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Title: Journal Club Presentation to the Utah HEP Group

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Basics of Bosonic dark matter ($m \ll \text{eV}$)

- $v \sim 10^{-3}c$ ("cd" $\underbrace{mv^2}_{\text{KE.}} \ll \underbrace{m}_{\text{Rest Mass.}}$)

- phase space density / occupation number

$$\underbrace{N}_{\text{Particle \#}} = \int d^3x d^3p f$$

$$\Rightarrow n = \frac{dN}{dV} = \int d^3p \cdot f \approx (mv)^3 \cdot f$$

$$\Rightarrow f \approx \frac{n}{(mv)^3} = \underbrace{n \cdot \lambda_{\text{dB}}^3}$$

Number of particles "occupying" the same momentum block.

- Saturating $P_{\text{DM}} = m \cdot n$

$$\Rightarrow f \sim \frac{P}{m^4 v^3} \sim 1 \cdot \left(\frac{\text{eV}}{m}\right)^4 \left(\frac{P}{P_{\text{DM}}}\right) \left(\frac{10^{-3}}{v}\right)^3$$

- "Scattering" processes are Bose-enhanced.

$$\begin{array}{ccc} \phi & & \phi \\ & \times & \\ \phi & & \phi \end{array} \quad \sigma \longrightarrow f \sigma$$

Formation of self-gravitating Structures

- Start w/ homogeneous distribution of ϕ
 - perturbations start to grow and collapse
- } $\Rightarrow$ DM halo

(the quantum pressure suppresses structure formation

$\Rightarrow$ Lyman- α bounds on ULDM at $m \lesssim 10^{20} \text{ eV}$)

- DM halo particles scatter & Relax to the ground state
 - self-gravitating system (Grav. potential $\longleftrightarrow$ Kinetic energy)
- } $\Rightarrow$ Soliton core
(@ center of the halo)
- $\downarrow$

tends to pull particles into a small Δx

$\downarrow$

$\Delta x \Delta p \gtrsim 1$

$K.E \sim \frac{\Delta p^2}{2m}$

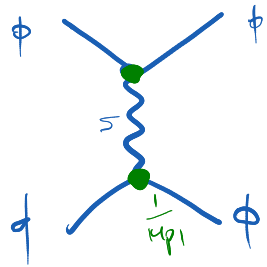
Formation of self-gravitating Structures

Scattering Rate $\approx$ Rate of the soliton core formation

- In the past, the scattering in the gravitational channel was focused.

(c.f. Hui, Ostriker, Tremaine & Witten 2016, 1610.08297
Bar, Blum, & CS. 2022 2111.03070)

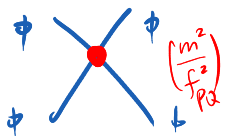
$$(\eta^{\mu\nu} + \frac{1}{M_p^2} h^{\mu\nu}) \partial_\mu \phi \partial_\nu \phi$$



$$\sigma \sim \frac{1}{M_p^4} \frac{1}{v^4} \cdot m^2 \Rightarrow \tau = \frac{1}{f \cdot (n \cdot \sigma \cdot v)} \sim \frac{m_\phi M_p^4 v^6}{n^2}$$

$$\tau_{\text{grav}} = \frac{b}{16\pi^3} \frac{m_\phi M_p^4 v^6}{n_\phi^2 \log(m_\phi v R)},$$

