

Title: Baryon-dark matter interactions and the radial acceleration relation

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Abstract: <p>The radial acceleration relation is an empirical universal scaling relation between the total gravitational field and the Newtonian acceleration generated by baryons at any given radius within spiral galaxies. In this talk, I will discuss the possibility that such a relation arises from interactions between baryons and dark matter (DM), rather than from feedback processes or modifications of gravity. Starting from this premise, I will discuss what we can infer about the nature of baryon-DM interactions. In particular, I will argue that such interactions must depend on the local DM density in order to correctly reproduce the observed behavior of spiral and elliptical galaxies. I will briefly revisit existing phenomenological, astrophysical and cosmological constraints on baryon-DM interactions in light of the unusual density dependence of our cross-section. I will conclude by mentioning possible ways of realizing this scenario in particle physics models, and discuss a non-relativistic toy model.</p>

# Baryon-dark matter interactions and the radial acceleration relation

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# Outline

1. Motivation

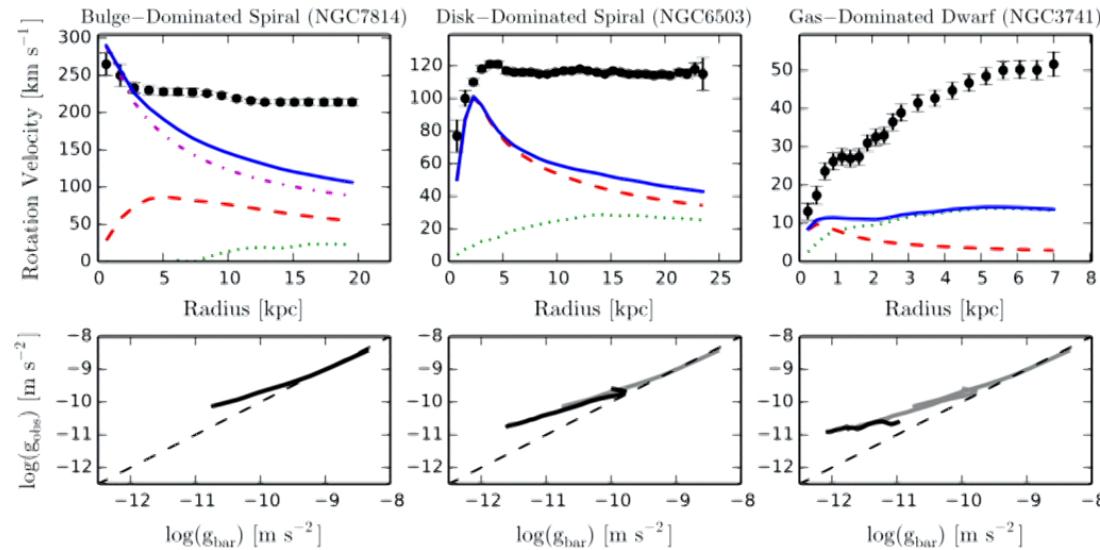
2. Setup

3. Galaxies

4. Constraints

5. Models

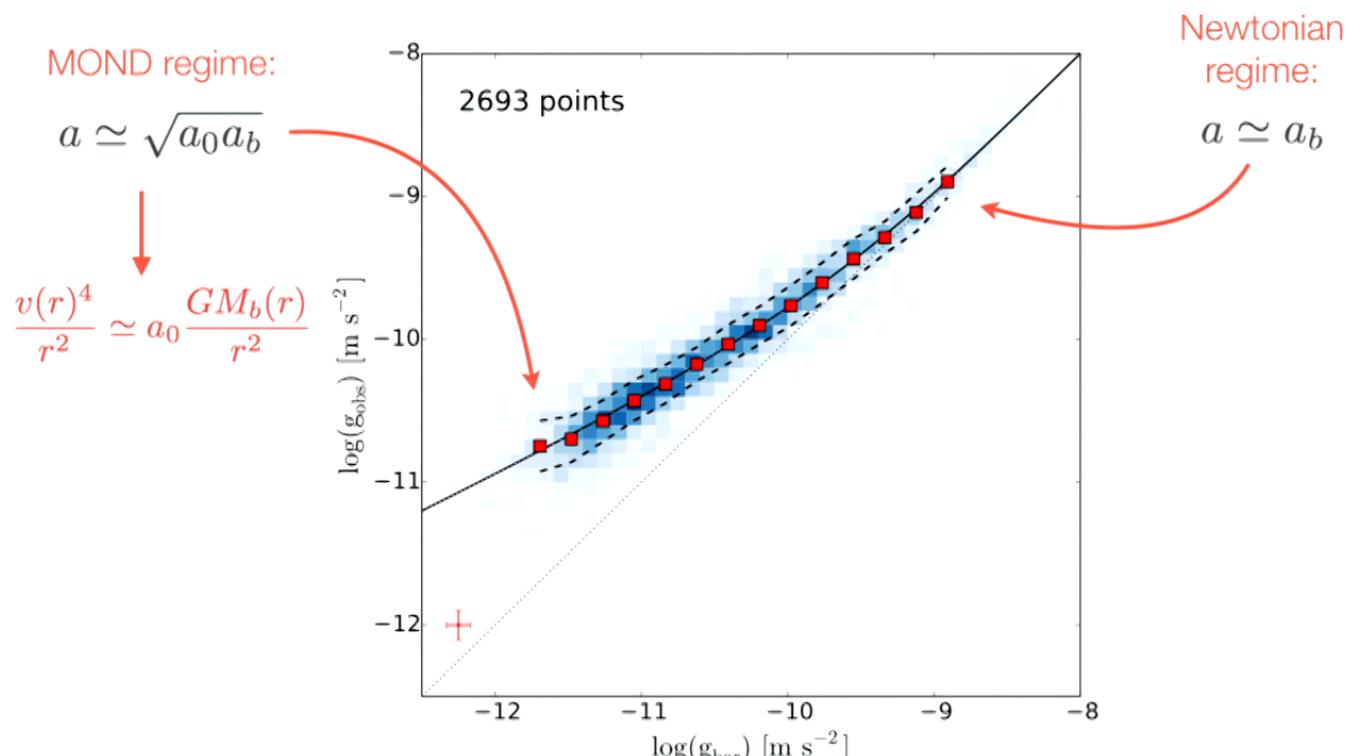
# Galaxy rotation curves



$$\text{Baryonic Tully-Fisher relation: } v_\infty^4 \simeq a_0 G M_{b,\infty} \quad (a_0 \sim 10^{-10} \text{ m/s}^2)$$

Source: McGaugh et al. (1609.05917)

