COSMOLOGICAL PARTICLE PRODUCTION AND GRAVITATIONAL WAVES

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MOTIVATION

What is the Cosmological Gravitational Particle Production (CGPP)?

Schwinger effect

Dark matter

MOTIVATION

What is the Cosmological Gravitational Particle Production (CGPP)?

Production of Gravitational Waves (GW)

Reheating

Primordial Black Holes (PBHs)

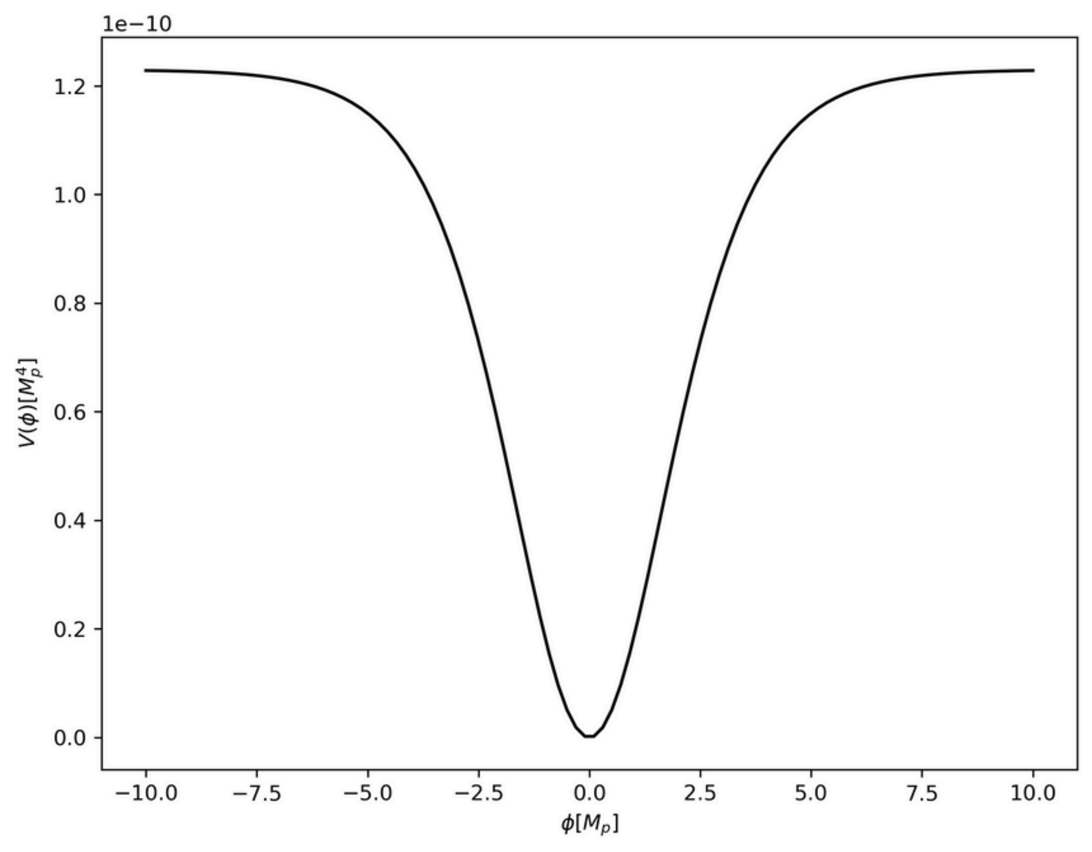
QFT IN CURVED SPACETIME

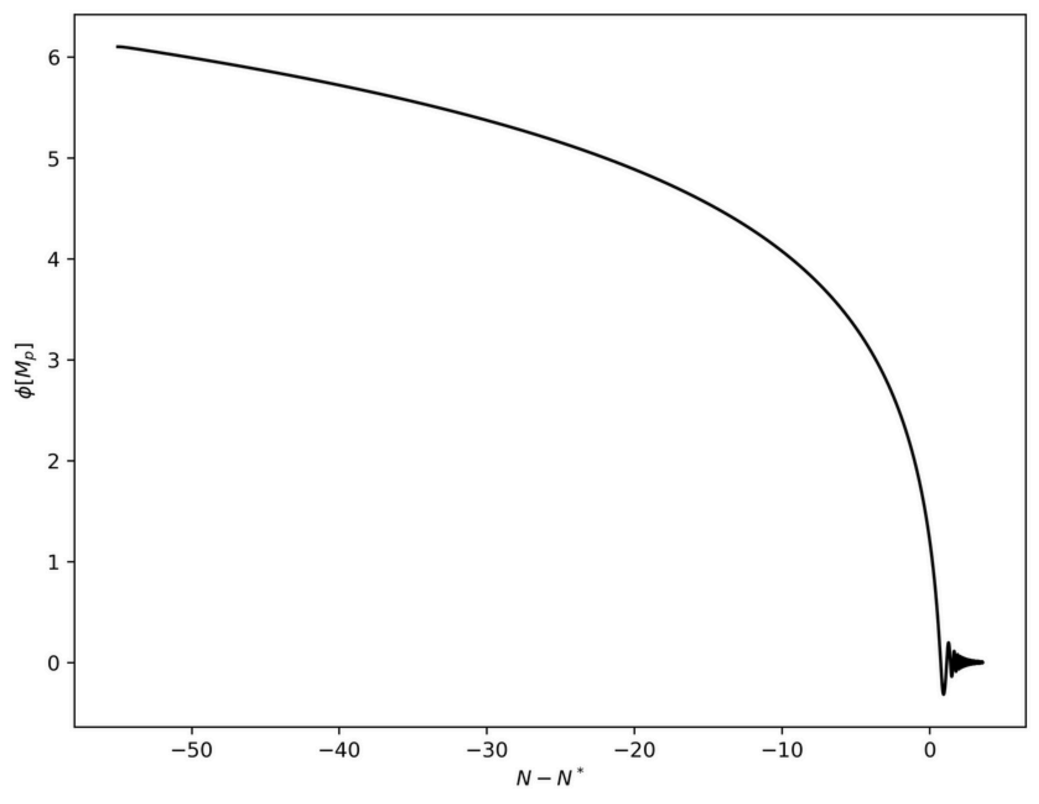
$$S[\chi, g_{\mu\nu}] = \int d^4x\sqrt{-g}\left(-\frac{M_p^2}{2}R + \frac{1}{2}(\partial\chi)^2 - \frac{1}{2}m^2\chi^2 - \frac{1}{2}\xi R\chi^2\right)$$

$$a(t)^{-3}\partial_t\left[a(t)^3\partial_t\chi(x)\right] - \frac{\nabla^2\chi(x)}{a(t)^2} + \left[m^2 + \xi R(t)\right]\chi(x) = 0$$

INFLATION MODEL

$$V(\phi) = \lambda M_p^4 \left[\sqrt{6}\tanh\left(\frac{\phi}{\sqrt{6}M_p}\right)\right]^2$$





$$\ddot{\phi}(t) + 3H\phi(t) + \frac{d}{d\phi}V(\phi) = 0$$

INFLATION MODEL

$$\lambda \approx 2 \times 10^{-11}, \phi_0 \approx 6M_p, N^* = 55, H_I \equiv \sqrt{2\lambda}$$

$$m_\chi = 0.55 M_p H_I \qquad \xi = 0$$

QFT IN CURVED SPACETIME

$$\hat{\chi}(x) = \int \frac{d^3k}{(2\pi)^3} \left[u_k(x)\hat{a}_{\mathbf{k}} + u_k^*(x)\hat{a}_{\mathbf{k}}^\dagger \right]$$

