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Stochastic Gravitational Waves from Modulated Reheating

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Gravitational Wave Probes of Physics Beyond Standard Model

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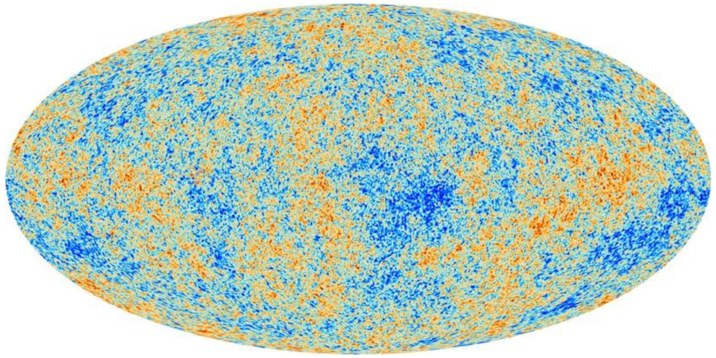
Introduction

- Fluctuations in the CMB and large-scale structure reveal key insights into the early Universe.
- In ΛCDM cosmology, they originate from quantum perturbations during cosmic inflation



→ It constrains the perturbations on scales much larger than that of galaxies

we investigate small-scale primordial perturbations sourced by spectator scalar field

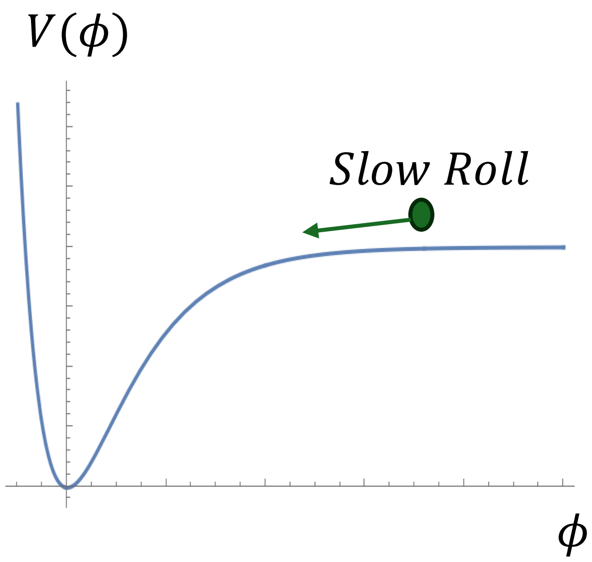
Our Setup

$$\mathcal{L} = -\frac{1}{2}\nabla^{\mu}\phi\nabla_{\mu}\phi - \Lambda_{\phi}^{4}\left(1 - e^{-\sqrt{2/3}\phi/M_{\rm P}}\right)^{2} - \frac{1}{2}\nabla^{\mu}\chi\nabla_{\nu}\chi - \frac{1}{2}\xi R\chi^{2} - \frac{1}{4}\lambda\chi^{4} + \mathcal{L}_{\rm dec}(\phi,\chi,X) + \ldots$$

ϕ =Inflaton field
Starobinskiy Inflation

χ = Spectator
R = Ricci scalar
ξ = Non minimal coupling

Interaction



χ is subdominant during inflation

Modulated Reheating: a mechanism for generating curvature perturbations

Dvali, Gruzinov & Zaldarriaga (2004), Phys. Rev.

What is the Modulated reheating?

- The **decay rate** of the inflaton is **modulated** by a light scalar field.
- This leads to **spatial variation in the reheating history**.