# Radial acceleration relation

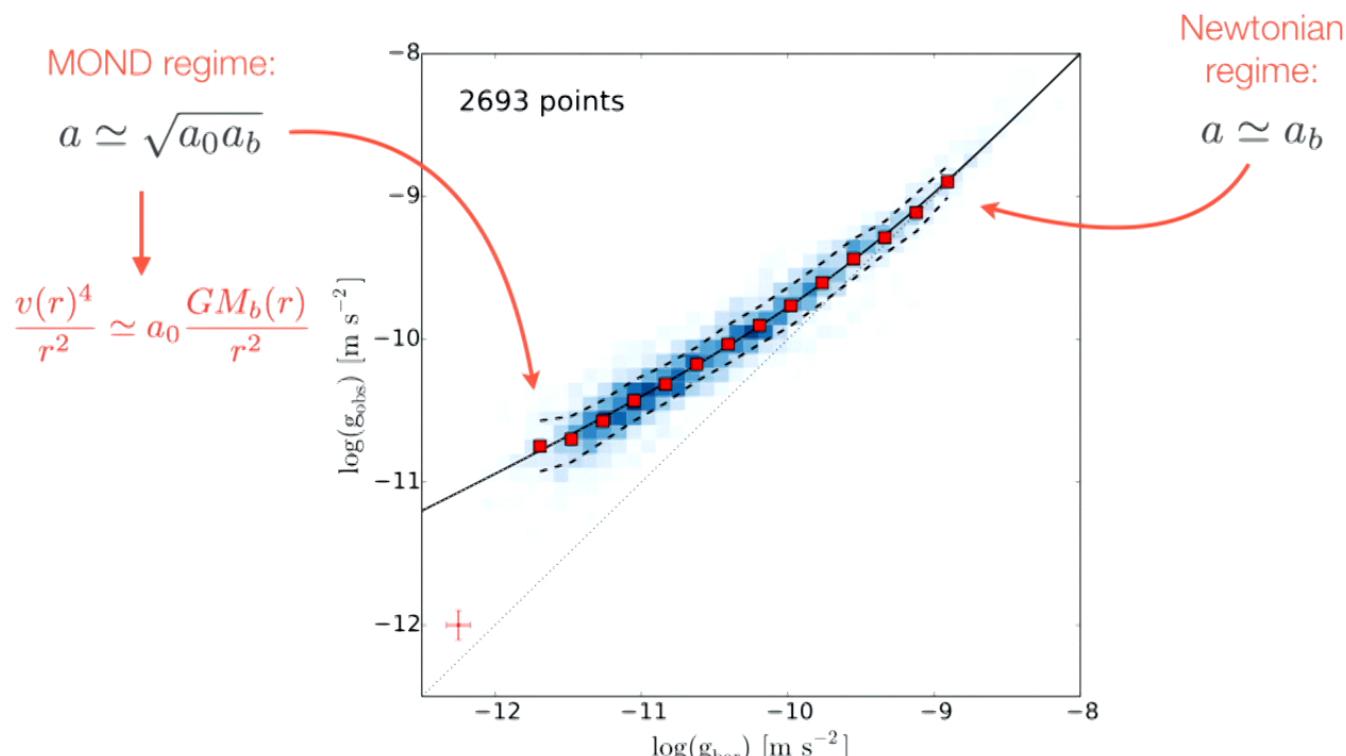


Source: McGaugh et al. (1609.05917)

# Possible origin of the RAR

- Standard  $\Lambda$ CDM cosmology
  - Feedback
- New interactions between baryons
  - Modified gravity (MOND, TeVeS, ...)
  - Superfluid DM
- New interactions between baryons and dark matter
  - This talk!

# Radial acceleration relation



Source: McGaugh et al. (1609.05917)

# Possible origin of the RAR

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# From Boltzmann equation...

- DM Boltzmann equation:  $\frac{\partial f}{\partial t} + \frac{\vec{k}}{m} \cdot \frac{\partial f}{\partial \vec{r}} + m \vec{g} \cdot \frac{\partial f}{\partial \vec{k}} = \mathcal{I}[f, f_b]$   
  
Baryon-DM interactions
- Poisson equation:  $\vec{\nabla} \cdot \vec{g} = -4\pi G (\rho + \rho_b)$
- We will consider equilibrium configurations,  
assume approximate isotropy in velocity space


$$\vec{u}(\vec{r}) \equiv \int \frac{d^3 k}{(2\pi)^3} \frac{\vec{k}}{m} f(\vec{r}, \vec{k}) \simeq 0$$

## ...to moments at equilibrium

- DM number density:  $n(\vec{r}) \equiv \int \frac{d^3k}{(2\pi)^3} f(\vec{r}, \vec{k})$
- **0th moment:** continuity equation (trivial)
- **1st moment:** Jean's equation (hydrostatic equilibrium)

$$\vec{\nabla} (\rho v^2) = \rho \vec{g} \quad (T \equiv mv^2, \rho \equiv mn)$$

- **2nd moment:** heat equation

