Cosmic inferences from the morphology of the Universe

Intensive Report

Mohammad Hosein Jalali Kanafi

Computational Cosmology Group
Department of Physics
Shahid Beheshti University

24 Aban 2023

Outline

- Introduction to " Cosmic inferences from the morphology of the Universe "
- Imprint of massive neutrinos on Persistent Homology of large-scale structure
- Probing the anisotropy and non-Gaussianity in redshift space through the derivative of excursion set moments
- Morphology of CMB fields: effect of weak gravitational lensing — In Progress
- Morphology of LSS in the presence of primordial non-Gaussianity: Scale dependent bias of critical Points — In Progress

Main Topics of Thesis

- Testing Cosmological Principles
- Morphology of LSS: Constraining the Modified Gravity
- Simulation Based Inference

Relevant Topics — In Progress

What is meant by morphology?

δ_1

-0.9	2.0	5.5	1.4	1.5	1.9	6.0
1.3	1.2	-1.3	1.5	0.2	-0.9	4.2
5.7	1.7	4.5	4.6	4.2	1.5	0.0
0.5	0.0	5.2	2.0	4.1	0.0	-0.2
2.1	2.4	4.5	4.3	4.9	3.0	3.4
2.4	-0.9	3.0	0.8	2.7	0.0	5.9
2.1	2.4	2.5	3.9	5.7	3.5	2.6

δ_2

1.3	1.2	-1.3	1.5	0.2	-0.9	4.2
0.5	0.0	5.2	2.0	4.1	0.0	-0.2
5.7	1.7	4.5	4.6	4.2	1.5	0.0
2.1	2.4	4.5	4.3	4.9	3.0	3.4
2.1	2.4	2.5	3.9	5.7	3.5	2.6
2.4	-0.9	3.0	0.8	2.7	0.0	5.9
-0.9	2.0	5.5	1.4	1.5	1.9	6.0

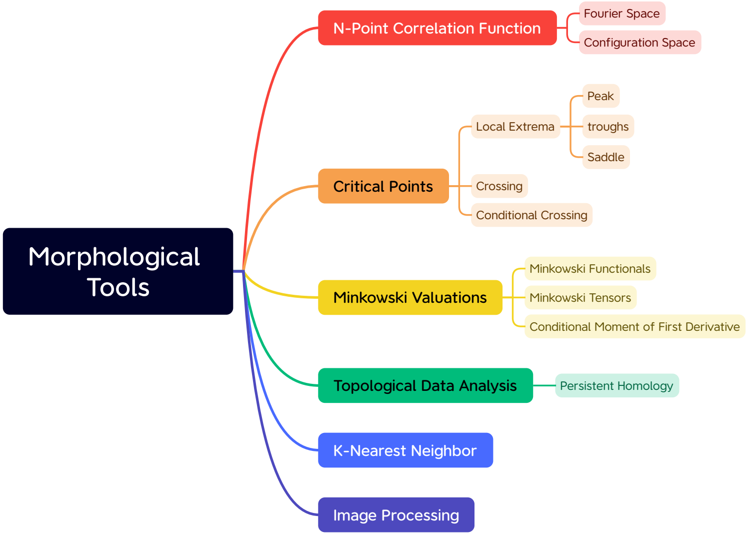
δ_3

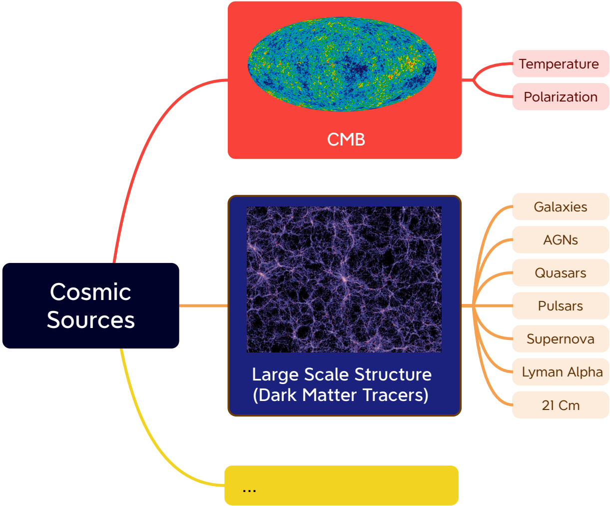
2.1	2.4	2.5	3.9	5.7	3.5	2.6
5.7	1.7	4.5	4.6	4.2	1.5	0.0
0.5	0.0	5.2	2.0	4.1	0.0	-0.2
-0.9	2.0	5.5	1.4	1.5	1.9	6.0
2.4	-0.9	3.0	0.8	2.7	0.0	5.9
1.3	1.2	-1.3	1.5	0.2	-0.9	4.2
2.1	2.4	4.5	4.3	4.9	3.0	3.4

