How to constrain the properties of self-interacting dark matter using observed dark matter halos?

[1712.06602]

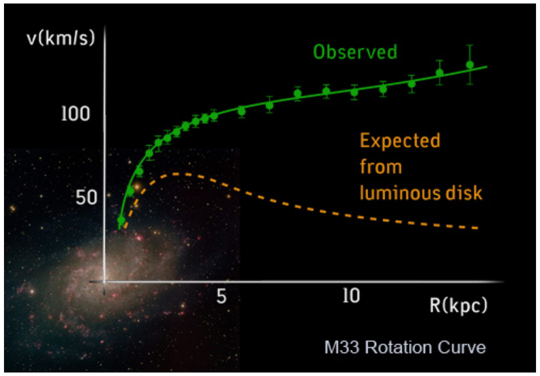
[1806.11539]

Anastasia Sokolenko (Oslo U.), K.Bondarenko (Leiden U.),
T.Brinckmann (Aachen U.) J. Zavala (Iceland U.),
M.Vogelsberger (MIT) T.Bringmann (Oslo U.)
and A.Boyarsky (Leiden U.)

TeVPA 2018, 28th August 2018

Why do we know that Dark Matter exists?

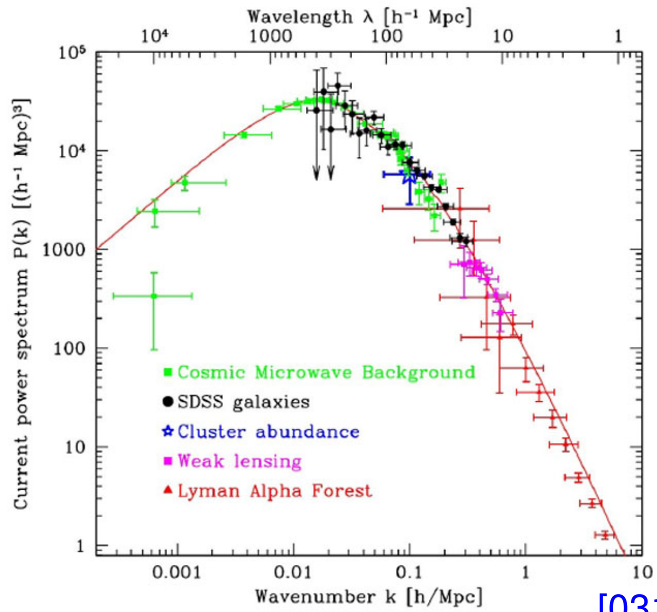
- Independent evidence prove that there are more gravitating mass than we see:
  - Rotation curves of stars in galaxies and of galaxies in clusters:
  Expected: $v(R) \propto 1/\sqrt{R}$
  Observed: $v(R) \approx$ const
  - Gravitational lensing:
  Direct measurement of total mass



- **- Cosmic Microwave Background:**
  CMB spectrum provides information about the density of baryonic matter and the *density of Dark Matter*
  - Structure formation:
  $\delta\rho/\rho = 10^{-5} \cdot \left(\frac{1+z_{\mathrm{CMB}}}{1+z_0}\right)$ $\qquad z_{\mathrm{CMB}} \approx 10^3$
  If there were only baryonic matter in the Universe, there would not have been enough time for density perturbations to grow into the galaxies and clusters that we see today

Cold Dark Matter

- **Dark matter: what do we know?**
  - Weakly (non-) interacting
  - Non-Standard Model particles
  - Without high velocities (cold or warm DM)
  - Mass density $\Omega_{\mathrm{DM}} h^2 = 0.112 \pm 0.006$



[0310723]

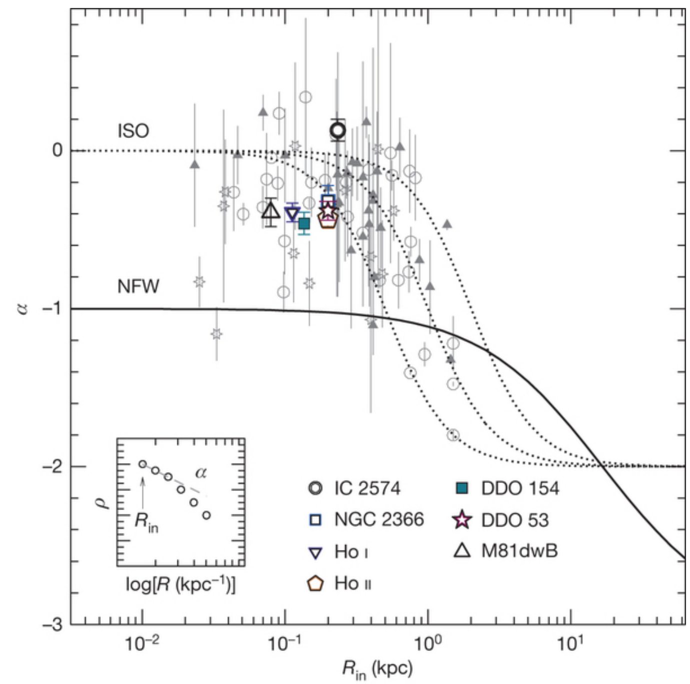
- Can we constrain particle physics properties of DM using astronomical data?

