Beyond Collisionless Dark Matter

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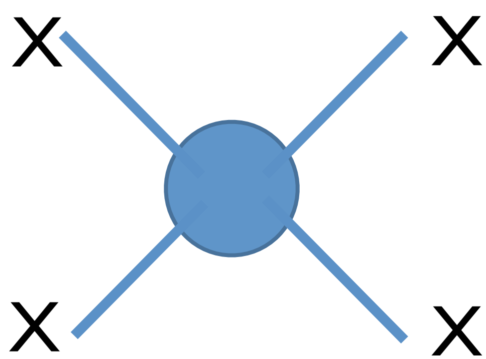
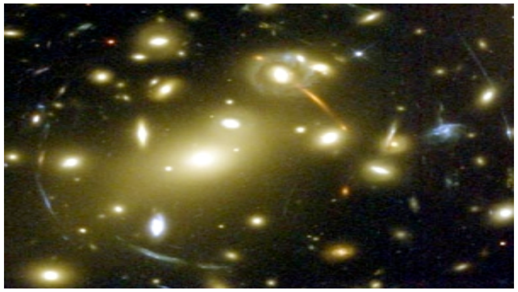
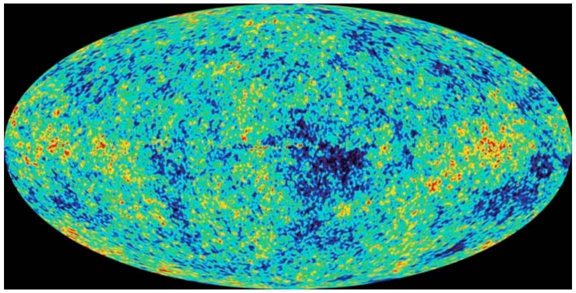


LANL 02/20/2014

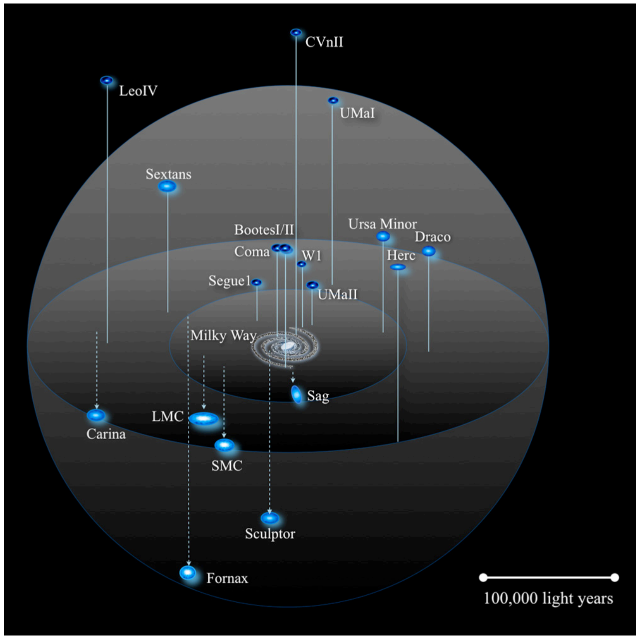
Collisionless Cold Dark Matter

- Large scales: very well



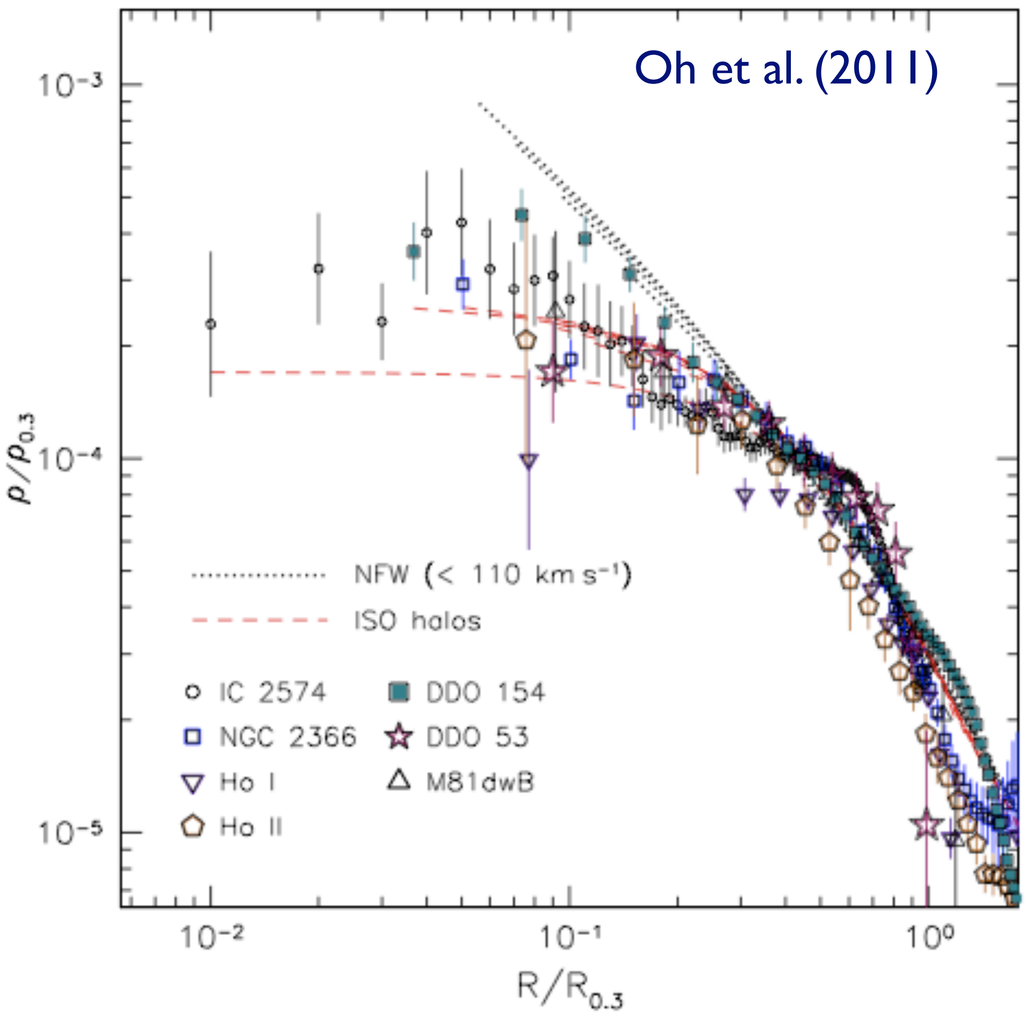


- Small scales (dwarf galaxies, subhalos, even clusters): ?



Core VS. Cusp Problem

- THINGS (dwarf galaxy survey)



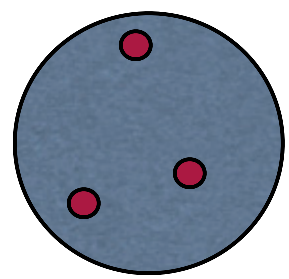
density profile: $\rho \sim r^{\alpha}$

predicted: $\alpha \sim -1$

observed: $\alpha = -0.29 \pm 0.07$

• Observed central density shows cores

• CDM-only simulations predict cusps

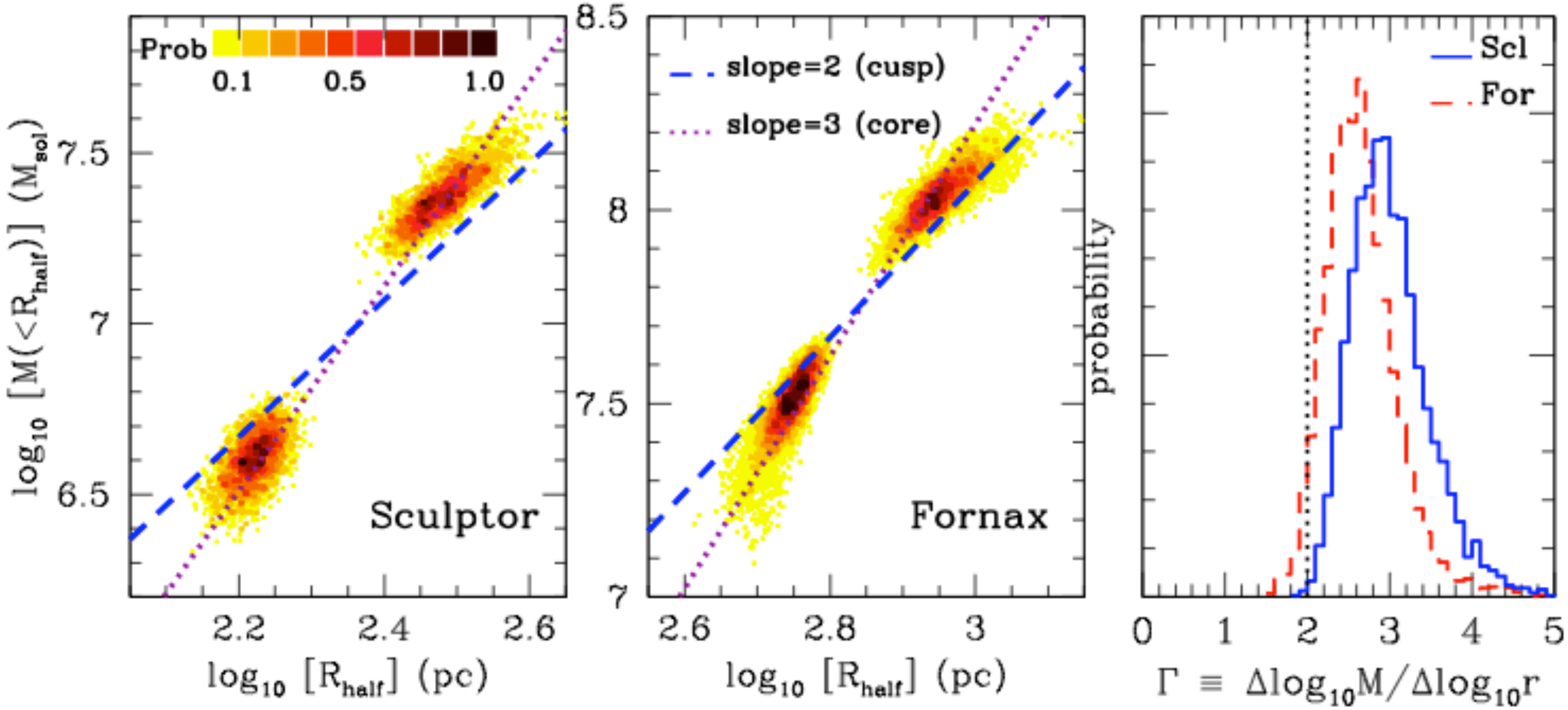


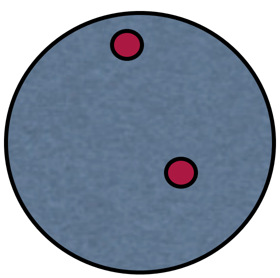
$$V \sim \sqrt{\frac{GM_<}{r}}$$

$$M_< \sim \int \rho r^2 dr$$

Core VS. Cusp Problem

- Milky Way dwarf galaxies — Walker, Penarrubia (2011)





