Title: Cosmological Particle Production and Pairwise Hotspots on the CMB

Speakers: Yuhsin Tsai

Series: Particle Physics

Date: October 05, 2021 - 1:00 PM

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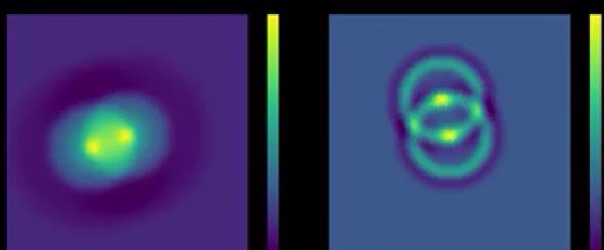
Abstract: Cosmic inflation provides an environment similar to particle colliders that can produce new particles and record the resulting signal. In this talk, I will describe a scenario in which new particles much heavier than the Hubble scale are produced during inflation via couplings to the inflaton. These heavy particles propagate classically and give rise to localized spots on the cosmic microwave background following their production. Momentum conservation during particle production dictates that these localized spots come in pairs. I will discuss the properties of such pairs of CMB spots and the prospect of their detection from the thermal fluctuation background in a position space search.

Cosmological Particle Production & Pairwise Spots on the CMB

Yuhsin Tsai

University of Notre Dame



Perimeter Institute 10/05/2021

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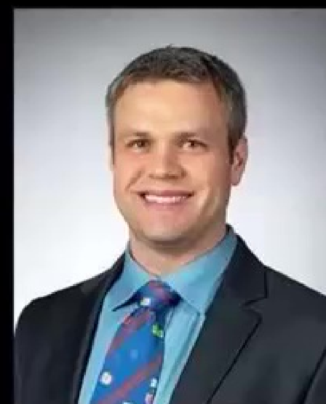
Based on 2107.09061 with

Jeong Han Kim
(Chungbuk National University)

Soubhik Kumar
(LBNL)

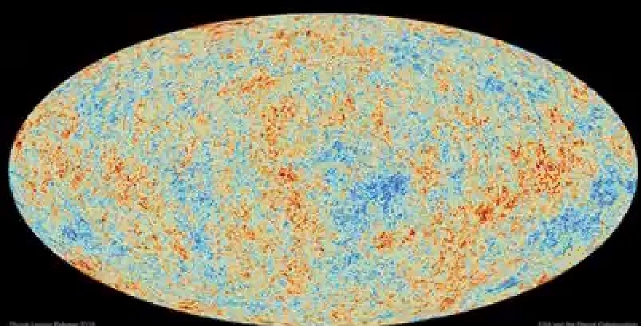


Adam Martin
(Notre Dame)

Our goal: probing extremely heavy particles

using inflationary dynamics + cosmological signals

Our particle detector: CMB



- radiation with wave length ~ 1mm
- blackbody radiation with $\bar{T} \approx 2.7\,K$
- temperature anisotropy $\sigma_{\rm CMB} \approx 100\,\mu K$

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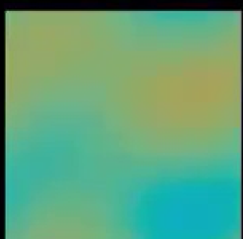
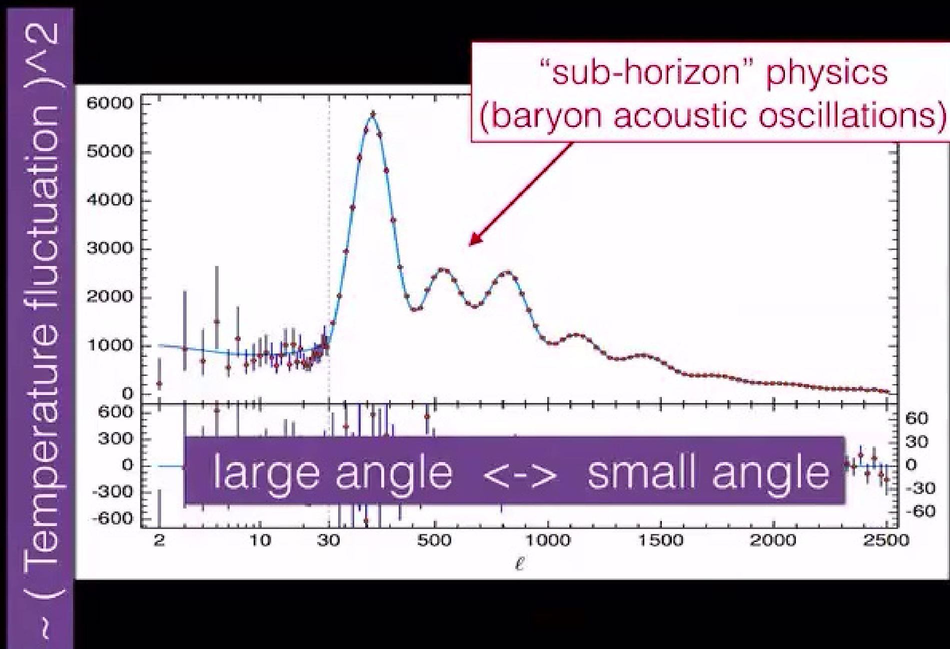
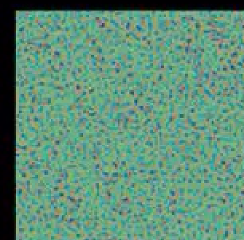
Typical CMB analysis: correlation functions

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







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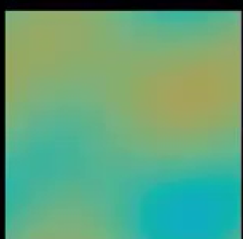

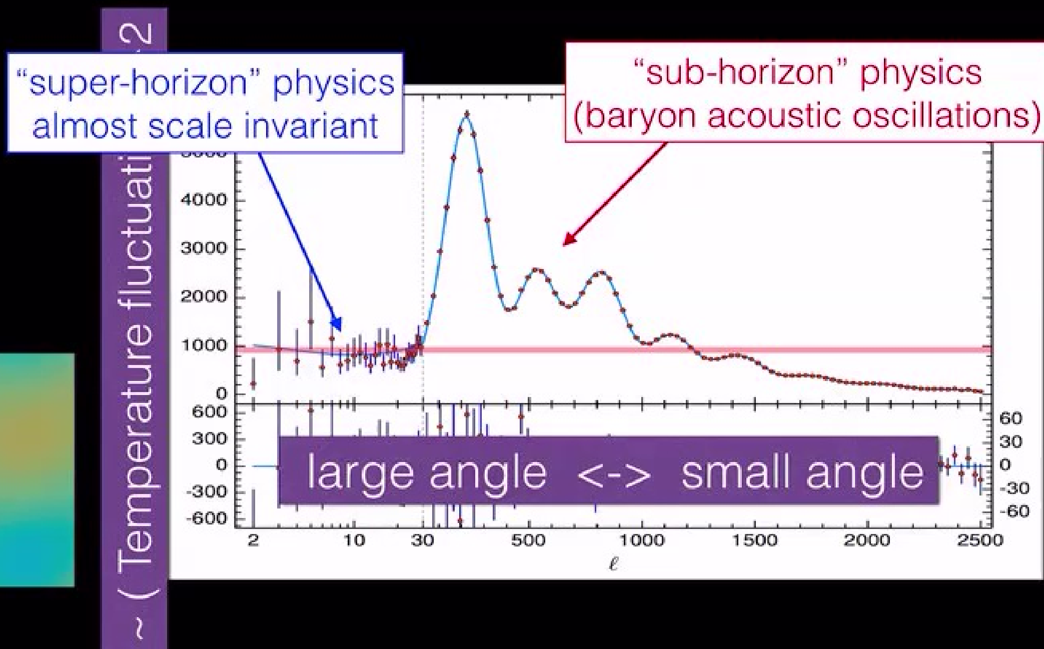

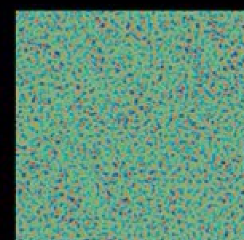

It makes sense to use N-point functions. The temperature anisotropy is almost a scale-invariant (not "localized" signals)

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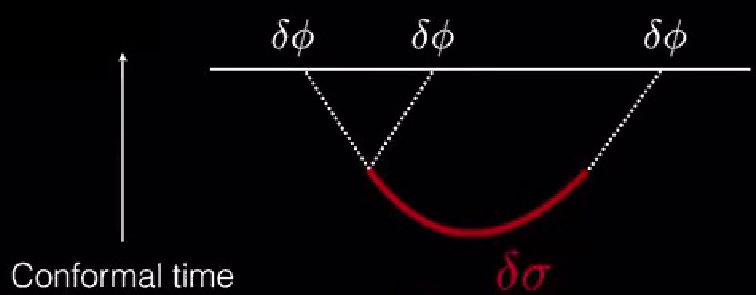
Cosmological collider & N-pt function analysis

- In the context of "cosmological collider physics", we usually focus on signals of non-Gaussianity ($\geq$ 3-pt functions)

- The signals are usually suppressed by $\sim \exp(-\pi M_\sigma / H_*)$



$$\langle \delta\phi\delta\phi\delta\phi \rangle \Rightarrow \langle \delta T \delta T \delta T \rangle$$

Done

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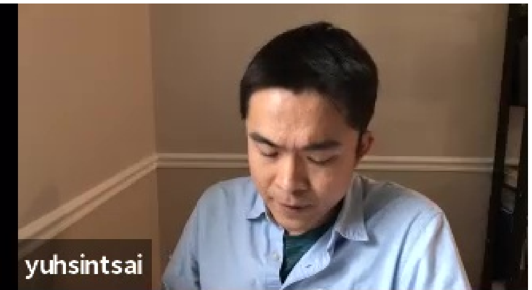
Cosmological collider & N-pt function analysis



- In the context of "cosmological collider physics", we usually focus on signals of non-Gaussianity ($\geq$ 3-pt functions)
- The signals are usually suppressed by $\sim \exp(-\pi M_\sigma / H_*)$

Question: Is is possible to probe mass $\gg H_*$?

What will be the signal look like?

PRODUCTIVE INTERACTIONS:
HEAVY PARTICLES AND NON-GAUSSIANITY

Raphael Flauger,[1] Mehrdad Mirbabayi,[2] Leonardo Senatore,[3,4,5] and Eva Silverstein,[3,4,5]

Higher N-point function data analysis techniques for heavy particle production and WMAP results

Moritz Münchmeyer[1] and Kendrick M. Smith[1]

[1]*Perimeter Institute for Theoretical Physics, Waterloo, ON N2L 2Y5, Canada*

Done

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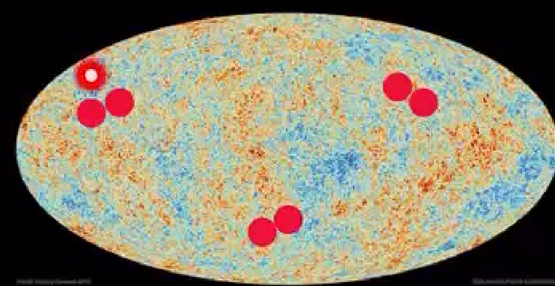
If the new particles are so heavy $\gg H_*$,

they only show up as localized signals in position space

Pairwise Spots on the CMB map

The heavy particle can directly modify the curvature fluctuation →



(cartoon picture)

Is position space search useful (vs. N-pt function study) for identifying these very heavy particles?

