Wide-field, field-level compression for simulation-based inference (SBI)



for Euclid cosmic shear

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Effectiveness of field-level SBI





Euclid wide-field survey



R.A. (2000)

Field-level SBI techniques must be extended to support wide-fields, requiring spherical methods defined on the curved sky.



Wide-field, field-level SBI pipeline





Aside: Learned harmonic mean estimator for Bayesian evidence

Enhanced Bayesian model selection with learned harmonic mean

(McEwen et al. 2021, Spurio Mancini et al. 2022, Polanska et al. 2024, Piras et al. 2024)

- Requires posterior samples only
 ~> Evidence almost for free
- Agnostic to sampling technique
 - \rightsquigarrow Leverage efficient samplers
 - \rightsquigarrow Simulation-based inference (SBI)
 - → Variational inference
- $\cdot\,$ Scale to high-dimensions
 - \rightsquigarrow Normalizing flows

Accelerated Bayesian inference (Piras *et al.* 2024) 37 parameter cosmic shear analysis of LCDM vs w_0w_a CDM

- CAMB + PolyChord → 8 months on 48 CPU cores
- CosmoPower-JAX + NumPyro/NUTS + Harmonic
 ~> 2 days on 3 GPUs

157 parameter 3x2pt analysis of LCDM vs w_0w_a CDM

- CAMB + PolyChord ~ 12 years on 48 CPUs (projected)
- CosmoPower-JAX + NumPyro/NUTS + Harmonic
 → 8 days on 24 GPUs



harmonic: Learnt harmonic mean estimator of Bayesian evidence https://github.com/astro-informatics/harmonic

- 1. Neural compression
 - ▶ CNNs: Convolutional neural networks (*e.g.* Jeffrey *et al.* 2024)
- 2. Statistical compression
 - ▶ Scattering transforms (e.g. Cheng et al. 2024, Gatti et al. 2023)

Require **spherical CNNs** (Ocampo, Price, McEwen 2023, Cobb *et al.* 2021) and **spherical scattering transforms** (McEwen *et al.* 2022, Mouset *et al.* in prep.) defined on the curved sky.



Categorization of spherical CNN frameworks



McEwen et al. 2022, ...)

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Efficient Generalized Spherical CNNs

(Cobb et al. McEwen 2021, ICLR, arXiv:2010.11661)

Scalable and Equivariant Spherical CNNs by Discrete-Continuous (DISCO) Convolutions (Ocampo, Price & McEwen 2023, ICLR, arXiv:2209.13603)

Equivariance \Rightarrow state-of-the-art performance on all problems considered to date.



Spherical scattering networks (first generation)

Scattering networks inspired by CNNs but designed rather than learned filters (Mallat 2012).

Scattering networks on the sphere (McEwen et al. 2022, ICLR, arXiv:2102.02828)

Cascade of spherical wavelet transforms (McEwen et al. 2018) and non-linearities (modulus).



Generative models of astrophysical fields with scattering transforms on the sphere (Mousset, Allys, Price, *et al.* McEwen, in prep.)

Scattering covariance statistics considered:

1.
$$S_1[\lambda] f = \mathbb{E} [|f \star \psi_{\lambda}|].$$

2. $S_2[\lambda] f = \mathbb{E} [|f \star \psi_{\lambda}|^2].$
3. $S_3[\lambda_1, \lambda_2] f = \operatorname{Cov} [f \star \psi_{\lambda_2}, |f \star \psi_{\lambda_1}| \star \psi_{\lambda_2}].$
4. $S_4[\lambda_1, \lambda_2, \lambda_3] f = \operatorname{Cov} [|f \star \psi_{\lambda_1}| \star \psi_{\lambda_3}, |f \star \psi_{\lambda_2}| \star \psi_{\lambda_3}].$



Emulation: Generative modelling with scattering covariances

Which field is emulated and which simulated?



Figure 2: Logarithm (for visualization) of weak lensing field



Differentiable and GPU-accelerated spherical transform codes (in JAX)



Differentiable and accelerated spherical transforms

S2FFT is a Python package for computing Fourier transforms on the sphere and rotation group (Price & McEwen 2023) using JAX or PyTorch. It leverages autodiff to provide differentiable transforms, which are also deployable on hardware accelerators (e.g. OPUs and TPUs).

s2fft: Spherical harmonic transforms https://github.com/astro-informatics/s2fft

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Differentiable scattering covariances on the sphere

SSEAT is a Python package for computing scattering covariances on the sphere (<u>Mousset et al</u> 2024) using JAX. It exploits autodiff to provide differentiable transforms, which are also deployable on hardware accelerators (e.g. GPUs and TPUs), leveraging the differentiable and accelerated spherical harmonic and wavelet transforms implemented in Syster; and SY2MV, prospectively.

s2scat: Spherical scattering transforms
https://github.com/astro-informatics/s2scat

) Tests 🛛 passing 🕐 codecov 💷 Licence MIT pypi package 1.0.4 arXiv 2402.01282 all contributors 🧃 👀 Open in Colab



Differentiable and accelerated wavelet transform on the sphere

S264W is a python package for computing wavelet transforms on the sphere and rotation group, both in JAX and PyTorch. It leverages autodiff to provide differentiable transforms, which are also deployable on modern hardware accelerators (e.g. GPUs and TPUs), and can be mapped access multiple accelerators.

s2wav: Spherical wavelet transforms https://github.com/astro-informatics/s2wav



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Scalable and Equivariant Spherical CNNs by Discrete-Continuous (DISCO) Convolutions

Many problems across computer vision and the natural sciences require the analysis of spherical data, for which representations may be learned efficiently by encoding equivalance to rotational symmetries. <u>DISC0</u> provides foundational convolutional layers which encode said equivalance, with the aim to support the development of

s2ai: Spherical Al Coming very soon! Contact us for early access.



Summary

▷ Field-level SBI highly effective.

- ▷ For Euclid, require spherical methods defined on the curved sky.
- ▷ Neural compression:
 - ▶ Spherical CNNs (Cobb et al. McEwen 2021, Ocampo, Price & McEwen 2023)
- Statistical compression:
 - ► Spherical scattering transforms (McEwen et al. 2022)
 - Spherical scattering covariances (Mousset, Allys, Price, et al. McEwen, in prep.)
- ▷ Can also be used to develop **spherical emulators**.

Have the methods and codes needed to **develop a highly effective** wide-field, field-level SBI pipeline for Euclid cosmic shear.

