

Time-of-flight constraints on neutrino millicharge from supernova neutrinos in galactic magnetic fields

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A millicharged neutrino propagating through magnetic fields experiences a small Lorentz-force deflection, which induces a geometric time delay. In the ultrarelativistic regime relevant for supernova neutrinos, this delay scales as $q_\nu^2 E_\nu^{-2}$, where q_ν and E_ν denote the neutrino millicharge and energy, respectively, and thus shares the same leading energy dependence as the standard time-of-flight delay induced by neutrino mass. Motivated by this similarity, we propose a framework to reinterpret supernova time-of-flight limits on neutrino mass as constraints on neutrino millicharge. We express both effects in terms of a common E_ν^{-2} dispersion coefficient and compute the millicharge-induced contribution using a line-of-sight-dependent magnetic delay kernel, extending the original SN1987A uniform-field estimate. Applying this translation to existing SN1987A limits and to projected sensitivities for future Galactic core-collapse supernova observations, we obtain bounds ranging from the $\sim 10^{-17}e$ level for SN1987A to the low- $10^{-19}e$ regime for next-generation Galactic bursts, with optimistic combinations of detector sensitivity and Galactic sightline approaching $\sim 10^{-20}e$. We compare these results with other bounds in the literature and discuss how nonzero neutrino mass affects the interpretation.

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I. INTRODUCTION

In the minimal Standard Model (SM) with the usual hypercharge assignments, neutrinos are electrically neutral. More generally, electric charge is associated with the generator Q of the unbroken electromagnetic symmetry and, in the electroweak theory, is given by $Q = T_3 + \frac{Y}{2}$, where T_3 is the third weak-isospin generator and Y is the weak hypercharge. The electric charges of quarks and leptons are therefore fixed by their electroweak quantum numbers. Whether this charge assignment is uniquely enforced by the theory is tied to the more general question of electric-charge quantization.

From a theoretical perspective, exact electric charge quantization is not automatic in all extensions of the

SM. Although anomaly cancellation and the Yukawa structure strongly constrain the allowed hypercharge assignments, it has long been recognized that more general Abelian gauge structures can permit electric charge dequantization [1–4]. In modern terms, one may view this as replacing the standard hypercharge embedding by a linear combination involving an additional anomaly-free $U(1)_X$ symmetry under which neutrinos transform nontrivially.

Neutrino oscillation experiments have established that neutrinos are massive and mixed, demonstrating that the minimal SM is incomplete and that new physics is required beyond its original formulation [5–7]. Although neutrino mass by itself does not imply a nonzero neutrino electric charge, the extensions introduced to account for neutrino masses can modify the conditions under which charge quantization is realized. In viable millicharged-neutrino scenarios, this issue is closely tied to the Dirac nature of neutrinos: once neutrinos carry electric charge, Majorana mass terms are forbidden by electromagnetic gauge invariance, so charged neutrinos are necessarily Dirac fermions [8,9]. Moreover, recent analyses indicate that not all anomaly-free $U(1)_X$ realizations remain phenomenologically viable once the observed neutrino masses and mixing are imposed: minimal flavor-dependent symmetries such as $U(1)_{L_\alpha-L_\beta}$ are disfavored, whereas flavor-universal possibilities such as $U(1)_{B-L}$ or $U(1)_L$ remain viable

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candidates for accommodating tiny neutrino charges [9]. More generally, minimal Dirac extensions with right-handed neutrinos can permit electric charge dequantization through anomaly-free Abelian symmetries such as $B - L$ [1,2,9].

In this context, a nonzero electric charge is especially interesting among the possible electromagnetic properties of neutrinos, because it is directly tied to the problem of charge quantization and to possible extensions of the SM gauge structure. More broadly, neutrino electromagnetic properties provide a window on physics beyond the Standard Model, including the Dirac or Majorana nature of neutrinos and the possible existence of hidden sectors or additional gauge interactions [8,10–12]. In particular, a neutrino millicharge can arise in representative beyond the Standard Model scenarios either through electric charge dequantization or through kinetic mixing involving an additional Abelian gauge sector [2,13].

Existing bounds on the neutrino millicharge have been derived from a broad range of laboratory, astrophysical, and cosmological probes, including reactor neutrino scattering, stellar cooling, big bang nucleosynthesis, and electromagnetic effects in astrophysical environments [8,14–20]. Although these constraints already require the neutrino charge to be extremely small, they probe distinct physical effects and do not exhaust the range of possible observables. In particular, the propagation of neutrinos over astrophysical distances through magnetic fields offers a complementary way to test tiny electric charges through the cumulative effect of small Lorentz force deflections.

Core-collapse supernovae (CCSNe) are especially well suited to this purpose. They emit intense bursts of MeV neutrinos over timescales of order seconds, and characteristic temporal features of the signal—such as the neutronization burst or, in failed explosions, an abrupt cutoff associated with black hole formation—can provide sharp timing markers for time-of-flight (ToF) studies. Even tiny energy dependent propagation delays can therefore accumulate over astrophysical baselines and leave an observable imprint on the detected burst profile.

In particular, the idea that neutrino mass could be constrained from the arrival time delay of neutrinos from a distant transient source goes back to Zatsepin, who pointed out that a massive neutrino acquires a ToF delay scaling as $m_\nu^2 E_\nu^{-2}$ over a fixed baseline [21]. This basic logic underlies the long standing supernova ToF literature, from early discussions and reanalyses of the SN1987A signal [22–24] to modern forecasts for a future Galactic burst in detectors such as DUNE, Hyper Kamiokande, JUNO, and IceCube [25–30].

The same timing logic can be applied to a millicharged neutrino, although the microscopic origin of the delay is different. A neutrino carrying electric charge q_ν is deflected by magnetic fields during propagation, and the associated increase in path length induces an additional geometric

time delay. In the ultra relativistic regime relevant for the supernova neutrinos, this delay also scales as $q_\nu^2 E_\nu^{-2}$ at leading order. Shortly after SN1987A, Barbiellini and Cocconi used this idea to derive a bound on the neutrino electric charge assuming propagation in a uniform magnetic field [31]. Their estimate captured the basic physical effect, but both the magnetic field description and the statistical treatment of the supernova signal were simplified relative to the modern supernova ToF analyses.

In this work, we revisit the supernova constraint on neutrino millicharge within a modern ToF framework. The key point is that, at the phenomenological level, supernova timing analyses are sensitive to the coefficient of an energy dependent dispersion term in the detected burst profile. Since the standard mass induced delay and the magnetic delay of a millicharged neutrino share the same leading E_ν^{-2} dependence, published and projected ToF bounds on neutrino mass can be systematically reinterpreted as bounds on neutrino millicharge. We implement this program by expressing both effects in terms of a common dispersion coefficient and by evaluating the millicharge induced contribution with a line-of-sight dependent kernel determined by the Galactic magnetic field model, thereby extending the original uniform field estimate of Ref. [31]. The resulting translated sensitivity depends explicitly on both the detector level ToF reach and the astrophysical propagation along the source direction, so the inferred charge bound is not a single universal number but a line-of-sight dependent sensitivity. Note that the present translation is intended for time-of-flight analyses that constrain a single effective leading E_ν^{-2} dispersion coefficient for the detected signal; analyses that become sensitive to the individual neutrino mass eigenstates fall outside this minimal recast.

The paper is organized as follows. In Sec. II, we introduce the ToF framework and define the dispersion coefficient parametrization used throughout the paper. In Sec. III, we translate the relevant supernova ToF bounds into limits on neutrino millicharge using our magnetic delay formalism. In Sec. V, we compare our results with other bounds in the literature, discuss their interpretation and main caveats, and present our conclusions.

II. FRAMEWORK

ToF studies of supernova neutrinos probe energy dependent distortions of the observed burst time structure. Existing ToF results are commonly quoted as constraints on an effective neutrino mass, corresponding to the usual interpretation in which the relevant propagation induced delay is attributed entirely to neutrino mass.

The recast developed in this work exploits the fact that the magnetic field induced delay of a millicharged neutrino has the same leading energy dependence. This allows a published bound on neutrino mass to be reinterpreted as a bound on neutrino millicharge at the level of the leading propagation induced delay.

