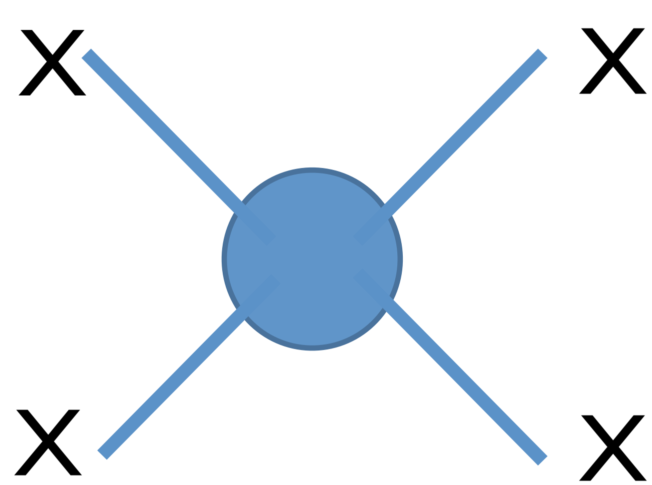
Self-interacting Dark Matter -some recent progress

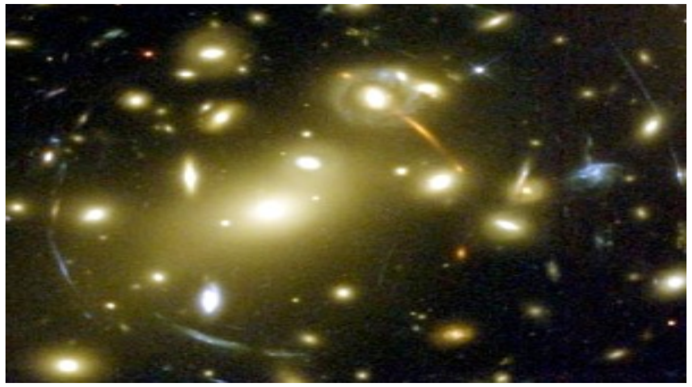
Hai-Bo Yu
University of California, Riverside