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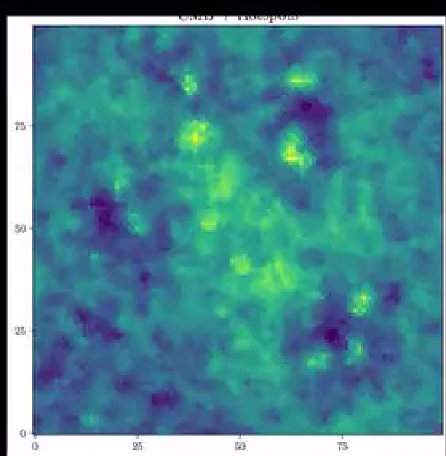
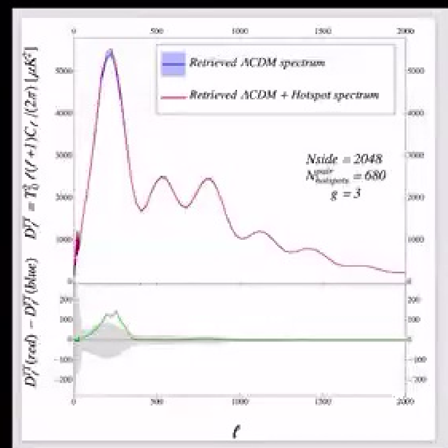
If yes, the searching strategy will be totally different





Looking for pairwise hotspots in position space

ℓ-dependent distortion of CMB TT-spectrum, N-point function analysis

Done

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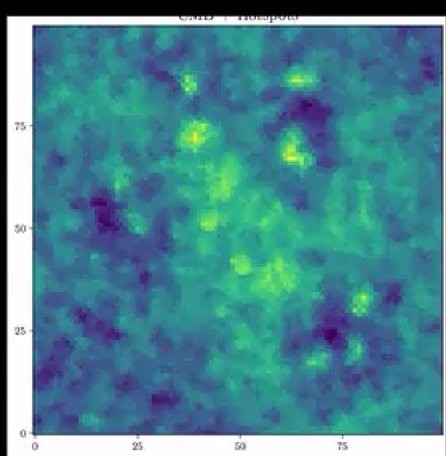

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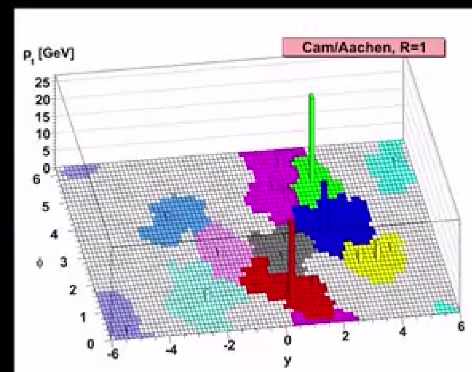

We were also motivated by Maldacena's work

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.

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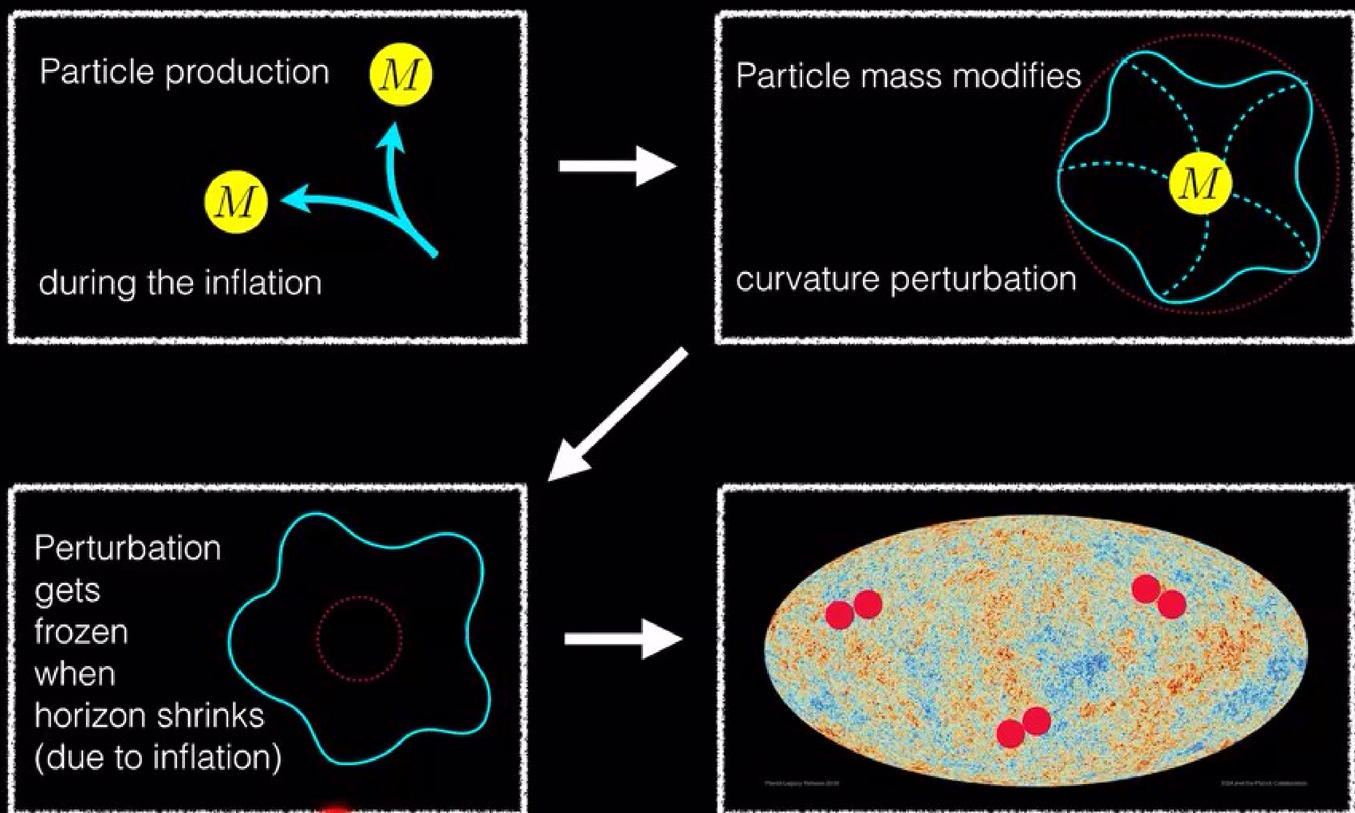
Production of the pairwise spots on the CMB



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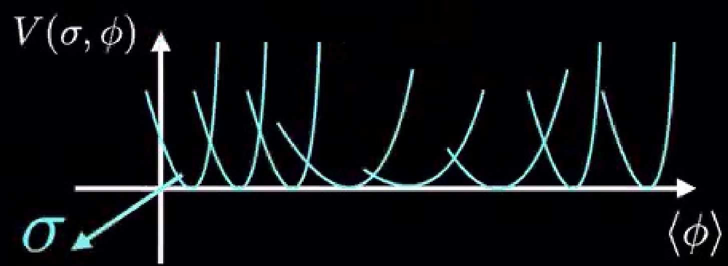
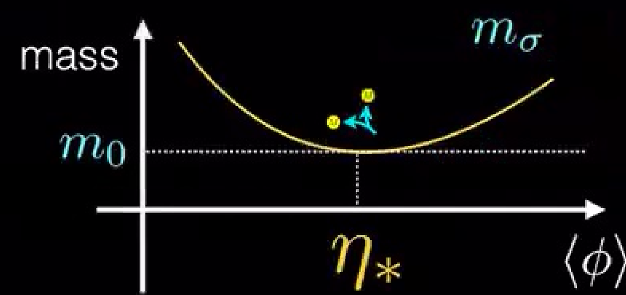
Consider a scalar particle σ that carries a mass depending on the inflaton-VEV





- Sigma mass is typically heavy (comparing to Hubble scale)
- mass takes its minimum value at time η_*

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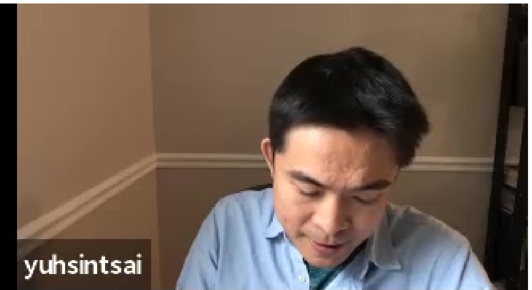

A toy model example

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

Minimum mass when $g\phi \sim M$

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

(also see a similar setup in Flauger et al. (2017),
and Muchmeyer et al. (2019) for the N-point function study)

Done

e.o.m. during the inflation

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

$$u = \sigma/\eta$$

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

simple harmonic oscillator
with time-dependent frequency

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

Done

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How to calculate the particle production?

- cannot calculate the production as in collider experiments.
  inflaton & sigma are time-dependent fields & the vacuum changes

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

Done

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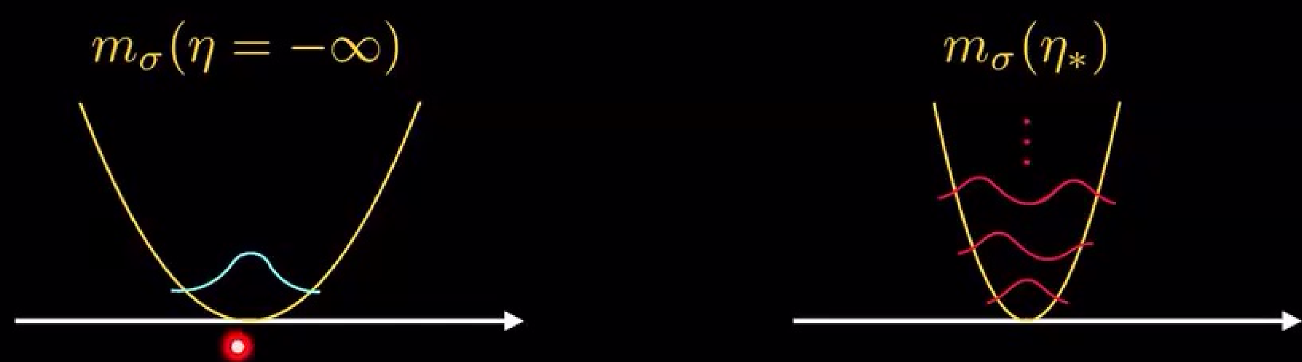
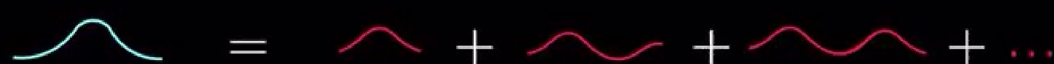
Particle production from time-variant vacuum





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

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

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

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Bogolyubov Transformation

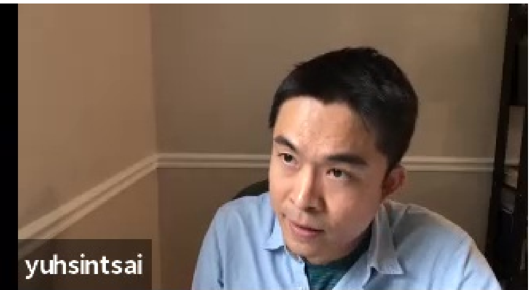
Relation between the raising/lowering operators defined in the initial and final vacua

