Collisional Dark Matter
A gentle overview

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Why?

- There appear to be (mild?) discrepancies in the small-scale structure behavior of the ΛCDM model. These point towards self-interactions:
  i) The Missing Satellites problem: we observe fewer satellite galaxies than we would expect. Slowly going away. [astro-ph/9901240]
  ii) Too Big to Fail problem: Related to the point above, it states that some of the missing satellites are so big we should not have missed them by accident. [1103.0007]
  iii) Core/Cusp problem: There is evidence for cores (flat density profiles) in the centers of dwarf galaxies. This may be due to baryons, or it may be due to DM.[Nature. 370 (6491): 629-631]
  iv) Diversity of Rotation curves: Real world rotation curves of large galaxies exhibit much larger diversity than the rotation curves we obtain from full simulations (including baryonic physics) [1504.01437]

Why Not?

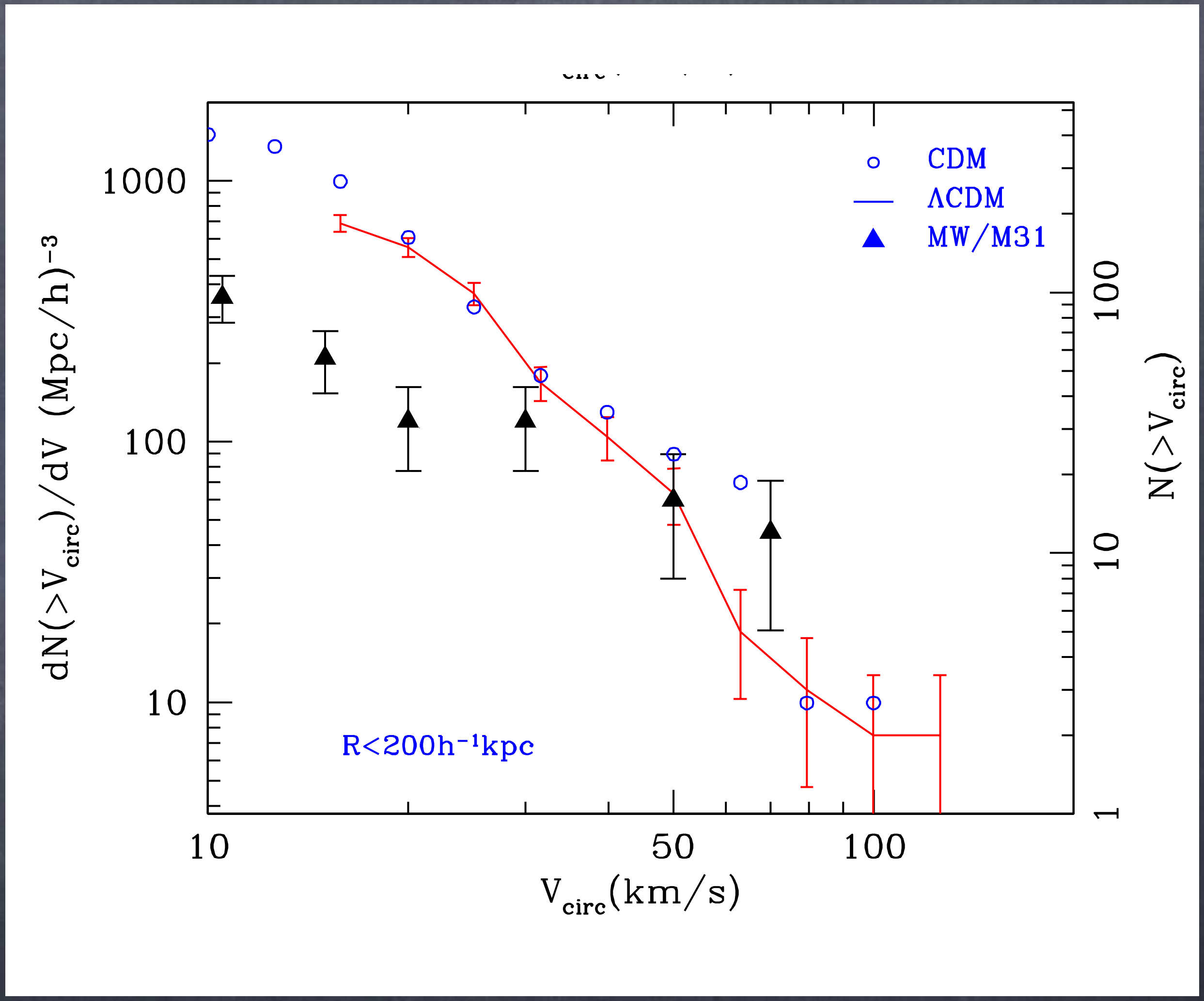
For more detailed overview see an excellent review by

Sean Tulin and Hai-Bo Yu:

[1705.02358]

