Faint light of old neutron stars from dark matter capture and detectability at the James Webb Space Telescope

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Neutron stars (NS) of age $> 10^9$ yrs exhaust thermal and rotational energies and cool down to temperatures below $O(100)$ K. Accretion of particle dark matter (DM) by such NS can heat them up through kinetic and annihilation processes. This increases the NS surface temperature to a maximum of $\sim 2600$ K in the best case scenario. The maximum accretion rate depends on the DM ambient density and velocity dispersion, and on the NS equation of state and their velocity distributions. Upon scanning over these variables, we find that the effective surface temperature varies at most by $\sim 40\%$. Black body spectrum of such warm NS peak at near infrared wavelengths with magnitudes in the range potentially detectable by the James Webb Space Telescope (JWST).

Using the JWST exposure time calculator, we demonstrate that NS with surface temperatures $\geq 2400$ K, located at a distance of 10 pc can be detected through the F150W2 (F322W2) filters of the NIRCAM instrument at SNR $\geq 10 (5)$ within 24 hours of exposure time.

1. Introduction. — Neutron stars (NS) are one of the most compact and dense astrophysical objects in the universe. They are stellar configurations that are supported against gravitational collapse by the neutron degeneracy pressure and that from neutron-neutron interactions [1]. NS are notoriously hard objects to detect observationally, especially if they are very old. Most of the detected NS $\sim O(10^4)$ have been observed as isolated radio pulsars with ages $\lesssim 100$ Myrs. Older NS, have been detected so far, only as companions in binary systems, e.g. millisecond pulsars [2-4]. A better understanding of these objects is emerging, thanks to recent gravitational wave observations of binary NS mergers [5], and other studies estimating their mass and radius [6-9]. Old ($> 10^9$ yrs) isolated NS have not been identified so far. According to the minimal cooling paradigm [10] such objects exhaust all their thermal and rotational energy, making it impossible to observe them. As a consequence very little is known about their physical and statistical properties [11-16].

The situation can change when dark matter (DM) particles in the galactic halo are efficiently captured by NS. These DM particles can deposit energy via scattering and annihilation processes, giving rise to kinetic [17] and annihilation heating [15, 18] of the NS, respectively. The resulting increase in the surface temperature of NS can be significantly larger than the case without DM heating. In the local bubble, NS older than Gyrs can have an increase in temperature from about $\sim 100$ K to $\sim 2000$ K due to DM heating mechanisms [17, 19]. Observation of such NS would place constraints on DM mass and their interaction strength with visible matter in a broadly model independent way [17-31].

During late evolutionary stages ($t_{\text{age}} > $ Gyrs), the luminosities of NS that accrete DM are solely controlled by the DM capture rate. This depends on several factors including the physics of the nuclear matter at near saturation densities, NS and DM phase space distributions, and the interaction strength of DM with visible matter, and their masses. For any given neutron star of mass M and radius R, the maximal rate of DM accretion is given by the so-called geometric rate corresponding to scattering cross section $\sigma_\lambda = \pi R^2 / N \sim 10^{-45}$ cm$^2$, where $N$ is the total number of target neutrons in the NS.

In this letter we evaluate the DM capture rate (and consequent change in the effective surface temperature of NS) for a range of equations of state (EoS) allowed by current observational data, and a viable range of NS and DM phase space distributions. We find that the maximal temperature is $\sim 2600$ K and varies only by 40% over this whole range of inputs. Subsequently, we study the prospect of observing such old maximally heated NS close to the Solar position. The spatial distribution of such objects are predicted using Monte-Carlo orbital simulations of galactic NS [11-16]. These simulations suggests that we can expect $1 \sim 2$ (100 -- 200) old isolated NS within 10 (50) pc. The black body spectrum of NS that are maximally heated by DM peaks at near infrared wavelengths of $\lambda \sim 2\mu$m, and fall in the range of observability for the recently launched James Webb Space Telescope (JWST) [17]. Using the publicly available JWST exposure time calculator [32], we discuss the optimal observation strategy that can be employed to hunt such old NS. Among the widest band filters available onboard JWST, we find that the NIRCAM filter F150W2 provides the best sensitivity and facilitates detection with signal to noise ratio (SNR) $\gtrsim 10$ within 24 hours of exposure time.
2. Maximal DM capture in NS.— The maximum rate at which DM particles can be gravitationally captured by the NS depends on its mass ($M$), radius ($R$), velocity ($v_*$), the DM dispersion velocity ($v_d$) and the ambient DM density ($\rho_\chi$). The geometric limit is considered for the capture rate when the DM mean free path is approximately smaller than the neutron star radius, which corresponds to DM scattering cross section $\sigma \gtrsim \sigma_e^2$ [18, 19, 30, 33–36]. For a given DM mass ($m_\chi$), the maximum capture rate (geometric rate) is given by [23]

