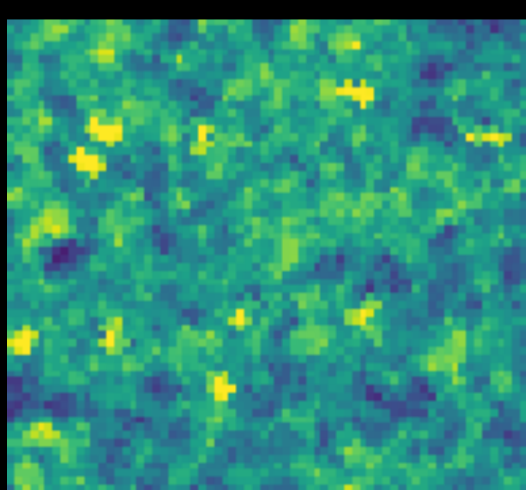
Cosmological Particle Production & Pairwise Hotspots on the CMB

Yuhsin Tsai

University of Notre Dame



CAU BSM Workshop

02/03/2021

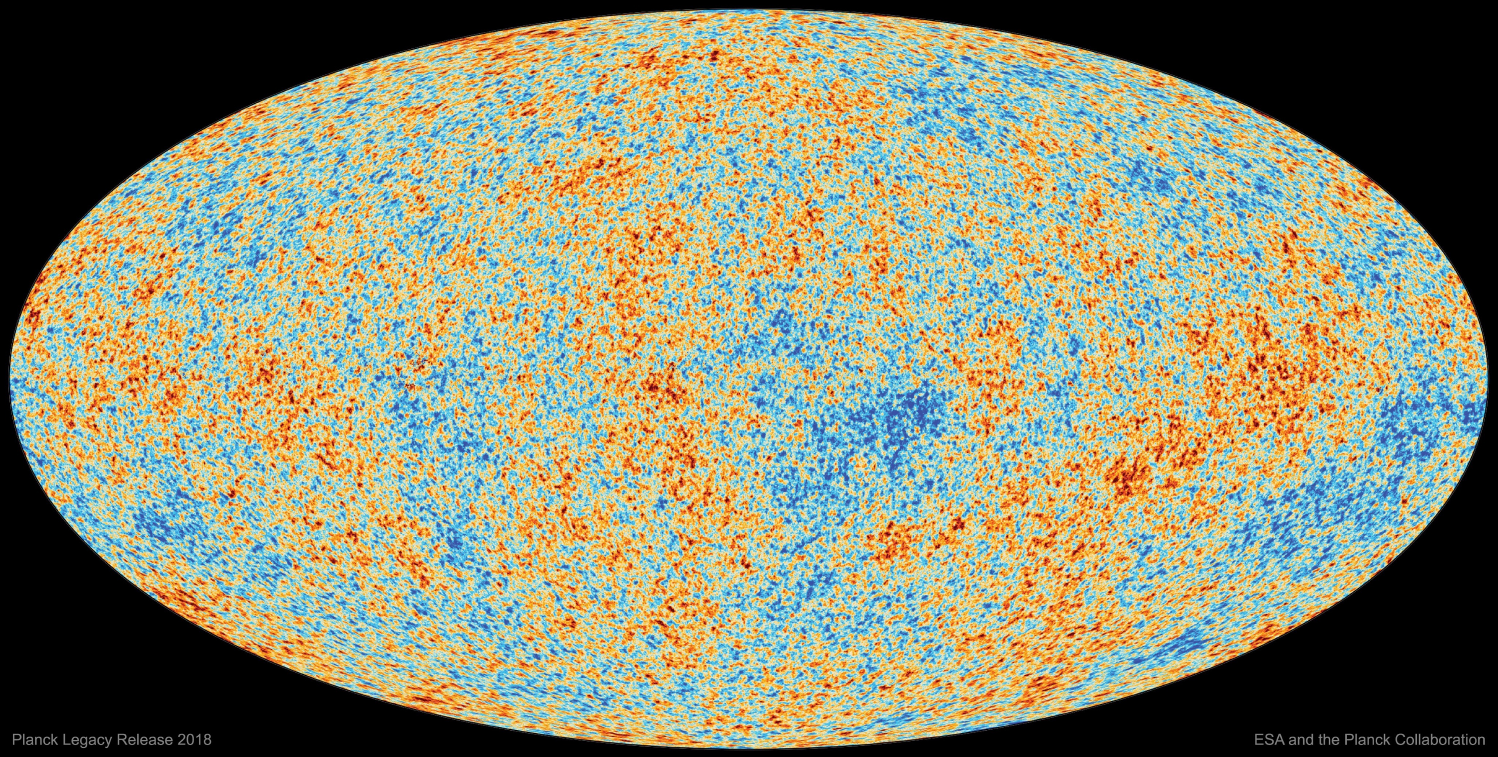
Based on an on-going work with

Jeong Han Kim
(Chungbuk National University)

Soubhik Kumar
(Berkeley)

Adam Martin
(Notre Dame)

The particle detector in this talk: CMB



- radiation with wave length ~ 1mm
- blackbody radiation with $\bar{T} \approx 2.7\,K$
- temperature anisotropy $\sigma_{\rm CMB} \sim 200\,\mu K$

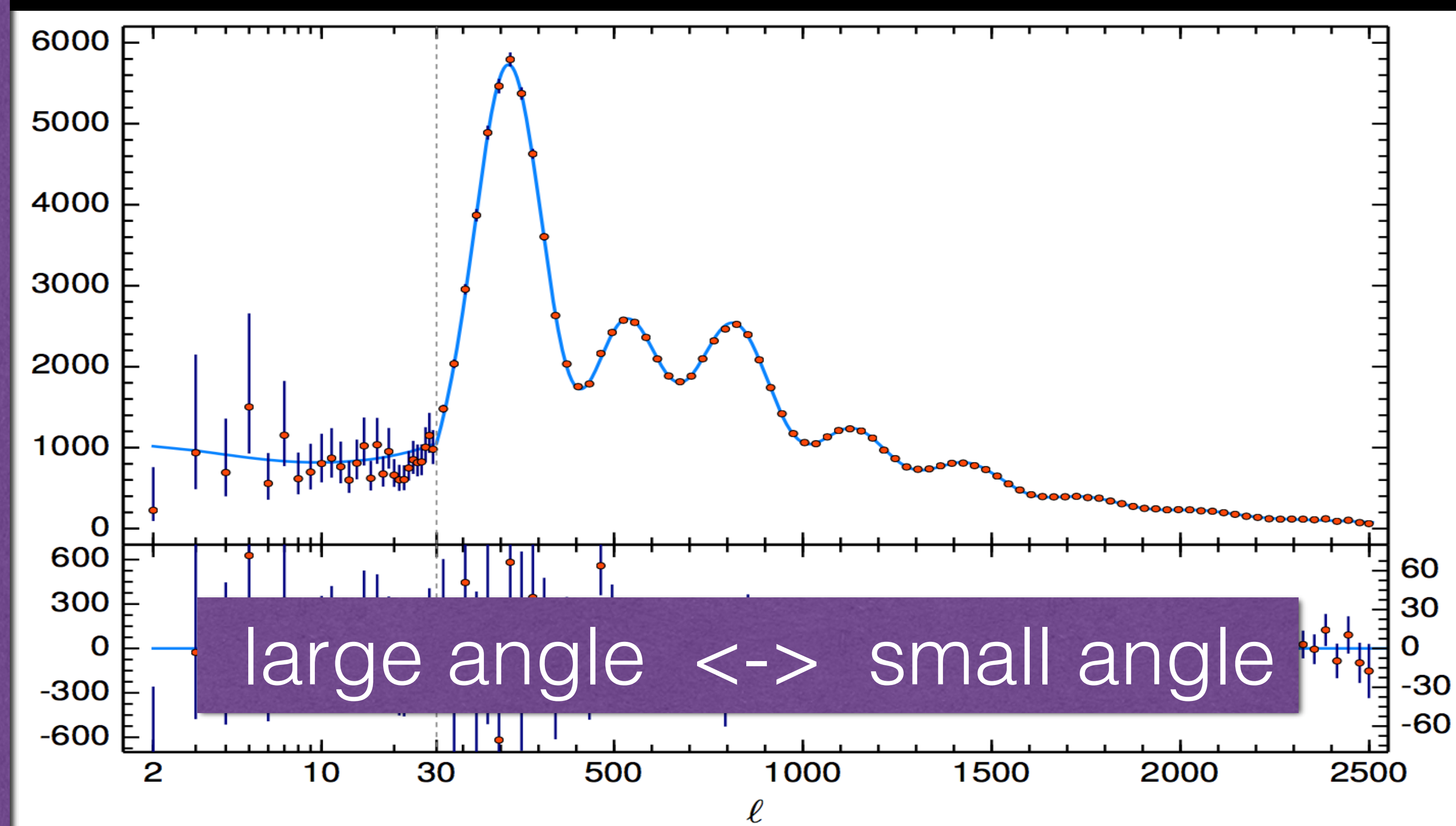
Our study is motivated by two questions:

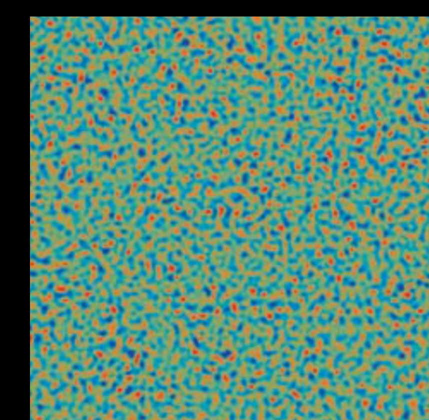
- What can new physics signals look like in the CMB?
- When using CMB to study cosmological particle production during inflation, is it possible to probe particle mass $\gg H_{\rm inf}$?

Typical CMB analysis: correlation functions

$$\langle \delta T(\theta_1, \phi_1) \delta T(\theta_2, \phi_2) \rangle \quad \langle \delta T(\theta_1, \phi_1) \delta T(\theta_2, \phi_2) \delta T(\theta_3, \phi_3) \rangle \ \ldots$$

~ (Temperature fluctuation)^2





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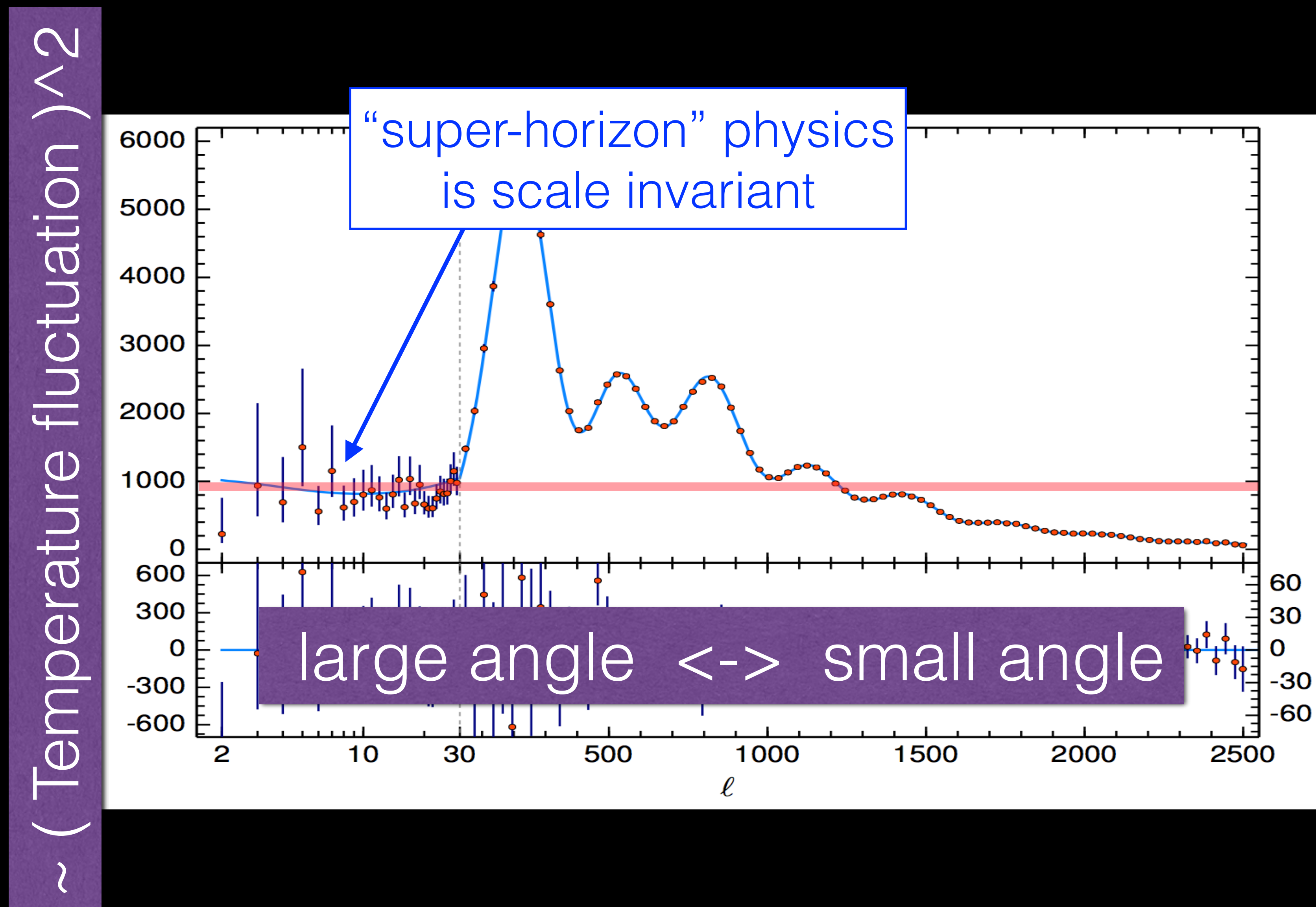
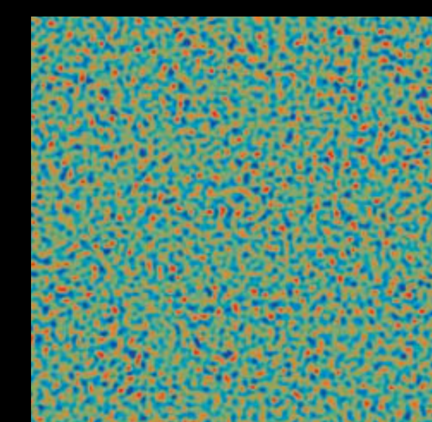
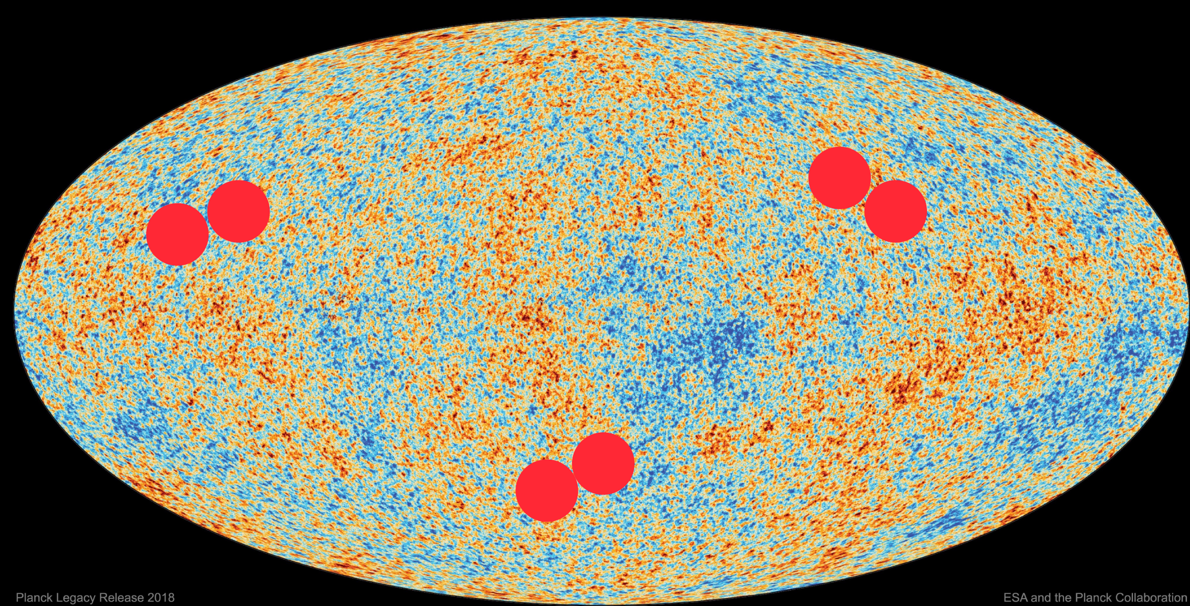