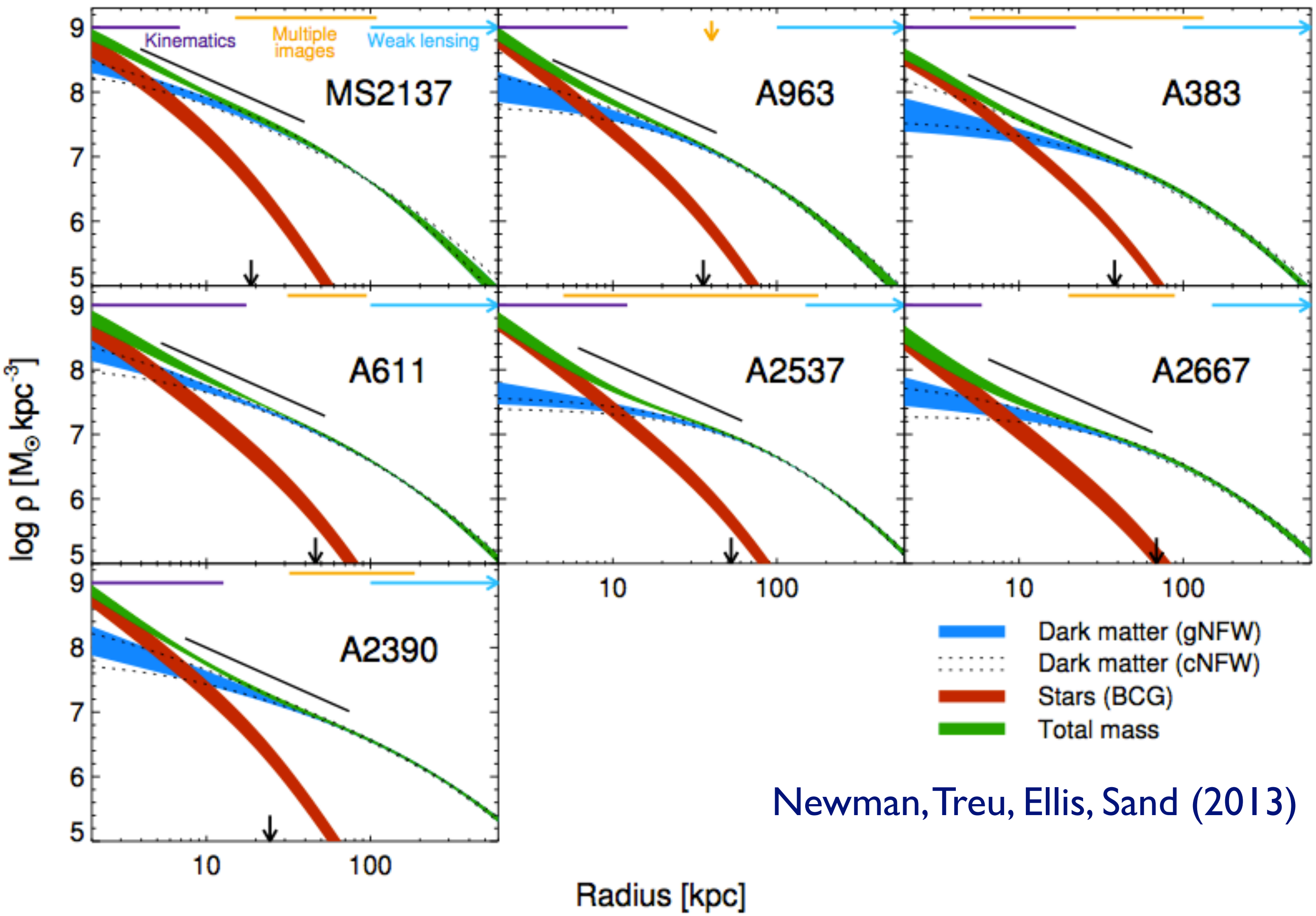
$$V \sim \sqrt{\frac{GM_<}{r}}$$

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

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

Two groups of stars as test particles

Even Clusters!

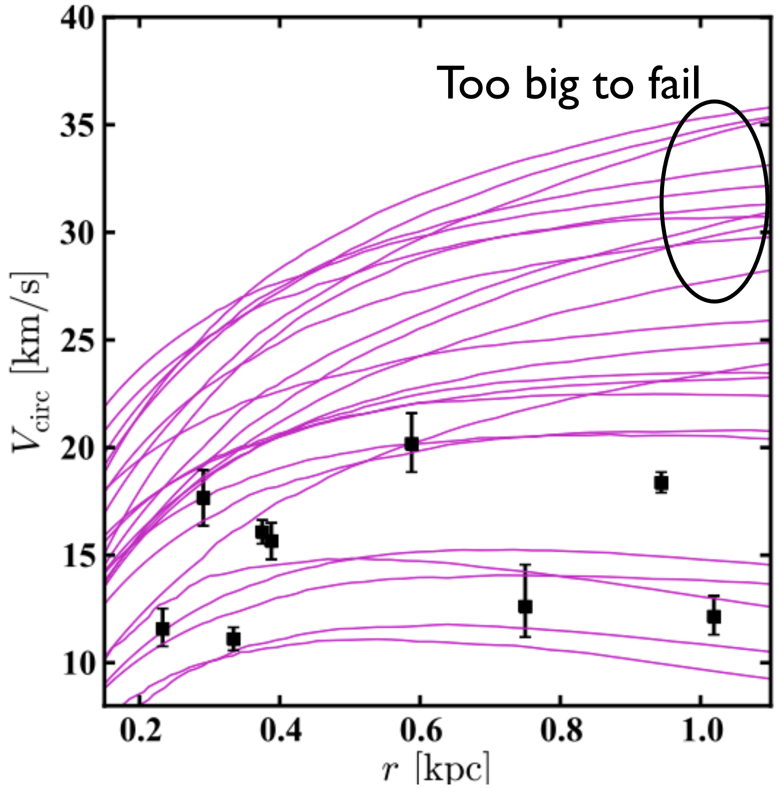


Newman, Treu, Ellis, Sand (2013)

Too Big to Fail Problem

- Milky Way dwarf galaxies   Boylan-Kolchin, Bullock, Kaplinghat (2011)

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



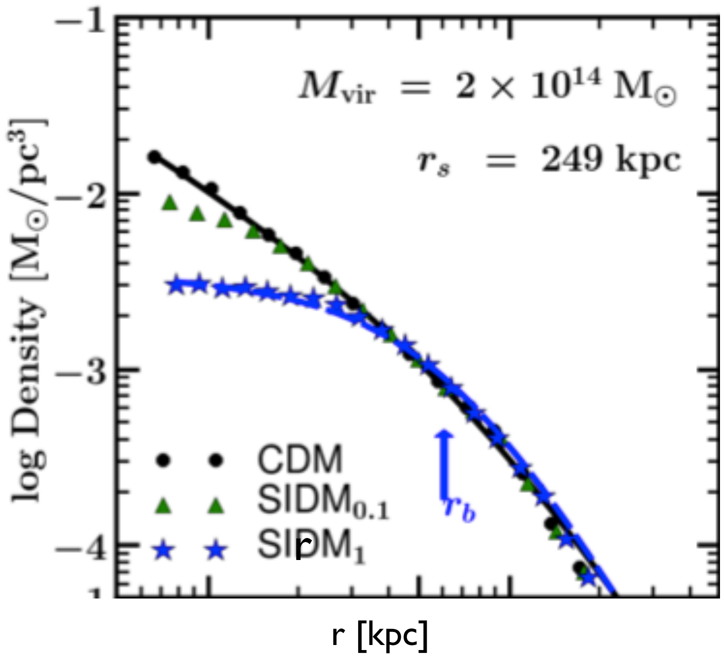
Biggest predicted satellites from CDM simulations

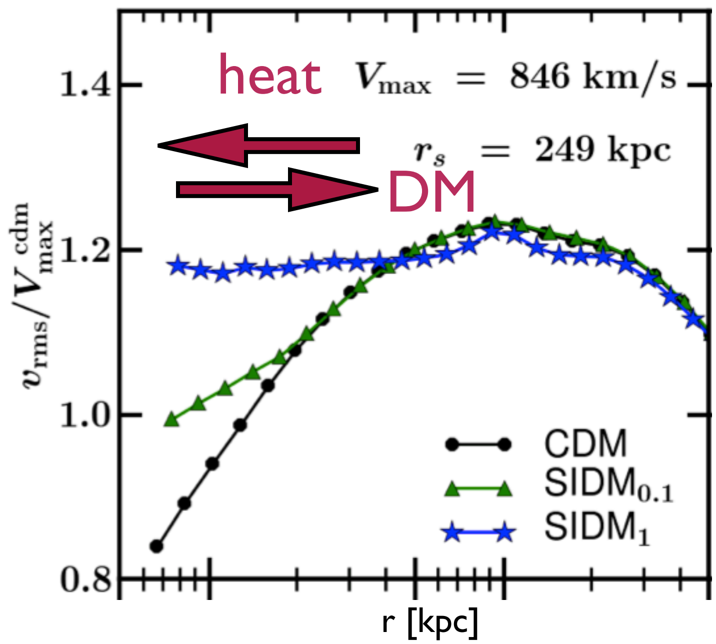
Brightest observed satellites in the MW

- Most massive subhalos in collisionless CDM simulations are too dense to host observed galaxies in the Milky Way
- On the other hand, it is easier for stars to form in massive subhalos

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

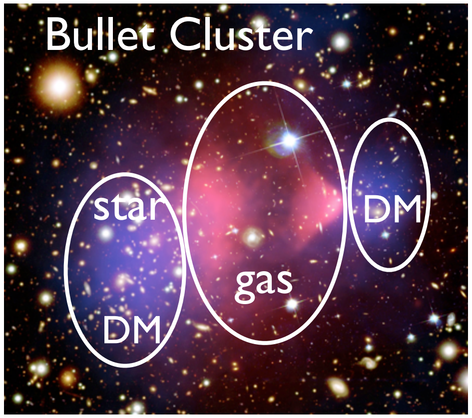
Astrophysics Summary

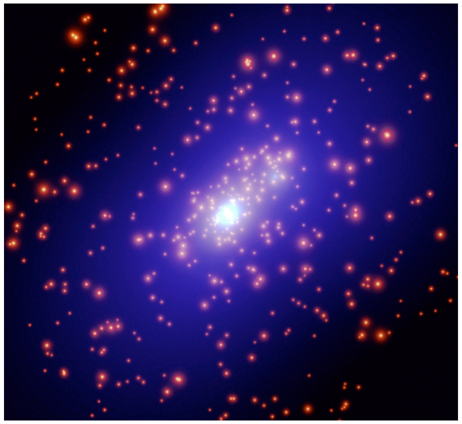
- Evidence for DM self-interactions on dwarf galaxy scales

$\sigma/m_X \sim 0.1\text{–}\ 10\ \mathrm{cm^2/g}$ 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 (?)





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

Peter, Rocha, Bullock, Kaplinghat (2012)

NOT $\sigma/m_X < 0.02\ \mathrm{cm^2/g}$ Miralda-Escude (2000)

Challenges

- A really large scattering cross section!

a nuclear-scale cross section

$\sigma \sim 1\,\mathrm{cm}^2\,(m_X/\mathrm{g}) \sim 2\times 10^{-24}\,\mathrm{cm}^2\,(m_X/\mathrm{GeV})$

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?