$$\frac{d^2}{d\theta^2}\chi_k(\theta) + \omega_k^2(\theta)\chi_k(\theta) = 0$$

$$u_k(x) = e^{-i\mathbf{k}\cdot\mathbf{x}}\chi_k(\theta)$$

$$d\theta = \frac{dt}{a^3(t)}$$

$$\omega_k^2(\theta) = a^4(t)k^2 + a^6(t)(m^2 + \xi R(t))$$

QFT IN CURVED SPACETIME

$|\Omega\rangle$

Vaccum

$$\chi_k^{\mathrm{IN}}(\theta \to -\infty) \longrightarrow \frac{1}{\sqrt{2\omega_k(\theta)}} \exp\left(-i \int^{\theta} d\theta' \omega_k(\theta')\right)$$

$$\chi_k(\theta) = \alpha_k(\theta)\chi_k^{\mathrm{IN}}(\theta) + \beta_k(\theta)\chi_k^{\mathrm{IN}*}(\theta)$$

QFT IN CURVED SPACETIME

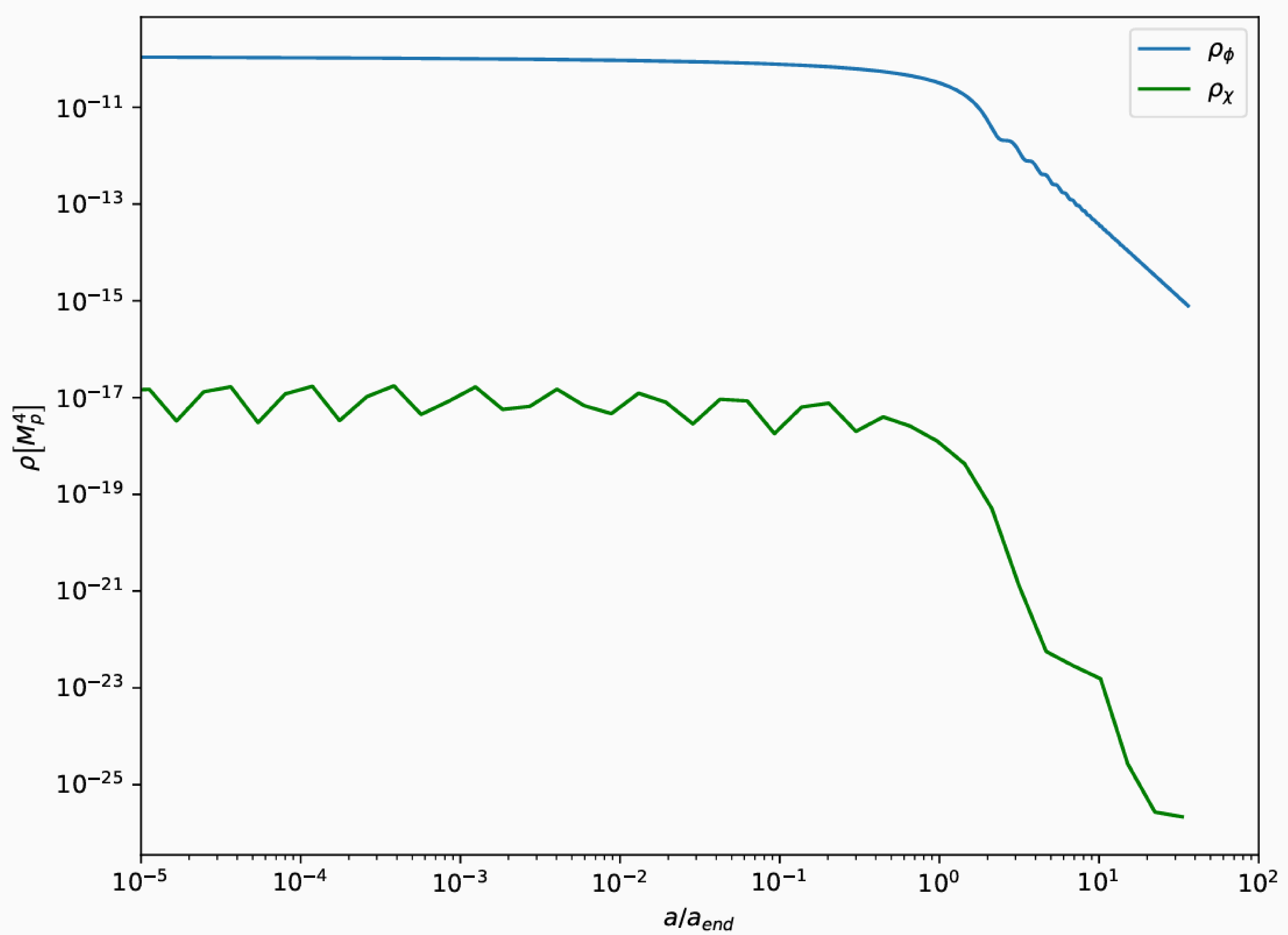
$$T_{\mu\nu} = \langle \hat{T}_{\mu\nu} \rangle$$

