Dark Matter and its Interactions with Baryons

Justin Khoury (U. Penn)

Berezhiani & JK, 1506.07877 + 1507.01019
JK, 1602.05961
Berezhiani, Famaey & JK, 1711.05478
Fig 8.17 (A. Sanchez) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007
The coarse-grained success
On large (linear) scales, only use the hydrodynamical limit of DM

$$T_{\mu\nu} = (\rho + P)u_\mu u_\nu + Pg_{\mu\nu}$$

⇒ Any perfect fluid with $P \approx 0$ and $c_s \approx 0$ does the job.

Cleanest evidence for DM, but does not offer much information about DM microphysics (SIDM, fuzzy DM etc.)
Dark matter is generally assumed of particles (WIMPs, axions, etc.), with negligible interactions among themselves and with ordinary matter (other than gravity).
Galaxies

Cosmic web

Galaxy clusters

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Cosmic web

Galaxy clusters

Galaxies
The Baryon-Dark Matter Conspiracy
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Observe how baryons (stars & gas) are spatially distributed:

\[ \rho_b = \rho_* + \rho_{\text{gas}} \]
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Solve Poisson eq’n to infer baryonic acceleration:

\[ g_{\text{bar}} \]
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Observe how baryons rotate to infer centripetal acceleration:

\[ g_{\text{obs}} = \frac{V^2}{r} \]
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Observe how baryons rotate to infer centripetal acceleration:

\[ g_{\text{obs}} = \frac{V^2}{r} \]

includes DM and/or modified gravity
Mass Discrepancy Acceleration Relation (MDAR)

\[ g_{\text{obs}} \approx \sqrt{a_0 g_{\text{bar}}} \]

2693 points
Mass Discrepancy Acceleration Relation (MDAR)


\[ g_\ast = \left( 1 \pm 0.2 \text{ (syst.)} \right) \times a_0 \]

\[ a_0 \approx 1.2 \times 10^{-8} \text{ cm/s}^2 \]

\( g_{\text{obs}} \approx \sqrt{a_0 g_{\text{bar}}} \)
Mass Discrepancy Acceleration Relation (MDAR)


\[ g_\text{obs} \simeq \sqrt{a_0 g_{\text{bar}}} \]

- Holds within 26% (0.1 dex).

- Scatter within observational uncertainties.

No need for intrinsic scatter!

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\[ a_0 \simeq 1.2 \times 10^{-8} \text{ cm/s}^2 \]
MDAR was predicted by Milgrom 30 years ago!

Milgrom (1983)

\[ a = \begin{cases} 
  a_N & a_N \gg a_0 \\
  \sqrt{a_Na_0} & a_N \ll a_0 
\end{cases} \]

\[ a_N = \frac{G_NM_b(r)}{r^2} \]

\[ a_0 \simeq 1.2 \times 10^{-8} \text{ cm/s}^2 \]
Historically proposed as alternative to DM + interpreted as modification to Newtonian dynamics (MOND)

But this is too extreme. Need DM for CMB, LSS, lensing, etc.
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Nevertheless a really powerful empirical statement about DM in galaxies

\[ \text{e.g. Milgrom predicted existence of low-surface brightness (LSB) galaxies!} \]
MOND effective theory:

$$\mathcal{L}_{\text{MOND}} = -\frac{2M_{\text{Pl}}^2}{3a_0} \left( (\partial \phi)^2 \right)^{3/2} + \frac{\phi}{M_{\text{Pl}}} \rho_b$$
For static, spherically-symmetric source,

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Bekenstein & Milgrom (1984)

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$$\vec{\nabla} \cdot \left( \frac{|\vec{\nabla}\phi|}{a_0} \vec{\nabla}\phi \right) = 4\pi G_N \rho$$

$$\Rightarrow \quad \phi' = \sqrt{a_0 \frac{G_N M(r)}{r^2}} = \sqrt{a_0 a_N}$$
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\[ a_{\text{tot}} = a_N + a_\phi = a_N + \sqrt{a_0 a_N} \]
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Do the scaling relations require new physics associated with dark matter?

