Self-interacting Dark Matter

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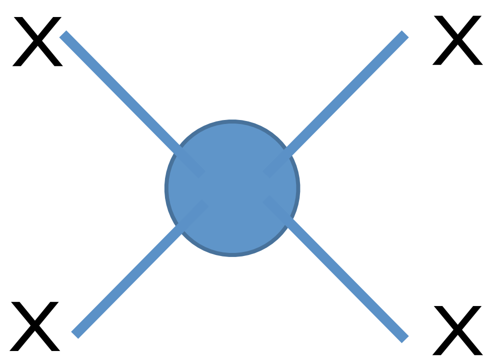
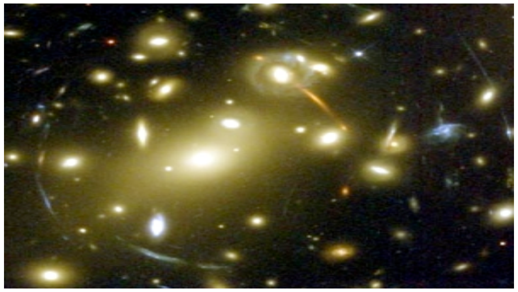
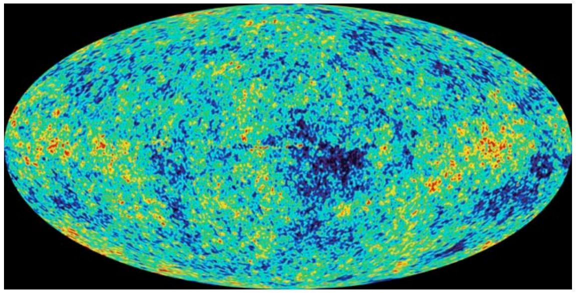


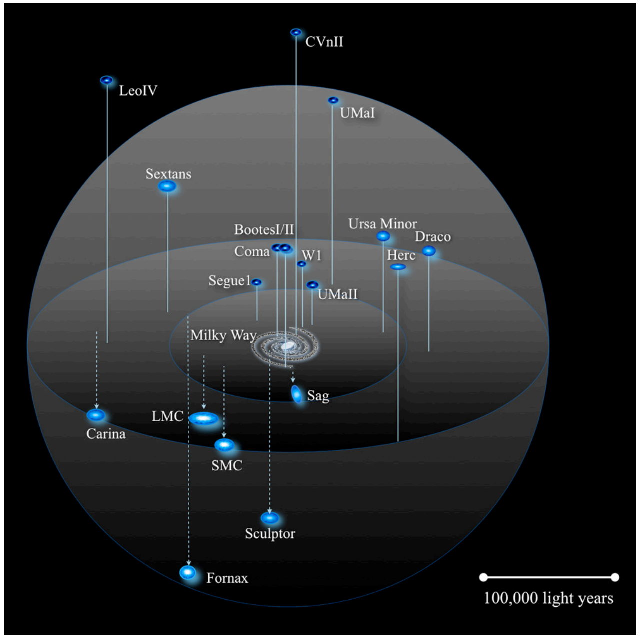
CosPA 12-15 November 2013, Honolulu, Hawai'i

Collisionless Cold Dark Matter

- Large scales: very well

- Small scales (dwarf galaxies, subhalos): ?



CDM vs. SIDM

- Small scales (dwarf galaxies, subhalos)?

cusp vs. core problem — See Manoj Kaplinghat`s talk

"too big to fail?" problem — Boylan-Kolchin, Bullock, Kaplinghat (2011)

- These anomalies can be solved if DM is sufficiently self-interacting

Recent simulation results

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

DM self-interactions lead to heat transfer and reduce central densities of DM halos

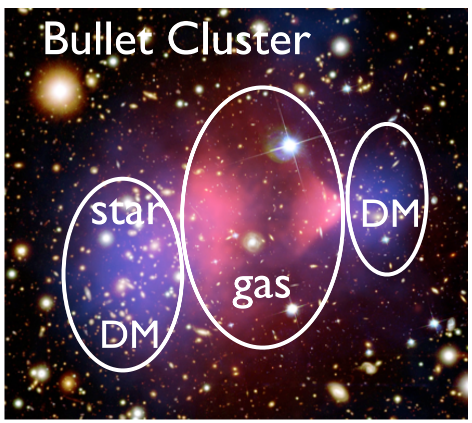
Astrophysics Summary

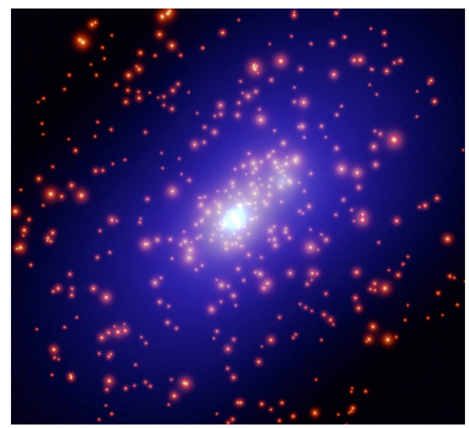
- Evidence for DM self-interactions on dwarf galaxy scales

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





$\sigma/m_X < 1\ cm^2/g$ for 3000 km/s (cluster), 300 km/s (NGC720)

Peter, Rocha, Bullock, Kaplinghat (2012)

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

Challenges

- A really large scattering cross section!

a nuclear-scale cross section

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

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

SIDM indicates a new mass scale

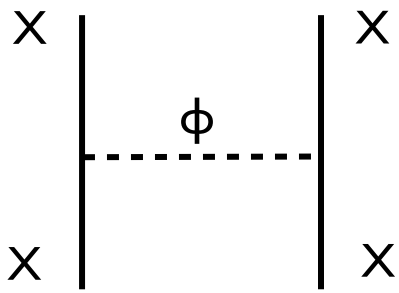
- How to avoid the constraints on large scales?