$$\vec{\nabla} \cdot \vec{Q} = \dot{\mathcal{E}}$$

# Heat conductivity

- Fourier's law:  $\vec{Q} \simeq \kappa \vec{\nabla} T$   $\left( \frac{\ell \nabla T}{T} \ll 1 \right)$
- Heat conductivity:  $\kappa \simeq \frac{c_v n \ell^2}{t_{\text{relax}}}$
- Heat equation  $\longrightarrow \vec{\nabla} \cdot (\kappa m \vec{\nabla} v^2) = \dot{\mathcal{E}}$

# Particle physics inputs

- Elastic interactions:  $\dot{\mathcal{E}} = n \Gamma_{\text{int}} \epsilon$   $(\Gamma_{\text{int}} = n_b \sigma_{\text{int}} v)$
- Master equation:  $\sigma_{\text{int}} \epsilon \simeq \frac{C a_0 m_b}{n}$   $(C \sim 1/10)$
- “Heavy” DM:  $\epsilon \simeq 2m_b v^2 > 0$   $(m \gg m_b)$
- On average, DM cools down by interacting with baryons

# To summarize

Today we are going to solve the following equations for  $\rho$  and  $v$  :

- Poisson equation:  $\vec{\nabla} \cdot \vec{g} = -4\pi G(\rho + \rho_b)$
- Hydrostatic equilibrium:  $\vec{\nabla}(\rho v^2) = \rho \vec{g}$
- Heat equation:  $\vec{\nabla} \cdot (\kappa m \vec{\nabla} v^2) \simeq C \rho_b a_0 v$

$$\mathcal{N} \sim \mathcal{N}_b$$

# Equilibrium

- Characteristic time for energy loss by DM:

$$\frac{d(mv^2)}{dt} \simeq -\Gamma_{\text{int}}\epsilon \equiv -\frac{mv^2}{\tau} \longrightarrow H_0\tau \simeq 10^2 v \frac{\rho}{\rho_b}$$

- Which systems do we expect to be in equilibrium?

