Light Scalars and the Koto Anomaly

Daniel Egana-Ugrinovic,[1] Samuel Homiller,[2] and Patrick Meade[2]
[1]Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada
[2]C. N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, New York 11794, USA

(Received 27 December 2019; accepted 17 April 2020; published 12 May 2020)

We show that the recent excess presented by KOTO in their search for $K_L \to \pi^0 \nu\bar{\nu}$ may be due to weakly coupled scalars produced from Kaon decays. We study two concrete realizations, the minimal Higgs portal and a hadrophilic scalar model, and demonstrate that they can explain the observed events while satisfying existing limits. The simplicity of these models, and their possible relations to interesting UV constructions, provides strong theoretical motivation for a new physics interpretation of the KOTO data.

DOI: 10.1103/PhysRevLett.124.191801

Introduction.—Recently, the KOTO experiment presented an excess of events in the signal region for the rare process $K_L \to \pi^0 \nu\bar{\nu}$ [1]. Four events were observed, compared to a Standard Model (SM) plus background expectation of only 0.1 ± 0.02 events. One event is believed to originate from SM activity upstream from the detector, but the remaining three are currently unexplained. The three events are consistent with

$$\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{KOTO}} = 2.1^{+2.0(+4.1)}_{-1.1(-1.7)} \times 10^{-9}, \qquad (1)$$

where the ranges are the $1\sigma(2\sigma)$ Poisson statistical uncertainties corresponding to the measurement of three events. This result is 2 orders of magnitude larger than the SM prediction, $\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{SM}} = (3.4 \pm 0.6) \times 10^{-11}$ [2].

In this Letter, we study a simple new physics interpretation of these results. We focus on the possibility that the excess is due to new decays, $K_L \to \pi^0 \varphi$, where φ is a light new scalar [3], which is long-lived and weakly interacting so that it appears as missing energy at KOTO.

We study two concrete realizations leading to $K_L \to \pi^0 \varphi$ via up-type quark mediated penguin diagrams. First, we consider the real-scalar singlet extension of the SM [4–7], also referred to as the minimal "Higgs portal." This model is the most trivial extension beyond the SM (BSM) and does not require any BSM flavor textures. As a second possibility, we study hadrophilic scalar models with flavor-aligned, generation-specific couplings to up-type quarks. These models allow us to explore the possibility that the KOTO excess is due to novel flavor textures, leading to different kinematics.

We show that in both our concrete realizations there are regions of parameter space that are both consistent with the KOTO results and with strong bounds from beam-dump and flavor experiments. Our selection of models allows us to illustrate gaps in bounds from charged Kaon factories that have been pointed out in the literature [3,8,9] and to find a few small open regions where searches need to be improved. We find that the minimal Higgs portal model with scalar mass in the range 110 MeV $\leq m_\varphi \leq$ 180 MeV may be the origin of the KOTO excess. We also find small regions of parameter space for masses below $\leq$ 60 MeV, which are consistent with the excess. Regarding our hadrophilic models, we categorize them assuming a dominant coupling to u, c, or t quarks. We find that top-philic scalars lead to similar conclusions as in the minimal Higgs portal. For charm-philic scalars, we find agreement with the KOTO excess for the range 100 MeV $\leq m_\varphi \leq$ 180 MeV, but also some tension with bounds from beam dump experiments. Finally, for a singlet coupling mostly to the up quark, we find no consistent interpretation of the KOTO results.

Our analysis demonstrates that *extremely simple* and *motivated* models of new physics, especially the minimal Higgs portal, may be the origin of the KOTO excess. From a theoretical perspective, this provides strong support for a new physics explanation of the announced results.

We organize this Letter as follows. In the first section, we present the minimal Higgs portal and hadrophilic scalar models. In the second and third sections, we study the KOTO excess in the context of each one of these models, respectively. We conclude with UV motivations and comment on experimental signatures that could test our scenario. We leave technical discussions to the Supplemental Material [10], which includes Refs. [11–28].

Scalars with flavored couplings.—Minimal Higgs portal: We extend the SM with *only* a light real scalar singlet. The renormalizable Lagrangian for the singlet and the Higgs can be found in [7]. The singlet and the Higgs mix,

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and the corresponding two mass eigenstates are the 125 GeV Higgs boson, and a new scalar boson φ with mass m_φ. The couplings of the new scalar to SM fields are equal to the SM Higgs couplings, up to the universal mixing angle θ. In particular, the couplings to fermions in the mass eigenbasis are flavor diagonal and given by

$$\lambda_\varphi^f = -\sin\theta \frac{m_f}{v}, \tag{2}$$

where m_f are the SM fermion masses.

