# Cosmological Particle Production & Pairwise Spots on the CMB


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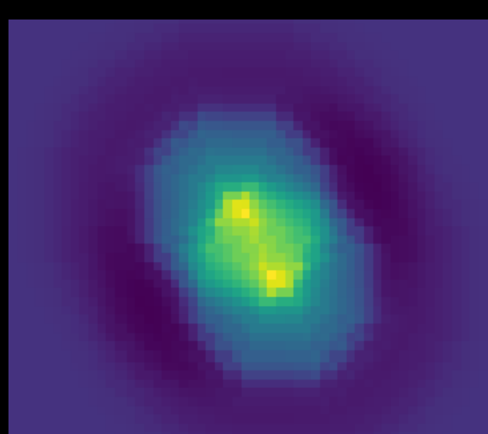
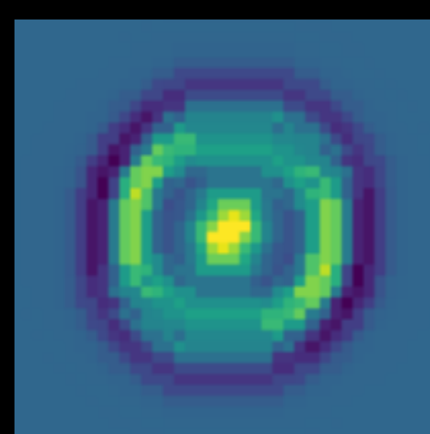


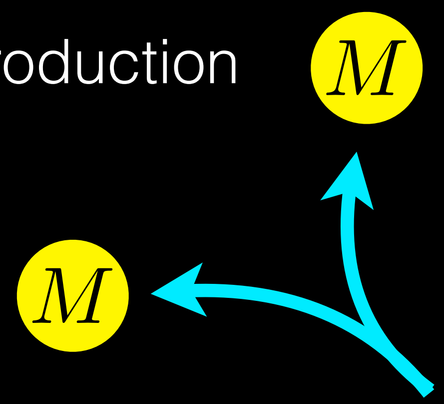


The Early Universe
A Window to New Physics
10/20/2023

# Cosmological Particle Production

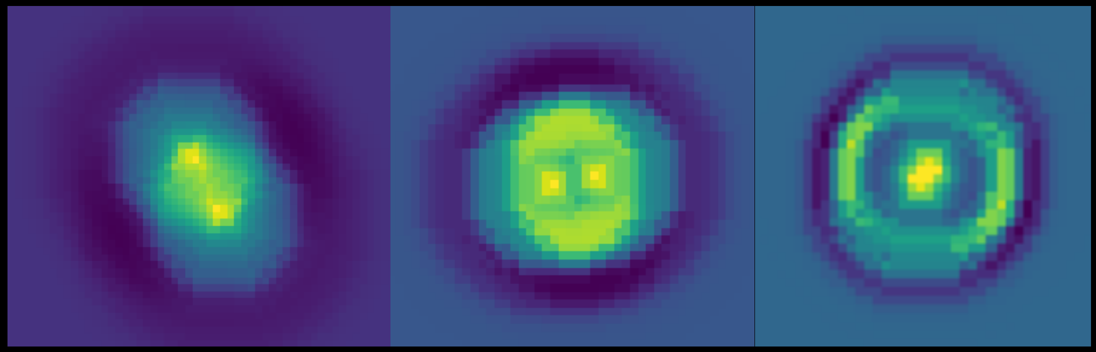
# => Pairwise Hotspot signals on CMB

Particle production

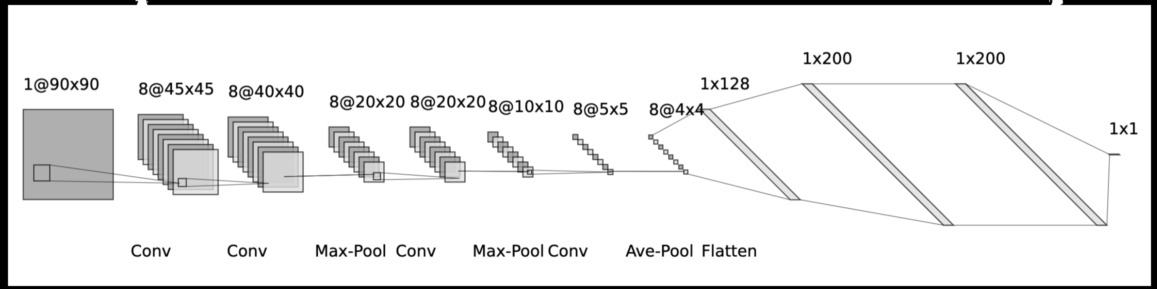



during the inflation

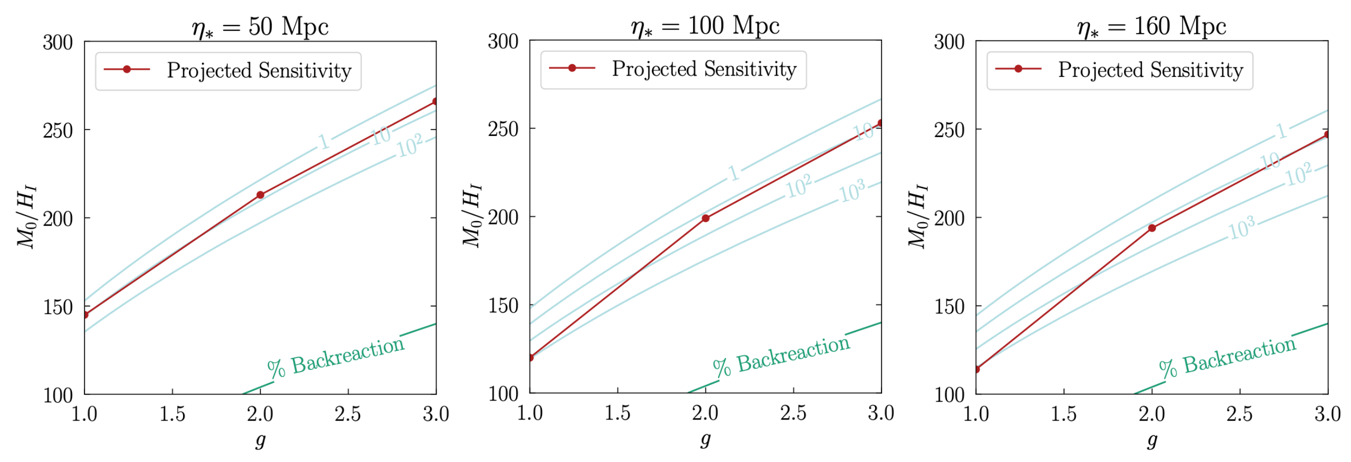
Imprint localized signals on the CMB



Search with Convolutional Neural Network (CNN) or Matched Filter




Can probe particle mass $\mathcal{O}(100) \times$ of inflationary Hubble scale

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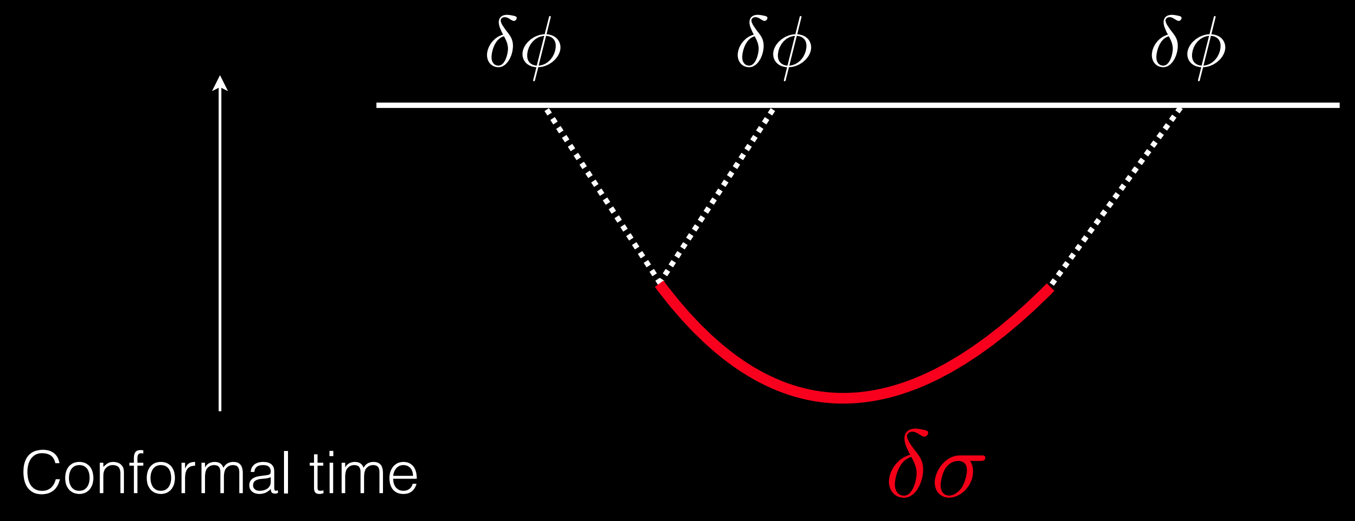
Our goal: probing extremely heavy particles

using inflationary dynamics + CMB signals

## Our goal: probing extremely heavy particles using inflationary dynamics + CMB signals

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




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

Our goal: probing extremely heavy particles

using inflationary dynamics + CMB signals

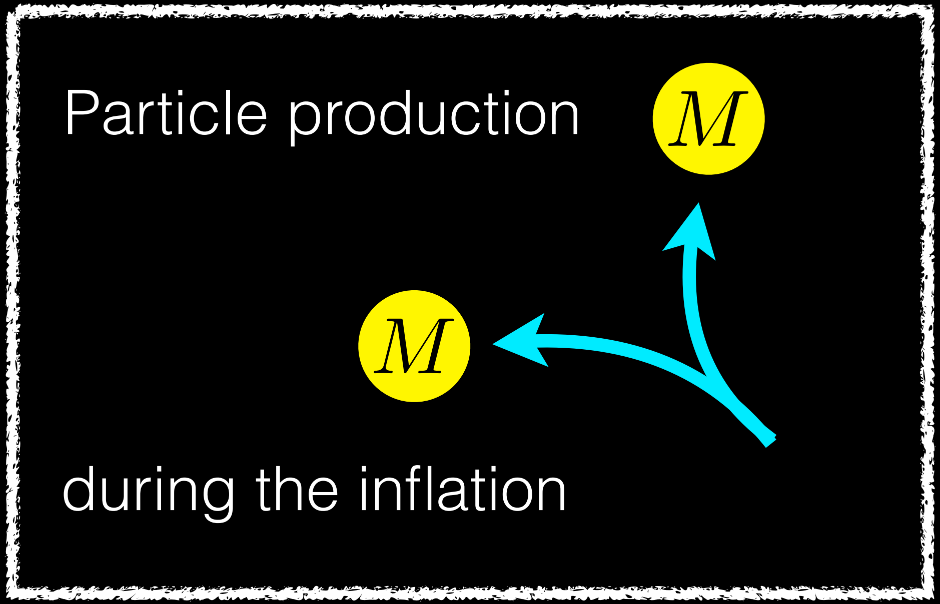
- In the context of "cosmological collider physics", we usually focus on signals of non-Gaussianity ($\geq$3-pt functions)

What if we elevate the particle mass even further,

leading to tiny production rate

that only occurs at specific moments?

