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Dark Kinetic Heating of Neutron Stars and An Infrared Window On WIMPs, SIMPs, and Pure Higgsinos

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We identify a largely model-independent signature of dark matter (DM) interactions with nucleons and electrons. DM in the local galactic halo, gravitationally accelerated to over half the speed of light, scatters against and deposits kinetic energy into neutron stars (NSs), heating them to infrared blackbody temperatures. The resulting radiation could potentially be detected by the James Webb Space Telescope, the Thirty Meter Telescope, or the European Extremely Large Telescope. This mechanism also produces optical emission from neutron stars in the galactic bulge, and X-ray emission near the galactic center, because dark matter is denser in these regions. For GeV - PeV mass dark matter, dark kinetic heating would initially unmask any spin-independent (SI) or spin-dependent (SD) dark matter-nucleon cross-sections exceeding 2×10^{-45} cm^2, with improved sensitivity after more telescope exposure. For lighter-than-GeV dark matter, cross-section sensitivity scales inversely with dark matter mass because of Pauli blocking; for heavier-than-PeV dark matter, it scales linearly with mass as a result of needing multiple scatters for capture. Future observations of dark sector-warmed neutron stars could determine whether dark matter annihilates in or only kinetically heats neutron stars. Because inelastic inter-state transitions of up to a few GeV would occur in relativistic scattering against nucleons, elusive inelastic dark matter like pure Higgsinos can also be discovered.

Despite ongoing searches, the identity of DM remains a mystery. Terrestrial detectors looking for DM impinging on known particles have found no dark sector scattering events in up to a hundred kilogram-years of data. While some DM models have been excluded by these searches, many well-motivated candidates remain untested. Earth-bound direct detection is considerably less sensitive to DM that couples to Standard Model (SM) particles primarily through inelastic or SD interactions, as well as DM much heavier or lighter than the nuclear masses of argon, germanium, or xenon.

A compelling insight developed in this document is that DM interactions with SM particles heat NSs through the deposition of kinetic energy that DM gains falling into steep NS gravitational potentials. Dark kinetic heating of NSs depends only on the total mass of accumulated DM, and is therefore sensitive to DM masses spanning dozens of orders of magnitude. As a consequence, dark kinetic heating of NSs provides a powerful complement to, and indeed could surpass, terrestrial direct detection searches for DM interactions.

This letter also demonstrates that the aggregate impact of DM falling onto NSs results in thermal emission detectable with imminent telescope technology. Detecting or constraining DM using nearby NSs requires dedicated searches and observation times a few orders of magnitude beyond standard surveys. In addition, locating an old NS within fifty parsecs of Earth, where ~ 100 old NSs reside, may be critical to near-future searches for dark kinetic heating. Such efforts are warranted by the extraordinary sensitivity dark kinetic heating has for a broad variety of DM models. This builds substantially on studies of DM that annihilates in compact stars [1–6], showing that well-motivated non-annihilating, asymmetric [7, 8] and inelastic DM can heat NSs appreciably.

1. *Dark kinetic heating.* DM's flux through a NS depends on the maximum impact parameter of incoming halo DM. For NS mass $M \sim 1.5\ M_\odot$ and radius $R \sim 10$ km, $b_{\rm max} = \left(\frac{2GMR}{v_{\rm x}^2}\right)^{1/2}\left(1-\frac{2GM}{R}\right)^{-1/2} \sim 10^3$ km, where $v_{\rm x}$ is the velocity of DM [9]. The total mass rate of DM passing through the NS is $\dot{m} = \pi b_{\rm max}^2 v_{\rm x}\rho_{\rm x}$, where $\rho_{\rm x}$ is the ambient density of DM. Using a best-fit DM density and halo velocity, $\rho_{\rm x} \sim 0.42$ GeV cm^{-3} and $v_{\rm x} \sim 230$ km s^{-1} [10], $\dot{m} \sim 4 \times 10^{25}$ GeV s^{-1}.