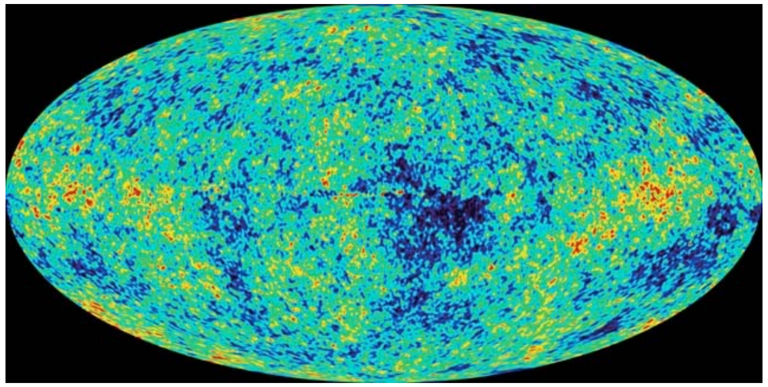


Mitchell Workshop on Collider and Dark Matter Physics
05/20/2015

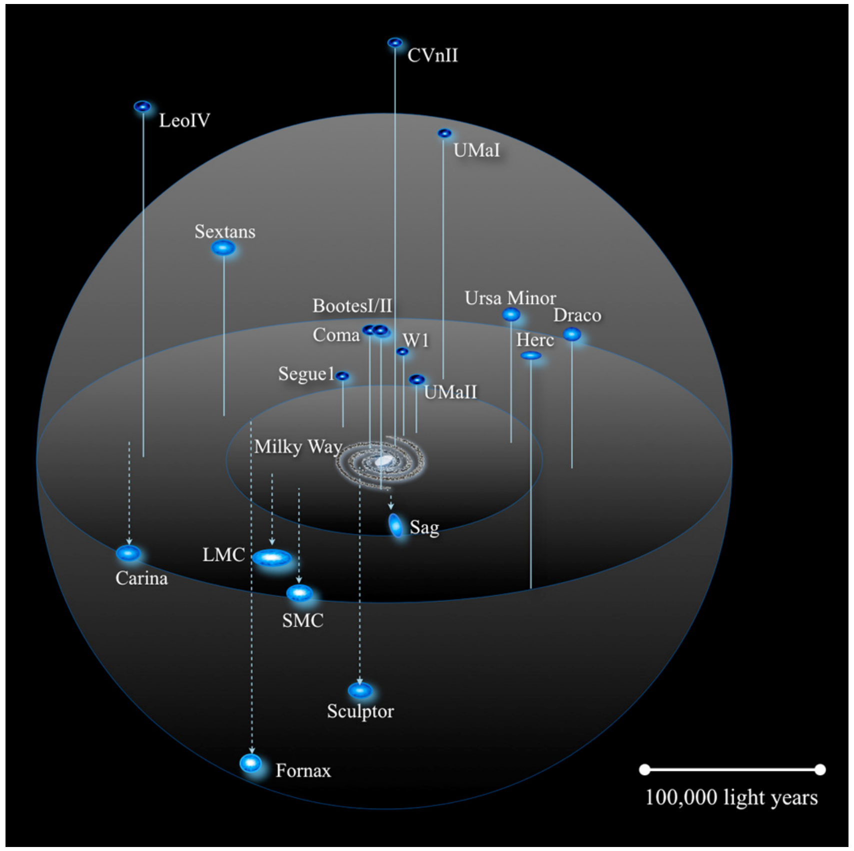
Collisionless Cold Dark Matter

- Large scales: very well





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

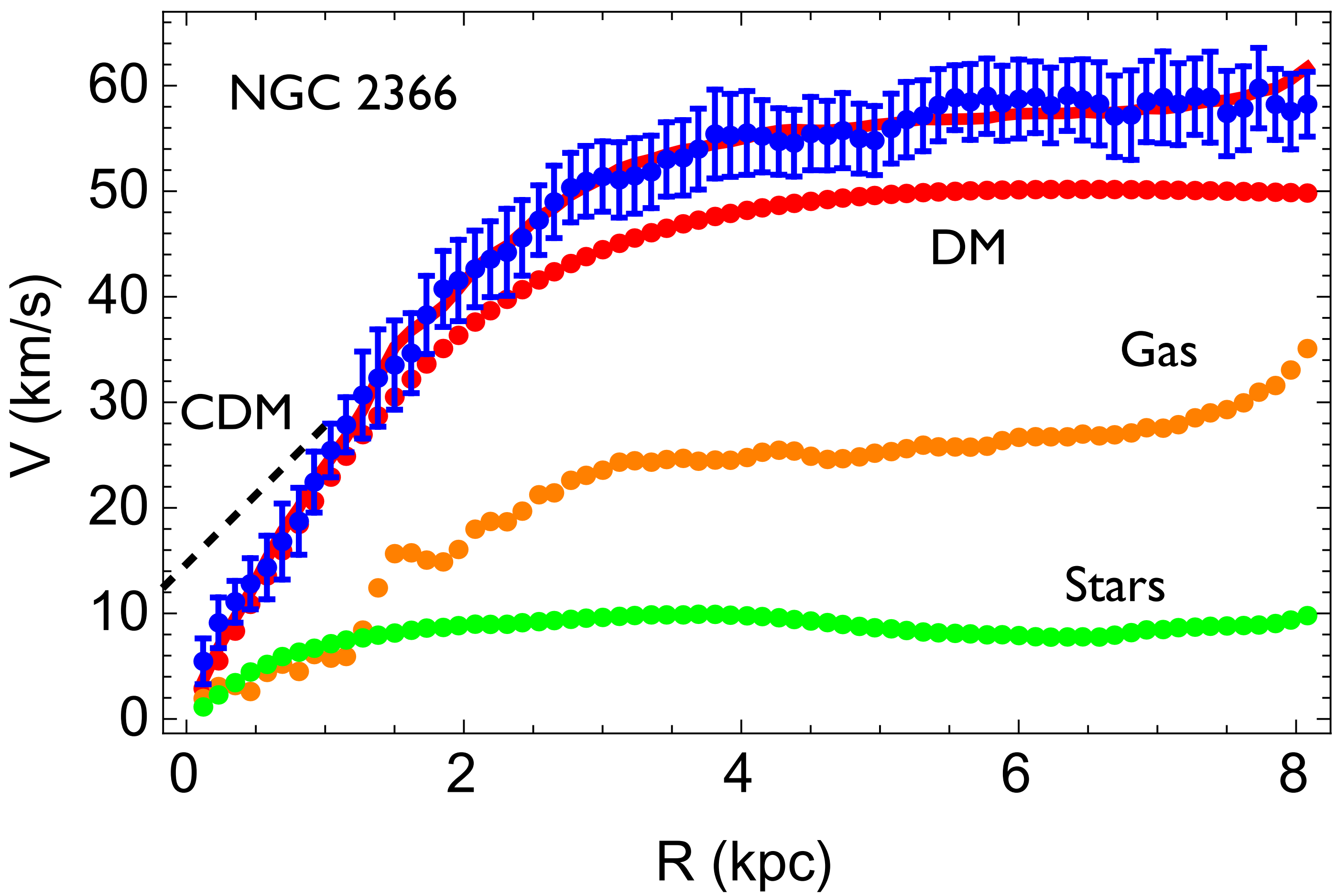


Core VS. Cusp
Too Big To Fail
Missing Satellite

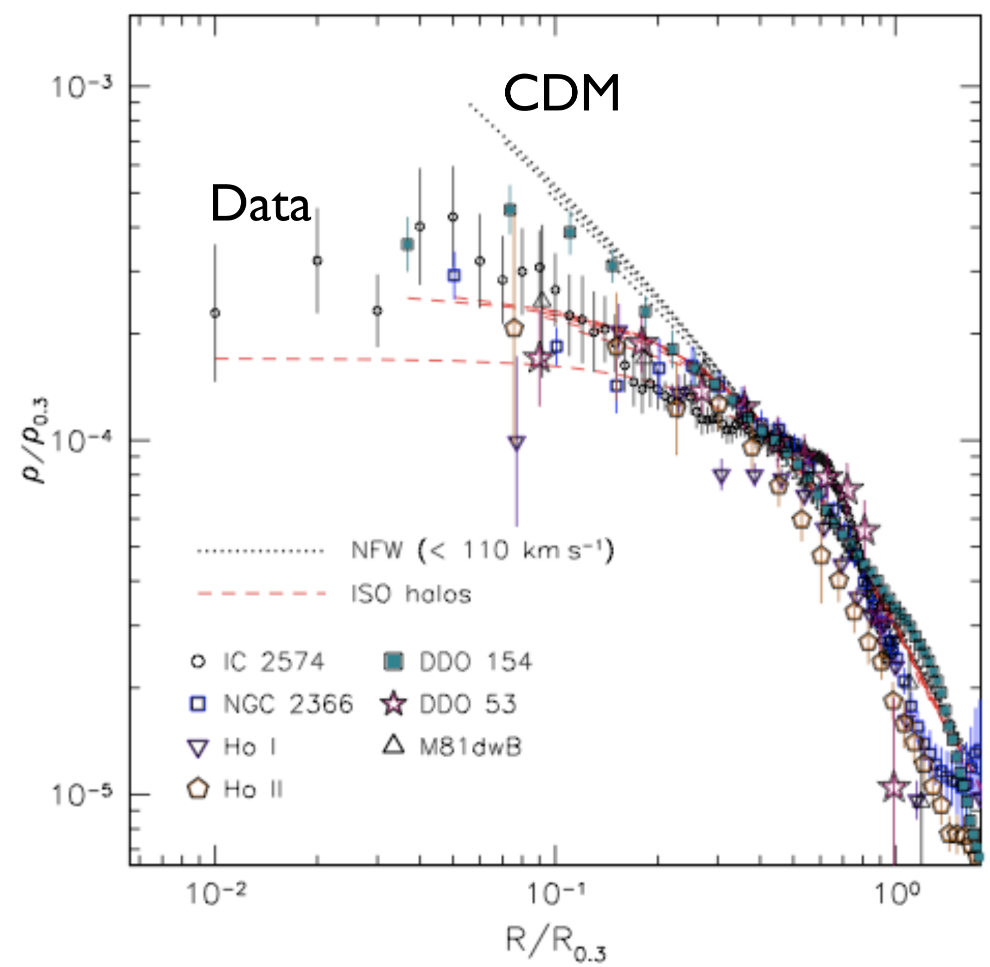
See Boylan-Kolchin's talk

Core VS. Cusp Problem

- THINGS (dwarf galaxy survey)



Oh et al. (2011)



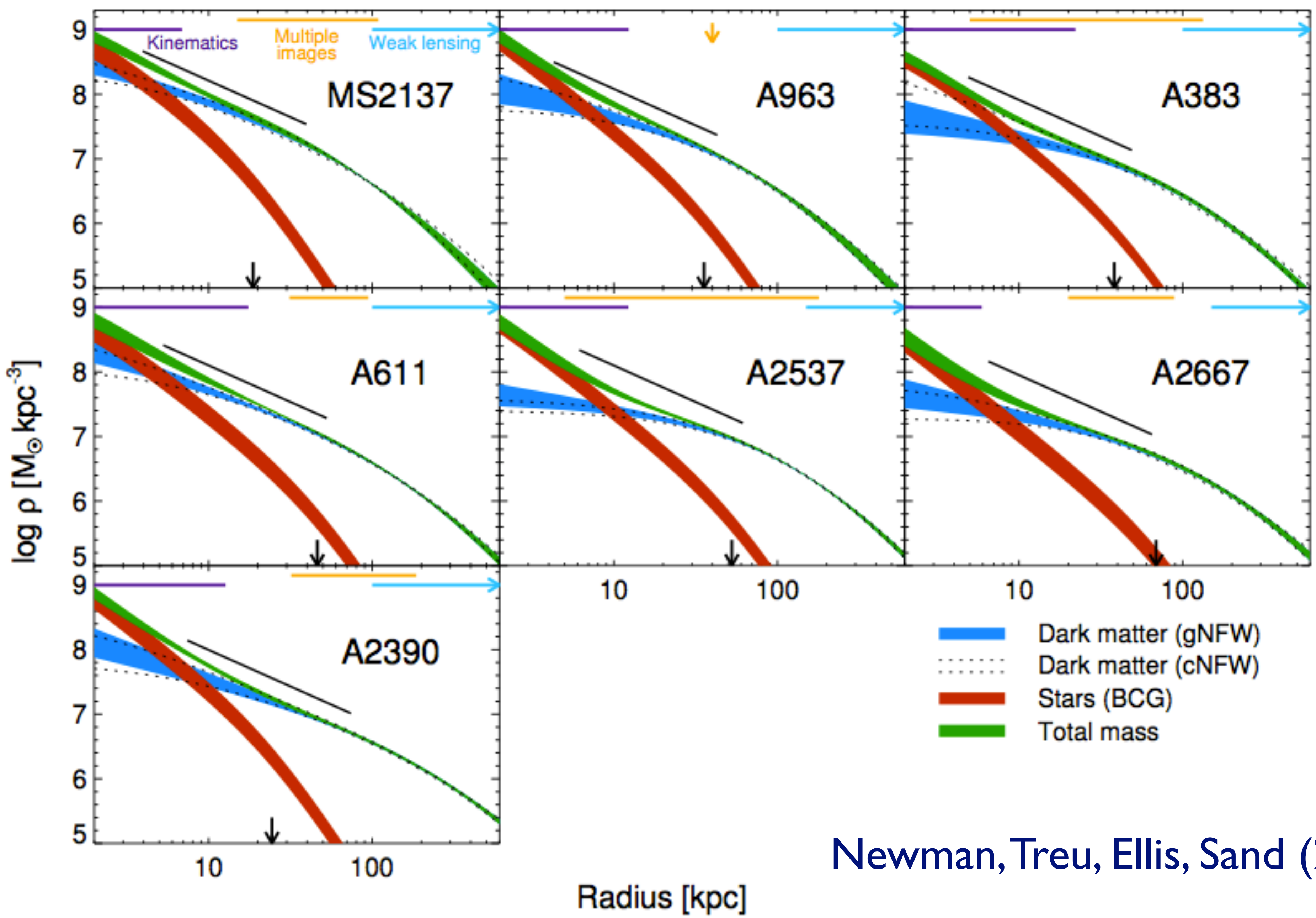
$$\rho_{\rm NFW} = \frac{\rho_s}{r/r_s(1+r/r_s)^2} \rightarrow \frac{\rho_s r_s}{r}$$

density profile: $\rho \sim r^{\alpha}$
observed: $\alpha=-0.29\pm0.07$

(ρ_s, r_s) are correlated

$$V \sim \sqrt{\frac{GM_<}{r}} \qquad M_< \sim \int \rho r^2 dr$$

Even Clusters!



