Self-interacting Dark Matter

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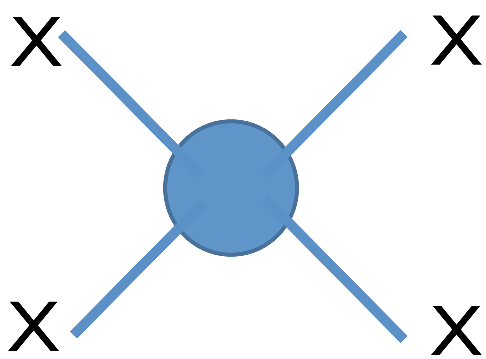
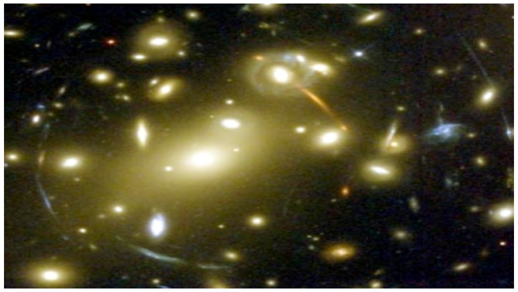
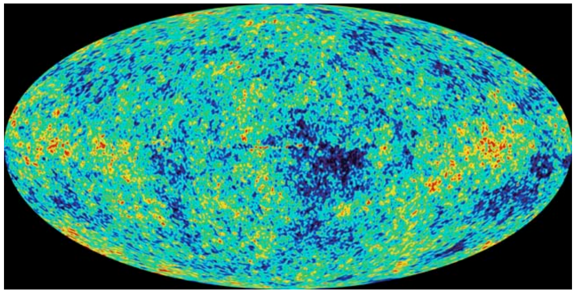


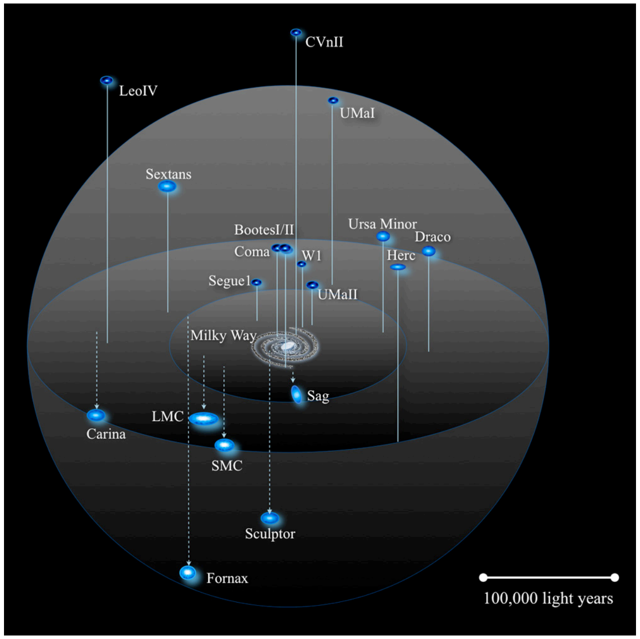
Aspen Winter Conference 01/23/2014

Collisionless Cold Dark Matter

- Large scales: very well

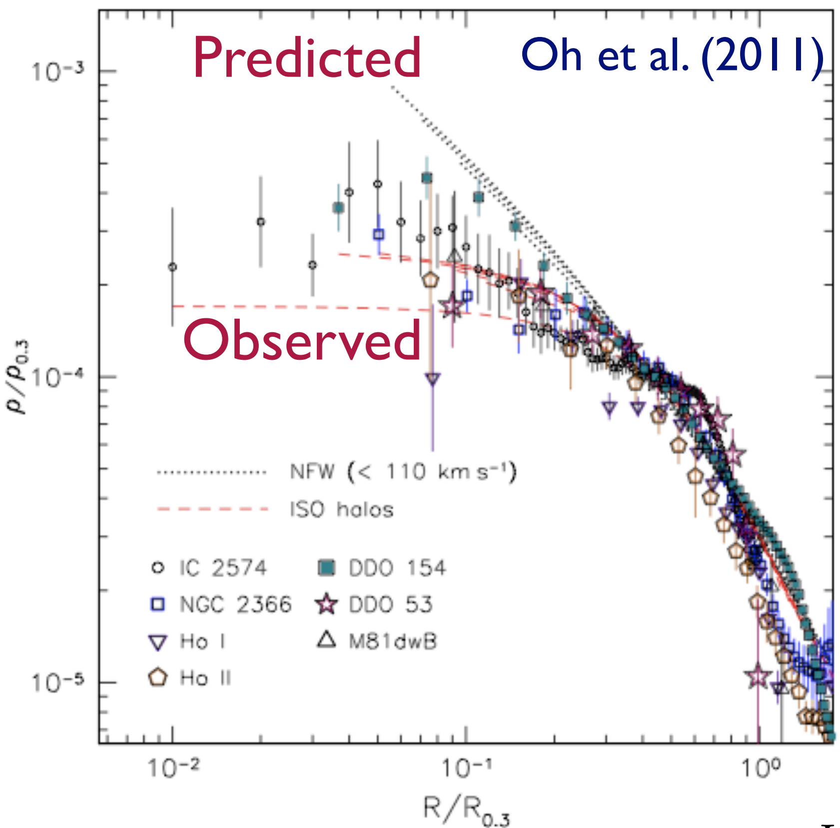




- Small scales (dwarf galaxies, subhalos, even clusters): ?

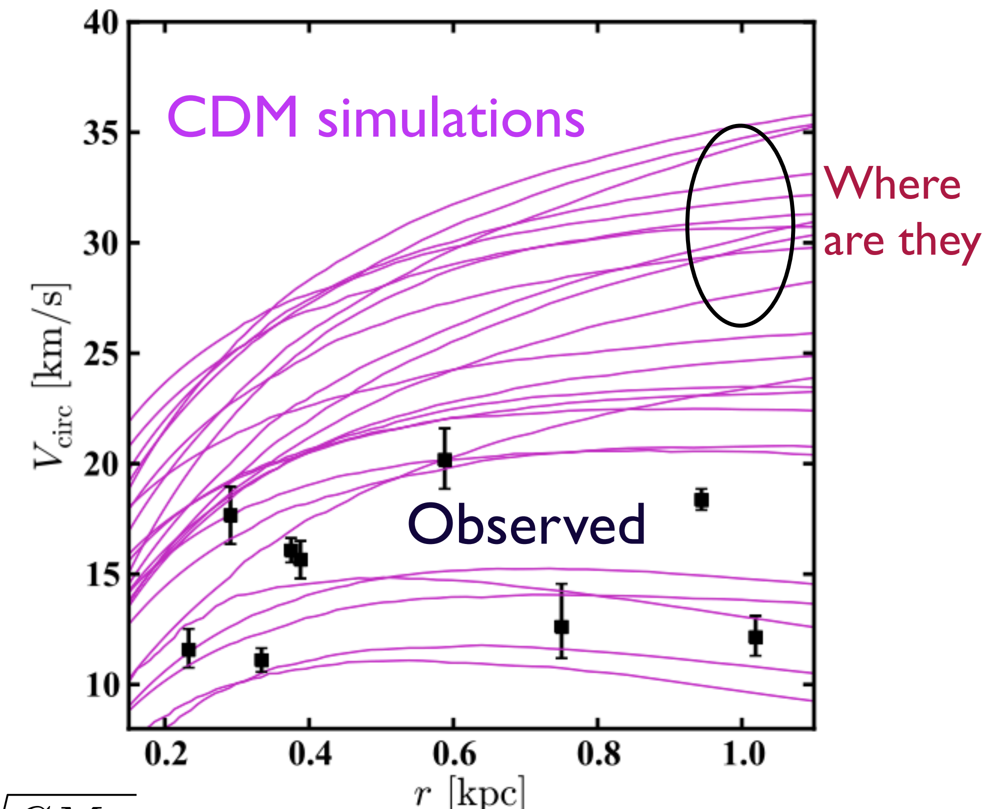


Issues with CDM

Core VS. Cusp



"Too big to fail"

