Cosmological Particle Production & Pairwise Spots on the CMB

Yuhsin Tsai

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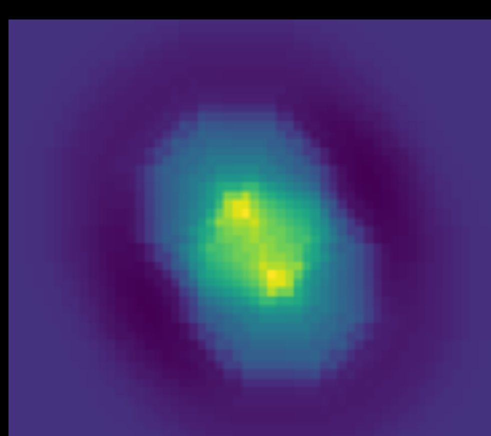

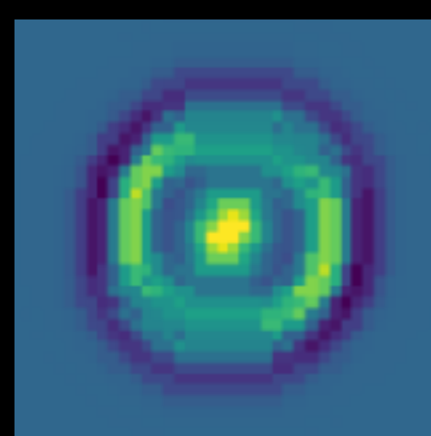

Cosmology from Home 2023

Based on 2107.09061 (JHEP 11 (2021) 158) with

Jeong Han Kim
(Chungbuk National University)

Soubhik Kumar
(LBNL)

Adam Martin
(Notre Dame)

And 2303.08869
with better signal calculation
+ neutral Network analysis

+

Taegyun Kim
(Notre Dame)

Moritz Munchmeyer
(UW Madison)

Our goal: probing extremely heavy particles

using inflationary dynamics + CMB signals

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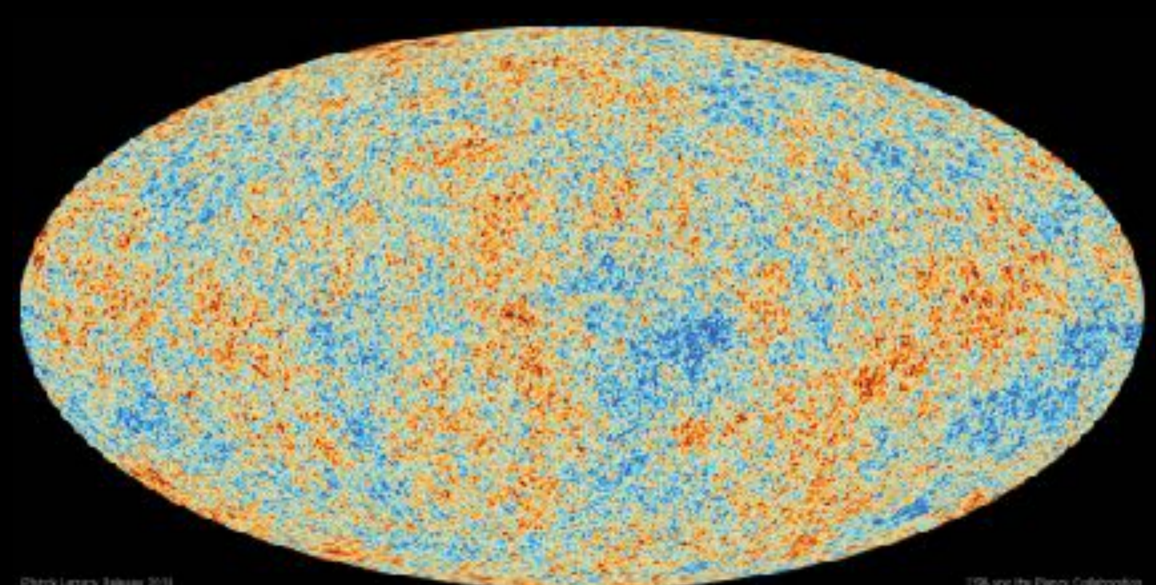
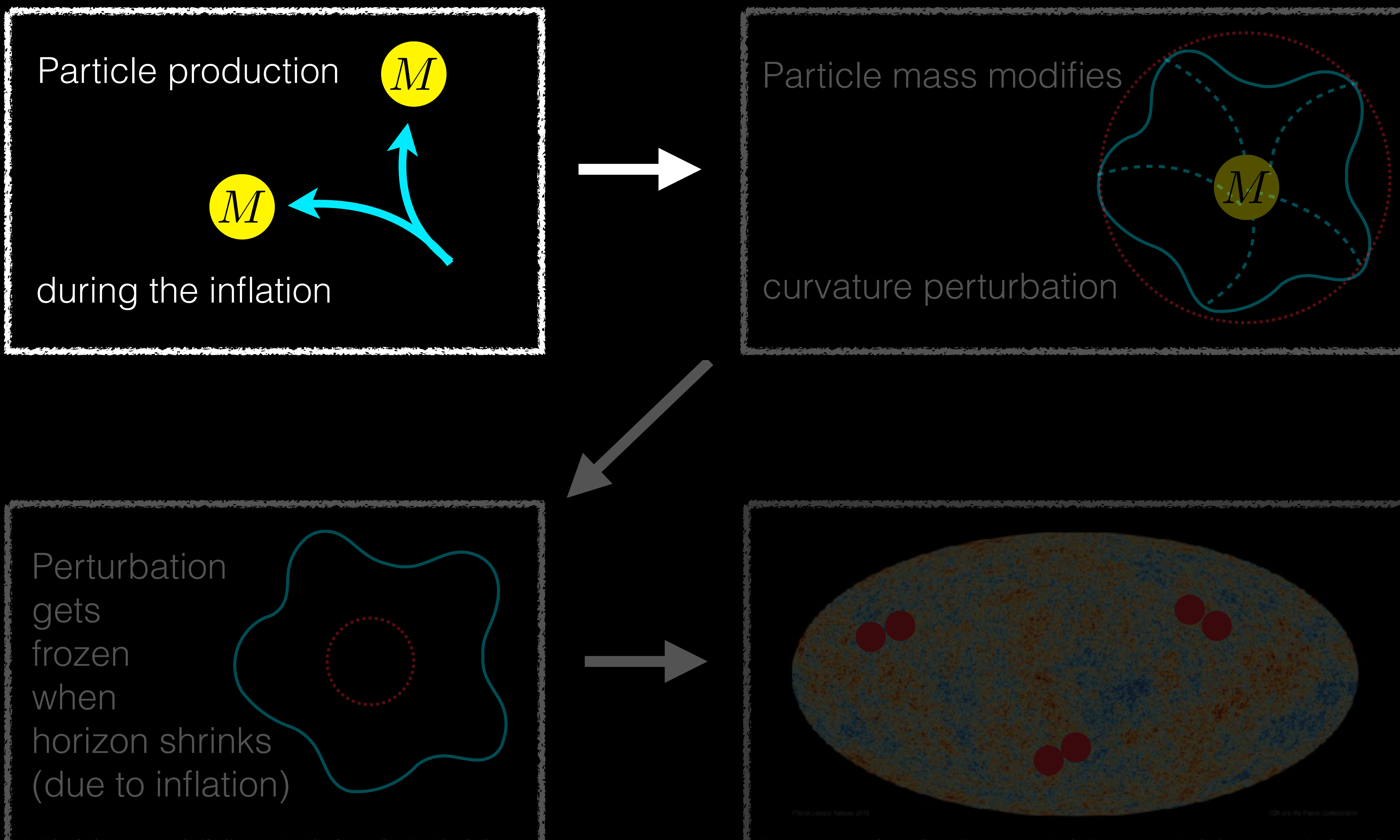
using inflationary dynamics + CMB signals

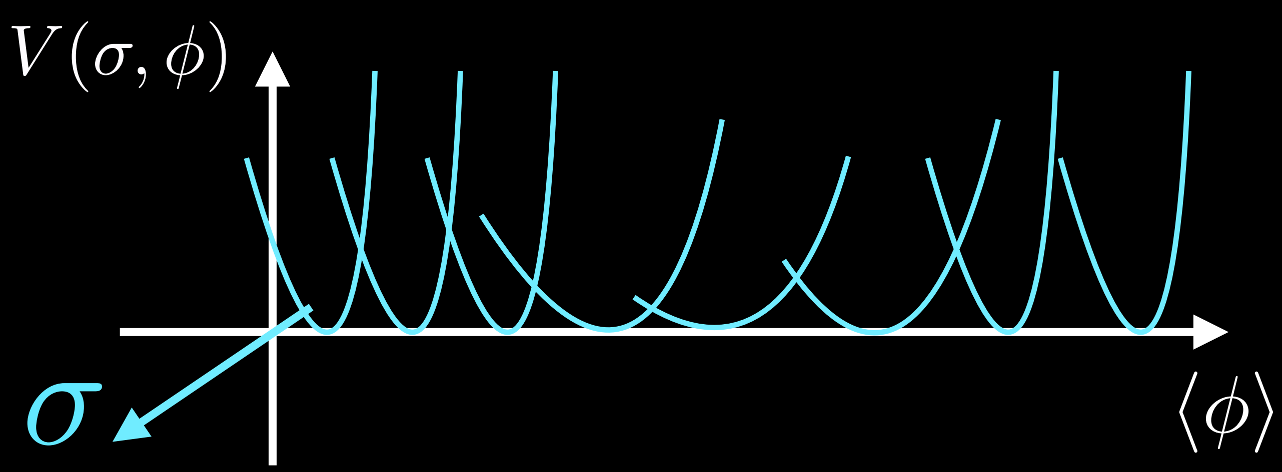
Our particle detector: CMB

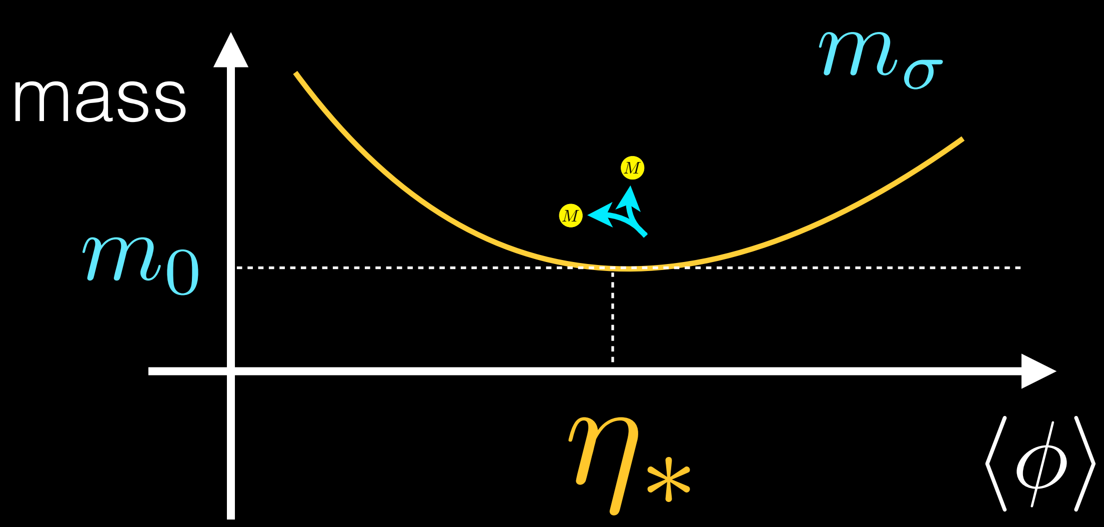


Step I : the non-adiabatic particle production



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_*

Consider inflation-dependent masses in general

Since particle production only happens around η_*

can re-parametrize the mass without loss of generality

$$\mathscr{L}_\sigma = -\frac{1}{2}(\partial_\mu \sigma)^2 - \frac{1}{2}\left[(g\phi - \mu)^2 + M_0^2\right]\sigma^2$$