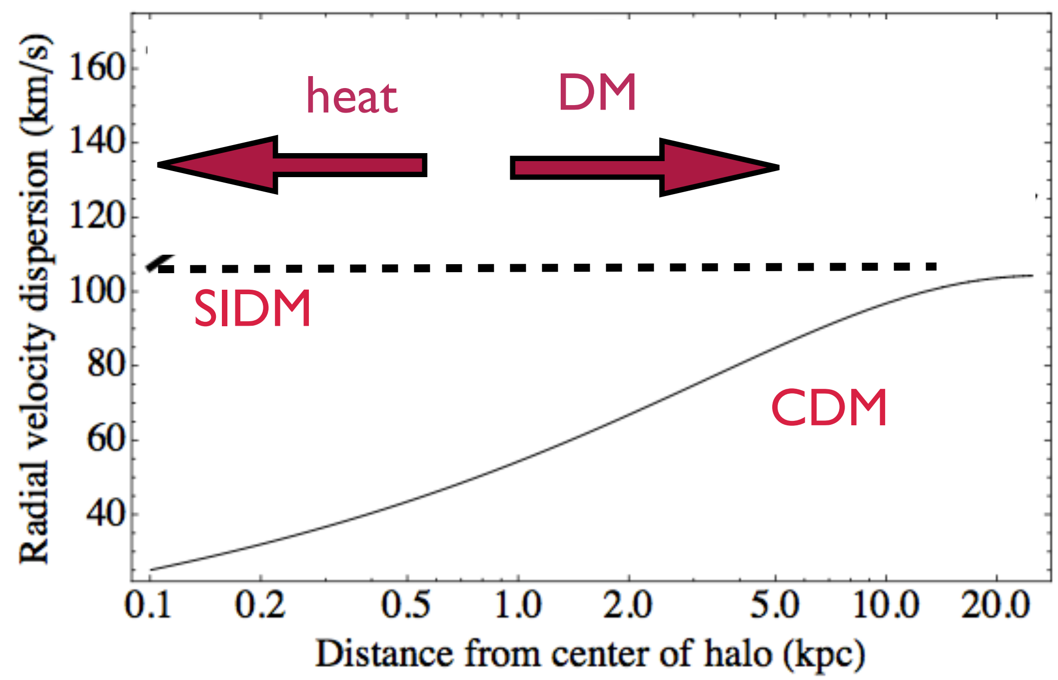
Newman, Treu, Ellis, Sand (2013)

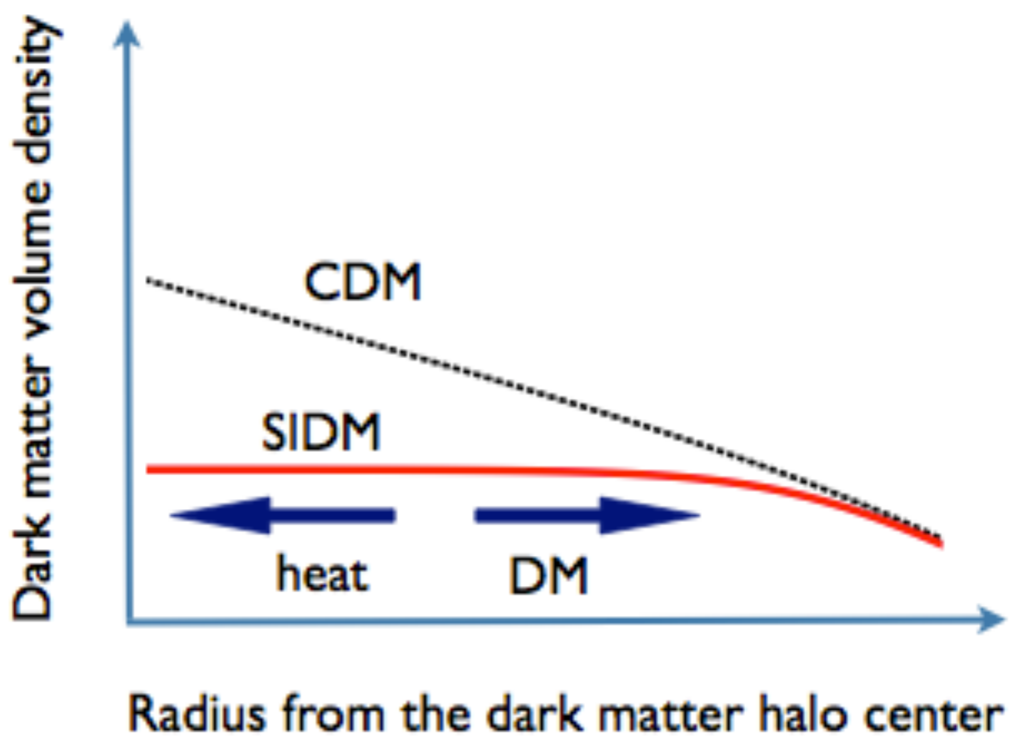
- CDM halos contain more DM in the central region than needed
- CDM may break down on (sub)-galactic scales

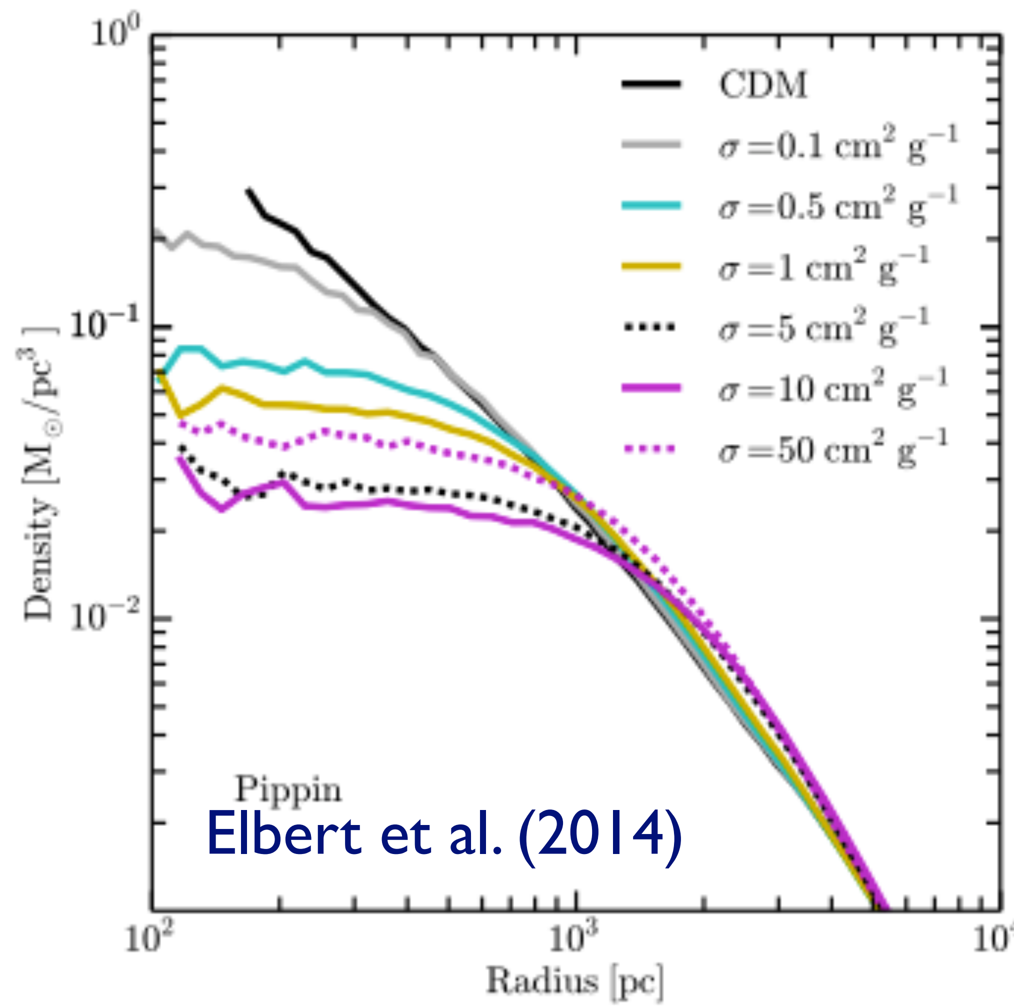
Self-interacting Dark Matter

- Self-interactions can reduce the central DM density

Spergel, Steinhardt (2000)







σ/m_X ~ 0.5– 50 cm^2/g

for v ~ 10-30 km/s

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

Challenges

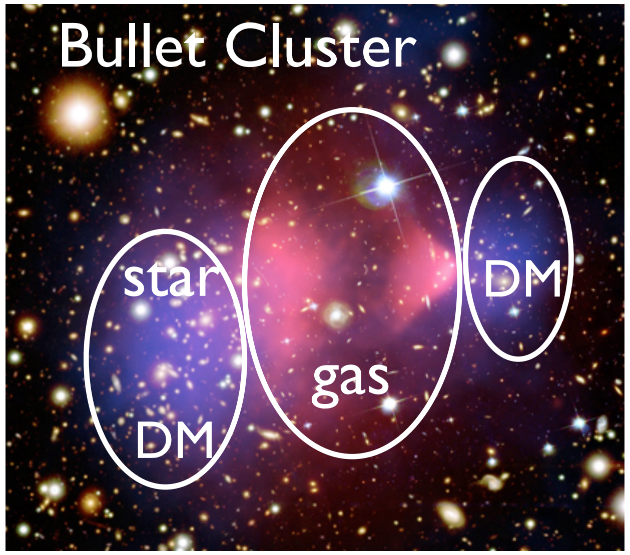
- A really large scattering cross section!

a nuclear-scale cross section

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

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

SIDM indicates a new mass scale



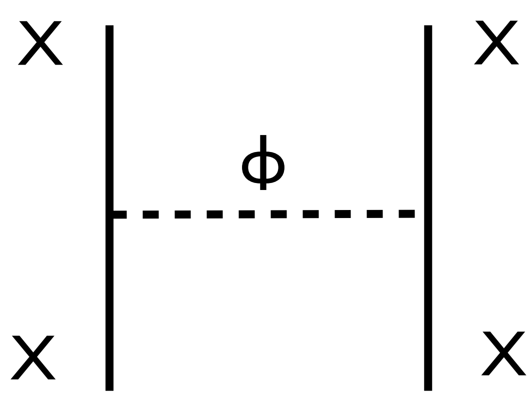
- How to avoid the constraints on large scales?