The total kinetic energy that can be deposited by DM is, to good approximation, given by DM's kinetic energy at the surface of the NS, $E_{\rm s} \simeq m_{\rm x}(\gamma - 1)$, where for a typical NS $\gamma \sim 1.35$. Then the rate of dark kinetic energy deposition is given by

$$\dot{E}_{\rm k} = \frac{E_{\rm s}\dot{m}}{m_{\rm x}} f \simeq 1.4 \times 10^{25}\ \text{GeV s}^{-1}\ \left(\frac{f}{1}\right), \qquad (1)$$

where $f \in [0,1]$ is the fraction of dark particles passing through the star that become trapped in the NS interior. This fraction depends on the cross-section for DM to scatter against nucleons and electrons. The capture probability is $f \equiv {\rm Min}\left[\frac{\sigma_{\rm nx}}{\sigma_{\rm sat}}, 1\right]$, where $\sigma_{\rm sat}$, which depends on $m_{\rm x}$, is the "saturation" cross-section for which all transiting DM is captured. DM becomes captured in the NS's gravitational potential, if the energy it deposits from scattering with the NS exceeds its initial halo kinetic energy far from the NS. We consider DM scattering off neutrons – this can be extended to electron and proton scattering [11].

2a. *Capture for* GeV $\lesssim m_{\rm x} \lesssim$ PeV*.* In this mass range, DM is captured after scattering once with the NS.

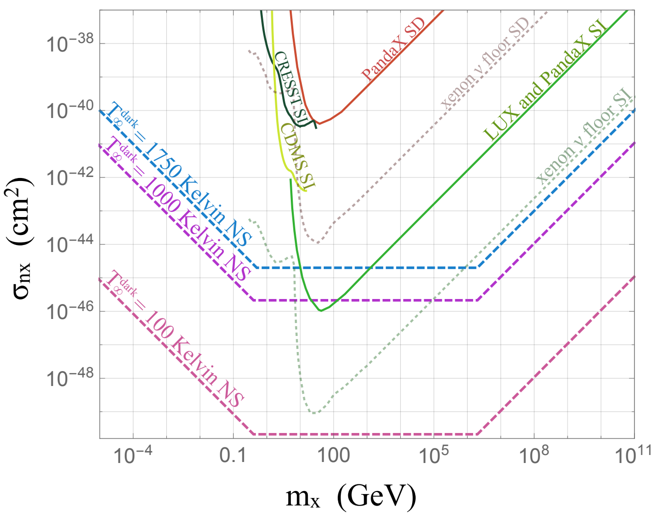

Figure 1. Dark kinetic heating sensitivity to DM-neutron cross-sections ($\sigma_{\rm nx}$), for NSs near Earth with blackbody temperatures of $100 - 1750$ K, indicated with dashed lines. A 1750 K blackbody temperature is the maximum imparted by dark kinetic heating, for a 1.5 $M_\odot$, $R = 10$ km NS that captures the entire flux of DM passing through it, for DM density $\rho_{\rm x} = 0.42$ GeV cm^{-3} [10]. While radiation from a 1750 K NS at 10 parsecs could be detected by JWST, TMT, or E-ELT, imaging a $\lesssim 1000$ K NS requires future telescopes. Old NSs cool to ~ 100 K after a billion years (see Sec. 3). Dark kinetic sensitivity curves apply to SD and SI interactions, since scattering occurs off individual neutrons. Bounds from LUX [12], PandaX [13, 14], CDMS [15], and CRESST [16] are shown, (assuming $\rho_{\rm x} = 0.3$ GeV cm^{-3}), alongside the SD and SI xenon direct detection neutrino floors [17].

