The Cosmic Web as a Probe of Inflationary Physics

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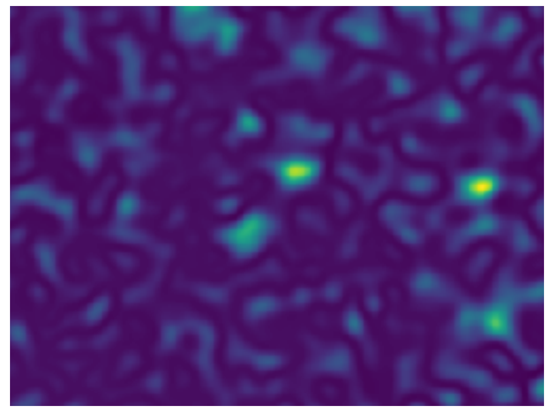
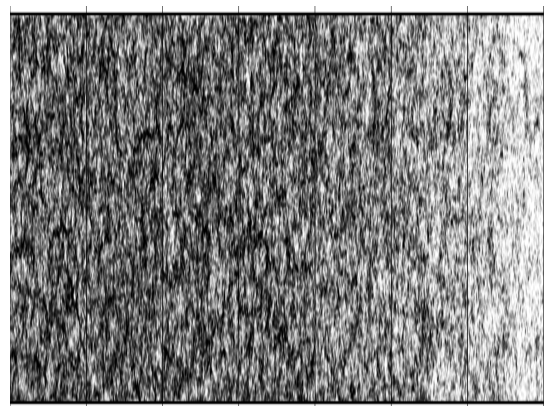
Cosmic Web @ KITP - 9 Feb 2023

In this talk I'll discuss how we can look for signatures of novel early-universe physics in the Cosmic Web



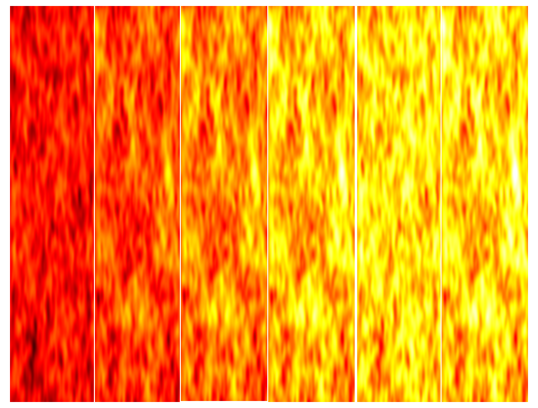
What is non-Gaussianity and how do we measure it?

$$|\mathrm{Web}\rangle \otimes \frac{|\mathrm{Ski}\rangle + |\mathrm{Sky}\rangle}{\sqrt{2}}$$



The Peak-Patch/WebSky Pipeline

for fast generation of mock cosmological observables

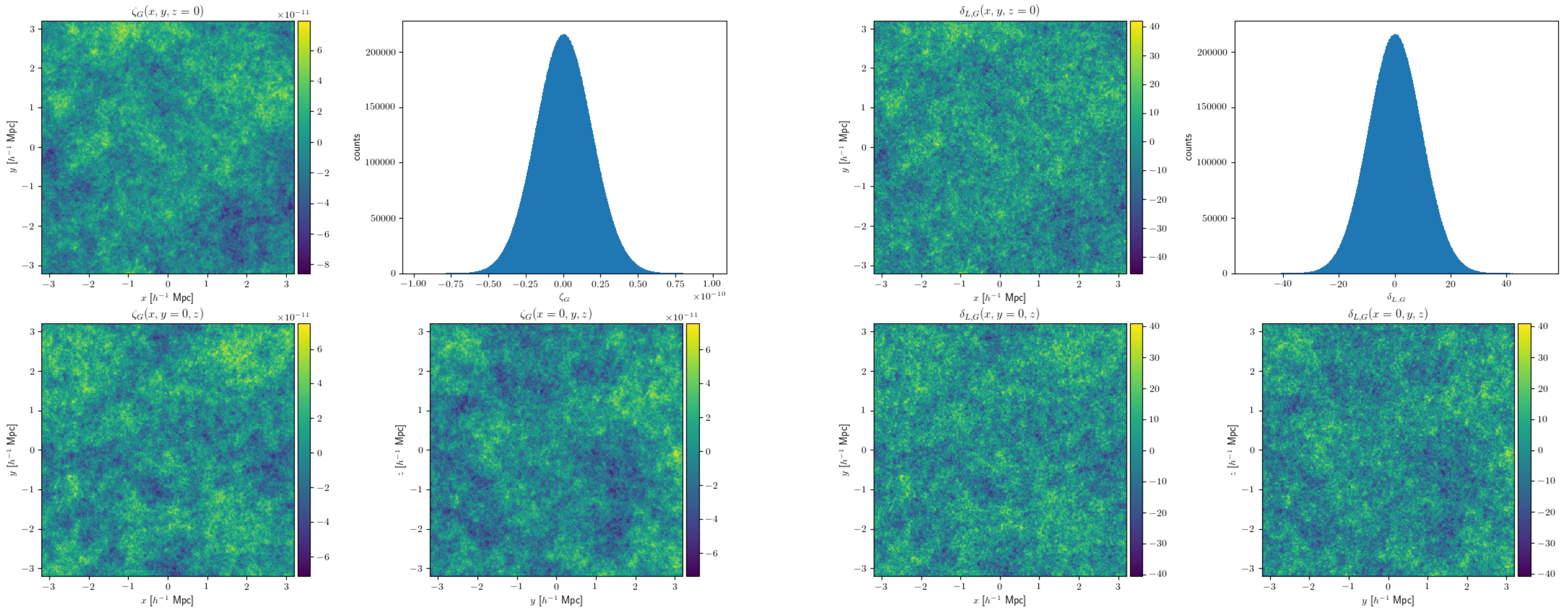


Constraining inflation

with statistics of mock sky maps

We will soon be putting out a new public release of WebSky catalogues with a range of non-Gaussian initial conditions.

The CMB is highly Gaussian, but all our theories predict some deviation. Inflation transports modes outside the horizon, the scalar perturbation field ζ *is a conserved quantity outside the horizon*



Gaussian zeta and overdensity fields. These are used as the initial conditions for Peak Patch.

The lowest-order non-Gaussian term that can arise from single-field inflation is from a quadratic coupling to a single underlying Gaussian field. This is tightly constrained by bispectrum.

$$\zeta(\mathbf{x}) = \zeta_g(\mathbf{x}) + f_{\mathrm{NL}} \left(\zeta_g^2(\mathbf{x}) - \langle \zeta_g^2(\mathbf{x}) \rangle \right)$$

Gaussian component

Amplitude (sort of…)

Non-Gaussian component is a function of Gaussian component

CMB bispectrum measurements put fairly tight constraints on various different types of perturbative non-Gaussianity $f_{\mathrm{NL}}^{\mathrm{local}} = -0.9 \pm 5.1, \quad f_{\mathrm{NL}}^{\mathrm{equil}} = -26 \pm 47, \quad f_{\mathrm{NL}}^{\mathrm{ortho}} = -38 \pm 24$ with 1-σ C.L. [1905.05697]

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Gaussian component

Non-Gaussian component is a function of Gaussian component

$$\zeta(\mathbf{x}) = \zeta_g(\mathbf{x}) + f_{\mathrm{NL}} \left(\zeta_g^2(\mathbf{x}) - \sigma_{\zeta_g}^2 \right)$$
$$= \zeta_g(\mathbf{x}) + \bar{f}_{\mathrm{NL}} \left(\frac{\zeta_g^2(\mathbf{x})}{\sigma_{\zeta_g}^2} - 1 \right)$$

