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Dark neutrinos and a three portal connection to the Standard Model

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We introduce a dark neutrino sector which respects a hidden $U(1)'$ gauge symmetry, subsequently broken by the vacuum expectation value of a dark scalar. Generically, this hidden sector communicates with the SM only via the three renormalizable portals, namely neutrino, vector and scalar mixing. We highlight the fact that in this unified picture the phenomenology can be significantly different from that of each individual portal taken separately. Several bounds become much weaker or can be avoided altogether. Novel signatures arise in heavy neutrino, dark photon and dark scalar searches, typically characterised by multi-leptons plus missing energy and displaced vertices. A minimal extension, possibly motivated by anomaly cancellations, can accommodate a dark matter candidate, strongly connected to the neutrino sector.

INTRODUCTION

The most important evidences that the Standard Model (SM) of particle physics is incomplete are neutrino masses and mixing, and the presence of dark matter (DM) in the Universe. Both call for extensions of the SM and the possible existence of dark sectors which do not partake in SM interactions, or do so with extremely weak couplings while displaying strong "dark" interactions [1, 2]. Such sectors might exist at relatively light scales below the electroweak one, being within reach of present and future non-collider experiments. Generically, a neutral dark sector can communicate with the SM via three renormalizable portals. New neutral fermions mix with light neutrinos unless a symmetry differentiates the two, a possibility usually denoted as the neutrino portal. New vector particles can kinetically mix with the SM hypercharge, and new scalars mix with the Higgs boson through the so-called vector and scalar portals, respectively. The latter terms are generically allowed in the Lagrangian and an explanation of their smallness requires specific UV completions.

In this article, we propose a new neutrino model with a hidden $U(1)'$ gauge symmetry under which no SM fields are charged. We introduce new SM-neutral fermions, ν_D and an additional sterile neutrino N. The symmetry is subsequently broken by the vacuum expectation value (vev) of a complex dark scalar Φ, which gives mass to the new gauge boson. For concreteness, we restrict the scale of the breaking to be below the electroweak one.

Models with heavy neutrinos which are not completely sterile and might participate in new gauge interactions have been studied in several contexts, including $B-L$, $L_\mu - L_\tau$ and left-right symmetric models [3–11], but here we focus on the possibility of a symmetry under which no SM fields are charged [12**?** –14]. New heavy neutral fermions that feel such hidden forces, such as ν_D, are referred to as *dark neutrinos*, since they define a dark sector separate from the SM. Nevertheless, the dark interactions "leak" into the SM sector via neutrino mixing, where they may dominate [15, 16]. Models of this type have been invoked to generate large neutrino non-standard interactions [17, 18], generate new signals in DM experiments [15, 19–21], weaken cosmological and terrestrial bounds on eV scale sterile neutrinos [22, 23], and as a potential explanation of anomalous short-baseline results at the MiniBooNE [24] and/or LSND [25] experiments with new degrees of freedom at the MeV/GeV scale [26–32].

Our model presents all the three renormalizable portals to the SM. The Yukawa interactions between the leptonic doublet and N, and between N and ν_D induce neutrino mixing. The gauge symmetry allows a cross-coupling term in the potential between the Higgs and the real part of the scalar, inducing mixing between the two after symmetry breaking. The broken gauge symmetry implies the existence of a light hidden gauge boson X_μ, which mediates the dark neutrino interactions and generically kinetically mixes with the SM hypercharge. The set-up is self-consistent and combines the three portals into a unified picture that exhibits significantly different phenomenology with respect to each portal taken separately, as we discuss. The interplay of the different portal degrees of freedom leads to novel signatures which would have escaped searches performed to date, and that can explain long-standing anomalies. For the latter, we focus on the MiniBooNE anomaly as discussed in Ref. [30] (see also [31]) and on new neutrino scattering signatures at

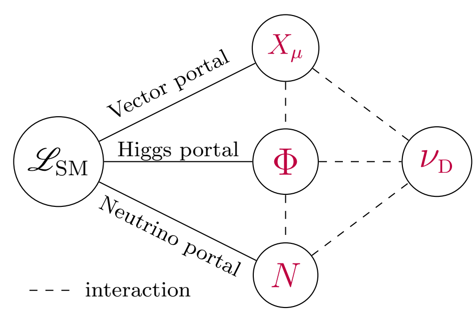

FIG. 1. Schematic representation of our model.

neutrino experiments [32]. We also reconsider the possibility to explain the discrepancy between the prediction and measurement of the anomalous magnetic moment of the muon (Δa_μ) [33] via kinetic mixing [34].

