Shear Mapping in Python (SMPy): Modular, Extensible, and Accessible Dark Matter Mapping

Georgios N. Vassilakis [1¶], **Jacqueline E. McCleary** [1], **Maya Amit** [1], and **Sayan Saha** [1]

1 Department of Physics, Northeastern University, Boston, MA, USA ¶ Corresponding author

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Summary

Understanding the universe's large-scale distribution of dark matter is a central objective in the era of precision cosmology. A key technique for the study of dark matter is weak gravitational lensing: a phenomenon where light from distant galaxies is sheared as it passes through the gravitational field of a massive object, like a galaxy cluster. This shear, which manifests as a slight (weak) distortion of shapes over thousands of galaxies, allows astrophysicists to infer the distribution of total matter, including both luminous and dark matter.

Obtaining a mass distribution from a catalog of galaxy shears requires an intermediate step. A common tool for this step is the mapping of convergence (κ), which quantifies how much a gravitational lens converges the light from distant galaxies, resulting in a magnification of their shapes. This value is directly proportional to the projected mass density, enabling easy visualization of the overall mass distribution. For a comprehensive review of weak gravitational lensing, refer to (Umetsu, 2020).

The **Shear Mapping in Python (SMPy)** package provides a standardized, well-documented, and open-source solution for creating convergence maps from weak lensing galaxy shear measurements. `SMPy` was initially developed to support the Superpressure Balloon-borne Imaging Telescope (SuperBIT), a stratospheric, near-UV to near-IR observing platform which completed its 45-night observing run in spring 2023 with over 30 galaxy cluster observations (Gill et al., 2024; Sirks et al., 2023). `SMPy` has since evolved into a general-purpose tool suitable for analyzing the weak lensing data from cosmological surveys.

Statement of Need

While mass maps are a key deliverable of many cosmological analyses (Jeffrey et al., 2021; Madhavacheril et al., 2024; Oguri et al., 2017), scientists are often left to make these maps from scratch. The weak lensing community is served by publicly available mapping tools like `lenspack` and `jax-lensing` (Remy et al., 2022), each with their own strengths. `jax-lensing` excels at neural network-based approaches and deep learning methods, while `lenspack` has a well-documented module with stand-alone mass-mapping functions. While both tools are powerful, the steep learning curve of `jax-lensing` and the rigid architecture of `lenspack` motivated the development of `SMPy` as an accessible and extensible alternative.

`SMPy` addresses an outstanding need for the lensing community: an accessible, well-documented, and extensible tool to construct publication-quality mass maps from galaxy shear data. Built on standard scientific Python packages, it provides an easy entry point for researchers new to mass mapping, while also being robust for more senior scientific use. There are currently three separate mapping methods implemented into `SMPy`: the classic Kaiser-Squires inversion (Kaiser & Squires, 1993), aperture mass mapping (Leonard et al., 2012; McCleary et al., 2020), and notably, to our knowledge, the first publicly available implementation of the KS+ algorithm (Pires, 2020). KS+ improves reconstruction quality by correcting for systematic effects including missing data, field borders, and reduced shear. SMPy also offers specialized and unique features valuable for mass mapping, such as flexible coordinate system support (both celestial and pixel space) and comprehensive signal-to-noise analysis with multiple noise randomization techniques. An example convergence map, created from simulated SuperBIT galaxy cluster observations (McCleary et al., 2023), is shown in Figure 1. SMPy is, to our knowledge, the first convergence mapping software to prioritize both accessibility and advanced features.

Software Features

SMPy was built with the following design principles in mind:

1. **Accessibility:** SMPy is written entirely in Python and deliberately relies only on widely-used scientific Python packages (NumPy, SciPy, Pandas, Astropy, Matplotlib, and PyYAML). This choice of standard dependencies ensures that users can easily install the packages without complex dependency chains, and that the codebase is maintainable and familiar to the scientific Python community.
2. **Extensibility:** SMPy's modular architecture enables seamless addition of new mass mapping techniques, encouraging open-source contribution. The framework's standardized abstract base class architecture allows for the integration of different mapping methods with minimal effort.
3. **Usability:** Creating convergence maps with SMPy requires minimal input—users need to only provide a catalog of galaxies with their associated shear components and coordinates. This straightforward input requirement makes the tool accessible to researchers at all levels. A flexible configuration system is integrated via a single YAML file that defines file paths, convergence map algorithm settings, plotting parameters, and more. With this configuration file, the user can create convergence and SNR maps with one line, either via terminal or within code.
4. **Robustness:** SMPy is designed to be mathematically and algorithmically accurate, allowing the user to create convergence maps with any galaxy shear data. The coordinate system abstraction handles both celestial coordinates (with proper spherical geometry approximations) or pixel-based coordinates through a unified interface. To quantify the significance of the weak lensing detection, multiple noise realizations can be generated using either spatial shuffling (randomizing galaxy positions while preserving shear values) or orientation shuffling (randomizing shear orientations while preserving positions). These noise realizations are used to create a signal-to-noise map with the observed convergence.

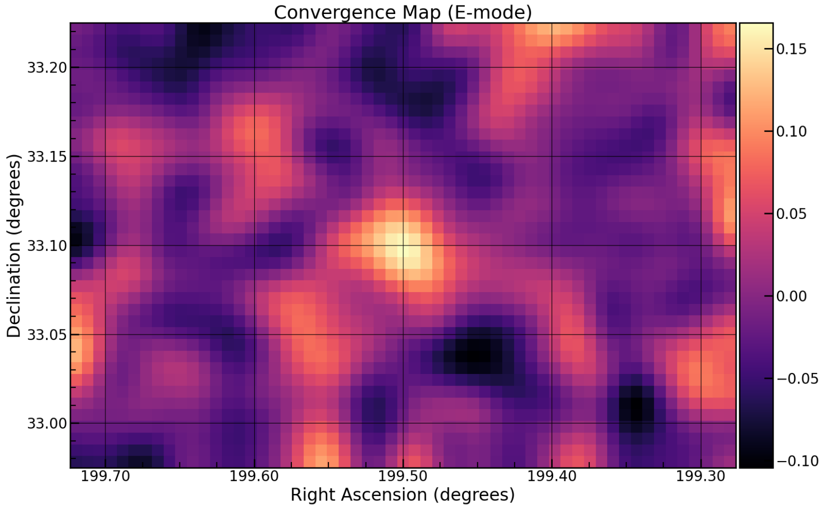

Figure 1: Example convergence map created with SMPy showing the mass distribution of a simulated galaxy cluster. The map was generated using the Kaiser-Squires inversion method on simulated weak lensing data from SuperBIT. The color scale represents the dimensionless surface mass density (convergence), with brighter regions indicating higher mass concentrations.

Software References

`SMPy` is written in Python 3.8+ and uses the following packages:

- `NumPy` (Harris et al., 2020)
- `SciPy` (Virtanen et al., 2020)
- `Pandas` (team, 2024)
- `Astropy` (Astropy Collaboration et al., 2013, 2018, 2022)
- `Matplotlib` (Hunter, 2007)
- `PyYAML` (Simonov, 2024)

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