A. Dispersion coefficient translation

For an ultrarelativistic neutrino of energy E and mass m_ν , the corresponding delay over a source distance L is

$$\Delta t_m(E) \simeq \frac{L}{2c} \frac{m_\nu^2}{E^2}. \quad (1)$$

It is therefore useful to isolate the coefficient of this common E^{-2} scaling and write the leading propagation induced delay as

$$\Delta t_{\text{prop}}(E) \simeq \frac{A_{\text{ToF}}}{E^2}, \quad (2)$$

where A_{ToF} denotes the *dispersion coefficient* of the leading delay term. In the mass-only interpretation, this coefficient reduces to

$$A_{\text{ToF}} = A_m \equiv \frac{L}{2c} m_\nu^2. \quad (3)$$

At leading order, the timing sensitivity of a ToF analysis can thus be expressed as sensitivity to the coefficient of the leading propagation delay. The usual interpretation in terms of neutrino mass corresponds to one particular realization of this coefficient. More generally, any mechanism with the same leading energy dependence contributes to the same effective quantity, so that

$$A_{\text{ToF}} \equiv A_m(m_\nu^2) + A_q(q_\nu^2) + A_{\text{other}}, \quad (4)$$

where A_m and A_q are the dispersion coefficients associated with the mass-induced and millicharge-induced delays, respectively, and A_{other} collects any additional contribution whose leading ToF effect scales as E^{-2} energy dependence.

A reported upper bound $m_\nu < m_{\text{lim}}$ therefore implies, under the mass-only interpretation,

$$A_{\text{ToF}} < A_{\text{lim}} \equiv \frac{L}{2c} m_{\text{lim}}^2, \quad (5)$$

i.e., for $A_q = A_{\text{other}} = 0$. Equation (5) maps a published ToF mass limit onto the more general coefficient entering our recast. Assuming instead that the entire constrained leading contribution is due to a millicharge, we require

$$A_q(q_\nu^2) \leq A_{\text{lim}}. \quad (6)$$

The problem is then reduced to computing the millicharge induced coefficient A_q for a specified magnetic field configuration.

B. Millicharged neutrino time delay in magnetic fields

A neutrino carrying electric charge q_ν is deflected by magnetic fields through the Lorentz force. In the small

deflection regime relevant here, the resulting increase in path length produces a geometric arrival time delay proportional to $(q_\nu/E)^2$.¹ The derivation of this scaling, together with the fixed endpoint kernel formulation used below, is given in Appendix A. In the parameter region relevant for the translated bounds obtained in this work, the net deflection remains extremely small, so the small angle approximation is well justified. Note that the delay is independent of the charge sign, such that our ToF analysis applies to both neutrinos and antineutrinos with the same charge magnitude $|q_\nu|$.

For Galactic supernova neutrinos, the magnetic delay is dominated by propagation through the Galactic magnetic field (GMF). In our numerical implementation, we model the GMF using the Jansson-Farrar (JF12) framework [32], with the corresponding parameter uncertainties propagated phenomenologically as described in Appendix B. The JF12 model explicitly includes regular, turbulent, and striated components, which we write as

$$\mathbf{B} = \mathbf{B}_{\text{reg}} + \mathbf{B}_{\text{turb}} + \mathbf{B}_{\text{str}}, \quad (7)$$

where $\mathbf{B}_{\text{turb}}$ is an isotropic random component with vanishing mean and finite correlation scale, while $\mathbf{B}_{\text{str}}$ is a striated component, locally aligned with $\mathbf{B}_{\text{reg}}$ but fluctuating in sign so that $\langle \mathbf{B}_{\text{str}} \rangle = 0$ while $\langle B_{\text{str}}^2 \rangle \neq 0$. We first consider the contribution of the regular component.

Let $\mathbf{B}_\perp(x)$ denote the magnetic field transverse to the unperturbed line-of-sight at position x along the trajectory. In the small-angle limit, the delay induced by the regular GMF component can be written as

$$\Delta t_q^{\text{reg}}(E) = \frac{1}{2c} \left(\frac{q_\nu}{E} \right)^2 \times \int_0^L dx \int_0^L dx' \mathbf{B}_\perp(x) \cdot \mathbf{B}_\perp(x') K(x, x'), \quad (8a)$$

$$K(x, x') = \min(x, x') - \frac{xx'}{L}. \quad (8b)$$

Here, the superscript “reg” indicates that only the regular GMF component is included. The kernel $K(x, x')$ is the

¹The common E^{-2} behavior is the leading ultrarelativistic and small-deflection term. For the standard mass delay, the next term scales as m_ν^4/E^4 . For the magnetic geometric delay, higher terms arise from the expansion of the path length and scale schematically as $(L/r_L)^4$ (r_L is the Larmor radius), corresponding to an E^{-4} correction relative to the leading L^2/r_L^2 contribution. Mixed mass-magnetic corrections are likewise of order $q_\nu^2 B^2 L^2 m_\nu^2/E^4$. Throughout the parameter region constrained here, $m_\nu^2/E^2 \ll 1$ and $L/r_L \ll 1$, so all such terms are entirely negligible.

geometric weighting appropriate to small transverse excursions with fixed source and observer positions.²

It is convenient to define an effective field strength B_{eff} by

$$B_{\text{eff}}^2 \equiv \frac{12}{L^3} \int_0^L dx \int_0^L dx' \mathbf{B}_\perp(x) \cdot \mathbf{B}_\perp(x') K(x, x'). \quad (9)$$

With this definition, Eq. (8) becomes

$$\Delta t_q^{\text{reg}}(E) = \frac{L^3}{24c} \left(\frac{q_\nu B_{\text{eff}}}{E} \right)^2 \equiv \frac{A_q^{\text{reg}}}{E^2}, \quad (10)$$

so that the corresponding dispersion coefficient is

$$A_q^{\text{reg}} = \frac{L^3}{24c} q_\nu^2 B_{\text{eff}}^2. \quad (11)$$

The stochastic GMF components may be treated in the regime where the propagation distance is much larger than their correlation scale. In that limit, the neutrino traverses many approximately independent magnetic domains along the line-of-sight, the accumulated transverse deflection behaves as a random walk, and the resulting time delay is well described by its ensemble average over realizations of the stochastic field. In this regime, the delay is controlled by the field variance and by the integral scale of the transverse two-point correlation function, λ_B , as defined in Appendix A.

Using the stochastic field limit of the kernel formulation, the turbulent contribution takes the form

$$\langle \Delta t_q^{\text{turb}}(E) \rangle = \frac{L^2 \lambda_B^{\text{turb}}}{9c} \left(\frac{q_\nu B_{\text{rms}}^{\text{turb}}}{E} \right)^2 \equiv \frac{A_q^{\text{turb}}}{E^2}, \quad (12)$$

so that

$$A_q^{\text{turb}} = \frac{q_\nu^2 L^2 \lambda_B^{\text{turb}}}{9c} (B_{\text{rms}}^{\text{turb}})^2. \quad (13)$$

Here $B_{\text{rms}}^{\text{turb}}$ is the full rms turbulent field strength; for an isotropic random field, the corresponding transverse variance satisfies $\langle |\mathbf{B}_{\text{turb},\perp}|^2 \rangle_x = (2/3)(B_{\text{rms}}^{\text{turb}})^2$, where $\langle \rangle_x$ denotes the average along the line of sight.

For the striated component, the general stochastic kernel expression remains valid, but the isotropic relation between the transverse variance and the full three dimensional rms field no longer applies. It is therefore convenient to parametrize the result directly in terms of the transverse variance

$$\mathcal{B}_{\text{str}}^2 \equiv \langle |\mathbf{B}_{\text{str},\perp}|^2 \rangle_x. \quad (14)$$

Thus, the corresponding dispersion coefficient is

$$A_q^{\text{str}} = \frac{q_\nu^2 L^2 \lambda_B^{\text{str}}}{6c} \mathcal{B}_{\text{str}}^2. \quad (15)$$

In practice, for each line of sight we generate multiple independent realizations of the JF12 turbulent and striated fields and estimate the corresponding combinations $(B_{\text{rms}}^{\text{turb}})^2 \lambda_B^{\text{turb}}$ and $\mathcal{B}_{\text{str}}^2 \lambda_B^{\text{str}}$ directly from the sampled transverse field components; see Appendix B for details. Their percentiles are then used to propagate the stochastic field uncertainty into the corresponding contributions to the time delay kernel.

The total millicharge contribution to the leading delay coefficient is therefore the sum of the regular and stochastic pieces,

$$A_q = A_q^{\text{reg}} + A_q^{\text{turb}} + A_q^{\text{str}}. \quad (16)$$

Finally, the contribution of extragalactic magnetic fields (EGMFs) is negligible for the Galactic supernova distances relevant here. Rotation measure studies constrain EGMFs to be at most at the nG level on Mpc coherence scales, and often much smaller in low density environments [33]. Since a coherent contribution scales as $B^2 L^3$, even an optimistic estimate with $B_{\text{EGMF}} \lesssim 1$ nG over a path of a few $\times 10$ kpc is at least $\sim 10^{-4}$ below a typical Galactic contribution with $B_{\text{GMF}} \sim \mu\text{G}$ and $L_{\text{gal}} \sim 10$ kpc. For weaker voidlike extragalactic fields, the suppression is far stronger. We therefore neglect the EGMF contribution throughout.

