Bosonic Dark Matter

How to mix Particle Physics, Cosmology and Cold atoms

Alex Soto

Science Gallery London – September 2024

Work with N. Proukakis and G. Rigopoulos:

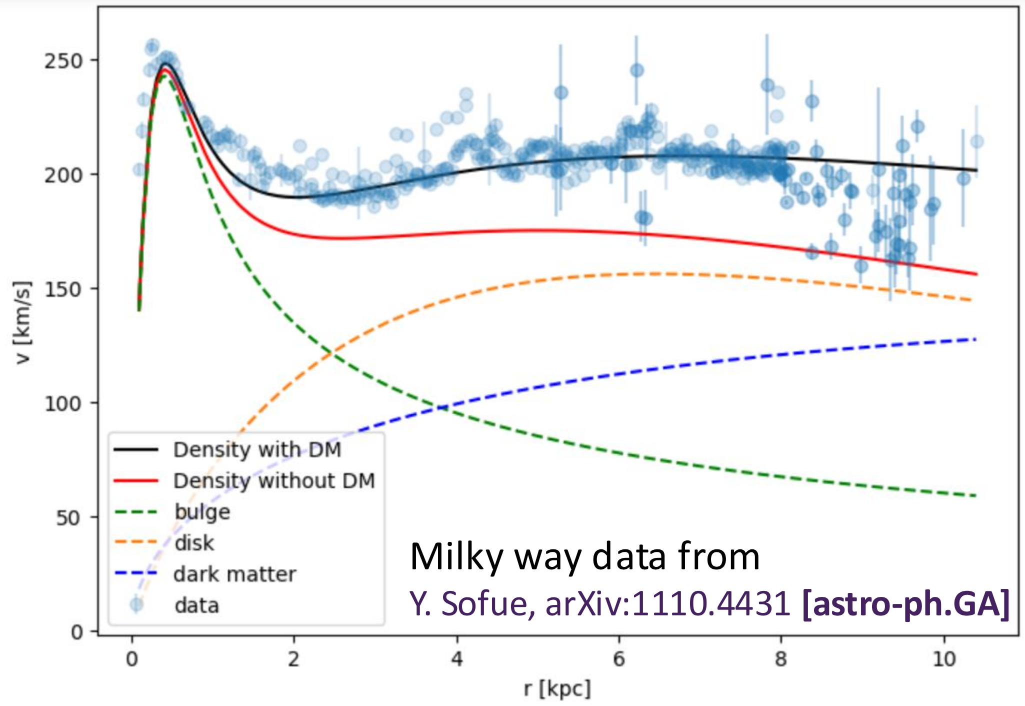
Phys.Rev.D 108 (2023) 8, 083513 (ArXiv:2303.02049 [astro-ph.CO])

Phys.Rev.D 110 (2024) 2, 023504 (ArXiv:2311.05280 [astro-ph.CO])

ArXiv:2407.08860 [astro-ph.CO]

Motivation: Dark Matter

Evidences suggest the existence of Dark Matter, but what is it?



Milky way data from
Y. Sofue, arXiv:1110.4431 **[astro-ph.GA]**

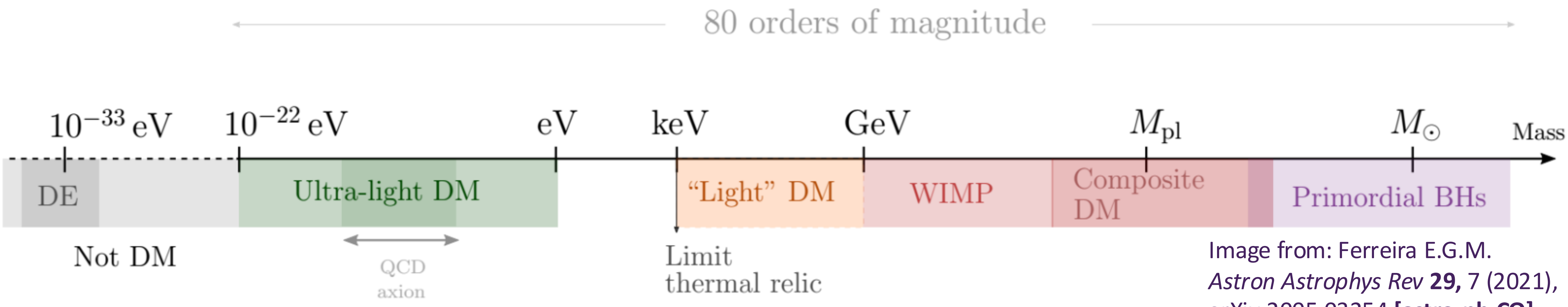
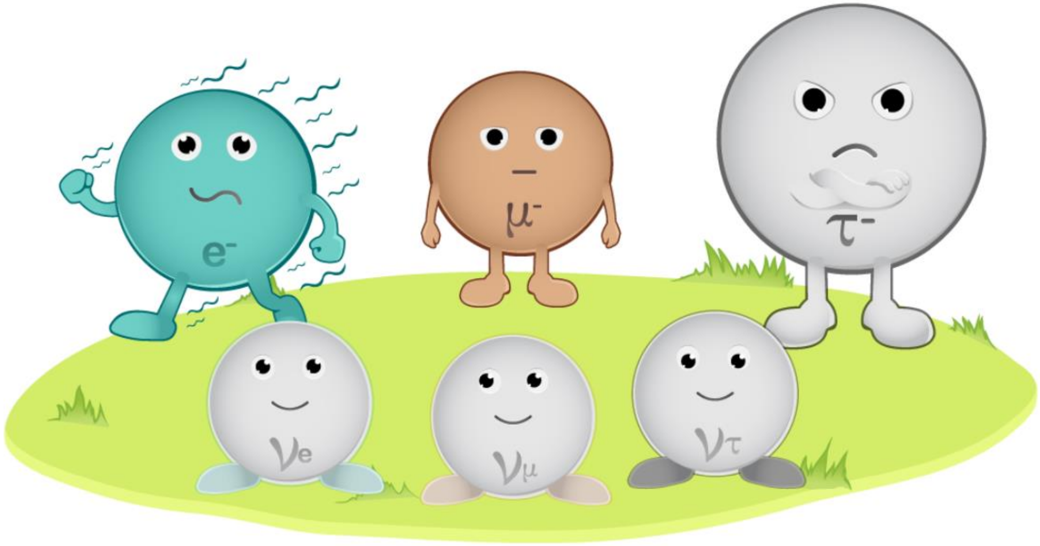


Image from: Ferreira E.G.M. *Astron Astrophys Rev* **29,** 7 (2021), arXiv:2005.03254 **[astro-ph.CO]**.

Motivation: Particles

Bosons

or



Fermions

Motivation: Particles

Bosons

- QCD Axion
  R. D. Peccei and H. R. Quinn. (1977)
  - Scalar field (10^{-5} to 10^{-3} eV/c^2, spin-0)
  - It solves the CP problem
- Axion like particles
  A. Arvanitaki et al., arXiv:0905.4720 **[hep-th]**
  - Motivated by String models (Axiverse)
  - Wide range of masses
- Higher spin particles

Motivation: Fuzzy Dark Matter

✓ FDM is a model with a non-relativistic ultralight bosonic particle (around 10^{-22} eV/c^2)

$$i\hbar\frac{\partial\Phi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\Phi + mV\Phi$$