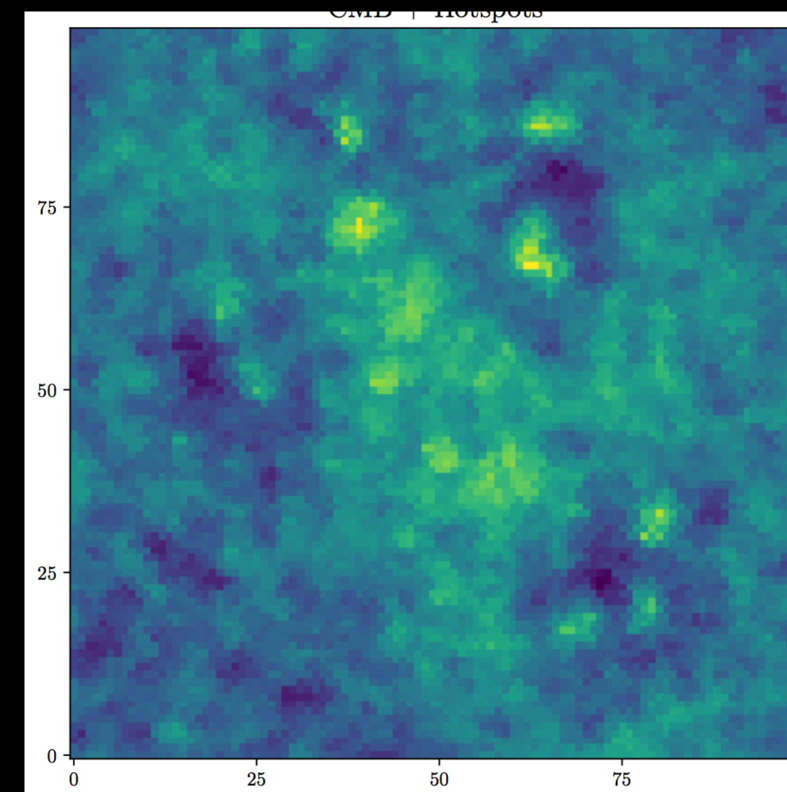
This makes sense since the temperature anisotropy
is almost a scale-invariant white noise (not “localized” signals)

Yuhsin Tsai yhtsai@nd.edu

We will instead discuss a scale-dependent & spatially localized signal



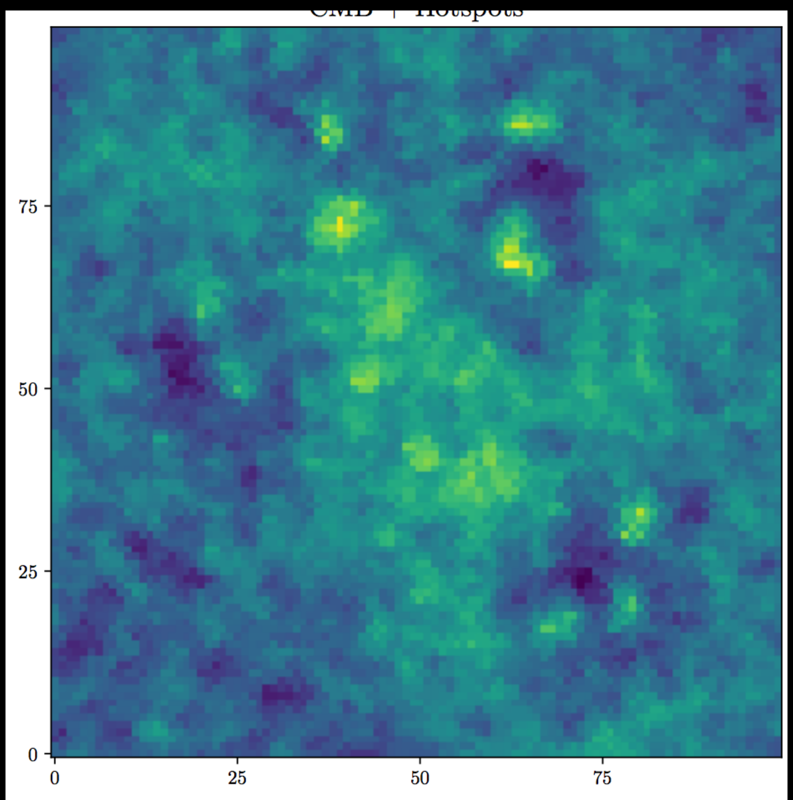
(cartoon picture)

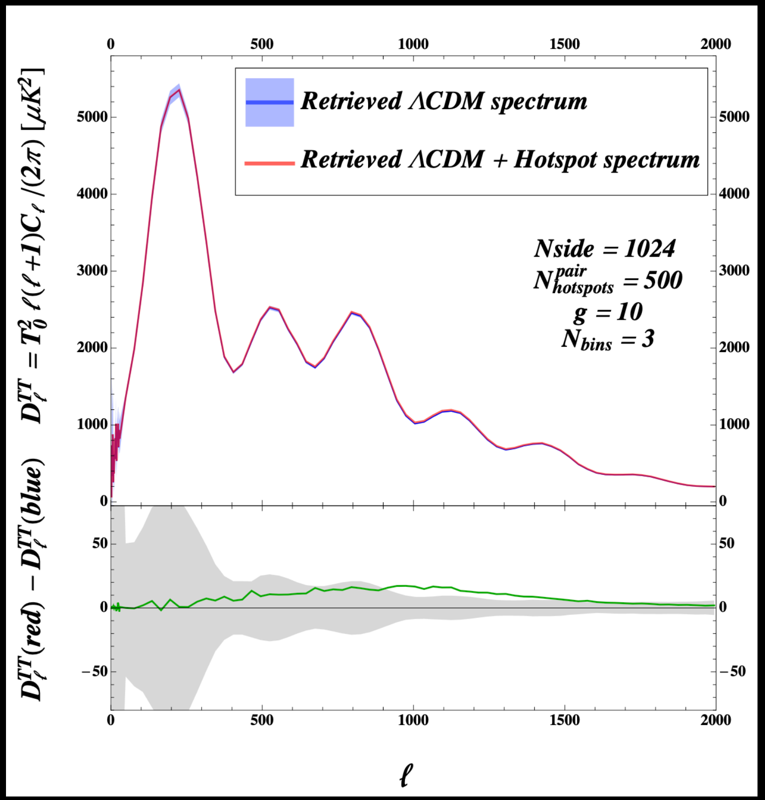


(HEALPix simulation)

- Easy to generate the signal from cosmo particle production
- Motivate different types of CMB analyses

Pairwise Hotspots from heavy particle productions

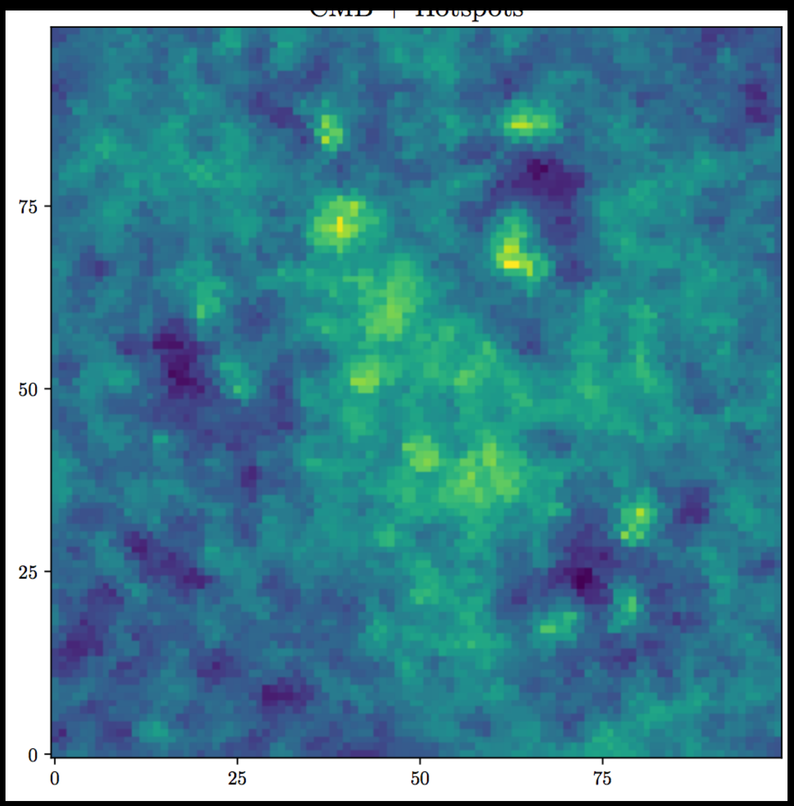




Looking for pairwise hotspots in spatial coordinate

ℓ-dependent distortion of CMB TT-spectrum

Pairwise Hotspots from heavy particle productions



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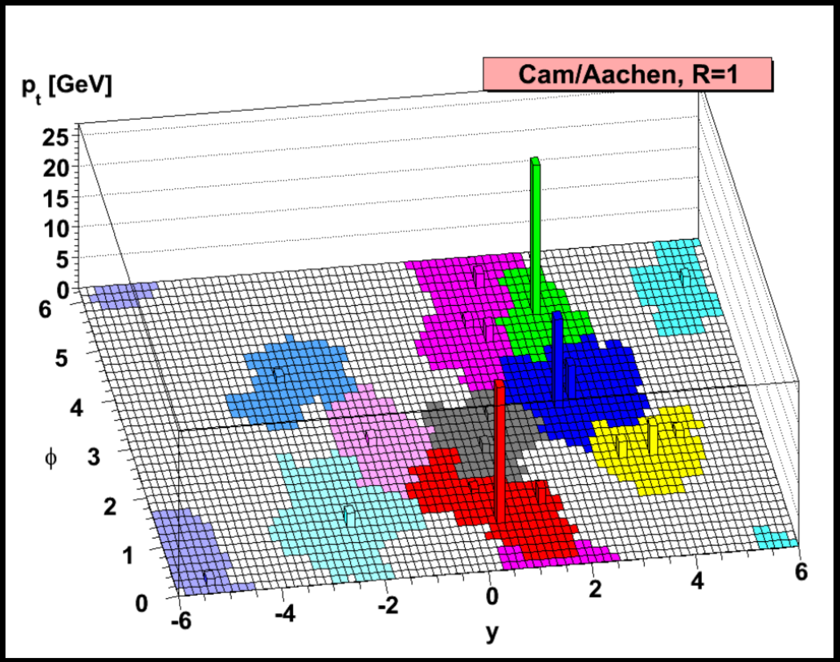
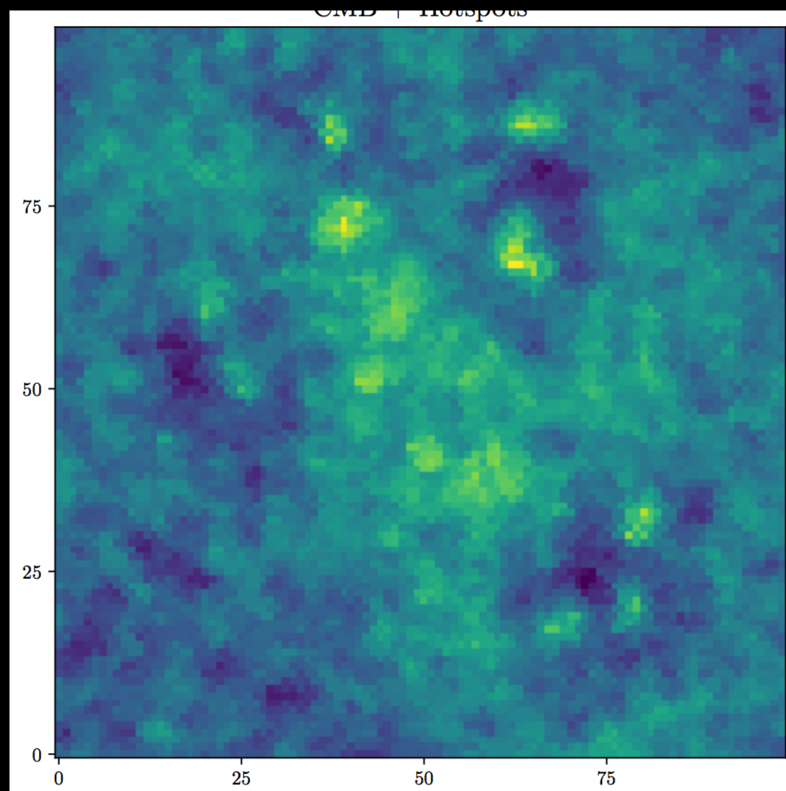