$$C^g_s = \pi R^2 \frac{\rho_\chi}{m_\chi} \frac{\langle v \rangle_0}{1 - v^2_{\text{esc}}} \sqrt{\frac{3\pi}{8}} \frac{v^2_{\text{esc}}}{v_* v_d} \text{Erf} \left( \sqrt{\frac{3}{2}} \frac{v_*}{v_d} \right), \quad (1)$$

with $\langle v \rangle_0 = \sqrt{8/(3\pi)} v_d$, the escape velocity $v_{\text{esc}} = \sqrt{2GM/R}$ from the neutron star, and the error function is denoted by Erf. The accretion rate strongly depends on the EoS of the neutron star through $v_{\text{esc}}$, and modestly on variables $\rho_\chi$, $v_*$ and $v_d$. When the DM mean free path is approximately larger than the NS radius the geometric capture rate above should be rescaled by factor $\sigma/\sigma_e^2$. The main goal of this work is to systematically evaluate how the maximal capture rate, and consequently, the maximal neutron star heating induced by DM capture and annihilation, are affected by the allowed range of these parameters.

2.1 Maximal DM heating of NS:— Ambient DM in the halo is accelerated to semi-relativistic velocities as it impinges on the NS. Scattering of the DM particles with particles in the stellar medium ($n, p, \mu, e$) can result in the capture of DM in NS as most of their initial kinetic energy is deposited to NS medium, thereby heating it up [17]. Next, if DM particles can annihilate during the current cosmological epoch, the accumulated DM in the core of NS would also annihilate upon thermalization with NS medium [18, 20, 37, 38]. Further heating of the NS is possible, if the products of annihilation process deposit all their energy in the NS medium. In this case, the total energy deposited is equal to the sum of kinetic and annihilation energies, dubbed here as KA heating. The kinetic and annihilation energies deposited are $m_\chi(\gamma - 1)C^g_s$ and $m_\chi C^g_s$, respectively. Here, $\gamma = (1 - 2GM/R)^{-1/2}$ is the gravitational redshift factor. Therefore, the deposited energies are independent of DM mass. Note, however, there exists a lower limit on the DM mass below which DM evaporation from the NS dominates [21, 24, 39, 40]. This lower limit is set when the ratio of escape energy from the core to the core temperature is $\sim 30$ [40]. For isolated and cold NS, the kinetic only, or the KA energy can effectively render the NS observable by increasing the surface temperature which translates directly to the luminosity, as given by the Stefan-Boltzmann law ($4\pi R^2 \sigma_B T^4_{\text{eff}}$). For an observer far away from the NS, the apparent temperature is $T^\infty = T_{\text{eff}}/\gamma$. The contributions from kinetic only, and KA heating can be computed as

$$T^\infty_{\text{kin}} \approx 1787 K \left[ \frac{\alpha_{\text{kin}}}{0.08} \left( \frac{\rho_\chi}{0.42 \text{GeV/cm}^3} \right) \right] \left( \frac{220 \text{ km/s}}{v_*} \right) \text{Erf} \left( \frac{270 \text{ km/s}}{v_d} \frac{v_*}{220 \text{ km/s}} \right)^{1/4}, \quad (2)$$

$$T^\infty_{\text{KA}} \approx 2518 K \left[ \frac{\alpha_{\text{KA}}}{0.33} \left( \frac{\rho_\chi}{0.42 \text{GeV/cm}^3} \right) \right] \left( \frac{220 \text{ km/s}}{v_*} \right) \text{Erf} \left( \frac{270 \text{ km/s}}{v_d} \frac{v_*}{220 \text{ km/s}} \right)^{1/4}, \quad (3)$$

with,

$$\alpha_{\text{kin}} = \frac{(\gamma - 1)(\gamma^2 - 1)}{\gamma^4} \quad \text{and} \quad \alpha_{\text{KA}} = \frac{\gamma(\gamma^2 - 1)}{\gamma^4}.$$

The above expressions are normalized to $M = 1.5 M_\odot$ and $R = 10$ km. Note that $\alpha_{\text{KA}}$ ($\alpha_{\text{kin}}$) is maximized for $\gamma = 1.732$ ($2.56$). If old NS exist in binary systems, then, depending on the period of their orbits, the DM capture rates (1) will be enhanced by factors up to 4 [41].