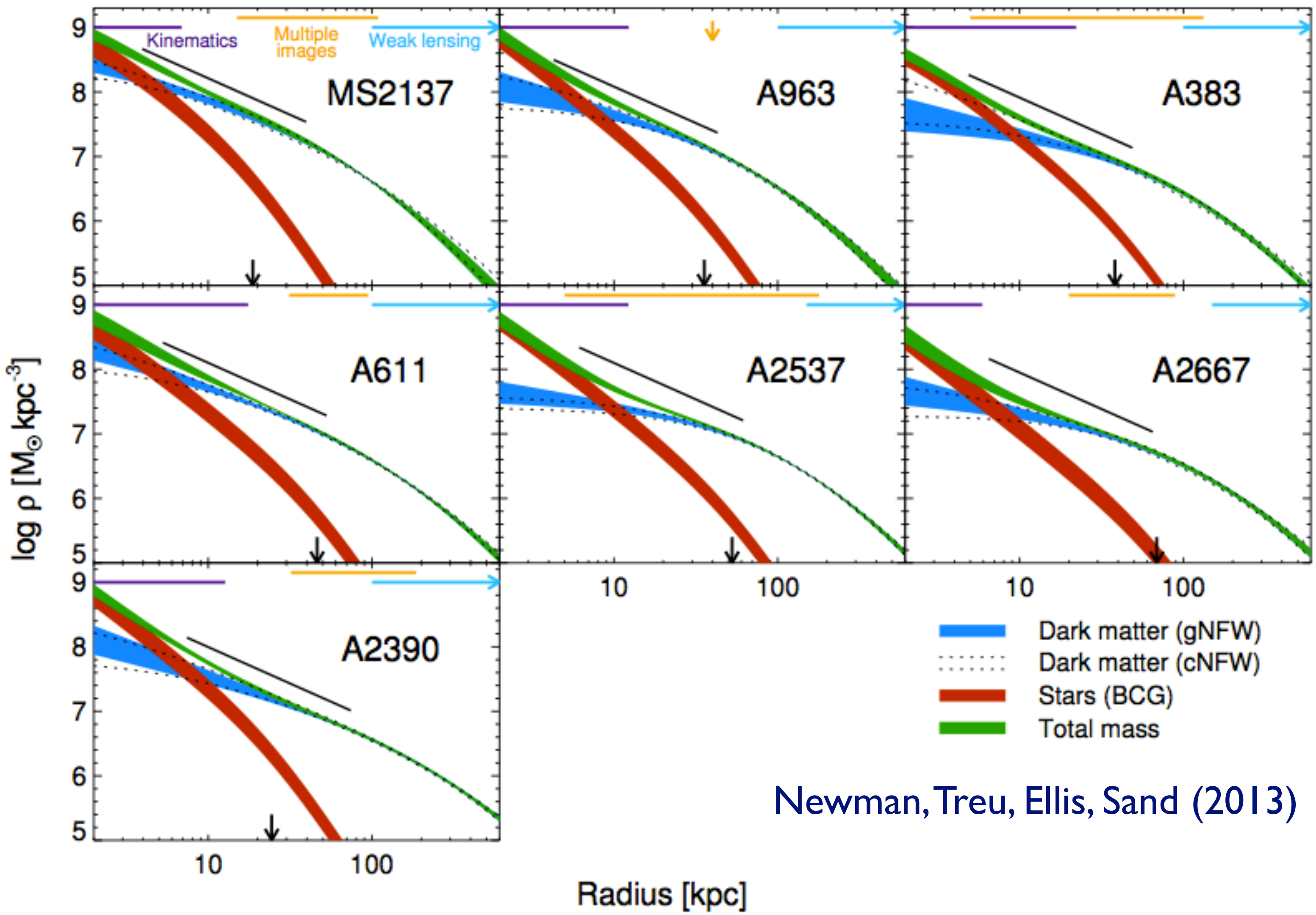


$$V \sim \sqrt{\frac{GM_<}{r}}$$

Boylan-Kolchin, Bullock, Kaplinghat (2011)

- These issues also exist in many other dwarf galaxies

Cores in Clusters!

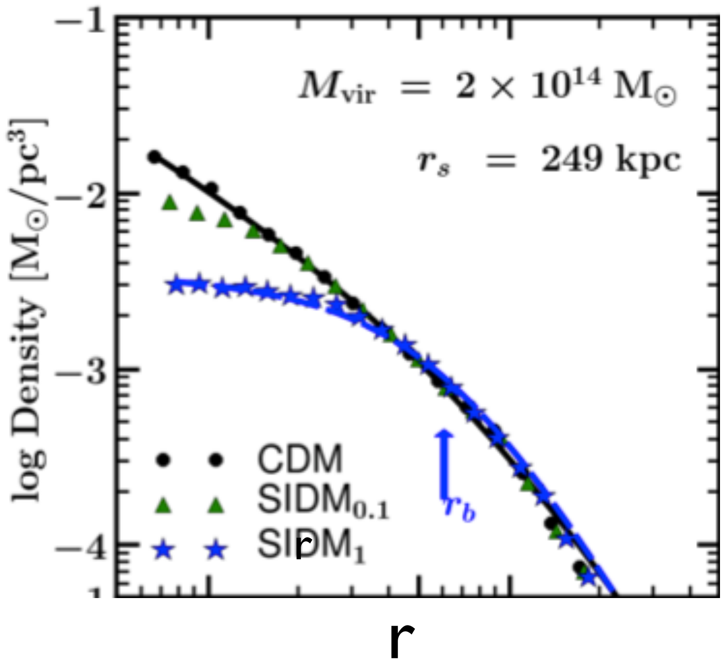


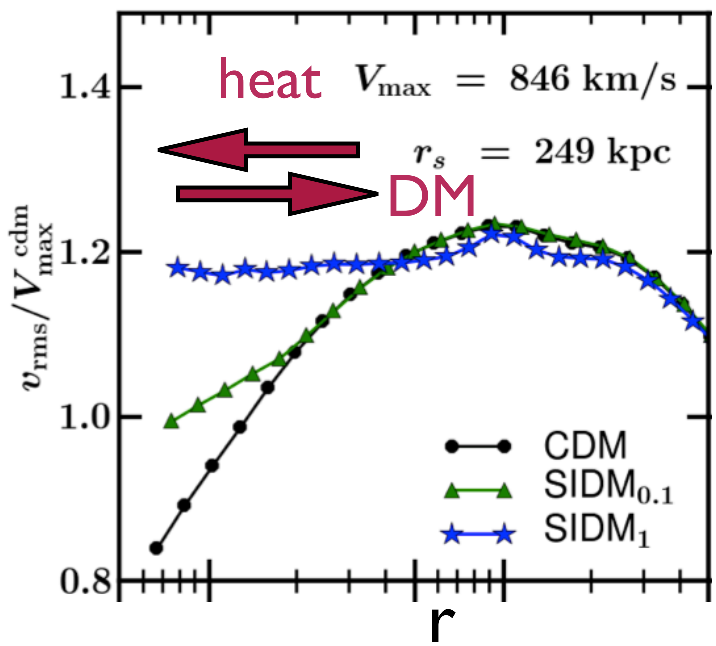
Newman, Treu, Ellis, Sand (2013)

Self-interacting Dark Matter

- All these anomalies can be solved if DM is strongly self-interacting

Spergel, Steinhardt (1999)





UCI group: Rocha, Peter, Bullock, Kaplinghat, Garrison-Kimmel, Onorbe, Moustakas (2012); Peter, Rocha, Bullock, Kaplinghat (2012)
Harvard group: Vogelsberger, Zavala, Loeb (2012); Zavala, Vogelsberger, Walker (2012)

Self-interactions reduce the central DM density

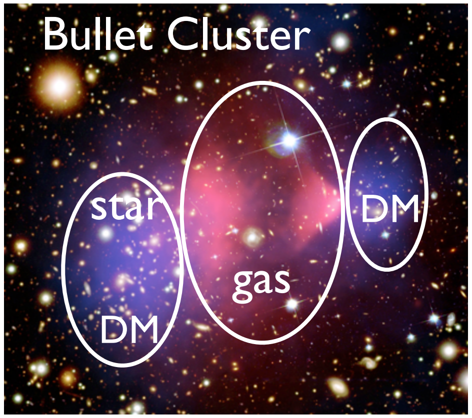
Astrophysics Summary

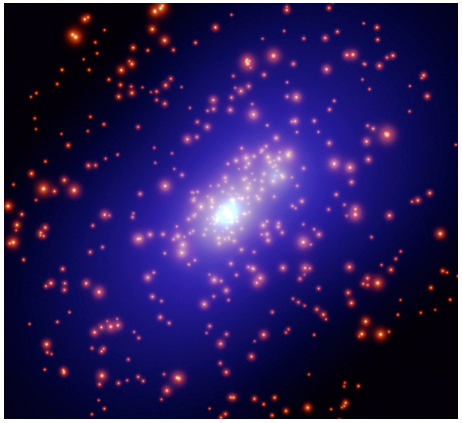
- Evidence for DM self-interactions on dwarf galaxy scales

$\sigma/m_X \sim 0.1\text{-}10 \text{ cm}^2/\text{g}$ for $v \sim 10\text{-}30$ km/s

$$\Gamma \simeq n\sigma v = (\rho/m_X)\sigma v \sim H_0$$

- Constraints: Bullet Cluster; elliptical halo shapes (?)