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

Number density of particles in the "final vacua" (in Heisenberg's picture)

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

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



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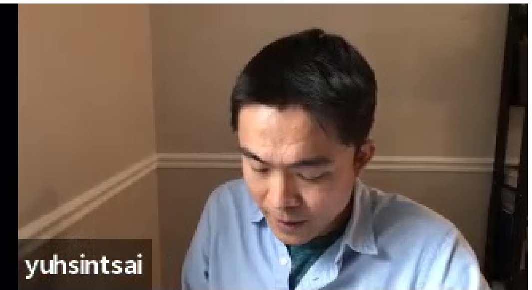
More details on the σ production



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

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

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

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

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

$$\tau \to -\infty$$

Done

More details on the 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 $\qquad$ α $\quad |\alpha|^2 - |\beta|^2 = 1$

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

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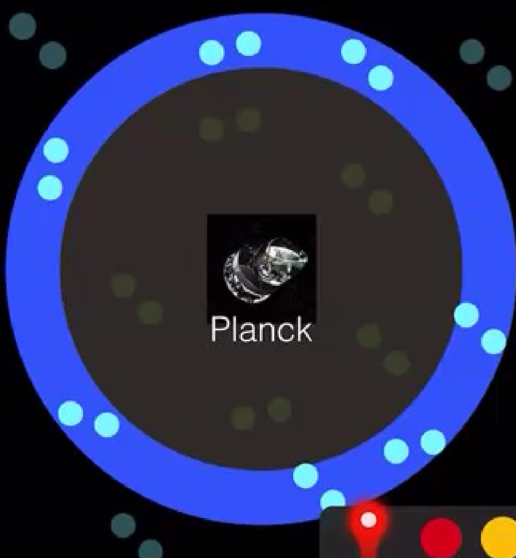
Number of σ pairs in the CMB last scattering surface (with a thickness)

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

looks like a thermal production suppressed by the Sigma mass



$\sqrt{\dot{\phi}} \approx 60H_*$ from CMB measurement, ~ kinetic energy of inflaton

CMB horizon with finite thickness

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

Done

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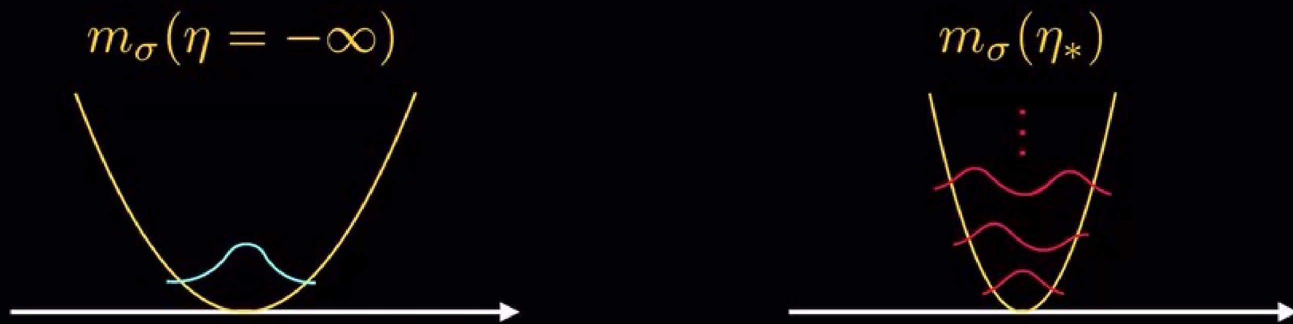
Particle production from time-variant vacuum



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

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

Done

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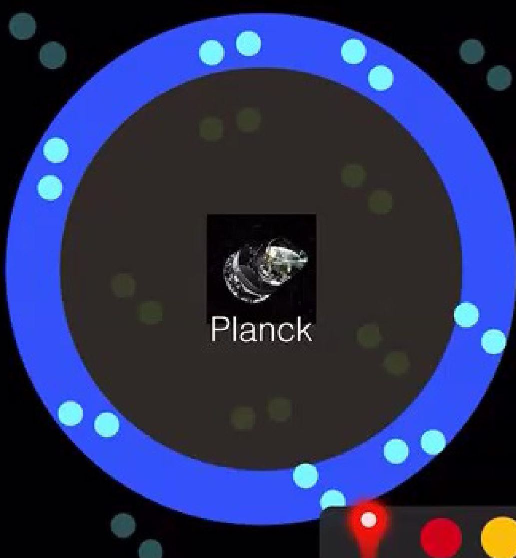

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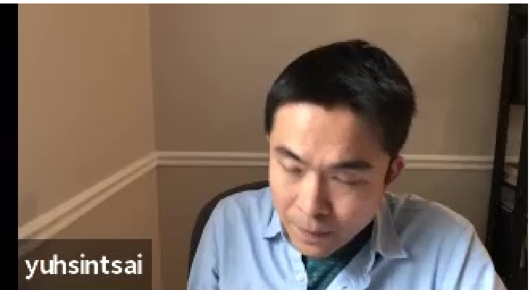

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As a reminder, $M_{\text{eff}}^2 \approx M_0^2 + g^2\phi'^2(\eta-\eta_*)^2$

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

and the spot size $\eta_* = 100/\text{Mpc}$

(similar to chopping the sky into $10^3 \times 10^3$ pieces)

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

Done

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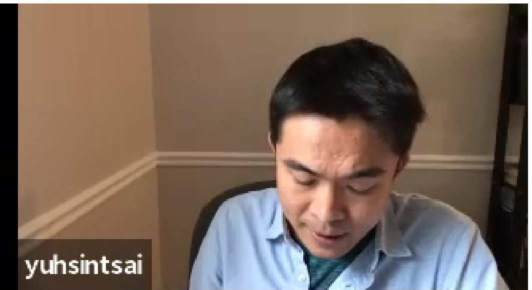
Back-reaction constraints



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

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

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

Done

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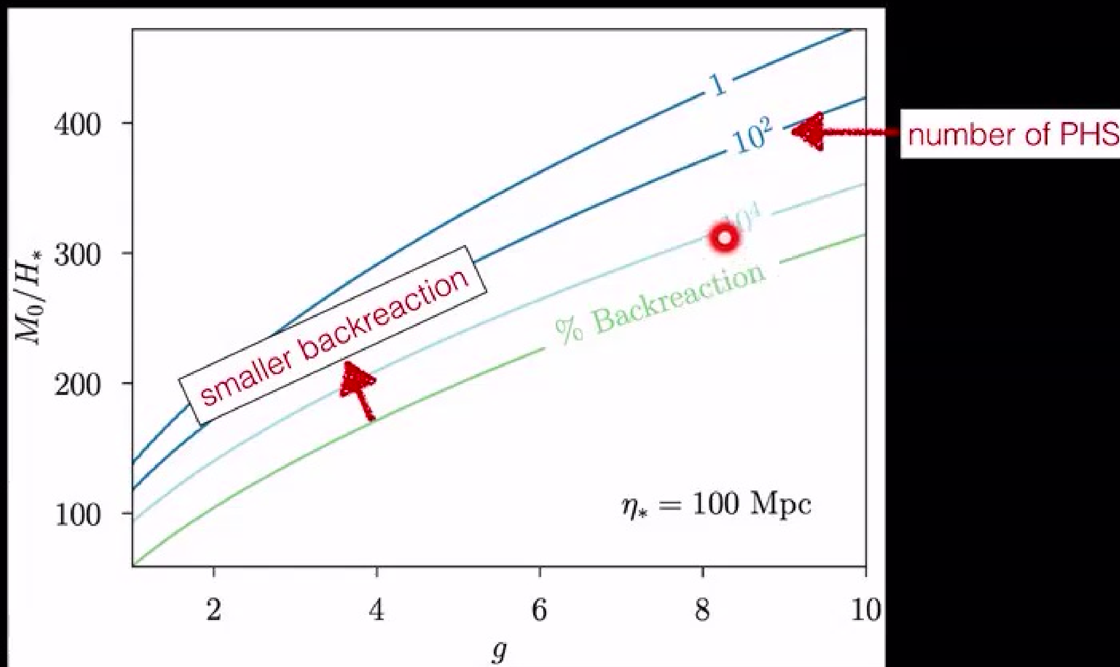
Back-reaction constraints



similar bound from not draining too much inflation energy $\dot{\phi}^2$

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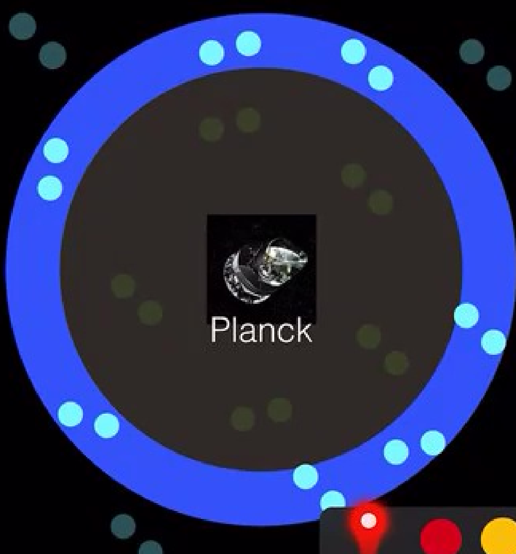

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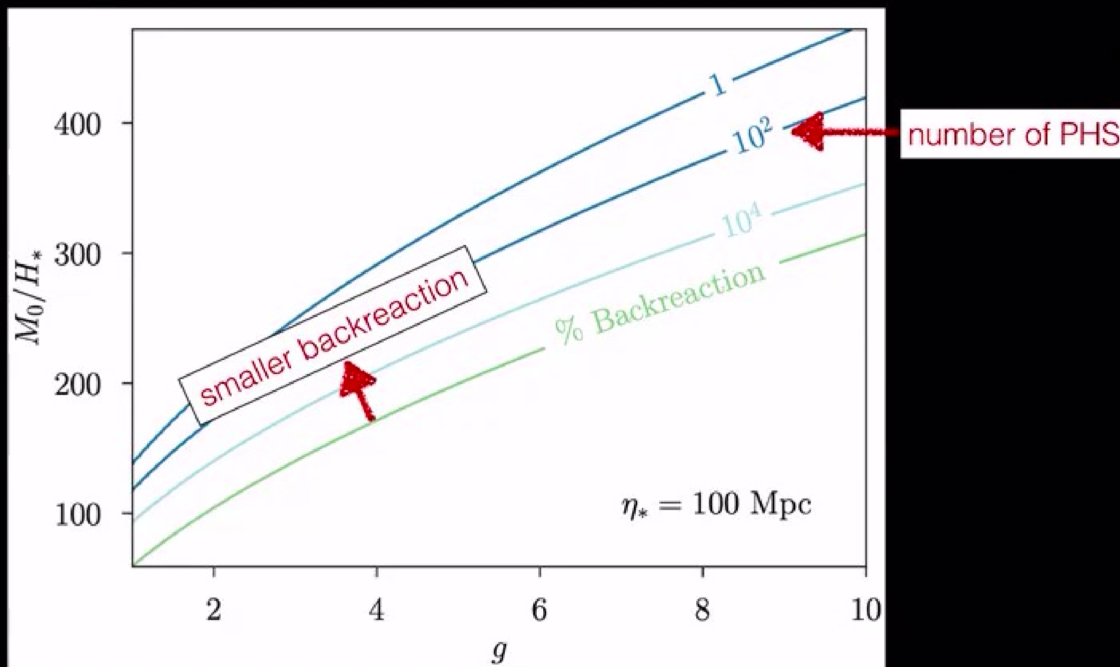

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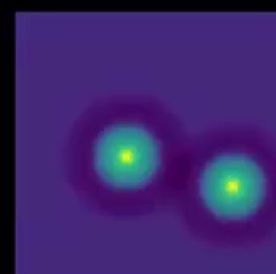
this requires $g(g\phi - M)\sigma^2 \sim gM_\sigma \sigma^2 \sim g\, n_\sigma \ll H_*\dot{\phi}$

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

Why pairs? Separation?