# Particle production

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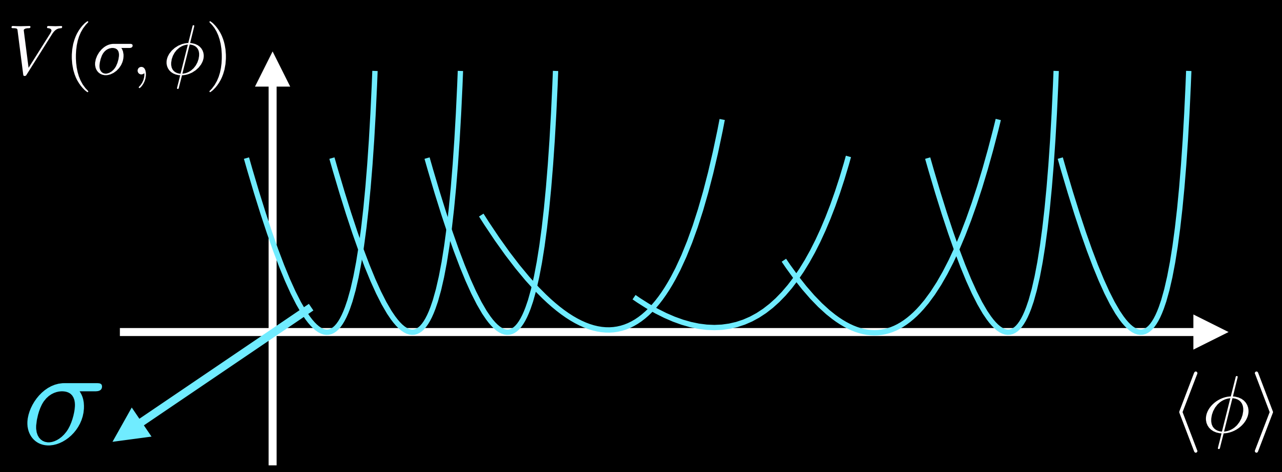
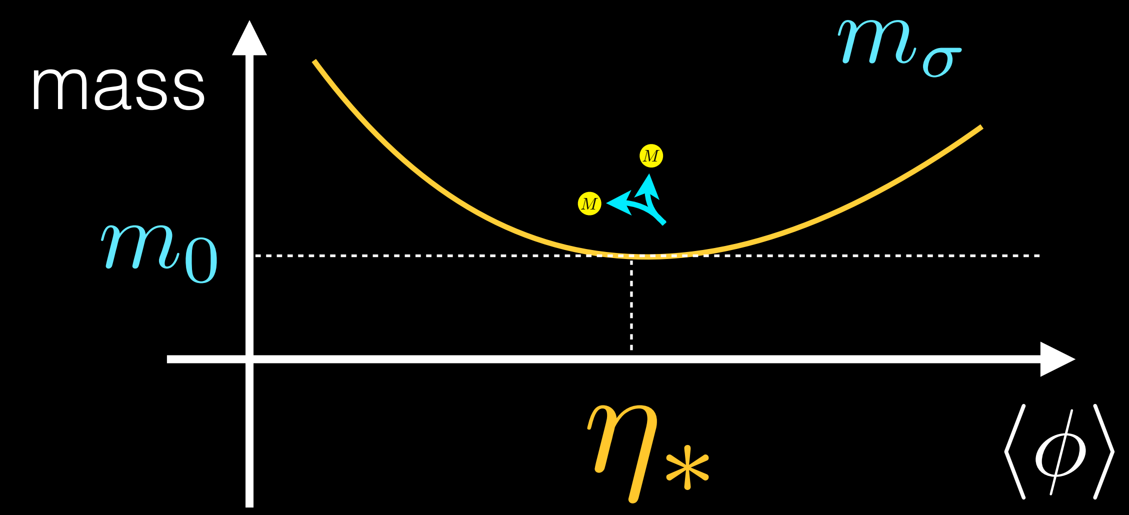
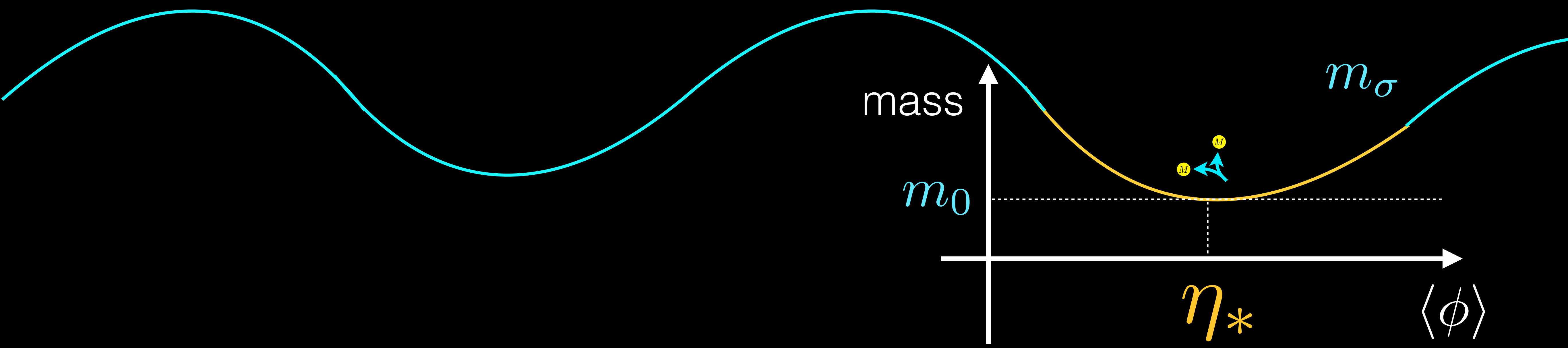
Consider a scalar particle $\sigma$ that carries a mass depending on the inflaton-VEV




- Sigma mass is typically heavy (compared to Hubble scale)
- mass takes its minimum value at time $\eta_*$

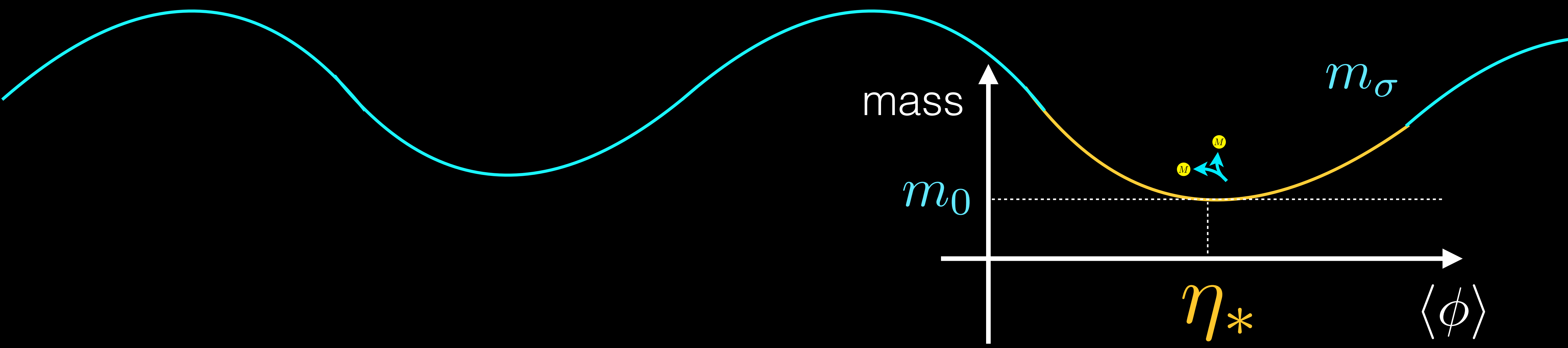
Consider a scalar particle $\sigma$ that carries a mass depending on the inflaton-VEV




- Can be embedded into a periodic potential $m_\sigma^2 = M + 0^2 + g^2 f^2 \cos(\phi/f)$ or with a monodromy structure $m_\sigma^2 = M_0^2 + g^2(\phi - 2\pi n f)^2$

see Flauger, Mirbabayi, Senatore, Silverstein (2017), and Munchmeyer and Smith. (2019) for the N-point function study

Since particle production only happens around $\eta_*$




can re-parametrize the mass without loss of generality

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

# e.o.m. during the inflation

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

$$u = \sigma/\eta$$

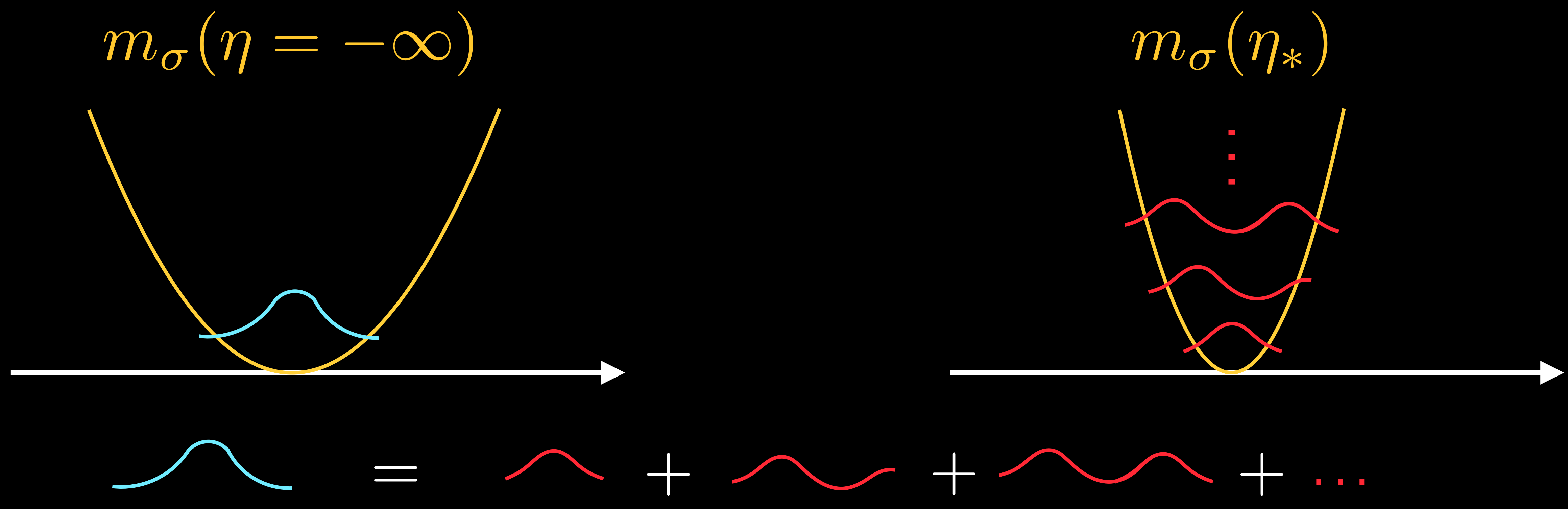
$$u'' + \left(k^2 + \frac{M^2(\eta)/H^2 - 2}{\eta^2}\right)u \equiv u'' + \omega(\eta)^2 u = 0$$

simple harmonic oscillator
with time-dependent frequency

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

# Non-adiabatic particle production

## Bogolyubov transformation




when promoting field into an operator, the initial raising and lowering operators will mix in the later time 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 mode functions