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

In particular, if $\sigma \sim$constant

Spergel, Steinhardt (2000)

Particle Physics of SIDM

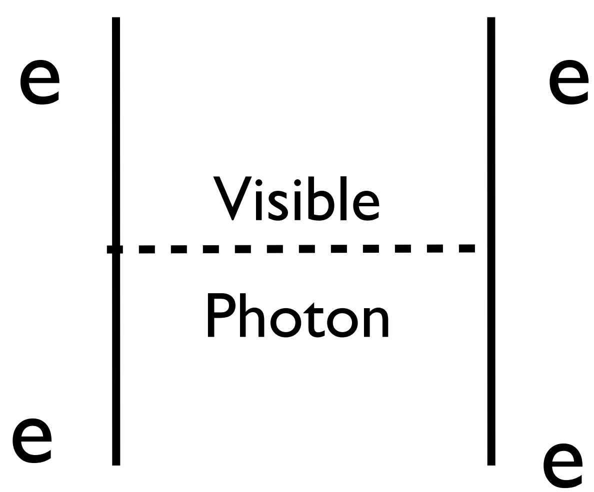


- SIDM indicates light mediators

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

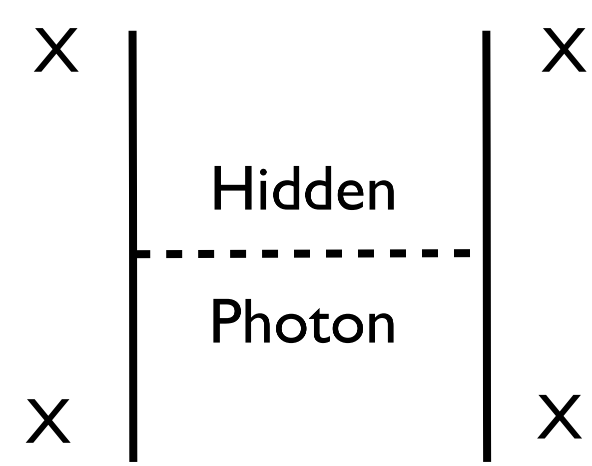
in the perturbative and small velocity limit

- With a light mediator, DM self-scattering is velocity-dependent



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

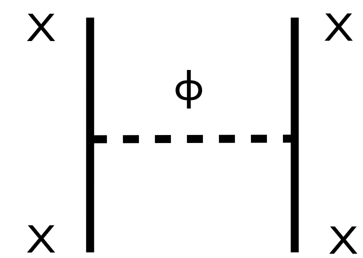
$m_X\, v >> m_\phi$



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

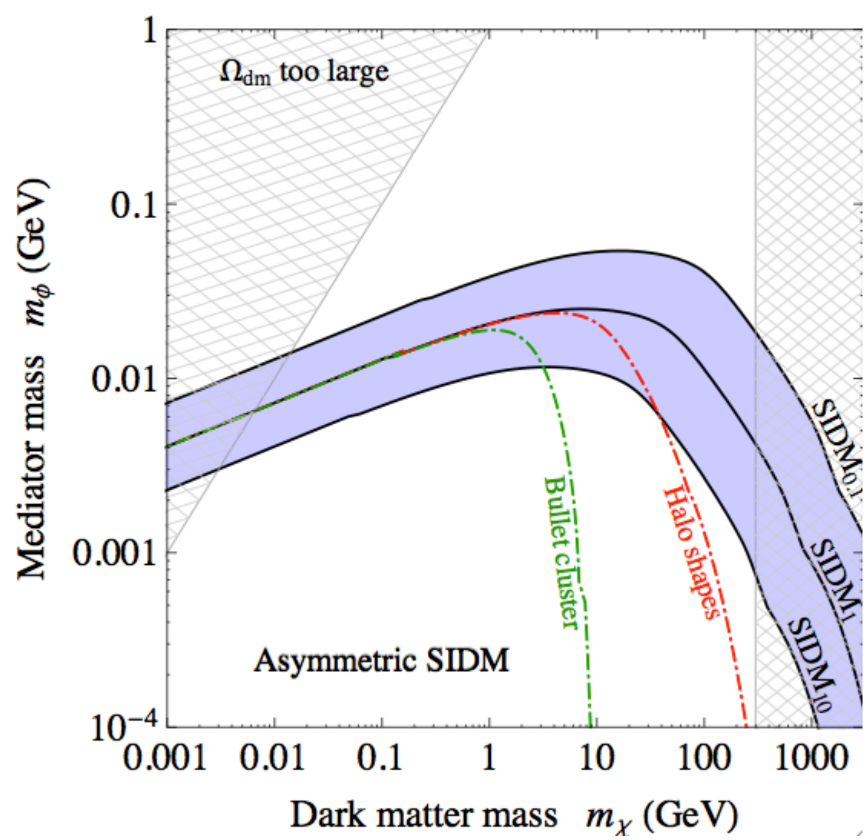
A Concrete Model

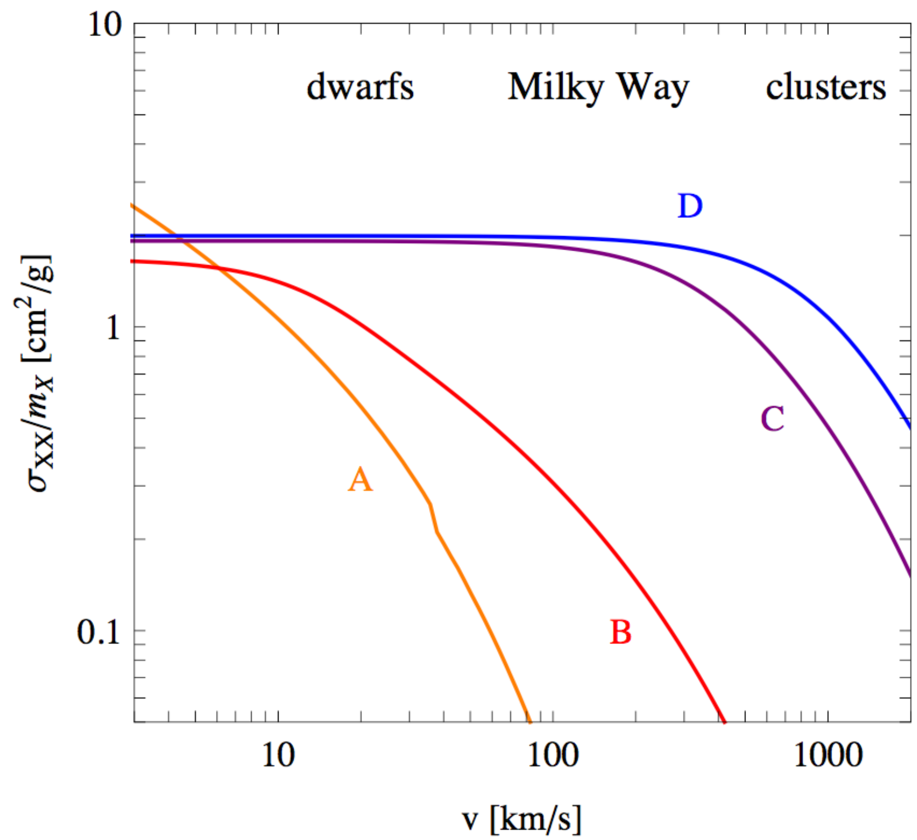
A Yukawa potential $$V(r) = \pm \frac{\alpha_X}{r} e^{-m_\phi r}$$