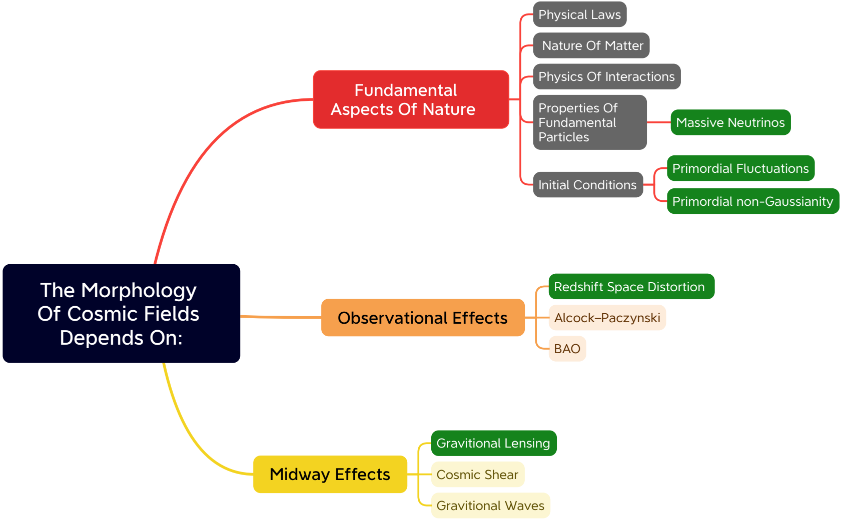
δ_4

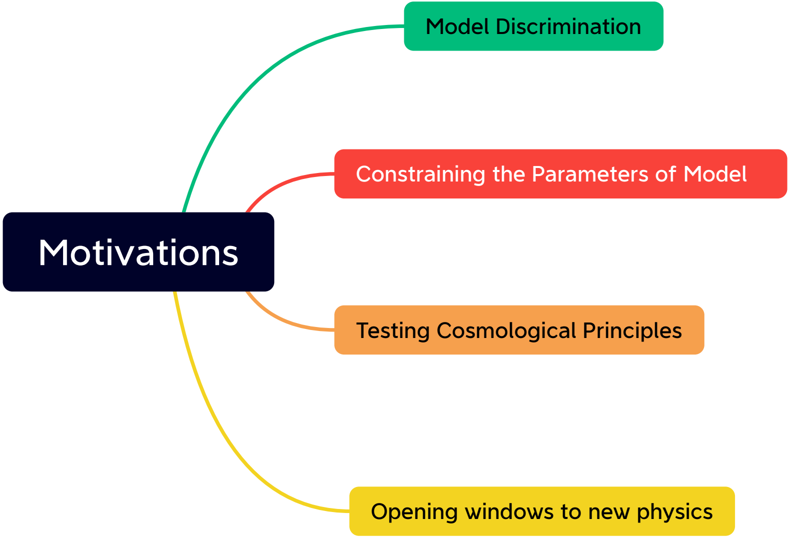
-0.9	2.0	5.5	1.4	1.5	1.9	6.0
2.4	-0.9	3.0	0.8	2.7	0.0	5.9
0.5	0.0	5.2	2.0	4.1	0.0	-0.2
5.7	1.7	4.5	4.6	4.2	1.5	0.0
2.1	2.4	2.5	3.9	5.7	3.5	2.6
2.1	2.4	4.5	4.3	4.9	3.0	3.4
1.3	1.2	-1.3	1.5	0.2	-0.9	4.2

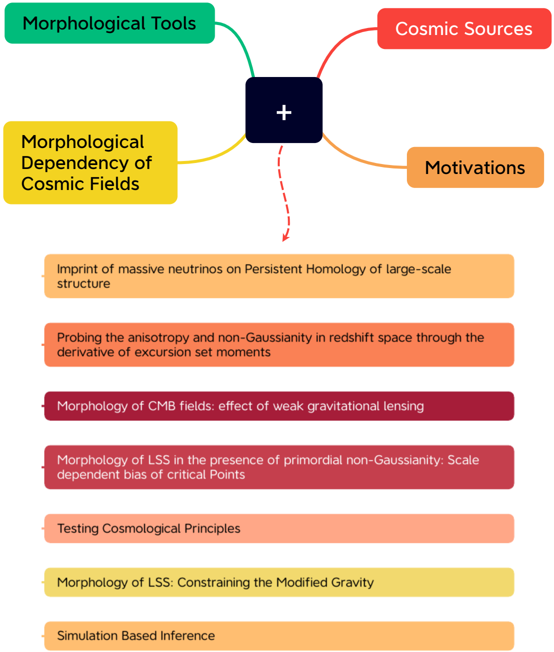
$$\mathrm{PDF}(\delta_1) = \mathrm{PDF}(\delta_2) = \mathrm{PDF}(\delta_3) = \mathrm{PDF}(\delta_4)$$


Morphological Tools
N-Point Correlation Function
Fourier Space
Configuration Space
Critical Points
Local Extrema
Peak
troughs
Saddle
Crossing
Conditional Crossing
Minkowski Valuations
Minkowski Functionals
Minkowski Tensors
Conditional Moment of First Derivative
Topological Data Analysis
Persistent Homology
K-Nearest Neighbor
Image Processing


Cosmic Sources
CMB
Temperature
Polarization
Large Scale Structure (Dark Matter Tracers)
Galaxies
AGNs
Quasars
Pulsars
Supernova
Lyman Alpha
21 Cm
...


