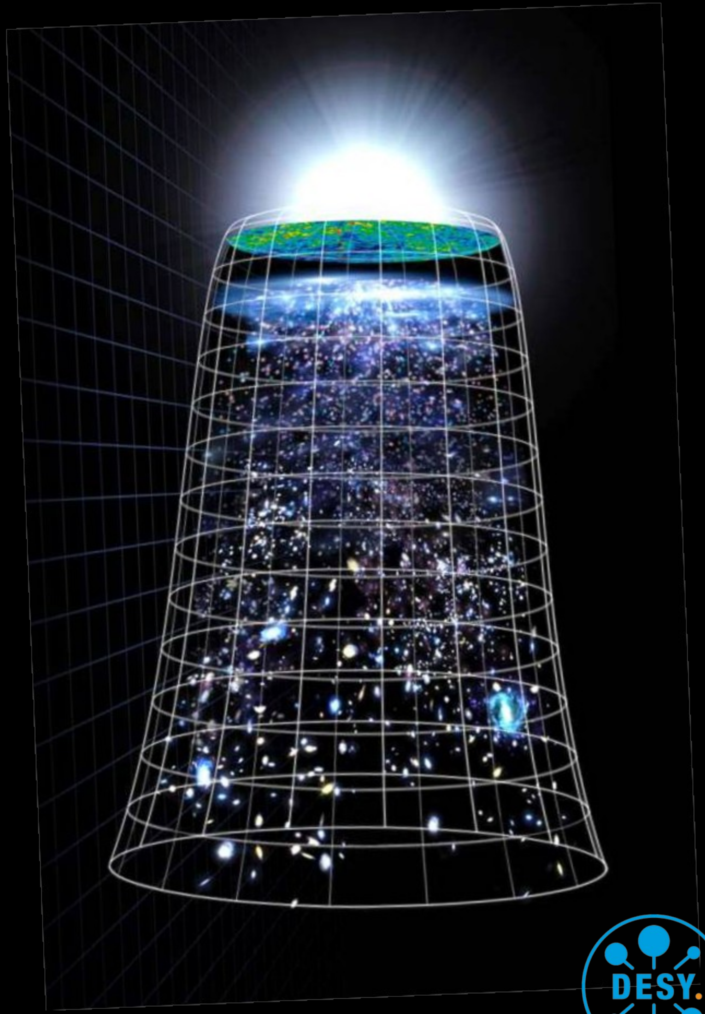
# CMB hotspots from tachyonic instability of the Higgs potential

Julia Ziegler
In collaboration with: Sven Ha, Gudrid Moortgat-Pick, Bibhushan Shakya



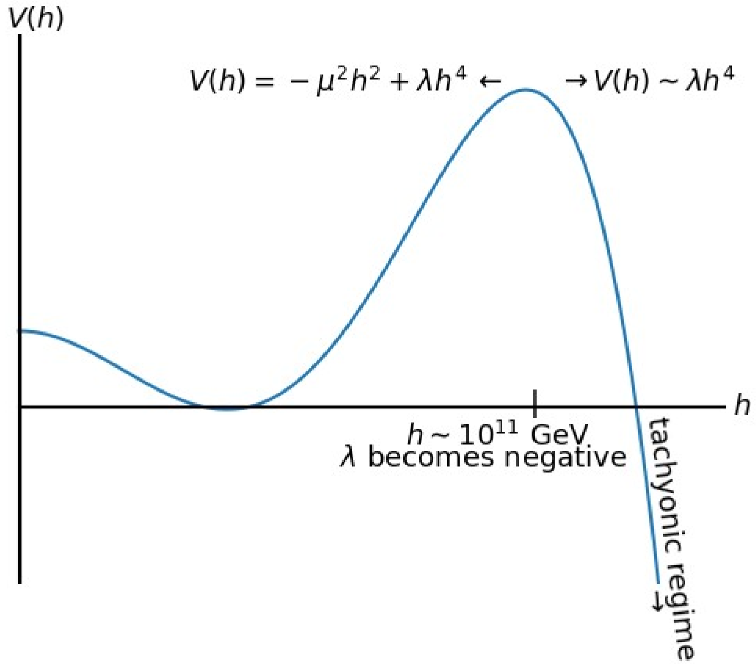
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE
DESY.

# Tachyonic instability of the Higgs potential

B. Shakya, arXiv: 2301.08754

Standard Model Higgs potential:

$$V(h) = -\mu^2 h^2 + \underbrace{\underbrace{\lambda}_{\approx -0.001 \text{ at high energies, } h \approx 10^{11}\text{ GeV}} h^4}_{\text{Dominates at high energies}}$$




