Stellar physics is foundational to our astrophysical understanding of the universe. Some of the strongest tests of our models come when they are pushed to their extremes, such as in the formation and evolution of compact objects (white dwarfs, neutron stars, and stellar-mass black holes) and the various associated transient events (e.g., supernovae). These areas are currently in the midst of a data-driven revolution: the exquisite time-series photometry of missions like *Kepler* and TESS (with PLATO to come) deliver on the promise of asteroseismology to reveal the properties of stellar interiors; large-area, high-cadence photometric surveys like ZTF and ASAS-SN (with LSST on the horizon) uncover fainter, faster, and rarer populations of transient phenomena; *Gaia* has measured the parallax, proper motion, and color of more than a billion stars; the detection of gravitational waves with LIGO (and eventually LISA) ushers in an era where stellar binaries are routinely probed by multiple messengers.

Theory must incorporate this deluge of new information. I am creating tools and insights that will allow our physical understanding to keep pace with observational progress. This includes predicting new classes of objects and new types of transients and providing frameworks in which to interpret new observational data and discoveries. It also includes developing software, most notably the MESA stellar evolution code, that can be applied by the wider astrophysics community. My work is distinguished by my quest for physical intuition, and I am rarely satisfied unless I can explain my numerical results with a toy model. I have a solid physical foundation that puts me in a strong position to study a range of important problems in the future.

Below, I describe four main themes of my research. I am a scientific leader in these areas and have initiated and organized international conferences within themes 1 and 2. I summarize my past and ongoing work and indicate important future directions for myself and my research group.

1. Double White Dwarf Mergers and Their Long-Term Outcomes

What remnants are left by the merger of two WDs and how do we identify them? What are the formation channels for peculiar types of hydrogen-deficient stars?

Gravitational wave emission drives the inspiral of close double white dwarf (WD) binaries and can eventually result in the tidal disruption of the less massive WD by the more massive one. The range of potential outcomes is wide, due to the different possible masses and compositions of the merging WDs. I developed a modeling framework that combines the results of hydrodynamics simulations (Schwab et al. 2012) and stellar evolution calculations to follow objects from the merger to their final fates. Decades of work modeled the aftermath of the merger as the slow accretion of one WD onto the other. However, I have demonstrated the importance of moving beyond this approach and showed that the post-merger evolution is instead a stellar evolution problem driven by the internal redistribution of heat and angular momentum. Explicitly modeling this phase has enabled new kinds of predictions, notably about the rotation rates of the remnant objects.

I have applied this understanding to the formation of single hot subdwarf stars (Schwab 2018) and the R Coronae Borealis stars (Schwab 2019). I also predicted a new class of remnants created by the merger of two massive carbon-oxygen WDs that corresponds to a phase preceding the collapse to form a neutron star (Schwab et al. 2016; Schwab 2021). Gvaramadze et al. (2019) discovered an object exhibiting many of the post-merger, pre-collapse properties predicted in my work, motivating further investigation of this scenario.

Future Work: The eventual remnant of many double WD mergers is a single WD. The remarkable expansion of the WD sample by *Gaia* has already revealed previously unknown structure in the HR diagram (Gaia Collaboration et al. 2018), the interpretation of which has spurred a flurry of work. For example, Cheng et al. (2019, 2020) used this data to demonstrate the existence of a population of massive carbon-oxygen WDs that show evidence of being merger products. Follow-up observations promise to unlock information about the detailed mass distribution of WDs, their rotation rates, and their magnetic properties. New data is on the horizon as subsequent *Gaia* data releases approach and multi-object survey spectrographs (SDSS-V, WEAVE, 4MOST) begin science operations. Theoretically well-motivated models are needed to transform the observed population of double WDs into predicted remnant populations. Doing so elucidates not only which double WD systems leave behind single WDs, but also which do not (meaning the mass transfer was stable, that the system was destroyed in a thermonuclear supernova, or that it collapsed to form a neutron star). This area is rapidly evolving and is well-suited in scope and prospects for a PhD thesis within my group.