An interesting feature of the model is the generation of neutrino masses at loop-level. This requires only two key features of our setup, namely a light Z' and neutrino mixing, but not the vector and scalar portals. For this reason, we discuss it elsewhere [35].

In its minimal form, the model is not anomaly-free. We discuss how this can be cured and propose a minor extension that introduces additional dark sector neutral fermions charged under the new symmetry [1]. Neutrinos, we argue, may be a window into such dark sectors, bridging the puzzles of neutrino masses and DM [36–46]. We briefly outline the key features of a DM extension and leave a more detailed analysis to future work.

THE MODEL

We extend the SM gauge group with a new abelian gauge symmetry $U(1)'$ with associated mediator X_μ and introduce three new singlets of the SM gauge group: a complex scalar Φ, and two left-handed fermions $\nu_{D,L} \equiv \nu_D$ and $N_L \equiv N$. The scalar Φ and the fermion ν_D are equally charged under the new symmetry, and N is neutral with respect to all gauge symmetries of the model. For simplicity, we restrict our discussion to a single generation of hidden fermions. The relevant terms in the gauge-invariant Lagrangian are

$$\begin{aligned}\mathscr{L} \supset & \left(D_\mu \Phi\right)^\dagger \left(D^\mu \Phi\right) - V(\Phi, H) \\ & - \frac{1}{4} X^{\mu\nu} X_{\mu\nu} + \overline{N} i \not{\partial} N + \overline{\nu_D} i \not{D} \nu_D \\ & - \left[y_\nu^\alpha (\overline{L_\alpha} \cdot \widetilde{H}) N^c + \frac{\mu'}{2} \overline{N} N^c + y_N \overline{N} \nu_D^c \Phi + \text{h.c.} \right],\end{aligned} \tag{1}$$

where $X^{\mu\nu}$ is the field strength tensor for X_μ, $D_\mu \equiv (\partial_\mu - i g' X_\mu)$ the covariant derivative, $L_\alpha \equiv (\nu_\alpha^T, \ell_\alpha^T)^T$ the SM leptonic doublet of flavour $\alpha = e, \mu, \tau$ and $\widetilde{H} \equiv i\sigma_2 H^*$ is the charge conjugate of the SM Higgs doublet. We write y_ν^α for the L_α–N Yukawa coupling, y_N for the ν_D–N one, and μ' for the Majorana mass of N, which is allowed by the SM and the new gauge interaction, although it breaks lepton number by 2 units.

The minimisation of the scalar potential $V(\Phi, H)$ leads the neutral component of the fields H and Φ to acquire vevs v_H and v_φ, respectively. The latter also generates a mass for both the new gauge boson X_μ and the real component of the scalar field φ. Although v_φ is arbitrary, we choose it to be below the electroweak scale, $v_\varphi < v_H$, as we are interested in building a model testable at low scales.

Neutrino portal In the neutral fermion sector and after symmetry breaking, two Dirac mass terms are induced with $m_D \equiv y_\nu^\alpha v_H/\sqrt{2}$ and $\Lambda \equiv y_N v_\varphi/\sqrt{2}$. It is useful to consider the form of the neutrino mass matrix in the single generation case to clarify its main features. For one active neutrino ν_α ($\alpha = e, \mu, \tau$), it reads

$$\mathscr{L}_\text{mass} \supset \frac{1}{2} \left(\overline{\nu}_\alpha \;\; \overline{N} \;\; \overline{\nu_D} \right) \begin{pmatrix} 0 & m_D & 0 \\ m_D & \mu' & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix} \begin{pmatrix} \nu_\alpha^c \\ N^c \\ \nu_D^c \end{pmatrix} + \text{h.c.} \tag{2}$$

The form of this matrix appears in Inverse Seesaw (ISS) [47] and in Extended Seesaw (ESS) [48] models. In fact, it is the same matrix discussed in the so-called Minimal ISS [49], with the difference that in our case its structure is a consequence of the hidden symmetry. After diagonalisation of the mass matrix, the two heavy neutrinos, ν_h with $h = 4, 5$, acquire masses. Assuming that $m_D \ll \Lambda$, we focus on two interesting limiting cases.