Mechanisms of kinetic and KA heating can heat the NS up to $10^{40}$ K after about 100 Myrs. However, for similar ages, other mechanisms of heating can begin to work, if exotic phases such as neutron/proton superfluidity are realized in their cores. Generically, heat can be injected into the NS by conversion of magnetic, rotational, and/or chemical energies [10, 15]. In such scenarios, the intrinsic heating signature is degenerate with that of DM heating, challenging its interpretation. Constraints on DM parameter space can nevertheless be placed if NS with effective surface temperature $\lesssim 2 \times 10^3 K$ were to be observed [42, 43].

3. Computational Inputs.— In this section we will discuss the inputs necessary to compute the quantities described by eqs. (1),(2), & (3). The primary variables are $v_*$, $\rho_\chi$ and $v_d$, and the NS EoS through $\gamma$. We detail the sources from where the range of values are obtained together with observational and or theoretical justifications.

3.1 DM parameters $\rho_\chi$ and $v_d$:— High-resolution hydrodynamical simulations of Milky Way-like galaxies were conducted by the EAGLE [44, 45] and APOSTLE [46, 47] projects. We consider the DM distributions

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1 For geometric values of cross section, DM particles thermalize within $O(10)$ Myrs for $10^{-8}$ GeV $< m_\chi < 10^{3}$ GeV. Capture and annihilation processes are in equilibrium as long as s-wave (p-wave) annihilation cross sections are greater than $\sim 10^{-33}$ cm$^3$/s ($10^{-44}$ cm$^3$/s) for Gyr old NS.
from these simulations (inclusive of baryon effects) that satisfy the observations of rotation curves and have total masses in the range $10^{12} - 10^{13} M_\odot$, as listed in [48]. We extract the dispersion velocities from the best-fit Maxwellian distributions to them. We consider two values for $v_b = 272, 356$ km/s and $\rho_0 = 0.41, 0.73$ GeV/cm$^3$, assuming a flat prior, corresponding to APOSTLE-blue and EAGLE-purple runs [48], respectively. Our choice of values of $\rho_0$ are consistent with that obtained from local stellar kinematics [49].

### 3.2 NS velocity distributions $v_*$

Population synthesis studies of galactic NS have been performed in several works which simulate the spatial and velocity distributions of old NS in the Milky Way [11, 13, 14, 16]. Historically, these studies were motivated by the observational hunt for isolated, accreting NS in near X-ray bands [11, 12, 50]. From the simulations above, we obtain several normalized probability distribution functions (PDFs) for NS velocities, at the current epoch. We choose two PDFs obtained in ref. [13], where the unknown initial NS velocities were modeled as unimodal and bimodal distributions. Similar studies of NS velocity distributions using different Galactic potential, progenitor distributions, and birth velocities, were reported in [14]. From those, we pick three models, namely 1C, 1E, and 1E*, which are representative of the full range of models studied in [14]. The PDF for model 1C corresponds to progenitor velocity distribution F06E [51] and galactic potential P90 [52]. While the PDF for models 2 1E and 1E* correspond to F06P [51] and P90.

### 3.2 NS Mass-Radius relationships

To compute the gravitational redshift factor, $\gamma = (1 - 2GM/R)^{-1/2}$, it is necessary to consider the full range of mass and radius allowed by viable NS EoS. The relation between the energy density and the pressure inside a NS is given by an EoS. Given that old NS matter is cold ($\lesssim 10^8$ K) and highly degenerate, it is a good approximation to assume the pressure to be independent of the temperature. A wide variety of NS EoS are studied and discussed in the literature [58–64]. In Fig. 1, we show the mass-radius relationship for NS composed predominantly of neutrons ($\sim 90\%$) and proton+lepton ($\sim 10\%$) matter. The multi-colored curves in this figure correspond to different assumptions of the physics and computational techniques, and are compiled in [53, 64]. The EoS WFF-1 [65] (orange) is obtained by variational methods. EoS Bsk-21 (red) is phenomenologically derived through fits to several low energy nuclear data [62, 66]. The AP4 EoS (olive green) is akin to WFF-1, simultaneously applying many-body and relativistic corrections [67]. EoS AP-3 (blue solid), is similar to AP-4, but it employs a different central pressure, energy and baryon density. The EoS MPA-1 (purple) is derived from microscopic ab-initio calculations based on Dirac-Brueckner-Hartree-Fock methods that include relativistic effects [68]. The phenomenological non-relativistic EoS PAL-1 [69] is shown in navy blue. The EoS H4 (pink) is obtained by adding hyperon matter to the canonical neutron and proton matter [70].