Can they be explained with ordinary physics?
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Can they be explained with ordinary physics?

“WITCH HUNT !”
Orthodoxy: It’s all feedback!

- Star formation model
- Stellar evolution
- Mass and metal return
- Supernovae rates
- Gas enrichment
- Cooling and heating rates
- Self-shielding
- Stellar feedback
- Local and non-local SNII feedback
- Black hole and AGN feedback

Can these feedback processes, which are inherently stochastic, result in tight correlation displayed in the MDAR?
Orthodoxy: It’s all feedback!

Desmond (2016)

See also
van den Bosch & Dalcanton (2000); Di Cintio & Lelli (2016)
Orthodoxy: It's all feedback!

...
The middle ground:

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  e.g. New emergent long-range forces

  Berezhiani & JK (2015, 2016)
  Berezhiani, Famaey & JK (2017)

  e.g. New particle (contact) interactions

  Famaey, JK & Penco (1712.01316)
2 Conditions for DM Condensation
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Overlapping de Broglie wavelength

\[ \lambda_{dB} \sim \frac{1}{mv} \gtrsim \ell \sim \left( \frac{m}{\rho_{\text{vir}}} \right)^{1/3} \]

\[ \implies m \lesssim 2 \text{ eV} \]
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- Thermal equilibrium
  \[ \Gamma \sim N v \sigma \frac{\rho_{\text{vir}}}{m} \gtrsim t_{\text{dyn}}^{-1} \]
  \[ \frac{\sigma}{m} \gtrsim \left( \frac{m}{\text{eV}} \right)^4 \frac{\text{cm}^2}{g} \]
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DM is quite cold:

\[ T_c = 6.5 \left( \frac{\text{eV}}{m} \right)^{5/3} (1 + z_{\text{vir}})^2 \text{ mK} \]

(\(^7\text{Li} \text{ atoms} \implies T_c \sim 0.2 \text{ mK} )
Temperature set by how rapidly DM particles move

\[ T \sim m v^2 \]

Galaxies

\[ T_{\text{galaxy}} \sim 0.1 \text{ mK} \]

Galaxy clusters

\[ T_{\text{cluster}} \sim 10 \text{ mK} \]
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MOND
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\[ \Rightarrow \text{ Superfluid} \]

\[ \Rightarrow \text{ MOND} \]

Galaxy clusters

\[ T_{\text{cluster}} \sim 10 \text{ mK} \]

\[ \Rightarrow \text{ NO Superfluid} \]

\[ \Rightarrow \text{ NO MOND} \]
Naturally distinguishes between galaxies (where MOND works) and galaxy clusters (where MOND doesn’t work).

Temperature set by how rapidly DM particles move

\[ T \sim mv^2 \]

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= Superfluid

= MOND

Galaxy clusters

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Temperature set by how rapidly DM particles move
Effective Description of Superfluids

A superfluid phase is defined as:

- Global U(1) symmetry, spontaneously broken

\[ \theta \rightarrow \theta + c \]

Greiter, Wilczek & Witten (1989)
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- State has finite charge density, \( \langle J^0 \rangle \sim \langle \dot{\theta} \rangle \neq 0 \)

  By redefining field, can set

  \[ \theta = \mu t + \phi \]
Effective Description of Superfluids

A superfluid phase is defined as:

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  $\implies$ Goldstone boson $\theta \rightarrow \theta + c$

- State has finite charge density, $\langle J^0 \rangle \sim \langle \dot{\theta} \rangle \neq 0$

By redefining field, can set

$$\theta = \mu t + \phi$$

- chemical potential
- phonons

Hence, at lowest order in derivatives the EFT of phonons is

$$\mathcal{L} = P(X) ; \quad X = \mu + \phi - \frac{(\vec{\nabla} \phi)^2}{2m}$$

Greiter, Wilczek & Witten (1989)
Effective Description of Superfluids

At lowest order in derivatives, the zero temperature effective action is

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Effective Description of Superfluids

