

Gravitational Waves from Graviton Bremsstrahlung in Scalar Leptoquark Decays

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Based on [Qian-Jiu Wang, Hua Tong, ZHY, arXiv:2606.28699](#)



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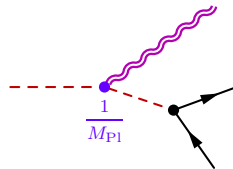
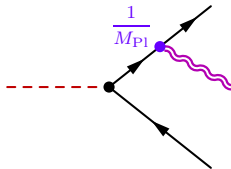
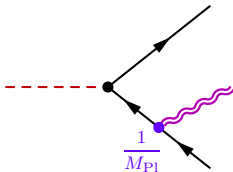
Graviton Bremsstrahlung

 **Gravitational waves** (GW) now serve as a new cosmic messenger for exploring **new physics** beyond the **standard model** (SM)

 **New physics** typically predicts **heavy particles** produced in the early universe

 **Their decays** and **scattering** can be accompanied by **graviton bremsstrahlung** via **quantum gravitational processes**, thereby inducing a potentially detectable **stochastic GW background** (SGWB) [Nakayama & Y Tang, 1810.04975, PLB]

 To produce an **appreciable SGWB** for GW observatories, a **decaying particle** must be **sufficiently heavy** to **overcome** the **suppression** of the **Planck scale**

$$M_{\text{Pl}} = 2.4 \times 10^{18} \text{ GeV}$$


Previous Studies

Previous studies have discussed many relevant processes, including

- **Inflaton decays** [Nakayama & Y Tang, 1810.04975, PLB; D Huang & L Yin, 1905.08510, PRD; Barman, Bernal, Y Xu & Zapata, 2301.11345, JCAP; ...]
- **Inflaton scattering** [Y Xu, 2407.03256, JCAP; XJ Xu, Y Xu, *et al.*, 2505.08868, JHEP]
- **Decays of right-handed neutrinos** [Datta & Sil, 2410.01900; Choi, Lkhagvadorj & Mahapatra, 2503.22465, JCAP; Murayama, Noether & Schütte-Engel, 2506.15772, JCAP]
- **Freeze-in production of dark matter** [Konar & Show, 2506.08106 (PRD), 2512.13799; YH Wang & W Chao, 2508.10665]
- **Particle scattering in the thermal plasma** [Ghiglieri & Laine, 1504.02569, JCAP; Ringwald, J. Schütte-Engel, & Tamarit, 2011.04731, JCAP; Q Chen, SY Jiang, DY Qiu, PL Chen & FP Huang, 2507.13916, JCAP; ...]
- **Decays of superheavy particles from preheating** [WY Hu, Nakayama, Takhistov & Y Tang, 2403.13882, PLB], from **type-II seesaw model** [YH Wang & W Chao, 2510.26235], and from **axion model** [YH Wang, LY He, W Chao & Y Gao, 2601.20767]

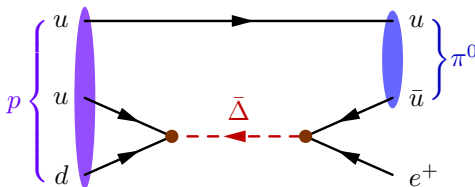
Scalar Leptoquarks

🚩 We focus on **scalar leptoquarks**, which are scalar bosons **simultaneously coupling** to a **quark** and a **lepton**, as predicted by **grand unified theories** (GUTs)

🎱 Interactions of **scalar leptoquarks** **violate** both **lepton** and **baryon numbers**, triggering **proton decay**

🪁 Stringent experimental limits on **proton decay** have pushed their **lower mass bounds** to $\mathcal{O}(10^{11})\text{--}\mathcal{O}(10^{13})$ GeV [Dorsner, Fajfer & Kosnik, 1204.0674, PRD]

🎃 Therefore, **graviton bremsstrahlung** from **decays** of such **superheavy scalar leptoquarks** offers a promising source for an **SGWB**



SU(5) Setup

 As an illustrative case study, we consider the **scalar leptoquarks** Δ_a ($a = 1, 2, 3$) from the **5_H Higgs multiplet** in the **SU(5) GUT** [Georgi & Glashow, PRL **32** (1974) 438]:

$$(\mathbf{5}_H)^\alpha = (\Delta_1, \Delta_2, \Delta_3, H_1, H_2) = \Delta(\mathbf{3}, \mathbf{1}, -1/3) \oplus H(\mathbf{1}, \mathbf{2}, 1/2), \quad \alpha = 1, 2, 3, 4, 5$$

 The vacuum expectation value (VEV) of a **24_H Higgs multiplet** at the **GUT scale** $\sim \mathcal{O}(10^{15})$ GeV leads to symmetry breaking $\text{SU}(5) \rightarrow \text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y$