Hadrophilic scalar coupling to up-type quarks: The minimal Higgs portal constrains the scalar-fermion couplings to follow the SM flavor hierarchies, limiting the phenomenology. To discuss scalar models in more generality, we now allow for flavor-specific couplings with the SM quarks. These couplings can be obtained by going beyond the renormalizable level and adding dimension-five operators. We limit ourselves to include such interactions between the scalar and up-type quarks only [26,29],

$$\mathcal{L} \supset \frac{\varphi}{M} c_{ij}^u Q_i H \bar{u}_j, \tag{3}$$

where H is the SM Higgs doublet, Q and $\bar{u}$ the left and up-type right-handed SM quarks, respectively, M points to the scale of the UV completion leading to the dimension-five operator, and c_{ij}^u is a new Yukawa matrix leading to novel flavored interactions. The operator (3) can be obtained in UV completions with an extra-Higgs doublet [30] or vectorlike quarks [29]. To avoid tree-level flavor-changing neutral currents (FCNC's) mediated by the new scalar, we impose that c_{ij}^u is simultaneously diagonalizable with the up-type quark SM Yukawa, i.e., that it is flavor aligned. This can be imposed by a UV flavor construction called down-type spontaneous flavor violation (SFV) [30,31].

In the limit of vanishing scalar mixing $\theta \to 0$, the new scalar is hadrophilic (and leptophobic) and couples to up-type quarks only due to the interaction Eq. (3). In the quark mass eigenbasis, these couplings are flavor diagonal and related to the dimension-five operator couplings via

$$\lambda_\varphi^q = v/(\sqrt{2}M)\kappa_q, \qquad q = u, c, t, \tag{4}$$

where $\kappa_{u,c,t}$ are the singular values of the matrix c_{ij}^u. The couplings $\lambda_\varphi^{u,c,t}$ are three independent Yukawas controlling the interactions of the singlet to up-type quarks, which do not necessarily follow the SM hierarchies.

Minimal Higgs portal explanation of the KOTO excess.—The effective branching fraction measured at KOTO, $\mathrm{Br}^{\mathrm{eff}}(K_L \to \pi^0 \nu\bar{\nu})$, is given by the number of measured events in their signal region, times the single-event sensitivity defined in [1,32]. Our light scalars contribute to the number of measured events if they escape KOTO invisibly, and therefore contribute to the effective branching fraction according to

$$\mathrm{Br}^{\mathrm{eff}}(K_L \to \pi^0 \nu\bar{\nu}) = \epsilon \mathrm{Br}(K_L \to \pi^0 \varphi) e^{\left(-\frac{m_\varphi L}{c\tau_\varphi p_\varphi}\right)}, \tag{5}$$

where $\mathrm{Br}(K_L \to \pi\varphi)$ is obtained from [25,27,33], the exponential suppression accounts for the scalars that decay visibly before escaping the detector, and ϵ is a correction factor taken from [34] that accounts for the kinematical difference between the three-body SM decays, and the two-body decays into our scalar. In the exponential, the KOTO detector size is $L = 3$ m and p_φ is the scalar's momentum. The typical momentum is obtained from a simulation in [3] and corresponds to an energy $E_\varphi = 1.5$ GeV. We limit ourselves to masses in the range $m_\varphi \lesssim 200$ MeV, motivated by the large transverse momentum of the pions in the observed events [3]. In Fig. 1, we show in blue the minimal Higgs portal model parameter space for which the effective branching fraction Eq. (5) is consistent with the KOTO measurement [67]. In dashed gray, we show contours of $c\tau_\varphi$. Note that for masses $2m_e \le m_\varphi \le 2m_\mu$ the scalar decays overwhelmingly to electrons [35].