The Morphology Of Cosmic Fields Depends On:
Fundamental Aspects Of Nature
Physical Laws
Nature Of Matter
Physics Of Interactions
Properties Of Fundamental Particles
Massive Neutrinos
Initial Conditions
Primordial Fluctuations
Primordial non-Gaussianity
Observational Effects
Redshift Space Distortion
Alcock–Paczynski
BAO
Midway Effects
Gravitional Lensing
Cosmic Shear
Gravitional Waves


Motivations
Model Discrimination
Constraining the Parameters of Model
Testing Cosmological Principles
Opening windows to new physics


Morphological Tools
Cosmic Sources
+
Morphological Dependency of Cosmic Fields
Motivations
Imprint of massive neutrinos on Persistent Homology of large-scale structure
Probing the anisotropy and non-Gaussianity in redshift space through the derivative of excursion set moments
Morphology of CMB fields: effect of weak gravitational lensing
Morphology of LSS in the presence of primordial non-Gaussianity: Scale dependent bias of critical Points
Testing Cosmological Principles
Morphology of LSS: Constraining the Modified Gravity
Simulation Based Inference

Imprint of massive neutrinos on Persistent Homology of large-scale structure

Neutrino Physics

- Neutrinos were first theorized in 1930 by Wolfgang Pauli to explain the continuous energy spectrum of protons and electrons in β-decays
- The first neutrino detection dates back in 1956
- According to the Standard Model of particle physics:
  - Neutrinos Come In Three Different Flavors
  - Only Interact Via The Weak Nuclear Force
  - Are Massless
    - There are wellmotivated physical models where neutrinos acquire mass (e.g. Gonzalez-Garcia & Nir (2003); Mohapatra & Smirnov (2006))

Confirmed by the latest experimental data (Tanabashi et al. (2018))

Massive Neutrino?

Neutrino oscillations: One way to detect whether neutrinos are massive

- To explain the measured flux of electron neutrinos from the Sun
- The measured neutrinos are not exact eigenstates of the Standard Model Lagrangian
- neutrino oscillations only depend on the difference of square masses between different species

Neutrinos are a linear combination of three mass states

$$M_\nu \equiv \sum_{i=1}^{3} m_i$$

Atmospheric neutrino:

$$|\Delta m_{31}^2| = |m_3^2 - m_1^2| \simeq |\Delta m_{32}^2| = |m_3^2 - m_2^2| \simeq 2.5 \times 10^{-3} eV^2$$

Solar neutrino:

$$\Delta m_{21}^2 = m_2^2 - m_1^2 \simeq 7.55 \times 10^{-5} eV^2$$

$$M_{\nu,\min} \approx \begin{cases} 0.058 \text{ eV} & \text{(NH)} \\ 0.1 \text{ eV} & \text{(IH)} \end{cases}$$

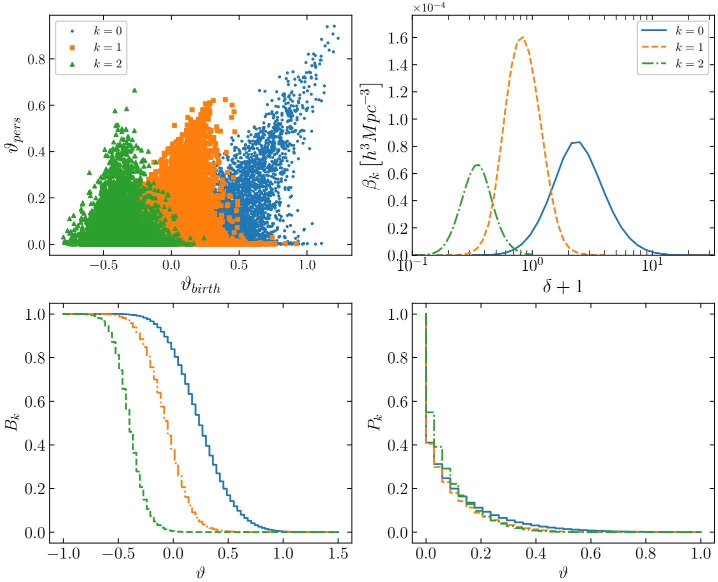
Cosmology is mainly sensitive to the sum of the three neutrino masses (M_ν)