$\sigma/m_X < 1 \text{ cm}^2/\text{g}$ for 3000 km/s (cluster); $v \sim 300$ km/s (NGC720)

Peter, Rocha, Bullock, Kaplinghat (2012)

Challenges

- A really large scattering cross section!

a nuclear-scale cross section

$\sigma \sim 1\,\mathrm{cm}^2\,(m_X/\mathrm{g}) \sim 2\times10^{-24}\,\mathrm{cm}^2\,(m_X/\mathrm{GeV})$

For a WIMP: $\sigma \sim 10^{-38}\,\mathrm{cm}^2\,(m_X/100\,\mathrm{GeV})$

SIDM indicates a new mass scale

- How to avoid the constraints on large scales?

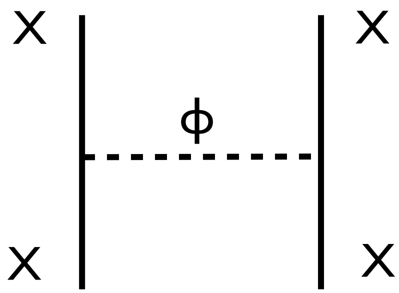
$\sigma/m_X < 1\,\mathrm{cm}^2/\mathrm{g}$ for 3000 km/s (cluster)

In particular, if $\sigma \sim$constant

Spergel, Steinhardt (1999)

Note: the constant cross section is still allowed if $\sigma/m_X \sim 0.5\text{-}1\,\mathrm{cm}^2/\mathrm{g}$

Particle Physics of SIDM

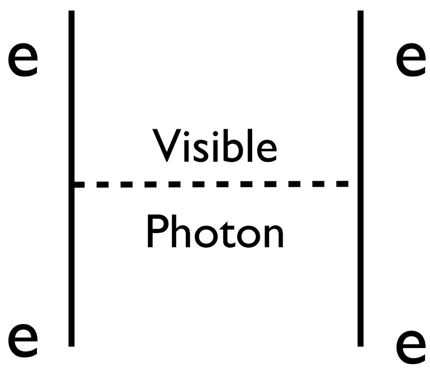


- SIDM indicates light mediators

$$\sigma \approx 5 \times 10^{-23}\,\mathrm{cm}^2 \left(\frac{\alpha_X}{0.01}\right)^2 \left(\frac{m_X}{10\,\mathrm{GeV}}\right)^2 \left(\frac{10\,\mathrm{MeV}}{m_\phi}\right)^4$$

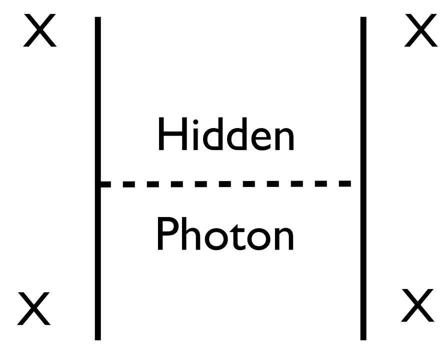
in the perturbative and small velocity limit

- With a light mediator, DM self-scattering is velocity-dependent (like Rutherford scattering)



$$\sigma \sim \frac{\alpha_X^2}{m_X^2 v^4}$$

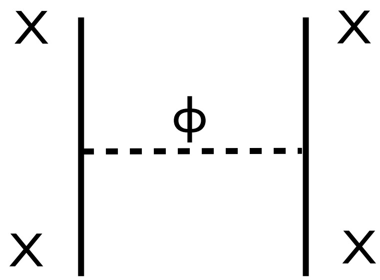
$m_X\, v >> m_\phi$



- DM is self-scattering on small scales (v~10-30 km/s)
- DM is collisionless on large scales (v~3000 km/s), specially for heavy SIDM

Feng, Kaplinghat, Tu, HBY (2009); Loeb, Weiner (2010)

A Simplified Model



$$\mathscr{L}_{\text{int}} = \begin{cases} g_X \bar{X} \gamma^\mu X \phi_\mu & \text{vector mediator} \\ g_X \bar{X} X \phi & \text{scalar mediator} \end{cases}$$

A Yukawa potential

$$V(r) = \pm \frac{\alpha_X}{r} e^{-m_\phi r}$$

$$\alpha_X = g_X^2/(4\pi)$$

$$\sigma_T = \int d\Omega \, (1 - \cos\theta) \frac{d\sigma}{d\Omega}$$

regulate forward scattering

Map out the parameter space (m_X, m_ϕ, α_X)

- Solve small scale anomalies (small v)
- Avoid constraints on large scales (large v)
- Get the relic density right