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

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





α_X=0.01

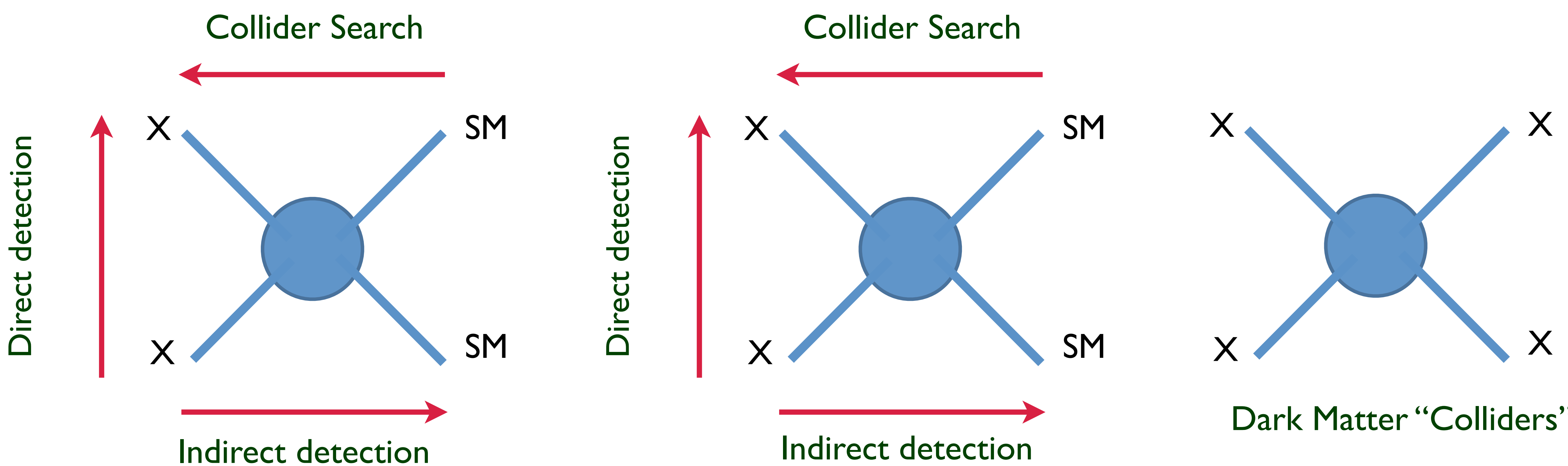
Model	m_X (GeV)	m_ϕ (MeV)
A	1000	3
B	100	15
C	10	20
D	5	20

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

$m_X v >> m_\phi$

SIDM Paradigm

- The SIDM paradigm is predictive



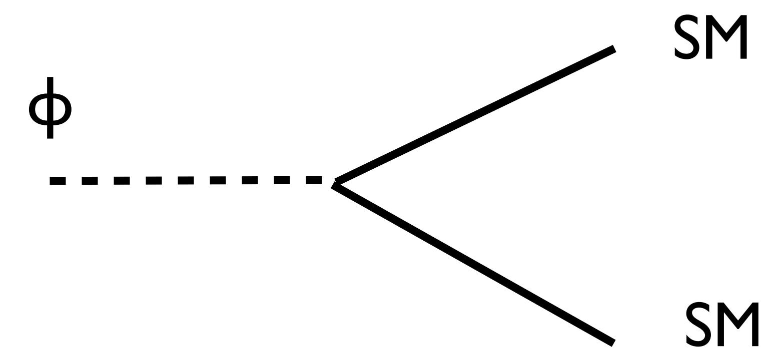
WIMP paradigm SIDM paradigm

Collider search: Bai, Rajaraman (2011), Daci, De Bruyn, Lowette, Tytgat, Zaldivar (2015)

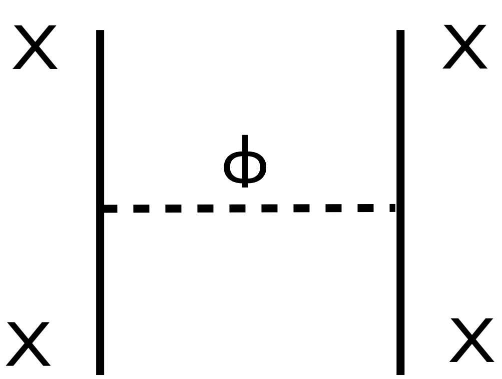
SIDM+SM

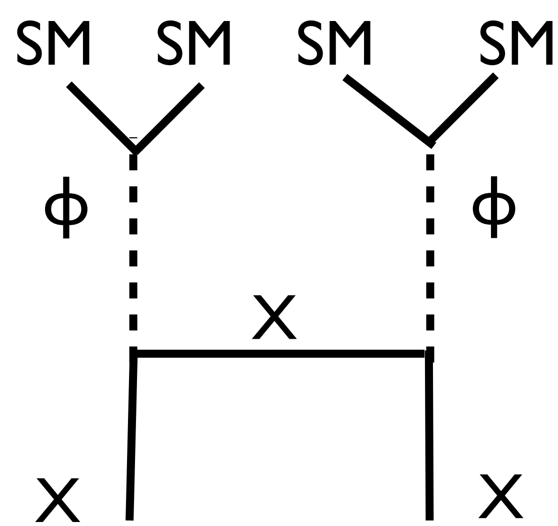
- The mediator may dominate the energy density of the Universe
- The mediator decays before BBN: lifetime of ϕ is ~1 second

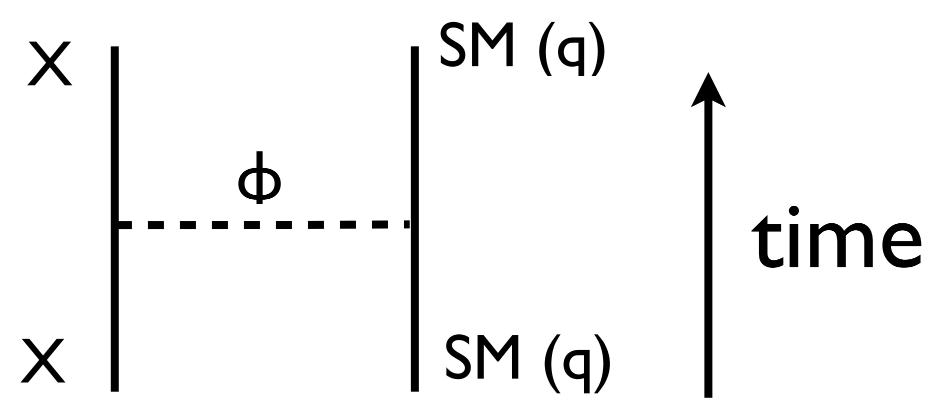
$$\epsilon \gtrsim 10^{-10}\sqrt{10\ \mathrm{MeV}/m_\phi}$$



A super model!