The Missing Satellites

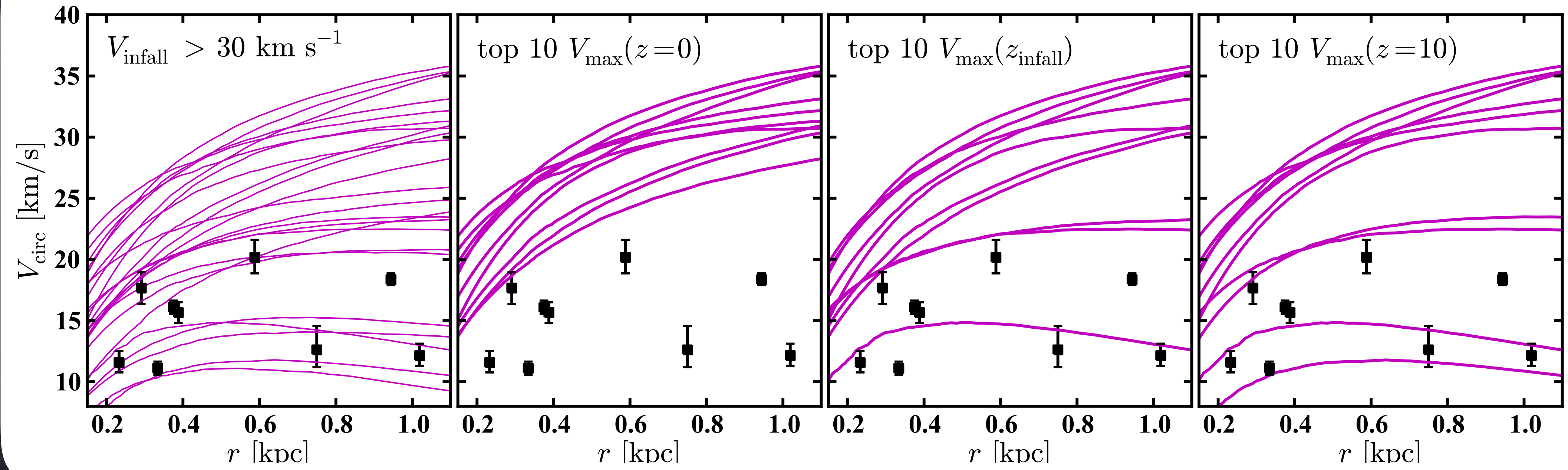
- In 1999 the number of observed satellite galaxies was much smaller (order of magnitude) than predicted.
- Since then, we have observed more thanks to SDSS and DES.
- And perhaps explained why some are unobservable (baryon feedback)



[astro-ph/9901240]

Too Big to Fail

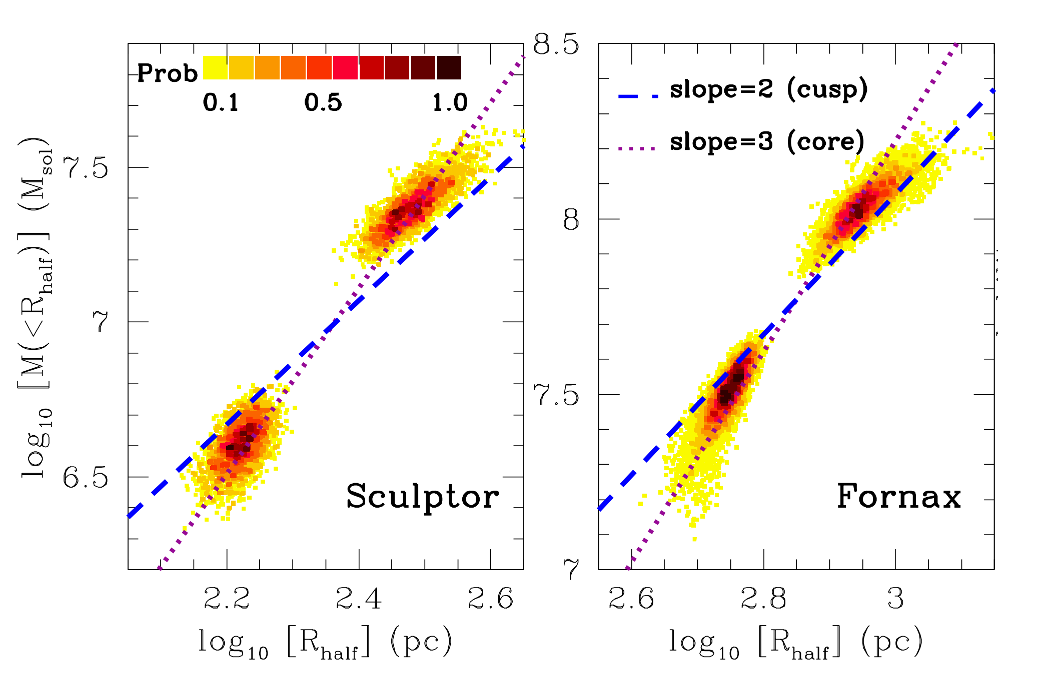
- Sharper take on the missing satellites
- The simulations show that we are missing satellites that are too big to fail in terms of star formation.



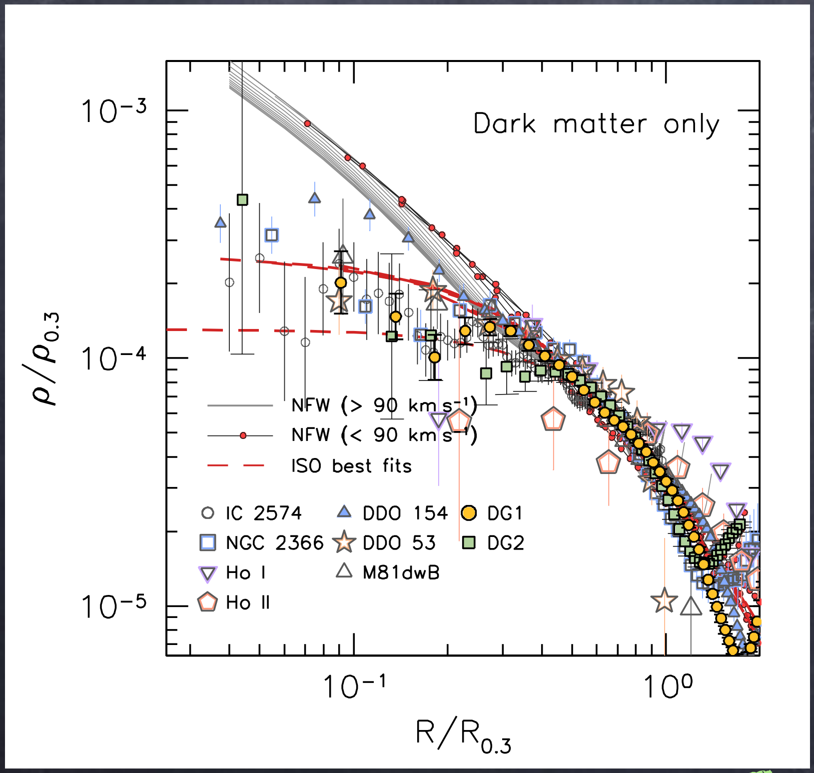
[1111.2048]

Core/Cusp

- NFW density profile predicts a "cuspy" density profile.
- Data seems to indicate a flatter profiles.
- The bigger the system, the more it is "polluted" by baryons.