Scattering with a Yukawa Potential

$$V(r) = \pm \frac{\alpha_X}{r} e^{-m_\phi r}$$

DM self-scattering

Perturbative (Born) regime
$\alpha_X m_X / m_\phi \ll 1$

Nonperturbative regime
$\alpha_X m_X / m_\phi \gtrsim 1$

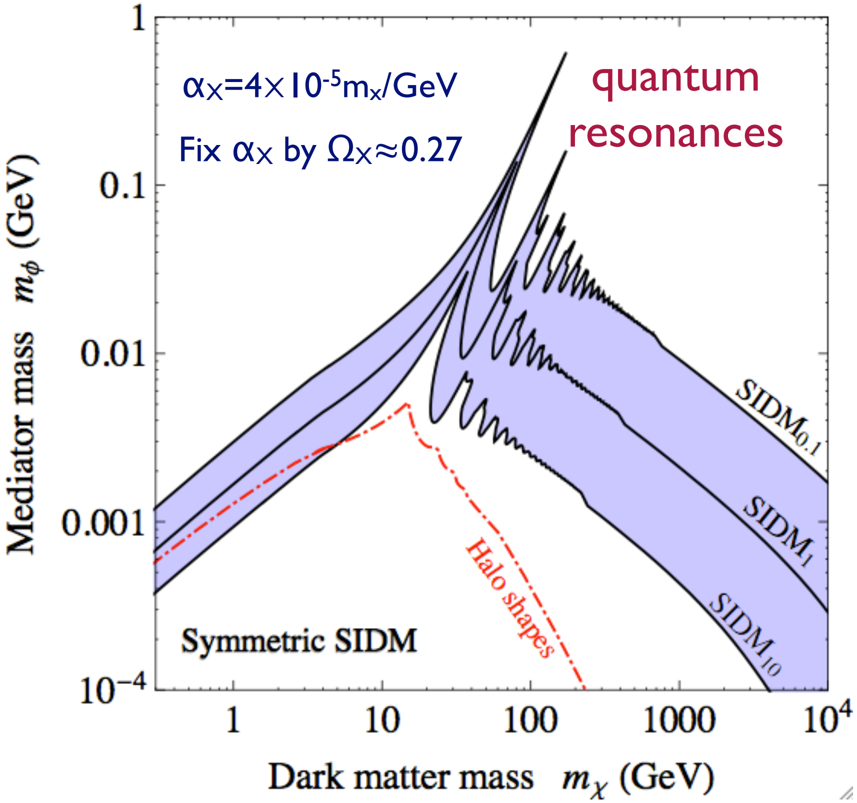
Classical regime
$m_X v / m_\phi \gg 1$

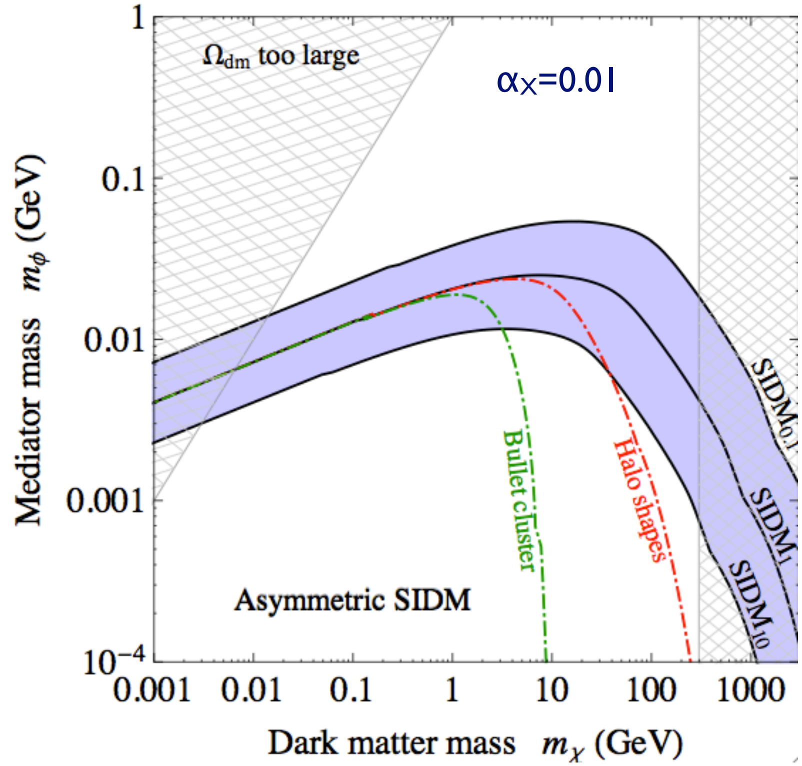
Resonant regime
$m_X v / m_\phi \lesssim 1$

Feng, Kaplinghat, HBY (2009); Buckley, Fox (2009);
Tulin, HBY, Zurek (2012)(2013)

SIDM Parameter Space

- Shaded region: Explain small scale anomalies





dw: dwarf (30 km/s); halo shapes: (300 km/s); cl: cluster (3000 km/s)

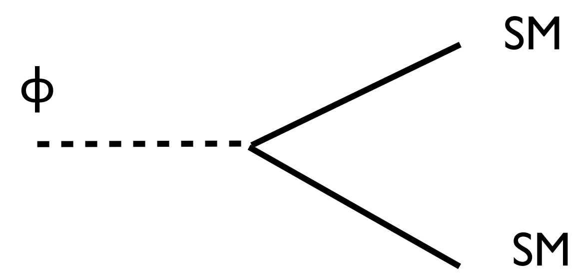
- SIDM predicts a 1-100 MeV light force carrier
- Bullet Cluster constraints are not sensitive to heavy SIDM

$m_X v \gg m_\phi$

Cosmology of SIDM

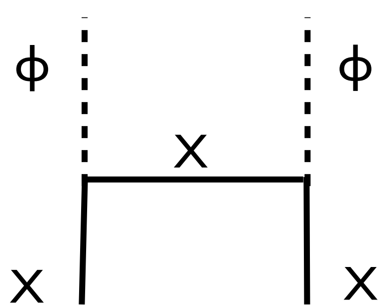
- The mediator may dominate the energy density of the Universe
- The mediator decays before BBN: lifetime of ϕ is ~1 second

$$\epsilon \gtrsim 10^{-10}\sqrt{10\ \mathrm{MeV}/m_\phi}$$

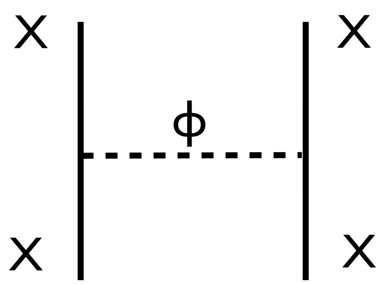


DD cross section:
- suppressed by the tiny coupling
- enhanced by the small mediator mass

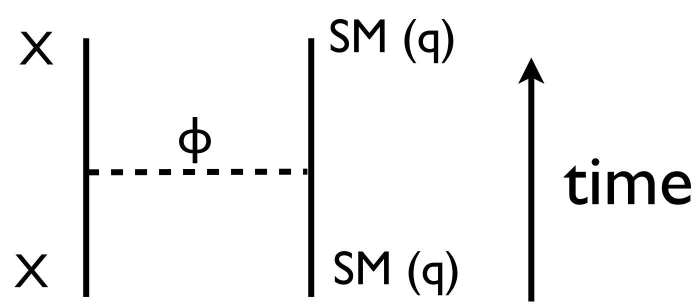
A super model!



DM relic density

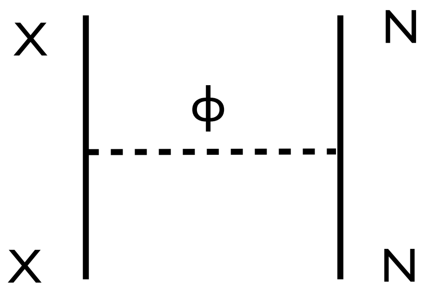


DM self-scattering



DM direct detection

Direct Detection of SIDM



$$\frac{d\sigma}{dq^2} = \frac{4\pi\alpha_{em}\alpha_X\epsilon^2 Z^2}{(q^2 + m_\phi^2)^2 v^2}$$