C. From published ToF limits to millicharge constraints

The phenomenological input to our translation consists of published or projected supernova ToF constraints, usually quoted as upper limits on an effective neutrino mass for an assumed source distance. In the present framework, these results enter through the corresponding upper limit on the leading dispersion coefficient, A_{lim} , obtained from Eq. (5). The translated bound on the neutrino millicharge then follows from Eqs. (6) and (16), namely

$$|q_\nu| \leq \left[\frac{A_{\text{lim}}}{\mathcal{F}(L, \ell, b)} \right]^{1/2}, \quad (17)$$

where the denominator is defined by

$$\mathcal{F}(L, \ell, b) = \frac{L^3}{24c} B_{\text{eff}}^2 + \frac{L^2 \lambda_B^{\text{turb}}}{9c} (B_{\text{rms}}^{\text{turb}})^2 + \frac{L^2 \lambda_B^{\text{str}}}{6c} \mathcal{B}_{\text{str}}^2. \quad (18)$$

Here (ℓ, b) denote Galactic longitude and latitude, respectively. We refer to $\mathcal{F}(L, \ell, b)$ as the *magnetic delay kernel*, or simply *delay kernel* hereafter, and report the final result in terms of the millicharge fraction $\epsilon_\nu \equiv q_\nu/e$.

²Equivalently, $K(x, x')$ is the Green's function of the associated fixed-endpoint transverse-displacement problem; after rescaling to the unit interval, it is mathematically identical to the covariance kernel of a Brownian bridge. See Appendix A.

TABLE I. Published and projected supernova ToF inputs used in this work. The quoted mass limit m_{lim} , confidence level (C.L.), and assumed source distance L are taken from the cited references. The corresponding upper limit on the leading E^{-2} dispersion coefficient is obtained from Eq. (5). For DUNE, we list optimistic and conservative entries corresponding to the lower and upper endpoints of the mass sensitivity ranges quoted in Refs. [27].

Analysis (Ref.)	m_{lim} (eV)	CL	L	A_{lim} (s MeV ²)
SN1987A (model indep.) [22]	$\lesssim 30$	(order of mag.)	50 kpc	$\lesssim 2.32 \times 10^3$
SN1987A (model dep.) [23]	< 5.7	95%	50 kpc	$< 8.36 \times 10^1$
Galactic CCSN (SK) [24]	< 0.8	95%	10 kpc	$< 3.29 \times 10^{-1}$
Galactic CCSN (IceCube) [30]	< 0.14	95%	10 kpc	$< 1.01 \times 10^{-2}$
Galactic CCSN (DUNE, optimistic) [27]	< 0.9	95%	10 kpc	$< 4.17 \times 10^{-1}$
Galactic CCSN (DUNE, conservative) [27]	< 2.1	95%	10 kpc	< 2.27
Galactic CCSN (JUNO) [28]	< 0.39	95%	10 kpc	$< 7.82 \times 10^{-2}$

The remaining ingredient is therefore the set of published or projected ToF mass limits entering the translation. Supernova ToF analyses do not measure an absolute propagation time. Rather, they constrain energy dependent distortions of the observed burst time structure, encoded in the time and energy distribution of the detected neutrino signal. In practice, the unknown emission time origin is absorbed into one or more offset time nuisance parameters, so the sensitivity arises from relative timing information within the burst. This point is especially important for SN1987A, where the clocks of different detectors were not synchronized, but it also underlies modern forecasts for a future Galactic CCSNe.

The literature inputs used in this work span two broad categories. The first consists of *model-independent* bounds, which infer a conservative limit on the leading propagation-induced dispersion from coarse burst properties such as the observed duration and energy spread. The second consists of *model-dependent* analyses or sensitivity forecasts, in which the detected time and energy information are combined with an assumed emission model, detector response, and nuisance-parameter treatment. In practice, the numerical reach of the latter depends not only on the statistical framework adopted, but also on which temporal structures of the neutrino signal are effectively resolved and used in the analysis.

Table I summarizes the literature inputs adopted in this work by listing the quoted mass limit, the corresponding confidence level when available, the assumed source distance, and the inferred value of A_{lim} . Below we outline the most relevant assumptions behind these ToF inputs.

SN1987A model-independent [22]. SN1987A was a core-collapse supernova in the Large Magellanic Cloud, at a distance of approximately 50 kpc. Its neutrino burst was detected on February 23, 1987, by Kamiokande-II [34], IMB [35], and Baksan [36]. The detected events are usually interpreted as being dominated by electron anti-neutrinos, $\bar{\nu}_e$, observed through inverse beta decay. Using only coarse properties of the signal, such as its duration,

energy spread, and source distance, one obtains the order-of-magnitude model-independent bound $m_{\bar{\nu}_e} \lesssim 30$ eV [22].

SN1987A model-dependent [23]. The model-dependent SN1987A input is based on the Bayesian analysis of Loredano and Lamb, which uses the observed event times and energies together with parametrized models of the emitted $\bar{\nu}_e$ flux. In particular, for an emission model including both accretion and cooling components, they obtain a limit $m_{\bar{\nu}_e} < 5.7$ eV at 95% confidence level.

Galactic CCSN at Super-Kamiokande [24]. Pagliaroli *et al.* consider a parametrized model of the supernova neutrino emission and generate mock data under the hypothesis of massless neutrinos. In their model-dependent approach, the same class of emission models is then used to fit the pseudodata while allowing for a nonzero neutrino mass. For a Galactic CCSN at 10 kpc observed in Super-Kamiokande, primarily through inverse beta decay, they obtain a projected sensitivity $m_\nu < 0.8$ eV at 95% confidence level.

Galactic CCSN at IceCube [30]. Ellis *et al.* investigate the possibility of detecting fast time variations in the supernova neutrino light curve, such as those induced by SASI and other hydrodynamical instabilities, with IceCube. Using the luminosity curve from a multidimensional CCSN simulation, they analyze the expected event-rate modulation with a wavelet-based method and determine the neutrino mass above which the shortest observable time structures would be washed out. If such fast hydrodynamical features are present and observable, they estimate a projected sensitivity $m_\nu < 0.14$ eV at 95% confidence level for a Galactic CCSN at 10 kpc.

Galactic CCSN at DUNE [27]. Pompa *et al.* consider the neutronization-burst luminosity profile obtained from CCSN simulations and compute the corresponding event rate at DUNE, whose sensitivity in this phase is mainly through ν_e -argon interactions. The event rate is used both to generate mock data and to construct a model-dependent unbinned likelihood, which is then fitted allowing for a nonzero neutrino mass. For a CCSN at 10 kpc, they quote

projected sensitivities in the approximate range $m_\nu \lesssim 0.9\text{--}2.1$ eV at 95% confidence level, depending on the assumed flavor-conversion scenario and mass ordering.

Galactic CCSN at JUNO [28]. Parker and Wurm study the sensitivity to neutrino mass from the abrupt termination of the neutrino signal associated with black-hole formation, focusing on JUNO. They generate simulated event samples including a sharp signal cutoff and use the detector energy resolution to test the energy-dependent delay expected from a nonzero neutrino mass. For a CCSN at 10 kpc, they estimate a projected sensitivity $m_\nu < 0.39$ eV at 95% confidence level at JUNO, with stronger reach possible for larger future detectors such as THEIA-100.

III. RESULTS

With the translation framework established in Sec. II, published and projected supernova ToF constraints can now be recast into bounds on the neutrino millicharge. The results depend on two ingredients: the Galactic magnetic field kernel, which controls the propagation induced delay for a given line-of-sight, and the experimental sensitivity to the common E_ν^{-2} dispersion coefficient. We therefore begin by characterizing the magnetic kernel and its directional dependence and then present the translated limits.

A. Galactic field kernel and line-of-sight dependence

The conversion from A_{lim} to a bound on ϵ_ν is controlled by the effective magnetic kernel $\mathcal{F}(L, \ell, b)$, defined in Eq. (18). This kernel encodes the cumulative impact of the GMF on the propagation of a millicharged neutrino from the supernova source to the Solar position. The translated limits therefore depend not only on the overall field strength, but also on the direction dependent path through

the GMF and on the relative importance of the regular and stochastic contributions entering the kernel.

Figure 1 illustrates this dependence in two complementary ways. The left panel displays the regular JF12 GMF configuration in the Galactic plane, together with representative lines of sight. The right panel shows the corresponding behavior of the $\mathcal{F}(L)$ as a function of path length, including the propagated uncertainty associated with the JF12 parameters. These curves make clear that the translation from ToF sensitivity to millicharge reach depends strongly on direction: some sightlines accumulate a substantially larger delay kernel and therefore yield stronger bounds on ϵ_ν , whereas others are comparatively weak and lead to less restrictive constraints. The SN1987A direction is also shown for direct comparison.

