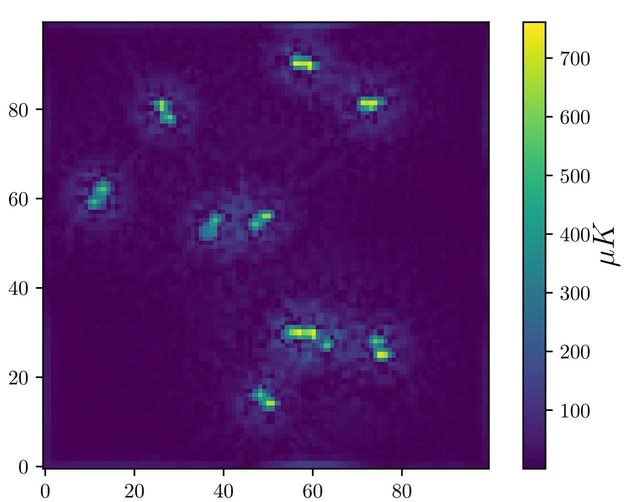
Cosmological Particle Production and Pairwise Hotspots on the CMB



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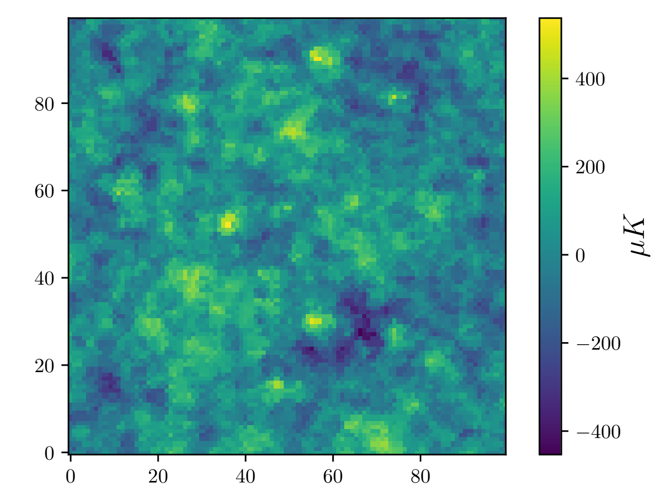
Work in progress

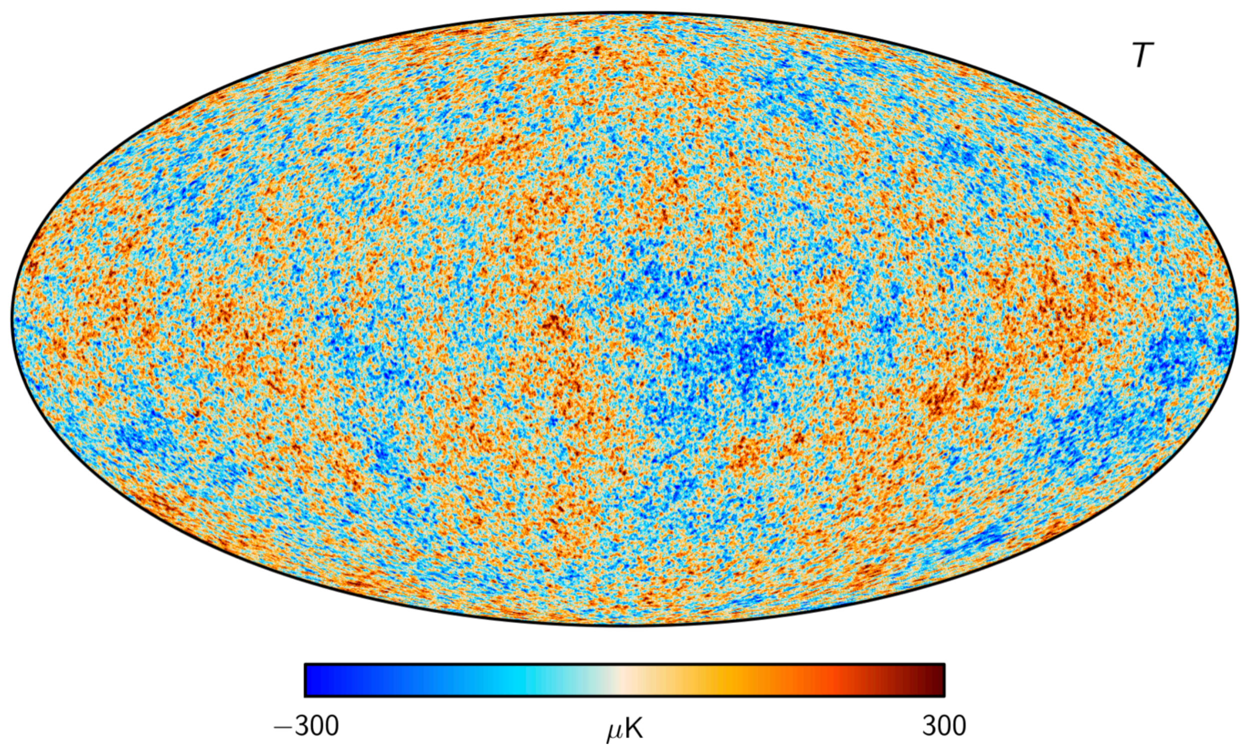
with Jeonghan Kim, Adam Martin and Yuhsin Tsai



