Non-Gaussianity in CMB Polarization by extending the Minkowski Functionals framework

Javier **Carrón Duque**

javier.carron@roma2.infn.it

INFN
TOR VERGATA UNIVERSITY OF ROME

In collaboration with:

Alessandro **Carones**
Domenico **Marinucci**
Marina **Migliaccio**
Nicola **Vittorio**

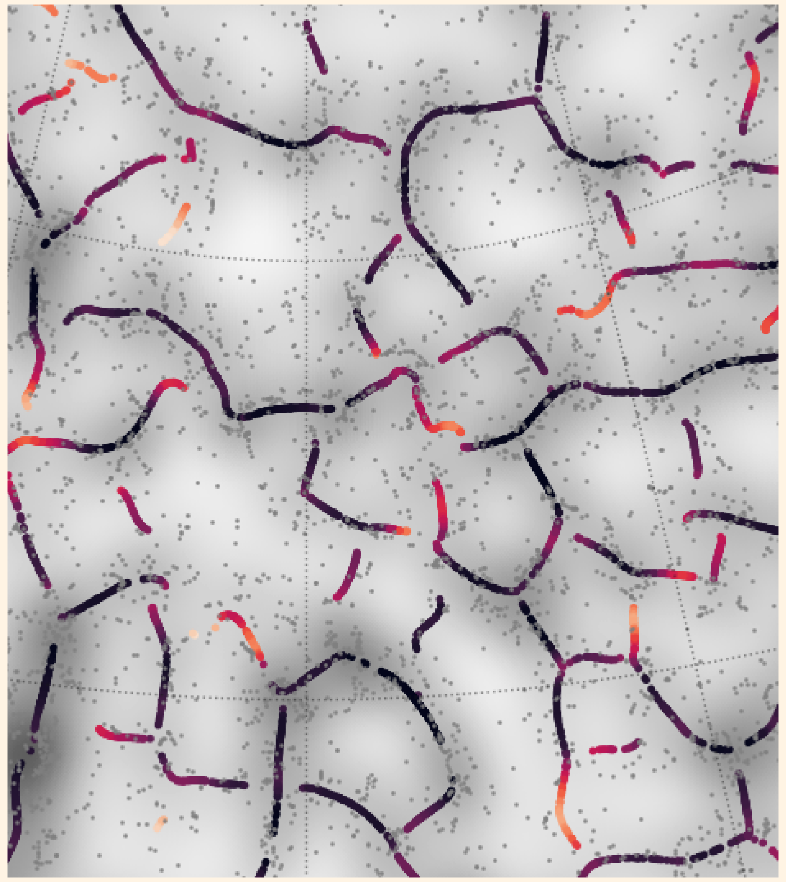
A Cosmic Window to Fundamental Physics: Primordial Non-Gaussianity and Beyond
September 2022 — IFT, Madrid, Spain

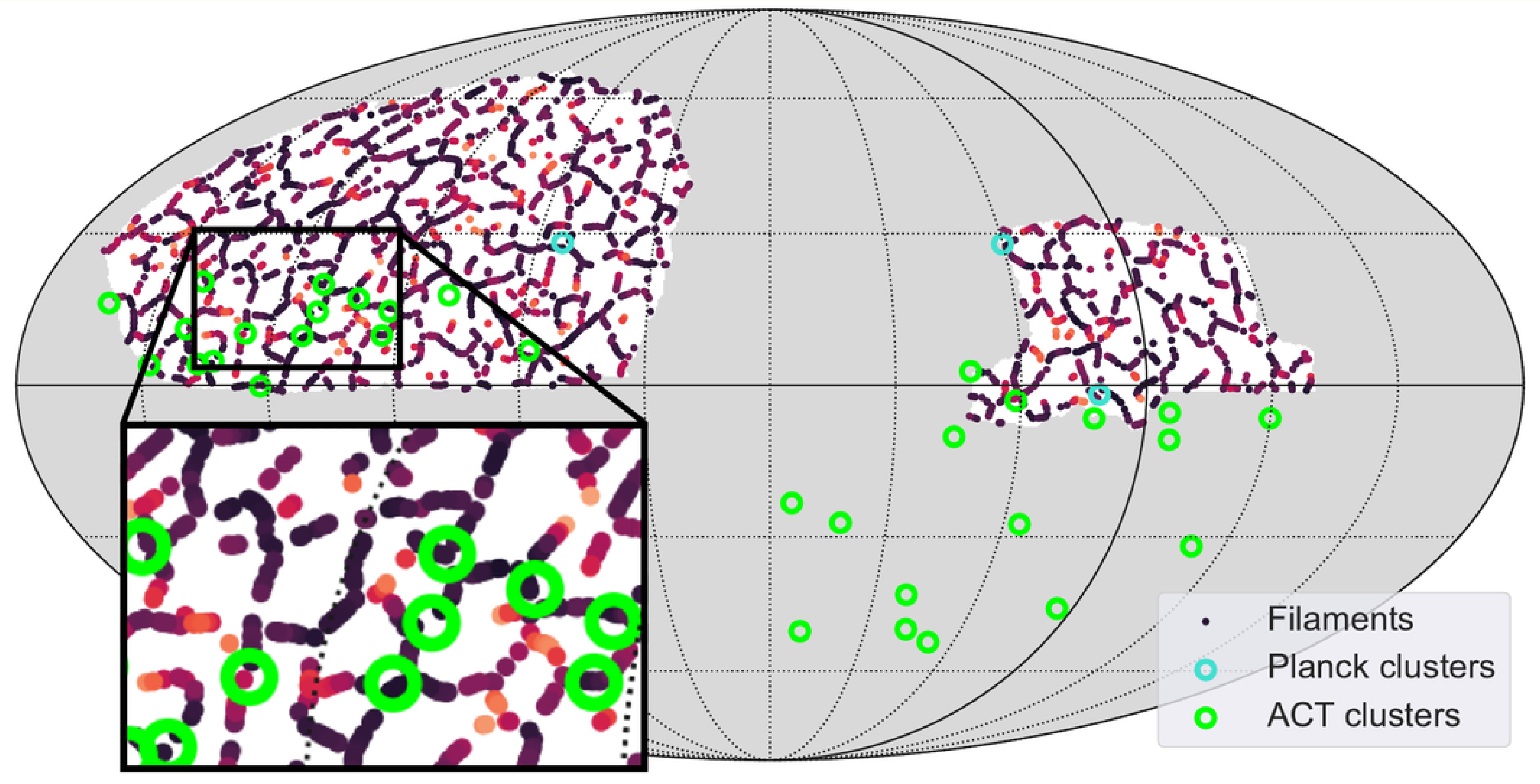
We produced a Cosmic Filaments catalogue