→ potential runs negative

# Tachyonic instability of the Higgs potential

B. Shakya, arXiv: 2301.08754

- Potential runs negative at $h \approx 10^{11}$ GeV

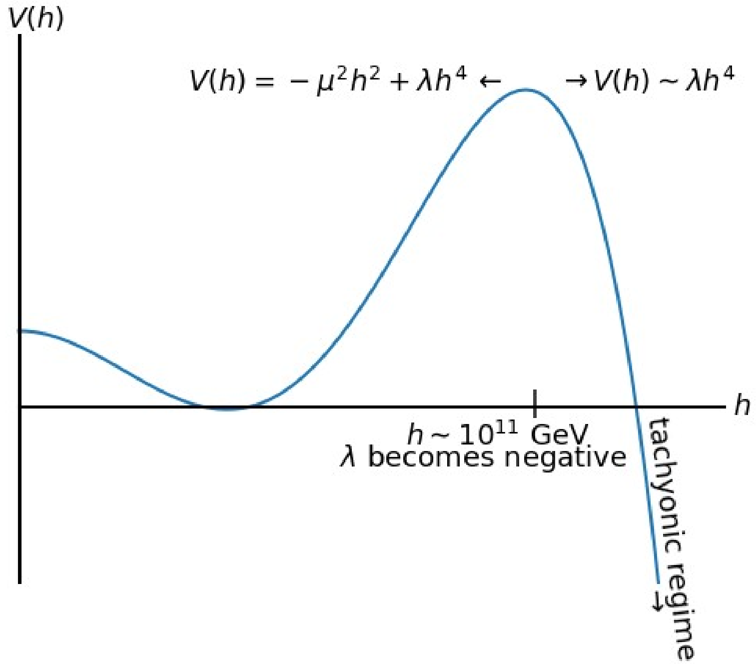
  → exponential enhancement of Higgs particle production:

- Equation of motion of Higgs field:

$$\ddot{h} + 3H\dot{h} = \frac{dV}{dh}$$

- Hubble friction causes Higgs field to slow-roll for several e-folds until $h \approx \sqrt{(-3/4\lambda)} \approx 17.3H$
- After this Hubble friction becomes negligible, Higgs field diverges quickly. Inflaton energy density dominates over Higgs potential energy until $h \approx (-3/8\pi\lambda)^{1/4} \sqrt{(HM_{PL})} \approx 3\sqrt{(HM_{PL})}$
- Higgs particle production becomes important for:

  $17.3H < h < 3\sqrt{(HM_{PL})}$



# Tachyonic instability of the Higgs potential

B. Shakya, arXiv: 2301.08754

- Higgs particle production becomes important for:

  $17.3H < h < 3\sqrt{(HM_{PL})}$

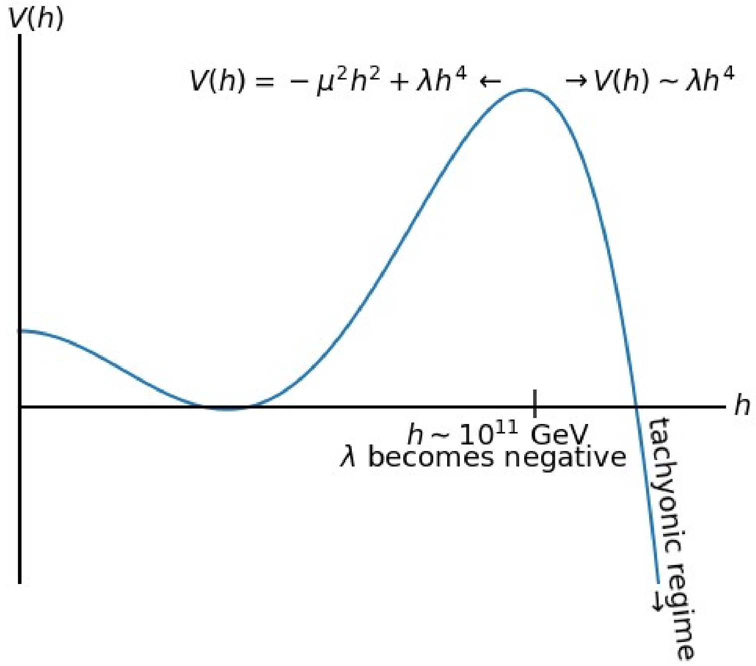
- Higgs mass evolves non-adiabatically
- Modes with momenta $k \lessapprox |m_h|$ get populated with occupation number

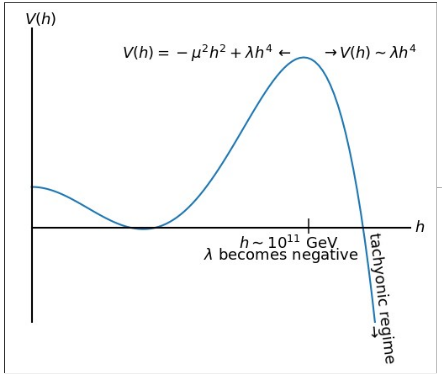
  $n_k = |\beta_k|^2 \sim 1$

- For tachyonic masses: $\beta_k$ gets enhanced exponentially as:

  $\beta \sim \exp(-i\omega t)$, $\omega^2 = m_h^2 + k^2$

- Observable effects: gravitational waves, primordial black holes (PBH), imprints on CMB



