Spectral distortions as a probe of PBH scenarios

Lightness @ Prague

17/09/2021

Based on arXiv: 21xx.xxxx, 2104.12792, 1912.01061
with Tasinato, G.

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MINISTRY OF EDUCATION,
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FZU

Ogan Özsoy-CEICO

Motivations

- PBH abundance is sensitive to the shape of the power spectrum around its peak & might require a non-perturbative treatment.

  *Germani, C. & Musco, I. arXiv:1805.04087

- Non-Gaussianity can influence PBH abundance

  *Franciolini et.al., arXiv: 1801.09415., Atal, V. & Germani, C., arXiv:1811.07857
  *De Luca, V. et.al., arXiv:1904.00970.

- Impact of Quantum diffusion on the power spectrum around the peak scale ?

  *Biagetti et.al., arXiv:1804.07124, Ezquiaga & Garcia-Bellido, arXiv:1805.06731, Cruces et.al., arXiv:1807.09057, F. Kuhnel & K. Freese, arXiv: 1906.02744

In this talk:

Can we probe the PBH formation mechanism by focusing on larger scales, well away from the peak scale?

- A universal feature present in PBH forming scenarios that we may utilize to test the underlying mechanism, independently on the details of non-linear PBH formation associated with the peak.

Super-horizon growth of scalar perturbations

$$\mathcal{R}_k'' + 2\frac{z'}{z}\mathcal{R}_k' + k^2\mathcal{R}_k = 0 \quad \longrightarrow \quad \frac{z'}{z} = aH(1+\frac{\eta}{2})$$

- Super-horizon solutions, $k \to 0$

$$\mathcal{R}_k(\tau) \simeq \mathcal{C}_1 + \mathcal{C}_2 \int^\tau \frac{\mathrm{d}\tau'}{z^2(\tau')} + \mathcal{O}(k^2) \quad \longrightarrow \quad z(a) \simeq z_i \exp\left[\int (1+\frac{\eta}{2})\, d\ln a\right]$$

- Slow-roll violation, for super-horizon growth

$\eta < -2 \longrightarrow$ decaying pump field, to resurrect the decaying modes

$$\mathcal{R}_k(\tau) \simeq \mathcal{C}_1 + \boxed{\mathcal{C}_2 \int^\tau \frac{\mathrm{d}\tau'}{z^2(\tau')} + \mathcal{O}(k^2)}$$

*Liddle&Leach, arXiv: astro-ph/0010082

Systematic gradient expansion

$$\mathcal{R}_k(\tau_f) = \alpha_k \mathcal{R}_k(\tau_k) \quad \rightarrow \quad \alpha_k = 1 + D(\tau_k)\, v_{\mathcal{R}} - F(\tau_k)\, k^2 + \mathcal{O}(k^4)$$

$$D(\tau) = 3\mathcal{H}_k \int_{\tau}^{\tau_f} \mathrm{d}\tau' \frac{z^2(\tau_k)}{z^2(\tau')} \qquad F(\tau) = \int_{\tau}^{\tau_f} \frac{d\tau'}{z^2(\tau')} \int_{\tau_k}^{\tau'} \mathrm{d}\tau'' z^2(\tau'')$$

$|\alpha_k| \gg 1$ for decaying pump field, as in PBH forming scenarios

$$z(\tau) = \begin{cases} z_0 (\tau/\tau_0)^{-1} & \rightarrow \text{Phase 1, slow-roll} \\ z_0 (\tau/\tau_0)^{-(\eta_c+2)/2} & \rightarrow \text{Phase 2, non-slow-roll} \end{cases}$$

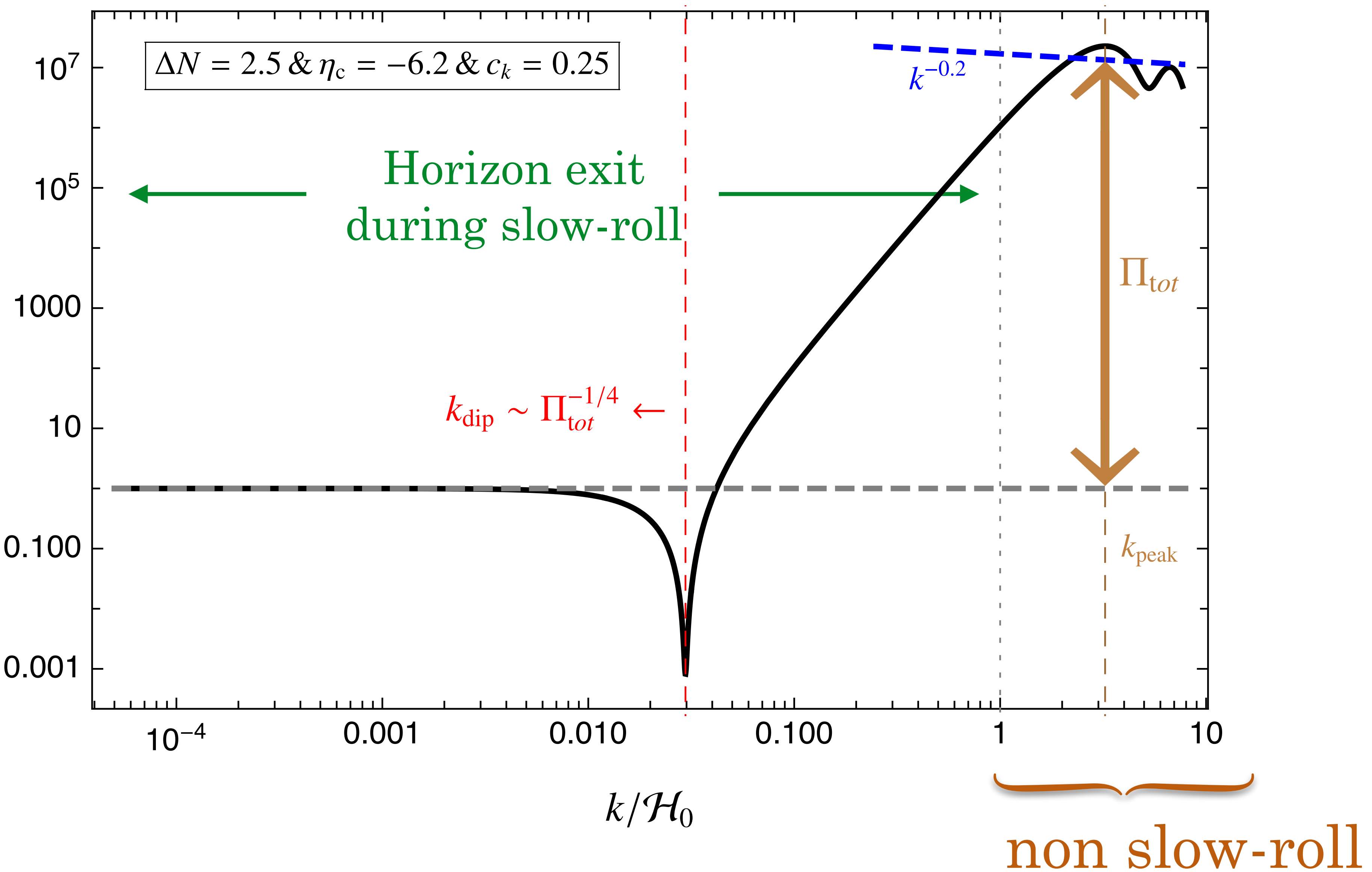
Growth can be characterized by $\{\Delta N, \eta_c\}$

*Leach et.al., arXiv: astro-ph/0101406

*OÖ and Tasinato, arXiv: 1912.01061

A universal feature: dip in the power spectrum

$$\frac{\mathcal{P}_{\mathcal{R}}(\tau_f, k)}{\mathcal{A}_s}$$



$\mathcal{H}_0$: the scale that exit the horizon at τ_0 → $k_{\rm peak} \simeq 3\mathcal{H}_0$

A dip in the power spectrum is a universal feature: $k_{\rm peak} \simeq 100\, k_{\rm dip}$