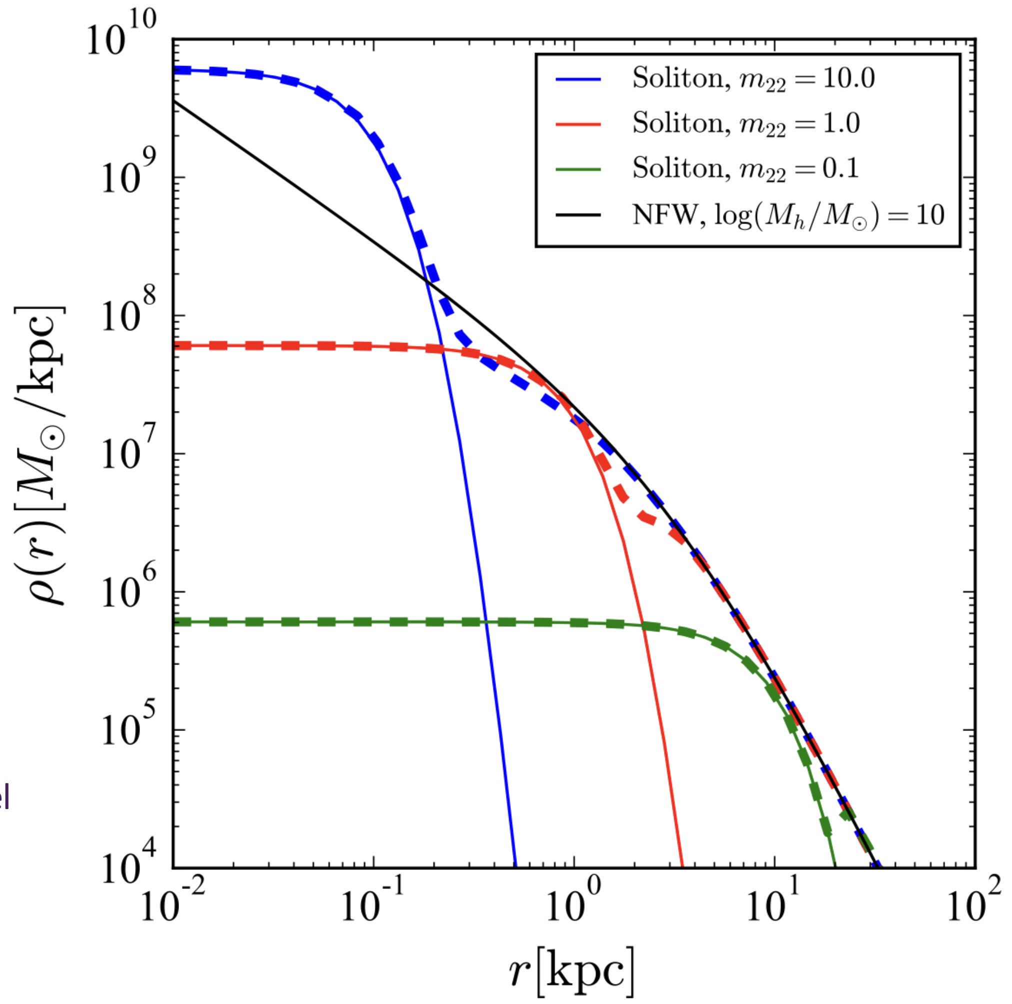
$$\nabla^2 V = 4\pi G m|\Phi|^2$$

Motivation: Fuzzy Dark Matter

✓ This simple model solves small scale problems of CDM:

➢ Cusp-Core problem

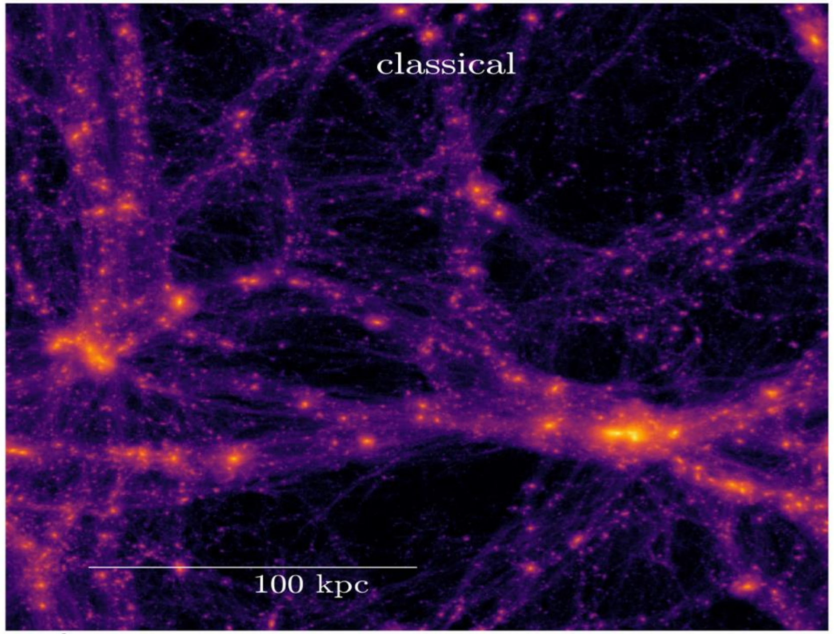
Image from: Safazardeh and Spergel ApJ **893**, 21 (2020), arXiv:1906.11848 **[astro-ph.CO]**

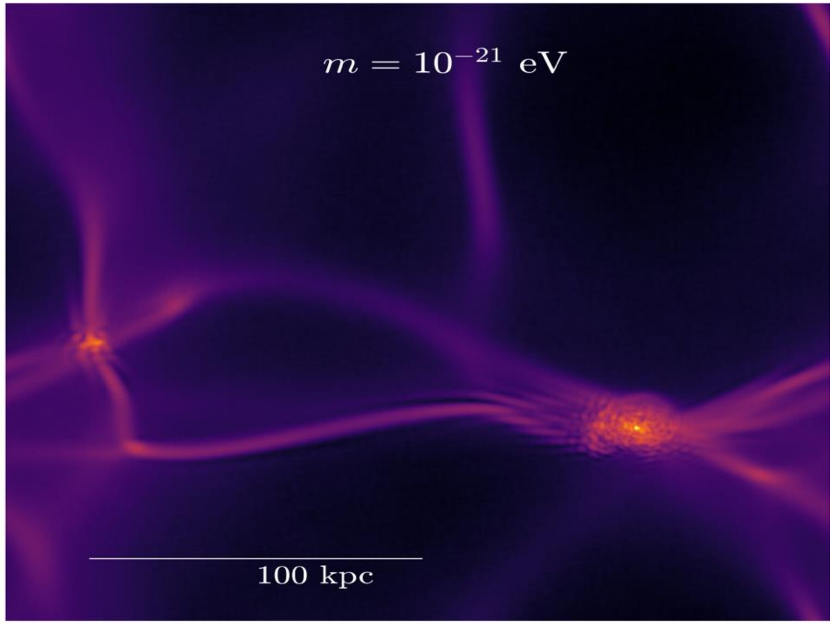


Motivation: Fuzzy Dark Matter

✓ This simple model solves small scale problems of CDM:

- Cusp-Core problem
- Missing satellites
- Etc.





Images from: Mocz *et al.*, Phys. Rev. D **97**, 083519 (2018), arXiv:1801.03507 **[astro-ph.CO]**

