1 PROJECT ACHIEVEMENTS

Semester 1 of our 2017 INCITE project, "Revealing the Physics of Galactic Winds with Petascale GPU Simulations" resulted in several notable achievements. First and foremost, the project has lead to the single largest hydrodynamic simulation of an isolated galaxy ever performed. With a volume containing over 17 trillion cells, our simulation dwarfs other simulations of this type by over an order of magnitude. In order to perform this simulation, our project utilized 8096 GPUs on *Titan* for a total of ~8 million core-hours. The simulation was the culmination of our work in Semester 1 which included generating specialized initial conditions for a stable galaxy model, implementing a supernova feedback scheme to drive a wind from the galaxy, and improving the hydrodynamics algorithms and other physics available in our GPU-based code *Cholla*. Each of these accomplishments is described in further detail in the sections below.

1.1 Significance of Accomplishments to Date

Our 2016 INCITE proposal focused on the role that radiatively-cooling galactic winds may play in galaxy evolution. While observations routinely show fast ($v > 1000$ km/s), cool ($T \sim 10^4$ K) winds being driven out of galaxies with high rates of star formation, numerical simulations of galaxies have thus far failed to reproduce them. Cosmological simulations lack the resolution required to generate the winds, and high-resolution simulations lack the volume to track gas once it has been driven out of the galaxy. Our project aims to bridge this gap by producing high resolution simulations of disk galaxies that span a sufficient distance from the wind-generation region within galaxies to demonstrate whether starburst-driven winds can cool in the manner suggested by recent theoretical work.
In order to carry out the simulations described in our proposal, a number of preparatory efforts were completed in the first semester. In Tables 1 and 2, we reproduce the research objectives and milestones from our 2016 proposal. We expand on the current status of each objective and related achievements in the following subsections.

Table 1: Research Objectives

RO.A	Simulate galactic outflows with numerical models that allow for supersonic wind velocities.
RO.B	Quantify the importance of radiative cooling for the multiphase structure of observed galactic outflows.
RO.C	Determine the mass and energy coupling of ISM gas to supernova-driven outflows.

Table 2: Research Milestones

Milestone		**Objective**
	Semester 1	
RM.A	Create and test initial conditions for galactic disk simulations.	RO.A
RM.B	Implement and calibrate feedback model for driving galactic outflows.	RO.A
	Semester 2	
RM.C	Model the multiphase structure and radiative cooling of galactic outflows on ~ 10kpc scales.	RO.A, RO.B
	Semester 3	
RM.D	Determine the role of full three-dimensionality on the velocity and density structure of galactic outflows.	RO.A, RO.B
	Semester 4	
RM.E	Simulate galactic outflows at large dynamic range to generate *ab initio* ~ 10kpc-scale winds from ~pc-scale supernovae bubbles.	RO.A, RO.B, RO.C

1.1.1 Research Milestone A: Create and test initial conditions for galactic disk simulations

The first major accomplishment of our project is the successful creation of an initial conditions generator for our global galactic disk simulations. Implemented as a module in our code, *Cholla*, the initial conditions for these simulations consist of a 10^4 K isothermal gas disk that is placed in vertical hydrostatic equilibrium with a background potential. The background potential consists of a Miyamoto-Nagai disk that represents the gaseous and stellar components of the galaxy, plus a Navarro-Frenk-White halo profile that accounts for the dark matter contribution to the potential. The disk is initially set to be differentially rotating, with the velocity gradient balancing the radial pressure profile. In addition to a disk, our initial conditions also contain a gaseous halo. The halo is set to be in adiabatic hydrostatic equilibrium with the background potential, which prevents it from collapsing onto the disk.

