Context & Aims Current and next-generation space- and ground-based observatories are revolutionizing precision observations in astrophysics. Discoveries ranging from exoplanets to black holes rely on high-precision stellar evolution models for calibration [19], and convection introduces uncertainty into these models. Mixing at the convective core boundary of massive stars ($M_* \gtrsim 1.1 M_\odot$) leads to core mass uncertainties of up to 70% [22], making the evolutionary pathway of a star from birth to death unclear. Strange iron-opacity-driven convection in the outer layers of massive stars can also inflate the stellar surface thereby altering mass loss via winds [24]. These processes result from nonlinear 3D convection, which is poorly modeled in stellar evolution calculations and theoretical prescriptions.

The goal of my research plan is to build a next-generation set of global and local 3D numerical simulations, which will answer the following questions:

1. How large are convective cores in massive stars?
2. How does iron-bump convection affect the stratification of massive stars? Does iron-bump convection block the signal of core-generated gravity waves?

My Prior Research My research is rooted in fluid dynamics and inspired by observations of stars. I use the *Dedalus* [9] pseudospectral code to design and run state-of-the-art simulations which I use to learn about mixing processes like convection in stars. **A core focus of my research has been to push the boundaries of *time* evolution, while other studies have focused on *spatial* resolution; my focus on the time domain has led to key discoveries in my career.** When I was a graduate student, I focused on fundamental studies of convection. I studied heat transport in compressible convection with [6] and without [1] rotation. I studied how fast convection interacts with the slow evolution of the background thermal structure in convective regions [2, 7]. I also studied convection at the smallest scales, examining individual downflows in the Sun's convection zone [5]. As a postdoctoral fellow at Northwestern, I have connected my theoretical research with modern observational puzzles. I have formed collaborations with observers and 1D modelers alike to understand what sets the position of a convective boundary [4], and I have discovered the process that inflates the convective cores of stars relative to standard models [3]. I am now finishing a project focusing on gravity wave generation by core convection and the observable signals of these waves, for direct comparison with e.g., asteroseismic observations.

Future Focus I: Convective Boundary Mixing Observations demonstrate a need for improved models of convective boundary mixing (CBM) [21]. For example, an unexplained mass-dependent CBM is required to reproduce observed eclipsing binary populations [13]. Asteroseismology also allows us to directly probe near-core CBM, revealing extensive mixing occurs near convective core boundaries [26, 28]. The amount of CBM used in a stellar evolution model modifies the evolution of a star's luminosity and effective temperature as well as the mass of the eventual remnant that it leaves behind [12, 16].

To understand the fluid dynamical picture behind CBM, I will create simulations of the cores of massive stars using the *Dedalus* [9] code. These simulations will differ from past simulations of massive stars, because they will include the full "ball" geometry of the convective core, they will employ the fully compressible equations without any luminosity boosting, and they will be relaxed into thermal equilibrium (See Fig. 1 for a preliminary example of one of these simulations). *Dedalus* was recently updated with the state-of-the-art

ability to simulate flows that pass through the coordinate singularity at $r = 0$ in spherical coordinates [33, 25]; most prior codes used a spherical shell geometry with a small interior "cutout" of the core. Our implicit-explicit (IMEX) timestepping scheme allows us to circumvent timestepping restrictions from fast sound waves [1], so we can take fast timesteps without boosting the luminosity as many prior simulations have done. Evolving a simulation to thermal equilibration using classic timestepping techniques can take thousands of convective overturn timescales [3, 4]. Fortunately, I have developed methods of "accelerated evolution" [2], which self-consistently equilibrate simulations using an order of magnitude fewer cpu-hours than traditional timestepping.

