Dark matter effects on the thermal properties of the neutron star

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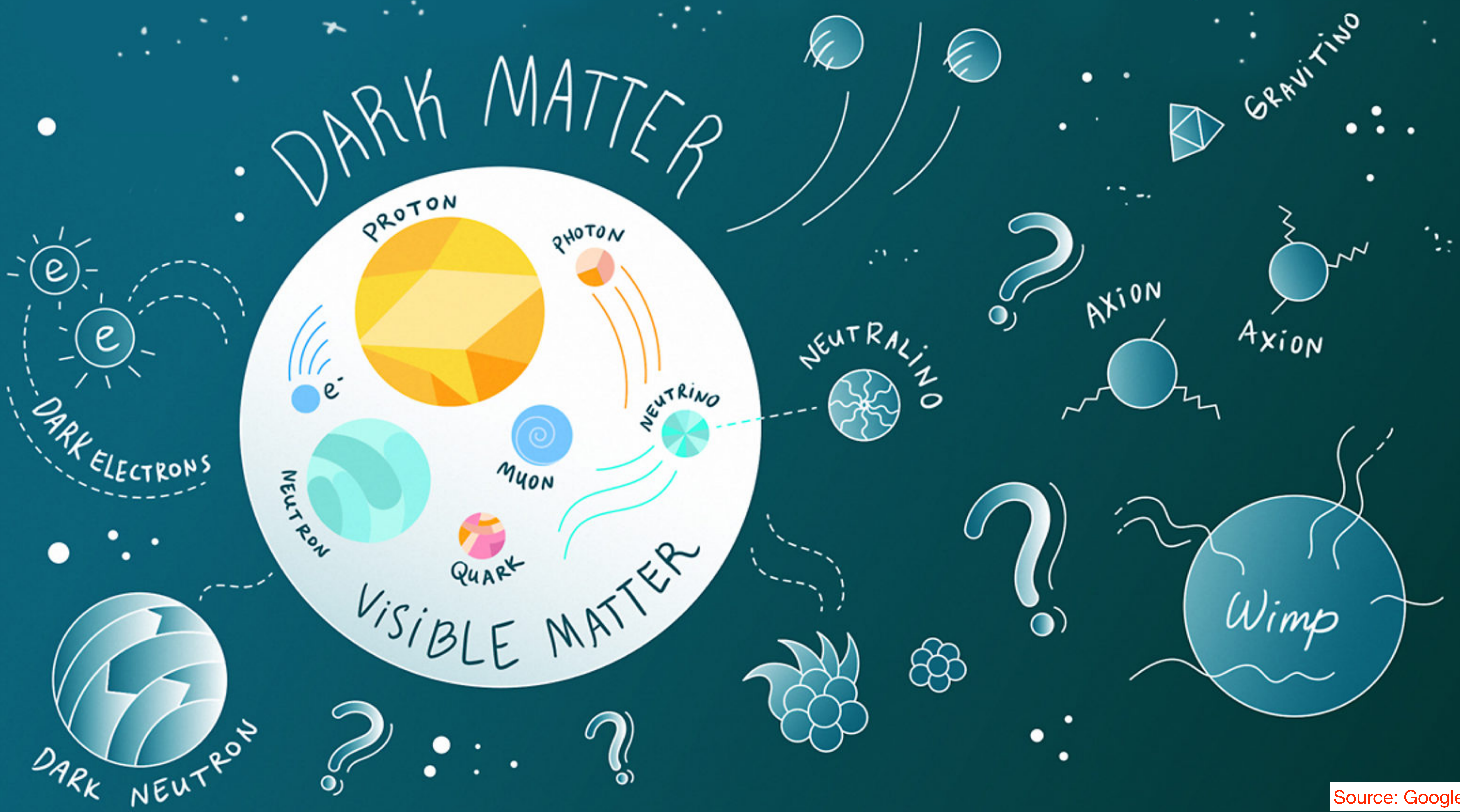

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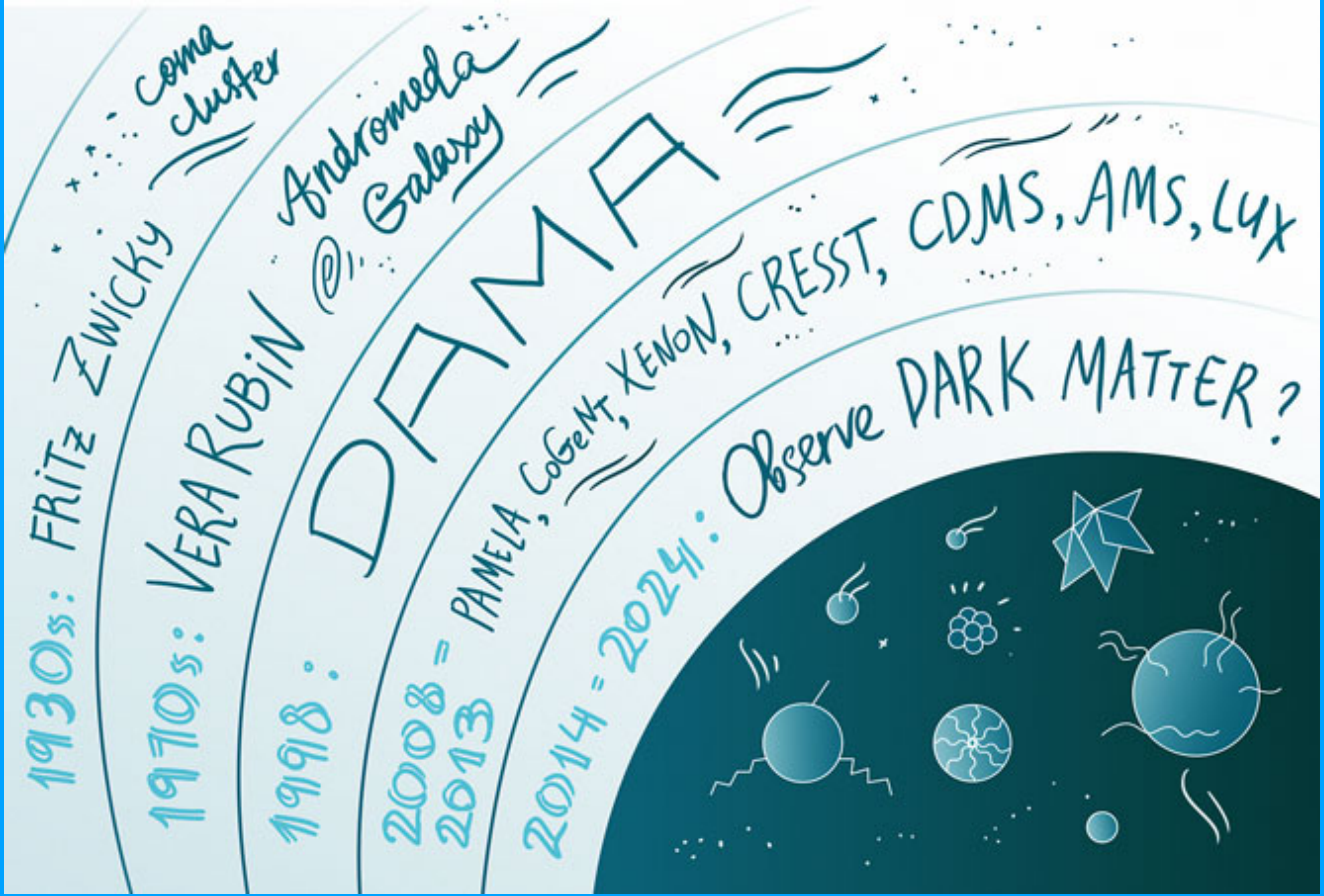
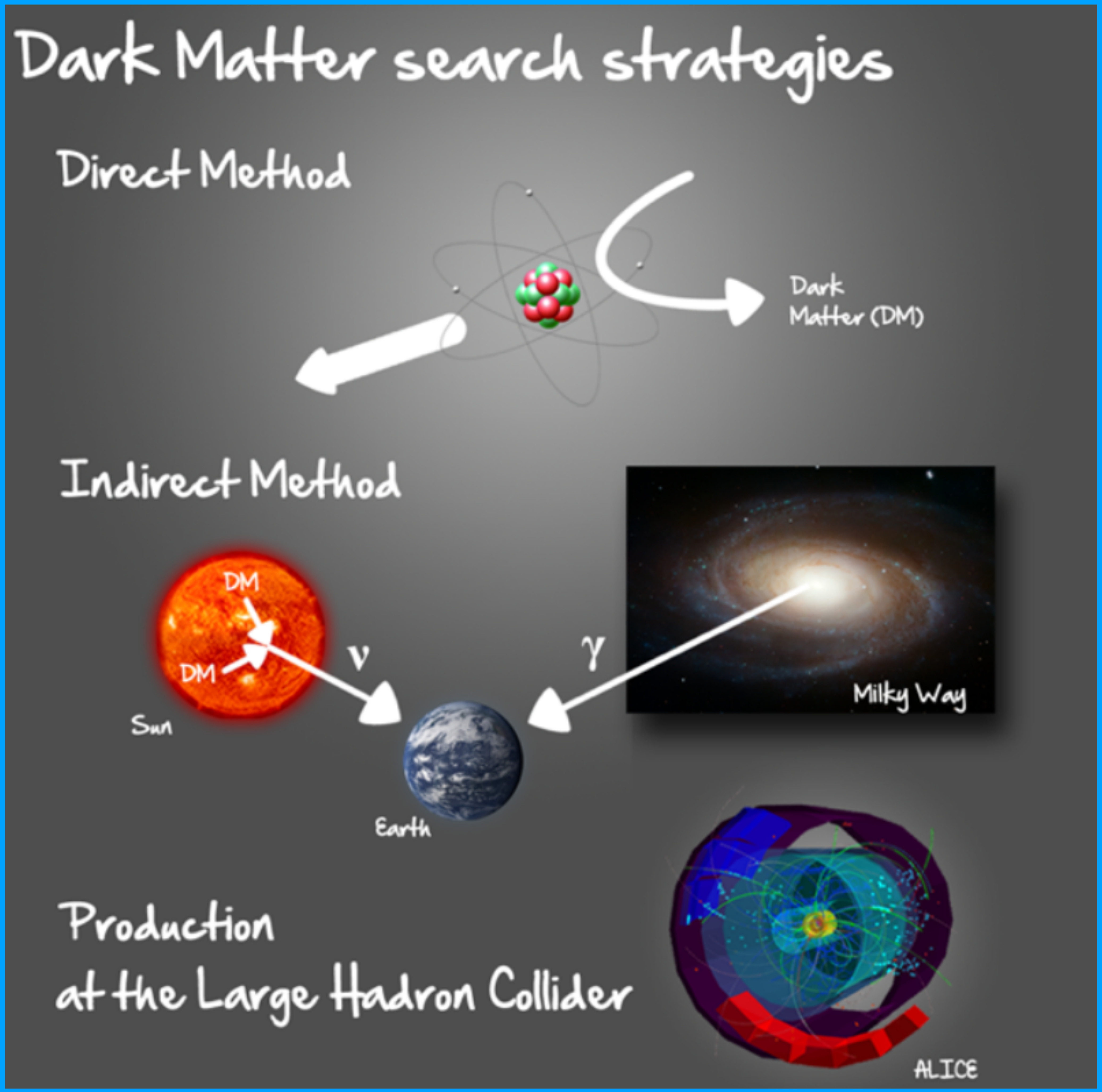
Observational Hints and Detections