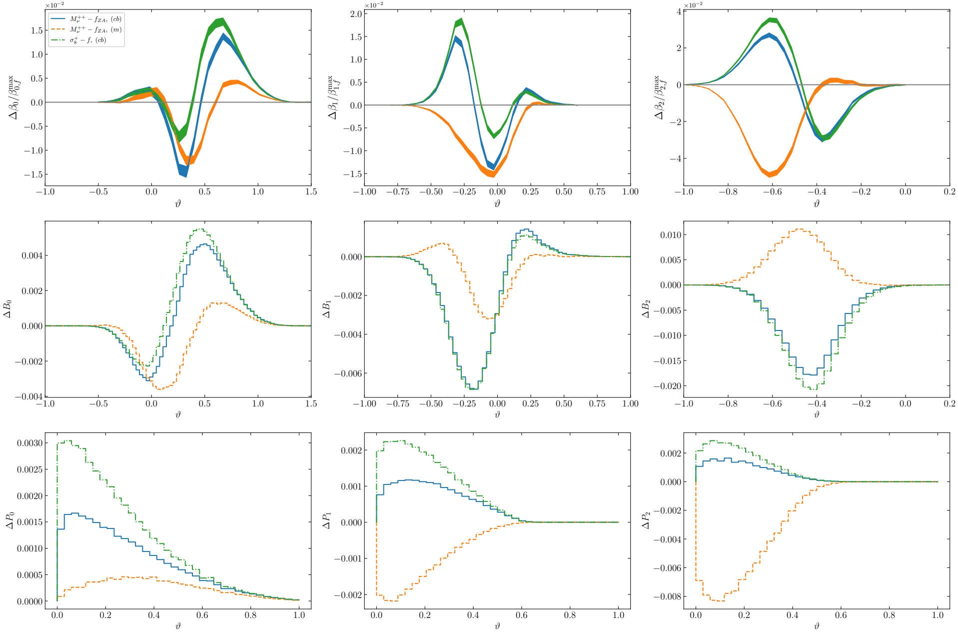
Upper limit from (CMB + BAO + CMB Lensing): $M_\nu \leq 0.115\ \mathrm{eV}$

$$\beta_k(\vartheta) = \sum_{i=1}^{n_k} \Theta\left(\vartheta^{(k)}_{(i),birth} - \vartheta\right) \Theta\left(\vartheta - \vartheta^{(k)}_{(i),death}\right)$$

$$B_k(\vartheta) \equiv \sum_{i=1}^{n_k} \Theta\left(\vartheta - \vartheta^{(k)}_{(i),birth}\right)$$

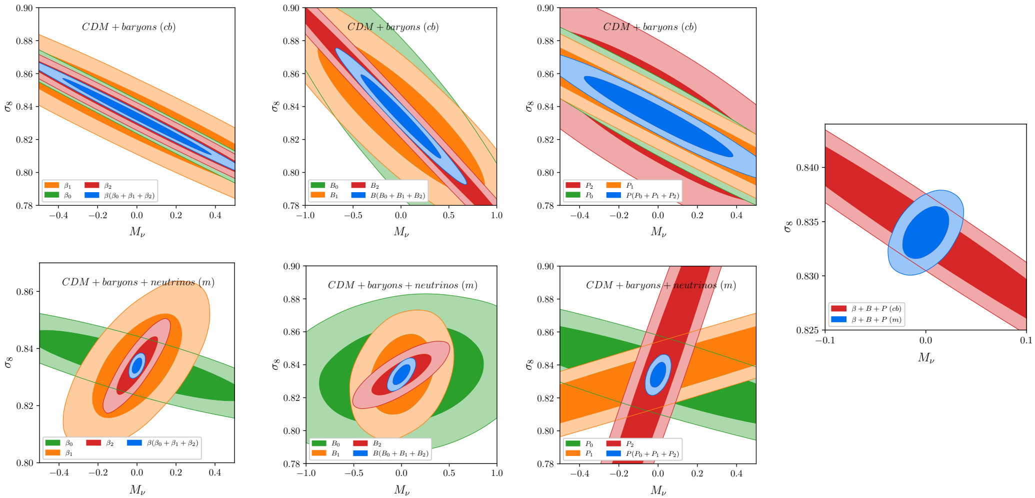
$$P_k(\vartheta) \equiv \sum_{i=1}^{n_k} \Theta\left(\vartheta - \vartheta^{(k)}_{(i),pers}\right)$$