In the *ISS-like* limit, where $\Lambda \gg \mu'$ and the two heavy neutrinos are nearly degenerate, we have

$$m_5 \simeq -m_4 \simeq \Lambda \;,\; m_5 - |m_4| = \mu' \;,\; U_{\alpha 5} \simeq U_{\alpha 4} \simeq \frac{m_D}{\sqrt{2}\Lambda} \;,$$
$$U_{Di} \simeq \frac{m_D}{\Lambda},\; U_{D5} \simeq U_{D4} \simeq \frac{1}{\sqrt{2}} \;,\; U_{N5} \simeq U_{N4} \simeq \frac{1}{\sqrt{2}} \;.$$

In the *ESS-like* case, $\Lambda \ll \mu'$, one neutral lepton remains very heavy and mainly in the completely neutral direction N, and the other acquires a small mass via the seesaw mechanism in the hidden sector. We find

$$m_4 \simeq -\frac{\Lambda^2}{\mu'} \;,\; m_5 \simeq \mu' \;,\; U_{\alpha 4} \simeq U_{\alpha 5} \sqrt{\frac{m_5}{|m_4|}} \simeq \frac{m_D}{\Lambda} \;,$$
$$U_{Di} \simeq \frac{m_D}{\Lambda},\; U_{N5} \simeq U_{D4} \simeq 1 \;,\; U_{D5} \simeq U_{N4} \simeq \frac{\Lambda}{\mu'} \;.$$

From the discussion above, it is clear that the masses of Z' and φ' are typically above the heavy neutrino ones, unless we are in the ESS-like regime.

The Yukawa terms in Eq. (1) induce *neutrino mixing* between the active (light) and heavy (sterile, dark) neutrinos. In this model, similarly to the ISS and the ESS cases, this mixing can be much larger than the typical values required in type-I seesaw extensions to explain neutrino masses, making its phenomenology more interesting. The determinant of the mass matrix in Eq. (2) is zero, and so light neutrino masses vanish at tree-level and do not constrain the values of the active-heavy mixing angles. This, however, is no longer the case at one-loop level, as light neutrino masses emerge through radiative corrections from diagrams involving the φ' and Z' degrees of freedom [35].

Scalar portal In the scalar potential, the symmetries of the model allow us to write down the following term

$$V(\Phi, H) \supset \lambda_{\Phi H} \, H^\dagger H \, |\Phi|^2 \,, \tag{3}$$

where we identify $\lambda_{\Phi H}$ as the scalar portal coupling [50], responsible for mixing in the neutral scalar sector. If such a term exists, the scalar mass eigenstates (h', φ') mix with the gauge eigenstates (h, φ) with a mixing angle α defined by

$$\tan(2\alpha) \equiv \frac{\lambda_{\Phi H} v_H v_\varphi}{\lambda_h v_H^2 - \lambda_\varphi v_\varphi^2}, \tag{4}$$

where λ_h and λ_φ are the quartic couplings of the Higgs and Φ scalars, respectively.

Vector portal Similarly, mixing also arises in the neutral vector boson sector from the allowed kinetic mixing term [51]

$$\mathscr{L} \supset -\frac{\sin\chi}{2} F^{\mu\nu} X_{\mu\nu}, \tag{5}$$

where $F_{\mu\nu}$ is the SM hypercharge field strength. This term may be removed with a field redefinition, resulting in three mass eigenstates $\left(A,\, Z^0,\, Z'\right)$, corresponding to the photon, Z^0-boson and the hypothetical Z'-boson. For a light Z', the Z' coupling to SM fermions f to first order in the small parameter χ is given by

$$\mathscr{L} \supset -(e\, q_f\, c_W)\chi\, \overline{f}\gamma^\mu f\, Z'_\mu\ , \tag{6}$$

with q_f the fermion electric charge.