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Neutron Star

(A Natural Dark Matter Detector)

- Neutron Star is a highly dense compact object → $M \sim 2.0\ M_{\odot}$ and $R \sim 10$ km.
- A certain amount of dark matter accumulated inside the neutron star (before and after its born).
- The dark matter undergoes scattering with nucleons and transfer its energy and captured inside the star.
- The amount of dark matter inside the NS depends on (i) velocity, mass and density of DM (ii) mass, radius of the NS etc.

Goldman and Nussinov PRD 40, 3221 (1989), Bertone and Fairbairn PRD 77, 043515 (2008)

Neutron Star

(Natural Dark Matter Detector)

- The accreted dark matter particles heat the neutron star through kinetic and annihilating process. Kouvaris PRD 77, 023006 (2008)

- The mechanism of producing heat in neutron star depends on the amount of dark matter and its mass.

- The effective temperature varies ~40% (2550 K) which in the range of near infrared wavelength. Chatterjee et al. PRD 108, L0021301 (2023)

- James Webb Space Telescope, Thirty Meter Telescope, European Extremely Large Telescope can able to detect the infrared peaks in the upcoming year.

Baryakhtar et al. PRL 108, 131801 (2017), Chatterjee et al. PRD 108, L0021301 (2023)

- Therefore, future observations of dark sector-warmed neutron stars could be the potential source of the detection of dark matter.

Dark Matter Models

One Fluid

- Dark matter interacts with nucleons via exchanging bosons (Higgs).
- Particle - Fermionic → WIMP (Neutralino)
- $\mathscr{L} = \bar{\chi}[i\gamma^\mu \partial_\mu - m_\chi + yh]\chi + \frac{1}{2}\partial_\mu \partial^\mu h - \frac{1}{2}M_h^2 h^2 + \frac{fM_n}{v}\bar{\psi}h\psi$
- Free parameters
  $\rightarrow m_\chi, f_\chi, f_p = 0.35, \text{ and } y = 0.07$
- $m_\chi = 100 - 10000 \text{ MeV}, f_\chi = 0 - 30\,\%$

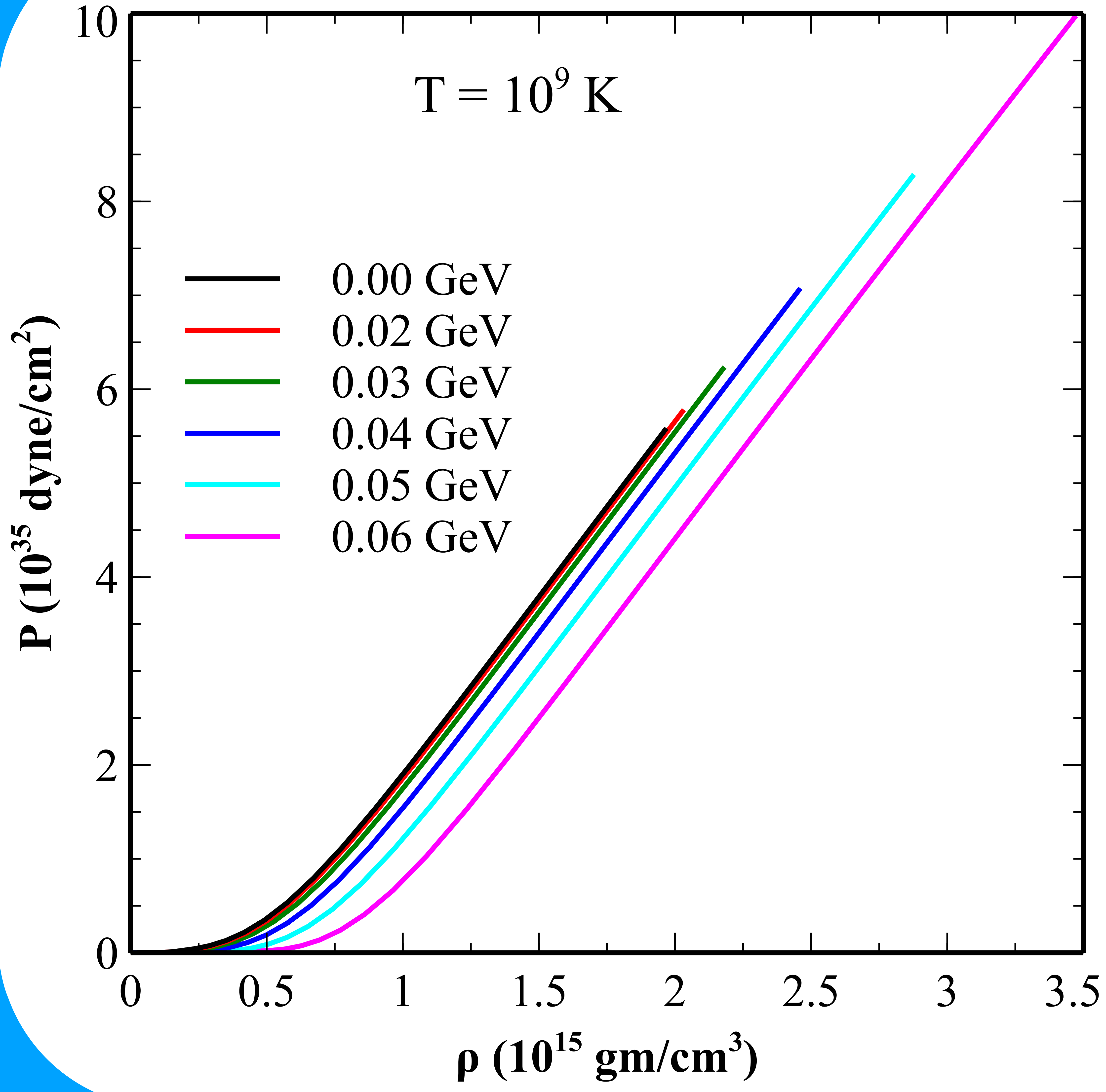
Kumar, Das and Patra, MNRAS 513, 1820 (2022)