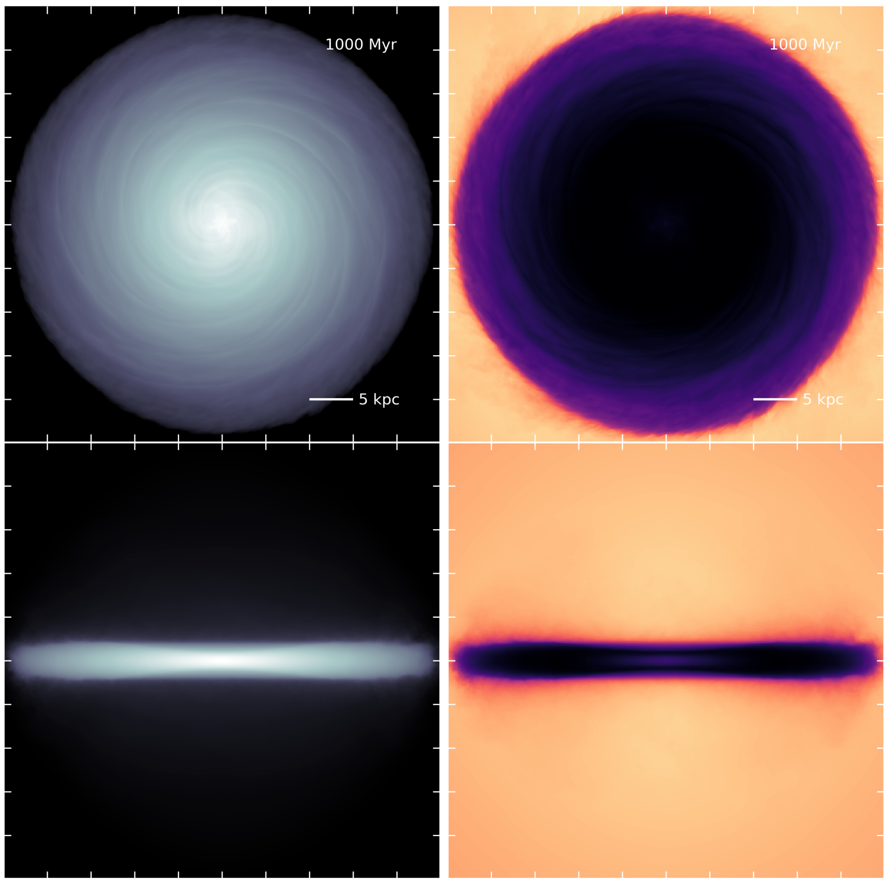

Figure 1. Figure caption.

We have created two versions of these initial conditions, one with parameters representative of a Milky-Way-like galaxy, and one with parameters that mimic those of the nearby starburst galaxy M82. An example of the Milky Way galaxy after 1 Gyr of evolution is shown in Figure 1. The left panels show projected gas density in the x-y and x-z planes, while the right panels show projected gas temperature. After many millions of years of evolution, the differential rotation of the gas in the disk leads to the spiral features that can be seen in the x-y density projection. A small amount of turbulence is generated on the surface of the disk due to the shear between disk and halo gas (only the disk gas is given an initial rotation). Otherwise, the disk and halo look almost identical to their initial setup. Adiabatic simulations using both versions of the initial conditions have demonstrated that they are stable for at least a gigayear, far longer than our wind simulations will be run. Compared to similar projects in the literature, our initial conditions are highly specialized (see e.g. Cooper et al. 2008, Fielding et al. 2017). Most models simply use an isothermal disk with no halo, or an isothermal halo. When experimenting with our initial conditions, we found that isothermal halo models were not stable over the long term. In addition, our simulations require the presence of an initial halo to determine the effect that swept-up hot halo gas may have on the evolution of galactic winds. Thus, our highly specialized initial conditions represent a necessary advancement of the field.

1.1.2 Research Milestone B: Implement and calibrate feedback model for driving galactic outflows

The second major accomplishment of our program is a unique implementation of a supernova feedback model that will allow us to test the premise that supernova-driven winds can cool radiatively at large radii. The theoretical studies that our project aims to test are extensions to the 1985 supernova-driven wind model of Chevalier & Clegg. This model, hereafter referred to as CC85, posits that a constant deposition of mass and energy within a spherical region in the center of a galaxy should result in a spherically-expanding flow of gas outward. Exact solutions for the density, velocity, and pressure of the wind can be calculated as a function of radius. Neither radiative cooling of the wind nor the effect of a gravitational potential are considered in the CC85 model. Despite this, X-ray observations indicate that the CC85 model is a good fit for the central region of the superwind in M82 (Strickland & Heckman, 2009).

More recent models have extended the CC85 model to include the effects of both gravity and radiative cooling (Wang 1995, Thompson 2016). These models suggest that given sufficient mass-loading of the hot wind, dramatic cooling can take place at radii 1 - 10 kpc from the wind-generation radius, which could account for the fast-moving, cool gas observed around starburst galaxies. In order to efficiently test this cooling model, we have created a supernova feedback model that matches the CC85 model as closely as possible. In Year 2, we will extend this model to incorporate more realistic versions of supernova feedback. Our current feedback model assumes a constant rate of mass and energy injection within the starburst radius, with the mass and energy injection set by three parameters: the star formation rate, the mass-loading factor, and the supernova thermalization efficiency. Our initial models use reasonable parameters for the past star formation rate, mass-loading, and supernova thermalization efficiency as calculated from observations of M82. The resulting wind can then be compared against the theoretically-calculated model, as shown in 2.