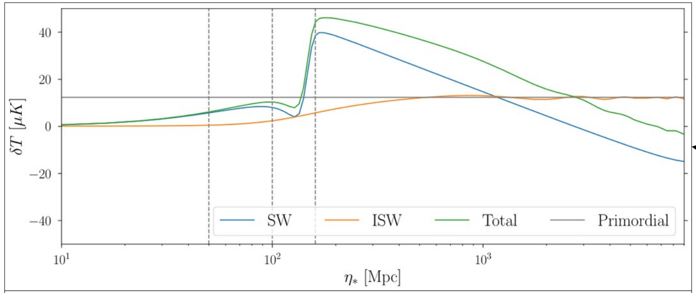



Inflation, $10^{-34}$ s:
Higgs particle production

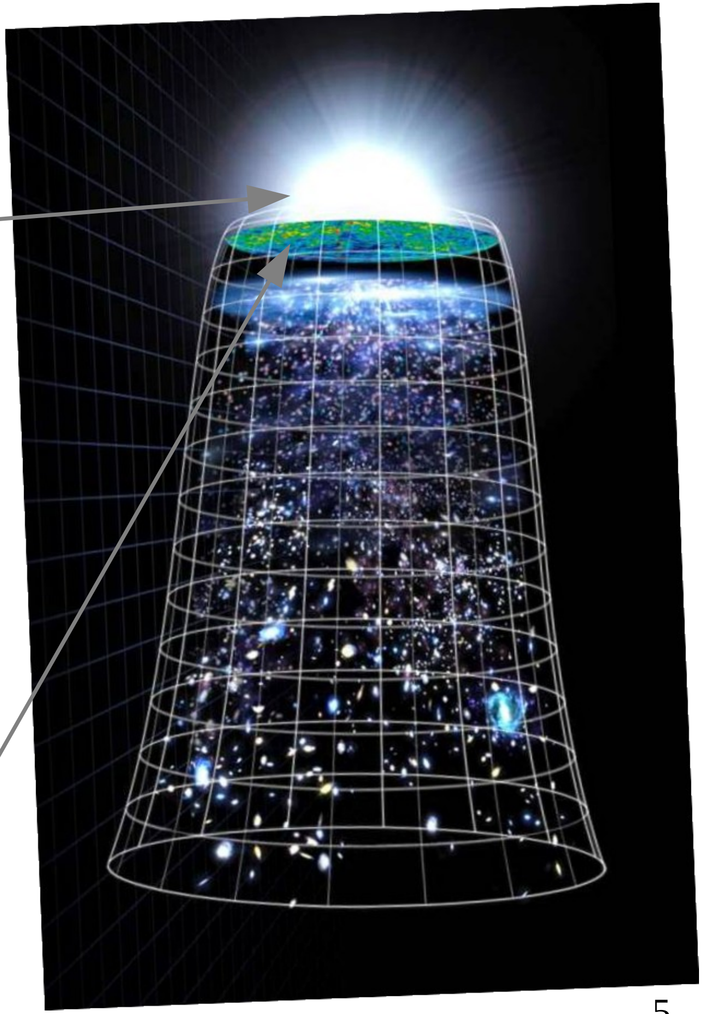
Massive Higgs particles modify curvature perturbations

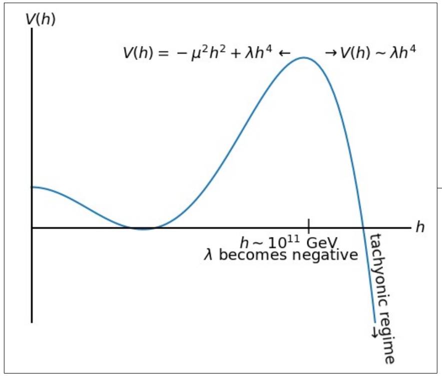
Localized curvature perturbations cause CMB hotspots

Recombination, $10^{5}$ y:
CMB radiation which we observe today




J. H. Kim, S. Kumar, A. Martin, Y. Tsai,
arXiv: 2107.09061



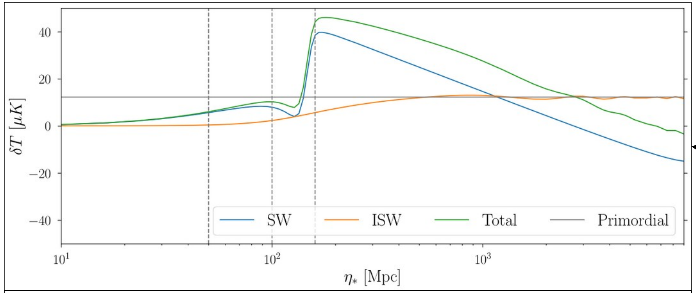



Inflation, $10^{-34}$ s: Higgs particle production

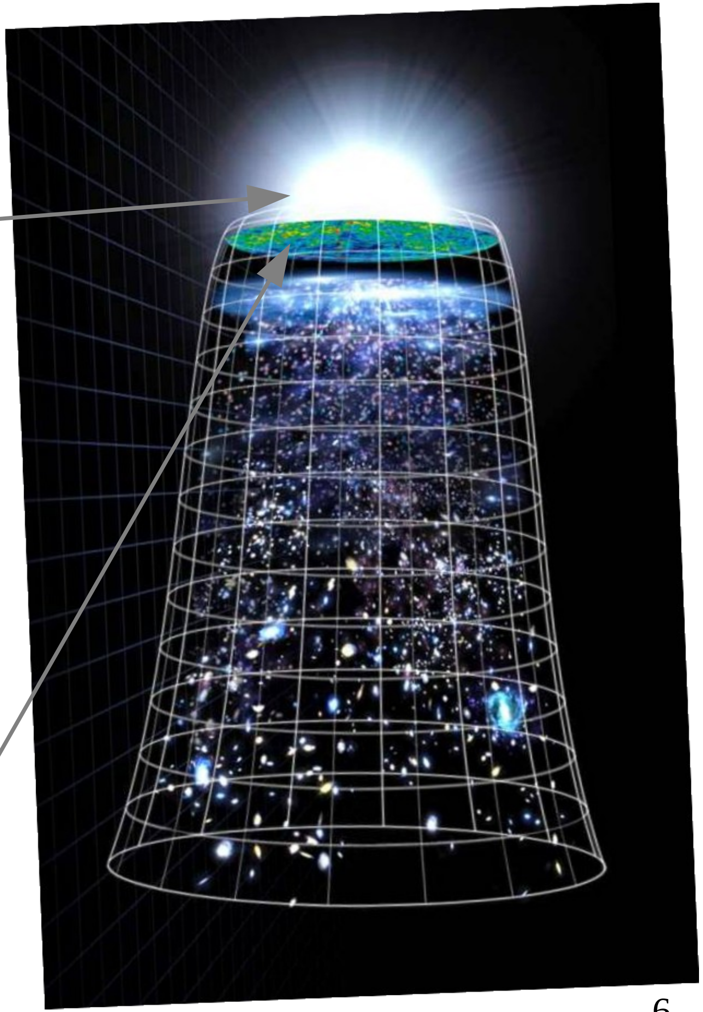
Massive Higgs particles modify curvature perturbations