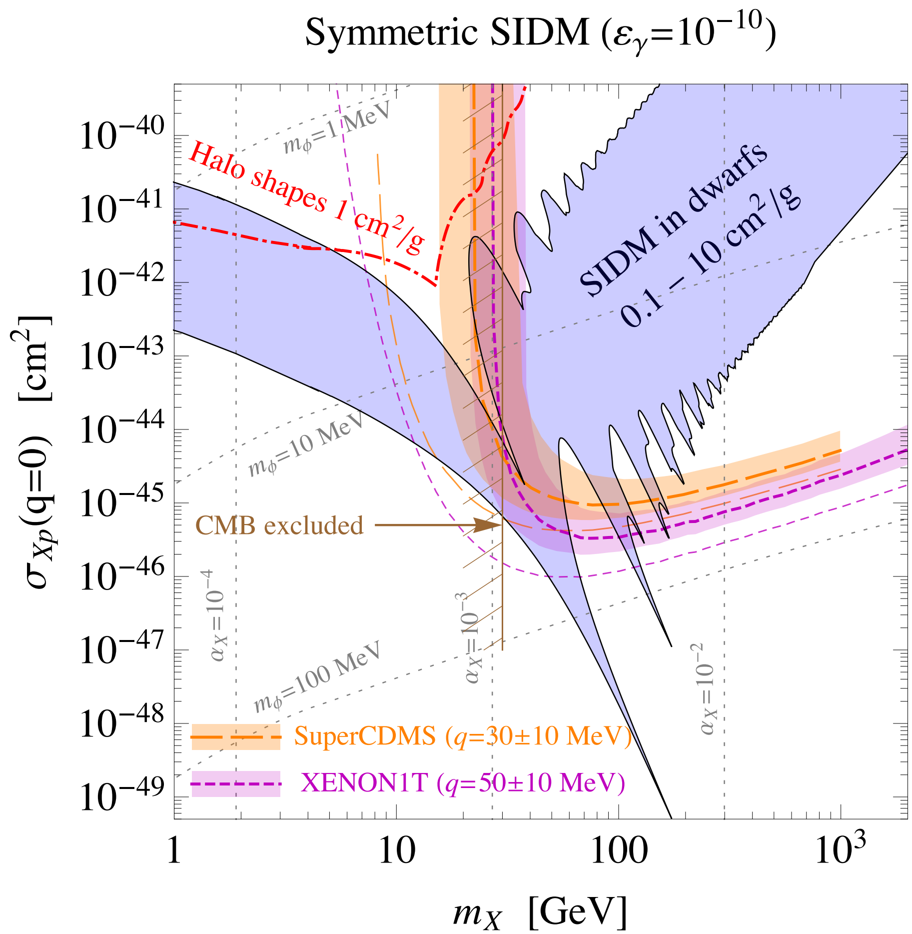
$$q^2 = 2m_N E_R$$

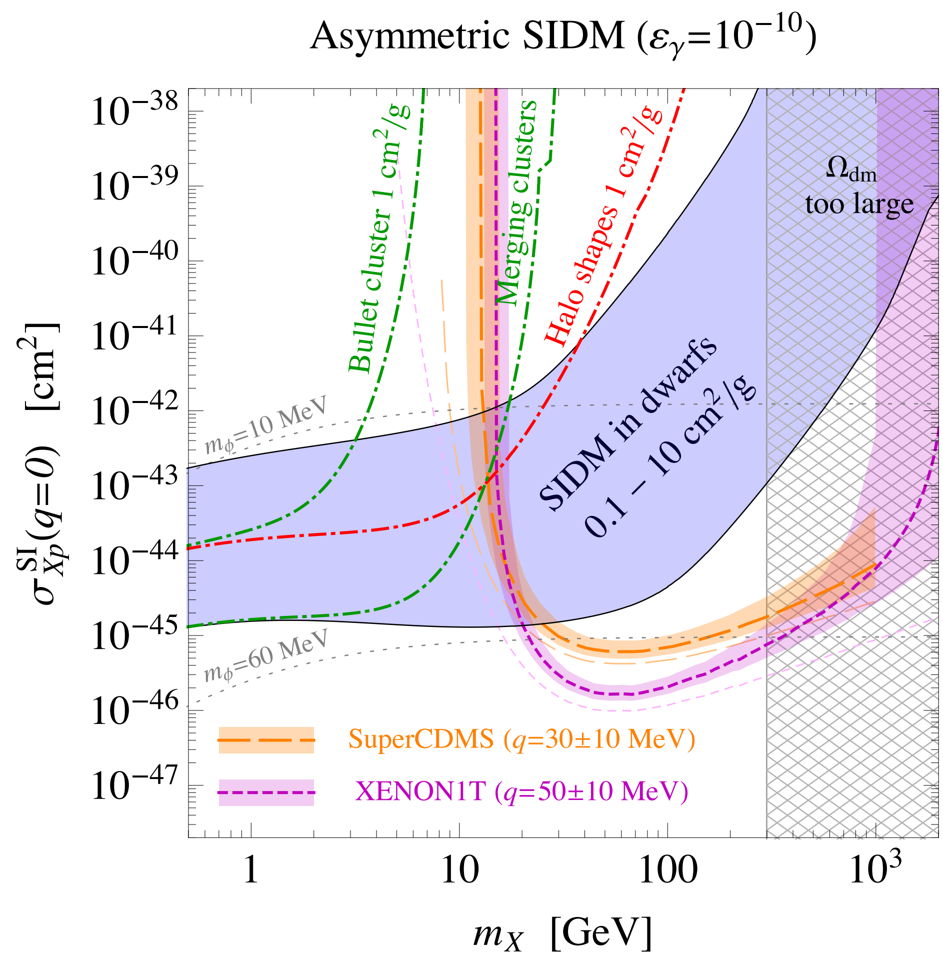
For XENON: q~50 MeV

- In the WIMP case, $m_\phi >> q$
- For SIDM, m_ϕ~1-100 MeV, which is comparable to q
- A NEW region for the direct detection community
- A dedicated study is required

Direct Detection of SIDM

- The lower limit of direct detection cross section





$$\sigma^{\rm SI}_{Xp} \approx 1.5 \times 10^{-24}\ {\rm cm}^2 \times \varepsilon_\gamma^2 \times \left(\frac{\alpha_X}{10^{-2}}\right)\left(\frac{m_\phi}{30\ {\rm MeV}}\right)^{-4}$$

Kaplinghat, Tulin, HBY (2013)

cross section in the zero momentum limit

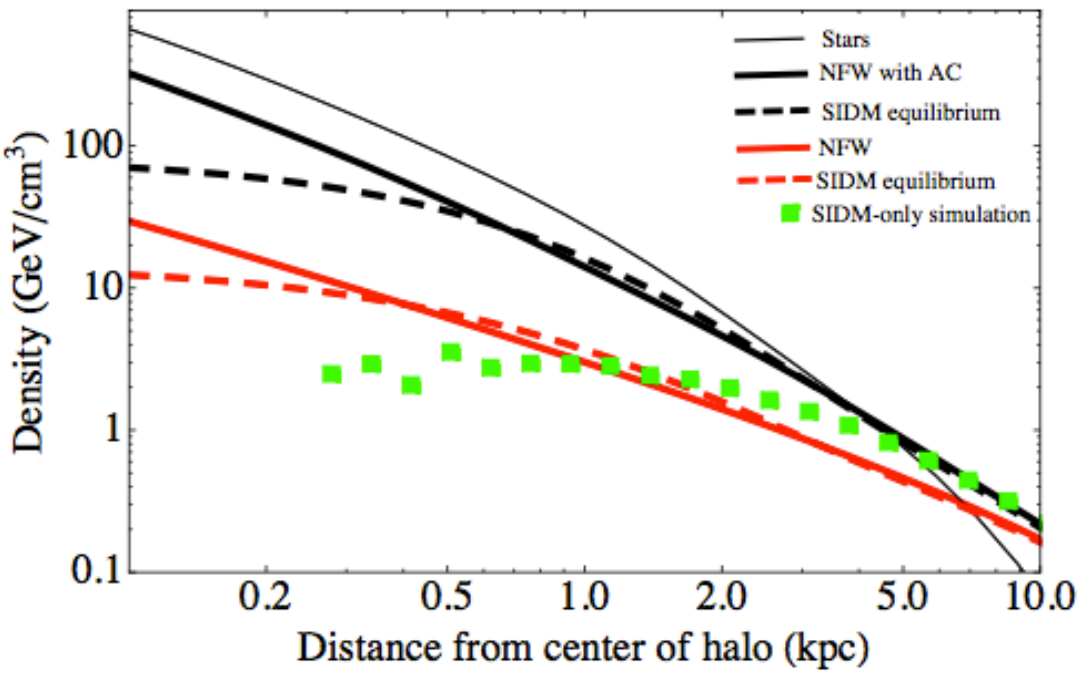
Complementarity!

Tying Dark Matter to Baryons

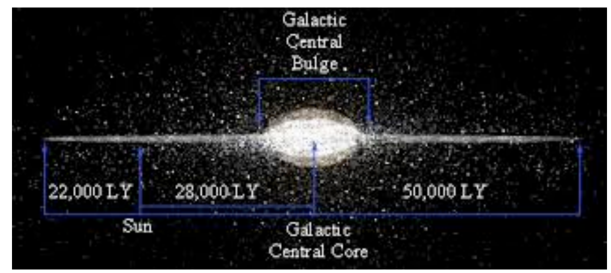
- Baryons dominate in the central region of the Milky Way

isothermal solution for the Jeans equation

$$\frac{\sigma^2}{\rho}\frac{d\rho}{dr} + \frac{d\sigma^2}{dr} = -\frac{d\Phi_B}{dr} - \frac{d\Phi}{dr}$$



Kaplinghat, Linden, Keeley, HBY (2013)



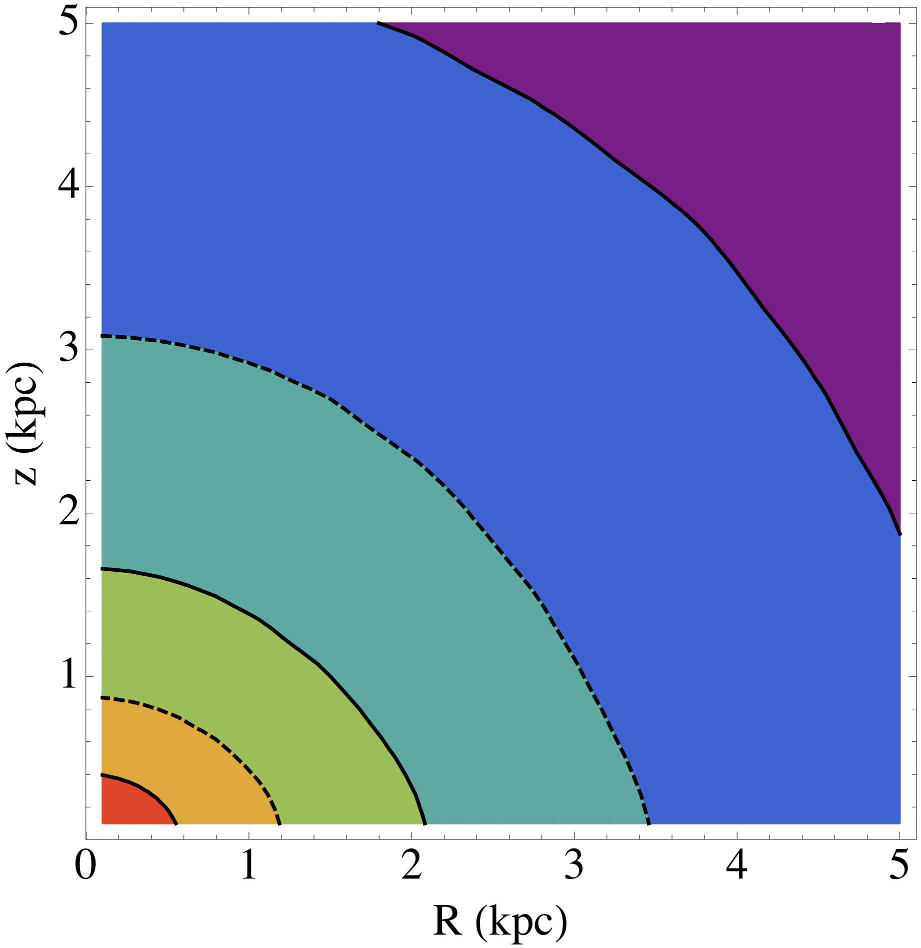
The core size for the MW halo:
SIDM+baryons: ~0.3 kpc
SIDM only: core size ~10 kpc