Two Fluid

- Dark matter interacts only via Gravity.
- Particle - Fermionic/Bosonic
- Either annihilating/non-annihilating or asymmetric etc.
- $\mathscr{L} = (D_\mu \chi)^*(D^\mu \chi) - m_\chi^2 \chi^* \chi$
- Free parameters $\rightarrow m_\chi \text{ and } f_\chi$
- $m_\chi = 100 - 1000 \text{ MeV}, f_\chi = 0 - 30\,\%$

Nelson, Reddy and ZHPU, JCAP 07, 012 (2019)

EOS, Mass and Radius of Dark Matter admixed Neutron Star



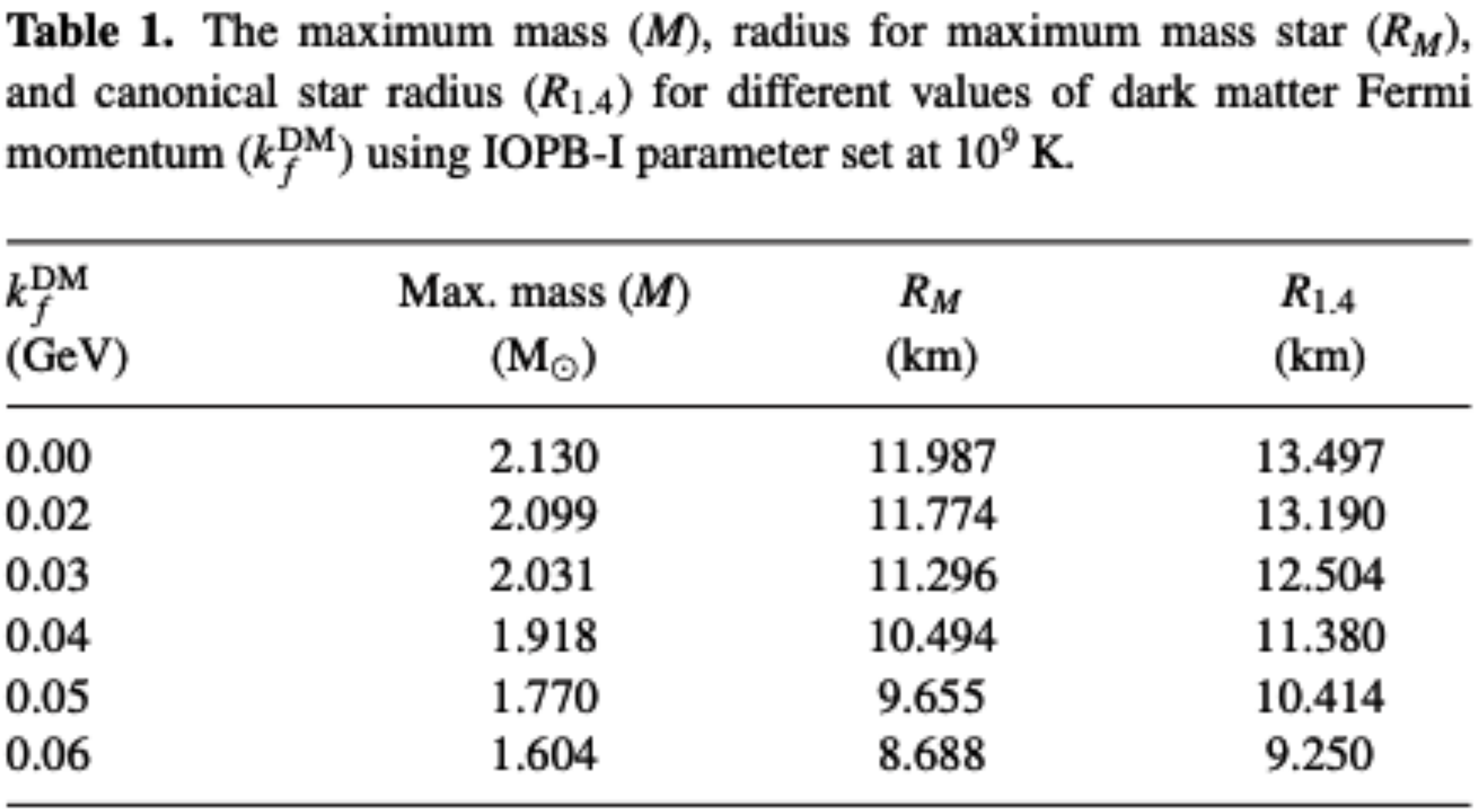


Table 1. The maximum mass (M), radius for maximum mass star (R_M), and canonical star radius ($R_{1.4}$) for different values of dark matter Fermi momentum (k_f^{DM}) using IOPB-I parameter set at 10^9 K.

k_f^{DM} (GeV)	Max. mass (M) ($M_\odot$)	R_M (km)	$R_{1.4}$ (km)
0.00	2.130	11.987	13.497
0.02	2.099	11.774	13.190
0.03	2.031	11.296	12.504
0.04	1.918	10.494	11.380
0.05	1.770	9.655	10.414
0.06	1.604	8.688	9.250

Kumar, Das and Patra, MNRAS 513, 1820 (2022)

Cooling of Neutron Star

$$\frac{\partial}{\partial r}(Le^{2\phi(r)}) = -\frac{4\pi r^2 e^{\phi(r)}}{\sqrt{1-\frac{2GM}{c^2 r}}}\left(C_V\frac{\partial T}{\partial t} - e^{\phi(r)}(Q_\nu + Q_h)\right)$$
$$\frac{\partial}{\partial r}(Te^{\phi(r)}) = -\frac{L}{\kappa\, 4\pi r^2}\frac{e^{\phi(r)}}{\sqrt{1-\frac{2GM}{c^2 r}}}$$

L → Luminosity (both neutrino and photon) $t, \phi(r)$ → time and gravitational potential

C_v → Specific heat (heating of the electron gas and nucleon), $C_v = \sum_i \frac{M_i^* n_i}{k_{Fi}^2}\pi^2 k_B T$

Q_ν, Q_h → Neutron emissivity for neutrino and heat production per uni volume (ignored in this study)
(URCA, mURCA, Plasmon decay, Bremsstrahlung etc.)

κ → Thermal conductivity, $\kappa_i = \frac{\pi^2 k_B^2 n_i T \tau_i}{3m_i^*}$

Throne APJ 212, 825 (1977)
Kumar, Das and Patra, MNRAS 513, 1820 (2022)