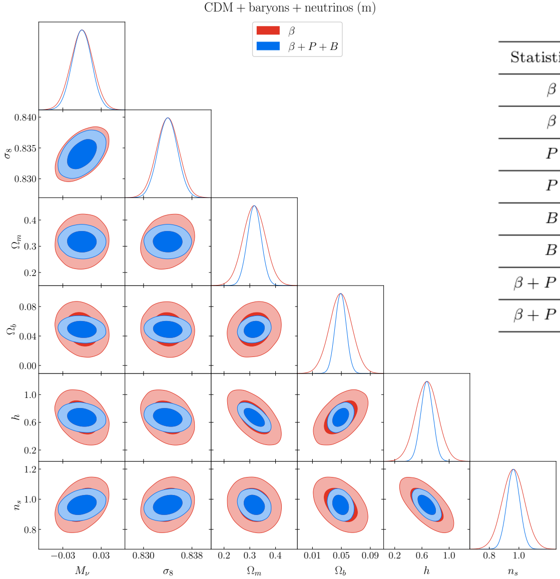




$M_\nu^{++} - f_{ZA}$, (cb)
$M_\nu^{++} - f_{ZA}$, (m)
$\sigma_8^+ - f$, (cb)
$\Delta\beta_0/\beta_{0,f}^{\max}$
$\Delta\beta_1/\beta_{1,f}^{\max}$
$\Delta\beta_2/\beta_{2,f}^{\max}$
ΔB_0
ΔB_1
ΔB_2
ΔP_0
ΔP_1
ΔP_2
ϑ

Fisher Forecast



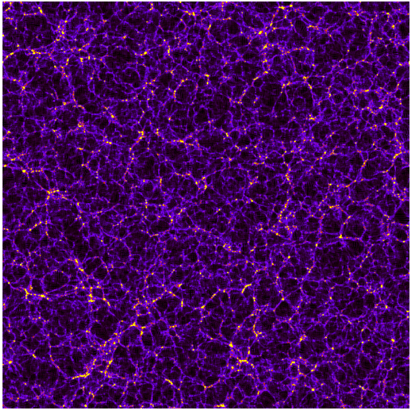


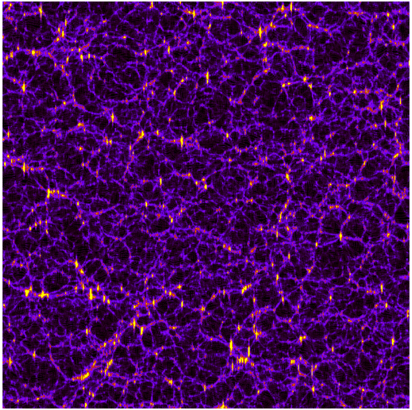
Statistics (field)	M_ν(eV)	σ_8	Ω_m	Ω_b	h	n_s
β (cb)	0.2504	0.0153	0.0442	0.0156	0.1546	0.0699
β (m)	0.0172	0.0018	0.0427	0.0152	0.1617	0.0747
P (cb)	0.2511	0.0162	0.0559	0.0163	0.1640	0.1128
P (m)	0.0269	0.005	0.0564	0.0163	0.1650	0.1224
B (cb)	0.2779	0.0168	0.062	0.0163	0.0138	0.1694
B (m)	0.0610	0.0041	0.0615	0.0139	0.1709	0.1473
$\beta + P + B$ (cb)	0.1242	0.0077	0.027	0.0075	0.0878	0.0423
$\beta + P + B$ (m)	0.0152	0.0015	0.0267	0.0075	0.0886	0.0436

Probing the anisotropy and non-Gaussianity in redshift space through the derivative of excursion set moments