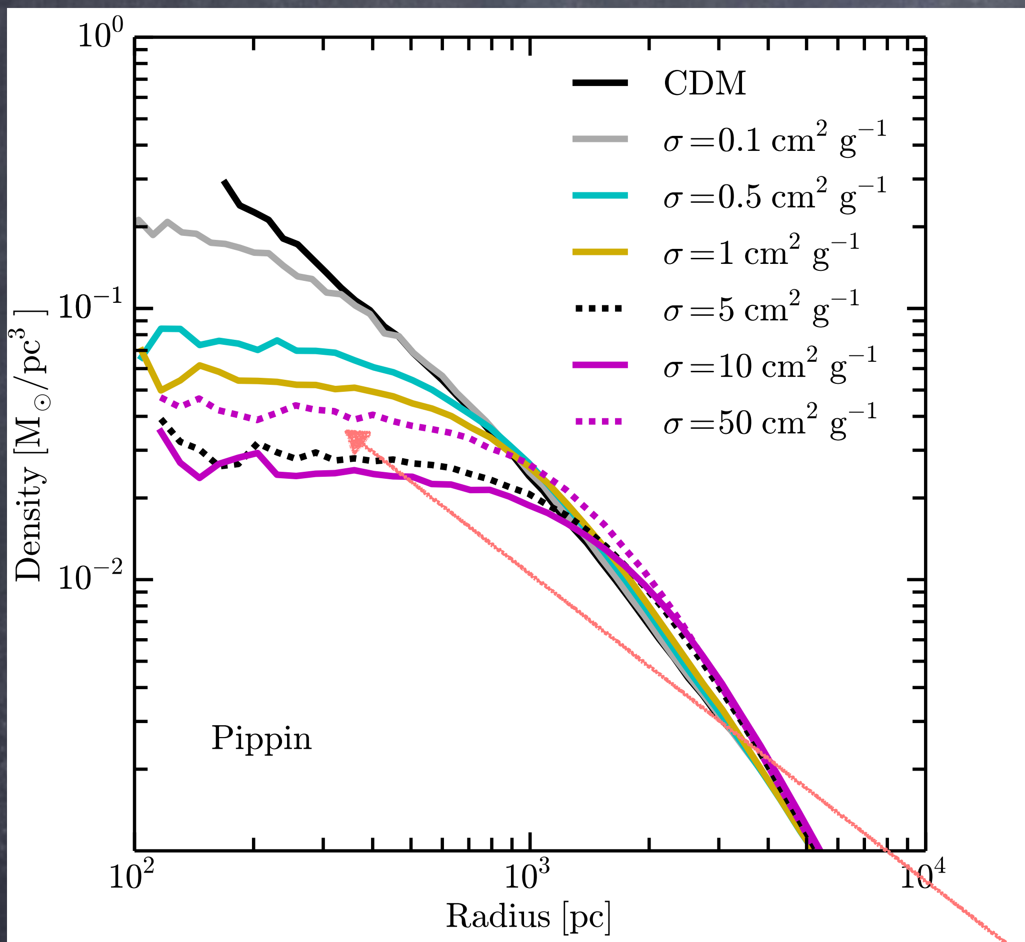
Walker&Penarrubia [1108.2404]