 The VEVs the **5_H** and **45_H**, v_5 and v_{45} , at the **electroweak scale** result in symmetry breaking $\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y \rightarrow \text{SU}(3)_C \times \text{U}(1)_{\text{EM}}$

 The **effective electroweak VEV** is given by $v \equiv \sqrt{v_5^2 + 24v_{45}^2} = 246.22$ GeV

 Three families of **SM fermions** live in

$$(\mathbf{5}_{F,i})^\alpha = (d_{1i}, d_{2i}, d_{3i}, \ell_i^C, -\nu_i^C)_R = d_{iR}(\mathbf{3}, \mathbf{1}, -1/3) \oplus (L_{iL})^C(\mathbf{1}, \mathbf{2}, 1/2)$$

$$(\mathbf{10}_{F,i})^{\alpha\beta} = (u_{iR})^C(\bar{\mathbf{3}}, \mathbf{1}, -2/3) \oplus Q_{iL}(\mathbf{3}, \mathbf{2}, 1/6) \oplus (\ell_{iR})^C(\mathbf{1}, \mathbf{1}, 1), \quad i = 1, 2, 3$$

 Three **right-handed neutrinos** $\mathbf{1}_{F,i} = N_{iR}(\mathbf{1}, \mathbf{1}, 0)$ are introduced to realize the **type-I seesaw mechanism**

Yukawa couplings and Mass Origin

🌱 Renormalizable **Yukawa couplings** among **5_H**, **45_H**, **5_{F,i}**, **10_{F,i}**, and **1_{F,i}**, together with the **Majorara mass terms** for **1_{F,i}**, are given by

$$\begin{aligned}\mathcal{L} \supset & -Y_{ij}^{10} \varepsilon_{\alpha\beta\gamma\delta\epsilon} (\overline{10_{F,i}^C})^{\alpha\beta} (10_{F,j})^{\gamma\delta} (5_H)^\epsilon + Y_{ij}^5 (\overline{5_{F,i}})_\alpha (10_{F,i})^{\alpha\beta} (5_H^*)_\beta \\ & + Y_{ij}^{45} (\overline{5_{F,i}})_\gamma (10_{F,i})^{\alpha\beta} (45_H^*)_{\alpha\beta} + \tilde{Y}_{ij}^{45} \varepsilon_{\alpha\beta\gamma\delta\epsilon} (\overline{10_{F,i}^C})^{\alpha\beta} (10_{F,j})^{\zeta\gamma} (45_H)_{\zeta}^{\delta\epsilon} \\ & + Y_{ij}^1 (\overline{5_{F,i}})_\alpha 1_{F,i}^C (5_H)^\alpha - M_{N,ij} \overline{1_{F,i}^C} 1_{F,j} + \text{H.c.}\end{aligned}$$

🌾 The initially massless fermions acquire **masses** after **5_H** and **45_H** develop **VEVs**

🌽 The **mass terms** for **fermions** are

$$\begin{aligned}\mathcal{L} \supset & -M_{u,ij} \overline{u_{iL}} u_{jR} - M_{d,ij} \overline{d_{iL}} d_{jR} - M_{\ell,ij} \overline{\ell_{iL}} \ell_{jR} \\ & - \frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{(N_R)^C} \end{pmatrix} \begin{pmatrix} \mathbf{0} & M_D \\ M_D^T & M_N \end{pmatrix} \begin{pmatrix} (\nu_L)^C \\ N_R \end{pmatrix} + \text{H.c.} \\ M_{u,ij} \equiv & \sqrt{2} v_5 (Y_{ji}^{10*} + Y_{ij}^{10*}) + 2\sqrt{2} v_{45} (\tilde{Y}_{ji}^{45} - \tilde{Y}_{ij}^{45}), \quad M_D \equiv \frac{v_5}{\sqrt{2}} Y^{1*} \\ M_{d,ij} \equiv & \frac{1}{2} Y_{ij}^{5*} v_5 + Y_{ij}^{45*} v_{45}, \quad M_{\ell,ij} \equiv \frac{1}{2} Y_{ji}^{5*} v_5 - 3 Y_{ji}^{45*} v_{45}\end{aligned}$$

Mixing Matrices

 We assume that the Yukawa coupling matrices Y^5 , Y^{45} , and $\tilde{Y}^{45}$ are **symmetric**, and the fermionic mass matrices can be diagonalized by **unitary** transformations

$$\begin{aligned}
 u_{iL}^m &\equiv (U_u^\dagger)_{ij} u_{jL}, & u_{iR}^m &\equiv (U_u^T)_{ij} u_{jR}, & d_{iL}^m &\equiv (U_d^\dagger)_{ij} d_{jL} \\
 d_{iR}^m &\equiv (U_d^T)_{ij} d_{jR}, & \ell_{iL}^m &\equiv (U_\ell^\dagger)_{ij} \ell_{jL}, & \ell_{iR}^m &\equiv (U_\ell^T)_{ij} \ell_{jR} \\
 (\nu_L^m)^C &\equiv U_\nu^T (\nu_L)^C, & N_R^m &\equiv U_N^T N_R
 \end{aligned}$$