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

In particular, if $\sigma \sim$constant

Spergel, Steinhardt (1999)

Particle Physics of SIDM

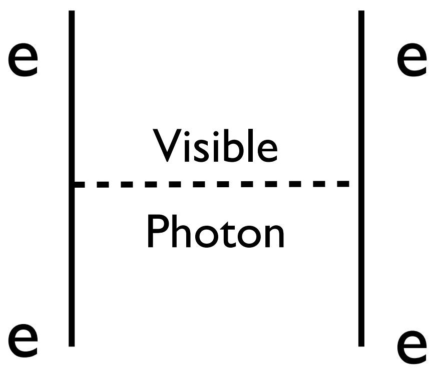


- SIDM indicates light mediators

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

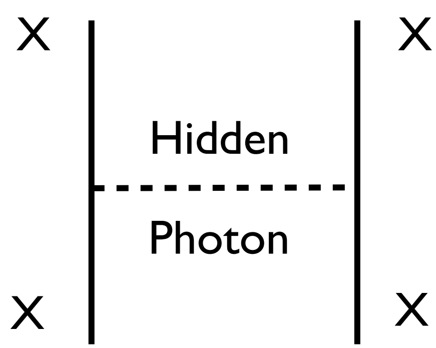
in the perturbative and small velocity limit

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



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

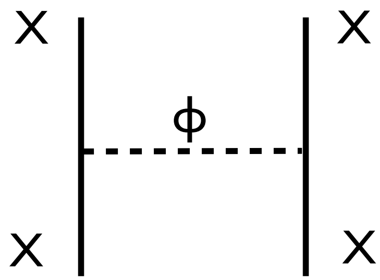
$m_X v >> m_\phi$



Feng, Kaplinghat, Tu, HBY (2009)
Feng, Kaplinghat, HBY (2009)
Buckley, Fox (2009)
Loeb, Weiner (2010)
Tulin, HBY, Zurek (2012)(2013)

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

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

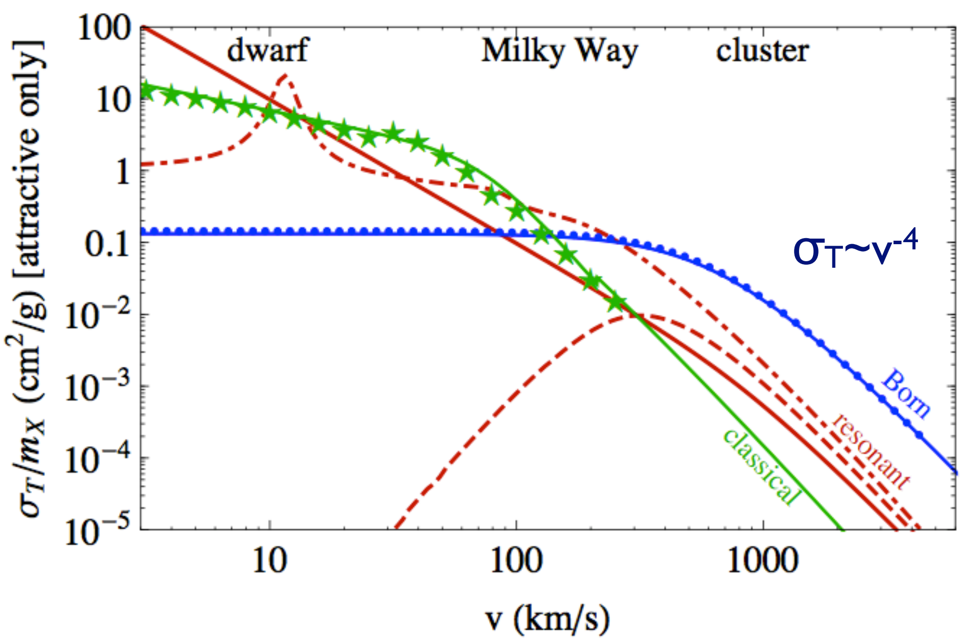
Map out the parameter space (m_X, m_ϕ, α_X)

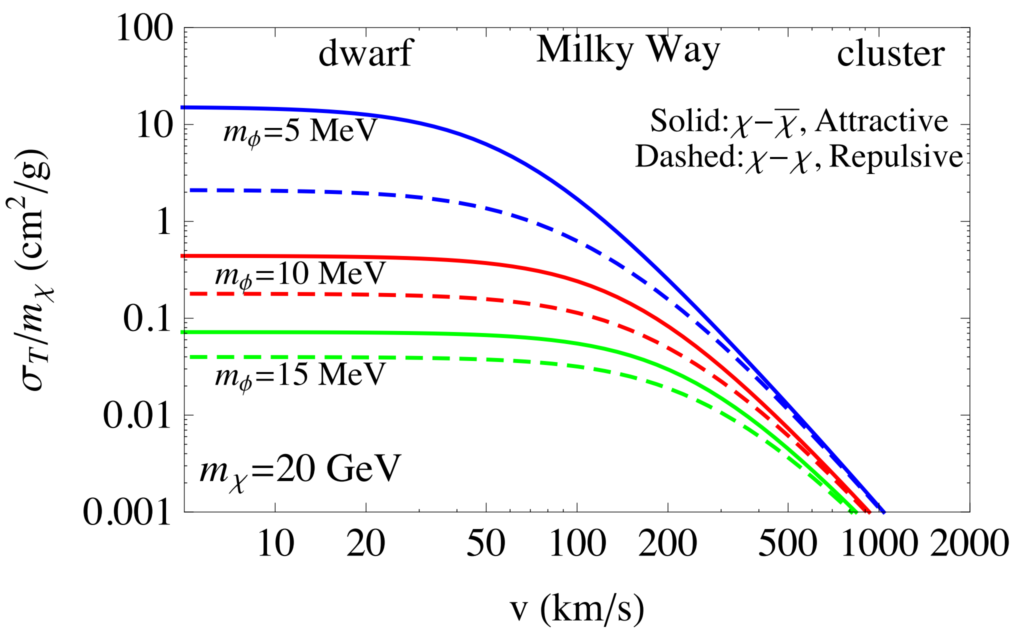
- Solve small scale anomalies (small v)
- Avoid constraints on large scales (large v)
- Get the relic density right

Velocity Dependence

- σ_T has a rich structure

Tulin, HBY, Zurek (2011) (2012)