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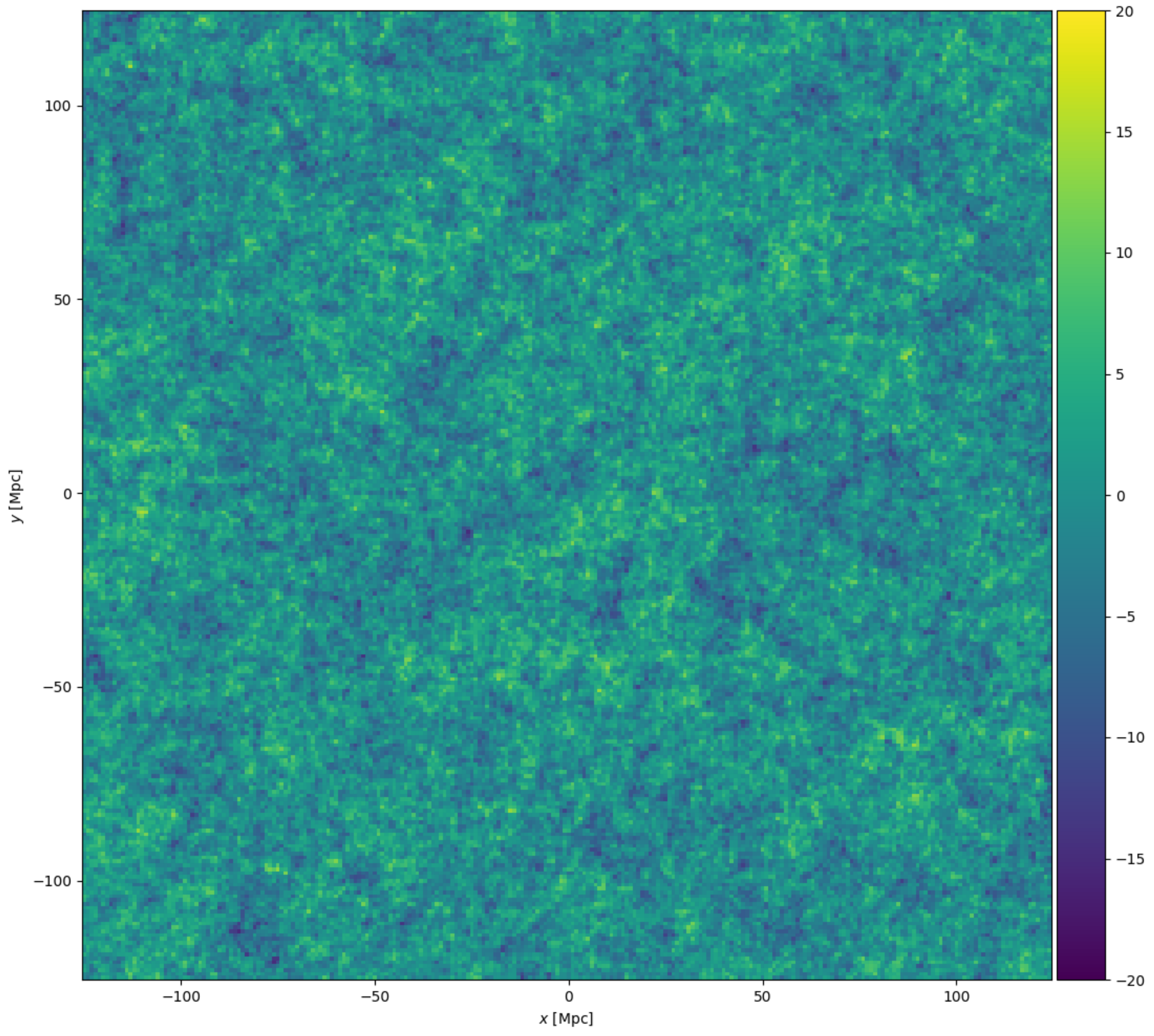
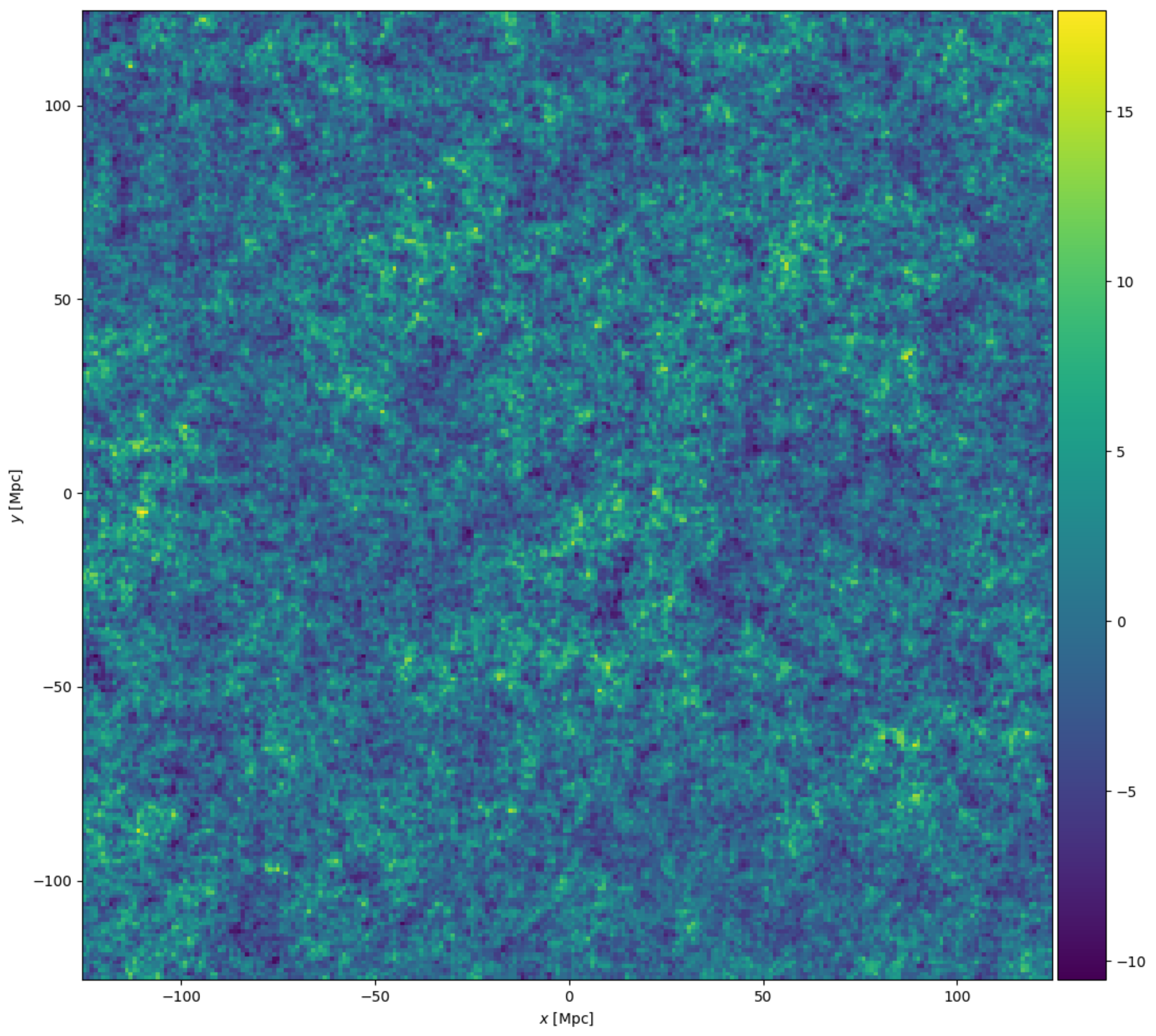
There are other mechanisms that can generate non-Gaussianity which is not correlated to the underlying Gaussian field. In such cases, similar “f_{NL}” give considerably less effect.