$$T_{\mu\nu}$$

Energy-Momentum Tensor

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

$$\rho(\theta) = a^{-6}(\theta) \int \frac{d^3k}{(2\pi)^3} \omega_k n_k$$



ρ_ϕ
ρ_χ
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-23}
10^{-25}
$\rho[M_p^4]$
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
a/a_{end}

QFT IN CURVED SPACETIME

$$T_{\mu\nu} = \langle \hat{T}_{\mu\nu} \rangle$$

$$T_{\mu\nu}$$

$$f_k(\theta) = \frac{1}{\sqrt{2\omega_k}} \exp\left(-i \int^{\theta} d\theta' \omega_k(\theta') \right)$$

Energy-Momentum Tensor

$$p(\theta) = a^{-6}(\theta) \int \frac{d^3k}{(2\pi)^3} \left[\frac{1}{3\omega_k} \left(\omega_k^2 - a^6 m^2 \right) n_k - \frac{2}{3} \left(\omega_k^2 + \frac{1}{2} a^6 m^2 \right) \mathrm{Re} \left(\alpha_k \beta_k^* f_k^2 \right) \right]$$

QFT IN CURVED SPACETIME

$$\Delta_\chi^2(k,\theta) = \frac{k^3}{2\pi^2}\mathcal{P}_\chi(k,\theta)$$

$$\mathcal{P}_\chi(k,\theta) = |\chi_k(\theta)|^2 - \frac{1}{2\omega_k(\theta)}$$