Neutrino Emissivity

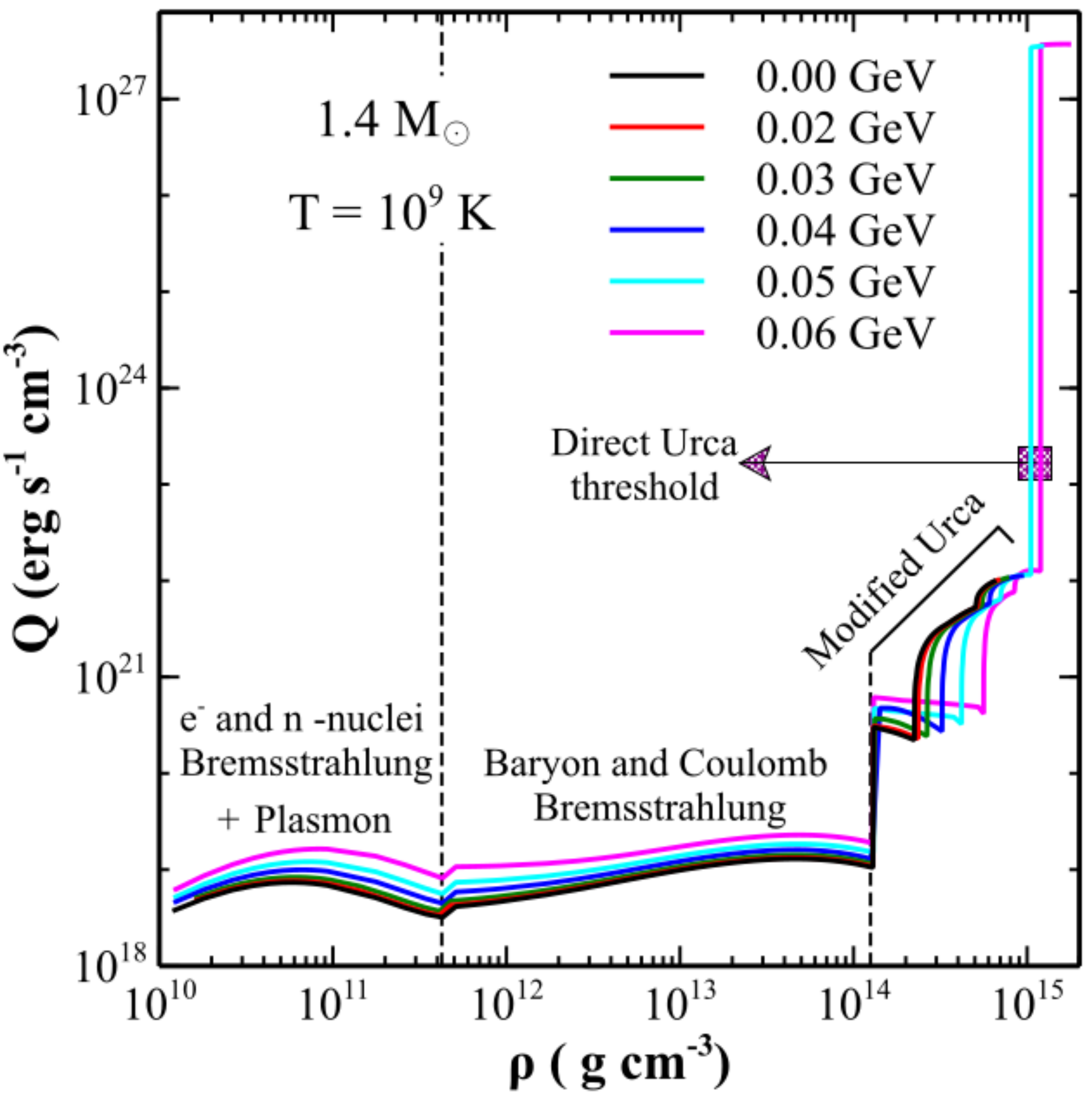
URCA Process

$$\left.\begin{array}{l} n \rightarrow p + e^- + \bar{\nu} \\ p + e^- \rightarrow n + \nu \end{array}\right\} Q \propto T^6$$