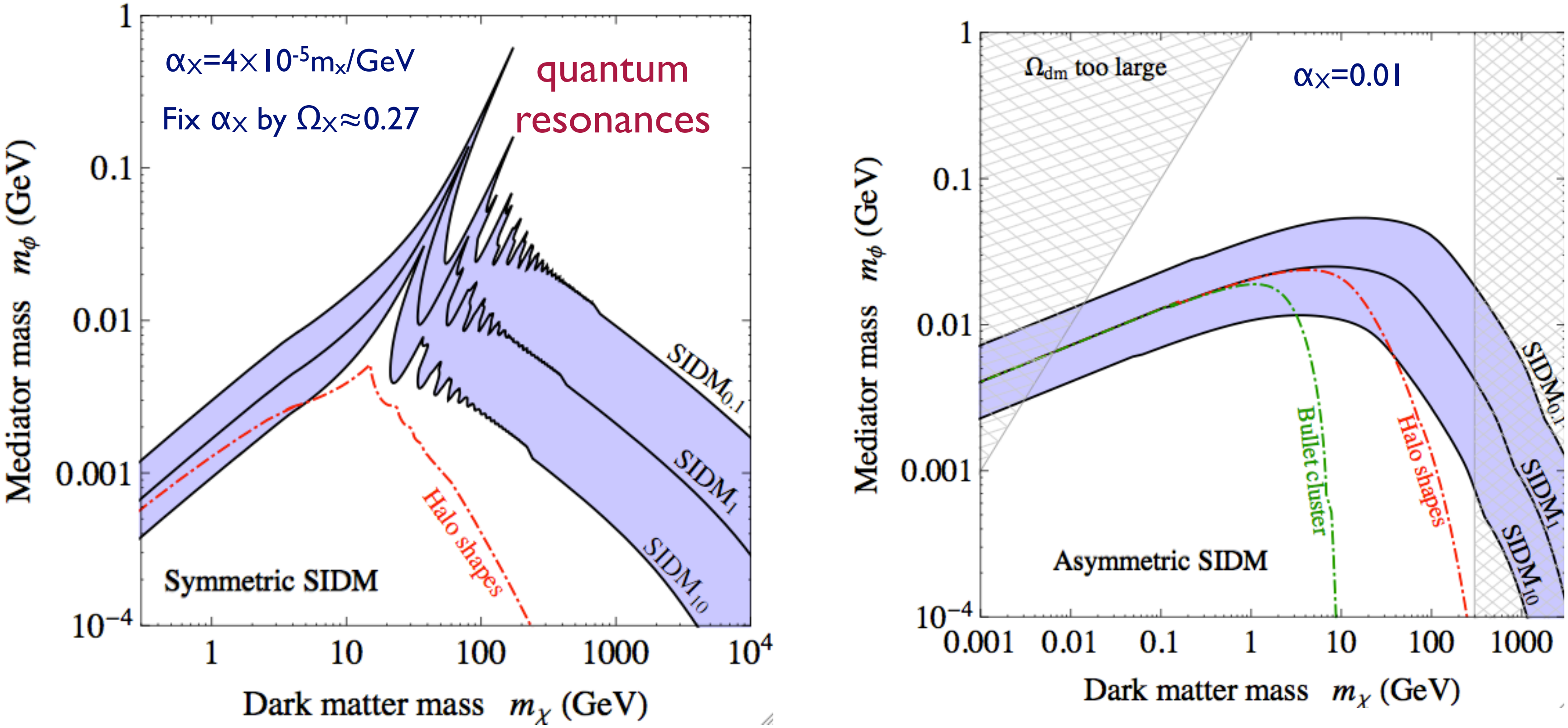




- In many cases, σ_T is enhanced on dwarf scales
- This helps us avoid constraints on cluster scales

SIDM Parameter Space

- Shaded region: Explain small scale anomalies



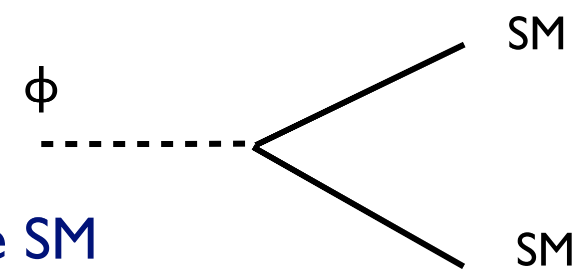
dw: dwarf (30 km/s); halo shapes: (300 km/s); cl: cluster (3000 km/s)

- SIDM predicts a 1-100 MeV light force carrier
- Light DM: σ~constant; heavy SIDM: a strong v-dependence
- Halo shape (?) and Bullet Cluster constraints are sensitive to light SIDM

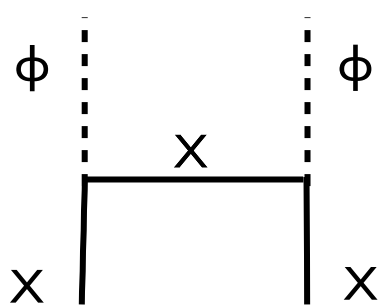
Cosmology of SIDM

- The mediator may dominate the energy density of the Universe
  - Decays to SM particles: BBN, entropy production
  - Decays to dark "neutrinos": CMB? Cyr-Racine, Putter, Raccanelli, Sigurdson (2013)

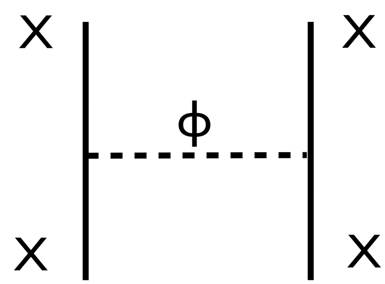
- The mediator decays before BBN
  - Maximal life for ϕ is ~1 second
  - Minimal coupling between the dark sector and the SM
  - A lower bound on direct detection cross section



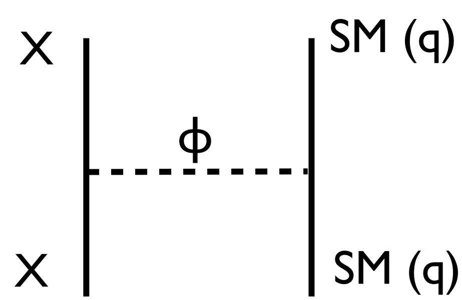
A super model!



DM relic density



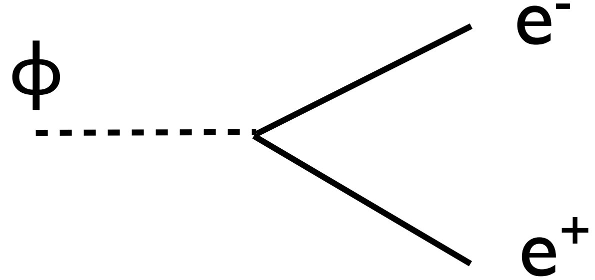
DM self-scattering



DM direct detection

Portals to the Dark Sector

- Vector mediator ϕ --------X---------- γ (Z)
- Focus on kinetic mixing case $\frac{\varepsilon_\gamma}{2}\phi_{\mu\nu}F^{\mu\nu}$ Holdom (1986)
- The mediator only decays to electron/positron pairs



