Dark Matter Superfluidity & Galactic Dynamics

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Dark Matter Distribution

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$$\rho(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2}$$

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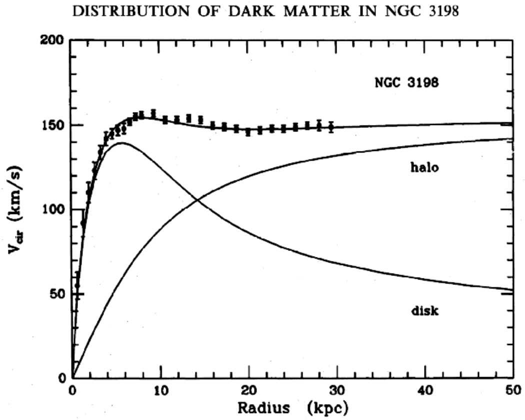
- Flat rotation curves require $\rho \propto 1/r^2$.
  Achieved in the neighbourhood of r_s.

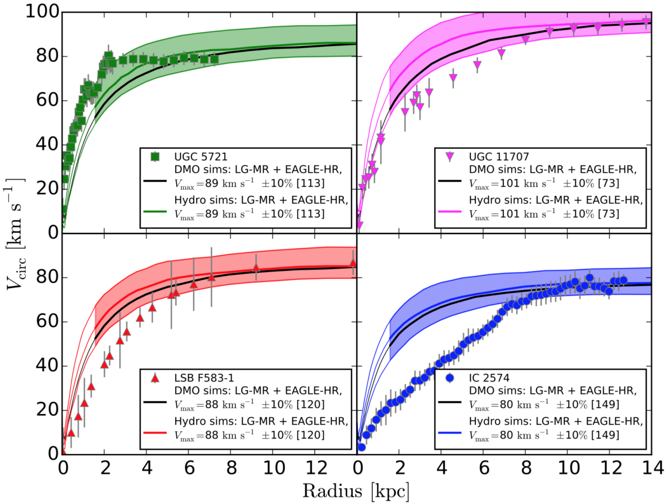
Rotation Curves



van Albada et al '84

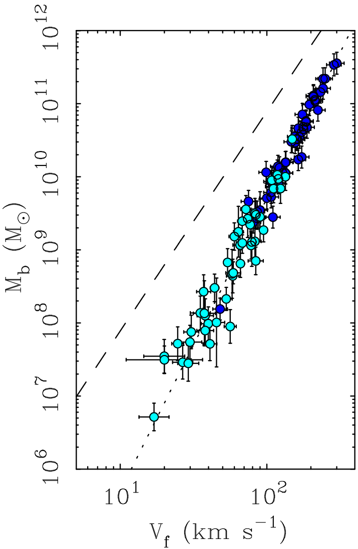
Not only should the dark matter density approach $1/r^2$ profile, but the way it approaches it should be sensitive to baryons.

Diversity of Rotation Curves



Oman et al '15

BTFR:



$$M_b \sim v_f^4$$

Famaey and McGaugh '12

MOdified Newtonian Dynamics (MOND):

Milgrom '83

$$a \simeq a_{\mathrm{N}} + \sqrt{a_0 a_{\mathrm{N}}}$$

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$$M_b = \frac{v_{\rm f}^4}{G_{\rm N} a_0}$$

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Q: What's the underlying principle?

- It could emerge from novel DM properties.
  e.g. through DM superfluidity.

Basic Idea:

LB, Khoury '15

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The superfluid phonon is a natural candidate.

This way MOND-like behaviour will be confined within the superfluid part of the structure.

MOND: Emergent phenomenon in superfluids

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$$\mathcal{L}_{\rm MOND} \sim \left[(\vec{\nabla}\varphi)^2\right]^{3/2}$$

vs

$$\mathcal{L}_{\rm superfluid} = P(X) \qquad \text{with} \qquad X \equiv \mu + \dot{\varphi} - \frac{(\vec{\nabla}\varphi)^2}{2m}$$

P depends on the properties of the superfluid.

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This simple example doesn't work!