Localized curvature perturbations cause CMB hotspots

Recombination, $10^5$ y: CMB radiation which we observe today




J. H. Kim, S. Kumar, A. Martin, Y. Tsai, arXiv: 2107.09061



# Massive particles → curvature perturbations

J. H. Kim et al, arXiv: 2107.09061

- Action of a single heavy particle with mass M:

$$S = -\int d\eta M \sqrt{-\dot{x}^{\mu 2}}$$
$$\approx -\int dt M \sqrt{-g_{00}}$$
$$= -\int dt M - \int dt M \frac{\dot{\zeta}}{H}$$

Comoving curvature perturbation (gauge invariant):

$$\zeta = \underbrace{\Psi}_{\text{Generalized gravitational potential}} + H \frac{\delta\phi}{\underbrace{\dot{\phi}}_{\text{Inflaton field}}}$$

# Massive particles → curvature perturbations

J. H. Kim et al, arXiv: 2107.09061

- Action of a single heavy particle with mass M:

$$
\begin{aligned}
S &= -\int d\eta M\sqrt{-\dot{x}^{\mu 2}} \\
&\approx -\int dt M\sqrt{-g_{00}} \\
&= -\int dt M - \int dt M\frac{\dot{\zeta}}{H}
\end{aligned}
$$

Comoving curvature perturbation (gauge invariant):

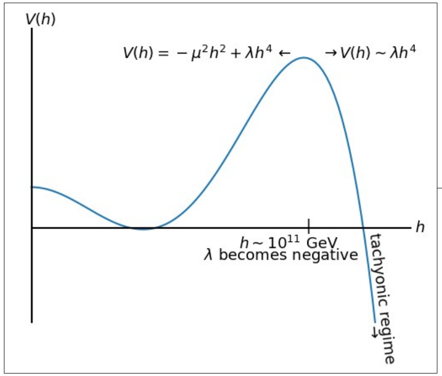
$$\zeta = \underbrace{\Psi}_{\text{Generalized gravitational potential}} + H\underbrace{\frac{\delta\phi}{\dot{\phi}}}_{\text{Inflaton field}}$$

→ switch to conformal time η, switch to momentum (k)-space, compute one point function using in-in formalism, integrate over time → curvature perturbation:

$$\langle\zeta\rangle = \frac{H^4}{\dot{\phi}_0^2}\int_{\eta_*}^{0} d\eta \frac{M}{H}\frac{\eta}{k}\sin(k\eta)e^{-i\vec{k}\vec{x}}$$