*OÖ et.al., arXiv: 1803.07626

*Tasinato, arXiv: 2012.02518, OÖ and Tasinato, arXiv: 1912.01061

Consistency Conditions: S-Field Inflation

$$\lim_{k_+ \to 0} B_{\mathcal{R}}(q, k_+) = \frac{12}{5} f_{\rm NL}^{\rm sq}(q)\, P_{\mathcal{R}}\left(\tau_f, q\right) P_{\mathcal{R}}\left(\tau_f, k_+\right)$$ 3-PT

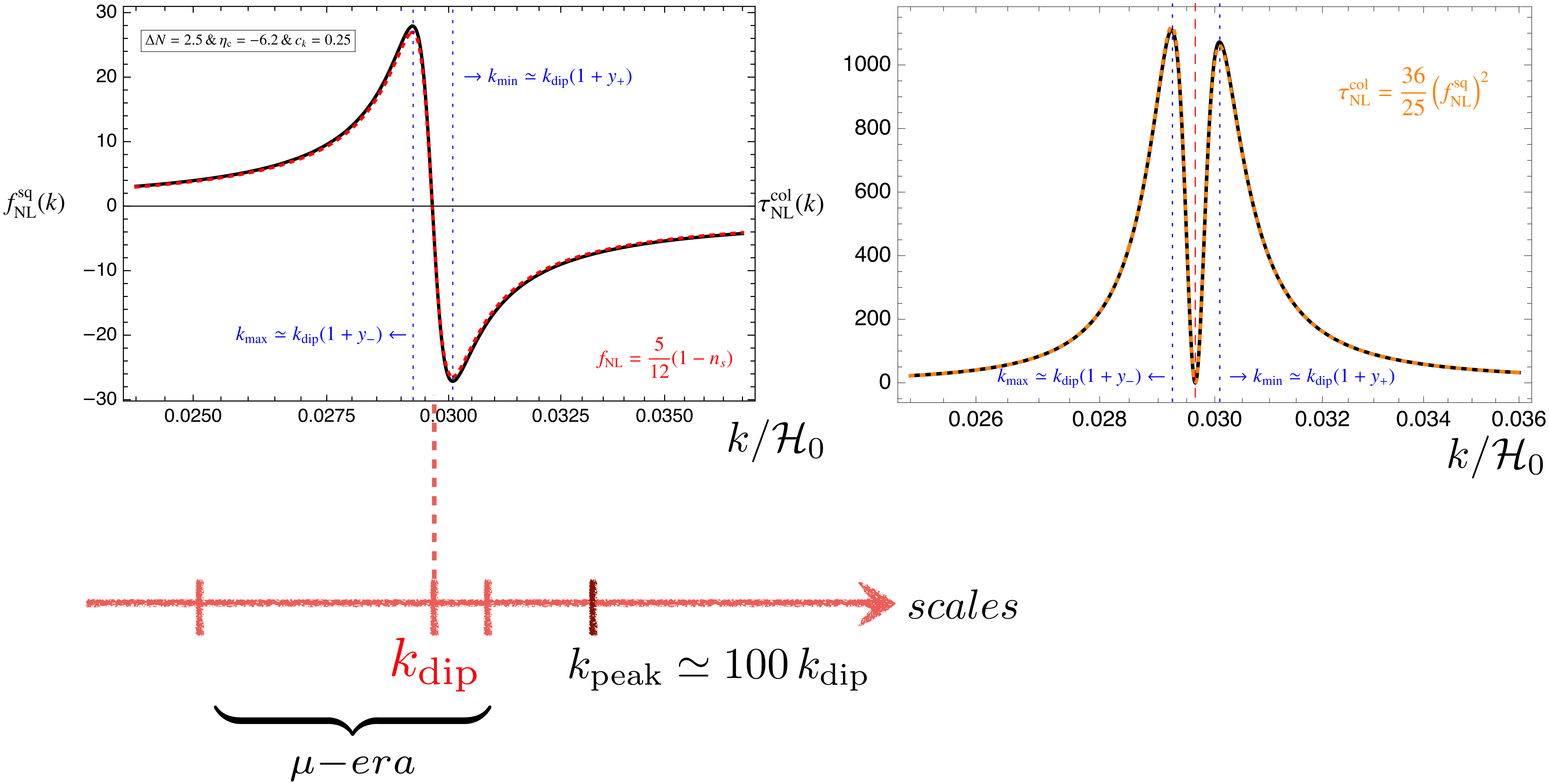
$$\lim_{k_+ \to 0} T_{\mathcal{R}}(q, k_+) = 4\, \tau_{\rm NL}^{\rm col}(q)\, P_{\mathcal{R}}\left(\tau_f, q\right) P_{\mathcal{R}}\left(\tau_f, q\right) P_{\mathcal{R}}\left(\tau_f, k_+\right)$$ 4-PT

$$|\vec{k}_1 + \vec{k}_2| \equiv k_+$$

$$f_{\rm NL}^{\rm sq}(q) = -\frac{5}{12}\left(n_s(q) - 1\right)$$

$$\tau_{\rm NL}^{\rm col}(q) = \frac{36}{25}\left(f_{\rm NL}^{\rm sq}(q)\right)^2$$

Cons. Conditions: S-Field PBH forming scenario



*OÖ, Tasinato. G, arXiv: 2104.12792,

*OÖ, Tasinato. G, arXiv: 21xx.xxxx,

*Atal, V., Germani C., arXiv: 1811.07857,

*Passaglia et.al., arXiv: 1812.08243,

*Q. Gao, arXiv: 2102.07369,

μ distortions as a probe of PBH scenarios

Energy injection caused by Silk damping of the acoustic waves in the pre-recombination plasma heats photons and leads to spectral distortions.

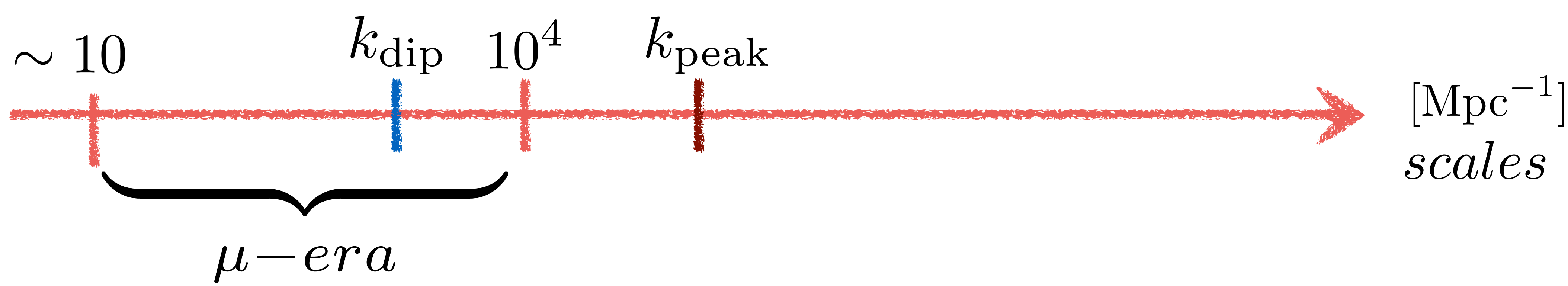
$$n(\nu) = \left[e^{h\nu/(k_B T)} - 1\right]^{-1} \longrightarrow \left[e^{h\nu/(k_B T)+\tilde{\mu}} - 1\right]^{-1}$$

Initial conditions are set on super-horizon scales:

$$\langle \mu \rangle \simeq 2.3 \int \mathrm{d}\ln k \; \mathcal{P}_{\mathcal{R}}(k) \left[e^{-2k^2/k_D^2}\right]_f^i$$

$$k_D \simeq \left(\frac{1+z}{10^5}\right)^{3/2} 130\mathrm{Mpc}^{-1}$$

Damping scale!



*Sunyaev, R. & Zeldovic, Y., Astrophys. Space Sci. 7 (1970)

*Hu, W., Scott, D.,Silk, J., arXiv: astro-ph/ 9402045

*Chluba et.al., arXiv: 1202.0057.

