

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

Georgios N. Vassilakis<sup>1</sup>, Jacqueline E. McCleary<sup>1</sup>, Maya Amit<sup>1</sup>, and Sayan Saha<sup>1</sup>

<sup>1</sup> Department of Physics, Northeastern University, Boston, MA, USA ¶ Corresponding author

DOI: [10.xxxxxx/draft](https://doi.org/10.xxxxxx/draft)

## Software

- [Review](#)
- [Repository](#)
- [Archive](#)

Editor: [Open Journals](#)

## Reviewers:

- [@openjournals](#)

Submitted: 01 January 1970

Published: unpublished

## License

Authors of papers retain copyright and release the work under a Creative Commons Attribution 4.0 International License ([CC BY 4.0](#)).

## 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 ( $\kappa$ ), 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 ([Madhavacheril et al., 2024](#)) ([Jeffrey et al., 2021](#)) ([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.

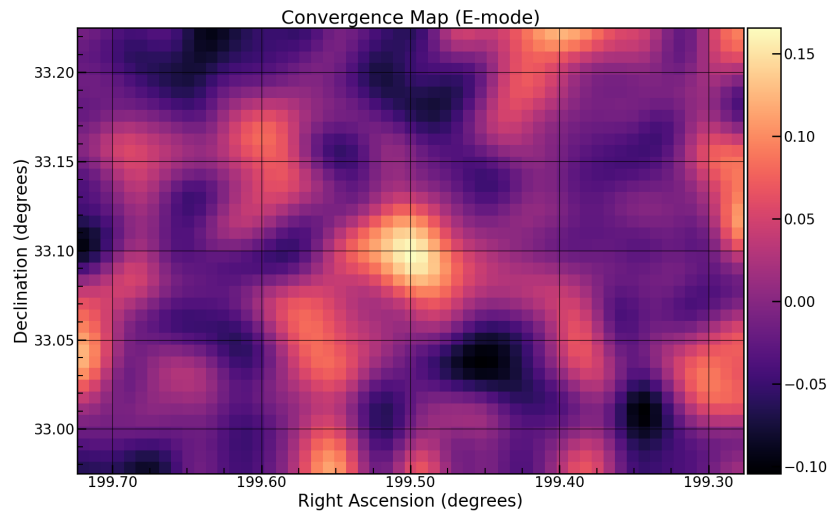
SMPy addresses an outstanding need for the lensing community: an accessible, well-documented, and extensible tool to construct publication-quality mass maps from galaxy shear data. Built on standard scientific Python packages, it provides an easy entry point for researchers new to mass mapping, while also being robust for more senior scientific use. It 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

41 randomization techniques. Its modular architecture also enables future contributions of new  
42 mapping methods. An example convergence map, created from simulated SuperBIT galaxy  
43 cluster observations (McCleary et al., 2023), is shown in Figure 1. SMPy is, to our knowledge,  
44 the first convergence mapping software to prioritize both accessibility and advanced features.

## 45 Software Features

46 SMPy was built with the following design principles in mind:

- 47 1. **Accessibility:** SMPy is written entirely in Python and deliberately relies only on widely-used  
48 scientific Python packages (numpy, scipy, pandas, astropy, matplotlib, and pyyaml).  
49 This choice of standard dependencies ensures that users can easily install the packages  
50 without complex dependency chains, and that the codebase is maintainable and familiar  
51 to the scientific Python community.
- 52 2. **Extensibility:** SMPy is built with a modular architecture that allows for easy implementation  
53 of new mass mapping techniques beyond the currently implemented Kaiser-Squires  
54 inversion algorithm (Kaiser & Squires, 1993). For example, we are planning to add  
55 aperture mass mapping (Leonard et al., 2012) and KS+ (Pires, 2020) algorithms to the  
56 codebase.
- 57 3. **Usability:** Creating convergence maps with SMPy requires minimal input—users need to  
58 only provide a catalog of galaxies with their associated shear components and coordinates.  
59 This straightforward input requirement makes the tool accessible to researchers at all  
60 levels. A flexible configuration system is integrated via a single YAML file that defines  
61 file paths, convergence map algorithm settings, plotting parameters, and more. With  
62 this configuration file, the user can create convergence & SNR maps with one line, either  
63 via terminal or within code.
- 64 4. **Robustness:** SMPy is designed to be mathematically and algorithmically accurate, allowing  
65 the user to create convergence maps with any galaxy shear data. The coordinate  
66 system abstraction handles both celestial coordinates (with proper spherical geometry  
67 approximations) or pixel-based coordinates through a unified interface. To quantify the  
68 significance of the weak lensing detection, multiple noise realizations can be generated  
69 using either spatial shuffling (randomizing galaxy positions while preserving shear values)  
70 or orientation shuffling (randomizing shear orientations while preserving positions). These  
71 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., 2022](#)) ([Astropy Collaboration et al., 2018](#)) ([Astropy Collaboration et al., 2013](#))
- Matplotlib ([Hunter, 2007](#))
- PyYAML ([Simonov, 2024](#))

## Acknowledgements

This material is based upon work supported by a Northeastern University Undergraduate Research and Fellowships PEAK Summit Award.