Our fiducial model uses a star formation rate of 20 $M_{\odot}$/yr, a mass-loading factor of $\beta = 1.4$, and a supernova thermalization efficiency of $\alpha = 0.9$. 2 displays the density, velocity, temperature, and pressure of the resulting wind as a function of radius. Plotted in this figure are both the exact solution (black line), as well as the values along the z-axis of one of our calibration simulations at 5, 15, and 25 Myr. We start the supernova feedback after 5 Myr, so the blue line is representative of the values of our initial conditions. The orange and green lines are difficult to detect, because they lie *directly* underneath the exact solution, demonstrating that within 10 million years, this feedback model has set up a stable wind with outflow parameters that match those expected. (Note that this is a simulation *without* radiative cooling. This figure represents an achievement both for the CC85 analytic model, as well as for our code *Cholla*.

As a control for our radiatively-cooling wind simulations, we have run a production-scale adiabatic simulation with these fiducial parameters. Our production simulation are run on grids with $2048 \times 2048 \times 2048$ cells, in a domain with dimensions 5 kpc $\times$ 5 kpc $\times$ 10 kpc, giving a resolution of 4.9 pc at all locations in the simulation volume. Density and temperature projections for this adiabatic control simulation after 30 million years of evolution are shown in Figure 3. The biconical outflow driven by the central energy and mass input is clearly visible in the temperature projection, as is the fall-off in temperature with radius due to the expansion of the flow. The energy injection has resulted in the blow-out of all of the gas from the central region of the disk. This simulation represents by far the largest hydrodynamic simulation of an isolated galaxy ever performed, and its hydrodynamic resolution tops that

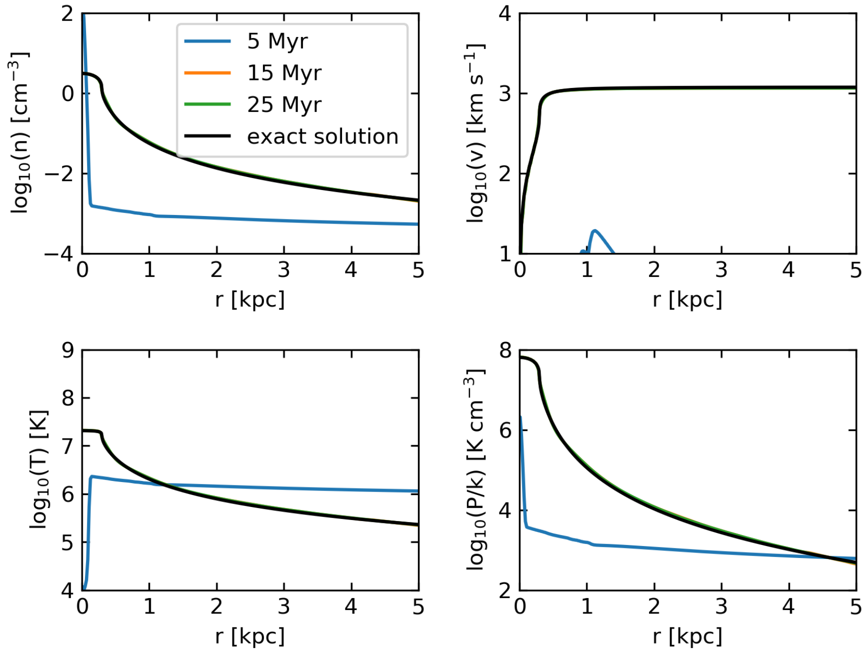

Figure 2. Figure caption.

of even the current largest cosmological simulations (e.g. the IllustrisTNG simulation, Nelson 2017, which has ~15.6 million hydrodynamic particles, vs. our ~17.2 million cells). Thus, despite the fact that this is merely our control simulation, it represents a major achievement and technological milestone for our program.

An advantage of our current simple feedback scheme is that it allows us to easily adjust the three parameters (SFR, mass-loading, and thermalization efficiency), in order to determine what range of parameters can cool on large scales. With our remaining 2017 allocation, we will be able to perform three production simulations with radiative cooling, that will explore the range of necessary mass-loading in order to achieve large-scale cooling in winds.

