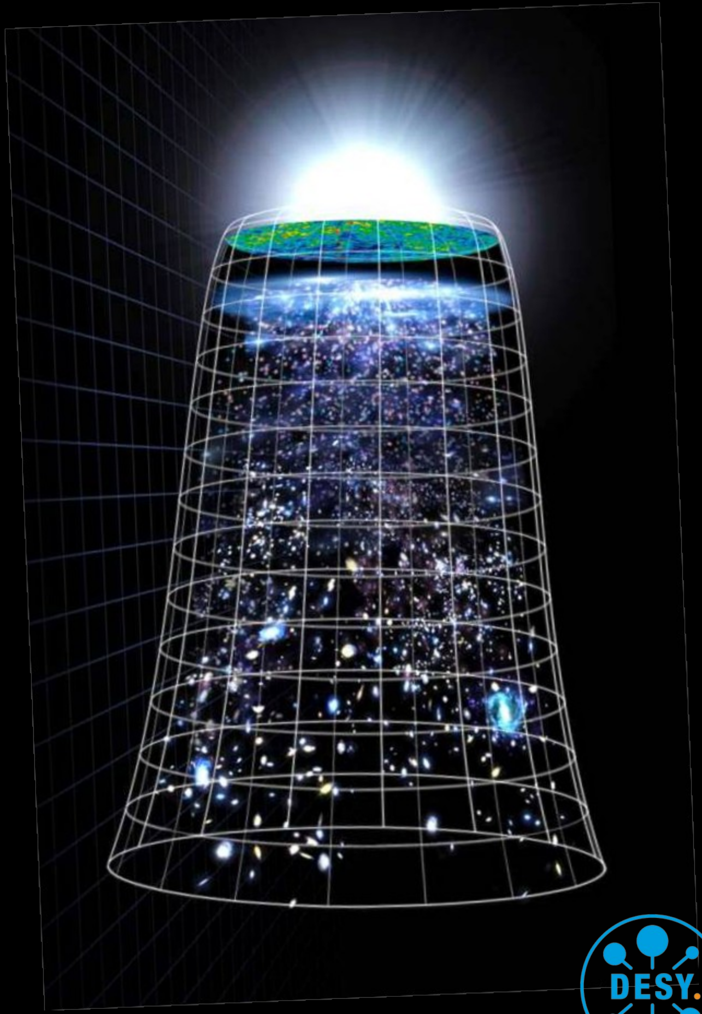
CMB hotspots from tachyonic instability of the Higgs potential

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



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DESY.

Tachyonic instability of the Higgs potential

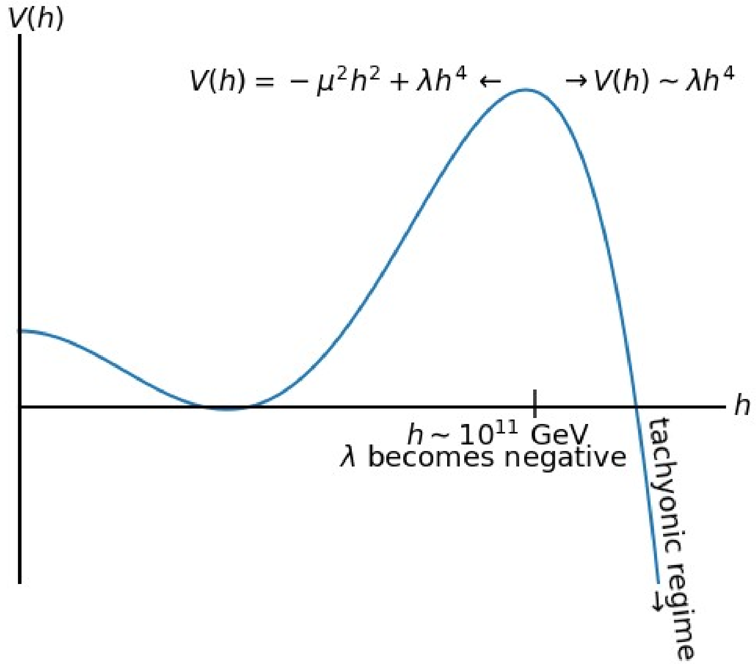
B. Shakya, arXiv: 2301.08754

Standard Model Higgs potential:

$$V(h) = -\mu^2 h^2 + \lambda h^4$$

≈ -0.001
at high energies,
h ≈ 10^{11} GeV

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:

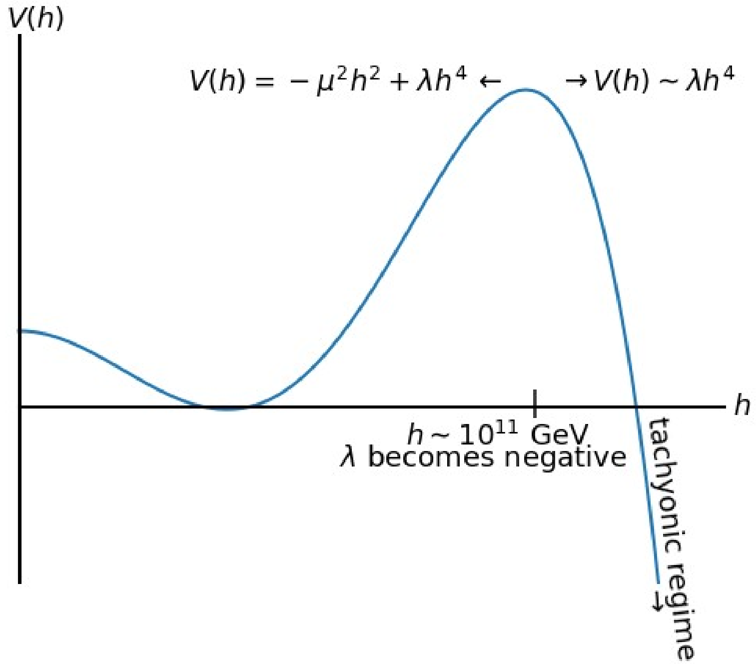
$$\ddot{h} + 3H\dot{h} = \frac{dV}{dh}$$

- 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

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- Higgs particle production becomes important for:

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

- Higgs mass evolves non-adiabatically

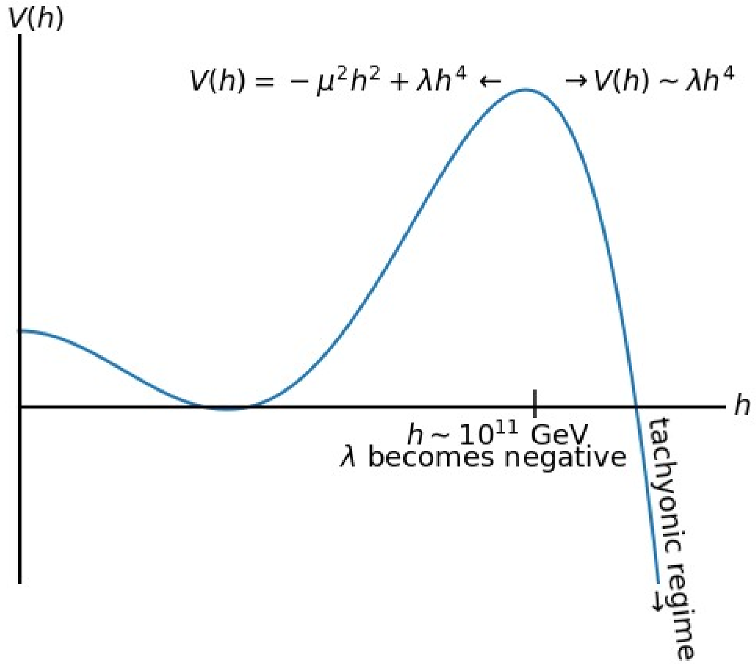
- Modes with momenta $k \lessapprox |m_h|$ get populated with occupation number