Motivation: Fuzzy Dark Matter

- ✓ FDM behaves as CDM at large scales

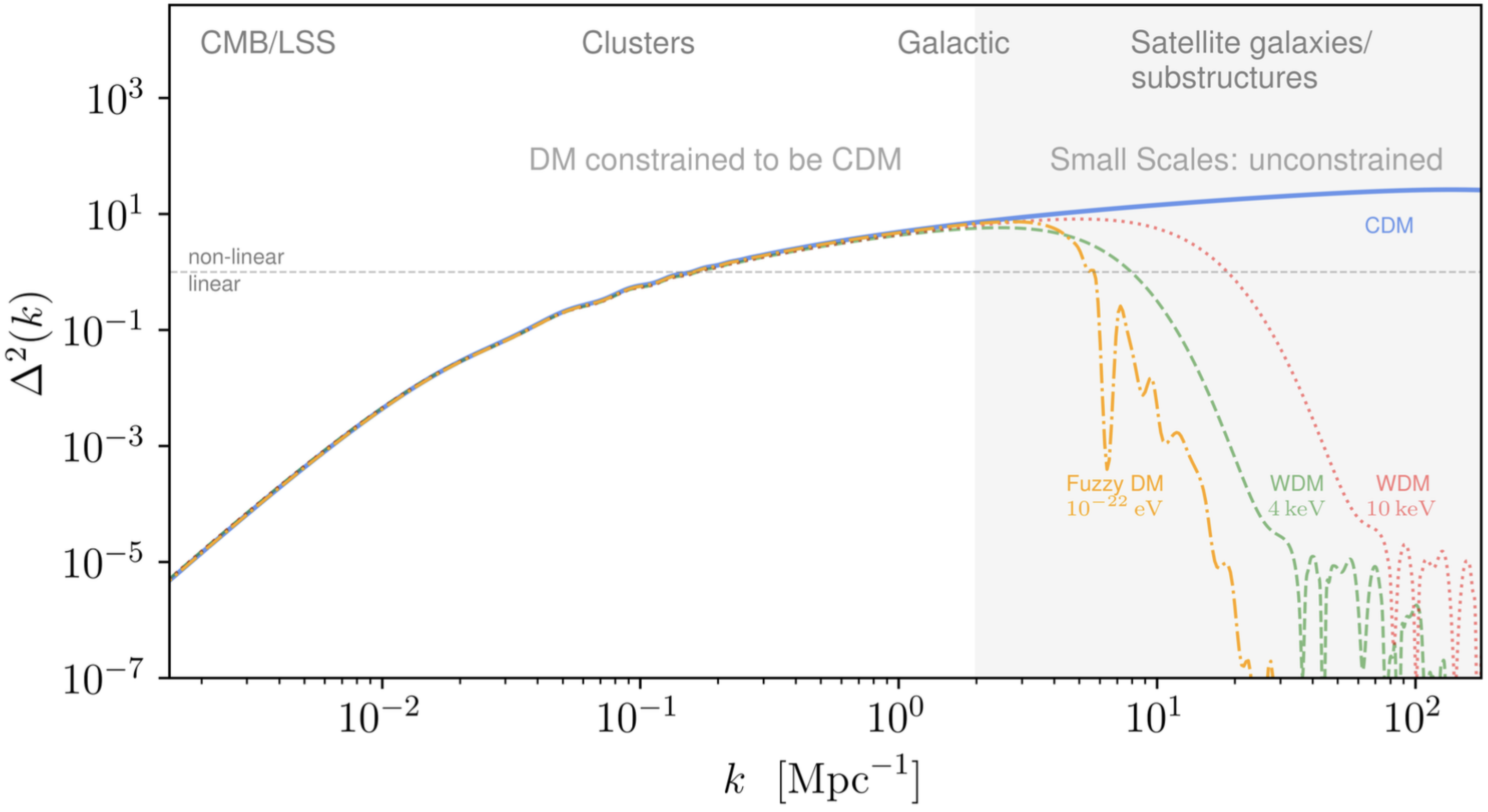


Image from: Ferreira E.G.M. *Astron Astrophys Rev* **29,** 7 (2021), arXiv:2005.03254 **[astro-ph.CO]**.

Motivation: Fuzzy Dark Matter

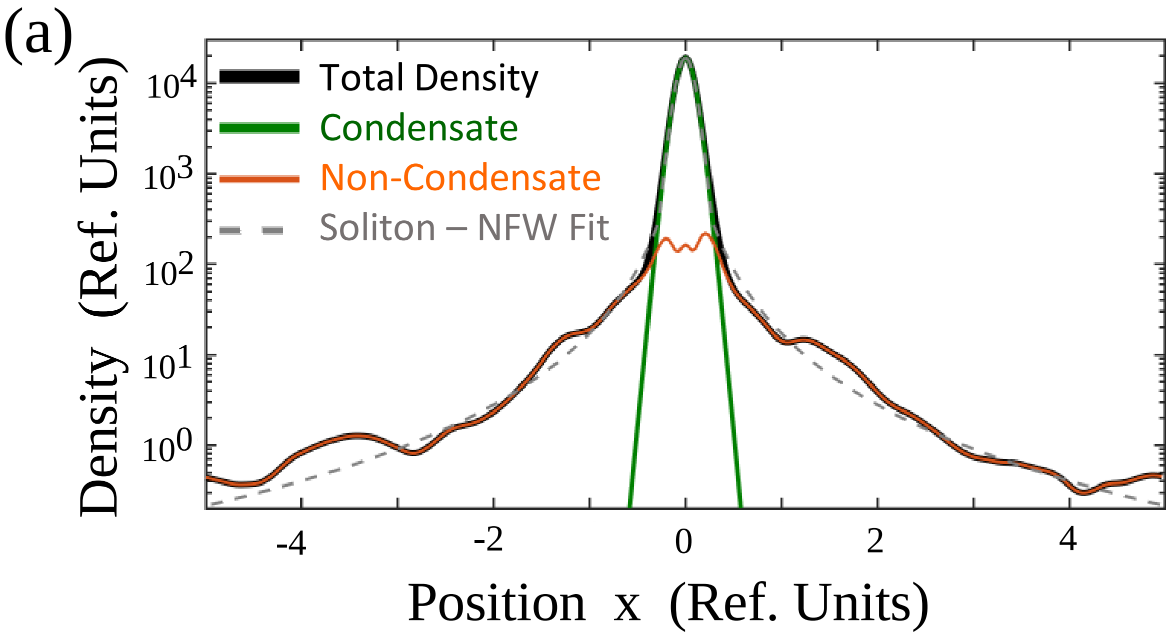
✓ FDM is a model with a non-relativistic ultralight bosonic particle (around 10^{-22} eV/c^2)

$$i\hbar\frac{\partial\Phi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\Phi + mV\Phi$$

$$\nabla^2 V = 4\pi G m|\Phi|^2$$

Small masses give high occupation number → **Bose-Einstein Condensate**

Motivation: Coherence



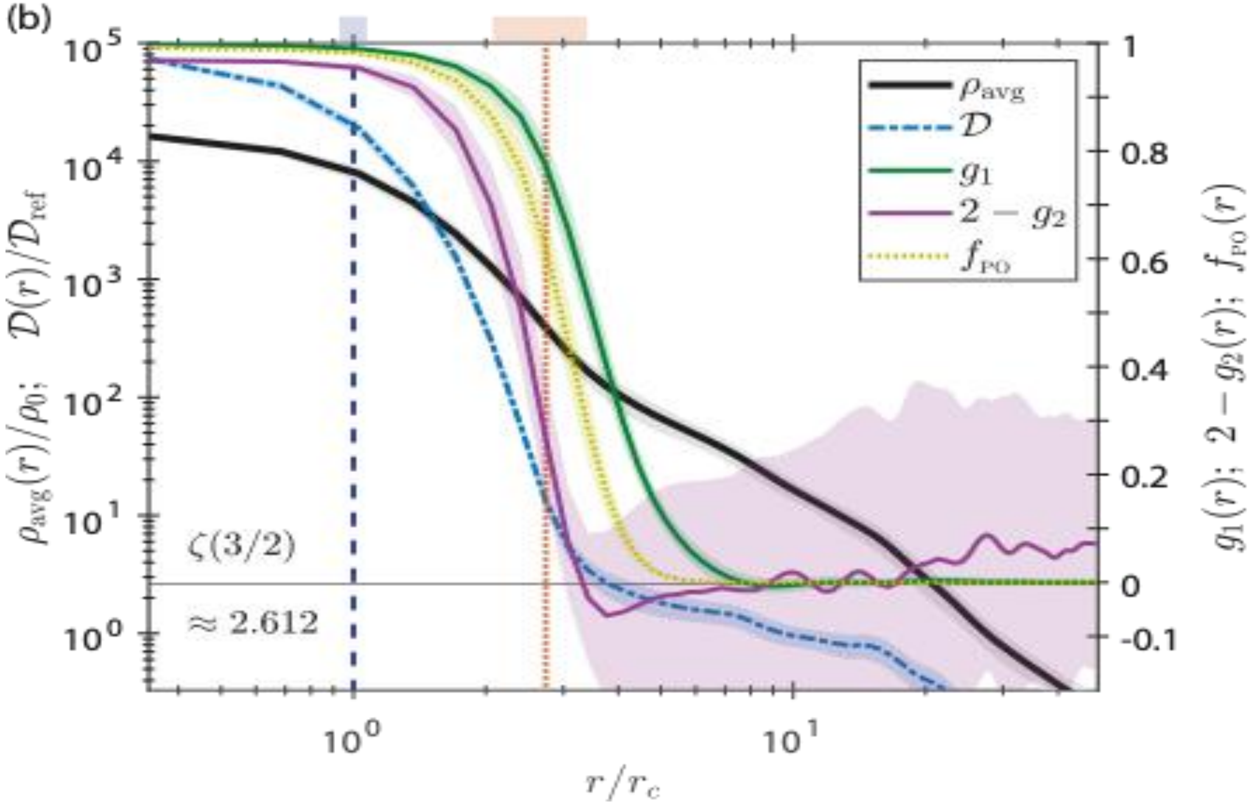


Image from: N. Proukakis, G. Rigopoulos and A.S., *Phys. Rev. D* 108 (8 2023), p. 083513 arXiv:2303.02049 **[astro-ph.CO]**.

Image from: G. Liu, N. Proukakis and G. Rigopoulos, MNRAS 521 (2023) 3, 3625-3647 arXiv:2211.02565 **[astro-ph.CO]**.