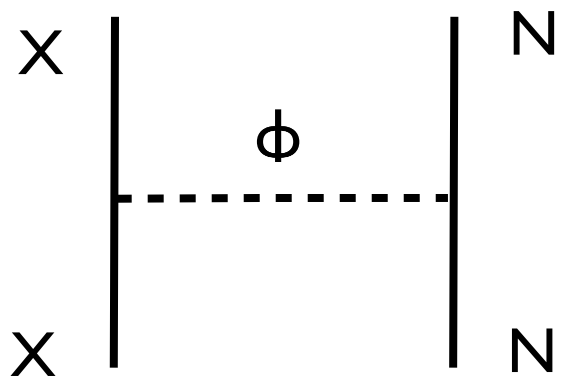




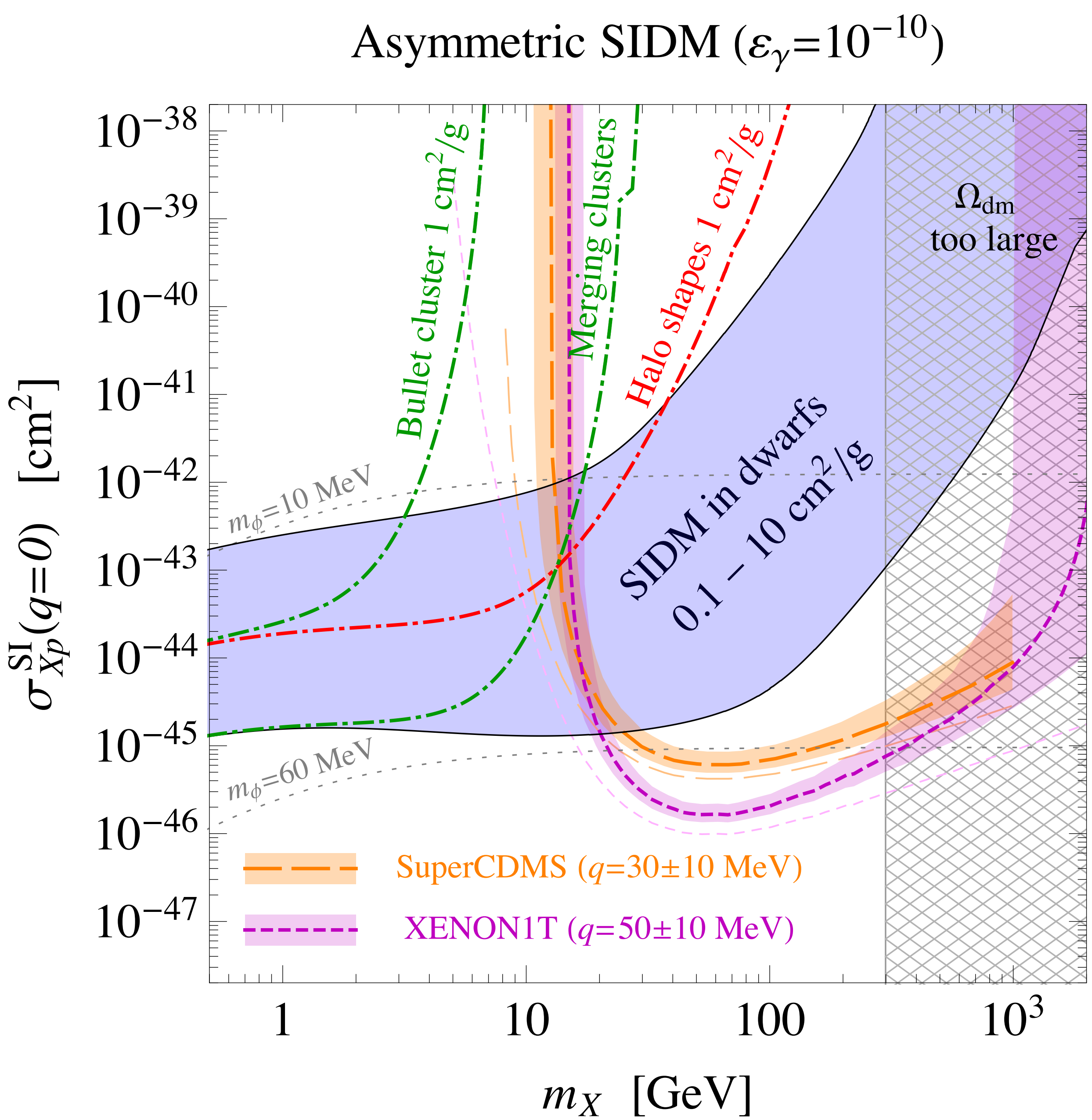


Direct Detection of SIDM

- Complementarity



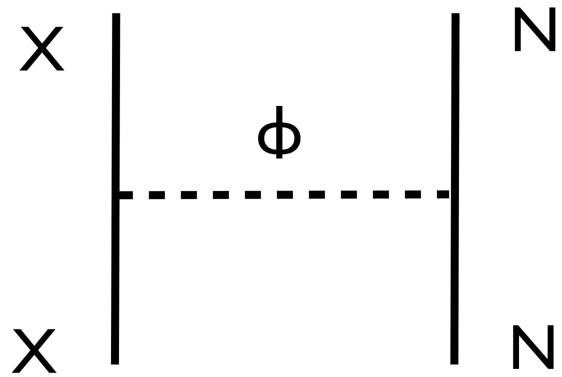
$$\frac{d\sigma}{dq^2} = \frac{4\pi\alpha_{em}\alpha_X\epsilon^2 Z^2}{(q^2+m_\phi^2)^2 v^2}$$



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

Kaplinghat, Tulin, HBY (2013)

Smoking-Gun Signatures

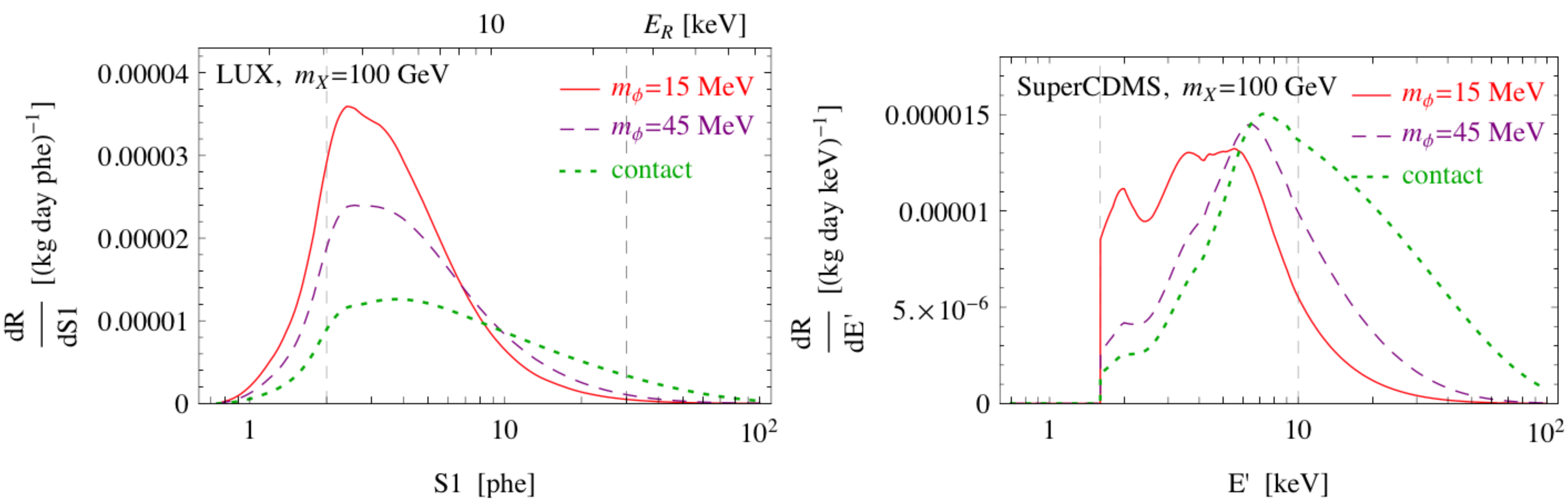


$$\frac{d\sigma}{dq^2} = \frac{4\pi\alpha_{em}\alpha_X\epsilon^2 Z^2}{(q^2+m_\phi^2)^2 v^2}$$

$$q^2 = 2m_N E_R$$

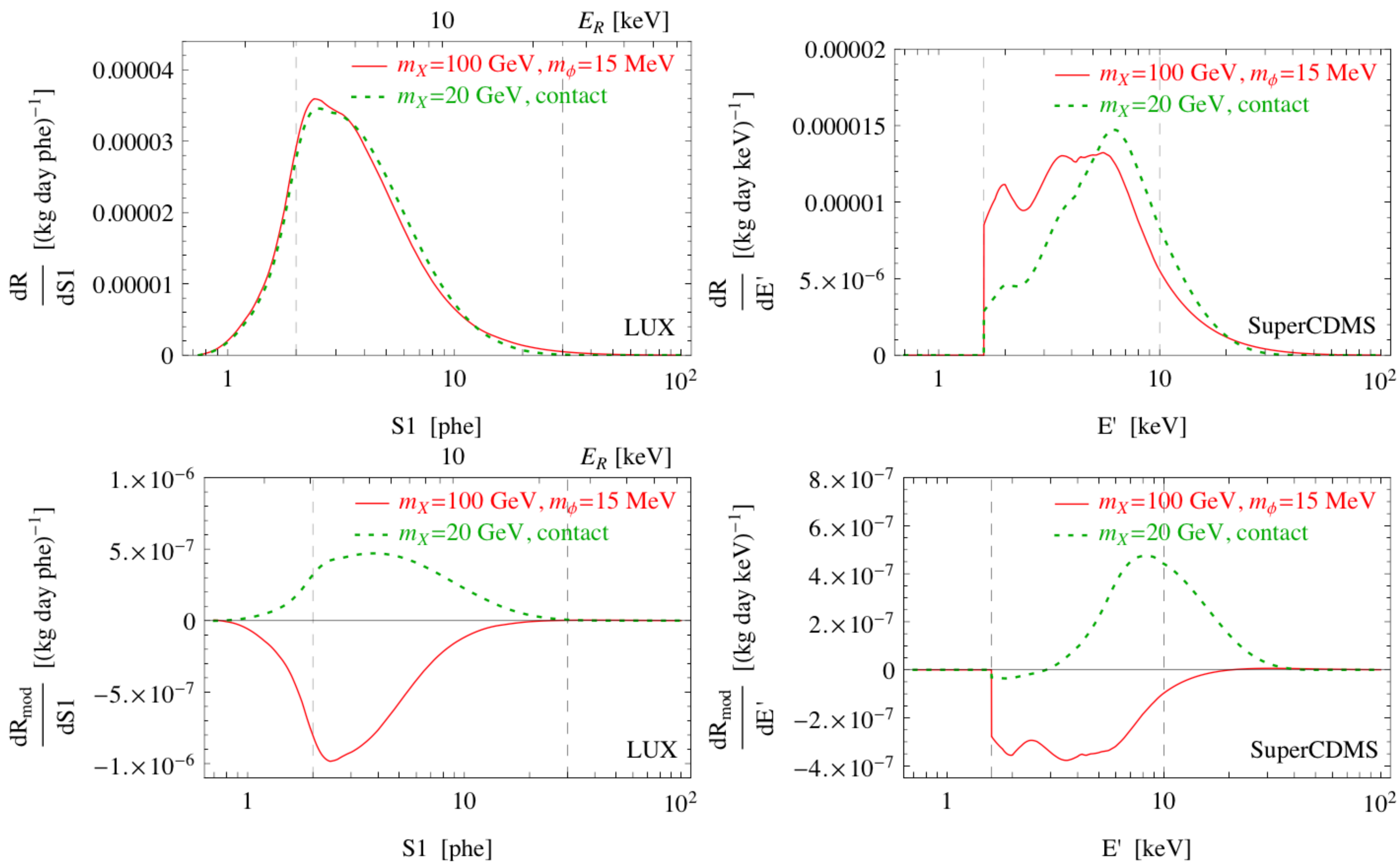
For XENON: q~50 MeV

- 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



Del Nobile, Kaplinghat, HBY (in preparation)

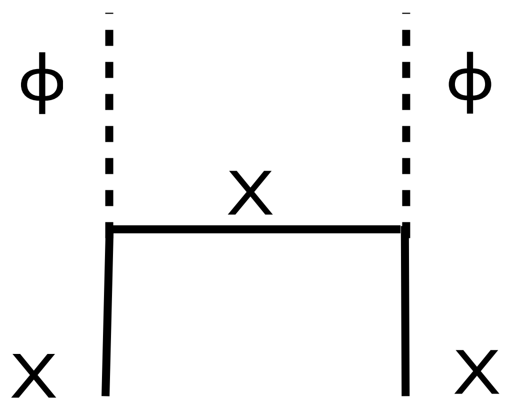
Smoking-Gun Signatures



Del Nobile, Kaplinghat, HBY (in preparation)

Indirect Detection

- Lighting up the galactic center, but not dwarf galaxies!