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

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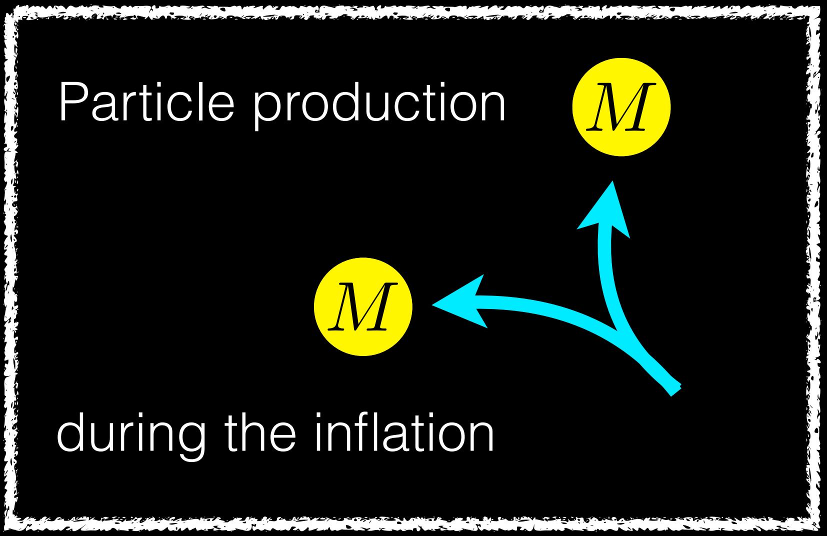
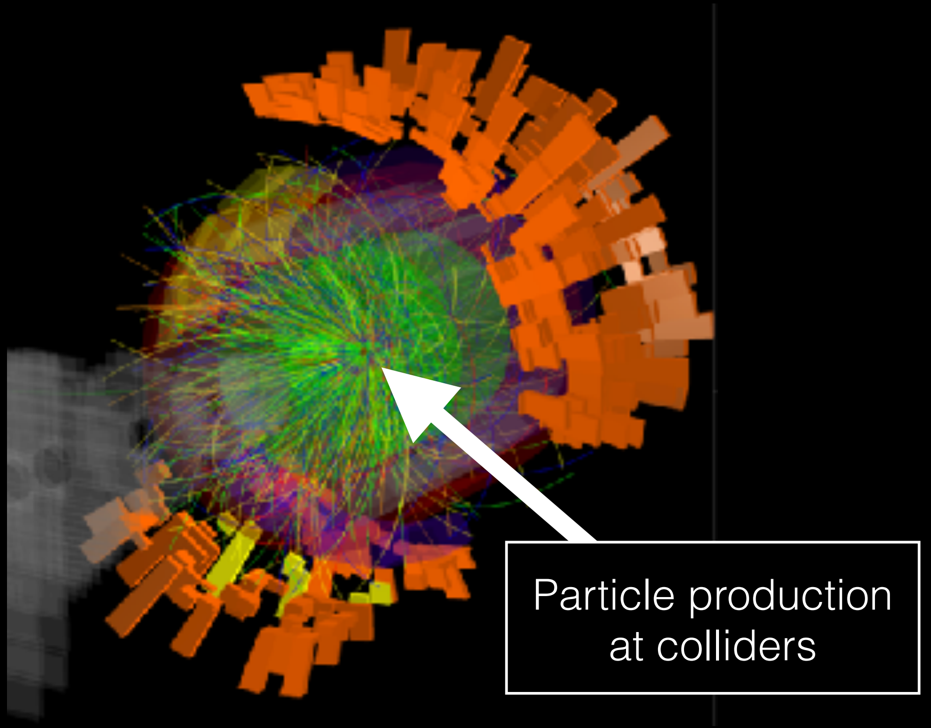
How to calculate the particle production?

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

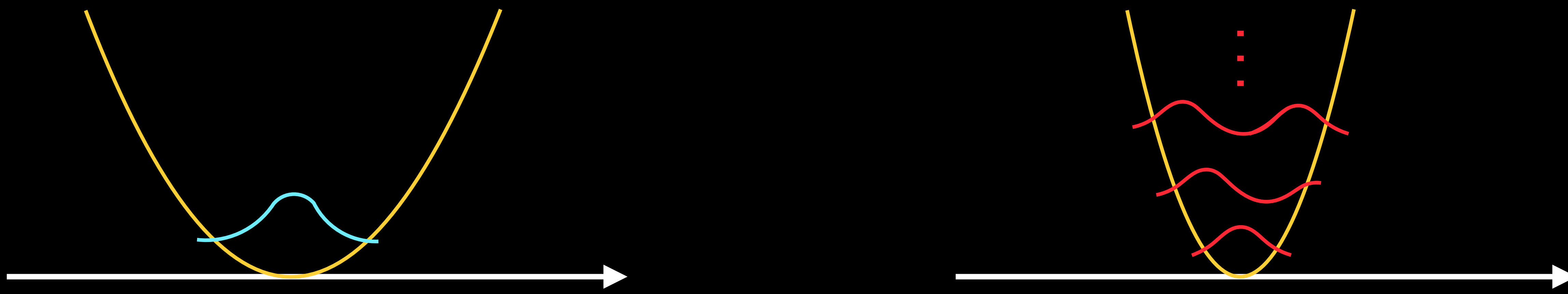
- calculate the number of non-adiabatic particle production
  from Bogolyubov transformation





Particle production from time-variant vacuum

$m_\sigma(\eta = -\infty)$ $\qquad\qquad$ $m_\sigma(\eta_*)$



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

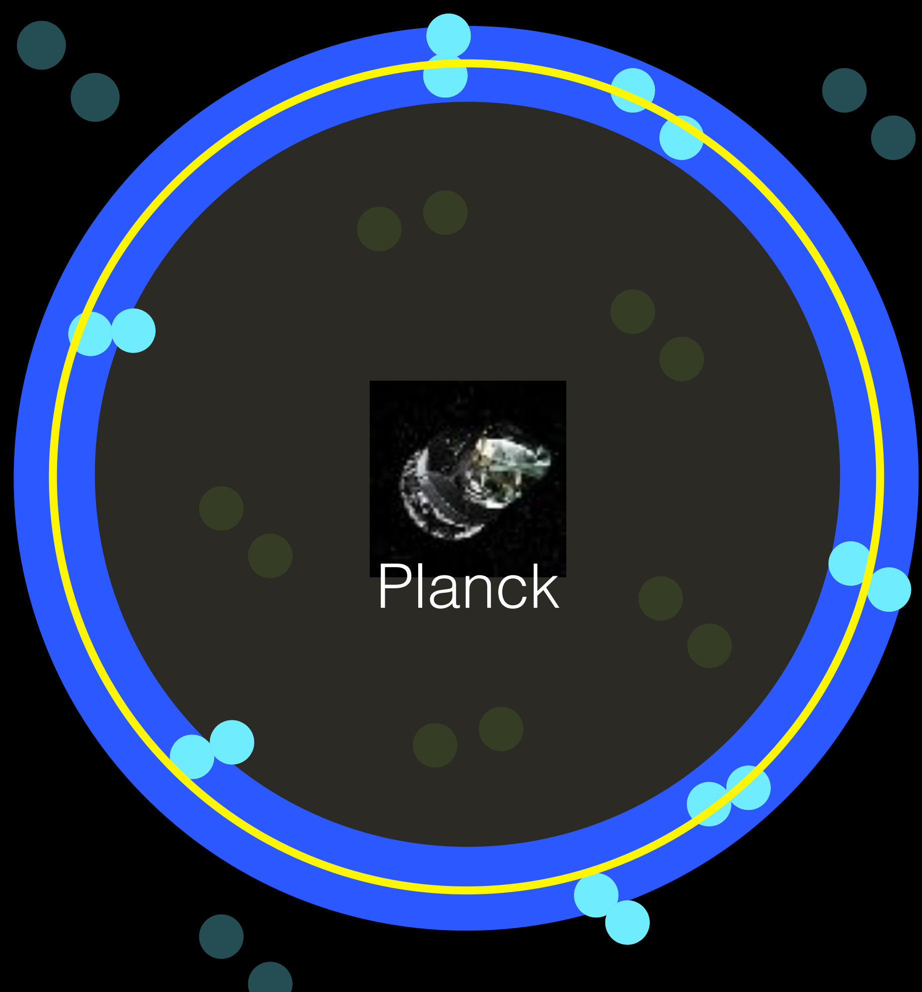
$$\hat{u}(\eta, \mathbf{x}) = \int \frac{d^3\mathbf{k}}{(2\pi)^{3/2}} \left[\hat{a}_\mathbf{k}\, \mathcal{I}_k(\eta)\, e^{i\mathbf{k}\cdot\mathbf{x}} + \hat{a}^\dagger_\mathbf{k}\, \mathcal{I}^*_k(\eta)\, e^{-i\mathbf{k}\cdot\mathbf{x}}\right]$$

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

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

Number of σ pairs around the CMB last scattering surface (with $\eta = \eta_{\rm rec} \pm \eta_*$)

$$N_{\sigma\ \rm pairs} = \frac{1}{2\pi^2}\left(\frac{g\dot{\phi}_0}{H_I^2}\right)^{3/2} e^{-\frac{\pi(M_0^2-2H_I^2)}{g|\dot{\phi}|}}\left(\frac{\eta_0}{\eta_*}\right)^3 \frac{\Delta\eta}{\eta_0}$$



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

If $g = 2,\ M_0 = 200\,H_I = 3.3\sqrt{\dot{\phi}}$

and $\eta_* = 100$ Mpc

(similar to chopping the sky into ~500x500 pieces)

$$N_{\sigma\ \rm pairs} \approx 30$$

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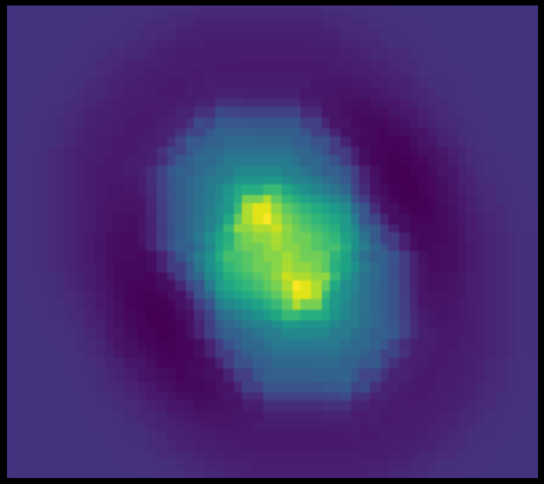
Why pairs? Separation?

- Particles are produced at least in pairs due to momentum conservation

- Particles tend to be produced with low momentum. Separation given by k^{-1} is comparable to the horizon size $|\eta_*|$

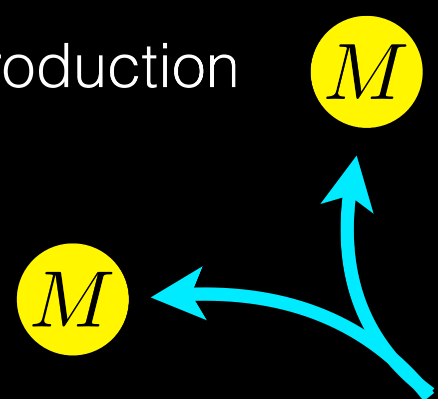
- We will model the separation as a random uniform distribution between 0 and $|\eta_*|$