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# Non-adiabatic particle production

## Bogolyubov transformation

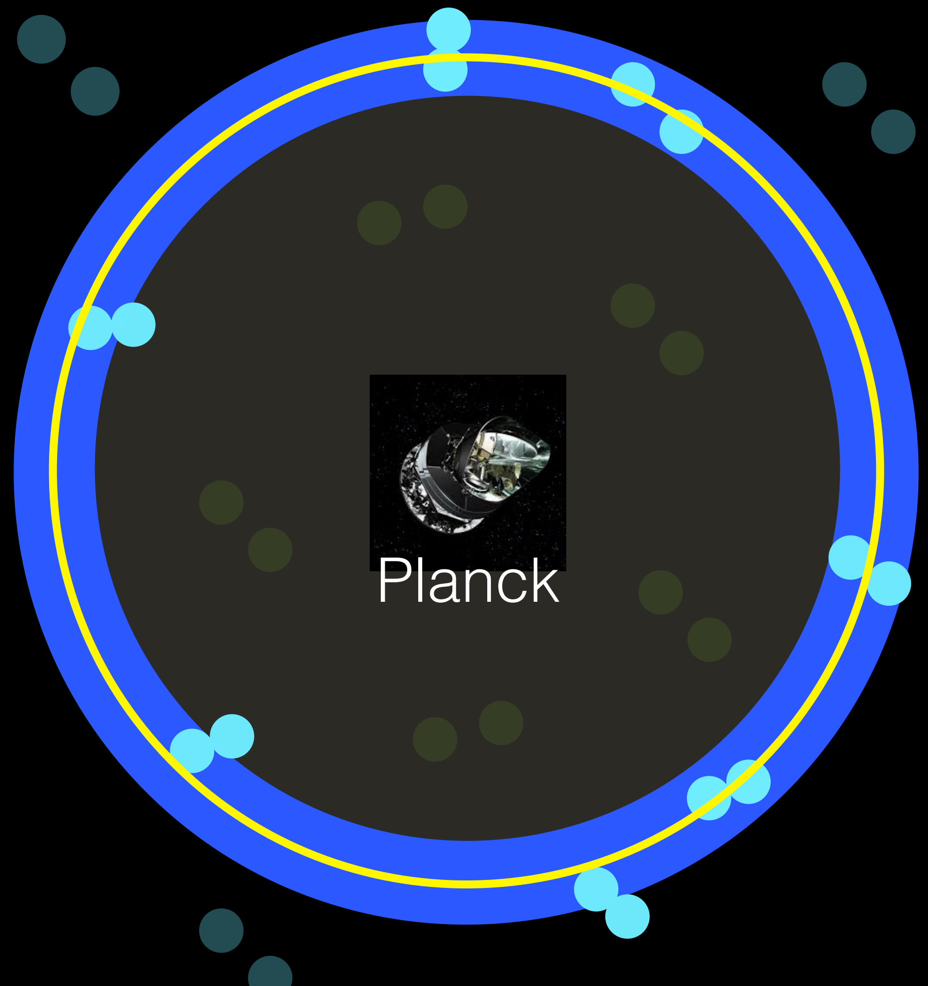


- Solve the time-dependent harmonic oscillation equation
- Choose initial condition with one sign of frequency
- Find the pre-factor of opposite signal frequency in the full solution
- The pre-factor contributes to particle production

(see the paper or backup slides for more details)

# Number of $\sigma$ 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)

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

# Back-reaction constraints

Need to make sure the scalar field

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

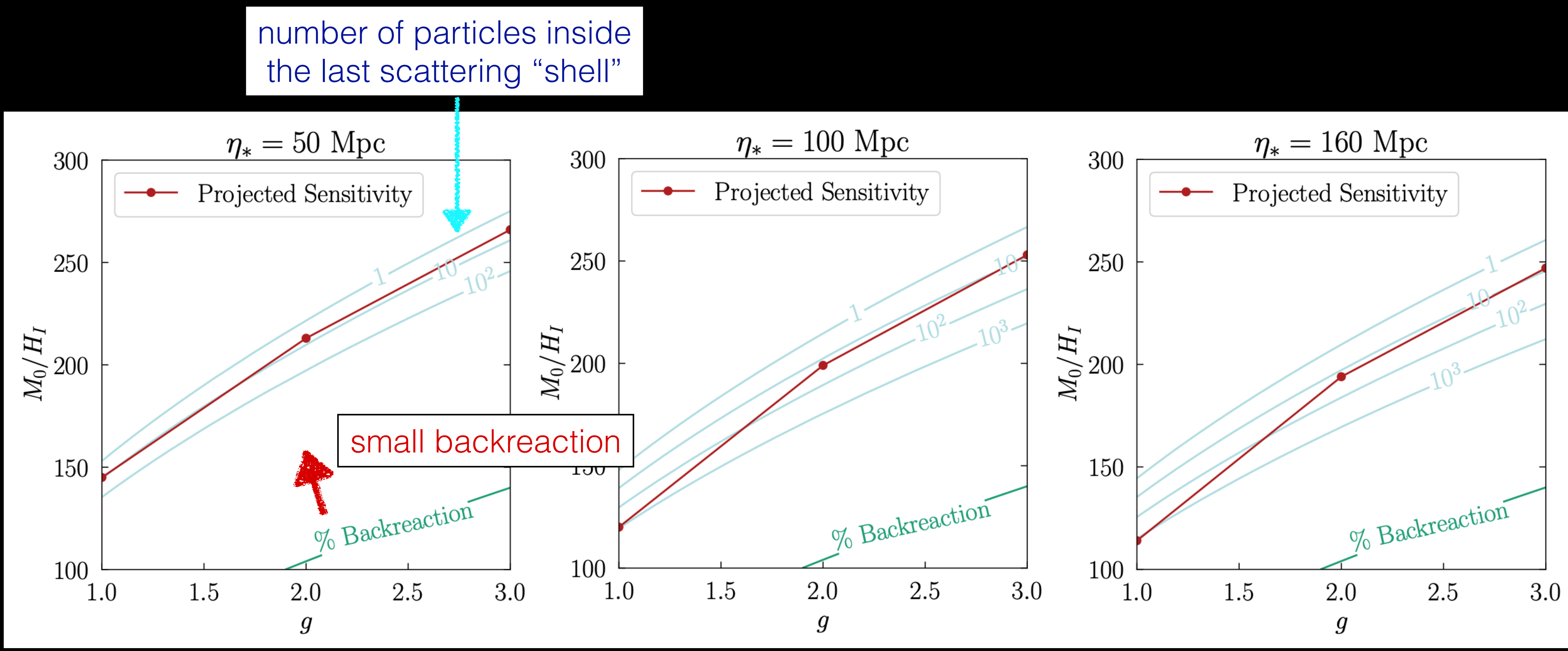
Since $\frac{\partial V}{\partial \phi} = \frac{\partial V_\phi}{\partial \phi} + g(g\phi - M)\sigma^2$

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) )

# Back-reaction constraints

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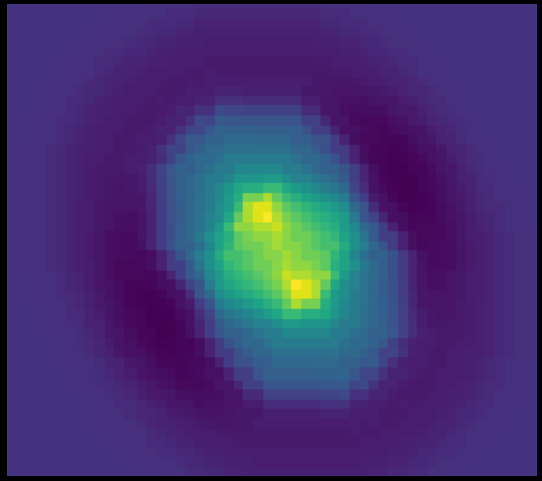
# Why pairs? Separation?

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

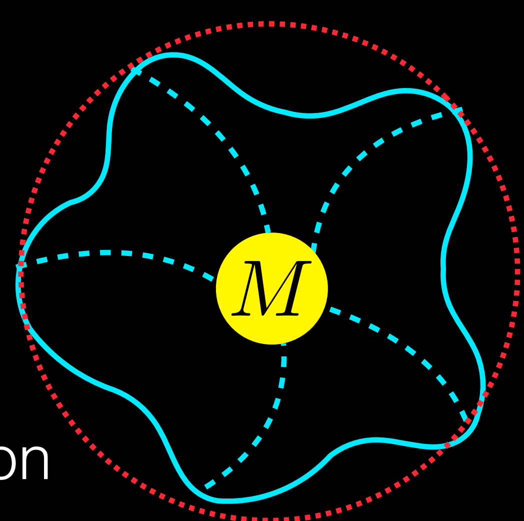
- Particles tend to be produced with low momentum. Separation given by $k^{-1}$ is comparable to the horizon size $|\eta_*|$