In the rest frame of the NS, a DM-nucleon scattering event depletes the DM kinetic energy by

$$\Delta E_s = \frac{m_n m_x^2 \gamma^2 v_{\rm esc}^2}{m_n^2 + m_x^2 + 2\gamma m_x m_n} \left(1 - \cos\,\theta_c\right), \qquad (2)$$

where $v_{\rm esc}^2 \simeq 2GM/R$ is the incoming speed of DM, and θ_c is the scattering angle in the center-of-mass frame. For DM masses smaller than $m_{\rm x} \simeq$ PeV, DM becomes bound after one scattering event. This follows from comparing DM's initial kinetic energy in the halo, blueshifted in the rest frame of the NS, $\gamma m_{\rm x} v_{\rm x}^2/2$, to the kinetic energy lost in an average scatter, ΔE_s. Equating these two quantities, the maximum mass for DM captured by one scatter is $m_{\rm x} \sim$ PeV. Therefore for GeV – PeV mass DM, the minimum cross-section for DM to deposit all of its kinetic energy into the NS is the per-neutron cross-section for which DM scatters once, $\sigma_{\rm sat}^{\rm single} \simeq \pi R^2 m_{\rm n}/M \simeq 2\times 10^{-45}$ cm^2 $\left(\frac{1.5\ {\rm M}_\odot}{M}\right)\left(\frac{R}{10\ {\rm km}}\right)^2$.

2b. *Capture for* $m_{\rm x} \lesssim$ GeV. For DM lighter than a GeV, the saturation cross section increases inversely with DM mass as a result of "Pauli blocking." Because the NS is composed of degenerate neutrons, protons, and electrons, the probability for DM to scatter with these fermions is diminished by the Pauli exclusion principle, which forbids degenerate fermions from becoming excited to a momentum state already occupied by another fermion. This reduces the number of nucleons available for the DM to scatter against by a factor $\sim \frac{\delta p}{p_{\rm F,n}}$, where the momentum transferred by the DM is $\delta p \sim \gamma m_{\rm x} v_{\rm esc}$, and a typical neutron Fermi momentum in the NS is $p_{\rm F,n} \simeq 0.45$ GeV $(\rho_{NS}/(4\times 10^{38}$ GeV cm$^{-3}))$ [18]. Therefore, the saturation cross-section for sub-GeV mass DM is $\sigma_{\rm sat}^{\rm Pauli} \simeq \pi R^2 m_{\rm n} p_{\rm f}/(M\gamma m_{\rm x} v_{\rm esc})$ $\simeq 2\times 10^{-45}$ cm^2 $\left(\frac{\rm GeV}{m_{\rm x}}\right)\left(\frac{1.5\ {\rm M}_\odot}{M}\right)\left(\frac{R}{10\ {\rm km}}\right)^2$.

2c. *Capture for* $m_{\rm x} \gtrsim$ PeV. A single scatter is insufficient to capture DM heavier than a PeV. In this case, multiple scatters during DM's passage through the star are required for the DM to become gravitationally bound. The energy lost after $N \sim n\sigma_{\rm nx}R$ scatters inside the NS is $\Delta E_{\rm s} N \sim \Delta E_{\rm s} n \sigma_{\rm nx} R$, where n is the number density of neutrons in the NS and N is the typical number of scatters for DM transiting the NS. Because the energy lost in multiple scatters scales linearly with $\sigma_{\rm nx}$, and DM's initial halo kinetic energy also scales linearly with $m_{\rm x}$, it follows that at masses $m_{\rm x} \gtrsim$ PeV, the cross-section required for DM capture increases linearly with the DM mass (see [6]) so that $\sigma_{\rm sat}^{\rm multi} \simeq 2\times 10^{-45}$ cm^2 $\left(\frac{m_{\rm x}}{\rm PeV}\right)\left(\frac{1.5\ {\rm M}_\odot}{M}\right)\left(\frac{R}{10\ {\rm km}}\right)^2$.

In all above cases, the amount of DM captured and the resulting dark kinetic heating decreases linearly with cross-sections smaller than $\sigma_{\rm sat}$, because $\dot{E}_{\rm k} \propto \sigma_{\rm nx}$. Minor refinements can be made to these capture calculations [19–22], *e.g.* accounting for the slightly increased escape velocity in the NS interior [4, 23, 24], enhanced multiscatter capture for $m_{\rm x} \sim$ PeV DM particles using a Boltzmann velocity distribution [6], and capture enhancement from scattering against heavy nuclei in the crust of the NS. These depend on the structure of the NS crust and degenerate core [25], typically yielding percent-level increases to the capture rate [3, 4, 6, 26].