Looking for pairwise hotspots in spatial coordinate

like studying jet substructure

Pairwise Hotspots from heavy particle productions



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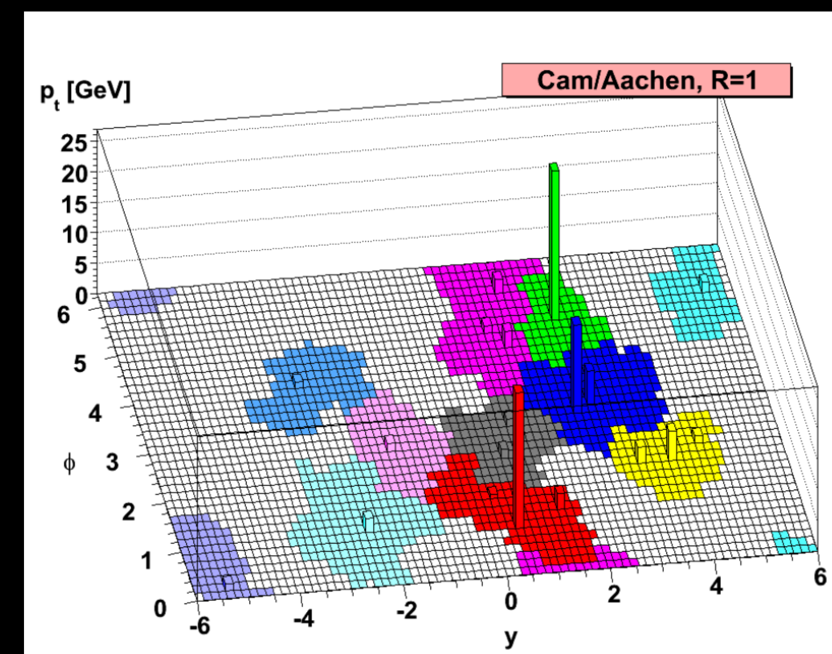

Also motivated by Maldacena's work

A model with cosmological Bell inequalities 1508.01082

Juan Maldacena

We discuss the possibility of devising cosmological observables which violate Bell's inequalities. Such observables could be used to argue that cosmic scale features were produced by quantum mechanical effects in the very early universe. As a proof of principle, we propose a somewhat elaborate inflationary model where a Bell inequality violating observable can be constructed.

Production of the pairwise hotspots

Non-adiabatic particle (pair) production during the inflation

→

Particle mass modifies nearby curvature perturbation before leaving the horizon (due to inflation)

→

Perturbation gets frozen outside of the horizon

→

(inflation ends, horizon re-entry)

Photon temperature follows local curvature perturbation

Pairwise hotspots (or cold spots)

Step I : cosmological particle production

Non-adiabatic particle (pair) production during the inflation

Particle mass modifies nearby curvature perturbation before leaving the horizon (due to inflation)

Perturbation gets frozen outside of the horizon

(inflation ends, horizon re-entry)

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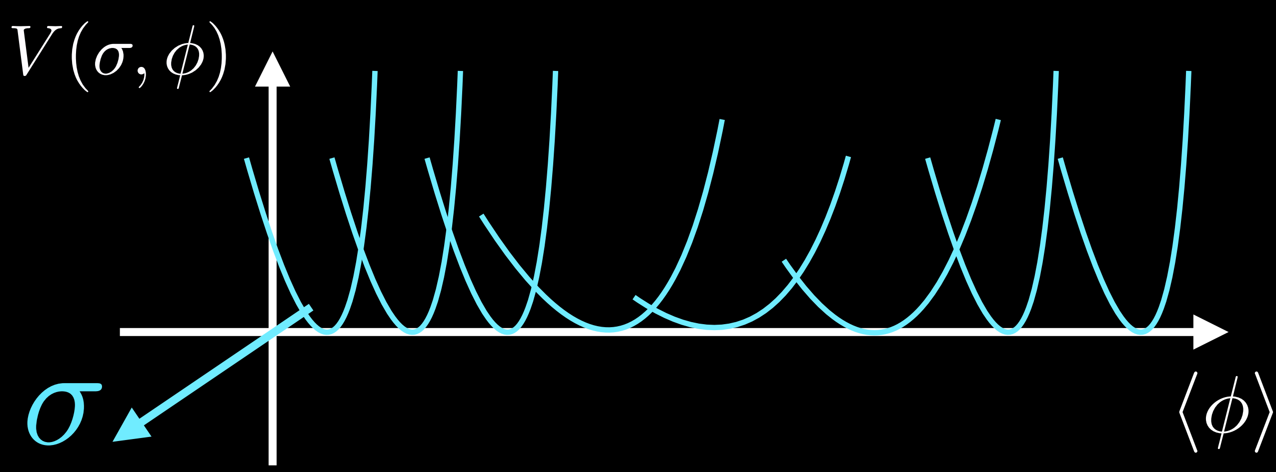
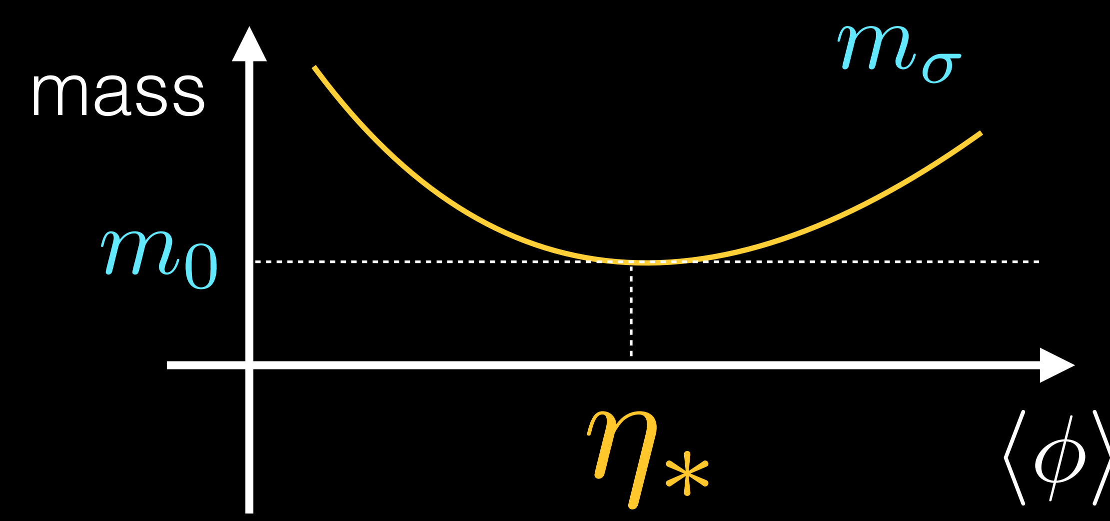
Pairwise hotspots (or cold spots)

Yuhsin Tsai yhtsai@nd.edu

Consider a scalar particle σ that carries an inflaton-dependent mass





- Sigma mass is typically heavy (comparing to Hubble scale)
- mass takes its minimum value at time η_*
- Sigma can be produced from the inflaton energy around η_*

A toy model example

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

Sigma mass is always larger than Hubble and $\sqrt{\dot\phi}$,
Minimum mass when $g\phi \sim M$.

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

(also see a similar setup in Flauger et al. (2016) for an N-point function study)

e.o.m. during inflation

$$\sigma'' - \frac{2}{\eta}\sigma' + \left(k^2 + \frac{M^2(\eta)}{H^2\eta^2}\right)\sigma = 0$$

$$u'' + \left(k^2 + \frac{M^2(\eta)/H^2 - 2}{\eta^2}\right)u \equiv u'' + \omega(\eta)^2 u = 0$$

$$u = \sigma/\eta$$

simple harmonic oscillator
with time-dependent frequency

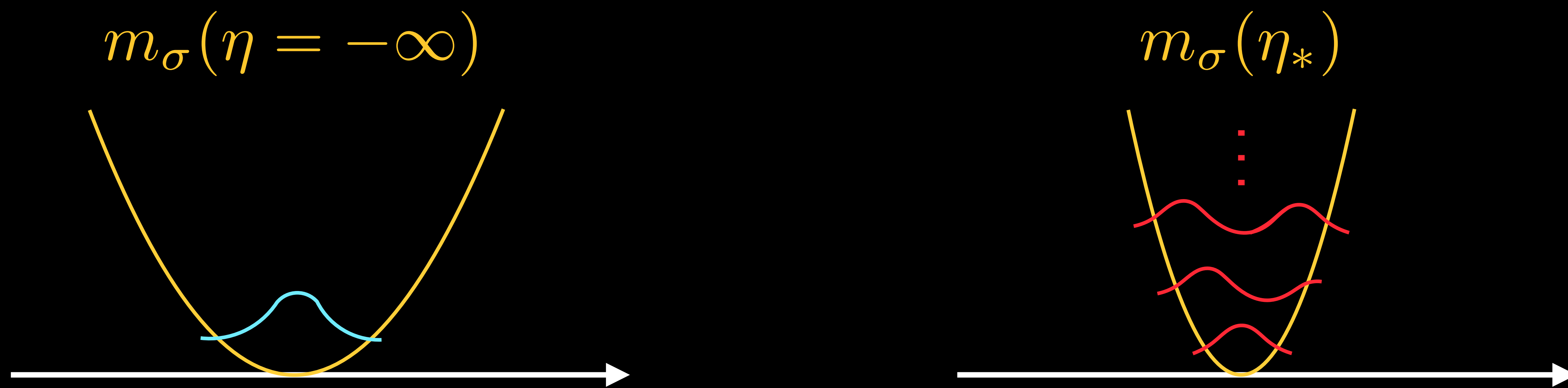
$$\omega(\eta)^2 = k^2 + \frac{M^2(\eta)}{\eta^2}$$

How to calculate the particle production?

- σ is produced from the energy of inflaton
- cannot calculate the production as in colliders
  since inflaton & sigma are not well-defined fields for particles
  (field with time varying VEV and mass)

- calculate the number of non-adiabatic particle production
  from Bogolyubov transformation

Particle production from time-variant vacuum



when promoting field into an operator, initial raising/lowering, operators will be a combination of later raising/lowering operators

$$\hat{u}(\eta, \mathbf{x}) = \int \frac{d^3\mathbf{k}}{(2\pi)^{3/2}} \left[\hat{a}_{\mathbf{k}}\, \mathcal{I}_k(\eta)\, e^{i\mathbf{k}\cdot\mathbf{x}} + \hat{a}^\dagger_{\mathbf{k}}\, \mathcal{I}^*_k(\eta)\, e^{-i\mathbf{k}\cdot\mathbf{x}} \right]$$
$$= \int \frac{d^3\mathbf{k}}{(2\pi)^{3/2}} \left[\hat{b}_{\mathbf{k}}\, \mathcal{F}_k(\eta)\, e^{i\mathbf{k}\cdot\mathbf{x}} + \hat{b}^\dagger_{\mathbf{k}}\, \mathcal{F}^*_k(\eta)\, e^{-i\mathbf{k}\cdot\mathbf{x}} \right]$$

$\mathcal{I}$, $\mathcal{F}$ are the initial & final wave functions

Bogolyubov Transformation

Relation between the raising/lowering operators defined in the initial and final vacua

$$\hat{b}_k = \alpha_k\,\hat{a}_k + \beta_k^*\,\hat{a}_k^\dagger, \qquad \hat{b}_k^\dagger = \beta_k\,\hat{a}_k + \alpha_k^*\,\hat{a}_k^\dagger\,,$$

Number density of particles in the “final vacua” (in Heisenberg’s picture)

$$\begin{aligned} {}_{\rm univ}\langle 0|\hat{N}_k|0\rangle_{\rm univ} &= {}_{\rm univ}\langle 0|\hat{b}_k^\dagger\hat{b}_k|0\rangle_{\rm univ} \\ &= {}_{\rm univ}\langle 0|(\beta_k\,\hat{a}_k + \alpha_k^*\,\hat{a}_k^\dagger)(\alpha_k\,\hat{a}_k + \beta_k^*\,\hat{a}_k^\dagger)|0\rangle_{\rm univ} \\ &= |\beta_k|^2\delta(0)\,. \end{aligned}$$

$$n \equiv \int d^3\mathbf{k}\, n_k = \int d^3\mathbf{k}\,|\beta_k|^2$$

Number of σ pairs in the CMB last scattering surface (with a thickness)

$$N_{\sigma\,\mathrm{pairs}} = \frac{1}{2\pi^2}\left(\frac{g\dot{\phi}}{H_*^2}\right)^{3/2} e^{-\frac{\pi(M_0^2-2H_*^2)}{|g\dot{\phi}|}} \left(\frac{k_*}{k_{\mathrm{CMB}}}\right)^3 \left(\frac{\Delta\eta_{rec}}{\eta_{rec}}\right)$$

looks like a thermal production suppressed by the Sigma mass

$$\sqrt{\dot{\phi}} \approx 60 H_*$$

from CMB measurement, ~ kinetic energy of inflaton

CMB horizon with finite thickness

$$\frac{\Delta\eta_{rec}}{\eta_{rec}} \approx 0.04$$

Yuhsin Tsai yhtsai@nd.edu

Number of σ pairs in the CMB last scattering surface (with a thickness)

$$N_{\sigma\,\text{pairs}} = \frac{1}{2\pi^2}\left(\frac{g\dot{\phi}}{H_*^2}\right)^{3/2} e^{-\frac{\pi(M_0^2-2H_*^2)}{|g\dot{\phi}|}} \left(\frac{k_*}{k_{\text{CMB}}}\right)^3 \left(\frac{\Delta\eta_{rec}}{\eta_{rec}}\right)$$

As a reminder, $M_{\text{eff}}^2 \approx M_0^2 + g^2\phi'^2(\eta-\eta_*)^2$

If $\quad g = 5 \qquad M_0 = 5.5\sqrt{\dot{\phi}} \approx 330 H_*$

and the spot size (η_*) is similar to a pixel of chopping CMB into 1000^2 pieces

$$N_{\sigma\,\text{pairs}} \sim 10^3$$

Yuhsin Tsai yhtsai@nd.edu

Back-reaction constraints

Need to make sure the produced heavy particles do not affect inflaton's slow-roll e.o.m. $3H_* \dot{\phi} \approx -\frac{\partial V_\phi}{\partial \phi}$