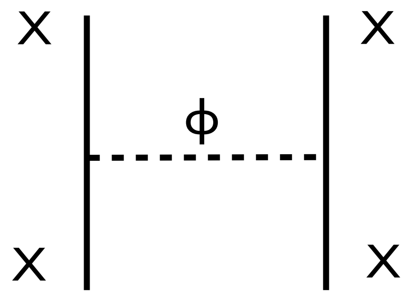
$\sigma/m_X < 1\,\mathrm{cm}^2/\mathrm{g}$ for 3000 km/s (cluster)

In particular, if σ~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

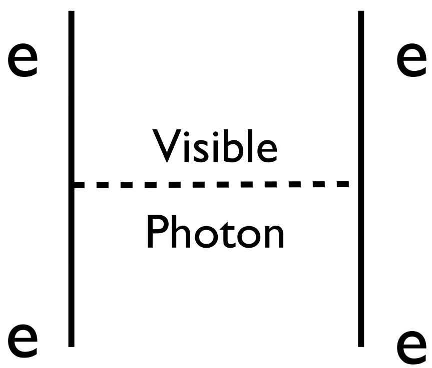


- SIDM indicates light mediators

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

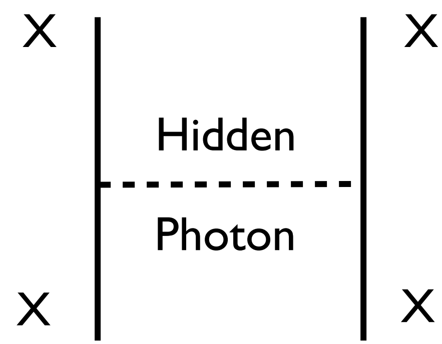
in the perturbative and small velocity limit

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



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

$m_X v >> m_\phi$

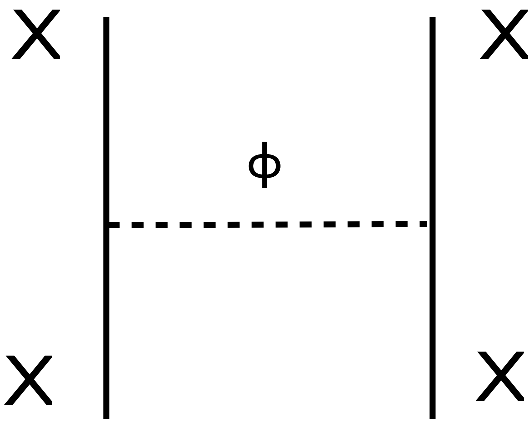


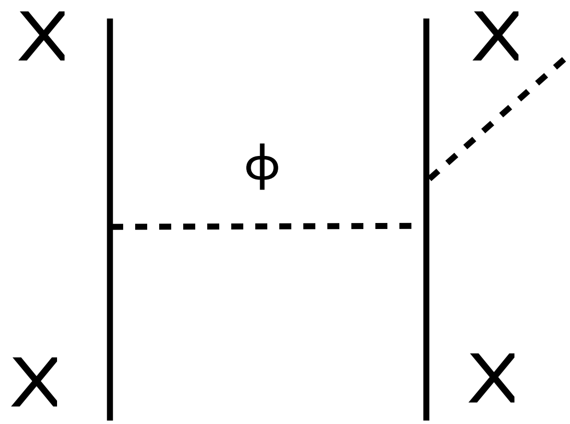
- DM is self-scattering on small scales (v~10-30 km/s)
- DM is collisionless on large scales (v~3000 km/s), specially for heavy SIDM

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

Not Dissipative

- SIDM is not dissipative

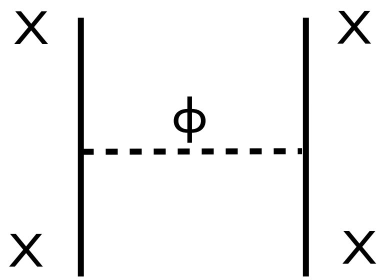




$\Gamma = n\sigma v \sim H_0$

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

A Simplified Model



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

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 ✓

$\alpha_X m_X / m_\phi \ll 1$

Feng, Kaplinghat, HBY (2009)

Lin, HBY, Zurek (2011)

Nonperturbative regime

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

Classical regime

$m_X v / m_\phi \gg 1$

Resonant regime

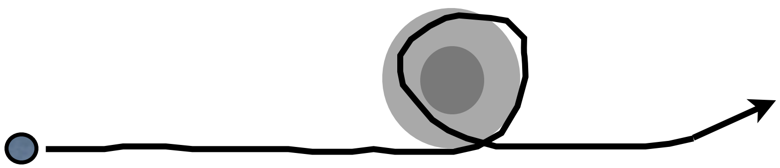
$m_X v / m_\phi \lesssim 1$

Exception: $m_\phi = 0$

Classical Regime

- Classical approximation from plasma physics

Khrapak et al. (2003) (2004)



Charged-particle scattering in plasma

$$\sigma_T^{\rm clas} \approx \begin{cases} \frac{4\pi}{m_\phi^2}\beta^2 \ln\left(1+\beta^{-1}\right) & \beta \lesssim 10^{-1} \\ \frac{8\pi}{m_\phi^2}\beta^2/\left(1+1.5\beta^{1.65}\right) & 10^{-1} \lesssim \beta \lesssim 10^3 \\ \frac{\pi}{m_\phi^2}\left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2 & \beta \gtrsim 10^3 \end{cases}$$

$$\pm\frac{\alpha_X}{r}e^{-m_\phi r} \qquad \alpha_X = \alpha_{\rm EM}$$

$$\beta \equiv 2\alpha_X m_\phi/(m_X v^2)$$

$$m_\phi = \text{Debye photon mass}$$

$\sigma_T \sim v^{-4}$ at large v

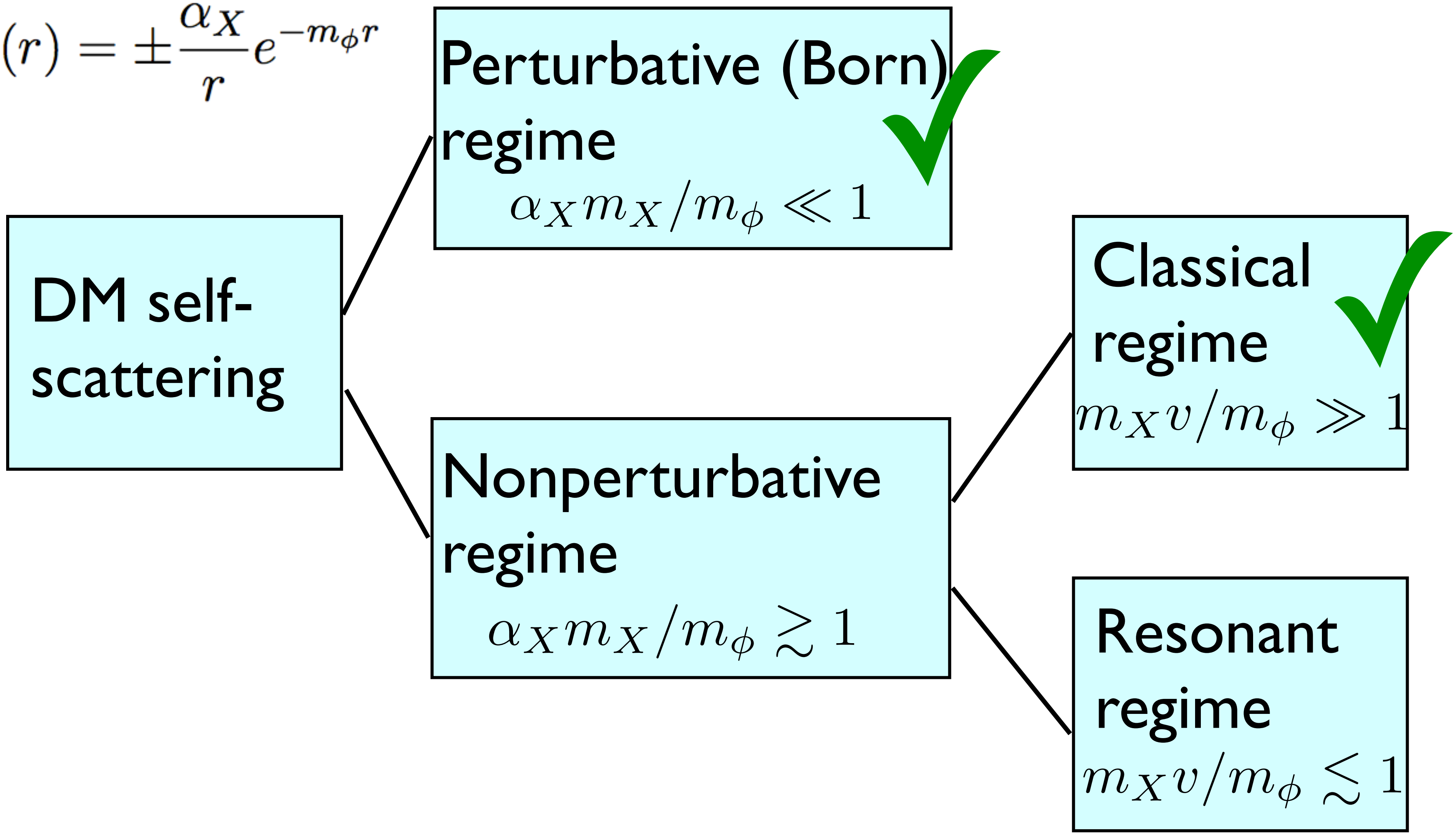
$\sigma_T \sim$const at small v (saturated)

Apply to DM: σ_T is enhanced on dwarf scales compared to larger scales

Feng, Kaplinghat, HBY (2009); Loeb, Weiner (2010); Vogelsberger, Loeb, Zavala (2012)...

Beyond Perturbation

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



Numerical Approach

- Quantum mechanics 101-partial wave analysis

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{dR_\ell}{dr}\right)+\left(k^2-\frac{\ell(\ell+1)}{r^2}-2\mu V(r)\right)R_\ell=0$$

- Transfer cross section

$$\frac{d\sigma}{d\Omega}=\frac{1}{k^2}\left|\sum_{\ell=0}^{\infty}(2\ell+1)e^{i\delta_\ell}P_\ell(\cos\theta)\sin\delta_\ell\right|^2 \qquad \sigma_T = \int d\Omega\,(1-\cos\theta)\,\frac{d\sigma}{d\Omega}$$

$$\frac{\sigma_T k^2}{4\pi}=\sum_{\ell=0}^{\infty}\left[(2\ell+1)\sin^2\delta_\ell-2(\ell+1)\sin\delta_\ell\sin\delta_{\ell+1}\cos(\delta_{\ell+1}-\delta_\ell)\right]$$

Rearrange ell→ell+1

$$\frac{\sigma_T k^2}{4\pi}=\sum_{\ell=0}^{\infty}(\ell+1)\sin^2(\delta_{\ell+1}-\delta_\ell)$$

✓

Tulin, HBY, Zurek (2012)(2013)

Both formulas are identical in the limit of ell→∞

But the second one converges much faster

Numerical Approach

- Partial wave analysis

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{dR_\ell}{dr}\right)+\left(k^2-\frac{\ell(\ell+1)}{r^2}-2\mu V(r)\right)R_\ell=0$$