Step II: mass modifies curvature perturbation

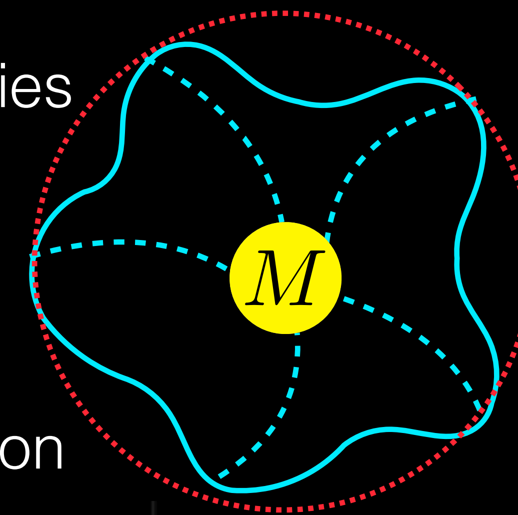
Particle production

during the inflation



Particle mass modifies

curvature perturbation



Perturbation
gets
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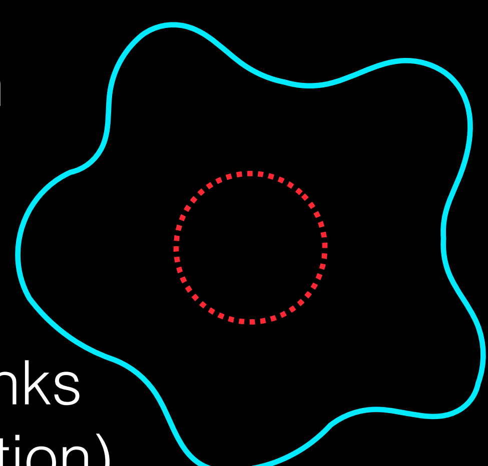
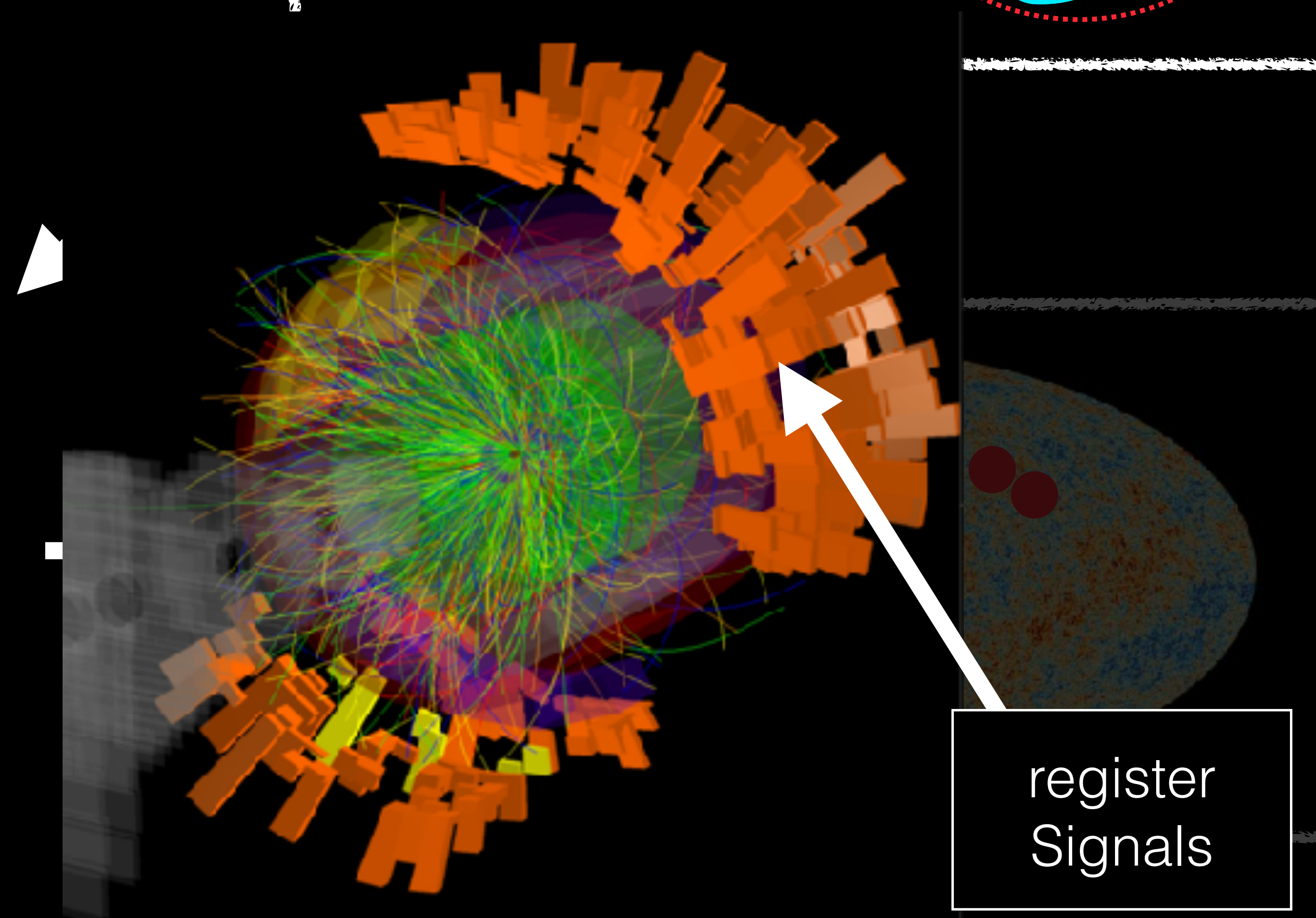
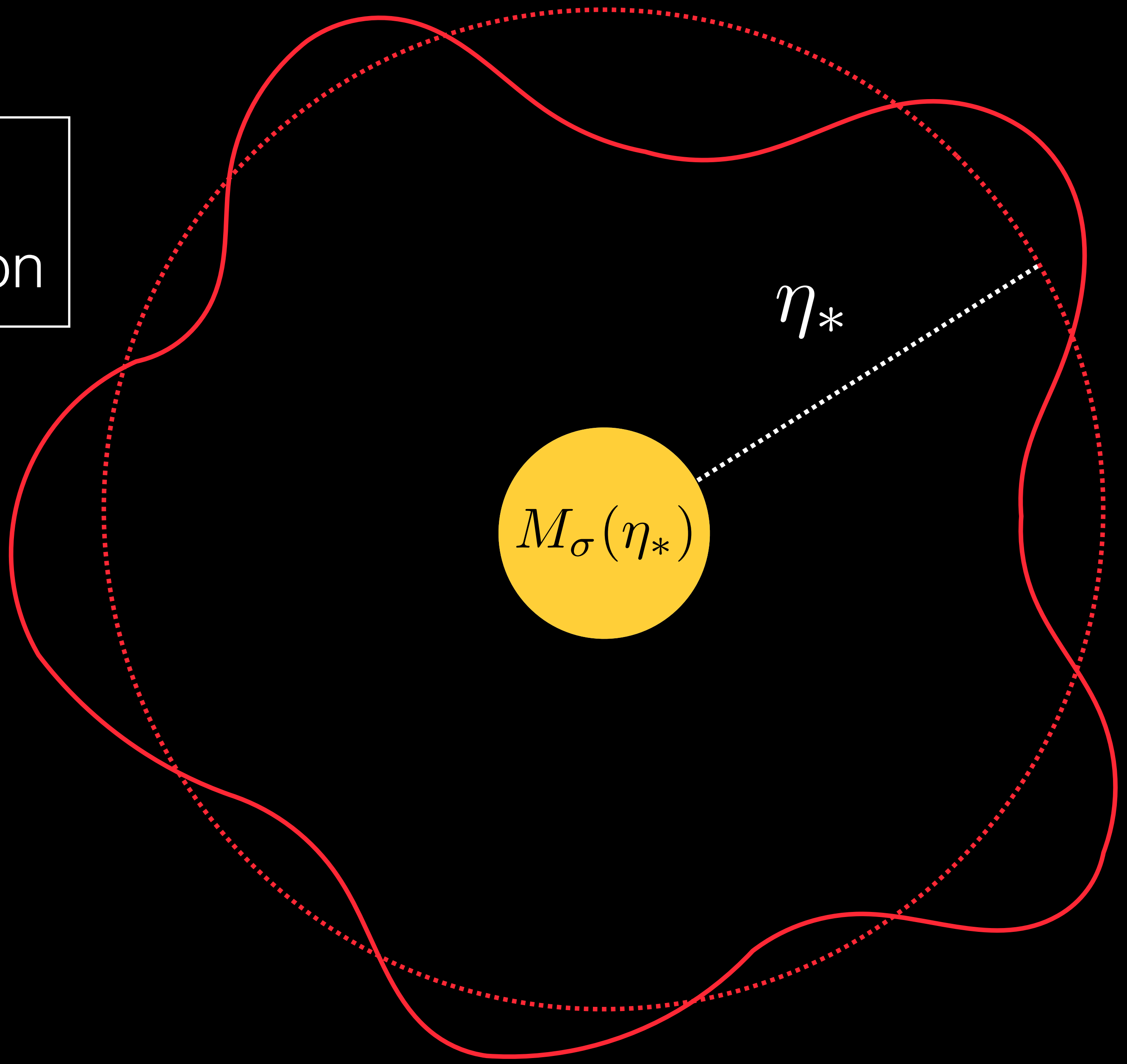
when
horizon shrinks
(due to inflation)