 The **CKM** and **PMNS** matrices are $V_{\text{CKM}} \equiv U_u^\dagger U_d$ and $V_{\text{PMNS}} \equiv U_\ell^\dagger U_\nu$

 The **diagonalization relations** are

$$M_u = U_u \tilde{M}_u U_u^T, \quad M_d = U_d \tilde{M}_d U_d^T, \quad M_\ell = U_\ell \tilde{M}_\ell U_\ell^T,$$

with $\tilde{M}_u = \text{diag}(m_u, m_c, m_t)$, $\tilde{M}_d = \text{diag}(m_d, m_s, m_b)$, and $\tilde{M}_\ell = \text{diag}(m_e, m_\mu, m_\tau)$

 Assume the **seesaw hierarchy** $M_N \gg M_D$, we have $M_\nu = -M_D M_N^{-1} M_D^T$ and

$$U_\nu \tilde{M}_\nu U_\nu^T = M_\nu, \quad U_N \tilde{M}_N U_N^T = M_N$$

 $\tilde{M}_\nu = \text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$ and $\tilde{M}_N = \text{diag}(m_{N_1}, m_{N_2}, m_{N_3})$ are the diagonalized mass matrices for **light** and **heavy Majorana neutrinos**

Parametrization

Any 3×3 unitary matrix U can be parametrized as

$$U = K(\rho_1, \rho_2) R_{23}(\theta_{23}) R_{13}(\theta_{13}, \delta) R_{12}(\theta_{12}) D(\eta_1, \eta_2, \eta_3)$$

$$R_{23}(\theta_{23}) = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix}, \quad R_{13}(\theta_{13}, \delta) = \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix}$$

$$R_{12}(\theta_{12}) = \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}, \quad K(\rho_1, \rho_2) = \text{diag}(1, e^{i\rho_1}, e^{i\rho_2})$$

$$D(\eta_1, \eta_2, \eta_3) = \text{diag}(e^{i\eta_1}, e^{i\eta_2}, e^{i\eta_3})$$

$$c_{ij} \equiv \cos \theta_{ij}, \quad s_{ij} \equiv \sin \theta_{ij}$$

The mixing matrices are expressed as

$$V_{\text{CKM}} \equiv U_u^\dagger U_d = R_{23}(\theta_{23}^{\text{CKM}}) R_{13}(\theta_{13}^{\text{CKM}}, \delta^{\text{CKM}}) R_{12}(\theta_{12}^{\text{CKM}})$$

$$V_{\text{PMNS}} \equiv U_\ell^\dagger U_\nu = R_{23}(\theta_{23}^{\text{PMNS}}) R_{13}(\theta_{13}^{\text{PMNS}}, \delta^{\text{PMNS}}) R_{12}(\theta_{12}^{\text{PMNS}}) D(\eta_1^{\text{PMNS}}, \eta_2^{\text{PMNS}}, 0)$$

$$U_u = K(\rho_1^u, \rho_2^u) R_{23}(\theta_{23}^u) R_{13}(\theta_{13}^u, \delta^u) R_{12}(\theta_{12}^u) D(\eta_1^u, \eta_2^u, \eta_3^u)$$

$$U_\ell = K(\rho_1^\ell, \rho_2^\ell) R_{23}(\theta_{23}^\ell) R_{13}(\theta_{13}^\ell, \delta^\ell) R_{12}(\theta_{12}^\ell) D(\eta_1^\ell, \eta_2^\ell, \eta_3^\ell)$$

Proton Decay

🍌 The **Yukawa couplings** of the **scalar leptoquarks** Δ_a with **SM fermions** are

$$\mathcal{L} \supset -2(Y_{ij}^{10} + Y_{ji}^{10})\overline{\ell_{iR}}(u_{ajR})^C\Delta_a + 2(Y_{ij}^{10} + Y_{ji}^{10})\varepsilon_{abc}\overline{(d_{aiL})^C}u_{bjL}\Delta_c \\ + \frac{Y_{ij}^5}{\sqrt{2}}\varepsilon_{abc}\overline{u_{aiR}}(d_{bjR})^C\Delta_c^* + \frac{Y_{ij}^5}{\sqrt{2}}\overline{(u_{aiL})^C}\ell_{jL}\Delta_a^* - \frac{Y_{ij}^5}{\sqrt{2}}\overline{(d_{aiL})^C}\nu_{jL}\Delta_a^* + \text{H.c.}$$

with $Y^{10\dagger} + Y^{10*} = \frac{1}{\sqrt{2}v_5}U_u\tilde{M}_uU_u^T$, $Y^{5*} = \frac{1}{2v_5}(3U_d\tilde{M}_dU_d^T + U_\ell\tilde{M}_\ell U_\ell^T)$

🥥 These couplings lead to **proton decay**

🍌 Based on **effective operators** and **chiral Lagrangian**, we calculate the partial widths for proton decay channels $p \rightarrow \ell_i^+\pi^0$ ($i = 1, 2$), $p \rightarrow \pi^+\bar{\nu}_i$ ($i = 1, 2, 3$), and $p \rightarrow K^+\bar{\nu}_i$ ($i = 1, 2, 3$) [Nath & Fileviez Perez, hep-ph/0601023, Phys. Rept.]