	$v$	$\rho/\rho_b$
Spiral Galaxies	$10^{-3}$	varies
Elliptical Galaxies	$10^{-3}$	$< 1$
Dwarf Spheroidals	$10^{-4}$	varies
Galaxy Clusters	$10^{-2}$	10

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# Disk Galaxies

## Knudsen regime

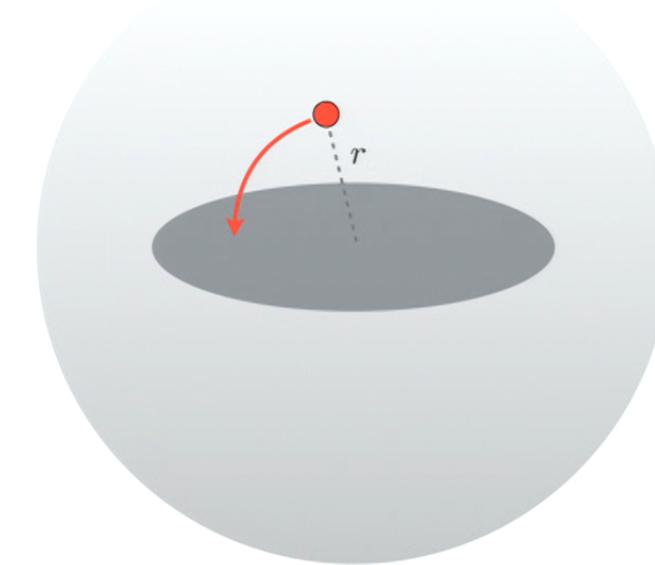
- Hierarchy of time scales:

$$\tau_{\text{halo}} > r/v \gtrsim \tau_{\text{disk}}$$

- Heat conductivity:

$$\kappa \simeq \frac{c_v n \ell^2}{t_{\text{relax}}} \sim n r v$$

- Spherical symmetry



$$\ell \simeq r$$

$$t_{\text{relax}} \simeq r/v$$

# Disk Galaxies

DM-dominated region

- Hydrostatic equation:

$$\frac{1}{\rho} \frac{d}{dr} (\rho v^2) \simeq -\frac{GM(r)}{r^2} \quad \xrightarrow{\text{power law}} \quad \rho(r) \sim \frac{v^2(r)}{2\pi Gr^2}$$

- Heat equation:

$$\frac{1}{r^2} \frac{d}{dr} \left( \rho v r^3 \frac{dv}{dr} \right) = C a_0 v \rho_b \quad \xrightarrow{\text{power law}} \quad \rho r \frac{dv^2}{dr} \sim C a_0 \frac{M_b(r)}{4\pi r^2}$$

power  
law

$$v^4(r) \sim C a_0 G M_b(r) \quad \xrightarrow{\text{power law}} \quad V_{\text{flat}}^4 \simeq 4 C a_0 G M_b \quad \xrightarrow{\text{MOND law}} \quad a^2 \sim a_0 a_b$$

$$V^2 \simeq 2v^2$$

MOND law

# Disk Galaxies

Baryon-dominated region

- Hydrostatic equation:

$$\frac{1}{\rho} \frac{d}{dr} (\rho v^2) \simeq - \frac{GM_b(r)}{r^2} \xrightarrow{\text{power law}} v^2(r) \sim \frac{GM_b(r)}{r}$$

- Heat equation:

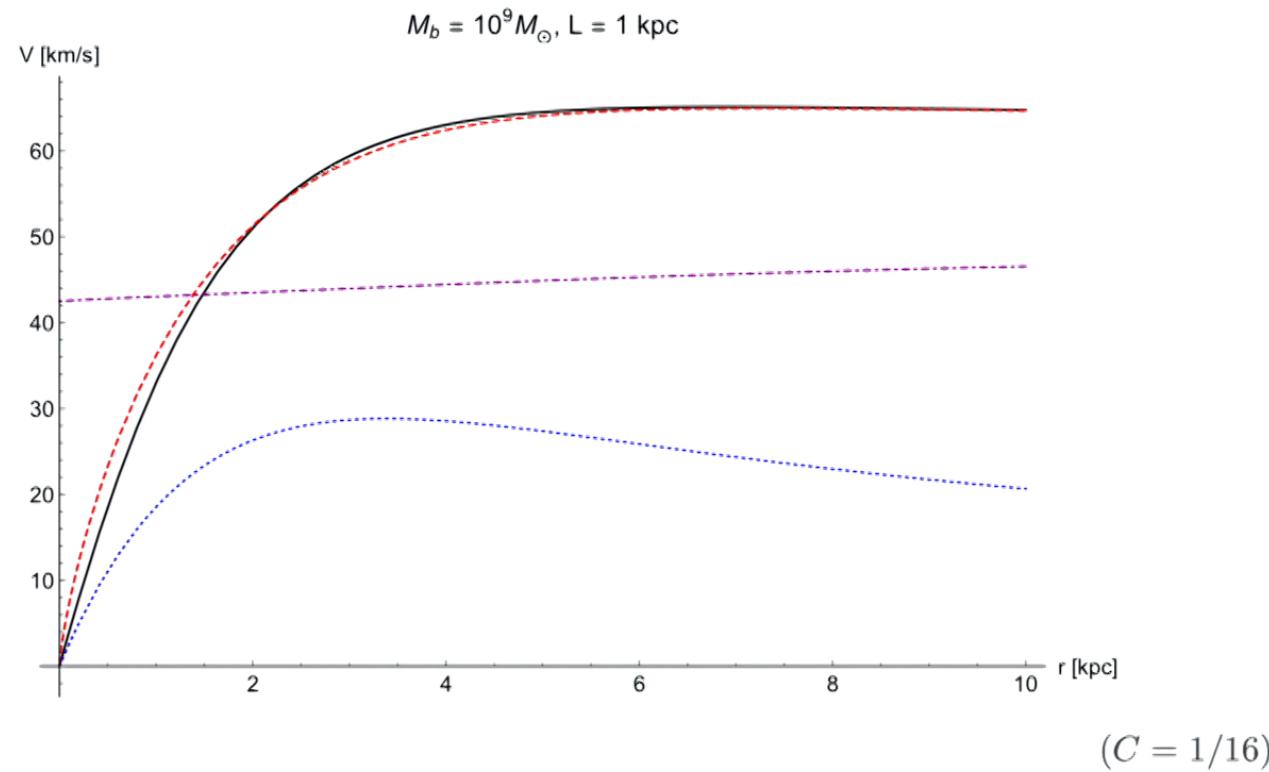
$$\frac{1}{r^2} \frac{d}{dr} \left( \rho v r^3 \frac{dv^2}{dr} \right) = C a_0 v \rho_b \xrightarrow{\text{power law}} \rho r \frac{dv^2}{dr} \sim C a_0 \frac{M_b(r)}{4\pi r^2}$$

$$\xrightarrow{} \rho(r) \sim \frac{C a_0}{4\pi G r} \left( \frac{d \log r}{d \log v^2} \right) \xrightarrow{\text{power law}} \Sigma_{\text{DM}}(r) \sim \rho(r) r \simeq \text{const.}$$

[ Donato et al., 0904.4054]

