Cosmological Particle Production and Pairwise Hotspots on the CMB

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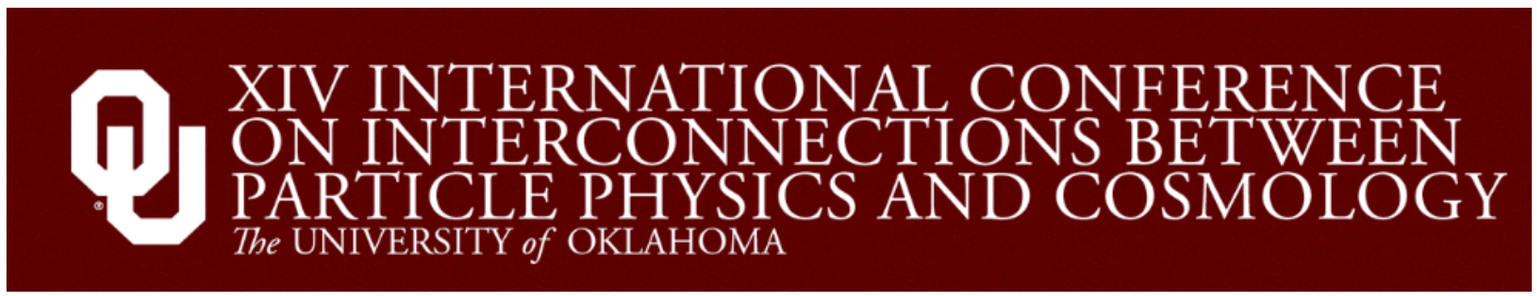
w/ Jeong Han Kim, Adam Martin and Yuhsin Tsai (in progress)

PPC 2021, Oklahoma/Zoom, May 19, 2021



Features of primordial perturbations

- Simplest models of inflation predict density fluctuations should be:
    - (almost) scale invariant
    - adiabatic
    - Gaussian

Planck '18

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Features of primordial perturbations

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

Planck '18

- Violation of scale invariance has been widely discussed before, focus on a class of scenarios whose observational features are less explored

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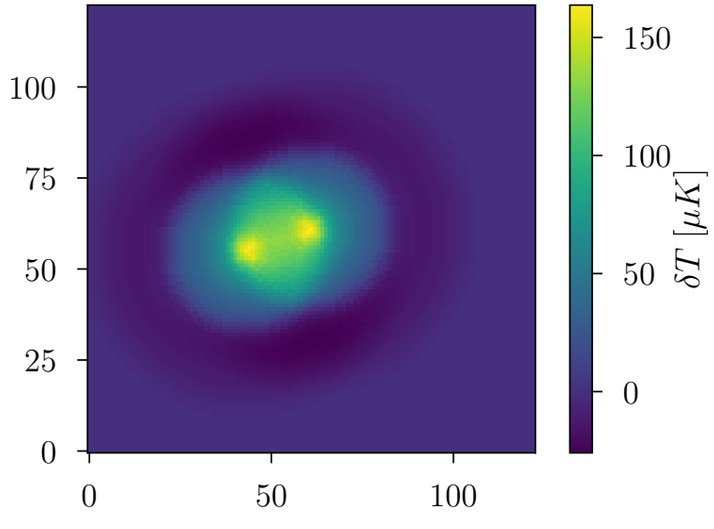
Goal of this talk

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

Chung et al. '99; Flauger et al. '16 ...

- 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.



How to search for these?

Münchmeyer, Smith '19 (another related model)