$$\delta\chi(x) \longrightarrow \delta\Gamma(x) \longrightarrow \delta N(x)$$

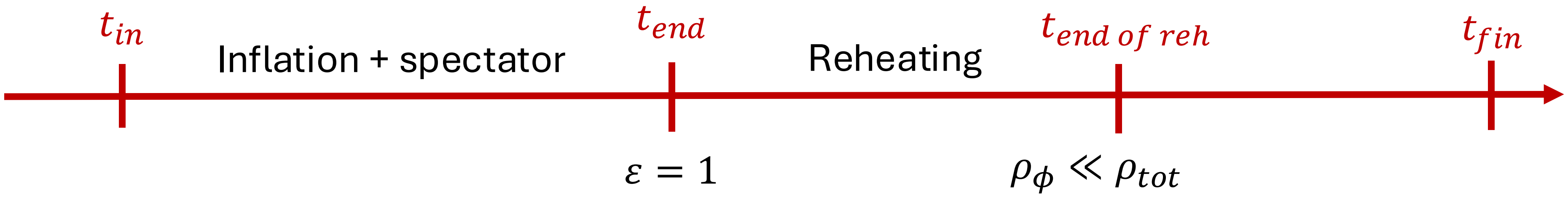
Two scenarios

- Vector: $$\mathcal{L}^{(1)}_{\rm dec} = \frac{1}{\Lambda_1}\phi F_{\mu\nu}\tilde{F^{\mu\nu}} \qquad \Gamma^{(1)} = g_1 \frac{m_\phi^3}{4\pi\Lambda_1^2}\left(1-\frac{g^2\chi^2}{m_\phi^2}\right)^{3/2},$$
- Fermion: $$\mathcal{L}^{(2)}_{\rm dec} = \frac{1}{\Lambda_2}\bar{\psi}(\partial\!\!\!/\phi)\gamma^5\psi\ . \qquad \Gamma^{(2)} = g_2 \frac{m_\phi m_{\psi_I}^2}{2\pi\Lambda_2^2}\left(1-\frac{2y_\psi^2\chi^2}{m_\phi^2}\right)^{1/2}$$

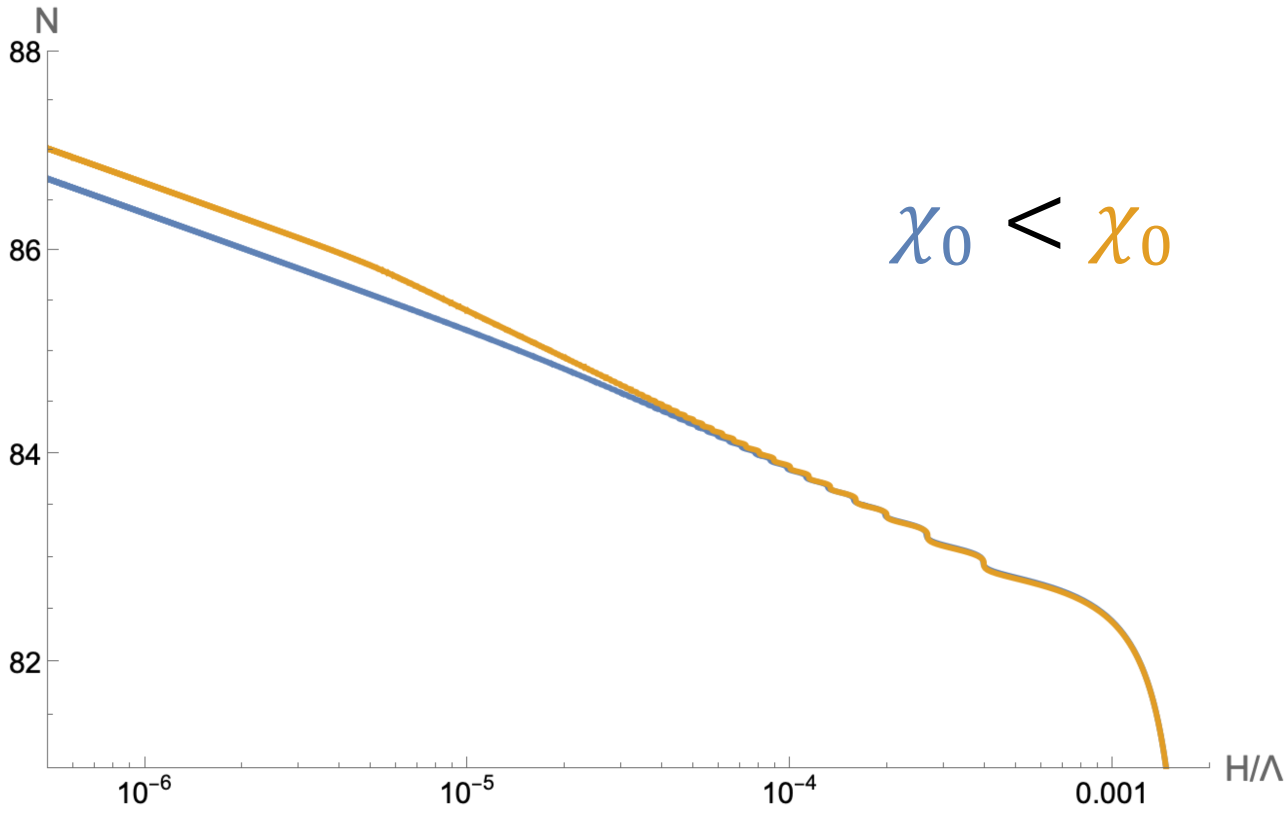
$F_{\mu\nu}$ = field strength tensors of a gauge field A_μ,
ψ = fermion