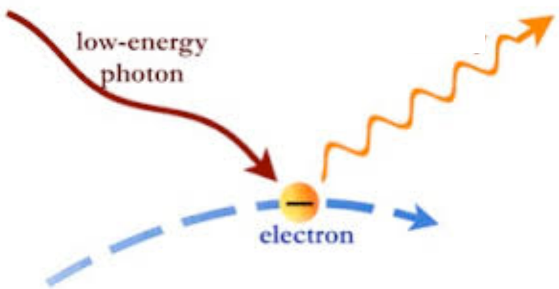


$m_\phi \sim 10$ MeV

$\phi \rightarrow$ electrons/neutrinos

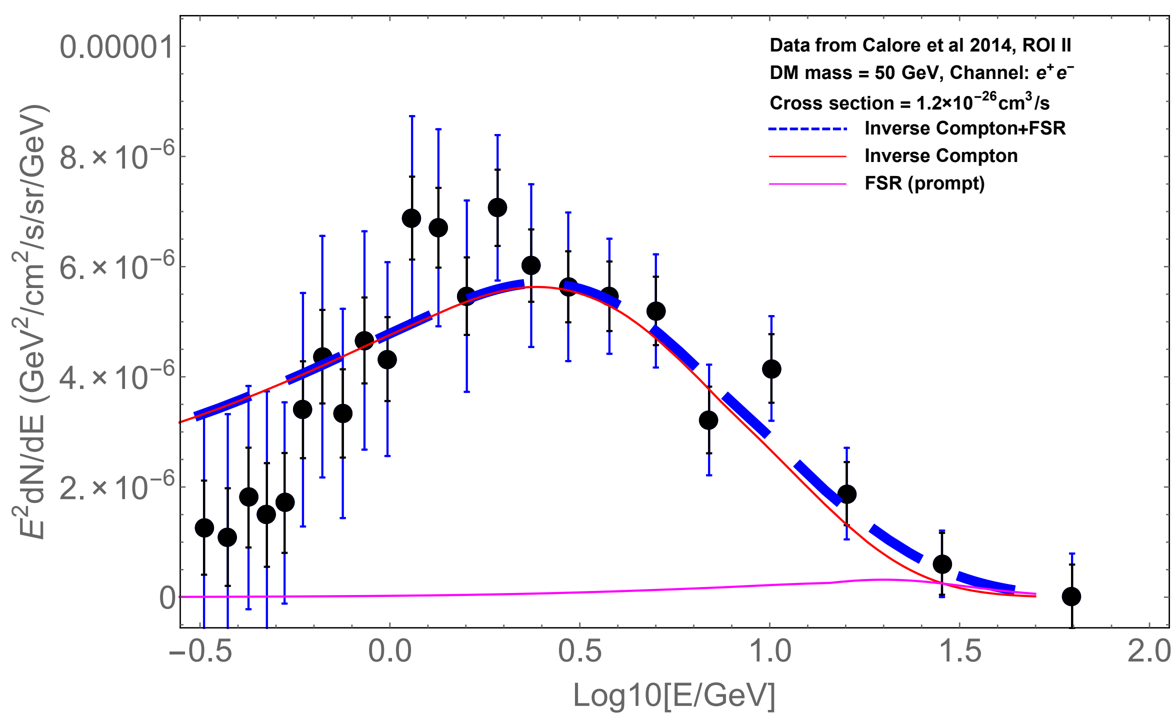
Inverse Compton scattering

starlight



$$\sim (20\ \mathrm{GeV}/m_e)^2 E_{\mathrm{ISRF}}$$

$$E_{\mathrm{ISRF}} \sim 1\ \mathrm{eV}$$



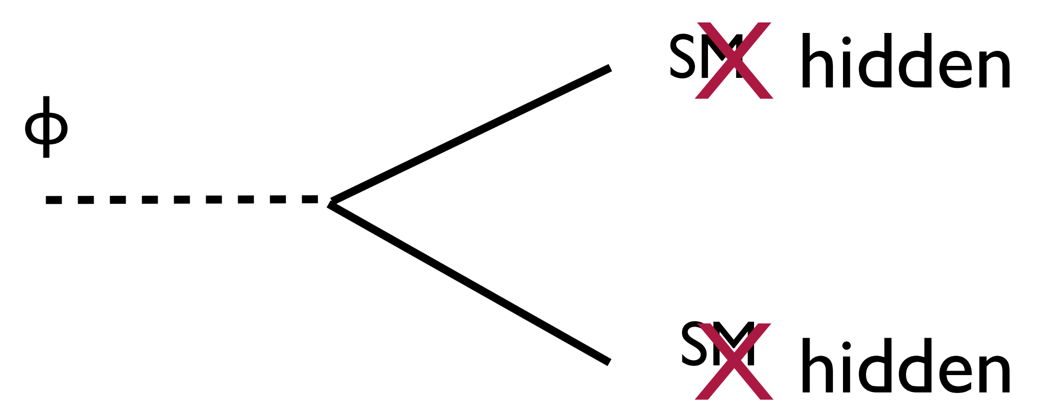
- No IC signal from dwarfs
- Soft electron spectrum
- The IC signal is spherically symmetric

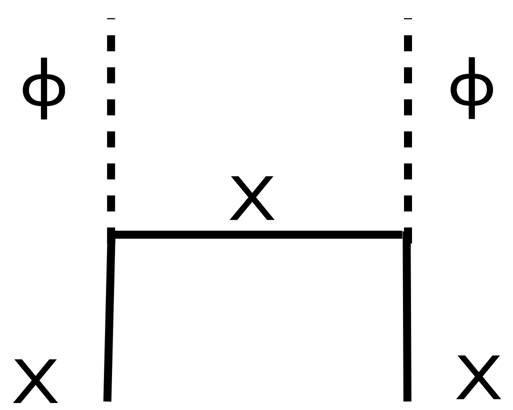
Kaplinghat, Linden, HBY (2015) (PRL Editors' suggestion)

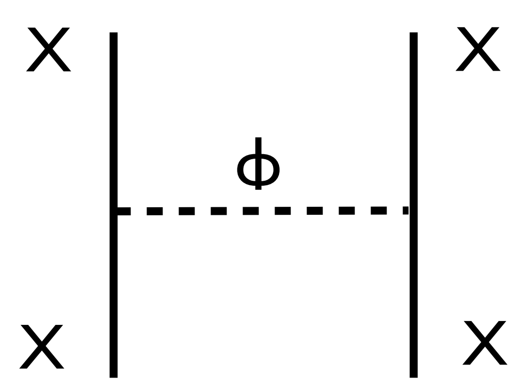
What If SIDM IS Hidden…

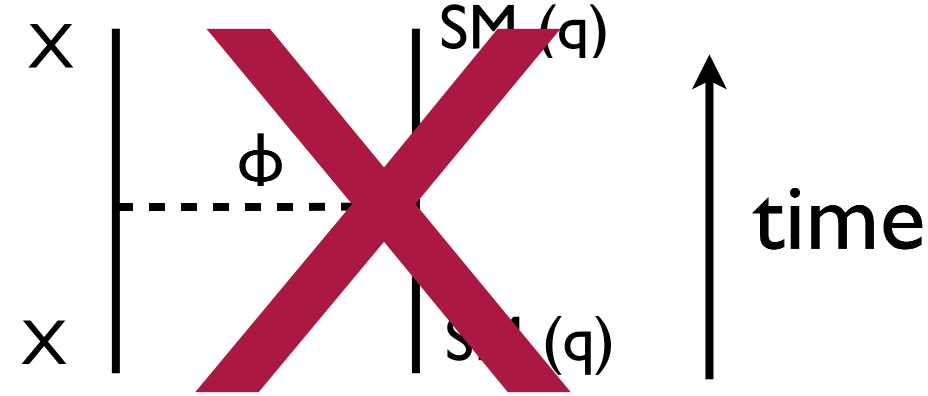
- The mediator decays before BBN: lifetime of ϕ is ~1 second

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







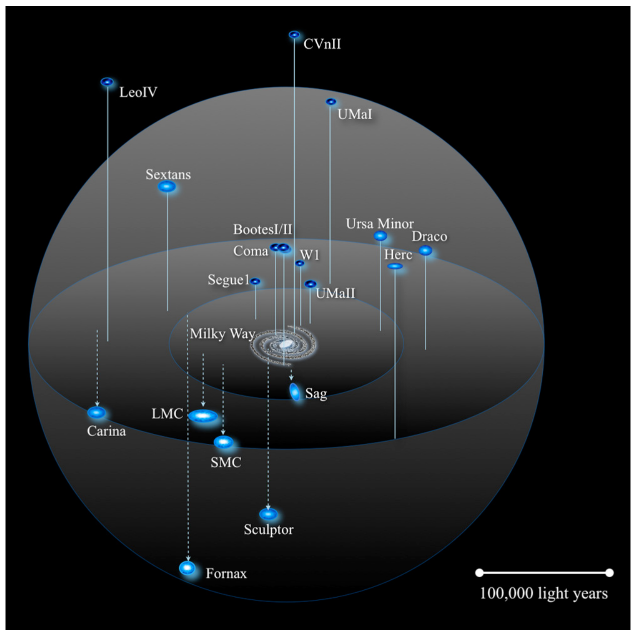


ϕ → ~~electrons/neutrinos~~

Nightmare scenario?