1. momentum space correlators
2. directly looking in position space

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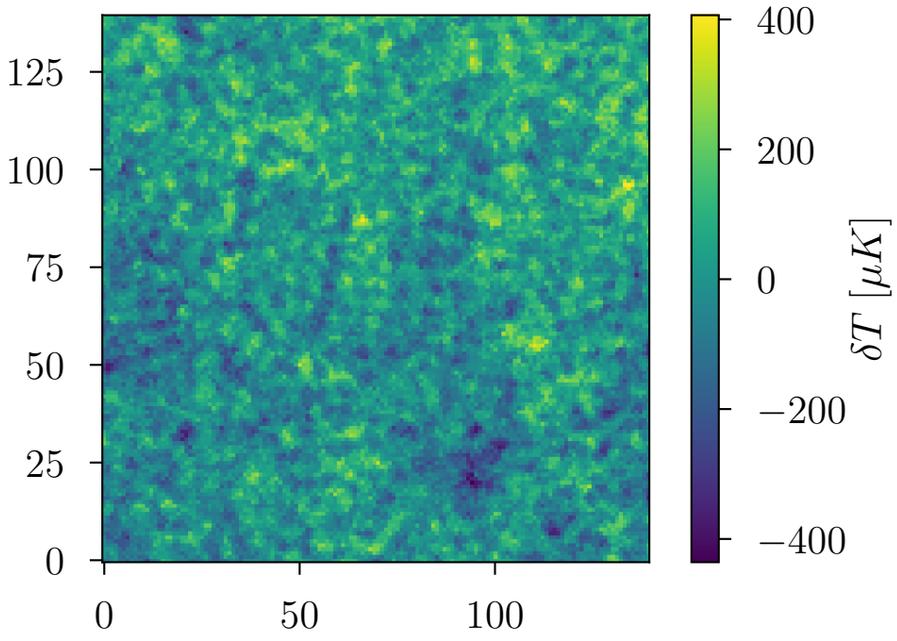
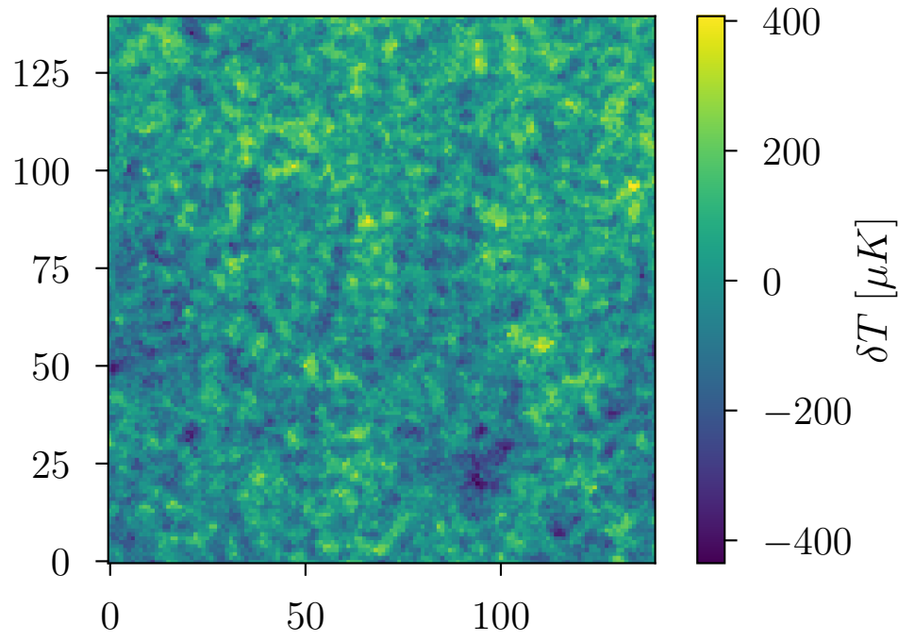
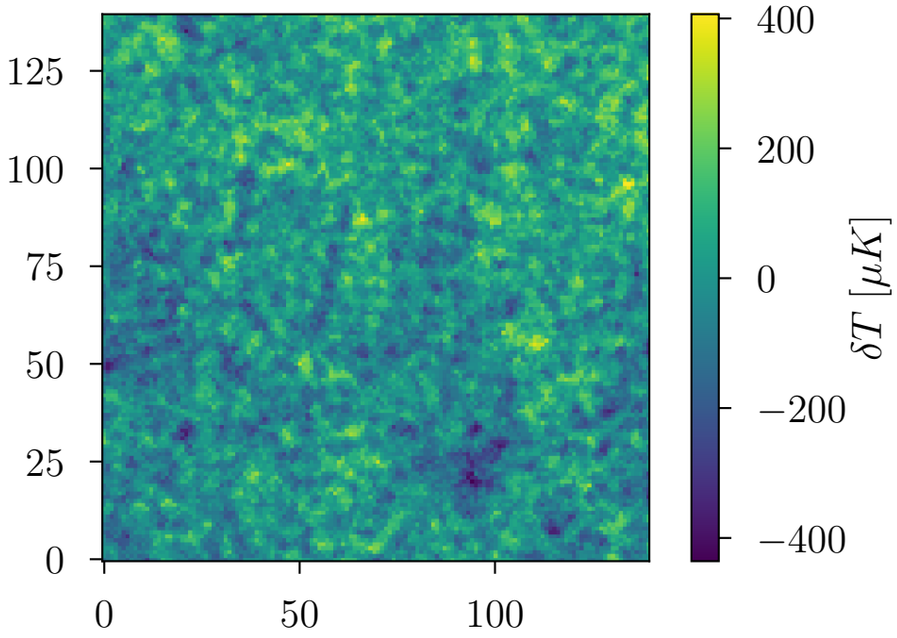
Goal of this talk: hunting profiles in the sky





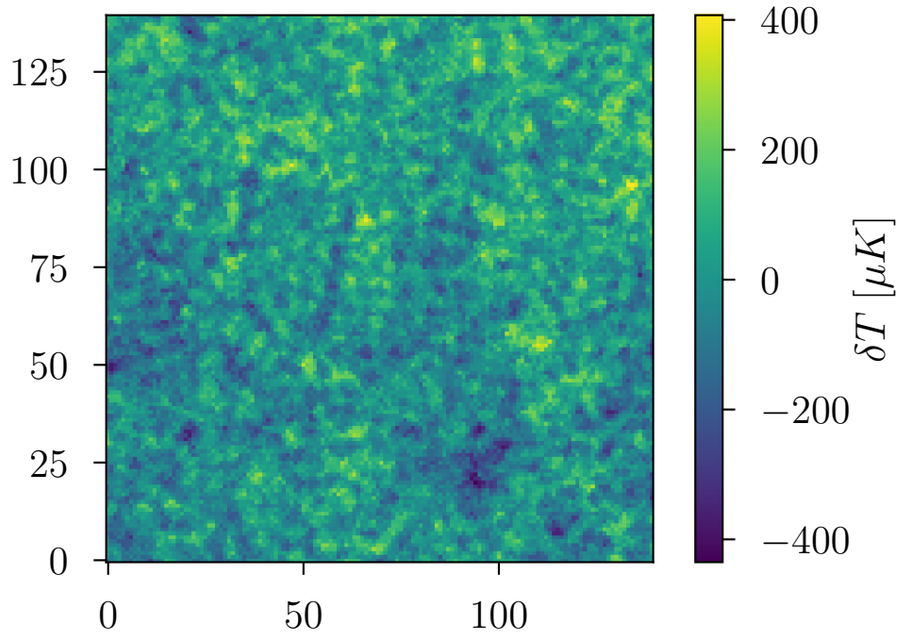
Is there a difference?