🍈 We perform a **random scan** over the **free parameters** within the following ranges:

$$0 < \theta_{ij}^u, \theta_{ij}^\ell < \frac{\pi}{2}, \quad 0 < \eta_i^{\text{PMNS}}, \eta_i^u, \rho_i^u, \delta^u, \eta_i^\ell, \rho_i^\ell, \delta^\ell < 2\pi \\ 50 \text{ GeV} < v_5 < 200 \text{ GeV}, \quad 10^{10} \text{ GeV} < m_\Delta < 10^{17} \text{ GeV}$$

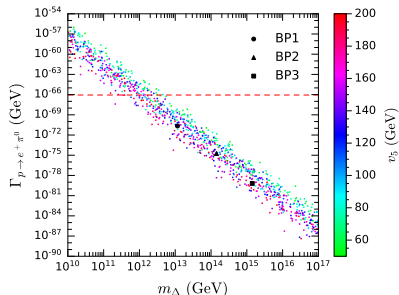
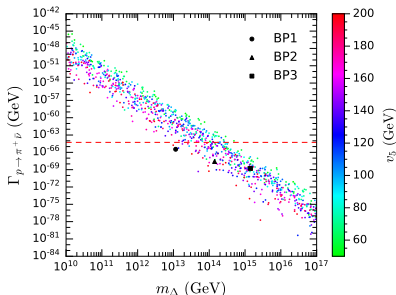
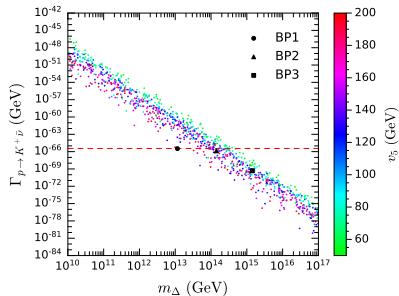
Parameter Scan and Proton Decay Constraints



We find that the **strongest** constraint arises from the $p \rightarrow K^+ \bar{\nu}$ channel, which **excludes** parameter points with the **scalar leptoquark mass** $m_\Delta \lesssim 10^{13}$ GeV



Three **benchmark points** (BPs) with $m_\Delta = 1.15 \times 10^{13}, 1.41 \times 10^{14}, 1.42 \times 10^{15}$ GeV are selected for further study

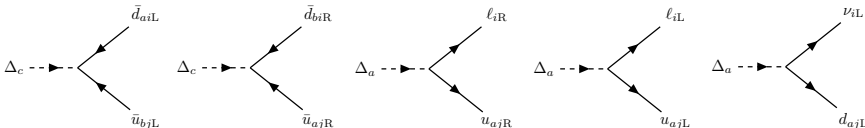


Boltzmann Equation

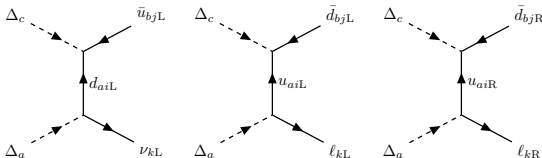
🚗 The evolution of the **number density** of **Δ_a particles**, n_{Δ_a} , in the early universe is governed by the Boltzmann equation with **annihilation**, **coannihilation**, and **decay**:

$$\frac{dn_{\Delta_a}}{dt} + 3Hn_{\Delta_a} = - \left(\sum_b \langle \sigma_{\Delta_a \bar{\Delta}_b} v \rangle + \sum_{c \neq a} \langle \sigma_{\Delta_a \Delta_c} v \rangle \right) (n_{\Delta_a}^2 - n_{\Delta_a, \text{eq}}^2) - \langle \Gamma_{\Delta_a} \rangle (n_{\Delta_a} - n_{\Delta_a, \text{eq}})$$