1.1.3 Research Objective A: Simulate galactic outflows with numerical models that allow for supersonic wind velocities

With the completion of Research Milestones A and B in Semester 1, we have also demonstrated that we have achieved the first research objective of our INCITE program: to simulate galactic outflows with numerical models that allow for supersonic wind velocities. While theoretical models had indicated that these starburst-driven winds should achieve supersonic velocities, the planar geometries employed in previous studies prevented winds from crossing the sonic point (see discussion in Martizzi et al. 2016). By simulating winds on a global scale, we have demonstrated that not only can winds achieve supersonic velocities, but that in scenarios where the injection rates can be well-approximated by the CC85 model, the large-scale features of those winds can be well-approximated by theory. We now turn to a discussion of the radiatively-cooling wind models that are the focus of our research program.

1.1.4 Research Milestone C: Model the multiphase structure and radiative cooling of galactic outflows on ~10 kpc scales

Our 2016 INCITE proposal devotes all of Semester 2 to achieving Research Milestone C. As we are only a few weeks into Semester 2, we do not yet have most of the results, but we do have some early indications that the predictions of the theoretical models with radiative cooling will be born out in our production simulations. Figure 4 shows the temperature in slices through the x-z plane for a calibration simulation (resolution $512 \times 512 \times 1024$ cells) with and without radiative cooling (left and right, respectively). Both snapshots show the simulations after 22 million years of evolution. While the 10^4 K disk is clearly visible on both simulations, the simulation with cooling also shows a large amount of gas between 2 - 5 kpc that has cooled to 10^4 K. Early analysis of this simulation suggests that the velocities of this cool gas may be consistent with observations, which would make these the first simulations to successfully reproduce gas in this phase in large-scale galactic winds.
We are currently finalizing the parameters for our production-scale radiative cooling wind simulations. Once we have decided on the appropriate parameters, we will run three production simulations with radiative cooling, which when compared with the adiabatic simulation presented in the previous section, will allow us to definitively answer the question posed by our Research Objective B: Quantify the importance of radiative cooling for the multiphase structure of observed galactic outflows.

1.2 Allocation Use

As of July 25th, our project has used 8.14 million core-hours, of the 46 million core-hours we were allotted for Year 1. This is in line with our planned usage, although the exact details of the simulations run differ slightly from those outlined in the proposal. In particular, our calibration simulations were more efficient than initially anticipated, which resulted in our usage for Semester 1 totaling ~ 1.5 million hours, rather than the 5 million we projected in the proposal. The large calibration simulations consisted of two 1024^3 simulations, each run on 512 GPUs, and a $1024 \times 1024 \times 2048$ simulation run on 1024 GPUs. The first two were tests of the stable Milky Way and M82 initial conditions (such as the simulation shown in Figure 1). The third, larger calibration simulation was a test of the supernova feedback model and wind generation scheme for the adiabatic model. The initial conditions test simulations took only $\sim 200,000$ core-hours, because they do not contain any very hot ($T > 10^7$ K) gas. The wind simulation took approximately ~ 1 million core-hours because the presence of very hot gas drives the simulation time-step down significantly. In the course of creating and testing our initial conditions and supernova feedback schemes, we have run many smaller (16 - 256 GPUs) simulations as well, but these have not contributed significantly to our allocation usage. We anticipate that we will continue to run these small test simulations throughout the first half of Semester 2, as we finalize the parameters for the remainder of our Year 1 production simulations. The majority of time spent thus far was used on the first of our Production Simulations, all scheduled to be run in Semester 2 in keeping with our proposal. Each production simulation will be run in a volume containing $2048 \times 2048 \times 4096$ cells, and will be run on 8192 GPUs. The first of these production simulations, shown in Figure 3, will take a total of ~ 10 million core-hours (it is currently about 70% of the way through). Based on this simulation, we anticipate running an additional three production simulations in Semester 2, ideally between August and October. The remaining three simulations will include the effects of radiative cooling on the outflow, and will differ in the parameters of the supernova feedback in order to test the conditions under which large-scale cooling does and does not occur.