Power Spectra

QFT IN CURVED SPACETIME

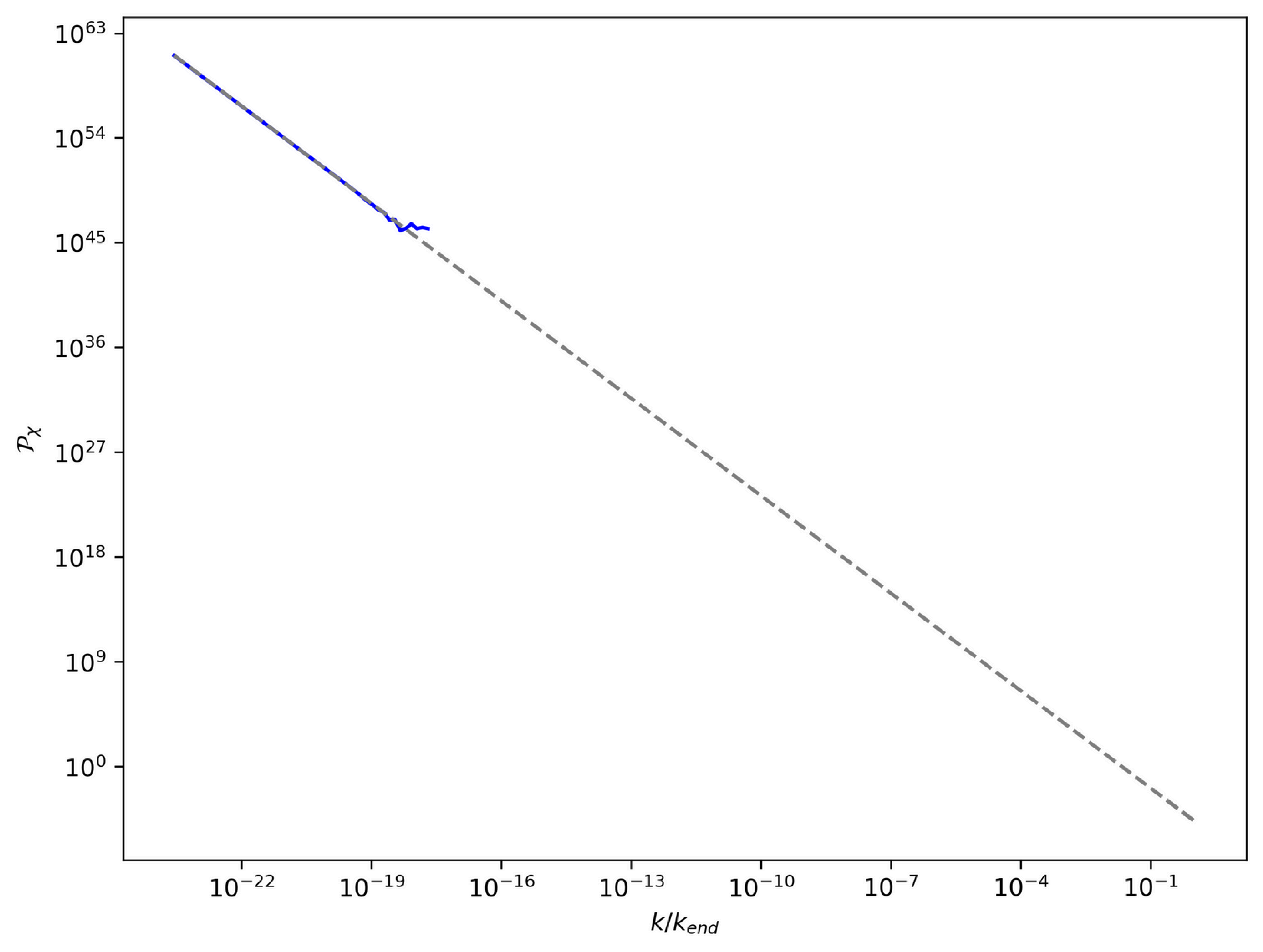
$$\mathcal{P}_\chi(k,\theta) = k_{\text{end}}^{-1}\mathcal{T}(a)P(k)$$

$$P(k) = \left(\frac{k_{\text{end}}}{k}\right)^{2\nu}$$

$$\nu = \sqrt{\frac{9}{4} - \frac{m_\chi^2}{H_I^2}}$$

Power Spectra

$$\mathcal{T}(a) = \mathcal{N} a^{-2}\left(\frac{aH}{k_{\text{end}}}\right)^{2\nu-1}$$



10^{63}
10^{54}
10^{45}
10^{36}
10^{27}
10^{18}
10^{9}
10^{0}
$\mathcal{P}_\chi$
10^{-22}
10^{-19}
10^{-16}
10^{-13}
10^{-10}
10^{-7}
10^{-4}
10^{-1}
k/k_{end}