- Particles are produced at least in pairs due momentum conservation
- Particles tend to be produced with low momentum. Separation given by k^{-1} is comparable to the horizon size
- The produced particles carry momentum ~< $(g\dot{\phi})^{1/2}$ and is much smaller than the mass => separation is determined by the production location
- We will model the separation as a random uniform distribution between 0 and $|\eta_*|$



Done

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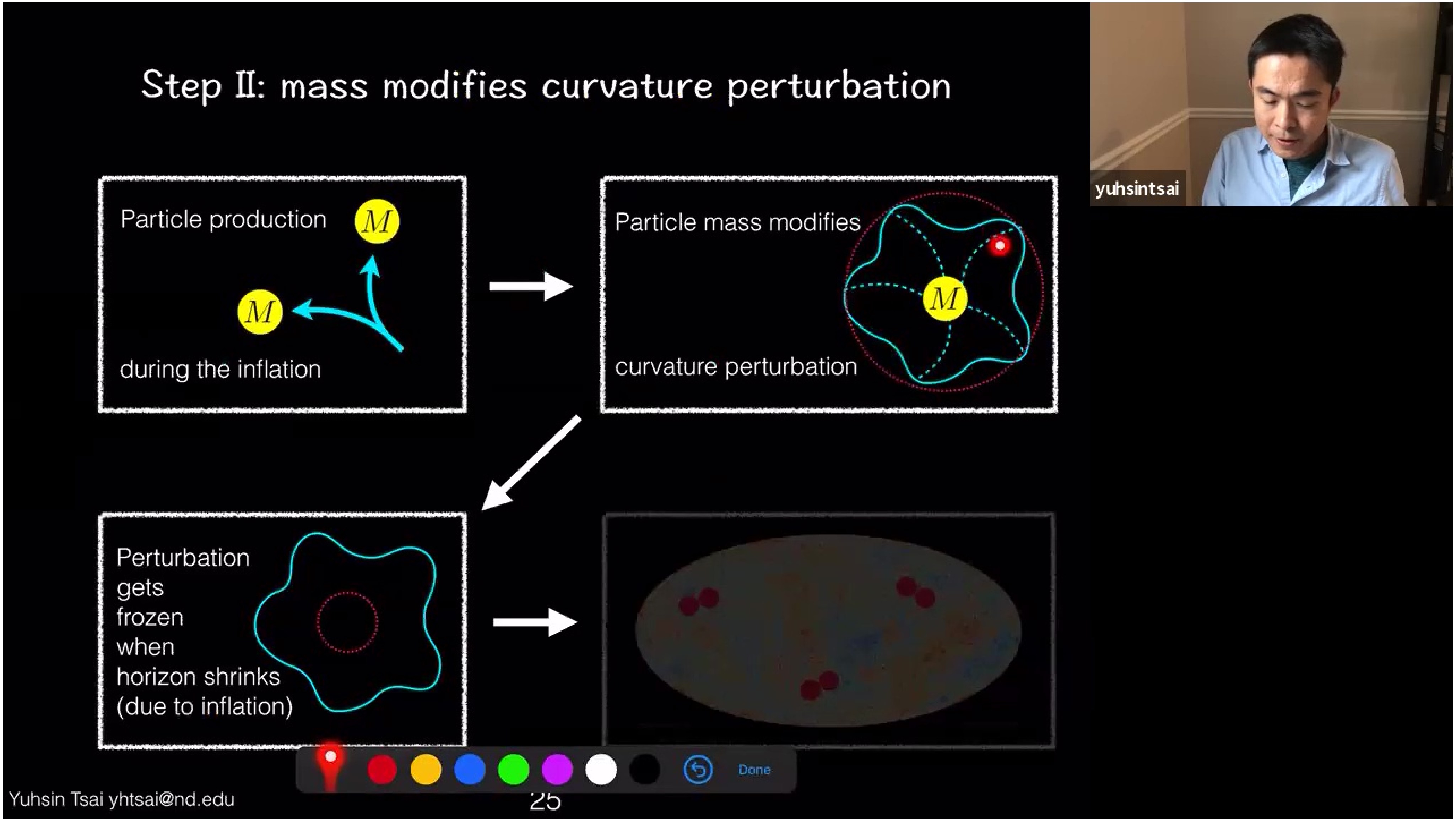
Step II: mass modifies curvature perturbation
Particle production
M
M
during the inflation
Particle mass modifies
M
curvature perturbation
Perturbation
gets
frozen
when
horizon shrinks
(due to inflation)
Done
yuhsintsai
Yuhsin Tsai yhtsai@nd.edu
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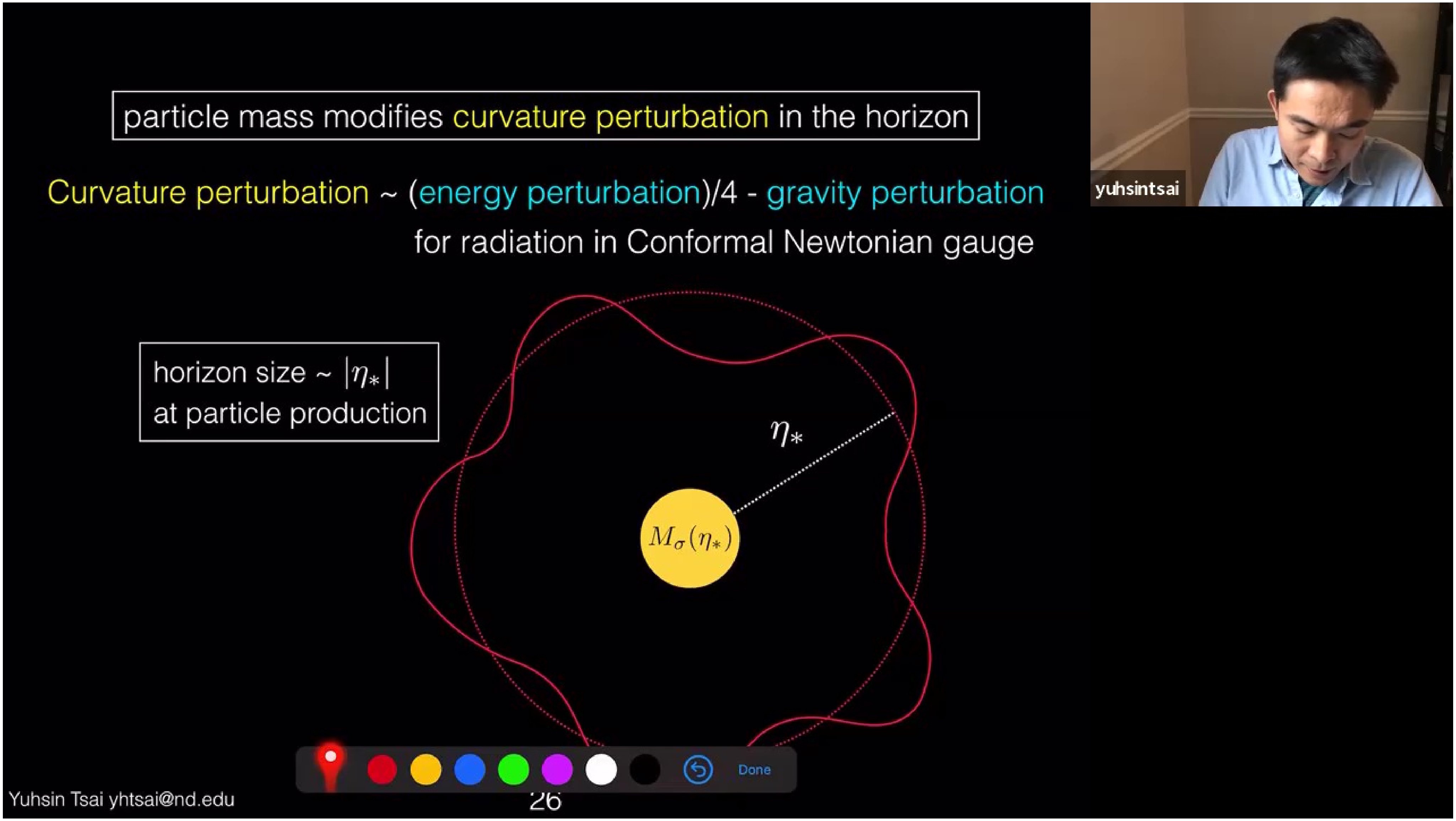
particle mass modifies curvature perturbation in the horizon
Curvature perturbation ~ (energy perturbation)/4 - gravity perturbation
for radiation in Conformal Newtonian gauge
horizon size ~ $|\eta_*|$
at particle production
η_*
$M_\sigma(\eta_*)$
yuhsintsai
Done
Yuhsin Tsai yhtsai@nd.edu
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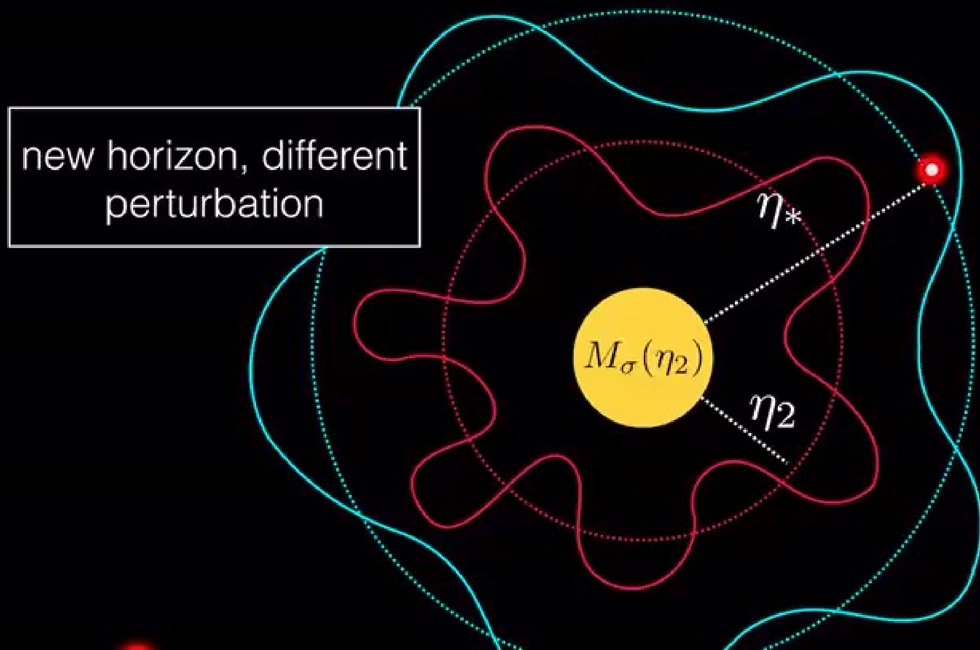
Once perturbation in the old horizon is frozen, **NEW** particle mass Modifies the perturbation in the **NEW** horizon



