The Standard Model (SM) in the Sky

(A new consequence of Inflation)

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arXiv:1402.1345

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I shall be talking about ...

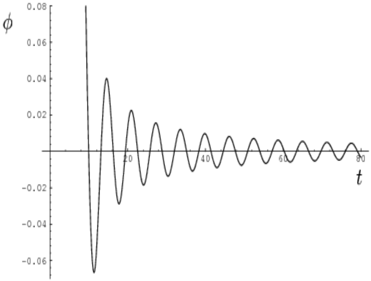
1. **Parametrically Excited Fermions $\Rightarrow$ GWs**

2. **INFLATION $\Rightarrow$ SM Higgs Condensate $\Rightarrow$ SM Fermions $\Rightarrow$ GWs**

1.1 Fermion Parametric Excitation

Scalar field (condensate) after Inflation:

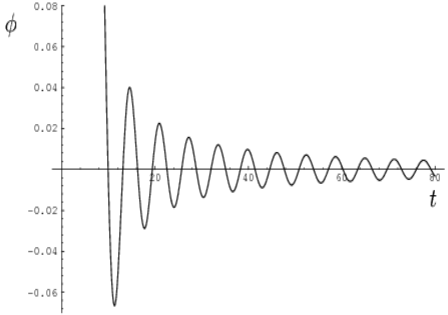
Coherent Oscillations: $\phi(t) \approx \Phi(t) f(t), \quad f(t+T) = f(t)$



1.1 Fermion Parametric Excitation

Fermions: $y\phi\bar{\psi}\psi$: Oscillations $\rightarrow$ ψ – Particle Creation
(Non-Pert., Out-of-Eq.)

$$\psi(\mathbf{x},t) = \int \frac{d\mathbf{k}}{(2\pi)^3}\, e^{-i\mathbf{k}\cdot\mathbf{x}} \left[\hat{a}_{\mathbf{k},r}\mathbf{u}_{\mathbf{k},r}(t) + \hat{b}^{\dagger}_{-\mathbf{k},r}\mathbf{v}_{\mathbf{k},r}(t)\right],$$



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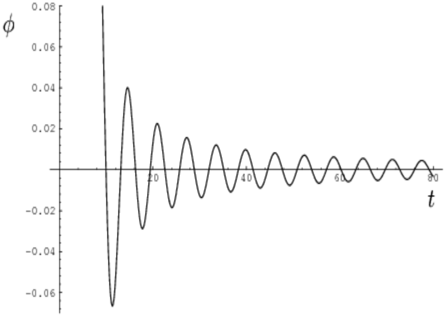

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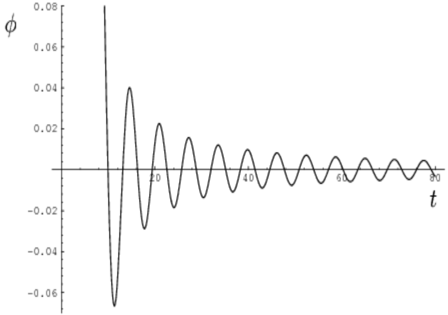

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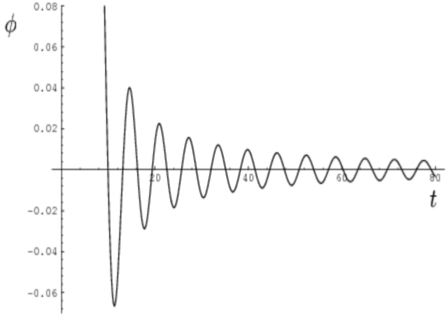

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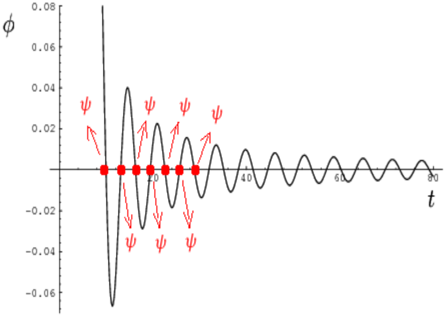