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

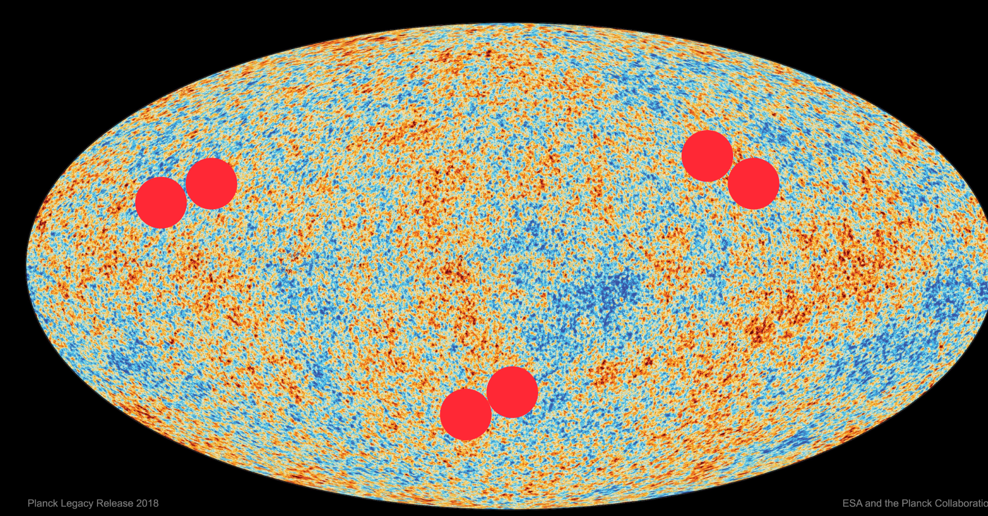


# Pairwise signals on the CMB

Time-dependent
particle mass
modifies

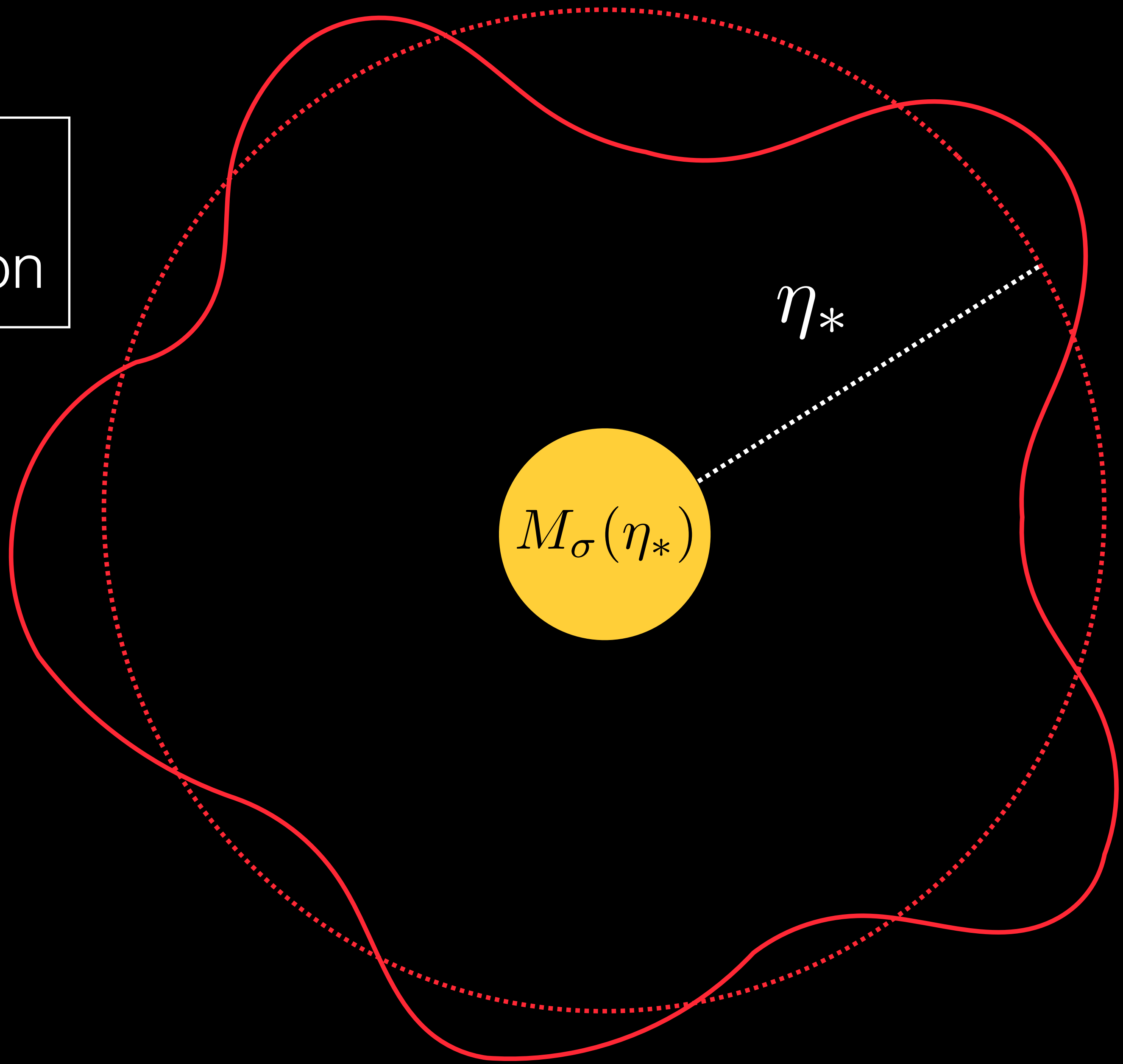



curvature perturbation



Coupling to inflaton modifies curvature perturbation in the horizon

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

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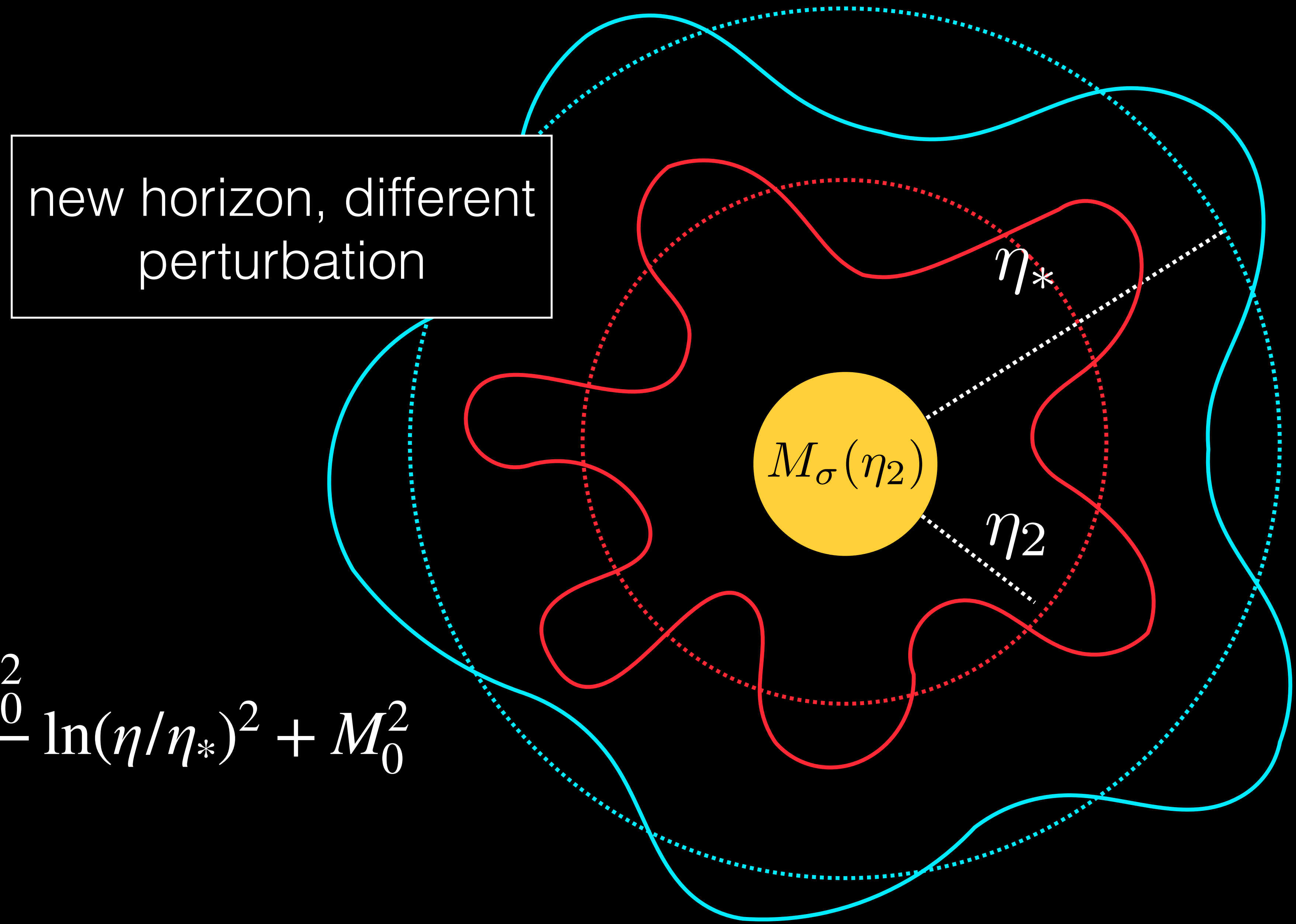
Once perturbation in the old horizon is frozen, **NEW** particle mass Modifies the perturbation in the **NEW** horizon




$$M(\eta)^2 = \frac{g^2 \dot{\phi}_0^2}{H_I^2} \ln(\eta/\eta_*)^2 + M_0^2$$

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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

# Curvature perturbation in position space

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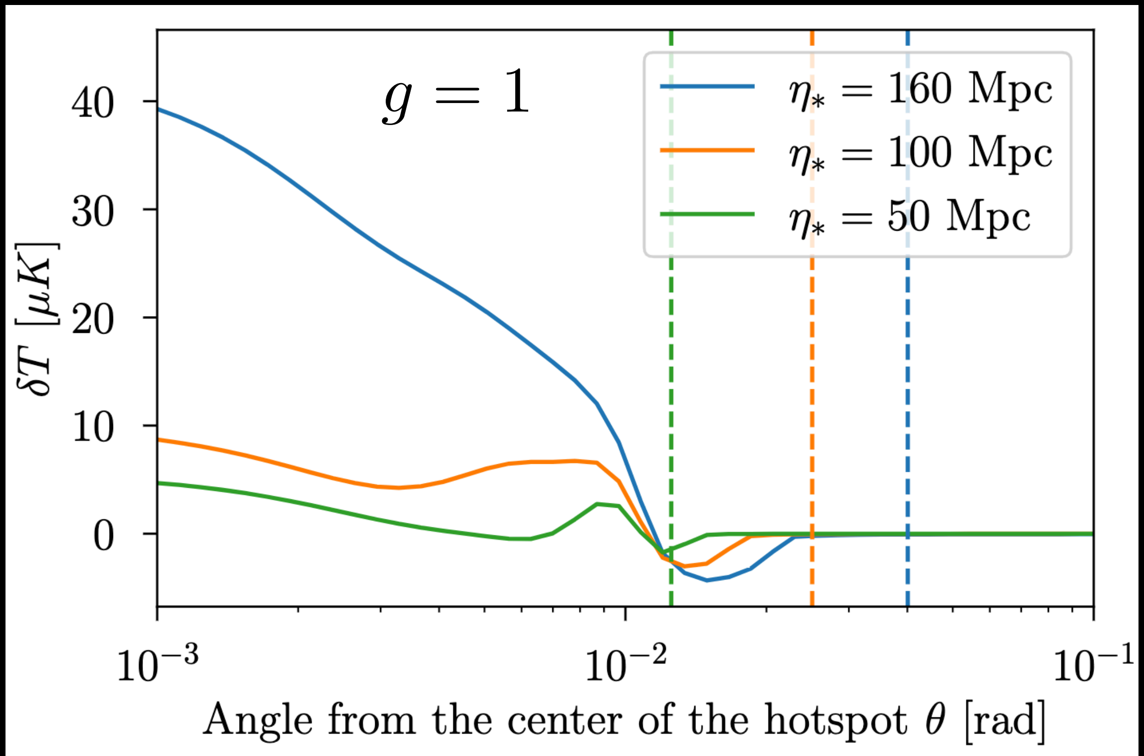
As long as the linear order expansion in time catches the mass evolution,

the primordial signal profile is universal

# Include the effect of "sub-horizon" physics

from baryon acoustic oscillations (the transfer functions)