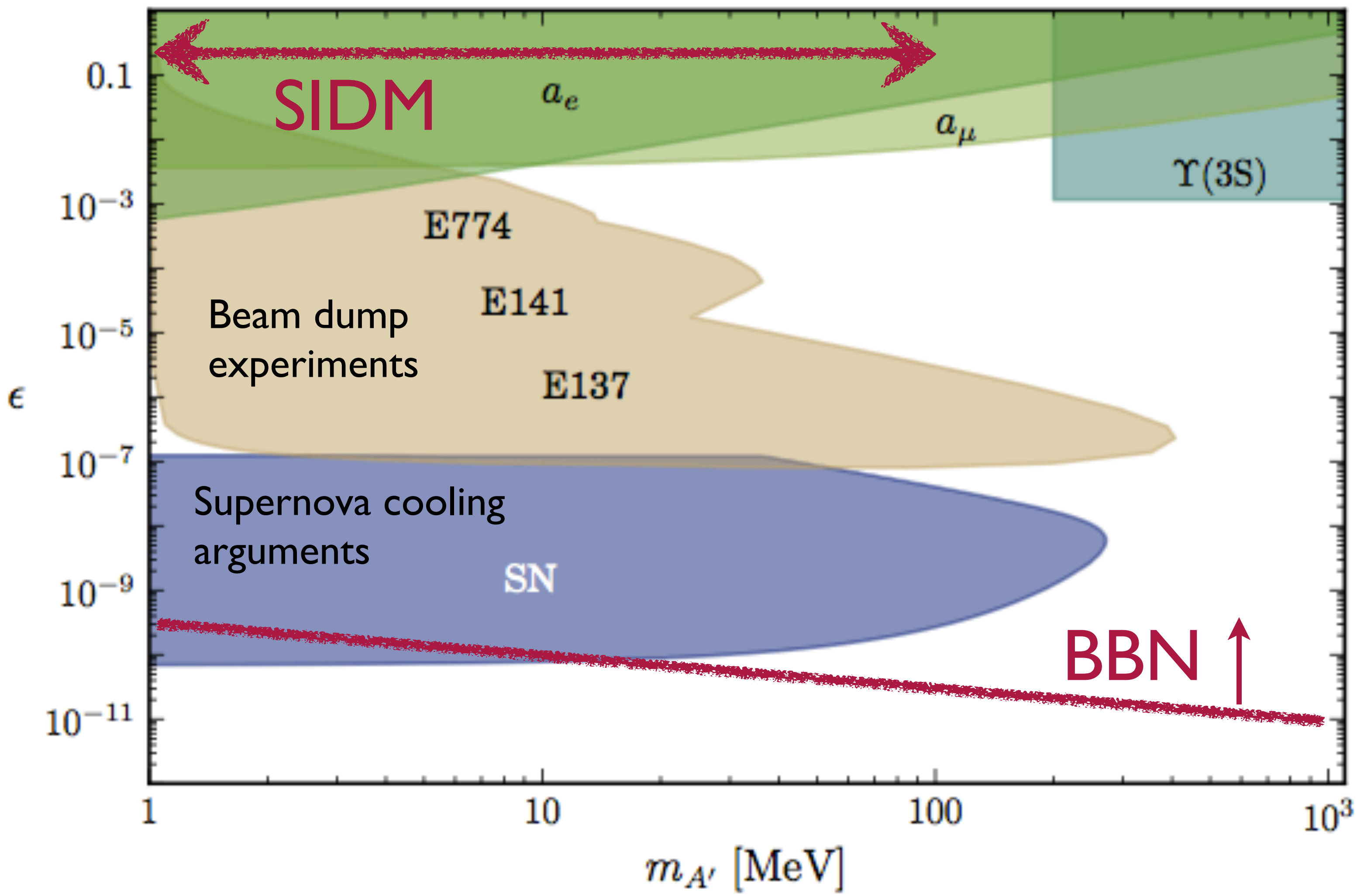
m_ϕ ~1-100 MeV

lifetime less than ~1 second

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

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

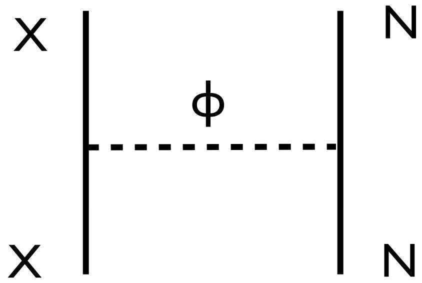
Constrains on Kinetic Mixing



Bjorken, Essig, Schuster, Toro (2009)

Dent, Ferrer, Krauss (2012)

Direct Detection of SIDM



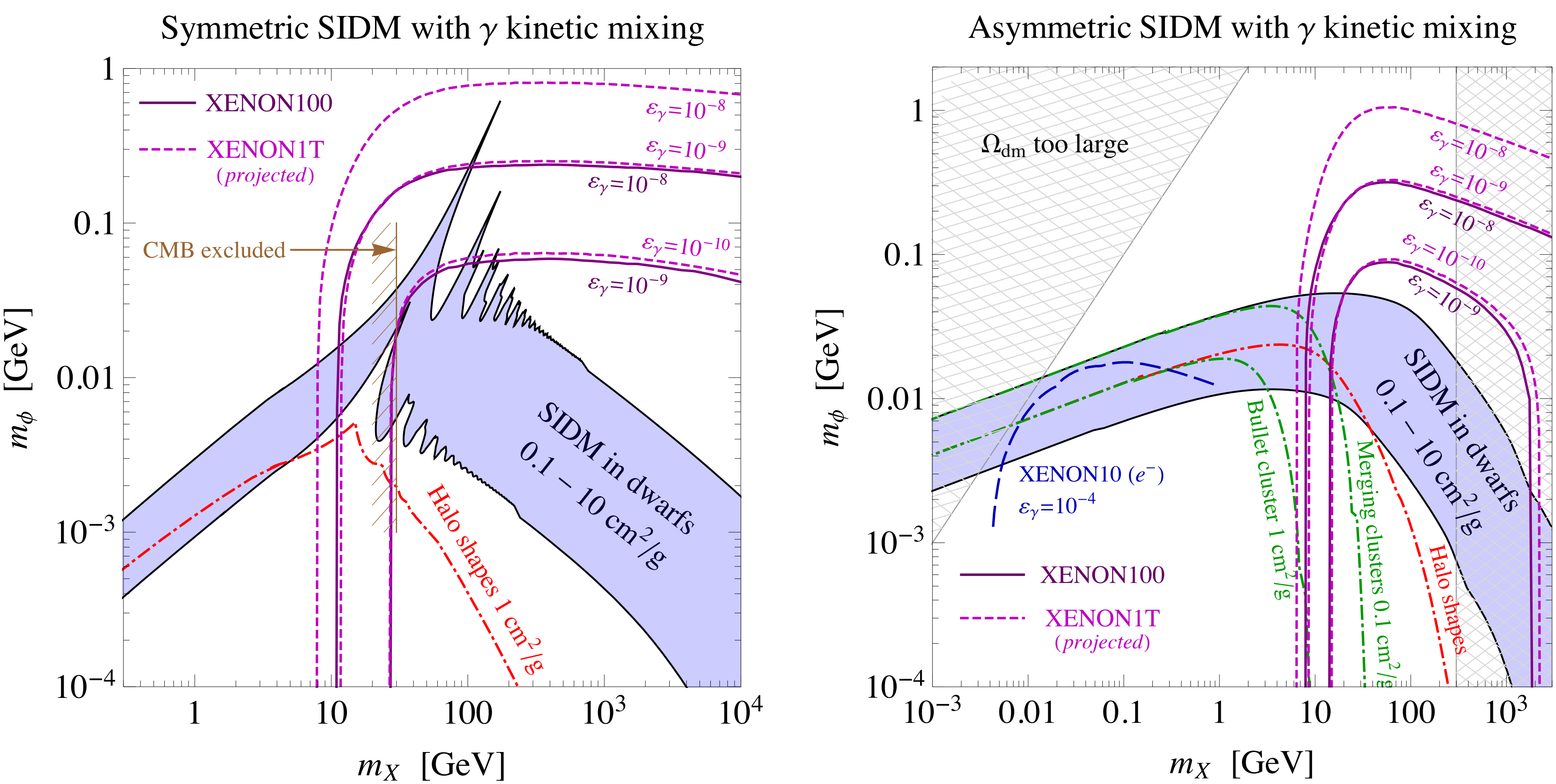
$$\frac{d\sigma}{dq^2} = \frac{4\pi\alpha_{em}\alpha_X\epsilon^2 Z^2}{(q^2+m_\phi^2)^2 v^2}$$