2. Accretion-Induced Collapse and Electron-Capture Supernovae

What are the signatures of stellar collapse initiated by electron-capture reactions and how do we determine if this process occurs in nature? Does this process play a role in the formation of close double neutron star binaries?

Stars that develop high-density, degenerate oxygen-neon cores have the potential to undergo a unique collapse process initiated by electron-capture reactions (e.g., Miyaji et al. 1980). Accreting oxygen-neon WDs are thought to form neutron stars via accretion-induced collapse (AIC). Single stars with masses $\approx 8 - 10\,\mathrm{M}_\odot$ or a range of interacting binary systems are thought to undergo electron-capture supernovae (ECSNe). ECSNe are frequently invoked in the formation of the close double neutron star systems that will become LIGO sources (e.g., Schwab et al. 2010; Tauris et al. 2017). Past work suggests that these events can occur at $\sim 10\%$ of the core-collapse and thermonuclear supernova rates (Poelarends et al. 2008; Ruiter et al. 2019). However, they have never been unambiguously detected, though increasingly promising candidates are being discovered in ongoing supernova searches (e.g., Hiramatsu et al. 2020).

Determining whether electron-capture-induced stellar collapse occurs in nature requires models that can identify the distinguishing features of these events. Current models of the final collapse in ECSNe/AIC (Jones et al. 2016; Leung & Nomoto 2019) are extremely close to the threshold between implosion (which forms an neutron star) and explosion (which may form a low-mass WD). As such, these large hydrodynamics simulations demand the highest fidelity initial conditions possible. My work has significantly advanced our understanding of the evolution of degenerate oxygen-neon cores, illustrating the importance of considering the detailed chemical composition of these objects and physical effects such as Urca-process neutrino cooling (Schwab et al. 2015, 2017; Schwab & Rocha 2019). In addition to providing more accurate progenitor structures, my work also provides required inputs for the sub-grid flame models used in these calculations (Schwab et al. 2020). Spurred by the Lorentz Center program on this topic that I organized in 2019, I am involved in a number of new collaborative projects working to capitalize on the results of my previous studies.

Future Work: Super-asymptotic giant branch (super-AGB) stars sit at the boundary between those that leave behind WDs and those that undergo iron-core collapse. This is a theoretical classification based on the interior structure. Linking this to the properties of the stellar surface, and thus describing how to observationally identify a super-AGB star, remains an important open question. New multi-year photometric data from surveys like ASAS-SN hint at the potential for progress in this area (O'Grady et al. 2020). ECSNe occur in this mass range, but there are other intriguing phenomena. Woosley & Heger (2015) suggest that $9 - 11\,\mathrm{M}_\odot$ stars may experience violent silicon-burning flashes that result in mass ejection. This area is ripe for a PhD thesis project within my group that has the potential to make a significant impact on our understanding of low-energy supernovae, supernova impostors, and stellar populations on the extreme AGB.

3. Thermonuclear Supernovae: Their Progenitor Systems and Remnants

Which binary star systems produce thermonuclear explosions? How do we establish links between these scenarios and classes of observed events? What kinds of objects may be left after an explosion?

We know that the exploding object in a thermonuclear supernova is a WD, but the precise identity of the progenitor systems remains elusive. Sub-classes within "normal" Type Ia supernovae, the related class of Type Iax supernovae, and numerous peculiar events suggest multiple progenitor channels to thermonuclear explosions. Peculiar WDs (specifically, massive hybrid carbon-oxygen-neon WDs) are often invoked as the progenitors of peculiar thermonuclear supernovae (e.g., Meng & Podsiadlowski 2014; Denissenkov et al. 2015). My work uses stellar evolution and hydrodynamics simulations to study the formation of these WDs and the mixing processes that occur as they cool (Lecoanet et al. 2016; Brooks et al. 2017a; Schwab & Garaud 2019).