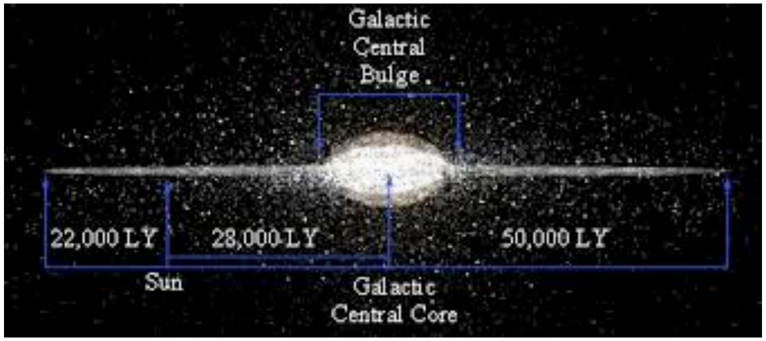
Important for indirect detection

Tying Dark Matter to Baryons

- SIDM halo shapes

Kaplinghat, Linden, Keeley, HBY (2013)



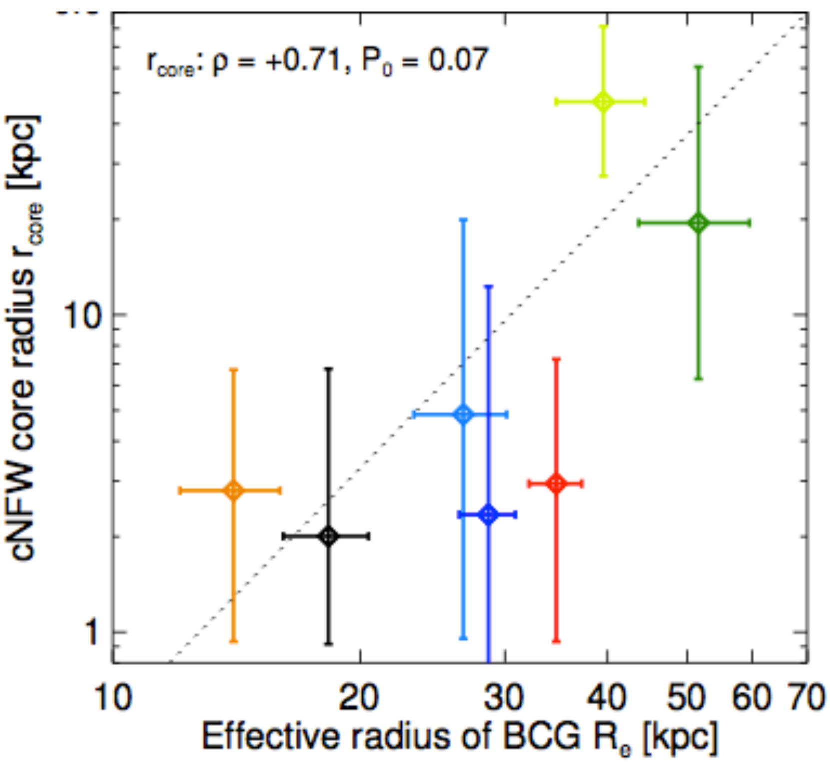


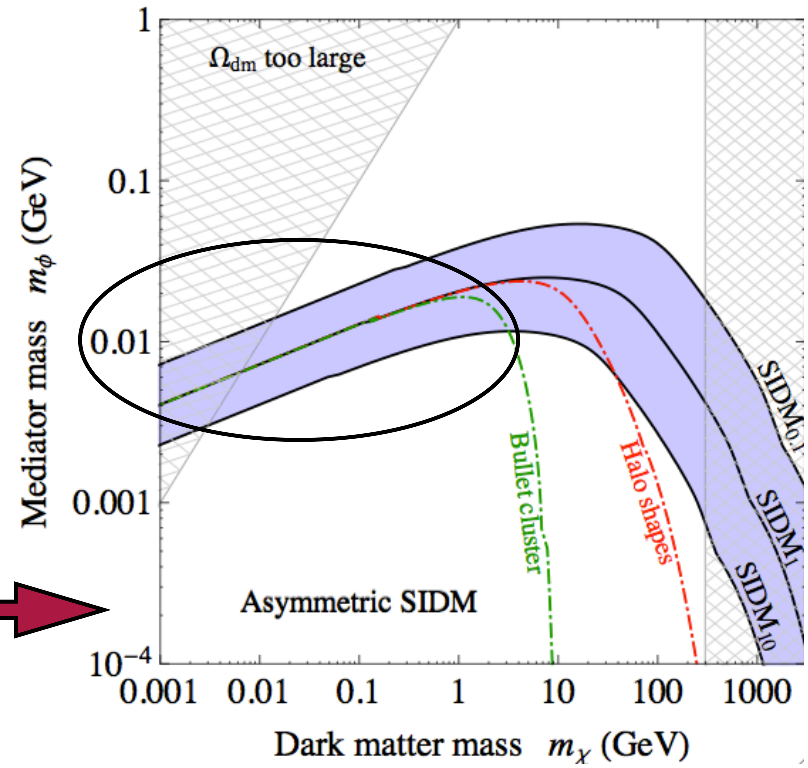
Rethink about halo shape constraints!

Constant density contours in cylindrical coordinates (R, z)

Tying Dark Matter to Baryons

- Cores in clusters





Newman, Treu, Ellis, Sand (2012)

Kaplinghat, HBY (work in progress)

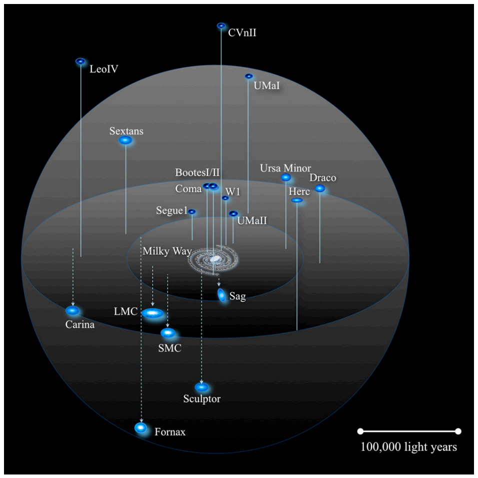
m_χ v<m_ϕ with v~800 km/s

m_χ <10 MeV/(800 km/s/c)~4 GeV

Cores in clusters indicate light SIDM

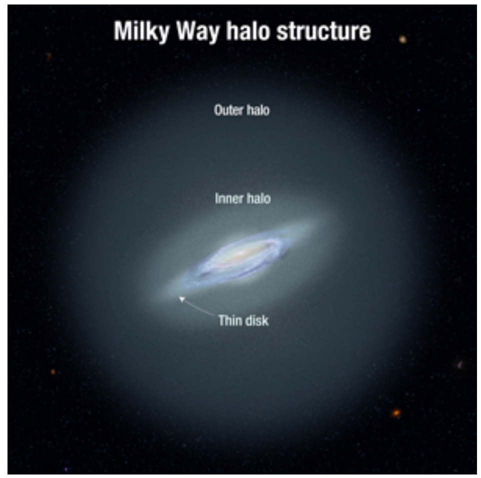
Dark Matter "Colliders"