Masses are given by: $m_A = \frac{g}{2}\chi\ ,\qquad m_\psi = \frac{y_\psi}{\sqrt{2}}\chi$

Wind It Up and Let It Go



Evolution of Number of e-folds for different spectator initial condition χ_0



Curvature Perturbation

- ΔN formalism

$$\zeta(\mathbf{x}) = N(\phi(\mathbf{x}), \chi(\mathbf{x})) - \langle N(\phi(\mathbf{x}), \chi(\mathbf{x}))\rangle$$

Sasaki & Stewart (1996), Prog. Theor. Phys.

- Initialization of the spectator
  - de Sitter equilibrium distribution
  - **From Stochastic formalism**
  - $\langle \chi \rangle = 0$

Starobinsky & Yokoyama, Phys. Rev. (1994)

- Expanding for small $\delta\phi$

$$\zeta(\mathbf{x}) = \zeta_\phi(\mathbf{x}) + \zeta_\chi(\mathbf{x})$$

$$\zeta_\phi(\mathbf{x}) = \partial_\phi N(\bar{\phi}, \chi(\mathbf{x}))\delta\phi(\mathbf{x})$$

$$\zeta_\chi(\mathbf{x}) = N(\bar{\phi}, \chi(\mathbf{x})) - \langle N(\bar{\phi}, \chi(\mathbf{x}))\rangle$$

The Power Spectrum

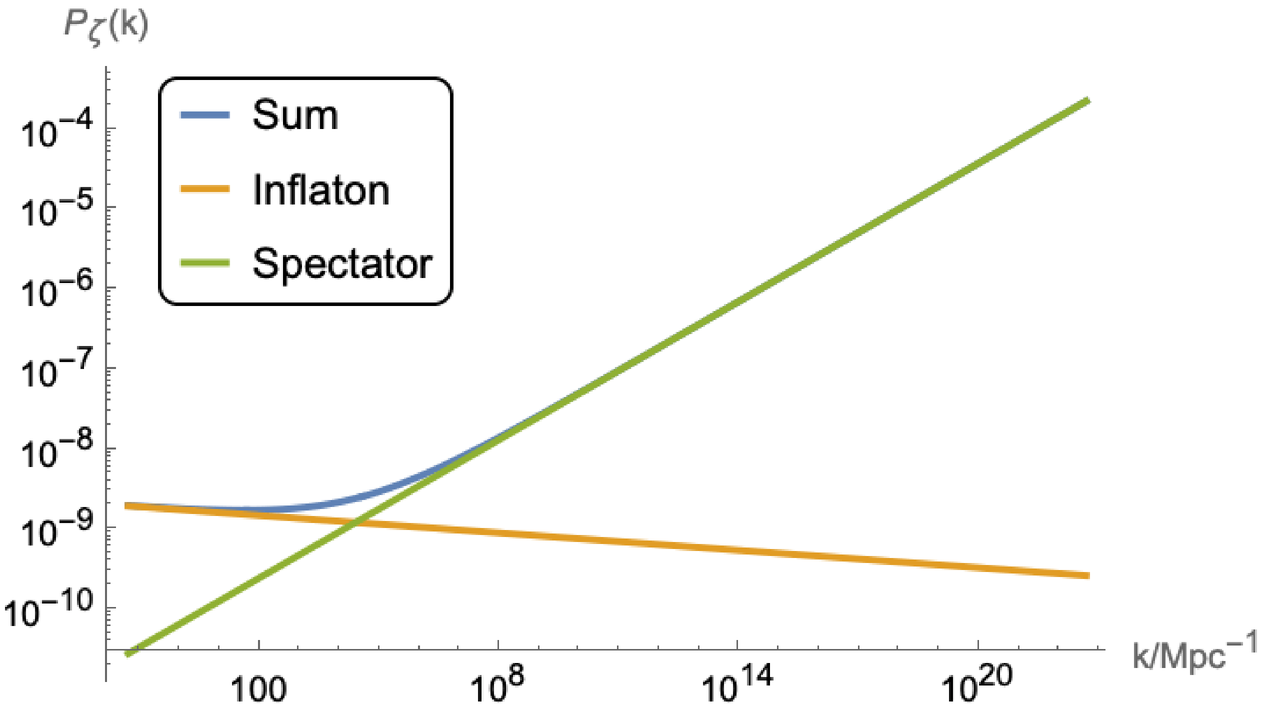
$$\langle \zeta(k)\zeta(k')\rangle = 2\pi^3\delta^3(k+k')\frac{2\pi^2}{k^3}\mathcal{P}_\zeta(k)$$

