Scattering Transforms and component separation for ISM Physics

Erwan Allys - ENS, Paris
with C. Auclair, F. Boulanger, C. Bot, J.-M. Delouis, L. Mousset

Colloque PCMI,
Bordeaux, October 28th 2024

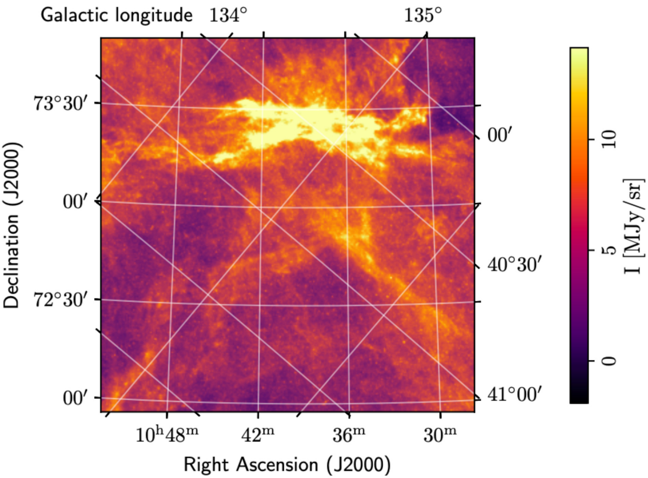
ENS ÉCOLE NORMALE SUPÉRIEURE | PSL RESEARCH UNIVERSITY PARIS

LPENS LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE

Outline

1. **Astrophysical data and component separation**
2. **An approach with Scattering Transforms**

- **Herschel SPIRE observation at 250 μm**



→ **Galactic dust emission + Cosmic Infrared Background (CIB)**
→ **Study Galactic dust at small scales?**

The need for component separation

- **Components mixture ubiquitous in ISM data**
  - Galactic dust emission and CIB (infrared)
  - Galactic foregrounds to CMB (microwaves)
  - Cold and Warn neutral media (radio)
  - ...

The need for component separation

- **Components mixture ubiquitous in ISM data**
  - Galactic dust emission and CIB (infrared)
  - Galactic foregrounds to CMB (microwaves)
  - Cold and Warn neutral media (radio)
  - ...

- **Lever arm for component separation**
  - Difference of spectral properties
  - Difference of spatial properties
    → Power spectrum
    → Morphology?

The need for component separation

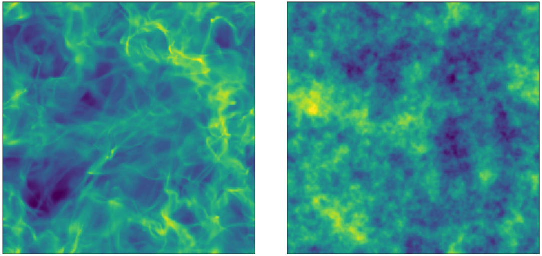
- **Components mixture ubiquitous in ISM data**
  - Galactic dust emission and CIB (infrared)
  - Galactic foregrounds to CMB (microwaves)
  - Cold and Warn neutral media (radio)
  - ...

- **Lever arm for component separation**
  - Difference of spectral properties
  - Difference of spatial properties
    → Power spectrum
    → Morphology?

→ Rely on morphological features for comp. sep.?
→ Directly applicable to astrophysical data?

Characterizing beyond Power Spectrum

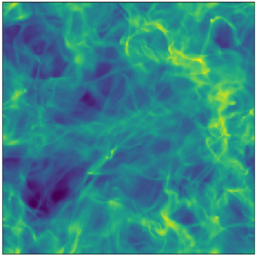
- **Limitations of the Power Spectrum**
  - Energy/Power in each Fourier mode
  - Each scale is treated independently
  - Do not characterize structures

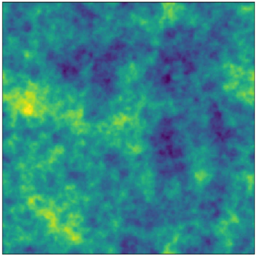


Fields of same power spectrum

Characterizing beyond Power Spectrum

- **Limitations of the Power Spectrum**
  - Energy/Power in each Fourier mode
  - Each scale is treated independently
  - Do not characterize structures

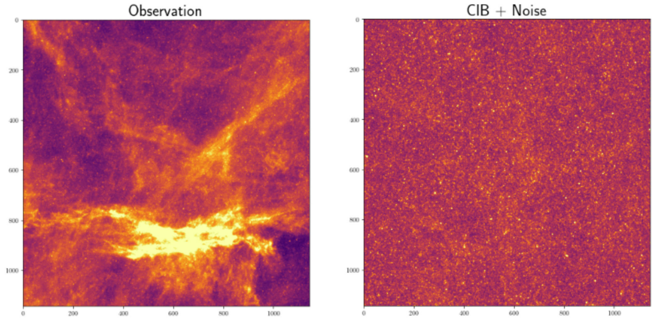




Fields of same power spectrum

→ Non-linearity ⇒ coupling between scales
→ Use dependency between scales as a lever arm?