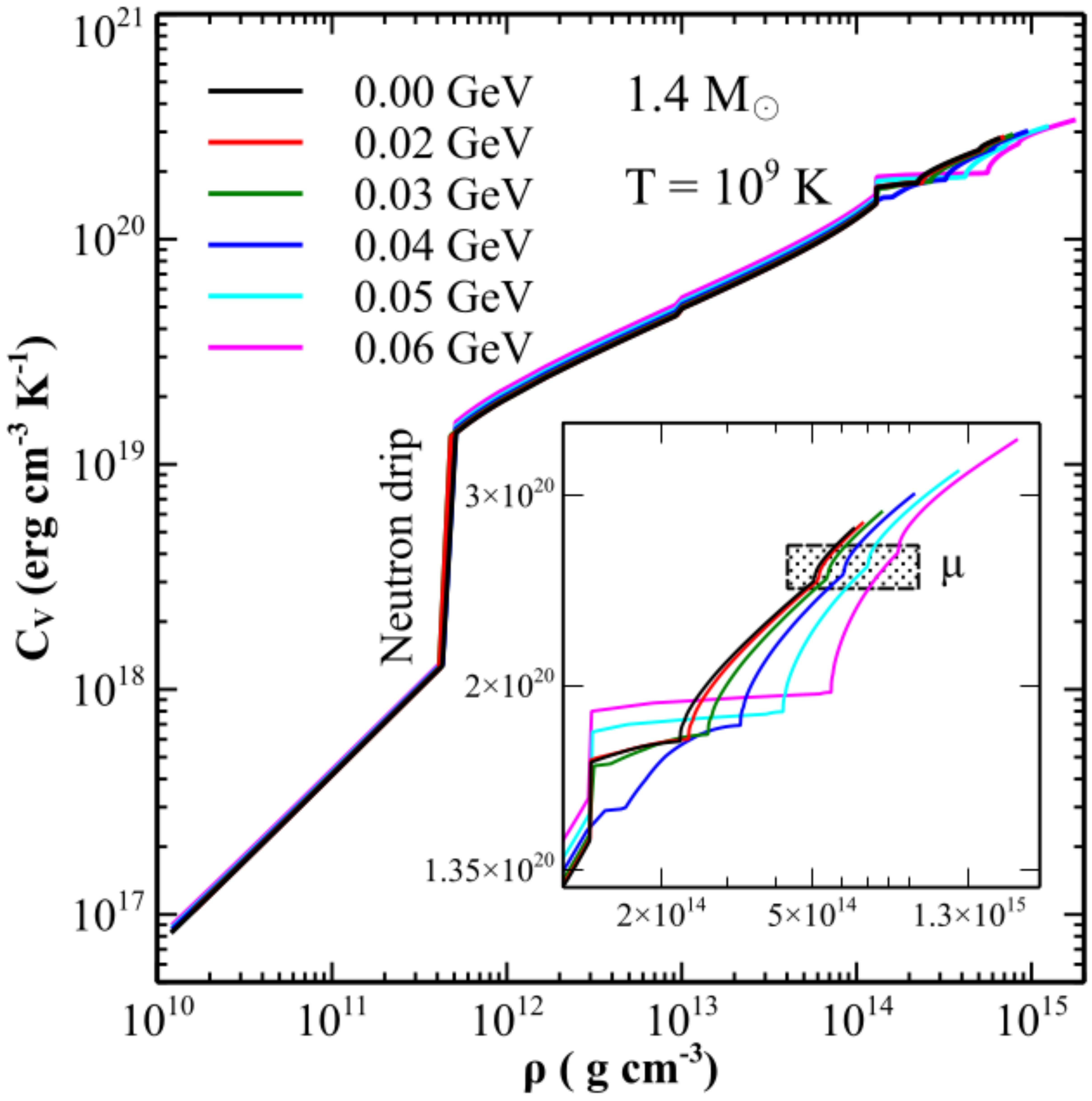
Modified URCA Process

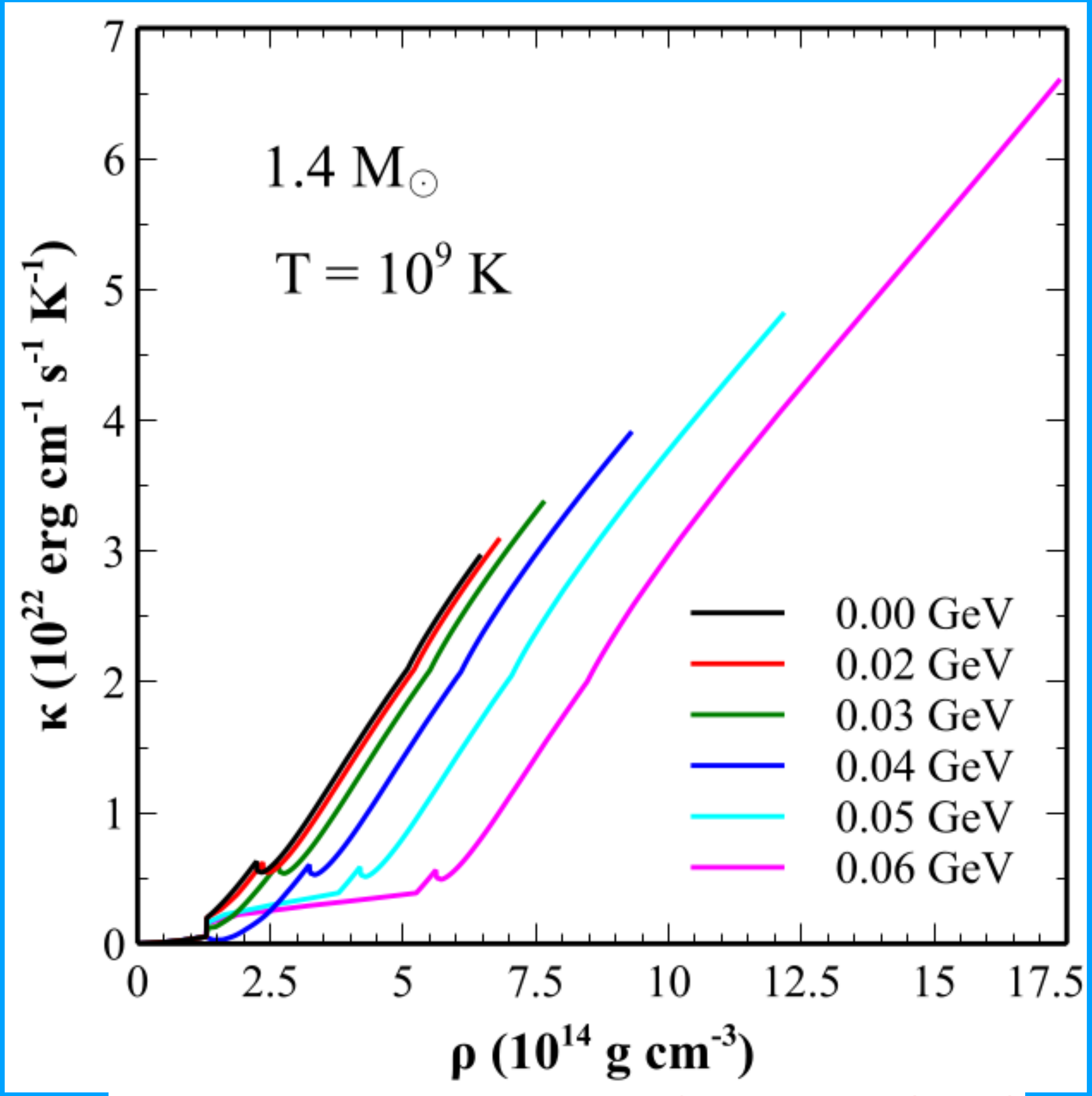
$$\left.\begin{array}{l} n + N \rightarrow p + N + l + \bar{\nu}_l \\ p + N + l \rightarrow n + N + \nu_l \\ N + N \rightarrow N + N + \nu + \bar{\nu} \end{array}\right\} Q \propto T^8$$

Kumar, Das and Patra, MNRAS 513, 1820 (2022)