- Boundary conditions $r\to\infty$

$$R_\ell(r)\to\sin(kr-\pi\ell/2+\delta_\ell)/r$$

$$R_\ell(r)\to\cos\delta_\ell j_\ell(kr)-\sin\delta_\ell n_\ell(kr)$$ ✓

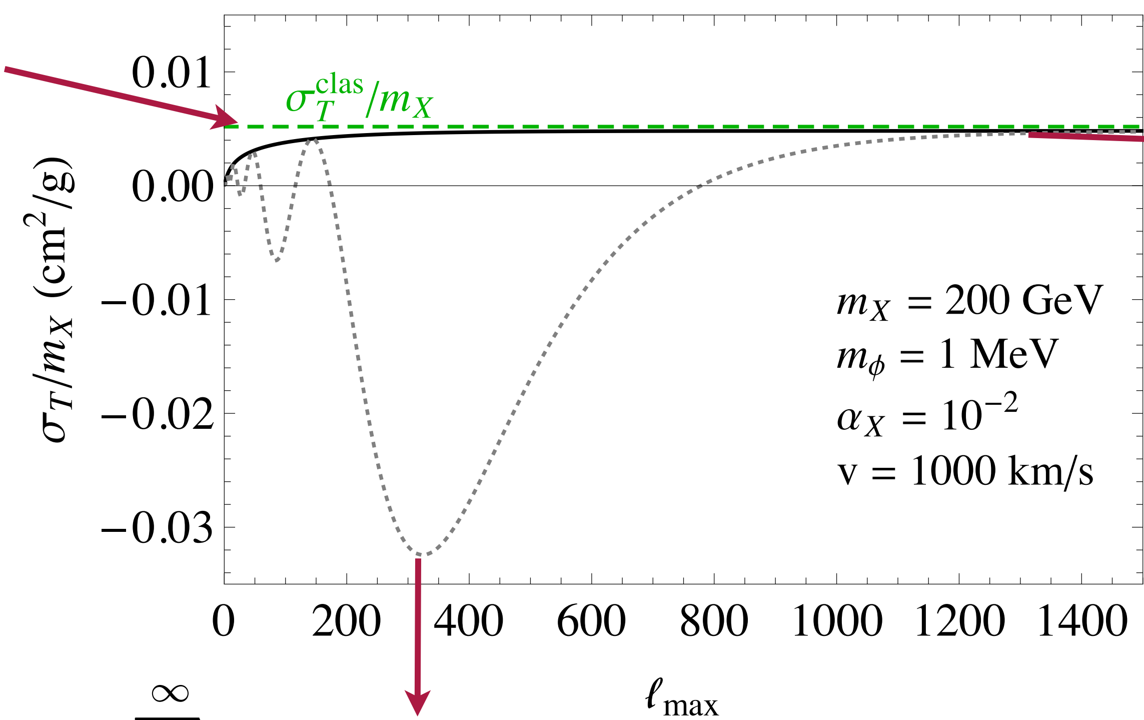
The second one is much more efficient

Numerical Approach

- Classical regime

Tulin, HBY, Zurek (2013)

Plasma



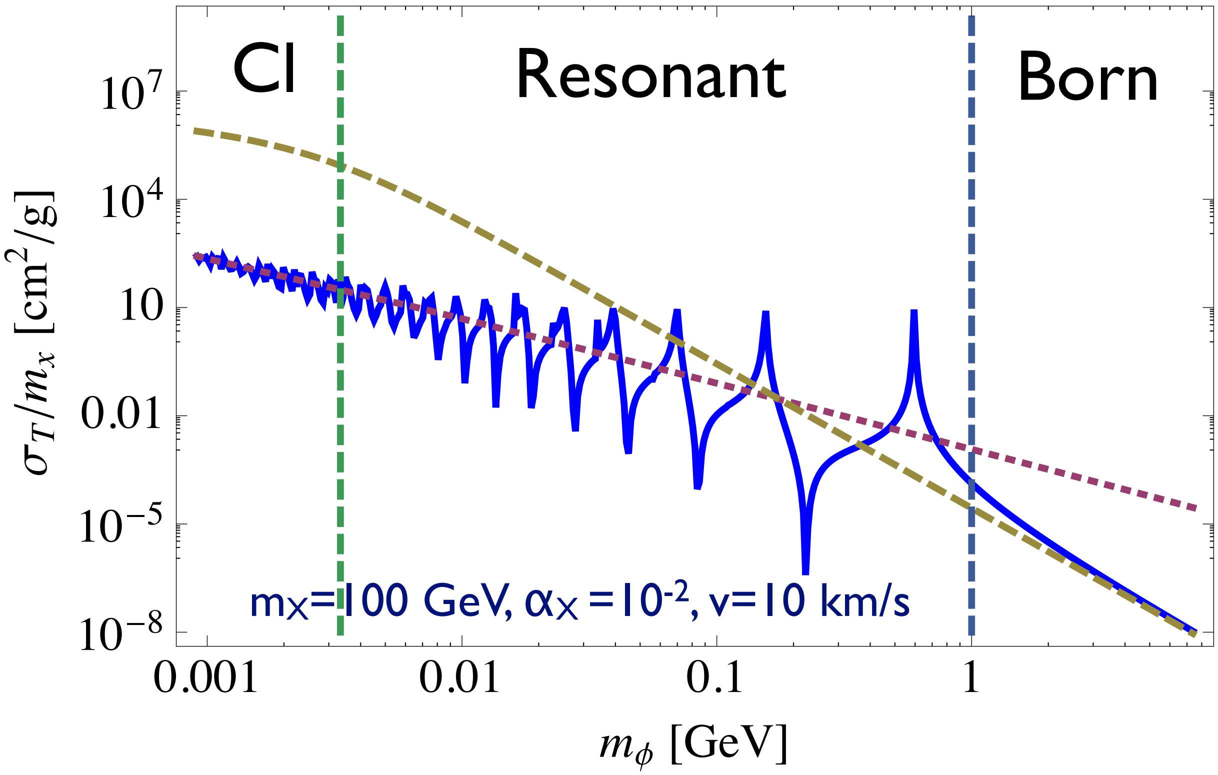
$$\sum_{\ell=0}^{\infty}(\ell+1)\sin^2(\delta_{\ell+1}-\delta_\ell)$$

$$\sum_{\ell=0}^{\infty}[(2\ell+1)\sin^2\delta_\ell - 2(\ell+1)\sin\delta_\ell\sin\delta_{\ell+1}\cos(\delta_{\ell+1}-\delta_\ell)]$$

We have confirmed the analytical formula from plasma physics

Numerical Approach

- All regimes



Solid: numerical; Dashed: Born; Dotted: plasma

In the resonant regime, the cross section can be enhanced or suppressed

Analytical Approach

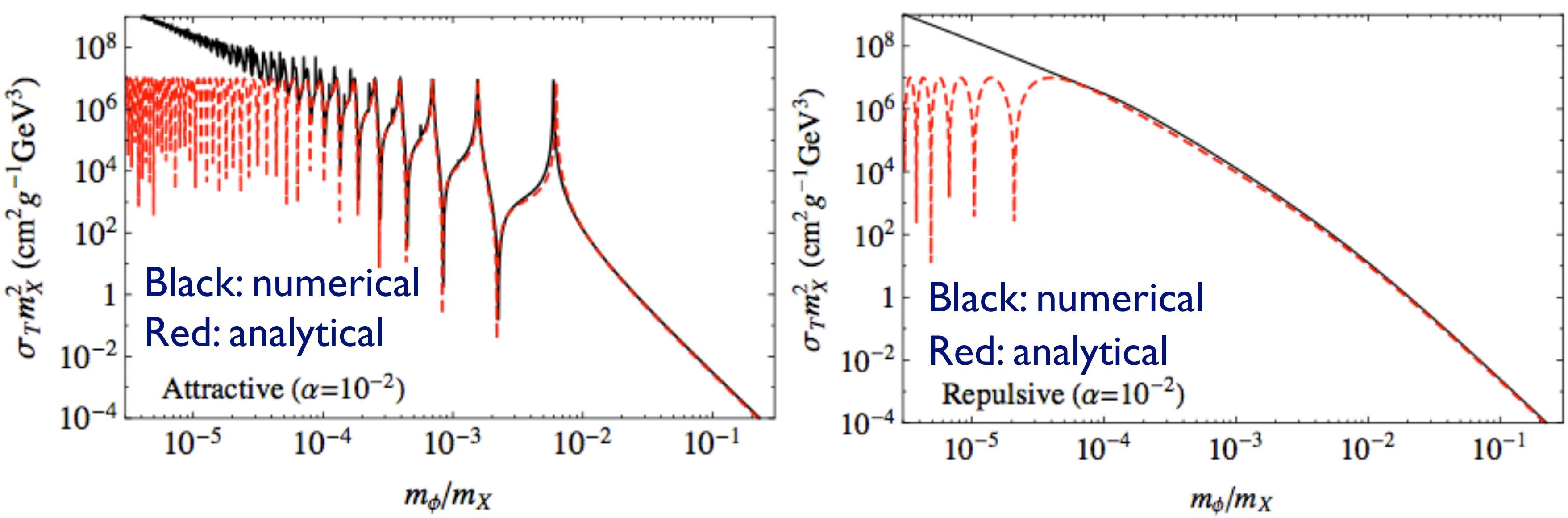
$$V(r) = \pm \frac{\alpha_X}{r} e^{-m_\phi r} \longrightarrow V(r) = \pm \frac{\alpha_X \delta\, e^{-\delta r}}{1 - e^{-\delta r}}$$