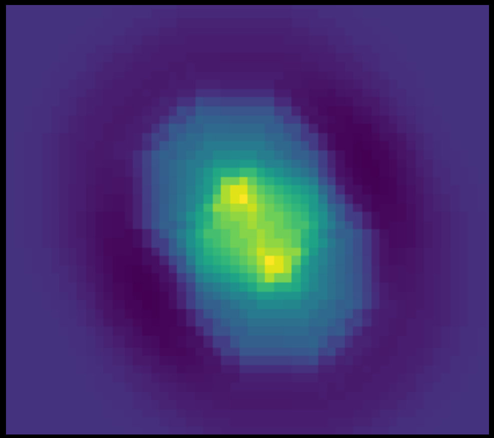



$$\eta_*$$

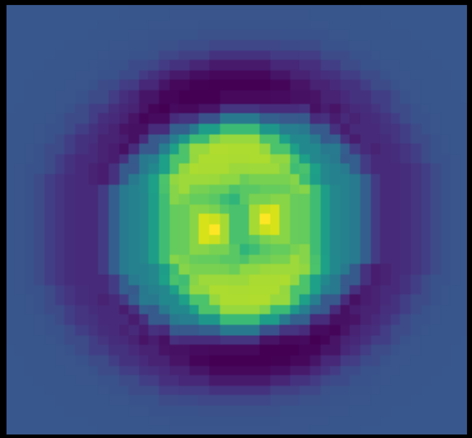
the conformal time & horizon size of particle production

Temperature profile

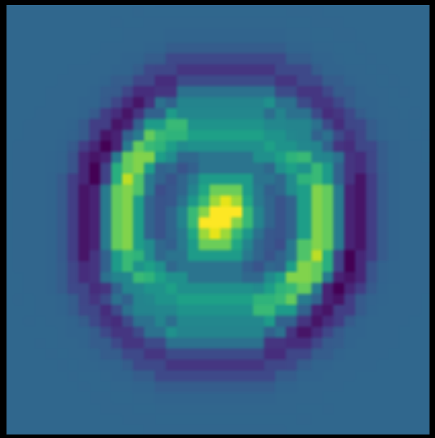
$\eta_* = 160\,\mathrm{Mpc}$



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



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



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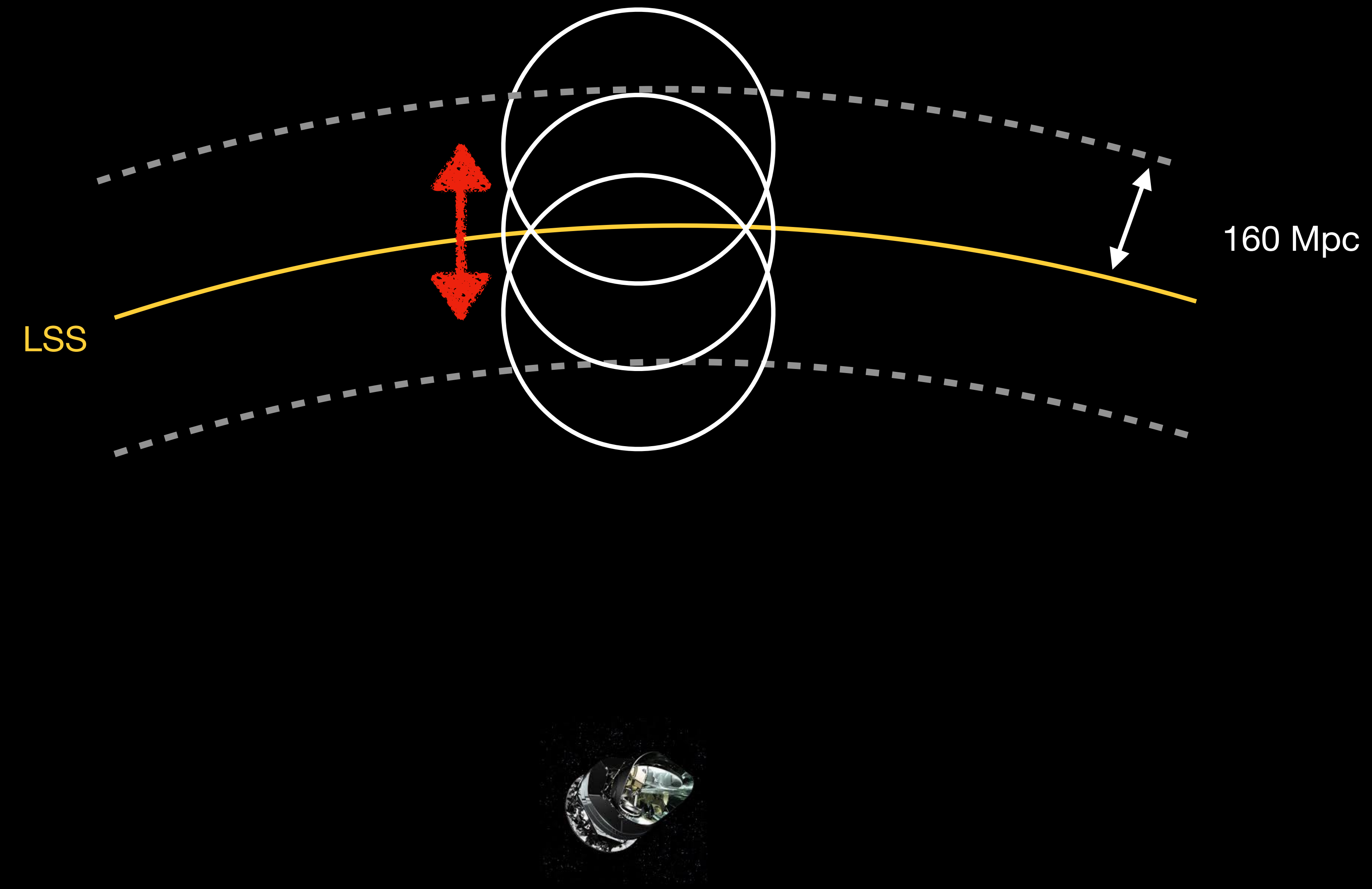
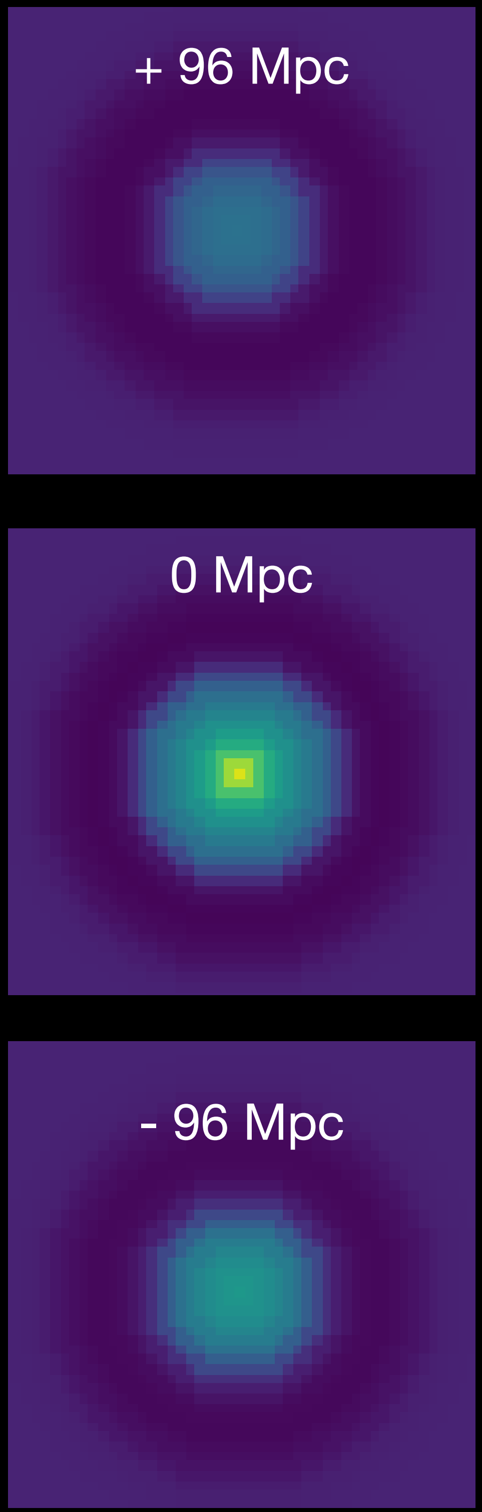
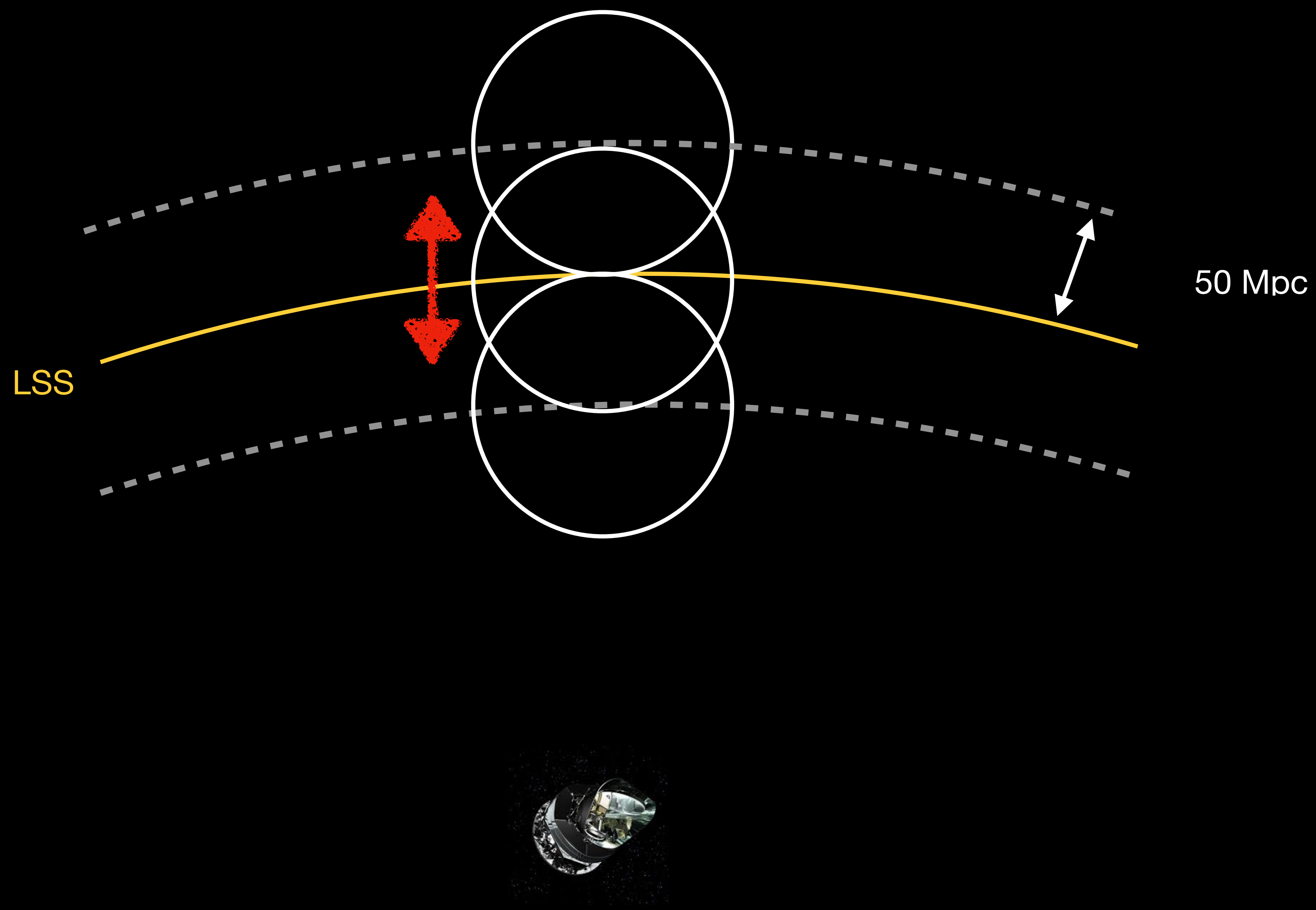
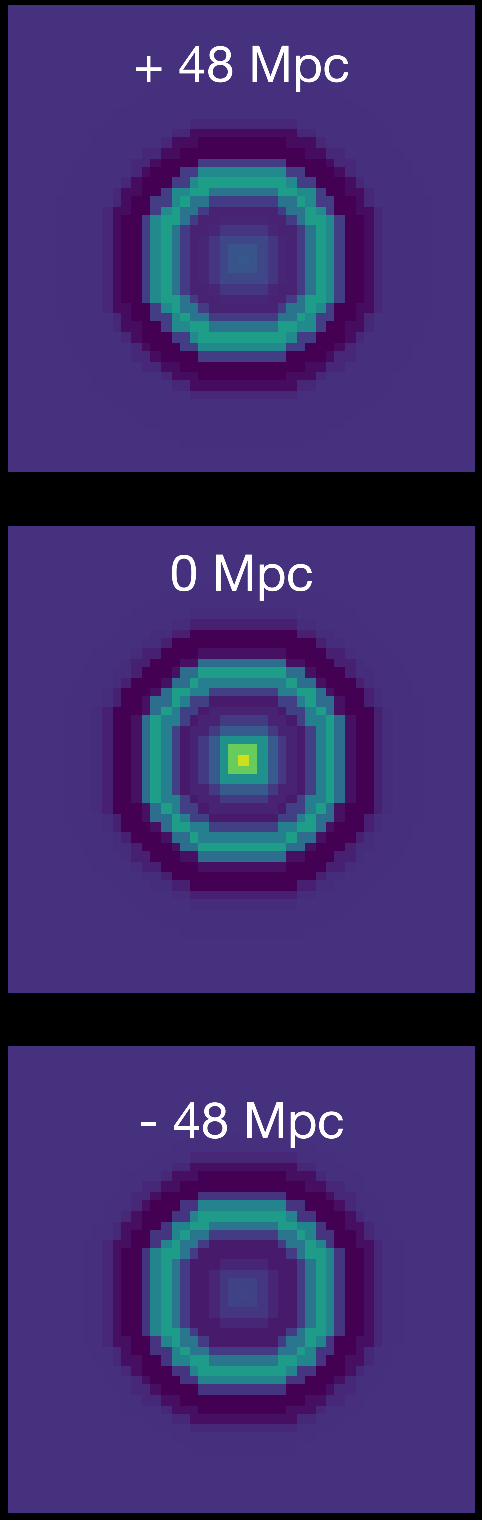
# When particles are away from the last scattering surface ($\eta_* = 160\,\mathrm{Mpc}$)