particle mass modifies curvature perturbation in the horizon

horizon size ~ $|\eta_*|$
at particle production



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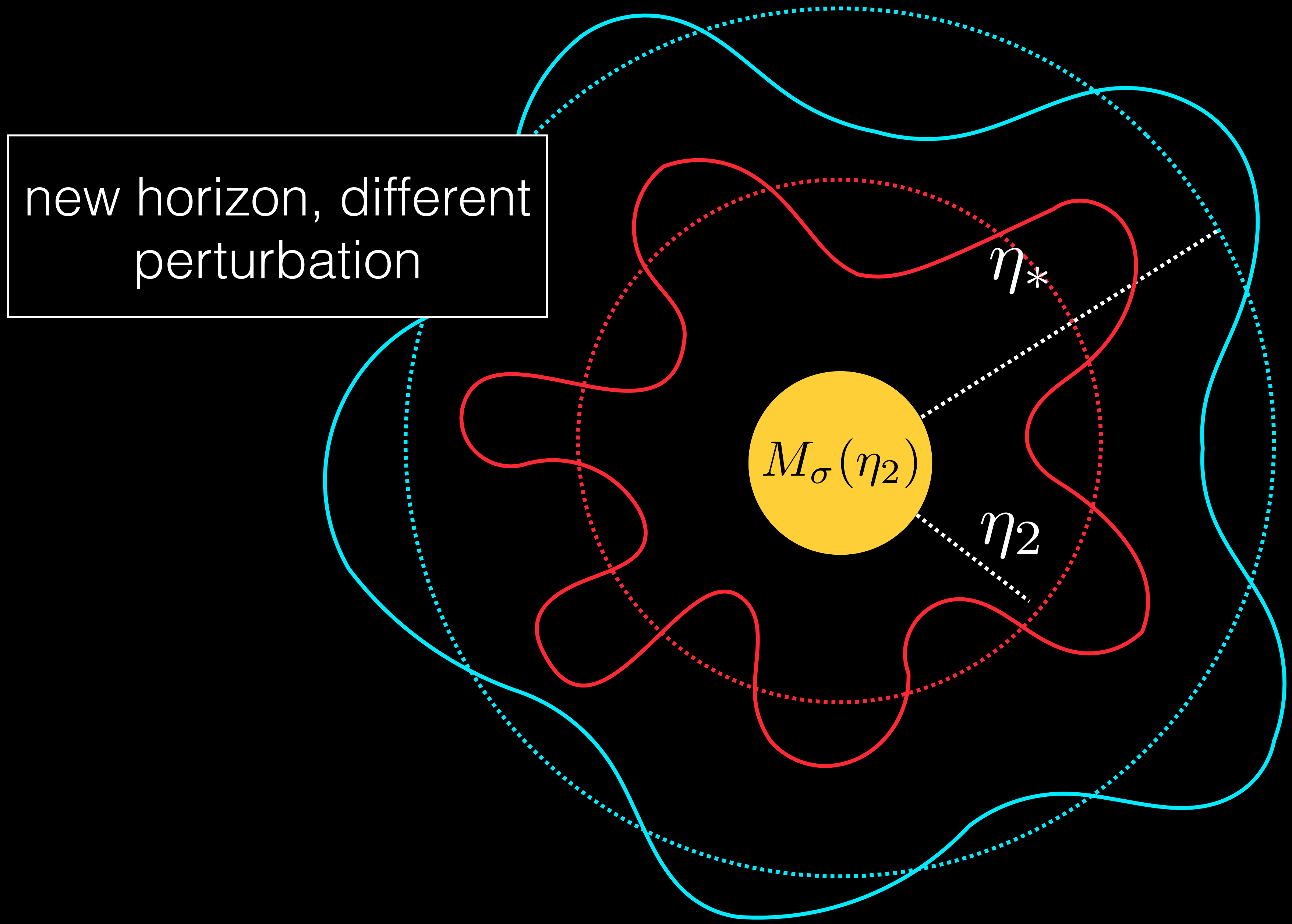
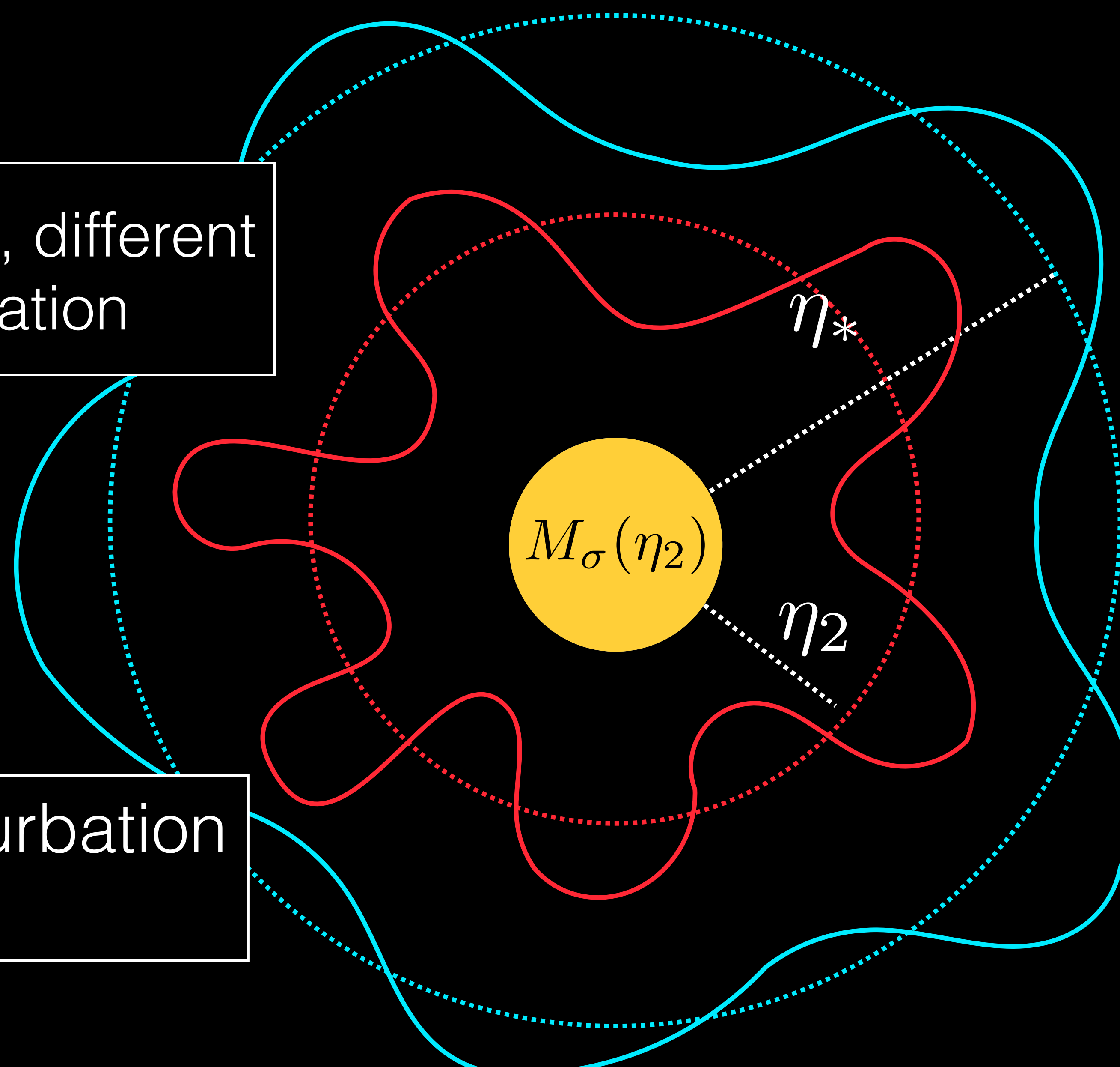
Once perturbation in the old horizon is frozen, **NEW** particle mass Modifies the perturbation in the **NEW** horizon



Once perturbation in the old horizon is frozen, **NEW** particle mass Modifies the perturbation in the **NEW** horizon

new horizon, different perturbation



radius-dependent perturbation with $r < |\eta_*|$

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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

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

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

from the exponential growth during inflation

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

Curvature perturbation in position space

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Therefore, the signal profile described below is quite universal!

Hot or Cold spots?

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

$$\left.\frac{\delta T}{T}\right|_{\rm CMB,\,RD} = -\frac{1}{3}\langle\zeta_\sigma\rangle \qquad \left.\frac{\delta T}{T}\right|_{\rm CMB,\,MD} = -\frac{1}{5}\langle\zeta_\sigma\rangle$$

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

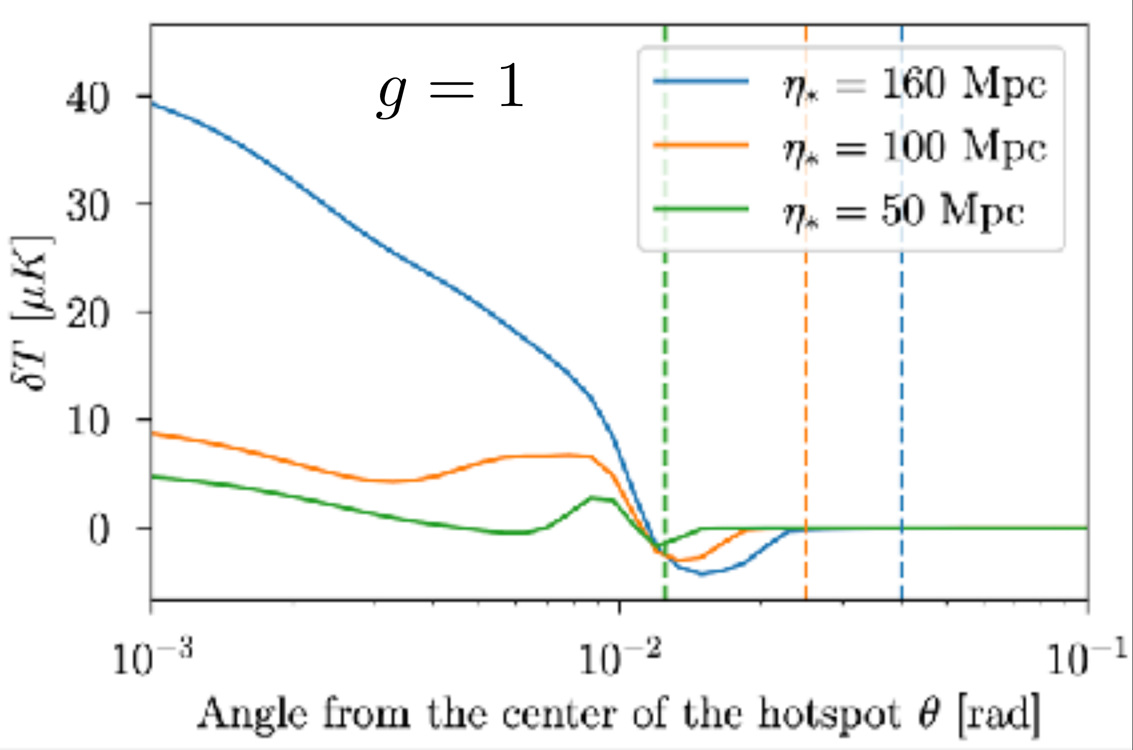
However, we find that the baryon acoustic oscillation (sub-horizon phys) converts the signal into ***HOT*** spots and further changes the fluctuation

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

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

Include the effect of "sub-horizon" physics

from baryon acoustic oscillations (the transfer functions)

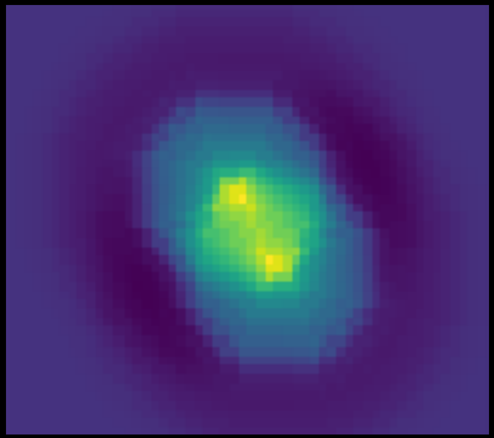


η_*

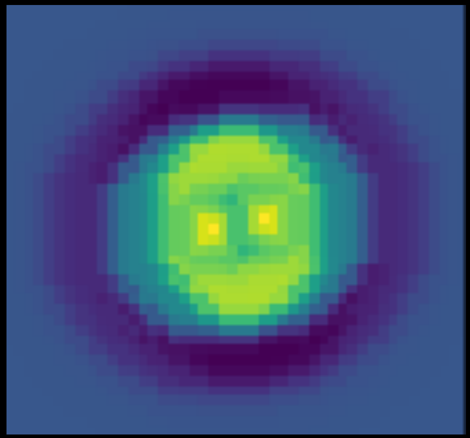
the conformal time & horizon size of particle production