## References

- Astropy Collaboration, Price-Whelan, A. M., Lim, P. L., Earl, N., Starkman, N., Bradley, L., Shupe, D. L., Patil, A. A., Corrales, L., Brasseur, C. E., Nöthe, M., Donath, A., Tollerud, E., Morris, B. M., Ginsburg, A., Vaher, E., Weaver, B. A., Tocknell, J., Jamieson, W., ... Astropy Project Contributors. (2022). The Astropy Project: Sustaining and Growing a Community-oriented Open-source Project and the Latest Major Release (v5.0) of the Core Package. *935*(2), 167. <https://doi.org/10.3847/1538-4357/ac7c74>
- Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., Günther, H. M., Lim, P. L., Crawford, S. M., Conseil, S., Shupe, D. L., Craig, M. W., Dencheva, N., Ginsburg, A., VanderPlas, J. T., Bradley, L. D., Pérez-Suárez, D., de Val-Borro, M., Aldcroft, T. L., Cruz, K. L., Robitaille, T. P., Tollerud, E. J., ... Astropy Contributors. (2018). The Astropy Project: Building an Open-science Project and Status of the v2.0 Core Package. *156*(3), 123. <https://doi.org/10.3847/1538-3881/aabc4f>

- 97 Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., Greenfield, P., Droettboom, M., Bray,  
98 E., Aldcroft, T., Davis, M., Ginsburg, A., Price-Whelan, A. M., Kerzendorf, W. E., Conley,  
99 A., Crighton, N., Barbary, K., Muna, D., Ferguson, H., Grollier, F., Parikh, M. M., Nair, P.  
100 H., ... Streicher, O. (2013). Astropy: A community Python package for astronomy. *558*.
- 101 Gill, A. S., Benton, S. J., Damaren, C. J., Everett, S. W., Fraisse, A. A., Hartley, J. W.,  
102 Harvey, D., Holder, B., Huff, E. M., Jauzac, M., Jones, W. C., Lagattuta, D., Leung, J.  
103 S.-Y., Li, L., Luu, T. V. T., Massey, R., McCleary, J. E., Nagy, J. M., Netterfield, C. B., ...  
104 Vitorelli, A. Z. (2024). SuperBIT superpressure flight instrument overview and performance:  
105 Near-diffraction-limited astronomical imaging from the stratosphere. *The Astronomical*  
106 *Journal*, *168*(2), 85. <https://doi.org/10.3847/1538-3881/ad5840>
- 107 Harris, C. R., Millman, K. J., Walt, S. J. van der, Gommers, R., Virtanen, P., Cournapeau, D.,  
108 Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., Kerkwijk,  
109 M. H. van, Brett, M., Haldane, A., Río, J. F. del, Wiebe, M., Peterson, P., ... Oliphant,  
110 T. E. (2020). Array programming with NumPy. *Nature*, *585*(7825), 357–362. <https://doi.org/10.1038/s41586-020-2649-2>
- 112 Hunter, J. D. (2007). Matplotlib: A 2D graphics environment. *Computing in Science &*  
113 *Engineering*, *9*(3), 90–95. <https://doi.org/10.1109/MCSE.2007.55>
- 114 Jeffrey, N., Gatti, M., Chang, C., Whiteway, L., Demirbozan, U., Kovacs, A., Pollina, G.,  
115 Bacon, D., Hamaus, N., Kacprzak, T., Lahav, O., Lanusse, F., Mawdsley, B., Nadathur, S.,  
116 Starck, J. L., Vielzeuf, P., Zeurcher, D., Alarcon, A., Amon, A., ... Collaboration, D. (2021).  
117 Dark energy survey year 3 results: Curved-sky weak lensing mass map reconstruction.  
118 *Monthly Notices of the Royal Astronomical Society*, *505*(3), 4626–4645. <https://doi.org/10.1093/mnras/stab1495>
- 119 Kaiser, N., & Squires, G. (1993). Mapping the dark matter with weak gravitational lensing.  
120 *404*, 441–450. <https://doi.org/10.1086/172297>
- 122 Leonard, A., Pires, S., & Starck, J.-L. (2012). Fast calculation of the weak lensing aperture  