Using:

- $\langle \zeta_\chi \zeta_\phi \rangle = 0$
- $\langle \delta\phi \chi^n \rangle = 0$

↓

$$\langle \zeta(\mathbf{x})\zeta(\mathbf{x}')\rangle = \langle \zeta_\phi(\mathbf{x})\zeta_\phi(\mathbf{x}')\rangle + \langle \zeta_\chi(\mathbf{x})\zeta_\chi(\mathbf{x}')\rangle$$



Constraints

Amplitude	$A = (2.101 \pm 0.25)10^{-9}$
Spectral Index	$n = 0.9649 \pm 0.0044$

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CMB constraint at *k* = 0.05 Mpc^{-1}

$$P(k) = A\left(\frac{k}{k_*}\right)^{1-n}$$

Non-Gaussianity

$$f_{\rm NL}^{\rm local} = -0.9 \pm 5.1$$

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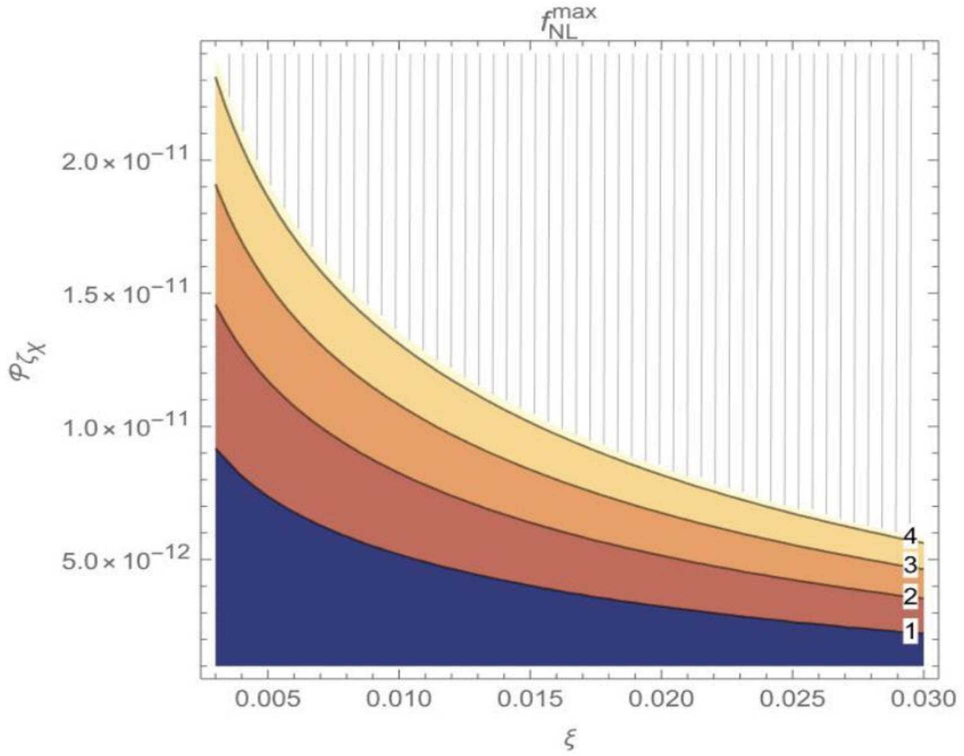
$$f_{\rm NL}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = \frac{5}{6}\frac{B(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)}{P_\zeta(k_1)P_\zeta(k_3) + P_\zeta(k_2)P_\zeta(k_3) + P_\zeta(k_1)P_\zeta(k_2)} \, .$$