Temperature profile

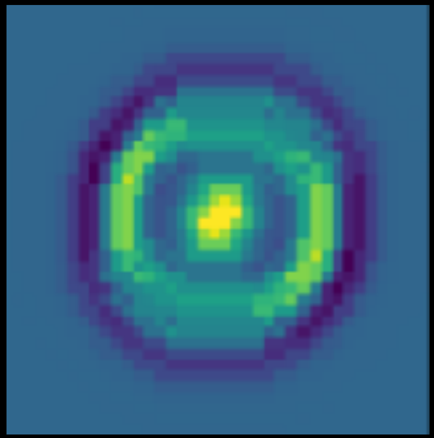
$\eta_* = 160\,\mathrm{Mpc}$



$\eta_* = 100\,\mathrm{Mpc}$



$\eta_* = 50\,\mathrm{Mpc}$



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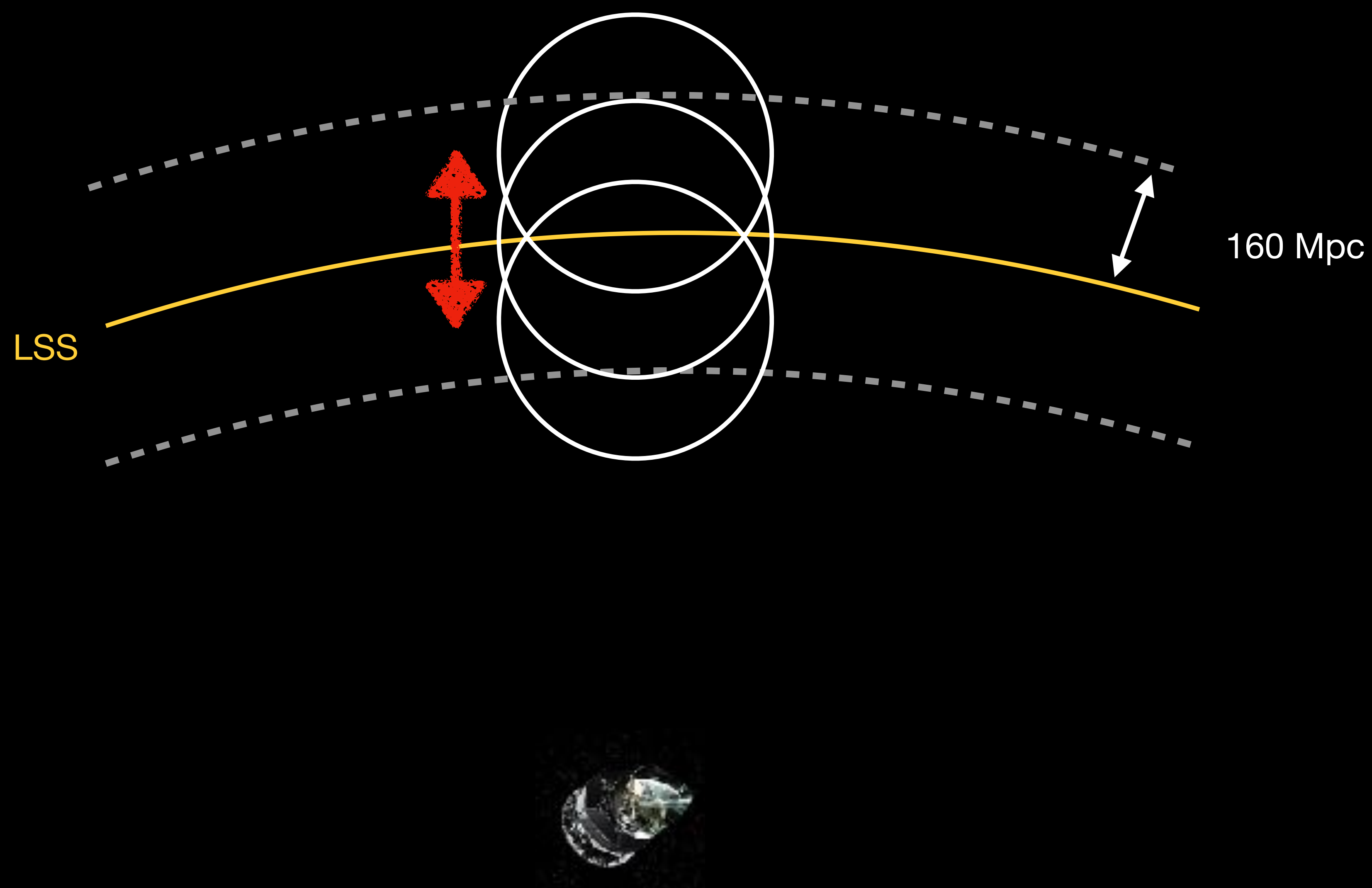
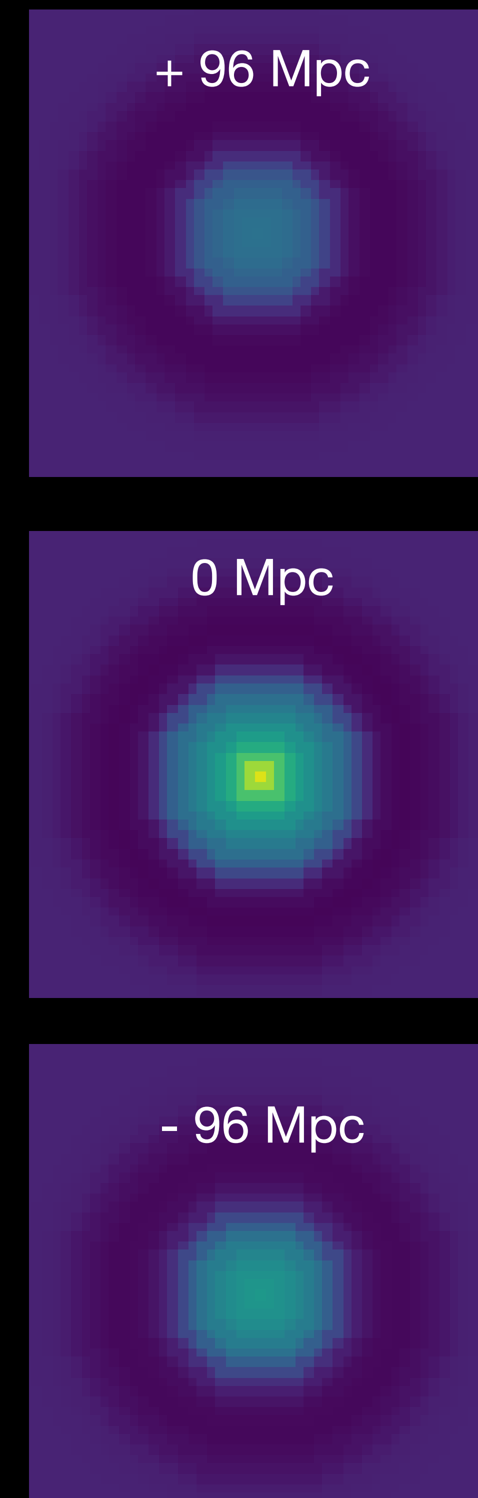
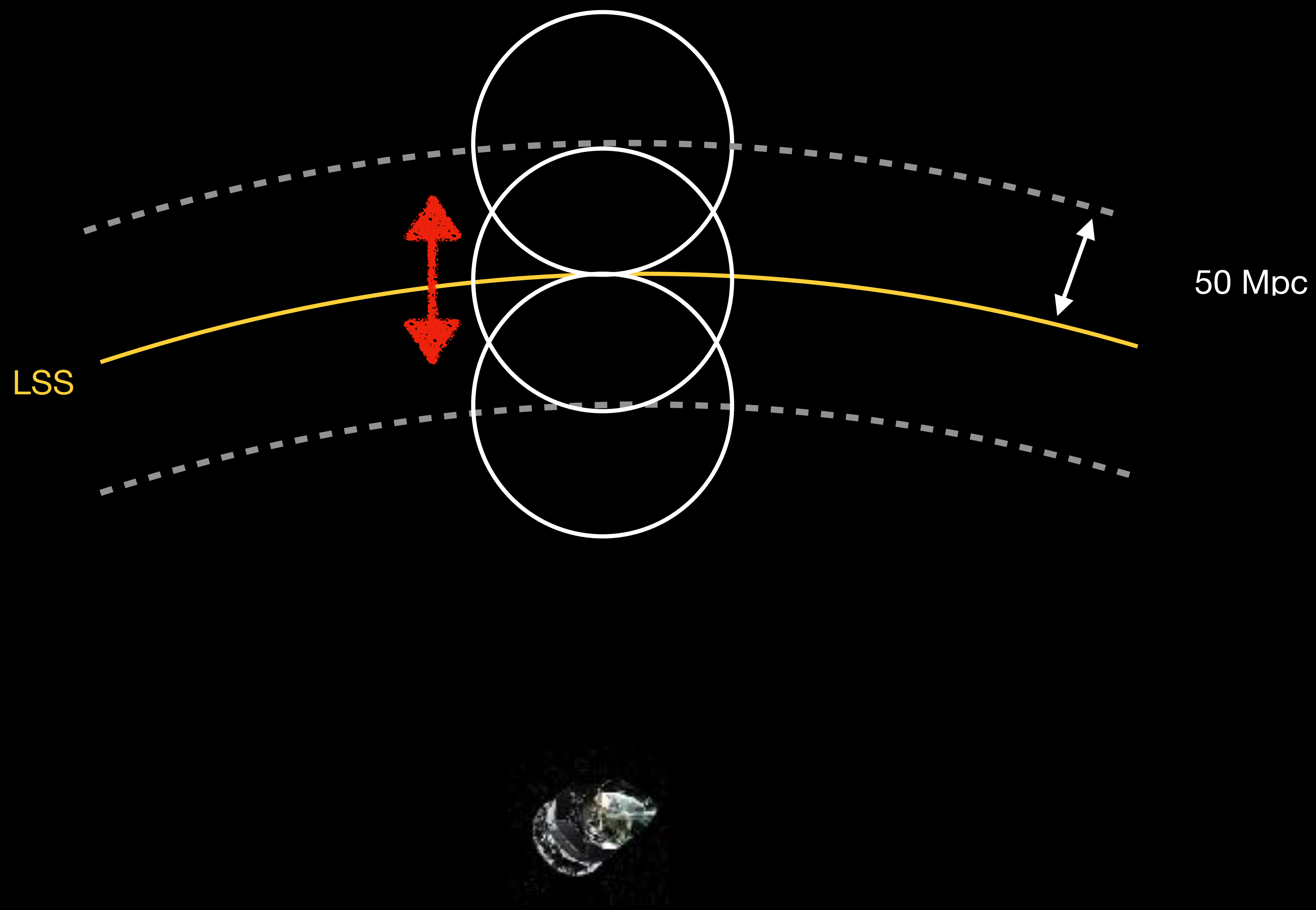
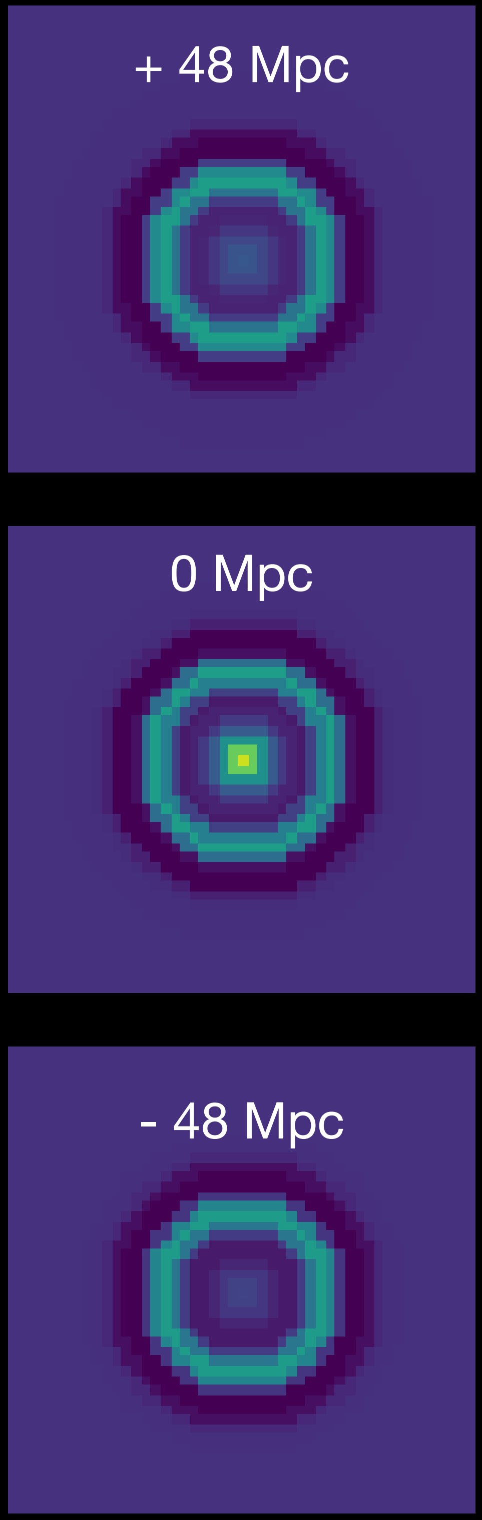
When particles are away from the last scattering surface $(\eta_* = 160\,\mathrm{Mpc})$





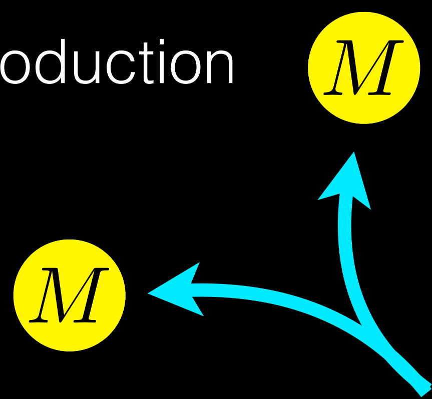
When particles are away from the last scattering surface ($\eta_* = 50\,\mathrm{Mpc}$)





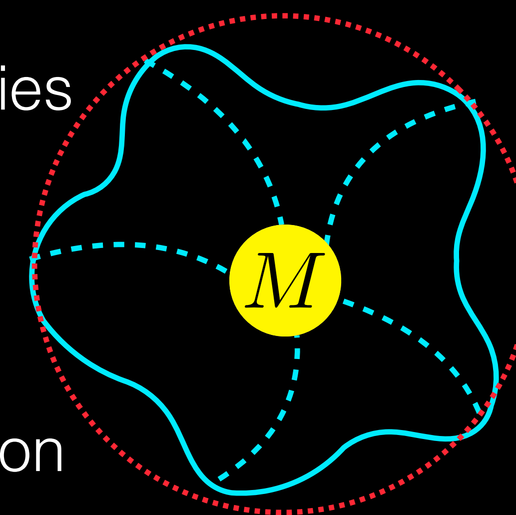
Step III: localized signals on the CMB

Particle production



during the inflation

Particle mass modifies



curvature perturbation

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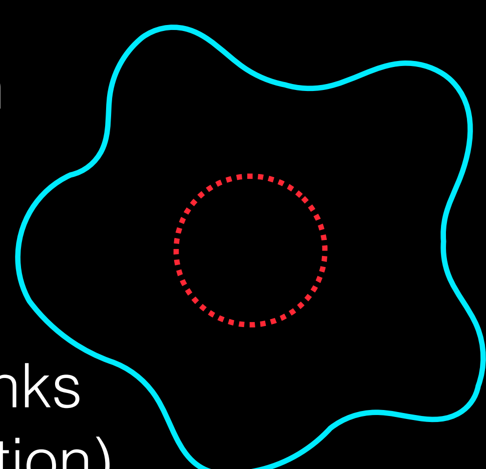