Soon after capture, DM injects its kinetic energy into the NS. For DM lighter than a GeV, most of its kinetic energy is deposited after a single scatter, as can be verified with Eq. (2). Heavier DM follows an orbital path that re-intersects the NS interior, re-scattering until most of its kinetic energy is deposited [24]. The energy lost in each transit is $\Delta E_{\rm t} \sim 2Gm_{\rm n}(R^{-1} - r_{\rm o}^{-1})(\sigma_{\rm nx}/10^{-45}{\rm cm}^2)$, where $r_{\rm o}$ is the size of the DM orbit. The time for DM to deposit most of its kinetic energy is short, $t_{\rm dep} \lesssim$ 10 days $\left(\frac{10^{-49}{\rm cm}^2}{\sigma_{\rm nx}}\right)\left(\frac{m_{\rm x}}{\rm PeV}\right)$, with this expression normalized to the longest deposition time for parameters of interest.

3. *NS temperature.* NSs primarily cool through neutrino and photon emission. While young NS cooling can depend strongly on the equation of state, NSs older than a few million years (most NSs in the Milky Way) have cooling curves of a simple form, $dT/dt = (\epsilon_{\rm ISM} + \epsilon_{\rm x} - \epsilon_\gamma)/c_{\rm v}$, where $c_{\rm v} = \sum c_{\rm i,v}$ is the total heat capacity with $c_{\rm n,v} \simeq \frac{2\pi^2 k_B^2 m_n n_n}{3p_{\rm Fn}^2} T$ and $c_{\rm p,v} \simeq \frac{2\pi^2 k_B^2 m_{\rm p} n_{\rm p}}{2p_{\rm Fp}^2} T$ the heat capacity for NS fluid with neutron (proton) number density $n_{\rm n}$ ($n_{\rm p}$) [27], and $\epsilon_\gamma = 4\pi\sigma R^2 T^4/(4\pi R^3/3)$ is the photon emissivity of the NS. Additional sources of NS thermal energy [28–30] include heating from accretion of interstellar matter (ISM) and DM, parameterized by $\epsilon_{\rm ISM}$ and $\epsilon_{\rm x}$, respectively. The blackbody emission outlined here matches the cooling model of [27], where NSs become isothermal and cool to $T \lesssim 10^3$ K within 20 Myr and $T \sim 100$ K after a Gyr [28], although this depends on whether there are additional mechanisms that heat old NSs. Note that $T \sim 1000$ K is a factor of a hundred below current temperature bounds on NSs [31].

One potential source of heating is ISM accretion onto NSs, which depends on their historic paths through the Milky Way [32, 33]. Present-day ISM heating may be discernible from dark kinetic heating, because accreted ions preferentially warm the poles of the NS and emit some X-ray photons [34, 35]. In practice, NS magnetic fields may deflect all but a fraction of incident ISM [36]. The local hundred parsecs of ISM [37] is relatively underdense, with ISM densities as low as $\sim 10^{-3}$ GeV cm^{-3}, making the present-day DM heating contribution predominant in this region.

The heating of NSs by DM is similar to heating by the ISM [30]: in both cases, a particle crosses the NS surface, scatters against nucleons, transferring its kinetic energy to the star. In cold NSs, the crust and core thermalize within less than a year [28, 38]. Following thermalization of scattered nucleons in the NS interior, dark kinetic heating imparts a NS luminosity at long distances of $L_\infty^{\rm dark} = \dot{E}_{\rm k}\left(1-\frac{2GM}{R}\right) = 4\pi\sigma_{\rm B} R^2 T_{\rm s}^4 \left(1-\frac{2GM}{R}\right)$, where $\sigma_{\rm B}$ is the Stefan-Boltzmann constant, and $T_{\rm s}$ is the blackbody temperature of the NS as would be seen at its surface. For a near-Earth DM mass flux of $\dot{m} \sim 4\times10^{25}$ GeV s^{-1}, the NS appears as a blackbody with a temperature up to $T_\infty^{\rm dark} \sim 1750$ K, depending on the fraction of DM captured. For NSs inside the galactic bulge, maximal dark kinetic heating produces optical emission, $T_\infty^{\rm dark} \sim 3850$ K $(\rho_{\rm x}/10~{\rm GeV~cm^{-3}})^{1/4}$. In Figure 1, the DM - neutron cross-section sensitivity is shown for $100 - 1750$ K NSs near Earth.