μ distortions as a probe of PBH scenarios

$\langle \mu T \rangle$ is sensitive to primordial bispectrum:

$$C_l^{\mu T} \simeq \frac{27.6}{20\pi^3} \int \mathrm{d}\ln k_+ \Delta_l\left(k_+\right) j_l\left(k_+ \chi_*\right) \int \mathrm{d}\ln q \left[k_+^3 q^3 B_{\mathcal{R}}\left(q, q, k_+ \rightarrow 0\right)\right] \left[e^{-2q^2/k_D^2(z)}\right]_f^i$$

Allow access to more squeezed configurations compared to <TTT> :

$$\frac{k_D\left(z_f\right)}{k_+} < \frac{q}{k_+} < \frac{k_D\left(z_i\right)}{k_+} \Rightarrow 10^5 \lesssim \frac{q}{k_+} \lesssim 10^8 \quad \text{vs.} \quad \frac{q}{k_+} \simeq \frac{l_q}{l_{k_+}} \lesssim 1500$$

$\langle \mu\mu \rangle$ is sensitive to primordial bispectrum:

$$C_{l,\mathrm{NG}}^{\mu\mu} \simeq \frac{2.65}{\pi^5} \int \mathrm{d}\ln k_+ j_l^2\left(k_+ \chi_*\right) \int \mathrm{d}\ln q \,\mathrm{d}\ln p \left(k_+^3 q^3 p^3 \lim_{k_+ \rightarrow 0} T_{\mathcal{R}}(q, p)\right) \left[e^{-2q^2/k_D^2(z)}\right]_f^i \left[e^{-2p^2/k_D^2(z)}\right]_f^i$$

*Pajer, E., Zaldarriaga, M., arXiv: 1201.5375

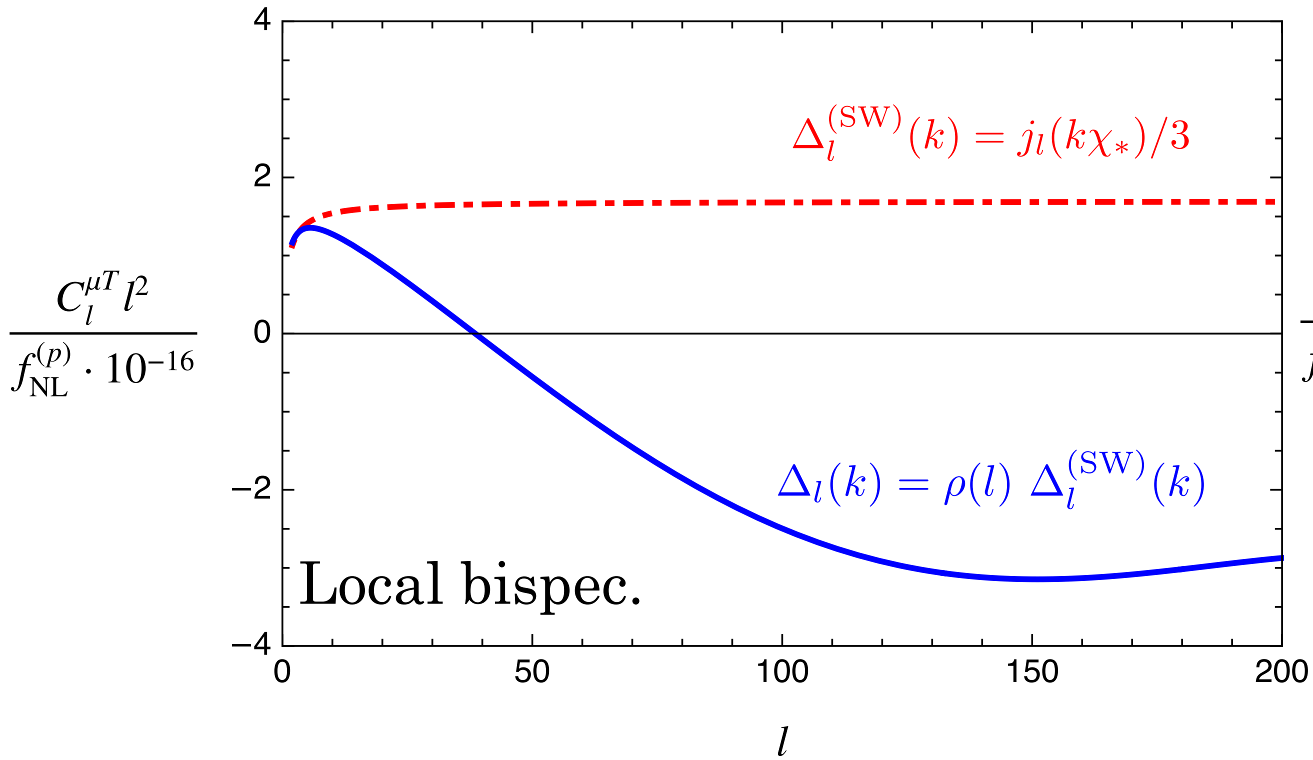
*Ganc, J., Komatsu, E., arXiv: 1204.4241

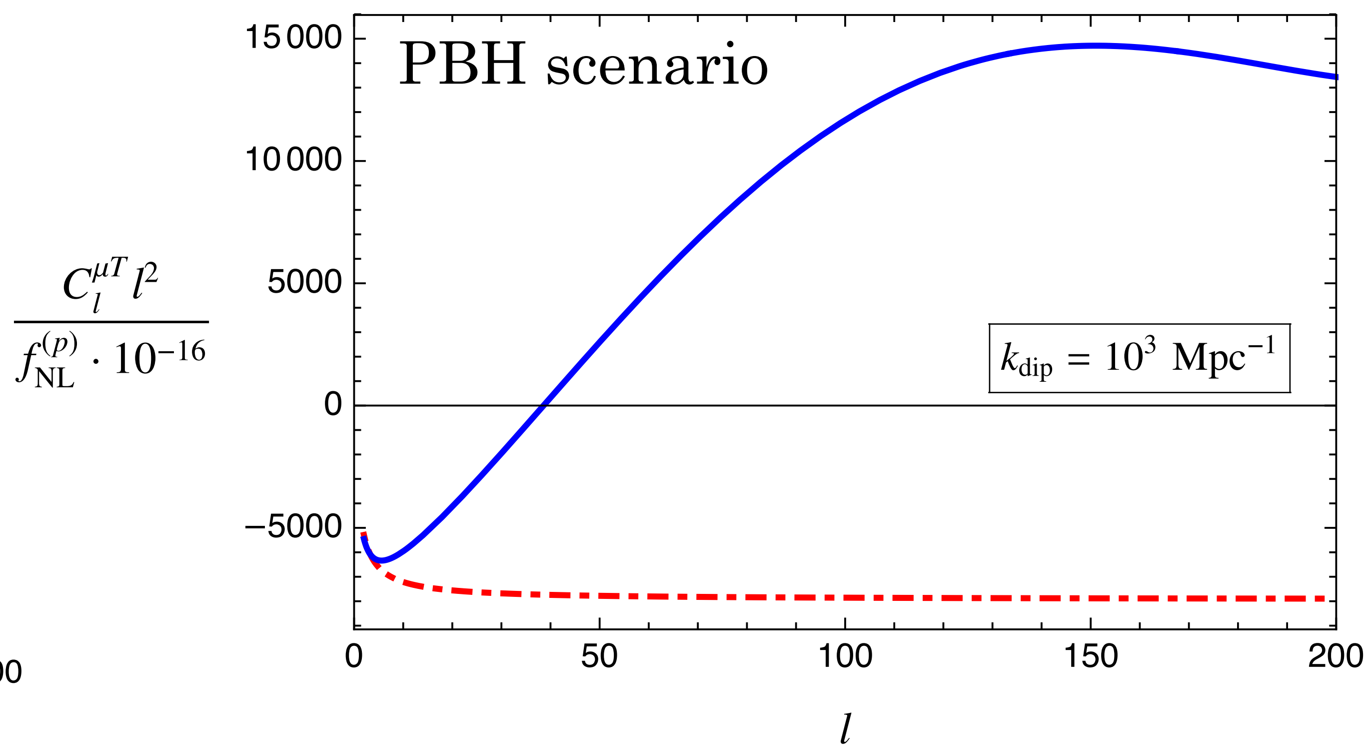
*OÖ, Tasinato. G, arXiv: 2104.12792

μ distortions as a probe of PBH scenarios

$$C_l^{\mu T} \simeq 2.7 \times 10^{-17} \frac{2\pi}{l(l+1)} f_{\rm NL}^{(\rm p)}\, b_{(\rm pbh)}(l)$$

$$b_{(\rm pbh)} \equiv \frac{6l(l+1)}{\ln\left(\frac{k_D(z_i)}{k_D(z_f)}\right)} \int {\rm d}\ln k\; \Delta_l(k)\, j_l(k\chi_*)\, W\left(\frac{k}{k_s}\right) \int {\rm d}\ln q\; \underbrace{\bar{f}_{\rm NL}^{\rm eff}(q,q,k)}_{\{k_{\rm dip},\, \eta_c,\, \Delta N\}} \left[e^{-2q^2/k_D^2(z)}\right]_f^i$$





$$b_{\rm pbh}(l) = \rho(l)\, b_{(\rm pbh)}^{(\rm SW)}$$

*Chluba et.al., arXiv:1610.08711.

