Dark Astronomical Extreme Compact Object (DAECO) and its implications

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Outline

Problems with Cold Dark Matter I

- Cusp-core problem: Simulation on Cold Dark Matter (CDM) has shown cuspy DM distribution (DM density increases at small radii) while rotational curves of most observed dwarf galaxies show that they have flat density distribution. Warm or self-interacting DM could produce DM core in low mass mass galaxies.

- Missing satellites: Overabundance of predicted number of MW dwarf satellites from CDM simulation compared to the number of satellite galaxies known to exist. There are 38 dwarf galaxies in Local Group and 11 orbiting Milky Way (MW) in compared to about 500 expected MW dwarf galaxies.

Problems with Cold Dark Matter II

- Too-big-to-fail problem: that the largest subhalos of the Milky Way are too massive to host the brightest observed dwarf spheroidal galaxy satellites as suggested by numerical simulations of Cold Dark Matter.

Inflationary Luminogenesis Model

- In the Inflationary Luminogenesis Model[1], it was assumed that there was an inflationary stage in the early universe. At the end of inflation, the inflatons decayed primarily to dark matter. Dark matter converted 15% of its energy density to luminous matter[2].

- Dark matter is represented by a gauge group which gets unified with electroweak gauge group $SU(2)$ at high energy scale Λ_{DUT} into $SU(6)$.

- Above Λ_{DUT}, the symmetry group $SU(3)_C \times U(1)_Y \times SU(6)$.

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[1] **P. Q. Hung**, **P. Frampton**, **arXiv:0903.0358[hep-ph]**.
[2] **P. Q. Hung**, **P. Frampton**, **arXiv:1309.1723v4 [hep-ph]**.

Inflationary Luminogenesis Model

Why $SU(6)$?[1]

- PAMELA results (2008)[2] observed an anomalous positron abundance in cosmic radiation where the origin of this excess may come from the decay of dark matter.
- Let the spin 1/2 dark matter field denoted by χ. To accommodate the PAMELA data, lifetime $\tau_{\bar{\chi}\chi}$ was studied:

$$\tau_{\bar{\chi}\chi} \sim \left(\frac{M_{DUT}^4}{M_{\bar{\chi}\chi}^5} \right) \sim 10^{26}(s)$$

  where $M_{DM} \simeq \mathcal{O}(2)$ TeV. Luminogenesis model was constructed to accomplish this life time.

- The unified gauge group is: $SU(3)_C \times SU(n+2) \times U(1)_Y$ where the $SU(n+2)$ will break according to:
  $SU(n+2) \rightarrow SU(n)_{DM} \times SU(2) \times U(1)$

[1] **P. Q. Hung, P. Frampton, arXiv:0903.0358[hep-ph].**
[2] **PAMELA Collaboration, arXiv:0810.4995.**

Inflationary Luminogenesis Model

- Let M_{DM} be the scale where $SU(n)_{DM}$ becomes strongly coupled. At M_{DUT}, we must have: $\alpha_2(M_{DUT}) = \alpha_{DM}(M_{DUT}) = \alpha_{DUT}$, which leads to:

$$M_{DUT} = M_{DM} exp \left[6\pi \frac{(\alpha_2^{-1}(M_{DM}) - \alpha_{DM}^{-1}(M_{DM}))}{(11n - 22 - (n_{S,DM} - n_{S,2})} \right]$$

- To determining n, it was assumed that $\alpha_{DM}(M_{DM}) = 1$ and $M_{DM} < M_{DUT} < m_{Pl}$ to obtain a reasonable lifetime for dark matter.

- It was shown[1] that the most appropriate value for n is 4 i.e $SU(4)$ and M_{DUT} was estimated to be $10^{14} - 10^{18}$ GeV[1].

[1] **P. Q. Hung, P. Frampton, arXiv:0903.0358[hep-ph].**

Inflationary Luminogenesis Model

- DUT gauge group breaks according to

$$SU(3)_C \times U(1)_Y \times SU(6) \rightarrow \\ SU(3)_C \times U(1)_Y \times SU(4)_{DM} \times SU(2)_W \times U(1)_{DM}. \quad (1)$$

- For $SU(3)_C \times U(1)_Y \times SU(6)$ to be anomaly-free, there must be mirror fermions of opposite chiralities to those of SM models. These mirror fermions give rise to a EW ν_R model with non-sterile electroweak-scale right-handed Majorana neutrinos with the test of seesaw mechanism being accessible at the Large Hadron Collider.[1,2]

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[1] **P. Q. Hung, Phys. Lett. B 649, 275 (2007) [hepph/0612004]**.