see arXiv:2308.03086

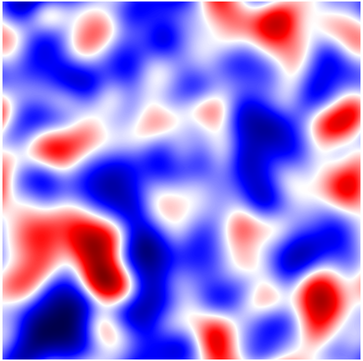
Redshift Space distortion

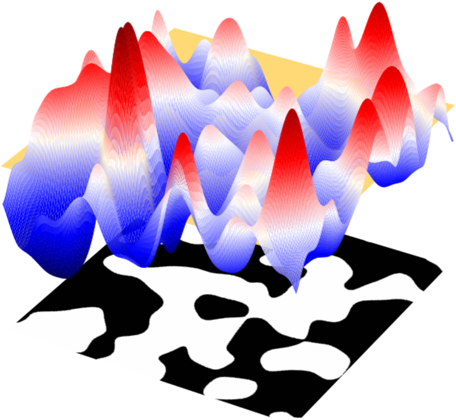


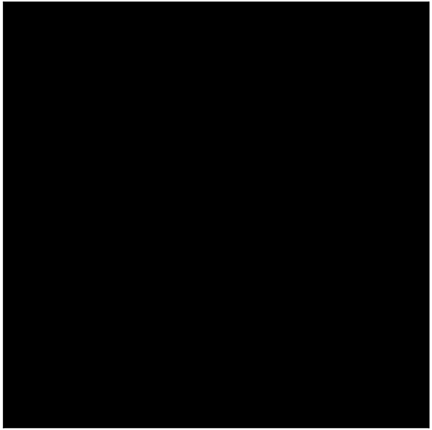


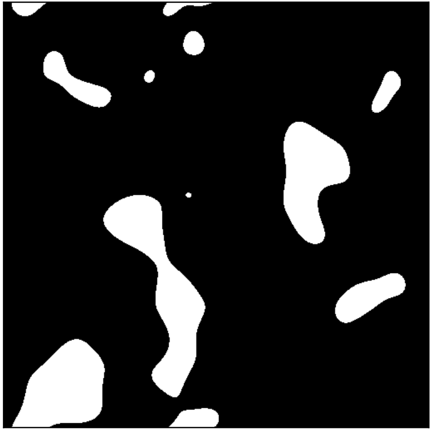
Minkowski Valuations

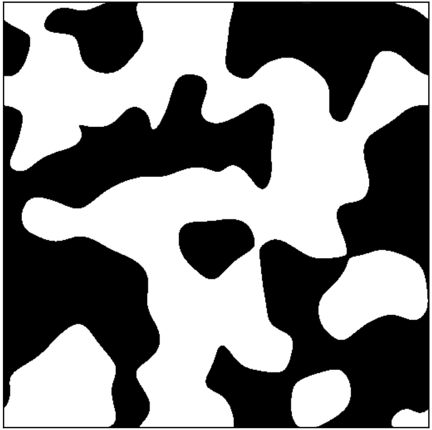
$$\mathcal{Q}_\vartheta = \{\boldsymbol{r} \in \mathcal{M} \mid \delta(\boldsymbol{r}) \geq \vartheta\}$$

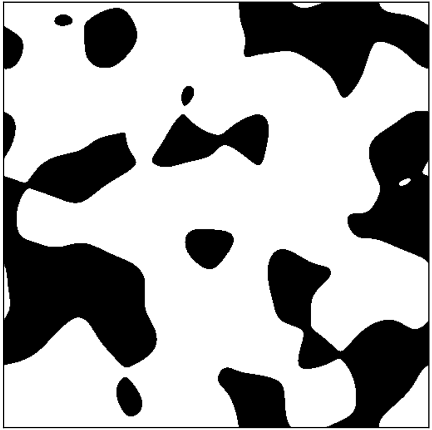


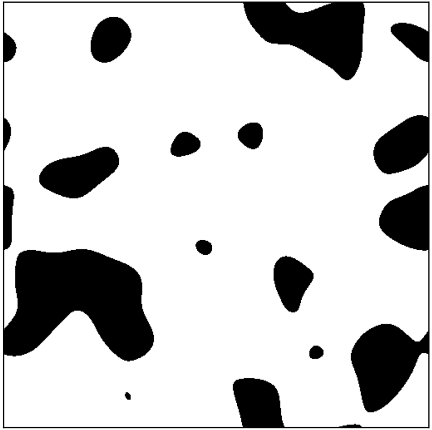


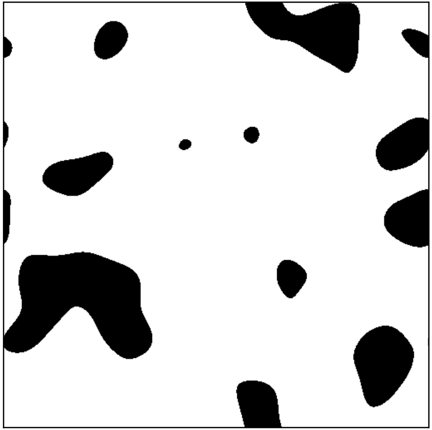


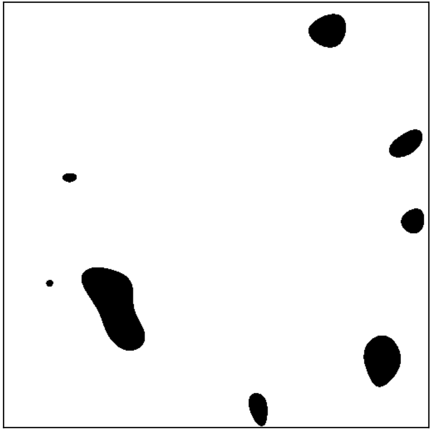












General Form

$$\Xi \equiv \int_{Q_\vartheta} dV_d\, \mathcal{G}(s_\nu; \vec{r}, \delta, \boldsymbol{\nabla}\delta, \ldots)$$

$$\mathcal{W}_\nu^{(p,q)} \equiv \int_{\partial Q_\vartheta} dA_d\, s_\nu \overbrace{\boldsymbol{r} \otimes \boldsymbol{r} \otimes \ldots \otimes \boldsymbol{r}}^{p-times} \otimes \underbrace{\frac{\boldsymbol{\nabla}\delta}{|\boldsymbol{\nabla}\delta|} \otimes \frac{\boldsymbol{\nabla}\delta}{|\boldsymbol{\nabla}\delta|} \otimes \ldots \otimes \frac{\boldsymbol{\nabla}\delta}{|\boldsymbol{\nabla}\delta|}}_{q-times}$$