Motivation: Coherence

Similarities between Fuzzy Dark Matter and Ultracold Atom gases

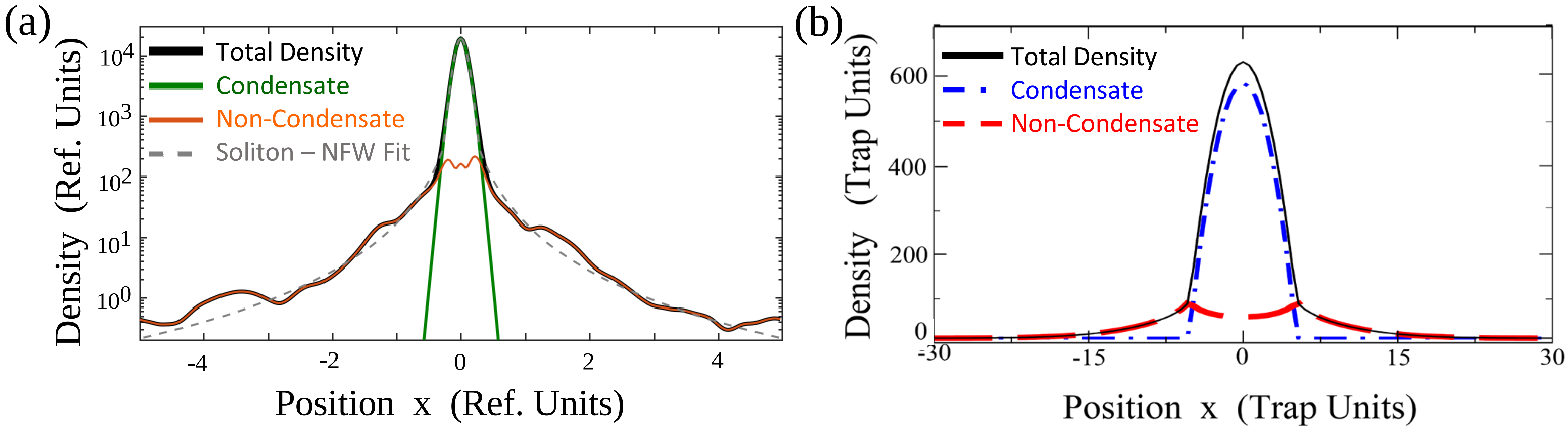


Image from: N. Proukakis, G. Rigopoulos and A.S.,
Phys. Rev. D 108 (8 2023), p. 083513
arXiv:2303.02049 [astro-ph.CO]

The Model: Starting point

- Our basic object is very general:

$$S = \int dt [\int d^3x \, i\psi^* \psi - H]$$

$$H = \int d^3x \left(-\frac{1}{2m}\psi^* \nabla^2 \psi + V_{\text{ext}} \psi^* \psi\right) + \frac{1}{2} \int d^3x \int d^3x' \, \psi^*(x) \psi^*(x') U(x, x') \psi(x') \psi(x)$$

Interaction term including contact and long-range: $U(x, x') = \alpha_1 \delta(x - x') + \alpha_2^2 \mathcal{O}^{-1}(x, x')$

- We can always write this action using a Hubbard-Stratonovich transformation as

$$S = \int d^4x \left(i\psi^* \dot{\psi} + \frac{1}{2m} \psi^* \nabla^2 \psi - \frac{\alpha_1}{2} (\psi^* \psi)^2 - V_{ext} \psi^* \psi + \frac{1}{2} V \mathcal{O} V - \alpha_2 V \psi^* \psi \right)$$

The Model: Starting point

- Dipolar gases: $\alpha_1 = g - \frac{C_{dd}}{3}$, $\alpha_2 = C_{dd}$, and $\mathcal{O} = C_{dd}\,\frac{\nabla^2}{(\mathbf{n}\cdot\nabla)^2}$

N. Proukakis, G. Rigopoulos and A.S.,
arXiv:2407.20178 **[cond-mat.quant-gas]**

- Gravitational: $\alpha_1 = g$, $\alpha_2 = m$, and $\mathcal{O} = \frac{1}{4\pi G}\nabla^2$

$$S = \int d^4x \left(i\psi^*\dot{\psi} + \frac{1}{2m}\psi^*\nabla^2\psi - \frac{g}{2}|\psi|^4 + \frac{1}{8\pi G}V\nabla^2 V - mV|\psi|^2 \right)$$

N. Proukakis, G. Rigopoulos and A.S.,
Phys. Rev. D 108 (8 2023), p. 083513
arXiv:2303.02049 **[astro-ph.CO]**
And arXiv:2407.08860 **[astro-ph.CO]**

Which is essentially the non-relativistic limit of

$$S = \int d^4x \sqrt{-g}\left(\frac{1}{2\kappa^2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{2}\phi^4 \right)$$

The Model: Starting point

To get our equations we split the field:

$$\psi = \Phi_0 + \varphi$$

Low energy-momentum High energy-momentum

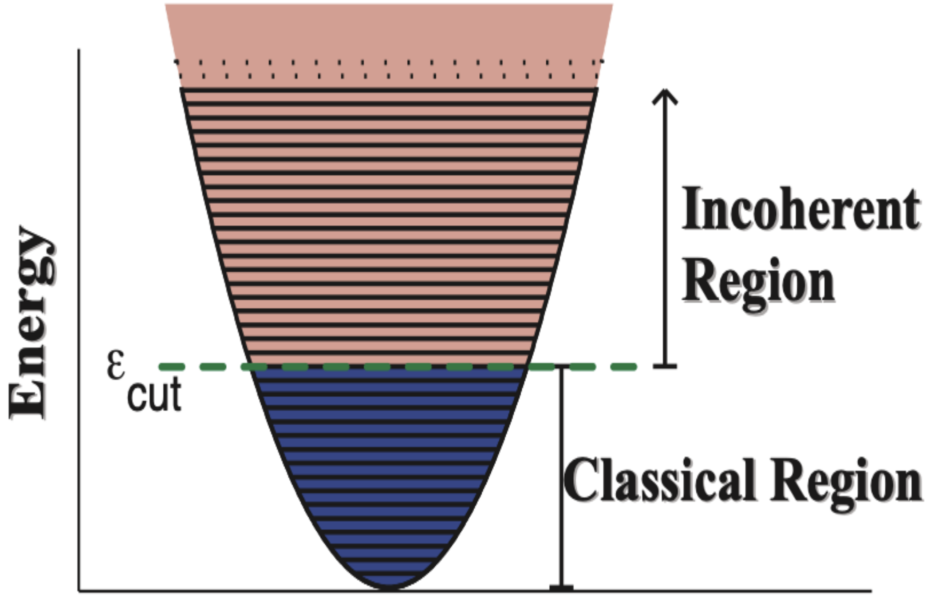


Image from: P. B. Blakie
Phys. Rev. E 78 (2 2008), p. 026704,
arXiv:0803.3664 **[physics.comp-ph]**

Similar in spirit to SPGPE models in cold atoms

Then we use Schwinger-Keldysh formalism, perturbation theory, approximations, Wigner transforms…

The Model: Main equations

We have three equations, one for the coherent part, one for the incoherent and one for the gravitational potential

$$i\frac{\partial\Phi_0(x)}{\partial t} = \left(-\frac{1}{2m}\nabla^2 + V_c(x)\right)\Phi_0(x) - i\,R\Phi_0(x) + \xi_1(x) - 2g\int d^4x'\Pi^R(x',x)V_{\rm nc}(x')\Phi_0(x) + g\xi_2(x)\Phi_0(x)$$

$$\frac{\partial f}{\partial t} + \frac{\boldsymbol{k}}{m}\cdot\nabla f - \nabla V_{\rm nc}\cdot\nabla_{\boldsymbol{k}} f = \frac{1}{2}(I_a + I_b)$$

$$\nabla^2 V^{\rm cl}(x) = 4\pi G m\left(n_c(x) + \tilde{n}(x) + \frac{1}{2}\xi_2(x)\right) - 4\pi G m\int d^4x'\,\Pi^R(x',x)V_{\rm nc}(x')$$

$$V_c(x) = mV^{\rm cl}(x) + g(n_c(x) + 2\tilde{n}(x))$$

$$V_{\rm nc}(x) = mV^{\rm cl}(x) + 2g(n_c(x) + \tilde{n}(x))$$

Mean field potentials

$$n_c = |\Phi_0|^2 \qquad \tilde{n} = \int\frac{d^3k}{(2\pi)^3}f$$

Coherent and incoherent number densities

The Model: FDM limit

For g $= 0$, order m, and all in the coherent part:

$$i\frac{\partial \Phi_0(x)}{\partial t} = \left(-\frac{1}{2m}\nabla^2 + V_c(x)\right)\Phi_0(x)$$