Dwarf galaxies



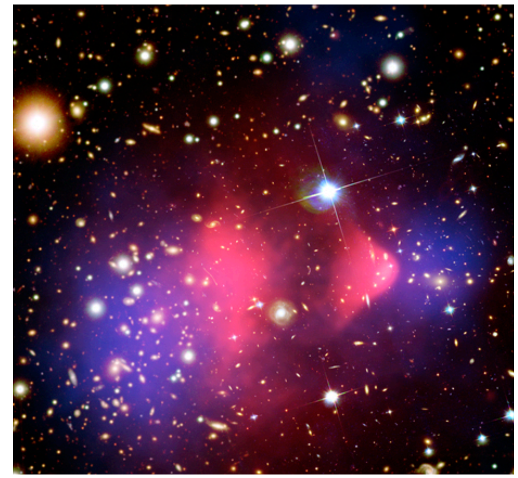
"B-factory"

MW-size galaxies

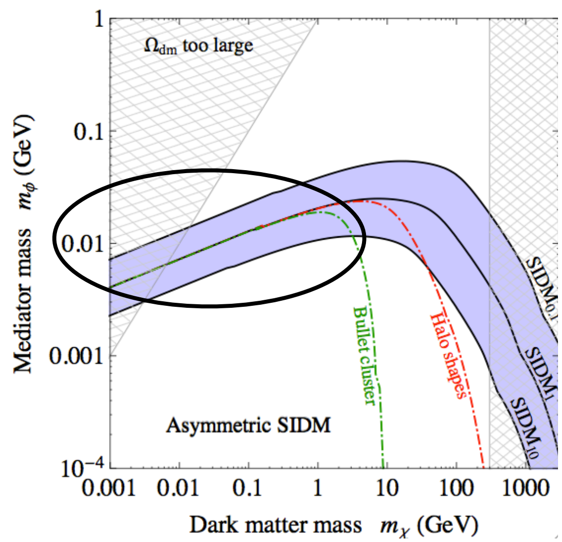


"LEP"

Clusters



"LHC"



The dark sector may not be as dark as you thought

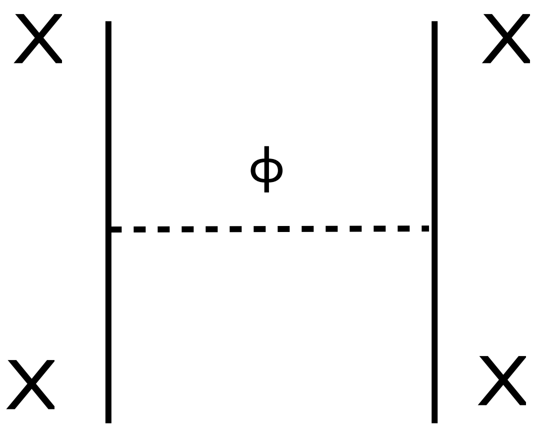
Conclusions

- No reason to believe DM has to be collisionless
- SIDM is an interesting alternative to CDM
- With a light dark force (with one coupling α_X)
  - Explain anomalies on small scales
  - Provide the correct DM relic density
  - Interesting direct detection signals
- Self-interactions ties DM to baryons

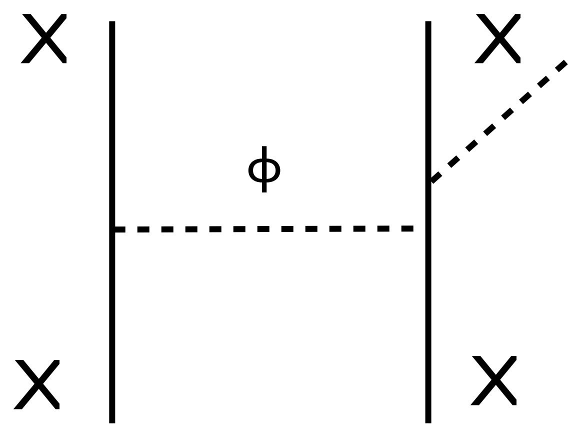
$$\Lambda\text{CDM} \longrightarrow \Lambda\text{SIDM}$$

Not Dissipative

- SIDM is not dissipative



$\Gamma = n\sigma v \sim H_0$



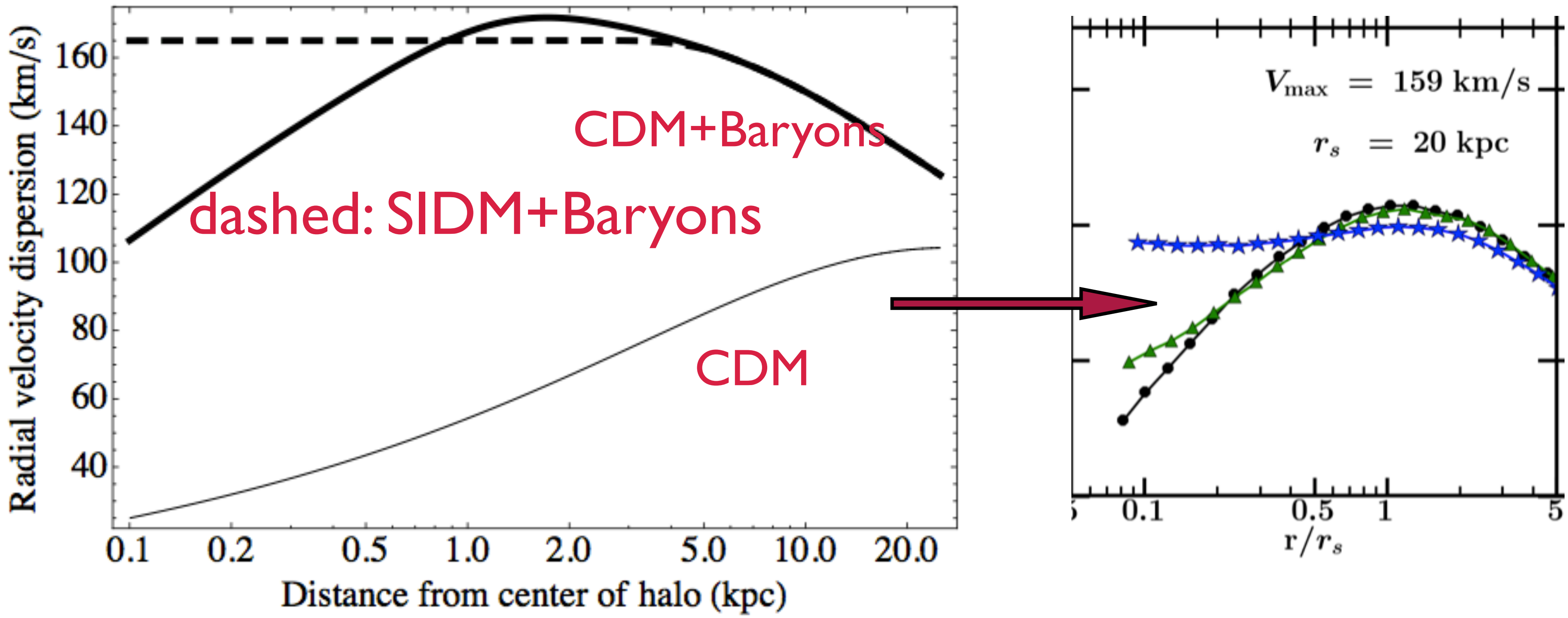
$\Gamma = \alpha_X n\sigma v << H_0$ as long as $\alpha_X < 1$

Tying Dark Matter to Baryons

- Baryons dominate in the central region of the Milky Way

the Jeans equation

$$\frac{\sigma^2}{\rho}\frac{d\rho}{dr} + \frac{d\sigma^2}{dr} = -\frac{d\Phi_B}{dr} - \frac{d\Phi}{dr}$$



