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Title: Journal Club Presentation to the Utah HEP Group

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Basics of Bosonic dark Matter ($m \ll eV$)

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

- phase space density / occupation number

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

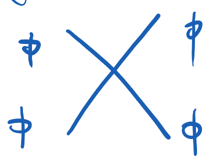
$$\Rightarrow \quad n = \frac{dN}{dV} = \int d^3p \cdot f \approx (mv)^3 \cdot f$$

$$\Rightarrow \quad f \approx \frac{n}{(mv)^3} = \underbrace{n \cdot \lambda_{dB}^3}_{\text{number of particles ``occupying'' the same momentum block.}}$$

- Saturating $\rho_{DM} = m \cdot n$

$$\Rightarrow \quad f \sim \frac{\rho}{m^4 v^3} \sim 1 \cdot \left(\frac{eV}{m}\right)^4 \left(\frac{\rho}{\rho_{DM}}\right) \left(\frac{10^{-3}}{v}\right)^3$$

- "Scattering" processes are Bose-enhanced.



$$\sigma \longrightarrow f \sigma$$

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 $m \lesssim 10^{-20}\,eV$)

- DM halo particles scatter & Relax to the ground state
- self-gravitating system (Grav. potential $\Longleftrightarrow$ Kinetic energy)

$\Rightarrow$ Soliton core (@ center of the halo)

Grav. potential $\downarrow$ tends to pull particles into a small Δx

Kinetic energy $\downarrow$ $\Delta x \Delta p \gtrsim 1$

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

Formation of self-gravitating structures

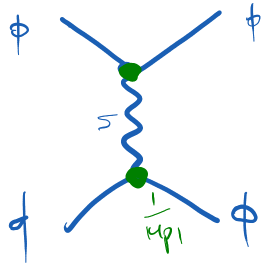
Scattering Rate $\approx$ Rate of the soliton core formation

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

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

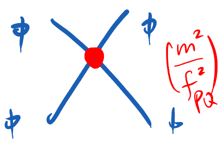
$$\left(\eta^{\mu\nu} + \frac{1}{M_p} h^{\mu\nu}\right) \partial_\mu \phi \, \partial_\nu \phi$$

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



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

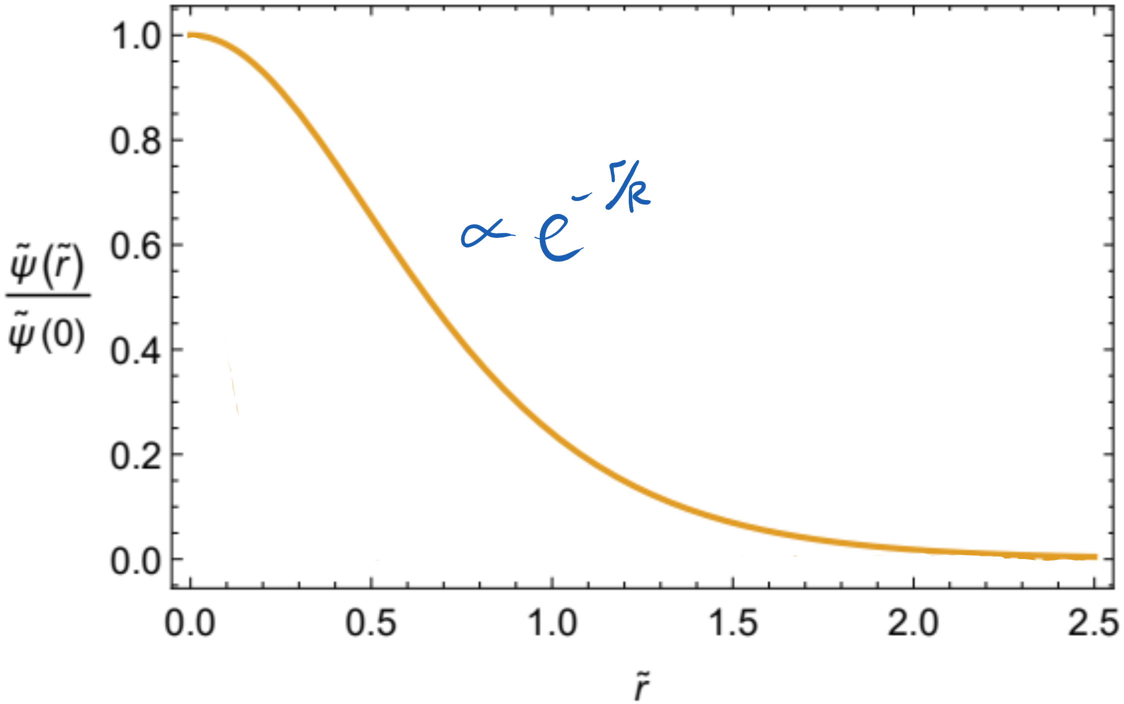
- Recently, it is noticed that self-interaction can also be important if f_{PQ} is small.
  (2011.01333, 2302.00685)



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

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

Stability of self-gravitating BEC.



c.f. Croon, Fan, C.S. 1810.01420

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

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

Stability of self-gravitating BEC.