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



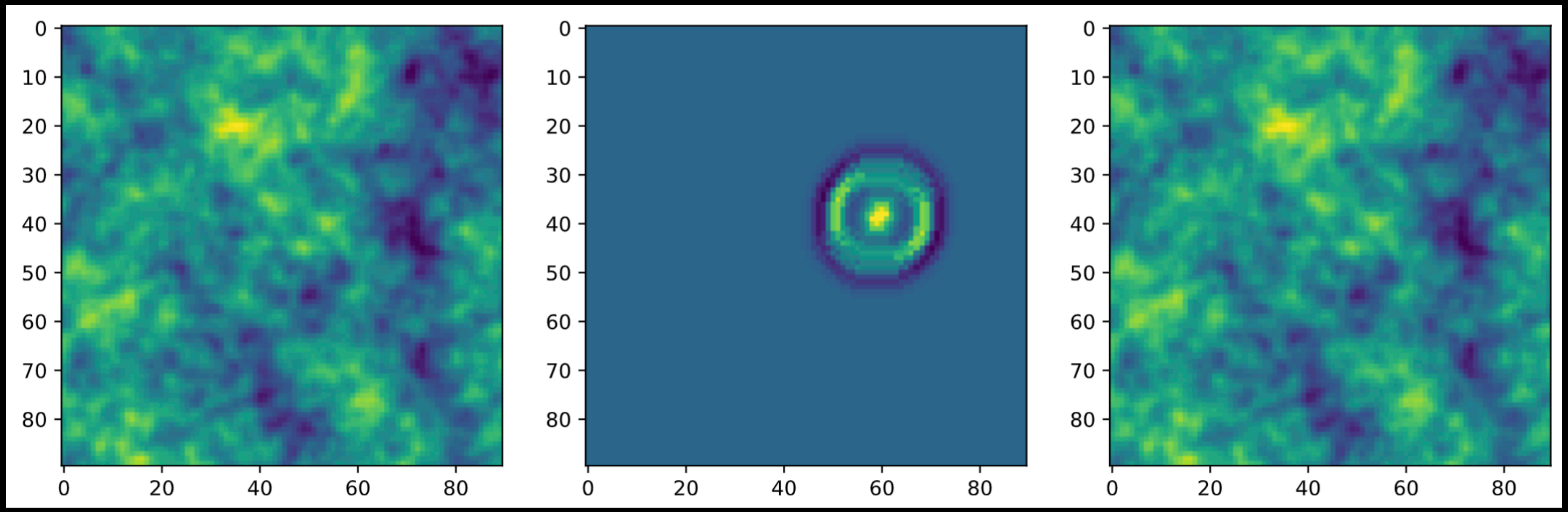



# Possibility of seeing the signal?

simulated CMB
QuickLens

signal

simulated CMB
+ signal




Assume foreground does not fake signals with size $\eta_* \gg 10\,\mathrm{Mpc}$

# Convolutional Neural Network (CNN)

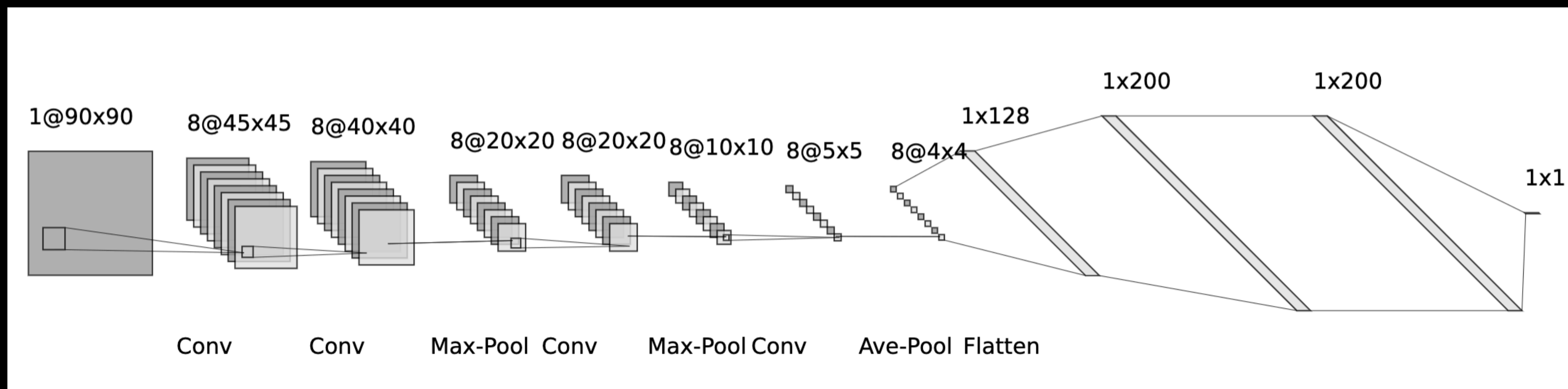
Instead of matched filter, we use the CNN
to dig out the signal from background

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

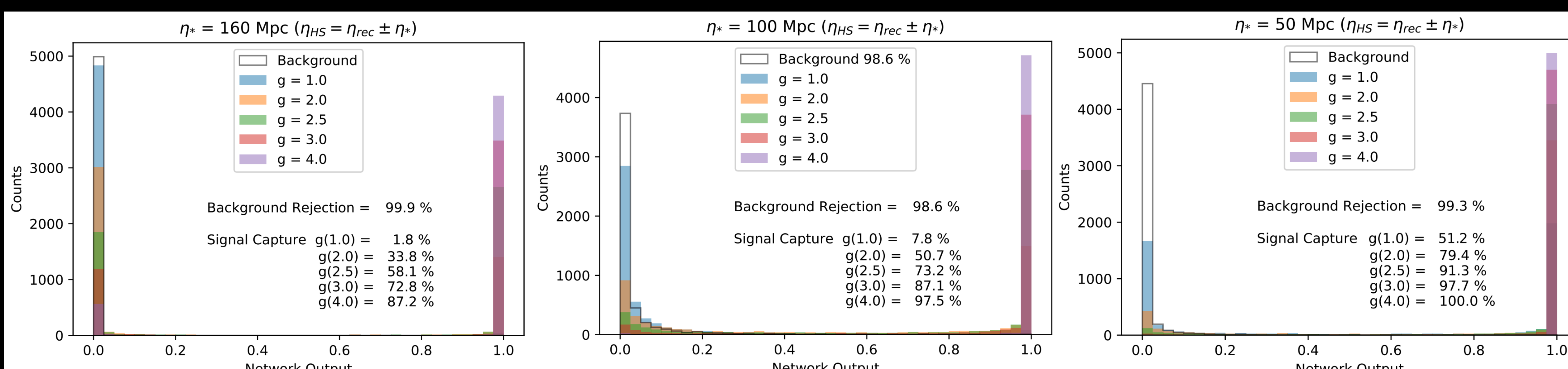
# Convolutional Neural Network (CNN)