- ΛCDM is known to describe observational data very well at **large scales**. However, **at small scales there are discrepancies** between *expectation and observation* [1705.02358]

Small scales problems

- I. **Less dwarf galaxies are observed** in the MW and M31 than CDM predicts. The smaller are haloes, the larger is discrepancy (*missing satellite problem*)

- II. Consider DM density scales as $r^{-\gamma}$ in the central part of the objects. Pure **CDM simulations predict** $\gamma = 1$ (**cusps**), but we observe $\gamma < 1$ in some objects (**cores**) (*core-cusp problem*)



[1402.1764]

- III. **Over-prediction of large satellites** (*too-big-to-fail problem*)

- Possible astrophysical explanations for each of these problems!
  But if not?

Possible Solutions

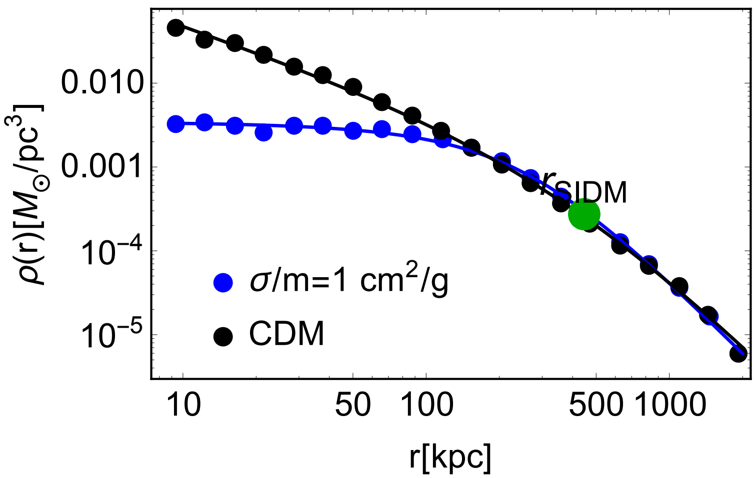
- Consider that the differences between simulation and observations come **not from baryonic physics**

- *Possible solution* to the **small-scale problems** is to modify the *nature* of DM:

  – **Warm Dark Matter**: Initial velocities vanish small structures
  – **Self-interacting Dark Matter**: DM particles self-scatter and particles get some pressures which prevents to form small structures
  – **Fermionic DM**: The Pauli principle tells that the density cannot exceed some maximum value, like for example neutron stars
  – **Ultra light bosons**: For such particles de Broglie wave-length can be huge. This could explain cores and suppression of small structures

- All these *"non-cold"* Dark Matter models have some *characteristic scale* at which all **density fluctuations are erased** and **gravitational clustering is suppressed**

Self-interacting Dark Matter



- **Far from the centre** the density is low, no scattering and the halo behaves as in CDM. **In the inner part** the density is high enough, an equilibrium can be established

- *We can expect that the DM density profile can be approximated by NFW outside certain characteristic radius* $r_{\mathbf{SIDM}}$ *and by a solution of the Jeans equation with constant velocity dispersion* σ_{tot} *inside* r_{SIDM}