Hulthén potential

$$\delta = \kappa m_\phi \qquad \kappa \simeq 1.6$$

The Schrödinger equation is solvable analytically for ell=0

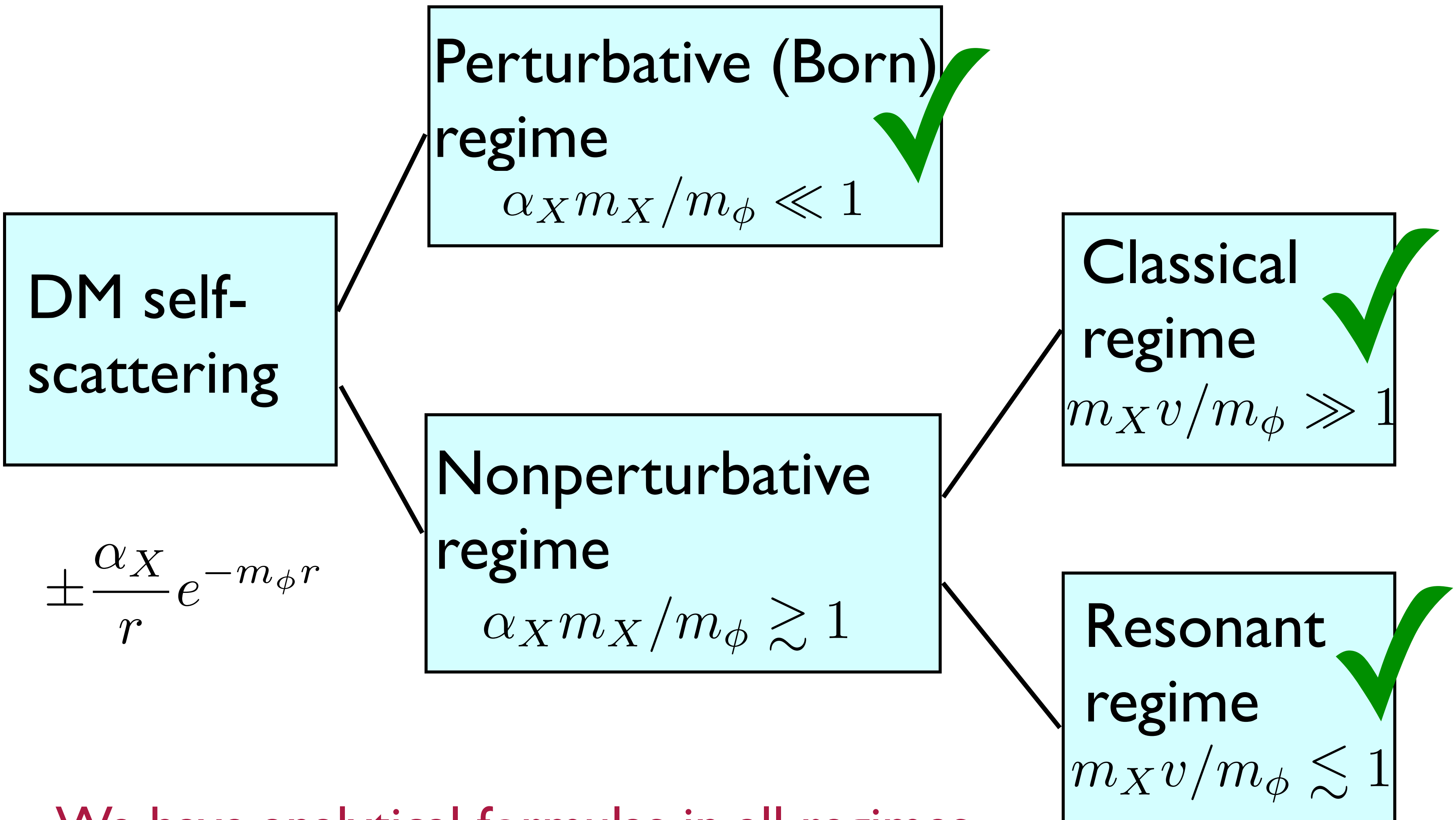
$$\sigma_T^{\text{Hulthén}} = \frac{16\pi}{m_X^2 v^2} \sin^2 \delta_0 \qquad \delta_0 = \arg\left(\frac{i\,\Gamma\left(\frac{i m_X v}{\kappa m_\phi}\right)}{\Gamma(\lambda_+)\Gamma(\lambda_-)} \right), \quad \lambda_\pm \equiv \begin{cases} 1 + \frac{i m_X v}{2\kappa m_\phi} \pm \sqrt{\frac{\alpha_X m_X}{\kappa m_\phi} - \frac{m_X^2 v^2}{4\kappa^2 m_\phi^2}} & \text{attractive} \\ 1 + \frac{i m_X v}{2\kappa m_\phi} \pm i\sqrt{\frac{\alpha_X m_X}{\kappa m_\phi} + \frac{m_X^2 v^2}{4\kappa^2 m_\phi^2}} & \text{repulsive} \end{cases}$$



It is useful for simulations

Tulin, HBY, Zurek (2013)

Beyond Perturbation

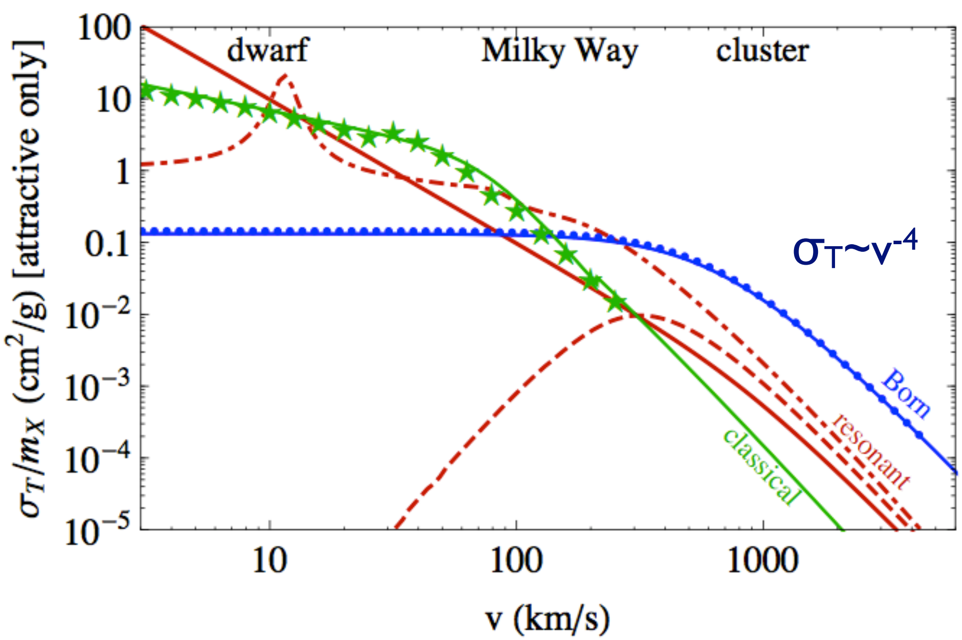


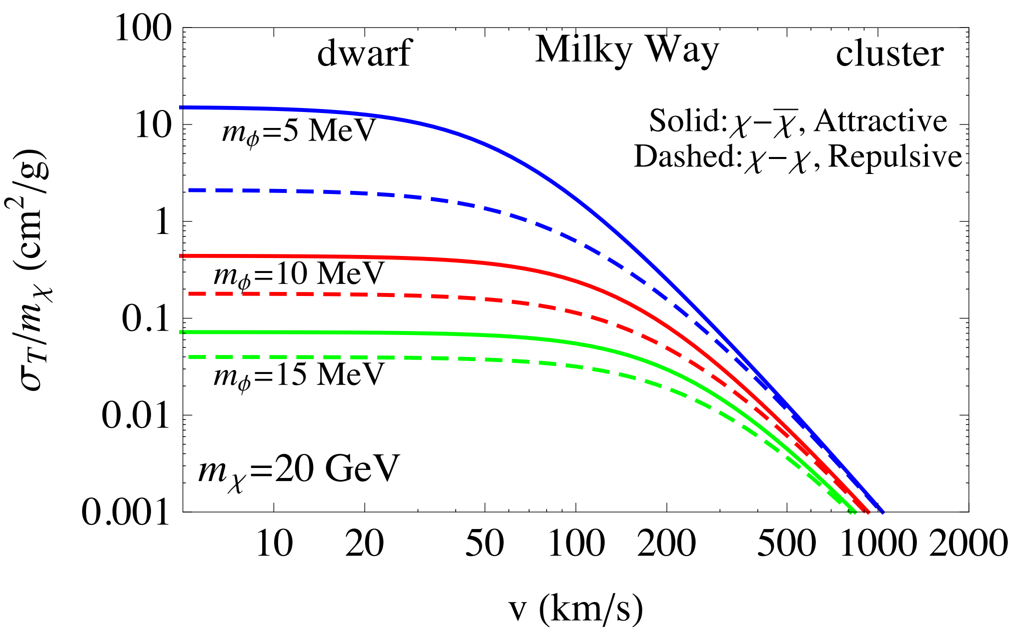
We have analytical formulas in all regimes

Velocity Dependence

- σ_T has rich structure

Tulin, HBY, Zurek (2011) (2012)

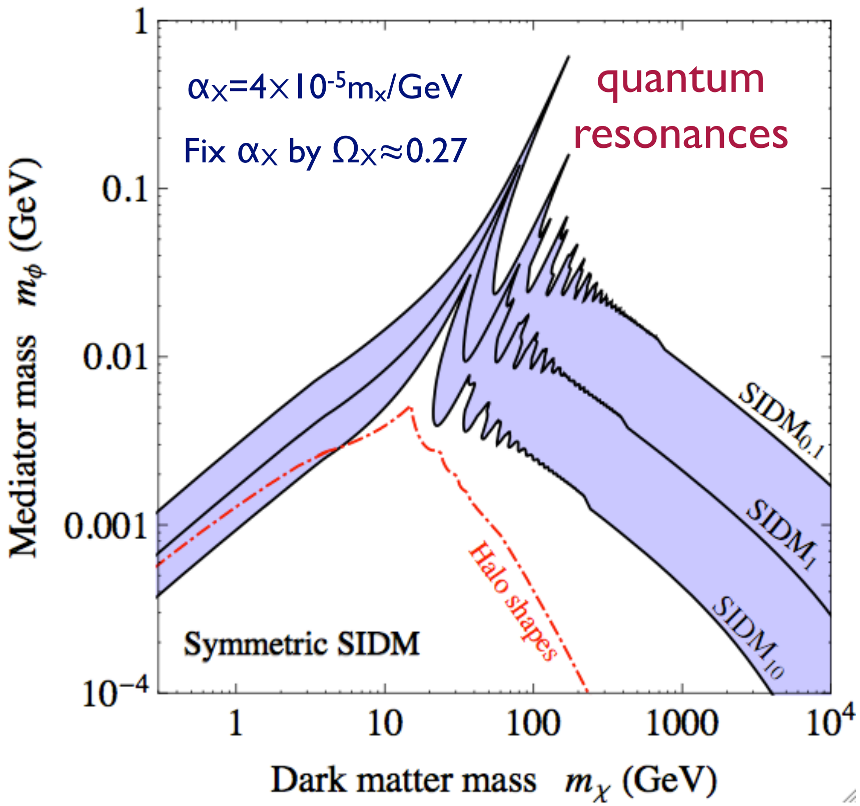


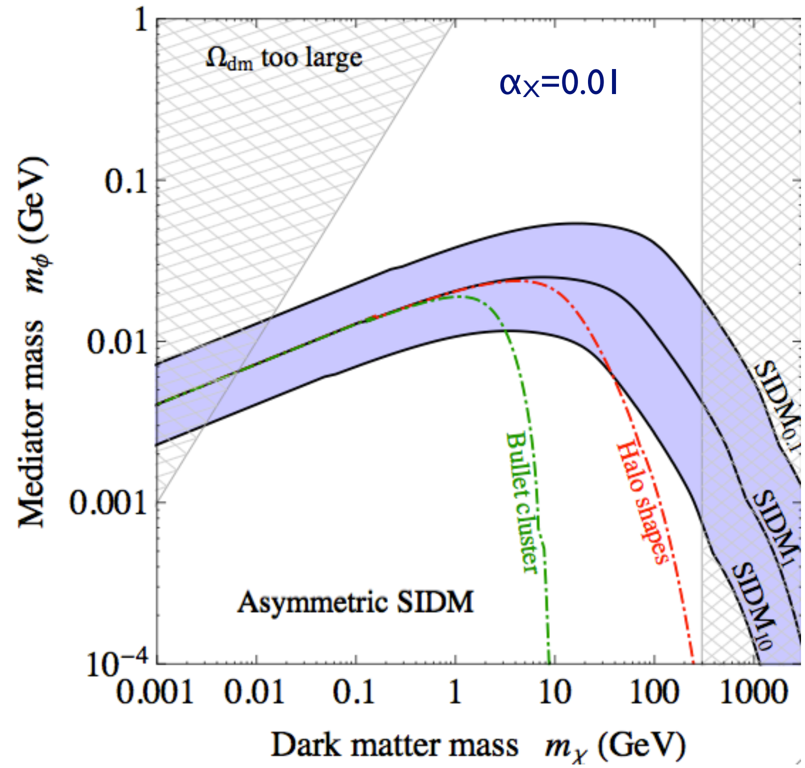


- In many cases, σ_T is enhanced on dwarf scales
- This helps us avoid constraints on cluster scales