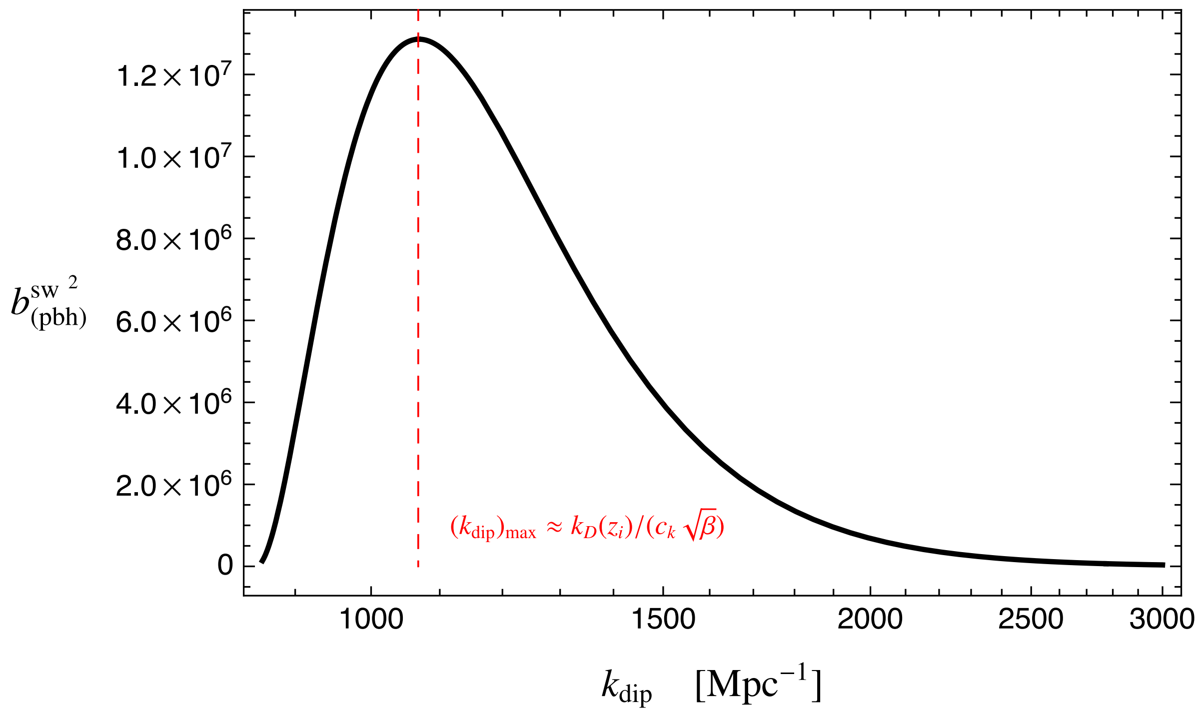
*OÖ, Tasinato. G, arXiv: 2104.12792

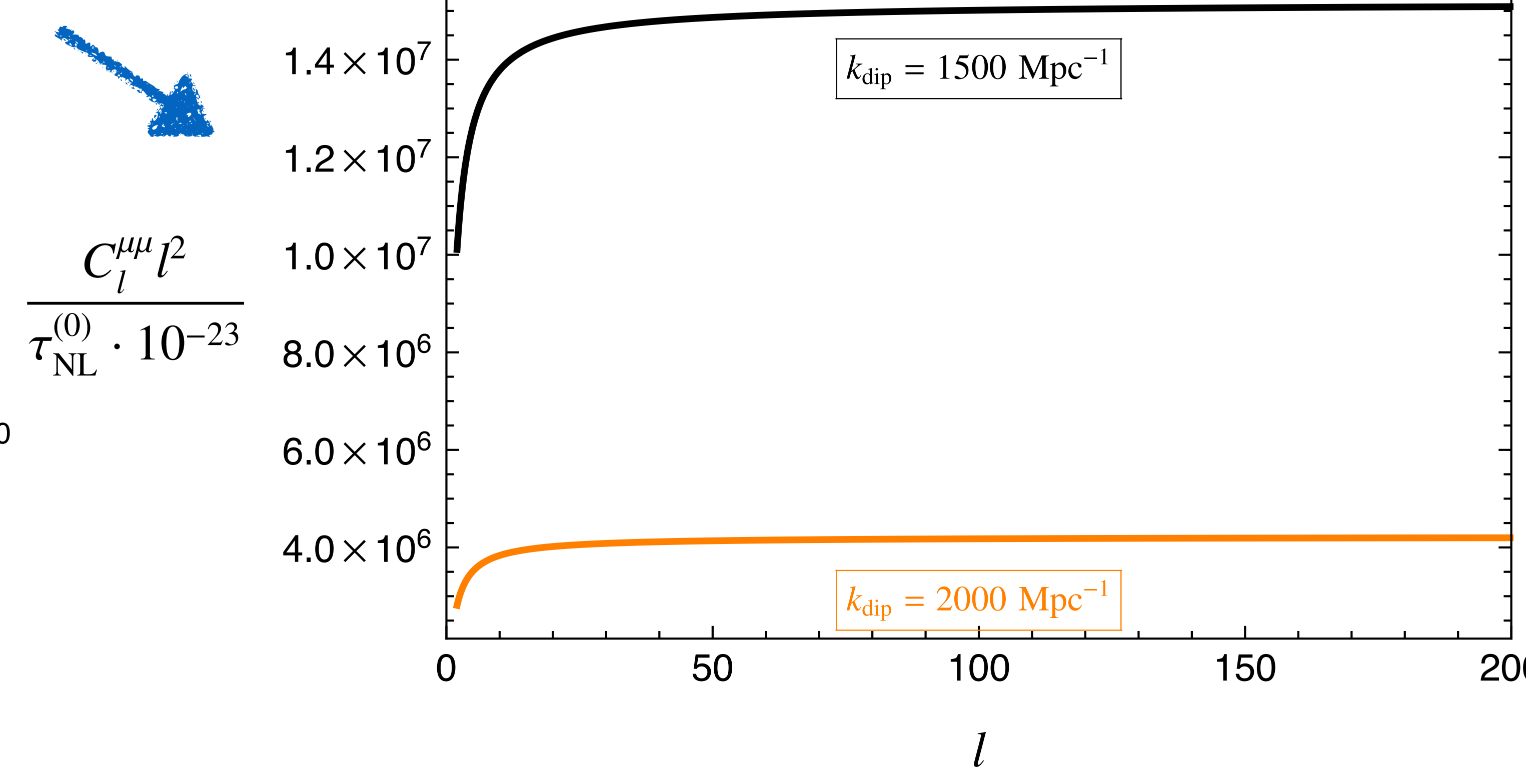
μ distortions as a probe of PBH scenarios