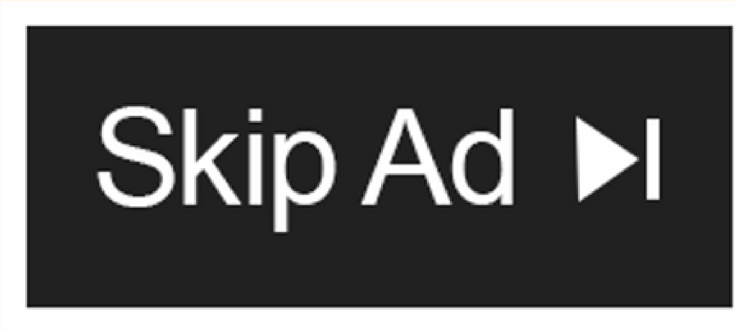
- Publicly available: www.javiercarron.com/catalogue
- *0.05 < z < 2.2*
- Promising results in different topics

A novel cosmic filament catalogue from SDSS data★

Javier Carrón Duque[1,2], Marina Migliaccio[1,2], Domenico Marinucci[3], and Nicola Vittorio[1,2]





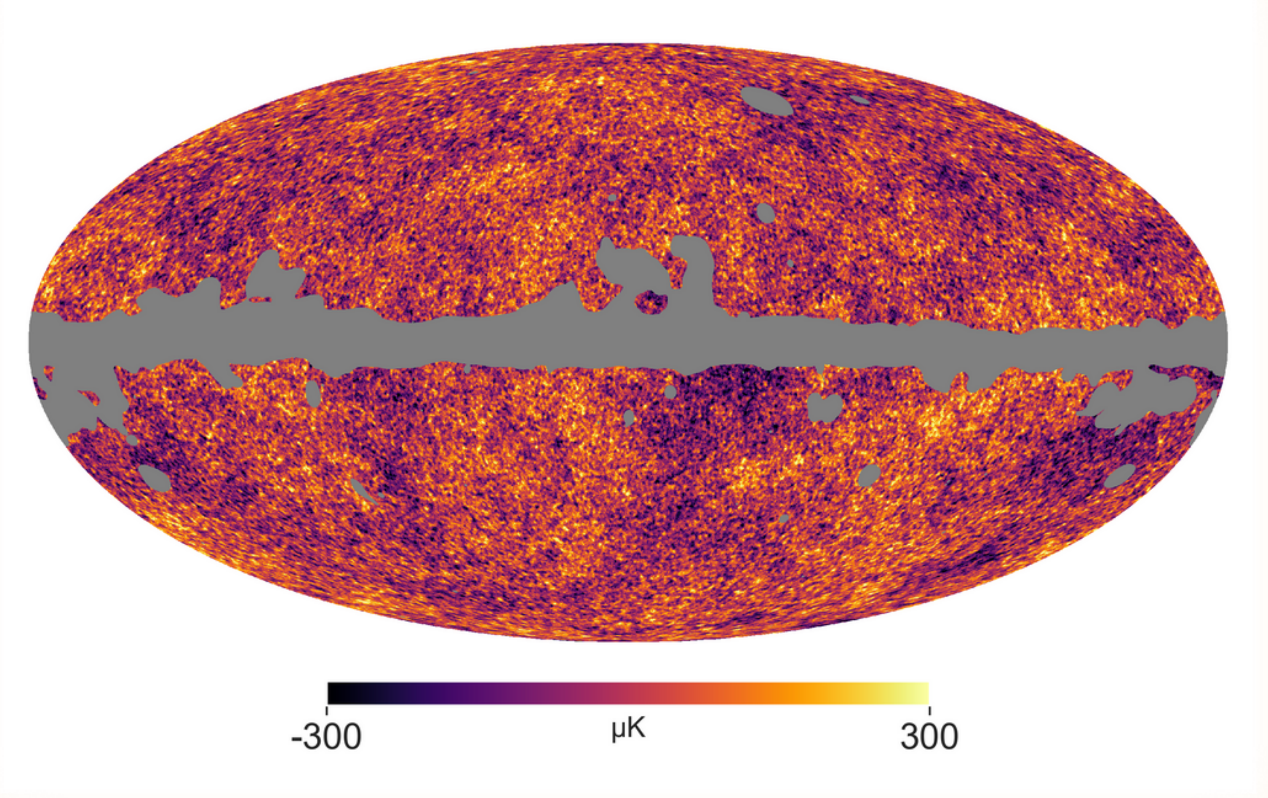


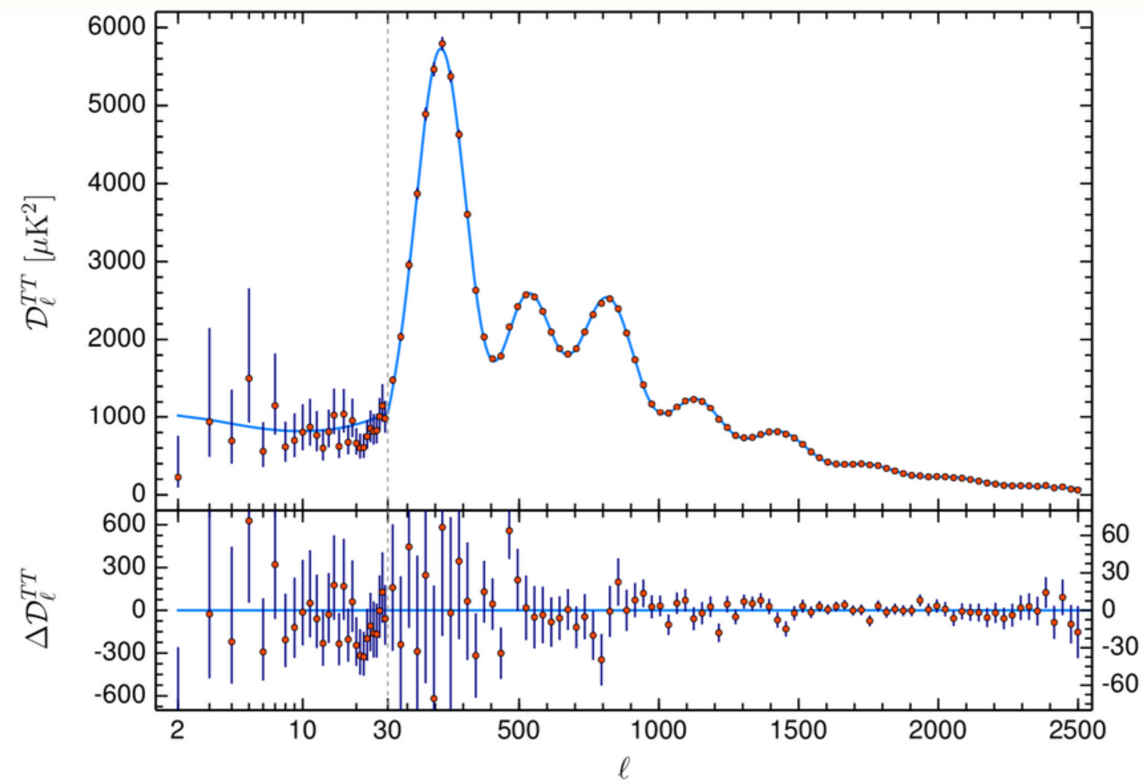
Outline

- Introduction
- Minkowski Functionals on CMB polarization
- Other applications of Minkowski Functionals
- Conclusions

Gaussian fields are easy to describe

- Gaussian → Physical process fully described by 2pt correlation function