Hubble factor

Conformal time of particle production

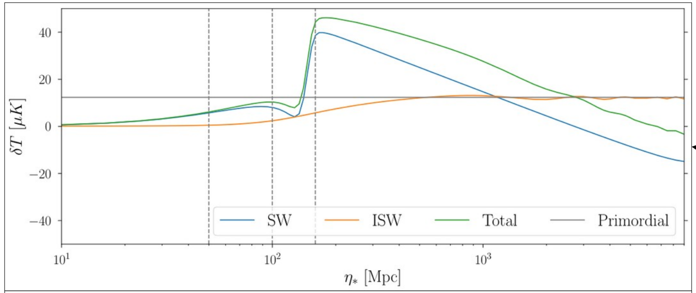



Inflation, $10^{-34}$ s: Higgs particle production

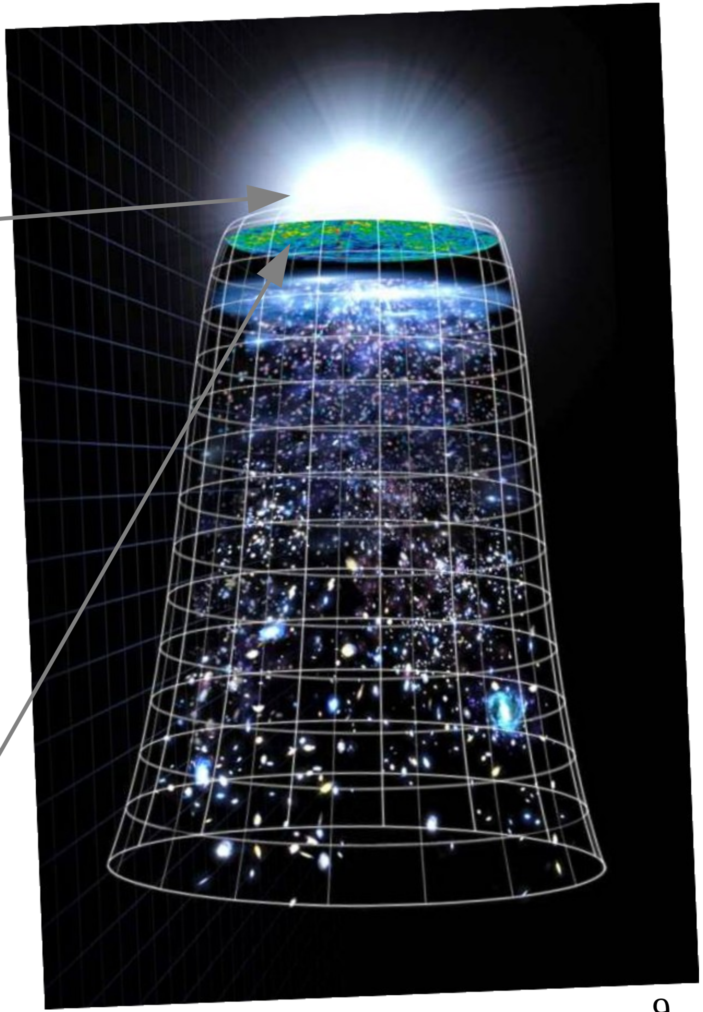
Massive Higgs particles modify curvature perturbations

Localized curvature perturbations cause CMB hotspots

Recombination, $10^5$ y: CMB radiation which we observe today




J. H. Kim, S. Kumar, A. Martin, Y. Tsai, arXiv: 2107.09061



# Curvature perturbations → CMB temperature anisotropies

A. Riotto, arXiv: 0210162

- First order perturbation of Friedmann-Lemaitre-Robertson-Walker metric:

$$g_{\mu\nu} = g^{(0)}_{\mu\nu} + \delta g_{\mu\nu}$$

  can be decomposed into scalar, vector and tensor perturbations

- Scalar perturbations: spin 0 → response of metric to irrotational distribution of matter → interesting for this work

# Curvature perturbations → CMB temperature anisotropies

A. Riotto, arXiv: 0210162

- First order perturbation of Friedmann-Lemaitre-Robertson-Walker metric:

$$g_{\mu\nu} = g^{(0)}_{\mu\nu} + \delta g_{\mu\nu}$$

- Line element, considering only scalar perturbations:

$$\begin{aligned} ds^2 &= g_{\mu\nu} dx^\mu dx^\nu \\ &= a^2\Big[-(1+\underbrace{2\Phi}_{\text{Distortion of scale factor a}})d\tau^2 + 2\underbrace{\partial_i B}_{\text{= 0 in Newtonian gauge}} d\tau dx^i + \big((1-\underbrace{2\Psi}_{\text{Generalized gravitational potential}})\delta_{ij} + \underbrace{D_{ij}E}_{\text{= 0 in Newtonian gauge}}\big)dx^i dx^j\Big] \end{aligned}$$

# Curvature perturbations → CMB temperature anisotropies

J. Lesgourges, arXiv: 1302.4640

- Temperature anisotropy due to curvature perturbations:

$$\frac{\delta T}{T} = \underbrace{\Theta}_{\text{Temperature anisotropy measured by observer}} = \int_{\eta_i}^{\eta_0} d\eta [g(\Theta_0 + \Psi + \hat{n} \cdot \vec{v}_b) + e^{-\tau}(\Phi' + \Psi')]$$

$$\approx (\underbrace{\underbrace{\Theta_0}_{\text{Temperature anisotropy at point of last scattering}} + \Psi}_{\textbf{Sachs-Wolfe effect}} + \underbrace{\hat{n} \cdot \vec{v}_b}_{\textbf{Doppler effect, can be neglected}})|_{dec} + \underbrace{\int_{\eta_{dec}}^{\eta_0} d\eta (\Phi' + \Psi')}_{\textbf{Integrated Sachs-Wolfe effect}}$$

Instantaneous decoupling approximation

Line element, considering only scalar perturbations:

$$ds^2 = a^2[-(1+2\Phi)d\tau^2 + (1-2\Psi)dx^i dx_i]$$

# Curvature perturbations → CMB temperature anisotropies

J. Lesgourges, arXiv: 1302.4640

- Temperature anisotropy due to curvature perturbations:

$$\begin{aligned}\frac{\delta T}{T} = \Theta &= \int_{\eta_i}^{\eta_0} d\eta [g(\Theta_0 + \Psi + \hat{n}\cdot\vec{v}_b) + e^{-\tau}(\Phi' + \Psi')] \\ &\approx (\Theta_0 + \Psi + \hat{n}\cdot\vec{v}_b)|_{dec} + \int_{\eta_{dec}}^{\eta_0} d\eta(\Phi' + \Psi') \\ &= f_{SW}(k)\langle\zeta(\vec{k})\rangle + f_{ISW}(k)\langle\zeta(\vec{k})\rangle\end{aligned}$$

Instantaneous decoupling approximation

Neglect Doppler contribution

Line element, considering only scalar perturbations:

$$ds^2 = a^2[-(1+2\Phi)d\tau^2 + (1-2\Psi)dx^i dx_i]$$

# Curvature perturbations → CMB temperature anisotropies

J. Lesgourges, arXiv: 1302.4640

- Temperature anisotropy due to curvature perturbations:

$$\frac{\delta T}{T} = \Theta = \int_{\eta_i}^{\eta_0} d\eta [g(\Theta_0 + \Psi + \hat{n}\cdot\vec{v}_b) + e^{-\tau}(\Phi' + \Psi')]$$

$$\approx (\Theta_0 + \Psi + \hat{n}\cdot\vec{v}_b)|_{dec} + \int_{\eta_{dec}}^{\eta_0} d\eta(\Phi' + \Psi')$$

$$= f_{SW}(k)\langle\zeta(\vec{k})\rangle + f_{ISW}(k)\langle\zeta(\vec{k})\rangle$$