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Curvature perturbation in position space

Maldacena (1508.01082)

Fialkov et. al. (0911.2100)

Produced heavy particles backreact on spacetime

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

comoving curvature perturbation

Give rise to a non-trivial one-point function

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

given by the inflaton fluctuation

Done

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given by the inflaton fluctuation

Profile in the position space

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

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Curvature perturbation in position space

The resulting curvature profile in $r \leq |\eta_*|$ from the spot center,

Adiabatic fluctuation $\langle \zeta_{ad} \rangle = \sqrt{A_s} \sim 10^{-5}$

$$\langle \zeta_\sigma \rangle = \left[\frac{g}{2} \log \left(\frac{|\eta_*|}{r} \right) \right] \frac{H}{2\pi \sqrt{2\epsilon} M_{pl}} \sim \left[\frac{g}{2} \log \left(\frac{|\eta_*|}{r} \right) \right] \langle \zeta_{ad} \rangle$$

Spot size $\sim |\eta_*|$ and the coupling g controls the spot temperature over CMB fluctuations

Done

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Curvature perturbation in position space

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Adiabatic fluctuation $\langle \zeta_{ad} \rangle = \sqrt{A_s} \sim 10^{-5}$

$$\langle \zeta_\sigma \rangle = \left[\frac{g}{2} \log\left(\frac{|\eta_*|}{r} \right) \right] \frac{H}{2\pi\sqrt{2\epsilon}M_{pl}} \sim \left[\frac{g}{2} \log\left(\frac{|\eta_*|}{r} \right) \right] \langle \zeta_{ad} \rangle$$

Spot size $\sim |\eta_*|$ and the coupling g controls the spot temperature over CMB fluctuations

from the exponential growth during inflation

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

$$e^{H_*(t-t_*)} = a/a_* \approx \eta_*/\eta$$

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Hot or Cold spots?

Perturbation enters in the radiation-dominant & matter-dominant era has temperature fluctuation

$$\frac{\delta T}{T}\Big|_{\mathrm{CMB,\,RD}} = -\frac{1}{3}\langle \zeta_\sigma \rangle \qquad \frac{\delta T}{T}\Big|_{\mathrm{CMB,\,MD}} = -\frac{1}{5}\langle \zeta_\sigma \rangle$$

The minus sign comes from the gravity potential (Sachs-Wolfe), makes pairwise spots **COLD** before entering the horizon

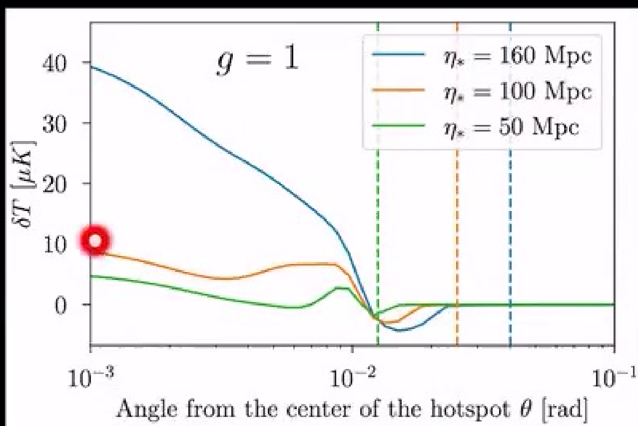
However, we find that the baryon acoustic oscillation (sub-horizon phys) converts the signal into **HOT** spots and further changes the fluctuation

$$\theta(\vec{x}_0, \hat{n}, \eta_0) = \frac{4\pi}{(2\pi)^3}\int_0^\infty \frac{dk}{k}\sum_l j_l(k\eta_0 - k\eta_{\rm rec})(2l+1)\mathcal{P}_l(\hat{n}\cdot\hat{n}_{\rm HS})\left(f_{\rm SW}(k) + f_{\rm ISW}(k)\right) f(k\eta_*).$$

$$f_{\rm SW}(k) = T_{\rm SW}(k) j_l(k\eta_0 - k\eta_{\rm rec})$$

Include the effect of "sub-horizon" physics

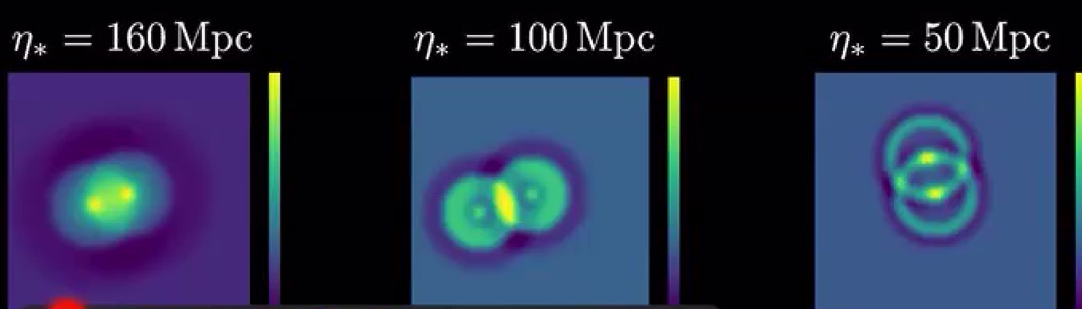
from baryon acoustic oscillations (the transfer functions)

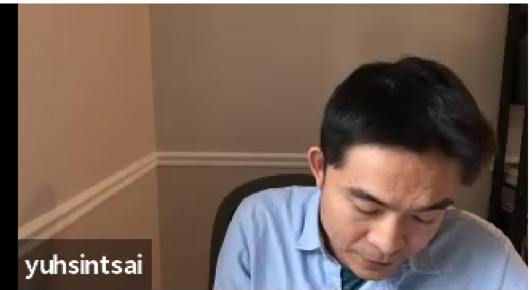


η_*

the conformal time & horizon size of particle production

Temperature profile





Done

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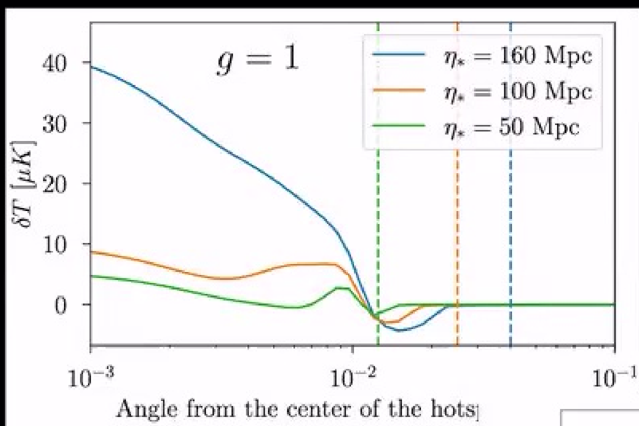
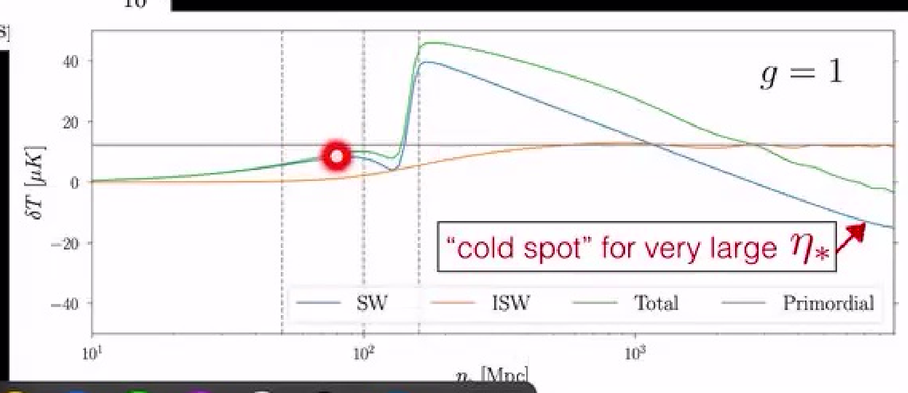
Include the effect of "sub-horizon" physics

from baryon acoustic oscillations (the transfer functions)



temperature of central hotspot pixel



see also Fialkov et al. (2009) for using the very large spots (different origin) to generate the CMB cold spot

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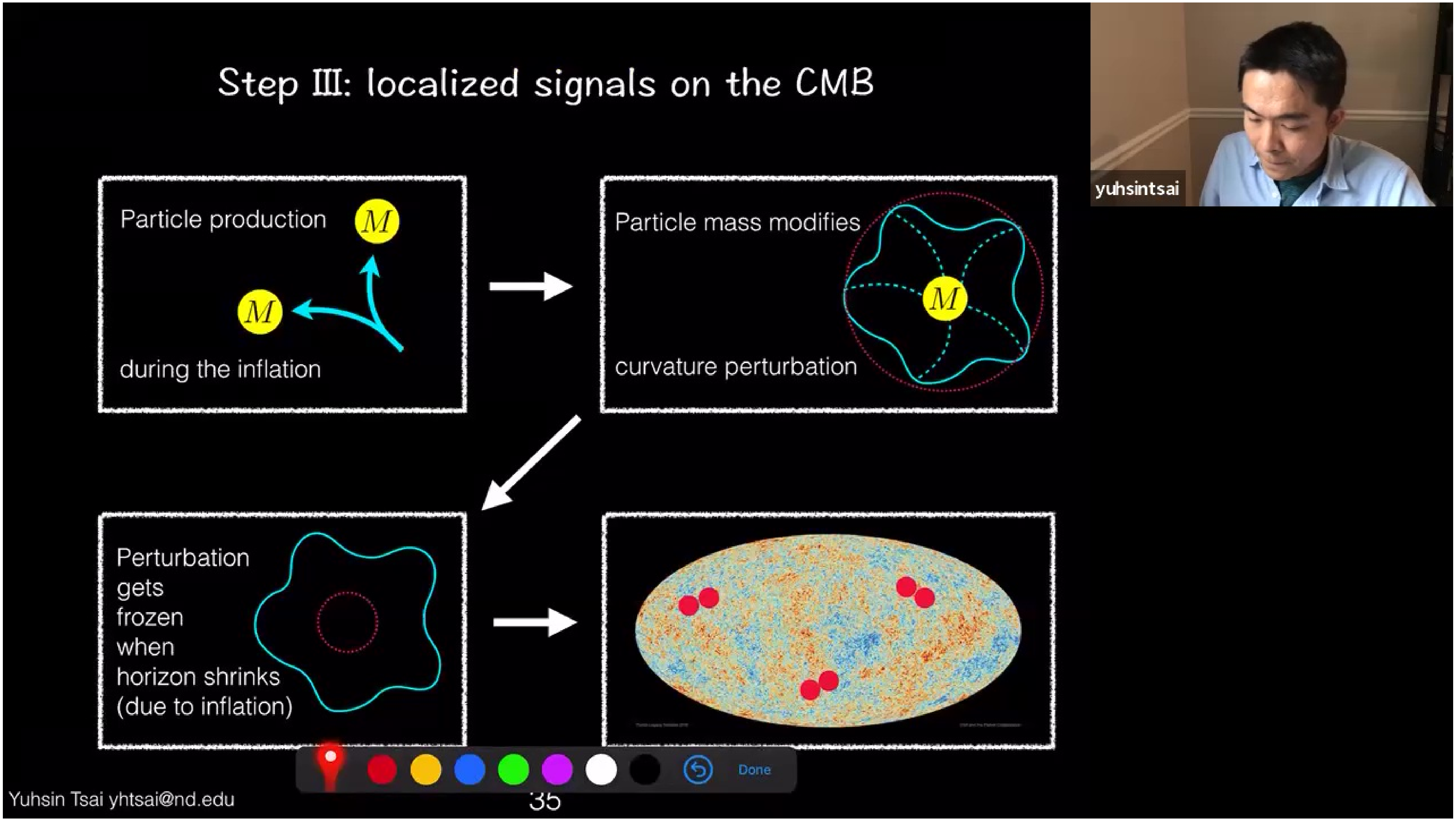
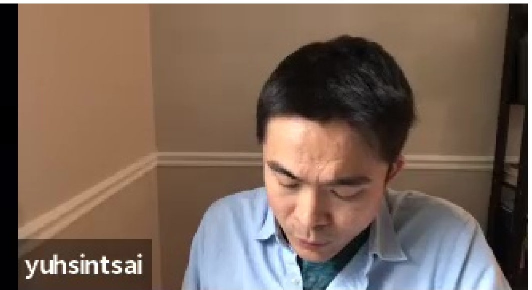
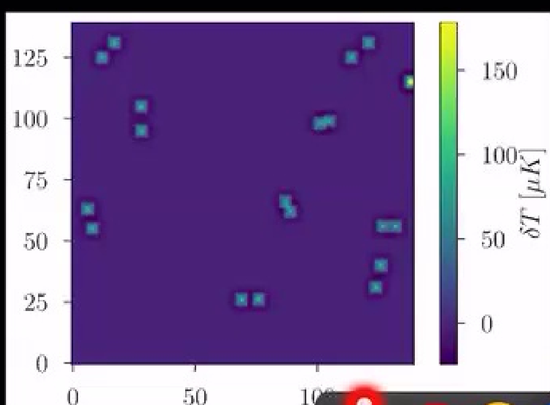