Since $\frac{\partial V}{\partial \phi} = \frac{\partial V_\phi}{\partial \phi} + g(g\phi - M)\sigma^2$

this requires $g(g\phi - M)\sigma^2 \sim gM_\sigma \sigma^2 \sim g\, n_\sigma \ll H_* \dot{\phi}$

and an upper bound $N_{\sigma\,\mathrm{pairs}} < 10^8$ for the same spot size

that gives < 1% of the correction

Radiative correction => assume a UV completion (e.g. SUSY) takes care of that (see e.g., Flauger et al. (2016))

Next step: mass modifies curvature perturbation

Non-adiabatic particle (pair) production during the inflation

→

Particle mass modifies nearby curvature perturbation before leaving the horizon (due to inflation)

↙

Perturbation gets frozen outside of the horizon

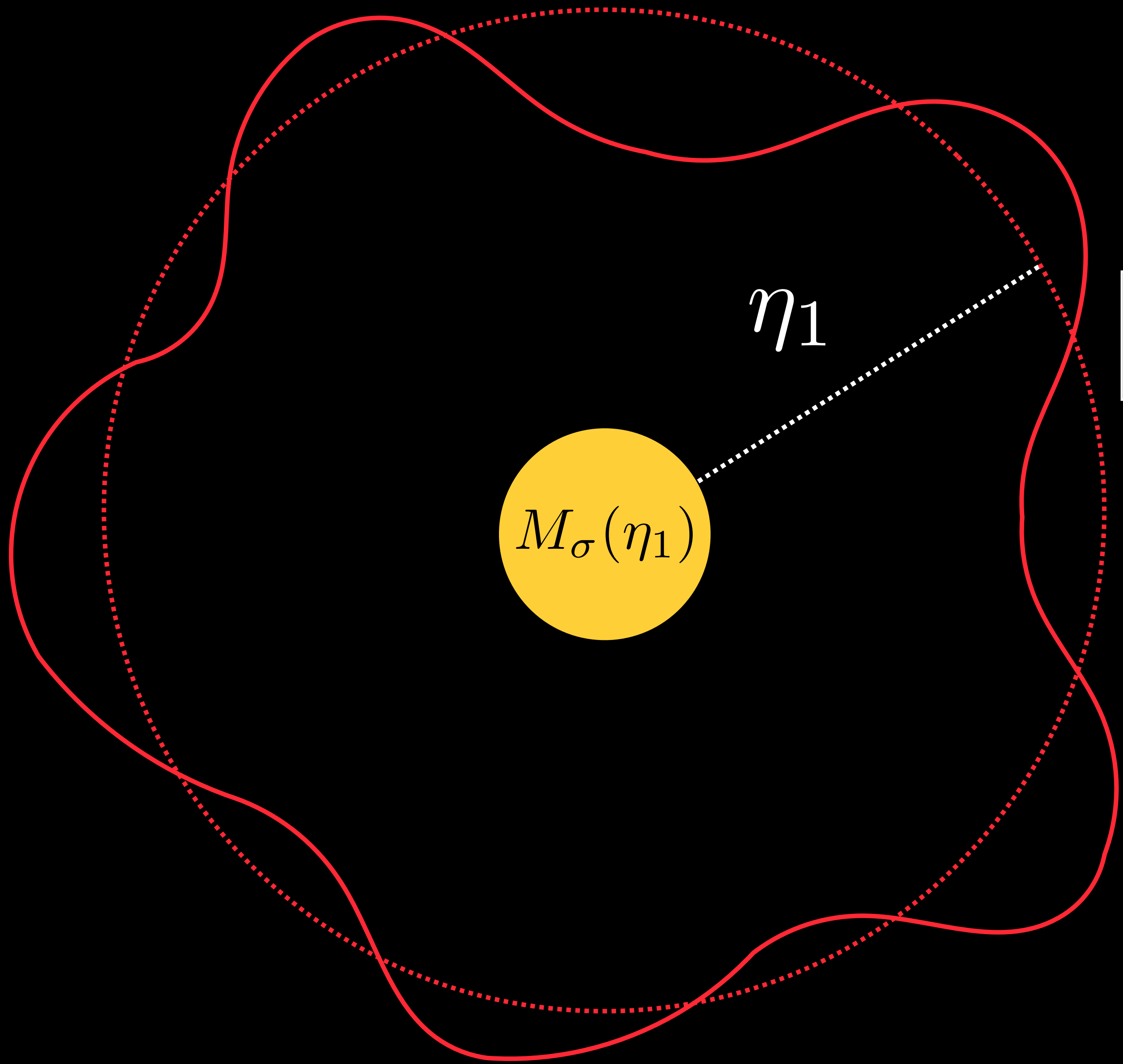
→

(inflation ends, horizon re-entry)

Photon temperature follows local curvature perturbation

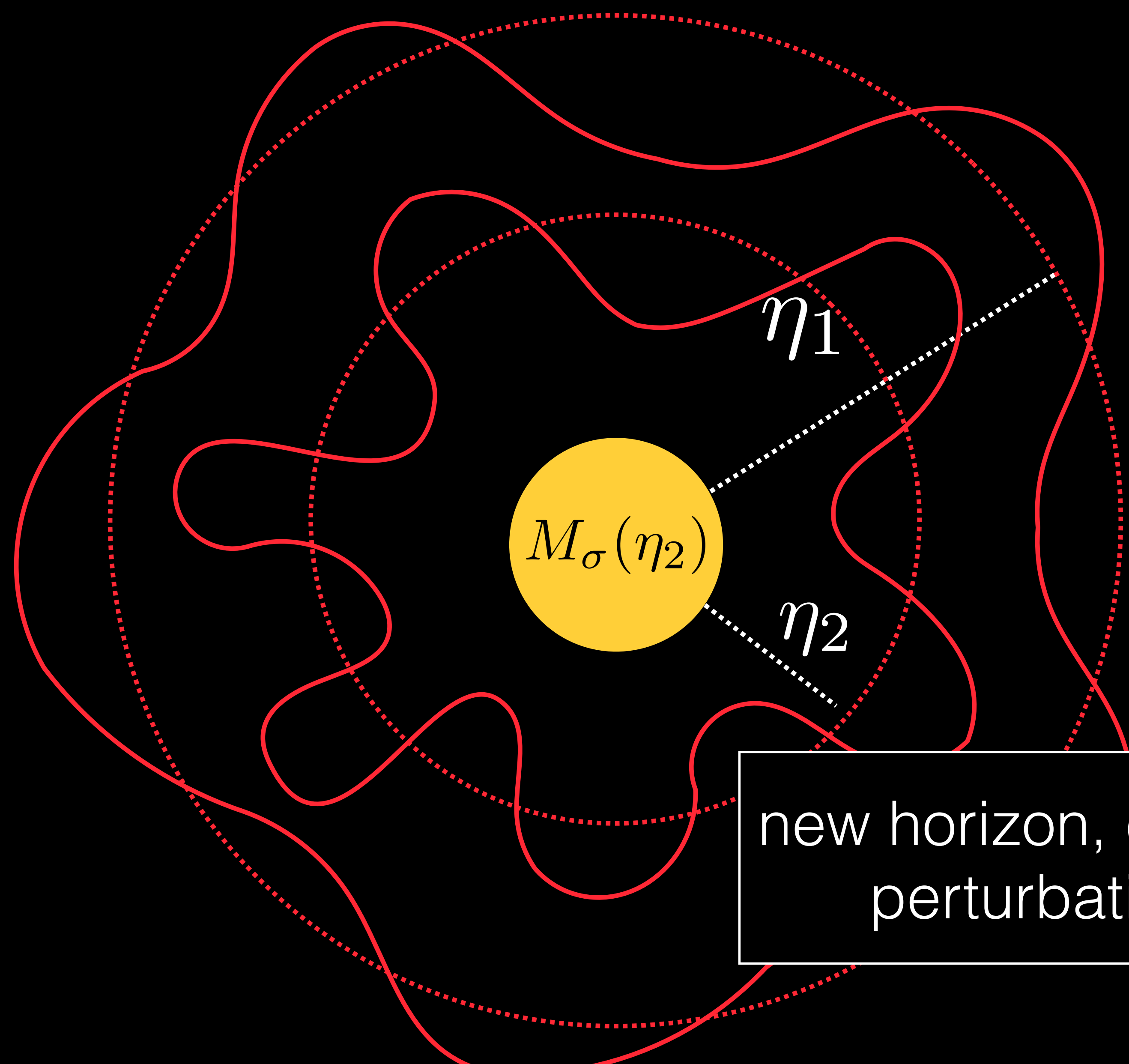
Pairwise hotspots (or cold spots)

particle mass changes the
curvature perturbation inside the horizon



horizon

After the old horizon is frozen, **NEW** particle mass changes the curvature perturbation inside the **NEW** horizon



new horizon, different perturbations

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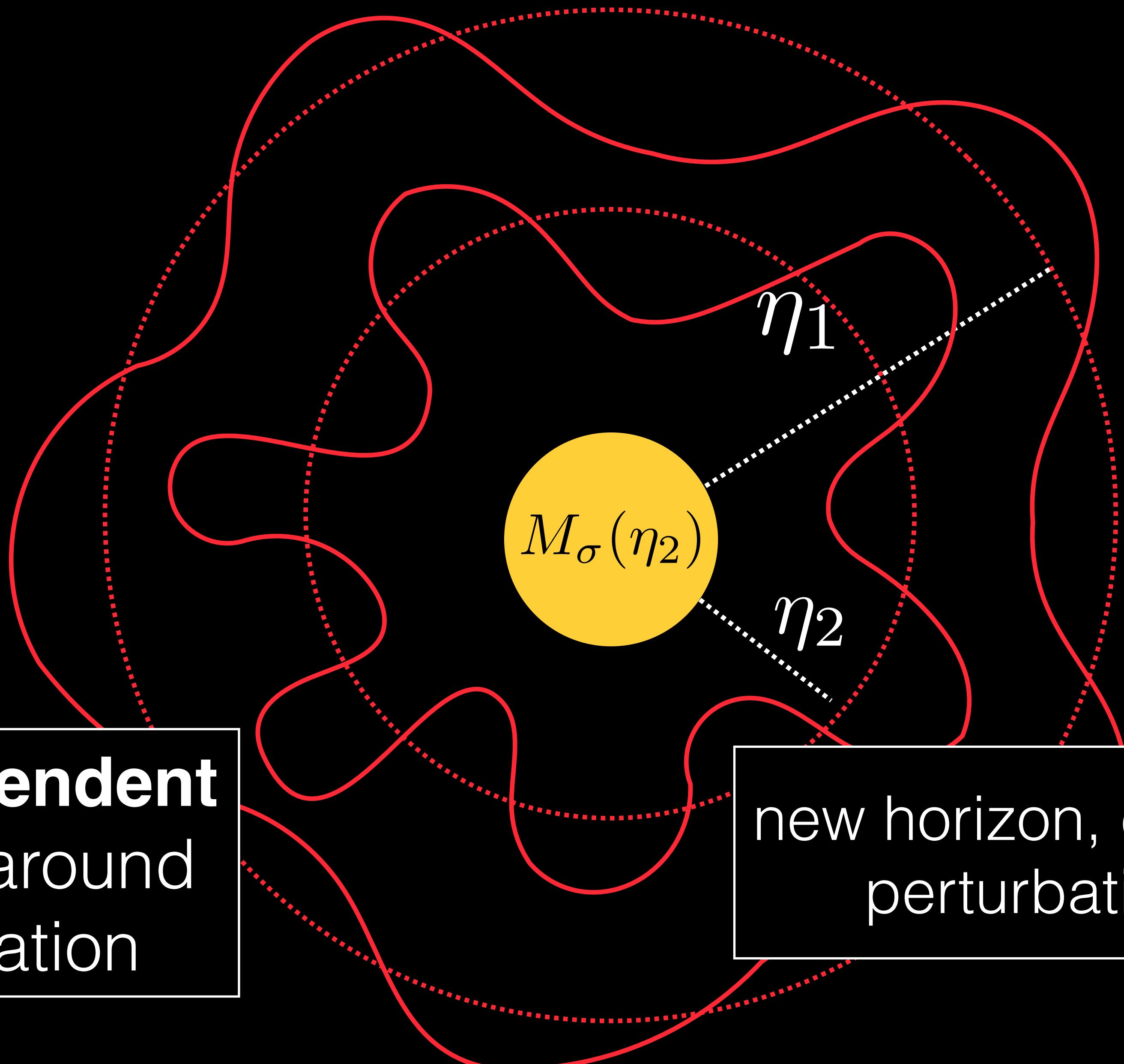


This gives a **radius-dependent** curvature perturbation around the heavy particle location

new horizon, different perturbations

Yuhsin Tsai yhtsai@nd.edu

Profile of the curvature perturbation from σ mass

Maldacena (1508.01082)

Fialkov et. al. (0911.2100)

Produced heavy particle backreacts on spacetime

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

comoving curvature perturbation

Give rise to a non-trivial one-point function

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

given by the inflaton

Profile in the position space

$$\langle \zeta_k \rangle = \left[\frac{M_{\rm eff}(|\eta| = r)}{2\sqrt{2\epsilon} M_{pl}} \right] \frac{H}{2\pi \sqrt{2\epsilon} M_{pl}} \quad |r| \leq |\eta_*| \qquad (= 0\ |r| > |\eta_*|)$$

How large and how hot is each hotspot?