There is a variety of constraints on the regions of parameter space where the Higgs portal explanation is naively successful. The most obvious comes from

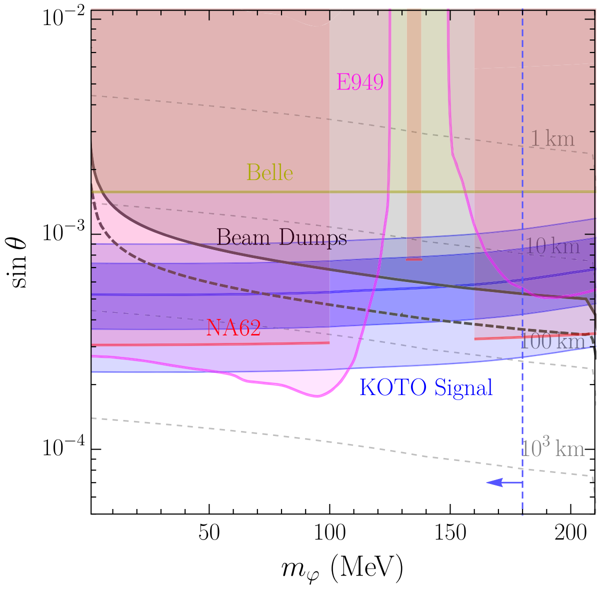

FIG. 1. Higgs portal interpretation of the KOTO excess, and bounds on the model, as a function of the new scalar mass and mixing angle with the Higgs. Blue: central value, 1σ and 2σ regions consistent with the number of $K_L \to \pi^0 \nu\bar{\nu}$ events observed at KOTO. The region to the left of the vertical dashed blue line has pion p_T consistent with the observed events. Red: limits from NA62 on $\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu})$ and $\mathrm{Br}(K^+ \to \pi^+ \pi^0)$ with π^0 decaying invisibly. Pink: limit from E949 on $\mathrm{Br}(K^+ \to \pi^+ X)$ with X a long-lived particle. Shaded gray and dashed black: bound on displaced decays of the scalar to electrons from the CHARM beam dump, with conservative and aggressive assumptions regarding uncertainties in the limit, respectively. Yellow: limit from Belle on $\mathrm{Br}(B \to K\nu\bar{\nu})$. Dashed gray: contours of $c\tau_\varphi$.

analogous decays $\mathrm{Br}(K^+ \to \pi^+ + \mathrm{inv.})$, constrained by NA62 and E949. These are normally related to the process of interest at KOTO via the Grossman-Nir bound [36], and the corresponding width in our model can be obtained from [25,27]. To apply these limits, we must take into account the effective branching fraction similarly to what was done for KOTO in Eq. (5). For the NA62 detector size, we use $L = 150$ m, while the scalar's energy is taken to be approximately half of the charged kaon energy at this experiment, $E_\varphi = 37$ GeV. For NA62, we neglect differences in three- and two-body kinematics, and set $\epsilon = 1$ in the effective branching fraction. The resulting limit is obtained by comparing the effective branching fraction with the 95% CL limits in [37] and is presented in Fig. 1 in red. For scalar masses around the pion mass, there is a gap in the bounds due to large pion backgrounds [8,9]. Part of this gap is covered by a different NA62 analysis, which sets a limit on the invisible decays of the neutral pions from $K^+ \to \pi^+\pi^0$ decays [37]. This limit applies to our model when $m_\varphi \sim m_\pi$, in which case $K^+ \to \pi^+\varphi$ mimics the invisible pion search topology. We present the bound with a red column centered around the pion mass, where the width of the column is set by the experimental pion mass resolution.

E949, on the other hand, reports 95% CL bounds on $\mathrm{Br}(K^+ \to \pi^+\varphi)$, as a function of the particle's mass and lifetime [38], so we can directly translate these bounds into the Higgs portal parameter space. The bound is shown in the figure in pink.

Given the long lifetime of the minimal Higgs portal scalar, there are bounds from proton beam-dump experiments, the most relevant of which is CHARM, looking for displaced lepton decays [23]. At CHARM, our scalars are obtained from B, K, and η meson decays, which are produced by the proton beam interactions on the fixed target. The event yield at the detector is

$$N_{\mathrm{obs}} = \varepsilon_{\mathrm{det}} N_\varphi \left(e^{-\frac{L_{\mathrm{dump}}}{c\tau_\varphi}\frac{m_\varphi}{p_\varphi}} - e^{-\frac{L_{\mathrm{dump}}+L_{\mathrm{fid}}}{c\tau_\varphi}\frac{m_\varphi}{p_\varphi}}\right), \tag{6}$$