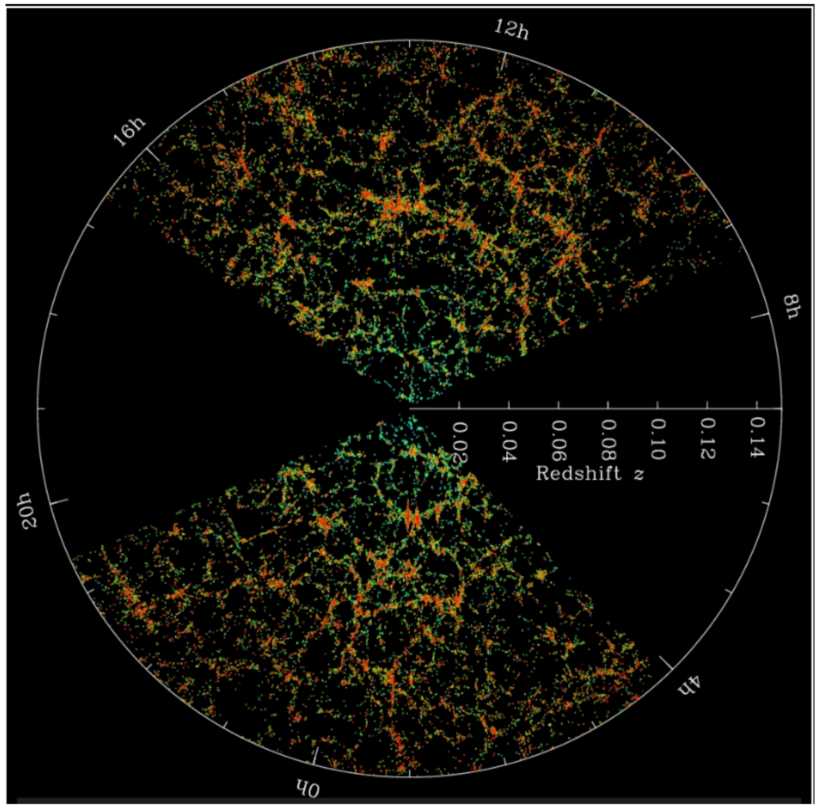
Cosmology from Home 2020

Aug 24 – Sep 04

Cosmic probes



CMB: Planck



LSS: SDSS

- Cosmic Inflation: leading paradigm for explaining fluctuations in CMB and LSS.

Features of primordial perturbations

- Standard inflationary paradigm: fluctuations of inflaton ϕ seeds the density fluctuations in CMB and LSS.
- Simplest models predict density fluctuations should be:
  - (almost) scale invariant
  - adiabatic
  - Gaussian

Planck '18

Features of primordial perturbations

- Standard inflationary paradigm: fluctuations of inflaton ϕ seeds the density fluctuations in CMB and LSS.

- Simplest models predict density fluctuations should be:
  - (almost) scale invariant ← Focus on this property
  - adiabatic
  - Gaussian

Planck '18

Violation of scale invariance

- Has been extensively discussed before:

  - massive fields $m \gtrsim H_{\text{inf}}$; monodromy can cause modulations in power spectrum.

    See Planck '18 for refs.

  - sharp features in the inflationary potential $\rightarrow$ features in power spectrum.

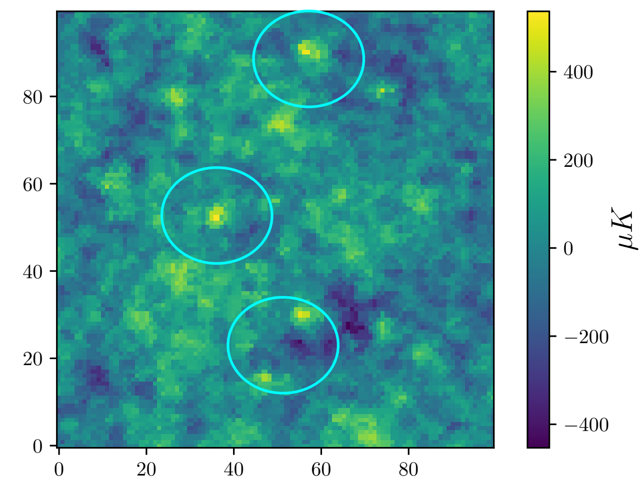
  - A different kind: time non-invariant production of $m \gg H_{\text{inf}}$ particles.

Basic idea of the talk

- At some particular time t_* during slow-roll inflation, an ultra-heavy particle σ becomes much lighter → efficient cosmological production.

- If σ doesn't immediately decay → due to its typically-high mass, it can create localized "dents" in the metric → hotspots on the CMB: break in scale invariance.

Hard to detect
via the momentum space
power spectrum,
but easily detectable
in position space!



CMB with
hotspots

Outline of the talk

- Theoretical set-up.
- Properties of hotspots on the CMB.
- Detection strategies.
- Conclusion.

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Set-up

- A simple model

$$V(\phi, \sigma) = V_{\text{inf}}(\phi) + \frac{1}{2}\left(M_0^2 + (g\phi - M)^2\right)\sigma^2 \quad \text{with} \quad M \sim g\phi \gg M_0$$

- σ-mass is time-dependent, and typically large, but for $g\phi \approx M$, effective mass

$$M_{\text{eff}}^2 \equiv M_0^2 + (g\phi - M)^2 \approx M_0^2 \ll M^2$$

- For $M_0 \sim \sqrt{\dot{\phi}_0} \sim 60 H_{\text{inf}}$, the kinetic energy of the inflaton can be used to produce σ.

Calculating particle production

- We estimate the number of particles produced using the standard Bogoliubov method.

Kofman et. al.
hep-ph/9704452
Chung et. al.
hep-ph/9910437
...

- A standard evaluation gives the probability of particle production

$$|\beta_k|^2 = e^{-\frac{\pi k^2 |\eta_*| H}{|g\dot{\phi}|}} e^{-\frac{\pi (M_0^2 - 2)}{|g\dot{\phi}|}}$$

"Boltzmann" suppression whenever energy of particle is bigger than $\sim \sqrt{g\dot{\phi}_0}$

Effects of produced particles

- Produced heavy particle backreacts on spacetime:

Maldacena 1508.01082
Fialkov et. al. 0911.2100

$$S_{\text{particle}} = \int dt \sqrt{-g_{00}} M_{\text{eff}} \supset \int d\eta \, \partial_\eta \zeta \, \frac{M_{\text{eff}}(\eta)}{H}$$

with ζ = comoving curvature perturbation

- Gives rise to a non-trivial one-point function,

$$\langle \zeta_k(\eta_0 \to 0) \rangle = -i \int_{\eta_*}^{0} d\eta \langle 0 | \zeta_k(\eta_0) \partial_\eta \zeta_k(\eta) | 0 \rangle \frac{M_{\text{eff}}(\eta)}{H} + \text{c.c.}$$

- The final position space profile of the result:

$$\langle \zeta(r) \rangle = \begin{cases} \left[\dfrac{M_{\text{eff}}(\eta = -r)}{2\sqrt{2\epsilon} M_{pl}} \right] \dfrac{H}{2\pi\sqrt{2\epsilon} M_{pl}}, & \text{if } |r| \leq |\eta_*| \\ 0, & \text{if } |r| > |\eta_*| \end{cases}$$

size of typical inflationary fluctuation $\equiv \sqrt{A_s}$

controls the visibility over the primordial fluctuation

size of the hotspot smaller than comoving horizon at η_*

We can wonder about ...