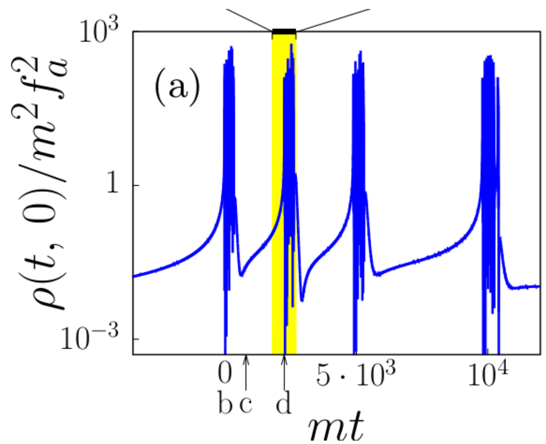
$$\Phi_{crit} \approx 10 f_{PQ} \left(\frac{f_{PQ}}{M_{Pl}}\right)$$

$$\Leftrightarrow \quad M_{crit} \approx 10 \frac{f_{PQ} M_P}{m} \approx 10^{11} M_{\odot} \left(\frac{f_{PQ}}{M_{Pl}}\right) \cdot \left(\frac{10^{-20}\,\mathrm{eV}}{m}\right)$$

(c.f. Levkov et al.)

Above which explosion happens "Bose nova"

which expels $O(1)$ fraction of the original soliton. c.f. 1609.03611



Summary: Self-interaction has two effects.

1) Speeds up the Relaxation. if $\frac{1}{f_{PQ}} > \frac{1}{M_{pl}\, v}$

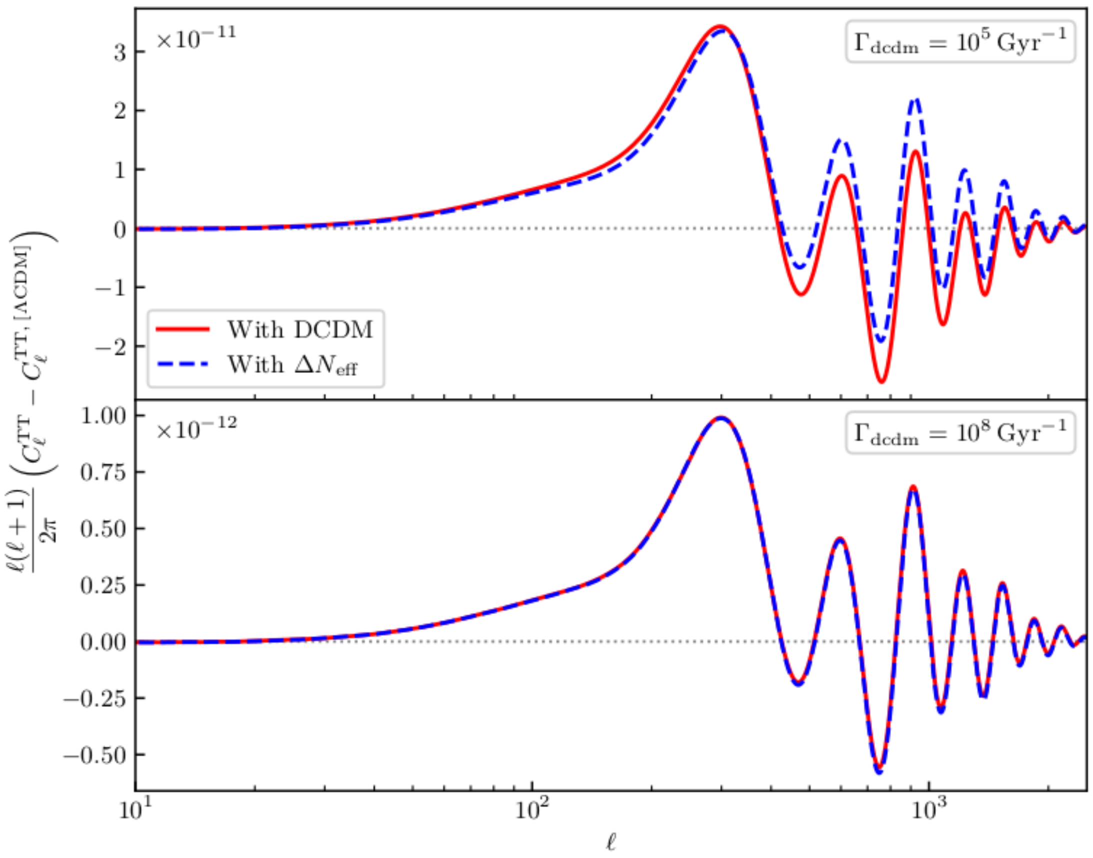
2) destablizes the BEC system if $\phi(0) > f_{PQ}\left(\frac{10 f_{PQ}}{M_{pl}}\right)$

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.

$\Rightarrow f_{PQ}^{-1} <$ (some bounds).