I will study CBM in fully compressible simulations whose background stratifications are based upon *MESA* (Modules for Experiments in Stellar Astrophysics) models of massive stars. I will study non-rotating and rotating stars with masses varying in the range $M_* = 1.1 - 40 M_\odot$ (the lowest masses where convective cores appear, up to high masses). My results will calibrate a 1D implementation of convective boundary mixing, which I will then implement into the open-source *MESA* software instrument. Throughout this process, I will build my simulation code with ease-of-use for the user in mind, and this code will be made publicly available and citeable so that the community has access to a robust tool for studying fluid dynamics in massive stars.

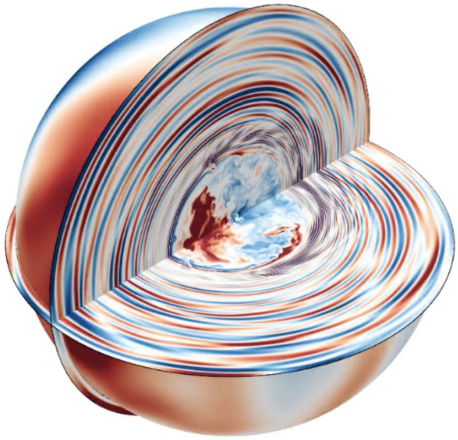

Figure 1: A simulation I ran in *Dedalus* of a $40\,M_\odot$ star. The entropy field is visualized; red is hot and buoyantly rises, blue is cold and falls. We see a convective core with a strong dipole flow and an outer radiative envelope with internal gravity waves.

Deliverable: **The first rotating, 3D simulations of core convection that include $r = 0$ and reach thermal equilibrium.**

Future Focus II: Optically thick, low-efficiency Iron-Bump Convection. In addition to vigorous core convection, massive stars have opacity-driven convective shells in their envelopes [11]. For stars with masses $\gtrsim 8M_\odot$, an "Iron-Bump Convection Zone" (FeCZ) appears as a result of the opacity of iron. These convection zones are odd: they approach the Eddington luminosity limit, are very thin, and exhibit high-Mach number, turbulent flows [18]. This odd convection has not been studied in detail, but the presence of these convection zones influences the stellar structure and evolution appreciably [24].

Numerical simulations of these convection zones are extremely limited. Those simulations which exist were performed using *Athena* [20, 29] and demonstrate interesting dynamics and thermodynamics. Unfortunately *Athena*'s robust inclusion of full radiative hydrodynamics makes these simulations very expensive. FeCZs are generally at high optical depth, and so simpler approximations for the radiative transfer can be used [18]. I will incorporate iron-bump opacity effects into *Dedalus* under various simplifying radiative transfer approximations. I will work with *Athena* experts at Princeton like Prof. Jim Stone at the IAS to benchmark and validate my *Dedalus* simulations against *Athena* simulations to determine

the range of stars where it is valid to approximate radiative transfer processes as optically thick. After validating my code, I will study the high-Mach number convection in FeCZs in simulations spanning stellar masses from $8 - 60 M_\odot$ and at various stellar ages. Flows in the FeCZ can support a large dynamic pressure, which can inflate the star; I will study how this turbulent pressure component varies across the HR diagram. I will calibrate a prescription for how the turbulent pressure modifies the background pressure, incorporate this into *MESA*, then study the observable consequences of this pressure. I am particularly interested in how this pressure modifies the star's effective temperature, and the consequences that has for wind-driven mass loss.

Seperately, there is a current debate about whether the source of "red noise" on hot, massive stars [8] is gravity waves generated in the convective core or turbulence generated by FeCZs [10]. Existing FeCZ simulations generate turbulent fields which could explain red noise signals as well as "macroturbulence" signals [30, 31]. Simulations of core generated gravity waves [14, 17] have also shown promising comparisons with red noise, but do not include the FeCZ, and so do not capture how the FeCZ modifies gravity wave signals from the core. I will study how gravity wave signals generated below the FeCZ change as they pass through this turbulent convection zone. I will include the stable radiative zones surrounding the FeCZ in my simulations and force a spectrum of gravity waves below the FeCZ, then measure how these waves are modified by the turbulent convection in the FeCZ.