While the multi-colored curves represent theoretical considerations, it is necessary to understand how much of it is supported by observations. The shaded regions display the M-R values supported by various observations and experiments. The green shaded area show 90% confidence limits obtained by performing a fit for the tidal deformability and mass using EoS-insensitive methods from recent gravitational wave observations of

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[2] The models 1E* and 1E differ by 20% in their choice of escape of velocity at the solar position and by 80% for the virial mass of the milky way, respectively.
mergers of binary NS. Tidal deformability data fit to purely hadronic EoS using the latest outer core model results in yellow shaded regions at 3-σ. Bayesian fits obtained by combining gravitational wave data with low energy nuclear and astrophysical data are shown as red regions at 90% confidence level. Radio and X-ray observation of pulsars [53] are shown by light blue area. Simultaneous mass-radius measurements of PSR J0030+0451 and J0740+6620 by NICER [7, 9] (6, 8) are shown as green dashed and brown shaded regions representing 68% confidence limits, respectively.

4. Luminosities of DM accreting NS. — Using the computational inputs discussed in section 3, we now compute the luminosities of NS from DM accretion heating. For each set of (M, R) given by EoS i we compute the DM geometric capture rate averaging over DM phase space parameters through

\[ C_{i,j}^g(M, R) = \kappa \int \frac{d\nu_s p_j(\nu_s)C_{i,i}^g(i, \nu_s, \nu_d, \rho_\gamma)}{\nu_d}, \]

where, \( j = 1, 5 \) corresponds to the different velocity probability distributions \( p_j \) of NS discussed above, and the averaging coefficient \( \kappa = (l_{\text{max}} k_{\text{max}})^{-1} \). Integers \( k_{\text{max}}(=2) \) and \( l_{\text{max}}(=2) \) denote the number of values we sample for parameters \( \nu_d \) and \( \rho_\gamma \), respectively. When both kinetic and annihilation heating processes are operative, the effective surface temperature \( T_{\text{avg}}^\gamma \) is obtained by summing both contributions \( (m_i (\gamma - 1) + m_j)C_{i,j}^g \) and equating it to the apparent luminosity (see eq. (3)). Next, we average over the NS velocity distributions by \( \langle C_{i,j}^g \rangle = \sum_j \frac{C_{i,j}^g}{l_{\text{max}}} \) to get an effective average surface temperature \( T_{\text{avg}, i}^\gamma \). Assuming the NS to be a black body, we compute the spectral energy distribution (SED) as follows

\[ f_{\lambda}(M, R) = \frac{4\pi^2}{\lambda^3} \left( e^{\frac{\pi\lambda T_{\text{avg}, i}^\gamma}{\lambda}} - 1 \right)^{-1} \left( \frac{R \gamma}{d} \right)^2. \]

Here \( R \) and \( d \) are the radius (typically 10 km) and distance (taken to be \( d=10 \) pc) to the NS, and the factor \( R \gamma/d \) is the angle subtended by the NS to the observer. The flux density at a given wavelength \( \lambda \) is denoted by \( f_{\lambda}(M, R) \), and \( T_{\text{avg}}^\gamma \) is the surface temperature of the NS (see eq. (3)). In Fig. 2 (left panel), we display the SEDs due to KA heating, encompassing the temperature range for each combination of mass and radius shown in Fig. 1, and NS velocity PDFs discussed above.