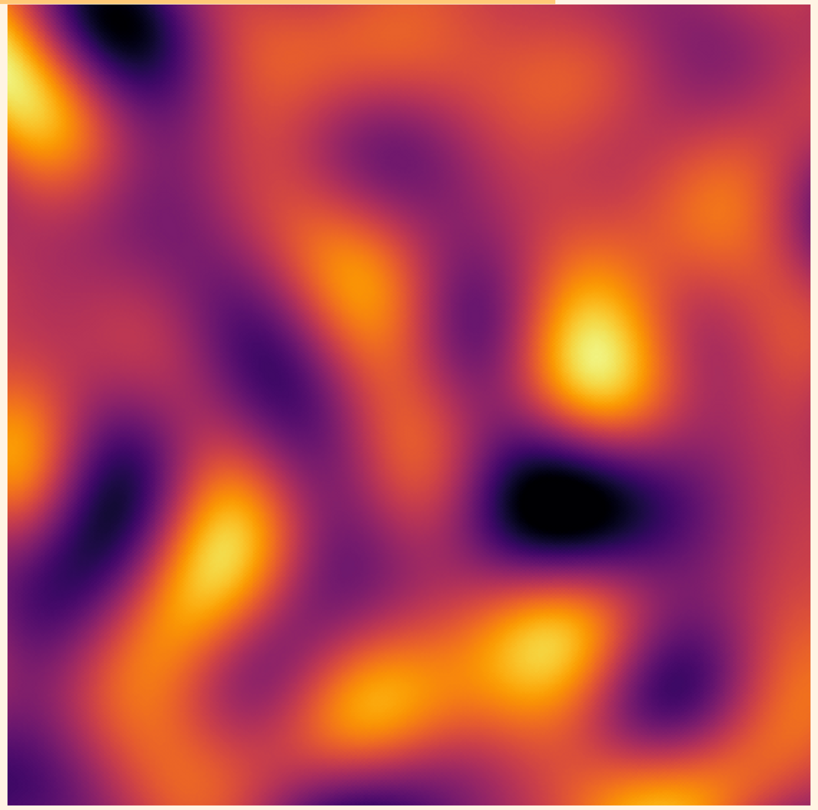




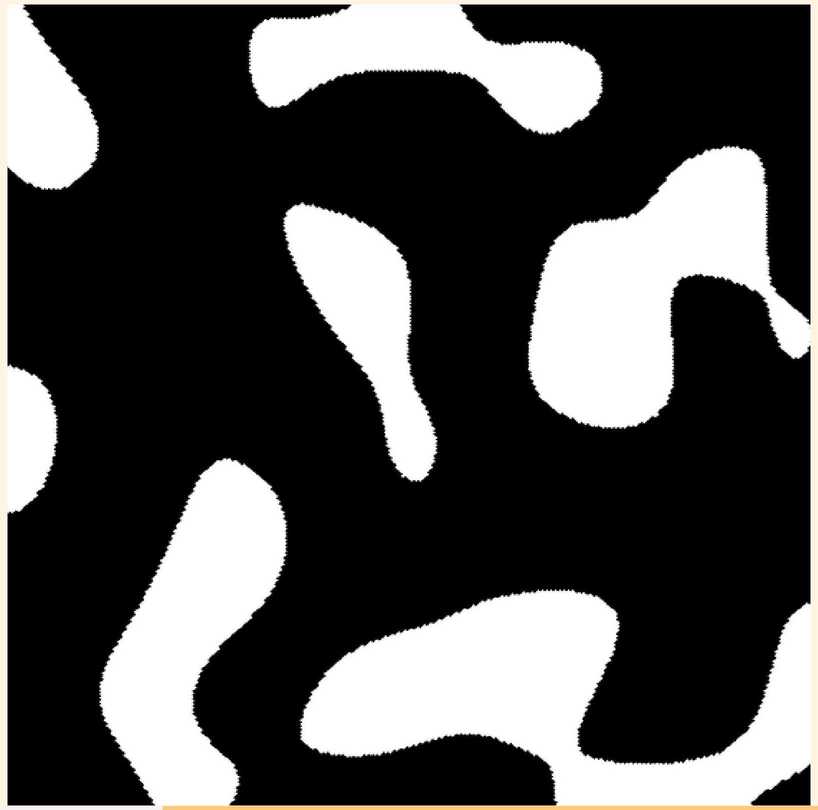
Source: Planck Collaboration

- Blind to non—Gaussianity
- Other tools: 3/4 pt correlation function (bi/tri-spectrum), extrema statistics, Minkowski Functionals

Minkowski Functionals are higher order statistics



- We consider a field (*e.g.*, *T*)
- Let *u* be a threshold (*e.g.*, 2σ)
- We define the **excursion set** *A(u)* as the regions of the field above *u*
- Minkowski Functionals are:
  - V_0 : area of *A(u)*
  - V_1 : boundary length of *A(u)*
  - V_2 : Euler—Poincaré characteristic of *A(u)*   (#regions — #holes)