- How many hotspots do we expect to see?

- How large and hot is each hotspot?

- How are the hotspots distributed?

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How many hotspots?

- Integrate $|\beta_k|^2$: $n = \int d^3\mathbf{k}\, |\beta_k|^2$

- Number of hotspots within the CMB horizon $k_{\rm CMB}$ with k_* being the scale that exits the horizon at η_*,

$$N_{\rm hotspots} = \frac{1}{8\pi^3}\left(\frac{g\dot{\phi}}{H^2}\right)^{3/2} e^{-\frac{\pi(M_0^2-2)}{|g\dot{\phi}|}} \left(\frac{k_*}{k_{\rm CMB}}\right)^3$$

denotes the usual volume dilution

- Benchmark: $g = 1$, $M_0 = 2(g\dot{\phi})^{1/2}$:

$$N_{\rm hotspots} \approx 3000 \text{ for } k_* = 100 k_{\rm CMB} \text{ i.e. } l \approx 100$$

How large and hot is a hotspot?

$$\langle \zeta(r) \rangle = \begin{cases} \left[\frac{M_{\text{eff}}(\eta = -r)}{2\sqrt{2\epsilon}M_{pl}} \right] \frac{H}{2\pi\sqrt{2\epsilon}M_{pl}}, & \text{if } r \le |\eta_*| \\ 0, & \text{if } r > |\eta_*| \end{cases}$$

- For $r \lesssim |\eta_*|$ we can approximate $M_{\text{eff}}(\eta) \approx g(\phi - \phi_*)$, which gives,

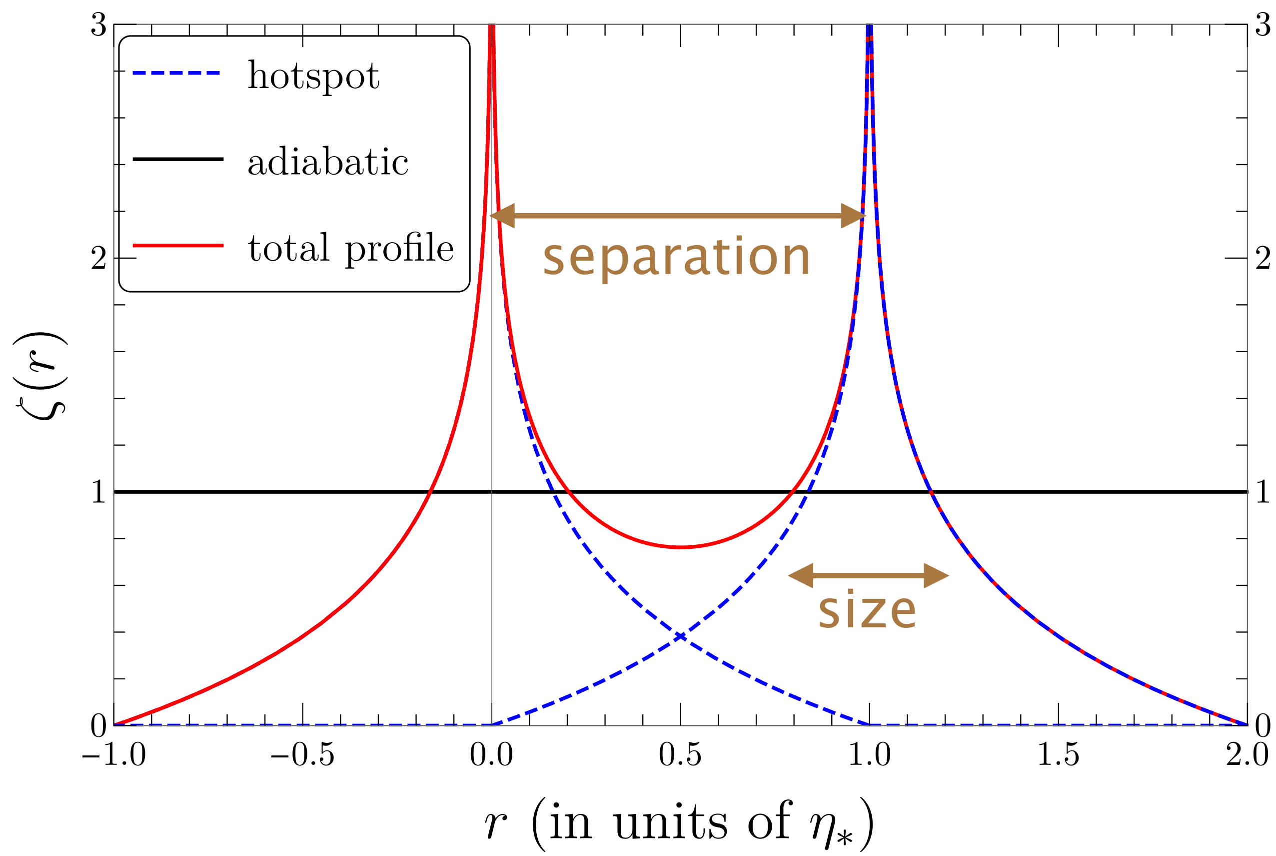
$$\langle \zeta(r \lesssim |\eta_*|) \rangle \approx \left[\frac{g}{2} \log \left(\frac{r}{|\eta_*|} \right) \right] \frac{H}{2\pi\sqrt{2\epsilon}M_{pl}}$$