[2] **Shreyashi Chakdar et al., arXiv:1606.08502 [hep-ph]**.

Inflationary Luminogenesis Model

- Some $SU(6)$ representations that are relevant to the model:

$SU(6)$	$SU(4)_{DM} \times SU(2)_L \times U(1)_{DM}$
$\mathbf{6}$	$(\mathbf{1},\mathbf{2})_{\mathbf{2}} + (\mathbf{4},\mathbf{1})_{-\mathbf{1}}$
$\mathbf{20}$	$(\mathbf{4},\mathbf{1})_{\mathbf{3}} + (\mathbf{4}^*,\mathbf{1})_{-\mathbf{3}} + (\mathbf{6},\mathbf{2})_{\mathbf{0}}$
$\mathbf{35}$	$(\mathbf{1},\mathbf{1})_{\mathbf{0}} + (\mathbf{15},\mathbf{1})_{\mathbf{0}} + (\mathbf{1},\mathbf{3})_{\mathbf{0}} + (\mathbf{4},\mathbf{2})_{-\mathbf{3}} + (\mathbf{4}^*,\mathbf{2})_{\mathbf{3}}$

- Luminous matter is represented by the $(1,2)_2$. Dark matter is represented by $(4,1)_3 + (4^*,1)_{-3}$ (χ and $\bar{\chi}$).

Inflationary Luminogenesis Model

	$SU(3)_C \times SU(6) \times U(1)_Y$
R $\supset$ SM fermions	$(3, 6, 1/6)_L + (1, 6, -1/2)_L +$ $(3, 1, 2/3)_R + (3, 1, -1/3)_R +$ $(1, 1, -1)_R$
R $\supset$ Mirror fermions	$(3, 6, 1/6)_R + (1, 6, -1/2)_R +$ $(3, 1, 2/3)_L + (3, 1, -1/3)_L +$ $(1, 1, -1)_L$
R $\supset$ dark matter fermions	$(1, 20, 0)$

Hadronic bound states of χ and $\bar{\chi}$

- Dynamical mass of dark matter was predicted by using astrophysics constraints[1]. By running $SU(2)_L$ gauge coupling from the EW scale up to DUT scale, and then run $SU(4)_{DM}$ down to appropriate scale for dark matter $\alpha_4(M_{DM}) \approx 1$, the dynamical mass of DM should be approximately equal to the confinement scale of $SU(4)$ of $\mathcal{O}$(TeV).

- Below $SU(4)_{DM}$ confinement scale, hadrons will be created and come in 2 types:
  - DM "baryon": 4χ (Chi Massive Particle or CHIMP) of mass $\sim \mathcal{O}$(1 - 100 TeV).
  - DM "meson": $\bar{\chi}\chi$ (Dark pion or π_{DM}). $m_{\pi_{DM}}$ was constrained to 1 - 10 MeV[2].

[1] **P.Q. Hung**, **Kevin J. Ludwick**, **arXiv:1411.1731v4 [hep-ph]**.
[2] **P.Q. Hung**, **Kevin J. Ludwick**, **arXiv:1508.01228 [hep-ph]**.

Minimum masses and radii of DAECOs

- Following Jean instability analysis, consider spherical object of constant mass M made of CHIMPs, average energy density ρ, $v_s^2 = \partial p/\partial\rho$, (P. Q. Hung and S. Nussinov). The energy density fluctuation ρ_1 characterized by constant mass M is governed by:

$$\frac{\partial^2 \rho_1}{\partial^2 t} = v_s^2 \nabla^2 \rho_1 + 4\pi G \rho \rho_1$$

Solution: $\rho_1 \propto exp(i\vec{k}\vec{x} - i\omega t)$ where $\omega^2 = v_s^2 \left[\vec{k}^2 - (4\pi G\rho/v_s^2)\right]$.