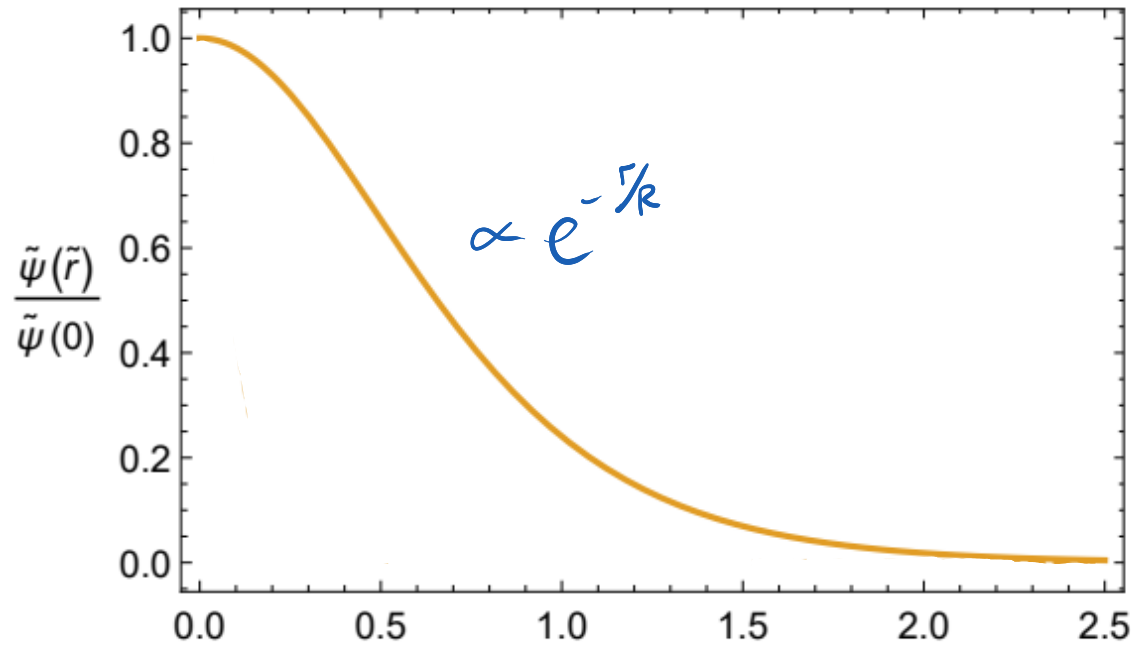
- Recently, it is noticed that self-interaction can also be important if $f_{\text{Pl}} is small.$
(2011.01333, 2302.00685)



$$\sigma \sim \left(\frac{m^2}{f_{\text{Pl}}^2}\right)^2 \cdot \frac{1}{m^2} \Rightarrow \tau = \frac{1}{f \cdot (n \cdot \sigma \cdot v)} \sim \frac{m v^2 f^4}{n^2}$$

$$\tau_{\text{self}} = d \left(\frac{64}{3\pi}\right) \frac{m_\phi f_\phi^4 v^2}{n_\phi^2},$$

Stability of self-gravitating BEC



c.f. Gross, Fan, Cs. 1810.01420

$$H \approx \underbrace{\frac{M}{2m^2 R^2}}_{\text{Kinetic energy}} - \underbrace{\frac{5G_N M^2}{16R}}_{\text{Self-grav.}} - \underbrace{\frac{M^2}{32\pi m^2 f_{\text{Pl}}^2 R^3}}_{\text{attractive Self-int.}}$$

$$\frac{\partial H}{\partial R} = 0 \quad \frac{\partial^2 H}{\partial R^2} > 0$$

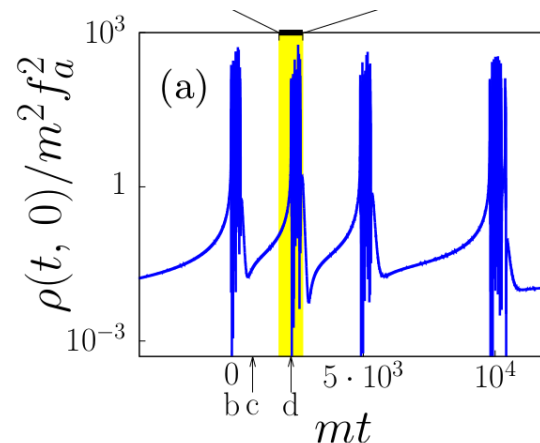
Stability of self-gravitating BEC.

$$\Phi_{\text{crit}} \approx 10 f_{\text{Pz}} \left(\frac{f_{\text{Pz}}}{M_{\text{Pl}}} \right)$$

$$\Leftrightarrow M_{\text{crit}} \approx 10 \frac{f_{\text{Pz}} M_{\text{P}}}{m} \approx 10'' M_{\odot} \left(\frac{f_{\text{Pz}}}{M_{\text{Pl}}} \right) \cdot \left(\frac{10^{-20} \text{eV}}{m} \right) \quad (\text{c.f. Leukov et al.})$$

Above which explosion happens "Bose nova"

which expels (11) fraction of the original soliton. c.f. 1609.03611



Summary: Self-interaction has two effects.