Our CNN structure

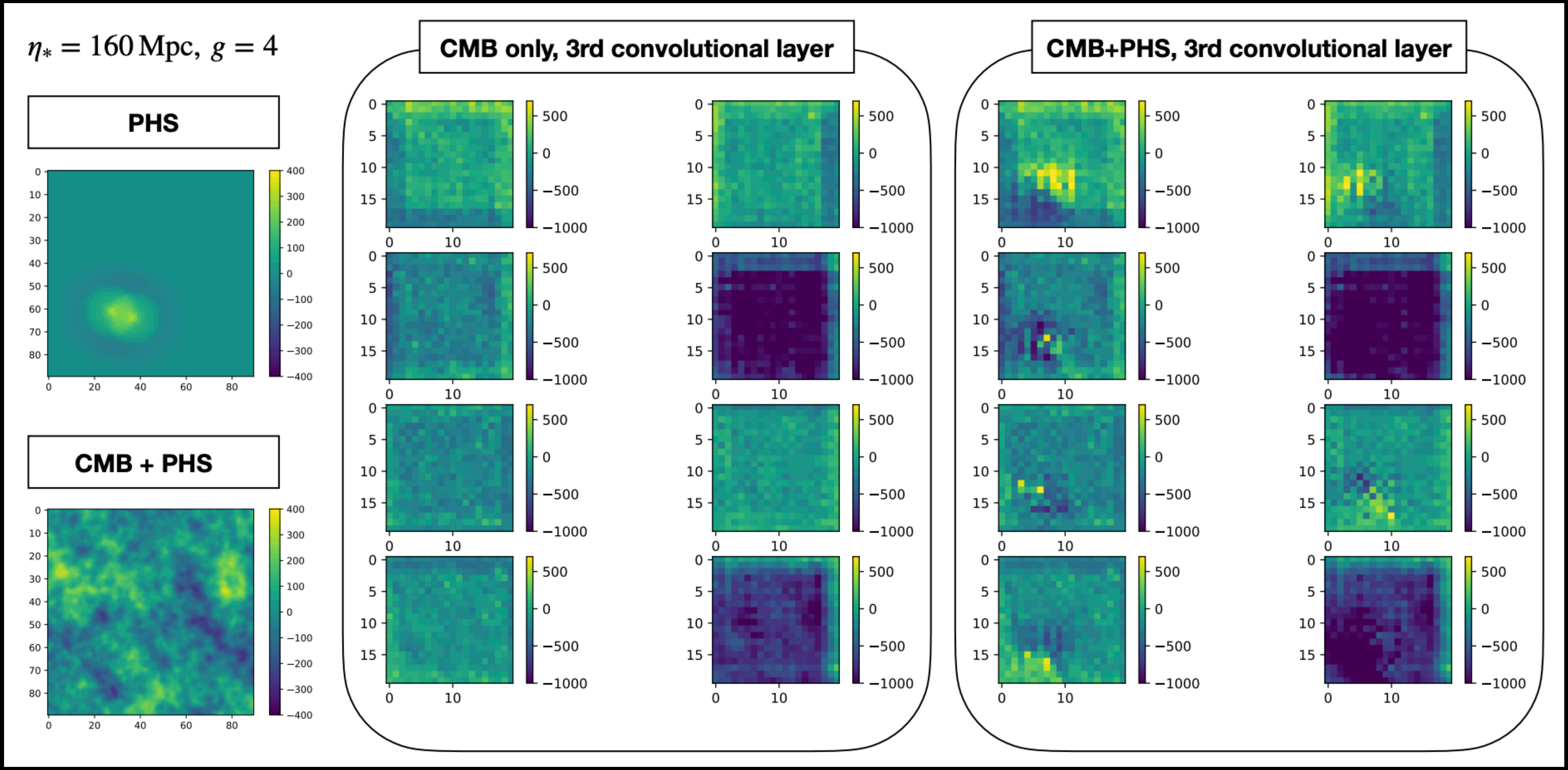



Train the CNN with 160k smaller size images (w/ & w/o signal injection)

Network outputs the probability of having a signal in the image



# Results from the 3rd convolution layer



# Result: $2\sigma$ exclusion bound

with sky fraction = 60%

| 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 |

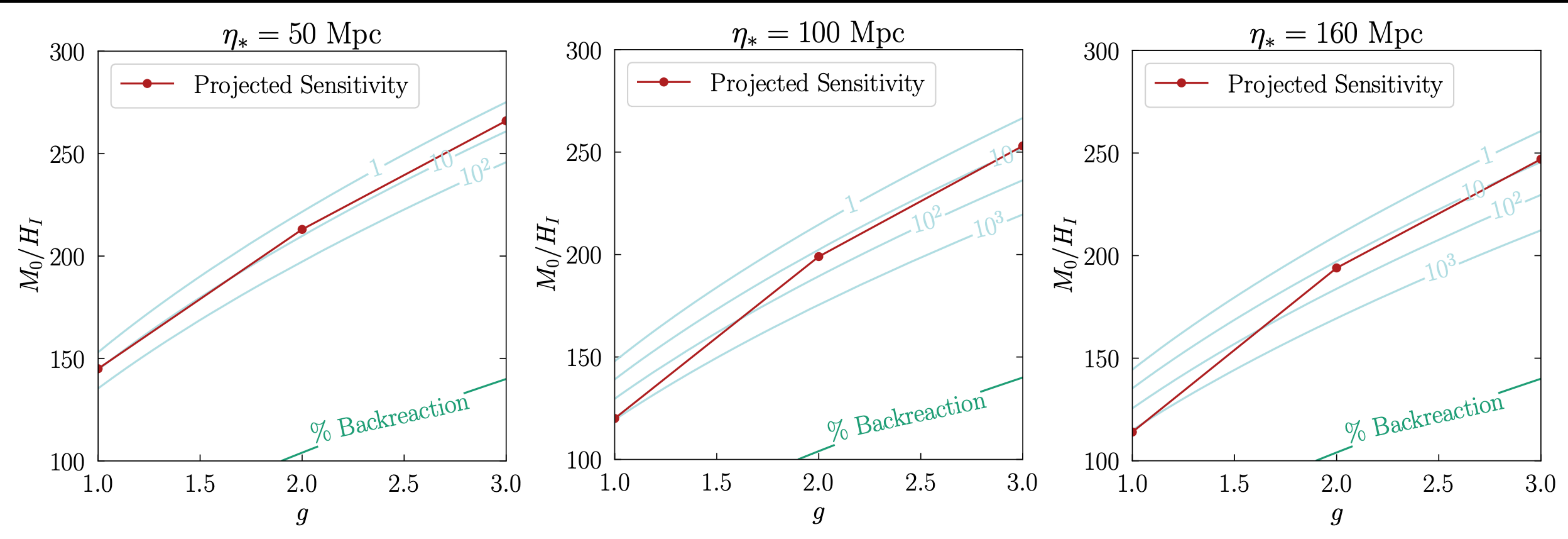
| $M_0/(g\dot{\phi}_0)^{1/2}$ | $\eta = 50$ | $\eta = 100$ | $\eta = 160$ |
|---|---|---|---|
| $g = 1$ | 2.5 | 2.0 | 2.0 |
| $g = 2$ | 2.6 | 2.4 | 2.4 |
| $g = 3$ | 2.6 | 2.5 | 2.4 |

**Table 2**. *Upper:* $2\sigma$ 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.

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

# Result: $2\sigma$ exclusion bound

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




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

# Result: $5\sigma$ 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 $5\sigma$ 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

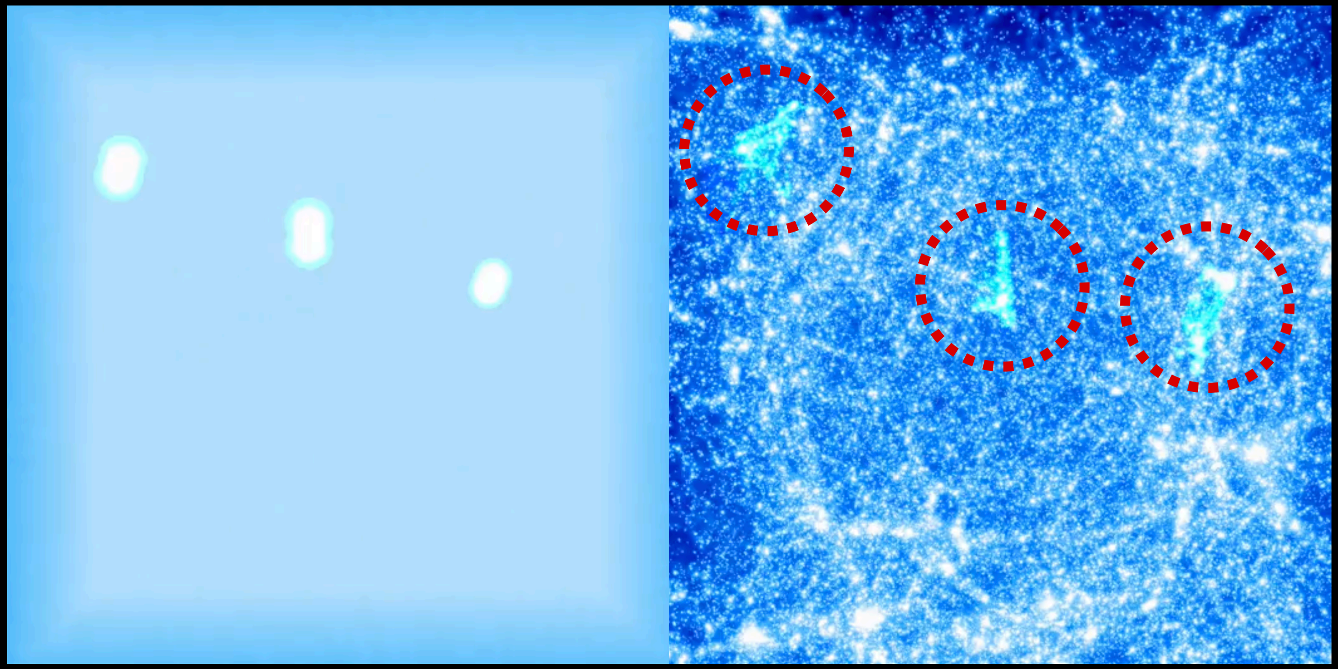
Production of heavy particles with inflaton-dependent mass generate pairwise spots on the CMB map

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

CNN can provide a powerful position space search of the signal

More things to explore:

- Search on real Planck image?
- Large Scale Structure signals?