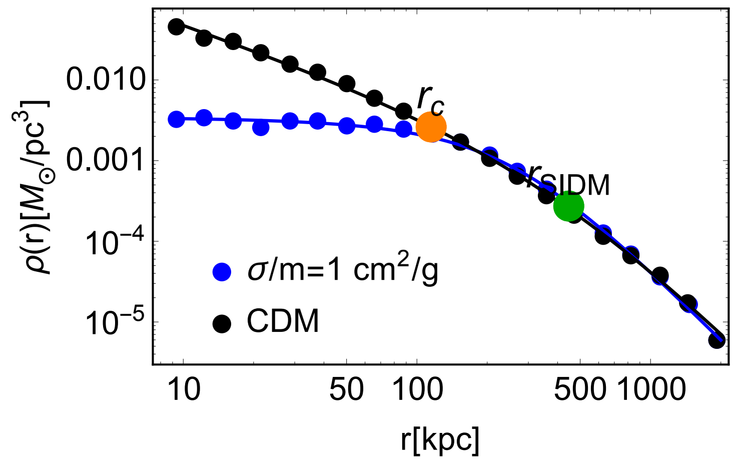
[1705.02358]

$$\frac{\sigma_{\rm tot}^2}{3}\frac{d}{dr}\left(\frac{r^2}{\rho}\frac{d\rho}{dr}\right) = -4\pi G r^2 \rho, \qquad (1)$$

where $\sigma_{\rm tot}$ is a constant 3D velocity dispersion of DM particles

- For **small** enough **cross-sections** σ/m we expect to have a **cored solution of Jeans equation** with finite density in the center $\rho(r)$

What do we expect from a SIDM halo?



- r_{SIDM} should *grow* with the cross-section σ/m. If we could find r_{SIDM} from observation, this could give also a *constraint* on σ/m

- In doing so, two problems arise:

  -*Theoretical*

  The core radius r_c is observed, but r_{SIDM} is related to σ/m!

  -*Observational*

  Determination of the core radius for each halo is **very uncertain**

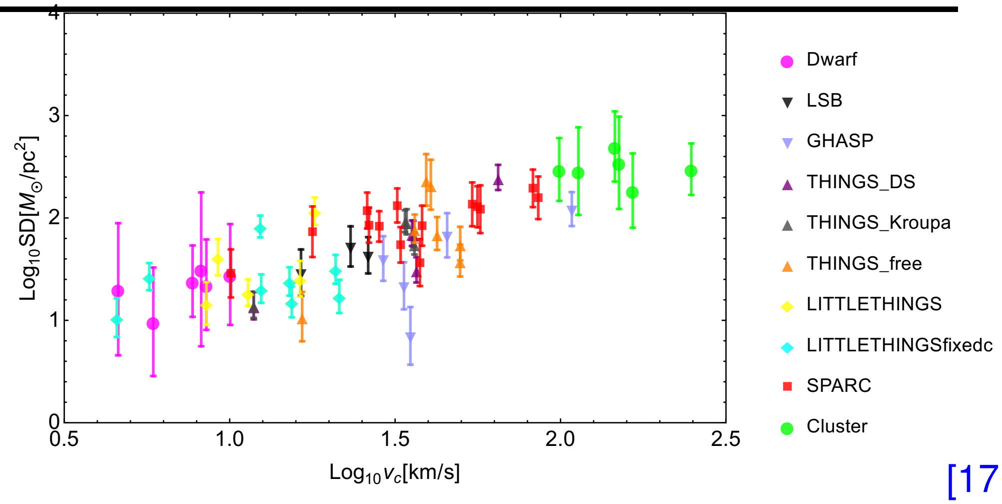
- Common lore: r_{SIDM} is defined by one collision per particle [1712.06602]

$$\frac{\sigma}{m}\langle\rho\rangle_{\text{SIDM}} v_{\text{SIDM}} t_{\text{age}} = \xi \qquad (2)$$

where $\langle\rho\rangle_{\text{SIDM}}$ is the the average density and v_{SIDM} is an average difference of velocities of DM particles within r_{SIDM}

Reducing observational uncertainties: Surface density

- To marginalize over uncertainties and find a universal DM property – use a quantity obeying a **scaling law**



[1712.06602]

- Surface density:

$$\boxed{SD(r) = \frac{M(r)}{\frac{4}{3}\pi r^2} = \langle\rho\rangle r}. \quad (3)$$

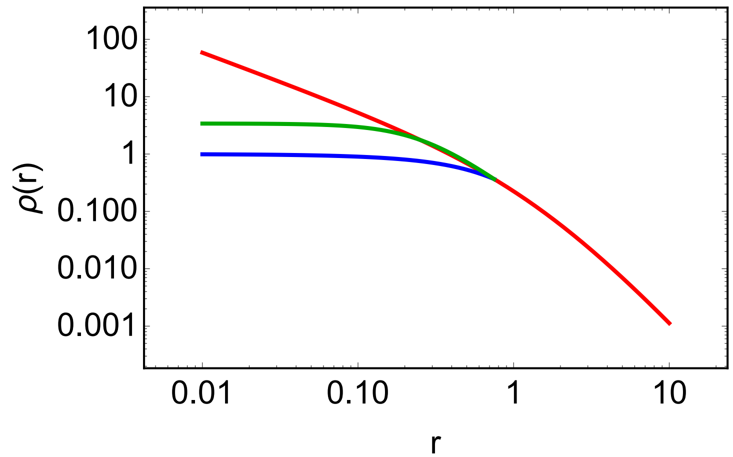
a simple scaling law that ranges from dwarfs to galaxy clusters!