# Disk Galaxies

## Numerical solutions



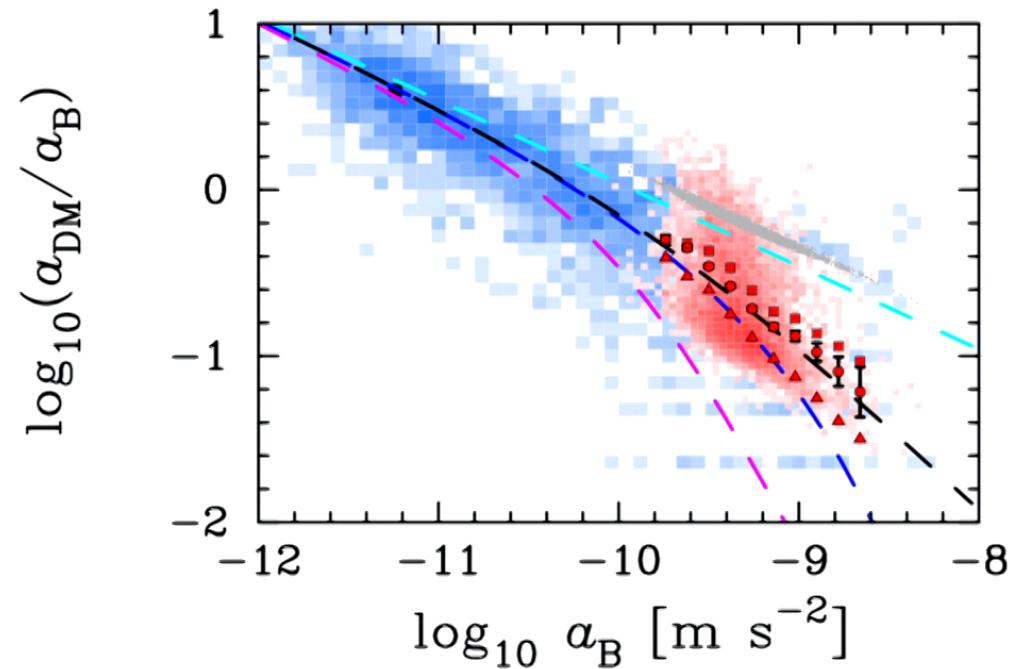
# Elliptical Galaxies

- Pressure-supported
- Baryon-dominated
- In equilibrium:  $H_0\tau \simeq \frac{9}{C} v \frac{\rho}{\rho_b} \lesssim 1$
- Baryons are not segregated in a disk
- Heat conductivity:  $\kappa \sim \frac{n\ell^2}{\tau} \sim nv^2\tau \sim \frac{v^3}{mCa_0} \frac{\rho^2}{\rho_b}$
- “Power-law arguments”

$$\boxed{\frac{GM(r)}{r^2} \simeq a_0}$$

# Elliptical Galaxies

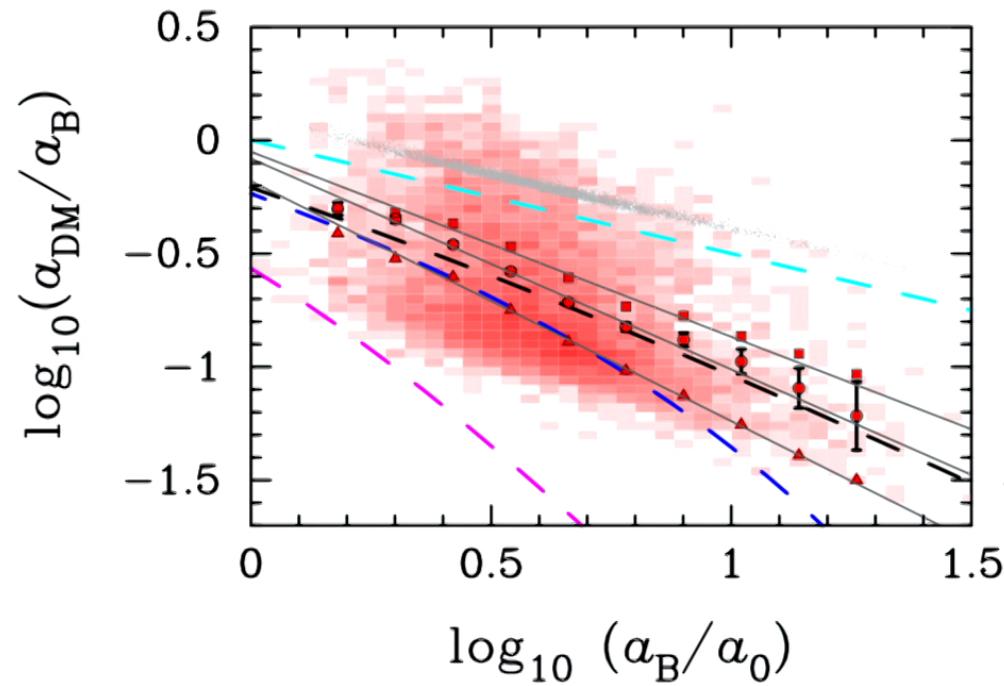
Observations



Source: Chae et al. (1707.08280)

# Elliptical Galaxies

## Observations



$$\frac{a_{\text{DM}}}{a_{\text{b}}} = 10^p \left( \frac{a_{\text{b}}}{a_0} \right)^q$$

$$p = -0.08 \pm 0.02 \pm 0.1$$

$$q = -0.93 \pm 0.03 \pm 0.1$$

Source: Chae et al. (1707.08280)