It demonstrates that these WDs should be fully mixed by the time of explosion, an insight that has now begun to be incorporated into calculations of their signatures (Augustine et al. 2019).

The helium star donor channel is currently a leading explanation for Type Iax supernovae (e.g., Jha 2017). My work self-consistently models the structure of both the He star donor and the WD accretor and their orbit, which is necessary for characterizing the final outcomes (Brooks et al. 2016, 2017b; Wong & Schwab 2019) and for predicting the pre-explosion appearance of these systems. Post explosion, observations of Type Iax supernovae suggest the presence of a surviving object (Foley et al. 2016). In Shen & Schwab (2017), we showed that delayed radioactive decay of ^{56}Ni can can power long-lived winds in objects that survive thermonuclear supernovae, be it the donor star (in a Type Ia) or the bound remnant (in a Type Iax). This work makes predictions about late-time supernova lightcurves and the presence of objects near supernova remnants. In Zhang et al. (2019), we extended predictions about the evolution of the Type Iax remnant objects from shortly after the explosion until they move down the WD cooling track. This scenario is actively being tested, for example via extremely late-time imaging of Type Iax supernovae using *Hubble*.

Future Work: My previous work has only started to explore the properties and evolution of objects left over after thermonuclear explosions. Intriguingly, several WDs (or WD-like objects) with low masses and peculiar compositions have recently been discovered (Gänsicke et al. 2010; Kepler et al. 2016; Vennes et al. 2017; Raddi et al. 2018b; Shen et al. 2018; Raddi et al. 2018a, 2019). There is the tantalizing possibility that these are the remnants of Type Iax supernovae that occurred in our own galaxy. Alternatively, these might be surviving supernova donor stars or even the remnants of "failed" ECSNe/AIC. It is important and timely to understand the origin and evolution of such objects, as more are likely to be discovered. This is relatively unexplored territory where simple, self-contained projects suitable for advanced undergraduates or first-year graduate students within my group can make an immediate impact.

4. MESA: An Open-Source Stellar Evolution Software Instrument

How do we ensure that stellar evolution tools are prepared to guide our interpretation of current and future observational data?

One of my primary research tools is the MESA software instrument (Modules for Experiments in Stellar Astrophysics; Paxton et al. 2011, 2013, 2015, 2018, 2019). My effort as a member of the MESA development team has been critical to the success of the work of myself and my collaborators. A freely-available, actively-maintained, open-source stellar evolution code is a tremendous resource for the astrophysics community. MESA has seen wide adoption, with hundreds of papers per year harnessing its power to model objects ranging from giant planets to accreting neutron stars. As a director of the annual MESA summer school, I am working to maximize the community benefit from this tool by training young scientists in its effective use.

The techniques of one dimensional stellar evolution are mature, but MESA nonetheless sits at the research frontier because new observations continuously motivate astrophysicists to ask new questions about stars. Defining future directions for MESA requires attentiveness to the new missions and instruments that will generate data that place demands on stellar models. As a member of the leadership team, I am actively planning the next decade of MESA development and thinking about how to enable the user community to unlock MESA's full scientific potential. I have also been leading an effort to prepare MESA for its next decade of software development and community engagement by migrating it to the GitHub platform.

Future Work: My work with MESA has given me a deep understanding of the physical and numerical aspects of stellar evolution. This positions me to easily engage with new research problems in this area. When Kumar et al. (2020) announced an exciting result demonstrating that the low-mass, helium-core-burning "red clump" stars show ubiquitous lithium enhancement on their surfaces, I quickly provided a physical explanation and supporting stellar models (Schwab 2020). I intend to continue to pursue this suggestion that the helium flash may lead to a mixing event in low-mass stars. Using MESA, I and my group will be able to rapidly respond to future unanticipated observational developments in stellar evolution.