- For a large data set the normalization and slope of power law can be fixed much better than the data for individual objects

Idea of the method

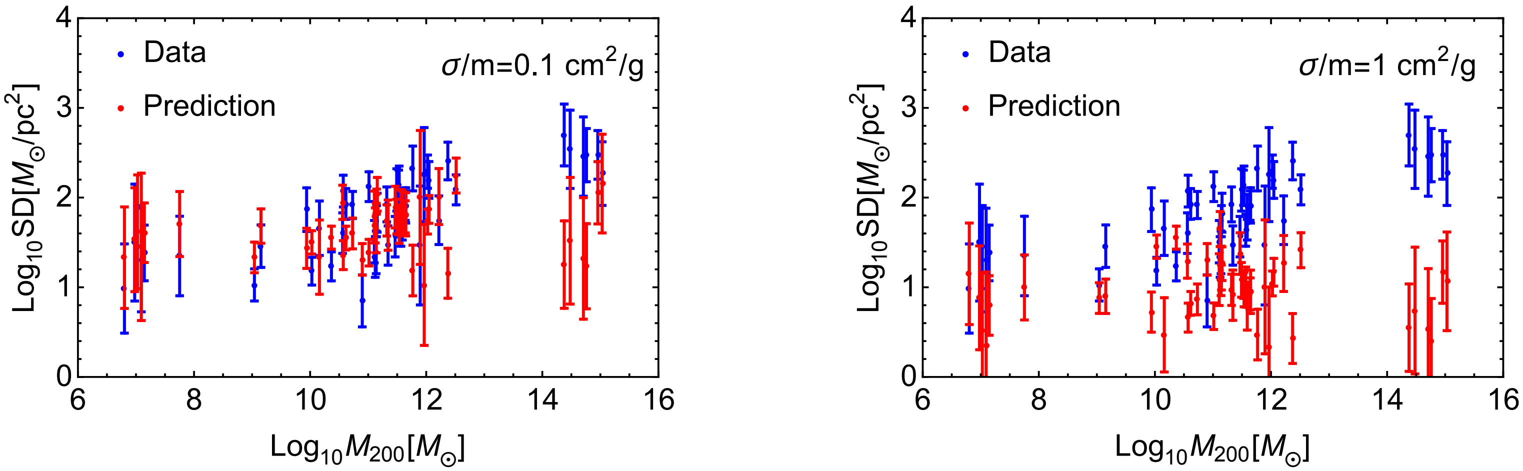
- Core radius increases with σ/m, core density decreases

- The inner surface density will **decrease** with core size for larger cores



- Predictions based on the literature:

”one collision per particle” + Jeans equation

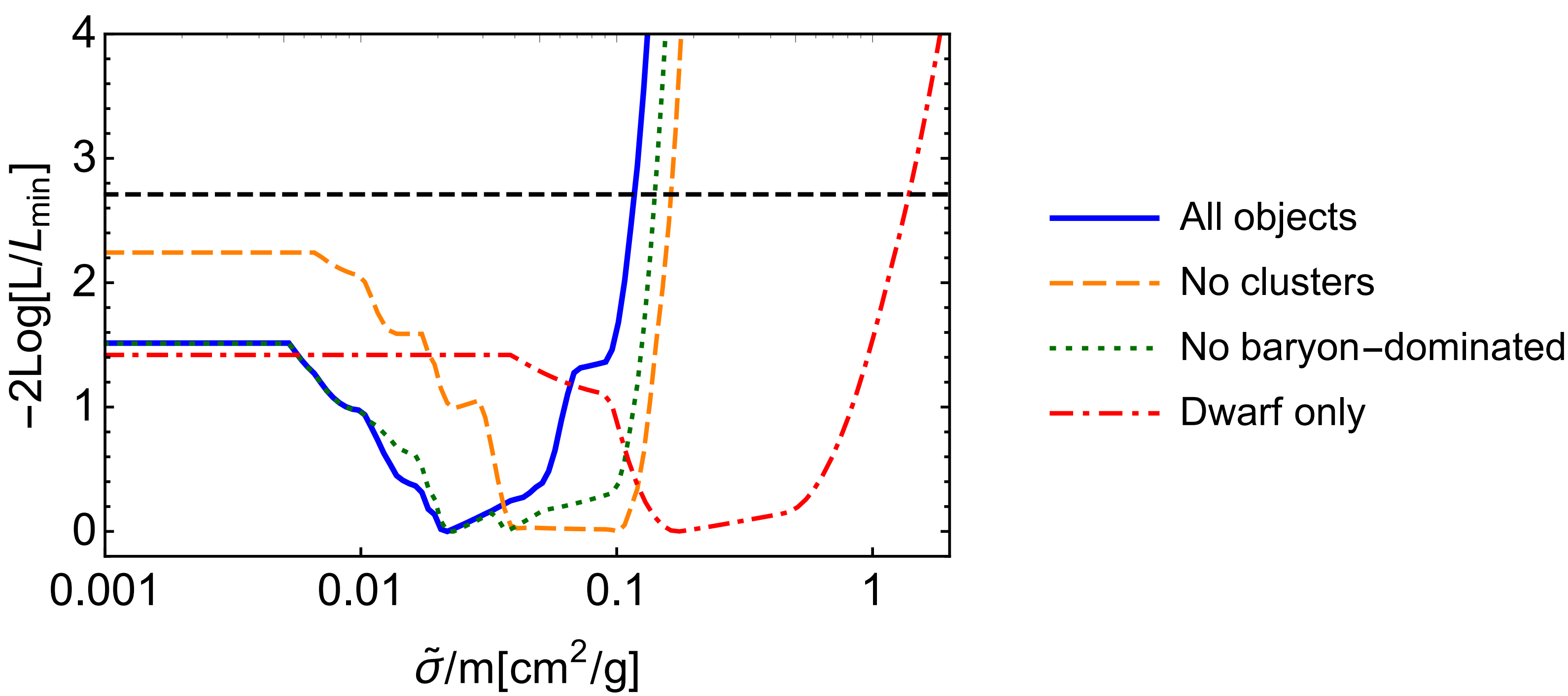


[1712.06602]

Constraints

- Using the **likelihood method** for Gaussian distribution and the predictions based on ”one collision per particle” + Jeans equation with calibrating factor from simulations we get [1712.06602]

$$\boxed{\sigma/m < 0.3\ \text{cm}^2/\text{g (at } 95\% \text{ confidence level)}} \quad (4)$$



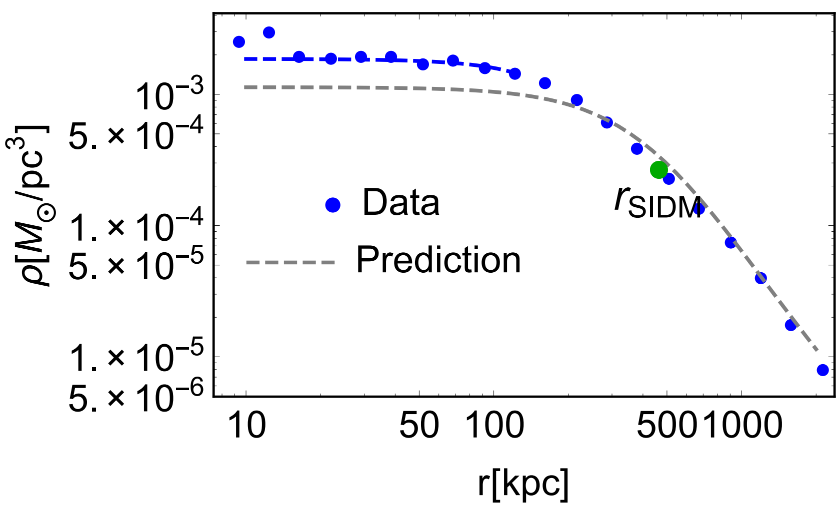
Theoretical uncertainties – test with 28 simulated clusters [1705.00623]