123 mass statistic. *Monthly Notices of the Royal Astronomical Society*, *423*(4), 3405–3412.  
124 <https://doi.org/10.1111/j.1365-2966.2012.21133.x>
- 125 Madhavacheril, M. S., Qu, F. J., Sherwin, B. D., MacCrann, N., Li, Y., Abril-Cabezas, I., Ade,  
126 P. A. R., Aiola, S., Alford, T., Amiri, M., Amodeo, S., An, R., Atkins, Z., Austermann, J. E.,  
127 Battaglia, N., Battistelli, E. S., Beall, J. A., Bean, R., Beringue, B., ... Zheng, K. (2024). The  
128 atacama cosmology telescope: DR6 gravitational lensing map and cosmological parameters.  
129 *The Astrophysical Journal*, *962*(2), 113. <https://doi.org/10.3847/1538-4357/acff5f>
- 130 McCleary, J. E., Everett, S. W., Shaaban, M. M., Gill, A. S., Vassilakis, G. N., Huff, E.  
131 M., Massey, R. J., Benton, S. J., Brown, A. M., Clark, P., Holder, B., Fraisse, A.  
132 A., Jauzac, M., Jones, W. C., Lagattuta, D., Leung, J. S.-Y., Li, L., Luu, T. V. T.,  
133 Nagy, J. M., ... Tam, S. I. (2023). Lensing in the blue. II. Estimating the sensitivity of  
134 stratospheric balloons to weak gravitational lensing. *The Astronomical Journal*, *166*(3),  
135 134. <https://doi.org/10.3847/1538-3881/ace7ca>
- 136 Oguri, M., Miyazaki, S., Hikage, C., Mandelbaum, R., Utsumi, Y., Miyatake, H., Takada,  
137 M., Armstrong, R., Bosch, J., Komiyama, Y., Leauthaud, A., More, S., Nishizawa, A. J.,  
138 Okabe, N., & Tanaka, M. (2017). Two- and three-dimensional wide-field weak lensing  
139 mass maps from the hyper supprime-cam subaru strategic program S16A data. *Publications*  
140 *of the Astronomical Society of Japan*, *70*(SP1), S26. <https://doi.org/10.1093/pasj/psx070>
- 141 Pires, S. (2020). Euclid: Reconstruction of weak-lensing mass maps for non-gaussianity studies.  
142 *Astronomy & Astrophysics*, *638*, A141. <https://doi.org/10.1051/0004-6361/201936865>
- 143 Remy, B., Lanusse, F., Jeffrey, N., Liu, J., Starck, J.-L., Osato, K., & Schrabback, T. (2022).  
144 Probabilistic mass-mapping with neural score estimation. *Astronomy & Astrophysics*, *672*.  
145 <https://doi.org/10.1051/0004-6361/202243054>

- 146 Simonov, K. (2024). *PyYAML*. <https://pyyaml.org/>
- 147 Sirks, E. L., Massey, R., Gill, A. S., Anderson, J., Benton, S. J., Brown, A. M., Clark, P.,  
148 English, J., Everett, S. W., Fraisse, A. A., Franco, H., Hartley, J. W., Harvey, D., Holder,  
149 B., Hunter, A., Huff, E. M., Hynous, A., Jauzac, M., Jones, W. C., ... Vassilakis, G. N.  
150 (2023). Data downloaded via parachute from a NASA super-pressure balloon. *Aerospace*,  
151 10(11). <https://doi.org/10.3390/aerospace10110960>
- 152 team, T. pandas development. (2024). *Pandas-dev/pandas: pandas* (Version v2.2.2). Zenodo.  
153 <https://doi.org/10.5281/zenodo.10957263>
- 154 Umetsu, K. (2020). Cluster–galaxy weak lensing. *The Astronomy and Astrophysics Review*,  
155 28(1), 106. <https://doi.org/10.1007/s00159-020-00129-w>
- 156 Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D.,  
157 Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S. J., Brett, M., Wilson,  
158 J., Millman, K. J., Mayorov, N., Nelson, A. R. J., Jones, E., Kern, R., Larson, E., ... SciPy  
159 1.0 Contributors. (2020). SciPy 1.0: Fundamental Algorithms for Scientific Computing in  
160 Python. *Nature Methods*, 17, 261–272. <https://doi.org/10.1038/s41592-019-0686-2>

DRAFT