For $|r| \leq |\eta_*|$ we can get

Primordial fluctuation $\delta T_{\rm CMB} \sim 27\,\mu K$

$$\langle \delta T \rangle = \left[\frac{g}{2} \log \left(\frac{|\eta_*|}{r} \right) \right] \frac{H}{2\pi\sqrt{2\epsilon} M_{pl}} \sim \left[\frac{g}{2} \log \left(\frac{|\eta_*|}{r} \right) \right] \delta T_{\rm CMB}$$

Hence hotspot size $\sim |\eta_*|$ and the amplitude g controls the hotspot temperature over CMB fluctuations

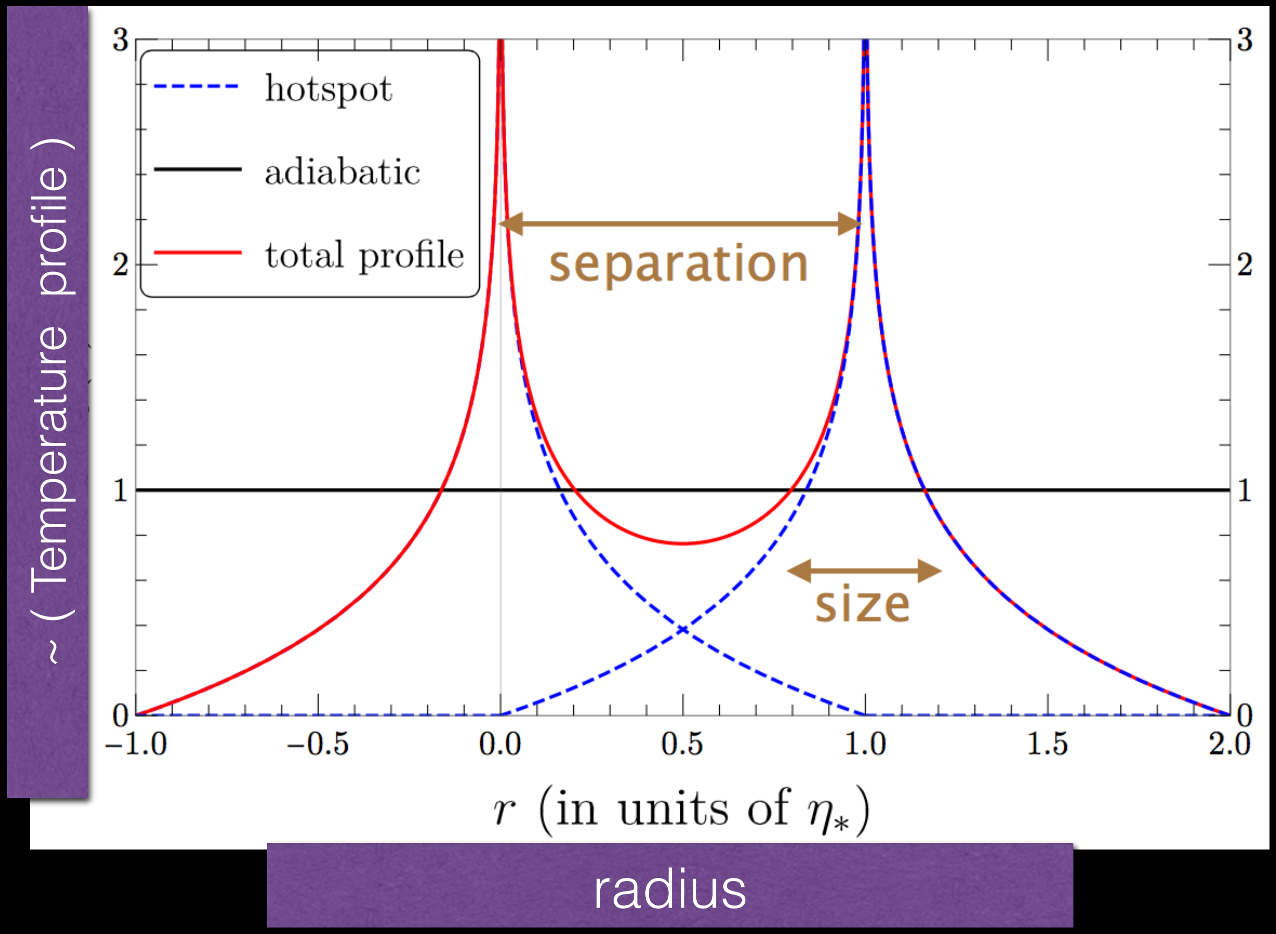
$$\phi - \phi_* = \dot{\phi}(t - t_*) = -\frac{\dot{\phi}}{H_*} \log \left(\frac{\eta}{\eta_*} \right)$$

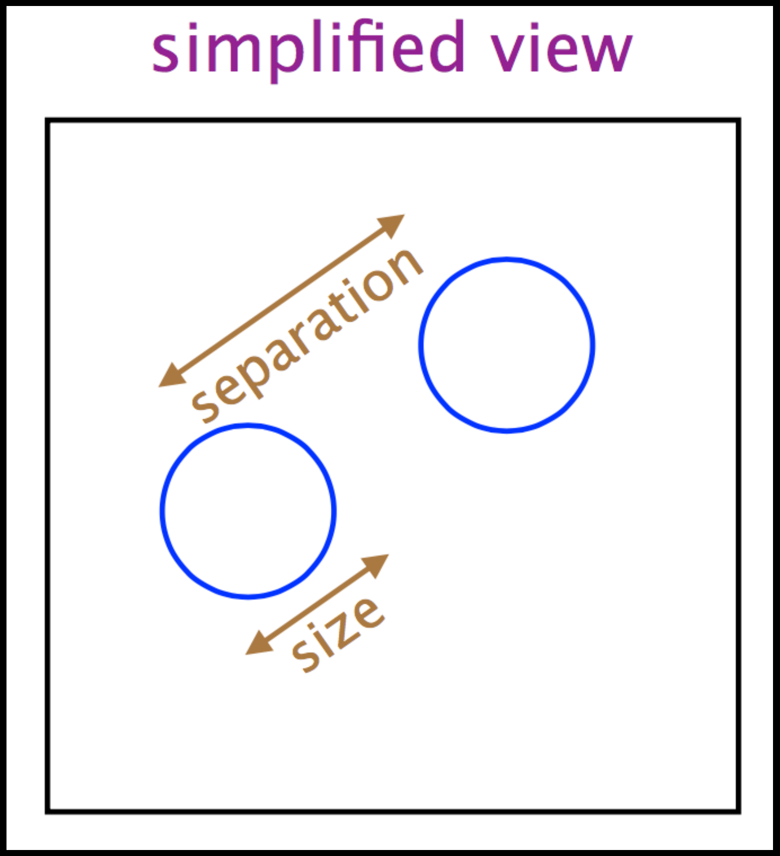
log comes from the exponentially growth of the scale factor during the inflation

Yuhsin Tsai yhtsai@nd.edu

How are the hotspots distributed?

Heavy particles are produced in pairs: momentum conservation





Structure formation may further change the profile

e.g., see Fialkov et al. (2009) for the pre-inflationary particle study

Final step: signals on the CMB

Non-adiabatic particle (pair) production during the inflation

→

Particle mass modifies nearby curvature perturbation before leaving the horizon (due to inflation)

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Perturbation gets frozen outside of the horizon

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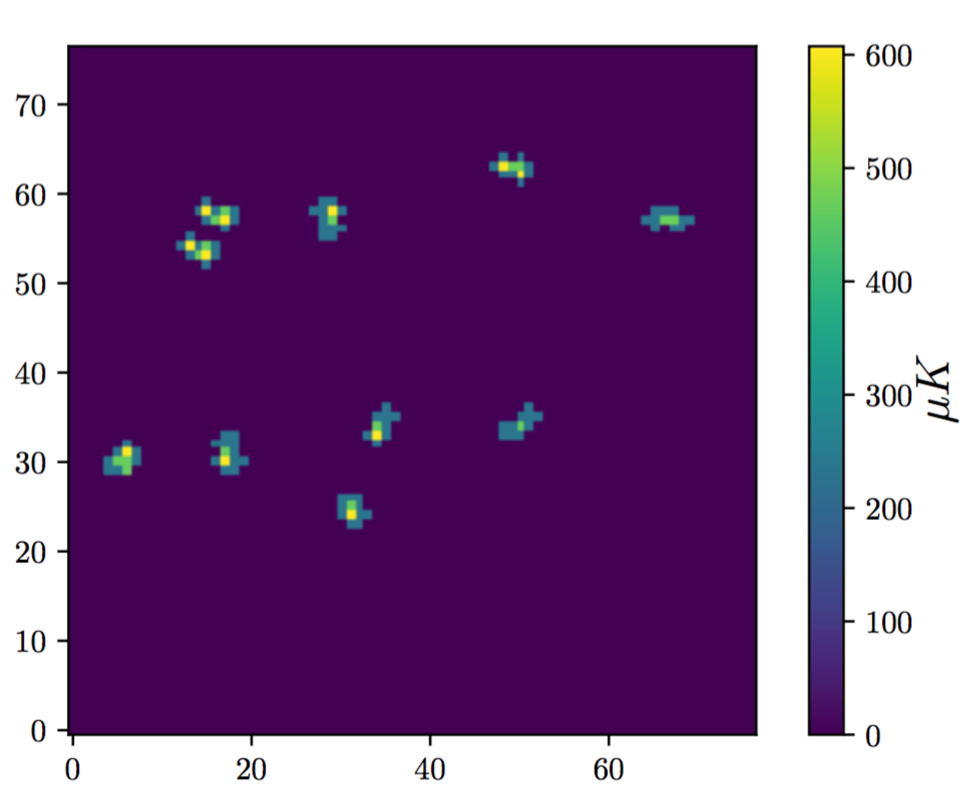
Pairwise hotspots (or cold spots)

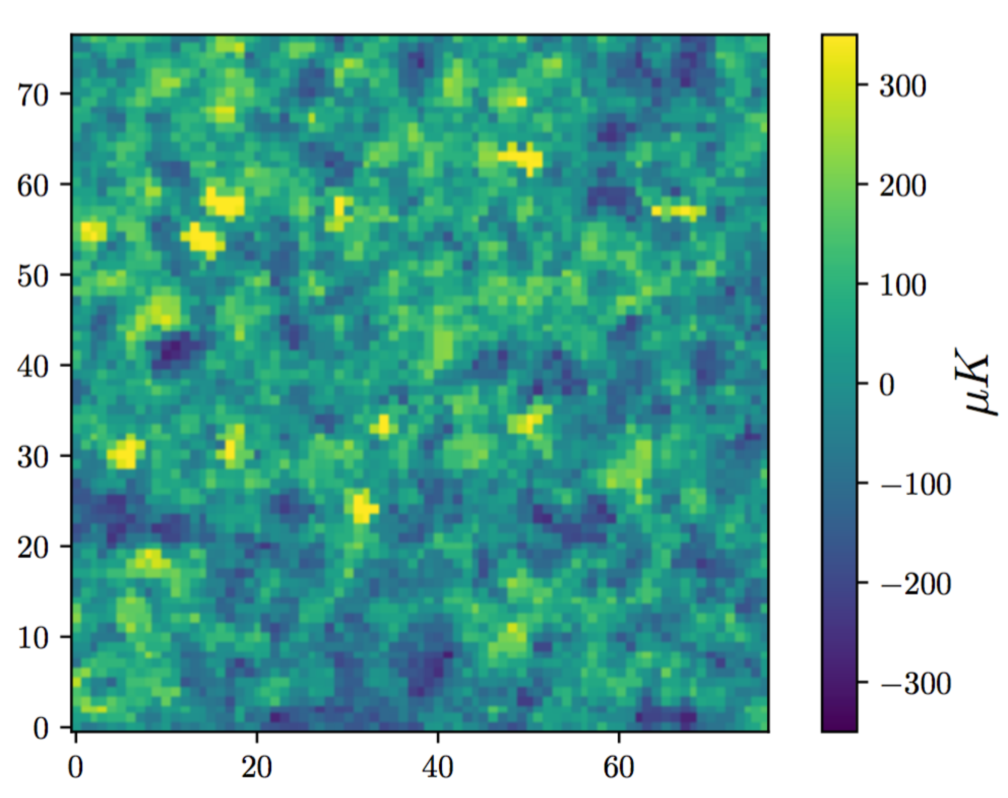
Simulate pairwise hotspot signals

- We use HEALPix to generate fake CMB image that follows the temperature fluctuation of the best fitted LCDM model
- for signal events, we add pairwise hotspots with a given temperature profile, pixel size, and separation between two spots

signal



signal + fake CMB



$$g = 30$$

only for illustration

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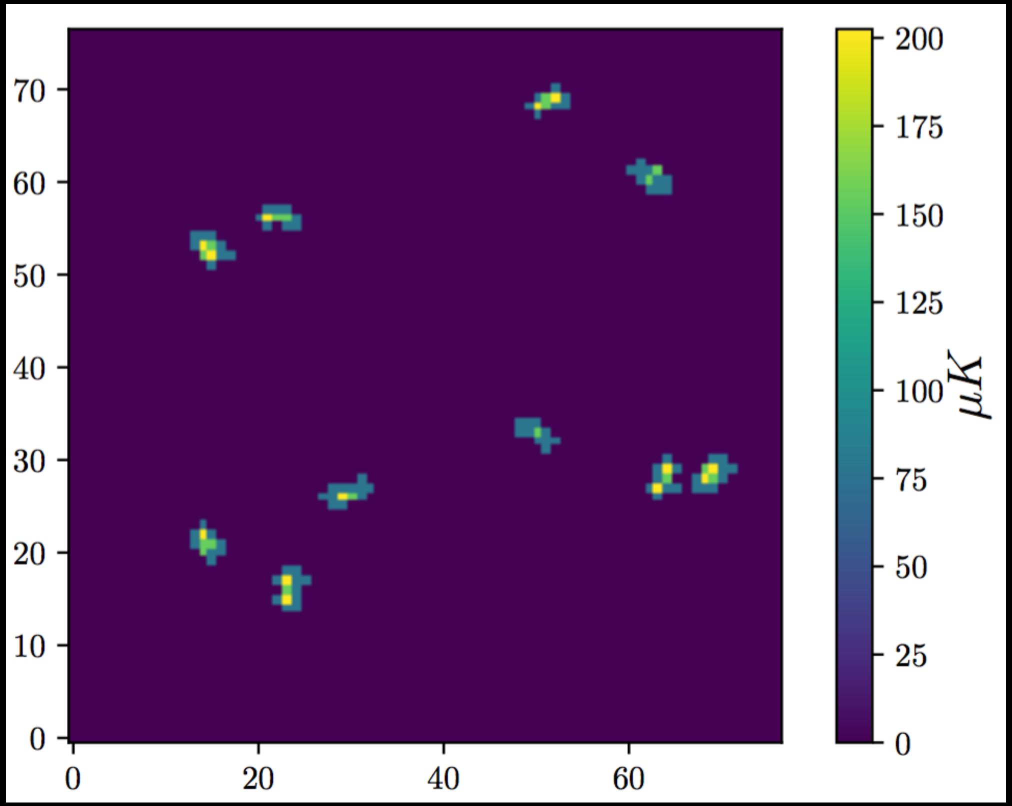