In practice, the delay kernel is typically enhanced for sightlines that remain close to the Galactic disk, since such trajectories sample the regular large scale GMF over a longer fraction of the propagation path. Even within the plane, however, the kernel is not uniform: the examples shown in Fig. 1 indicate that changing the Galactic longitude can modify $\mathcal{F}(L, \ell, b)$ by a factor of a few, while the direction toward the Galactic center ($\ell = 0^\circ$, $b = 0^\circ$) can yield a substantially larger kernel, approaching an order of magnitude enhancement relative to less favorable in-plane directions at large distances.

A caveat concerns directions approaching the Galactic center. In the original JF12 implementation, the regular field is manually set to zero in the innermost region ($r < 1$ kpc), so the model is not strictly divergence free there. A solenoidal improvement of JF12 has been developed in Ref. [37], where the regular disk and X-field components are modified to satisfy $\nabla \cdot \mathbf{B} = 0$ more consistently. In addition, dedicated magnetic field models exist for the central molecular zone (CMZ), i.e., the inner

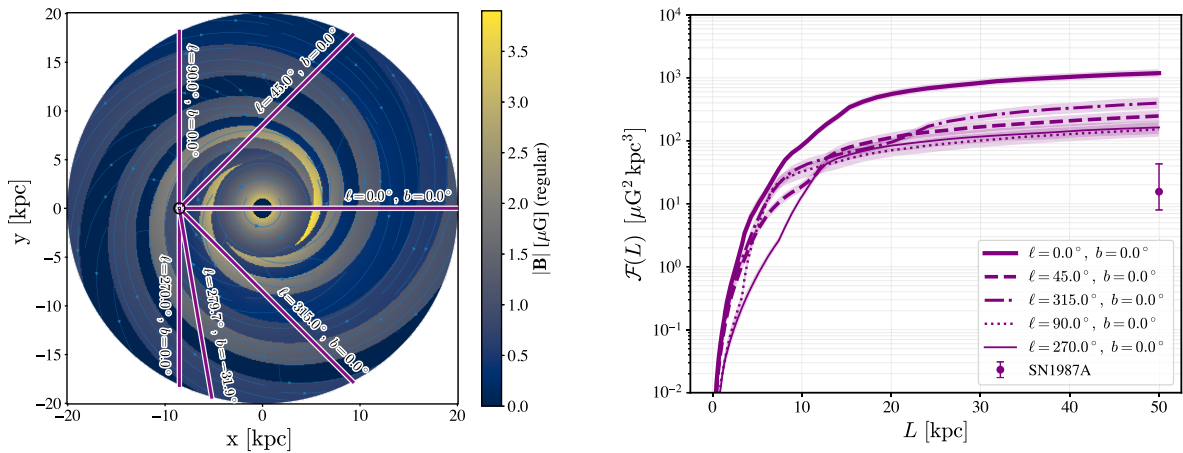


FIG. 1. (Left) Galactic plane map of the regular JF12 magnetic field model in Galactocentric coordinates, with the selected lines of sight used for the $\mathcal{F}$ curves shown in the right panel. The $\odot$ illustrates the Earth's position. (Right) Magnetic kernel $\mathcal{F}(L, \ell, b)$ along the lines of sight indicated in the left panel. Shaded regions show the propagated 1σ band from the JF12 parameter uncertainties. The marker corresponds to the SN1987A direction ($\ell = 279.7^\circ$, $b = -31.9^\circ$) evaluated at the source distance, 50 kpc.

$\lesssim 200$ pc of the Galaxy, where the field structure is known to differ from the large scale disk and halo components [38]. In this work, however, we adopt the original JF12 model throughout in order to retain a single, conservative baseline GMF model throughout the analysis. In our context, these considerations mainly affect the interpretation of directions very close to $(\ell, b) = (0^\circ, 0^\circ)$. For such lines of sight and for the distance $L = 10$ kpc relevant to our translated Galactic CCSN benchmarks, using a solenoidal JF12 realization enhances the field kernel by $\sim 60\%$, corresponding to a strengthening of the translated millicharge bound by $\sim 20\%$. Considering a CMZ scale component is expected to have a smaller impact on the quantities of interest here, since the spatial extent of the central region is small compared with the Galactic propagation length entering the kernel.

A complementary view is provided by the decomposition shown in Figure 2 for the benchmark direction $(\ell, b) = (45^\circ, 0^\circ)$. This example also reflects the broader trend found in our scan: the striated contribution is consistently subdominant, remaining about one to two orders of magnitude below the regular and turbulent terms over the full distance range considered. By contrast, the regular and turbulent components are both important for the total kernel: although the regular quantity $B_{\text{eff}}^2 L^3$ is systematically larger than the turbulent combination $B_{\text{rms}}^2 \lambda_B L^2$, their different prefactors in the delay kernel, $1/24$ and $1/9$, make their final contributions to $\mathcal{F}$ comparable in magnitude.

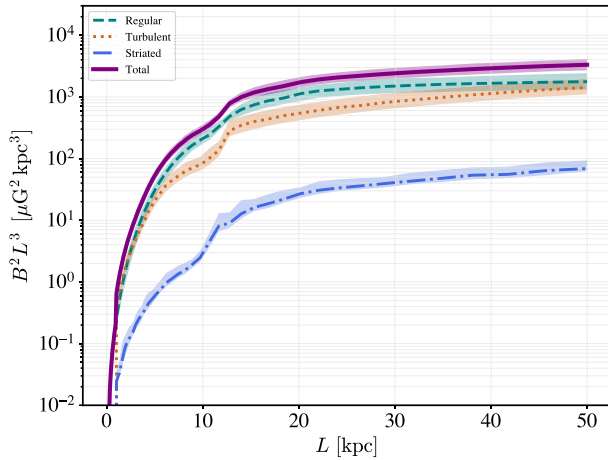


FIG. 2. Decomposition of the magnetic kernel building blocks for the benchmark direction $(\ell, b) = (45^\circ, 0^\circ)$ as a function of source distance. We show the regular contribution through $B_{\text{eff}}^2 L^3$ and the stochastic contributions through $B_{\text{rms}}^2 \lambda_B L^2$ for the turbulent and striated components. The striated term is consistently subdominant, while the regular and turbulent terms are both relevant for the total kernel. Although the regular quantity is systematically larger, the different prefactors entering Eq. (18) make the regular and turbulent contributions to the final kernel comparable in magnitude.

The SN1987A line of sight is qualitatively different from typical Galactic-plane directions. Because the SN1987A lies significantly off the Galactic plane ($b = -31.9^\circ$), the neutrino trajectory samples a smaller portion of the strong large-scale GMF, while the rest of the propagation occurs predominantly outside the Milky Way, where the magnetic field is expected to be much weaker. As a result, the associated delay kernel is suppressed by more than an order of magnitude relative to directions close to the Galactic plane, as seen in the right panel of Fig. 1. This suppression is accompanied by a comparatively larger relative uncertainty band. The reason is that, for such an off-plane trajectory, the kernel receives a larger fraction of its contribution from the toroidal halo and poloidal X-field components, rather than from the disk field. The disk field is more directly anchored by the stronger rotation measure and synchrotron signal near the Galactic plane, while the out of plane components are comparatively more sensitive to the global modeling assumptions entering the fit. As a result, the uncertainty on $\mathcal{F}$ is larger for off-plane directions than for typical in-plane lines of sights.

B. Limits on the neutrino millicharge

We summarize the translated limits in two complementary ways. First, we quote a benchmark result for the in-plane direction $(\ell, b) = (45^\circ, 0^\circ)$, together with the associated 1σ uncertainty obtained by propagating the uncertainty on the full delay kernel $\mathcal{F}$. We adopt this line of sight because it is favorable yet nonextremal, and it avoids the additional modeling ambiguity associated with the innermost Galactic center region. Second, we quantify the directional spread of the central prediction by scanning a grid over $-5^\circ < b < 5^\circ$ and $0^\circ < \ell < 360^\circ$ at fixed $L = 10$ kpc. This restricted scan is intended as an illustration of how the GMF translation varies across near-plane line-of-sights relevant to Galactic CCSNe. Extending the scan to the full sky would mainly broaden the quoted directional interval by introducing additional off-plane sightlines with smaller magnetic kernels and hence weaker translated bounds, while leaving the favorable near-plane end essentially unchanged. From this restricted sky scan we extract the percentile bounds $\epsilon_{\nu, p5}$ and $\epsilon_{\nu, p95}$, which enclose 90% of the sampled directions.

Thus, we probe two different aspects of the problem: the benchmark result characterizes the propagated field model uncertainty for one representative in-plane sightline, while the percentile interval captures the directional variation of the central prediction across the near-plane region.

For completeness, we also identify the strongest translated bound found within our scanned grid. This value should be interpreted with caution, however, since it depends on the adopted GMF model and is influenced by directions approaching the poorly constrained Galactic center region. We therefore use it only as an optimistic directional extreme, rather than as the benchmark result.