🚗 **2-body Δ_a decays:**



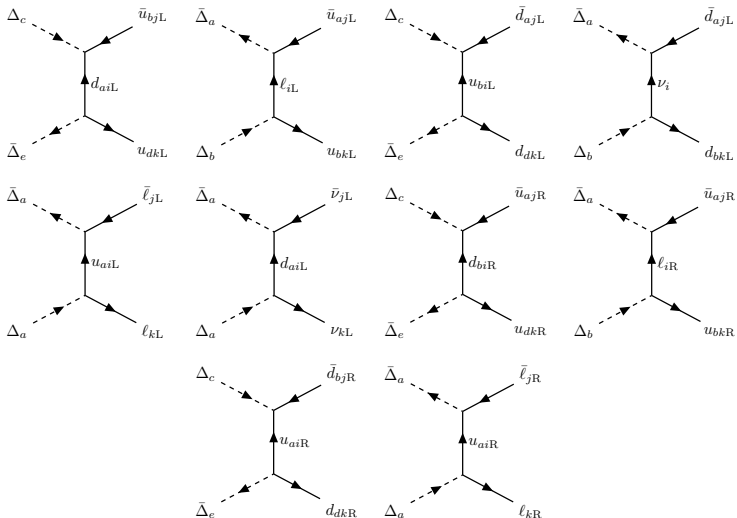
🚗 **$\Delta_a \Delta_c$ coannihilation ($c \neq a$) via Yukawa couplings:**



Annihilation of Scalar Leptoquarks



$\Delta_a \bar{\Delta}_b$ annihilation via Yukawa couplings:



Initial Conditions

 The **initial conditions** depend on the **reheating** process

 We assume that at the **reheating temperature** T_{reh} , the **SM fermions** are **thermalized**, while the **scalar leptoquark number density** is **zero**

 The CMB upper limit on the **tensor-to-scalar ratio** $r_{0.05} < 0.036$ [BICEP/Keck Coll., 2110.00483, PRL] implies a upper bound on the **inflation scale**:

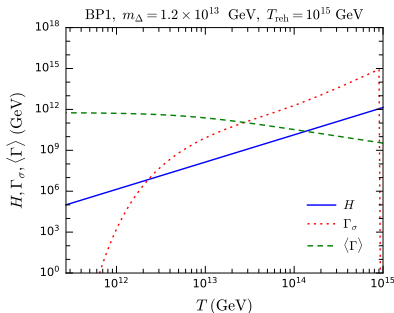
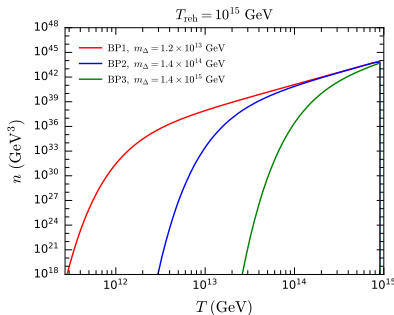
$$V_*^{1/4} = \left(\frac{3\pi^2}{2} A_s r M_{\text{Pl}}^4 \right)^{1/4} < 1.4 \times 10^{16} \text{ GeV}$$

 Assuming **instantaneous reheating** with $g_* \sim 100$, the **maximum reheating temperature** is given by

$$T_{\text{reh}}^{\text{max}} \simeq \left(\frac{30V_*}{\pi^2 g_*} \right)^{1/4} < 5.8 \times 10^{15} \text{ GeV}$$

 We adopt two values of the **reheating temperature**, $T_{\text{reh}} = 10^{15} \text{ GeV}$ and 10^{13} GeV , and calculate the evolution of scalar leptoquark number density

Number Density of Scalar Leptoquarks ($T_{\text{reh}} = 10^{15}$ GeV)



The results for $T_{\text{reh}} = 10^{15}$ GeV are shown above



The obtained **total number density** of scalar leptoquarks $n = \sum_{a=1}^3 (n_{\Delta_a} + n_{\bar{\Delta}_a})$

quickly achieve its **equilibrium value** and **maintains equilibrium afterwards**

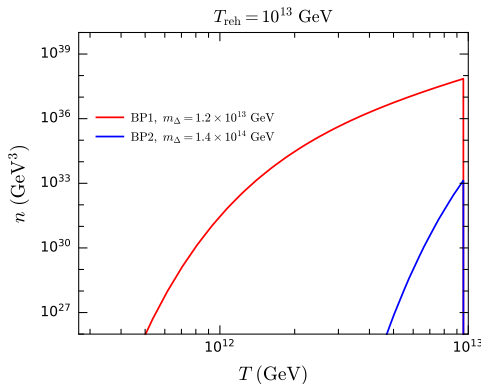


Actually, either the **total annihilation and coannihilation rate** Γ_{σ} or **total decay rate** $\langle \Gamma \rangle$ is **larger** than the **Hubble rate** H throughout the relevant epochs

Number Density of Scalar Leptoquarks ($T_{\text{reh}} = 10^{13}$ GeV)

🚗 If $T_{\text{reh}} = 10^{13}$ GeV, the scalar leptoquarks for **BP1** ($m_{\Delta} = 1.2 \times 10^{13}$ GeV) can still be **effectively produced**

🚌 However, the scalar leptoquark number density for **BP2** ($m_{\Delta} = 1.4 \times 10^{14}$ GeV) is **substantially suppressed**, while that for **BP3** ($m_{Delta} = 1.4 \times 10^{15}$ GeV) is **negligible**