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Conjecture: DM superfluid phonons are governed by MOND action

\[ P_{\text{MOND}}(X) = \frac{2\Lambda (2m)^{3/2} X^{3/2}}{3} \]

Phonons couple to baryons:

\[ \mathcal{L}_{\text{coupling}} = -\frac{\Lambda}{M_{\text{Pl}}} \phi \rho_b \]

\[ \Lambda = \sqrt{a_0 M_{\text{Pl}}} \approx 0.8 \text{ meV} \]

(Match to MOND scale)
Cold Atoms Analogue?

\[ \mathcal{L}_{\text{UFG}} \sim m^{\frac{3}{2}} X^{\frac{5}{2}} \]

Son & Wingate (2005)
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3-body interactions?

\[ \mathcal{L} = \frac{i}{2} (\Psi \partial_t \Psi^* - \Psi^* \partial_t \Psi) - \frac{|\nabla \Psi|^2}{2m} - \frac{\lambda}{24m^3} |\Psi|^6 \]

Split into \( \Psi = \sqrt{2m} \rho e^{i\theta} \), and integrate out \( \rho \),

\[ \Longrightarrow \quad \mathcal{L} = \frac{4}{3} \frac{m^{3/2}}{\sqrt{\lambda}} X^{3/2} \]
Density profile

Assuming hydrostatic equilibrium,

\[
\frac{1}{\rho_{\text{cond}}(r)} \frac{dP_{\text{cond}}(r)}{dr} = -\frac{4\pi G N}{r^2} \int_0^r dr'r'^2 \rho(r')
\]

Using equation of state \( P_{\text{cond}} \sim \rho_{\text{cond}}^3 \), find:

\[
R_{\text{core}} = \left( \frac{M}{10^{12} M_\odot} \right)^{1/6} (1 + z_{\text{vir}})^{1/4} \left( \frac{m}{\text{eV}} \right)^{-9/5} \left( \frac{\Lambda}{\text{meV}} \right)^{-3/5} \quad 21 \text{ kpc}
\]

Remarkably, realistic size cores with \( m \sim \text{eV} \) and \( \Lambda \sim \text{meV} \)!
Superfluid

$\rho_s \simeq \text{const.}$
Rotation curves

\[ m = 1 \text{ eV} \]

Low surface brightness (IC 2574)

\[ R_{SF} = 40 \text{ kpc} \]

High surface brightness (UGC 2953)

\[ R_{SF} = 76 \text{ kpc} \]

\[ \alpha_0 = 0.87 \times 10^{-8} \text{ cm/s}^2 \]
Observational Signatures
Vortices

When spun faster than critical velocity, superfluid develops vortices.

\[ \omega_{cr} \sim \frac{1}{mR^2} \sim 10^{-41} \text{s}^{-1} \]

For a halo of density \( \rho \),

\[ \omega \sim \lambda \sqrt{G_N \rho} \sim 10^{-18} \lambda \text{ s}^{-1} ; \quad 0.01 < \lambda < 0.1 \]

\[ \rightarrow \quad \text{Vortex formation is unavoidable} \]

Line density:

\[ \sigma_v \sim m\omega \sim 10^2 \lambda \text{ AU}^{-2} \]

Observational consequences?

cf. Silverman & Mallett (2002); Rindler-Daller & Shapiro (2012)
Vortices

When spun faster than critical velocity, superfluid develops vortices.

$$\omega_{cr} \sim$$

For a halo of density $\rho_G$, $\lambda$,

$$\omega \sim \lambda$$

$\rightarrow$ Vortex formation is unavoidable

Line density:

$$v \sim m \sim 10^{24} \text{AU}^2$$

Observational consequences?

cf. Silverman & Mallett (2002); Rindler-Daller & Shapiro (2012)

Sreenivasan’s group at U. Maryland
Galaxy mergers: Dynamical friction

Triangulum Galaxy (M33)

Andromeda Galaxy (M31)

Milky Way Galaxy

1.932 billion years
Galaxy mergers: Dynamical friction

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Dynamical Friction 1

Triangles represent stars in the galaxy.