4. *Detecting dark kinetic heating.* While the radio observability of isolated, ∼Gyr old pulsars is a topic of active research, the faintest, oldest pulsars are likely to be uncovered by the recently operational FAST radio telescope [41]. After radio detection, infrared telescopes trained on old NSs can measure or bound their thermal emission. For $\rho_{\rm x} = 0.42$ GeV cm^{-3}, dark kinetic heating can warm NSs up to $T_\infty^{\rm dark} \sim 1750$ K, with a spectrum peaking at $1-2~\mu$m. More precisely the blackbody spectral flux density of the NS is

$$f_\nu = \pi B(\nu, T_\infty^{\rm dark}) \times \frac{4\pi (R\gamma)^2}{4\pi d^2}, \qquad (3)$$

where $B(\nu,T) = 4\pi\nu^3\left(e^{\frac{2\pi\nu}{k_b T}}-1\right)^{-1}$. Figure 2 displays the dark kinetic heating spectral flux density for a range of NS masses and radii, at a distance $d = 10\,$pc (where

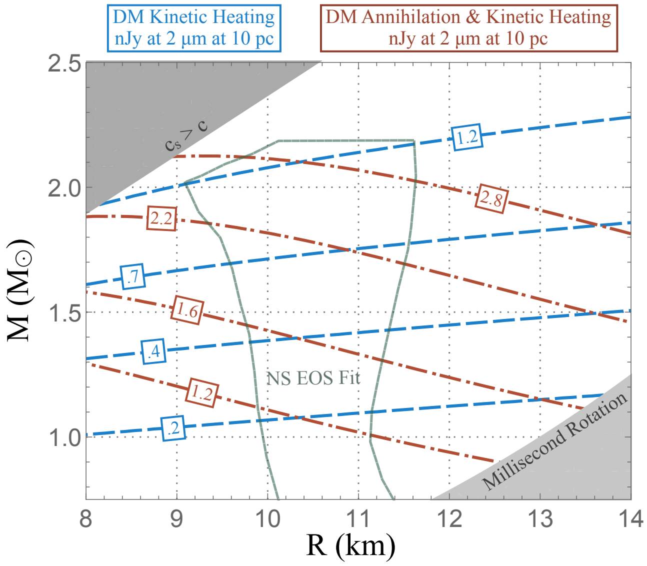

Figure 2. Contours of infrared photon spectral flux density for a NS ten parsecs from Earth with mass M and radius R, maximally heated by DM with $\rho_{\rm x} \sim 0.42$ GeV cm^{-3} and $v_{\rm x} \sim 230$ km s^{-1}. Dashed blue contours indicate dark kinetic heating only, while dotted-dashed red contours indicate DM that also annihilates in the NS. The green region encloses a fit to pulsar data [39]; gray regions are excluded by causality and the fastest rotating pulsars [40].

1 - 5 old, cold NSs should abide [32]) and at wavelength $\nu^{-1} = 2~\mu$m. This results in a spectral flux density of $f_\nu \simeq 0.5$ nJy, which is potentially detectable by upcoming telescopes like JWST, TMT, and E-ELT.