$$q^2 = 2m_N E_R$$

For XENON: q~50 MeV

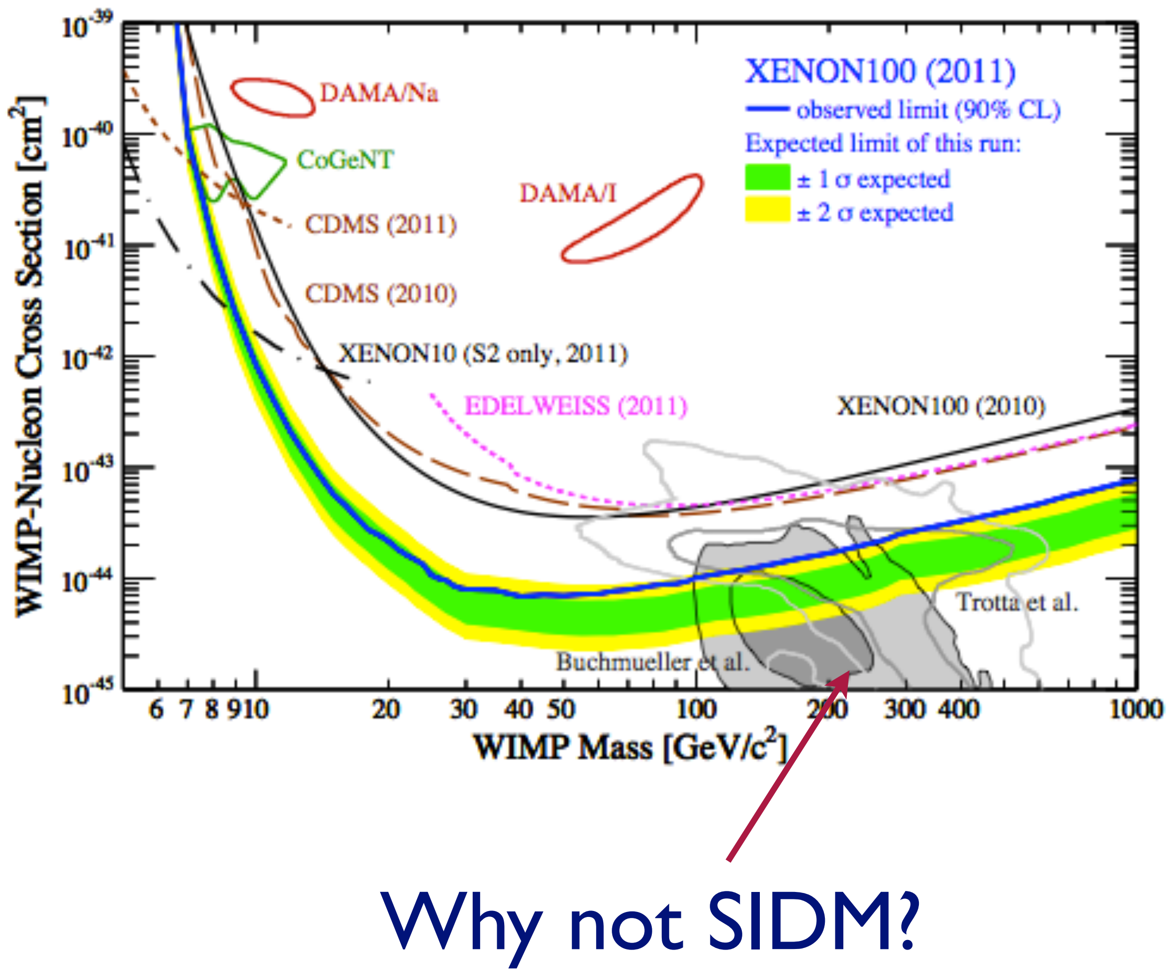
- In the WIMP case, m_ϕ>>q
- For SIDM, m_ϕ~1-100 MeV, which is comparable to q
- A new region for the direct detection community
- A dedicated study is required

Direct Detection of SIDM



Current experiments are not sensitive to the mixing parameter $\sim 10^{-10}$, which is the lower limit set by cosmology