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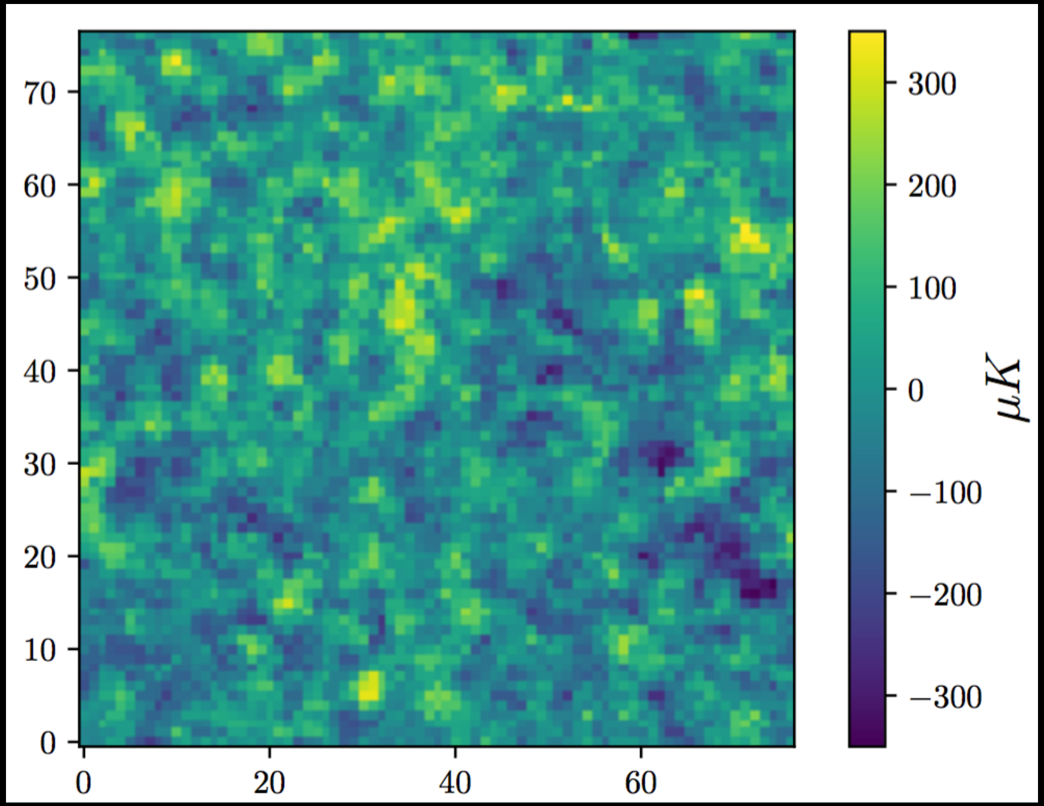

$g = 10$

Yuhsin Tsai yhtsai@nd.edu

Identify signal on the CMB map

Different types of backgrounds to consider:

- instrumental noise
- fore-ground from compact objects (stars, galaxies,…)
- primordial fluctuation background (indistinguishable)

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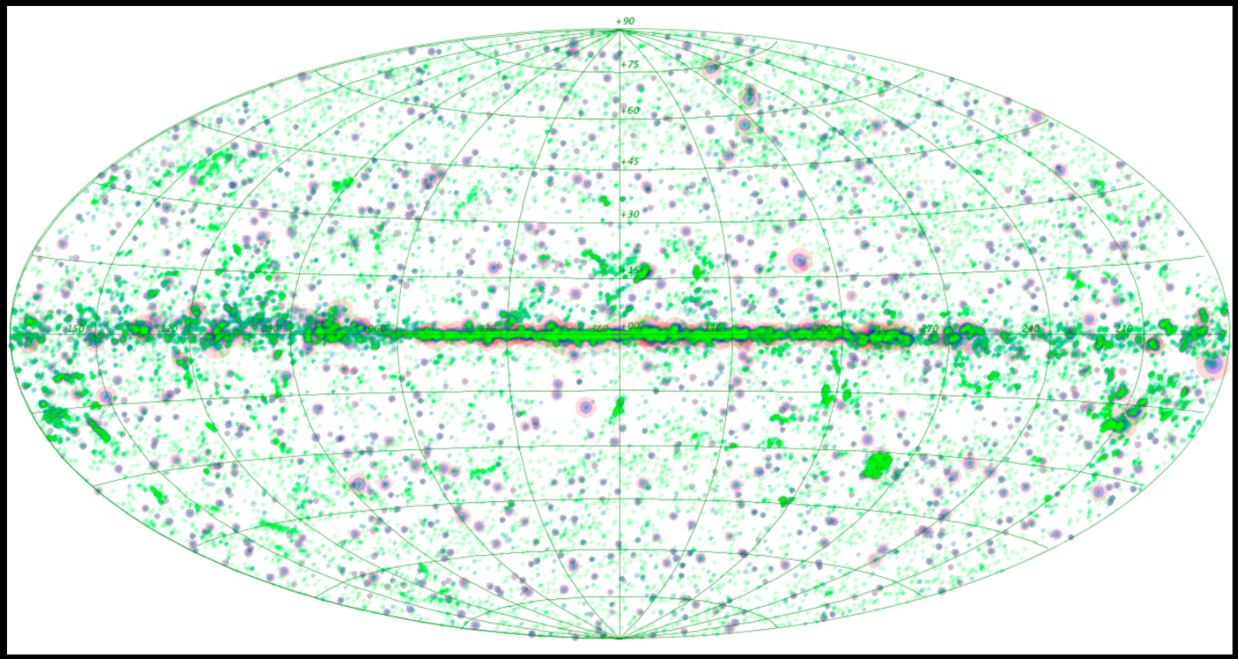

"May" veto the background by correlating Planck's maps in 9 frequency bands (need more study)

Planck 2013 results. XXVIII

Fig. 1. Sky distribution of the PCCS sources at three different channels: 30 GHz (pink circles); 143 GHz (magenta circles); and 857 GHz (green circles). The dimension of the circles is related to the brightness of the sources and the beam size of each channel. The figure is a full-sky Aitoff projection with the Galactic equator horizontal; longitude increases to the left with the Galactic centre in the centre of the map.

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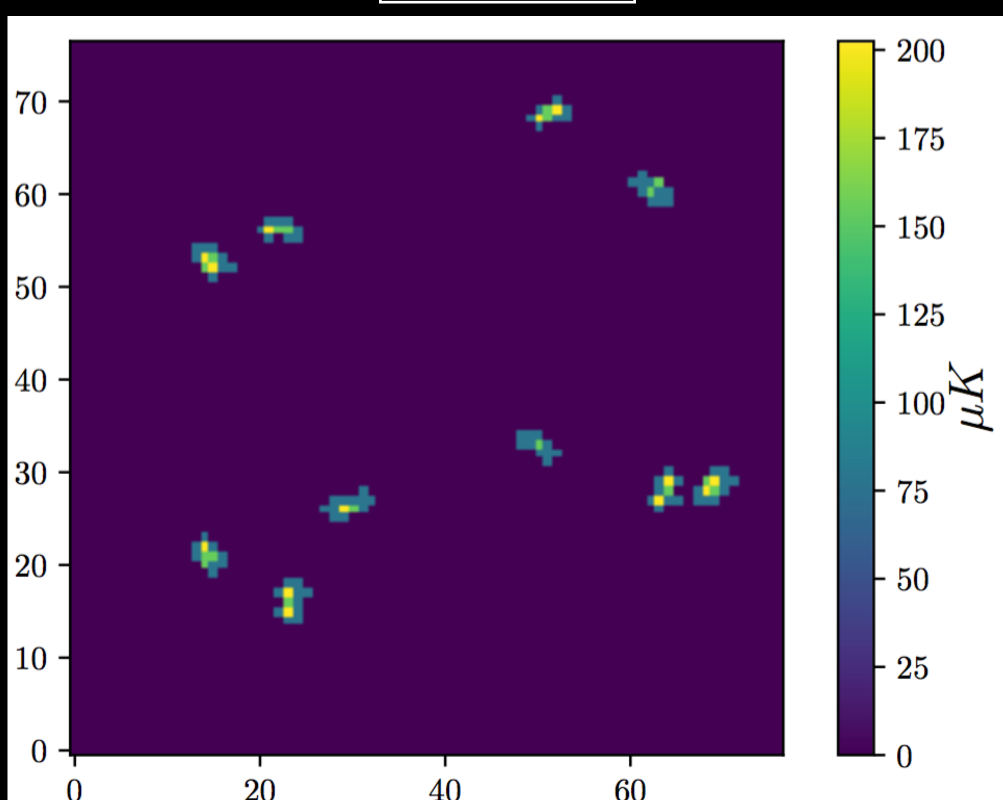

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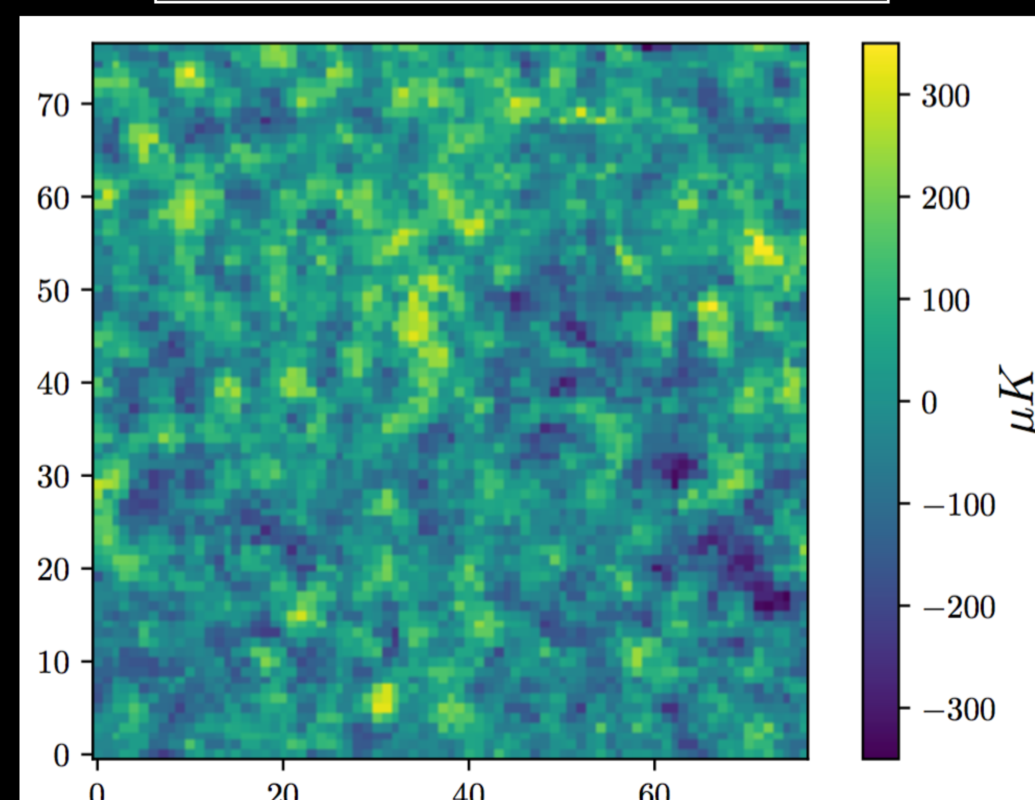

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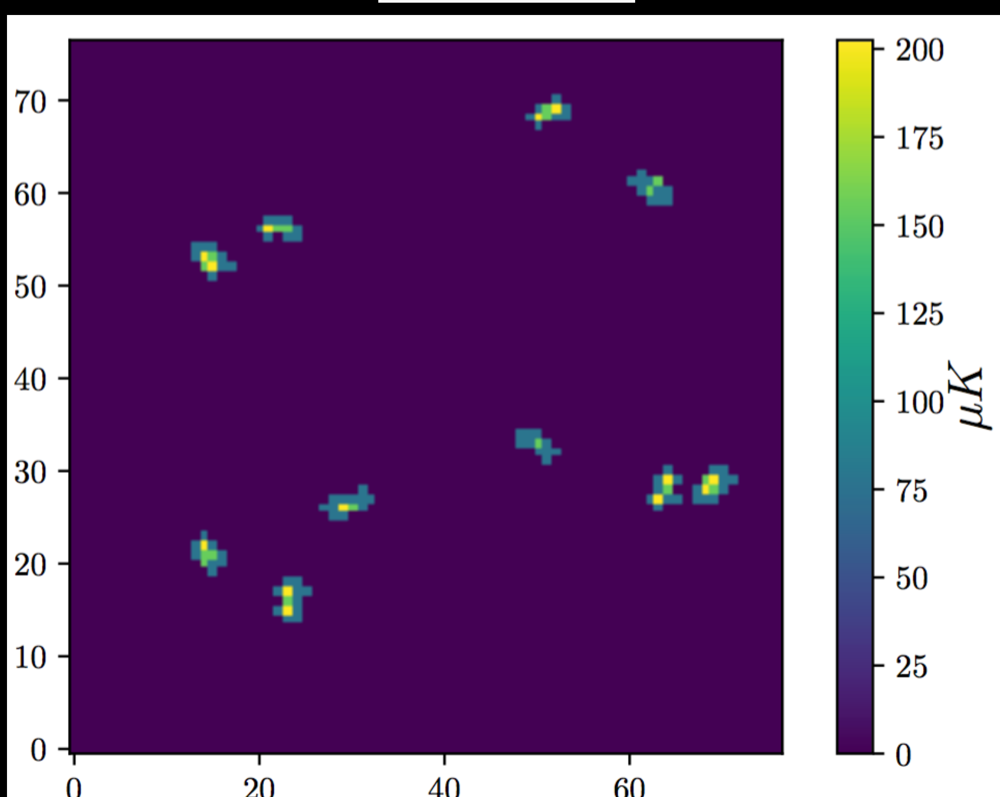