Goal of this talk: hunting profiles in the sky

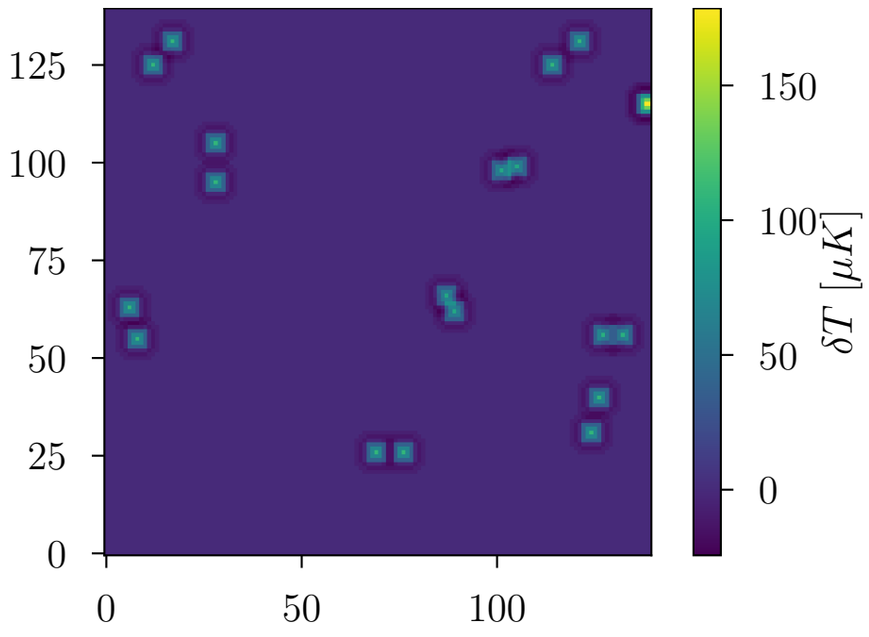


CMB+hotspots

Yes!



CMB only



hotspots

How to tell?

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Outline

- Theoretical setup
- Hotspot phenomenology
- Detection strategies
- Conclusion

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Set up

- A simple model

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

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

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

- For $M_0 \sim \sqrt{\dot\phi_0} \sim 60 H_{\rm inf}$, the kinetic energy of the inflaton can be used to produce σ.

Curvature perturbation from heavy particles

- Compute particle production with the standard Bogoliubov method:

Chung et al. hep-ph/9910437; Flauger et al. 1606.00513

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

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

- Each massive particle backreacts on the spacetime metric: compute using "in-in" formalism:

Maldacena 1508.01082
Fialkov et al. 0911.2100

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

standard "size" of quantum fluctuation

g controls the overall size

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Central temperature of a hotspot

- Tracking the sub-horizon evolution:

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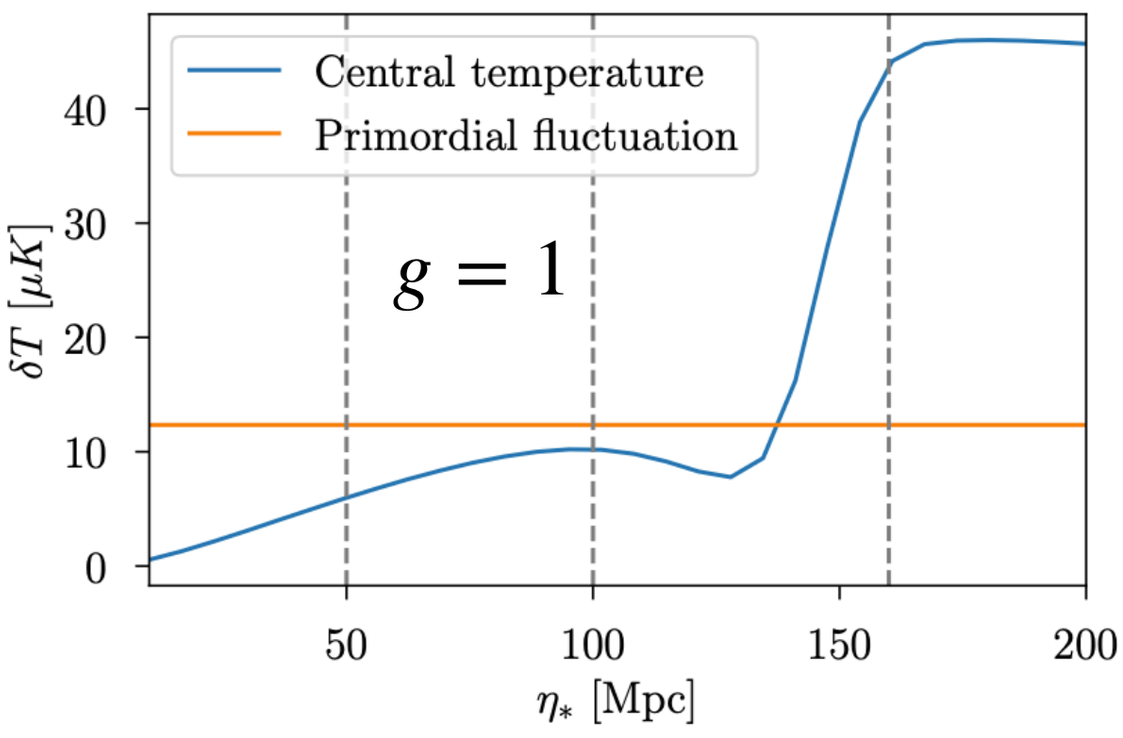
$$\theta(\vec{k}, \hat{n}, \eta_0) = \sum_l i^l (2l+1) \mathcal{P}_l(\hat{k} \cdot \hat{n}) \theta_l(k, \eta_0)$$

