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 [18], 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% [21], 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 [22]. 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) [20]. 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 [24, 25]. 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, 15].

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 [29, 23]; 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 *Dedalus* 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.

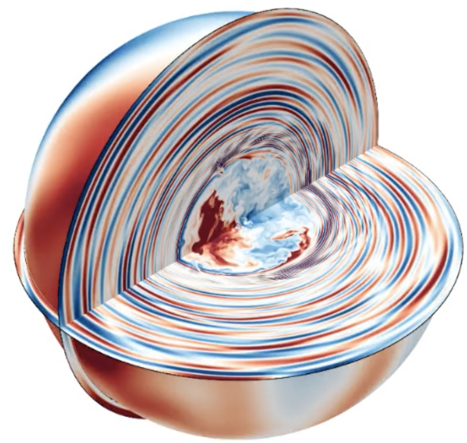

Figure 1: A simulation I ran in *Dedalus* of a $40\,M_\odot$ star. The entropy field is visualized; red is hot and buoyantly rises, blue is cold and falls. We see a convective core with a strong dipole flow and an outer radiative envelope with internal gravity waves.

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 $\gtrsim 8 M_\odot$, 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 [17]. This odd convection has not been studied in detail, but the presence of these convection zones influences the stellar structure and evolution appreciably [22].

Numerical simulations of these convection zones are extremely limited. Those simulations which exist were performed using *Athena* [19, 26] 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 [17]. I will incorporate iron-bump opacity effects into *Dedalus* under various simplifying radiative transfer approximations. After validating my code against past optically-thick *Athena* FeCZs, I will study the high-Mach number convection in FeCZs in simulations spanning stellar masses from

$8 - 60M_{\odot}$ 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 [27, 28]. Simulations of core generated gravity waves [14, 16] 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 grid of 3D FeCZ simulations spanning the HR diagram.**

Connections at KITP KITP is the ideal location for me to carry out this work. I'm particularly excited to collaborate with Prof. Lars Bildsten, who has extensively studied iron-bump convection zones in the past and who helped me develop these interesting ideas on this frontier in stellar astrophysics. I'm also excited to take advantage of the broad expertise of visiting scientists on the problems I discuss here; I'm especially excited about collaboration potential with the "Turbulence in Astrophysical Environments" program. I also hope to collaborate with Profs. Blaes and Brandt during my time at KITP, and with the other postdoctoral and graduate scholars at KITP. In the broader LA area, I also hope to work collaboratively with experts like Prof. Jim Fuller at Caltech and Prof. Jon Aurnou at UCLA on these and other topics in astrophysical fluid dynamics.

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