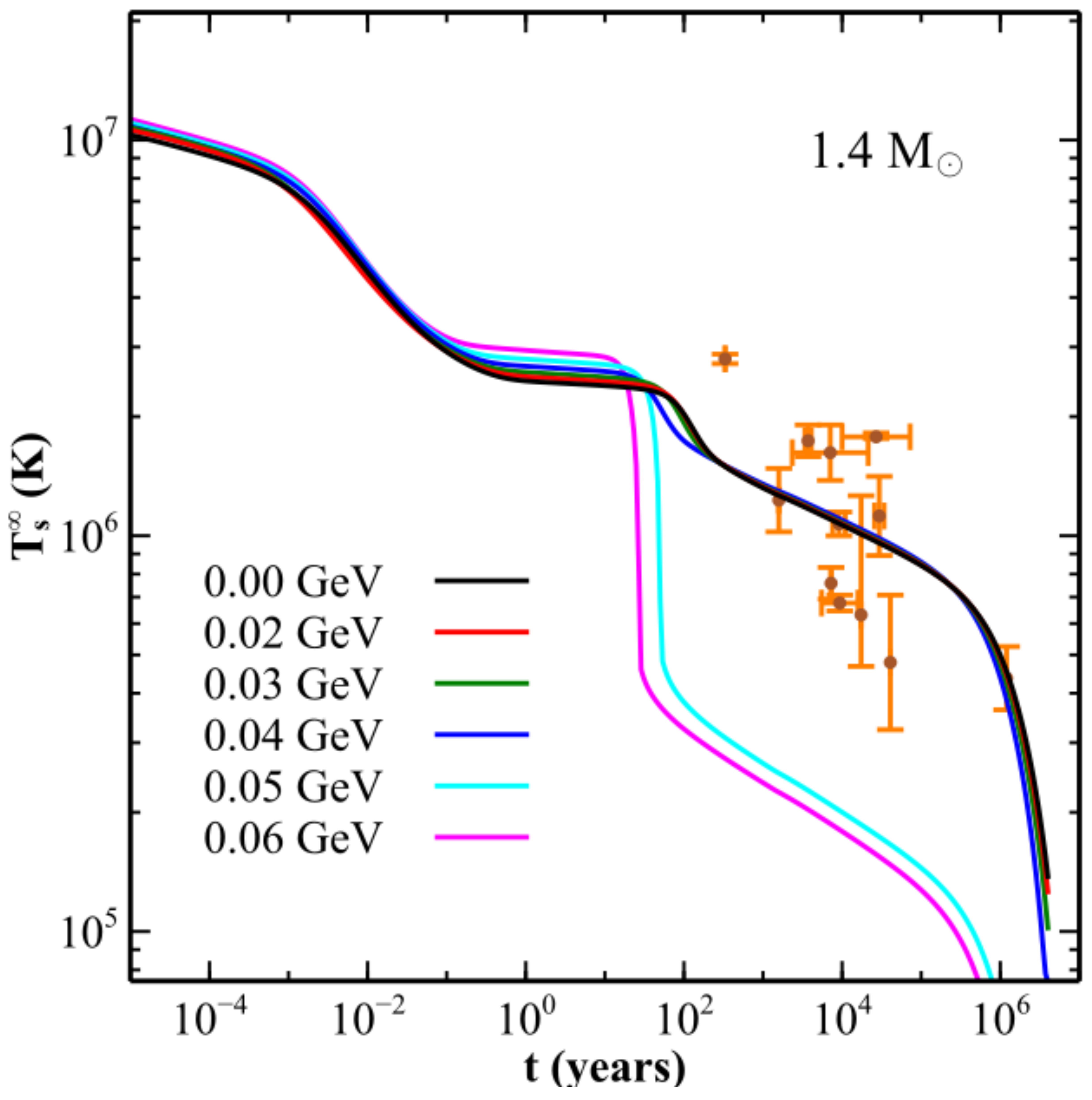
Specific Heat and Thermal Conductivity

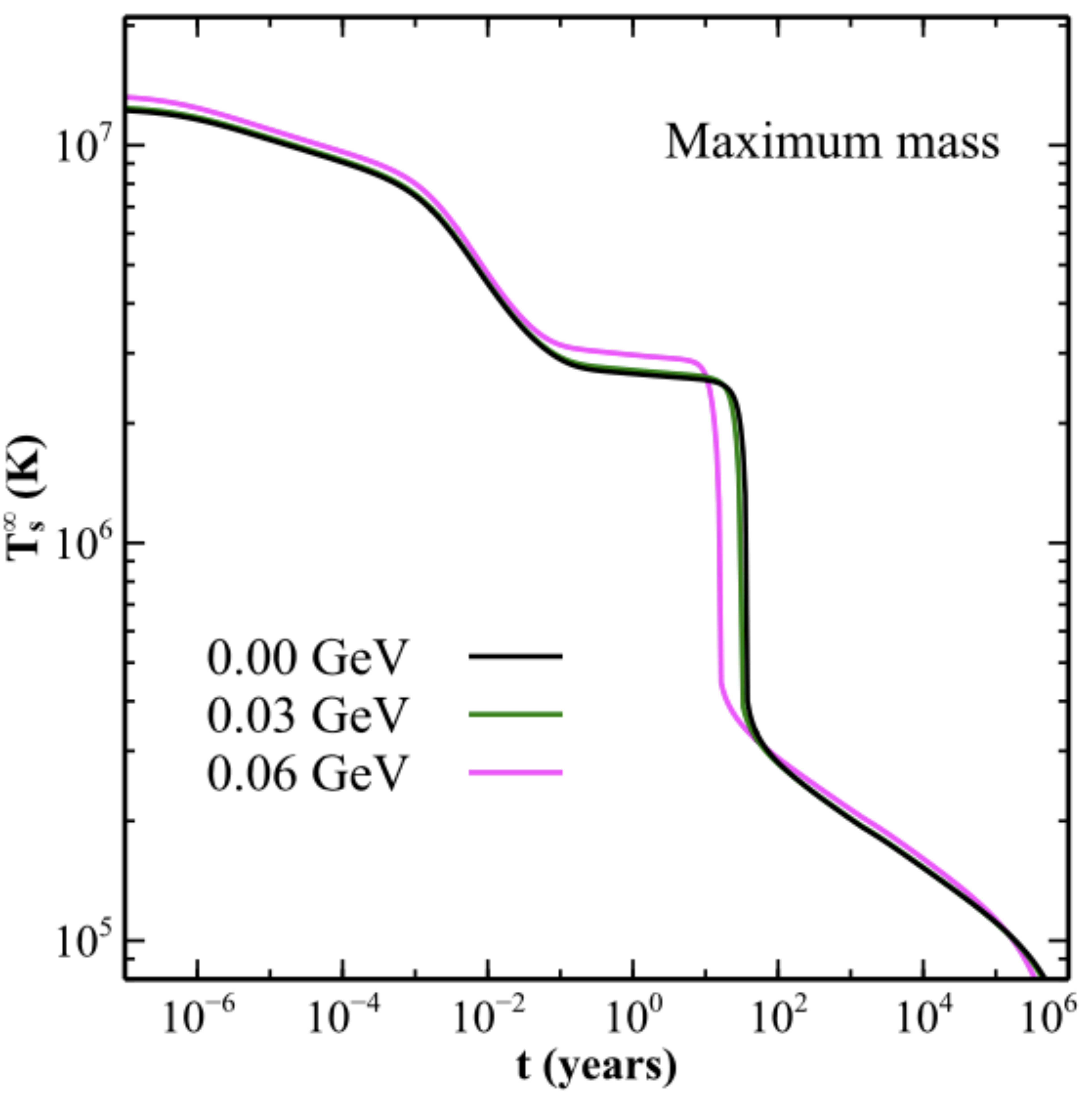




Kumar, Das and Patra, MNRAS 513, 1820 (2022)