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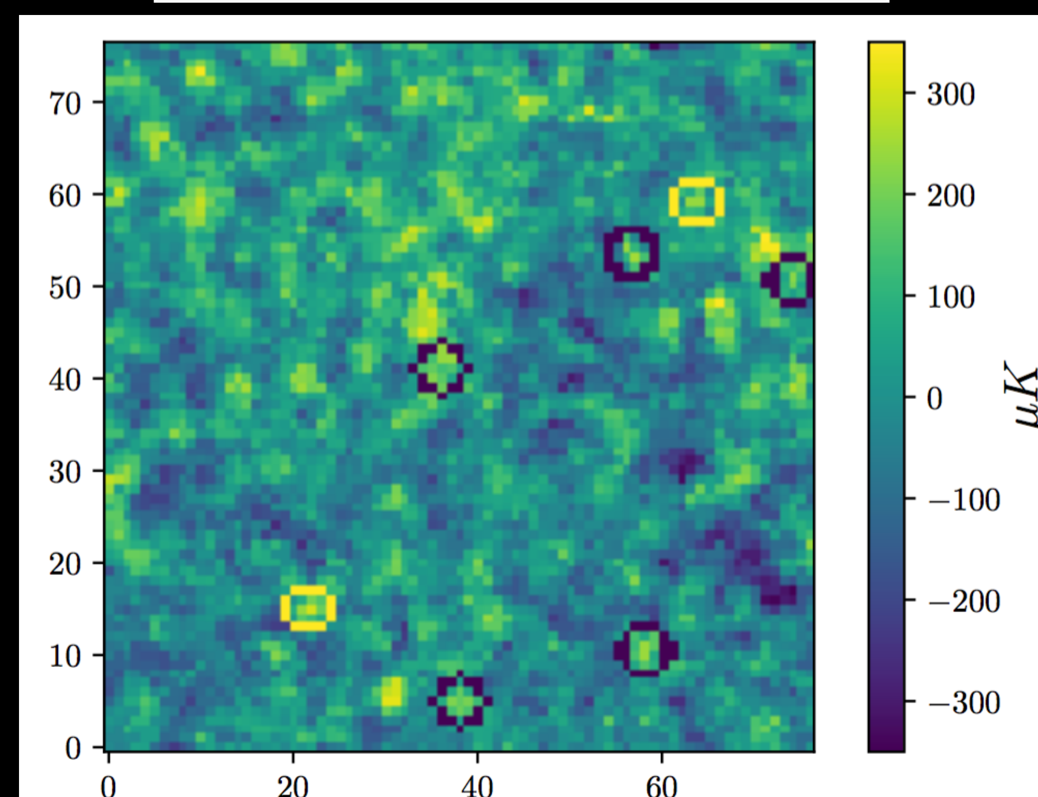


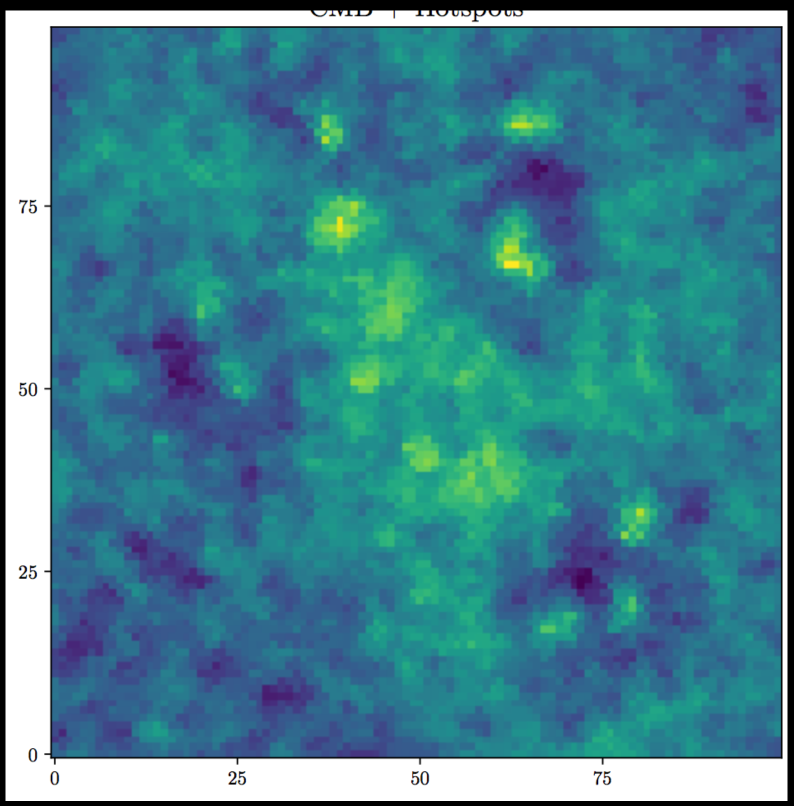
$g = 10$

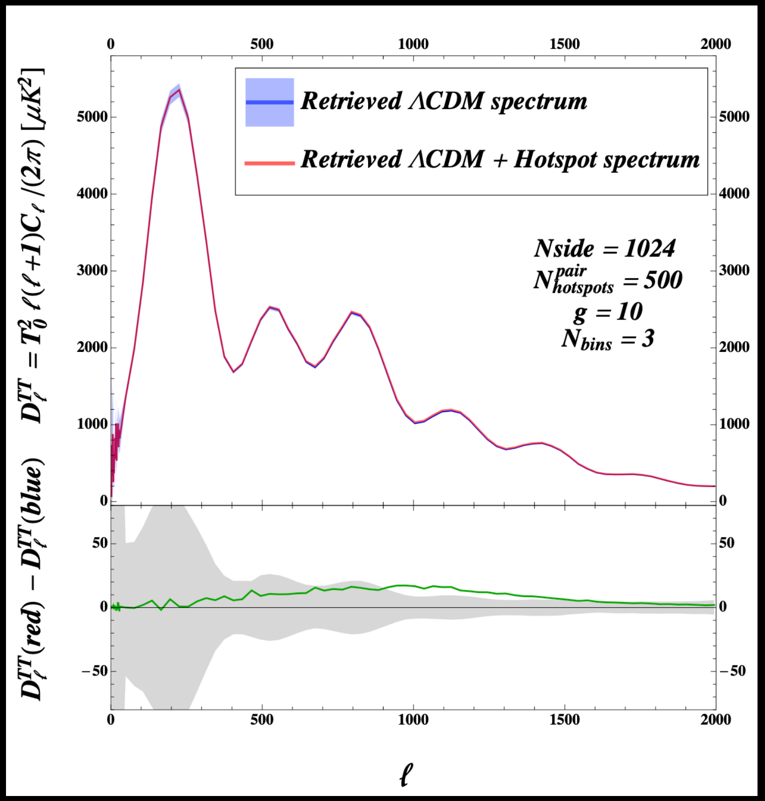
Here we only focus on the primordial fluctuation bkg

For the heavy particle bounds below,
we should consider them as

- The best sensitivity that we may achieve even with a perfect CMB measurement
- Minimum number of pairwise hotspots that can hide from any CMB searches

How to probe the signal?





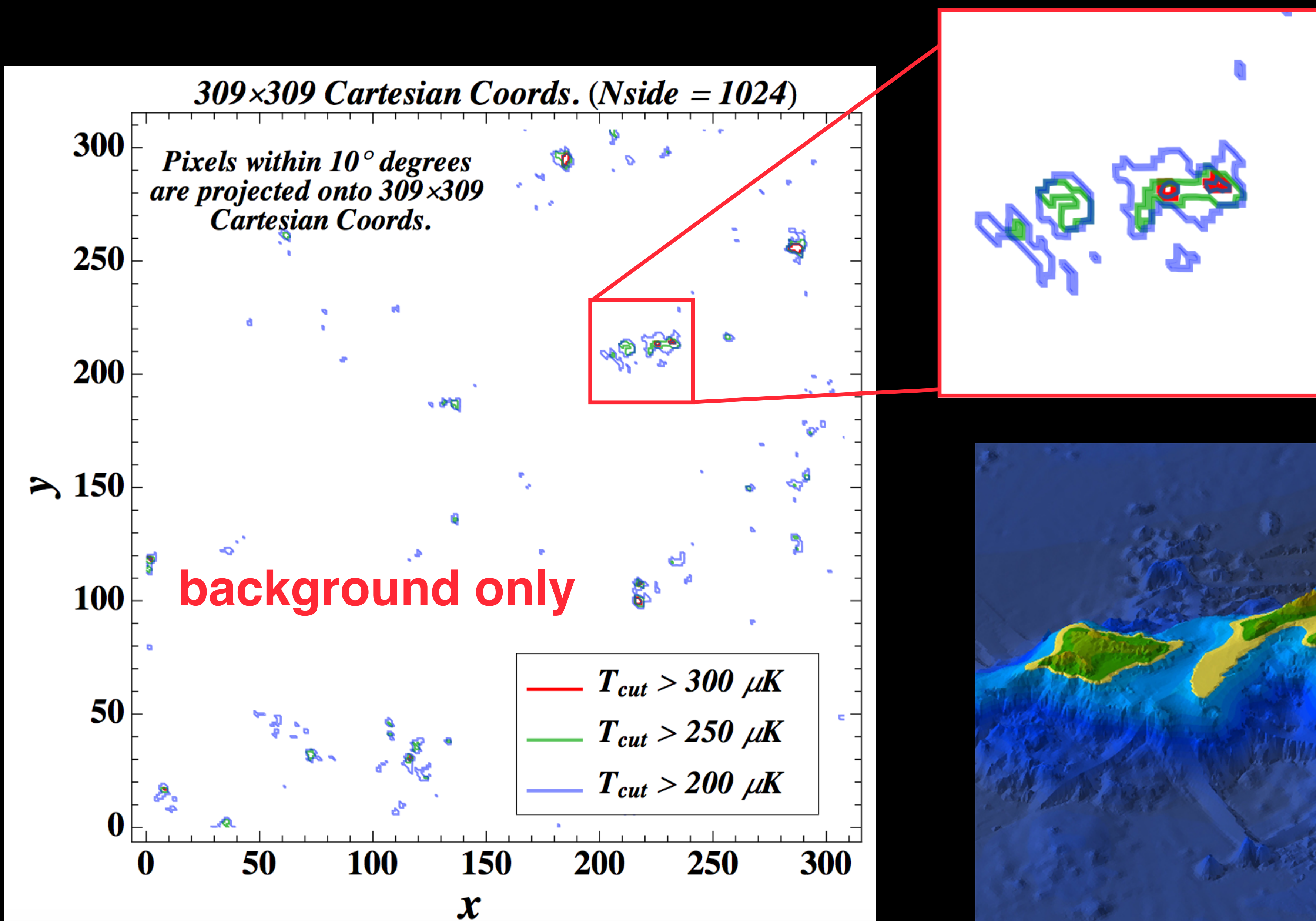
Looking for pairwise hotspots in spatial coordinate

ℓ-dependent distortion of CMB TT-spectrum (or non-Gaussianity)

Yuhsin Tsai yhtsai@nd.edu

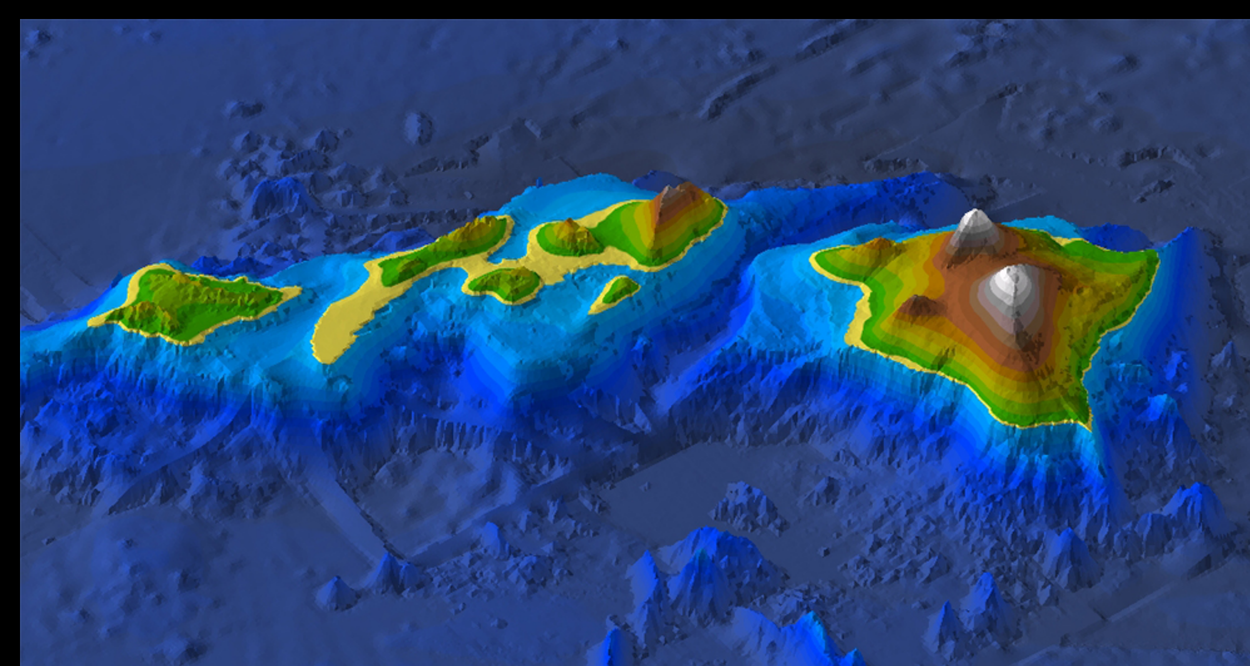
Primordial fluctuations can produce very hot spots

And these hotspots even like to show up in nearby locations that can look similar to our signal



$$\sigma_{\rm CMB} \sim 200\,\mu K$$

$$\delta T_{\rm sig} \approx \frac{g}{2}\,27\,\mu K$$

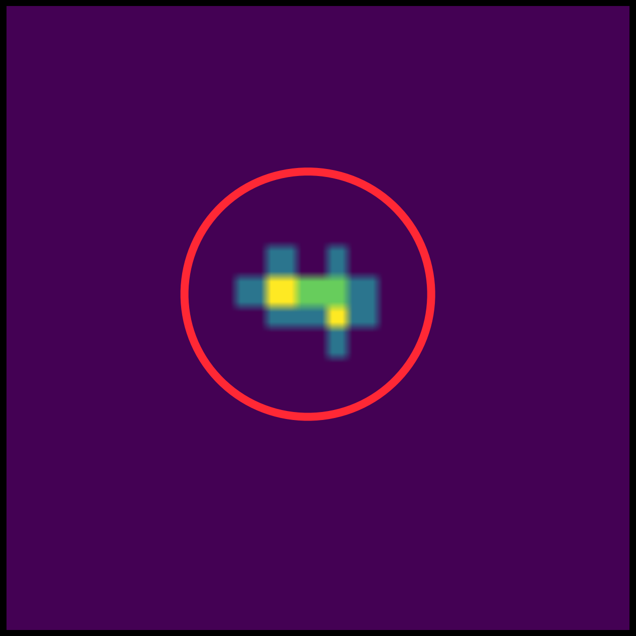


Yuhsin Tsai yhtsai@nd.edu

Need to pick the "cuts" carefully to veto the bkg

For example, using cuts based on the **high T** & **pairwise** features

- subtract average temperature from a target region of the map
- apply a temperature cut $T_{\rm cut} > \sigma_{\rm cmb} \approx 200\,\mu{\rm K}$
- find the hottest spot on the map
- draw a cone around the spot with radius $\sim \eta_*$
- require exactly 2 surviving hotspots inside the cone
- require the average temperature of the 2 spots $T^{avg}_{\rm cone} \gg T_{\rm cut}$