Minkowski Functionals are sensitive to non—Gaussianity

- For isotropic Gaussian fields, the expectation is known:

$$\mathbb{E}\left[V_i(u)\right] \sim \underbrace{f_1(u)}_{\text{Threshold}} \cdot \underbrace{f_2(\mathbb{S}^2)}_{\text{Ambient manifold}} \cdot \underbrace{f_3(\mu)}_{\text{Characteristics of the map (angular power spectrum)}}$$

- Any deviation is due to non—Gaussianity and/or anisotropy

Minkowski Functionals are sensitive to non—Gaussianity

- For isotropic Gaussian fields, the expectation is known:

$$\mathbb{E}\left[V_i(u)\right] \sim \underbrace{f_1(u)}_{\text{Threshold}} \cdot \underbrace{f_2(\mathbb{S}^2)}_{\text{Ambient manifold}} \cdot \underbrace{f_3(\mu)}_{\text{Characteristics of the map (angular power spectrum)}}$$

- Any deviation is due to non—Gaussianity and/or anisotropy
- Early Universe (*e.g.*, *T*): test for primordial non—Gaussianity
- Late Universe (*e.g.*, *κ*): extract more cosmological information

Javier Carrón Duque javier.carron@roma2.infn.it

We extend MFs to modulus of polarization P^2

Paper coming soon!

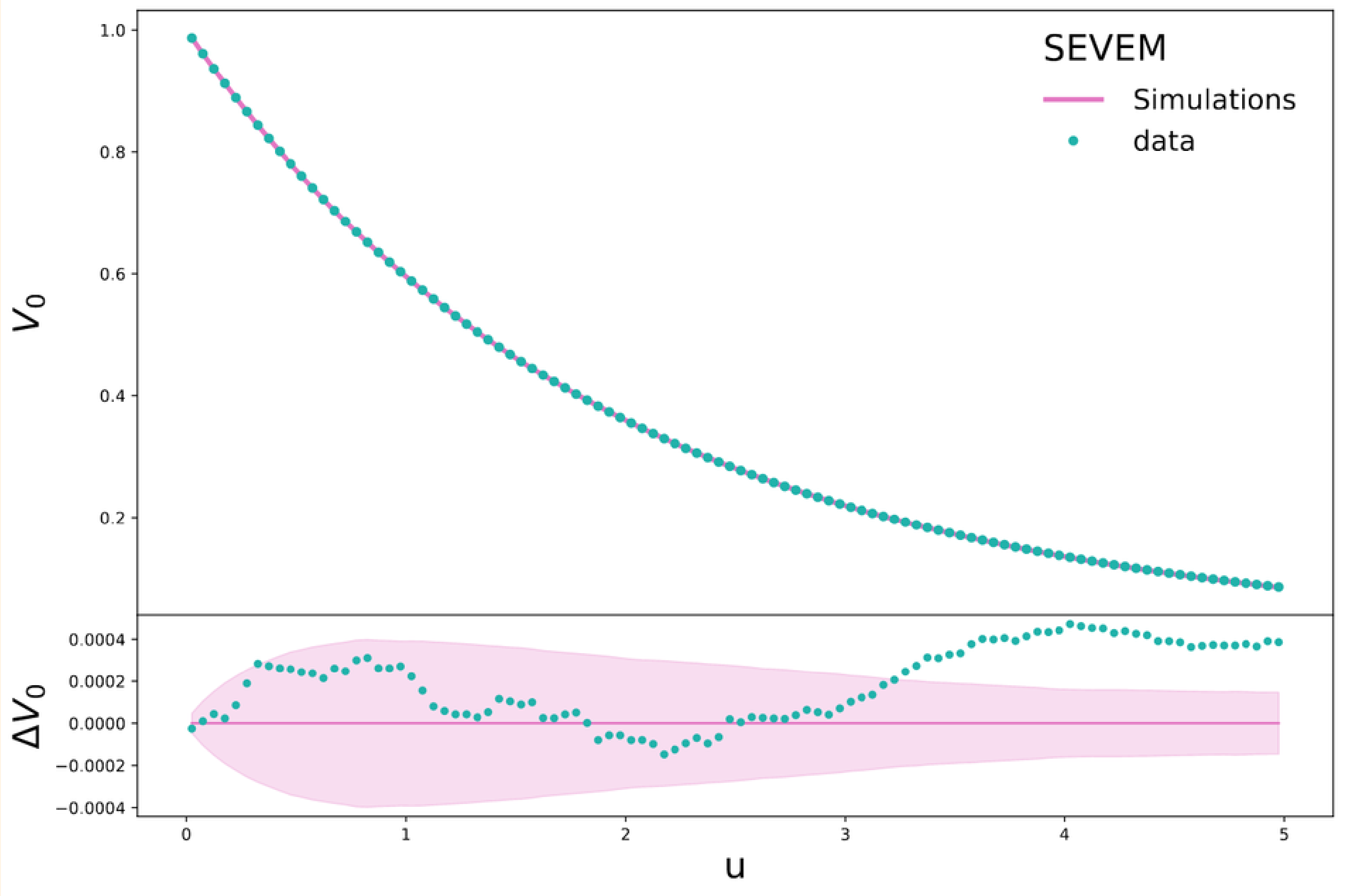
- We generalize the theoretical formula for $P^2 = Q^2 + U^2$
- Excellent compatibility between theory and Gaussian simulations
- Planck data in agreement with realistic simulations (with anisotropic noise)