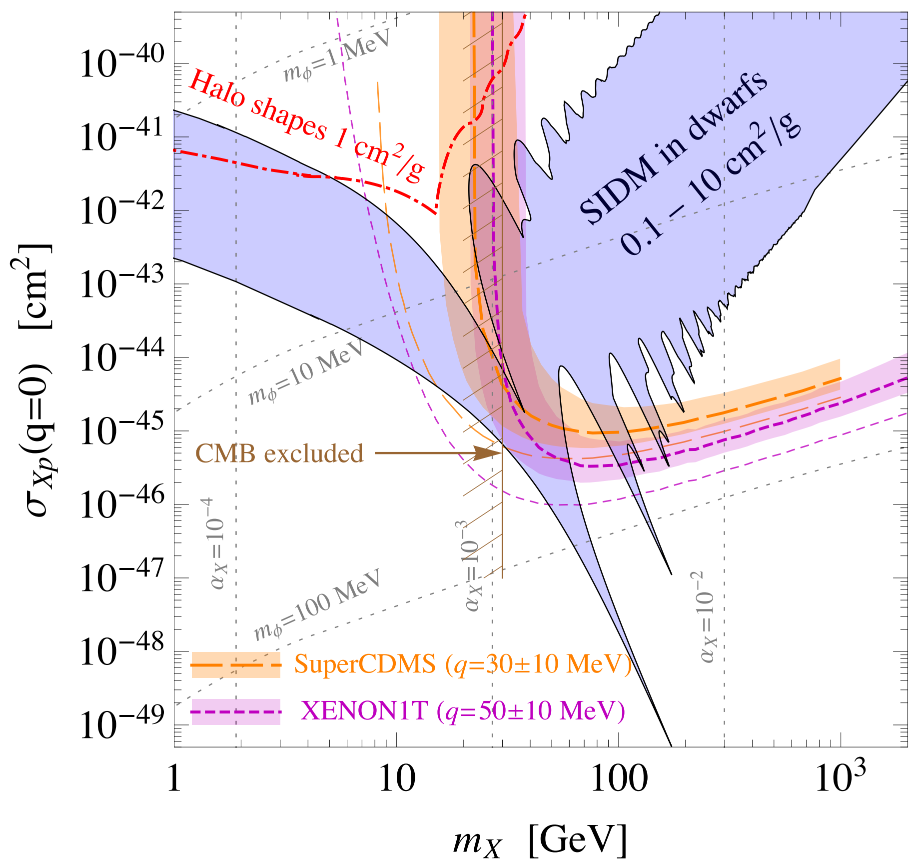
Direct Detection



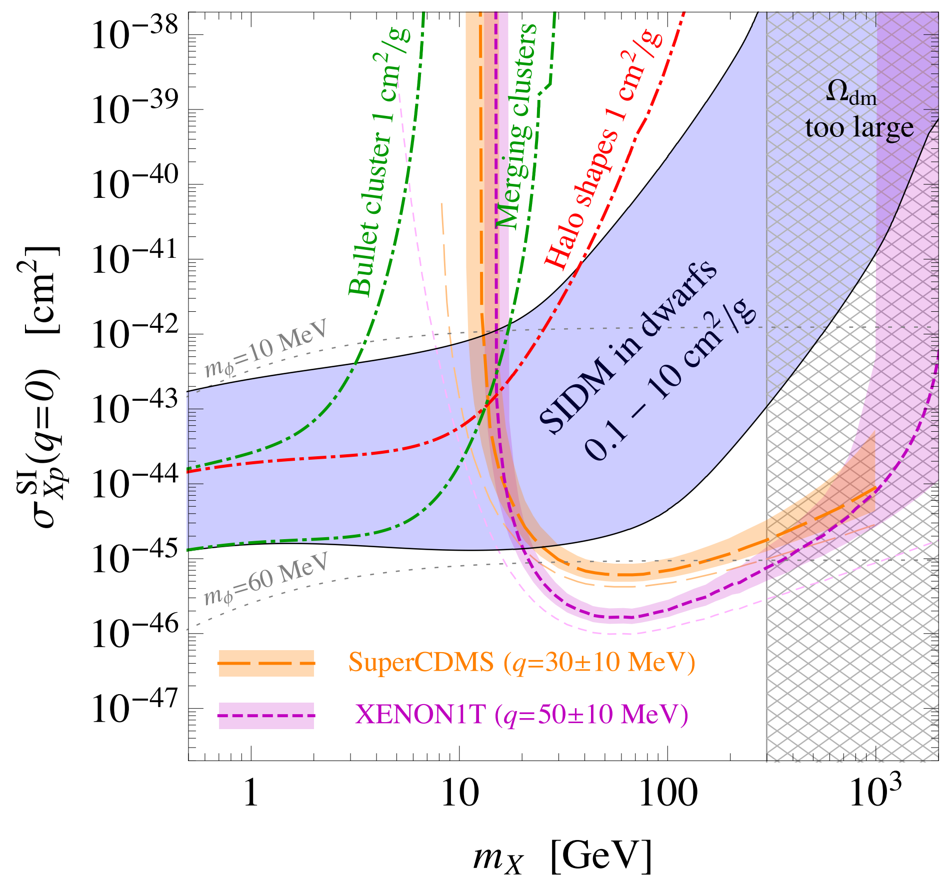
Direct Detection of SIDM

- The lower limit of direct detection cross section

Symmetric SIDM ($\varepsilon_\gamma = 10^{-10}$)



Asymmetric SIDM ($\varepsilon_\gamma = 10^{-10}$)



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

Kaplinghat, Tulin, HBY (2013)

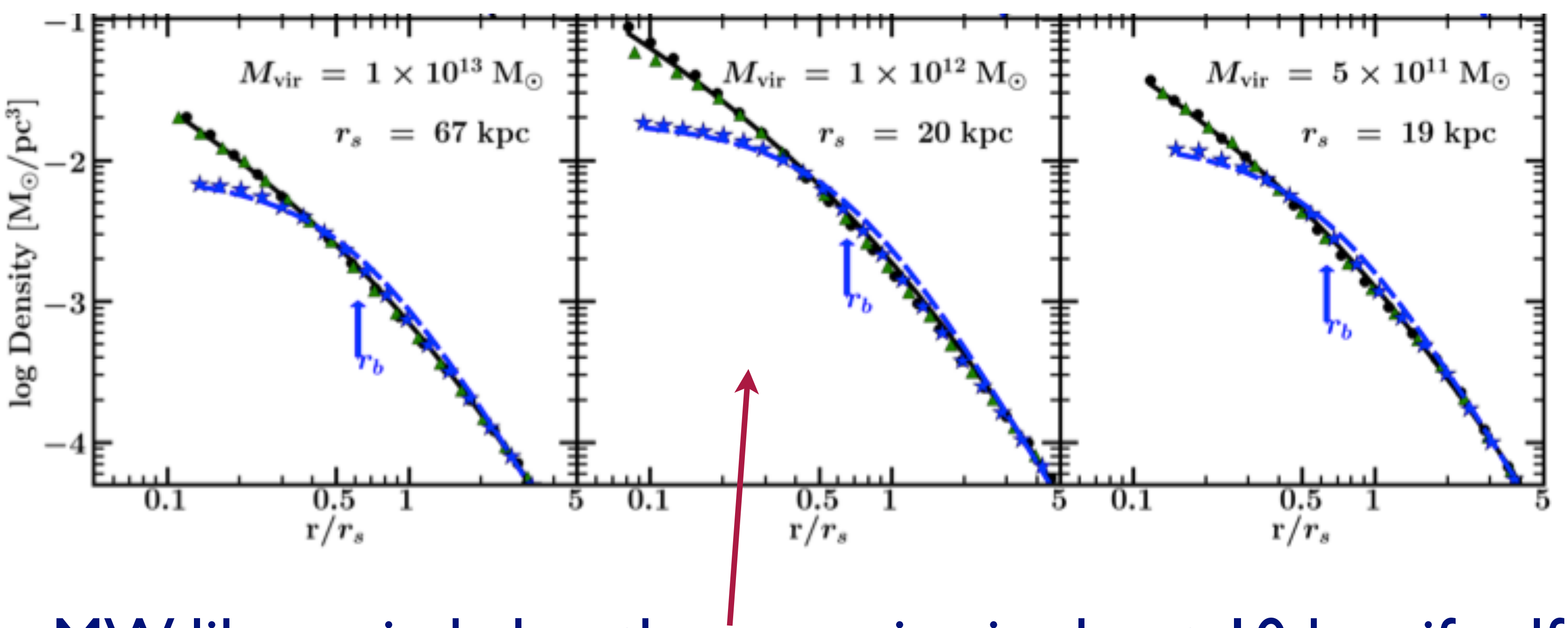
cross section in the zero momentum limit

Complementarity!