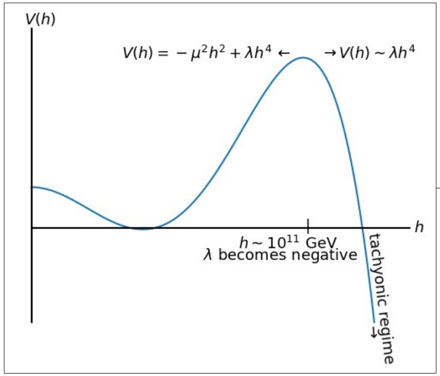
  $n_k = |\beta_k|^2 \sim 1$

- For tachyonic masses: β_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



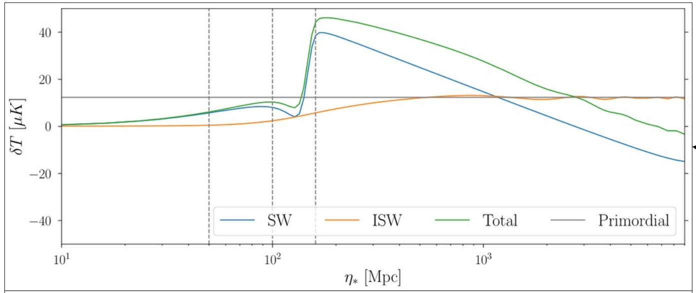


Inflation, 10^{-34} s: Higgs particle production

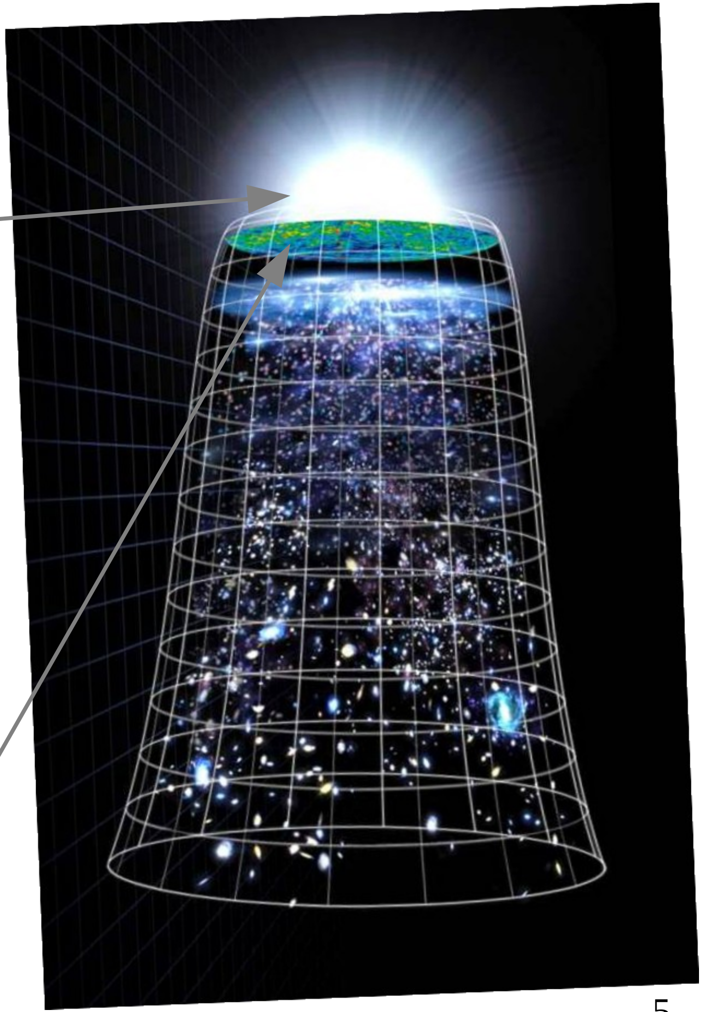
Massive Higgs particles modify curvature perturbations

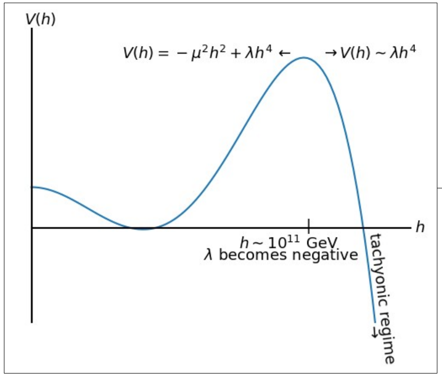
Localized curvature perturbations cause CMB hotspots