Characterizing beyond Power Spectrum



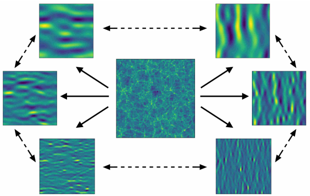
- **Galactic dust emission and Cosmic Infrared Background (CIB)**
  - Independent Lockman Hole observation (right)
  - Very distinct couplings between scales
  - Use small scale to infer intermediate scales?

→ How to perform such a separation?

Outline

Scattering transform (ST) statistics

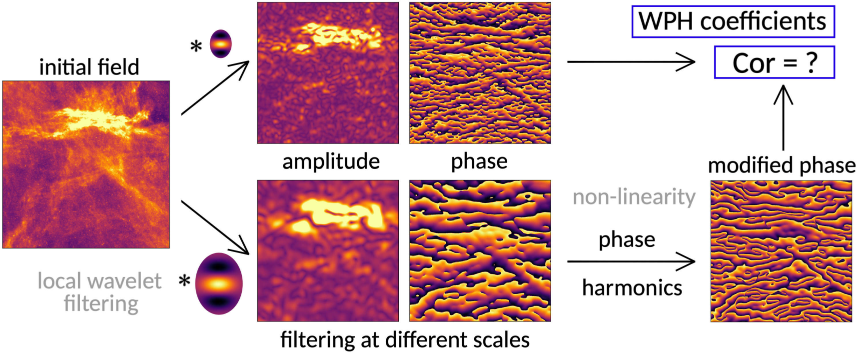
- **Scattering transform (ST) statistics** (Mallat+, 2010+)
  - Initially developed in data science
  - Inspired from neural networks
    $\rightarrow$ efficient characterization and reduced variance
  - Do not need any training stage
    $\rightarrow$ explicit mathematical form and interpretability



$\rightarrow$ Wavelet filters separating the different scales
$\rightarrow$ Coupling between scales with non-linearities

Scattering Transform (ST) statistics

- **Wavelet Phase Harmonics and phase alignment** *(EA+20)*



→ 1 coeff / pair of scales / type of interaction
→ Can be extended to cross-statistics between maps

Scattering Transform (ST) statistics

- **A family of statistics**
  - Different generations of statistics
    → Wavelet Scattering Transforms (WST) *(EA+19)*
    → Wavelet Phase Harmonics (WPH) *(EA+20)*
    → Scattering covariances/spectra *(Cheng+24)*
  - All share the same framework

Scattering Transform (ST) statistics

- **A family of statistics**
  - Different generations of statistics
    → Wavelet Scattering Transforms (WST) *(EA+19)*
    → Wavelet Phase Harmonics (WPH) *(EA+20)*
    → Scattering covariances/spectra *(Cheng+24)*
  - All share the same framework

- **Characterization and parameter inference**
  - Interstellar medium *(EA+19, Regaldo+20, Saydjari+20, Lei+22)*
  - Weak lensing *(Cheng+20, 21)*
  - Large scale structures *(EA+20, Eickenberg+22, Valogiannis+22a, 22b)*
  - 21cm epoch of reionization *(Greig+22, Hothi+23)*
  - ...

→ Very informative (sometimes on par with CNN!)
→ Wide range of applicability (generic, training-less)

Generative models from Scattering transforms

- **Generative model from ST statistics** *(Bruna+19)*
  - From the ST statistics $\Phi(s)$ of a map s
  - Maximum entropy microcanonical model
  - New approximate samples of a process from examples

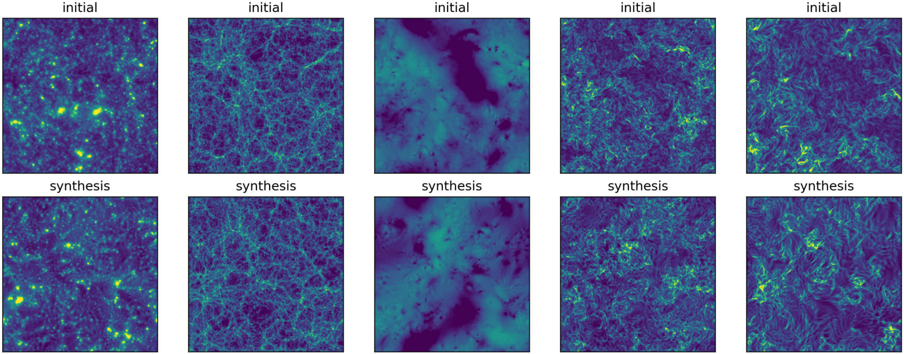
Generative models from Scattering transforms

- **Generative model from ST statistics** *(Bruna+19)*
  - From the ST statistics $\Phi(s)$ of a map s
  - Maximum entropy microcanonical model
  - New approximate samples of a process from examples