From the best set of cuts we found so far…

(may be further improved)

For signal hotspots with size around $\ell \sim 10^3$ mode

g	10	7	5
$\frac{\delta T_{\rm sig}}{\delta T_{\rm cmb}} \approx$	5	3.5	2.5
Signal number for 2σ excess	90	549	811

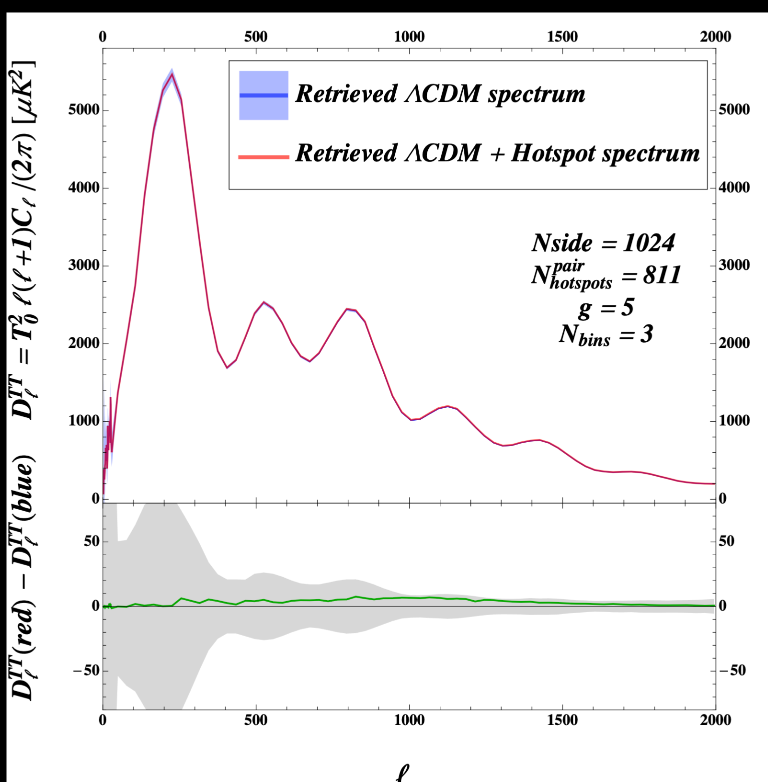
preliminary

Cut the sky into $N_{\rm pixel} = 3.1 \cdot 10^6 = \ell^2_{\rm max}$, from simulation of $2 \cdot 10^4$ CMB maps

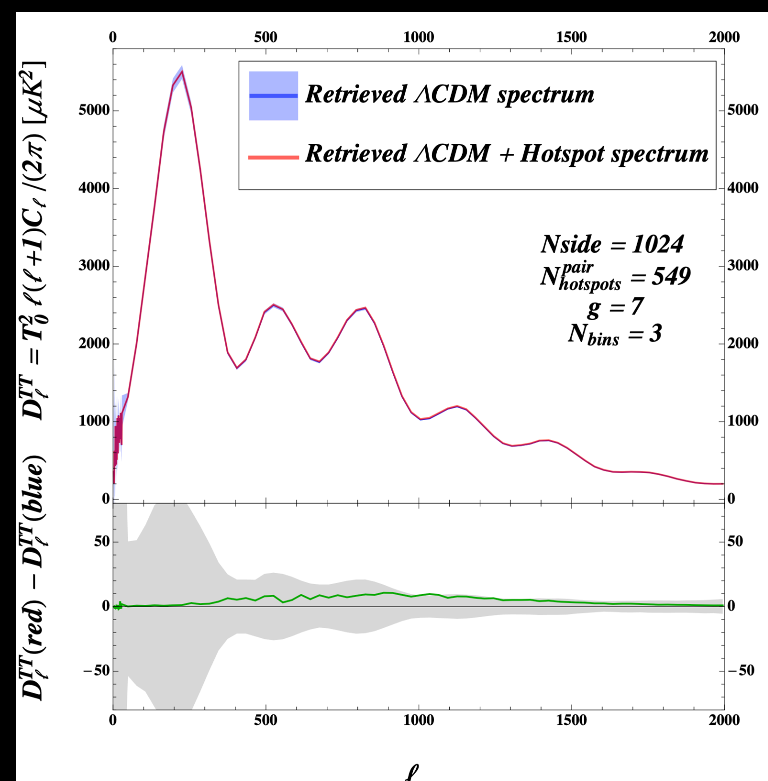
Yuhsin Tsai yhtsai@nd.edu

The corresponding C_ℓ^{TT} distortion

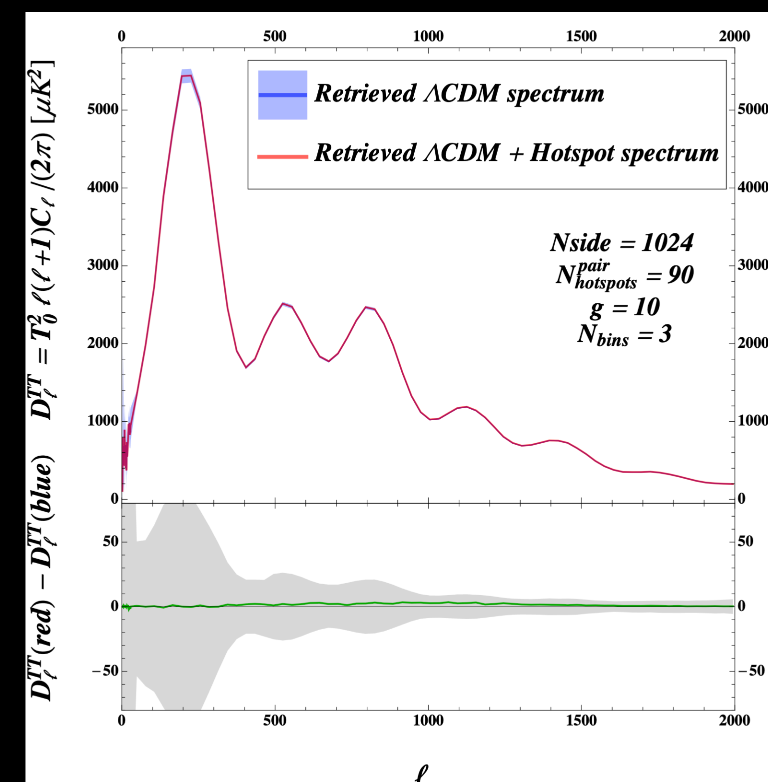
$g = 5,\ N_{\mathrm{sig}} = 811$



$g = 7,\ N_{\mathrm{sig}} = 549$



$g = 10,\ N_{\mathrm{sig}} = 90$



All the reduced chi2 are much less than 2sigma when including bins around l = 1000

The cut & count search provides a better probe of the signal for these g values

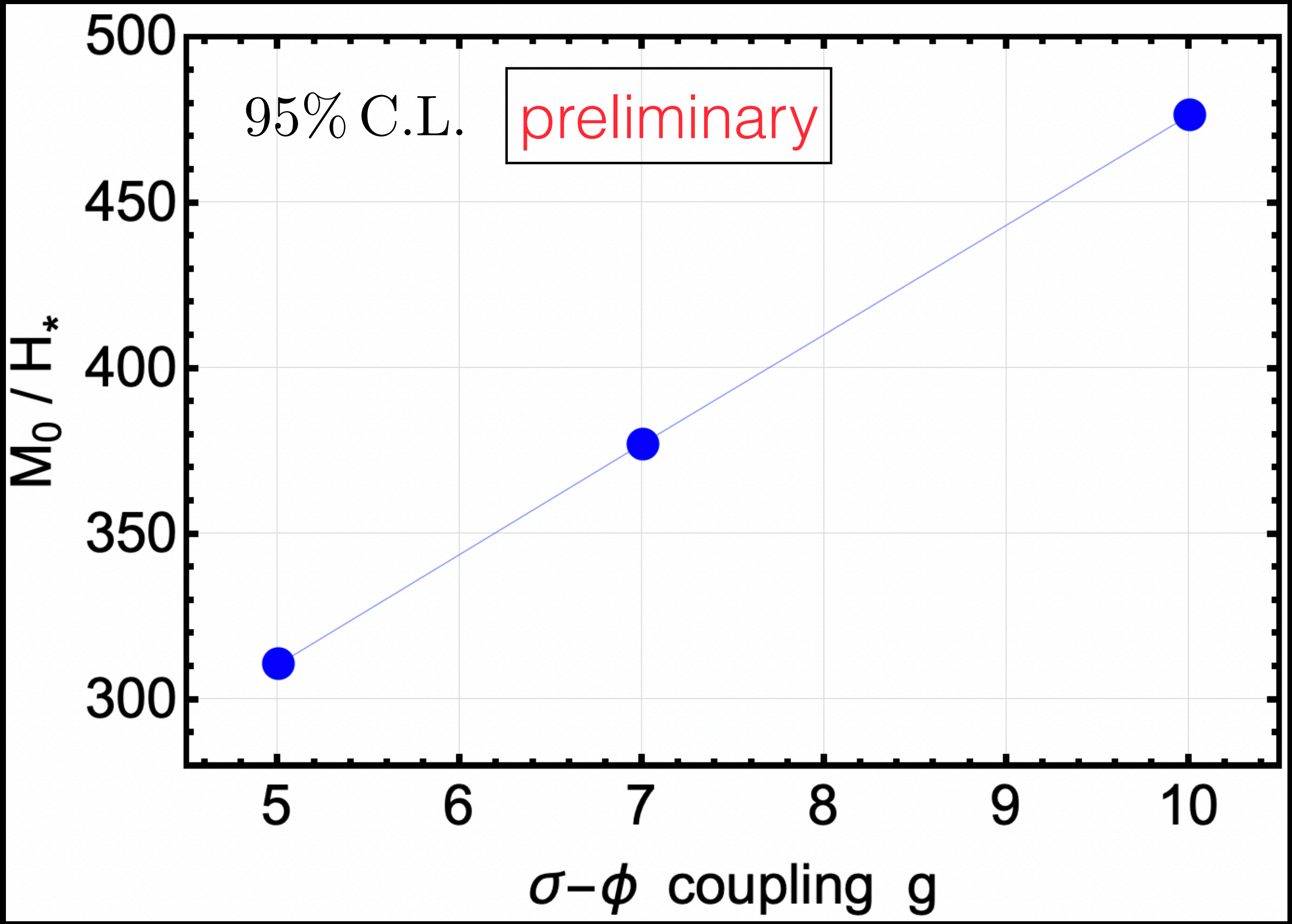
Bounds on the heavy particle mass

$$N_{\sigma\ \mathrm{pairs}} = \frac{1}{2\pi^2}\left(\frac{g\dot{\phi}}{H_*^2}\right)^{3/2} e^{-\frac{\pi(M_0^2-2H_*^2)}{|g\dot{\phi}|}} \left(\frac{k_*}{k_{\mathrm{CMB}}}\right)^3 \left(\frac{\Delta\eta_{rec}}{\eta_{rec}}\right)$$

$$M_{\mathrm{eff}}^2 \approx M_0^2 + g^2\phi'^2(\eta-\eta_*)^2$$

Lower bounds on the bare mass M_0 of σ .

The result is much larger than Hubble at the inflation



Yuhsin Tsai yhtsai@nd.edu

Conclusion

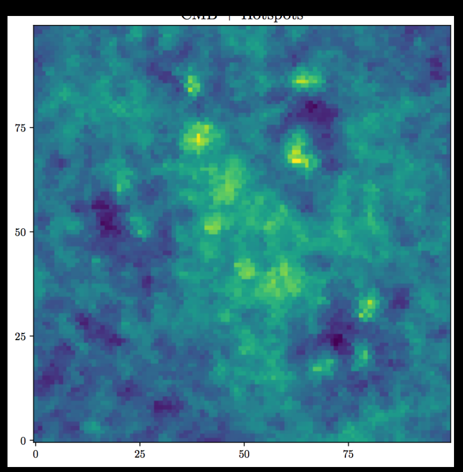
Production of heavy particle with an inflaton-dependent mass during inflation can generate pairwise hotspots on CMB map

Can use both "cut & count" and "N-point function" studies to dig out the signal

Assuming a perfect CMB measurement, a scalar coupling to inflaton can be probed up to $\mathcal{O}(100)H_*$ mass with $g = \mathcal{O}(1)$.

More things to explore: improving search by deep learning and wavelets? pairwise clumps in Large Scale Structure?

Thank you!



Backup Slides

(more details) for our Sigma production

Expand σ mass around
inflaton value at η_*
(min- m_σ for particle production)

$$\frac{\mathrm{d}^2 u}{\mathrm{d}\tau^2} + (\kappa^2 + \tau^2)u = 0$$

$$\tau = \gamma(\eta - \eta_*) \quad \kappa^2 = \frac{k^2}{\gamma^2} + \frac{M_0^2 - 2}{\eta_*^2 \gamma^2} \quad \gamma^4 = \frac{g^2 \phi'^2}{\eta_*^2}$$

The solution is a combination of parabolic cylinder functions

$$u = i\sqrt{\sigma} W(-\frac{\kappa^2}{2}, +\sqrt{2}\tau) + \frac{1}{\sqrt{\sigma}} W(-\frac{\kappa^2}{2}, -\sqrt{2}\tau) \qquad \sigma = \sqrt{1 + e^{-\pi\kappa^2}} - e^{-\pi\kappa^2/2}$$

have chosen the initial condition that the solution gives
a positive frequency function at initial time

$$u \sim e^{-i\frac{1}{2}\tau^2}$$

$$\tau \to -\infty$$

(more details) for our Sigma production

$$u = i\sqrt{\sigma}W(-\frac{\kappa^2}{2}, +\sqrt{2}\tau) + \frac{1}{\sqrt{\sigma}}W(-\frac{\kappa^2}{2}, -\sqrt{2}\tau)$$

$$u \sim e^{-i\frac{1}{2}\tau^2}$$
$$\tau \to -\infty$$

However, at the late time, the solution contains a negative frequency mode

$$\tau \to +\infty \quad u = \frac{2^{1/4}}{\sqrt{\tau}}\left[\left(\frac{i\sigma}{2} - \frac{i}{2\sigma}\right)e^{+\frac{i}{2}\tau^2} + \left(\frac{i\sigma}{2} + \frac{i}{2\sigma}\right)e^{-\frac{i}{2}\tau^2}\right]$$

β α $|\alpha|^2 - |\beta|^2 = 1$

Therefore, Sigma is produced with a number density

$$n = \int \mathrm{d}^3k\,|\beta|^2$$