size of typical inflationary fluctuation $\equiv \sqrt{A_s}$

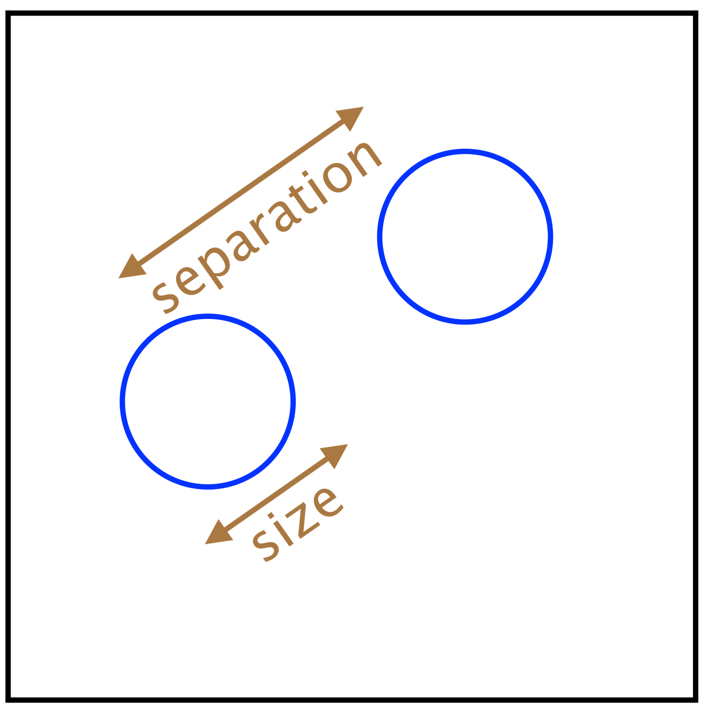
- Hence hotspot size $\sim |\eta_*|$ and the amplitude g controls the visibility over the random CMB fluctuation.

How are the hotspots distributed?

- Heavy particles are produced from fluctuating spacetime
  → they always come in pairs: momentum conservation



simplified view



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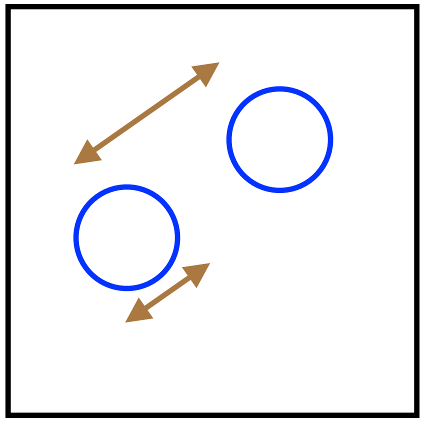
Parametrizing the pair-wise signal



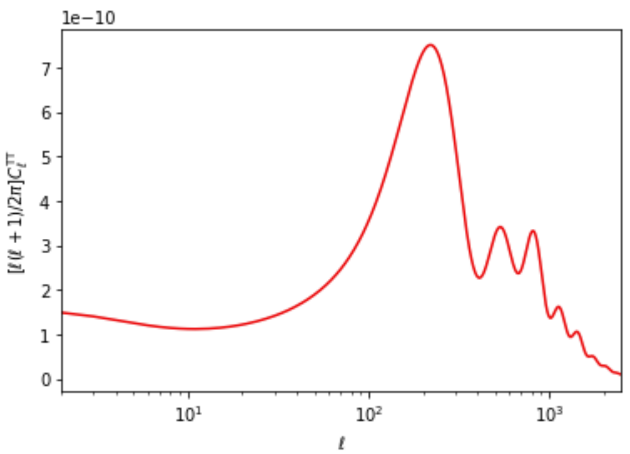
- Single hotspot: amplitude and size
- For pairs, a third parameter: separation between hotspots.
- Position space methods best suited $\rightarrow$ use Wavelet Analysis.

delocalization of position space peaks when Fourier transforming

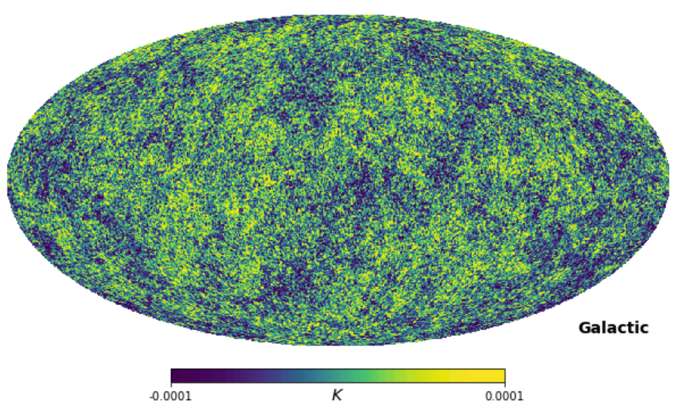
already used by Planck for point source detection