Quantum Gravity Treatments

🌲 Based on **Einstein's general relativity**, the **gravitational action** is given by

$$S = \int d^4x \sqrt{-\det(g_{\mu\nu})} \left(\frac{M_{\text{Pl}}^2}{2} R + \mathcal{L} \right)$$

🌳 R is the Ricci scalar, and the Lagrangian $\mathcal{L}$ involves all fields in the SU(5) GUT

🌿 In **linearized gravity** for **weak gravitational field**, the **metric tensor** can be decomposed as $g_{\mu\nu} = \eta_{\mu\nu} + \kappa h_{\mu\nu}$ with **gravitational coupling constant** $\kappa \equiv \frac{2}{M_{\text{Pl}}}$

🍒 The **symmetric tensor field** $h_{\mu\nu}$ is a **perturbation** around the **Minkowski metric** $\eta_{\mu\nu}$, and, upon **quantization**, corresponds to the **massless spin-2 graviton field**

🍇 The **gravitational interaction Lagrangian** can be constructed to any order in κ
[Choi, Shim & Song, hep-th/9411092, PRD]

🍏 **Feynman rules** for the **graviton couplings** to **spin-0**, **spin-1/2**, and **spin-1 particles** at $\mathcal{O}(\kappa)$ are given in Ref. [Barman, Bernal, Y Xu & Zapata, 2301.11345, JCAP]

Graviton Bremsstrahlung

 Within the **effective quantum field theory** based on **Einstein gravity**, **differential decay rates** for **graviton bremsstrahlung** in **scalar leptoquark decays** are

$$\frac{d\Gamma_{\Delta_c \rightarrow \bar{d}_{aiL} \bar{u}_{bjL} h}}{dE} = \frac{\varepsilon_{abc}^2 |Y_{ij}^{10} + Y_{ji}^{10}|^2 m_\Delta^2}{96\pi^3 M_{Pl}^2} f\left(\frac{E}{m_\Delta}\right)$$

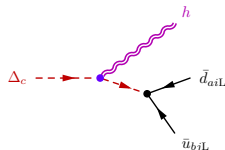
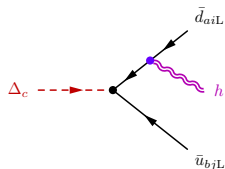
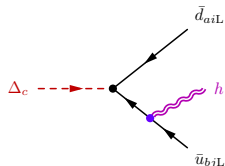
$$\frac{d\Gamma_{\Delta_c \rightarrow \bar{d}_{biR} \bar{u}_{ajR} h}}{dE} = \frac{\varepsilon_{abc}^2 |Y_{ij}^5|^2 m_\Delta^2}{768\pi^3 M_{Pl}^2} f\left(\frac{E}{m_\Delta}\right)$$

$$\frac{d\Gamma_{\Delta_a \rightarrow \ell_{iR} u_{ajR} h}}{dE} = \frac{|Y_{ij}^{10} + Y_{ji}^{10}|^2 m_\Delta^2}{96\pi^3 M_{Pl}^2} f\left(\frac{E}{m_\Delta}\right)$$

$$\frac{d\Gamma_{\Delta_a \rightarrow \ell_{iL} u_{ajL} h}}{dE} = \frac{d\Gamma_{\Delta_a \rightarrow \nu_{iL} d_{ajL} h}}{dE} = \frac{|Y_{ij}^5|^2 m_\Delta^2}{768\pi^3 M_{Pl}^2} f\left(\frac{E}{m_\Delta}\right)$$

$$f(x) \equiv \frac{1-2x}{x} (1-2x+2x^2)$$

 E is the **energy** of the **bremsstrahlung graviton** h



SGWB Energy Density



The incoherent superposition of **bremsstrahlung gravitons** emitted from **scalar leptoquark decays** forms an **SGWB**



The **differential SGWB energy density** with respect to the **present graviton energy** $E_0 = E(t)a(t)$ is estimated as

$$\frac{d\rho_{\text{GW}}}{dE_0} = E_0 \int dt n(t) a^2(t) \frac{d\Gamma_h}{dE}$$



$a(t)$ is the **cosmological scale factor**



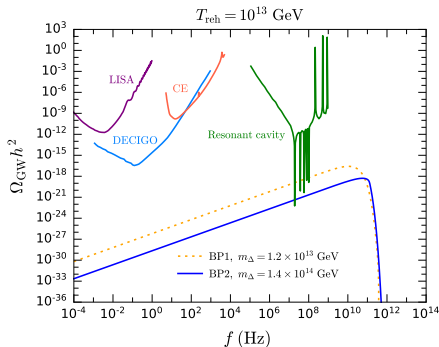
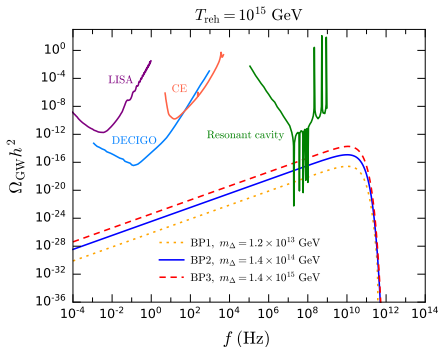
$\frac{d\Gamma_h}{dE}$ is the **total differential decay rates** for **graviton bremsstrahlung**