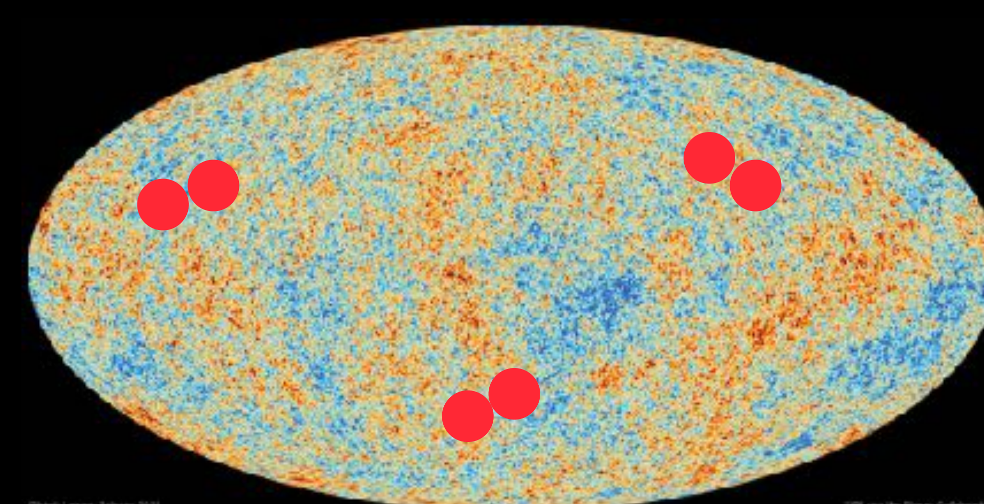

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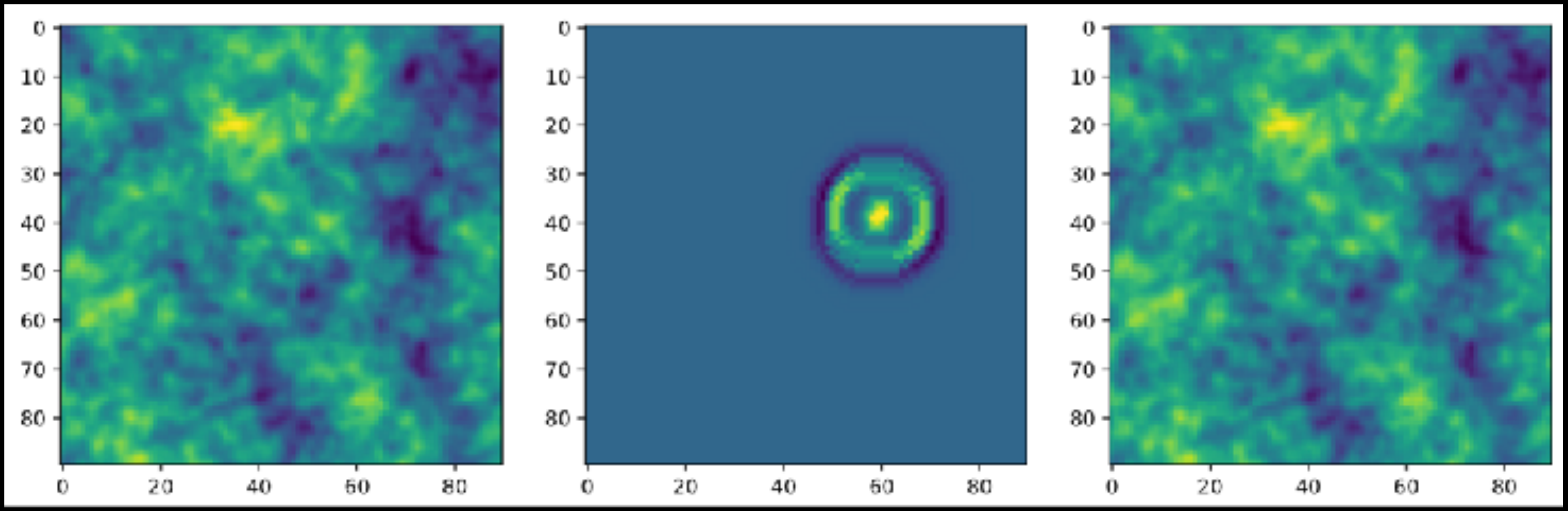
Simulate pairwise spot signals

- use QuickLens 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

simulated CMB | signal | simulated CMB + signal



$\eta_* = 50\,\mathrm{Mpc}$

$g = 4$

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Identify signal on the CMB map

Different types of backgrounds to consider:

- instrumental noise: (not an issue for Planck)
- fore-ground from compact objects (stars, galaxies,….)
- primordial fluctuation background (indistinguishable)

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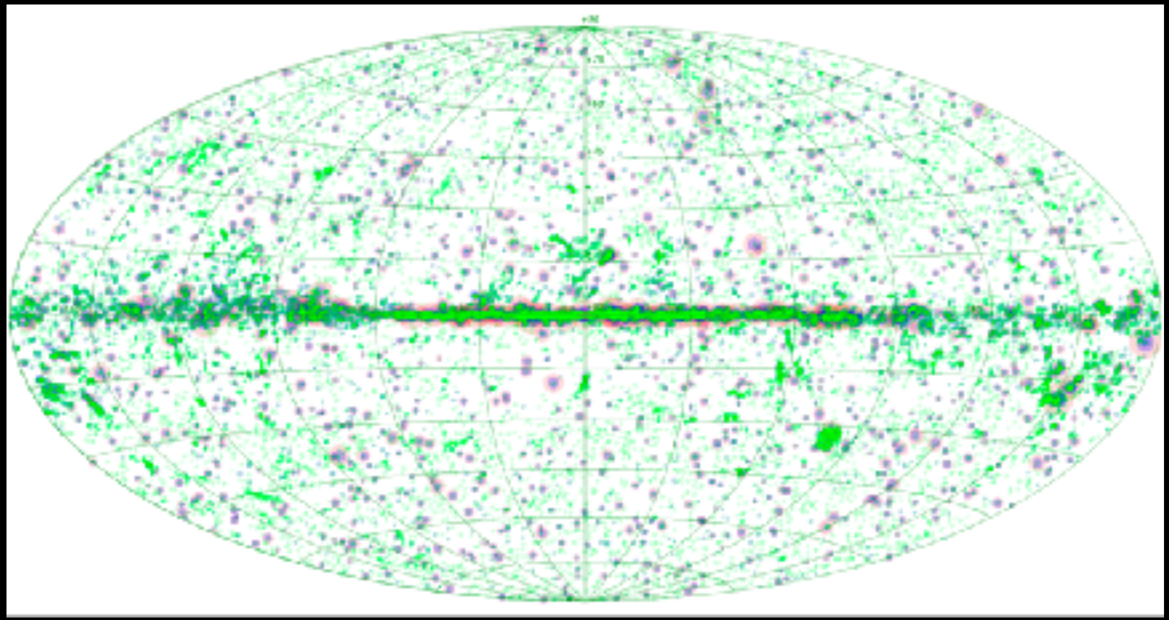


Can veto the background by correlating Planck's maps with 9 frequency bands

Easier to identify compact objects >~ 10 Mpc
A common lore is that "WMAP is foreground-free"

Planck 2013 results. XXVIII

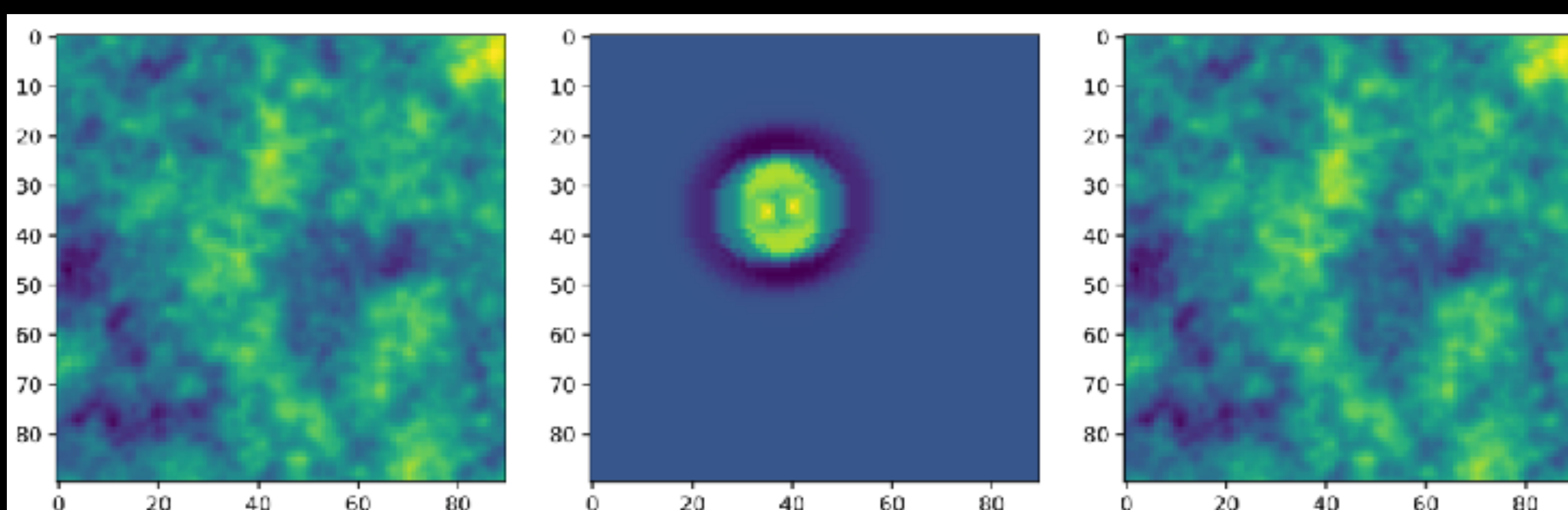
Fig. 1. Sky distribution of the PCCS sources at three different channels: 30 GHz (pink circles); 143 GHz (magenta circles); and 857 GHz (green circles). The dimension of the circles is related to the brightness of the sources and the beam size of each channel. The figure is a full-sky Aitoff projection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

Identify signal on the CMB map

Different types of backgrounds to consider:

- instrumental noise: (not an issue for Planck)
- fore-ground from compact objects (stars, galaxies,…)
- primordial fluctuation background (indistinguishable)

simulated CMB | signal | simulated CMB + signal



$\eta_* = 50\,\mathrm{Mpc}$

$g = 4$

Convolutional Neural Network (CNN)

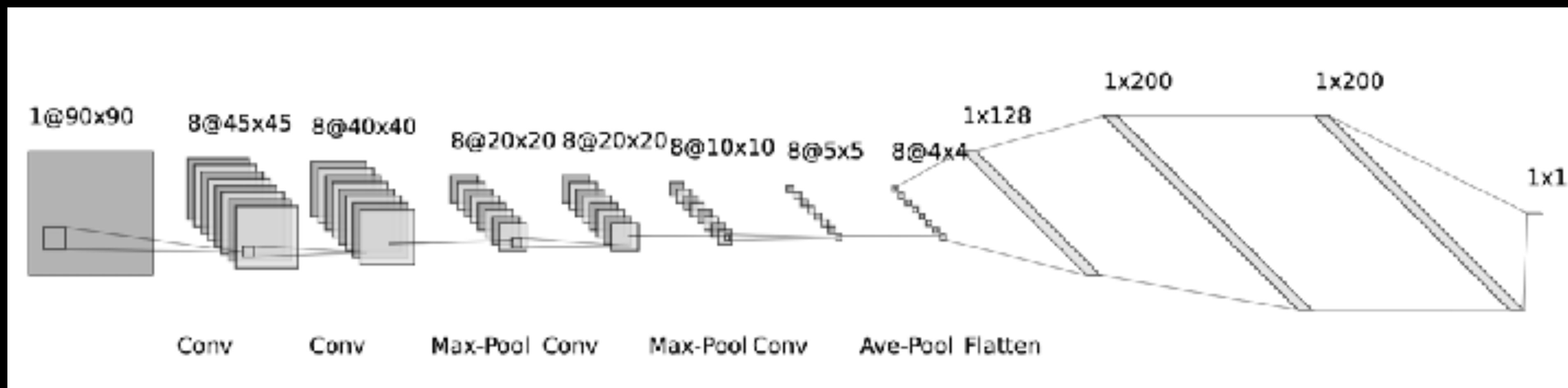
Instead of matched filter, we use the CNN
to dig out the signal from background