Gaussian overdensity $\delta_g(\mathbf{x})$



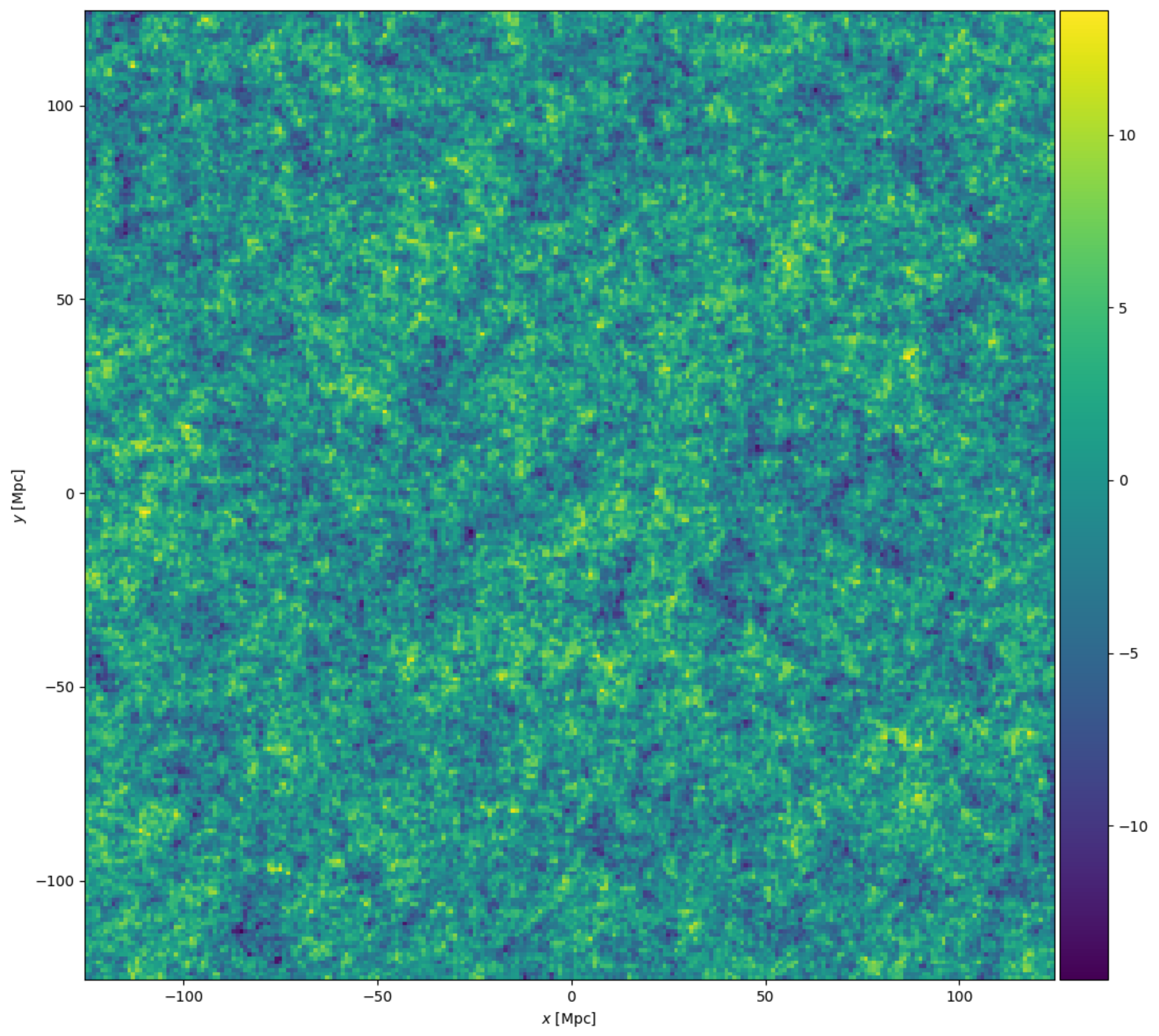
Underlying Gaussian sourced only by $\zeta_g(\mathbf{x})$

Correlated Gaussian overdensity $\delta_g(\mathbf{x})$



Classical f_{NL} non-Gaussianity sourced by $\zeta(\mathbf{x}) = \zeta_g(\mathbf{x}) + f_{\mathrm{NL}}\left(\zeta_g^2(\mathbf{x}) - \langle \zeta_g^2(\mathbf{x})\rangle\right)$ with $f_{\mathrm{NL}} = 10^5$.

Uncorrelated Gaussian overdensity $\delta_g(\mathbf{x})$



Uncorrelated gaussian field $\chi_g(\mathbf{x})$ with nearly scale-invariant power spectrum giving rise to non-Gaussianity sourced by $\zeta(\mathbf{x}) = \zeta_g(\mathbf{x}) + \tilde{f}_{\mathrm{NL}}\left(\chi_g^2(\mathbf{x}) - \langle \chi_g^2(\mathbf{x})\rangle\right)$ with $\tilde{f}_{\mathrm{NL}} = 10^5$

Other mechanisms generate non-Gaussianity from uncorrelated primordial fields coupling to observables via functional forms that don't fit the f_{NL} series expansion approach

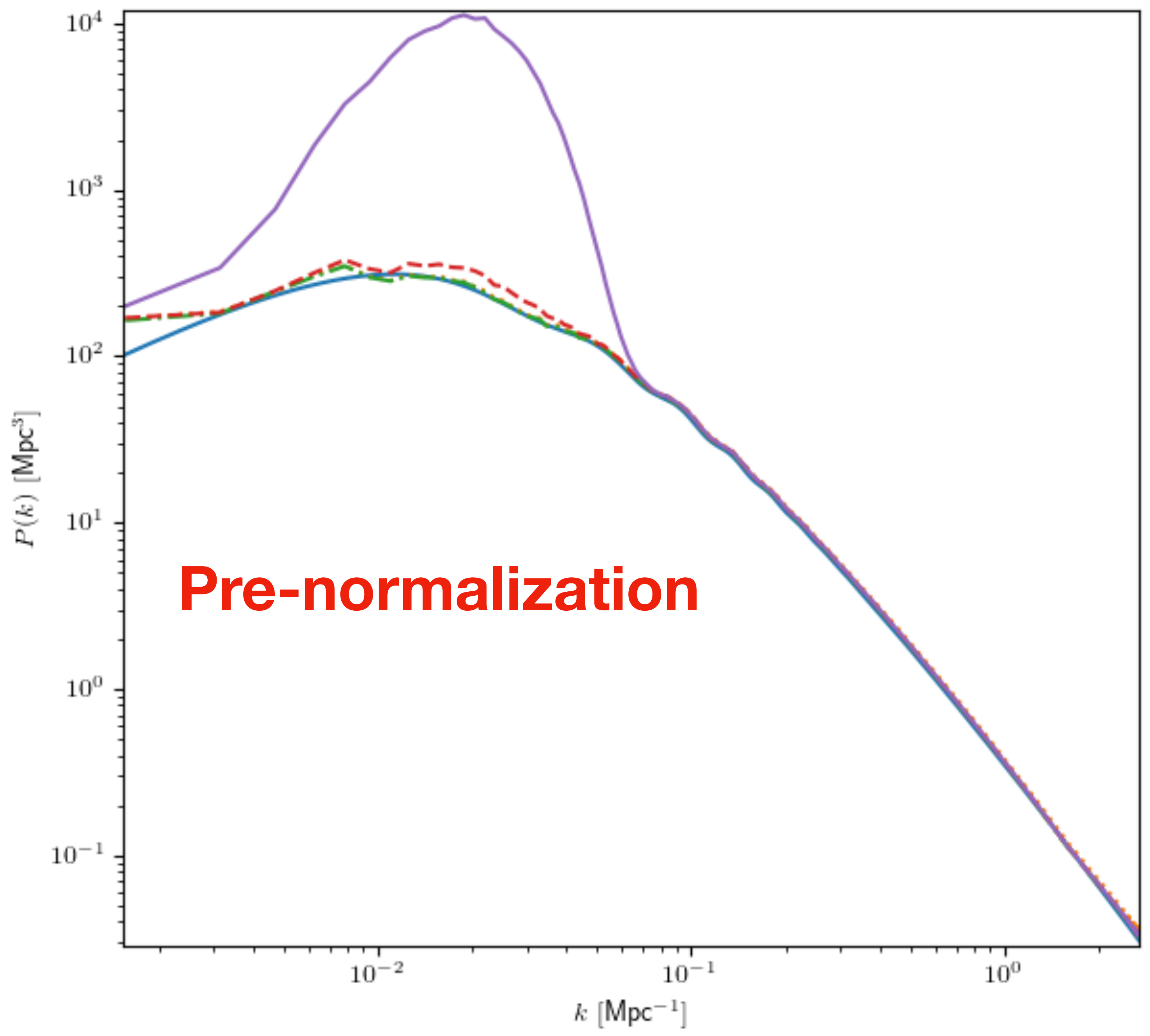
Generalized functional form

$$\zeta(\mathbf{x}) = \zeta_g(\mathbf{x}) + F_{\mathrm{NL}}\left[\chi_g(\mathbf{x})\right]$$

