A tight MDAR: a clue to the nature of DM?

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France
- CMB+large-scale structure => existence of a non-baryonic dust fluid
- Whatever it is: must reproduce ΛCDM on large scales
Dark Matter

- CMB+large-scale structure $\Rightarrow$ existence of a non-baryonic dust fluid
- Whatever it is: must reproduce $\Lambda$CDM on large scales

- Is cosmology solved? Is something missing? Is the devil in the details?
- Can the narrowness of scaling relations in rotationally-supported galaxies at $z=0$ imply something fundamental beyond gastrophysics, on the nature of DM? What drives the small dispersion??
Disk galaxies: diversity & regularity

Oman et al. 2015, Bullock & Boylan-Kolchin 2017

\[ V_{\text{circ}}(2 \text{ kpc}) = (2 \text{ kpc} \times \xi_{\text{obs}})^{1/2} \]
Disk galaxies: diversity & regularity

\[
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\]

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Scatter < 0.13 dex
Li et al.: 0.057 dex intrinsic
The BTFR twin paradox

BTFR implies MDAR at large radii, but not at the center of galaxies

Ghari et al.
The « strong » core-cusp problem

The rotation curves shapes of late-type dwarf galaxies

R. A. Swaters\textsuperscript{1,2,*}, R. Sancisi\textsuperscript{3,4}, T. S. van Albada\textsuperscript{3}, and J. M. van der Hulst\textsuperscript{3}

HI observations for a sample of 62 galaxies [...] procedure takes the rotation curve shape, the HI distribution, the inclination, and the size of the beam into account, and makes it possible to correct for the effects of beam smearing.

In spiral galaxies and even in the central regions of late-type dwarf galaxies, the shape of the central distribution of light and the inner rise of the rotation curve are related. This implies that galaxies with stronger central concentrations of light also have higher central mass densities, and it suggests that the luminous mass dominates the gravitational potential in the central regions, even in low surface brightness dwarf galaxies.
Disk galaxies: diversity & regularity

\[ V_{\text{circ}}(2 \text{ kpc}) = (2 \text{ kpc} \times g_{\text{obs}})^{1/2} \]

⇒ Baryonic TFR \( V_f^4 \propto M_b \) (see C. Wheeler’s talk) with scatter of only 0.1 dex in \( M_b \) (Lelli et al. 2016) when ‘best distances’ sample used (since \( M_b \propto D^2 \))

Theoretical scatter of the BTFR from AM (Di Cintio & Lelli 2016, Desmond 2017): 0.2-0.25 dex (>3.5 \( \sigma \) disagreement)

Note that observed mass-size relation is NOT tight (which would have helped)
Disk galaxies: diversity & regularity

Oman et al. 2015, Bullock & Boylan-Kolchin 2017

MOND (see also A. Dutton’s talk last tuesday)

Note: at larger radii, SDSS satellite velocity dispersions (Klypin & Prada) can be fit with mildly varying anisotropy (see e.g. Tiret et al. 2007) consistent with (controversial) isothermal profile fits in gravitational lensing (e.g. Brimioulle et al. 2013)

\[ V_{\text{circ}}(2 \text{ kpc}) = (2 \text{ kpc} \times g_{\text{obs}})^{1/2} \]
Self-interacting DM

Kamada, Kaplinghat et al. 2017

Creasey et al. 2017
DM-baryon interactions?

Justin Khoury (Penn)

Lasha Berezhiani (MPP Munich)

Riccardo Penco (Carnegie Mellon)
Superfluid dark matter

Idea of Berezhiani & Khoury: DM could have strong self-interactions and enter a superfluid phase when
- cold enough (i.e.; their de Broglie wavelength $\lambda \sim 1/(mv)$ is large
- dense enough (i.e. the interparticle separation is smaller than $\lambda$)

$\Rightarrow$ Superfluid core (~50-100 kpc in MW) where collective excitations (phonons) are the only relevant degree of freedom (represented by a scalar field in EFT) and can couple to baryons and mediate a long-range force + NFW-like « normal » atmosphere outside of the core
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Parameters of the theory (or rather, of the toy-model theory):

- DM particle mass $m$ (~eV)
- Self-interaction cross-section $\sigma$ ($\sigma/m<< 1 \text{ cm}^2/\text{g}$)
- Self-interaction « strength » $\Lambda$ (~0.05 meV)
- Coupling constant of the scalar field to baryons $\alpha$
- Parameter accounting for non-zero temperature effects $\beta$

combination of $\Lambda^2$ and $\alpha^3$ related to $a_0$
UGC 2953 (sphericized profile, $a_0 \sim 0.9 \times 10^{-10}$ m/s$^2$)