Javier Carrón Duque javier.carron@roma2.infn.it

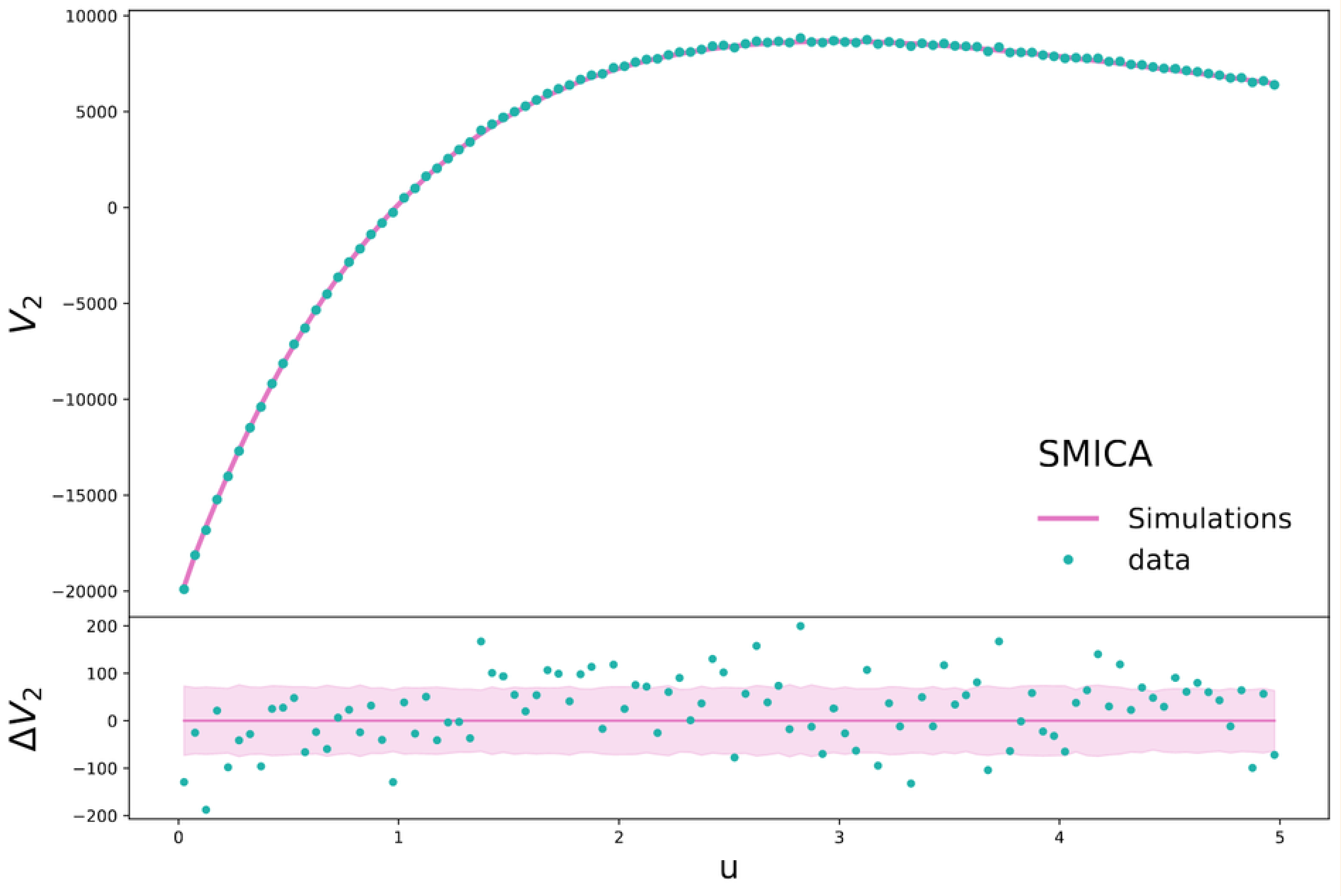
We extend MFs to modulus of polarization P^2

Paper coming soon!

- We generalize the theoretical formula for $P^2 = Q^2 + U^2$
- Excellent compatibility between theory and Gaussian simulations
- Planck data in agreement with realistic simulations (with anisotropic noise)



		χ^2	σ
V_0	SMICA	1.074	0.37
	SEVEM	0.885	-0.70
V_1	SMICA	1.135	0.72
	SEVEM	1.022	0.09
V_2	SMICA	1.051	0.27
	SEVEM	1.263	1.55



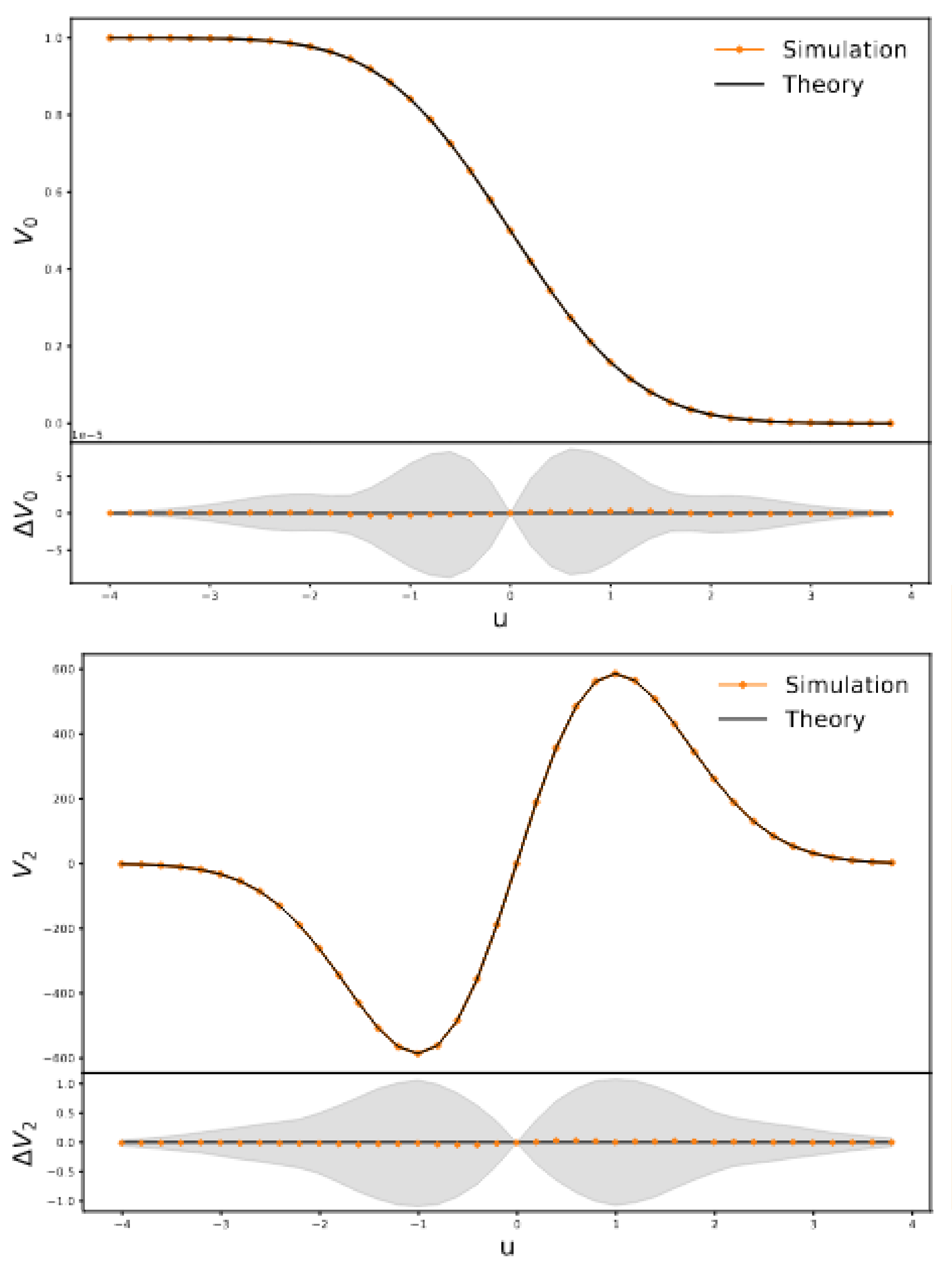
And we extend MFs to full polarization *P(φ, θ, ψ)*