SIDM Parameter Space

- Shaded region: Explain small scale anomalies





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

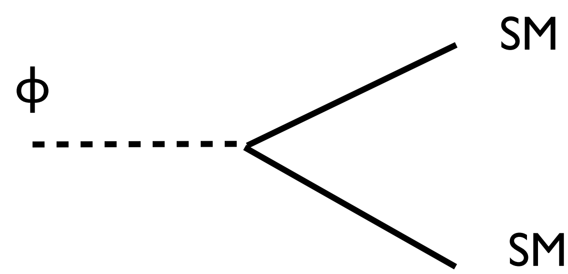
- SIDM predicts a 1-100 MeV light force carrier
- Bullet Cluster constraints are not sensitive to heavy SIDM

$m_X v >> m_\phi$

Cosmology of SIDM

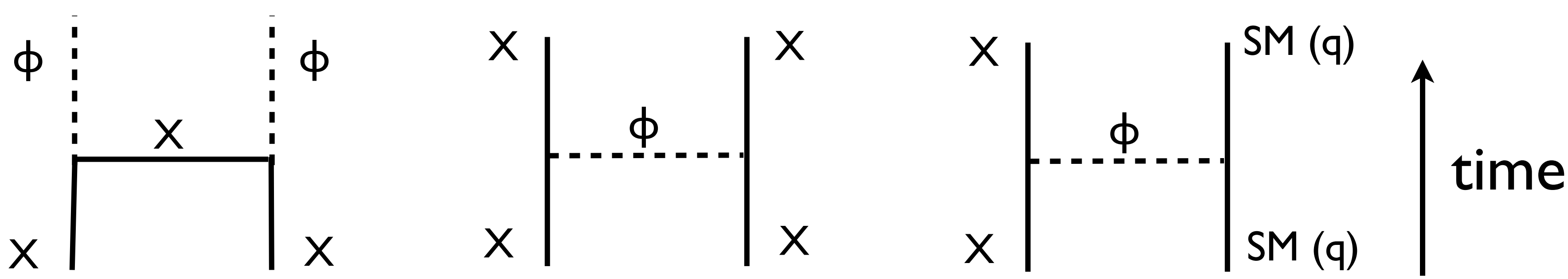
- The mediator may dominate the energy density of the Universe
- The mediator decays before BBN: lifetime of ϕ is ~1 second

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



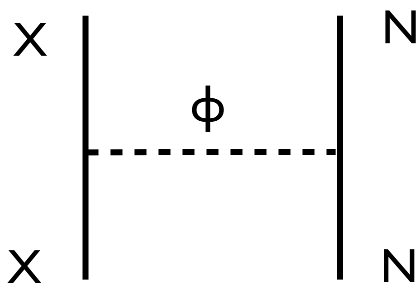
DD cross section:
- suppressed by the tiny coupling
- enhanced by the small mediator mass

A super model!



DM relic density   DM self-scattering   DM direct detection

Direct Detection of SIDM



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

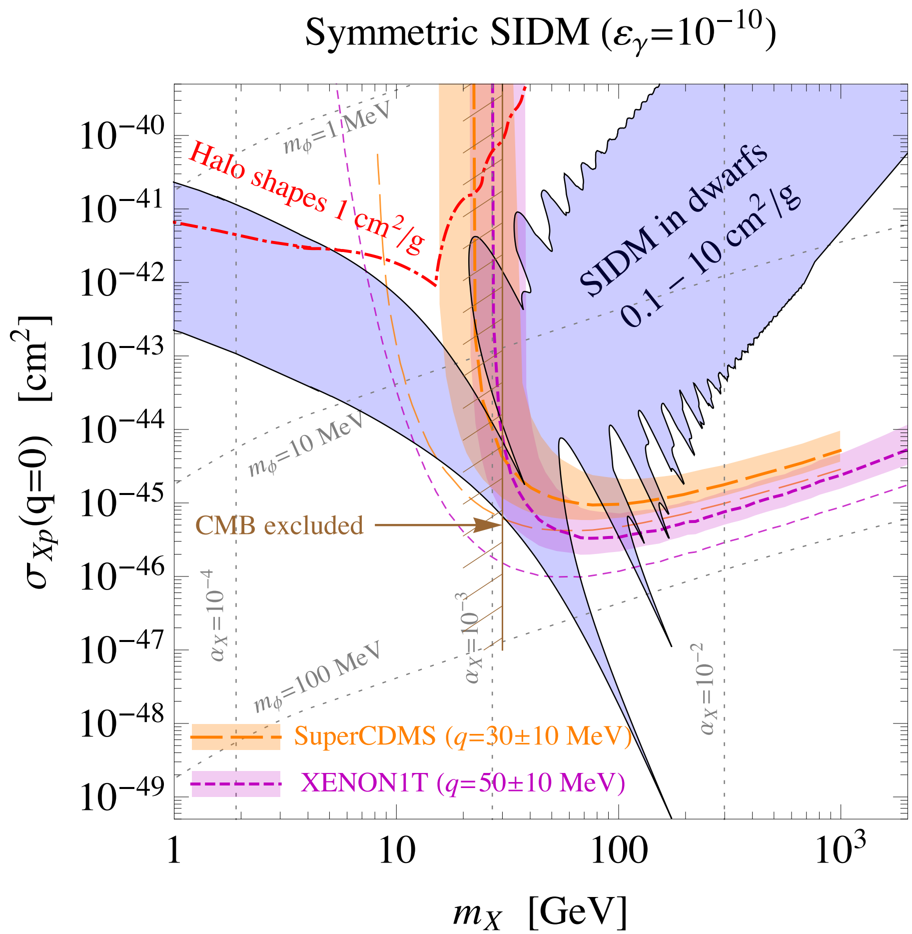
$$q^2 = 2m_N E_R$$

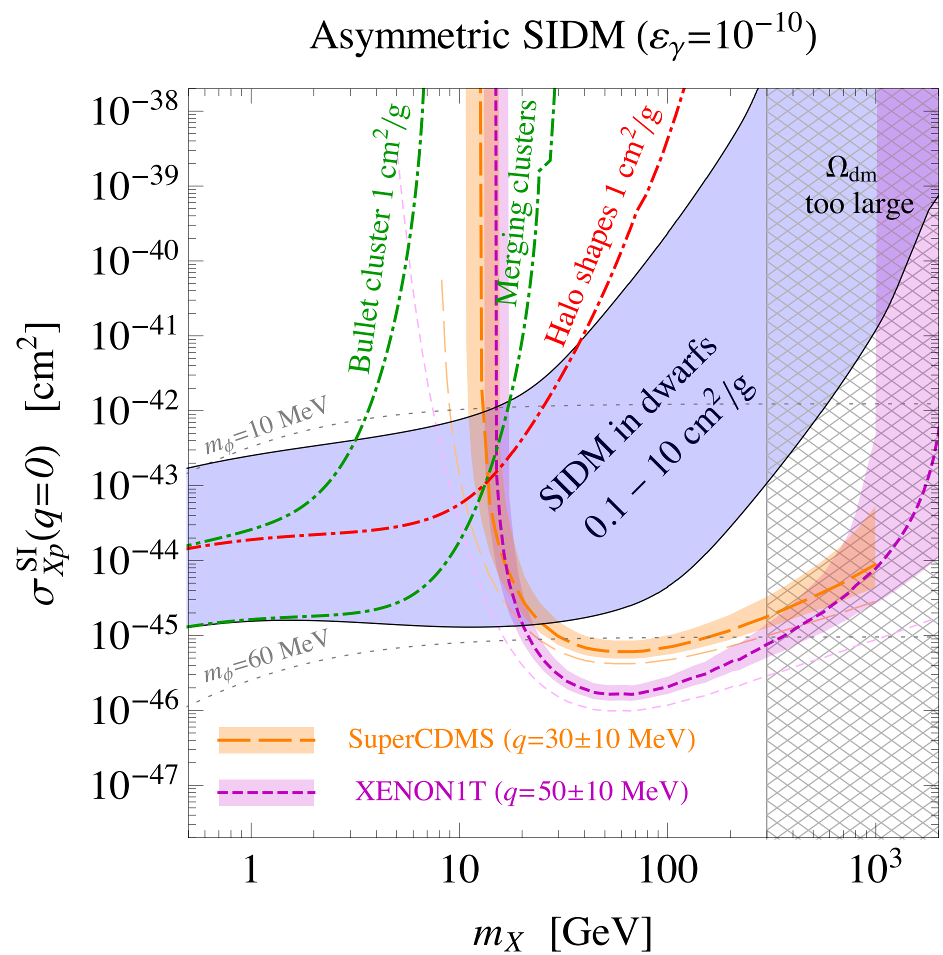
For XENON: q~50 MeV

- In the WIMP case, $m_\phi >> q$
- For SIDM, $m_\phi \sim 1\text{-}100$ 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





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

cross section in the zero momentum limit

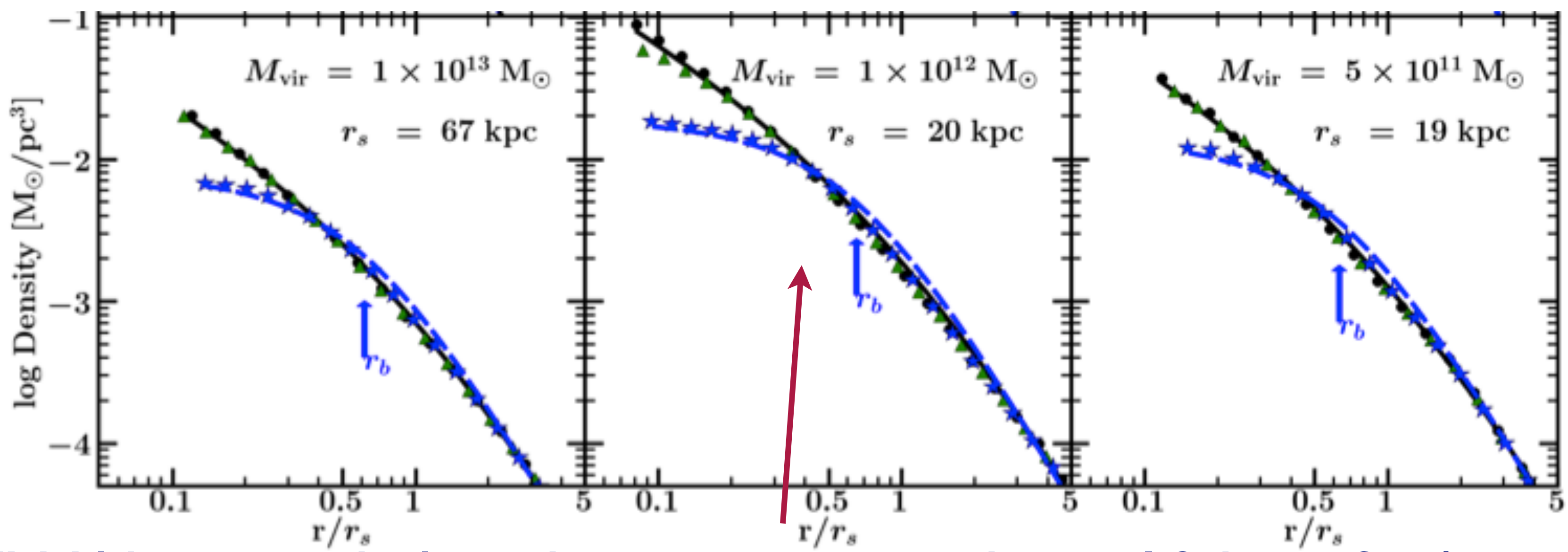
Kaplinghat, Tulin, HBY (2013)

Complementarity!