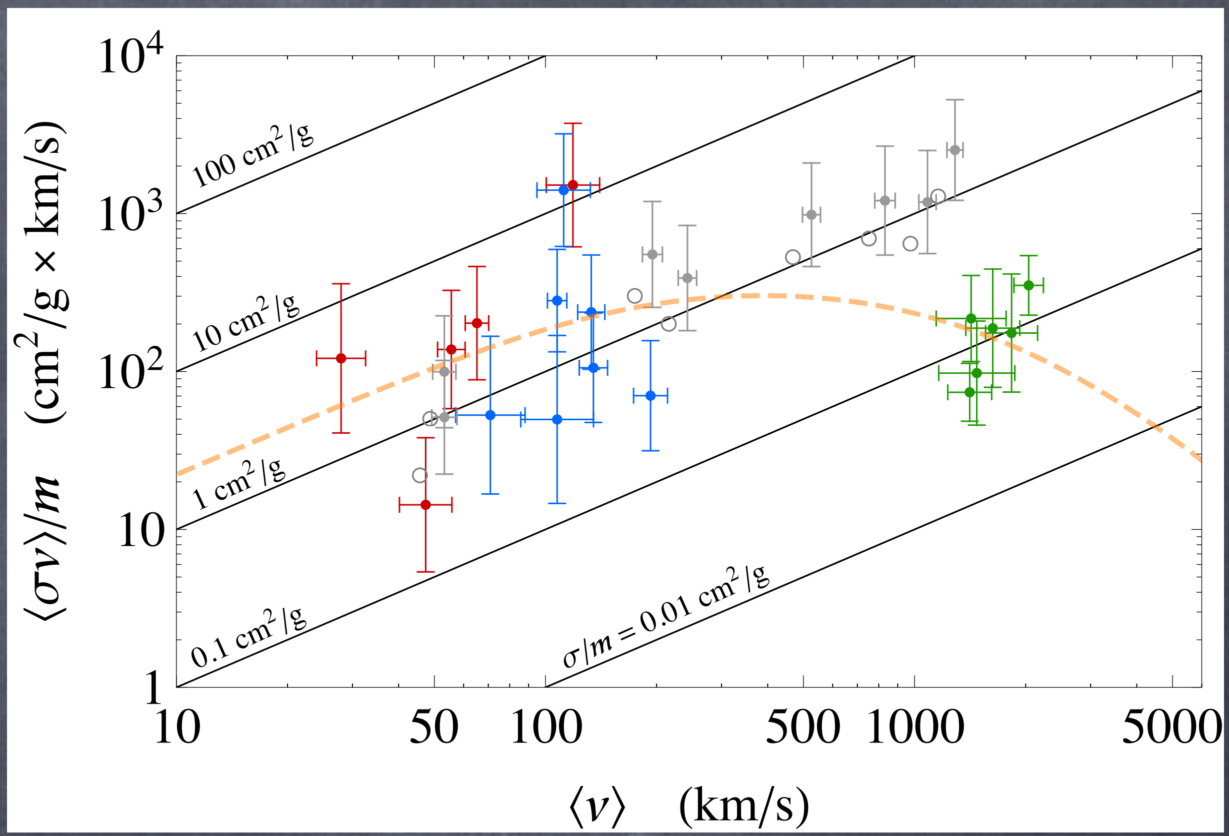


THINGS [1011.2777]

- The effects of baryonic physics might be irrelevant for light dwarfs => We should wait for more data.

Core/Cusp II



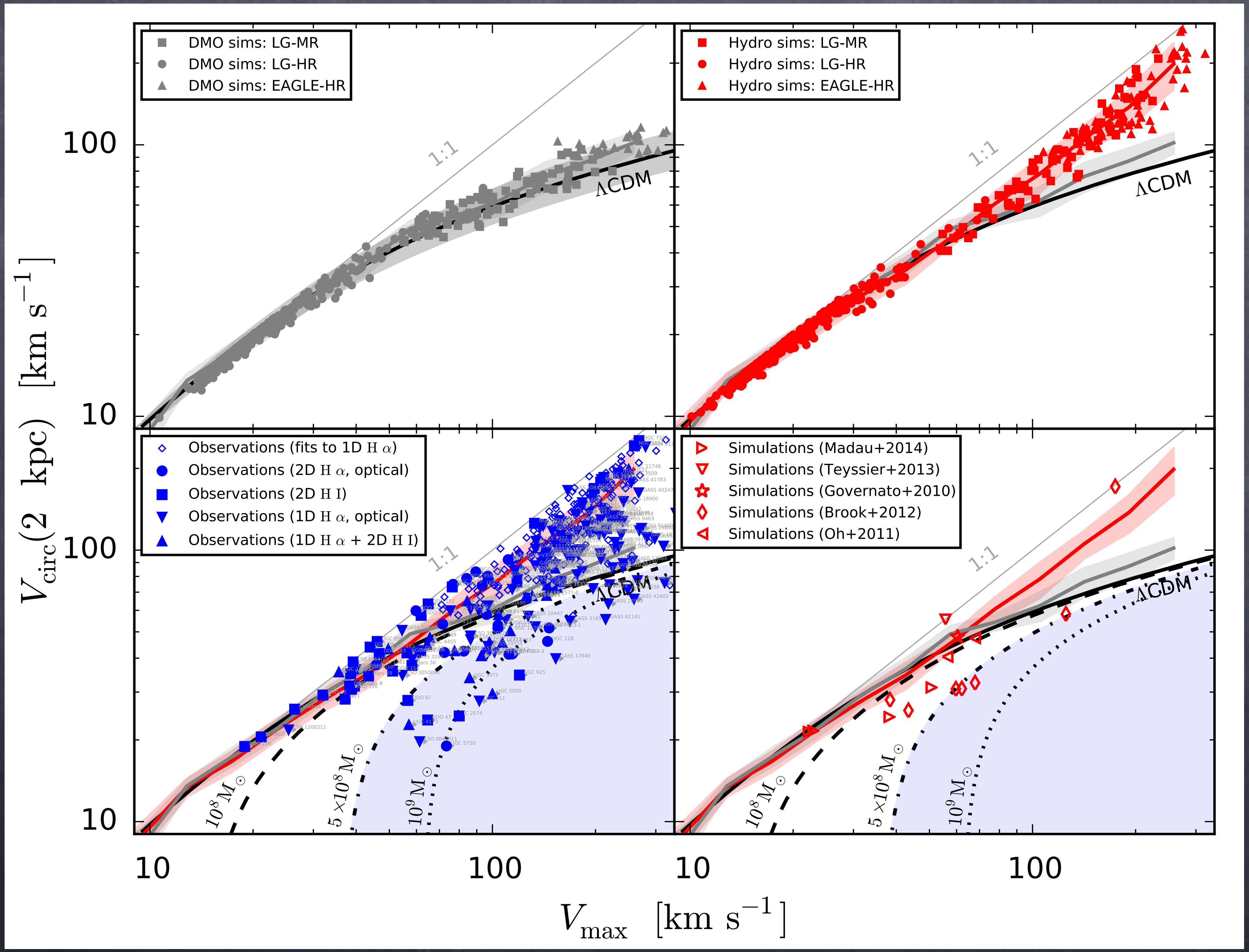


Simulations
[1412.1477]

[1508.03339]

!

Diversity of Rotation Curves Problem



[1504.01437]

My Personal Definition

Dark Matter particle X is collisional if a typical X scatters with another X at least once per characteristic time-scale of the system.

This requires that the four-point function is non-zero:

$$\langle \bar{X}(p_f)\bar{X}(q_f)X(p_i)X(q_i)\rangle \neq 0$$

As a result we expect a non-zero cross-section for 2-to-2 scattering*.