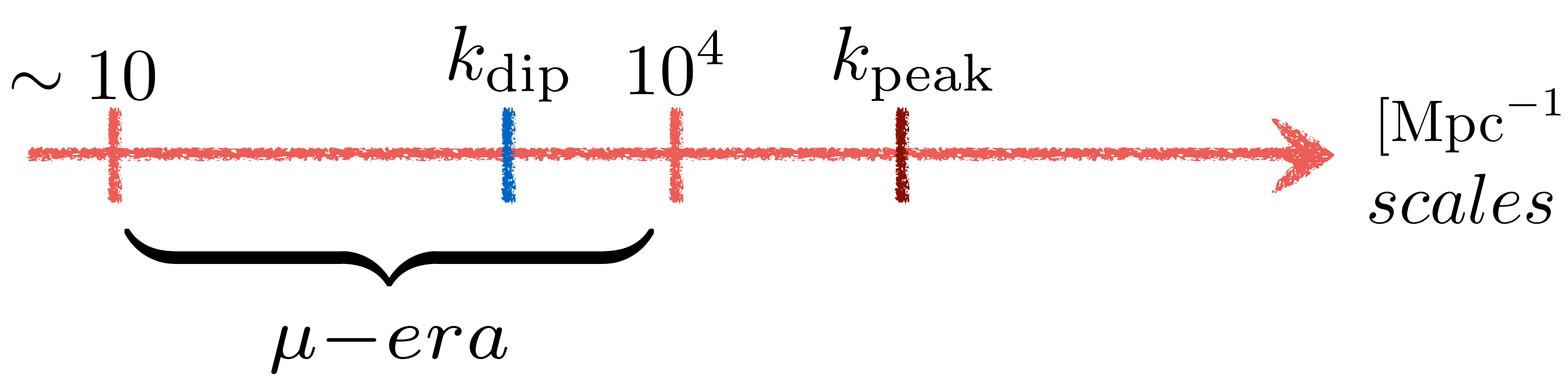
Consistency conditions we found allow relations between $\langle \mu T \rangle$ and $\langle \mu\mu \rangle$

$$C_{l,\mathrm{NG}}^{\mu\mu} \simeq 6.1 \times 10^{-24} \tau_{\mathrm{NL}}^{(0)} \frac{2\pi}{l(l+1)} \left(b_{(\mathrm{pbh})}^{\mathrm{sw}}\right)^2$$

$$C_{l,\mathrm{NG}}^{\mu\mu} \simeq 8.4 \times 10^{9} \frac{l(l+1)}{2\pi} \frac{36}{25} \left(C_l^{\mu T,\mathrm{sw}}\right)^2$$







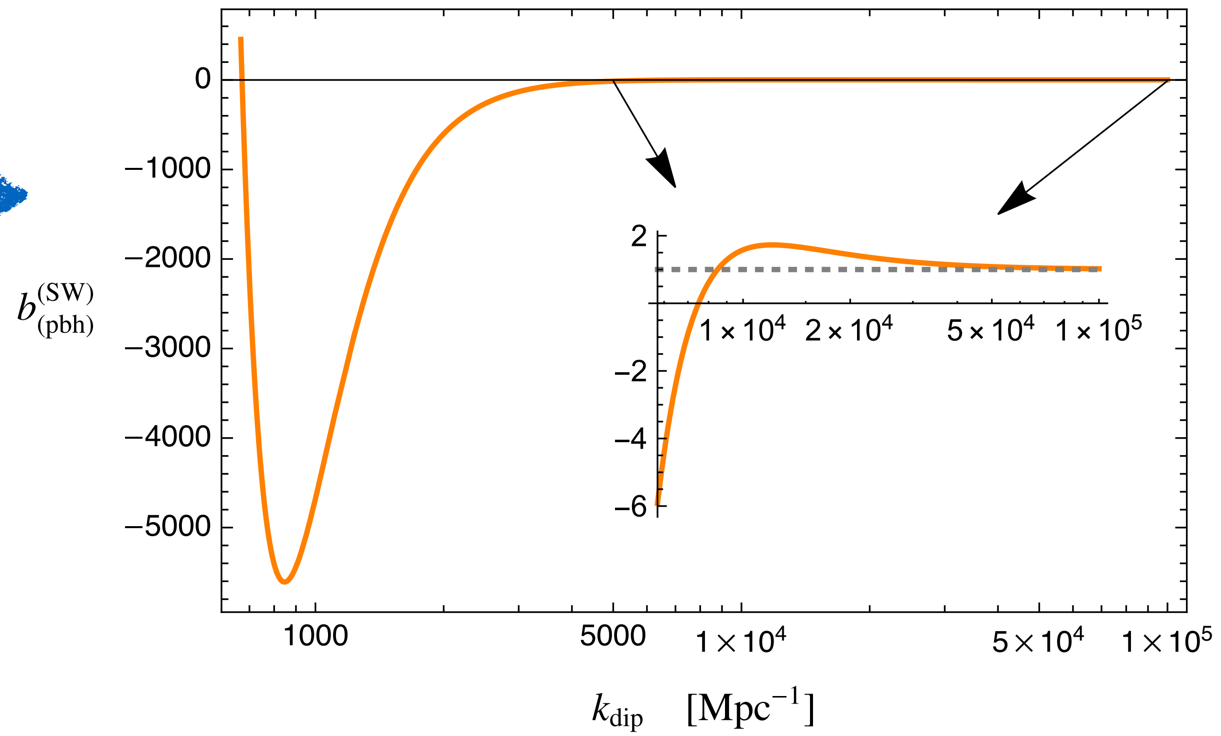
Detectibility of $\langle \mu T \rangle$ and its implications

Cumulative Signal to Noise ratio:

$$\left(\frac{S}{N}\right)^2 = \sum_{l=2}^{l_{\rm max}} (2l+1) \frac{\left(C_l^{\mu T}\right)^2}{C_l^{TT} C_l^{\mu\mu,N}} \quad \longrightarrow \quad \left(\frac{S}{N}\right) \simeq 0.35 \times 10^{-3} \left| f_{\rm NL}^{\rm (p)} b_{\rm (pbh)}^{\rm (SW)} \right| \left(\frac{10^{-8}}{\mu_{\rm min}}\right)$$

$$\left| f_{\rm NL}^{\rm (p)} b_{\rm (pbh)}^{\rm (SW)} \right| \gtrsim 2892 \quad \text{PIXIE}$$

$$\left| f_{\rm NL}^{\rm (p)} b_{\rm (pbh)}^{\rm (SW)} \right| \gtrsim 290 \quad \text{PRISM}$$



$$M_{\rm pbh}(k_{\rm peak}) \simeq \underbrace{(1-100)\, M_\odot}\, {\rm gr} \left(\frac{k_{\rm peak}}{10^6 - 10^5\ {\rm Mpc}^{-1}}\right)^{-2} \qquad k_{\rm peak} \simeq 100\ k_{\rm dip}$$

Seeds of SMBH via accretion and mergers

*Chluba et.al., arXiv:1610.08711.

*OÖ, Tasinato. G, arXiv: 2104.12792

Conclusions & Outlook

- Squeezed NG present around $k_{\rm dip} \ll k_{\rm peak}$ in PBH generating inflationary scenarios might lead to observable $C_l^{\mu T}$: $M_{\rm pbh} \simeq 1 - 100\, M_{\odot}$ (seeds of SMBH)

- $\langle \mu T \rangle$ an independent observable induced on much larger scales than the peak ($k_{\rm peak}$) associated with PBH production.

- It can be utilized to distinguish between astrophysical vs primordial origin of BH.

- Can be utilized as a tool for model comparison: e.g Single vs Multi-field

See e.g, *OÖ, arXiv: 2005.10280, Garcia-Bellido et.al. arXiv: 1610.03763

Outlook:

- Bispectrum also has support for equilateral configurations. Corresponding predictions on $C_l^{\mu T}$ should be carried.

- Expected $C_l^{\mu T}$ for scenarios that can generate SGWB induced via enhanced scalar fluctuations, i.e at SKA scales.