We recover FDM

$$\nabla^2 V^{\rm cl}(x) = 4\pi G m \ n_c(x)$$

$$V_c(x) = m V^{\rm cl}(x)$$

$$n_c = |\Phi_0|^2$$

Mean field potentials

Coherent and incoherent number densities

The Model: CDM limit

For g $= 0$, order m, and all in the non-coherent part:

$$\frac{\partial f}{\partial t} + \frac{\boldsymbol{k}}{m}\cdot\nabla f - \nabla V_{\rm nc}\cdot\nabla_{\boldsymbol{k}} f = 0$$

$$\nabla^2 V^{\rm cl}(x) = 4\pi G m \qquad \tilde{n}(x)$$

We recover Vlasov-Poisson used in CDM

$$V_{\rm nc}(x) = m V^{\rm cl}(x)$$

Mean field potentials

$$\tilde{n} = \int \frac{d^3k}{(2\pi)^3} f$$

Coherent and incoherent number densities

The Model: Main equations

$$i\frac{\partial\Phi_0(x)}{\partial t} = \left(-\frac{1}{2m}\nabla^2 + V_c(x)\right)\Phi_0(x) - i\,R\Phi_0(x) + \xi_1(x) - 2g\int d^4x'\Pi^R(x',x)V_{\rm nc}(x')\Phi_0(x) + g\xi_2(x)\Phi_0(x)$$

$$\frac{\partial f}{\partial t} + \frac{\boldsymbol{k}}{m}\cdot\nabla f - \nabla V_{\rm nc}\cdot\nabla_{\boldsymbol{k}} f = \frac{1}{2}(I_a + I_b)$$

$$\nabla^2 V^{\rm cl}(x) = 4\pi G m\left(n_c(x) + \tilde{n}(x) + \frac{1}{2}\xi_2(x)\right) - 4\pi G m\int d^4x'\,\Pi^R(x',x)V_{\rm nc}(x')$$

The Model: Particle collisions

$$i\frac{\partial\Phi_0(x)}{\partial t}=\left(-\frac{1}{2m}\nabla^2+V_c(x)\right)\Phi_0(x)-iR\Phi_0(x)+\xi_1(x)-2g\int d^4x'\,\Pi^R(x',x)V_{\rm nc}(x')\Phi_0(x)+g\xi_2(x)\Phi_0(x)$$

$$\frac{\partial f}{\partial t}+\frac{\boldsymbol{k}}{m}\cdot\nabla f-\nabla V_{\rm nc}\cdot\nabla_{\boldsymbol{k}}f=\frac{1}{2}(I_a+I_b)$$

Collisional terms

$$\nabla^2V^{\rm cl}(x)=4\pi Gm\left(n_c(x)+\tilde{n}(x)+\frac{1}{2}\xi_2(x)\right)-4\pi Gm\int d^4x'\,\Pi^R(x',x)V_{\rm nc}(x')$$

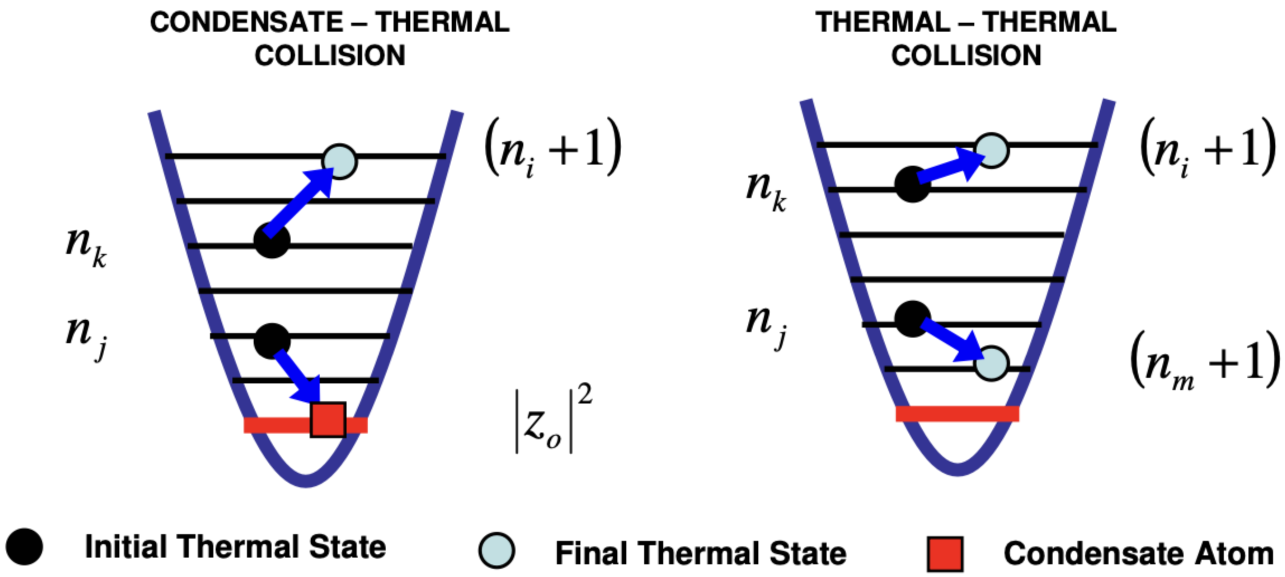


Image from: N. Proukakis and B. Jackson
J. Phys. B : At. Mol. Opt. Phys 41 (2008),
arXiv:0810.0210 **[cond-mat.other]**

The Model: Particle collisions

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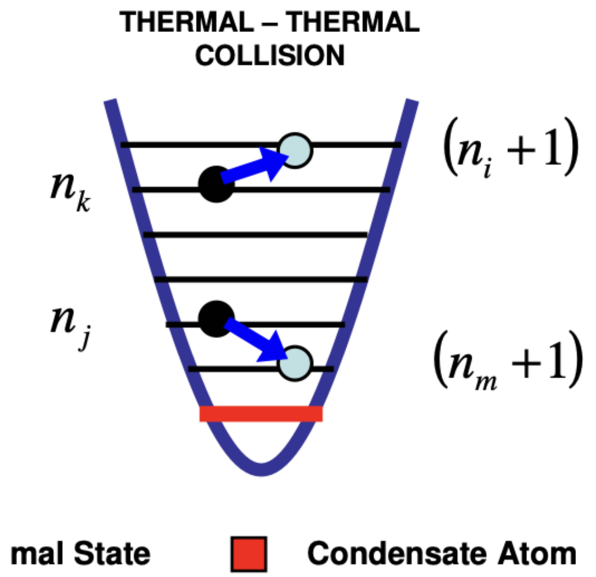
$$\frac{\partial f}{\partial t} + \frac{\boldsymbol{k}}{m}\cdot\nabla f - \nabla V_{\rm nc}\cdot\nabla_{\boldsymbol{k}} f = \frac{1}{2}(I_a + I_b)$$

Collisional terms

$$\nabla^2 V^{\rm cl}(x) = 4\pi G m\left(n_c(x) + \tilde{n}(x) + \frac{1}{2}\xi_2(x)\right) - 4\pi G m\int d^4x'\,\Pi^R(x',x)V_{\rm nc}(x')$$

$$I_b = 4g^2\int\frac{d^3p_2d^3p_3d^3p_4}{(2\pi)^5\hbar^7}\delta(\varepsilon_{\boldsymbol{p}_3} + \varepsilon_{\boldsymbol{p}_4} - \varepsilon_{\boldsymbol{p}_2} - \varepsilon_{\boldsymbol{p}})\delta(\boldsymbol{p} + \boldsymbol{p}_2 - \boldsymbol{p}_3 - \boldsymbol{p}_4)$$
$$\times[f_3f_4(f+1)(f_2+1) - ff_2(f_3+1)(f_4+1)]$$



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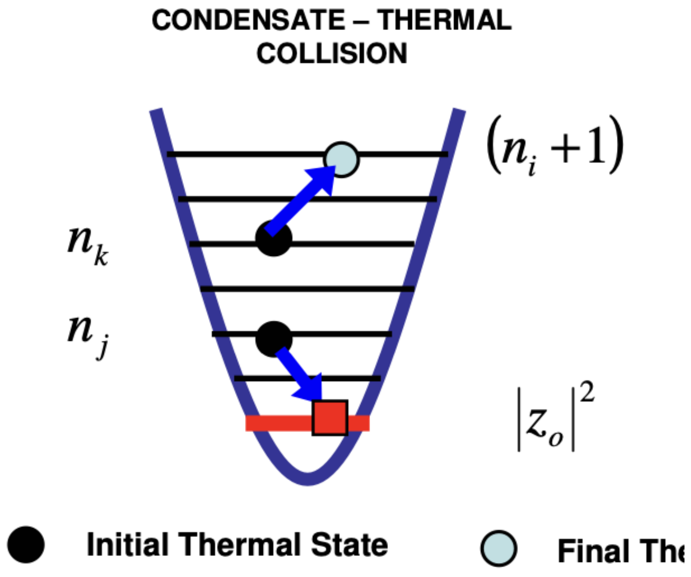
$$i\frac{\partial \Phi_0(x)}{\partial t} = \left(-\frac{1}{2m}\nabla^2 + V_c(x)\right)\Phi_0(x) - iR\Phi_0(x) + \xi_1(x) - 2g\int d^4x'\,\Pi^R(x',x)V_{\rm nc}(x')\Phi_0(x) + g\xi_2(x)\Phi_0(x)$$

$$\frac{\partial f}{\partial t} + \frac{\boldsymbol{k}}{m}\cdot\nabla f - \nabla V_{\rm nc}\cdot\nabla_{\boldsymbol{k}} f = \frac{1}{2}(I_a + I_b)$$

