at CERN.
- Postdoctoral Researcher—**Gilly Elor**. After MIT: Postdoctoral Researcher at U. Oregon.

- Postdoctoral Researcher—**Simone Marzani**. After MIT: Assistant Professor at SUNY Buffalo.
- Postdoctoral Researcher—**Wei Xue**. Continuing at MIT.
- Graduate Student—**Francesco D'Eramo**. PhD awarded June 2012. After MIT: Miller Fellowship at U.C. Berkeley. Currently: Postdoctoral Researcher at U.C. Santa Cruz.
- Graduate Student—**Zachary Thomas**. PhD awarded June 2014. After MIT: Postdoctoral Researcher at U. Minnesota.
- Graduate Student—**Yonatan Kahn**. PhD awarded June 2015. After MIT: Postdoctoral Researcher at Princeton.