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



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





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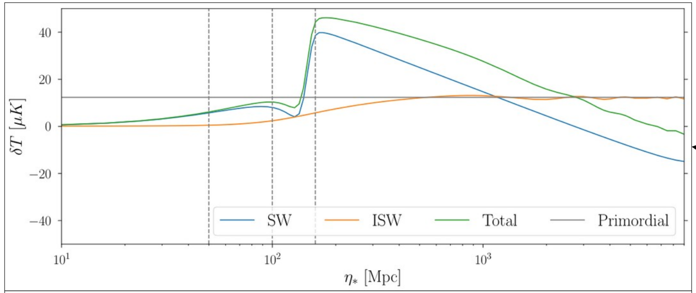

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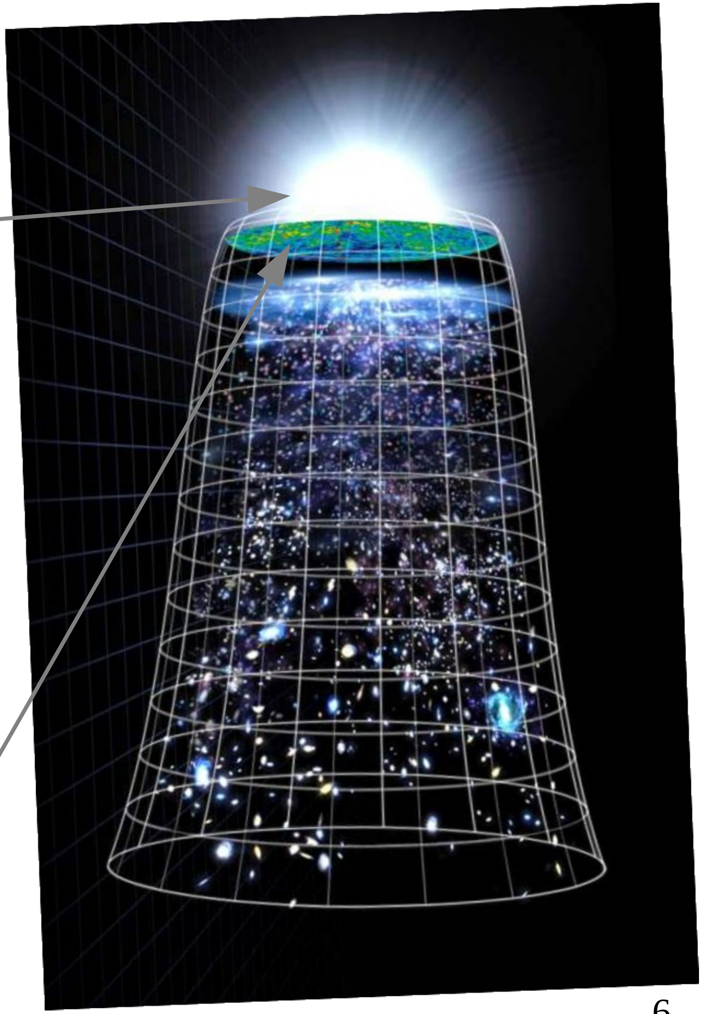

Massive particles → curvature perturbations

J. H. Kim, S. Kumar et al, arXiv: 2107.09061

- Action of to 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):

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

Generalized gravitational potential

Inflaton field

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Generalized gravitational potential