TABLE II. Translated limits on the (anti)neutrino millicharge obtained by combining the ToF inputs of Table I with the Galactic magnetic field kernel in the JF12 framework. We report the benchmark bound for the reference in-plane direction $(\ell, b) = (45^\circ, 0^\circ)$ together with its propagated 1σ GMF uncertainty, as well as the directional spread of the central prediction over the scanned grid $-5^\circ < b < 5^\circ, 0^\circ < \ell < 360^\circ$, summarized by the percentile interval $[\epsilon_{\nu,p5}, \epsilon_{\nu,p95}]$. For completeness, we also quote the strongest translated bound found in the scanned grid; this value should be interpreted as an optimistic directional extreme rather than a benchmark result.

Analysis (Ref.)	Benchmark $ \epsilon_\nu /10^{-20}$	1σ GMF	Directional spread $[\epsilon_{\nu,p5}, \epsilon_{\nu,p95}]/10^{-20}$	Strongest grid bound $ \epsilon_\nu /10^{-20}$
SN1987A (model-indep.) [22]	4138.5	$+1663$ -1657	...	...
SN1987A (model-dep.) [23]	785.6	$+315.9$ -314.5	...	...
Galactic CCSN (SK) [24]	44.5	$+4.0$ -3.7	[20.2, 67.3]	17.1
Galactic CCSN (IceCube) [30]	7.8	$+0.7$ -0.6	[3.54, 11.8]	3.0
Galactic CCSN (DUNE, optimistic) [27]	50.1	$+4.5$ -4.1	[22.8, 75.8]	19.3
Galactic CCSN (DUNE, conservative) [27]	116.8	$+10.5$ -9.7	[53.2, 176.9]	44.9
Galactic CCSN (JUNO) [28]	21.6	$+1.9$ -1.8	[9.8, 32.8]	8.3

Table II summarizes the translated millicharge limits corresponding to the ToF inputs of Table I.

A few remarks are in order. First, for fixed source distance, the spread of translated bounds across the scanned grid is controlled entirely by the distribution of the delay kernel $\mathcal{F}(L, \ell, b)$, while the ToF input fixes only the overall normalization. Since $|\epsilon_\nu|_{\text{lim}} \propto \mathcal{F}^{-1/2}$, the directional spread of the translated limits corresponds to the square root of the inverse kernel spread; in our scanned grid, this amounts to a factor of about ~ 3 in $|\epsilon_\nu|_{\text{lim}}$. Numerically, for the projected Galactic burst sensitivities considered here, this astrophysical spread is comparable to the differences among nearby detector forecasts. Second, the translated SN1987A bounds remain substantially weaker than the Galactic forecasts. This reflects both the limited statistics of the SN1987A signal and the fact that its off-plane direction samples a much smaller delay kernel than a typical near-plane CCSN.

For DUNE, the literature quotes a range of projected mass sensitivities rather than a unique value. We therefore retain both optimistic and conservative entries corresponding to the endpoints of the quoted range, rather than compressing them into a single representative number. For future Galactic CCSNe observations, the most favorable translated bounds arise when strong ToF sensitivity is combined with a favorable in-plane line-of-sight; in such cases, the translated reach can enter the low- $10^{-19}e$ regime and, for the most favorable directions in our scan, approach the $10^{-20}e$ level.

C. Variation with the GMF models

The limits derived in this Section depend on the adopted GMF model. To quantify this dependence, we repeat the calculation of the regular field contribution using the recent Unger-Farrar regular GMF models, hereafter UF23 [39].

As in JF12, the UF23 models constrain the coherent GMF using the Faraday rotation measures of extragalactic radio sources and the polarized synchrotron intensity of Galactic cosmic ray electrons, however, employing new divergence-free parametrizations of the large-scale field and updated full-sky rotation measure and polarized intensity maps. The suite also explores different assumptions about the thermal electron and cosmic ray electron distributions entering the rotation measure and synchrotron predictions. Based on these assumptions eight benchmark models, *base*, *neCL*, *expX*, *spur*, *cre10*, *synCG*, *twistX*, and *nebCor*, were selected to span the present modeling uncertainties in the regular GMF.

For each UF23 benchmark model, we compute the same quantity used in the baseline analysis, $B_{\text{eff}}^2 L^3$, along the line of sight. The result is shown in Fig. 3 for the benchmark direction $(\ell, b) = (45^\circ, 0^\circ)$, together with the corresponding JF12 regular component and its phenomenological propagated 1σ band described in Appendix B. For the UF23 models, the shaded bands are obtained by propagating the model-specific covariance matrices supplied with the public UF23 implementation through the full $B_{\text{eff}}^2 L^3$ calculation.³ The lines show the best-fit prediction of each model.

Several features are apparent from Fig. 3. First, the spread among the UF23 benchmark models is larger than the within-model covariance band for a fixed UF23 model. This indicates that, for the present observable, the dominant regular field uncertainty is associated with the choice of global GMF reconstruction rather than with the local covariance of the parameters within a given reconstruction. Second, the UF23/JF12 ratio depends on both distance and

³<https://zenodo.org/records/11321212>, also see Appendix C in [39].

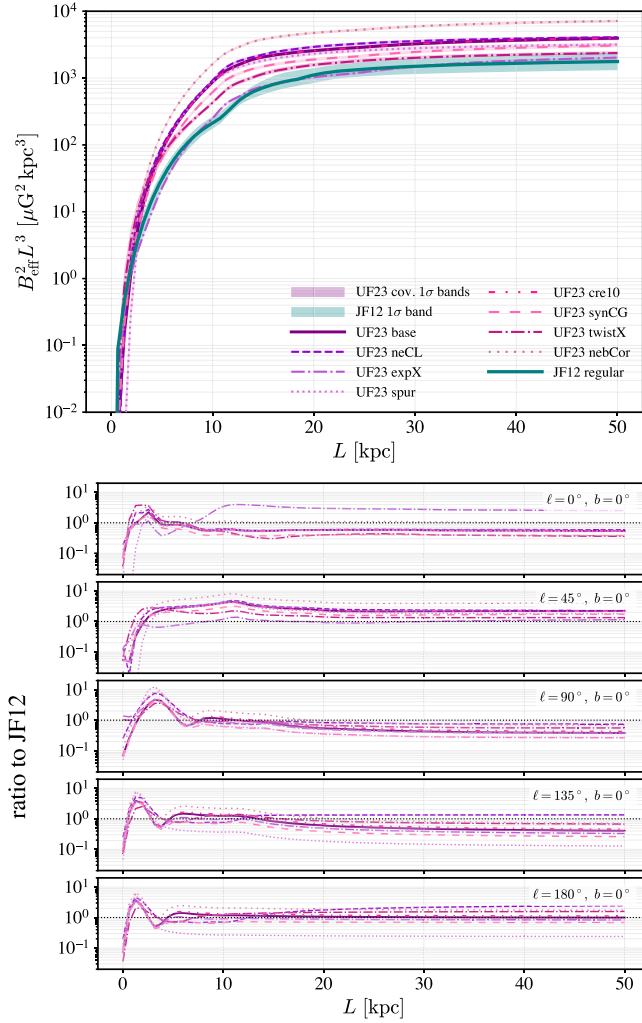


FIG. 3. (Top) The quantity $B_{\text{eff}}^2 L^3$ for the benchmark direction $(\ell, b) = (45^\circ, 0^\circ)$. The teal curve shows the JF12 reference baseline, together with its phenomenological propagated 1σ band. The purple/pink curves show the eight UF23 benchmark coherent-field models. The UF23 shaded regions show the propagated 1σ bands obtained from the model-specific covariance matrices supplied with the public UF23 implementation. In all cases, the central curve corresponds to the best-fit prediction. (Bottom) Ratio of $B_{\text{eff}}^2 L^3$ obtained with the eight UF23 benchmark models to the corresponding JF12 result. The panels show directions in the Galactic plane as in Fig. 1. The same colors and line styles as in top panel are used for the UF23 models.

direction. For example, for the benchmark direction $(\ell, b) = (45^\circ, 0^\circ)$ and $L = 10$ kpc, some UF23 models give $\frac{(B_{\text{eff}}^2 L^3)_{\text{UF23}}}{(B_{\text{eff}}^2 L^3)_{\text{JF12}}} \simeq 8$. This corresponds to a stronger limit by a factor $\lesssim 2.8$ on the ϵ_ν . More generally, the regular-field contribution to $B_{\text{eff}}^2 L^3$, and therefore to the magnetic delay kernel, can be either enhanced or reduced, by a factor of $\sim \text{few}$, relative to the JF12 reference, depending on the assumed coherent GMF model and on the Galactic line-of-sight. These variations lead to more stringent or weaker bounds, respectively. The directional comparison in the

bottom panel of Fig. 3 illustrates this model dependence more directly.