Paper next month

- Full polarization information in

$$f(\phi,\theta,\psi) = Q(\phi,\theta)\cos(2\psi) - U(\phi,\theta)\sin(2\psi)$$

- We obtain the theoretical prediction for the MFs
- Simulations fully compatible with theory



We explore the non—Gaussianity of Galactic dust

w/ Giuseppe **Puglisi**

- Galactic dust is intrinsically non—Gaussian and anisotropic
- Good realistic simulations should include non—Gaussianities from realistic foreground
- We use MFs to compare several methods used to simulate polarized dust emission

MFs can be applied to the CMB power asymmetry

w/ Giacomo **Galloni**

- Typically: variance + Gaussianity $\Rightarrow$ theoretical MFs
- But also: measured MFs + Gaussianity $\Rightarrow$ variance
- Stay tuned for results

We develop Pynkowski as a Python package

- Pynkowski is fully documented and modular
- Theory module: computes the theoretical prediction of different kinds of fields
- Data module: computes the MFs on different kinds of data structures
- Both modules are easy to expand

https://github.com/javicarron/pynkowski

Now available!

Takeaway points

- **Minkowski Functionals** are useful tools to study **non—Gaussianity**
- It has many **applications** in both Early and Late Universe
- We created **Pynkowski** to ease the application of MFs to the community