Analysis pipeline

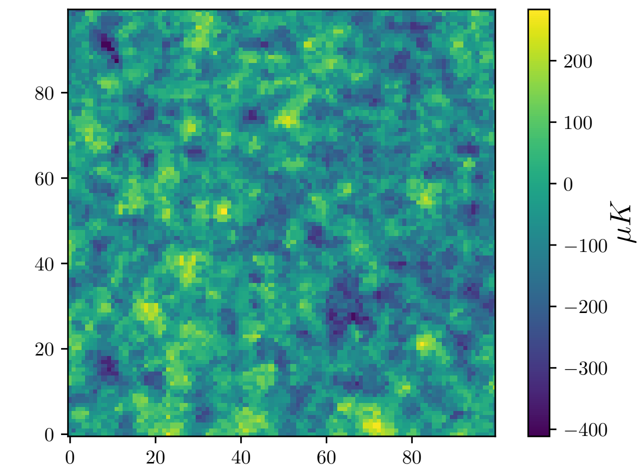
Preliminary



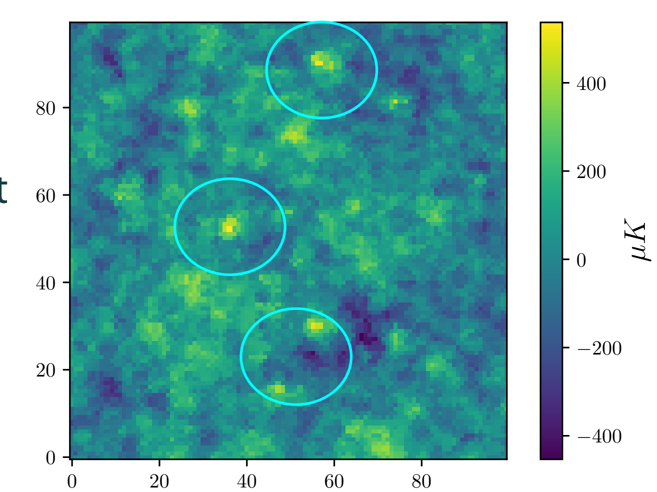
HEALPix



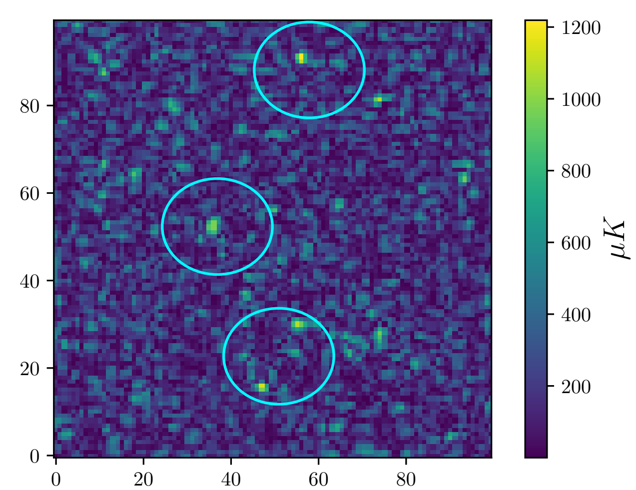
Small patch



Inject Hotspots

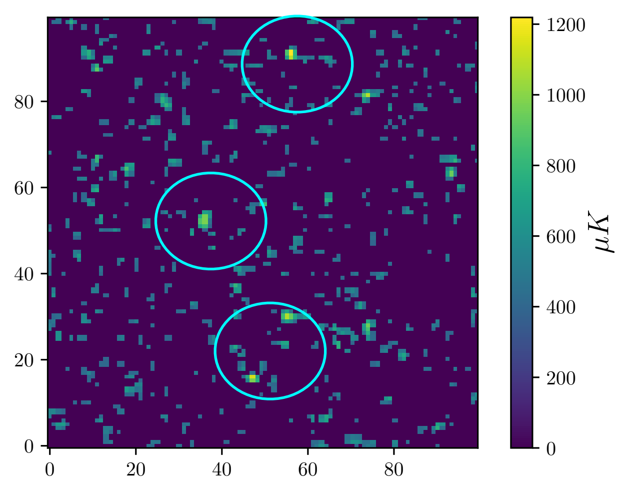


Mexican Hat Wavelet



Further Selection

$\delta T_{\rm cut} = 400\mu K$

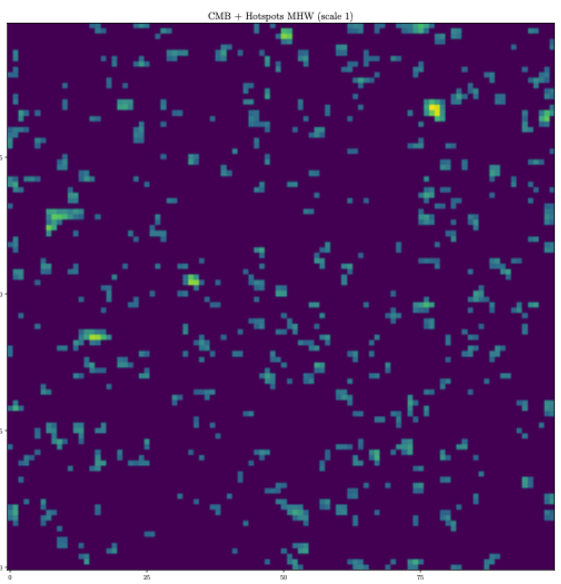


Signal-to-Noise > 2 can already be achieved

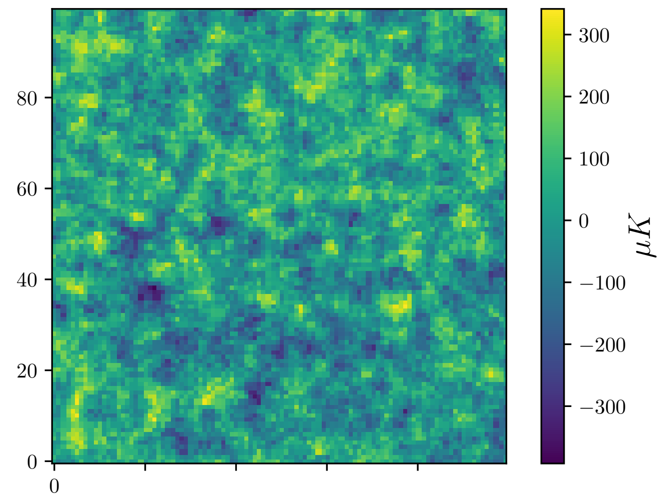
Estimating backgrounds

Preliminary

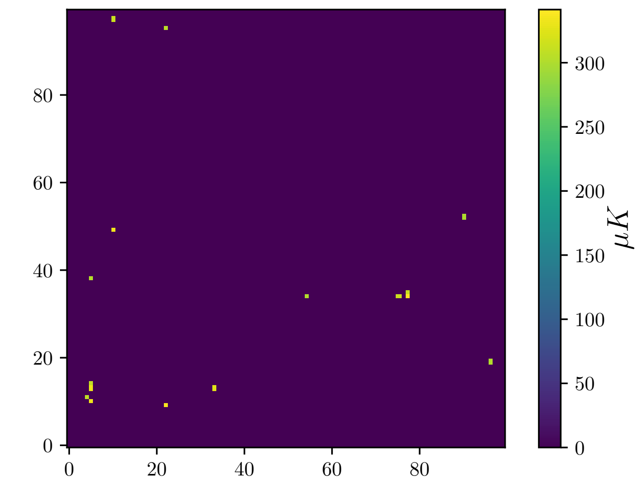
- Statistical: originating from CMB itself. Focus