CNN analysis works better for signals
with non-spherical and varying profiles

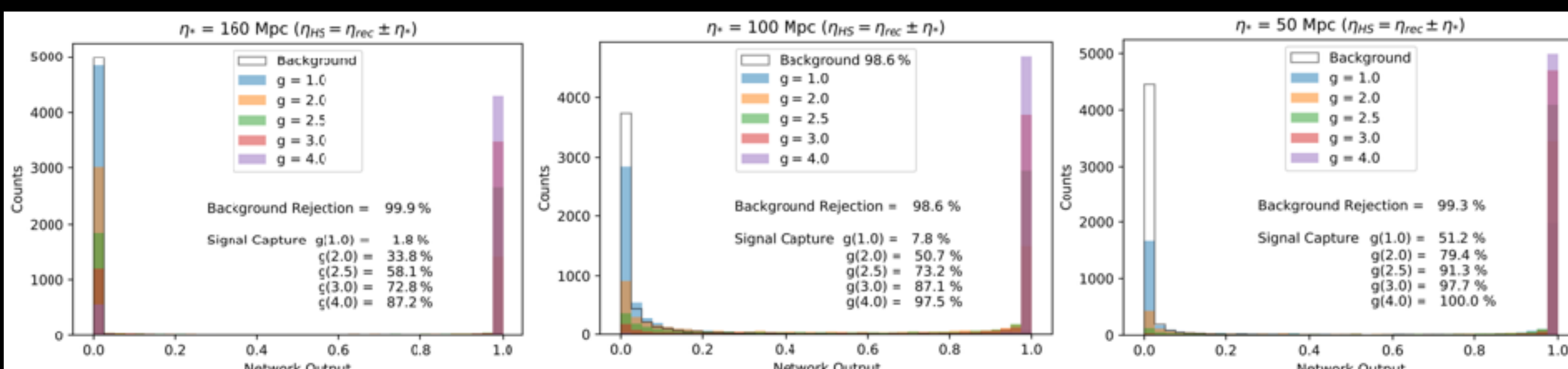
We cross check the result between CNN and MF
using signals with fixed profiles, and most of the results are similar

Convolutional Neural Network (CNN)

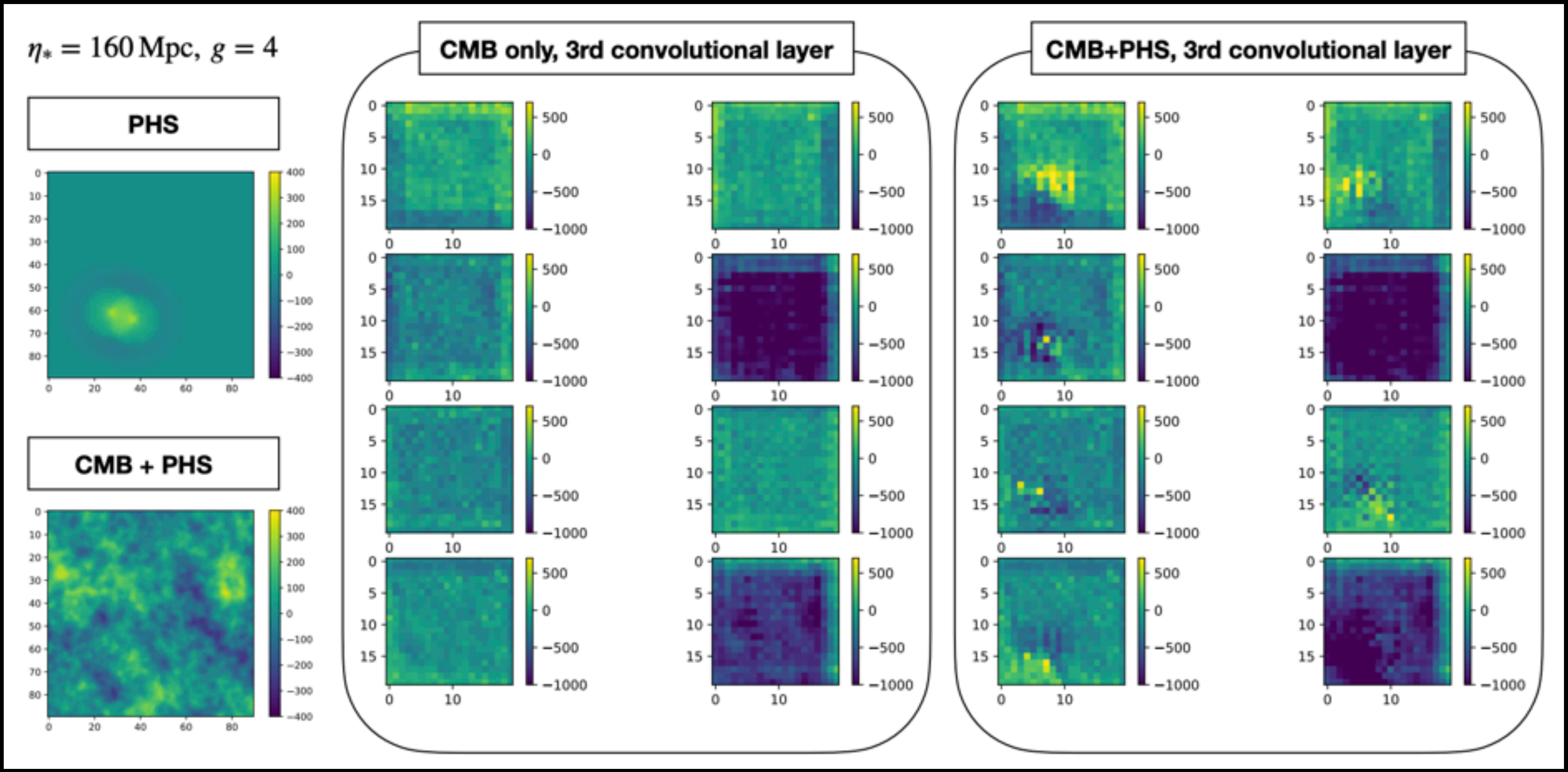
Our CNN structure



Train the CNN with 160k smaller size images (w/ & w/o signal injection)
Network outputs the probability of having a signal in the image

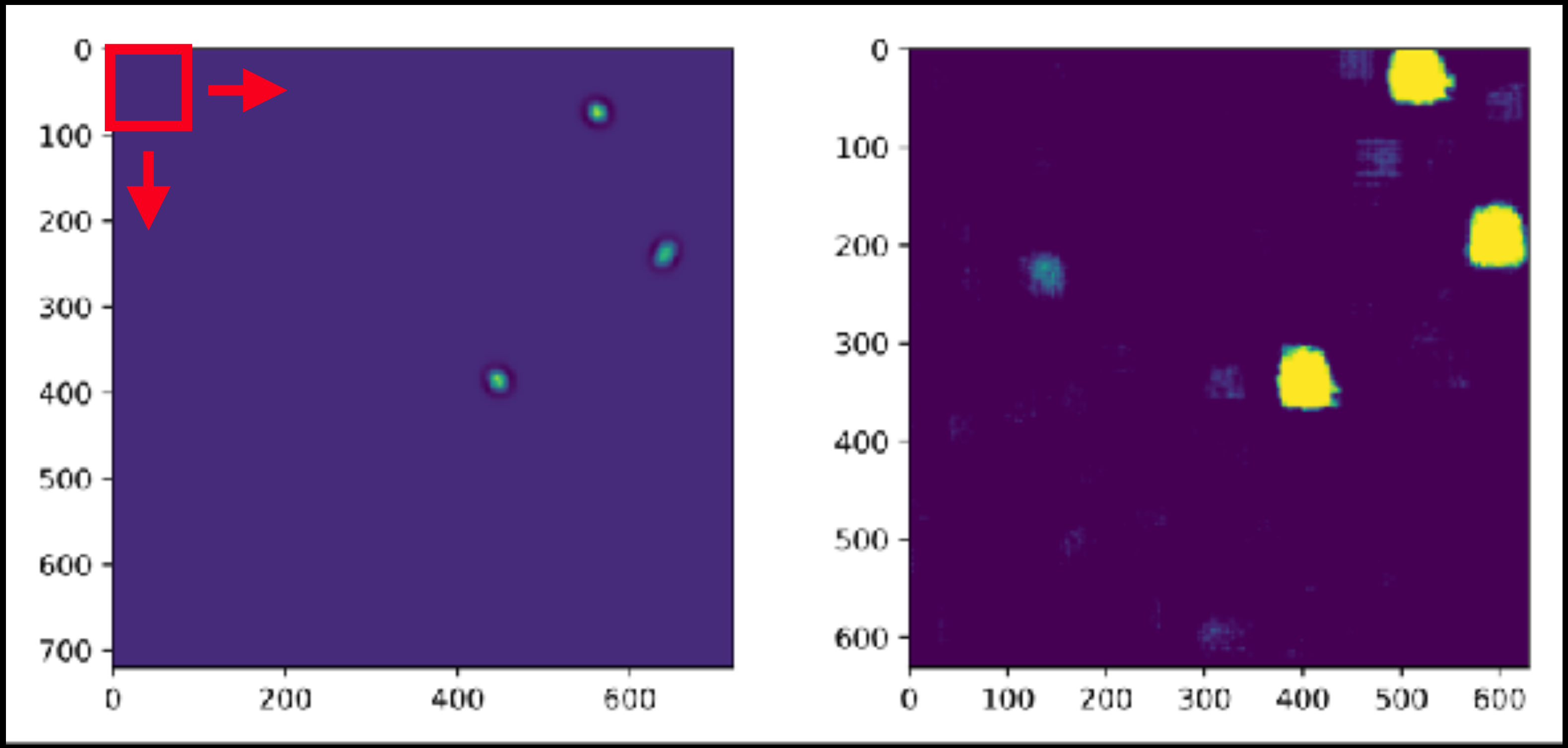


Results from the 3rd convolution layer



Convolutional Neural Network (CNN)

Apply the same network to a larger image (~1/25 of the sky), sliding the search box, convert the map into a "probability map"



With "clustering" and vetoing clusters with small pixel numbers, we calculate the signal capture rate & false positive rate

Result: 2σ exclusion bound

with sky fraction = 60% (similar to the Planck analysis)

Number of PHS	$\eta = 50$	$\eta = 100$	$\eta = 160$
$g = 1$	8	840	1162
$g = 2$	5	20	17
$g = 3$	4	9	8

M_0/H_I	$\eta = 50$	$\eta = 100$	$\eta = 160$
$g = 1$	145	120	114
$g = 2$	213	199	194
$g = 3$	266	253	247

$M_0/(g\dot{\phi}_0)^{1/2}$	$\eta = 50$	$\eta = 100$	$\eta = 160$
$g = 1$	2.5	2.0	2.0
$g = 2$	2.6	2.4	2.4
$g = 3$	2.6	2.5	2.4

Table 2. *Upper:* 2σ upper bound on the number of PHS in the whole CMB sky with both hotspot centers located within $\eta_{\rm rec} \pm \eta_*$ window around the last scattering surface. In the calculation we assume sky fraction $f_{\rm sky} = 60\%$. *Lower left*: lower bounds on the bare mass of the heavy scalar field in units of the Hubble scale during the inflation. *Lower right*: lower bounds on the bare mass in units of the rate of the mass, $(g\dot{\phi}_0)^{1/2}$, owing to the inflaton coupling.