1.3 Application Parallel Performance

Our primary tool, the hydrodynamics code *Cholla*, was built natively to run on GPUs. The efficiency of the GPU kernels in *Cholla* ranges from 10 - 20%. As the code was being built, great care was taken to optimize it for the GPU architectures, but register pressure on the K20's currently limits the efficiency of most kernels. (This effect will be mitigated on newer GPU architectures that devote more registers / GPU - for example, our code runs 5x faster on the P100 vs K20x without any modification.) An additional 25% of each timestep is spent on copying memory to and from the GPU, so we estimate that our overall performance (percent of peak) is around 10%. The weak scaling of our code is quite good. A time step takes about 50% longer when running on 8192 nodes vs. 16. The additional time is due entirely to the MPI communications, which, although optimized, are the only part of the code that does not scale perfectly. We have not run into any technical challenges in scaling *Cholla* from dozens to thousands of nodes, a testament to the planning that went into construction of the code.

1.4 Data Storage

Our project is currently using about 40 terabytes of data storage. Each of the production simulations that will be run this semester is expected to fill about that much, so we anticipate needing ~160 TB by the end of 2017. This gives us 100 full snapshots throughout the 100 million year evolution of the simulation. If necessary, we could reduce the frequency of output for the full grid. In an effort to reduce the amount of data required to be stored, we have written new routines in the code that output more frequent projections in several variables. This allows us to make high time resolution movies of the simulations, without accumulating nearly as much data (the size of the projected snapshots is negligible compared to the full grid).

Thus far, we have relied entirely on writing our own routines to reduce and analyze the data. This has been working well - all of the images shown in this proposal were made with our analysis and visualization code. We are working on setting up a website to share movies and animations from our project. We will also share what data we can, but at present we do not have the resources to store 10's of terabytes at our home institutions. All of our code and analysis routines are already publicly available on github.

REFERENCES (optional, not included in the page count)

1. Chevalier, R.A. and Clegg, A.W. "Wind from a starburst galaxy nucleus" *Nature*, **317**(6032): 44–45 (1985).
2. Cooper, J.L., et al. "Three-Dimensional Simulations of a Starburst-driven Galactic Wind" *ApJ*, **674**(1): 157–171 (2008).
3. Fielding, D., et al. "How Supernovae Launch Galactic winds" *arxiv e-posting*:1704.01579 (2017).
4. Martizzi, D., et al. "Supernova Feedback in a Local Vertically Stratified Medium: Interstellar Turbulence and Galactic Winds" *MNRAS*, **459**(3): 2311–2326 (2016).
5. Nelson, D. et al., "First Results from the IllustrisTNG Simulations: the Galaxy Color Bimodality" *arxiv e-posting*:1707.03395 (2017).
6. Strickland, D.K. and Heckman, T.M. "Supernova Feedback Efficiency and Mass Loading in the Starburst and Galactic Superwind Exemplar M82" *ApJ*, **697**(2): 2030–2056 (2009).
7. Thompson, T.A., et al. "An Origin for Multiphase Gas in Galactic Winds and Haloes" *MNRAS*, **455**(2): 1830–1844 (2016).
8. Wang, B. "Cooling Gas Outflows from Galaxies" *ApJ*, **444**: 590–609 (1995).