Gravitational Wave: tensor perturbation

Tensor perturbation →

$$h''_\lambda(\tau,\mathbf{k}) + 2\mathcal{H}h'_\lambda(\tau,\mathbf{k}) + k^2 h_\lambda(\tau,\mathbf{k}) = 4\mathcal{S}_\lambda(\tau,\mathbf{k})$$

$\mathcal{S}_\lambda$ = Source →

Contains combination of Φ squared (scalar perturbation)

$$\mathrm{d}s^2 = -(1+2\Phi)\,\mathrm{d}t^2 + a^2(1-2\Phi)\,\delta_{ij}\,\mathrm{d}x^i\mathrm{d}x^j$$

Green's method →

$$h_\lambda(\tau,\mathbf{k}) = \frac{4}{a(\tau)}\int_{\tau_0}^{\tau} d\bar{\tau}\; a(\bar{\tau})\mathcal{S}_\lambda(\bar{\tau},\mathbf{k})\; G_{\mathbf{k}}(\tau,\bar{\tau})$$

Gravitational Wave: scalar perturbation

EOM for the scalar perturbation

$$\Phi''(\tau, \mathbf{k}) + 3(1+w)\mathcal{H}\Phi'(\tau, \mathbf{k}) + w\,k^2\Phi(\tau, \mathbf{k}) = 0\,.$$

For RD Universe $w = 1/3$ →

$$\Phi(\tau, \mathbf{k}) = \frac{2}{3}\zeta(k)T_\Phi(k\tau)$$

Φ is proportional to ζ

Where the transfer function is given by

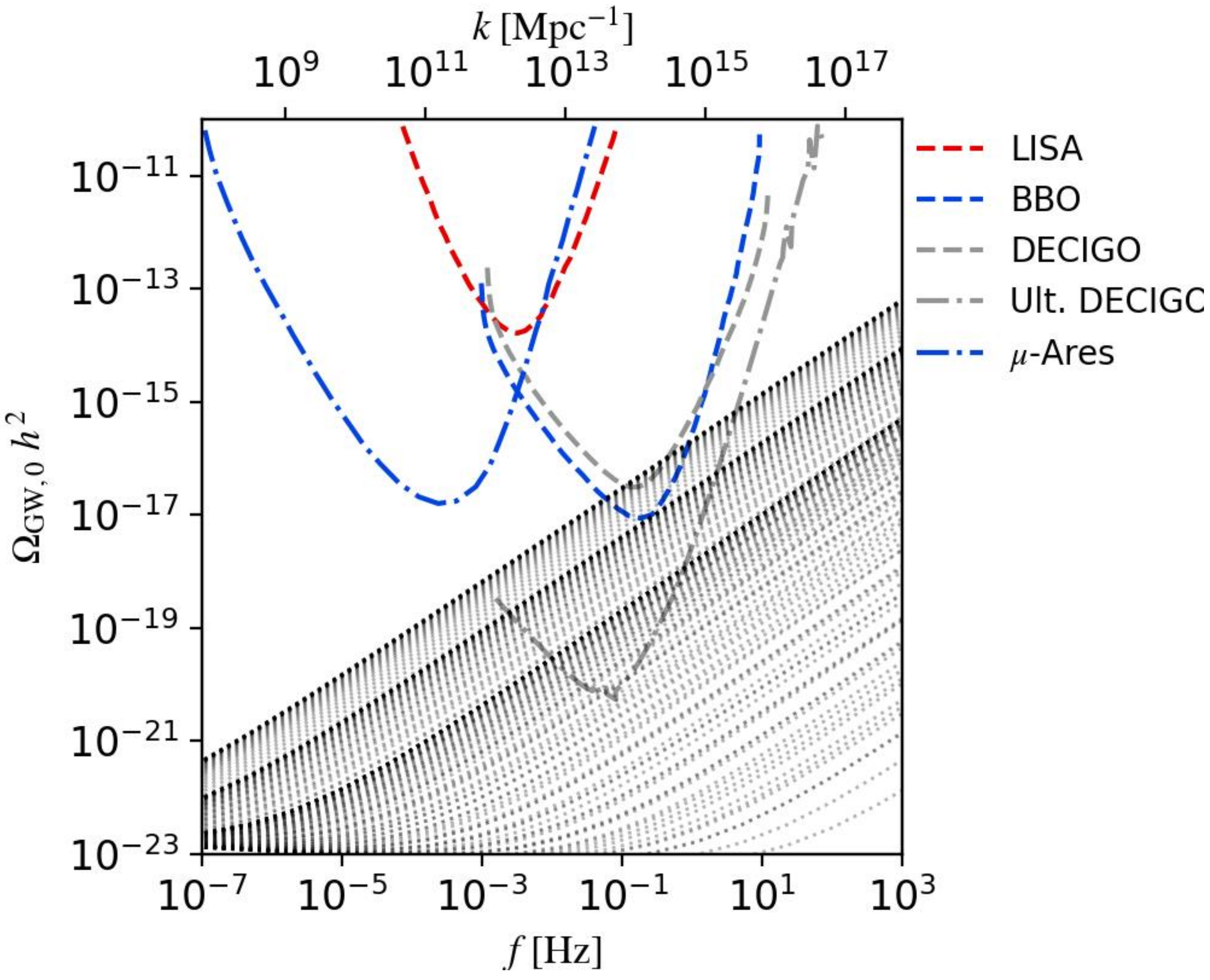
$$T_\Phi(k\tau) = \frac{3}{(k\tau/\sqrt{3})^3}\left(\sin\frac{k\tau}{\sqrt{3}} - \frac{k\tau}{\sqrt{3}}\cos\frac{k\tau}{\sqrt{3}}\right)$$