In more detail, the NIRCam on JWST is a 0.6 to 5 micron imager, with a smorgasbord of filters available [42]; the F200W filter, centered at 2 μm obtains 7.9 nJy at 10 SNR in 10^4 seconds, where for such long exposures, added sensitivity scales with root integration time, $\propto \sqrt{t_{\rm int}}$. Using these values, a NS at distance d, maximally heated by DM kinetic energy (to 0.5 nJy at 2 μm), could be detected at SNR 2 in $\sim 10^5\,(d/(10~{\rm pc}))^4$ seconds. At the TMT, the IRIS instrument [43] has coverage from 0.8 to 2.5 μm, with a projected K-band (2.0 to 2.4 μm) sensitivity that permits SNR 2 detection of the aforementioned NS in $\sim 7\times10^4\,(d/(10~{\rm pc}))^4$ seconds.

While asymmetric DM would primarily heat NSs through deposition of kinetic energy, less integration time is required to detect DM that would annihilate in NSs. Assuming DM interacts with the NS via a contact operator and the mass scale of the mediating force is $\gg$ GeV, it has been shown that for all $m_{\rm x}$-$\sigma_{\rm n}$ parameter space in Figure 1, DM cools to the NS's temperature after a Myr [25], collecting into a region of radius $r_{\rm th} \simeq 1$ cm $(T_{\rm s}/10^3~{\rm K})^{1/2}({\rm TeV}/m_{\rm x})^{1/2}$ [22]. DM with a velocity-averaged self-annihilation cross-section $\langle\sigma_{\rm a} v\rangle$, will reach capture-annihilation equilibrium after a time $t_{\rm eq} \simeq$

$0.1\ \mathrm{yr}\left(\frac{\mathrm{TeV}}{m_{\mathrm{x}}}\right)^{1/4}\left(\frac{0.4\ \frac{\mathrm{GeV}}{\mathrm{cm}^3}}{\rho_{\mathrm{x}}}\right)^{1/2}\left(\frac{T_{\mathrm{s}}}{10^3\ \mathrm{K}}\right)^{3/4}\left(\frac{10^{-45}\ \mathrm{cm}^2}{\langle\sigma_{\mathrm{a}}v\rangle}\right)^{1/2}\frac{1}{\sqrt{f}}$ [6]. Note that a typical weakly-interacting massive particle ($\langle\sigma_{\mathrm{a}}v\rangle \sim 10^{-36}\ \mathrm{cm}^2$) will reach capture-annihilation equilibrium much faster. Because telescopes like TMT do better at detecting NSs that emit higher energy photons, for which the Earth's infrared atmospheric background is reduced, a 10 pc distant NS maximally warmed to a blackbody temperature of $T_\infty = 2480$ K (1.7 nJy at 2 μm) by DM annihilation and kinetic heating can be resolved in 9000 s with the F200W filter in NIRCam at JWST versus 2000 s in Y-band (0.9 to 1.2 μm) with the TMT IRIS instrument.

Finally, it is plausible to consider detecting NSs $\gtrsim 50$ parsecs from Earth, using longer integration times. At 50 parsecs, which is near the distance to a number of known pulsars, TMT using the IRIS Y-band would detect NS thermal emission arising from maximal DM annihilation and kinetic heating after $\sim 10^6$ s. Large next-generation telescopes have the benefit of adaptive optics, which result in an integration time that decreases as the fourth power of telescope diameter ($t_{\mathrm{int}} \propto D^{-4}$) for background-dominated surveys. This scaling holds when comparing IRIS's H-band sensitivity [44] to MICADO's [45]. Extrapolating to a Y-band sensitivity at E-ELT, this implies that an annihilation-heated, 70 parsec-distant NS can be detected in $\lesssim 10^6$ s. Likewise, E-ELT detects a 25 parsec-distant NS warmed by only maximal dark kinetic heating in $\lesssim 10^6$ s. Depending on the NS's position relative to Earth, it may be possible to combine a lengthy NS observation with a deep field survey; we leave a proposal along these lines to future investigation.

5. *Parsing DM models with dark heating.* An old NS observed to have $T < 1750$ K would bound DM-nucleon cross-sections (see Figure 1). On the other hand, if a $T \lesssim 2000$ K population of NSs begins to emerge, dark kinetic heating can be used both to characterize the dark sector and to begin confirming that NSs are heated by DM as opposed to a SM heating process.