We keep JF12 as the baseline GMF model for the full analysis because it provides the regular, striated, and turbulent components used in our treatment, whereas UF23 updates only the regular field and its parameter covariance. The UF23 comparison therefore quantifies the model dependence of the regular field contribution alone.

IV. COMPARISON WITH THE EXISTING BOUNDS

The translated bounds derived above may be viewed in the broader landscape of existing constraints on neutrino millicharge.

Direct bounds on neutrino millicharge come from scattering measurements, where a nonzero charge would modify the low-recoil event spectrum. For reactor neutrinos, the strongest limits reach the $\sim 10^{-12}e$ level [16,40,41]. Accelerator-based experiments probe other flavors, with CE ν NS/COHERENT analyses constraining the muon-neutrino millicharge at the $\sim 10^{-10}e$ level [20,42]. More recently, solar-neutrino scattering in xenon-based dark-matter detectors has pushed this class substantially further, yielding constraints at the $\sim 10^{-13}e$ level [43], depending on the flavor assumptions and treatment of atomic effects.

A second class of bounds comes from stellar-cooling arguments. There, the relevant effect is the enhancement of photon-mediated plasma processes, most notably plasmon decay to $\nu\bar{\nu}$, which would increase the stellar energy-loss rate. Such considerations typically lead to limits at the $\sim 10^{-14}e$ level, with some dependence on the stellar environment and adopted cooling criterion [8,14,44].

The strongest commonly quoted benchmark is instead an indirect constraint, obtained from laboratory tests of the electrical neutrality of matter together with bounds on the neutron charge and the assumption of charge conservation in β decay. This implies a neutrino-charge constraint at the level of $|q_\nu| \lesssim \text{few} \times 10^{-21}e$ [8,14].⁴

Moreover, an astrophysical bound is provided by the “neutrino star turning” mechanism in rotating magnetized neutron-star matter, which yields a constraint of order $|q_\nu| \lesssim 10^{-19}e$ from the requirement that escaping millicharged neutrinos does not induce an excessive change in the observed pulsar rotation rate [46]. That result is derived in a specific dense matter setting namely neutrino propagation in rotating magnetized neutron-star matter, where the relevant observable is the torque exerted on the stellar medium by the escaping neutrino flux.

⁴A recent reassessment has argued that the much stronger $10^{-35}e$ -level bound sometimes quoted in the literature is based on a controversial cosmological argument and should not be regarded as comparably robust. In that sense, the laboratory neutrality-based bound remains the relevant benchmark for comparison with direct or phenomenological probes [45].

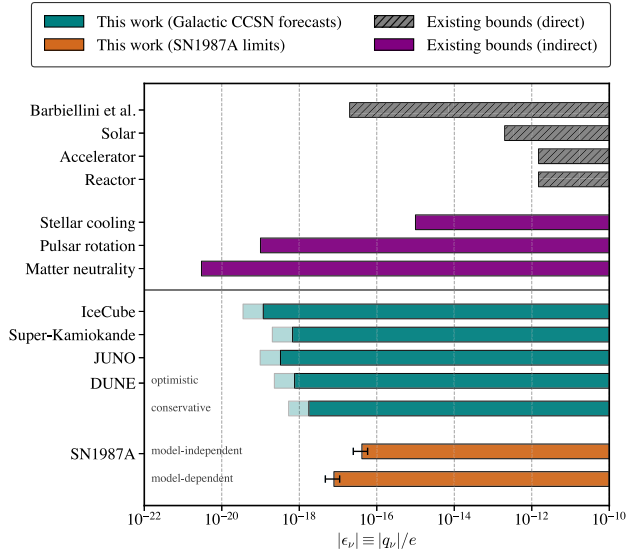


FIG. 4. Comparison of neutrino-millicharge bounds from different probes, with the excluded region lying to the right. Lower panel shows the limits derived in this work: SN1987A constraints (orange) and projected sensitivities for a future Galactic CCSNe (green). For the Galactic forecasts, the lighter extension at the end of each bar indicates the variation across the percentile interval reported in Table II; for SN1987A, the error bars represent the propagated GMF systematic uncertainty. Upper panel shows the existing bounds in the literature. Hatched gray bars denote direct probes, including the earlier SN1987A ToF estimate of [31] and scattering constraints from reactor, accelerator, and solar neutrino measurements [17,40,41,43]. Purple bars denote indirect or model-dependent bounds, including the neutrality of matter [14], the pulsar rotation constraint [46], and stellar cooling limits [14,47].

In this context, the supernova limits derived in this work probe neutrino millicharge through a qualitatively distinct observable: energy dependent distortions in the time profile of a transient neutrino signal after astrophysical distance propagation through the adopted GMF model. In this sense, they are complementary to laboratory scattering, stellar-cooling, neutrality-based, and more specialized astrophysical arguments. Unlike the pulsar-rotation bound discussed above, the present translation is formulated directly in terms of the effective millicharge governing propagation through the GMF, and is therefore less tied to the detailed microphysics of a particular dense matter environment. Figure 4 summarizes these bounds together with the translated SN1987A limits and the projected Galactic-core-collapse-supernova sensitivities derived in this work.

V. DISCUSSION AND CONCLUSION

A few additional remarks clarify the scope of the recast and the interpretation of the translated bounds:

- (i) the Galactic forecasts quoted in Table I are benchmark sensitivities evaluated at $L = 10$ kpc, while

the SN1987A entries correspond to $L \simeq 50$ kpc as adopted in the original analyses. For a source at a different distance, the translated charge bound changes through two distinct effects: the delay kernel $\mathcal{F}(L, \ell, b)$ changes with the propagation length and direction, while the underlying ToF sensitivity A_{lim} changes because both the event statistics and the resolvability of the relevant temporal structures depend on distance in a detector- and analysis-specific way. The former effect can be recomputed directly within our framework and, as illustrated in Fig. 1, generally enhances the propagation kernel with increasing distance. For the representative in-plane sightlines, we find $\mathcal{F}(25 \text{ kpc})/\mathcal{F}(10 \text{ kpc}) \sim 2-9$, which at fixed A_{lim} would strengthen the translated millicharge bound by a factor $\sqrt{\mathcal{F}(25)/\mathcal{F}(10)} \sim 1.4-3$. The detector-side dependence, however, is not captured by a universal distance rescaling. As one explicit example, the DUNE analysis of Ref. [27] finds that the mass sensitivity worsens by about a factor of ~ 2 as the source distance increases from 5 to 25 kpc. Combining this with the propagation-side enhancement above suggests that, for such a case, the translated charge reach may improve only modestly with distance, rather than following a simple monotonic scaling. More generally, precise distance-dependent millicharge limits require the corresponding distance-dependent ToF analysis for each experiment.

- (ii) In the parameter region relevant here, the net magnetic deflection remains extremely small, so the small-angle approximation underlying the magnetic-delay derivation is well satisfied. In this regime, the delay is dominated by the geometric propagation length increase, while the associated angular shift is far too small to be resolved by MeV supernova neutrino detectors.
- (iii) The translation developed in this work is most straightforward in the null-delay regime, where the observed ToF data are interpreted as setting an upper bound on a common leading E_ν^{-2} dispersion coefficient. In that case, the standard mass-induced delay and the millicharge-induced magnetic delay are degenerate at the level of their leading energy dependence, and the allowed timing budget may be reinterpreted as an effective millicharge contribution. If the standard mass-induced delay is itself non-negligible at the relevant level of sensitivity, however, the translation to q_ν is no longer independent and should instead be treated in a joint analysis.

Neutrino oscillation data establish nonzero mass-squared splittings and therefore imply a standard mass-induced contribution to the propagation delay. Even in the minimal-mass scenario, in which the

lightest neutrino is approximately massless, the largest mass eigenvalue is of order $\sqrt{|\Delta m_{3\ell}^2|} \simeq 50$ meV [48]. The resulting timing distortion depends on the mass-eigenstate composition of the detected signal and hence on flavor conversion and detector response. Nevertheless, this mass scale is below the effective-mass sensitivities adopted in Table I, so its contribution is subdominant for the present coefficient-level recast. For the most aggressive sensitivity, $m_{\text{lim}} = 0.14$ eV, a 50 meV mass corresponds to at most a fraction $(0.05/0.14)^2 \simeq 0.13$ of the limiting E_ν^{-2} dispersion coefficient. Thus, in such a minimal-mass spectrum, neglecting the standard mass contribution has little effect on most of the translated limits. For neutrino masses realizations close to current upper limits, such as those from cosmology, $\sum_i m_i < 0.12$ eV from *Planck* [49], or from direct kinematic measurements, $m_\nu < 0.45$ eV from KATRIN [50], the standard mass-induced delay may contribute at a non-negligible level to the timing budget, and a joint mass-charge analysis would be required.