SIDM Profiles in Main Halos

- SIDM-only simulations

Rocha, Peter, Bullock, Kaplinghat, Garrison-Kimmel, Onorbe, Moustakas (2012)

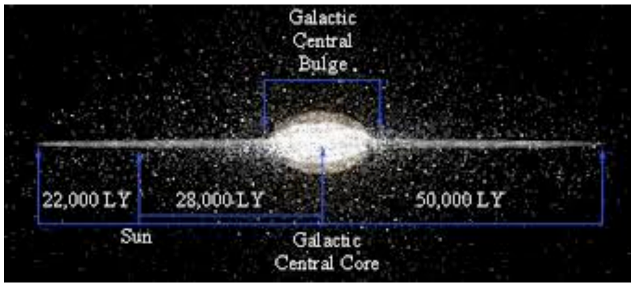


MW-like main halos: the core size is about 10 kpc if $\sigma/m_X \sim 1 cm^2/g$

Indirect detection signals would be very weak

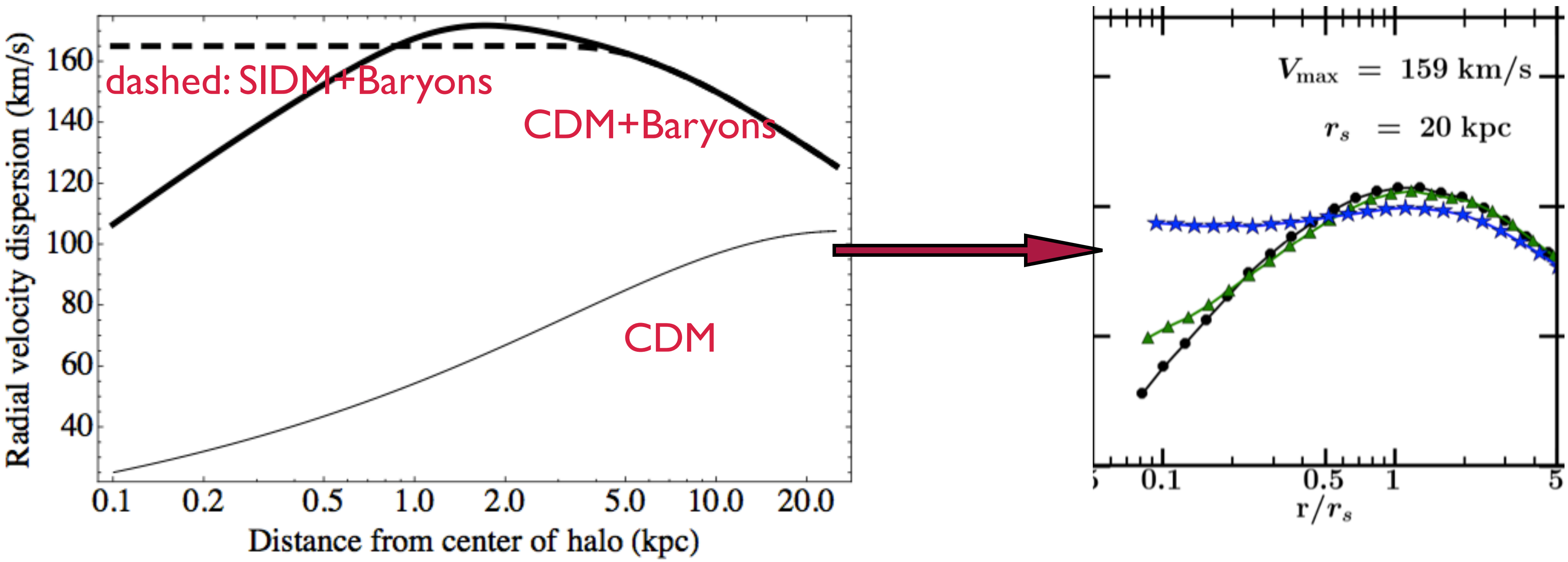
Tying Dark Matter to Baryons

- Baryons dominate in the central region of the Milky Way



Bulge: ~2 kpc

Kaplinghat, Linden, Keeley, HBY (2013)



Baryons dictate the DM temperature profile

SIDM Profiles with Baryons

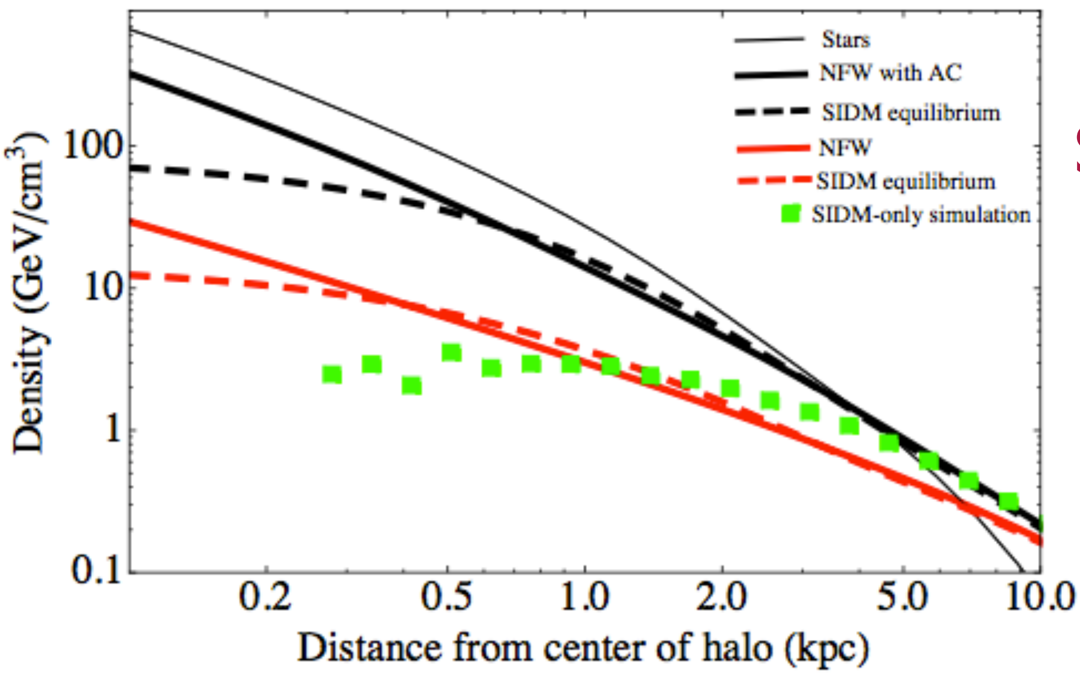
- Baryons dominate in the central region of the Milky Way

isothermal solution for the Jeans equation

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

vanishes

σ, ρ_0 are unknown



Kaplinghat, Linden, Keeley, HBY (2013)

SIDM and CDM have the same

total energy

total halo mass

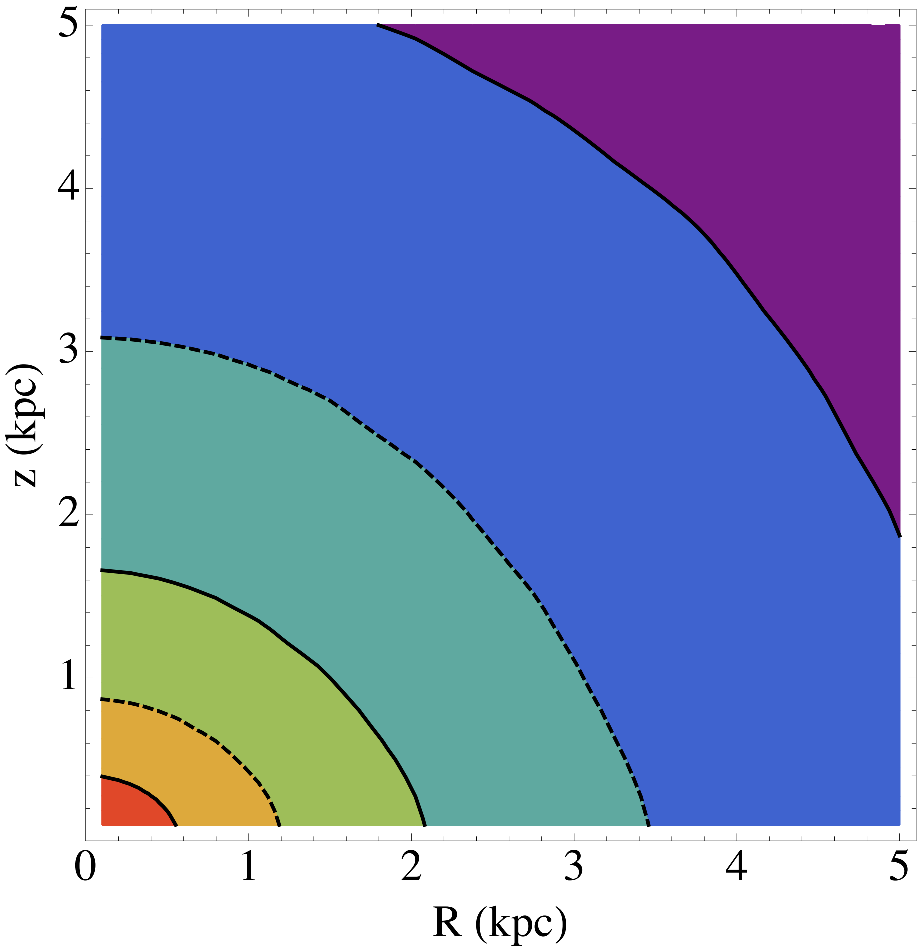
The core size for the MW halo:
SIDM+baryons: ~0.3-0.5 kpc
SIDM only: core size ~10 kpc

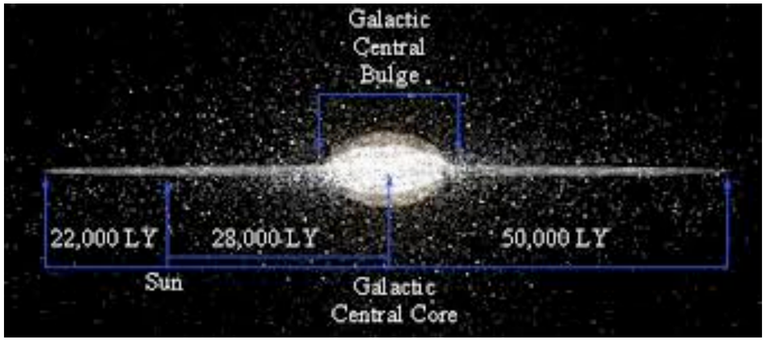
Important for indirect detection

Halo Shapes with Baryons

- SIDM halo shapes

Kaplinghat, Linden, Keeley, HBY (2013)



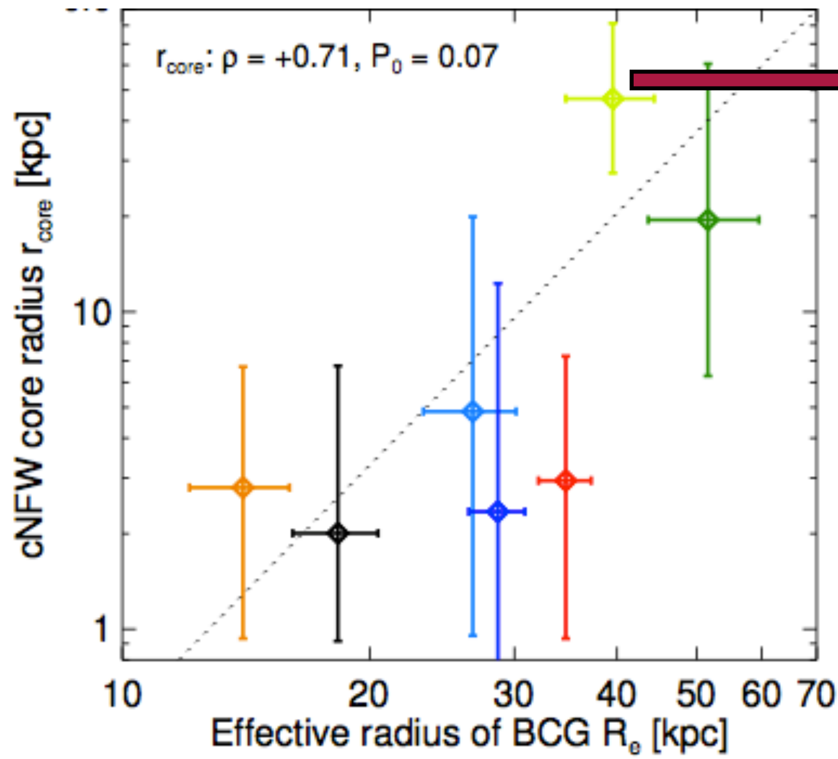


Rethink about halo shape constraints!