---

Dynamical Friction 2

Triangles represent stars in the galaxy.

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Dynamical Friction 3

Triangles represent stars in the galaxy.

---

Dynamical Friction 4

Triangles represent stars in the galaxy.

---

Dynamical Friction 5

Triangles represent stars in the galaxy.
Galaxy mergers: Dynamical friction

Illustration Sequence of the Milky Way and Andromeda Galaxy Colliding

NASA, ESA, Z. Levay and R. van der Marel (STScI), T. Hallas, and A. Mellinger • STScI-PRC12-20b
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Superfluid cores should pass through each other with negligible dissipation if

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(Landau's criterion)
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- If \( v_{\text{infall}} < c_s \approx 200 \text{ km/s} \), then negligible dynamical friction between superfluids
  - Longer merger time scale + multiple encounters

- If \( v_{\text{infall}} > c_s \), then encounter will excite DM particles out of the condensate, which will result in dynamical friction
  - Merged halo thermalize and settle back to condensate
Galaxy mergers

If $v_{\text{infall}} \ll c_s \ll 200 \text{ km/s}$, then dynamical friction between superfluids is negligible.

If $v_{\text{infall}} > c_s$, then encounter will excite DM particles out of the condensate, which will result in dynamical friction.

Longer merger time scale + multiple encounters
Merged halo thermalize and settle back to condensate.

Superfluid cores should pass through each other with negligible dissipation if $v_{\text{infall}} \ll c_s$ (Landau's criterion).

Fornax
No DM $\implies$ No MOND

Globular clusters
Ibata et al. (2011)

Tidal dwarfs
Lelli et al. (2015)
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No superfluid $\implies$ No external field effect

Ultra-diffuse galaxies
van Dokkum et al. (2015); Koda et al. (2015)
How does dark energy fit into the picture?
Unified Superfluid Dark Sector

Suppose have mixture of 2 superfluids, e.g. DM ground state + excited state, with energy difference $\delta E = E_1 - E_0$.

$$\mathcal{L} = P_0(X_0) + P_1(X_1)$$
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Interact through Rabi/Josephson coupling:

$$V(\theta_1, \theta_2) = \Lambda^4 \cos^2 \left( \frac{\theta_1 - \theta_2 + \delta E t}{2f} \right) \approx \Lambda^4 \cos^2 \left( \frac{\delta E t}{2f} \right) \cdot \Lambda \sim \text{meV}.$$
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\( \Lambda \sim \text{meV} \).

Individual number densities no longer conserved, but total superfluid particle number is conserved:

\[
n = P_0, x_0 + P_1, x_1 \sim \frac{1}{a^3}
\]
Unified Superfluid Dark Sector: Cosmology

Background:

\[ 2\dot{H} + 3H^2 = \frac{\Lambda^4}{M_{P1}^2} \cos^2 \left( \frac{\delta E t}{2f} \right) . \]

Perturbations: Both superfluids are non-relativistic

\[ c_{s0}^2 = \frac{P_{0,x0}}{m_0 P_{0,x0} x_0} \ll 1 \]
\[ c_{s1}^2 = \frac{P_{1,x1}}{m_1 P_{1,x1} x_1} \ll 1 \]

\[ \rightarrow \text{clustering DE model} \]

\[ \text{e.g. Creminelli et al. (2011)} \]

\[ \text{e.g. Sandvik, Tegmark, Zaldarriaga & Waga (2004)} \]
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\[ \rightarrow \quad \text{clustering DE model} \quad \quad \text{e.g. Creminelli et al. (2011)} \]

(Different from other "unified" DMDE attempts, e.g. Chaplygin gas, where sound speed for DMDE fluid is \( O(1) \) at late times.)

\[ \text{e.g. Sandvik, Tegmark, Zaldarriaga & Waga (2004)} \]
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**e.g.** New particle (contact) interactions

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