- (iv) Directional information provides, in principle, a way to separate the mass and charge effects in a future positive observation, because the mass-induced delay depends on the source distance and neutrino mass spectrum, whereas the millicharge-induced contribution also depends on the source direction through the magnetic-delay kernel $\mathcal{F}(L, \ell, b)$. For a single supernova, the measured direction selects the relevant Galactic magnetic-field kernel but does not by itself remove the leading E_ν^{-2} degeneracy. However, a set of supernova observations along different Galactic lines of sight would test whether the inferred dispersion follows a universal mass-induced coefficient or instead correlates with the line-of-sight-dependent magnetic kernel. In practice, such a separation would require sufficiently precise timing and spectral information, together with a reliable description of the Galactic magnetic field. The rarity of nearby Galactic CCSNe makes this possibility challenging, but it illustrates how the different directional dependence of the two effects could be used in principle.
- (v) In the flavor-universal millicharge scenario considered here, the magnetic contribution to the propagation delay is the same for all neutrino flavors at fixed energy and depends only on the common charge magnitude $|q_\nu|$. Flavor conversion therefore does not modify the magnetic delay kernel itself, but it can change the time- and energy-dependent composition of the signal observed by a given detector. Since we do not perform a new detector-level analysis, the translated limits inherit the supernova-emission, flavor-conversion, and detector-response assumptions of the

underlying ToF studies listed in Table I. A dedicated analysis of an observed burst would require these effects to be included jointly with the mass- and millicharge-induced delays, but such an analysis is beyond the scope of the present coefficient-level recast.

- (vi) A further subtlety is that a supernova detector does not, in general, observe a single mass eigenstate, but rather a signal built from an incoherent mixture of neutrino mass eigenstates. Accordingly, a ToF analysis admits a direct reinterpretation in terms of a single millicharge bound only when it constrains a single effective leading E_ν^{-2} dispersion coefficient for the detected signal. By contrast, once the analysis becomes sensitive to the individual neutrino mass eigenstates, there is no longer, in general, a unique single coefficient to translate. In that regime, the mapping to neutrino millicharge becomes model dependent, because one must specify how the electric charge interaction is realized in the mass basis. A direct eigenstate-by-eigenstate translation is straightforward only under additional assumptions, such as a diagonal charge assignment for the propagating mass eigenstates, while a more general treatment would require a dedicated analysis and is beyond the scope of this work. This issue is relevant, for example, to the JUNO forecast of Ref. [29], which is formulated in terms of sensitivity to the individual neutrino mass eigenstates rather than to a single effective dispersion coefficient; accordingly, we do not include such results among the direct inputs to our translated bounds.

Within this scope, the translated millicharge bounds inherit the assumptions of the underlying ToF analyses, including the adopted supernova emission model, flavor-conversion scenario, detector thresholds and resolutions, nuisance-parameter treatment, and the temporal structures that remain experimentally accessible. They also depend explicitly on the adopted GMF model through the magnetic-delay kernel $\mathcal{F}(L, \ell, b)$. We emphasize that the sensitivities quoted above are conditional on the magnetic-delay kernel for a given line of sight and on the underlying GMF model. They should therefore be interpreted as model-dependent, line-of-sight-dependent sensitivities rather than model-independent limits on q_ν .

The analysis of Ref. [31] established the essential time-of-flight idea underlying this class of probes. The present framework recasts that idea in the common A_{ToF} language and replaces the original uniform field estimate with a line-of-sight dependent translation based on the adopted GMF model. In this sense, SN1987A serves both as a historical benchmark and as a genuine data based constraint, while the strongest prospective reach of the method is provided by a future high statistics Galactic CCSNe. Among existing bounds, the most demanding benchmark remains the

neutrality of matter limit: surpassing it would require sensitivity an exceptionally small allowed E_ν^{-2} dispersion coefficients, and hence to very fine temporal structure in the supernova signal, whose physical presence and experimental resolvability both remain uncertain.

Subject to these qualifications, the framework developed here provides a map from supernova ToF sensitivity to neutrino millicharge sensitivity, complementary to the existing laboratory, stellar, and indirect bounds.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

APPENDIX A: DERIVATION OF THE MAGNETIC-DELAY KERNEL

In this appendix, we derive the line-of-sight expression used in Eq. (8) for the small-angle time delay of a millicharged neutrino propagating through a prescribed transverse magnetic field. The derivation is carried out in the small-angle deflection limit.

Consider a neutrino propagating from the source at $x = 0$ to the observer at $x = L$. In the absence of magnetic deflection, the trajectory is a straight line along the x axis. In the small-angle regime, the actual trajectory may be written as

$$\mathbf{r}(x) = x\hat{\mathbf{x}} + \mathbf{y}(x), \quad (\text{A1})$$

where $\mathbf{y}(x)$ is the two-dimensional transverse displacement, with

$$|\mathbf{y}'(x)| \ll 1. \quad (\text{A2})$$

The source and observer positions are held fixed, so the transverse displacement satisfies Dirichlet boundary conditions,

$$\mathbf{y}(0) = \mathbf{y}(L) = 0. \quad (\text{A3})$$

The physical path length is

$$s = \int_0^L dx \sqrt{1 + |\mathbf{y}'(x)|^2}. \quad (\text{A4})$$

Expanding to leading nontrivial order in the small-angle approximation gives

$$s \simeq L + \frac{1}{2} \int_0^L dx |\mathbf{y}'(x)|^2. \quad (\text{A5})$$

Therefore the geometric arrival time delay relative to the undeflected straight path is

$$\Delta t \simeq \frac{s - L}{c} = \frac{1}{2c} \int_0^L dx |\mathbf{y}'(x)|^2. \quad (\text{A6})$$

Equation (A6) is the standard small-angle expression: the delay is controlled by the integrated squared transverse slope of the trajectory.

For an ultrarelativistic particle of charge q_ν and energy E , the Lorentz force induces a transverse acceleration governed by

$$\frac{d\hat{\mathbf{n}}}{ds} \simeq \frac{q_\nu c}{E} \hat{\mathbf{n}} \times \mathbf{B}, \quad (\text{A7})$$

where $\hat{\mathbf{n}}$ is the local propagation direction. In the small angle limit, $\hat{\mathbf{n}} \simeq \hat{\mathbf{x}}$, $ds \simeq dx$, so only the magnetic field component transverse to the unperturbed line of sight contributes. The transverse equation of motion may therefore be written as

$$\mathbf{y}''(x) = \frac{q_\nu}{E} \hat{\mathbf{x}} \times \mathbf{B}_\perp(x). \quad (\text{A8})$$

Since $\hat{\mathbf{x}} \times$ act as a fixed orthogonal rotation in the transverse plane, it preserves the norms and inner products and therefore does not affect the final quadratic delay formula.

To solve Eq. (A8) with the boundary conditions in Eq. (A3), we introduce the Green's function $G(x, x')$ of the one-dimensional operator $-d^2/dx^2$ on the interval $[0, L]$,

$$-\frac{d^2}{dx^2} G(x, x') = \delta(x - x'), \quad G(0, x') = G(L, x') = 0. \quad (\text{A9})$$

The solution is

$$G(x, x') = \frac{1}{L} \begin{cases} x(L - x'), & x < x', \\ x'(L - x), & x > x'. \end{cases} \quad (\text{A10})$$

Equivalently,

$$G(x, x') = \min(x, x') - \frac{xx'}{L}. \quad (\text{A11})$$

We then have

$$\mathbf{y}(x) = \frac{q_\nu}{E} \int_0^L dx' G(x, x') \mathbf{B}_\perp(x'). \quad (\text{A12})$$

Differentiating with respect to x gives

$$\mathbf{y}'(x) = \frac{q_\nu}{E} \int_0^L dx' \partial_x G(x, x') \mathbf{B}_\perp(x'). \quad (\text{A13})$$

Substituting Eq. (A13) into Eq. (A6), we obtain

$$\Delta t = \frac{1}{2c} \left(\frac{q_\nu}{E} \right)^2 \int_0^L dx \int_0^L dx' \int_0^L dx'' \partial_x G(x, x') \partial_x G(x, x'') \times \mathbf{B}_\perp(x') \cdot \mathbf{B}_\perp(x''). \quad (\text{A14})$$

Using the identity

$$\int_0^L dx \partial_x G(x, x') \partial_x G(x, x'') = G(x', x''), \quad (\text{A15})$$

which follows by integrating by parts and using Eq. (A9) together with the Dirichlet boundary conditions, Eq. (A14) reduces to

$$\Delta t = \frac{1}{2c} \left(\frac{q_\nu}{E} \right)^2 \int_0^L dx' \int_0^L dx'' \mathbf{B}_\perp(x') \cdot \mathbf{B}_\perp(x'') G(x', x''). \quad (\text{A16})$$

Renaming the dummy variables and defining

$$K(x, x') \equiv G(x, x') = \min(x, x') - \frac{xx'}{L}, \quad (\text{A17})$$

we obtain

$$\Delta t_q^{\text{reg}}(E) = \frac{1}{2c} \left(\frac{q_\nu}{E} \right)^2 \int_0^L dx \int_0^L dx' \mathbf{B}_\perp(x) \cdot \mathbf{B}_\perp(x') K(x, x'), \quad (\text{A18})$$

which is Eq. (8) of the main text.