Minkowski Tensors

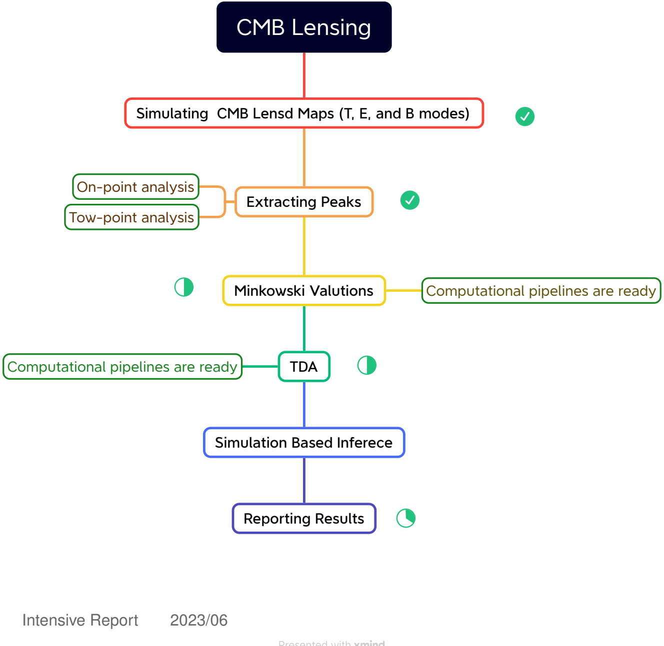
$$N_{cr}^{(r,s)}(\vartheta, i; n) = \frac{1}{V}\int_V dV\, \delta_D\left(\delta^{(r,s)} - \vartheta\sigma_0^{(r,s)}\right) \left|\delta_{,i}^{(r,s)}\right| = \frac{1}{V}\int_{\partial Q_v} dA\, \frac{\left|\delta_{,i}^{(r,s)}\right|}{\left|\boldsymbol{\nabla}\delta^{(r,s)}\right|}$$

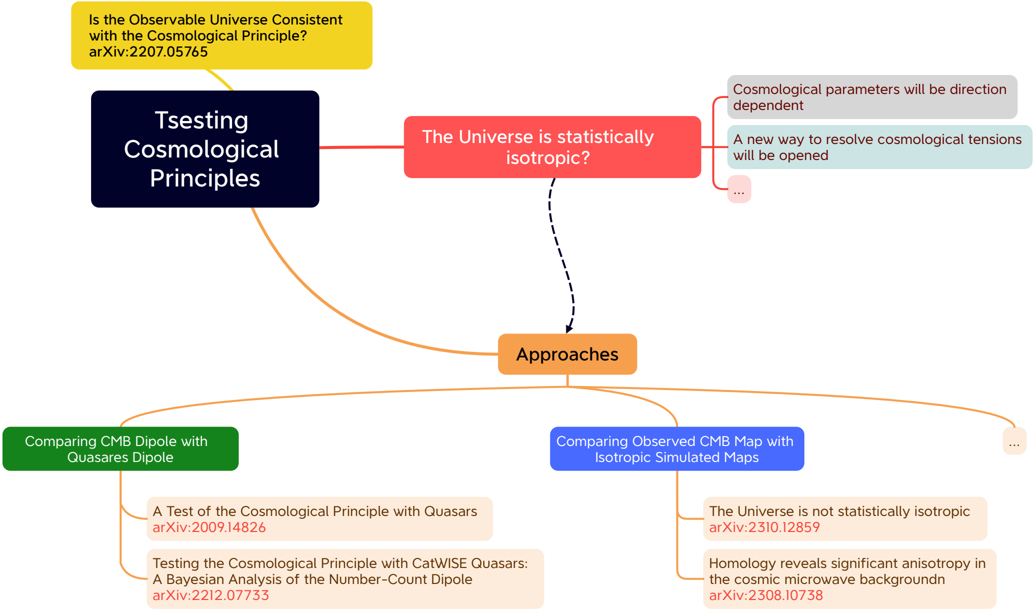
Crossing Statistics

$$N_{cmd}^{(r,s)}(\vartheta, i; n) \equiv \frac{1}{V}\int_V dV\, \delta_D\left(\delta^{(r,s)} - \vartheta\sigma_0^{(r,s)}\right) \left(\delta_{,i}^{(r,s)}\right)^n = \frac{1}{V}\int_{\partial Q_v} dA\, \frac{\left(\delta_{,i}^{(r,s)}\right)^n}{\left|\boldsymbol{\nabla}\delta^{(r,s)}\right|}$$