Gravitational Wave signals

$$\Omega_{GW} = \frac{1}{\rho_{tot}} \frac{d\rho_{GW}}{d\log k}$$

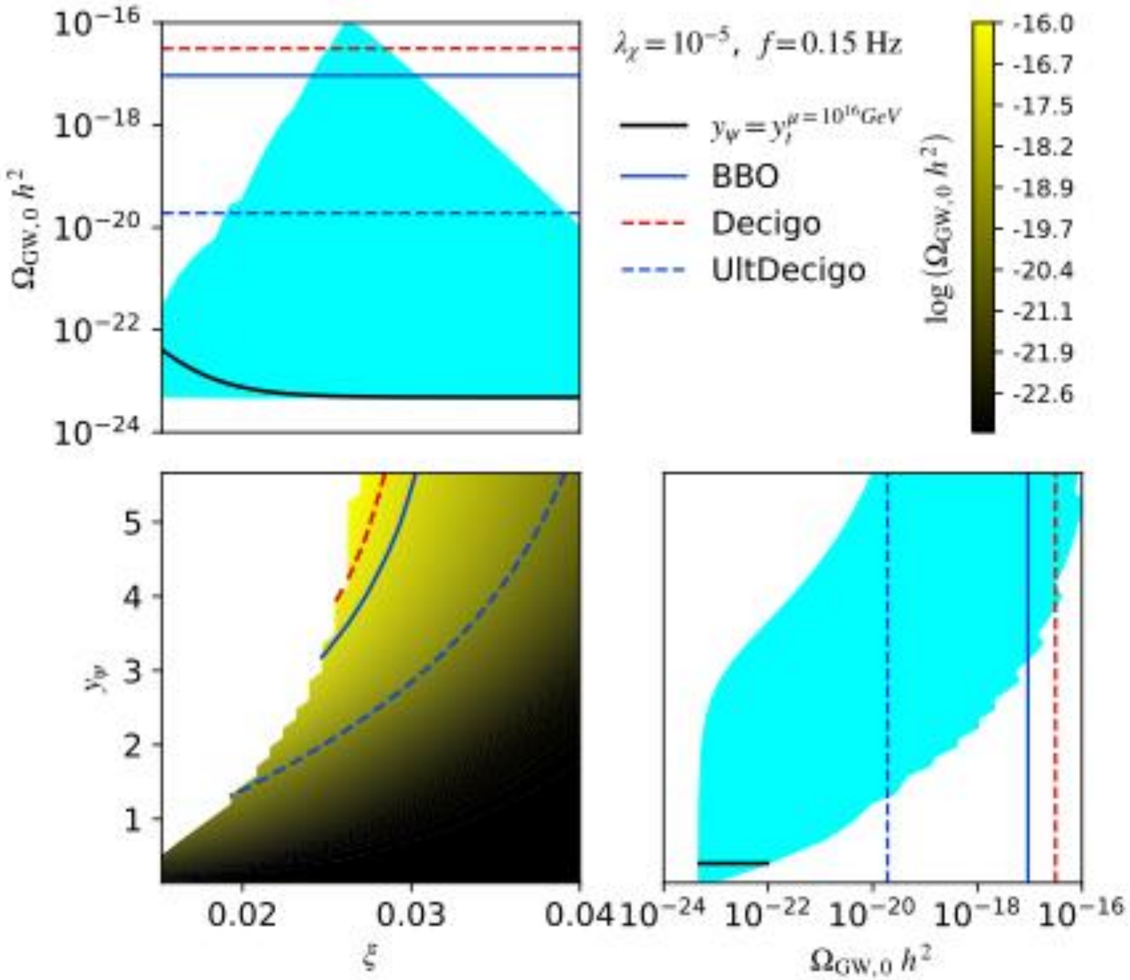
$k \gg 0.05\ Mpc^{-1}$
spectator contribution dominates