where N_φ is the number of scalars falling within the CHARM angular acceptance and $\varepsilon_{\mathrm{det}} = 0.51$ is the efficiency to detect the electron-positron pair. The exponential factors in (6) determine the number of scalars that reach and decay within the detector volume. $L_{\mathrm{dump}} = 480$ m is the CHARM beam-dump baseline, while $L_{\mathrm{fid}} = 35$ m is the detector fiducial length. The scalar momentum is obtained assuming an average scalar energy of $E_\varphi = 12.5$ GeV. This energy is obtained by assuming that the scalar takes half the energy of the parent meson, and that the parent meson's energy is similar to the typical 25 GeV pion energy reported in [23]. The calculation of N_φ has uncertainties inherited from the parent meson production rates and momentum distributions. We have found that the uncertainties in hadronic beam-dump bounds are often underappreciated in generic BSM searches, so in the Supplemental Material [10] we discuss them in detail, and provide the calculation of N_φ. To account for these uncertainties, in Fig. 1 we present two bounds, in shaded gray and dashed black, corresponding to conservative and aggressive assumptions regarding production rates and acceptances.

We now comment on subleading bounds. First, Belle sets bounds on $B \to K\nu\bar{\nu}$ [39], which apply to the minimal Higgs portal when the scalar escapes Belle undetected. We compute this branching ratio as in [40,41], compare with the limit in [39], and present the bound in Fig. 1 in yellow.

Second, KTeV sets a limit on the branching fraction of Kaons to a pion and electron-positron pairs [42], which in our model is generated from $\mathrm{Br}(K_L \to \pi^0\varphi)$ followed by scalar decays into electrons. However, in the range of mixing angles allowed by CHARM and charged kaon factory bounds, our scalar is rather long-lived. As a consequence, most scalars produced from Kaon decays escape the KTeV fiducial volume unobserved. Accounting for this effect, we have checked that the KTeV bound in [42] is weaker than the bounds from CHARM and NA62/E949.

Finally, for scalar masses around an MeV, bounds from BBN apply. However, these bounds depend on the value of the scalar-Higgs quartic coupling, and on assumptions regarding the reheating temperature [43], so they are not presented here. Bounds from supernovae do not apply for the range of scalar mixing angles that we explore [44] (see also [45]).

From Fig. 1, we conclude that the Higgs portal model may explain the central value of the KOTO anomaly for a region of parameter space around $m_\varphi \simeq 120$ MeV, $\theta \simeq 5 \times 10^{-4}$. Including the 2σ KOTO uncertainty bands, the model leads to a realistic explanation of the anomaly even in regions outside the pion mass window.

Hadrophilic scalars and the KOTO excess.—In the context of our hadrophilic model, for simplicity we set the Higgs-scalar mixing angle to zero, $\theta = 0$, so that the Yukawa couplings of our singlet to quarks are exclusively given by Eq. (4). In this case, for the range of masses that we explore our scalar may only decay to two photons via one-loop up-type quark mediated diagrams, with a rate given in [25].

We first explore a purely charm-philic scalar, setting $\lambda_\varphi^u = \lambda_\varphi^t = 0$ in Eq. (4). In this model, the relevant parameters are the scalar-charm Yukawa λ_φ^c and the scalar mass. We calculate the model's contribution to the branching fraction measured at KOTO as in the previous section, and in Fig. 2 we show in blue the parameter space consistent with the KOTO measurement. We also show contours of $c\tau_\varphi$ in dashed gray. We identify two ranges of values for the scalar-charm Yukawa that can accommodate the KOTO anomaly. First, we find a band of sizable Yukawas, $\lambda_\varphi^c \geq 10^{-3}$, where the scalar production rate from K_L decays is large, but the number of events reconstructed as $K_L \to \pi^0\nu\bar{\nu}$ at KOTO is exponentially suppressed since