Main Dark Matter Halos

- Important for SIDM indirect detection
- SIDM-only simulations

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



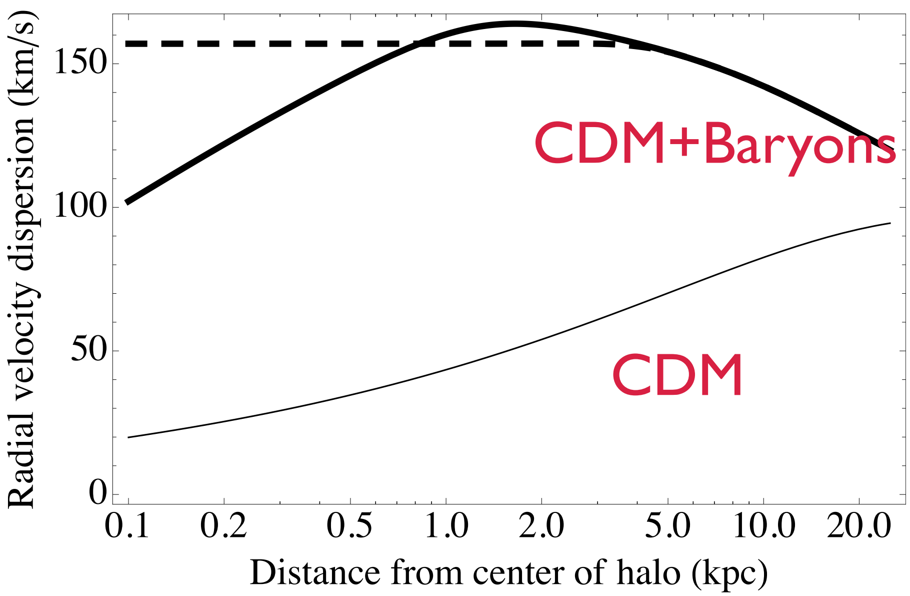
MW-like main halos: the core size is about 10 kpc if self-scattering happens at least once per Hubble time

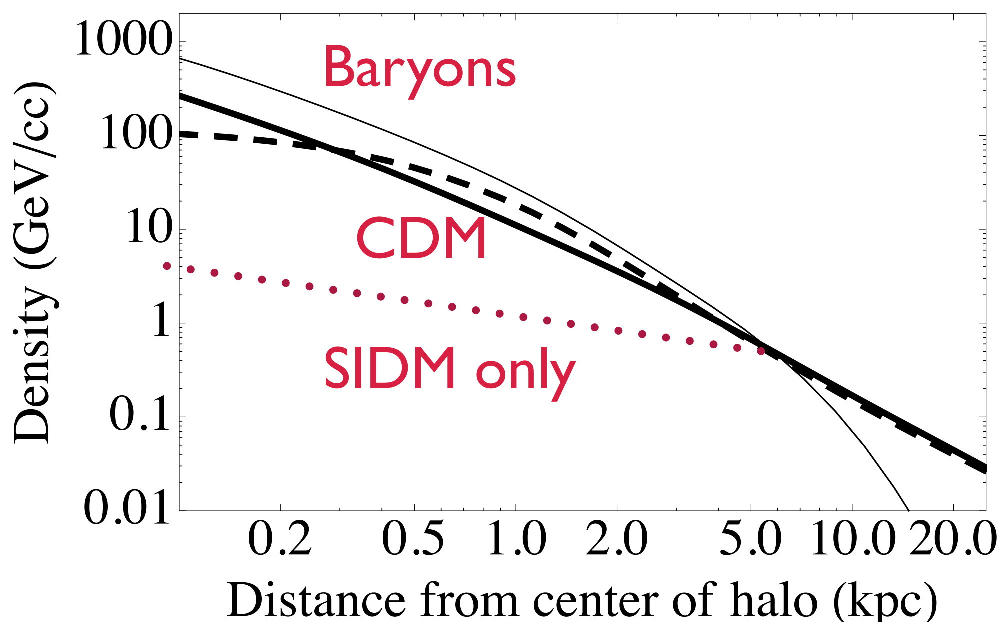
Baryons Change Everything

- Baryons dominate in the central region of the Milky Way

Isothermal solution for the Jeans equation

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





dashed: SIDM+Baryons

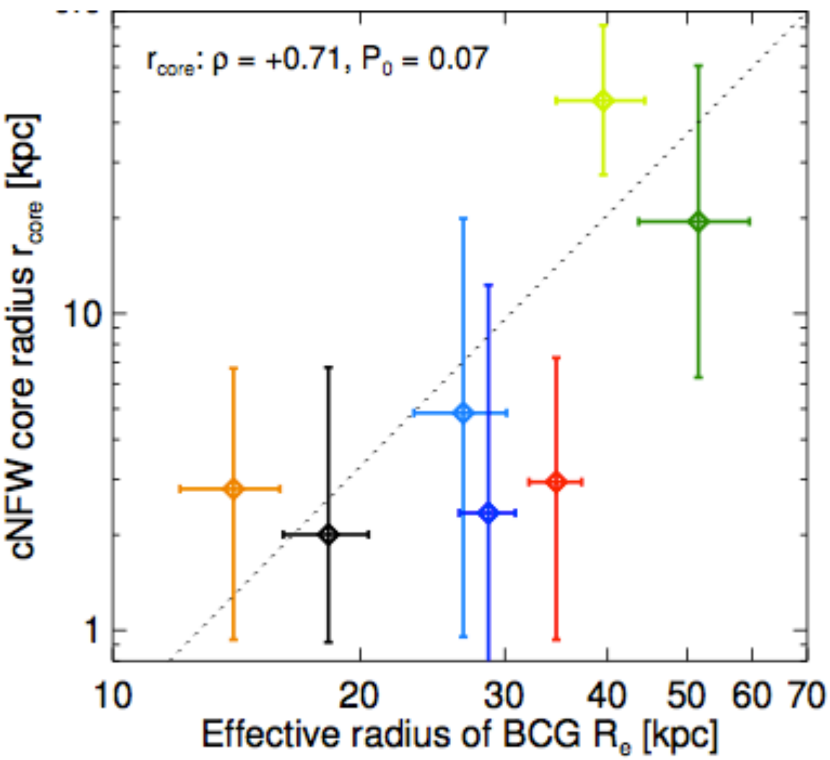
For MW-like halo:
SIDM only: core size ~10 kpc;
SIDM+baryons: core size <0.5 kpc