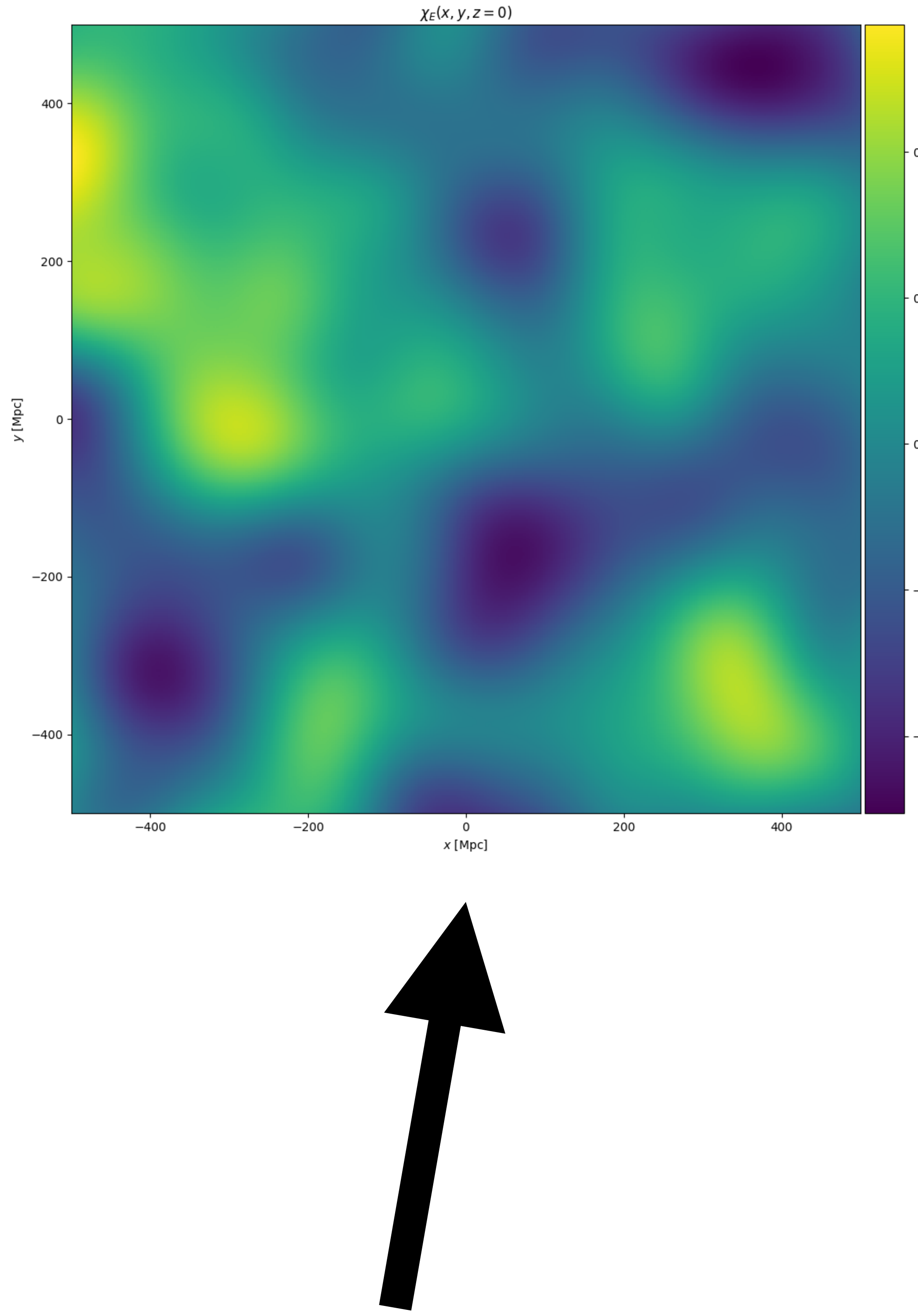
We are particularly interested in models that give rise to intermittent non-Gaussianity peaks.

Model by Morrison et al 2023 (in prep)

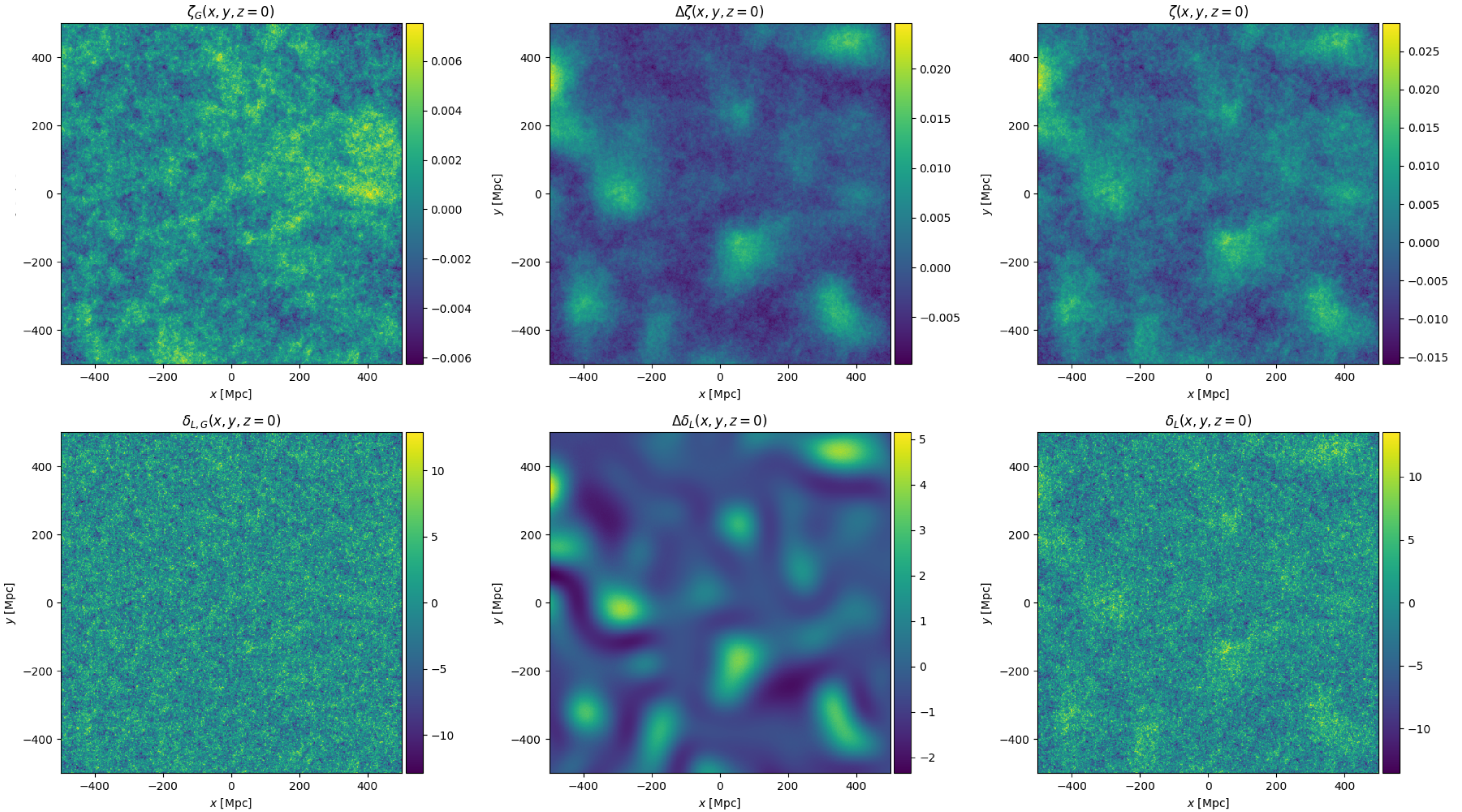
inflationary fields traverse an instability in the potential and injects power at some characteristic scale