The kernel

$$K(x, x') = \min(x, x') - \frac{xx'}{L} \quad (\text{A19})$$

is the Green's function of the one-dimensional Dirichlet Laplacian on the interval $[0, L]$. Equivalently, after

rescaling to the unit interval, it is also identical to the covariance kernel of a Brownian bridge. In the present context, however, its role is purely geometric: it weights the correlated transverse field sampled along the trajectory under fixed source and observer endpoints.

As a simple check, consider a constant transverse field $\mathbf{B}_\perp(x) = \mathbf{B}_0$. Then

$$\int_0^L dx \int_0^L dx' K(x, x') = \frac{L^3}{12}, \quad (\text{A20})$$

so that

$$\Delta t_q^{\text{reg}}(E) = \frac{1}{2c} \left(\frac{q_\nu}{E} \right)^2 B_0^2 \frac{L^3}{12} = \frac{L^3}{24c} \left(\frac{q_\nu B_0}{E} \right)^2. \quad (\text{A21})$$

Thus $B_{\text{eff}} = B_0$, and the general result reduces to the familiar small-angle expression

$$\Delta t \sim \frac{L\theta^2}{4c}, \quad \theta \sim \frac{q_\nu B_0 L}{E}, \quad (\text{A22})$$

up to the expected order-unity geometric factor.

The same kernel formulation also yields the ensemble-averaged delay for a stochastic transverse magnetic field. Let $\mathbf{B}_{\text{stoch},\perp}(x)$ denote the transverse component of a stationary, zero-mean stochastic magnetic field sampled along the line of sight, and define its two-point correlator by

$$C_\perp(s) \equiv \langle \mathbf{B}_{\text{stoch},\perp}(x) \cdot \mathbf{B}_{\text{stoch},\perp}(x+s) \rangle. \quad (\text{A23})$$

Averaging the kernel expression over realizations gives

$$\langle \Delta t \rangle = \frac{1}{2c} \left(\frac{q_\nu}{E} \right)^2 \int_0^L dx \int_0^L dx' C_\perp(|x - x'|) K(x, x'). \quad (\text{A24})$$

Using the symmetry of the integrand, this may be rewritten as

$$\begin{aligned} & \int_0^L dx \int_0^L dx' C_\perp(|x - x'|) K(x, x') \\ &= 2 \int_0^L ds C_\perp(s) \int_0^{L-s} dx K(x, x+s). \end{aligned} \quad (\text{A25})$$

Since

$$K(x, x+s) = x - \frac{x(x+s)}{L} = \frac{x(L-s-x)}{L}, \quad (\text{A26})$$

the inner integral is

$$2 \int_0^{L-s} dx K(x, x+s) = \frac{(L-s)^3}{3L}. \quad (\text{A27})$$

Equation (A24) therefore becomes

$$\langle \Delta t \rangle = \frac{1}{6cL} \left(\frac{q_\nu}{E} \right)^2 \int_0^L ds (L-s)^3 C_\perp(s). \quad (\text{A28})$$

If the propagation distance is much larger than the correlation length, $L \gg \lambda_B$, only separations $s \lesssim \lambda_B \ll L$ contribute appreciably, and one may approximate $(L-s)^3/L \simeq L^2$. This yields

$$\langle \Delta t \rangle \simeq \frac{L^2}{6c} \left(\frac{q_\nu}{E} \right)^2 \int_0^\infty ds C_\perp(s). \quad (\text{A29})$$

Defining the normalized transverse correlation function

$$\rho_\perp(s) = \frac{C_\perp(s)}{C_\perp(0)}, \quad \lambda_B = \int_0^\infty ds \rho_\perp(s), \quad (\text{A30})$$

one obtains

$$\langle \Delta t \rangle \simeq \frac{L^2 \lambda_B}{6c} \left(\frac{q_\nu}{E} \right)^2 C_\perp(0). \quad (\text{A31})$$

For an isotropic turbulent field,

$$C_\perp(0) = \langle |\mathbf{B}_{\text{turb},\perp}|^2 \rangle = \frac{2}{3} B_{\text{rms}}^2, \quad (\text{A32})$$

so that

$$\langle \Delta t_q^{\text{turb}}(E) \rangle = \frac{L^2 \lambda_B}{9c} \left(\frac{q_\nu B_{\text{rms}}}{E} \right)^2. \quad (\text{A33})$$

This is the origin of the numerical factor 1/9 used for the turbulent contribution in the main text.

For an anisotropic component such as the JF12 striated field, the isotropic relation between $C_\perp(0)$ and a full three-dimensional rms field does not apply. In that case, the relevant quantity is the transverse variance itself. Defining $\mathcal{B}_{\text{str}}^2 \equiv \langle |\mathbf{B}_{\text{str},\perp}|^2 \rangle_x$,

one has

$$C_\perp(0) = \mathcal{B}_{\text{str}}^2, \quad (\text{A34})$$

and therefore

$$\langle \Delta t_q^{\text{str}}(E) \rangle = \frac{L^2 \lambda_B}{6c} \left(\frac{q_\nu}{E} \right)^2 \mathcal{B}_{\text{str}}^2. \quad (\text{A35})$$

APPENDIX B: BASELINE GMF MODEL AND UNCERTAINTY TREATMENT

Our baseline description of the large-scale regular GMF is the original Jansson-Farrar (JF12) model, which decomposes the coherent field into disk, toroidal-halo, and poloidal “X-field” components and was fit to extragalactic rotation measures together with Galactic synchrotron

observables [32]. In addition to the large-scale regular field, JF12 includes a striated component locally aligned with it and a purely turbulent random component. In our implementation, the regular and striated components are evaluated with in-house routines built directly from the published JF12 parametrization, while the turbulent component is sampled using the JF12Field implementation provided by CRPropa 3.2 [51].

1. Regular component

To estimate the uncertainty on the regular field contribution to the kernel, we sample the JF12 regular field parameters around their published best fit values using independent Gaussian draws with widths given by the quoted 1σ errors. For each sampled parameter set, we recompute the corresponding contribution to the effective field strength $B_{\text{eff}}^2(L, \ell, b)$, and hence to the regular part of the time delay kernel. The uncertainty bands shown in the main text are then constructed from the resulting ensemble of realizations.

This procedure should be understood as a phenomenological propagation of the published JF12 parameter uncertainties. A full reconstruction of the original JF12 likelihood would require the joint posterior, or equivalently, the full covariance structure, of the fitted parameters, which is not available in the published analysis. The purpose of the present treatment is therefore not to reproduce the original fit statistically, but to quantify the sensitivity of the magnetic delay kernel to the variations of the regular GMF JF12 parameters. Since the benchmark 1σ uncertainty bands on the translated charge limits shown in the main text are already at the $\mathcal{O}(10\%)$ level, residual effects associated with a full covariance-aware treatment are expected to be subleading.

2. Stochastic components

For the stochastic components, the time delay kernel depends on a transverse field variance together with a correlation length along the line-of-sight given by Eq. (A30). In practice, this integral is evaluated numerically from the transverse correlation function estimated along the line of sight.

For the turbulent field, we use the CRPropa realization of the JF12 turbulent component with the regular and striated components switched off. Assuming local isotropy, the full rms field is related to the transverse variance by Eq. (A32). The quantity entering the delay kernel is therefore the product

$$B_{\text{rms}}^2 \lambda_B = \frac{3}{2} \langle |\mathbf{B}_{\text{turb},\perp}|^2 \rangle_x \lambda_B. \quad (\text{B1})$$

For each line-of-sight and source distance L , we generate multiple independent turbulent realizations, compute the

corresponding values of $(B_{\text{rms}}^{\text{turb}})^2 \lambda_B^{\text{turb}}$, and use the median together with the 16th and 84th percentiles of the product $(B_{\text{rms}}^{\text{turb}})^2 \lambda_B^{\text{turb}}$ to characterize the turbulent contribution.

For the striated component, the isotropic relation of Eq. (A32) does not apply, since the field is anisotropic by construction: it is locally aligned with the regular field and fluctuates primarily in sign. The relevant quantity is

therefore the transverse variance $\mathcal{B}_{\text{str}}^2$ introduced in Appendix A. Multiple striated realizations are generated by varying the sign-field realization. For each realization we compute $\mathcal{B}_{\text{str}}^2$, the corresponding correlation length λ_B^{str} , and the product $\mathcal{B}_{\text{str}}^2 \lambda_B^{\text{str}}$, and use the median together with the 16th and 84th percentiles of that product to characterize the corresponding uncertainty.

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