The **dimensionless SGWB spectrum** is

$$\Omega_{\text{GW}}(f) \equiv \frac{f}{\rho_c} \frac{d\rho_{\text{GW}}}{df} = \frac{E_0}{\rho_c} \frac{d\rho_{\text{GW}}}{dE_0}$$

SGWB Spectra



 If $T_{\text{reh}} = 10^{15}$ GeV, the SGWB spectra for the three BPs lie in the **high frequency** range, **peaking around 10 GHz**

 **High-frequency GW detectors** employing **resonant cavity techniques** [Herman, Lehoucq & Fúzfá, 2203.15668, PRD] are **promising** for detecting the signals

 If $T_{\text{reh}} = 10^{13}$ GeV, **BP1** and **BP2** can still produce **significant** SGWB signals

Summary

- We study the **SGWB** originated from **graviton bremsstrahlung** in **decays** of **scalar leptoquarks** based on **SU(5) GUT**
- Stringent experimental bounds on **proton decay** force the **scalar leptoquark mass** $\gtrsim 10^{13}$ GeV, which in turn renders their **graviton bremsstrahlung**, induced by **quantum gravity effects**, **less suppressed**
- We find that **high-frequency GW detectors** employing **resonant cavity techniques** may be a **promising** means to probe the **SGWB signal**

Summary

- We study the **SGWB** originated from **graviton bremsstrahlung** in **decays** of **scalar leptoquarks** based on **SU(5) GUT**
- Stringent experimental bounds on **proton decay** force the **scalar leptoquark mass** $\gtrsim 10^{13}$ GeV, which in turn renders their **graviton bremsstrahlung**, induced by **quantum gravity effects**, **less suppressed**
- We find that **high-frequency GW detectors** employing **resonant cavity techniques** may be a **promising** means to probe the **SGWB signal**

Thanks for your attention!

Effective Operators for Proton Decay

🍌 In the framework of **effective field theory**, the **dimension-6 effective operators** involving **three quarks** and **one lepton**, induced by the **exchange** of Δ_a , are

$$\begin{aligned} \mathcal{L}_{\text{eff}} \supset & a(d_{iL}, \ell_{jL}) \varepsilon_{abc} \overline{(u_{a1L}^m)^C} d_{biL}^m \overline{(u_{c1L}^m)^C} \ell_{jL}^m - a(d_{iL}, \ell_{jR}) \varepsilon_{abc} \overline{(u_{a1L}^m)^C} d_{biL}^m \overline{(u_{c1R}^m)^C} \ell_{jR}^m \\ & - a(d_{iR}, \ell_{jL}) \varepsilon_{abc} \overline{(d_{a1R}^m)^C} u_{b1R}^m \overline{(u_{c1L}^m)^C} \ell_{jL}^m + a(d_{iR}, \ell_{jR}) \varepsilon_{abc} \overline{(d_{a1R}^m)^C} u_{b1R}^m \overline{(\ell_{jR}^m)^C} u_{c1R}^m \\ & + a(d_{iL}, d_{jL}, \nu_{kL}) \varepsilon_{abc} \overline{(u_{a1L}^m)^C} d_{biL}^m \overline{(d_{cjL}^m)^C} \nu_{kL}^m - a(d_{iR}, d_{jL}, \nu_{kL}) \varepsilon_{abc} \overline{(d_{a1R}^m)^C} u_{b1R}^m \overline{(d_{cjL}^m)^C} \nu_{kL}^m \end{aligned}$$

$$a(d_{iL}, \ell_{jL}) = -\frac{\sqrt{2}}{m_\Delta^2} [U_u^T (Y^{10} + Y^{10T}) U_d]_{1i} (U_u^T Y^5 U_\ell)_{1j}$$

$$a(d_{iL}, \ell_{jR}) = -\frac{4}{m_\Delta^2} [U_u^T (Y^{10} + Y^{10T}) U_d]_{1i} [U_\ell^\dagger (Y^{10\dagger} + Y^{10*}) U_u^*]_{j1}$$

$$a(d_{iR}, \ell_{jL}) = \frac{1}{2m_\Delta^2} (U_d^\dagger Y^{5\dagger} U_u^*)_{i1} (U_u^T Y^5 U_\ell)_{1j}$$

$$a(d_{iR}, \ell_{jR}) = \frac{\sqrt{2}}{m_\Delta^2} (U_d^\dagger Y^{5\dagger} U_u^*)_{i1} [U_\ell^\dagger (Y^{10\dagger} + Y^{10*}) U_u^*]_{j1}$$

$$a(d_{iL}, d_{jL}, \nu_{kL}) = \frac{\sqrt{2}}{m_\Delta^2} [U_u^T (Y^{10} + Y^{10T}) U_d]_{1i} (U_d^T Y^5 U_\nu)_{jk}$$

$$a(d_{iR}, d_{jL}, \nu_{kL}) = -\frac{1}{2m_\Delta^2} (U_d^\dagger Y^{5\dagger} U_u^*)_{i1} (U_d^T Y^5 U_\nu)_{jk}$$