- **Practical implementation**
  - Constraints $\Phi(s)$ from a (set of) data s
  - Sampled with a gradient-descent algorithm
    $\rightarrow$ from a white noise realization
    $\rightarrow$ optimizing $\tilde{s}$ such that $\Phi(\tilde{s}) \simeq \Phi(s)$

Generative models from Scattering transforms

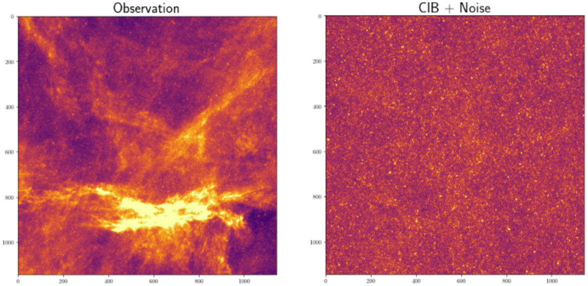
- **Syntheses from a single image** *(Cheng+24)*
  - Scattering spectra + physical dimensionality reduction



→ **Realistic NG models from a few hundreds coefficients!**

(see also EA+20, Régaldo+23, Mousset+24)

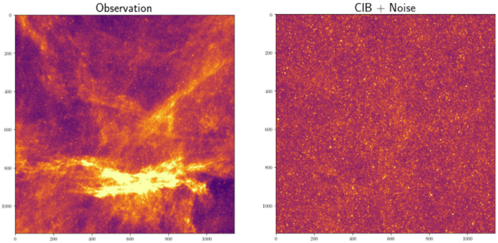
Application to component separation



- **Dust emission/Cosmic Infrared Background (Auclair+, 24)**
  - $d = s + c$, s thermal dust emission, c CIB
  - Independent CIB observation from Lockman hole

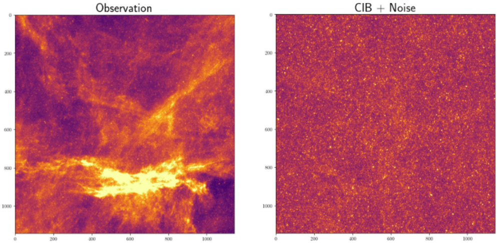
→ From generative models to components separations?

Application to component separation



- **1. Build a CIB model**
  - ST generative model from CIB data (cosmological ⇒ homogeneous)
  - Generate an ensemble of $\{c_i\}$ CIB maps

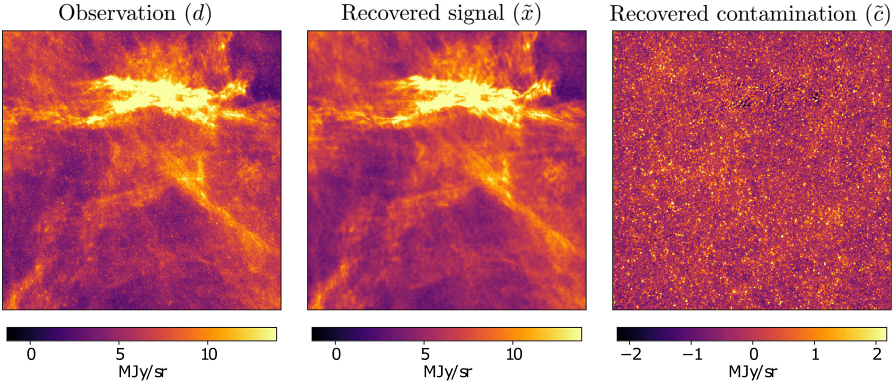
Application to component separation



- **1. Build a CIB model**
  - ST generative model from CIB data (cosmological ⇒ homogeneous)
  - Generate an ensemble of $\{c_i\}$ CIB maps
- **2. Gradient descent to generate a $\tilde{s}$ dust map**
  - $\tilde{s}$ should be compatible with d when added to c_i
  - $\tilde{c} = d - \tilde{s}$ should be compatible with CIB c

$$\left\langle \Phi(\tilde{s} + c_i) \right\rangle_i \simeq \Phi(d), \qquad \Phi(\tilde{c}) = \Phi(c)$$

- Recovered components (Auclair+, 24)



→ Statistical component separation solely from obs. data
→ Galactic dust statistically recovered up to Herschel beam

Conclusion

- **Scattering Transforms**
  → Efficient non-Gaussian statistics inspired from neural network
  → Characterize interaction between scales in non-linear ISM processes

- **Component separations with ST**
  → New efficient algorithms leveraging morphological differences
  → Ability to work with a very limited amount of data
  → Very flexible and versatile algorithms!
  → ***See also Régaldo+21, Delouis+22***

- **Generative models with ST**
  → Low-dim parametrized models (by the ST!)
  → Can be combined with other approaches
  → Allow to work without physically-driven prior models!
  → ***See also Siahkoohi+24, Lei+, in prep.***

Thanks for your attention!