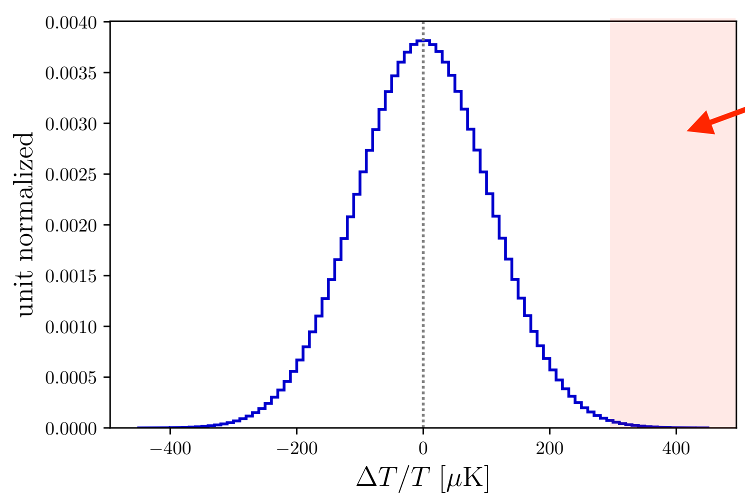


spurious "hotspots" survive



apply $\delta T_{\rm cut} > 300\mu K$





calculate the probability of having $\Delta T/T > 300\mu K$

gives the correct statistical number of backgrounds

- Astrophysical: dust, point sources etc. In progress

comparison b/n different frequency channels might help

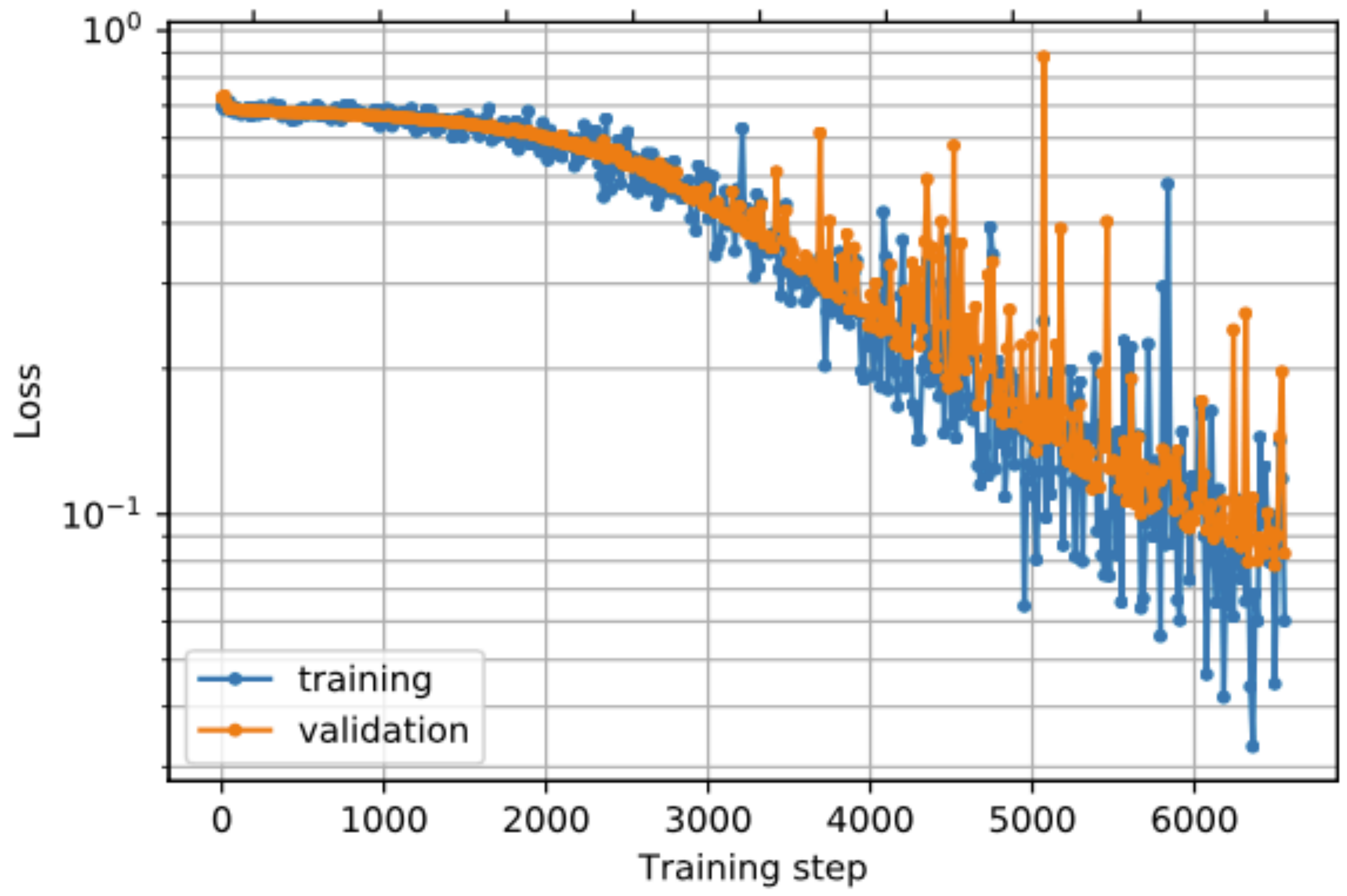
Conclusions

- Described a simple model for particle production and calculated effect on metric perturbation.
- The number of hotspots can be significant and be observable.
- Position space methods such as wavelet analysis can be very useful.
- Work on optimizing detection strategy ongoing.