Other mechanisms generate non-Gaussianity from uncorrelated primordial fields coupling to observables via functional forms that don't fit the $f_{\rm NL}$ series expansion approach



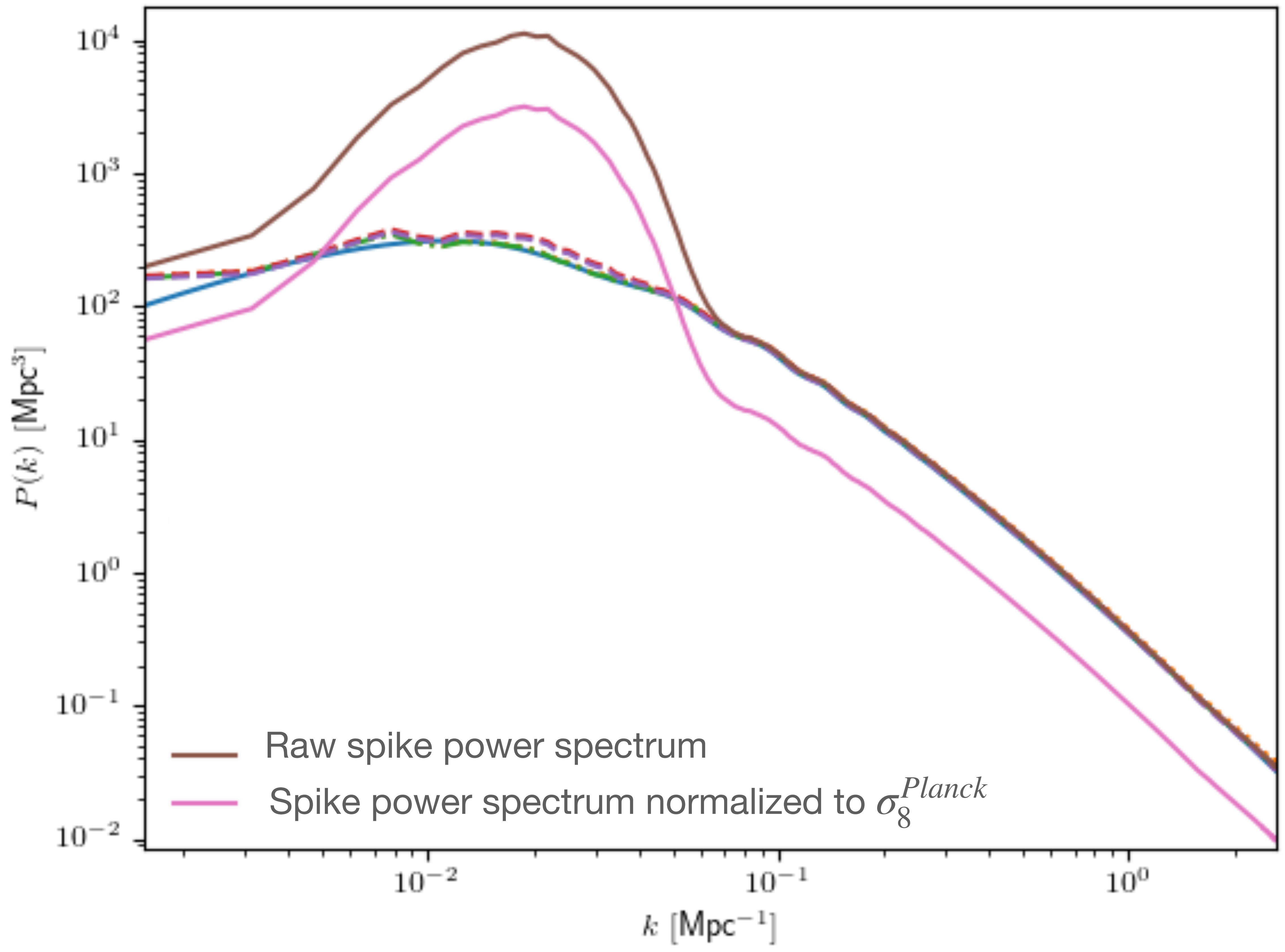
Transverse inflationary field χ



Relative power is a better measure of the amplitude of non-Gaussianity than f_{NL}

$$\zeta(\mathbf{x}) = \frac{\sigma_8^{Planck}}{\sigma_8^{\mathrm{ng}}}\left[\zeta_g(\mathbf{x}) + F_{\mathrm{NL}}\left[\chi_e(\mathbf{x})\right]\right]$$

Where $\sigma_{8,\mathrm{obs}}$ is the standard deviation in the density perturbations $\delta(\mathbf{x})$ smoothed at a scale of $8\ h^{-1}$Mpc so we can use the *Planck* result for instance.



The (*mass*) Peak Patch-WebSky pipeline has native support for a diversity of non-Gaussian initial conditions, provides a fast and robust

Gaussian DM halo catalogue

Peak Patch dark matter halo catalogues showing a 50 Mpc thick slab projected onto a plane (Carlson+23 in prep).

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Non-Gaussianity on the sky with the WebSky simulations

tSZ and kappa slices from z ~ 2.5 to z ~ 3.5

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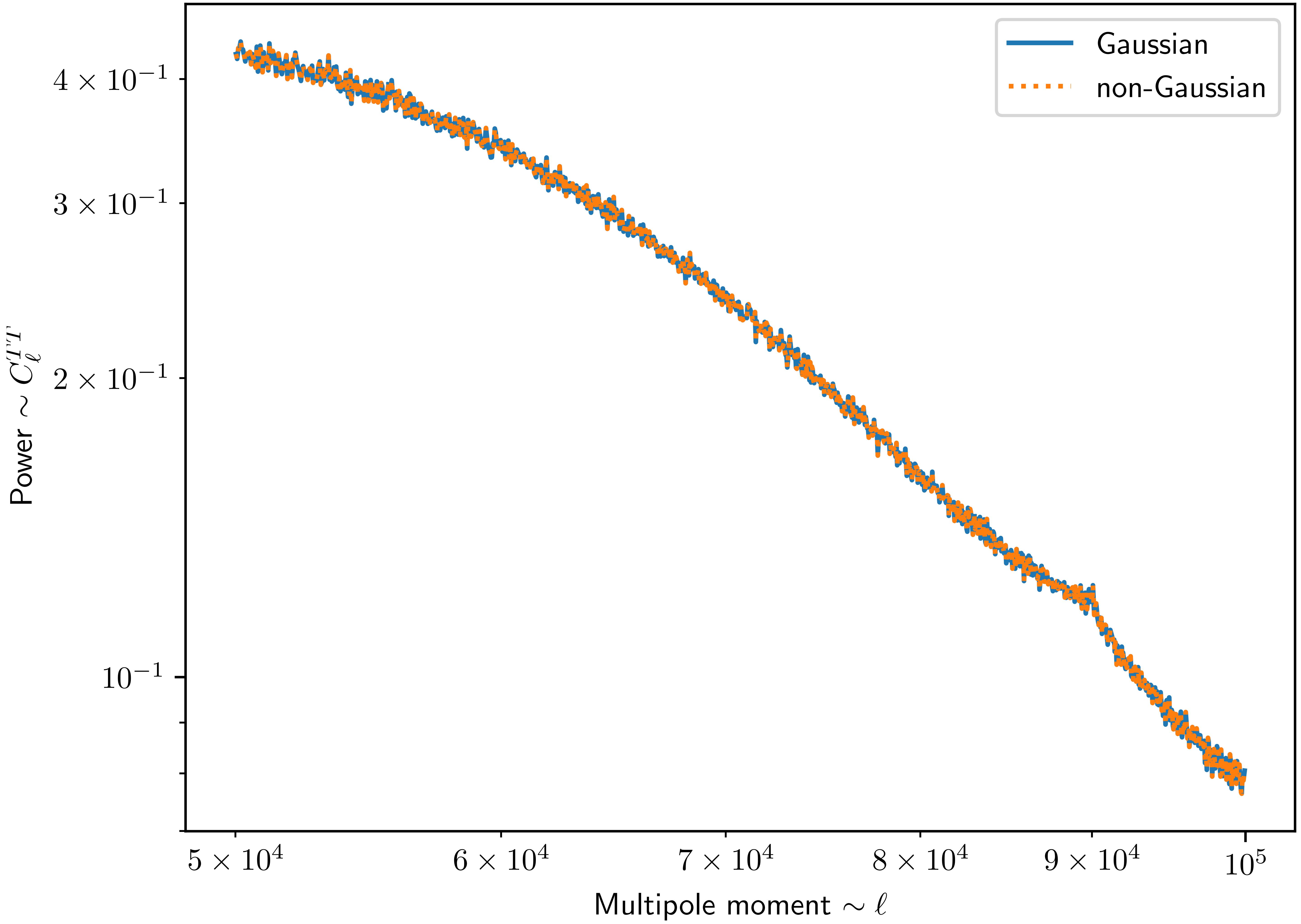
Non-Gaussianity on the sky with the WebSky simulations

$8.182^{\circ} \times 8.182^{\circ}$ integrated CIB signal from $z \in [2.53,\ 3.56]$ with Gaussian initial conditions.