The energy injected by dark kinetic heating alone has a different dependence on the NS's mass and radius than energy from DM which also annihilates in the NS. This follows from comparing the maximum dark kinetic heating rate, $(\gamma-1)\dot{m}$, with the maximum annihilation and dark kinetic heating rate, $\gamma\dot{m}$. Note that $\dot{m}$ and γ depend on the NS radius and mass, and these range over $R \sim 10-12$ km [39, 46] and $M \sim 1-2M_\odot$ [47]. Consequently, annihilating DM heats populations of old NSs to luminosities that range over a factor of $\lesssim 3$, while DM that only deposits kinetic energy heats NSs to luminosities ranging over a factor of $\sim 10-15$. This can be seen in Figure 2, which shows the spread in luminosity from dark kinetic heating as a function of NS mass and radius, both with and without DM annihilation in the star. This methodology can also be used in future observations, to differentiate DM annihilation in NSs, from NSs warmed by ISM accretion – the spread in NS luminosities is broader for the latter scenario.

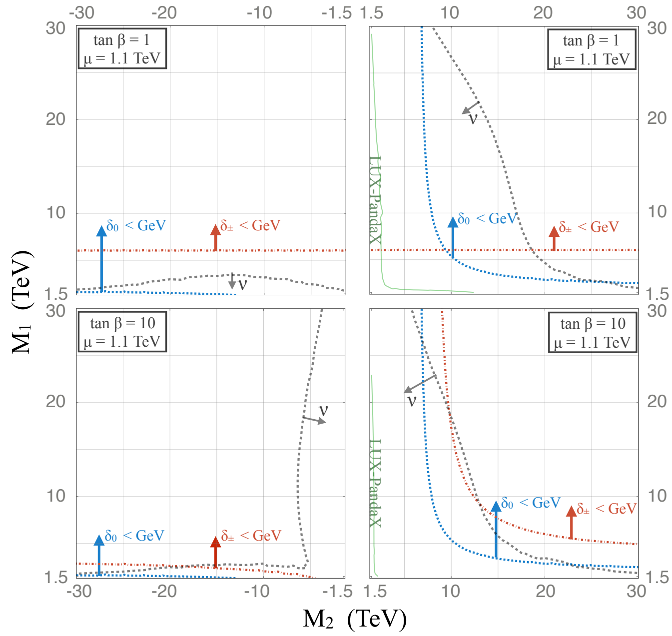

Figure 3. Electroweakino mass parameters M_1, M_2 are shown with Higgsino mass $\mu = 1.1$ TeV, which results in the observed DM relic abundance [48]. Regions where the Higgsino inelastic mass splitting is less than one GeV would be uncovered by the first (non-)observation of NS dark kinetic heating. These regions are indicated above the blue dotted (red dot-dashed) lines where $\delta_0 <$ GeV ($\delta_\pm <$ GeV), permitting tree-level $Z(W)$ boson exchange between semi-relativistic Higgsinos and neutrons in the NS. Regions below the black dotted line would be ruled out by direct detection searches sensitive to cross-sections as small as the xenon direct detection neutrino floor. LUX and PandaX exclude parameters below the green solid line for $M_2 > 0$, and have no sensitivity for $M_2 < 0$. SI cross-sections were computed using `SuSpect` [49] and `micrOMEGAs` [50] with non-neutralino supersymmetric mass parameters set to 8 TeV [51].

6. *Infrared window on pure Higgsinos.* We demonstrate, using an explicit model of Higgsino DM, that NS dark kinetic heating could reveal inelastic DM otherwise inaccessible to direct detection experiments. Neutralinos are the spin $\frac{1}{2}$ superpartners of electroweak bosons, "electroweakinos," and Higgs bosons, "Higgsinos" [52–54]. If the electroweakino mass parameters M_1 ("bino") and M_2 ("wino") are much larger than the Higgsino mass parameter μ, the two lightest neutralino mass eigenstates (χ_1^0, χ_2^0) and the lightest charged mass eigenstate ($\chi_1^\pm$) is mostly Higgsino.