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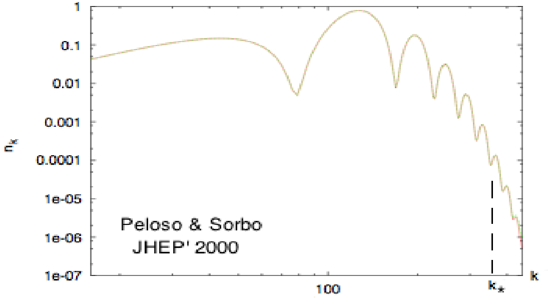

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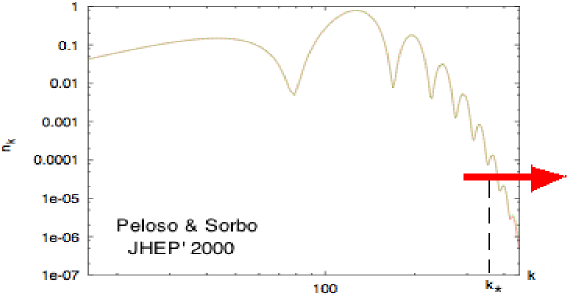

1.2 GWs from Fermions

Fermi-Sphere: $\left\{ \begin{array}{l} n_k(k \lesssim k_*) \lesssim 1, \\ n_k(k \gg k_*) \to 0 \end{array} \right\} \Rightarrow T_{\mu\nu}^{(\psi)} \sim \left(\bar{\psi}\gamma_{(\mu}D_{\nu)}\psi\right)[u_{k,\pm}(t)]$

$$\left[\left(T_{\mu\nu}^{(\psi)}\right)^{\rm TT} \rightarrow \text{ GW Source !} \right]$$

GWs: $\frac{d\rho_{\rm GW}}{d\log k}(k,t) = \#\, \frac{Gk^3}{a^4(t)} \int_0^t \int_0^t dt_1 dt_2\, \mathcal{G}(k, t_2 - t_1)\, \Pi^2(k, t_1, t_2)$

UTC: $\left\langle T_{ij}^{\rm TT}(\mathbf{k}, t_1)\, T_{ij}^{\rm TT}(\mathbf{k}', t_2)\right\rangle \equiv (2\pi)^3\, \Pi^2(k, t_1, t_2)\, \delta^{(3)}(\mathbf{k}-\mathbf{k}')$

Enqvist, DGF, Meriniemi
PRD'12, JHEP'13

2.1 SM Higgs during/after Inflation

Inflation: dS(H_*), $(H_* \gg v \equiv 246$ GeV)

SM Higgs: $\Phi = \frac{\varphi}{\sqrt{2}} \;\rightarrow\; V(\varphi) = \frac{\lambda(\mu)}{4}\varphi^4, \quad \mu = \varphi \gg v$

Prob. Dist: φ light $(|V''| < H_*^2) \Rightarrow \begin{cases} \text{Random Walk } (k < aH_*) \\ P_{\rm eq}(\varphi) \propto \text{Exp}\{-c\lambda_*(\varphi/H_*)^4\} \end{cases}$

End of Inflation: $\varphi_* = \alpha H_*/\lambda_*^{1/4} \qquad \alpha \in [0.01, 1]$ (98 %)

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End of Inflation: $\varphi_* \neq 0 \;\; (V \propto \varphi^4) \quad \Rightarrow \quad$ Higgs Oscillations (!)

Higgs Osc. $\rightarrow$ SM Ψ's Param. Exc. $\rightarrow$ GWs

$$y_j \varphi \bar{\psi}_j \psi_j : \quad \frac{d^2}{d\tau^2} u_{k,\pm}^{(j)} + \left(\kappa^2 + q_j (a\varphi)^2 \pm i\sqrt{q_j} \frac{d}{d\tau}(a\varphi)\right) u_{k,\pm}^{(j)} = 0\,, \quad q_j \equiv \frac{y_j^2}{\lambda_{\rm I}}$$

Higgs Osc. $\rightarrow$ SM Ψ's Param. Exc. $\rightarrow$ GWs

$$j = \left\{ \begin{array}{c} \{t, b, c, s, u, d\} \\ \{e, \mu, \tau\} \end{array} \right\} \quad \Rightarrow \quad \Omega_{\rm GW}^{(j)}(k) \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\log k}(k; q_j)\,, \quad q_j \equiv \frac{y_j^2}{\lambda_{\rm I}}$$