The values of χ and $\lambda_{\Phi H}$ are arbitrary and could be expected to be rather large. As such, we treat them as free parameters within their allowed ranges. Here, we merely note that with our current minimal matter content, χ and $\lambda_{\Phi H}$ receive contributions at loop level from the $(\overline{L}_\alpha \cdot \widetilde{H})N^c$ and $\overline{N}\nu_D^c\Phi$ terms, which are necessarily suppressed by neutrino mixing ($\chi \propto g' e|U_{\alpha h}|^2$ and $\lambda_{\Phi H} \propto |U_{\alpha h}|^2$). These values constitute a lower bound and larger values should be expected in a complete model.

Portal phenomenology

The interplay between portal couplings and the heavy neutrinos ν_h ($h = 4, 5$) leads to a distinct, and possibly richer, phenomenology to what is commonly discussed in the presence of a single portal. We present here some of the most relevant signatures, devolving a longer study to future work.

Heavy neutrino searches The strongest bounds on heavy neutrinos in the MeV–GeV mass range come from peak searches in meson decays [52–54] and beam dump experiments [55–60] looking for visible ν_h decays. These, however, can be weakened if the ν_h decays are sufficiently different from the case of "standard" sterile neutrinos with SM interactions suppressed by neutrino mixing. We now discuss how this may happen, depending on the mass hierarchy of the two heavy neutrinos and the values of neutrino and kinetic mixing. For concreteness, we focus on specific benchmark points (BP) that illustrate the key features. In the ISS-like regime, we take $m_4/m_5 = 99\%$ and choose $m_4 \simeq m_5 = 100$ MeV. If χ is negligible, we have that ν_h decays as in the standard sterile case via SM interactions. This is because the $\nu_5 \to \nu_4 \bar{\nu}_\alpha \nu_\alpha$ decay is phase-space suppressed ($\Gamma_{\nu_5 \to \nu_4 \nu\nu} \propto \mu'^5$), and because Z' mediated decays into three light neutrinos are negligible for small mixing, as $\Gamma_{\nu_h \to \nu\nu\nu} \propto |U_{\alpha h}|^6 m_h^5/m_{Z'}^4$. If χ is sizeable, on the other hand, new visible decay channels dominate, specifically $\nu_4 \to \nu_\alpha e^+ e^-$ for this BP. The corresponding decay rate is given by

$$\Gamma(\nu_4 \to \nu_\alpha e^+ e^-) \approx \frac{1}{2} \frac{e^2 \chi^2 g'^2 |U_{\alpha 4}|^2}{192\pi^3} \frac{m_4^5}{m_{Z'}^4}. \tag{7}$$

Depending on the value of χ and m'_Z this decay can be much faster than in the SM, implying stronger constraints on the neutrino mixing parameters as discussed in Ref. [61]. For heavier masses, additional decay channels, e.g. $\nu_4 \to \nu_\alpha \mu^+ \mu^-$, would open. A feature of the model is that such channel would have the same BR as the electron one, albeit phase space suppressed. No two-body decays into neutral pseudoscalars arise due to the vector nature of the gauge coupling, unless mass mixing is introduced (see [62] for a thorough discussion of the decay products of a dark photon). We consider also a BP in the ESS-like regime. We take $m_4 = m_5/10$. In this case, ν_5 decays into 3 ν_4 states very rapidly. The subsequent decays of ν_4 would proceed as discussed above and would be much slower than the ν_5 one, given the hierarchy of masses and the further suppression due to neutrino and/or kinetic mixing.

For large χ, peak searches and bounds on lepton number violation (LNV) from meson and tau decays may be affected [63, 64]. Despite simply relying on kinematics, we note that in peak searches the strict requirement of a single charged track in the detector [53] would, in fact, veto a large fraction of new physics events if ν_h decays promptly into $\nu_\alpha e^+ e^-$, for instance. In addition, LNV meson and tau decays would need to be reconsidered as the intermediate on-shell ν_h could decay dominantly via the novel NC interactions, and the $\ell\pi$ and ℓK final states would be absent.