Pure Higgsinos ($m_Z \ll |\mu| \ll |M_1|, |M_2| \lesssim 10^7$ GeV) scatter elastically with nucleons ($\chi_1^0 n \to \chi_1^0 n$) at terrestrial direct detection experiments through weak boson loops with a small cross-section, $\sigma_{\mathrm{nx}} \lesssim 10^{-48}\ \mathrm{cm}^2$ [55, 56], beyond the reach of any planned direct detection experiment [51, 57, 58]. On the other hand, pure Higgsino inelastic processes $\chi_1^0 n \to \chi_2^0 n$ and $\chi_1^0 n \to \chi_1^\pm p^\mp$ proceed through tree-level exchange of Z and W bosons with a much larger nucleon scattering cross-section, $\sigma_{\rm nx} \sim 10^{-39}$ cm^2 [59]. These tree-level weak boson exchange scattering processes are forbidden if the recoil energy exchange is less than the inelastic mass splitting $\delta_0 \equiv m_{\chi_2^0} - m_{\chi_1^0} > \Delta E_{\rm s}$ [59, 60]. We will see that nearly all pure Higgsino parameter space inaccessible to direct detection experiments is accessible with dark kinetic heating, because inelastic inter-state transitions up to $\delta \sim$ GeV are permitted for semi-relativistic DM scattering against NSs, compared with $\delta \lesssim 500$ keV at direct detection experiments [59].

Neutral and charged Higgsino components $(\chi_1^0, \chi_2^0, \chi_1^\pm)$ are split in mass by mixing with electroweakinos and by electroweak loop corrections [61, 62], $\delta_0 \simeq \frac{v^2}{4}\left(\frac{g_1^2}{M_1} + \frac{g_2^2}{M_2}\right)$ and $\delta_\pm^{\rm tree} \simeq \frac{v^2}{4}\left(\frac{g_1^2}{M_1}(1+\sin 2\beta) + \frac{g_2^2}{M_2}(1-\sin 2\beta)\right)$, where $\tan\beta$ is the ratio of the Higgs vevs, and for $|\mu| \gg m_Z$, $\delta_\pm^{\rm loop} \simeq 355$ MeV. Efficient dark kinetic heating occurs for regions where either δ_0 or $\delta_\pm = \delta_\pm^{\rm tree} + \delta_\pm^{\rm loop}$ are < 1 GeV, which allows for tree level scattering via Z or W exchange. Fig. 3 shows that for most parameter space outside the reach of future direct detection experiments, $\delta_0, \delta_\pm \lesssim$ GeV, implying that all Higgsinos passing through the NS deposit their kinetic energy. The time for Higgsinos to thermalize in a small sphere [25] in the NS and annihilate will depend on the loop-induced, low-energy Higgsino-nucleon cross-section, which has only been bounded to be $\sigma_{\rm n}^{\rm loop} \lesssim 10^{-48}$ cm^2 [56]. However, we have shown kinetic heating provides a minimum energy $\sim 10^{25}$ GeV/s that Higgsino DM impart to NSs.

7. *Concluding with strong interactions.* DM's interactions with SM particles could be unmasked by looking for infrared thermal emission from NSs near the solar position. This effect applies to many DM models, including weakly interacting (WIMP), asymmetric, pure Higgsino, and strongly-interacting (SIMP) DM. For SIMPs [63–68] with up to nuclear cross-sections, the sensitivity shown in Figure 1 extends to $m_{\rm x} \sim 10^{27}$ GeV. For super-nuclear cross-sections, some DM scattering occurs near enough to the NS surface that high energy photons are produced alongside IR blackbody emission [30]. SIMP-scattered high energy photons, dark kinetic X-rays from NSs near Sagittarius A*, and other exciting applications of dark kinetic heating will be explored in future work.

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