SW ISW

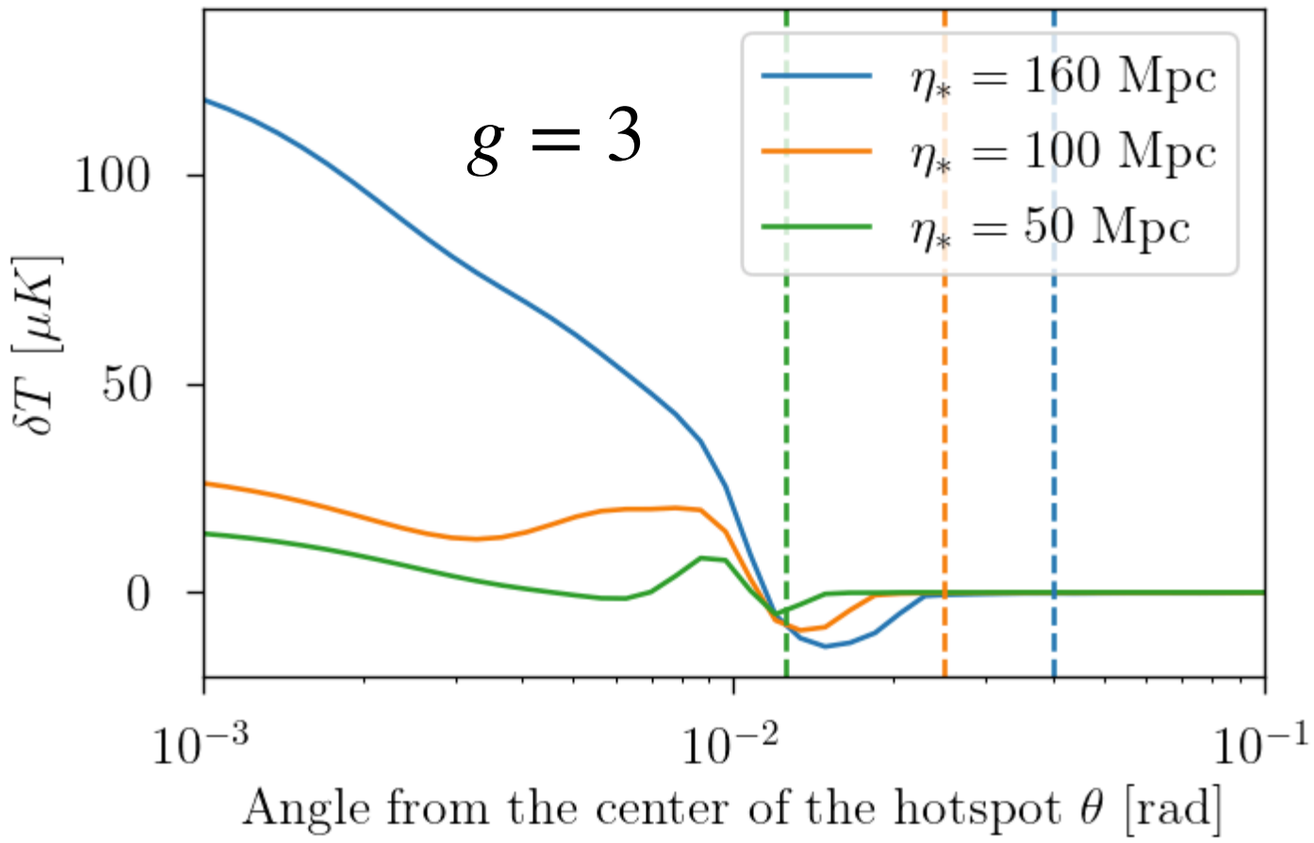
$$\theta_l(k, \eta_0) \approx (\theta_0(k, \eta_{\rm rec}) + \Psi(k, \eta_{\rm rec})) j_l(k(\eta_0 - \eta_{\rm rec})) + \int_0^{\eta_0} d\eta e^{-\tau} \left(\Psi'(k, \eta) - \Phi'(k, \eta)\right) j_l(k(\eta_0 - \eta))$$



horizon size at production

like the acoustic peaks, the central temperature varies depending on the scale

Temperature profiles of hotspots



pairs due to momentum conservation

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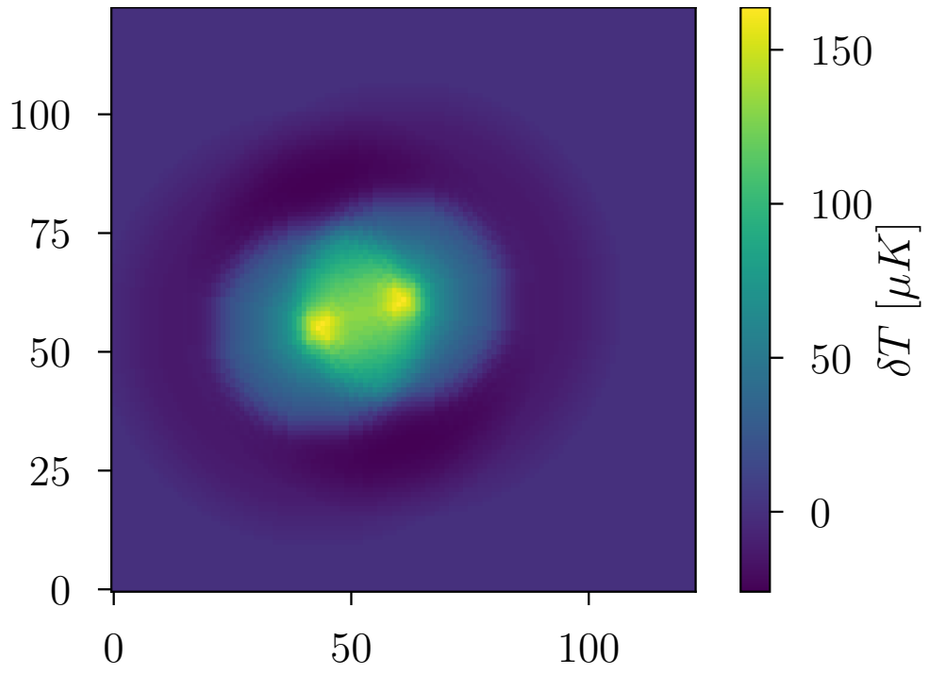
two overlapping hotspots on blank sky



$\eta_* = 160$ Mpc

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A (very) rough search strategy

Preliminary

- We have a prediction for the temperature profile of the hotspot → ideally want to use that information for the search.

- First pass: ask how well can a very naive cut-and-count approach do without profile information.