1) Speeds up the Relaxation. if $\frac{1}{f_{\text{P2}}} > \frac{1}{\eta_{\text{P1}} v}$

2) destabilizes the BEC system if $\phi(0) > f_{\text{P2}} \left(\frac{10 f_{\text{P2}}}{\eta_{\text{P1}}} \right)$

Fox, Weiner, & Xiao combines the two effects.

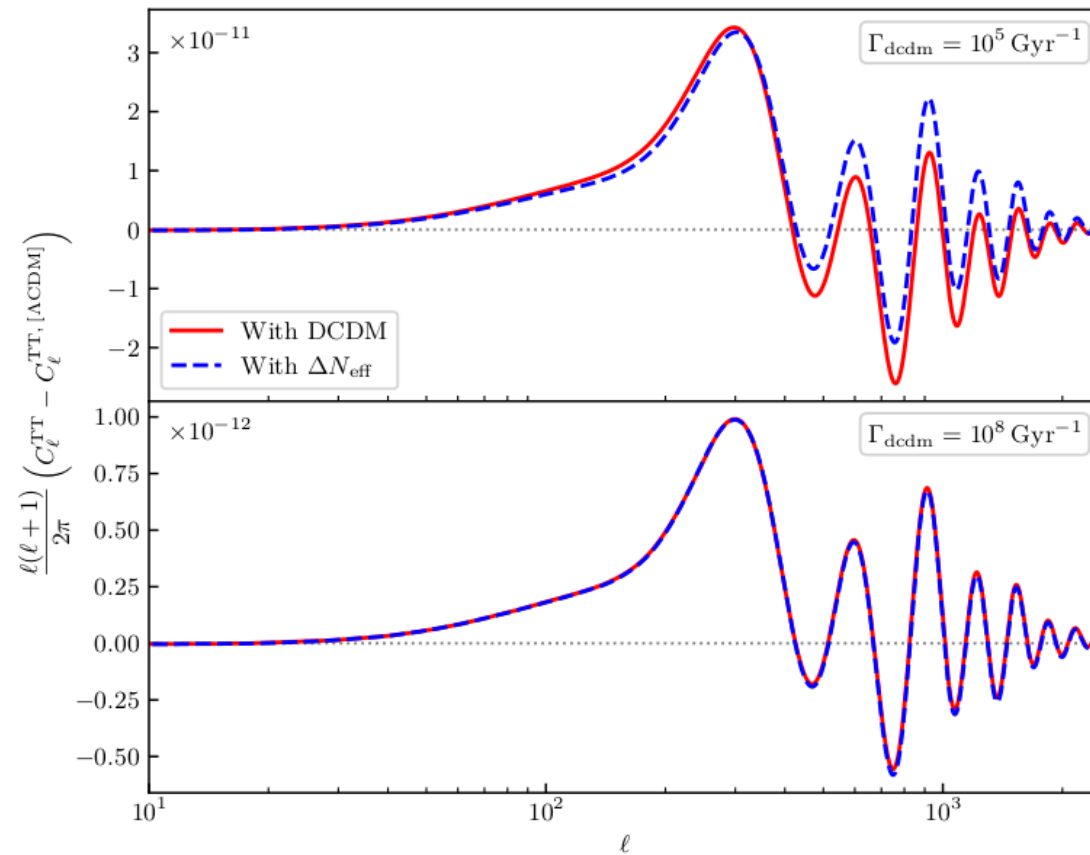
show that this is a new mechanism to

boost axion dark matter into Relativistic axions.

From CMB. Late decaying DM $< 2.62\%$ total DM.

Nygaard et al. 2021

2011.01632



From CMB. late decaying DM $< 2.62\%$ total DM.
 $\Rightarrow f_{\text{PD}}^{-1} < (\text{some bounds})$.