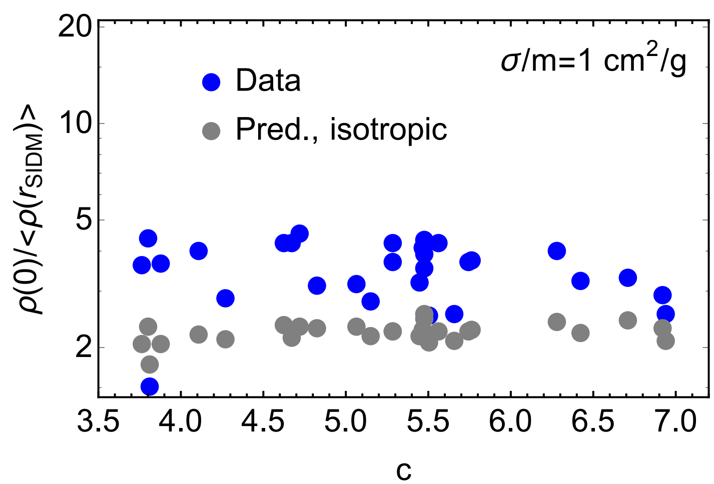
- Reminder: we assume **equilibrium** inside r_{SIDM} (Jeans equation)

$$\frac{\sigma_{\text{tot}}^2}{3}\frac{d}{dr}\left(\frac{r^2}{\rho}\frac{d\rho}{dr}\right) = -4\pi G r^2 \rho$$

- 2 boundary conditions for second order equation + fix σ_{tot}.
  I. Core $(\rho'(0) = 0)$ II. $M_{\text{SIDM}}(r_{\text{SIDM}}) = M_{\text{CDM}}(r_{\text{SIDM}})$ III. fix σ_{tot} ? [1806.11539]

- However, the predicted profiles do not agree with the data



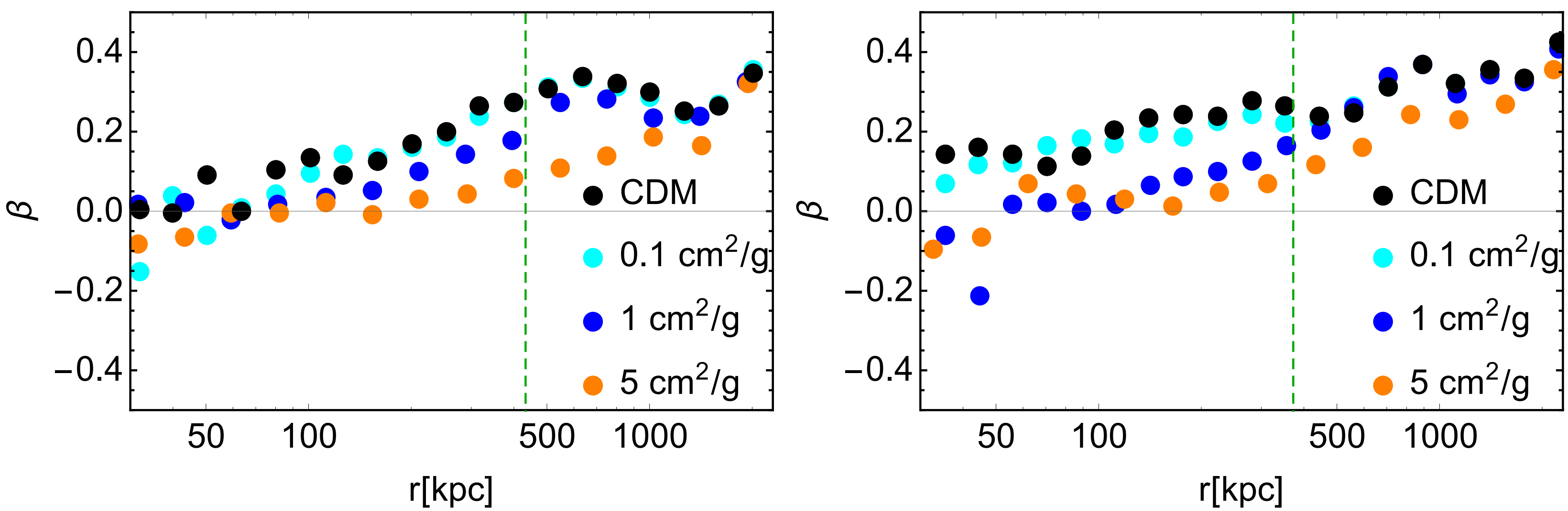


Anisotropy: imperfect equilibrium

- Simulated SIDM haloes have **significant** anisotropy inside r_{SIDM}! [1806.11539]