Kaplinghat, Linden, Keeley, HBY (soon)

Baryons+SIDM Correlation

- SIDM and baryon distributions are strongly correlated

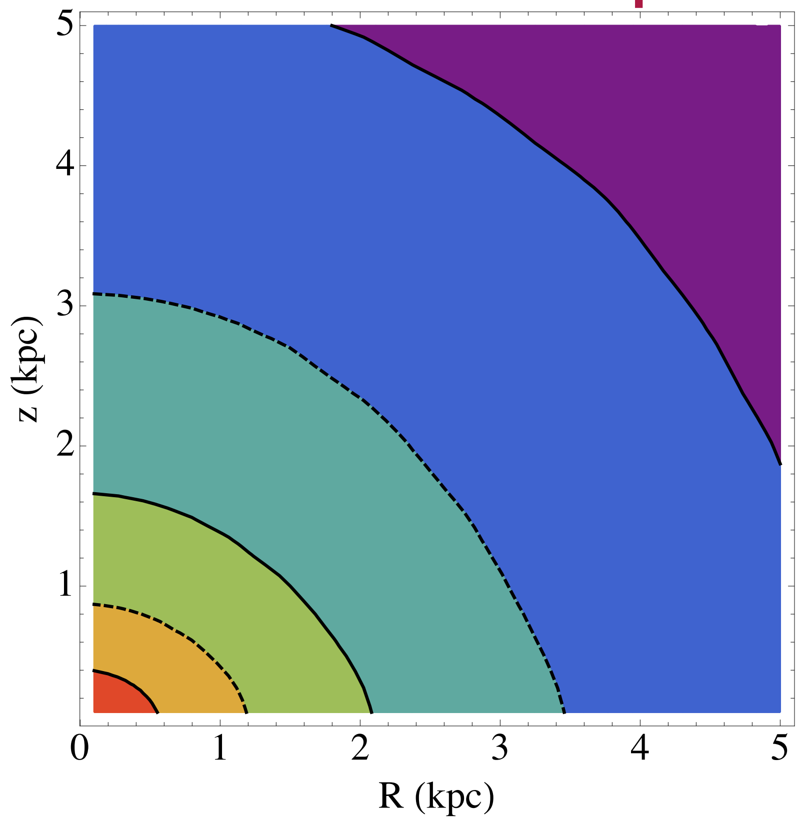
SIDM core size



Newman, Treu, Ellis, Sand (2012)

Evidence?

SIDM halo shapes



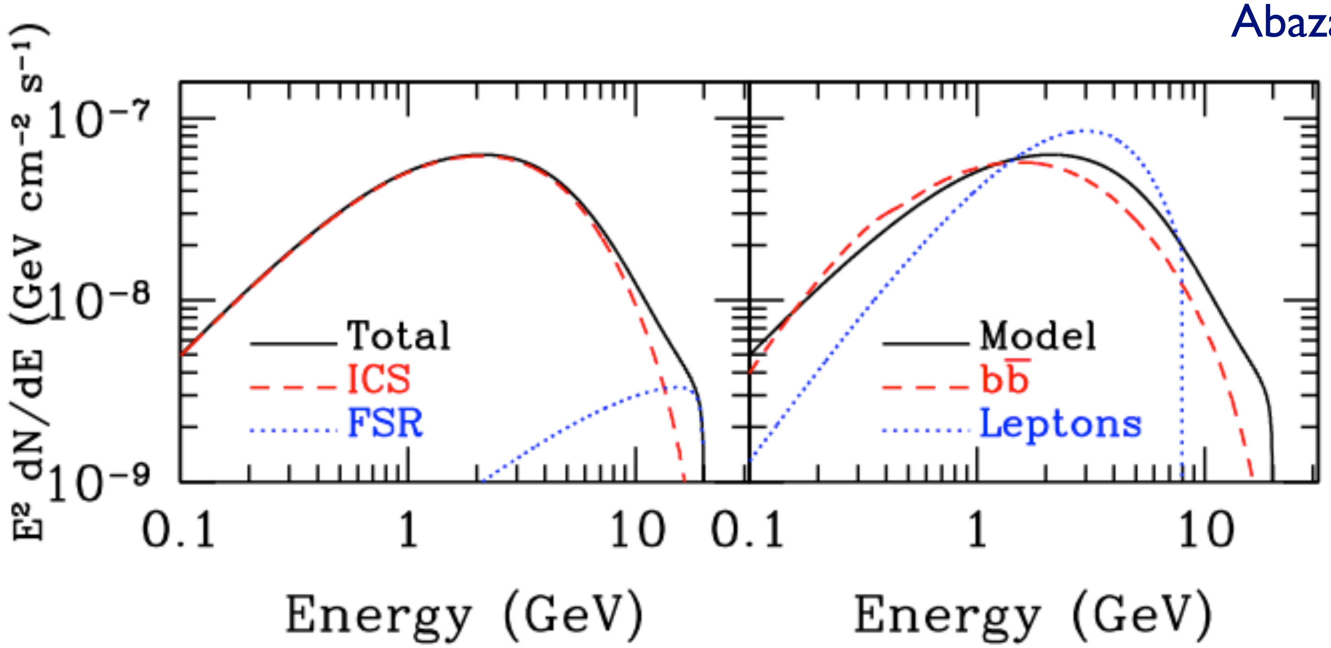
Kaplinghat, Linden, Keeley, HBY (soon)

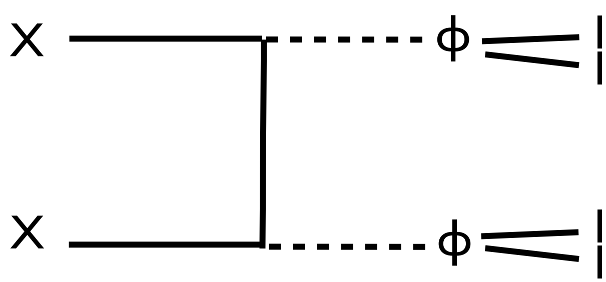
Constant density contours in cylindrical coordinates (R, z)

An Application

- Explain the Galactic center photon excess

Hooper, Goodenough (2011)
Hooper, Linden (2011)
Abazajian, Kaplinghat (2012)





Take the super model
~10-30 GeV SIDM; 10 MeV mediator

Kaplinghat, Linden, HBY (soon)

Conclusions

- No reason to believe DM has to be collisionless
- With a light dark force (with one coupling α_X)
  - Explain anomalies on dwarf galaxy scales
  - Satisfy bounds on larger scales
  - Provide the correct DM relic density
- Implications for direct/indirect detection
- Baryons & SIDM are strongly correlated!