Collisional terms

$$\nabla^2 V^{\rm cl}(x) = 4\pi G m\left(n_c(x) + \tilde{n}(x) + \frac{1}{2}\xi_2(x)\right) - 4\pi G m\int d^4x'\,\Pi^R(x',x)V_{\rm nc}(x')$$

$$I_a = 4g^2 n_c \int \frac{d^3p_1\, d^3p_2\, d^3p_3}{(2\pi)^2\hbar^4}\delta(\varepsilon_{\boldsymbol{q}} + \varepsilon_{\boldsymbol{p}_1} - \varepsilon_{\boldsymbol{p}_2} - \varepsilon_{\boldsymbol{p}_3})\delta(\boldsymbol{p}_2 - \boldsymbol{p}_1 - \boldsymbol{q} + \boldsymbol{p}_3)$$
$$\times(\delta(\boldsymbol{p}_1 - \boldsymbol{p}) - \delta(\boldsymbol{p}_2 - \boldsymbol{p}) - \delta(\boldsymbol{p}_3 - \boldsymbol{p}))[(1 + f_1)f_2 f_3 - f_1(1 + f_2)(1 + f_3)]$$



The Model: Coherent part processes

$$i\frac{\partial \Phi_0(x)}{\partial t} = \left(-\frac{1}{2m}\nabla^2 + V_c(x)\right)\Phi_0(x) - i\,R\Phi_0(x) + \xi_1(x) - 2g\int d^4x'\Pi^R(x',x)V_{\rm nc}(x')\Phi_0(x) + g\xi_2(x)\Phi_0(x)$$

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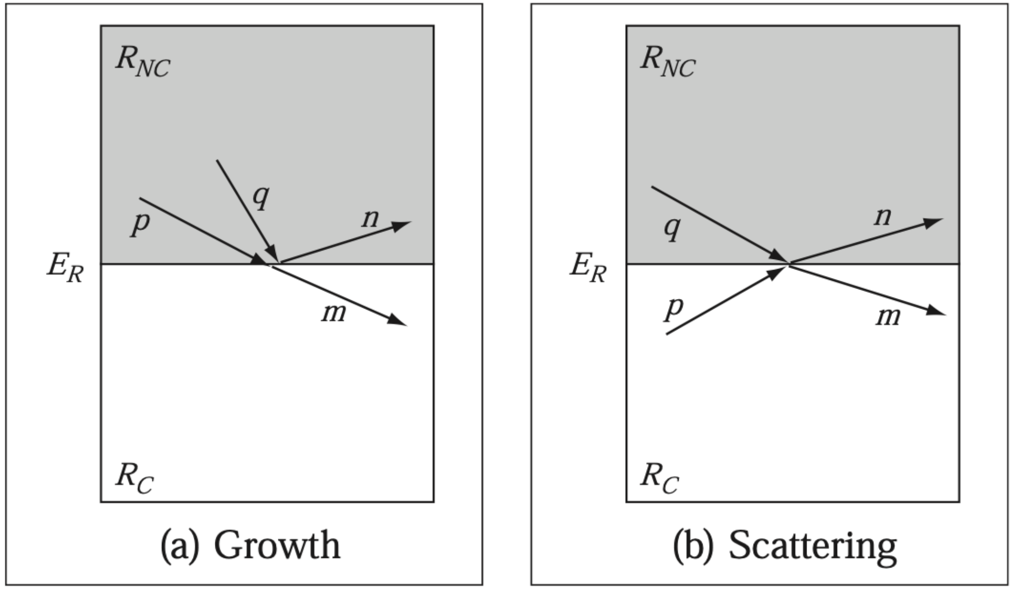

Image from: A. S. Bradley and C. W. Gardiner
arXiv:cond-mat/0602162

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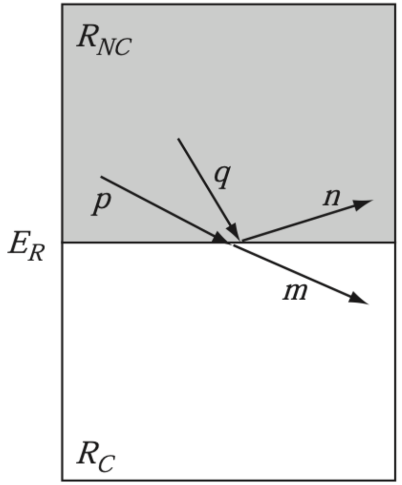
$$\frac{\partial f}{\partial t} + \frac{k}{m}\cdot\nabla f - \nabla V_{\rm nc}\cdot\nabla_k f = \frac{1}{2}(I_a + I_b)$$

$$\nabla^2 V^{\rm cl}(x) = 4\pi G m\left(n_c(x) + \tilde{n}(x) + \frac{1}{2}\xi_2(x)\right) - 4\pi G m\int d^4x'\,\Pi^R(x',x)V_{\rm nc}(x')$$

$$R = \frac{1}{4n_c}\int\frac{d^3p}{(2\pi)^3}I_a$$

The condensate can grow or decrease



(a) Growth

The Model: Coherent part processes

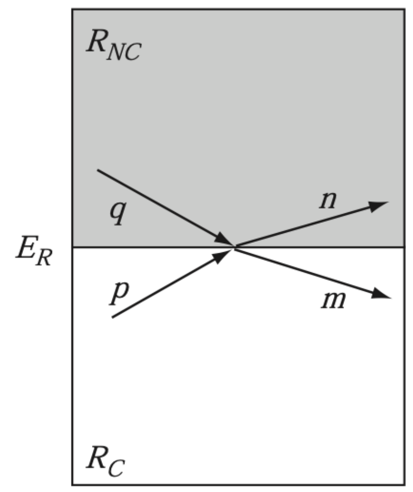
$$i\frac{\partial\Phi_0(x)}{\partial t} = \left(-\frac{1}{2m}\nabla^2 + V_c(x)\right)\Phi_0(x) - i\,R\Phi_0(x) + \xi_1(x) - 2g\int d^4x'\Pi^R(x',x)V_{\rm nc}(x')\Phi_0(x) + g\xi_2(x)\Phi_0(x)$$

Energy damping term

$$\frac{\partial f}{\partial t} + \frac{k}{m}\cdot\nabla f - \nabla V_{\rm nc}\cdot\nabla_k f = \frac{1}{2}(I_a + I_b)$$

$$\nabla^2 V^{\rm cl}(x) = 4\pi G m\left(n_c(x) + \tilde{n}(x) + \frac{1}{2}\xi_2(x)\right) - 4\pi G m\int d^4x'\,\Pi^R(x',x)V_{\rm nc}(x')$$

The term changes the energy of the coherent part



(b) Scattering

The Model: Coherent part processes

$$i\frac{\partial \Phi_0(x)}{\partial t} = \left(-\frac{1}{2m}\nabla^2 + V_c(x)\right)\Phi_0(x) - iR\Phi_0(x) + \xi_1(x) - 2g\int d^4x'\Pi^R(x',x)V_{\rm nc}(x')\Phi_0(x) + g\xi_2(x)\Phi_0(x)$$

Complex Noise

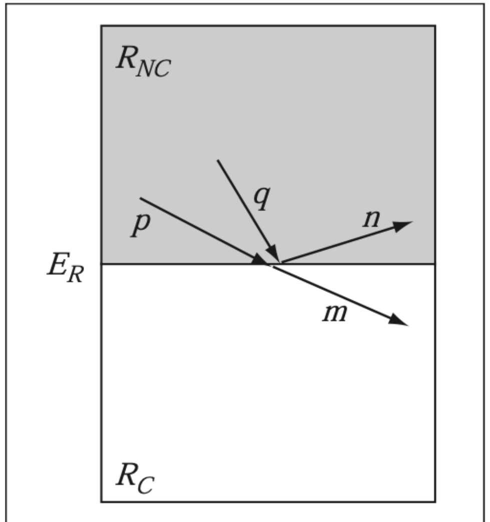
$$\frac{\partial f}{\partial t} + \frac{k}{m}\cdot\nabla f - \nabla V_{\rm nc}\cdot\nabla_k f = \frac{1}{2}(I_a + I_b)$$

$$\nabla^2 V^{\rm cl}(x) = 4\pi G m\left(n_c(x) + \tilde{n}(x) + \frac{1}{2}\xi_2(x)\right) - 4\pi G m\int d^4x'\,\Pi^R(x',x)V_{\rm nc}(x')$$