Dark photon searches Bounds on the vector portal come from several different sources [65, 66]. Electroweak precision data and measurements of the $g-2$ of the muon and electron constrain our model [67]. Major efforts at collider and beam dump experiments led to strong constraints on dark photons by searching for the production and decay of these particles. Such bounds, however, depend on the lifetime of the Z' and on its branching ratio (BR) into charged particles. In our model, the Z' decays invisibly into heavy fermions if $m_{Z'} > 2m_4$ and into light neutrinos otherwise. In the latter case, constraints would be much weaker than usually quoted with only mono-photon searches [68] applying. In the former case, however, new signatures arise, where the subsequent decay of ν_h leads to multi-lepton/multi-meson events, potentially with displaced vertices and providing a very clean experimental signature. Notably, if the Z' decays into ν_h states that subsequently decay sufficiently fast within the detector, even the "invisible decay" bounds will be weakened.

Revisiting Δa_μ The above possibility opens the option to explain the discrepancy between the theoretical prediction [69] and the experimental value [33] of the $(g-2)$ of the muon via kinetic mixing. For instance, a 1 GeV Z' with $\chi = 2.2 \times 10^{-2}$ can explain a_μ. Taking ν_4 around 400 MeV (800 MeV) and $m_5 > m_{Z'}$, then the Z' would decay into 2 ν_4 ($\nu_4 \nu_\alpha$) immediately. For the quoted value of the kinetic mixing and the largest neutrino mixing allowed, these heavy fermions would further decay into e^+e^- and $\mu^+\mu^-$ pairs plus missing energy with sub-meter decay lengths. This region of the χ parameter space is constrained only by the BaBar e^+e^- collider searches for visible [70] and invisible decays [68] of a standard dark photon. Both of these searches would veto the three-body decays of ν_4, opening up a large region of parameter space (see Ref. [71] for a similar discussion in an inelatic DM model). Resonance searches still constrain the Z' BR into e^+e^- and $\mu^+\mu^-$ which are proportional to χ^2, providing a weak upper bound. In order to shorten the lifetime of ν_4, we can increase mixing with the tau neutrino in order to avoid constraints from neutrino scattering. A detailed analysis to identify the viable parameter space is required and will be done elsewhere.

Fake rare meson decays The ν_h states can fake leptonic decays of charged mesons $M^\pm$ and charged leptons $\ell^\pm$ through the decay chains $M^\pm \to \ell^\pm_\alpha\,(\nu_h \to \nu\,\ell^+_\beta\,\ell^-_\beta)$ and $\ell^\pm_\alpha \to \ell^\pm_\beta\,\nu\,(\nu_h \to \nu\,\ell^+\,\ell^-)$. If the decays of ν_h are prompt, these could mimic rare SM 5-body decays, setting stringent constraints on $\Gamma_{M^\pm \to \ell^\pm_\alpha \nu_h} \propto |U_{\alpha h}|^2$. Measurements compatible with the SM prediction exist for pions [72] and kaons [73], where the BR are of the order of 10^{-8}, and for muons [74] and taus [75], where the BR are around 10^{-5}. This type of signature can also lead to displaced vertices and are complementary to peak searches.

Neutrino scattering The presence of a light vector mediator and kinetic mixing can also enhance neutrino scattering cross sections. For a hadronic target Z, the active neutrinos may upscatter electromagnetically into ν_h, which subsequently decays into observable particles $(\nu_\alpha\,Z \to (\nu_h \to \nu\,\ell^+_\beta\,\ell^-_\beta)\,Z)$. Beyond explaining MiniBooNE, see below, such upscattering signatures can also produce exotic final states in neutrino detectors such as $\mu^+\mu^-$, $\tau^+\tau^-$ and multi-meson final states.

MiniBooNE low energy excess The above signatures with $\ell^\pm = e^\pm$ have been invoked as an explanation of the excess of electron-like low energy events at MiniBooNE in Ref. [30], where a good fit to energy and angular data is achieved with a similar model containing a single heavy neutrino with $m_4 = 140$ MeV, $m_{Z'} = 1$ GeV and $\chi^2 = 5 \times 10^{-6}$. There, the prompt decays of ν_4 were achieved by requiring large mixing with the tau flavour. In a ESS-like limit of our current model, ν_4 would be dominantly produced via upscattering, decaying into $\nu_\alpha e^+ e^-$ inside the detector. A dedicated analysis to understand the resulting energy and angular distribution is underway.

