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# AstroPaint: A Python Package for Painting Halo Catalogs into Celestial Maps

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**Software**

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## Overview

`AstroPaint` is a python package for generating and visualizing sky maps of a wide range of astrophysical signals originating from dark matter halos or the gas that they host. `AstroPaint` creates a whole-sky mock map of the target signal/observable, at a desired resolution, by combining an input halo catalog and the radial/angular profile of the astrophysical effect (see the workflow section for details). The package also provides a suite of tools that can facilitate analysis routines such as catalog filtering, map manipulation, and cutout stacking. The simulation suite has an Object-Oriented design and runs in parallel, making it both easy to use and readily scalable for production of high resolution maps with large underlying catalogs. Although the package has been primarily developed to simulate signals pertinent to galaxy clusters, its application extends to halos of arbitrary size or even point sources.

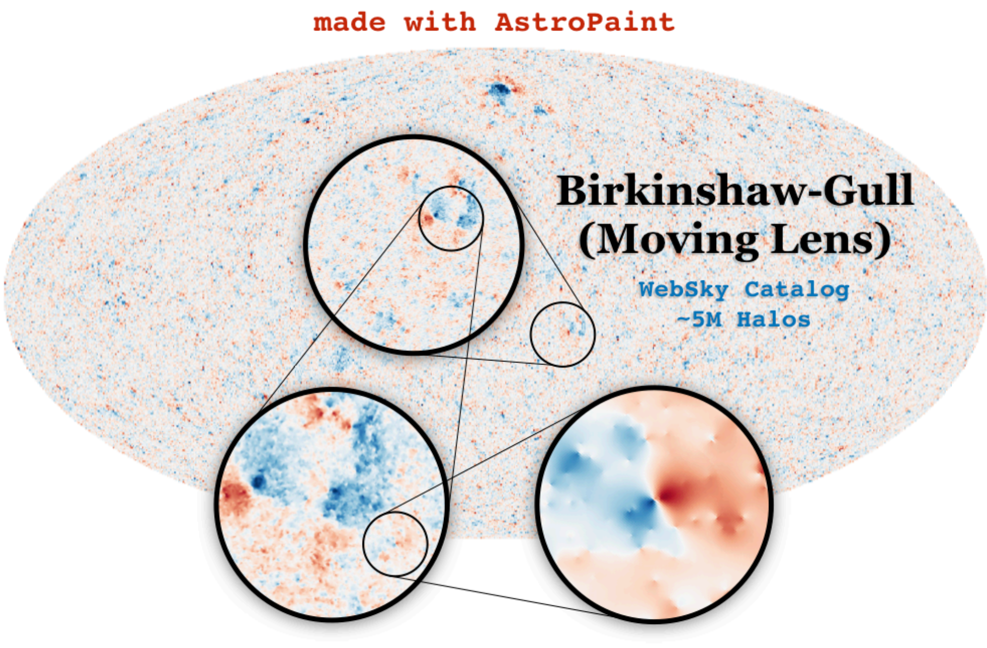


**Figure 1:** Map of the Birkinshaw-Gull effect painted with AstroPaint using the WebSky catalog

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## Statement of Need

Studying the large scale structure of the universe heavily relies on observations of astrophysical signals at various frequencies. Examples of such studies include detection or characterization of objects such as galaxies, clusters, or voids through either gravitational lensing, electromagnetic scattering, absorption or emission events in the optical, radio, or x-ray frequency bands. Such studies typically require simulated high resolution maps of various astrophysical effects to emulate both the signal and noise (foregrounds) components. For example, in a study that aims to evaluate the detection significance of the Birkinshaw-Gull (BG) effect – a probe of the transverse velocities of halos (Birkinshaw & Gull, 1983; Yasini et al., 2019) – using the Simons Observatory (Abitbol & others, 2019) or CMB-S4 (Abazajian & others, 2019), one needs a mock map of the BG effect Figure 1 as well as maps of potential contaminants such as kinetic and thermal Sunyaev-Zeldovich effects (kSZ and tSZ) (Sunyaev & Zeldovich, 1970) for the same set of objects.

While it is possible to create realistic maps of astrophysical effects through hydrodynamical simulations (Dolag et al., 2016), these methods are numerically expensive for large numbers of objects and reproducing them under different cosmologies and initial conditions can be prohibitive. An alternative strategy for creating mock observations of extended objects such as galaxies and galaxy cluster halos is to simulate the positions of these objects (either semi-analytically or through N-body simulations (Sehgal et al., 2010; Stein et al., 2019; Stein et al., 2020)) and then synthetically paint the desired signal at the location of the halos. `AstroPaint` is developed to help researchers in creating mock maps using the latter strategy.

AstroPaint can also be used to create templates for detecting astrophysical effects in image data. For example, to detect kSZ for an ensemble of galaxies in a CMB map, one needs a template of this effect for the observed patch of the sky. Such a template can be generated by taking the catalog of the target galaxies along with their velocities and painting kSZ profiles around them on a map using `AstroPaint`.

## Package Structure and Workflow

`AstroPaint` consists of three main objects that interact with each other: `Catalog`, `Canvas`, and `Painter`.

`Catalog` contains the locations, velocities, and masses of the objects. `Canvas` contains the map of the astrophysical signal in HEALPix format (Zonca et al., 2019). `Painter` contains the template for the radial profile of the signal to be painetd on the `Canvas` in circular discs centered at the location of the halos in the `Catalog`.

These objects are sequentially passed into each other according to the following workflow:

```
from astropaint import Catalog, Canvas, Painter

catalog = Catalog(data=input_data)
canvas = Canvas(catalog, nside)
painter = Painter(template=radial_profile)

painter.spray(canvas)
```

The output map array can be accessed via `canvas.pixels` or directly visualized using `canvas.show_map()`. Here `input_data` is the dataframe that hold the locations, velocities, and masses of the halos. `nside` is a parameter in `healpy` that determines the total number of pixels (`npix = 12 * nside ** 2`) and consequently the resolution of the map . Finally, `radial_profile` is a one-dimensional function that determines the shape of the profile. A mind map visualization of the package structure can be found in here.

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