Thank you !

arXiv: 2104.12792, 1912.01061
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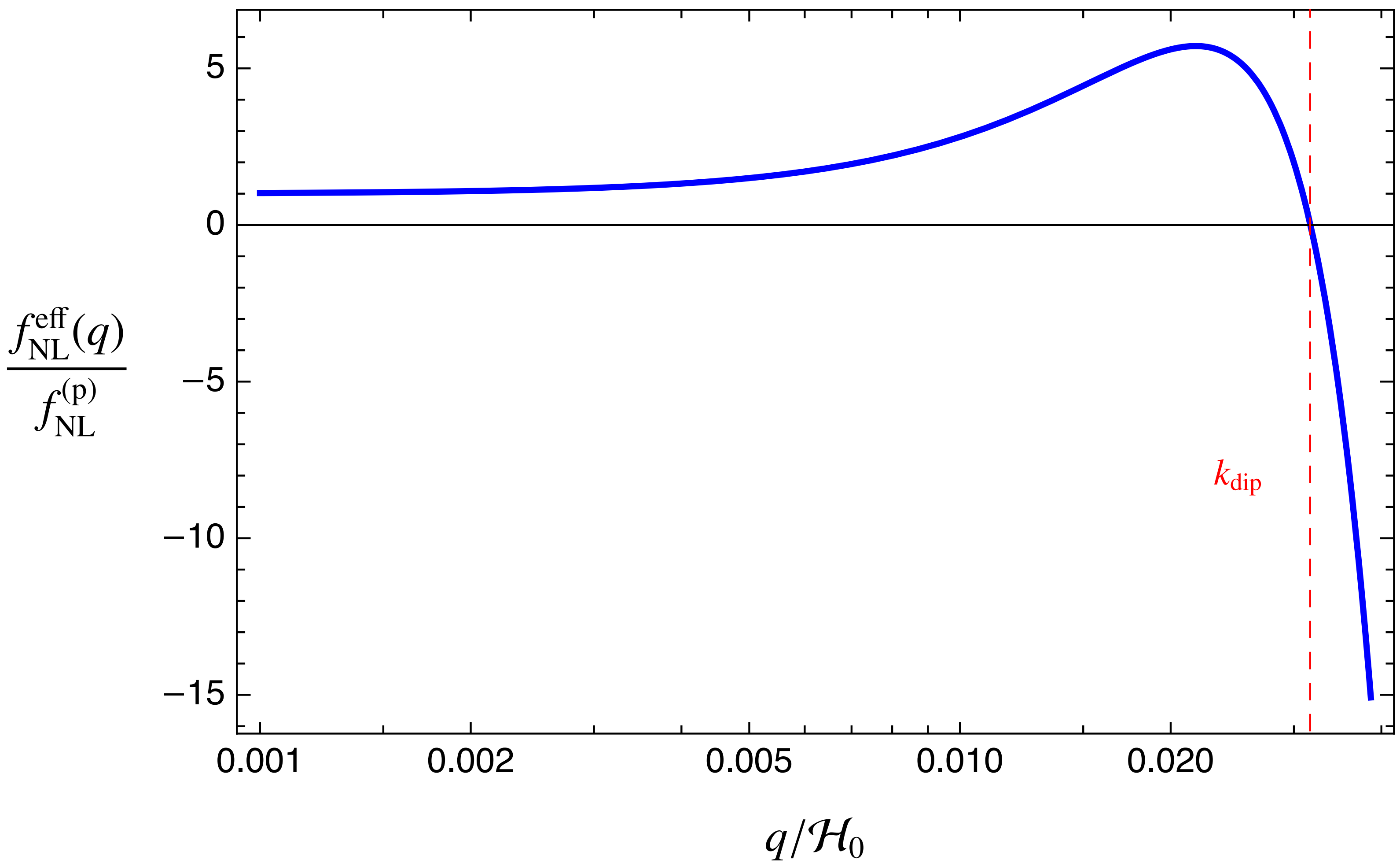
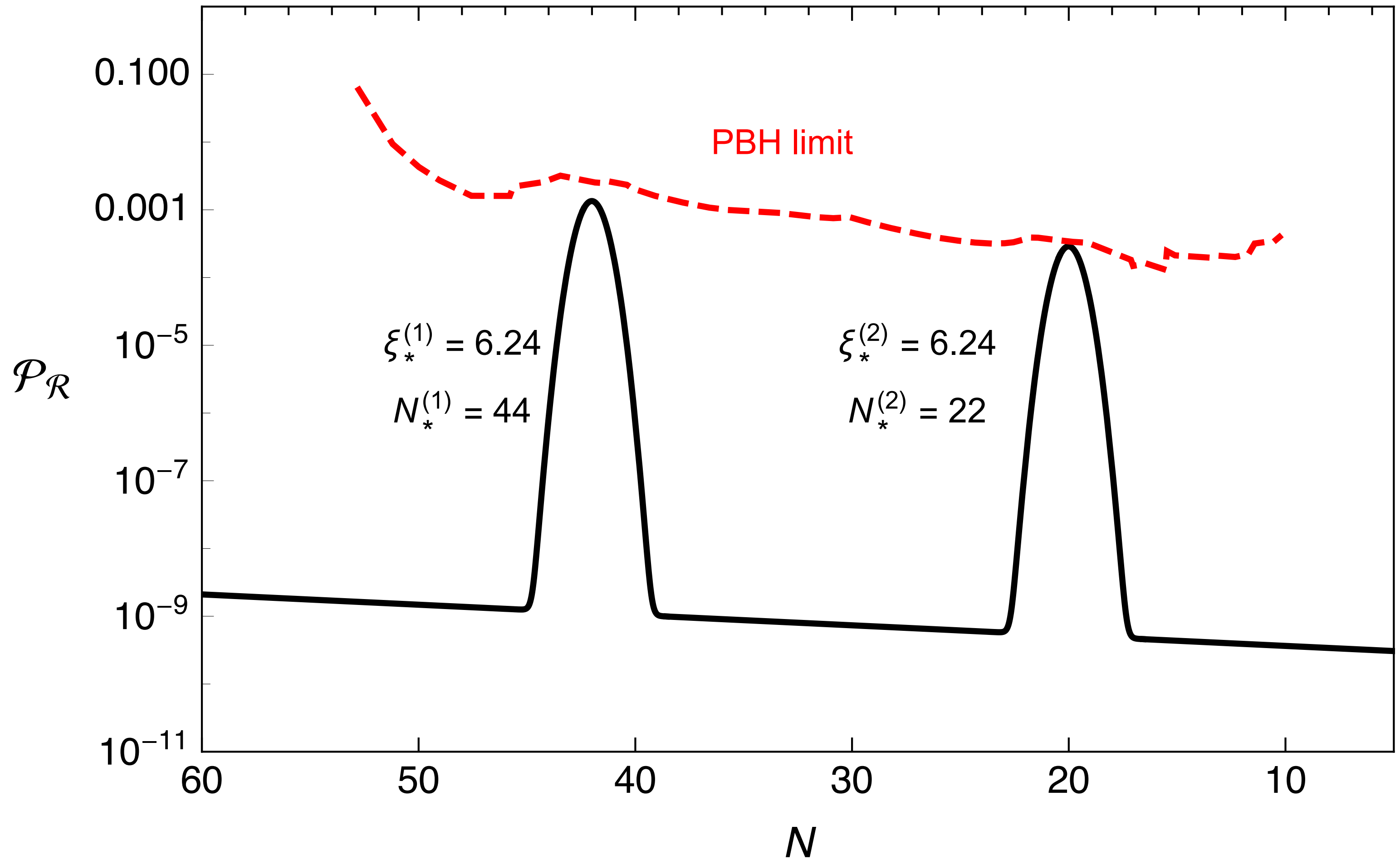
Backup



$$b_{(\rm pbh)} \equiv \frac{6l(l+1)}{\ln\left(\frac{k_D(z_i)}{k_D(z_f)}\right)} \int {\rm d}\ln k \; \Delta_l\,(k)\, j_l\,(k\chi_*)\, W\left(\frac{k}{k_s}\right) \int {\rm d}\ln q \; \bar{f}_{\rm NL}^{\rm eff}\,(q,q,k) \left[e^{-2q^2/k_D^2(z)}\right]_f^i$$

$$C_l^{\mu T} \simeq 2.7\times 10^{-17}\, \frac{2\pi}{l(l+1)}\, f_{\rm NL}^{(\rm p)}\, b_{(\rm pbh)}(l)$$