Step III: localized signals on the CMB
Particle production
during the inflation
M
M
Particle mass modifies
curvature perturbation
M
Perturbation
gets
frozen
when
horizon shrinks
(due to inflation)
Done
Yuhsin Tsai yhtsai@nd.edu
35
yuhsintsai

Simulate pairwise spot signals

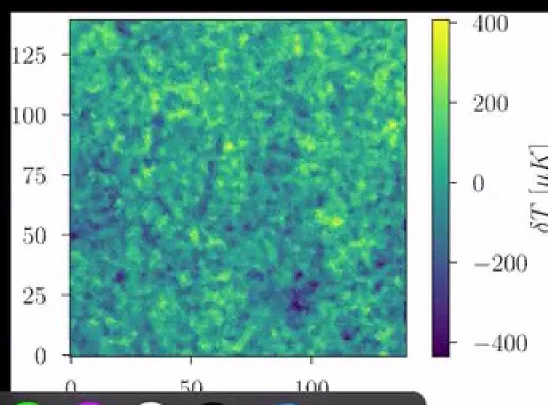


- use HEALPix to generate fake CMB images that follow the temperature fluctuation of the best fitted LCDM model
- for signal events, add pairwise hotspots with a given temperature profile, pixel size, and separation between two spots

signal



fake CMB background



$g = 3$

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Simulate pairwise spot signals

- use HEALPix to generate fake CMB images that follow the temperature fluctuation of the best fitted LCDM model
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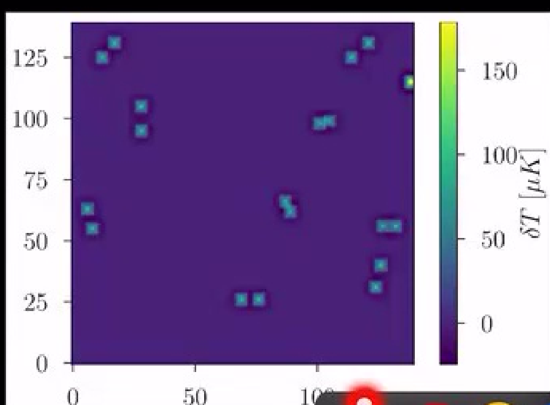
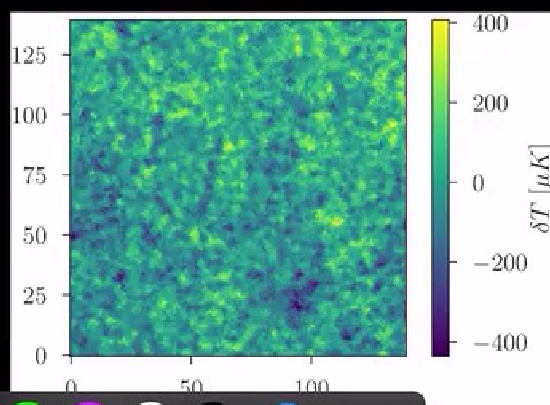
signal



Signal + background



$g = 3$

hard to see by eye

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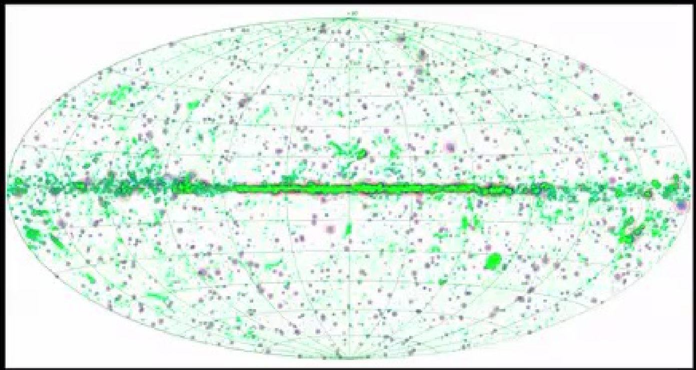
Identify signal on the CMB map

Different types of backgrounds to consider:

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



“may” veto the background by correlating Planck’s maps with 9 frequency bands

galaxies usually have non-spherical image, which is different from the PHS signal

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.

Done

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- instrumental noise
- fore-ground from compact objects (stars, galaxies,…)
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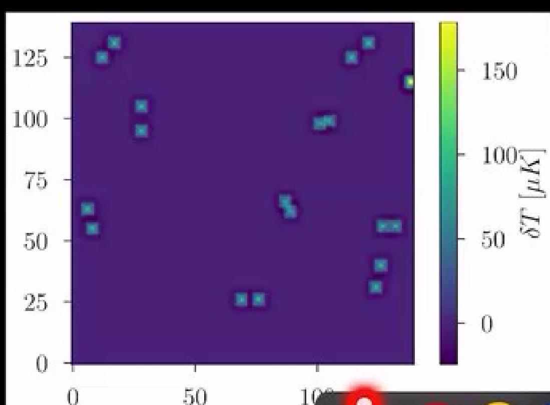
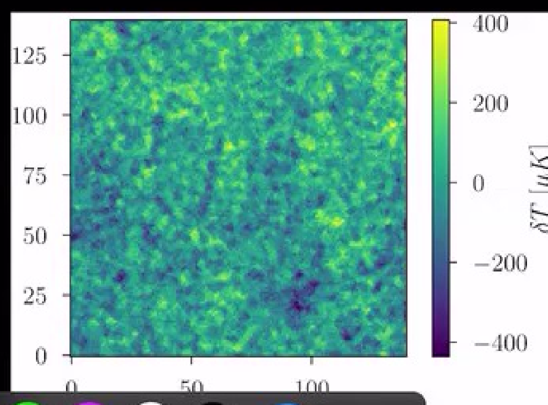
signal



Signal + background



$g = 3$

hard to see by eye

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Let's only consider background
from primordial temperature fluctuations

Assume perfect CMB measurements :
zero noise & perfect foreground subtraction
with sky fraction = 60% (similar to the Planck analysis)

Power spectrum and N-point function are also important!
(Will comment on this later)

Done

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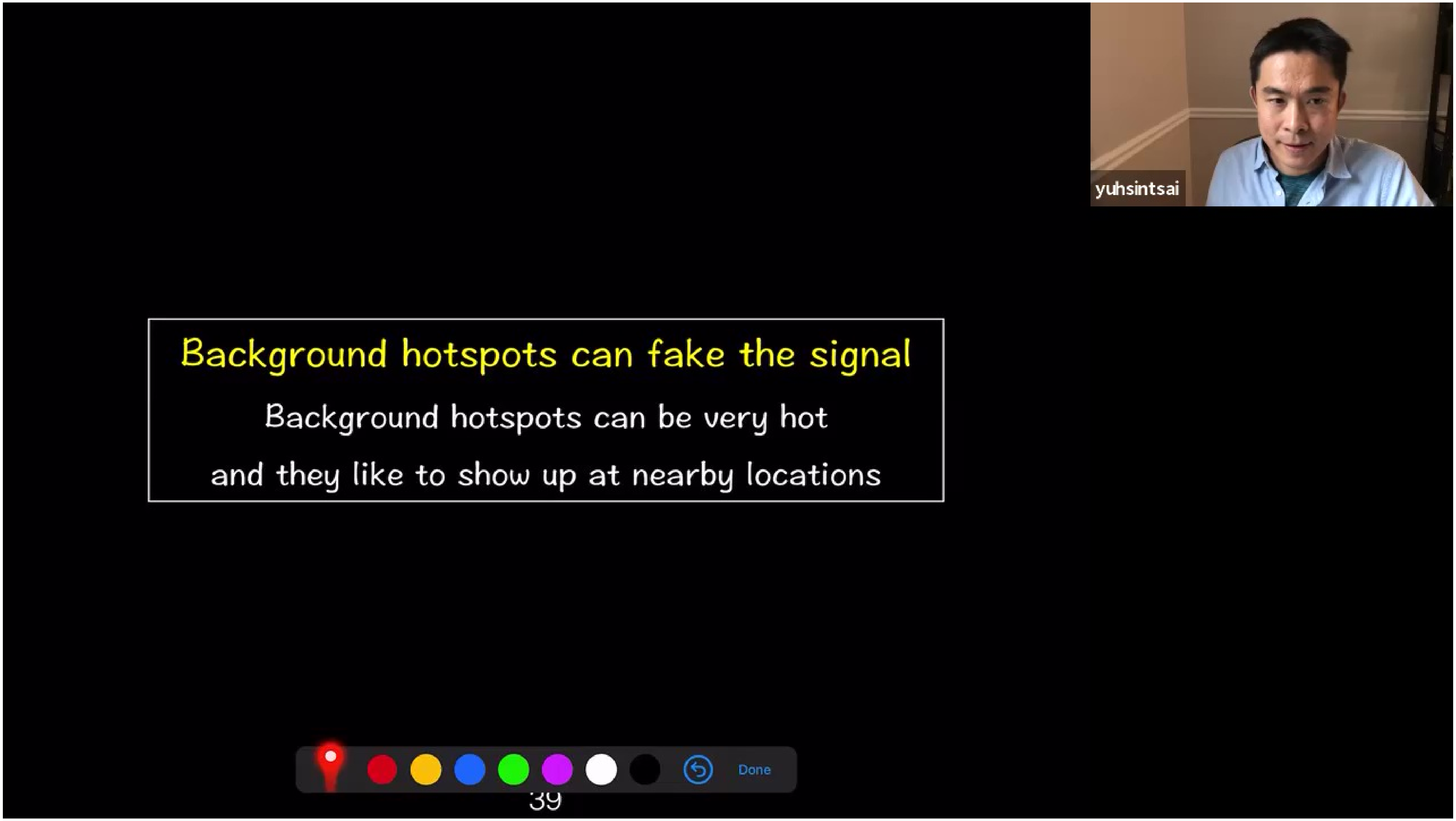
yuhsintsai
Background hotspots can fake the signal
Background hotspots can be very hot
and they like to show up at nearby locations
Done
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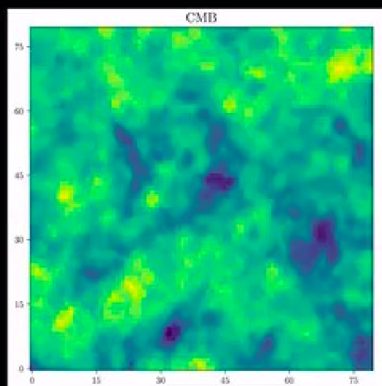
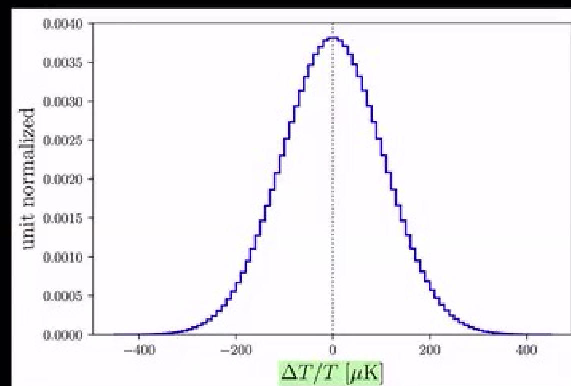
Primordial T-fluctuation can be very hot (or cold)