Conditional Moments of the First Derivative (cmd)

Morphology of CMB fields: effect of weak gravitational lensing

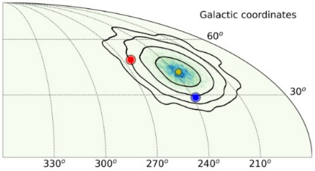



Is the Observable Universe Consistent with the Cosmological Principle? arXiv:2207.05765
Tsesting Cosmological Principles
The Universe is statistically isotropic?
Cosmological parameters will be direction dependent
A new way to resolve cosmological tensions will be opened
...
Approaches
Comparing CMB Dipole with Quasares Dipole
A Test of the Cosmological Principle with Quasars arXiv:2009.14826
Testing the Cosmological Principle with CatWISE Quasars: A Bayesian Analysis of the Number-Count Dipole arXiv:2212.07733
Comparing Observed CMB Map with Isotropic Simulated Maps
The Universe is not statistically isotropic arXiv:2310.12859
Homology reveals significant anisotropy in the cosmic microwave backgroundn arXiv:2308.10738
...

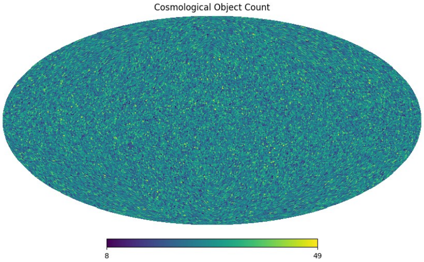
$$N_{\text{obs}}(\boldsymbol{n}, > S) = N_{\text{rest}}(\boldsymbol{n}, > S)\left[1 + A\,\boldsymbol{n}\cdot\hat{\boldsymbol{\beta}}\right]$$

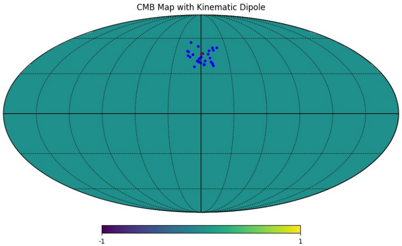
$$A = \left[2 + x(1+\alpha)\right]\beta$$

$$\min \sum_p \frac{\left[N_p(\boldsymbol{n}, > S) - \bar{N}(> S)\ \left(1 + A\cos\theta_p\right)\right]^2}{\bar{N}(> S)\ \left(1 + A\cos\theta_p\right)}$$



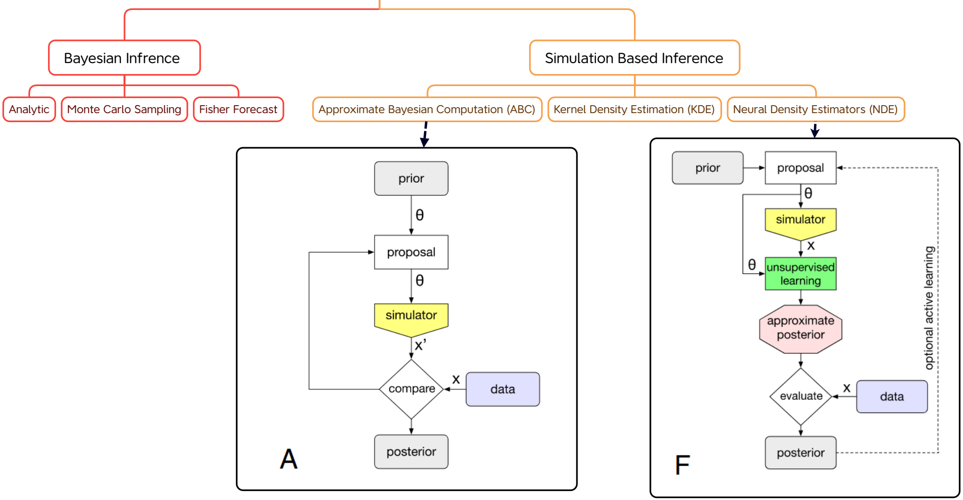
Bengaly, Carlos AP, et al. MNRS (2019): 1350-1357





Data Modeling: Estimating the posterior function

$$\mathcal{P}(\theta|\mathcal{D}) \sim \mathcal{L}(\mathcal{D}|\theta)\ \mathcal{P}(\theta)$$



Cranmer, Kyle, Johann Brehmer, and Gilles Louppe. Proceedings of the National Academy of Sciences 117.48 (2020): 30055-30062.