For each dissipative term we will have a noise term (Fluctuation-Dissipation theorem)

$$\langle \xi_1^*(x')\xi_1(x)\rangle = \frac{i}{2}\Sigma^K_{(c)}(x)\delta(x-x')$$

Noise can induce condensate production



(a) Growth

The Model: Coherent part processes

$$i\frac{\partial \Phi_0(x)}{\partial t} = \left(-\frac{1}{2m}\nabla^2 + V_c(x)\right)\Phi_0(x) - i R\Phi_0(x) + \xi_1(x) - 2g\int d^4x' \Pi^R(x',x)V_{\rm nc}(x')\Phi_0(x) + g\xi_2(x)\Phi_0(x)$$

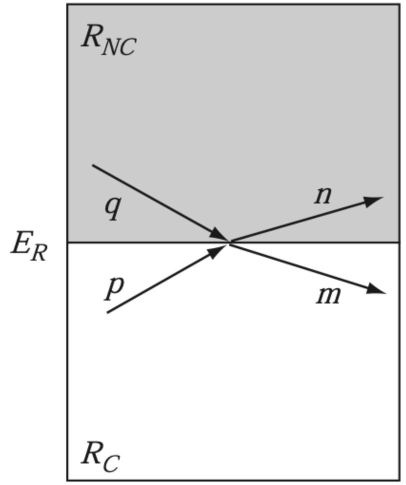
Real noise

$$\frac{\partial f}{\partial t} + \frac{\boldsymbol{k}}{m}\cdot\nabla f - \nabla V_{\rm nc}\cdot\nabla_{\boldsymbol{k}} f = \frac{1}{2}(I_a + I_b)$$

$$\nabla^2 V^{\rm cl}(x) = 4\pi G m\left(n_c(x) + \tilde{n}(x) + \frac{1}{2}\xi_2(x)\right) - 4\pi G m\int d^4x'\, \Pi^R(x',x)V_{\rm nc}(x')$$

For each dissipative term we will have a noise term (Fluctuation-Dissipation theorem)

$$\langle \xi_2(x)\xi_2(x')\rangle \;=\; -2i\Pi^K(x,x')$$



(b) Scattering

The Model: Poisson Equation

$$i\frac{\partial \Phi_0(x)}{\partial t} = \left(-\frac{1}{2m}\nabla^2 + V_c(x)\right)\Phi_0(x) - i\,R\Phi_0(x) + \xi_1(x) - 2g\int d^4x'\Pi^R(x',x)V_{\rm nc}(x')\Phi_0(x) + g\xi_2(x)\Phi_0(x)$$

$$\frac{\partial f}{\partial t} + \frac{k}{m}\cdot\nabla f - \nabla V_{\rm nc}\cdot\nabla_k f = \frac{1}{2}(I_a + I_b)$$

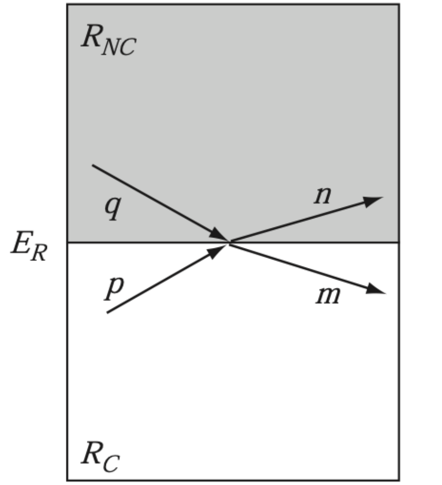
$$\nabla^2 V^{\rm cl}(x) = 4\pi G m\left(n_c(x) + \tilde{n}(x) + \frac{1}{2}\xi_2(x)\right) - 4\pi G m\int d^4x'\,\Pi^R(x',x)V_{\rm nc}(x')$$

Real noise

Energy damping term

$$V_c(x) = mV^{\rm cl}(x) + g(n_c(x) + 2\tilde{n}(x))$$

$$V_{\rm nc}(x) = mV^{\rm cl}(x) + 2g(n_c(x) + \tilde{n}(x))$$



(b) Scattering

Fuzzy Dark matter constraints

Lyman-α Forest sets important bounds on this model

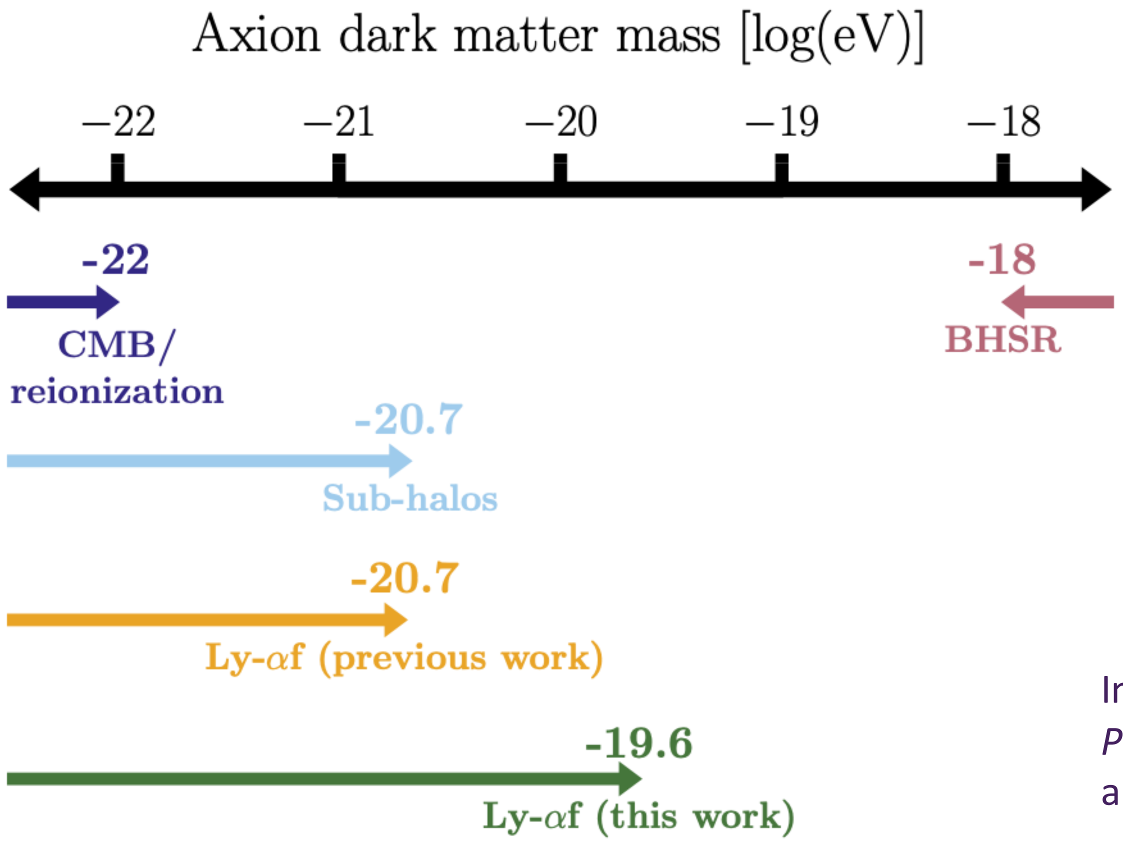


Image from: Rogers K. K., and Peiris H. V., *Phys. Rev. Lett.* ***126*** (2021), arXiv:2007.12705 **[astro-ph.CO]**.

Hydrodynamic equations

We work up to order g with universe expansion: $\nabla^2 V = 4\pi G a^2(\rho_c + \tilde{\rho})$

Condensate → Madelung transformation

$$\frac{\partial \rho_c}{\partial t} + 3H\rho_c + \frac{1}{a}\nabla\cdot(\rho_c \boldsymbol{v}) = 0$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + \frac{1}{a}\boldsymbol{v}\cdot\nabla\boldsymbol{u} = -\nabla\left(-\frac{\hbar^2}{2m^2a^3}\frac{\nabla^2\sqrt{\rho_c}}{\sqrt{\rho_c}} + \frac{1}{a}V + \frac{g}{m^2 a}(\rho_c + 2\tilde{\rho})\right)$$

Non-condensed particles → Moments and truncation (assuming isotropy and distribution function even respect bulk velocity)

$$\frac{\partial \tilde{\rho}}{\partial t} + 3H\tilde{\rho} + \frac{1}{a}\nabla\cdot(\tilde{\rho}\tilde{\boldsymbol{v}}) = 0$$

$$\frac{\partial \tilde{\boldsymbol{u}}}{\partial t} + \frac{1}{a}\tilde{\boldsymbol{v}}\cdot\nabla\tilde{\boldsymbol{u}} = -\nabla\left(\frac{1}{a}V + \frac{2g}{m^2 a}(\rho_c + \tilde{\rho})\right) - \frac{1}{a\tilde{\rho}}\nabla P$$

$$\frac{\partial P}{\partial t} + 5HP + \frac{1}{a}\nabla\cdot(\tilde{\boldsymbol{v}}P) = -\frac{2}{3a}P\nabla\cdot\tilde{\boldsymbol{v}}$$