- Rather, rely on the fact that if there are hotspots, various regions of CMB would be brighter on average → choose a $T_{\rm cut}$

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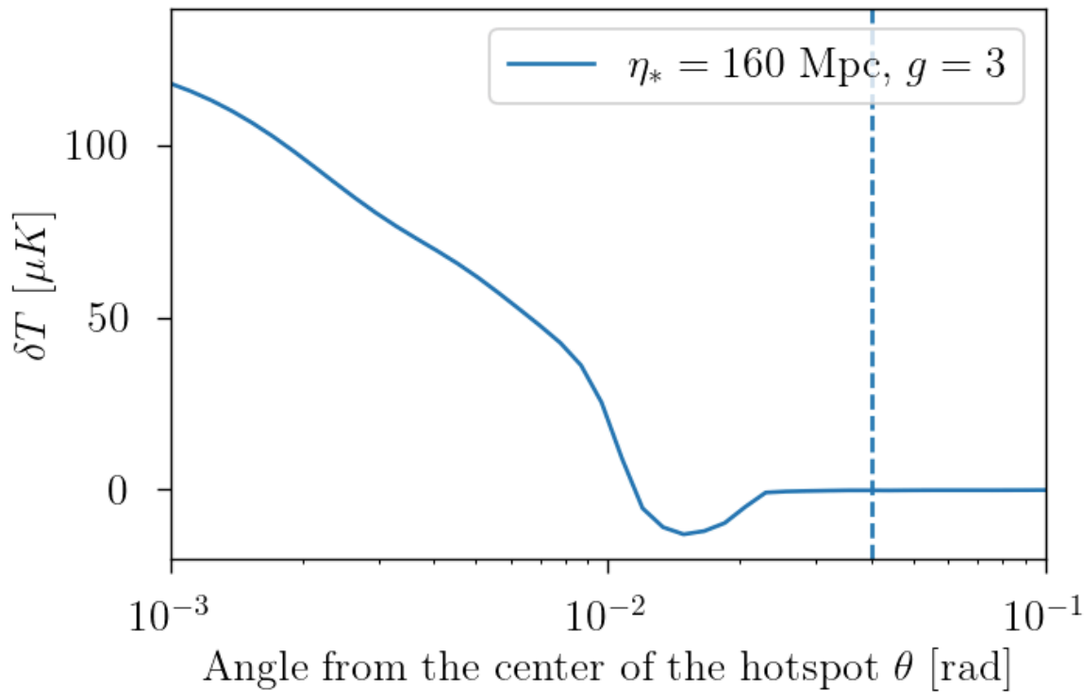
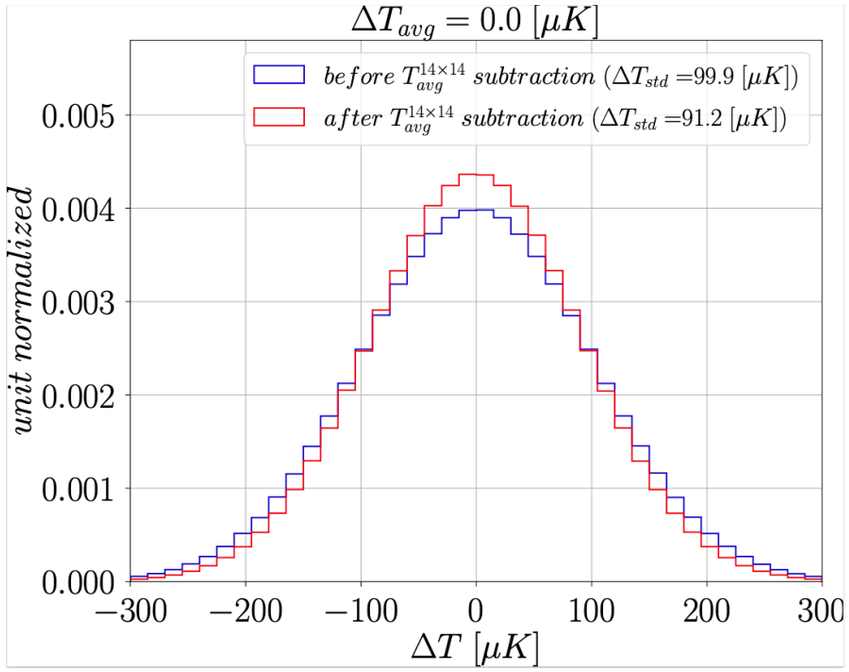
(in progress)

A (very) rough search strategy

Preliminary

- $T_{\rm cut}$ motivated by two facts:





- Therefore, at least a $T_{\rm cut} \sim 220 \mu K$ would be needed

- The basic idea then is to ask how many hotspots can be hidden with a given significance?

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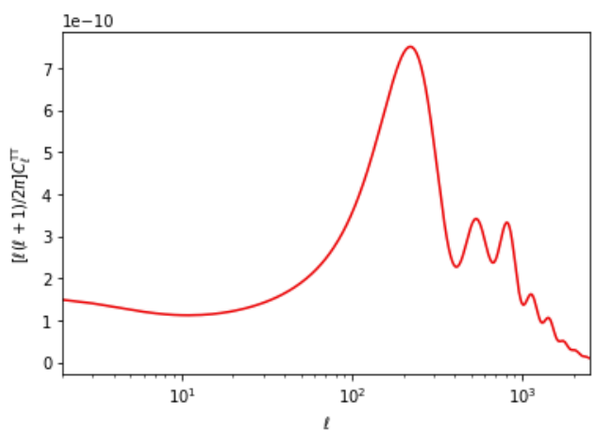
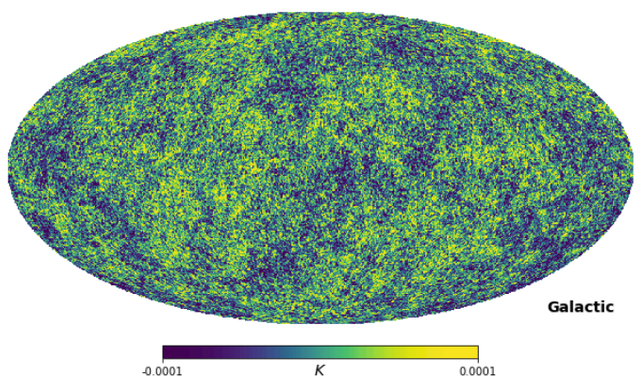
Analysis pipeline