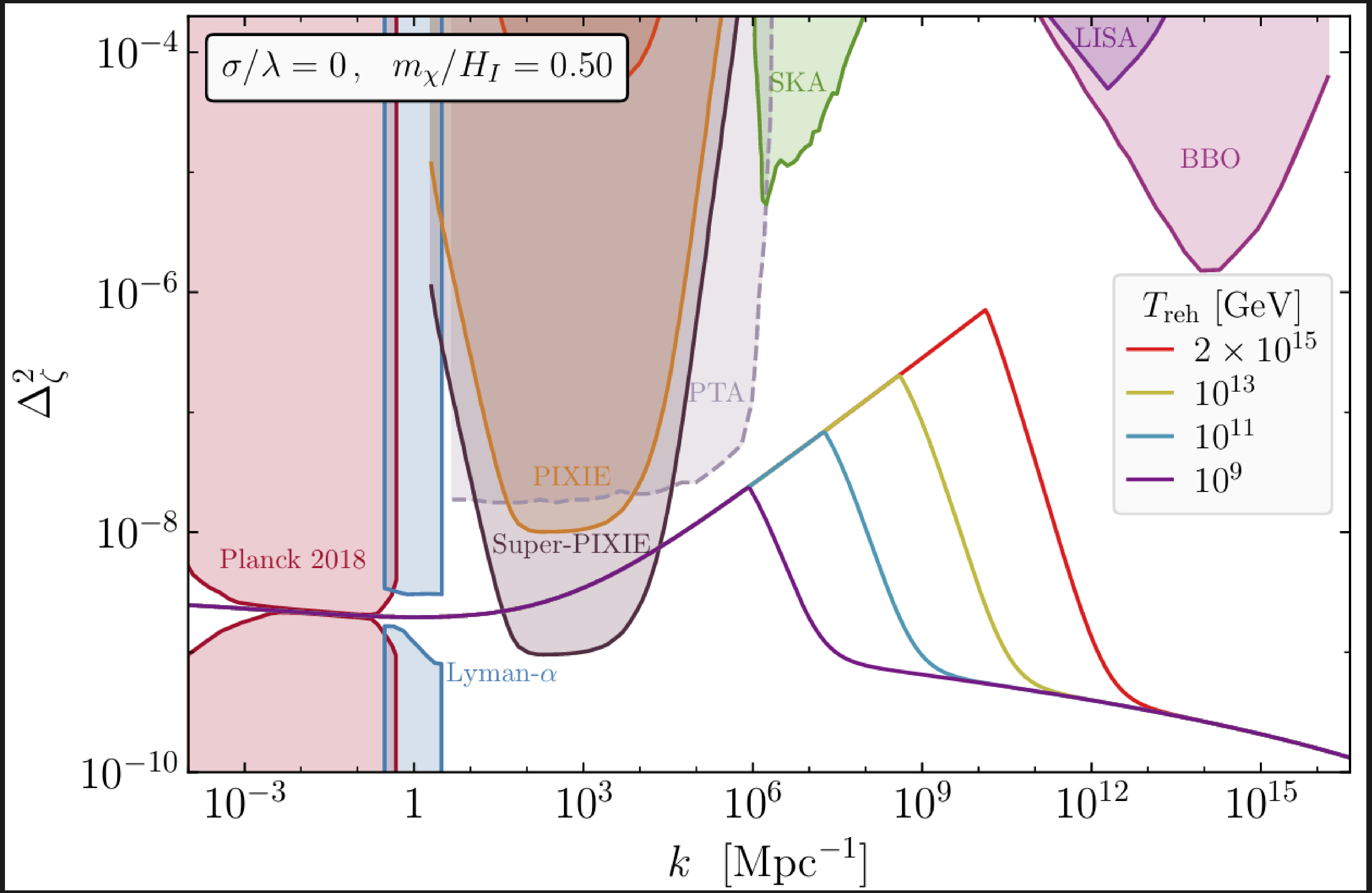
GRAVITATIONAL WAVES

$$\boxed{h''_{\mathbf{k},\lambda}(\eta) + 2\mathcal{H}h'_{\mathbf{k},\lambda}(\eta) + k^2 h_{\mathbf{k}(\eta),\lambda}(\eta) = S_\lambda(\eta, \mathbf{k})}$$