Superfluid Properties:

Low energy degrees of freedom are phonons.
In general

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To mediate MOND force, phonons must couple to baryons

$$\mathcal{L}_{\rm int} = -\alpha\frac{\Lambda}{M_{\rm pl}}\varphi\rho_{\rm b}$$

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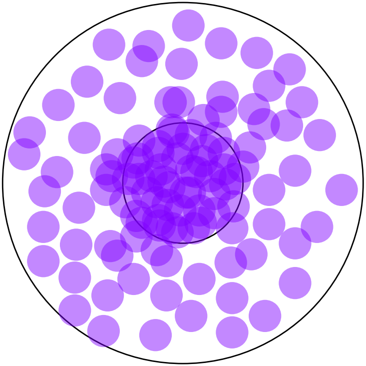
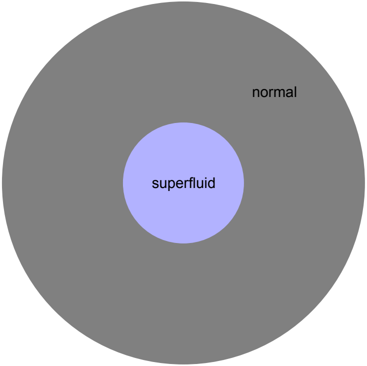


Halo Structure:

LB, Famaey, Khoury '17



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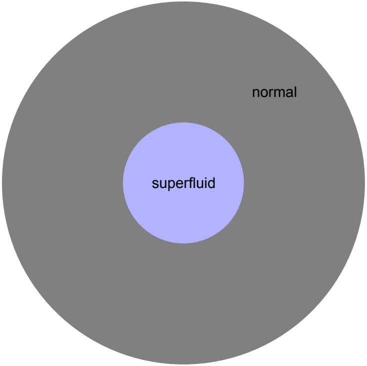
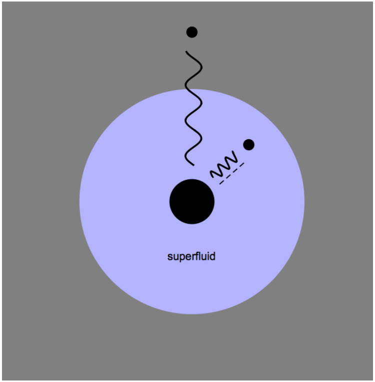


$$2\left(\frac{\sigma/m}{\mathrm{cm}^2/\mathrm{g}}\right)^{1/4} \lesssim \frac{m}{\mathrm{eV}} \lesssim 4\left(\frac{\sigma/m}{\mathrm{cm}^2/\mathrm{g}}\right)^{1/4}$$

Forces:



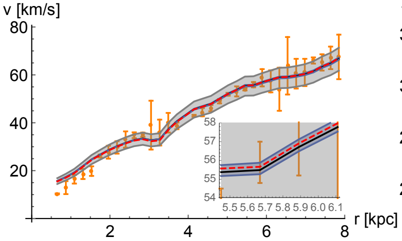
Inside the superfluid: $a = a_b + a_{\mathrm{DM}} + a_{\mathrm{phonon}}$

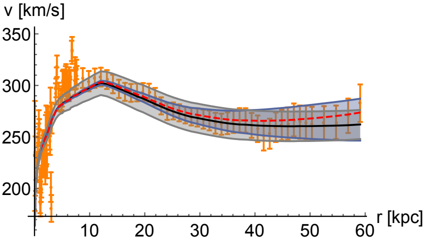
Outside the superfluid: $a = a_b + a_{\mathrm{DM}}$

Rotation Curves

IC 2574: $M_b = 2 \times 10^9 M_\odot$

UGC 2953: $M_b = 1.6 \times 10^{11} M_\odot$





Regime of Validity

Baryons distort the DM density profile

$$\rho_{DM} \simeq \Lambda m^2 \sqrt{\frac{\alpha M_b}{8\pi M_{\rm pl} r^2}} \qquad < \qquad \Lambda_0^4$$

Validity of the idea requires

$$\Lambda_0 \gg \Lambda$$

Regime of Validity

e.g. for the Sun

$$\rho_{\rm DM} < \Lambda_0^4 \qquad \text{gives} \qquad r > r_* \equiv \left(\frac{m}{\Lambda_0}\right)^4 \sqrt{\frac{M_b}{M_\odot}} 10^5 \mathrm{km}$$

For Milky-Way, $r_* < 10\mathrm{kpc}$ requires

$$\Lambda_0 > 5 \times 10^2 \Lambda$$

In case of $\Lambda_0 = 5 \times 10^2 \Lambda$, for the Sun we'd get

$$r_* \simeq 10^{11} \mathrm{km}$$

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Challenge: Finding a microscopic theory.