We consider three scenarios for the NS luminosity. The MAX scenario is obtained for the NS EoS WFF-1 and the 1E velocity PDF, while, the MIN scenario is realized by EoS PAL-1 and bimodal velocity PDF. The MED scenario, however, is obtained by averaging over all NS velocity PDFs, and corresponds to EoS AP3. The maximal

FIG. 2. Left panel: Range of black body spectral energy distributions for the case of kinetic+annihilation heating for old isolated NS at 10 pc are shown in red. The thick solid line, dashed line, thin line, correspond to effective temperatures of 2639 K, 2190 K, 1564 K, and mass (radius) of \( M = 1.99 M_\odot \) (10.05 km), \( M = 1.5 M_\odot \) (12.07 km), \( M = 0.5 M_\odot \) (14.18 km), respectively.

Dashed lines delimit the bandwidth of filters F150W2 and F322W2. See text for details.
\[ T = \frac{\rho}{\chi} \cdot \frac{1}{\sqrt{M}} \] 

The very faint nature of the targets requires integration times longer than 1000 s, therefore observations will require the DEEP8 readout pattern in order to minimize data volume. Given that this readout pattern will be strongly affected by cosmic-rays, we assumed 21 dithers. From this figure, it is seen that NS with maximal KA heating (MAX) has excellent prospects to be detected at SNR \( \sim 5-10 \) in <15 hrs of observing time with F150W. Detecting MED scenario is possible only at a SNR \( \sim 5 \) after 24 hrs of exposure (25 hr limit for a JWST small program) for the filter F150W.

### 4.2 Observational prospects:

In Fig. 3, we summarize the prospects of detecting KA heated isolated old NS located at 10 pc distance. In the effective temperature vs NS mass plane, we plot contours of SNR = 2, 5, 10 for exposure times of 24.3 hrs (5.5 hrs) in solid (dashed) red, obtained by imaging through the F150W2 filter. The absolute maximum (minimum) temperatures for each NS mass are plotted with black thick (thin) curves. The dashed line represents the temperature obtainable upon averaging over the inputs \( \rho_1, v_\perp, v_\parallel \) for EoS AP3. We find that the prospect for detection at SNR \( \geq 10 \) of KA heated isolated NS is realized for the heaviest NS \( \sim 2 M_\odot \) in our sample, corresponding to \( T^\infty \geq 2350 \) K. While the prospect for detection of lightest of the NS \( \leq 1 M_\odot \) in our sample is not encouraging.

For a given M-R, the SNR typically increases with the surface temperature, however, close to the \( T_{KA}^{\text{max}} \) curve the SNR contours display features that bend rightwards. This is because the luminosity is proportional to the radius of the NS which varies while scanning through the EoS. The kink in \( T_{KA}^{\text{max}} \) curve at \( M_{NS} = 2.1 M_\odot \) is due to a jump from the end point of EoS WFF-1 to another.

For the scenario involving only kinetic heating, the maximum temperature is \( \sim 2120 \) K for a NS of \( 2.1 M_\odot \) and 9.56 km, corresponding to EoS WFF-1 and NS velocity PDF 1E. For this case, after 24.3 hrs of exposure through the F150W2 filter, a maximum SNR \( \sim 5 \) can be obtained. As shown in this section, detecting old cold NS with JWST has good prospects.
prospects, however, observational implementation will require assembling candidate target lists for such objects through deep surveys from space and ground based facilities, such as the WFIRST or Vera C. Rubin observatory.

5. Conclusion.— DM from the halo can accrete on to old NS leading to anomalous heating of these objects during late evolutionary stages [18]. Leveraging this argument, it was pointed out in ref. [17] that NS heated by DM could be observable by a state-of-the-art facility such as the JWST, and that the discovery of sufficiently cold and old NS in the local bubble would constrain the interactions of particle DM with the Standard Model in a model independent way.

In this letter, we have quantified the observational prospects for maximal (kinetic and annihilation) DM heating scenario of NS, corresponding to geometric values of scattering cross section $\sim 10^{-45}$ cm$^2$. The effective surface temperature of NS due to DM heating depends on the NS mass and radius through the EoS, the NS velocity in the local bubble, DM velocity and number density. The corresponding variations of the effective surface temperature has been assessed together with its impact on the observability of such NS using the NIRCAM instrument on the JWST. Our study implies that NS warmer than $\gtrsim 2600$ K, in the local bubble, are observable with strategies requiring shorter exposure times than discussed here. Such scenarios can be realized in a particle physics model dependent way through ‘Auger effect’, if DM is charged under baryon number [75–77], or through DM capture from a clumpy halo with large boost factors [78], or due to other internal heating mechanisms [15, 42]. Observation of such NS would not only shed light on late evolutionary stages, but also on their equation of state.

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