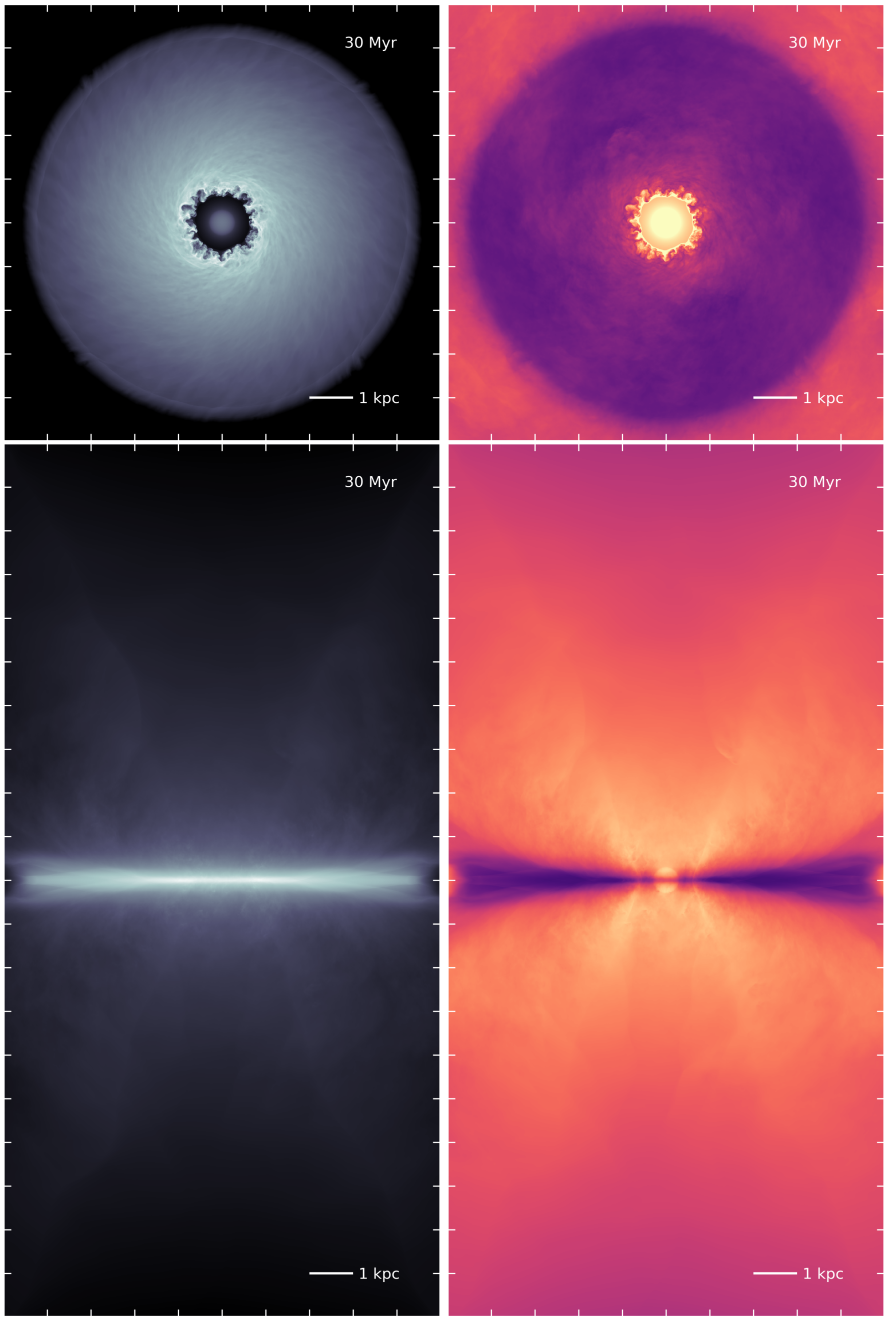

Figure 3. Figure caption.

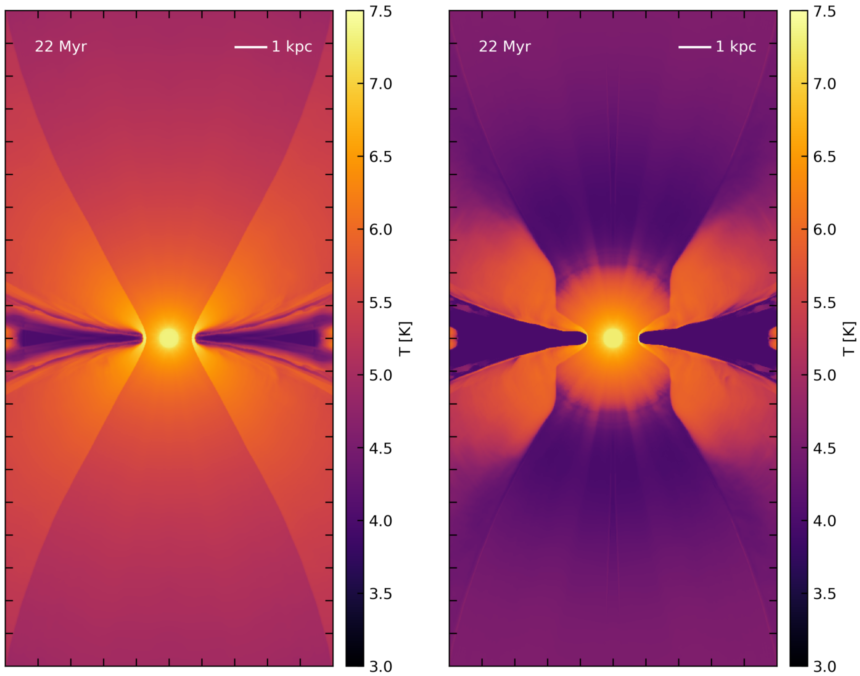

Figure 4. Figure caption.