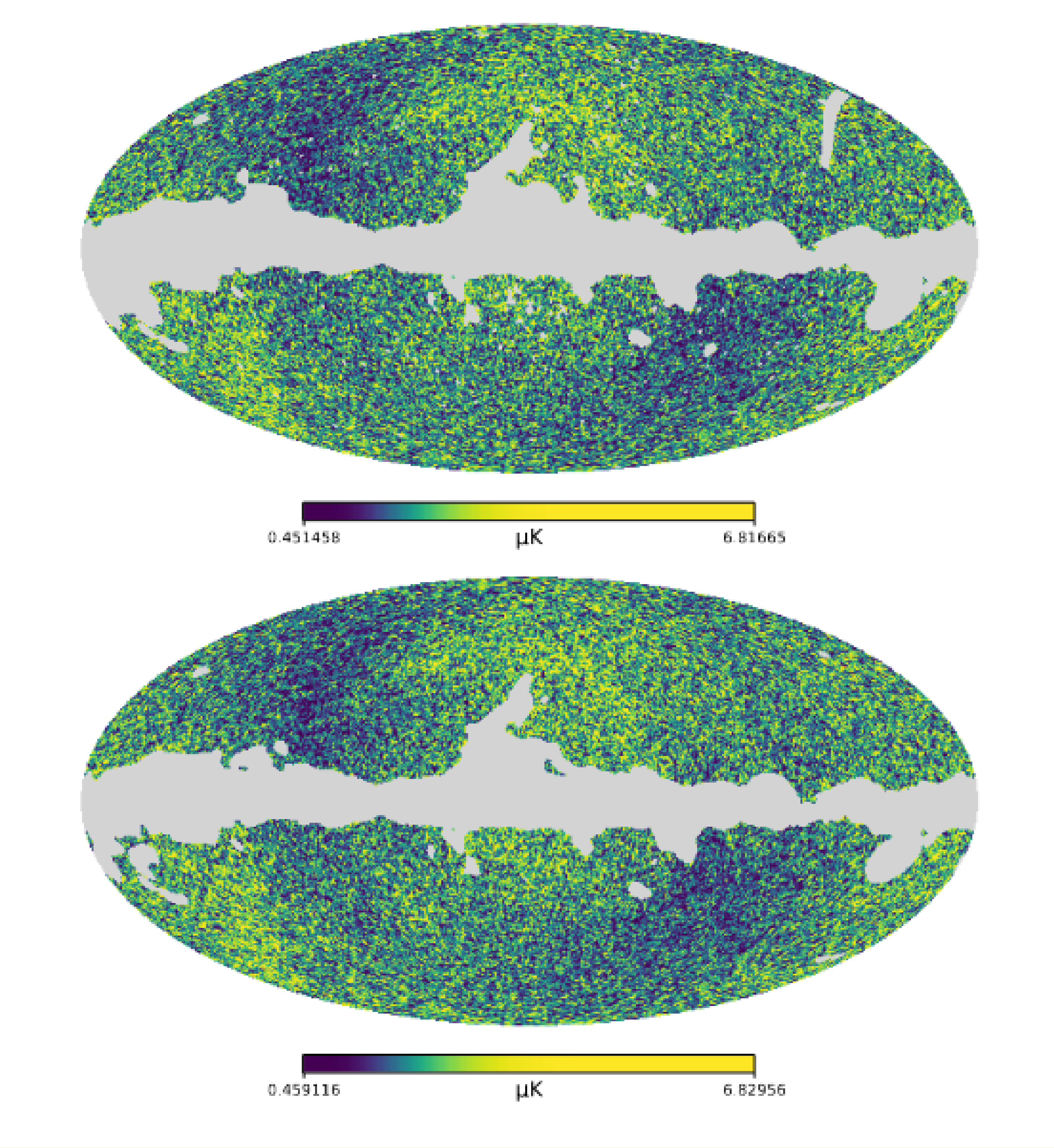
Takeaway points

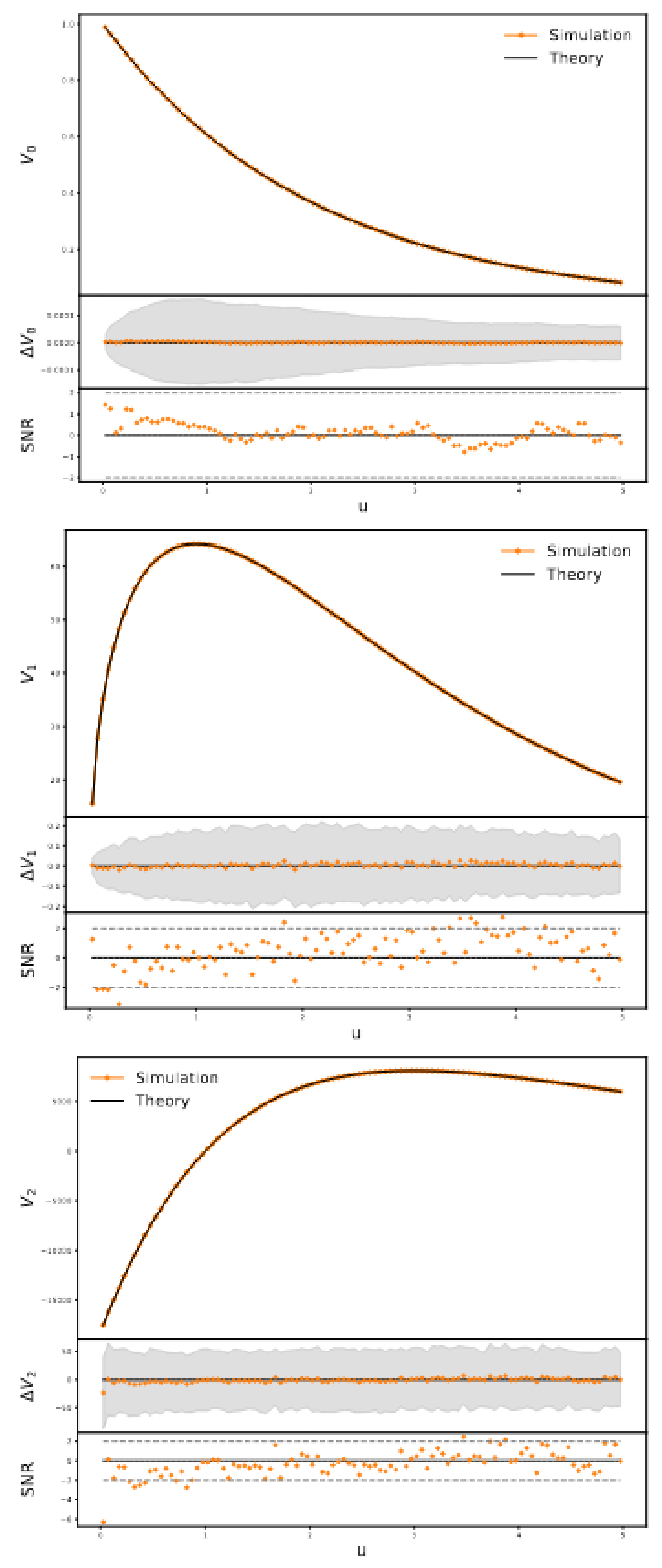
- **Minkowski Functionals** are useful tools to study **non—Gaussianity**
- It has many **applications** in both Early and Late Universe
- We created **Pynkowski** to ease the application of MFs to the community

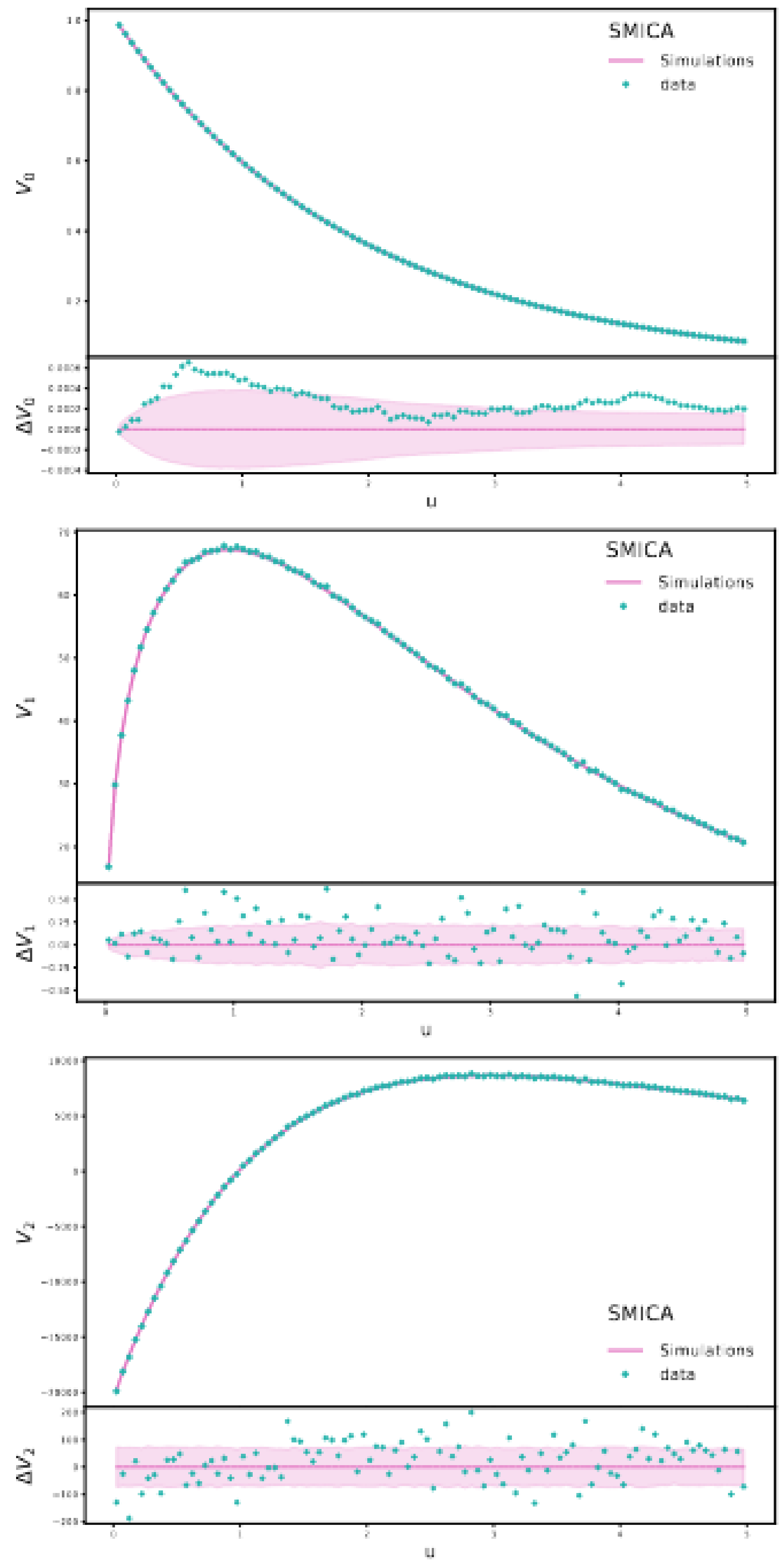
Thank you!