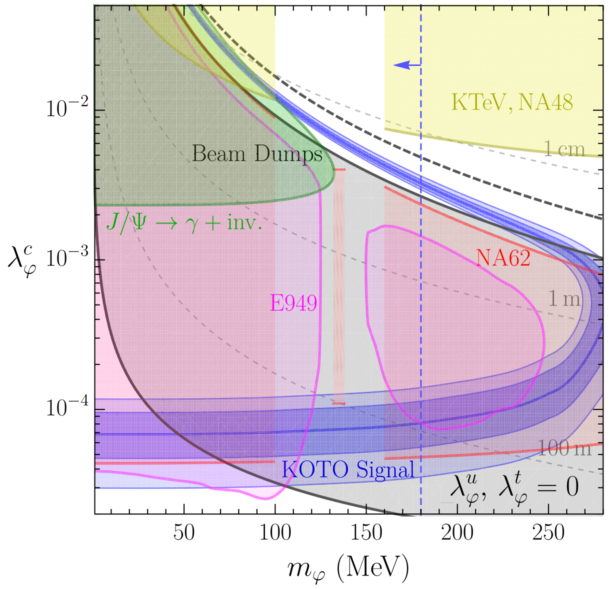

FIG. 2. Charm-philic scalar interpretation of the KOTO excess and bounds on the model, as a function of the scalar's mass and its charm-Yukawa coupling. Blue, red, pink, and dashed gray: same color coding as in Fig. 1. Shaded gray and dashed black: bound on displaced decays of the scalar to photons from the NuCal beam dump, with conservative and aggressive assumptions regarding uncertainties in the limit, correspondingly. Green: limit on $\mathrm{Br}(J/\Psi \to \varphi\gamma)$. Yellow: limit from KTeV on $\mathrm{Br}(K_L \to \pi^0\gamma\gamma)$.

the scalar decays into photons before reaching the detector. Second, we find a band where Yukawas are small, $3 \times 10^{-5} \leq \lambda_\varphi^c \leq 10^{-4}$, where the rate is small but the scalar lifetime is large, so most scalars escape the KOTO fiducial volume unobserved and are thus tagged as $K_L \to \pi^0\nu\bar{\nu}$.

In Fig. 2, we also present the leading bounds on the charm-philic model. Bounds from NA62 and E949 are calculated as in the previous section and presented in red and pink. We observe that for large λ_φ^c these bounds disappear, since the scalar decays into photons before reaching the corresponding detectors. This is a specific realization of the finite lifetime effects discussed in [3], that we refer to as a "lifetime gap."

Additional bounds are set by measurements of $\mathrm{Br}(J/\psi \to \varphi\gamma)$ in the Crystal Ball detector and BESIII, when φ escapes the detectors invisibly [46,47]. We compute this branching fraction using [48,49], including an exponential suppression factor to account for the scalars decaying to photons before escaping the 25 cm radius Crystal Ball or 1 m BESIII drift chamber. The limit is shown in Fig. 2 in green.

Regarding beam-dump limits, the CHARM experiment is impuissant in this scenario due to the scalar's short lifetime compared to the experiment's long baseline. The strongest beam-dump bounds instead come from NuCal [16,50,51], which has a shorter baseline and lower beam energy. The bounds are obtained as for CHARM in the previous section, using Eq. (6) with $N_{\mathrm{POT}} = 4 \times 10^{17}$, beam-dump baseline $L_{\mathrm{dump}} = 64$ m, and fiducial length $L_{\mathrm{fid}} = 23$ m. To account for the uncertainties in the scalar production rate, in Fig. 2, we present both a conservative and an aggressive bound, with different assumptions on scalar production at NuCal discussed in [10].

On the other hand, KTEV and NA48 have measurements of $\mathrm{Br}(K_L \to \pi^0\gamma\gamma)$ consistent with the SM [52,53]. In our model, the same final state is obtained from $K \to \pi^0\varphi$ with $\varphi \to \gamma\gamma$. The measurement assumes that the two photons and the pion originate at the same vertex. We may obtain a conservative bound by considering only the scalar decays that appear prompt given KTeV's and NA48's vertex resolution, which we take to be 25 cm on KTEV, based on the bin widths for decay locations given in [52], and 10 cm on NA48, based on the calorimeter energy resolution, used to reconstruct the vertex. To calculate the decay displacement, we assume that the scalars have an average energy of 50 GeV at KTeV and 15 GeV and NA48. The bound is shown in yellow in the figure.

Finally, MAMI sets a constraint on $\mathrm{Br}(\eta \to \varphi\pi^0)$ [54,55]. We calculate the corresponding branching fraction in our model in [10], and comparing with the experimental limit we find that this bound is subleading. The same conclusion applies to constraints on $B \to K\nu\bar{\nu}$ from Belle [39].