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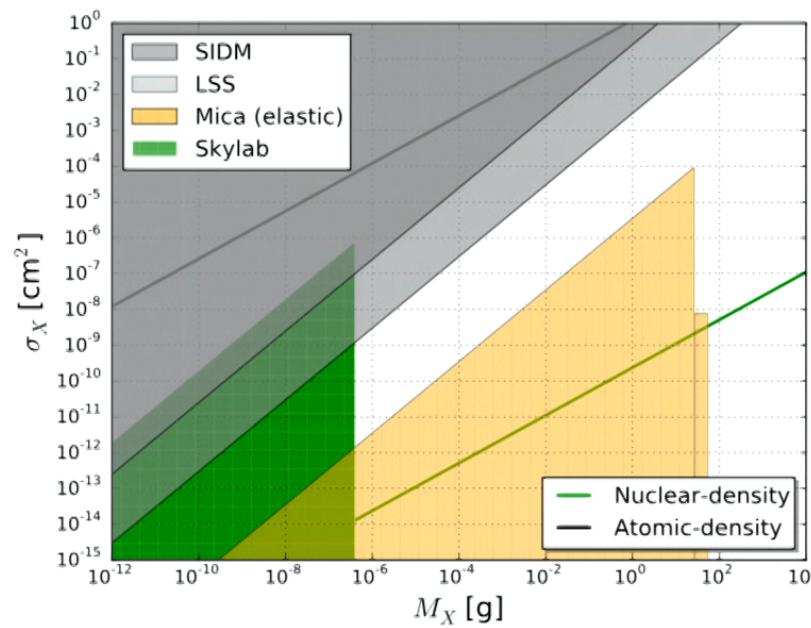
# Cross sections

## Estimate

- Local values:  $\rho \simeq 10^{-24} \text{ g/cm}^3$ ,  $v \simeq \frac{220}{\sqrt{2}} \text{ km/s}$
- From our master equation:  $\frac{\sigma_{\text{int}}}{m} \simeq 5 \frac{\text{cm}^2}{\text{g}}$ ,  $(m \gg m_b)$
- DM self-interactions:  $\frac{1}{\sigma n} > r$   $\xrightarrow[\text{eq.}]{\text{master}} \frac{\sigma}{\sigma_{\text{int}}} \lesssim 10 \frac{a}{a_0} \lesssim 10^{-1}$

# Cross sections

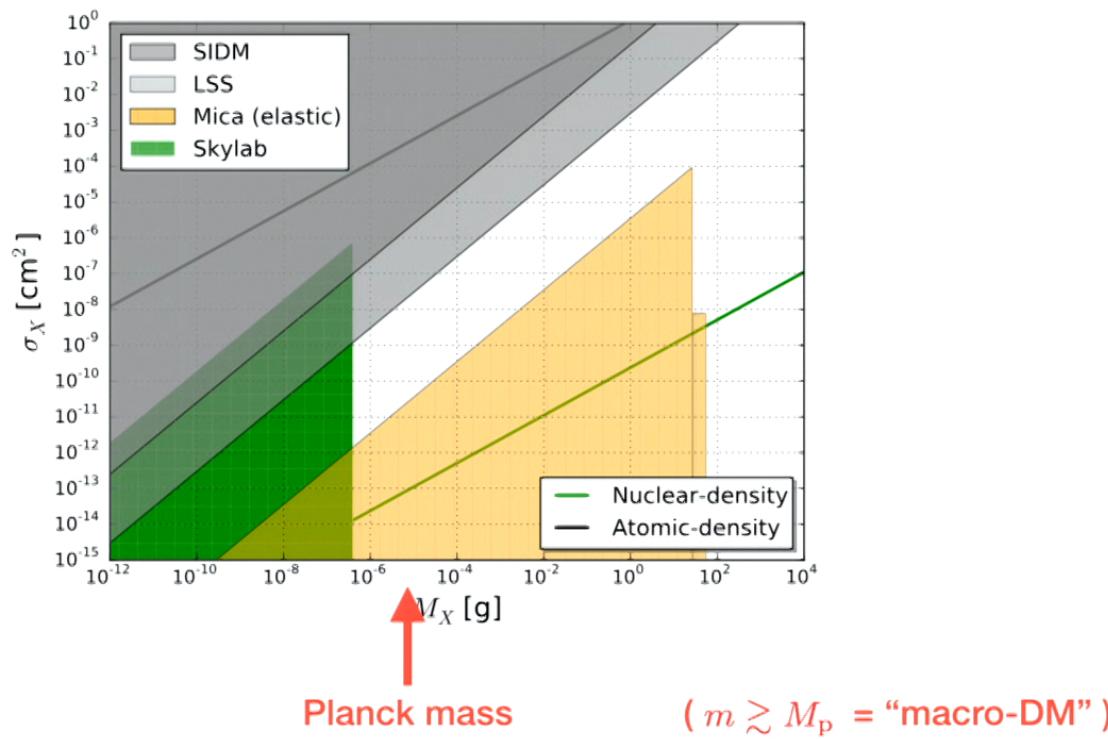
## Large mass constraints



Source: Jacobs et al. (1410.2236)

# Cross sections

## Large mass constraints



Source: Jacobs et al. (1410.2236)