Partial widths for Proton Decay Channels



Using the **chiral Lagrangian** techniques, the **partial widths** for **proton decay channels** $p \rightarrow \ell_i^+ \pi^0$ ($i = 1, 2$), $p \rightarrow \pi^+ \bar{\nu}_i$ ($i = 1, 2, 3$), and $p \rightarrow K^+ \bar{\nu}_i$ ($i = 1, 2, 3$) are

$$\begin{aligned}\Gamma_{p \rightarrow \ell_i^+ \pi^0} &= \frac{(m_p^2 - m_{\pi^0}^2)^2}{64\pi f_\pi^2 m_p^3} (1 + D + F)^2 \\ &\quad \times [|\alpha a(d_{1L}, \ell_{iL}) + \beta a(d_{1R}, \ell_{iL})|^2 + |\alpha a(d_{1L}, \ell_{iR}) + \beta a(d_{1R}, \ell_{iR})|^2] \\ \Gamma_{p \rightarrow \pi^+ \bar{\nu}_i} &= \frac{(m_p^2 - m_{\pi^+}^2)^2}{32\pi f_\pi^2 m_p^3} (1 + D + F)^2 |\alpha a(d_{1R}, d_{1L}, \nu_{iL}) + \beta a(d_{1L}, d_{1L}, \nu_{iL})|^2 \\ \Gamma_{p \rightarrow K^+ \bar{\nu}_i} &= \frac{(m_p^2 - m_{K^+}^2)^2}{32\pi f_\pi^2 m_p^3} \left| \beta a(d_{1L}, d_{2L}, \nu_{iL}) + \alpha a(d_{1R}, d_{2L}, \nu_{iL}) \right. \\ &\quad - \frac{m_p}{2m_{\Sigma^0}} [\beta a(d_{2L}, d_{1L}, \nu_{iL}) + \alpha a(d_{2R}, d_{1L}, \nu_{iL})] (D - F) \\ &\quad + \frac{m_p}{6m_\Lambda} \{ \beta a(d_{2L}, d_{1L}, \nu_{iL}) + \alpha a(d_{2R}, d_{1L}, \nu_{iL}) \\ &\quad \left. + 2[\beta a(d_{1L}, d_{2L}, \nu_{iL}) + \alpha a(d_{1R}, d_{2L}, \nu_{iL})] \} (D + 3F) \right|^2 \\ f_\pi &= 130.2(1.2) \text{ MeV}, \quad D = 0.80(1), \quad F = 0.47(1) \\ \alpha &= -0.0112(25) \text{ GeV}^3, \quad \beta = 0.0120(26) \text{ GeV}^3\end{aligned}$$

Benchmark Points



Among the parameter points that satisfy the experimental bounds on **proton decay**, we select **three benchmark points**, denoted as **BP1**, **BP2**, and **BP3**

	● BP1	▲ BP2	■ BP3
m_{Δ} (GeV)	1.15×10^{13}	1.40×10^{14}	1.41×10^{15}
v_5 (GeV)	164.75	106.43	148.58
$\eta_1^{\text{PMNS}}, \eta_2^{\text{PMNS}}$	4.76, 5.13	1.23, 4.47	6.20, 3.13
$\theta_{12}^u, \theta_{13}^u, \theta_{23}^u$	1.52, 0.25, 1.53	1.32, 0.21, 0.91	1.47, 0.64, 0.42
$\delta^u, \rho_1^u, \rho_2^u$	1.54, 2.75, 4.43	0.12, 0.33, 1.53	2.66, 1.50, 2.73
$\eta_1^u, \eta_2^u, \eta_3^u$	1.67, 3.21, 1.05	5.58, 0.26, 4.34	3.62, 5.91, 2.04
$\theta_{12}^\ell, \theta_{13}^\ell, \theta_{23}^\ell$	1.17, 0.25, 0.71	1.35, 1.35, 0.18	0.34, 0.10, 0.03
$\delta^\ell, \rho_1^\ell, \rho_2^\ell$	4.26, 3.66, 1.80	1.85, 0.26, 2.45	5.01, 1.47, 4.82
$\eta_1^\ell, \eta_2^\ell, \eta_3^\ell$	5.21, 5.67, 2.35	6.10, 0.78, 1.07	1.97, 1.48, 6.00