- Let's define the wave number $k_J = \sqrt{4\pi G\rho/v_s^2}$:
  - $k < k_J$: $\omega^2 < 0 \rightarrow \rho_1$ grows exponentially.
  - $k > k_J$: $\omega^2 > 0 \rightarrow \rho_1$ oscillates like a sound wave.
- In the expanding universe, we can characterize the disturbance by a constant rest mass M enclosed in a sphere of radius $2\pi/k$:

$$M = \frac{4\pi}{3} nm \left(\frac{2\pi}{k}\right)^3 \qquad M_{Jean} = \frac{4\pi}{3} nm \left(\frac{2\pi}{k_{Jean}}\right)^3$$

Minimum masses and radii of DAECOs

- What does M_{Jean} tell us?
  - $k < k_J \rightarrow M > M_{Jean}$: energy density fluctuation grows exponentially.
  - $k > k_J \rightarrow M < M_{Jean}$: energy density fluctuation oscillates like a sound wave.

  $\rightarrow M_{Jean}$ is the minimum mass for DM clump must have in order for energy density fluctuation to grow to form DAECO.

- When CHIMP is non-relativistic: $kT < m_B$. Equations of state:

$$\rho = nM_B + \frac{3}{2}nkT,$$
$$p = nkT$$
$$\rightarrow M_{Jean} = \left(\frac{4\pi}{3}\right)^{\frac{5}{2}} \left(\frac{5k}{G}\right)^{\frac{3}{2}} T_i^{\frac{3}{4}} T^{-\frac{3}{4}} n_i^{-\frac{1}{2}} m_B^{-2}.$$

where $kT_i = m_B$, $n_i = 3.7\frac{a}{k}T_i^3$.

The growth of $\delta\rho/\rho$

- Having M_J being achieved, the energy density fluctuation $\delta(t) = \delta\rho(t)/\rho$ is governed by:

$$\frac{d^2\delta(t)}{dt^2} + 2\frac{\dot{R}(t)}{R(t)}\frac{d\delta(t)}{dt} + \left(v_s^2\frac{q^2}{R^2(t)} - 4\pi G\rho\right)\delta(t) = 0,$$

- At the early state of galaxy or star formation, δ started at a small value. Galaxies or stars would be formed when $\delta(t)$ evolved to 1.

- $\delta(t_M D)$ of DAECOs at different values of M_B:

M_B (TeV)	1	10
t_{MD}(s)	2.69×10^{-11}	2.69×10^{-13}
$\delta_M(t_{MD})$	5.07×10^{-1}	5.07×10^{-1}

The growth of $\delta\rho/\rho$

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$\delta_M(t_{MD})$	5.07×10^{-1}	5.07×10^{-1}

- To compare, normal galaxies have $\delta \sim 10^{-2} - 3 \times 10^{-4}$ at the time they started to grow.
- DAECO will be formed when $\delta(t) \simeq 1$:

$$\delta(t_1) = \delta(t_{MD}) \left(\frac{t_1}{t_{MD}} \right)^{\frac{2}{3}} = 1$$

$$t_1 = t_{MD} \times \delta(t_{MD})^{-\frac{3}{2}} = 2.77 t_{MD}.$$

Yoshimura-Tagasugi limit

- For neutron stars, the balance of Fermi pressure and gravity will keep them stable. Oppenheimer - Volkoff limit:

$$M \sim \frac{0.4}{G^{3/2} m_N^2}.$$

- As CHIMPs have spin 0, DAECO has no Fermi pressure. M. Yoshimura and E. Tagasugi studied the stability of bose stars assuming that particles at the center of that star occupy energy of momentum π/R. Result from this studied show the maximum mass a bose star can sustain[1]

$$M_{Y-T} = 0.57 \frac{m_{Pl}^2}{m}.$$

[1] **Takasugi, E., Yoshimura, M. Z. Phys. C - Particles and Fields (1984) 26: 241. doi:10.1007/BF01421759.**

Yoshimura limit

- Jean masses and Yoshimura-Tagasugi limits at different m_B's:

M_B (TeV)	1	10
M_{Jean} (grams)	3.14×10^{28}	3.14×10^{26}
M_{Y-T} (grams)	1.41×10^{11}	1.41×10^{10}

- What does this mean? As $M_{Y-T} < M_{Jean}$, by the time DM clump is heavy enough to form DAECO, it is already bigger than the Yoshimura-Tagasugi limit.

  $\rightarrow$ DAECO will be unstable and collapse radially inward. Gravitational pressure is now large enough to deconfine CHIMP to its constituents: χ's, which are fermions.