*Maybe, we should also consider other 2n-point functions (typically suppressed)

How?
Single Particle Dark Sector

Either there is truly one single particle, or we are dealing with some effective theory. Either way, we can write:

$$\mathcal{L}_{\rm int} = \alpha\left(\bar{X}X\right)^2 + \beta\left(\bar{X}\partial X\right)^2 + \gamma\left(\bar{X}X\right)\left(\bar{X}\partial^2 X\right)\ldots$$

Since $v_{\rm DM} \sim 10^{-3}c$, the leading operator for self-scattering today leads to an isotropic velocity independent scattering. As a result we can only probe a particular linear combination of $\alpha, \beta, \gamma, \ldots$

How?
Particle and a Messenger

- That is the way we usually think about forces with a messenger Y:

$$\mathcal{L}_{\rm int} \sim \bar{X} f(\partial) Y X$$

- Heavy* messengers reduce to the case of effective theory described on the previous slide.
- However, light messengers lead to a plethora of interesting phenomena.
- Cannot be treated by an effective theory of just X (pointed out many times before, e.g. 1603.08002)

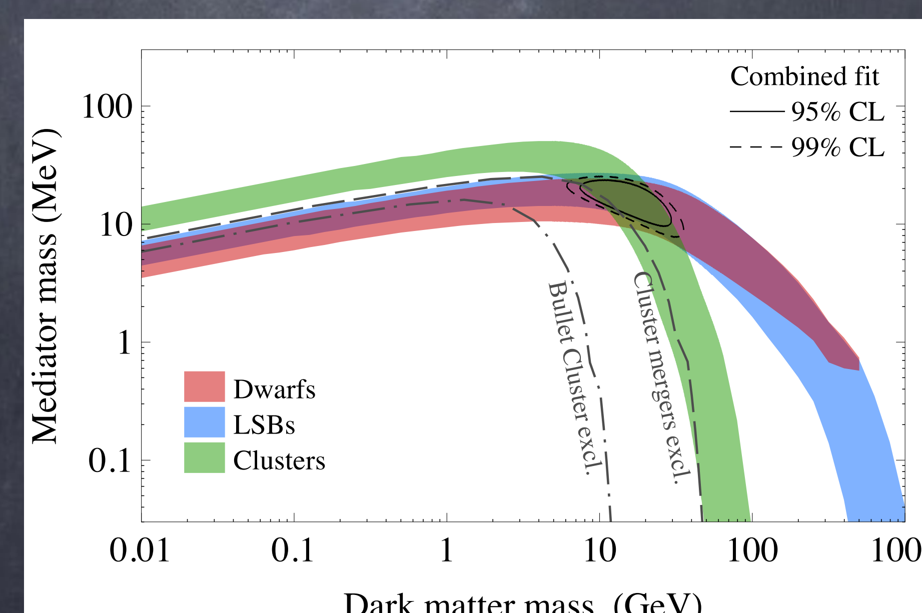
*Heavy in comparison with the available scales (quite different at colliders)

Light Messengers

$$\frac{d\sigma}{dq^2} \propto \frac{1}{\left(m_{\mathrm{Y}}^2 + q^2\right)^2}$$

Leads to Thermalization

Leads to Dissipation



[1508.03339]

Examples
(in no particular order)

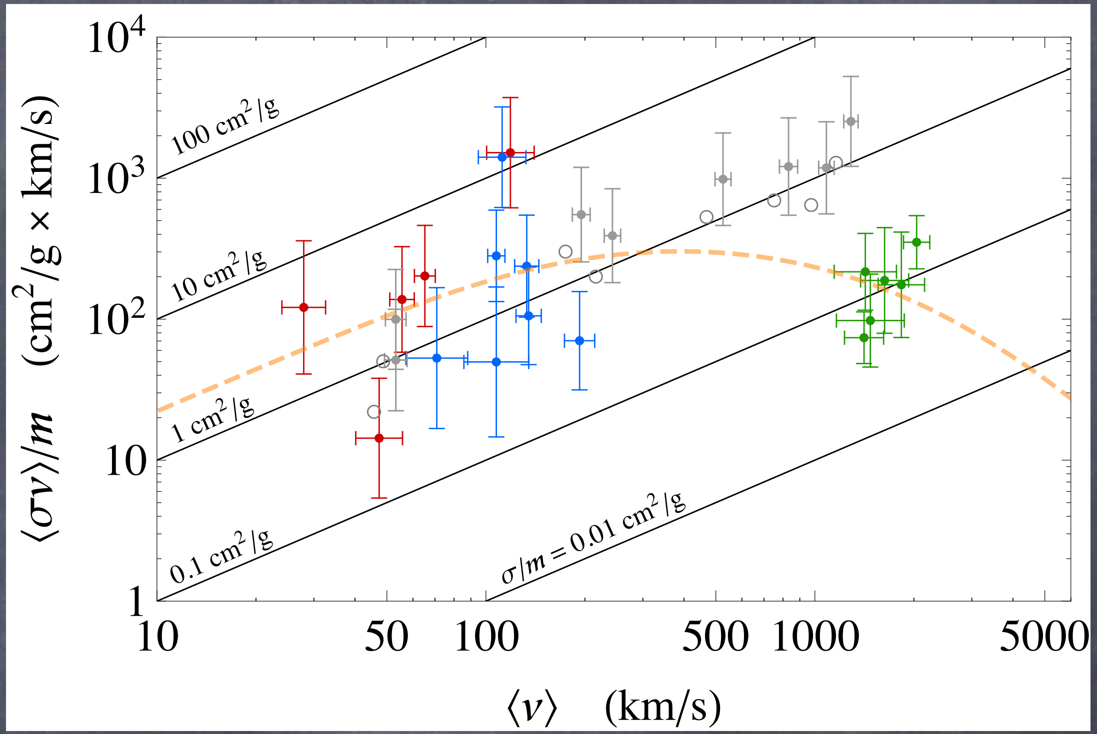
- Self-Interacting DM (SIDM)
- Charged DM
- Dissipative DM/ Double Disk DM
- SIMP
- Forbidden DM
- Fermionic DM, Axions, Fuzzy DM