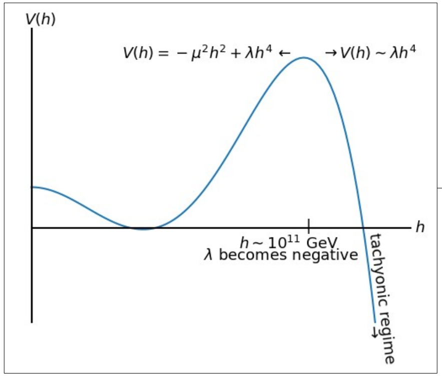
Inflaton field

→ 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



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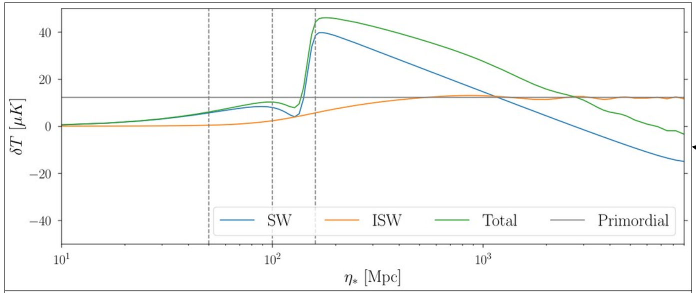

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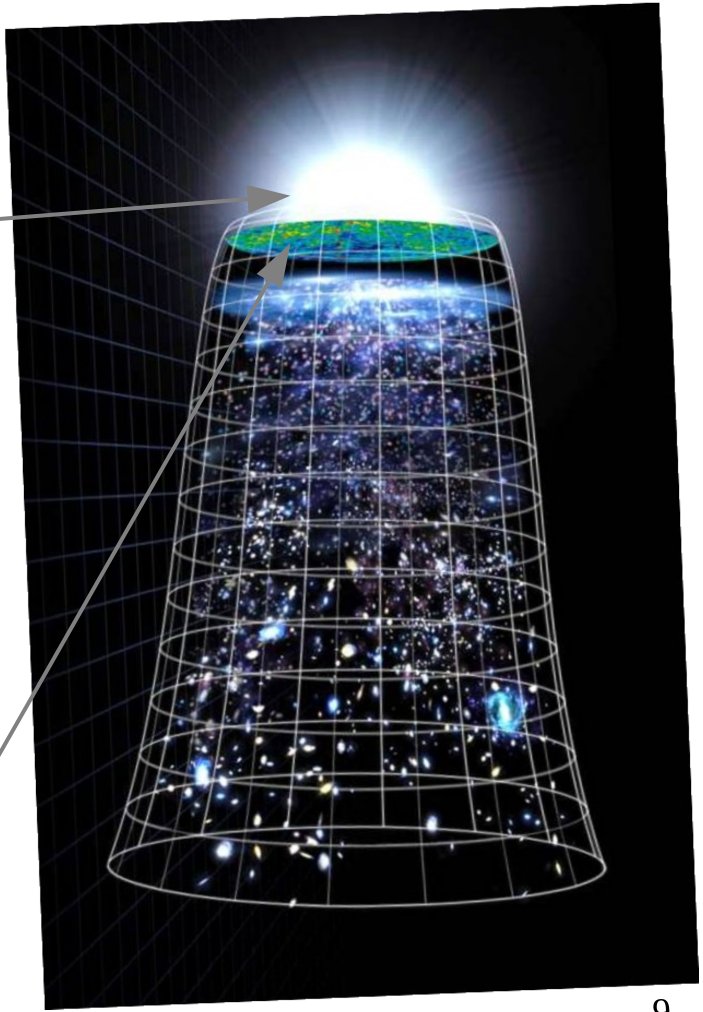

Curvature perturbations → CMB temperature anisotropies

A. Riotto, arXiv: 0210162

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

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

  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:

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

Distortion of scale factor a

= 0 in Newtonian gauge

Generalized gravitational potential

= 0 in Newtonian gauge

Curvature perturbations → CMB temperature anisotropies

J. Lesgourges, arXiv: 1302.4640

- Temperature anisotropy due to curvature perturbations:

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

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

Instantaneous decoupling approximation

Sachs-Wolfe effect

Doppler effect, can be neglected

Integrated Sachs-Wolfe effect

Temperature anisotropy measured by observer

Temperature anisotropy at point of last scattering

Line element, considering only scalar perturbations:

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

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

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

Instantaneous decoupling approximation ↓

Neglect Doppler contribution ↓

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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