Dark scalar searches For the scalar portal, the coupling $\lambda_{\Phi H}$ is rather weakly bound by electroweak precision data and the measurement of the Higgs invisible decay at the level of $\lambda_{\Phi H} \lesssim 0.1$ [76]. For processes involving $\lambda_{\Phi H}$, the physical observables are suppressed by mass insertions due to the nature of the Higgs interaction. Nevertheless, if φ' decays to ν_h states, this scalar may also lead to multi-lepton signatures inherited from ν_h decays, potentially also in the form of displaced vertices.

In the limiting case of a neutrinophilic model ($\chi = \lambda_{\Phi H} = 0$), the vector and scalar particles present a challenge for detection. Nonetheless, if light, they can be searched for in meson decays [77, 78] and at neutrino experiments [79].

Finally, the faster decays of ν_h and its self-interactions can help ameliorate tensions with cosmological observations. We do not comment further on this, but note that great effort has been put into accommodating eV scale sterile neutrinos charged under new forces with cosmological observables [22, 80] (see also Ref. [81] for an interesting discussion where the Z' decay to neutrinos leads to an altered expansions history of the Universe). We note that an eV sterile neutrino with relatively large mixing could be easily accommodated in our ESS framework. The eV neutrino would be mainly in the ν_D direction and would have strong hidden gauge interactions.

DARK MATTER

Given the presence of a dark sector, we can ask if the model can accommodate a DM candidate. This can be achieved introducing new fermions that do not mix with the neutrinos, in order to preserve their stability. A minimal solution would be to introduce a fermionic field ψ_L which has $U(1)'$ charge 1/2. The different charges of ψ, ν_D and N would forbid neutrino mixing. A Majorana mass term $\psi_L^T C^\dagger \psi_L$ would emerge after hidden-symmetry breaking leading to a Majorana DM candidate.

Another minimal realisation has the advantage of being anomaly free. Following Ref. [46], we introduce a pair of chiral fermion fields ψ_L and ψ_R, and charge only the latter under the $U(1)'$ symmetry with the same charge as ν_D. This choice ensures anomaly cancellation, and allows us to write $y_\psi \overline{\psi_L} \psi_R \Phi^\dagger$, which after hidden-symmetry breaking yields a Dirac mass m_ψ. In order to avoid $\psi_R - \nu_D$ and $\psi_L - N$ mixing, an additional $\mathbb{Z}_2$ symmetry may be imposed, under which all particles have charge $+1$, except for ψ_L and ψ_R, which have charge -1.

If the scalar and vector portal couplings are small in such scenarios, DM interacts mainly with neutrinos. Direct detection bounds are then evaded, since interactions with matter are loop-suppressed. Indirect detection, on the other hand, is more promising as DM annihilation into neutrinos would dominate. For instance, take the mass of ψ to be smaller than the masses of the Z', φ' and of both heavy neutrinos. In this case, the DM annihilation is directly into light neutrinos via $\psi\overline{\psi} \to \nu_i\nu_i$. This yields a mono-energetic neutrino line that can be looked for in large volume neutrino [82, 83] or direct detection experiments [21]. Alternatively, if m_ψ is larger than the mass of any of our new particles, then the annihilation may be predominantly into such states via $\psi\overline{\psi} \to XX$, where $X = \varphi', Z'$ or ν_h, which subsequently decay to light neutrinos. In this secluded realisation [84], the search strategy for DM can be very different since the neutrino spectrum from such annihilation is continuous [42]. Nevertheless, neutrino-DM interactions are expected to be large and can be searched for in a variety of ways [45, 85–88].

CONCLUSIONS

We have proposed a new model which invokes the existence of a hidden $U(1)'$ symmetry confined to a new dark neutrino sector. The dark sector particles can communicate with the SM via portal couplings, which may be sizeable. The simultaneous presence of neutrino, vector kinetic and scalar mixing in a self-consistent framework allows for a rich phenomenology in present and future experiments, which can be very different from that of each individual portal. In particular, we identified novel signatures such as multi-lepton final states with missing energy, displaced vertices, rare leptonic decays and unique neutrino upscattering processes. We have also argued that existing bounds on heavy neutrinos and dark photons might be significantly weaker as new visible and invisible decay channels appear, opening up previously excluded parameter space. In addition, the model offers a new mechanism for neutrino mass generation and provides a possible connection to dark matter, where the annihilation into neutrinos is the dominant channel.

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