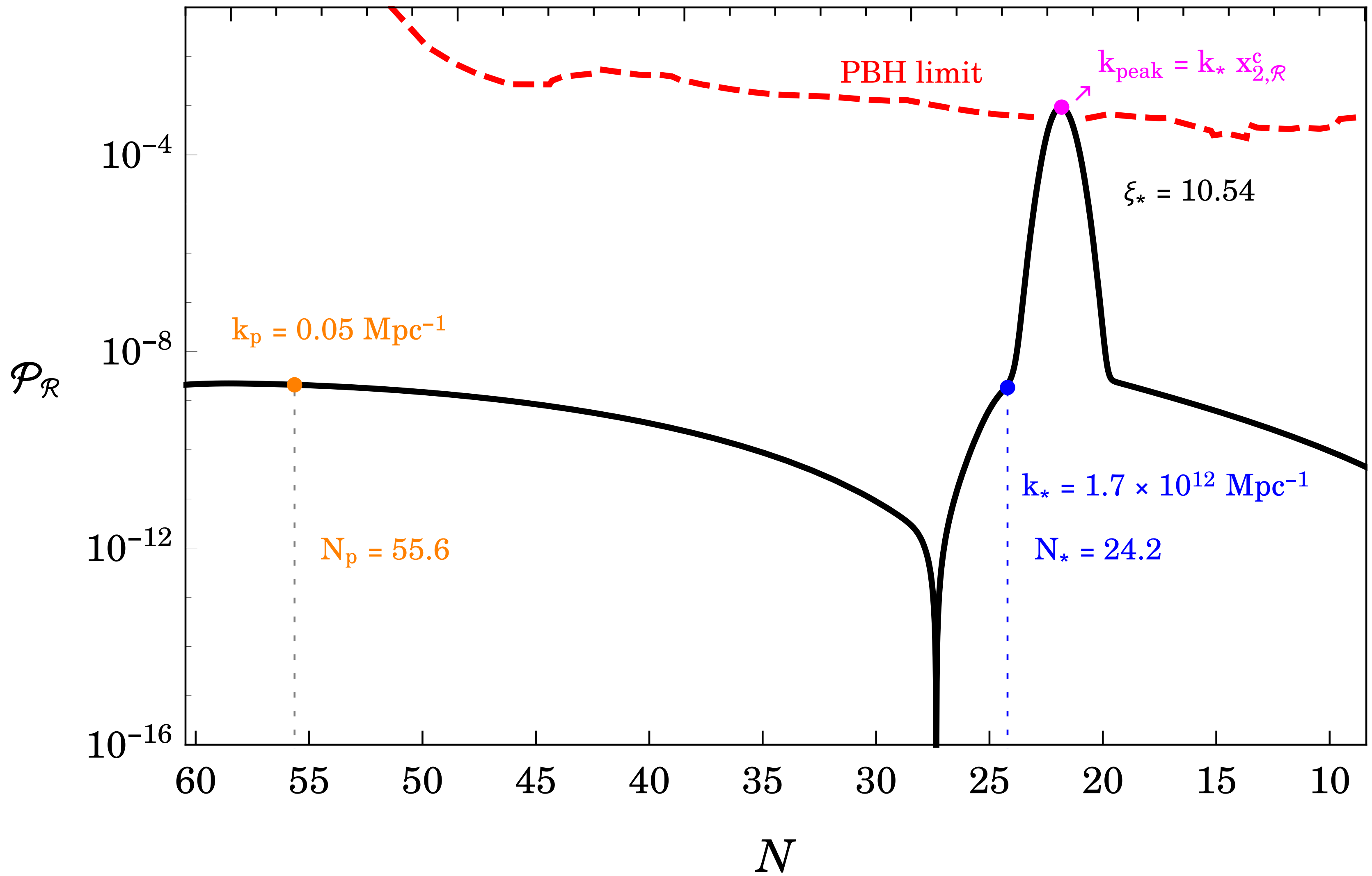
Models without a dip



- Particle production in a spectator axion-gauge field sector boosts the power spectrum at small scales.