$$\Omega_{GW}(k) \propto P_\zeta(k)^2$$

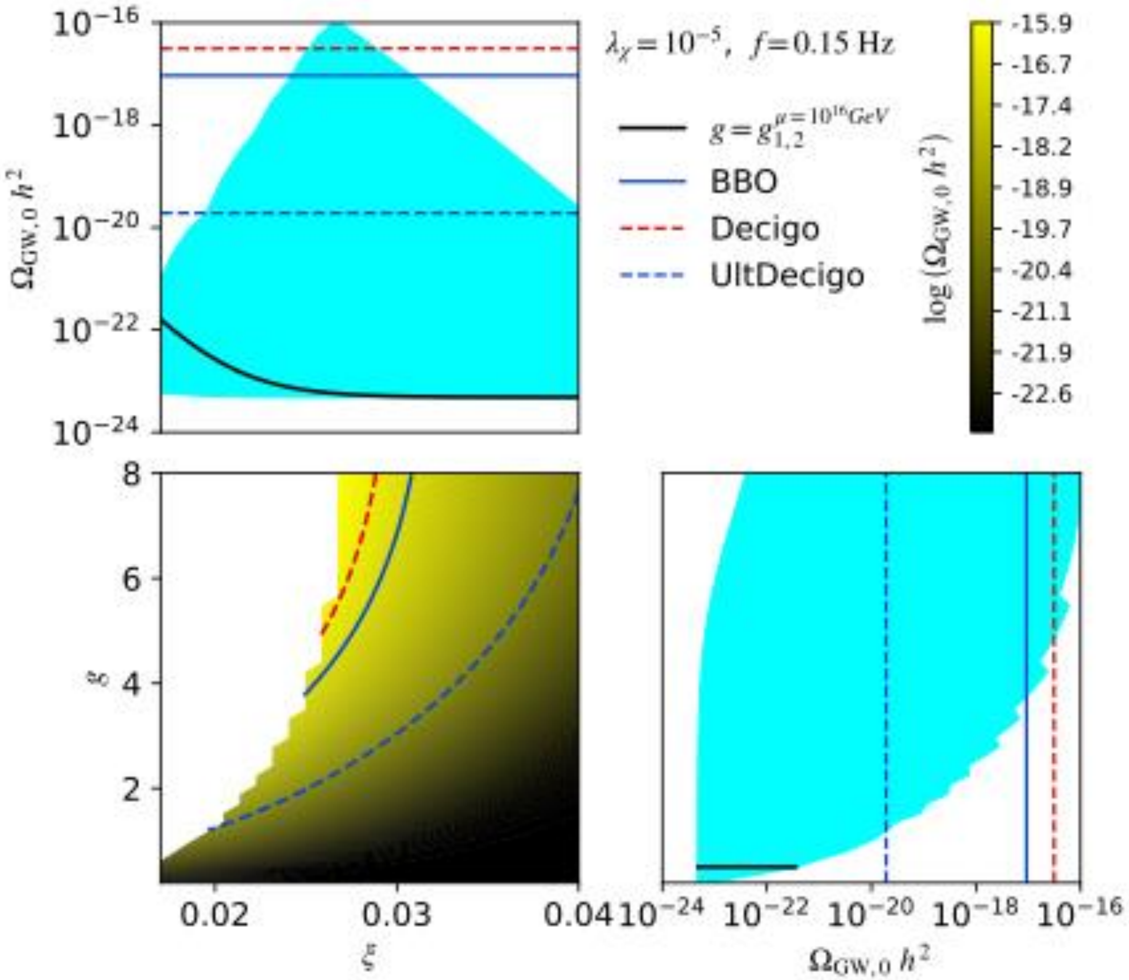


Results

Fermion



Vector



Conclusions

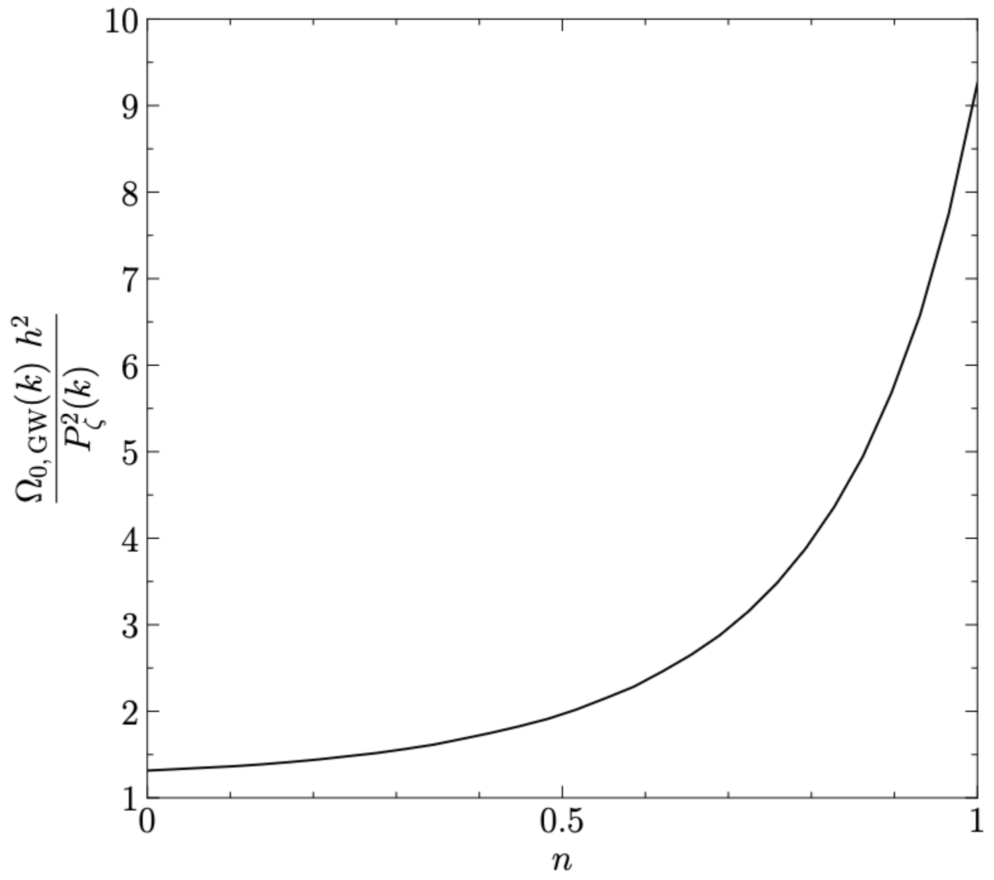
✅ **Modulated reheating** with a spectator field χ can source **gravitational waves** from curvature perturbations on small scales.

🔭 Signals may fall **within reach of future detectors** like **Ultimate DECIGO** and **BBO,** in a given interval of the parameter**.**

🚫 SM gauge and Yukawa coupling cannot produce an observable signal .

Thank you for the attention

Exemple of Omega/P



The dependence of the GW signal on the spectral index, factoring out the power-spectrum k-dependence.

Energy and number of e-fold