Instantaneous decoupling approximation

Neglect Doppler contribution

Get from CLASS:
https://lesgourg.github.io/class_public/class.html#download

One point function of
comoving curvature perturbation

Line element, considering only scalar perturbations:

$$ds^2 = a^2[-(1+2\Phi)d\tau^2 + (1-2\Psi)dx^i dx_i]$$

# Curvature perturbations → CMB temperature anisotropies

J. Lesgourges, arXiv: 1302.4640

- Temperature anisotropy due to curvature perturbations:

$$\frac{\delta T}{T} = \Theta = \int_{\eta_i}^{\eta_0} d\eta [g(\Theta_0 + \Psi + \hat{n}\cdot\vec{v}_b) + e^{-\tau}(\Phi' + \Psi')]$$

Instantaneous decoupling approximation

$$\approx (\Theta_0 + \Psi + \hat{n}\cdot\vec{v}_b)|_{dec} + \int_{\eta_{dec}}^{\eta_0} d\eta (\Phi' + \Psi')$$

Neglect Doppler contribution

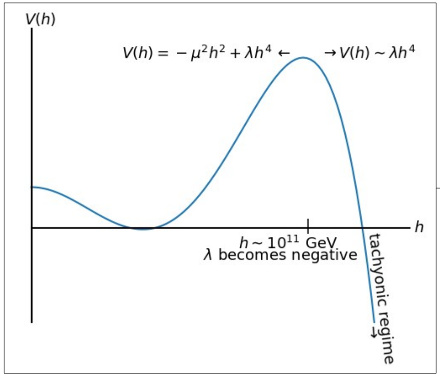
$$= f_{SW}(k)\langle\zeta(\vec{k})\rangle + f_{ISW}(k)\langle\zeta(\vec{k})\rangle$$

Got to position space, evaluate at $x_0$

$$= \int \frac{d^3\vec{k}}{(2\pi)^3} e^{i\vec{k}\vec{x}_0} \sum_l i^l (2l+1)\mathcal{P}_l(\hat{k}\hat{n})(f_{SW}(k) + f_{ISW}(k))\langle\zeta(\vec{k})\rangle$$

Line element, considering only scalar perturbations:

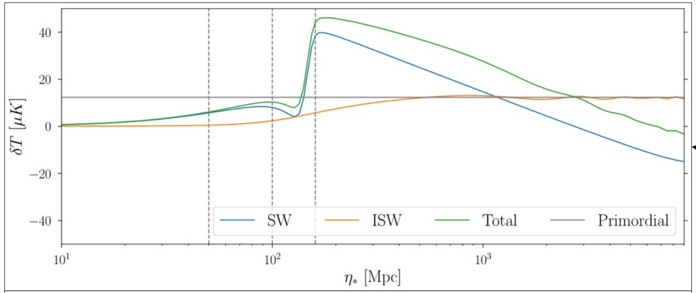
$$ds^2 = a^2[-(1+2\Phi)d\tau^2 + (1-2\Psi)dx^i dx_i]$$




Inflation, $10^{-34}$ s: Higgs particle production

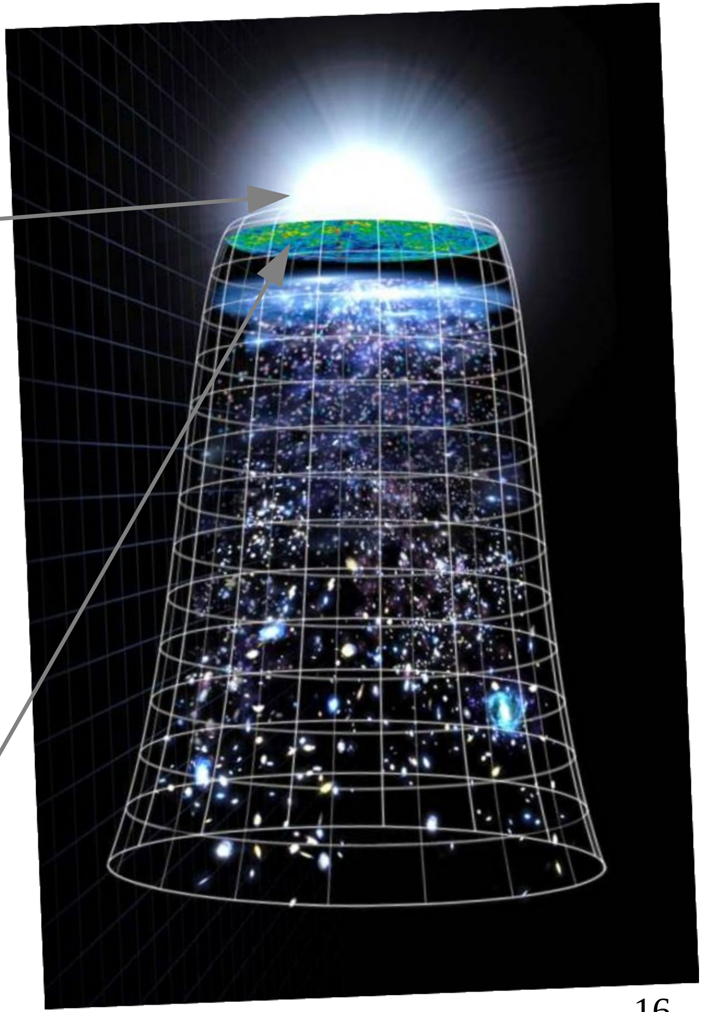
Massive Higgs particles modify curvature perturbations