Isocurvature

Second-order perturbation theory

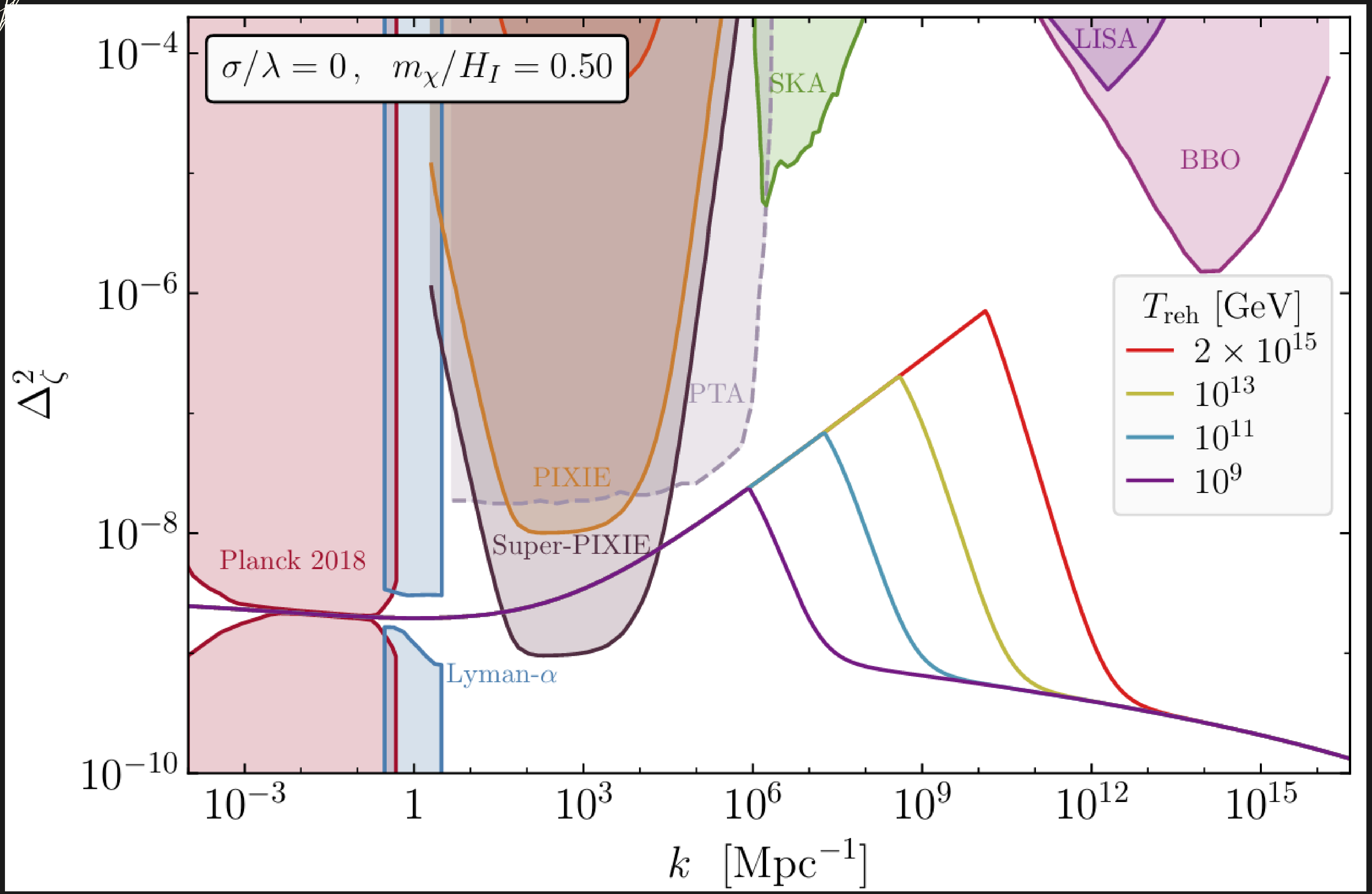
GRAVITATIONAL WAVES



- Curvature perturbation $\left(k < 0.1\mathrm{Mpc}^{-1}\right)$
- Isocurvature $\left(k > 1\mathrm{Mpc}^{-1}\right)$

García, M. A. G, & Verner, S. (2025). Gravitational waves from spectator scalar fields. arXiv. https://arxiv.org/abs/2506.12126

GRAVITATIONAL WAVES



This spectrum can lead to:

- Production of PBHs
- Constraints on the RH era

García, M. A. G, & Verner, S. (2025). Gravitational waves from spectator scalar fields. arXiv. https://arxiv.org/abs/2506.12126

FUTURE WORK

1. POWER SPECTRA OF GW
2. ISOCURVATURE
3. PBHS

THANK YOU!

Instituto de Física
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