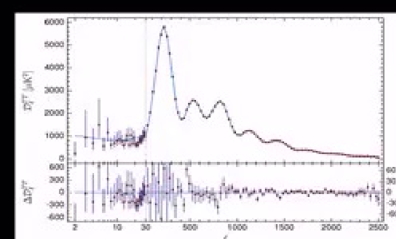
Our signal $\delta T_{\rm sig} \approx \frac{g}{2} 27\,\mu K$





Standard deviation of CMB fluctuation $\approx 100\,\mu\mathrm{K}$

This is 4x larger than the primordial $\delta T \approx 27\mu\mathrm{K}$ of each l-mode in the CMB spectrum

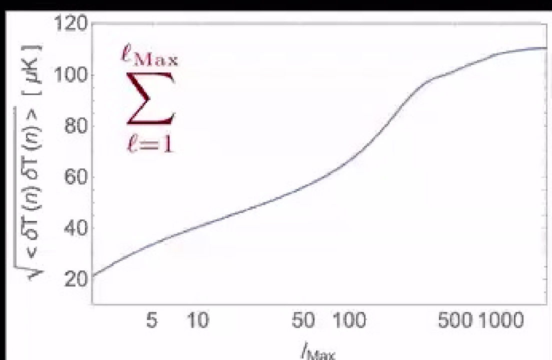


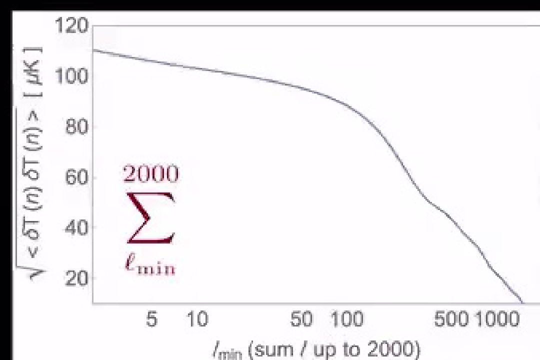
Done

Primordial T-fluctuation can be very hot (or cold)

The large temperature fluctuation in position space comes from the sum of fluctuations with different wavelengths

$$\delta T^2\Big|_{\rm CMB} = \langle \delta T(\hat\theta)\delta T(\hat\theta)\rangle = \sum_\ell \frac{2\ell+1}{4\pi} C_\ell^{TT}$$





Done

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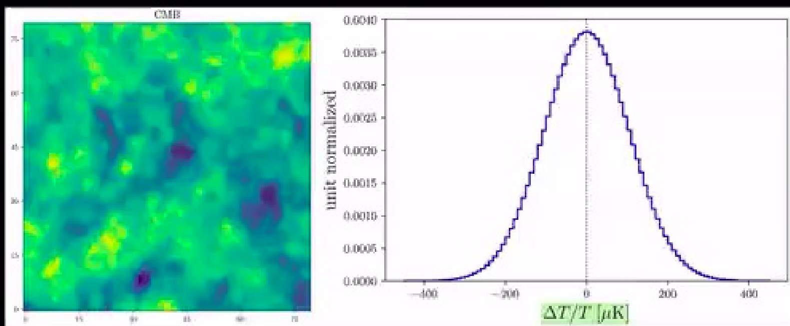
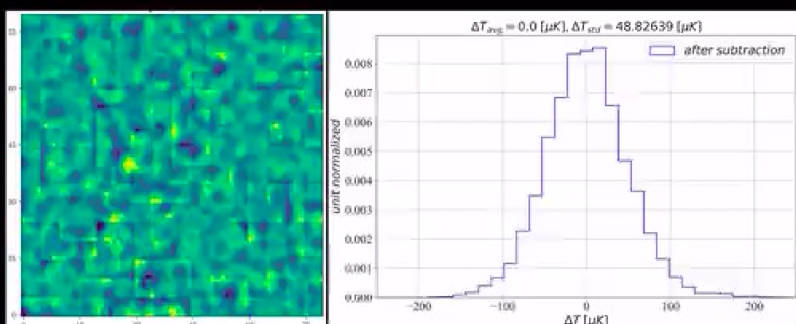
Subtract background from lower l-modes



Standard deviation $\approx 100\,\mu\mathrm{K}$

subtract avg T from each patch with area ~ l=500 mode



Standard deviation $\approx 50\,\mu\mathrm{K}$

The subtraction plus additional δT cut does veto most of the fake signals

Done

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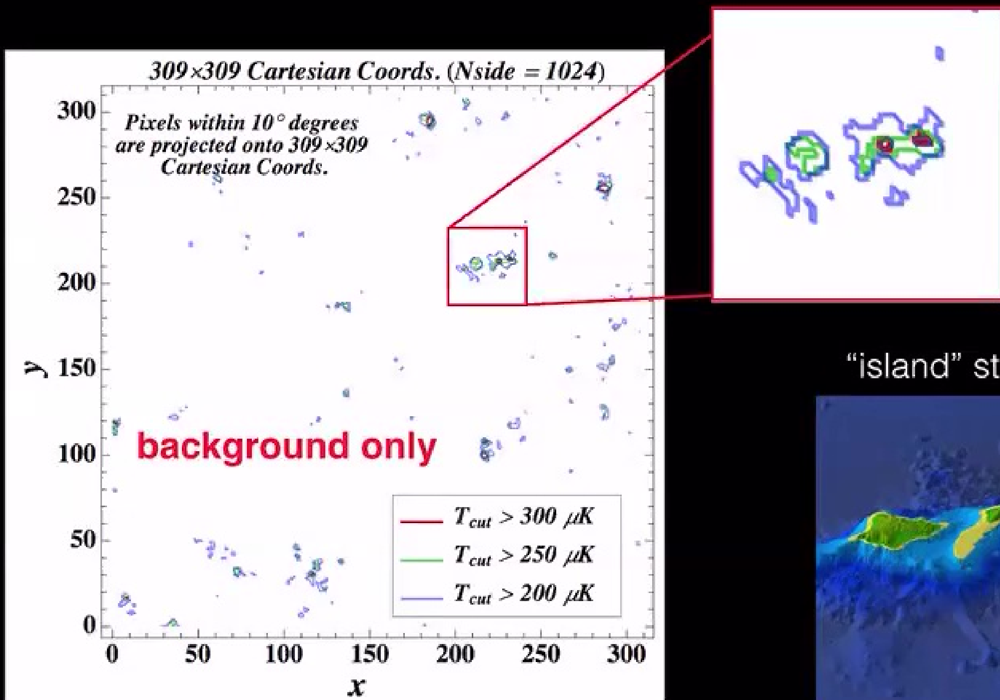
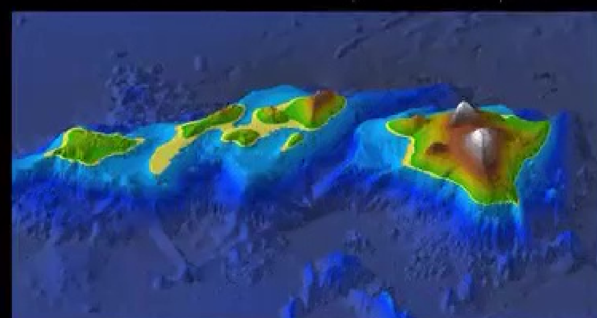
The very hot (or very cold) CMB spots