# Backup Slides

# More details on the $\sigma$ production

Expand $\sigma$ mass around
inflaton value at $\eta_*$
(min- $m_\sigma$ 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

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

$$\tau \to -\infty$$

# 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

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

$\beta$ $\qquad$ $\alpha$ $\qquad |\alpha|^2 - |\beta|^2 = 1$

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

# Curvature perturbation in position space

Maldacena (1508.01082)

Fialkov et. al. (0911.2100)

Produced heavy particles backreact on spacetime

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

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 fluctuation

Profile in the position space

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

# 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

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

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

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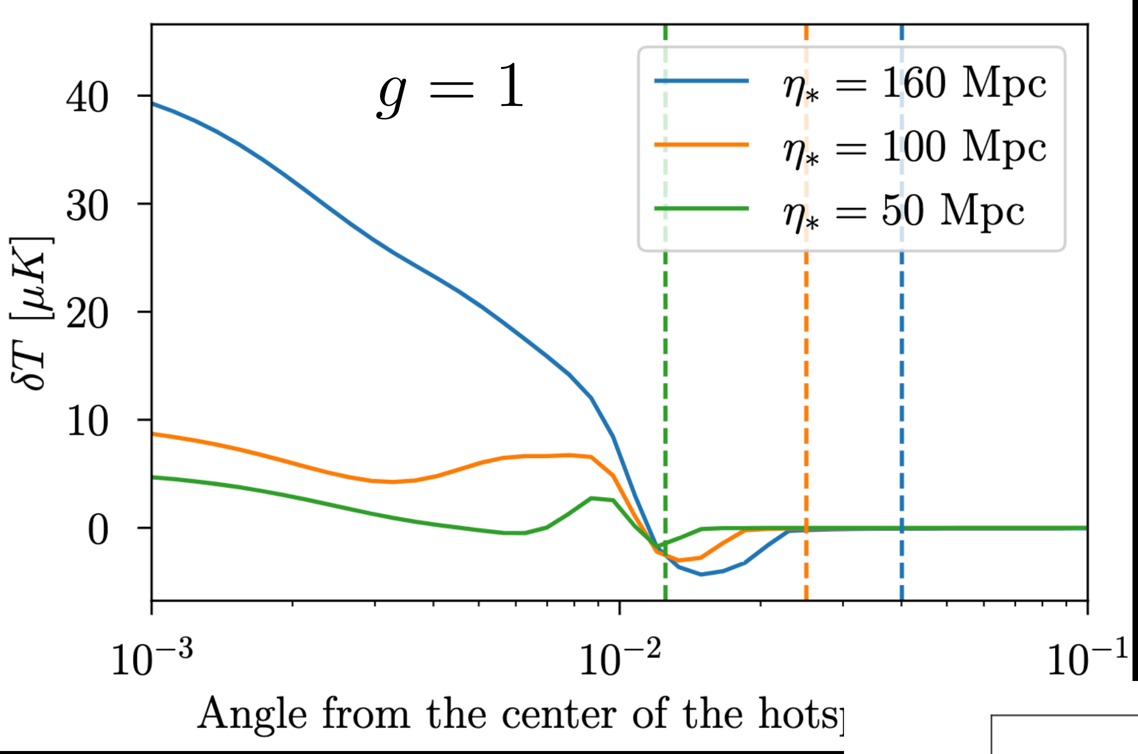
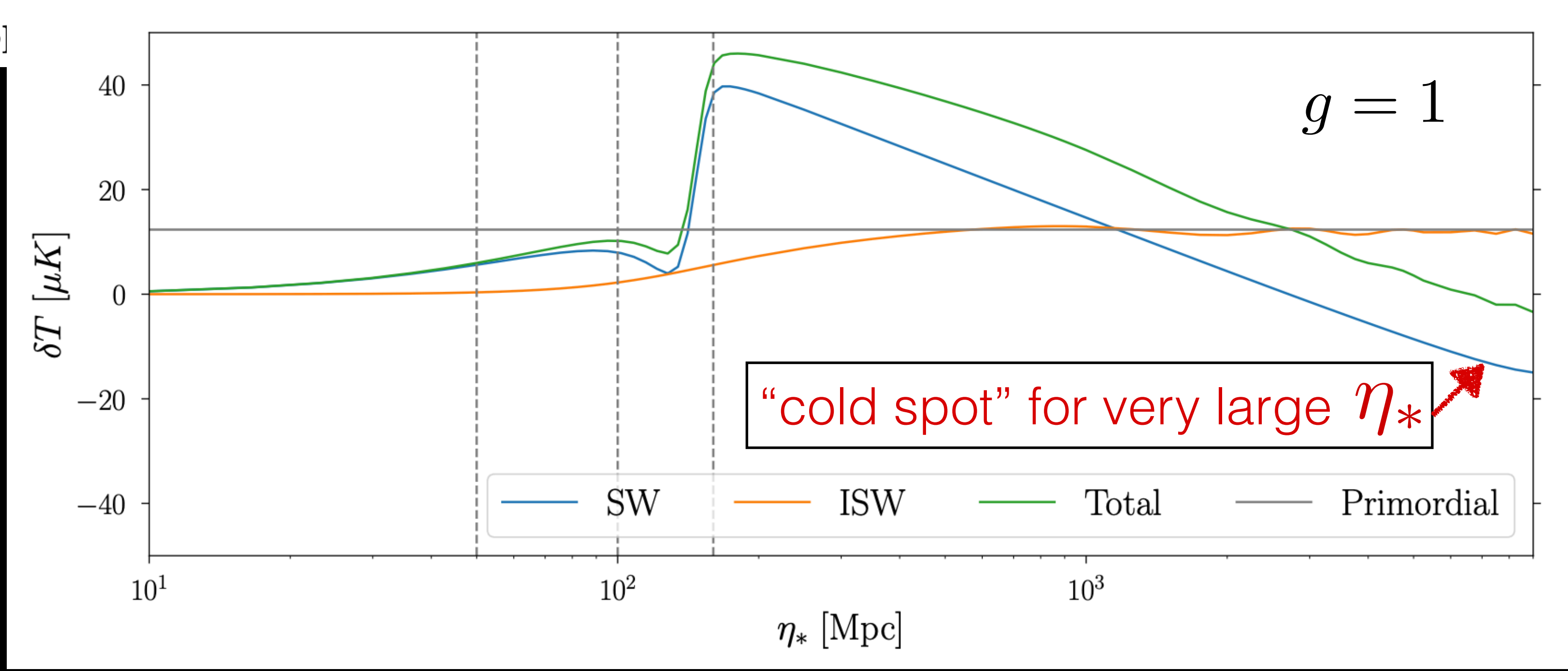
# Include the effect of "sub-horizon" physics

from baryon acoustic oscillations (the transfer functions)



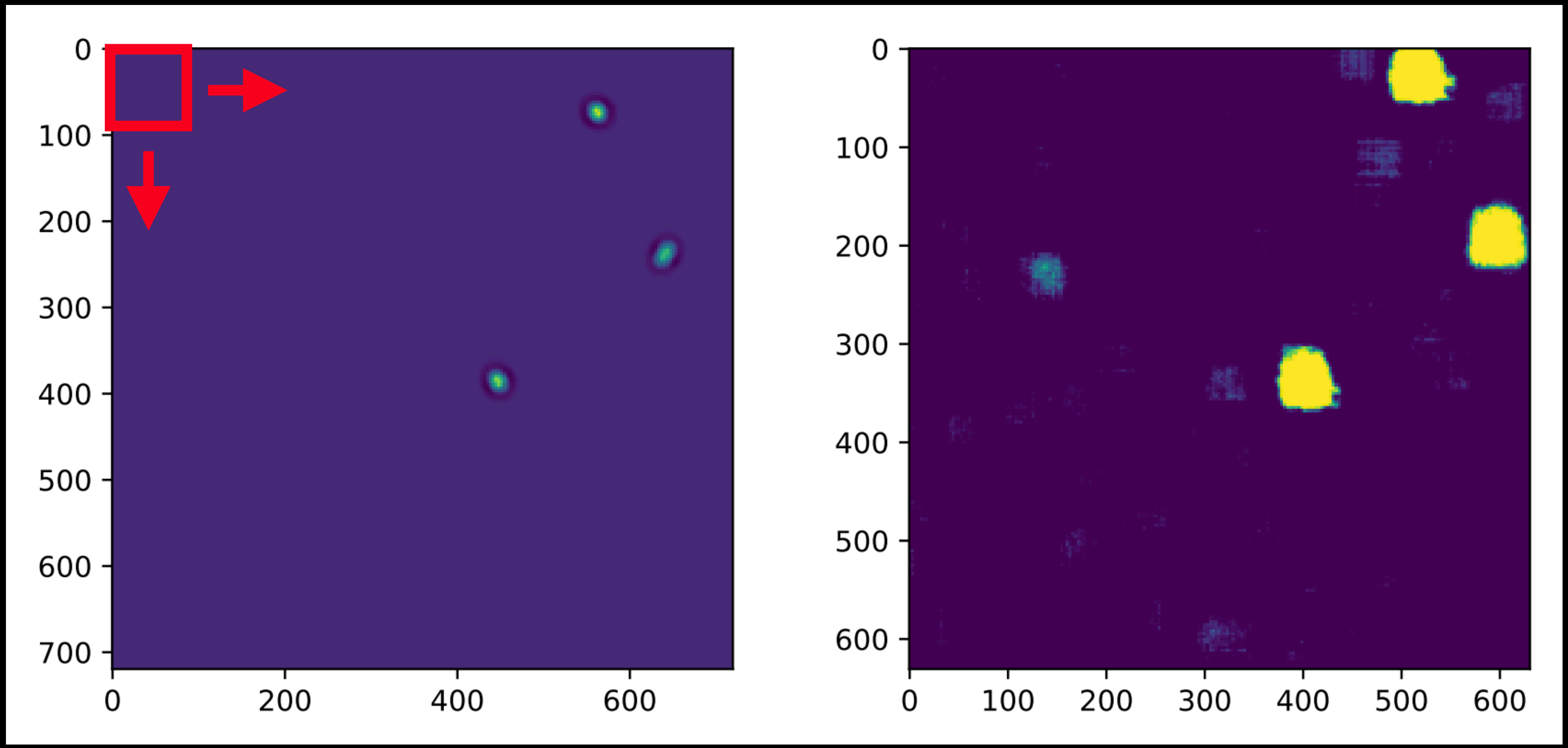

temperature of central hotspot pixel




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

# 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