SIDM

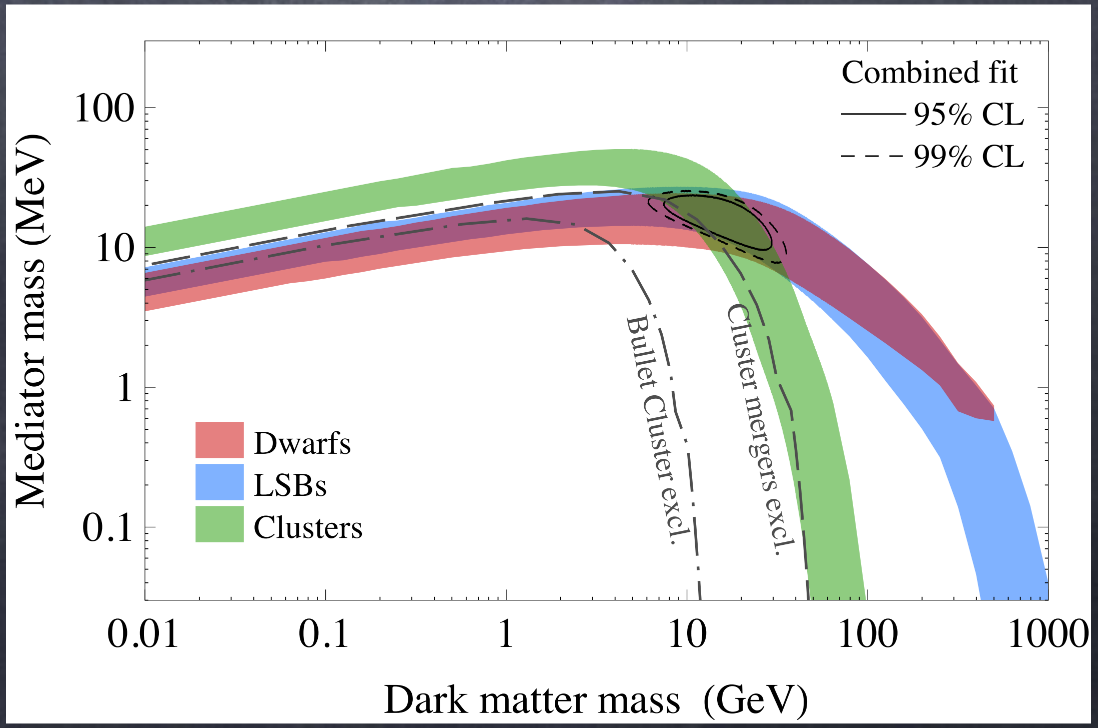
- Fitting to dwarfs:

$$\sigma/m = 1\ \mathrm{cm}^2/\mathrm{g} \sim \frac{1}{(60\ \mathrm{MeV})^3}$$

- It seems to solve all of the small scale problems.
- The model does not determine the interaction strength with the SM.
- The self-interactions will make the velocity distribution at Sun's orbit closer to Maxwellian.



[1508.03339]