$$\beta(r) = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2}$$

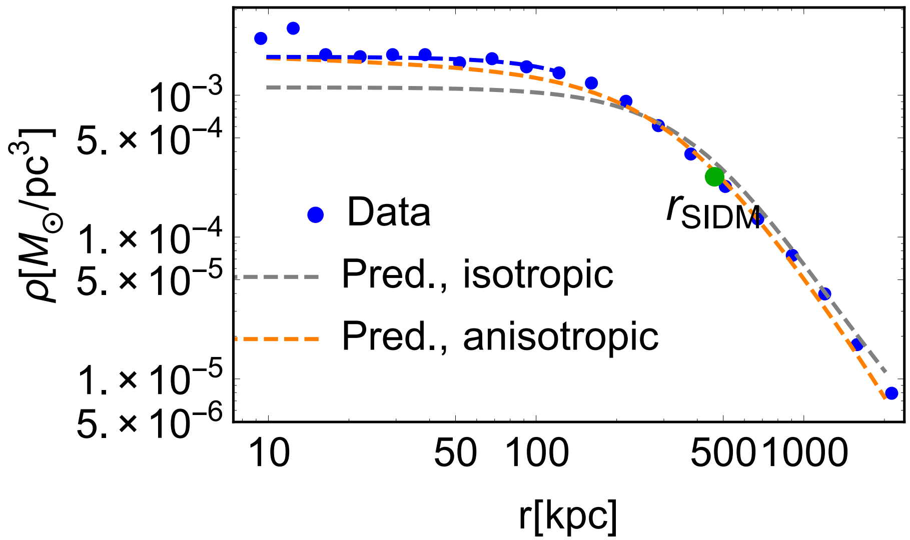
- Surprising - expect no anisotropy in the ”equilibrium”

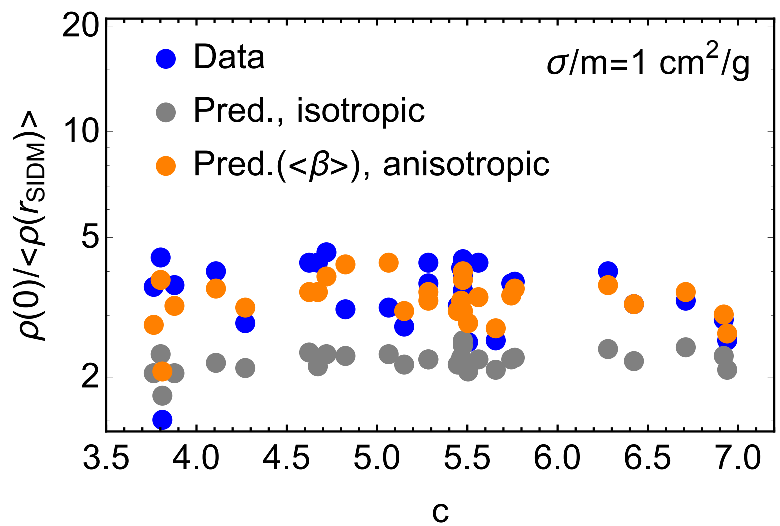


- For each cross-section, we find a simple *ansatz* for $\beta(r)$, and use it for anisotropic Jeans equations

Anisotropy: successful predictions

- Anisotropic Jeans equation gives **much better result!**





- The profile predicted with **our boundary conditions** at r_{SIDM} describes simulations well! We have related r_{SIDM} and r_c !

- Let us now check the last step: the relation between r_{SIDM} and σ/m (the 1-collision-per-particle condition) using our simulations