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

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

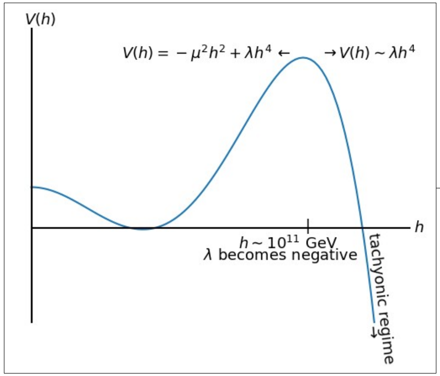
Instantaneous decoupling approximation ↓

Neglect Doppler contribution ↓

Got to position space, evaluate at x_0 ↓

Line element, considering only scalar perturbations:

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



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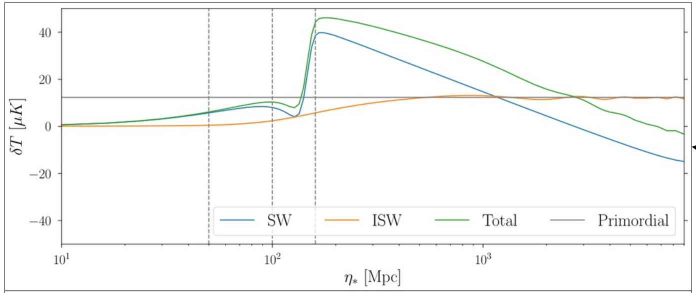

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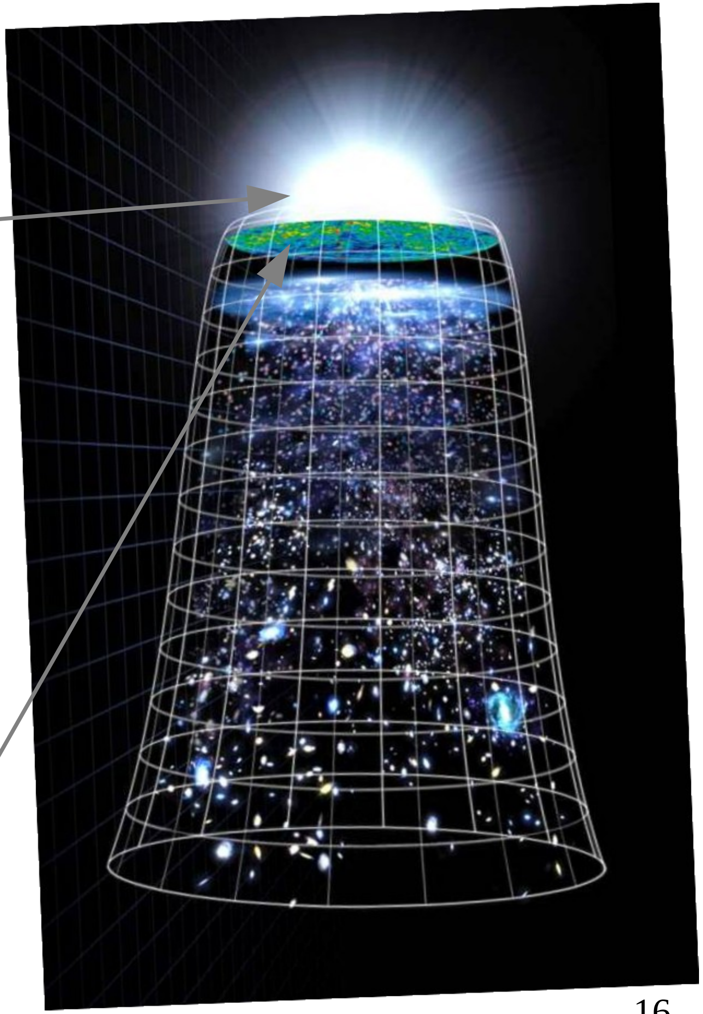