Black: $M_{DM}=1.6 \times 10^{12}$ $M_{\text{sun}}$ ($R_T = 82$ kpc, $R_{NFW} = 76$ kpc)

Red-dashed: $M_{DM}=10^{13}$ $M_{\text{sun}}$ ($R_T = 129$ kpc, $R_{NFW} = 95$ kpc)

Berezhiani, Famaey, Khoury 2018
Q: Can the MDAR result from a quasi-equilibrium configuration linked to **baryon-DM particle short-range interactions/collisions**? (with high cross sections > $10^{-30}$ cm$^2$ => not WIMPS)

A: perhaps, but not easy… but let’s try! (Famaey, Khoury, Penco 2018)
Q: Can the MDAR result from a quasi-equilibrium configuration linked to **baryon-DM particle short-range interactions/collisions**? (with high cross sections $> 10^{-30}$ cm$^2$ $\Rightarrow$ not WIMPS)

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Change from CBE to BTE with two fluids
$\Rightarrow$ second order moments then give a heat equation which can resemble the MOND equation given (to zeroth order) $T \propto \Phi$

$$
\frac{3}{2} \left( \frac{\partial}{\partial t} + \vec{u} \cdot \vec{\nabla} \right) T + \frac{m}{\rho} P^{ij} \partial_i u_j + \frac{m}{\rho} \vec{\nabla} \cdot \vec{q} = \dot{\mathcal{E}}
$$

Spherical symmetry+isotropy+no spin+equilibrium for DM halo:

$$
\vec{\nabla} \cdot \left( \kappa \vec{\nabla} (mv^2) \right) = -n \dot{\mathcal{E}}.
$$

Two things to fix: thermal conductivity and heating/cooling rate
Thermal conductivity: baryonic disk acting as efficient mediator allowing heat to flow within the DM fluid (… not true because baryons concentrated in stars)

⇒ \( t_{\text{relax}} \sim t_{\text{dyn}} \Rightarrow \kappa \sim n rv \)

It might be easier to force this through self-interactions.

Heating rate: heavy DM case (quark nugget style) leads to a cooling \( \propto m_b v^2 \)

Include \( a_0 \) as a particle physics quantity related to the cross-section:

\[
\frac{n}{m_b} \frac{\sigma_{\text{int}}}{\epsilon} \sim a_0 \Rightarrow \nabla \cdot \left( \frac{\kappa}{a_0} m \nabla v^2 \right) = C v \rho_b
\]

Main requested feature: density dependence of the cross-section, inversely proportional to DM density!
Combining Poisson, Jeans & heat conduction for spherical exponential profiles, we can show that fixing the BTFR at large radii yields the MDAR everywhere and solves the BTFR twins paradox:

\[
M_b = 10^8 M_\odot, \ L = 0.5 \text{ kpc}
\]

\[
V \ [\text{km/s}] \quad r \ [\text{kpc}]
\]

\[
M_b = 10^8 M_\odot, \ L = 1 \text{ kpc}
\]

\[
V \ [\text{km/s}] \quad r \ [\text{kpc}]
\]

\[
M_b = 10^8 M_\odot, \ L = 2 \text{ kpc}
\]

\[
V \ [\text{km/s}] \quad r \ [\text{kpc}]
\]
Galaxy clusters:

Timescale $\tau$ for energy exchange such that $\Delta E/E \sim \mathcal{O}(1)$

\[
\frac{d(mv^2)}{dt} = -\frac{2}{3} \Gamma_{\text{int}} c \rho_{\text{b}} v \frac{Ca_0}{n} \equiv -\frac{mv^2}{\tau}
\]

\[a_0 \simeq cH_0/6 \implies H_0 \tau \sim 5 \text{ for typical galaxy cluster values}\]

CMB:

\[
v^2 \sigma_{\text{int}} \lesssim 6 \times 10^{-10} \text{ cm}^2/\text{g}
\]

comfortably obeyed at $z \sim 10^4$ (high density)

Main perspectives:

1) Study the (much more interesting) light DM/heating case (because transforming NFW cusps into cores needs heating of the DM, not cooling, plus allows to reach BTFR in the time-dep. case)

2) Get the thermal conductivity as required (long-range force: superfluid phonons?)