Javier Carrón Duque javier.carron@roma2.infn.it

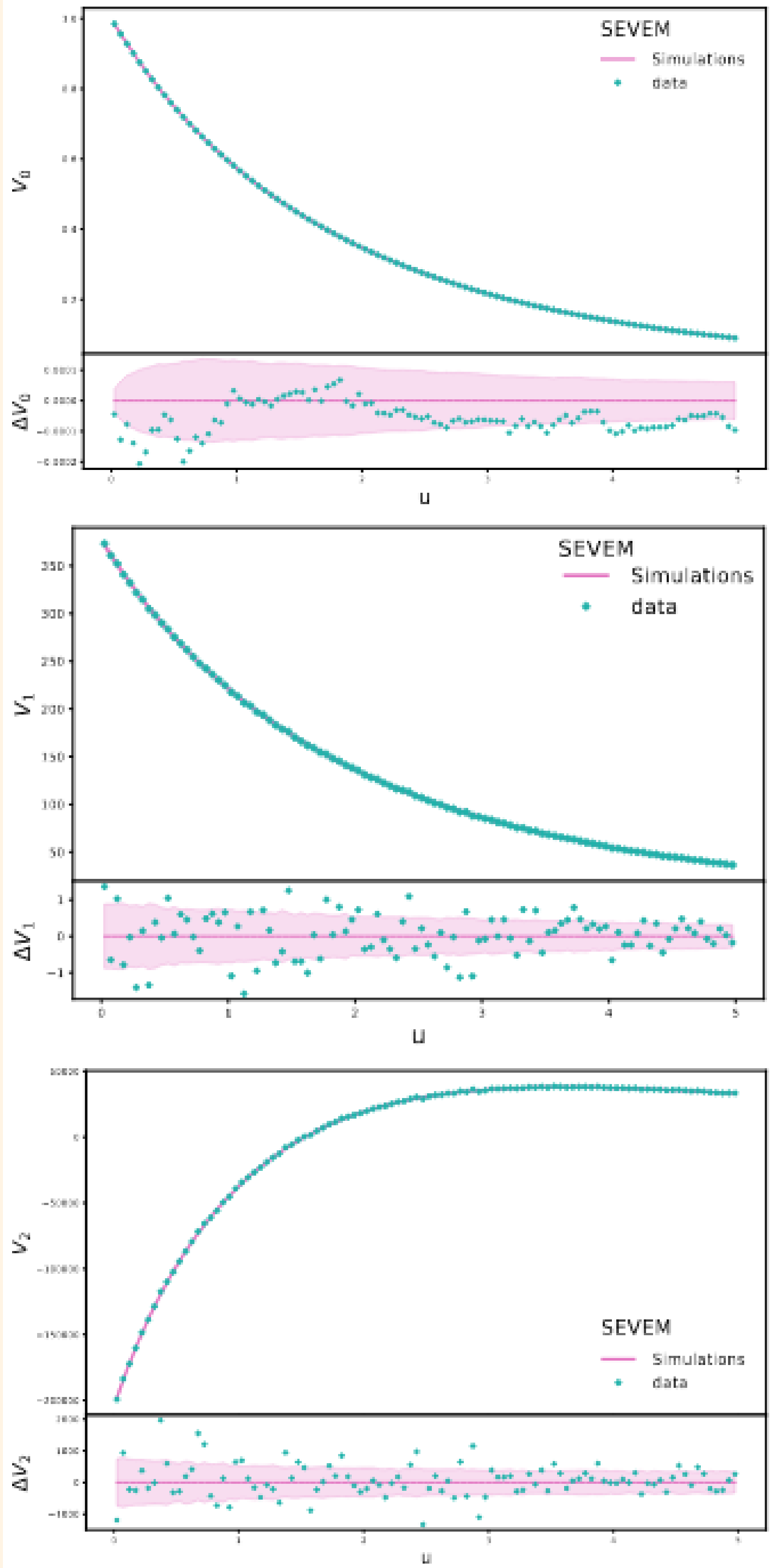
Backup images


0.451458
μK
6.81665
0.459116
μK
6.82956


Simulation
Theory
V_0
ΔV_0
SNR
u
Simulation
Theory
V_1
ΔV_1
SNR
u
Simulation
Theory
V_2
ΔV_2
SNR
u



		χ^2	p_{exc} (%)	σ
V_0	SMICA	1.074	30.7	0.37
	SEVEM	0.885	74.0	-0.70
V_1	SMICA	1.135	19.7	0.72
	SEVEM	1.022	43.7	0.09
V_2	SMICA	1.051	39.3	0.27
	SEVEM	1.263	0.09	1.55



$$\mathbb{E}\left[V_j(A(u))\right] \propto \sum_{k=0}^{j} \rho_k(u)\, V_{j-k}(\mathbb{S}^2)\, \mu^{k/2}$$

Threshold

Ambient manifold

Characteristics of the map (angular power spectrum)

$$\frac{\mathbb{E}\left[V_0(A_u)\right]}{4\pi} = 1 - \Phi(u)$$

$$\frac{\mathbb{E}\left[V_1(A_u)\right]}{4\pi} = \frac{1}{8}\exp(-\frac{u^2}{2})\mu^{1/2}$$

$$\frac{\mathbb{E}\left[V_2(A_u)\right]}{4\pi} = \frac{2\mu}{\sqrt{(2\pi)^3}}\exp(-\frac{u^2}{2})$$

$$\frac{\mathbb{E}\left[V_0(A_u)\right]}{4\pi} = \exp(-u/2)$$

$$\frac{\mathbb{E}\left[V_1(A_u)\right]}{4\pi} = \frac{\sqrt{2\pi}}{8}\sqrt{\mu u}\,\exp(-\frac{u}{2})$$

$$\frac{\mathbb{E}\left[V_2(A_u)\right]}{4\pi} = \mu\frac{(u-1)\exp(-u/2)}{2\pi}$$