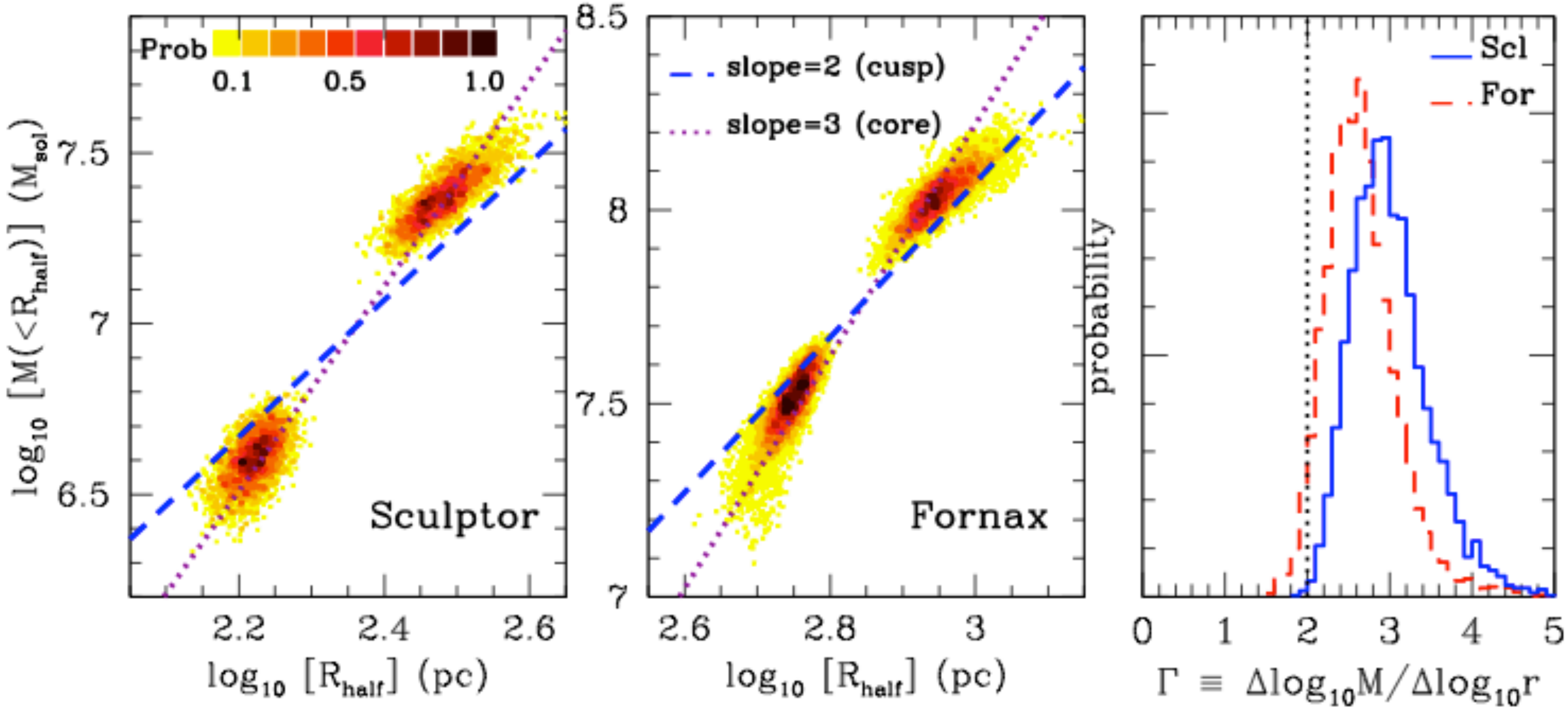
Kaplinghat, Linden, Keeley, HBY (2013)

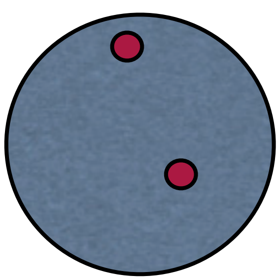
Baryons dictate the DM temperature profile

Core VS. Cusp Problem

- Milky Way dwarf galaxies

Walker, Penarrubia (2011)





$$V \sim \sqrt{\frac{GM_<}{r}}$$

cusp $\rho \sim r^{-1} \rightarrow M \sim \int \rho d^3r \sim r^2$

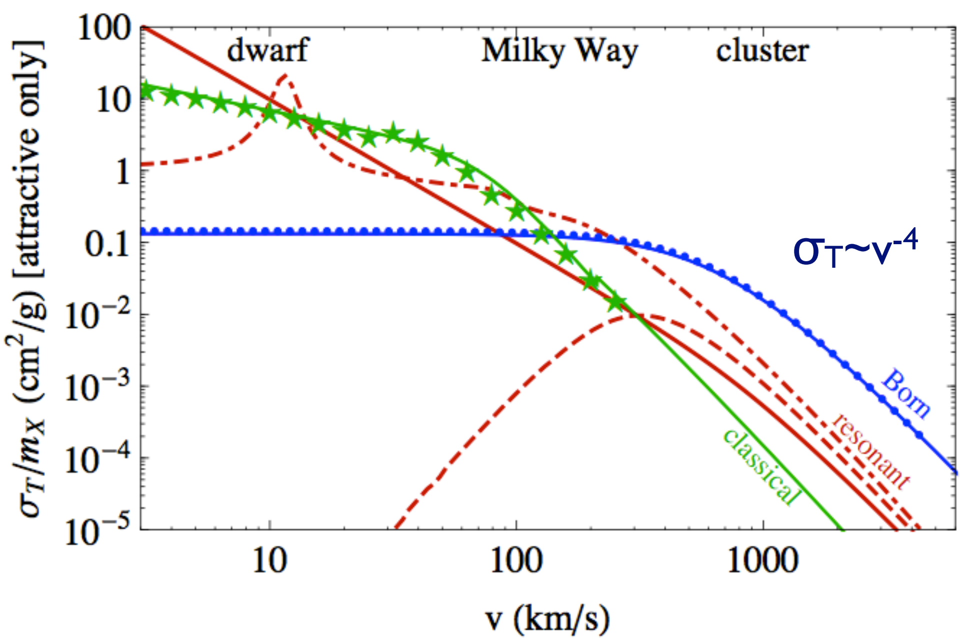
core $\rho \sim const \rightarrow M \sim \int \rho d^3r \sim r^3$

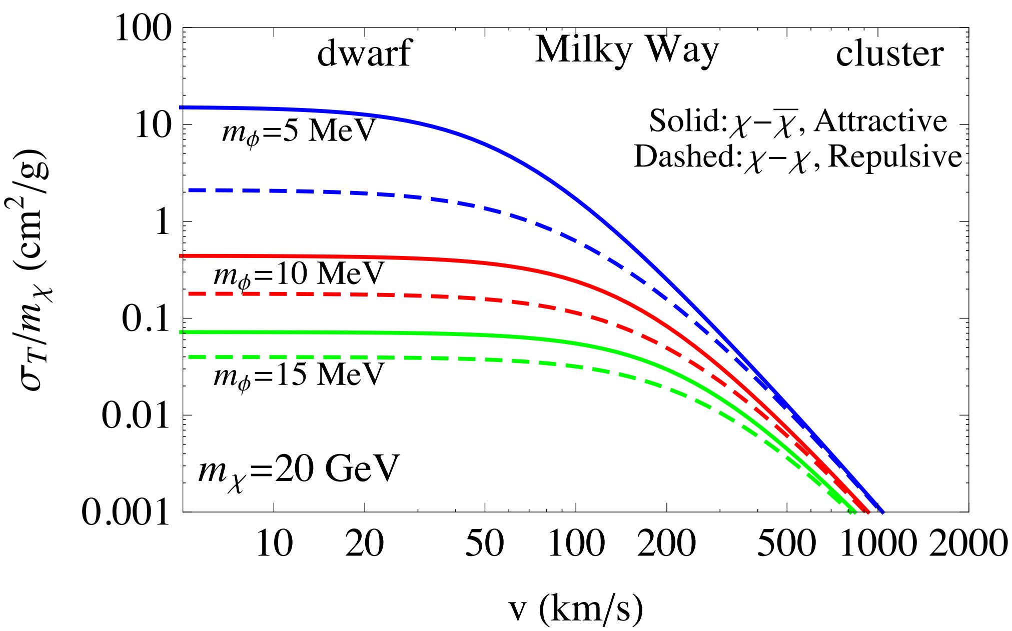
Two groups of stars as test particles

Velocity Dependence

- σ_T has rich structure

Tulin, HBY, Zurek (2011) (2012)





- In many cases, σ_T is enhanced on dwarf scales
- This helps us avoid the Bullet Cluster constraint