Higgs Osc. $\rightarrow$ SM Ψ's Param. Exc. $\rightarrow$ GWs

$$n_k^{(j)}(k \lesssim k_*^{(j)}) \quad \rightarrow \quad \Omega_{\rm GW}^{(j)}(k) : \left\{ \begin{array}{l} k_p \sim k_*^{(j)} \ (\text{Max.}) \\ \propto k^3, \ k \ll k_p \\ \propto k^{-1.5}, \ k \gg k_p \end{array} \right\}$$

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$$k_*^{(j)} \simeq q_j^{\,\frac{1}{4}} \sqrt{\lambda_{\rm I}}\varphi_{\rm I} \qquad\qquad (\delta \ll 1)$$

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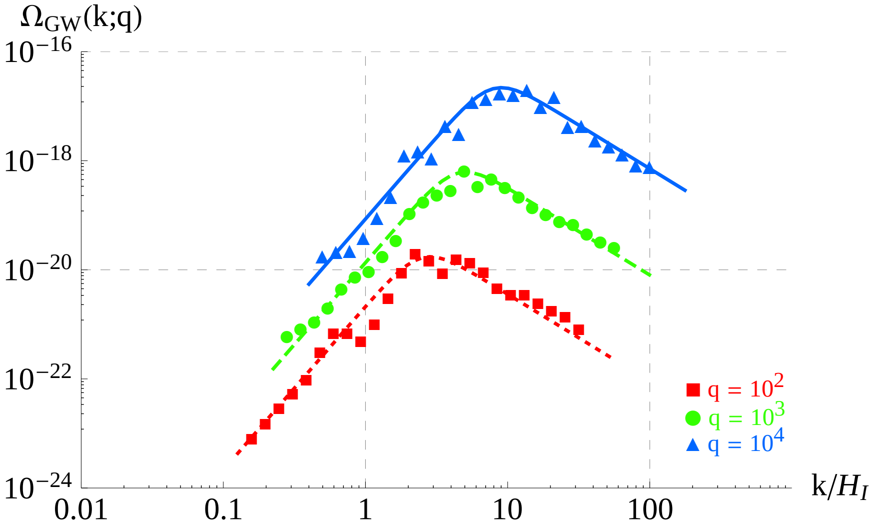


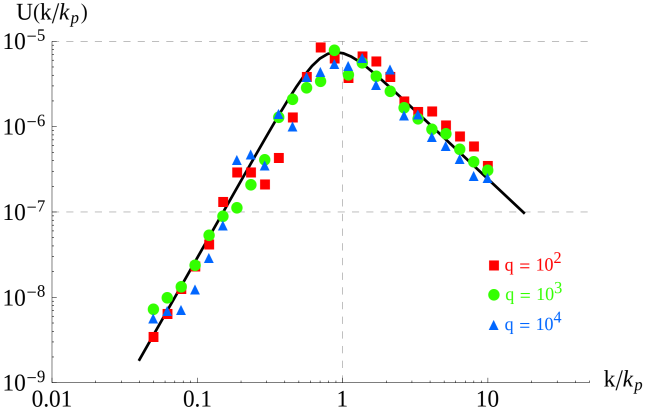
Higgs Osc. $\rightarrow$ SM Ψ's Param. Exc. $\rightarrow$ GWs

SCALING (Universal Shape) :

$$\Omega_{\rm GW}(k; q_j) = (H_{\rm I}/M_p)^4 \, (a_{\rm I}/a_{\rm F})^{1-3w} \times {q_j}^{1.55} \, \mathcal{U}(k/k_p)$$

Higgs Osc. $\to$ SM Ψ's Param. Exc. $\to$ GWs

$$\mathcal{U}(x) \equiv \mathcal{U}_1 \frac{x^3}{(\alpha+\beta x^{4.5})}\,, \begin{cases} \mathcal{U}_1 \equiv \mathcal{U}(1)\ [\sim 10^{-5}(\mathrm{RD}), \sim 10^{-6}(\mathrm{MD})] \\ \alpha + \beta = 1\ \ [\alpha = 0.25, \beta = 0.75\ (\mathrm{RD}, \mathrm{MD})] \end{cases}$$