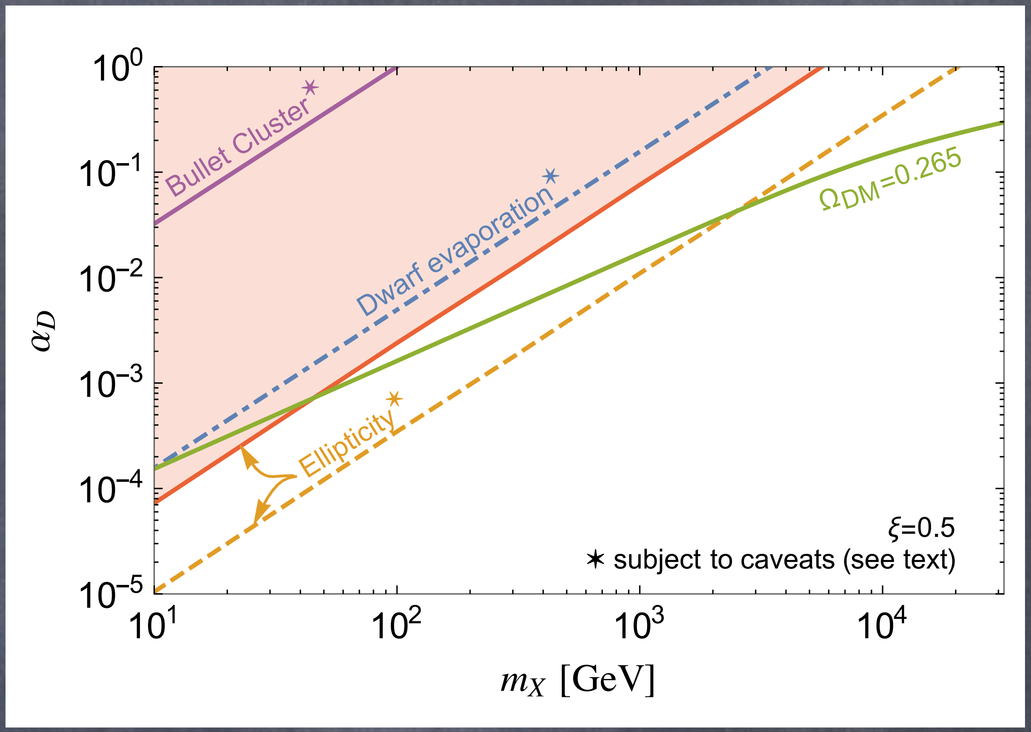


Charged Dark Matter

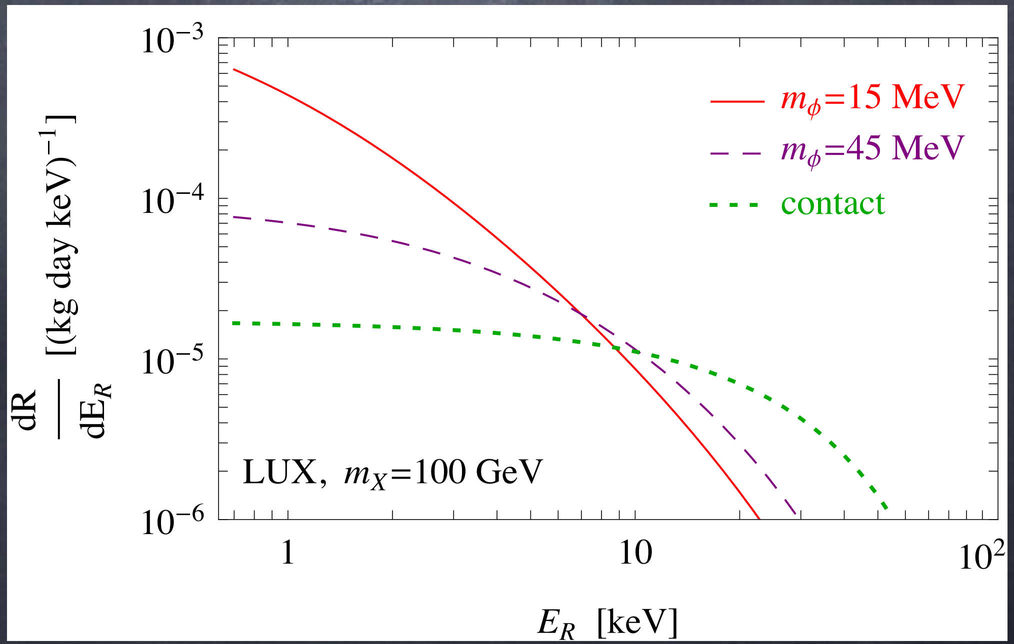
- Type of SIDM: a fermion coupled with a dark U(1)′
- Would couple to the SM through kinetic mixing with the photon.
- A light mediator would enhance the low energy scattering

  => Even though the DM particle is heavy, we benefit from low threshold detectors.

- Variable cross-section



[1610.04611]



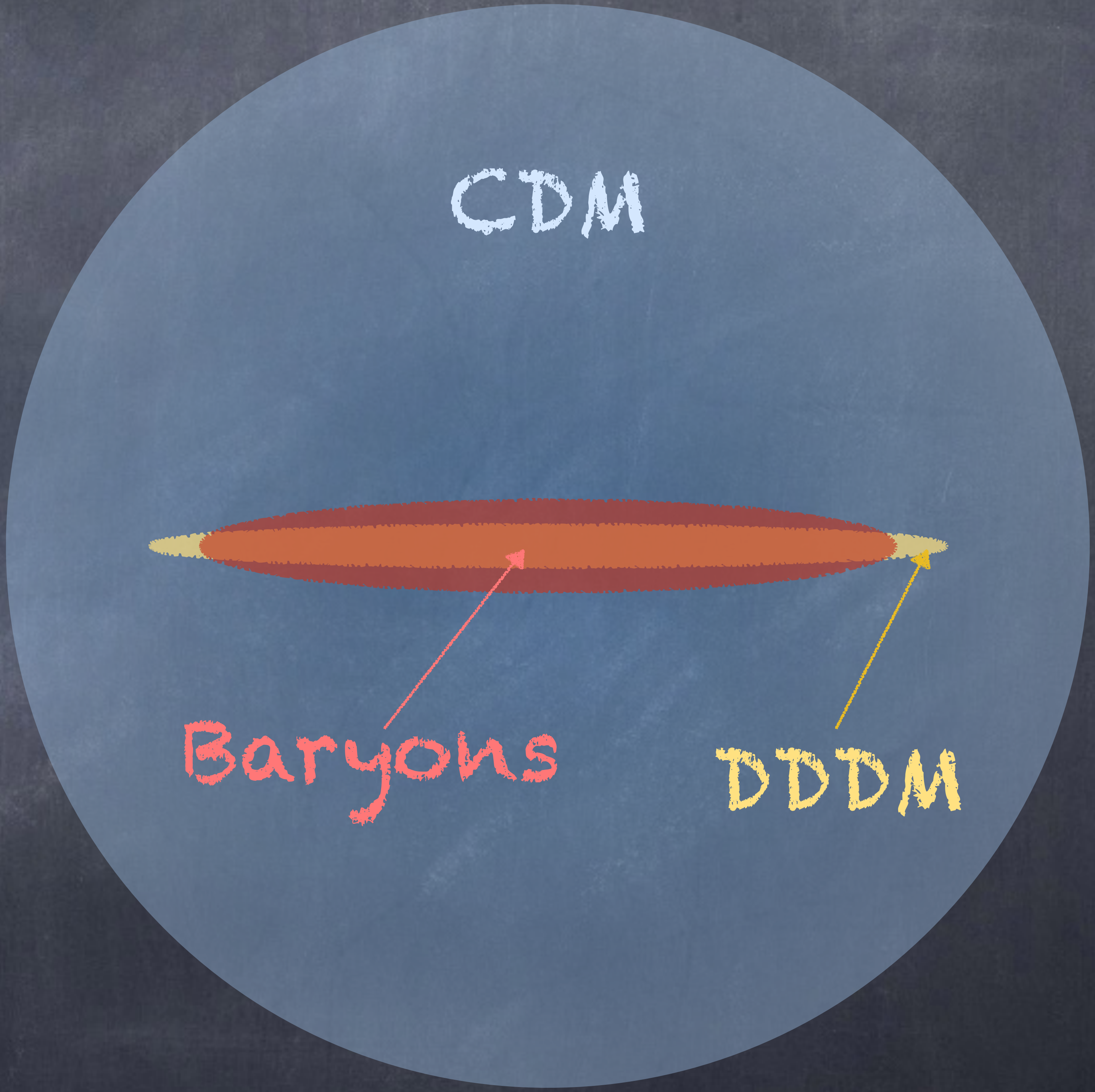
[1507.04007]