Localized curvature perturbations cause CMB hotspots




J. H. Kim, S. Kumar, A. Martin, Y. Tsai, arXiv: 2107.09061

Recombination, $10^5$ y: CMB radiation which we observe today



# Preliminary Results/First estimates

T.N. Ukwatta et al, arXiv: 1510.04372

- Higgs particles collapse into micro black holes (microBH), with lifetime:

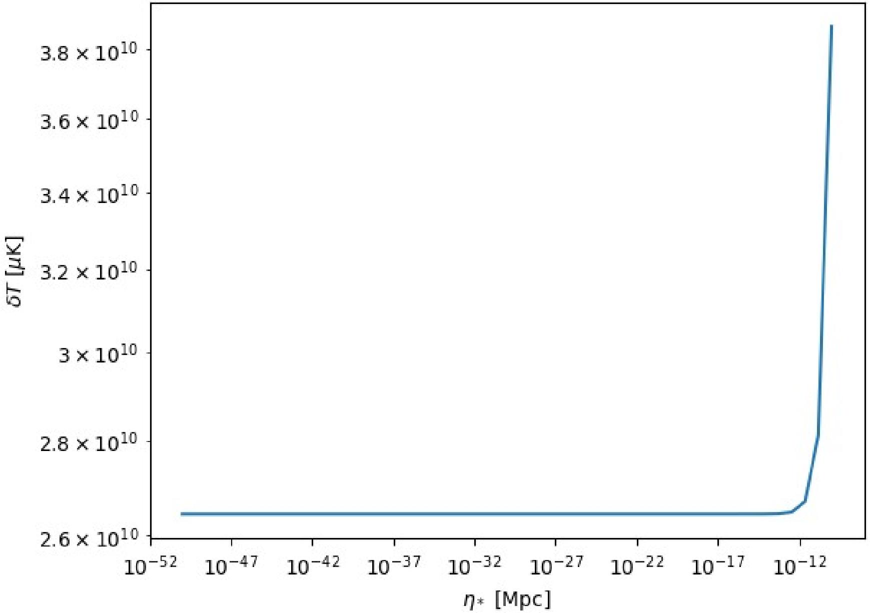
$$\tau_{BH} = \frac{M_{BH}^3}{f(M_{BH})}$$

- use step function as first estimate, with mass:

  1000 kg

  and lifetime:

  45.5 ns



# Preliminary Results/First estimates

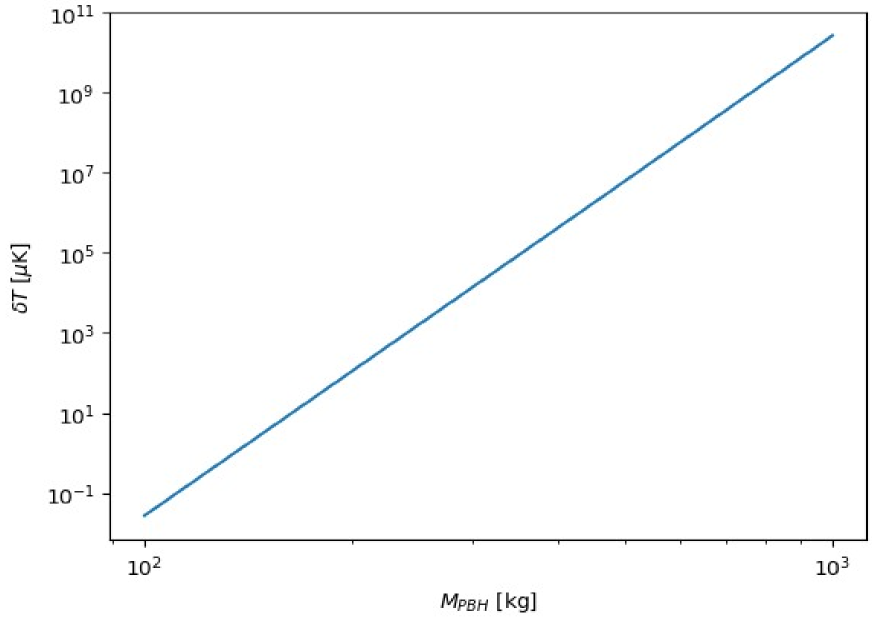
T.N. Ukwatta et al, arXiv: 1510.04372

- Higgs particles collapse into micro black holes (microBH), with lifetime:

$$\tau_{BH} = \frac{M_{BH}^3}{f(M_{BH})}$$

- use step function as first estimate, with varying mass and lifetime, produced at the end of inflation:

  100 – 1000 kg



# Preliminary Results/First estimates

A. Escriva et al, arXiv: 2211.05767

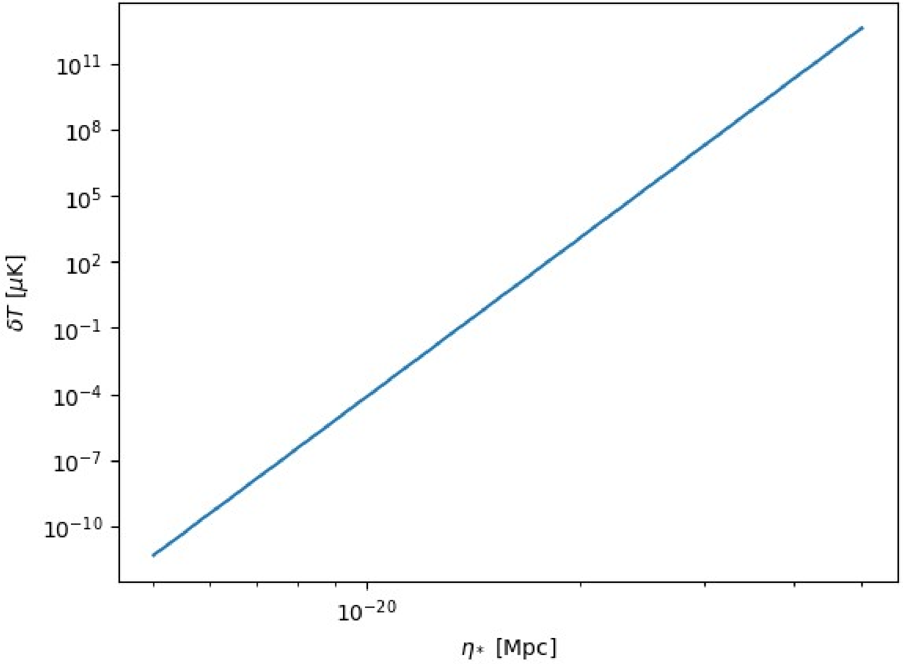
- We also try out results for general primordial black holes (PBH), with mass:

$$M_{PBH} \approx \left(\frac{g_*}{10.75}\right)^{-1/6} \left(\frac{k}{4.22 \cdot 10^6\,\mathrm{Mpc}^{-1}}\right)^{-2} M_\odot$$

and lifetime:

$$\tau_{BH} = \frac{M_{BH}^3}{f(M_{BH})}$$

and $k=2\pi/\eta_*$ is the wave number of modes entering the horizon at time $\eta_*$



# Future directions

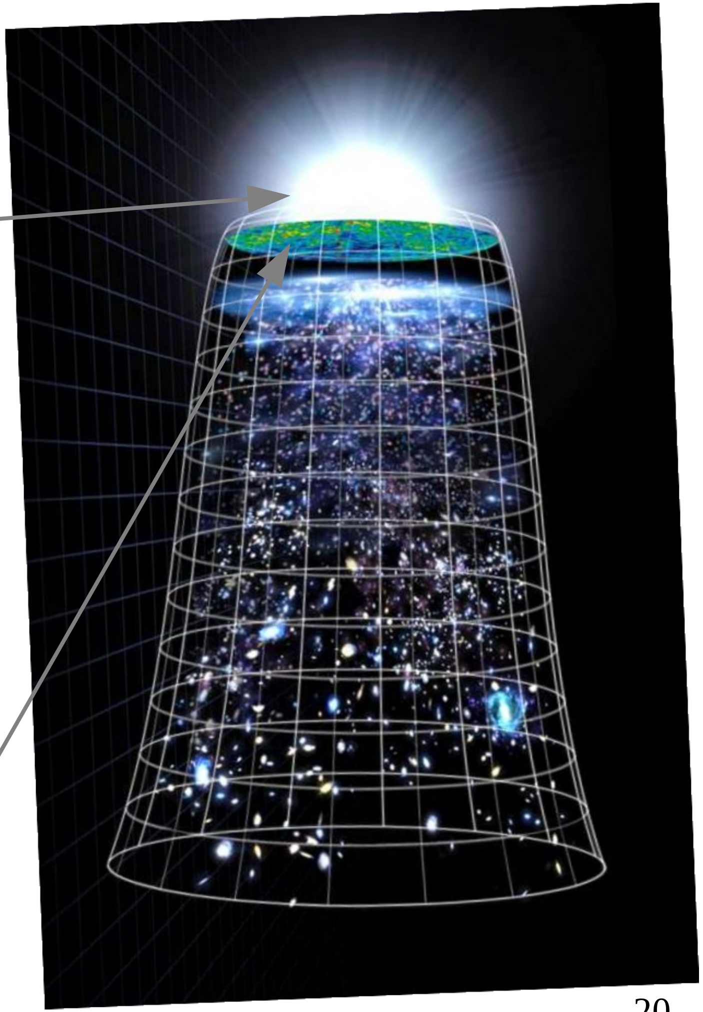
- Include exact calculation for Higgs particle production
- Include distribution of Higgs particles/black holes
- Look into further effects

Inflation, $10^{-34}$ s: Higgs particle production

Massive Higgs particles modify curvature perturbations

Localized curvature perturbations cause CMB hotspots

Recombination, $10^{5}$ y: CMB radiation which we observe today



# Conclusions

- Potential possibility to produce observable signals
- Dependence on time of production only important for late times
- Strong dependence on mass input

  → Need to include exact results for the tachyonic Higgs

Inflation, $10^{-34}$ s: Higgs particle production

Massive Higgs particles modify curvature perturbations

Localized curvature perturbations cause CMB hotspots

Recombination, $10^{5}$ y: CMB radiation which we observe today