Deliverable: **The first 3D simulations of FeCZs across the HR diagram.**

Connections at Princeton Princeton is the ideal location for me to carry out this work. I'm particularly excited to collaborate with Prof. Eliot Quataert, who has expertise studying convective boundary mixing and convective wave generation and would be a key collaborator to help me unravel the questions I have discussed. I also look forward to extensive collaboration with Prof. Jim Stone, who I have spoken with briefly about the dynamics of FeCZs and who is keen on comparing *Athena* and *Dedalus* in these strange convection zones. I hope to expand my research horizons and forge many collaborations with the broad network of scientists in Princeton. For example, I'd be excited to explore applications of *Dedalus* to planetary atmospheres with Prof. Adam Burrows, and I'd be excited to forge interdisciplinary collaborations with geophysicists like Drs. Jeevanjee and Donner at GFDL.

Statement on Broadening Opportunities in the Field STEM has a demographics crisis which is particularly dire in the physical sciences. Our fields are more male and more white than the U.S. population as a whole, which means that these fields are missing out on diverse perspectives and talent [27]. Identity-based inequities are further ingrained in the disparate nature in which we distribute credit in the form of citations [32]. These inequities are immoral, and it is the work of all members of the STEM, Physics, and Astrophysics community—especially white men like myself, who are an overrepresented majority with excess power—to make the field more welcoming and inclusive. There is a high differential attrition rate of underrepresented groups in baccalaureate and post-graduate programs [35], and university researchers can make immediate impacts at these levels.

My focus on improving retention of underrepresented groups is rooted in social cognitive career theory [23], which has three axes: "physics self-concept and self-efficacy", "expectancy-value and planned behavior", and "motivation and self-determination".

Physics self-concept and self-efficacy negatively manifests as feelings of inadequacy, lack of social support, and communication anxiety. To combat this, we need to build young peoples' identities as scientists by providing opportunities to build competance, to perform science skills, and to receive recognition [15]. In addition to building knowledge and competence, STEM education (in classrooms and research groups) must give students experience to *perform* as scientists by e.g., giving talks or collaborating on projects *in low-stakes environments*. Furthermore, students deserve positive recognition for their accomplishments, but often only receive criticism (even if constructive) on a regular basis. As a research mentor, I frequently encourage and complement my students for their work. Even small victories deserve to be celebrated, and I try to instill that mindset in my students.

Expectancy-value and planned behavior manifests as buying into negative stereotypes about oneself or experiencing negative environments. I have a track record of making my departments more just, equitable, diverse, and inclusive spaces. As a graduate student, I created the first rubric used on the graduated admissions committee, iterated on that rubric, and led the push to adopt rubrics in this process permanently. This rubric has measurably reduced the bias of reviewers which has led to the admission of more diverse classes. As a postdoc at Northwestern, I have been an integral part of the push to hire Visceral Change to perform a climate survey this academic year. I aim to use my power and privilege in the field to make systemic changes within my own departments to improve outcomes for all scientists regardless of their identity. I still have a lot to learn about how to make e.g., my *classroom or research group* more inclusive, and plan to take the Inclusive STEM Project MOOC course in the coming year.

Motivation and self-determination can drive students out of STEM because they do not find it intrinsically motivating or socially relevant, or because they lack encouragement. In my mentoring relationships, I practice active listening [34] with my students to try to understand what motivates them so that I do not steer them out of intrinsically motivating questions. Another way to build relevance is by employing lesson plans which allow students to engage with their culture *and* science simultaneously. One example of such a lesson plan—which was developed for middle school but is applicable to introductory undergraduate astronomy classes or public outreach—can be found online here: https://www.openscied.org/instructional-materials/8-4-earth-in-space/. I would be excited to try to design public lectures (e.g., through astronomy on tap) or other outreach lesson plans rooted in this motivation principle through the public outreach programs at Princeton.

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