EFFECT OF DARK MATTER IN COMPACT REALISTIC NEUTRON STARS MATTER

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INTRODUCTION

Summary of dark matter evidence:
85% of matter in the universe is of unknown nature
Normal matter: ~15% of total matter
Is dark matter an elementary particle?

No known particle can be nonbaryonic cold dark matter!
What do we know about dark matter?

Mostly have “negative” information from astrophysics and searches for new particles:

- No electric charge
- No colour charge (property of quarks and gluons that is related to the particles' strong interactions)
- No strong self-interaction
- Does not seem to decay: stable, or very long-lived
- Not a particle in the Standard Model of particle physics
Approaching dark matter theories

**Top down:**
Begin with theory motivation (hierarchy problem, strong CP problem.) develop model (SUSY [supersymmetry], axion) look for stable, neutral particle (LSP [light supersymmetric particle], axion)

**Bottom up:**
Motivated often by specific experimental anomalies, theories constructed. Implications for other experiments (and often SUSY)

**Phenomenological:** Motivated by considering whether a viable and detectable model could exist of a certain type.

Our most **conservative idea for dark matter:**
Some exotic particle that we have not yet detected [note: it does not have to be just one particle]

Two most important parameters of such particles
(1) **Mass** and (2) **Strength of interaction with normal matter**
How to search for dark matter particles

Annihilation in core of Sun
\[ \chi \chi \rightarrow \nu^+ \ldots ? \]
galactic center, galaxies, \( \rightarrow \gamma^+ \ldots ? \)

- Indirect detection
- Direct detection
- Production at LHC

Search for things
dark matter can decay to
\[ \chi \chi \rightarrow e^+ e^- , pp \]

Annihilation in galactic halo

Build a trap for dark matter
\[ \chi N \rightarrow \chi N \]

Scattering on nucleus in Lab.

Make dark matter particles
\[ p + p \rightarrow \chi + \text{a lot} \]

Hadron-hadron collider

Supersymmetric lightest neutralino \( \rightarrow \) fermionic DM \( (\chi) \),
interact with nucleon by exchanging standard model Higgs boson
Dark matter effect on relativistic nuclear EOS model

\[ L = L_{\text{had}} + \chi \left( i \gamma \mu \partial^\mu - M + \nu h \right) \chi + \frac{1}{2} \partial^\mu h \partial^\mu h - V(h) + \frac{f m_N}{V} \Psi h \Psi \]

The relativistic nuclear model is consider here is Chiral Sigma Model

\[ L_{\text{had}} = \frac{1}{2} \left( \partial^\mu \pi \cdot \partial_\mu \pi + \partial^\mu \sigma \cdot \partial_\mu \sigma \right) - \frac{1}{4} F_{\mu \nu} F^{\mu \nu} \]

\[ - \frac{\lambda}{4} \left( x^2 - x_0^2 \right)^2 - \frac{\lambda b}{6 m^2} \left( x^2 - x_0^2 \right)^3 - \frac{\lambda c}{8 m^4} \left( x^2 - x_0^2 \right)^4 \]

\[ - \sum_i g_\sigma \overline{\psi}_i \left( \sigma + i \gamma_5 \tau. \pi \right) \psi_i + \overline{\psi}_i \left( i \gamma \mu \partial^\mu - g_\omega \gamma_\mu \omega^\mu \right) \psi_i \]

\[ + \frac{1}{2} g_\omega^2 x^2 \omega_\mu \omega^\mu + \frac{1}{24} \xi g_\omega^4 \left( \omega_\mu \omega^\mu \right)^2 - D \sigma \]

Where \( F_{\mu \nu} \equiv \partial_\mu \omega_\nu - \partial_\nu \omega_\mu \) and \( x^2 = \pi^2 + \sigma^2 \).

\[ m = g_\sigma x_0 \quad m_\sigma = \sqrt{2\lambda} x_0 \quad \text{and} \quad m_\omega = g_\omega x_0 \]

DM-Higgs Yukawa coupling

Nucleon-Higgs Yukawa coupling

PRD 96, 083004 (2017)

PKS et al, PRC 81,014002 (2010)
\[ V(h) = \frac{1}{2} M_h^2 h^2 - \lambda V h^3 - \frac{1}{4} \lambda h^4 \]

**Higgs potential along with higgs mass term**

**Applying mean-field approximation to model**

\[ g_s = g_\sigma, \ g_v = g_\omega \]

\[ \varphi_0 = \sigma_0, \ V_0 = \omega_0 \]

\[ m^i_* = -g^i_s \varphi_0 - fh_0 \]

\[ M^* = M - yh_0 \]

\[ h_0 = \frac{f n_s(m^n_*) + y n_s(M^*)}{M_h^2} \]