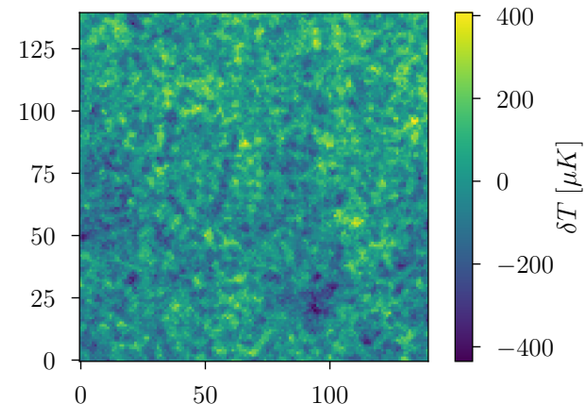
Preliminary



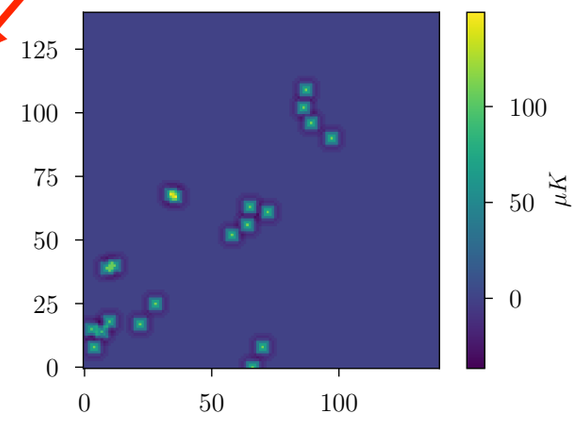
HEALPix

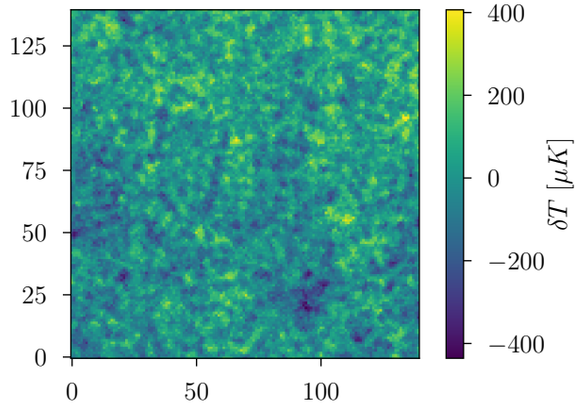


Small patch

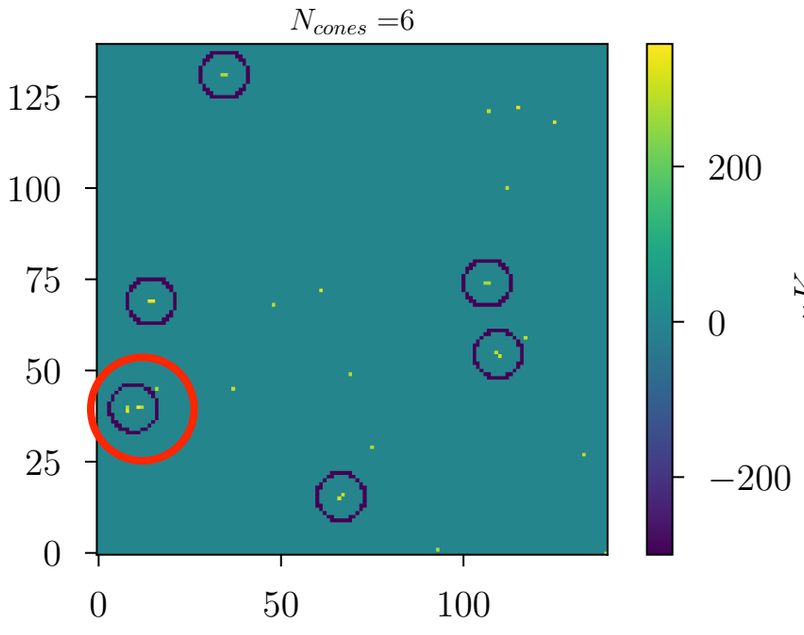


Inject Hotspots





$T_{\rm cut} = 270\mu K$



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A (very) rough first result

Preliminary

- For $\eta_* = 160$ Mpc, $g = 3$, we can hide $N_{\rm hotspots} \approx 680$ in the entire sky

$$M_0 > 190\ H_{\rm inf}$$

- Non-trivial result, but expected to improve further with more dedicated search (ongoing)

- Preliminary comparison shows this rough search to be at least as powerful as Planck 18 TT+lowE (ongoing)

Kim, **SK**, Martin, Tsai (in progress)

Conclusions and future direction

- Simplified model for particle production → temperature profile.

- A first attempt at a rough position space search → already competitive or even better than TT+low E power spectrum search.

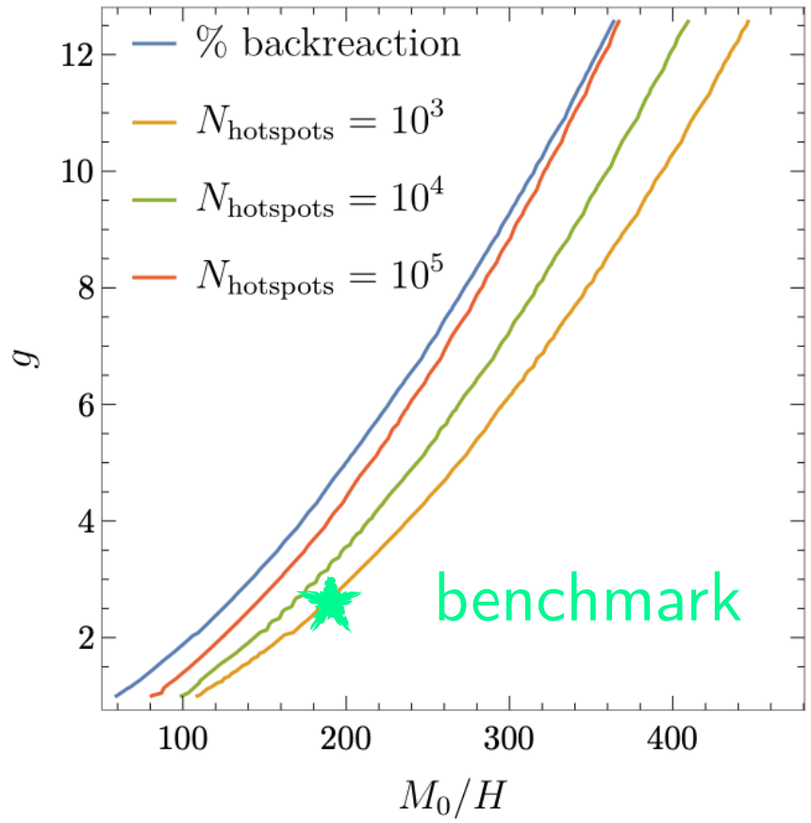
- Improve position space search further
  - wavelet analysis
  - image recognition