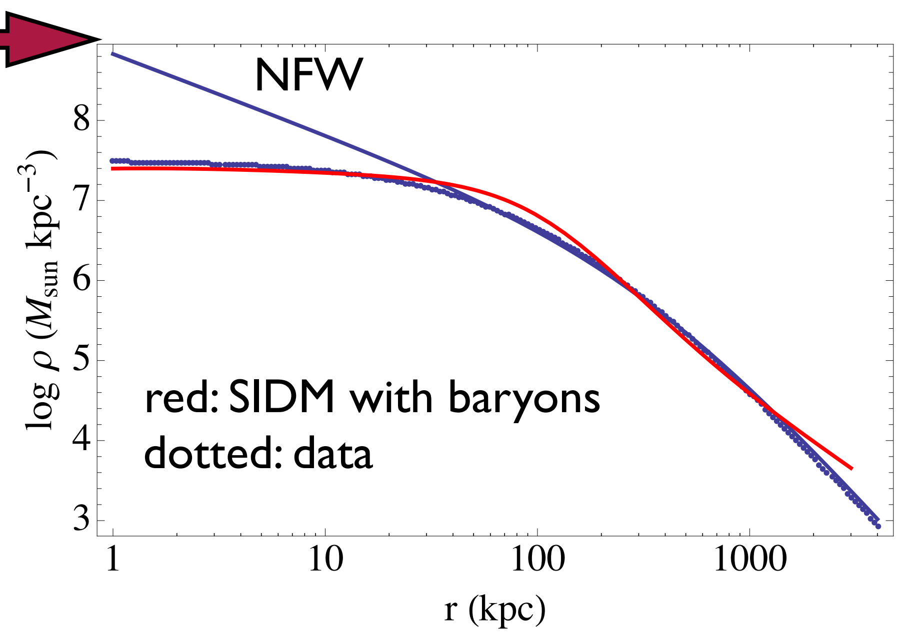
Constant density contours in cylindrical coordinates (R, z)

Tying Dark Matter to Baryons

- Cores in clusters



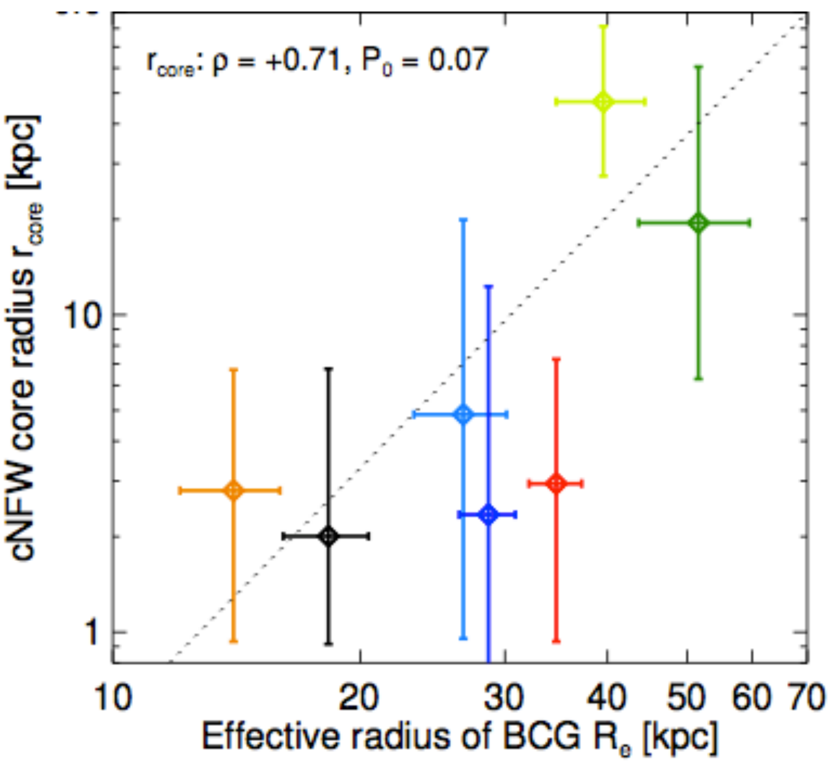
Newman, Treu, Ellis, Sand (2012)

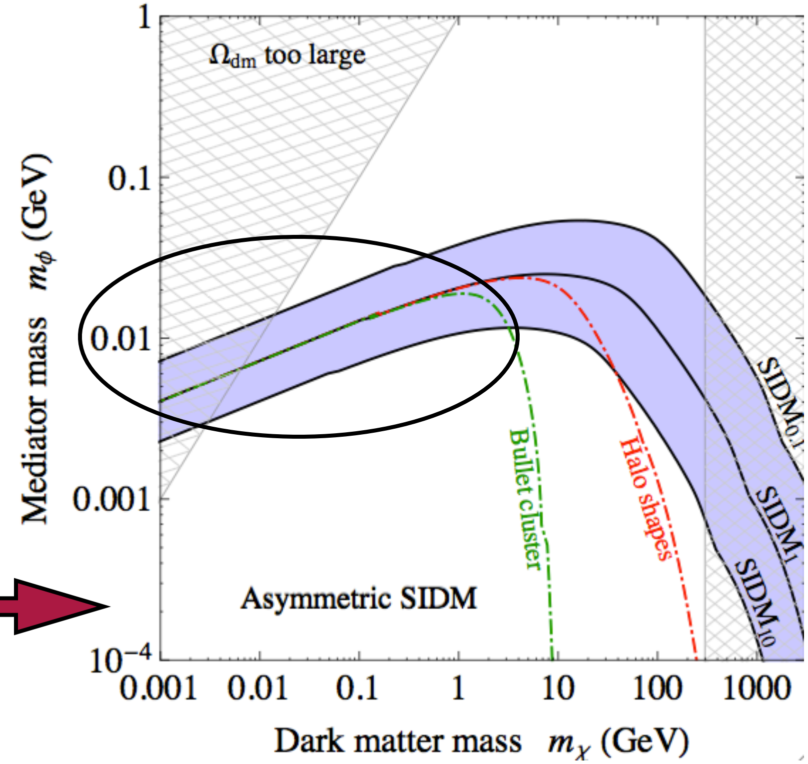


Kaplinghat, HBY (work in progress)

Tying Dark Matter to Baryons

- Cores in clusters





Newman, Treu, Ellis, Sand (2012)

Kaplinghat, HBY (work in progress)

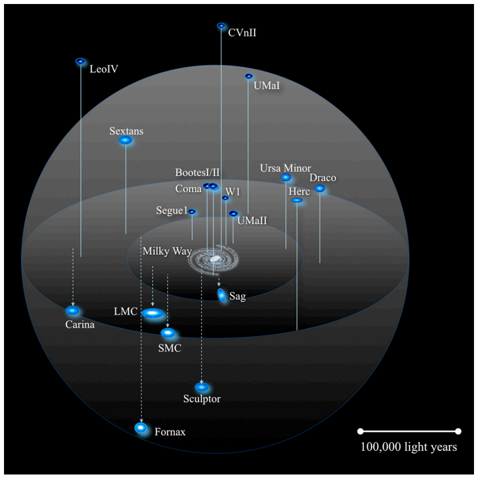
$m_\chi v < m_\phi$ with v~800 km/s

m_χ <10 MeV/(800 km/s/c)~4 GeV

Cores in clusters indicate light SIDM

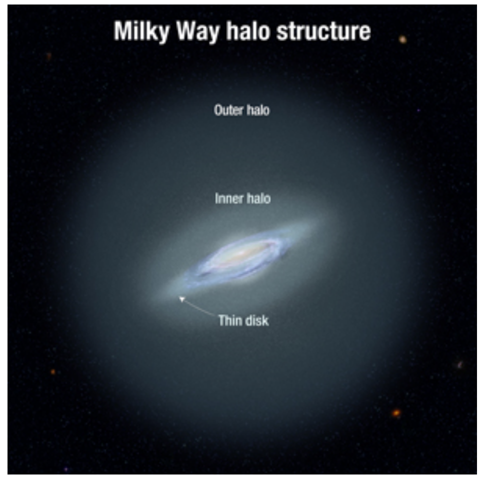
Dark Matter "Colliders"

Dwarf galaxies



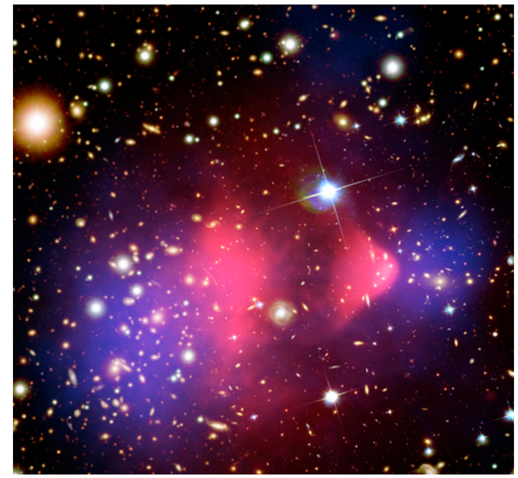
"B-factory"

MW-size galaxies

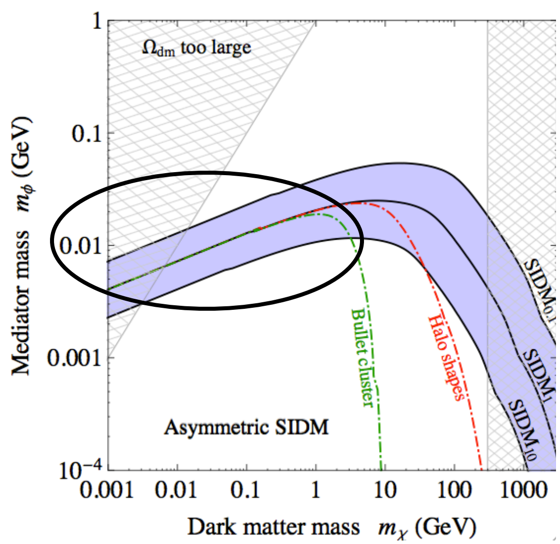


"LEP"

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

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