Thank you!

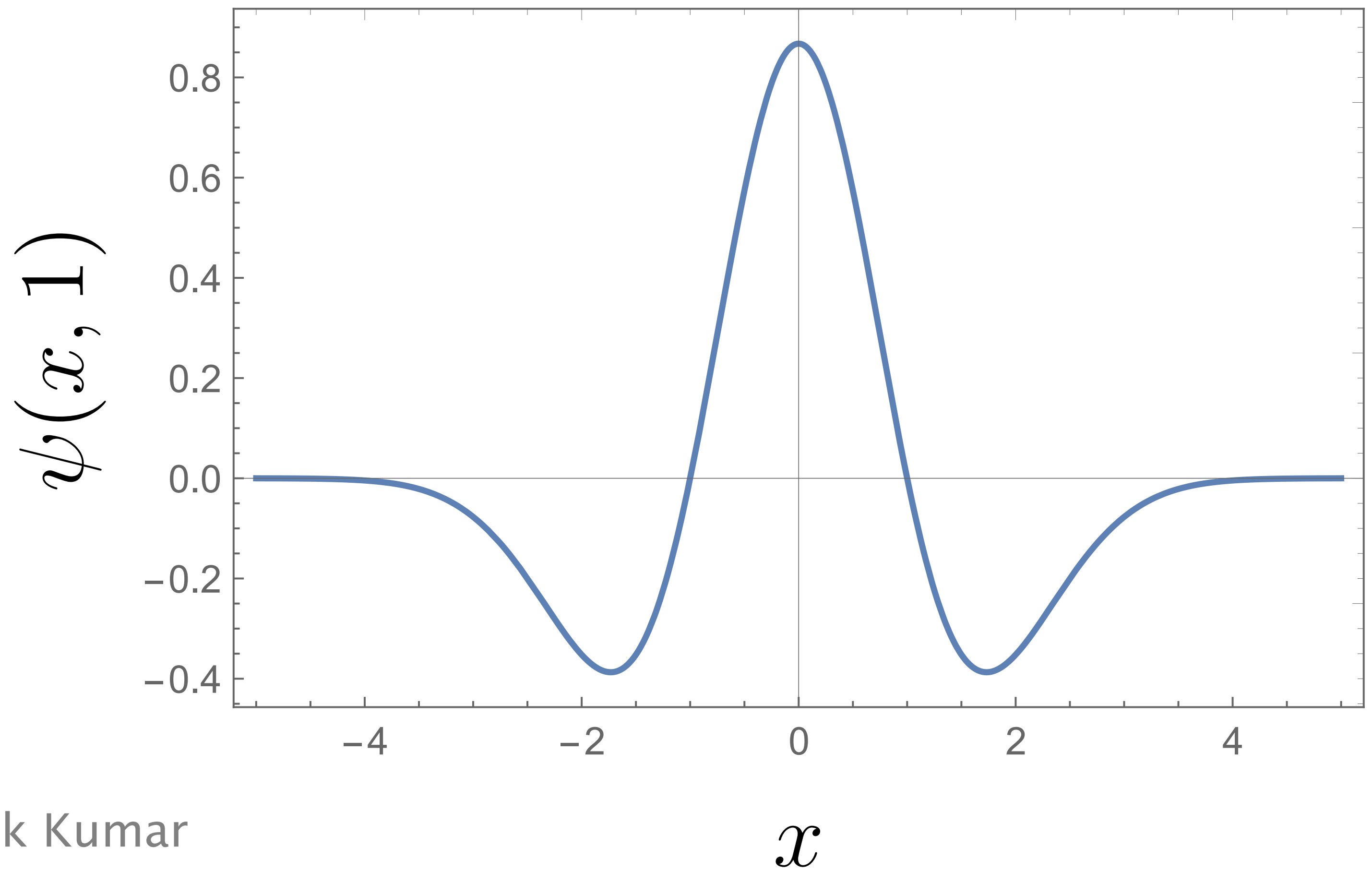
Using of machine learning (ongoing)

- Treat as a classification problem between images with and without hotspots using DeepSphere



Description of wavelets

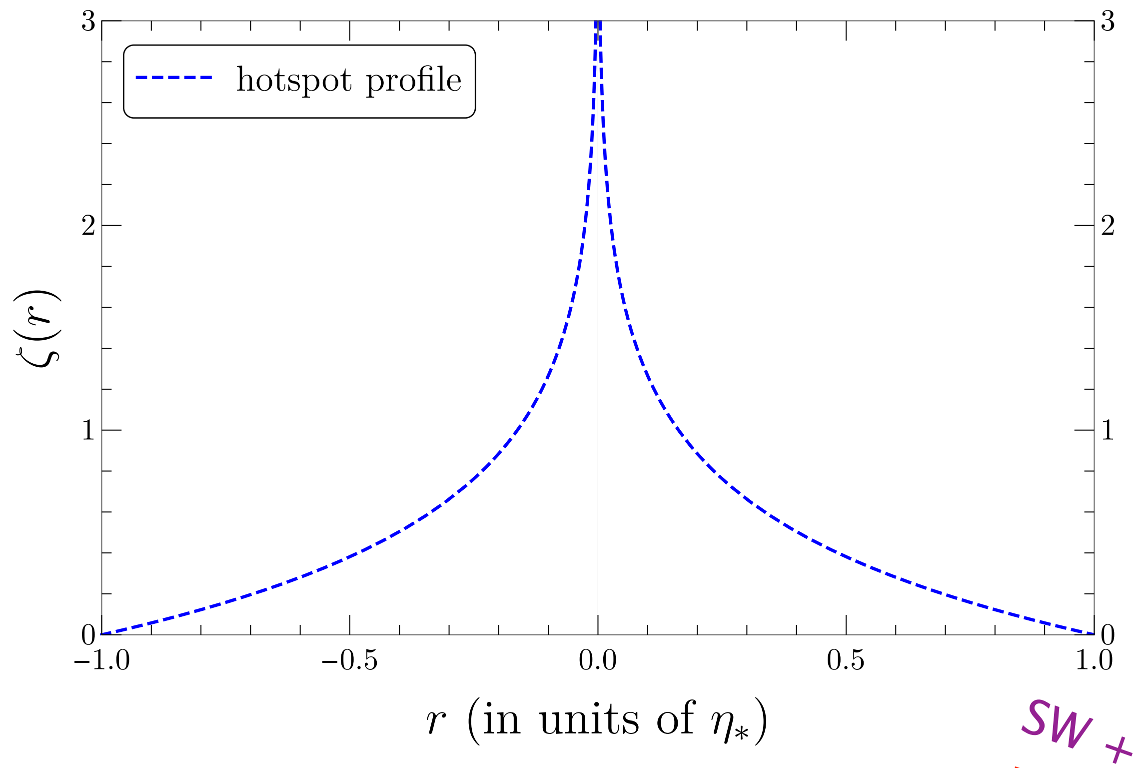
- Fourier transforms: not ideal to characterize sudden changes in data or images.
- Wavelets are localized. By scaling and translating a wavelet, we can characterize sudden changes aptly.