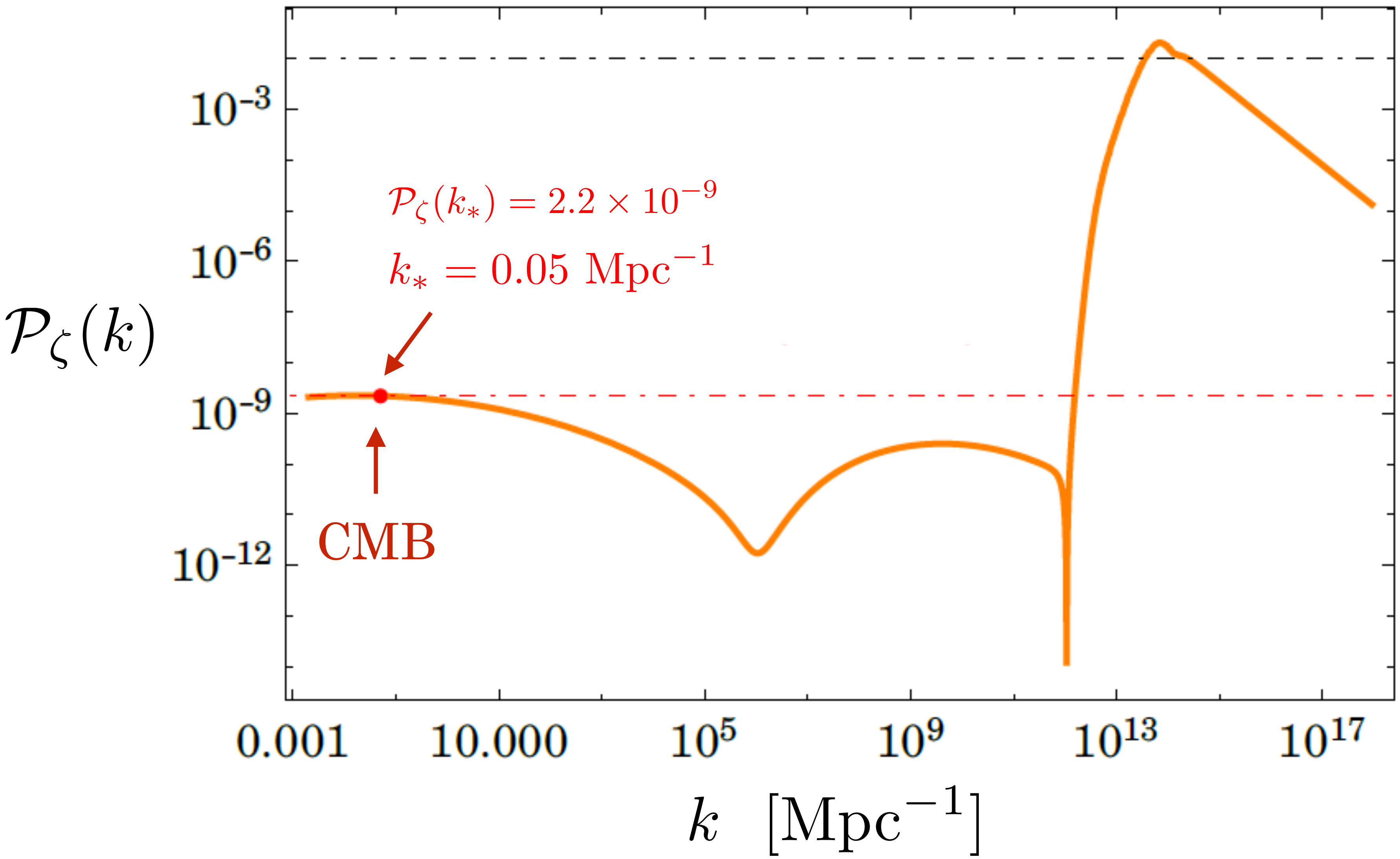
*OÖ, arXiv: 2005.10280

A hybrid model with a pronounced dip



*OÖ & Lalak, Z., arXiv: 2008.07549

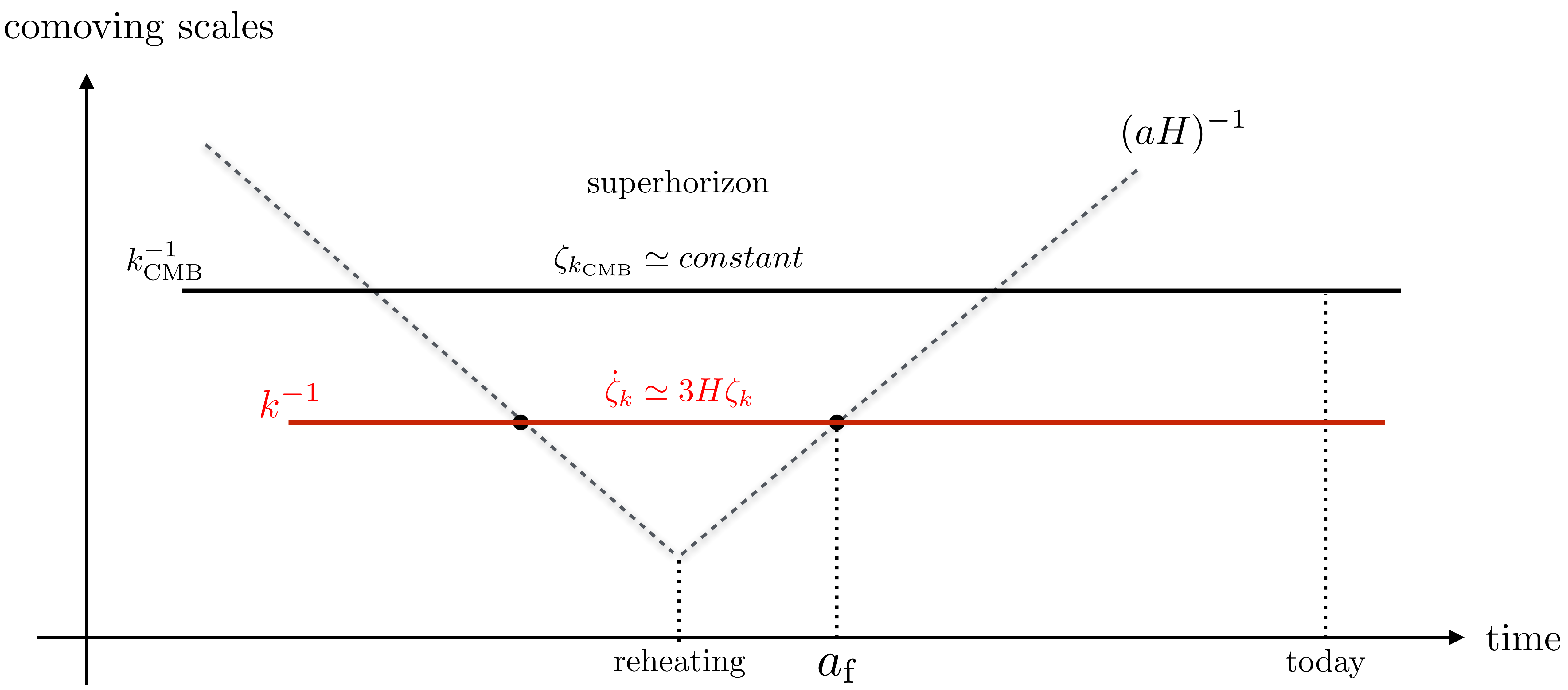
PBHs from non-perturbative effects



PBHs can be formed through the gravitational collapse of large fluctuations upon horizon re-entry during RDU.

*Multimode code: Price et.al. arXiv: 1410.0685

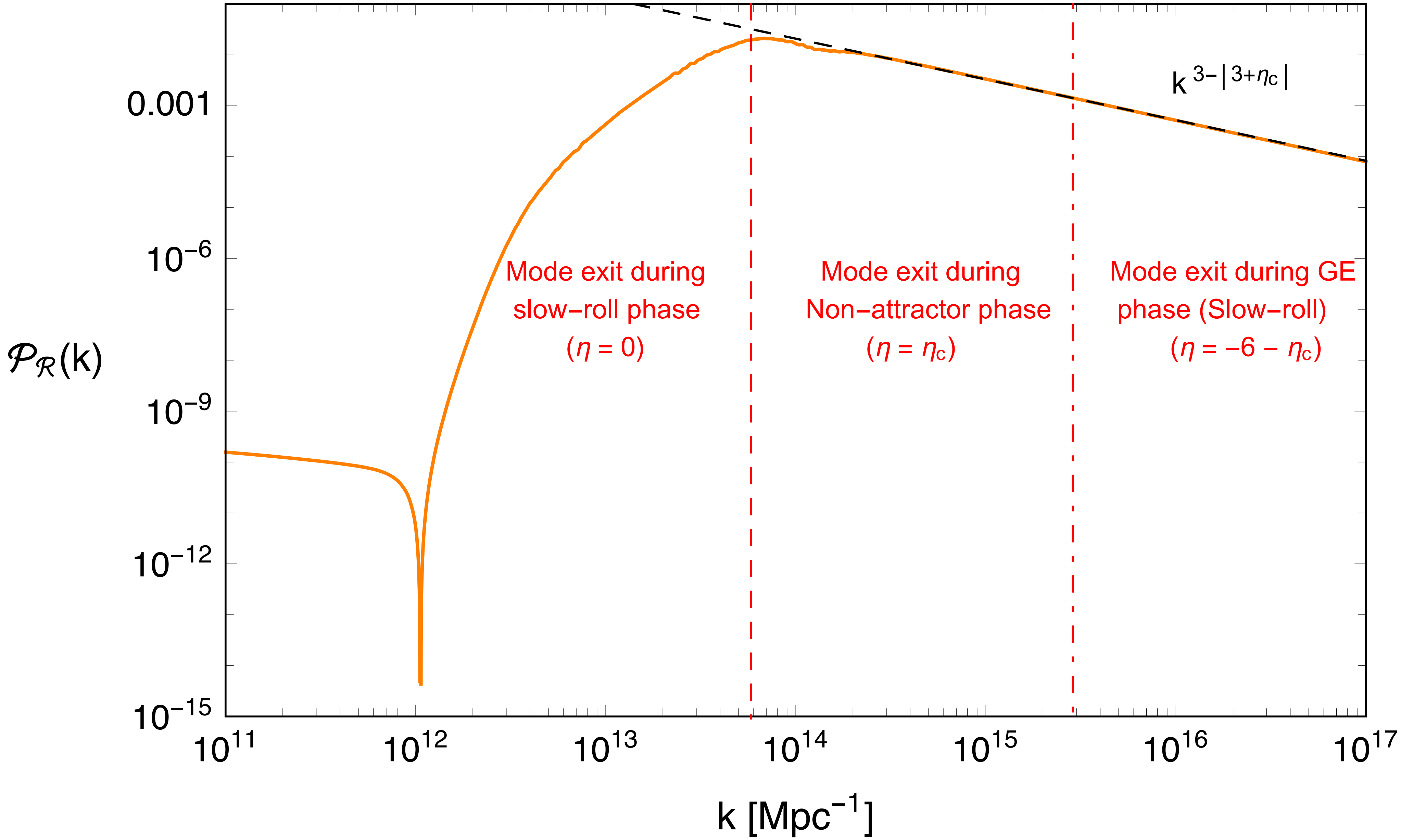
PBHs in non-attractor scenarios



$$M(k) = \gamma \frac{4\pi}{3} \rho H^{-3} \Big|_{k=a_{\rm f} H_{\rm f}} = 10^{18} {\rm gr} \left(\frac{k}{5.5 \times 10^{13}\ {\rm Mpc}^{-1}} \right)^{-2}$$

Characterizing the spectral profile

- Spectral profile of fluctuations is generically studied numerically, i.e model by model basis
- However, non-attractor scenarios have shared features:



PBH Abundance (Press-Schecter)

Mass Function

$$\beta(M(k)) = 2\int_{\delta_c}^{\infty} \frac{d\delta}{\sqrt{2\pi}\sigma(M(k))} \exp\left(-\frac{\delta^2}{2\sigma^2(M(k))}\right)$$

Shape dependent*

$\delta_c = 0.3 - 0.5$

*Musco, 1809.02127

$$\sigma^2(M(k)) = \frac{16}{81}\int_0^{\infty} d\ln q \, \left(\frac{q}{k}\right)^4 \mathcal{P}_\zeta(q) \, W(q/k)$$

$$\frac{\Omega_{\rm PBH}(M(k))}{\Omega_{\rm DM}} = [\text{ redshift factor }] \, \beta(M(k)) \longrightarrow \frac{\Omega_{\rm PBH}^{\rm tot}}{\Omega_{\rm DM}} = \int d\ln(M(k)) \frac{\Omega_{\rm PBH}(M(k))}{\Omega_{\rm DM}}$$

Cases	δ_c	$M_{\rm peak}/M_\odot$	$\Omega_{\rm PBH}^{\rm tot}/\Omega_{\rm DM}$
$M_{\rm pl}/f = 1.6$	0.34	8×10^{-16}	0.113
$M_{\rm pl}/f = 1.7$	0.5	2×10^{-16}	0.514