Preliminary Results/First estimates

T.N. Ukwatta et al, arXiv: 1510.04372

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

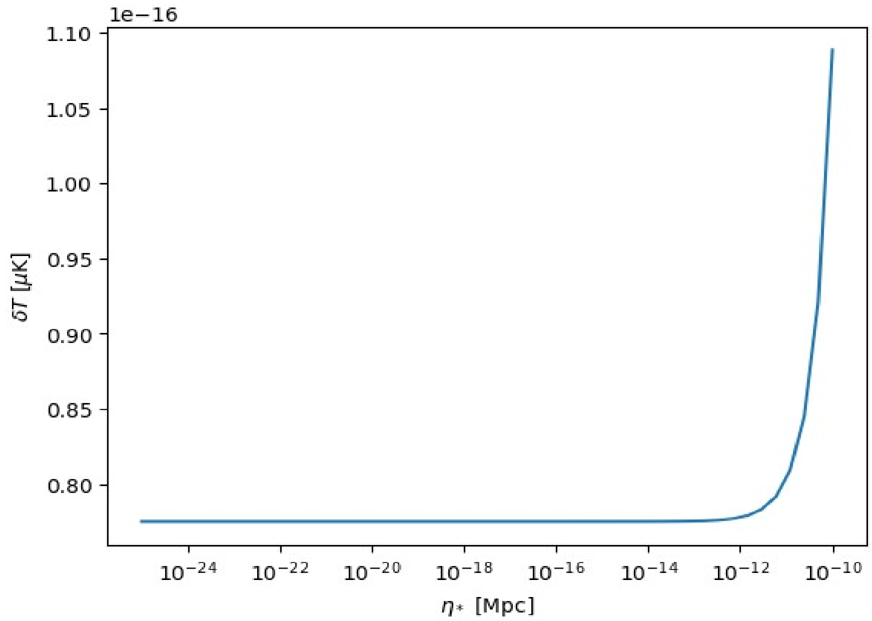
$$\tau_{BH} = \frac{M_{BH}^3}{f(M_{BH})}$$

- use step function as first estimate, with mass:

  1000 kg

  and lifetime:

  45.5 ns



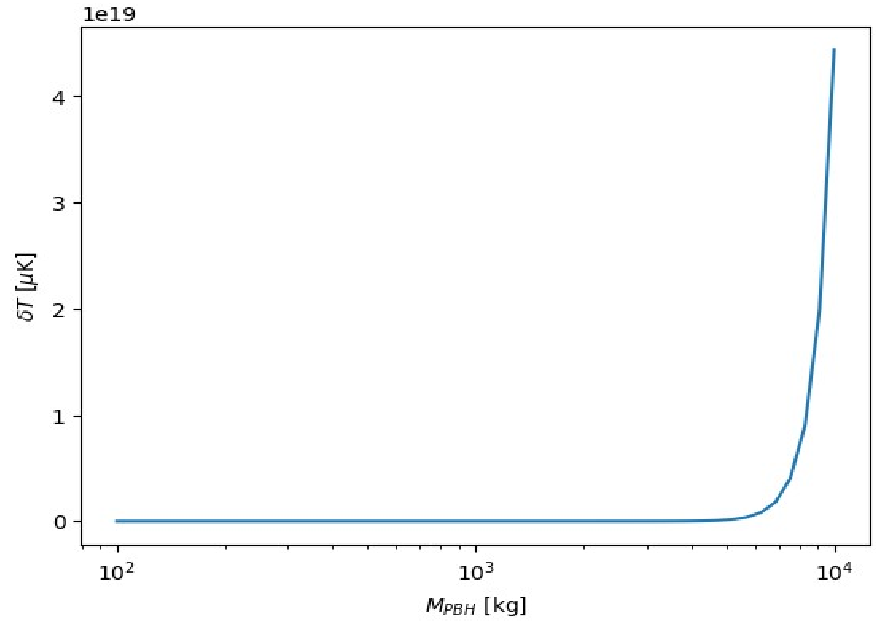
Preliminary Results/First estimates

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



Preliminary Results/First estimates

A. Escriva et al, arXiv: 2211.05767

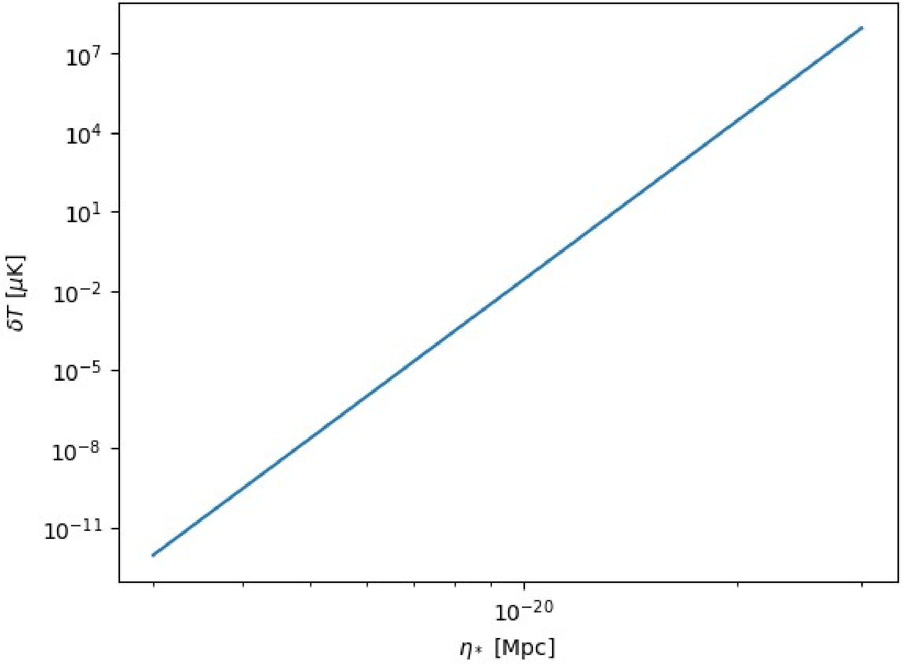
- We also try out results for general primordial black holes (PBH), with mass:

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

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 η_*



Future directions

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

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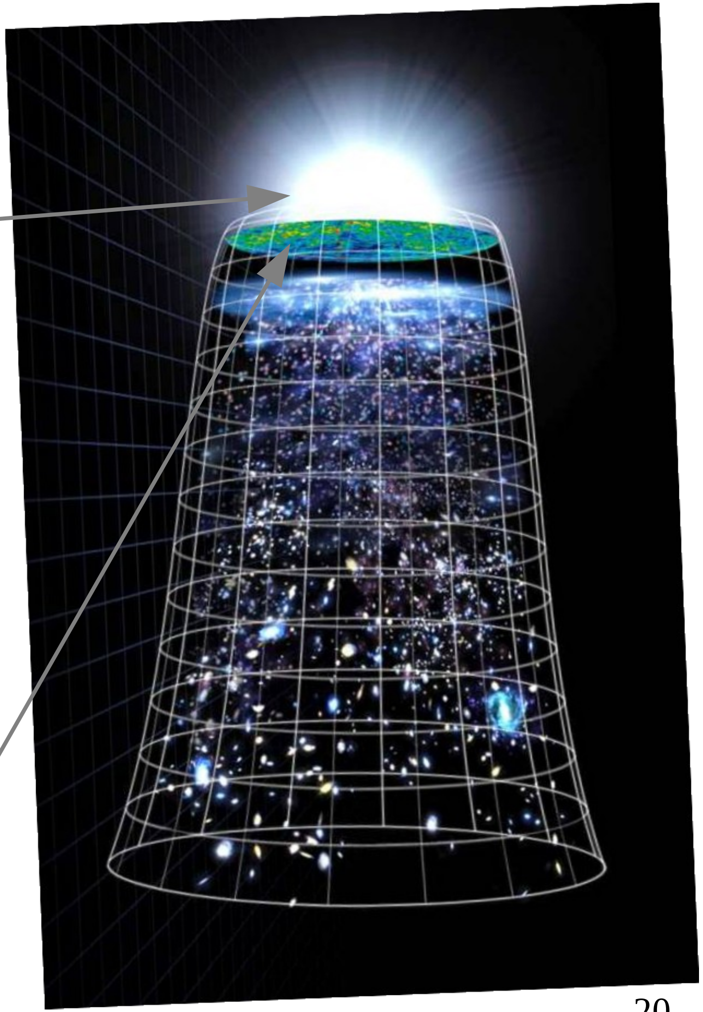

Conclusions

- 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

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