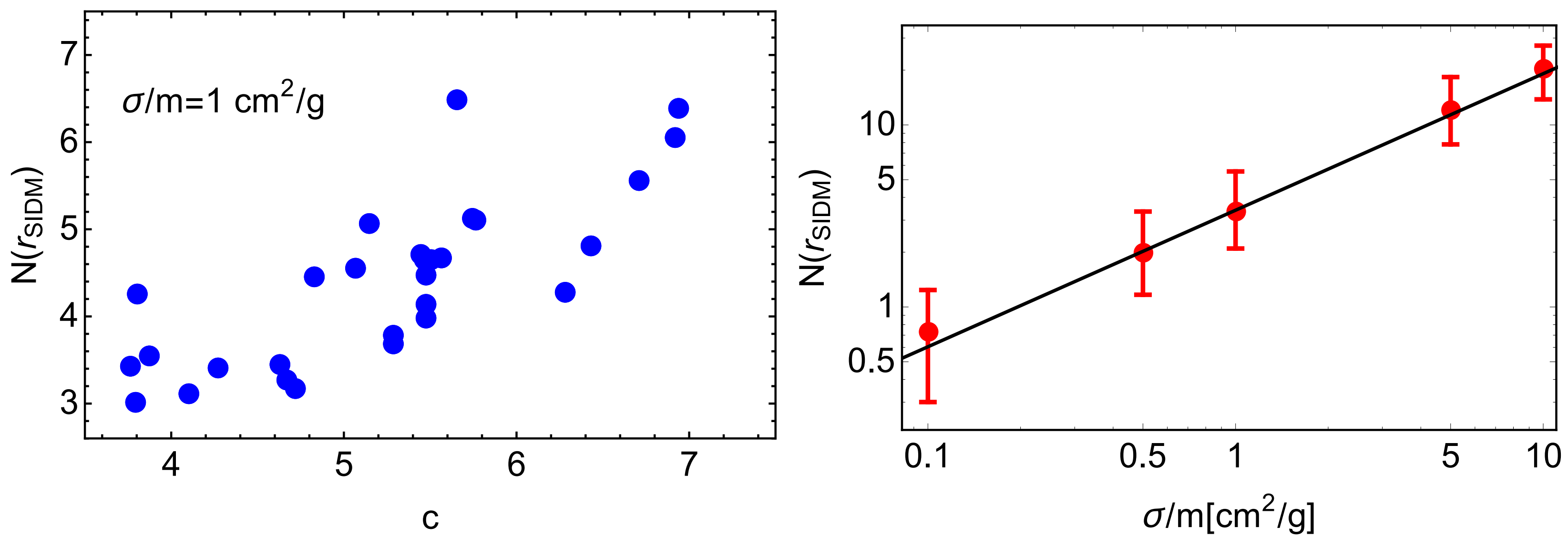
Can we reconstruct σ/m from $r_{\mathtt{SIDM}}$?

- Naively we should relate $r_{\rm SIDM}$ with σ/m by ”one collision per particle”

$$\frac{\sigma}{m}\langle\rho\rangle_{\rm SIDM} v_{\rm SIDM} t_{\rm age} = \boldsymbol{\xi} \quad (5)$$

- Unfortunately, the number of collisions per particle at $r_{\rm SIDM}$ can differ from 3 to 6 for the same cross-section (left figure) [1806.11539]

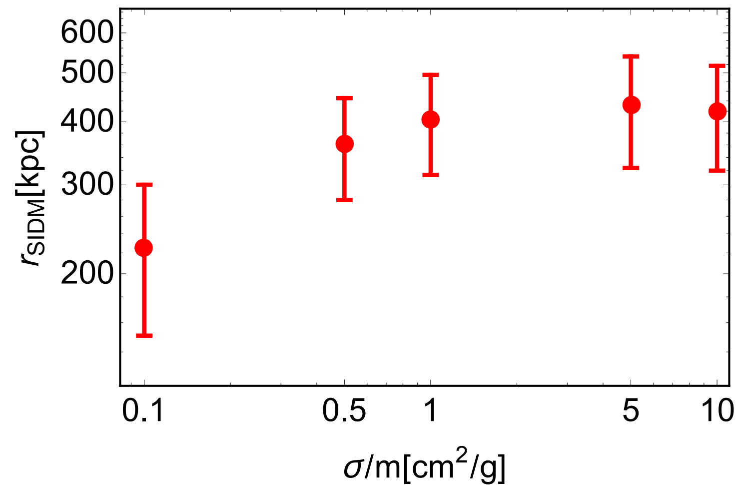
- Its mean value grows from 1 to 10 with cross-section (right figure)



Can we constrain the cross section?

- Let us forget "1-collision-per-particle" and see how r_{SIDM} depends on σ/m directly from simulations

- As expected, for $\sigma/m < 1$ cm^2/g it grows



- But when when σ/m changes from 1 to 10 cm^2/g r_{SIDM} remains constant !

- We can not distinguish between large cross-sections $\sigma/m > 1$ cm^2/g using observations.

- For $\sigma/m < 1$ cm^2/g, we can directly compare with observations

Conclusions

- Inner DM surface density obeys a universal power law - an efficient way to constrain DM properties! Hope to obtain meaningful results despite large observational uncertainties for individual objects
- Existing constraints suffer from theoretical uncertainty - the analytic relation of σ/m with ”observed” core radius is not known!
- Try to compare the whole families of simulated and observed halos!
- Current data are marginally inconsistent with $\sigma/m = 1$ cm^2/g. Direct derivation of surface density from the data can shrink the scatter