Maximum masses and radii of DAECOs

After all CHIMPs are deconfined to χ's, which are fermions. For DAECO to be stable, Fermi pressure and gravitational pressure have to be balanced. The Oppenheimer–Volkoff limit can then be estimated as followed:

- Consider a sphere of degenerate gas of χ at $T \ll E_F/k$. Fermi energy: $E_F = m_\chi c^2 = k_F c$.

$$n = \frac{k_F^3}{6\pi^2\hbar^3} = \frac{N}{\frac{4}{3}\pi R^3} \rightarrow k_F = \left(\frac{9\pi}{2}\right)^{1/3} \frac{\hbar}{R} N^{1/3}.$$

- Gravitational energy per particle:

$$E_G = -\frac{GNm_\chi^2}{R}$$

- DAECO will remain stable as long as total energy is positive:

$$E = E_F + E_G \geq 0$$

Maximum masses and radii of DAECOs

- $E_F + E_G \geq 0 \rightarrow$

$$N < N_{critical} = \left(\frac{9\pi}{2}\right)^{1/2} \left(\frac{\hbar c}{G m_\chi^2}\right)^{3/2}$$

$$M < M_{critical} = N_{critical} m_\chi = \left(\frac{9\pi}{2}\right)^{1/2} \left(\frac{\hbar c}{G}\right)^{3/2} m_\chi^{-2}$$

$$R < R_{critical} = \left(\frac{9\pi}{2}\right)^{1/3} \left(\frac{\hbar c}{m_\chi c^2}\right) N_{critical}^{1/3}.$$

Maximum masses and radii of DAECOs

- Jean masses, Yoshimura limits, maximum masses, critical radii at different values of M_B:

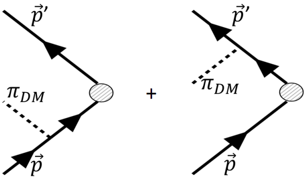
M_B (TeV)	1	10
M_{Jean} $(M_\oplus)$	5.23	5.23×10^{-2}
M_{Y-T} $(M_\oplus)$	2.37×10^{-17}	2.37×10^{-18}
$M_{crit}(M_\oplus)$	32.8	3.28×10^{-1}
$R_{crit}(m)$	1.46×10^{-1}	1.46×10^{-3}

Cooling mechanism

- Why do we need an energy dissipation mechanism?

  Without one, energetic CHIMPs cannot settle down in the gravitational potential well and hence cannot gather to form DAECO.

- How can this be done? Via Bremsstrahlung of dark pions ($\chi\bar{\chi}$).



Astronomical detection of DAECOs

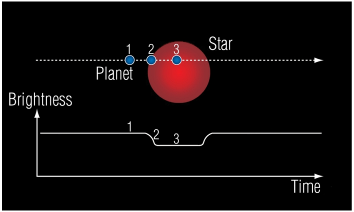
- If DAECOs of "solar-system" masses are captured by stars, the search for exoplanets is the best way to look for DAECOs:
  - Radial velocity method: Spectral lines emitted a star in star-DAECOs systems may be shifted due to the motion of star around their center of mass.
  - Pulsar timing: Gravitational field close to a heavy object may result in delay of light-travel-time of radiation from pulsar.

- There may possibly be a situation where DAECOs cluster in to a mini galaxy of physical size of a neutron star and a few tenths of solar mass. The merging of two such galaxies can generate detectable gravitational waves.

- For a rough estimate: From the mean dark matter density and star number density in MW, there are about 0.2 stars per pc^{-3} and about 33 DAECOs per pc^{-3}. Therefore, it is not impossible that DAECOs can be captured by stars.

Astronomical detection of DAECOs

- How do we distinguish a DAECOs and luminous matter exoplanets?
- Transit photometry method is used to detect exoplanets. If a planet crosses in front its parent star, the observed brightness drops by a small amount.[1]



Since DAECOs are transparent, the absence of a signal using transit method in conjunction with a positive signal from radial velocity method would be an indication for presence of DAECOs orbiting such a star.

[1] **NASA, ESA, G. Bacon (STSci)**.

Conclusion

- Based on the Inflationary Luminogenesis Model, we have used dark matter to propose the existence of a Dark Astronomical Extreme Compact Object with mass of about $30 M_{\oplus}$ and radius of 15 cm for CHIMP of mass 1 TeV.
- The minimum and maximum mass were estimated based on the Jean analysis and Oppenheimer-Volkoff limit calculation.
- An Energy dissipation mechanism which is needed for energetic particles to lose their energy and settle down in the gravitational potential well, was expected to be achieved through Bremsstrahlung of dark pions.
- Some possibilities that can be used to detect DAECOs were also discussed.