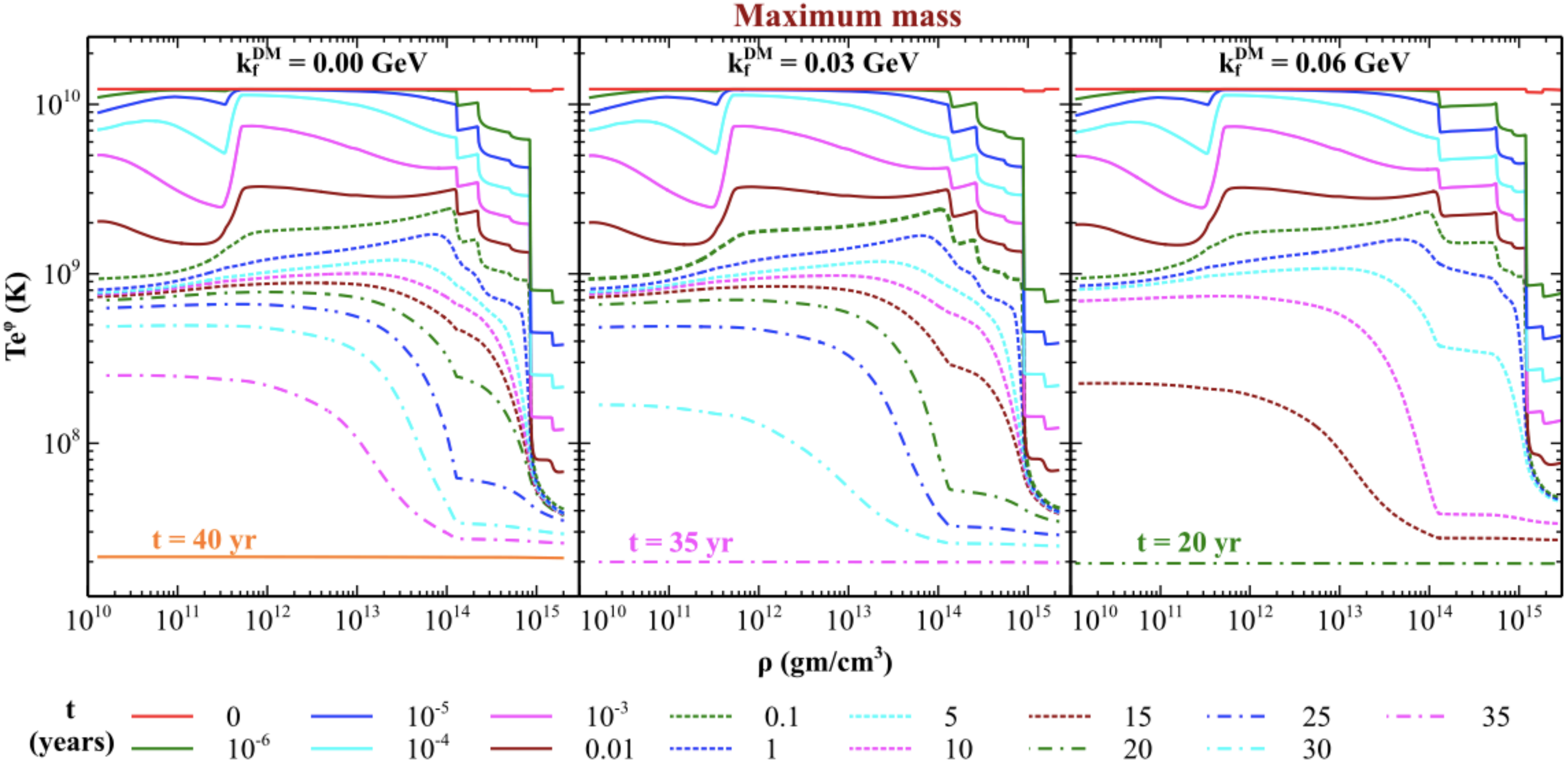
Cooling Curves



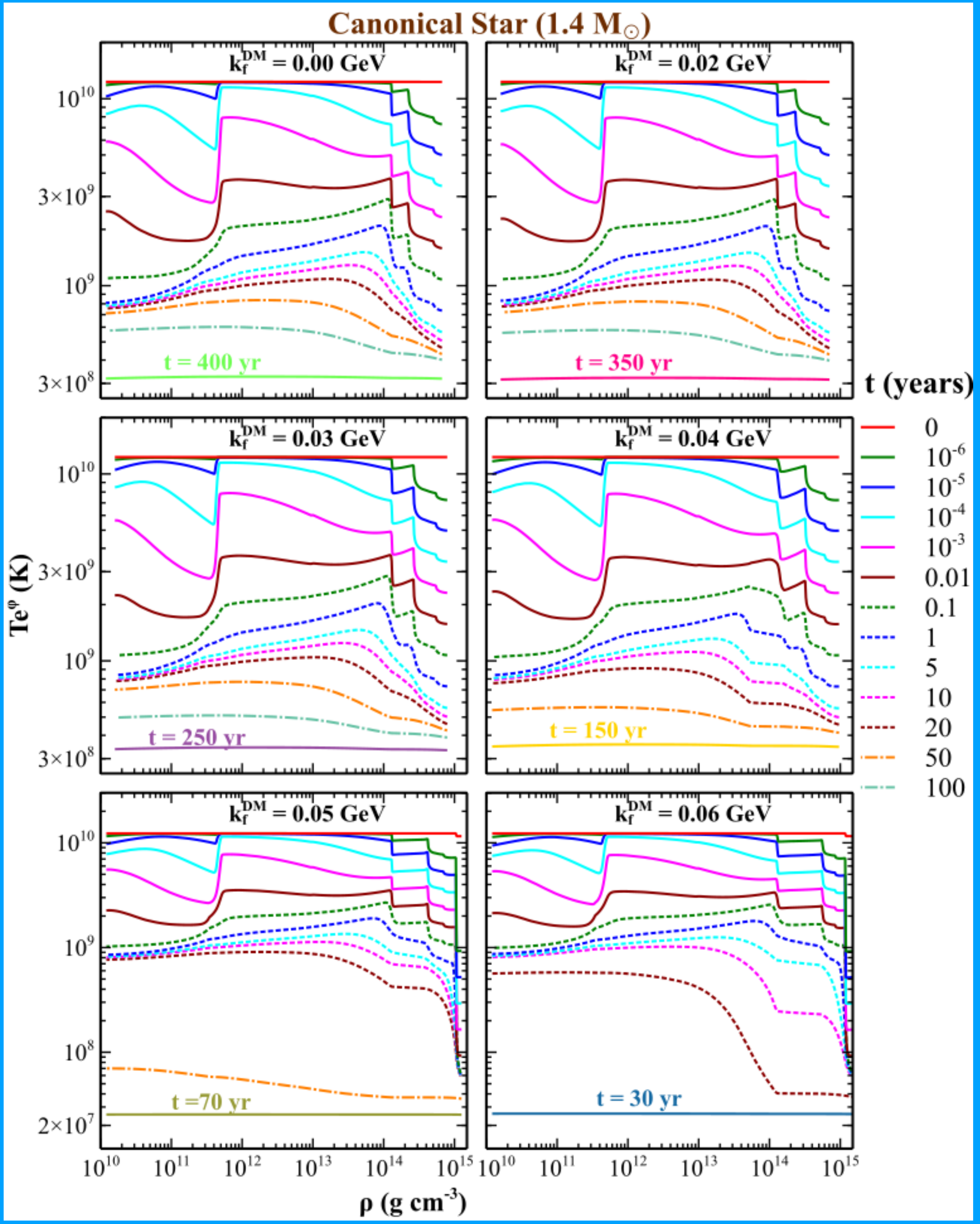


Kumar, Das and Patra, MNRAS 513, 1820 (2022)

Thermal Relaxation

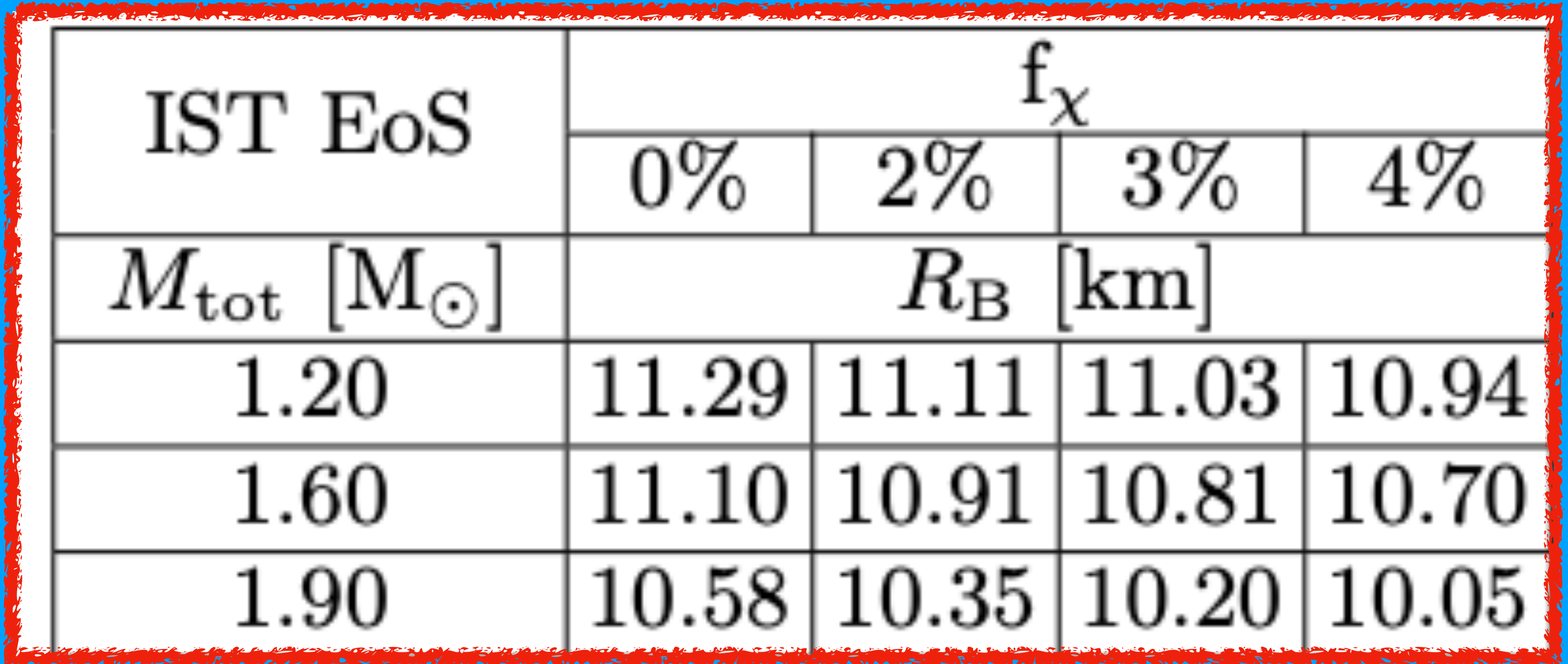


Kumar, Das and Patra, MNRAS 513, 1820 (2022)

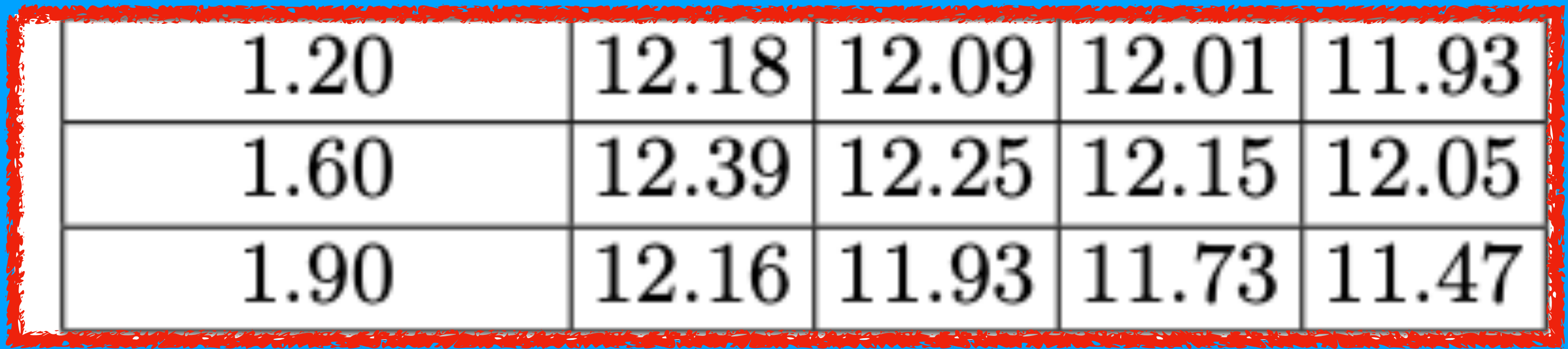


Dark Matter Percentage (GeV)	RelaxationTime (Years)
0.00	400
0.02	350
0.03	250
0.04	150
0.05	70
0.06	30
For maximum mass configuration	
0.00	40
0.03	35
0.06	20