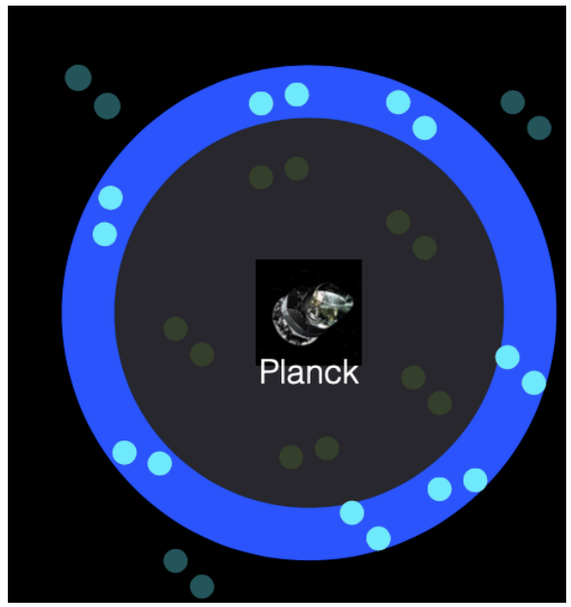
Thanks for your attention!

Total number of hotspots

- Looking for signatures in the CMB:

$$N_{\text{hotspots}} = \frac{1}{2\pi^2}\left(\frac{g\dot{\phi}}{H^2}\right)^{3/2} e^{-\frac{\pi(M_0^2-2H^2)}{|g\dot{\phi}|}} \left(k_* \eta_0\right)^3 \times \frac{\Delta\eta_{\text{rec}}}{\eta_0}$$





finite thickness of recombination

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Curvature perturbation: derivation

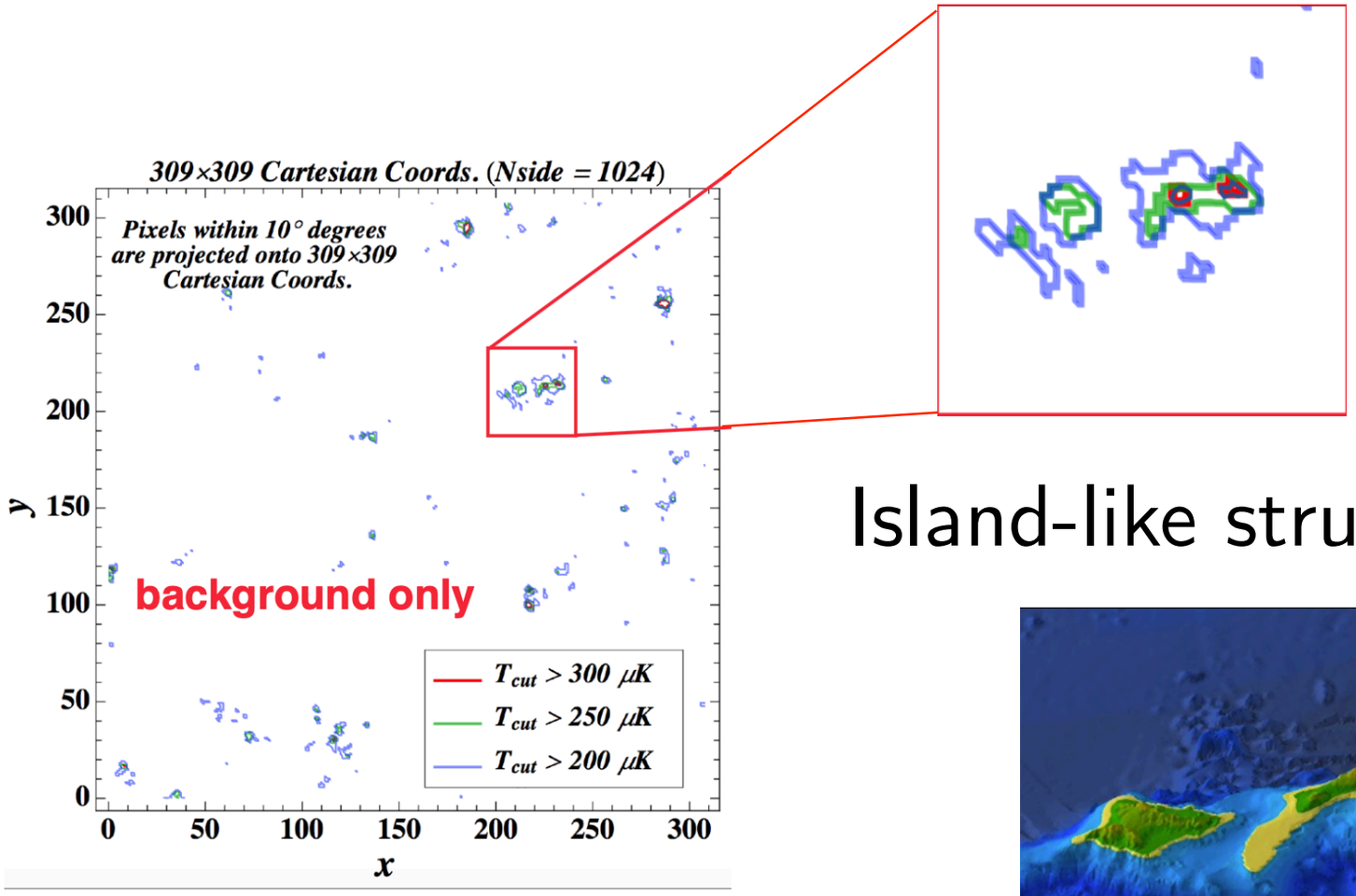
$$S_{\text{particle}} = -\int dt\sqrt{-g_{00}}M = -\int dt\, N\, M = -\int dt\left(1+\frac{\dot{\zeta}}{H}\right) M = -\int dt\, M - \int dt\,\dot{\zeta}\,\frac{M}{H}$$

$$S_{\text{particle}} \supset -\int d\eta\,\partial_\eta\zeta\,\frac{M(\eta)}{H}$$