Non-Gaussianity on the sky with the WebSky simulations

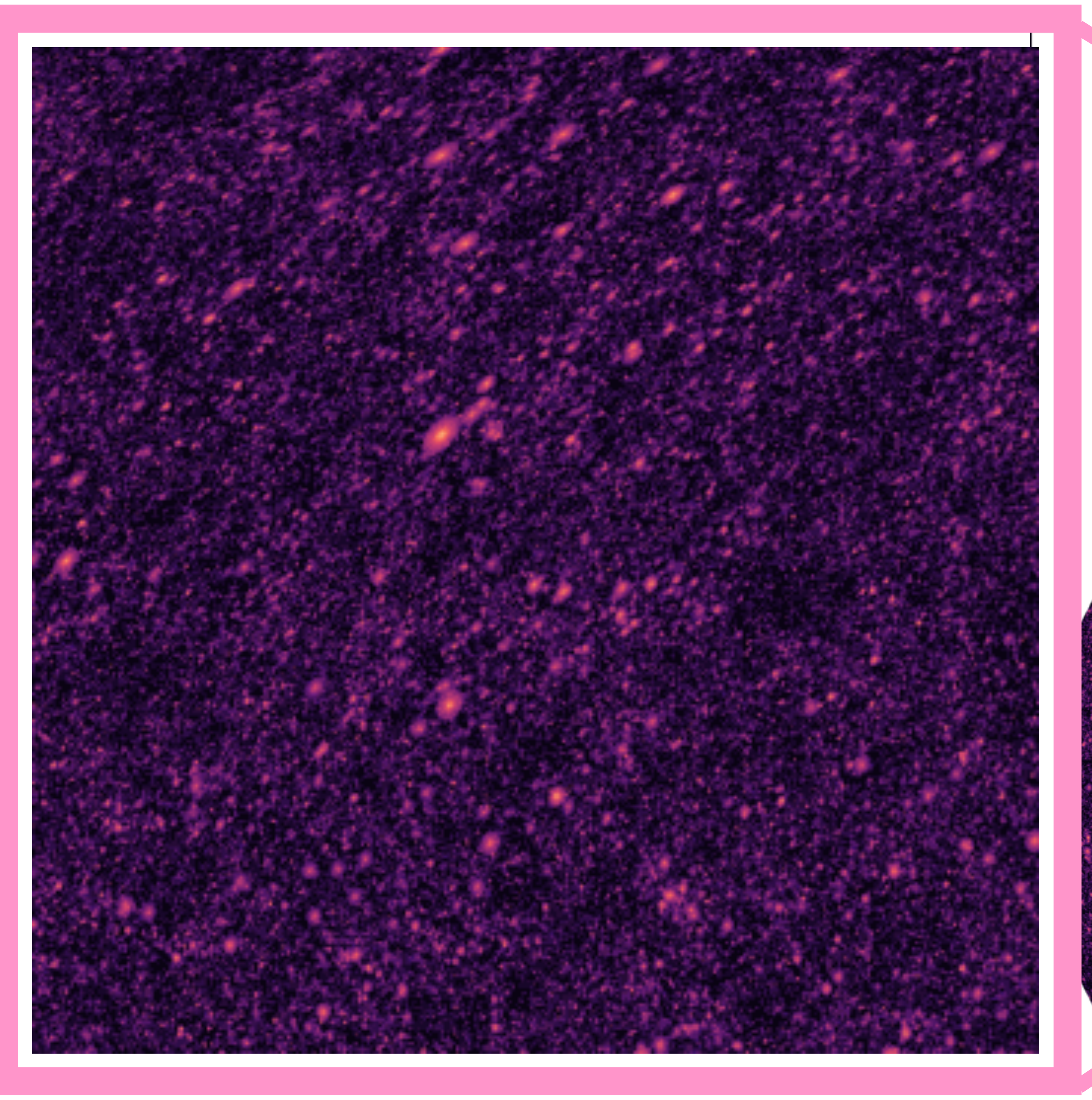
$8.182^{\circ} \times 8.182^{\circ}$ integrated CIB signal from $z \in [2.53,\ 3.56]$ with non-Gaussian initial conditions.

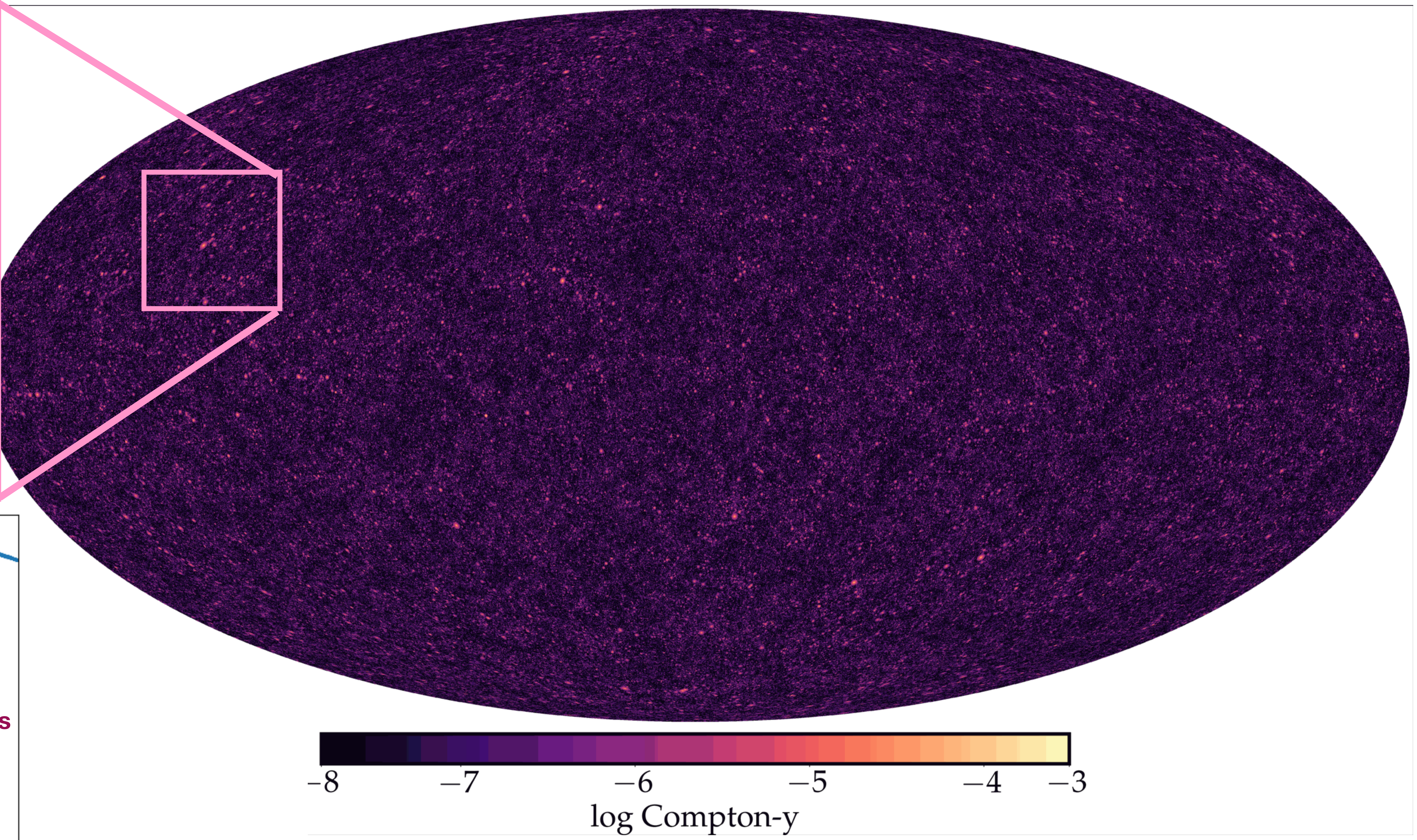
By measuring harmonic power spectra from these mock observables, we can directly compare the results of these novel non-Gaussian cosmologies to data