Dissipative DM & DDDM

- Only a fraction of DM can be dissipative!
- Need a light particle in the spectrum, to allow efficient cooling.
- May form co-rotating dense disk:

$$v_{\text{rel}} = 30\text{km/s}$$

- Different velocity spectrum, modulation peak, local density...



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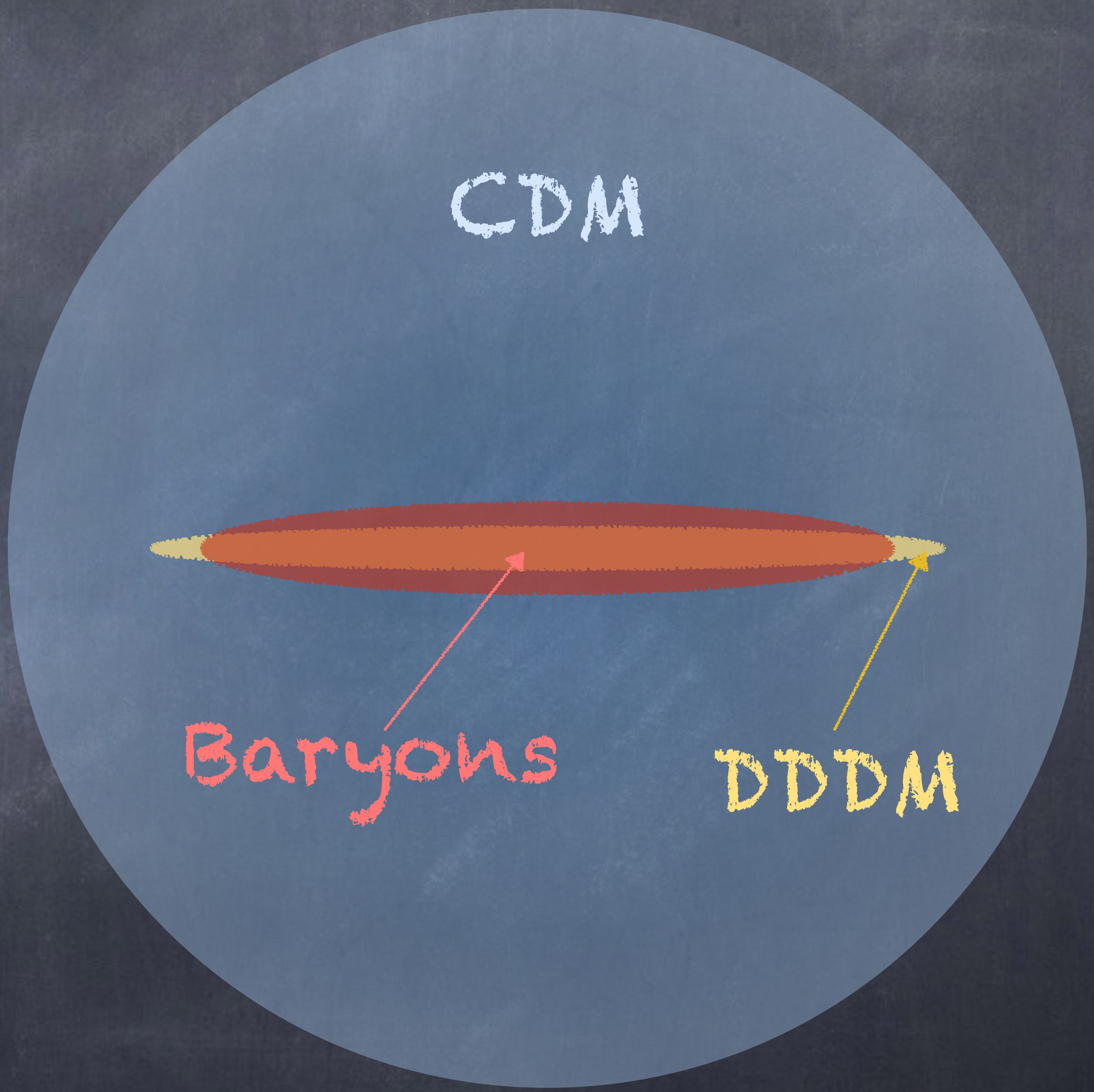

SIMPs and Forbidden DM

- Josh Ruderman already introduced these (thanks):
  - SIMPS: [1402.5143]
  - Forbidden DM: [1505.07107]

Quantum Interactions

Fermionic DM

- A 200 eV fermion cores dwarf galaxies just because of its Fermi Degeneracy Pressure. [1611.04590]
- Dwarf galaxies behave like white dwarf stars.

Axions/Fuzzy DM

- For even smaller masses

$$m_a \sim 10^{-23}\ \mathrm{eV}$$

one can solve the core/cusp problem. This is the lightest you can go.

Conclusions

- Astrophysics probes may help us towards a particular subset of models to look for.
- Self-interactions may open up some low mass parameter space (SIMP).
- Interesting self-interactions come with light mediators - change the detection strategy.
- Self-Interactions may also change the energy distribution of DM.