$$N_{\sigma \text{ pairs}} = \frac{1}{2\pi^2}\left(\frac{g\dot{\phi}_0}{H_I^2}\right)^{3/2} e^{-\frac{\pi(M_0^2 - 2H_I^2)}{g|\dot{\phi}|}} \left(\frac{\eta_0}{\eta_*}\right)^3 \frac{\Delta\eta}{\eta_0}$$

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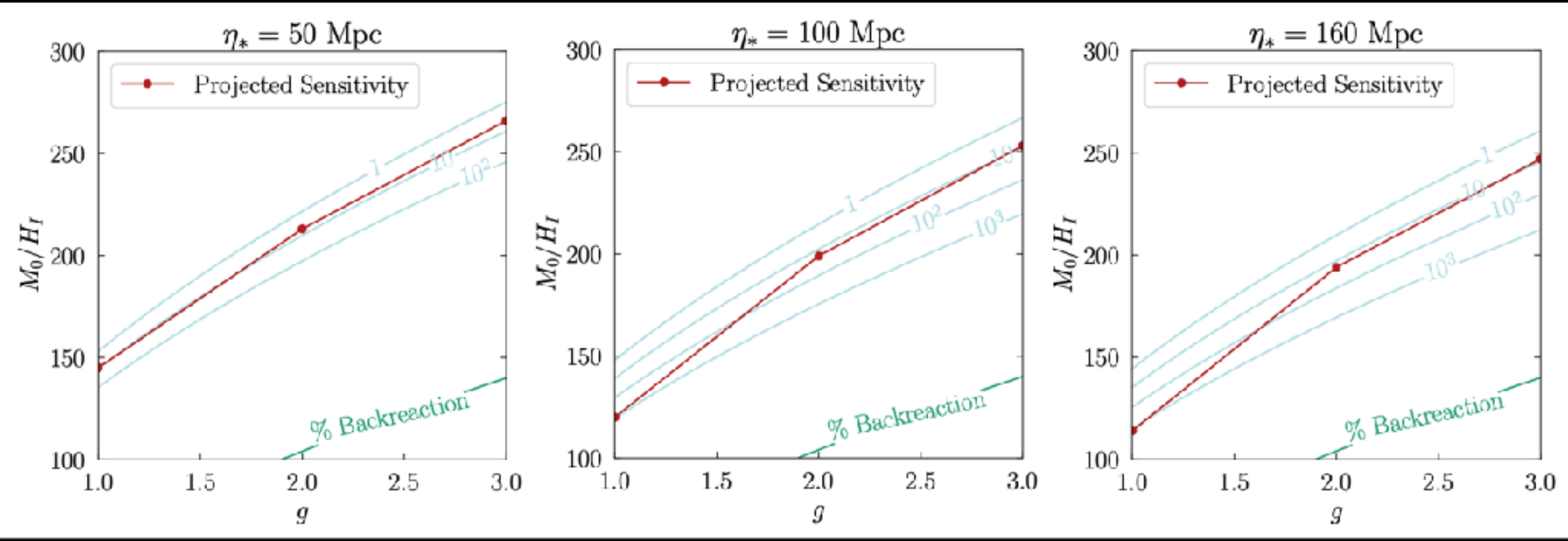

The CNN analysis can (in principle) set mass bounds close to the optimal limit allowed by the CMB search

Back-reaction constraints

Need to make sure the scalar field

does not affect inflaton's slow-roll motion $3H_*\dot{\phi} \approx -\frac{\partial V_\phi}{\partial \phi}$

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

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

(similar bound for not depleting inflaton's energy $M_\sigma n_\sigma \ll \dot{\phi}$)

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

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Result: 5σ discovery reach

with sky fraction = 60% (similar to the Planck analysis)

Number of PHS	$\eta = 50$	$\eta = 100$	$\eta = 160$
$g = 1$	16	2047	2757
$g = 2$	10	48	40
$g = 3$	9	21	19

M_0/H_I	$\eta = 50$	$\eta = 100$	$\eta = 160$
$g = 1$	143	116	110
$g = 2$	210	194	189
$g = 3$	262	247	241

$M_0/(g\dot{\phi})^{1/2}$	$\eta = 50$	$\eta = 100$	$\eta = 160$
$g = 1$	2.4	2.0	1.9
$g = 2$	2.5	2.3	2.3
$g = 3$	2.6	2.4	2.4

Table 3. Same as Table 2 but for the 5σ discovery reach.

$$N_{\sigma \text{ pairs}} = \frac{1}{2\pi^2}\left(\frac{g\dot{\phi}_0}{H_I^2}\right)^{3/2} e^{-\frac{\pi(M_0^2 - 2H_I^2)}{g|\dot{\phi}|}} \left(\frac{\eta_0}{\eta_*}\right)^3 \frac{\Delta\eta}{\eta_0}$$

Conclusion

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

Signal hotspots have a well-predicted profile that only depends on (g, η_*)

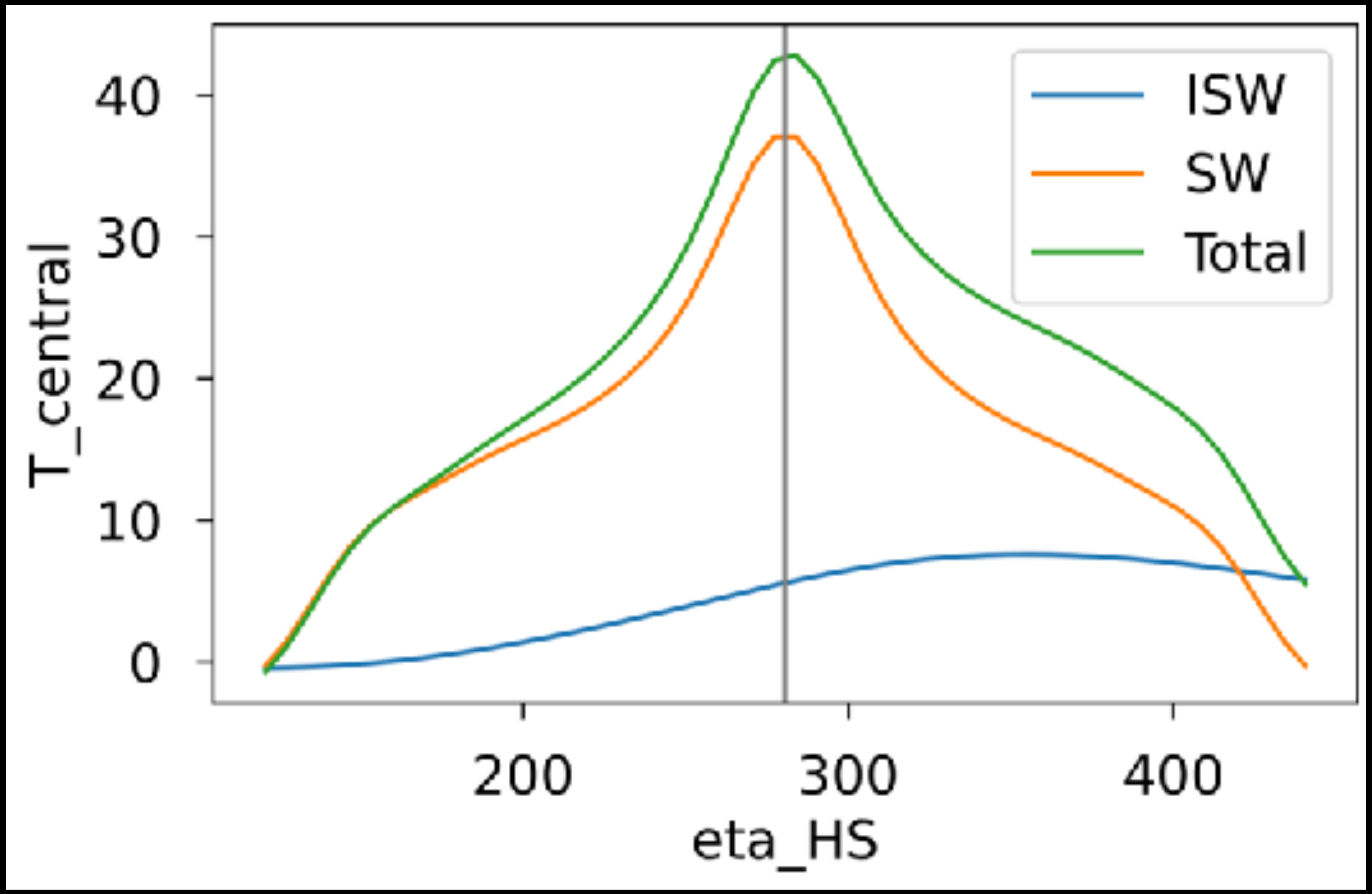
CNN can provide a powerful position space search of the signal

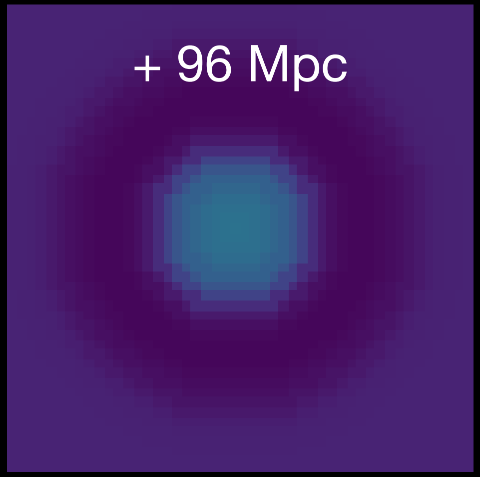
More things to explore:

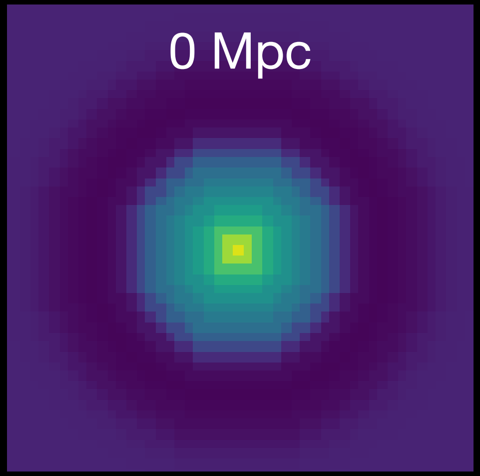
- other localized signals for the position space search?
- pairwise clumps in Large Scale Structure? CMB lensing, cosmic shear, etc?
- Including the foreground?

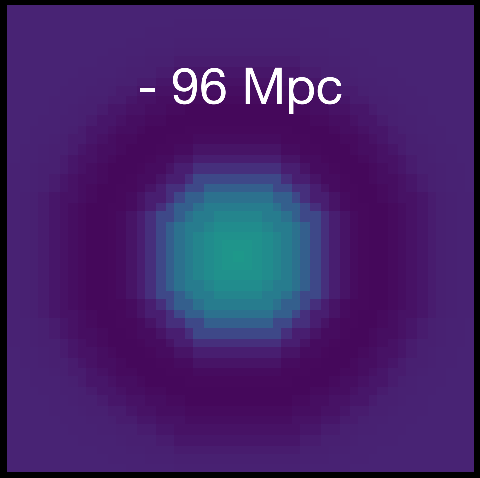
Backup Slides

When particles are away from the last scattering surface ($\eta_* = 160\,\mathrm{Mpc}$)









	ω_b	ω_{cdm}	$10^9 A_s$	n_s	τ_{re}	Bg rejection	Sig capture
Planck18	0.0224	0.120	2.10	0.966	0.0543	99.8%	74.0%
Case 1		+0.004				99.8%	72.3%
Case 2			+0.07			99.2%	74.1%
Case 3				+0.01		99.6%	69.9%
Case 4	+0.0003					99.8%	73.4%
Case 5					+0.014	99.2%	74.4%
Case 6	+0.0003	−0.004	+0.05	−0.01	−0.014	99.8%	72.4%

Table 4. The response of the signal capture and background rejection rates with varying ΛCDM parameters, labeled with the difference to the ΛCDM parameters. The variation of the rates is comparable to the fluctuations in our CNN analysis due to finite sampling and therefore is insignificant. For this test, we used $g = 2$ and $\eta_* = 160$ Mpc for the PHS signal.