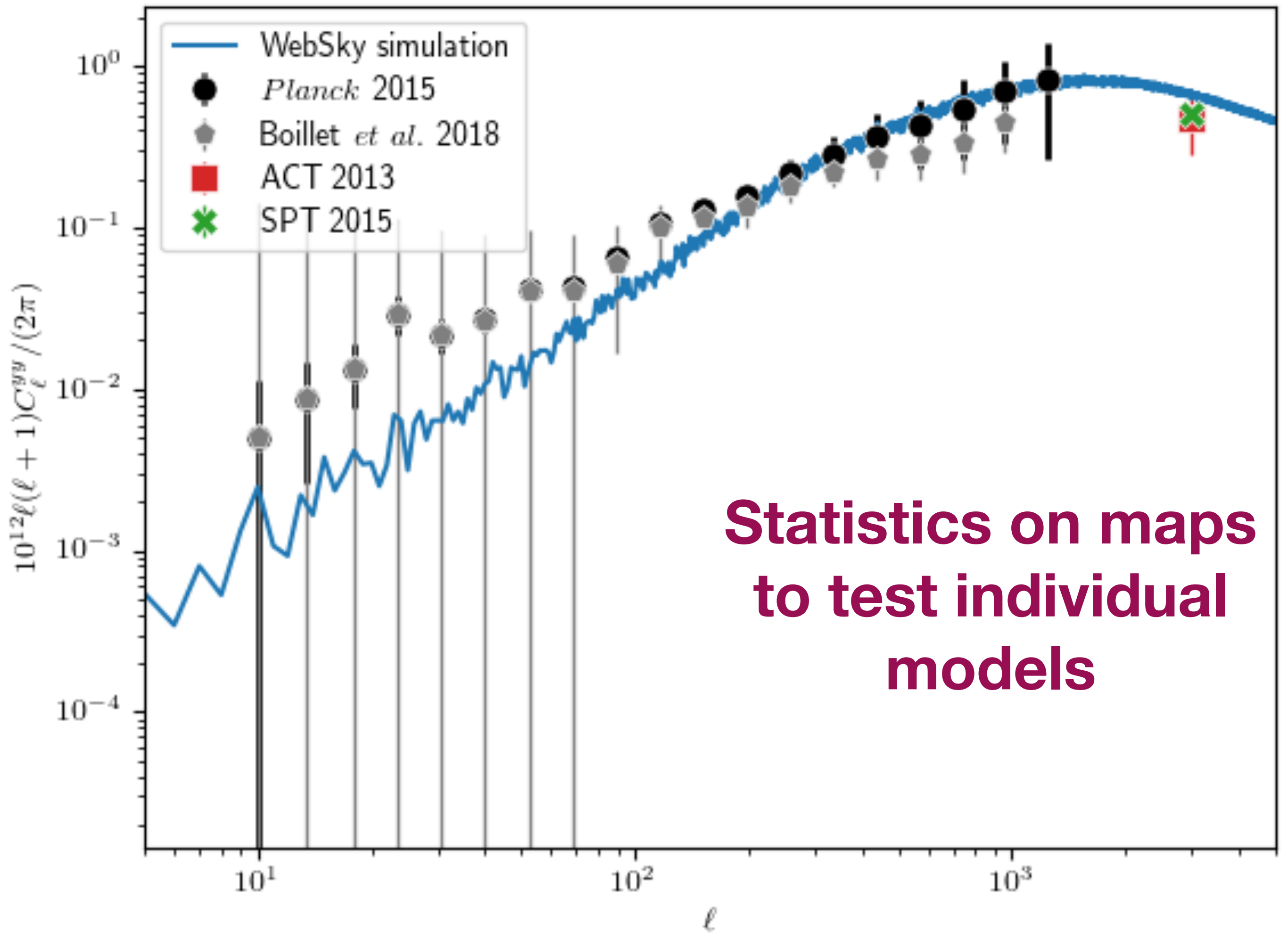


Angular power spectra in strong agreement with the Gaussian case which was validated by Stein et al. [1810.07727]

Upcoming Public non-Gaussian WebSky catalogue, we (may) take requests







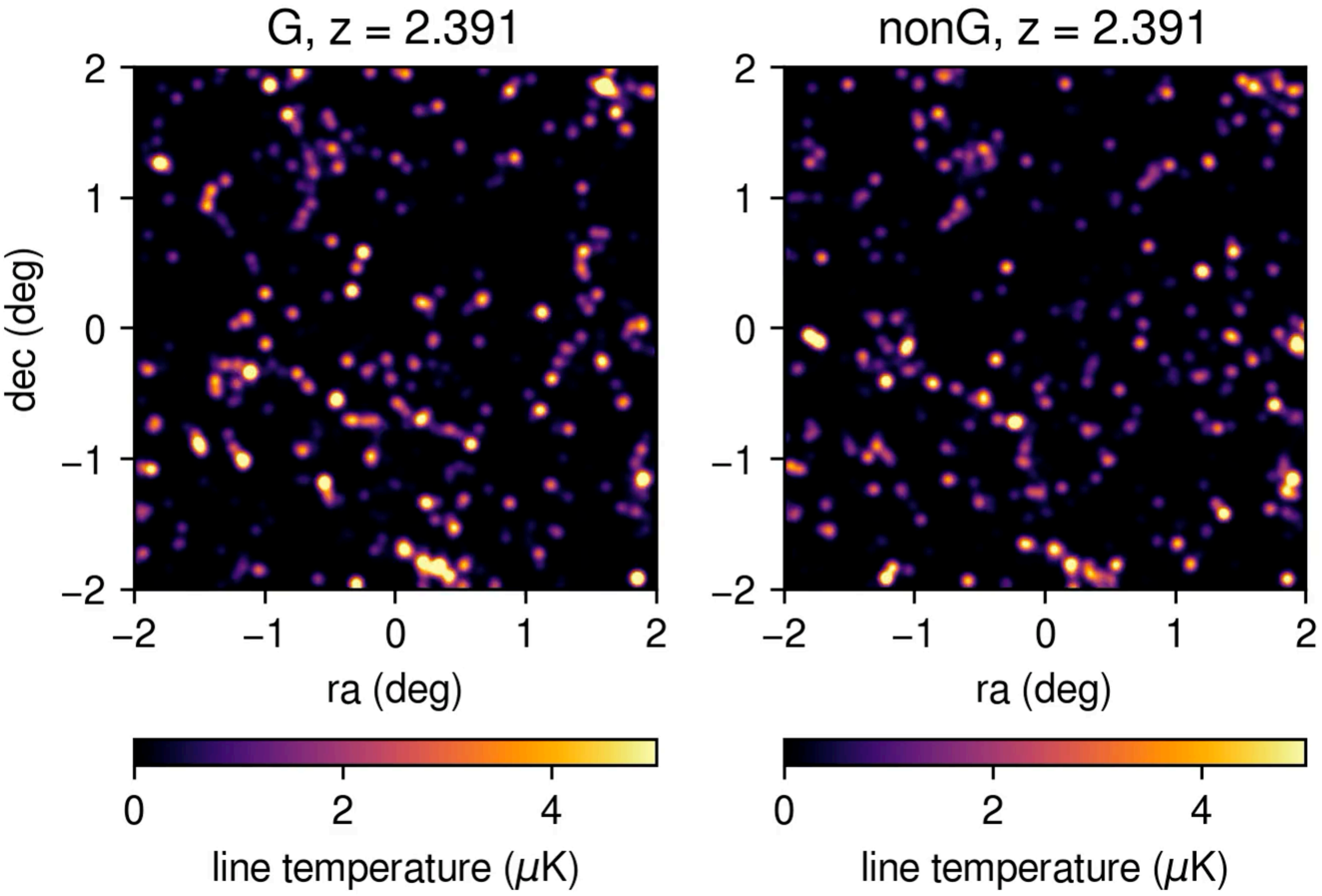
Statistics on maps to test individual models

Conclusion

- The (mass) Peak-Patch/WebSky pipeline is well-suited for mocking universes with any non-Gaussian initial conditions.

