EXOTIC COMPACT OBJECTS IN A DISSIPATIVE DARK SECTOR

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Q: Can we learn about the particle nature of DS if it interacts with SM sector only gravitationally?
A: Yes!

If it forms compact objects

- Called exotic compact objects (ECO)
- Can be found by high-precision observatories (GW or weak lensing)
- Properties of compact objects are determined by particle nature of DS
Goal: Using a simple DS model, find properties of the exotic compact objects according to model parameters
A SIMPLE DARK SECTOR MODEL FOR ECO FORMATION
Conditions for the Model

- **Self-Interaction**
  - Otherwise behaves like CDM
  - Sub-dominant (We assume 1% of total DM)

- **No annihilation**
  - For stable final objects
  - Ex) Asymmetry, Bound states, …

- **Cooling process**
  - Necessary for “fragmentation”
Baryons are too complicated!

- They form bound states, a lot of cooling processes…
- Hard to handle analytically
- As a starting point, we consider a DS model as simple as possible
The Simplified Model in this Work

- Contains only two particles
  - Dark electron $e_D^-$: Compose matter
  - Dark photon $\gamma_D$: Mediate interactions

- Has charge asymmetry
  - Negligible dark positron
  - Not simple in terms of model building, but simple to handle astrophysical phenomenon
Interactions in the Model

Self Interaction
Bremsstrahlung cooling

Satisfies all the conditions
Advantages of the Model

- There are no bound-states
- Only one cooling process
- Only three model parameters: $m_{e_D}$, $m_{\gamma_D}$, $\alpha_D$
SCHEMATIC OF COMPACT OBJECT FORMATION
In early Universe, there are overdensities and underdensities—described by primordial power spectrum.
• Perturbation grows with time
• Can be analyzed with linear theory
• Enters non-linear regime at some point
Jeans Mass $M_J$

- Maximum mass of gas that pressure can support

- If $M > M_J$, a mass clump collapses

$$M_J = \frac{\pi}{6} c_s^3 \left( \frac{\pi}{G} \right)^{3/2} \left( \frac{1}{\rho} \right)^{1/2}$$

- $c_s$ depends on particle nature
Schematic of Non-linear Regime

- A big mass perturbation from linear growth
- Suppose $M > M_J$
Adiabatic Collapse

- Temperature increases
- $M_J$ increases
Adiabatic Collapse

- Adiabatic collapse stops at $M_J = M$
- The mass perturbation is virialized
Virialized Collapse

- If there’s cooling, it keeps collapsing.
- Cooling is slower than collapse, temperature increases.
Fragmentation

- Cooling becomes important as number density increases.
- Temperature and $M_J$ decrease.
Compact Objects Formation

- Cooling stops as optical depth becomes large
- Fragmentation stops
QUANTITATIVE ANALYSIS
Master Equation

\[ dE = -PdV - \Lambda dt \]

\[ \frac{d \log T}{d \log \rho} = \frac{2}{3} \frac{mP}{\rho T} - 2 \frac{t_{\text{collapse}}}{t_{\text{cooling}}} \]

- Mass perturbation is parameterized with \( \rho \) and \( T \)

\( \Lambda \) is cooling rate
Evolution Trajectory \((M = 10^{10} M_\odot)\)

- \(m_{\epsilon_D} = 1\ \text{GeV}\)
- \(m_{\gamma_D} = 100\ \text{eV}\)
- \(\alpha_D = 10^{-1}\)

- To analysis of individual fragments
  - Last fragmentation
  - Fragmentation
  - \(t_{\text{cooling}} \sim t_{\text{ff}}\)
  - Nearly virialized contraction
  - \(\epsilon_D\) halo virialization
  - Adiabatic free-fall
  - \(\rho_{\epsilon_D} = \rho_{\text{CDM}}\)
  - Adiabatic free-fall
  - Hubble decoupling
  - To linear regime
Results According to Model Parameters

- Black lines: Minimum $M_J$ in $M_\odot$ after fragmentation
- Blue lines: Corresponding compactness ($C = GM/R$)
Conclusion

- We described the complete history of structure formation of a simple dissipative dark sector model.

- We provided a map between astronomical properties and particle physics parameters.
Conclusion

• A wide range of opportunities lies ahead,
  ◦ What is the behavior of more complicated dark sector models?
  ◦ What are the astronomical signatures of such models?
  ◦ Numerical simulations?

• Lots of progress to make from the theory side, even if DM interacts with us only gravitationally
THANK YOU