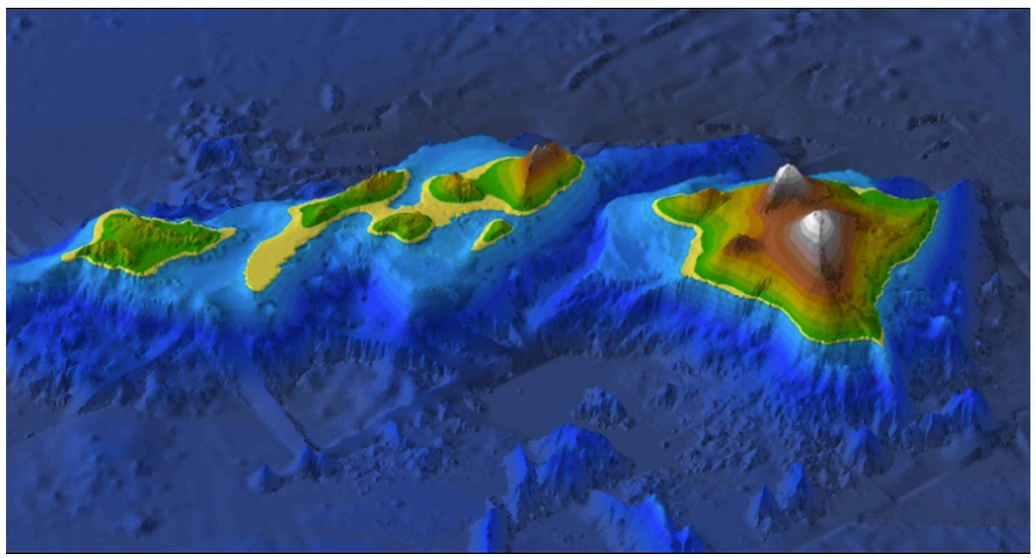
$$\langle\zeta_{\vec{p}}(\eta=0)\rangle = (-i)\int_{\eta_p}^{0} d\eta \int \frac{d^3\vec{k}}{(2\pi)^3}\frac{M(\eta)}{H}\langle\zeta_{\vec{p}}\partial_\eta\zeta_{\vec{k}}\rangle e^{i\vec{k}\cdot\vec{x}_{\text{HS}}} + \text{anti-time ordered piece}$$

$$\langle\zeta_{\vec{k}}\rangle = \frac{gH^2}{\dot{\phi}_0}\frac{1}{k^3}\left(\text{Si}(|k\eta_p|) - \sin(|k\eta_p|)\right)e^{-i\vec{k}\cdot\vec{x}_{\text{HS}}}$$

Background spots from CMB itself



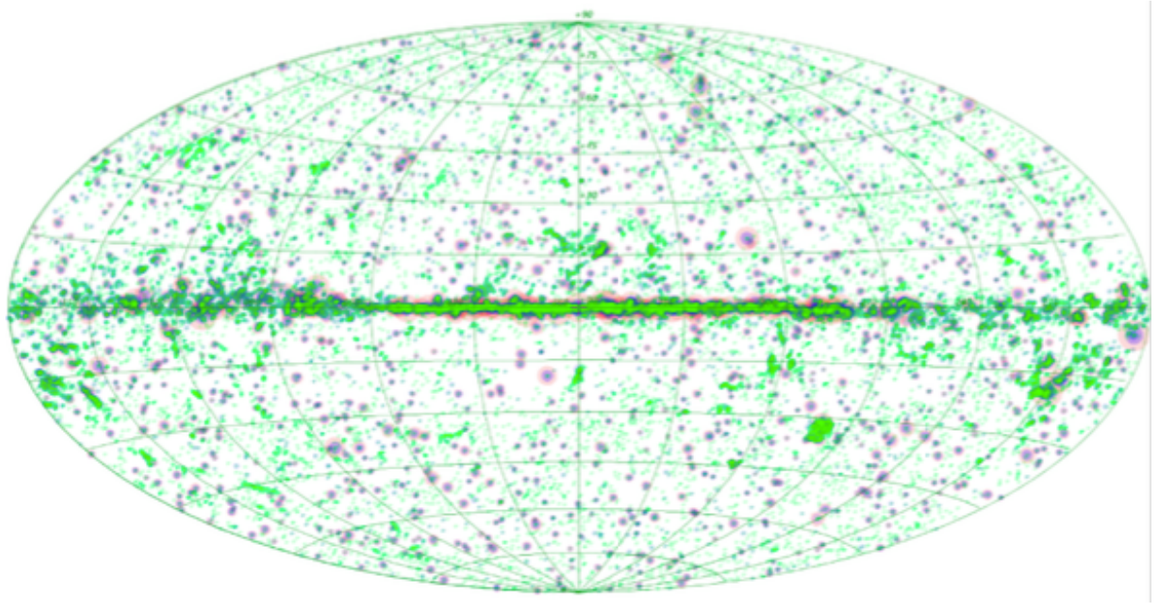
Island-like structure: also pairwise



Other backgrounds

- Instrumental noise

- Foregrounds from compact objects (stars, galaxies ...)



correlating maps at different frequency channels can help

need further study