- WebSky mocks can be used to put constraints on multi-field inflation models.

- We will be updating the existing public WebSky catalogues to include various non-Gaussian models. If you have a favourite model, let us know, we may include it!



Fly-through CO line intensity maps
with and without the inflaton traversing an instability during inflation (courtesy of Dongwoo Chung)

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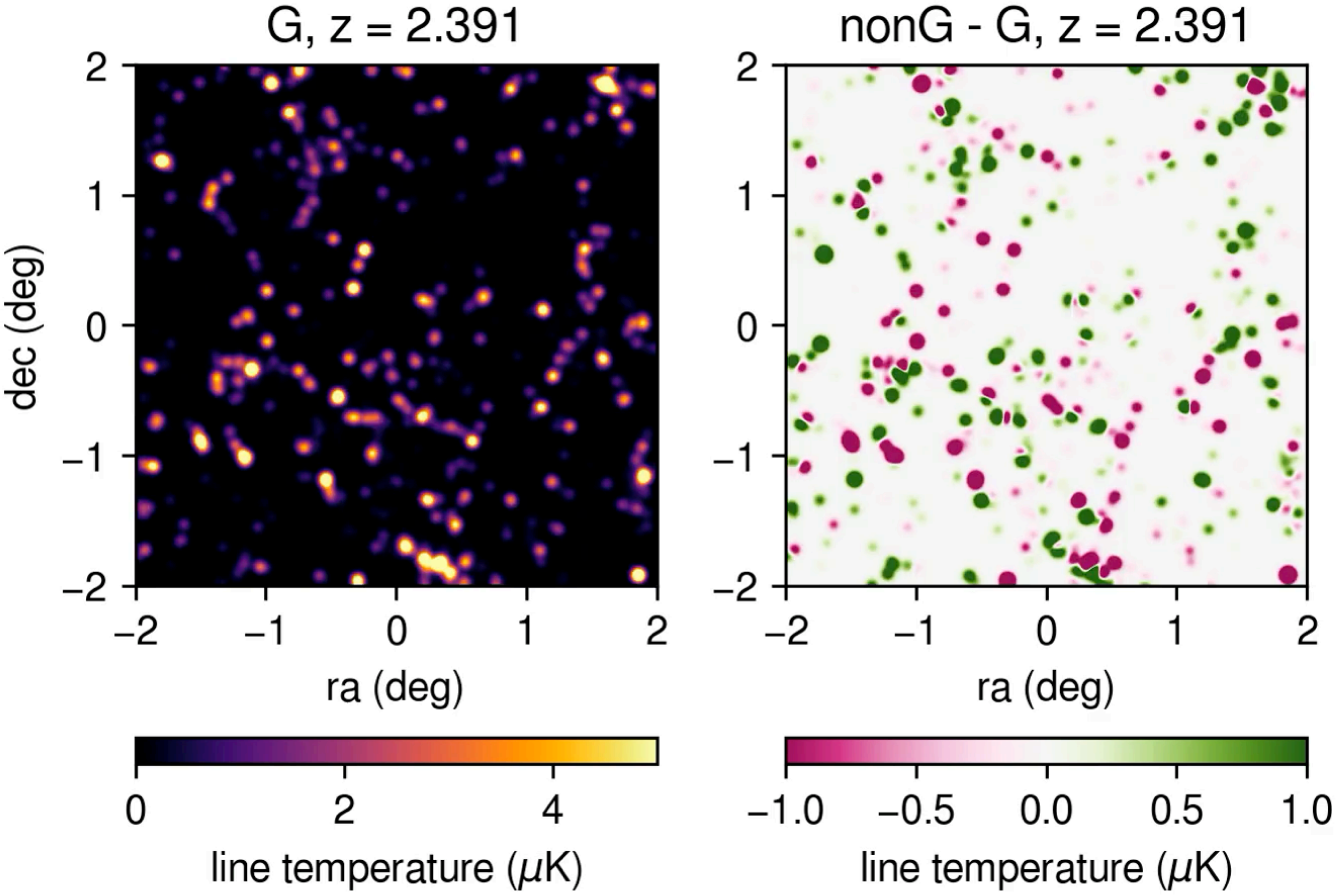

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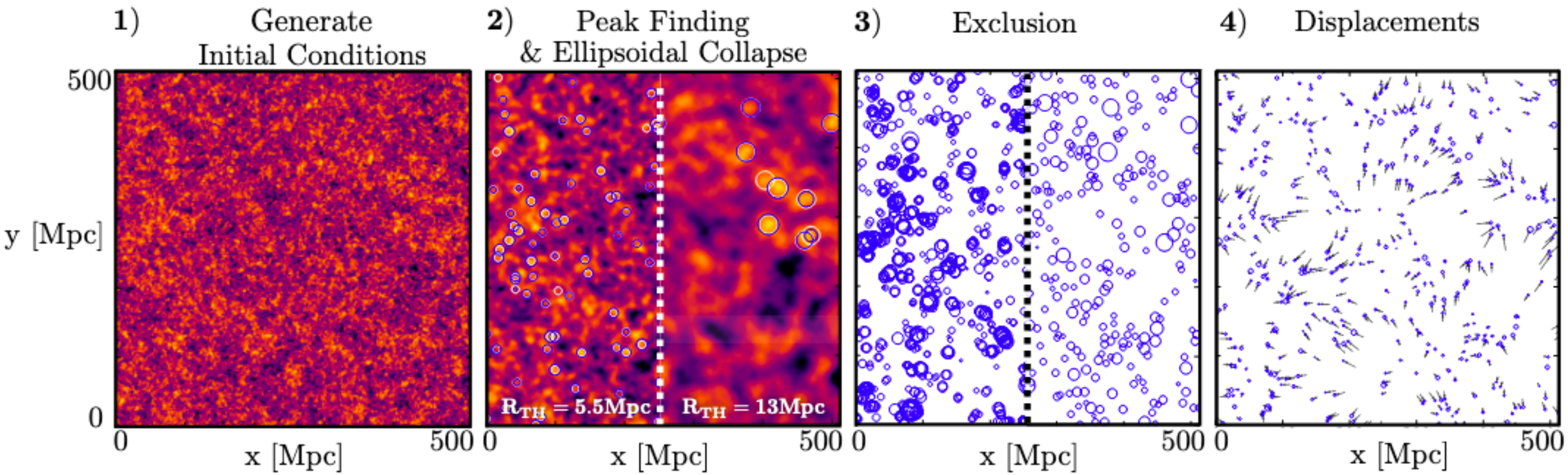
Dark matter halo catalogues are generated using the mass Peak Patch algorithm

- *Peak Patch* uses RG flow and approximate dynamics to **identify structures that will form DM halos** in the DM overdensity field of the early universe. A **merging and exclusion** algorithm is run to avoid double counting mass.
- Density **peaks** in initial fields are treated as **patches** of dynamically hot fluid with highly nonlinear dynamics. In the space between patches, flows are laminar, with a mix of warm and cool dynamics, well-described by low-order perturbations from a uniform fluid, so **patch displacement can be done with low-order perturbations**.
- **DM halo catalogues** from general initial conditions without expense of full *N*-body simulations.



Stein *et al.*, 2020 (arXiv:1810.07727)