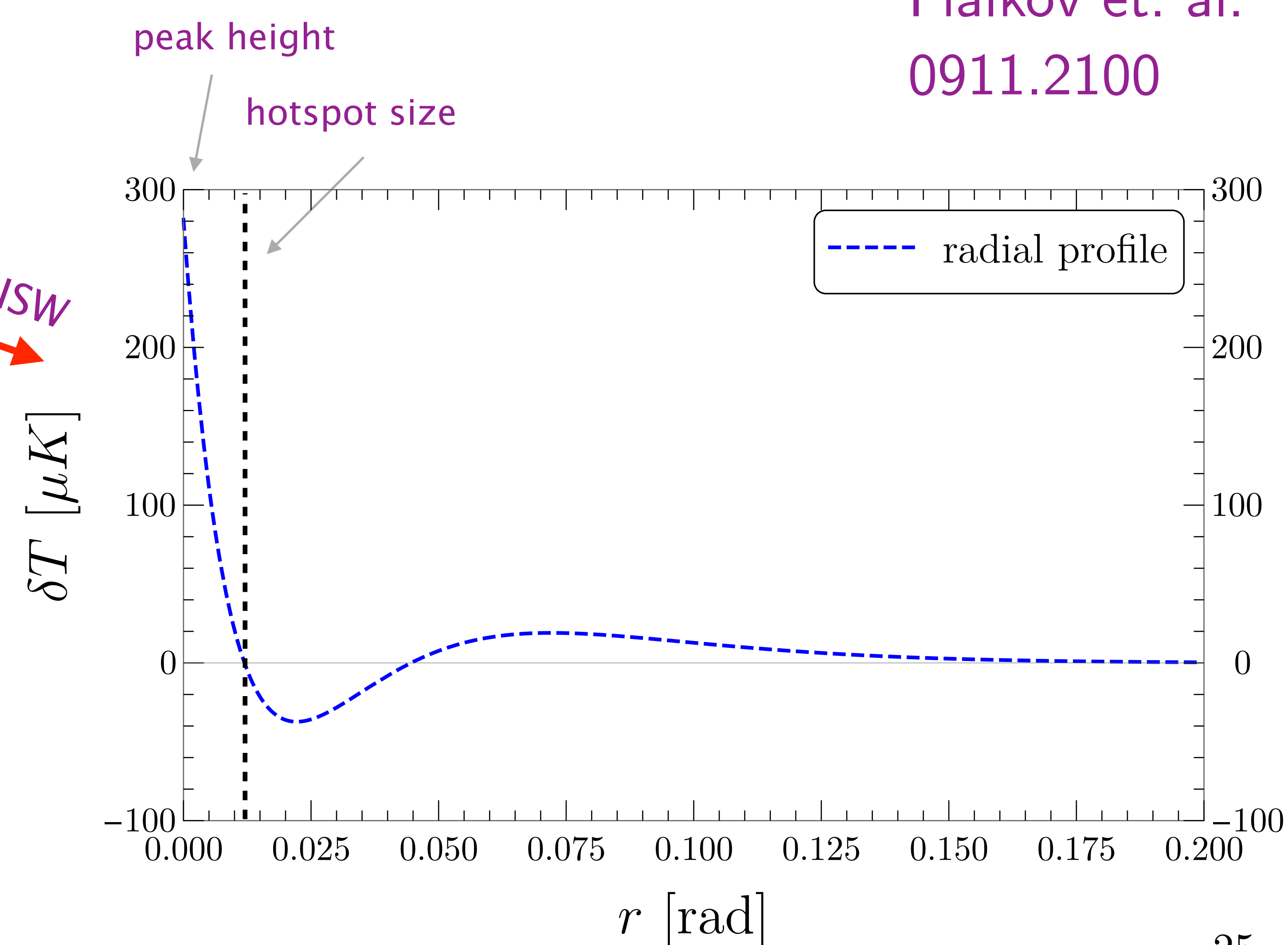
Mexican Hat Wavelet

$$\psi(x,\sigma) = -\frac{2e^{-\frac{x^2}{2\sigma^2}}\left(\frac{x^2}{\sigma^2}-1\right)}{\sqrt{3}\sqrt[4]{\pi}\sqrt{\sigma}}$$

Temperature profile



SW + ISW



Fialkov et. al.
0911.2100

Calculating particle production

- Simplify: study the evolution of mode function around conformal time η_* when $\phi \approx \phi_* \equiv M/g$:

$$\frac{d^2u}{d\eta^2} + \left(k^2 + \frac{(g^2\phi'^2(\eta - \eta_*)^2 + M_0^2)/H^2 - 2}{\eta_*^2}\right)u = 0$$

$$|\beta_k|^2 = e^{-\frac{\pi k^2 |\eta_*| H}{|g\dot{\phi}|}} e^{-\frac{\pi(M_0^2 - 2)}{|g\dot{\phi}|}}$$