like to show up close to each other in position space



"island" structure in position space



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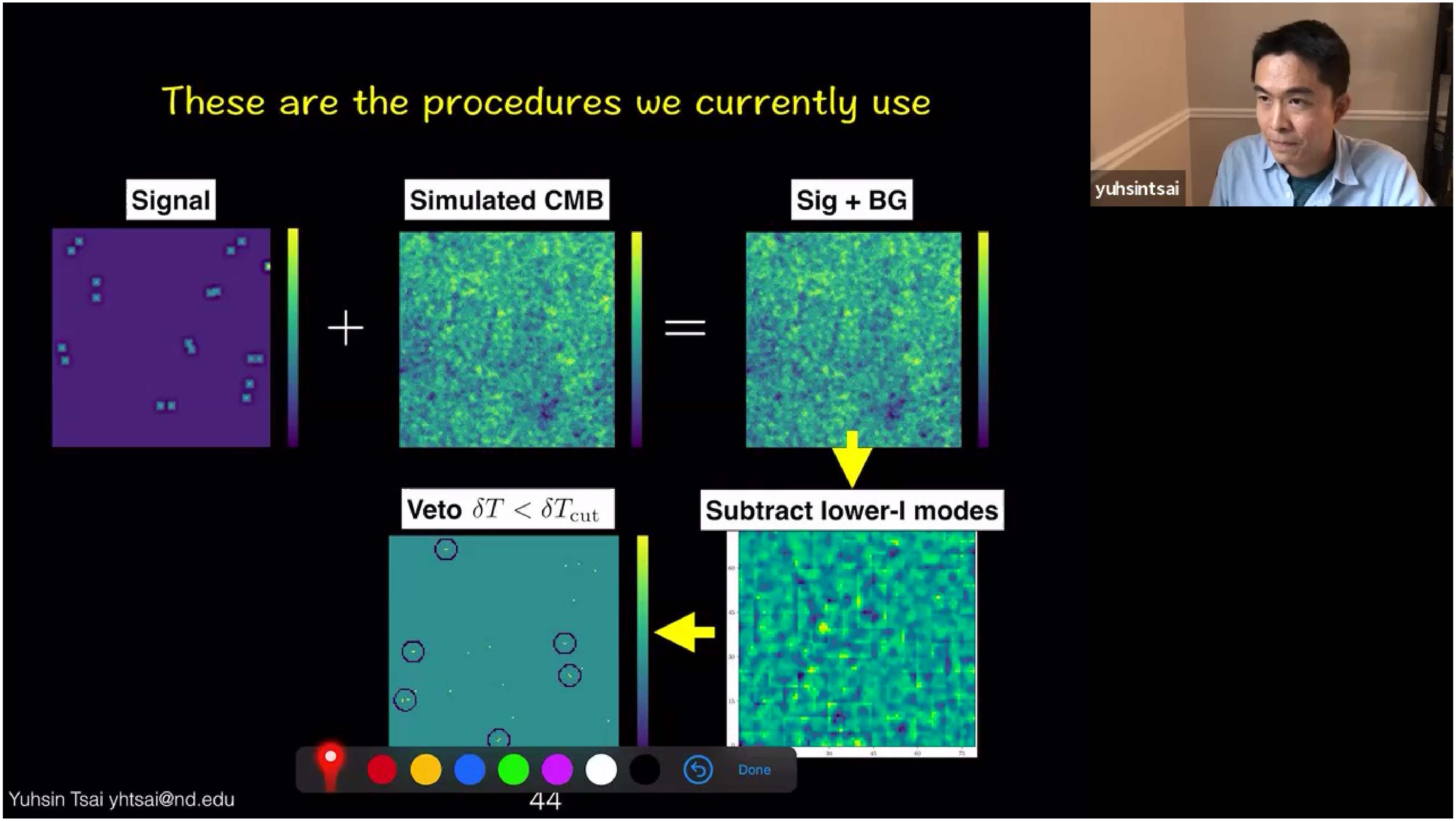
These are the procedures we currently use
Signal
Simulated CMB
Sig + BG
Subtract lower-l modes
Veto $\delta T < \delta T_{\rm cut}$
Done
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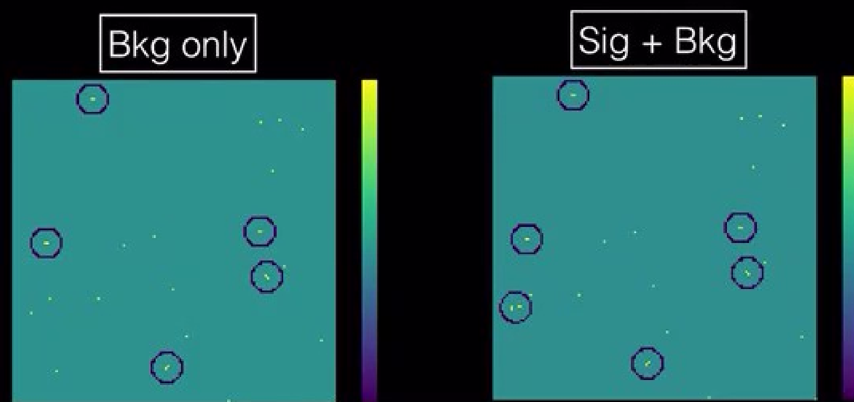
44
yuhsintsai

Number of pairwise hotspots for 2 sigma excess

Compare number of identified signals with and without signals
(using 1000 images)

Image after applying all the cuts



Can solve the number of signals for a 2 sigma excess

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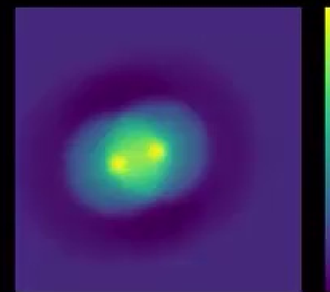
Bounds on the heavy particle mass

For example, the signal with $\eta_* = 160\,\mathrm{Mpc}$

(~1/10^4 of the sky) and g = 3 has 2 sigma excess

if the number > 270



Using

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

this simplified search sets a lower bound $M_0 > 192\,H_* \approx 2\sqrt{g\dot{\phi}}$

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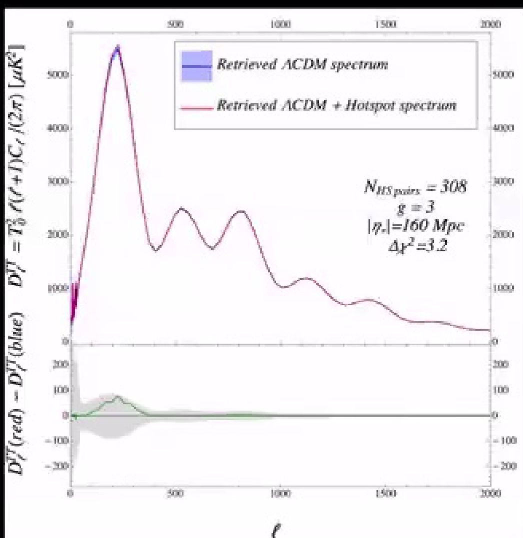
The corresponding C_ℓ^{TT} distortion

$\eta_* = 160\mu\mathrm{K},\ g = 3,\ N_{\mathrm{sig}} = 308\,(1\sigma\ \mathrm{cut\&count})$



The deviation from 1σ cut & count excess gives

$$\Delta\chi^2 = 3.2$$

The difference of chi2 between best-fit vs mean LCDM parameters for *TTTEEE+lowl+lowE+lensing* = 6

TTTEEE+lowl+lowE = 26

Since the best-fit parameters are all within 1σ variation of the mean values, deviations from the hotspots should be within the current sensitivity (in this example)

Need an MCMC study for this. A "bump hunt" in power spectrum can probe the signals

Done

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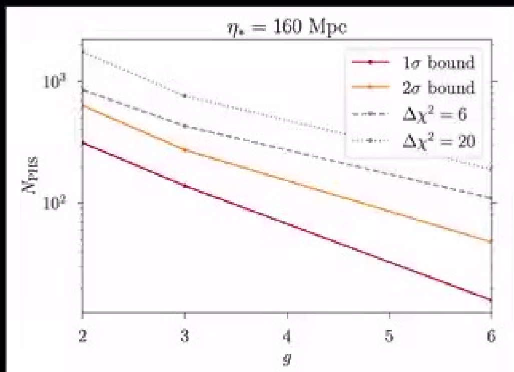
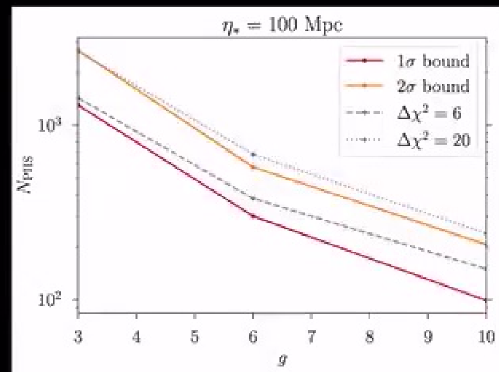
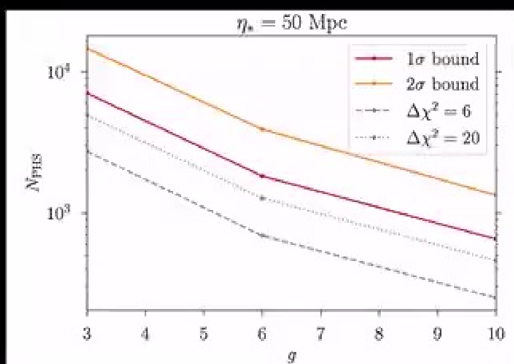
Lower bounds on the number of PHS in the entire sky







This naive cut-and-count search sets a stronger lower bound on the PHS number than using CITT, unless the spot size $\eta_* \ll 100/\mathrm{Mpc}$ and the signals get smeared out

Done

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N-point function analysis

Proposed in Flauger et al. (2017) for similar models but with repeated particle production at different comoving time

A study using actual data

Higher N-point function data analysis techniques for heavy particle production and WMAP results

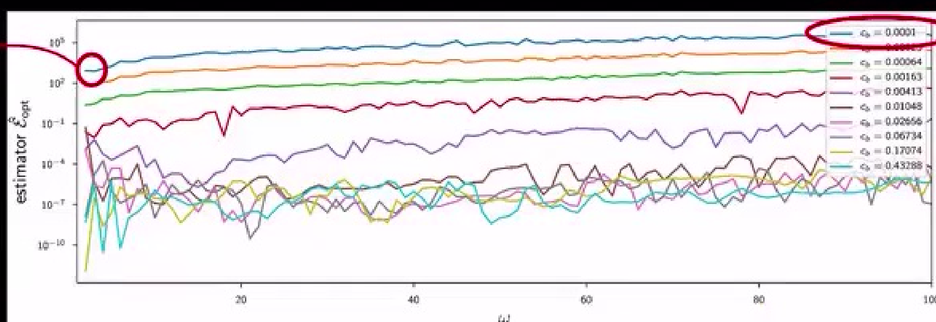
Moritz Münchmeyer[1] and Kendrick M. Smith[1]
[1]*Perimeter Institute for Theoretical Physics, Waterloo, ON N2L 2Y5, Canada*

Bound on the number density of produced particles

similar to the curvature we consider g=O(1)

corresponds to $\frac{n_{\rm HS}}{H_*^3} = \mathcal{O}(1)$

the cut-and-count example we use $\frac{n_{\rm HS}}{H_*^3} = \mathcal{O}(0.1)$



The sensitivity of position space search may be better than the N-p

Done

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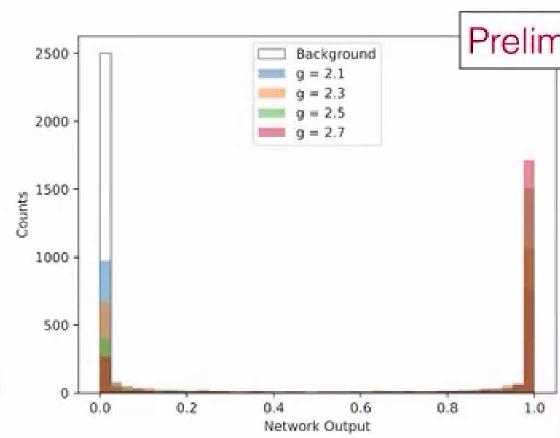
Profile fitting: Neural network analysis

The CNN study may greatly improve the signal identification

Training the CNN using 100k images of simulated CMB vs. CMB+PHS (g=6)
then apply the machine to CMB+PHS with smaller g values

with Tae Kim
(Notre Dame)

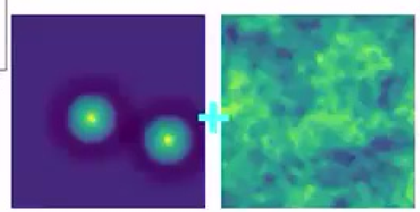


g = 2.1, signal capture = 45 %

g = 2.3, signal capture = 58 %

g = 2.5, signal capture = 72 %

g = 2.7, signal capture = 80 %



- Eta = 160, g = vary
- 2500 sample for each g value

Almost a background free search
with sizable signal capture rate

N_PHS ~ few for 95% CL bound (?)

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Conclusion

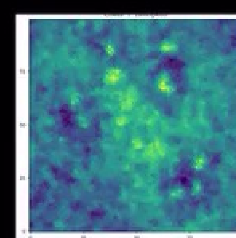
Production of heavy particles with inflaton-dependent mass generate pairwise spots on the CMB map

Can use both “position space” and “N-point function” studies to dig out the signal

More things to explore:

- other localized signals for the position space search?
- improving search by deep learning technique?
- pairwise clumps in Large Scale Structure? CMB lensing, cosmic shear, etc?

Thank you!



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