# Large scale structure

- For elastic scattering  $\epsilon \simeq 2m_b v^2$ , and our master equation implies  $\sigma_{\text{int}} \sim 1/v^2$
- Growth of DM structures at redshifts  $10^4 \lesssim z \lesssim 10^5$  places constrains such a cross section:

Dvorkin et al. (1311.2937)

$$v^2 \frac{\sigma_{\text{int}}}{m} \lesssim 6 \times 10^{-10} \frac{\text{cm}^2}{\text{g}} \quad (m \gg m_b, \text{elastic})$$

- Using the cosmological density  $\rho \simeq 2 \times 10^{-30} (1+z)^3 \text{ g/cm}^3$  our master relation yields

$$v^2 \frac{\sigma_{\text{int}}}{m} \simeq \frac{C a_0}{\rho} \simeq \frac{0.7}{(1+z)^3} \frac{\text{cm}^2}{\text{g}}$$

# Bullet cluster

- Galaxy clusters are not in equilibrium because  $H_0\tau \gtrsim 1$
- $\tau$  is also the typical time scale for energy transfer between merging clusters:

$$\tau \gtrsim H_0^{-1} \simeq 4 \times 10^{17} \text{ s}$$

- Bullet cluster constraint:

$$\tau \gtrsim 10^{16} \text{ s}$$



$$\sigma_{int} \in = \frac{C m_b n_0}{n} \quad U \sim N_U$$



$$\sigma_{\text{int}} = \frac{C \rho n_0}{N m v^2} \quad v \sim N$$



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# Model building

- Master equation:  $\sigma_{\text{int}} \simeq \frac{Ca_0}{nv^2}$  ( $m \gg m_b$ )
- Velocity: e.g. Sommerfeld enhancement, magnetic dipoles
- Density: e.g. plasma frequency, phonons?
- Challenge: getting correct velocity **and** density dependence

# A toy model

$$S = \int dt d^3x \left\{ \frac{e^{-3q\Phi}}{2} (\vec{\nabla}\Phi)^2 + \varepsilon e^{-5q\Phi} \right. \\ \left. + e^{q\Phi} \left[ \frac{i}{2} \psi^* (\vec{\partial}_t - \overleftarrow{\partial}_t) \psi - \frac{|\nabla\psi|^2}{2m} + \mu |\psi|^2 \right. \right. \\ \left. \left. - \frac{q}{m} (\psi^* \vec{\nabla} \psi + \psi \vec{\nabla} \psi^*) \cdot \vec{\nabla} \Phi - 2 \frac{q^2}{m} |\psi|^2 (\vec{\nabla}\Phi)^2 \right] \right\}$$

Symmetries in vacuum: Galilei + Schrödinger invariance:

$$t \rightarrow e^{2\lambda} t$$

$$\vec{x} \rightarrow e^\lambda \vec{x}$$

$$\psi \rightarrow e^{-2\lambda} \psi$$

$$\Phi \rightarrow \Phi + \lambda/q$$

Scale inv. spontaneously broken at finite density:  $n = \langle |\psi|^2 \rangle \neq 0$

# A toy model

- Expanding  $\Phi = \Phi_* + \sigma$ , we get cubic couplings with DM:

$$q\sigma \left[ \frac{i}{2} \psi_c^* (\vec{\partial}_t - \overleftarrow{\partial}_t) \psi_c - \frac{|\nabla \psi_c|^2}{2m} + \mu |\psi_c|^2 \right] - \frac{q}{m} (\psi_c^* \vec{\nabla} \psi_c + \psi_c \vec{\nabla} \psi_c^*) \cdot \vec{\nabla} \sigma$$

- Symmetry-breaking coupling with baryons:  $q_b \sigma |\psi_b|^2$
- Baryon-DM amplitude and cross section:

$$\sim \frac{e^{3q\Phi_*}}{(\vec{k} - \vec{k}')^2 + m_\Phi^2} \times (\vec{k} - \vec{k}')^2 \sim \frac{1}{\sqrt{nv^2}}$$

→  $\sigma_{\text{int}} = \frac{\text{const.}}{nv^2}$

# Summary & future directions

- Baryon-DM interactions could explain observed behavior of **spiral** and **elliptical** galaxies provided they satisfy the master equation  $\sigma_{\text{int}}\epsilon \sim 1/n$
- **Model building:** relativistic model? zero sound?
- **Phenomenology:** light dark matter?
- **Astro:** approach to equilibrium?

Thank you,

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$$\sigma_{\text{int}} = \frac{C \rho_b n_0}{n m_b v^2} \quad v \sim v_b$$

$\dot{\Sigma}$