From Fig. 2, we see that the KOTO result may be explained by a charm-philic scalar with a lifetime $c\tau_\varphi \sim \mathcal{O}(1\text{–}10\ \mathrm{cm})$ while retaining consistency with strong bounds from beam dumps and charged kaon factories, mostly due to the aforementioned lifetime gaps in the bounds. However, we find that these lifetime gaps are excluded by NuCal when considering aggressive assumptions regarding the uncertainties in this limit.

We conclude by commenting on up-philic and top-philic scalars. In the up-philic case, $\lambda_\varphi^c = \lambda_\varphi^t = 0$, the penguin diagram leading to $K_L \to \pi\nu\bar{\nu}$ is suppressed by one up-quark mass insertion. While it is possible to explain the number of events observed at KOTO in this scenario, doing so requires a large up-quark scalar Yukawa, which is excluded by various experiments [26]. In the top-philic case, $\lambda_\varphi^u = \lambda_\varphi^c = 0$, the situation is similar to the minimal Higgs portal setup presented in Fig. 1, with $\sin\theta$ replaced by λ_φ^t. In this situation, the KOTO events are again consistent with bounds from charged kaon factories mostly in a region of masses around the pion mass. Neither the up-philic nor top-philic scenarios lead to any additional regions of parameter space consistent with the KOTO excess due to the lifetime gap suggested in [3]. Overall, we find that in a hadrophilic scenario it is challenging to implement the lifetime gap solution of the KOTO excess while retaining consistency with bounds. Allowing for different combinations of $\lambda_\varphi^u, \lambda_\varphi^c$, and λ_φ^t to be simultaneously nonzero does not modify this conclusion.

Conclusions.—We investigated a possible new physics explanation of the observed KOTO excess in $K_L \to \pi\nu\bar{\nu}$. In our setup, the neutrinos are replaced by a singlet scalar that escapes the detector invisibly. Interestingly, the simplest possible extension of the SM, the minimal Higgs portal, can explain the anomaly. Models with hadrophilic scalars were also studied, and we found that a top-philic or charm-philic scalar could also be the origin of the excess.

If the observed events are due to new physics, a similar number of events should be observed in future KOTO datasets and may also be seen at NA62. Hadronic beam-dump experiments may also be efficient at testing these solutions but suffer from rate uncertainties, which may be overcome by future experiments relying only on hard QCD production such as MATHUSLA [56]. Both MATHUSLA and KLEVER [57] could in the future probe the minimal Higgs portal explanation of the KOTO results [44].

Models with light new scalars can be accommodated in well-motivated UV constructions and also provide portals into the dark sector. A real scalar in the sub-GeV range may seem tuned, but solutions to the Higgs hierarchy problem such as large extra dimensions [58] automatically mitigate the new scalar's hierarchy problem. Light dilatons/radions [59–66] have similar couplings to our Higgs portal scalar, so they could perhaps be the origin of the KOTO excess. Within supersymmetry, complex singlet fields are accommodated in the NMSSM, yet another interesting alternative to explore. Hadrophilic light scalars consistent with strong bounds from FCNCs, on the other hand, may arise in flavor-aligned SFV UV completions [31].

The experimental result obtained by KOTO may ultimately be due to statistics or unaccounted backgrounds. Nevertheless, we have demonstrated that from a purely theoretical perspective, the observation is incredibly simple to explain and is motivated by interesting UV constructions.

We would like to thank Kohsaku Tobioka for helpful comments on the Letter. We would also like to thank Asimina Arvanitaki, Yang-Ting Chen, Rouven Essig, Evgueni Goudzovski, Junwu Huang, George Sterman, and Michael Wilking for helpful discussions. D. E.-U. is supported by Perimeter Institute for Theoretical Physics. Research at Perimeter Institute is supported in part by the Government of Canada through the Department of Innovation, Science and Economic Development Canada and by the Province of Ontario through the Ministry of Economic Development, Job Creation and Trade. D. E.-U. thanks the Galileo Galilei Institute for Theoretical Physics for the hospitality and the INFN for partial support during the completion of this work. The work of S. H. and P. M. was supported in part by the National Science Foundation Grant No. PHY-1915093. P. M. would like to thank the Mt. Sinai West maternity ward for its hospitality in the final stages of this project.

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