Linear Regime

Our system admits consistently a particle pressure $P = \kappa\tilde{\rho}^{\,5/3}$

$$\ddot{\delta}_c + 2H\dot{\delta}_c + \left(\frac{\hbar^2 k^4}{4m^2a^4} - 4\pi G\bar{\rho}f + \frac{g\bar{\rho}fk^2}{m^2a^2}\right)\delta_c - (1-f)\left(4\pi G\bar{\rho} - \frac{2g\bar{\rho}\,k^2}{m^2a^2}\right)\delta_{\rm nc} = 0$$

$$\ddot{\delta}_{\rm nc} + 2H\dot{\delta}_{\rm nc} - \left(4\pi G\bar{\rho}(1-f) - \frac{1}{a^2}\left(\frac{2g\bar{\rho}(1-f)}{m^2} + \frac{5\kappa\bar{\rho}^{2/3}(1-f)^{2/3}}{3}\right)k^2\right)\delta_{\rm nc} - f\left(4\pi G\bar{\rho} - \frac{2g\bar{\rho}\,k^2}{m^2a^2}\right)\delta_c = 0$$

Parameters →

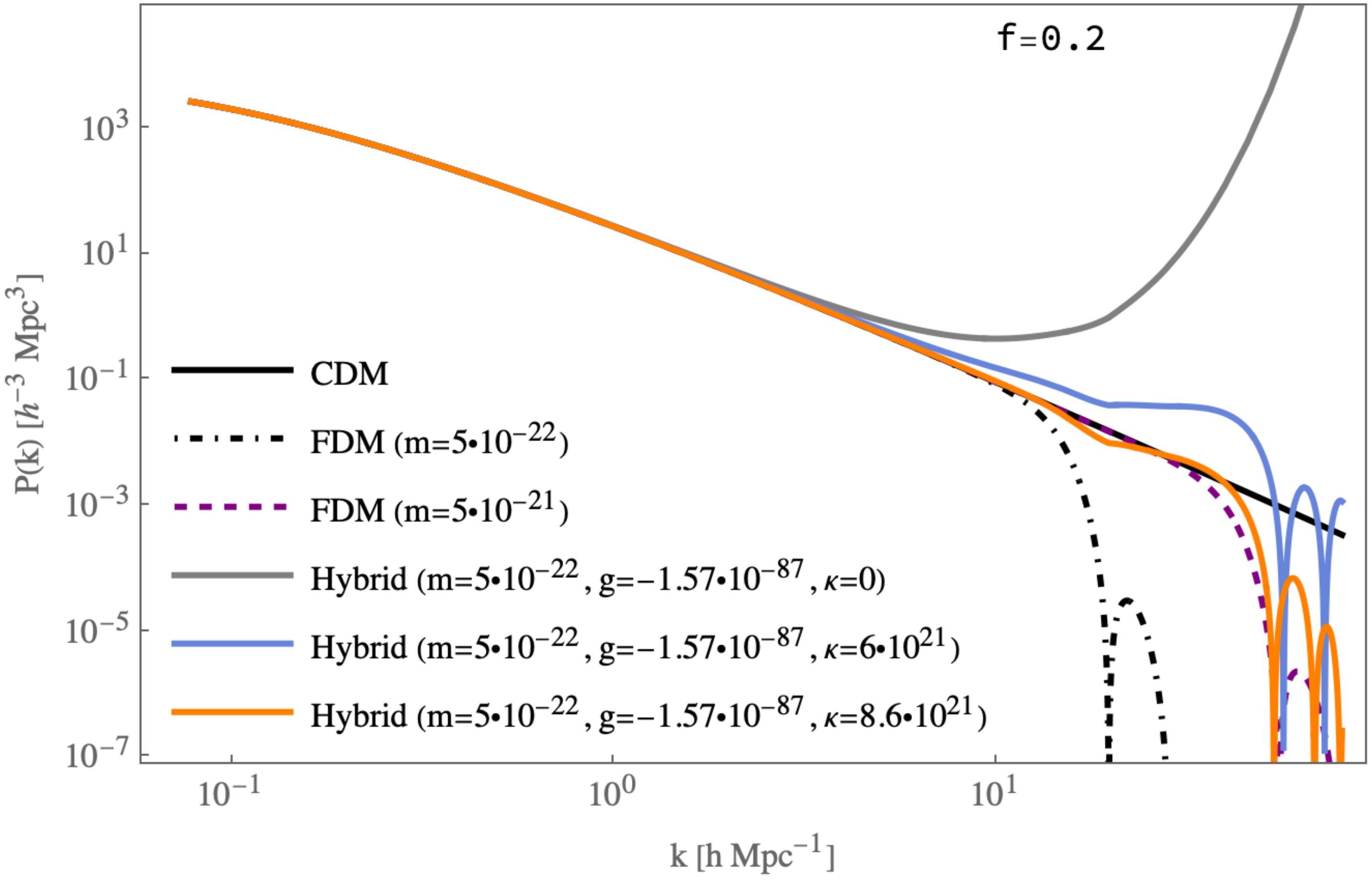
m: boson mass

f : condensate fraction

g : self-interaction

κ : particle pressure $(P = \kappa\tilde{\rho}^{5/3})$

Linear Regime



Hybrid model looks like FDM of higher mass.

We must be careful with statements about constraints on the mass.

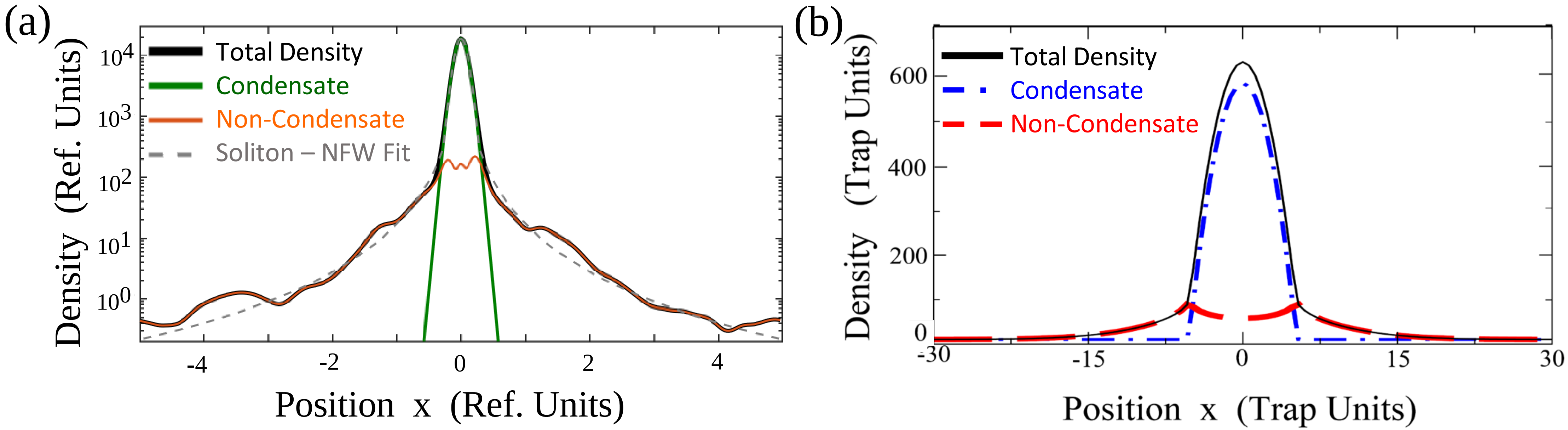
N. Proukakis, G. Rigopoulos and A.S., *Phys. Rev. D* 110 (2 2024), p. 023504
ArXiv:2311.05280 **[astro-ph.CO]**

Summary and Comments

- We have a general model for bosonic Dark Matter (condensate + particles). Known models are recovered under the appropriate limits.

- This full picture can give a rich phenomenology and physical effects.

- The model with both components with self-interaction can mimic FDM, so we need to be careful with placing constraints.


(a)
Total Density
Condensate
Non-Condensate
Soliton – NFW Fit
Density (Ref. Units)
10^4
10^3
10^2
10^1
10^0
-4
-2
0
2
4
Position x (Ref. Units)
(b)
Total Density
Condensate
Non-Condensate
Density (Trap Units)
600
400
200
0
-30
-15
0
15
30
Position x (Trap Units)

Thanks!