Parameters: \( g_s, g_v, b, c, D \); nuclear matter: B.E.=-14.5 MeV, Saturation density=0.14fm\(^{-3}\) and \( K=327 \) MeV; PKS,Tsubakihara and Ohnishi, PRC 81,014002, (2010)

\( M^\chi=200 \text{ GeV}, y=0.07 \) (free parameters in model), \( M_h=125 \text{ GeV}, f=0.3, v=246 \text{ GeV} \); supersymmetric lightest neutralino \( \chi \); Panotopoulos and Lopes PRD 96, 083004 (2017)
\[
\varepsilon = \varepsilon_{st}(m_{*}^{n}) + \varepsilon_{st}(M_{*}^{x}) + \frac{m_s^2 \phi_0^2}{2} + \frac{m_\omega V_0^2}{2} + \frac{M_{h}^2 h_0^2}{2}
\]

\[
p = p_{st}(m_{*}^{n}) + p_{st}(M_{*}^{x}) - \frac{m_s^2 \phi_0^2}{2} + \frac{m_\omega V_0^2}{2} + \frac{M_{h}^2 h_0^2}{2}
\]

\[
\varepsilon_{st} = \frac{2}{(2\pi)^3} \int_{0}^{k_f} d^3k \sqrt{k^2 + m_*^2}
\]

\[
p_{st} = \frac{1}{3} \frac{2}{(2\pi)^3} \int_{0}^{k_f} d^3k \frac{k^2}{\sqrt{k^2 + m_*^2}}
\]

\[
n_s = \frac{2}{(2\pi)^3} \int_{0}^{k_f} d^3k \frac{m_*}{\sqrt{k^2 + m_*^2}} \quad n_B = \frac{\gamma}{(2\pi)^3} \int_{0}^{k_F} d^3k,
\]

\[
n_D = n_B/(500-150); \quad K_{F} = 0.2-0.6 \text{ GeV}
\]
Neutron Star Matter Equation of State (EOS):

Charge neutrality using beta equilibrium: from weak decays

\[ \mu_p = \mu_n - \mu_e, \quad \mu_\Lambda = \mu_n, \]

\[ \mu_{\Sigma^-} = \mu_n + \mu_e, \quad \mu_\mu = \mu_e, \]

\[ n_p = n_e + n_\mu + n_{\Sigma^-}. \]

\[ n_B = n_n + n_p + n_\Lambda. \]
TOV equations for nonrotating Neutron Star: Gross Structure

Due to GR

\[
p'(r) = -(\varepsilon(r) + p(r)) \frac{m(r) + 4\pi p(r)r^3}{r^2(1 - 2m(r)/r)}
\]

\[
m'(r) = 4\pi r^2 \varepsilon(r)
\]

Surface redshift ratio \( \phi \):

\[
\phi = (1 - 2GM_g/Rc^2)^{1/2}
\]

Boundary condition to solve TOV equation

\[
m(r = R) = M, p(r = R) = 0,
\]

\[
m(r = 0) = 0, p(r = 0) = p_c, \varepsilon(r = 0) = \varepsilon_c
\]
• KD=0, without Dark Matter

• KD=0.2fm⁻¹, \(n_D \approx n_B/500\)

• KD=0.3fm⁻¹, \(n_D \approx n_B/150\)
• Without Dark Matter
Max. mass = 2.2
Solar mass,
$\phi = 0.5$, $I = 2.1 \times 10^{45}$ g/cm$^2$

• With $n_D \approx n_B/500$ Max. Mass $\approx 1.8$ Solar mass,
$\phi = 0.5$, $I = 1.6 \times 10^{45}$ g/cm$^2$

• If $n_D \approx n_B/150$, Max. Mass $\approx 1.7$ Solar mass, $\phi = 0.5$,
$I = 1.2 \times 10^{45}$ g/cm$^2$
Conclusion and Future outlook

- DM effect on EOS $\rightarrow$ makes EOS softer
- It does not affect composition of star particles ratios
- It affects only gross structure only.....
- As a result the maximum mass is within the range of observed mass $1.7 < M/M_\odot < 2.0$ (See the plenary talk by J. M. Lattimer and the current record is $2.01 \pm 0.04 M_\odot$, Science, 340, 448 (2013))
- Also, we checked the DM effect on Quark matter EOS $\rightarrow$ which again EOS is softer and maximum mass is much below the current record mass; range around $1.3-1.6 M_\odot$. 
Future outlook

- It may affect significantly the period of rotation and oscillation of the Neutron Star.

- Is Dark Matter affects to Heavy-ion Collisions such as including in Hadronic Models?


Thank you for your attention.