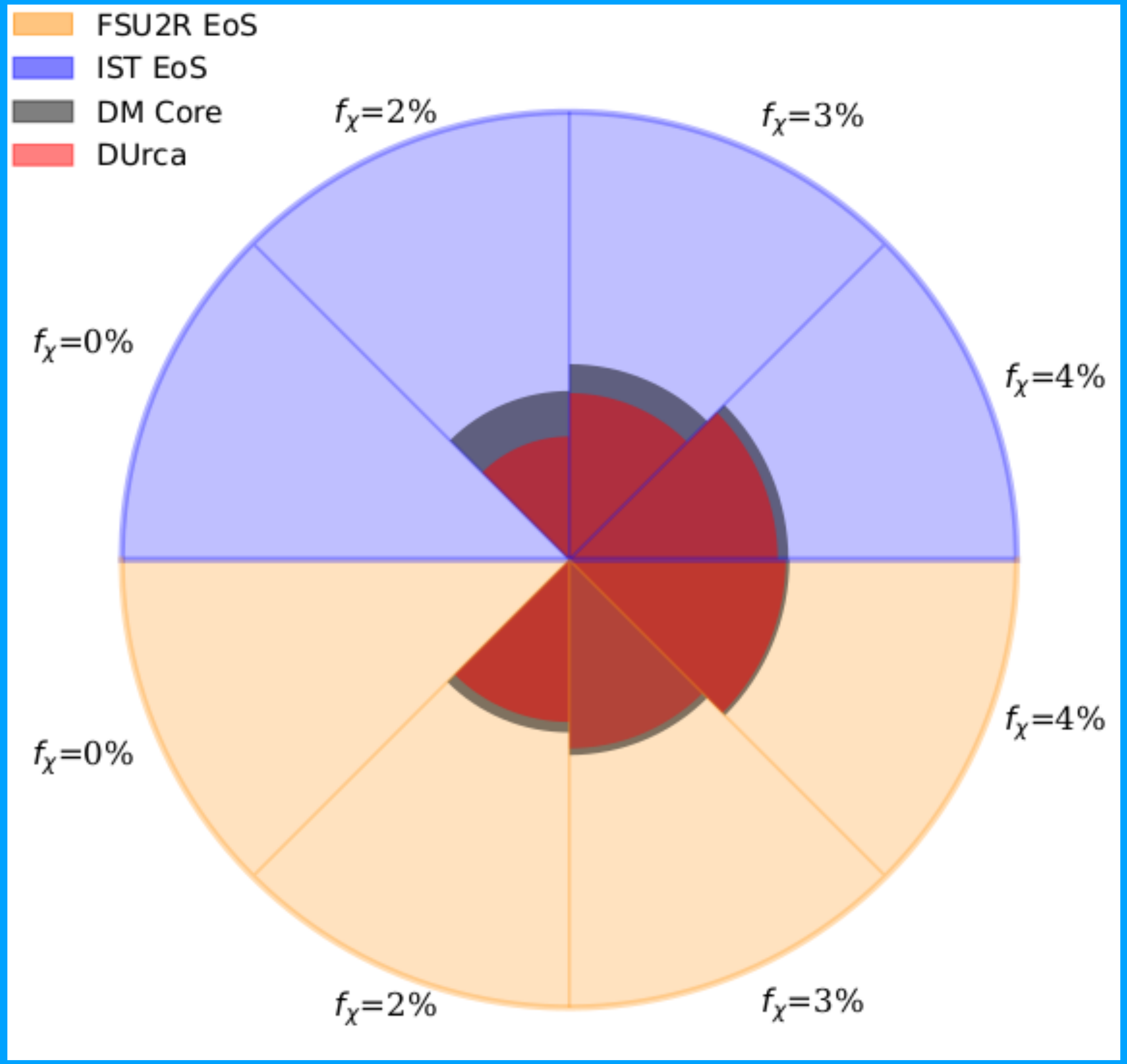
2-Fluid Cooling

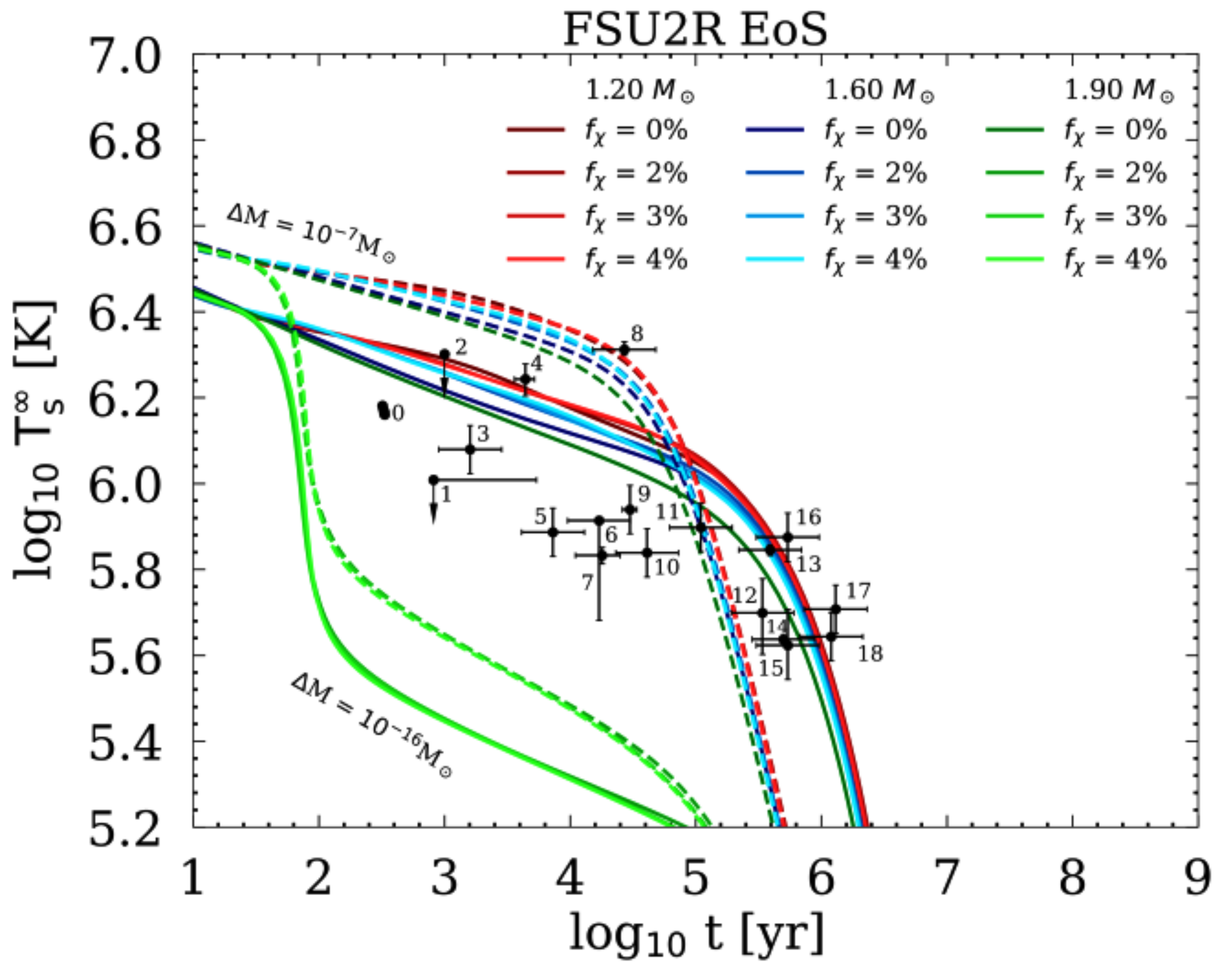


IST EoS	f_χ			
	0%	2%	3%	4%
$M_{\rm tot}$ [$M_\odot$]	R_B [km]			
1.20	11.29	11.11	11.03	10.94
1.60	11.10	10.91	10.81	10.70
1.90	10.58	10.35	10.20	10.05



1.20	12.18	12.09	12.01	11.93
1.60	12.39	12.25	12.15	12.05
1.90	12.16	11.93	11.73	11.47





Avila et al., MNRAS 528, 6319 (2024)

Extension of this work

- The extension of the work is needed to understand the cooling behaviour of different neutron stars/pulsars.
- I am working with Fiorella Burgio and Hans Josef Schulze for this extension.
- The microscopic (V18) and RMF (DD2 and TW99) models are taken for our work. (soon be communicated).
- Already, we roughly estimate the mass distribution of some isolated pulsars with the help of the cooling observational data.
- However, more cooling data needed for the good estimation.

Conclusion

- The thermal properties of the dark matter admixed neutron star are explored in this study.
- Single fluid (boson exchange) and Two-fluid (gravity) scenarios are taken for dark matter-nucleons interaction.
- Important thermal properties neutrino emissivity, heat capacity, thermal conductivity and cooling of the neutron star admixed with dark matter are obtained within the RMF model.
- Dark matter has significant affect mainly on neutrino emissivity and cooling of the star.
- Fast cooling scenario both for single and two fluid depends on the percentage of DM.
- The time required for the thermal relaxation between core and crust is reduced for the star, if it's more than 30%.
- With the help of future observation from JWST and other telescope data, we can find the hint of DM inside the NS.

Source: Google

THANK YOU