Higgs Osc. $\rightarrow$ SM Ψ's Param. Exc. $\rightarrow$ GWs

Total GWs :

$$h^2\Omega^{(0)}_{\rm GW}(f) \simeq \epsilon_{\rm I}\, 10^{-6}\, (H_{\rm I}/M_p)^4 \sum_j {q_j}^{1.55}\, \mathcal{U}({q_j}^{-1/4}(k/H_{\rm I}))$$

Higgs Osc. $\rightarrow$ SM Ψ's Param. Exc. $\rightarrow$ GWs

SM Yukawa Couplings : $y_t > y_b > y_\tau > y_c > y_\mu \gtrsim y_s > y_d > y_u > y_e$

$$h^2\Omega^{(0)}_{\rm GW}(f) \propto q^{3/2} \propto y^3 \Rightarrow \text{Top Quark dominates (!)}$$

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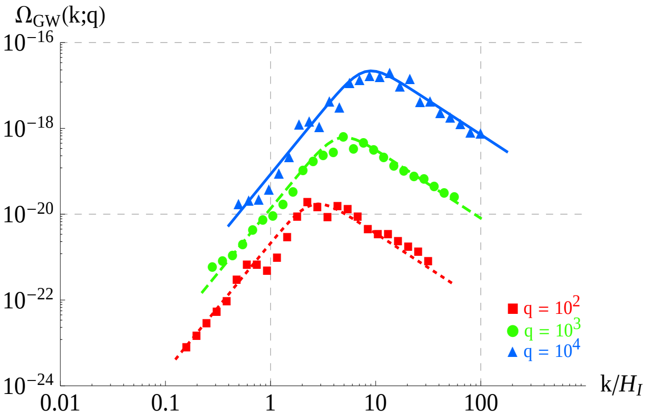


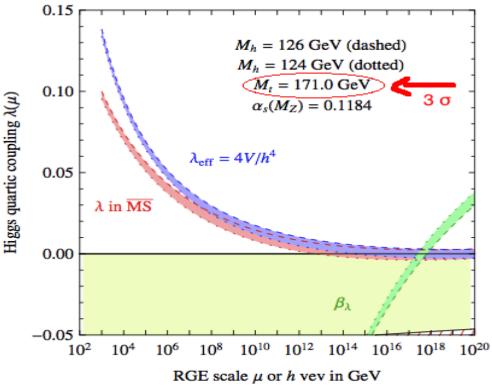
Higgs Osc. $\to$ SM Ψ's Param. Exc. $\to$ GWs

Top Quark GW Peak Today:
$(H_* \sim 10^{14}$ GeV, $y_t \sim 0.5)$

Today: $f_p^{(t)} \sim 10^7\,\mathrm{Hz}\,, \qquad h^2\Omega_{\rm GW}^{(\rm p)}\big|_{\rm t} \sim 10^{-30}\,\lambda_{\rm I}^{-1.55}$

Higgs Osc. $\rightarrow$ SM Ψ's Param. Exc. $\rightarrow$ GWs

$$\lambda_{\rm I} \lesssim 10^{-7}, 10^{-10}, 10^{-13} \quad \Rightarrow \quad h^2\Omega_{\rm GW}^{\rm (p)}\big|_{\rm t} \gtrsim 10^{-20}, 10^{-15}, 10^{-10}$$



(Degrassi et al, 2012)

Conclusions

1. Inflation, $dS(H_*) \Rightarrow$ Higgs Osc.$\Rightarrow$ $\Psi' s$ (Param. Excitation).
2. $\{\Psi_a\} \quad \rightarrow \quad h^2\Omega^{(0)}_{\rm GW}(f) \propto q_a^{3/2} \propto y_a^3 \quad \Rightarrow$ Top Quark dominates (!)
3. $0 < \lambda_{\rm I} \lll 1, \;\; H_* \sim 10^{14}$ GeV, Peak's Frequency: $f_* \sim 10^7$ Hz

   $h^2\Omega^{(\rm p)}_{\rm GW}\big|_{\rm t} \gtrsim 10^{-20}, 10^{-15}, 10^{-10} \;\; (\lambda_{\rm I} \lesssim 10^{-7}, 10^{-10}, 10^{-13})$.
4. Similar Conclusions for Higgs Inflation ! Also expected in BSM !
5. Universal Effect: Inflation + SM Higgs $\Rightarrow$ GWs: Spectroscopy of Particle Physics: Probing the Most Strongly Interacting Particle (!)

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