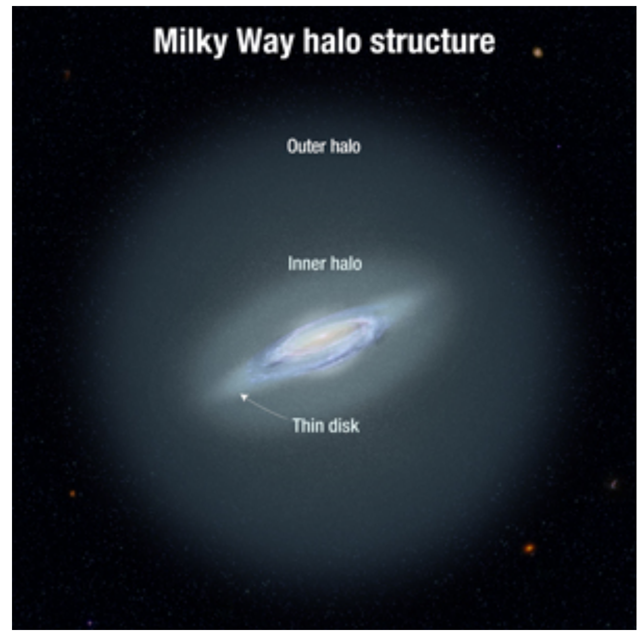
Idea 1: Dark Matter "Colliders"

Dwarf galaxies



"B-factory" (v~30 km/s)

MW-size galaxies



"LEP" (v~200 km/s)

Clusters

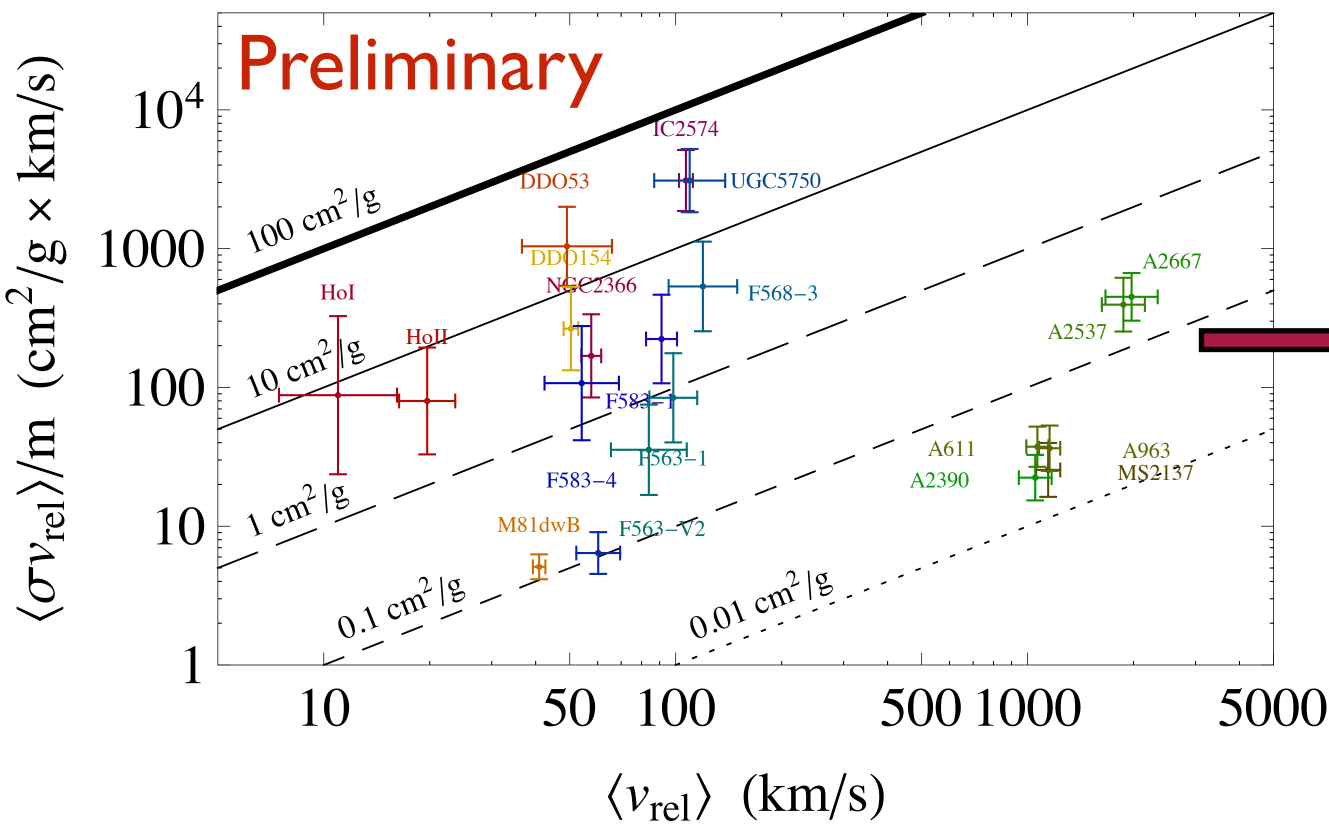
"LHC" (v~1000 km/s)

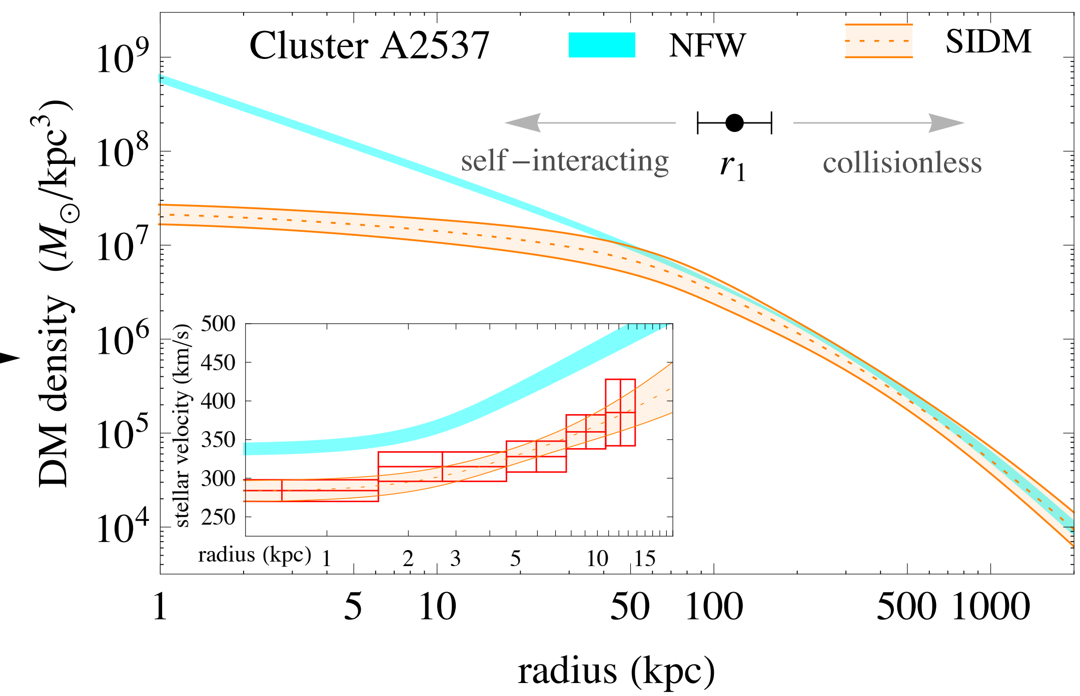
Self-scattering kinematics

Observations on all scales → Measure particle physics parameters

SIDM On All Scales

- Consider 7 THINGS dwarfs, 7 LSBs (blue), and 6 galaxy clusters





Kaplinghat, Tulin, HBY (in preparation)

$$\Gamma t_{\rm age} = \frac{\rho_0}{m_X}\langle\sigma v\rangle = N$$

$$\rightarrow \frac{\langle\sigma v\rangle}{m_X} = \frac{N}{\rho_0 t_{\rm age}}$$

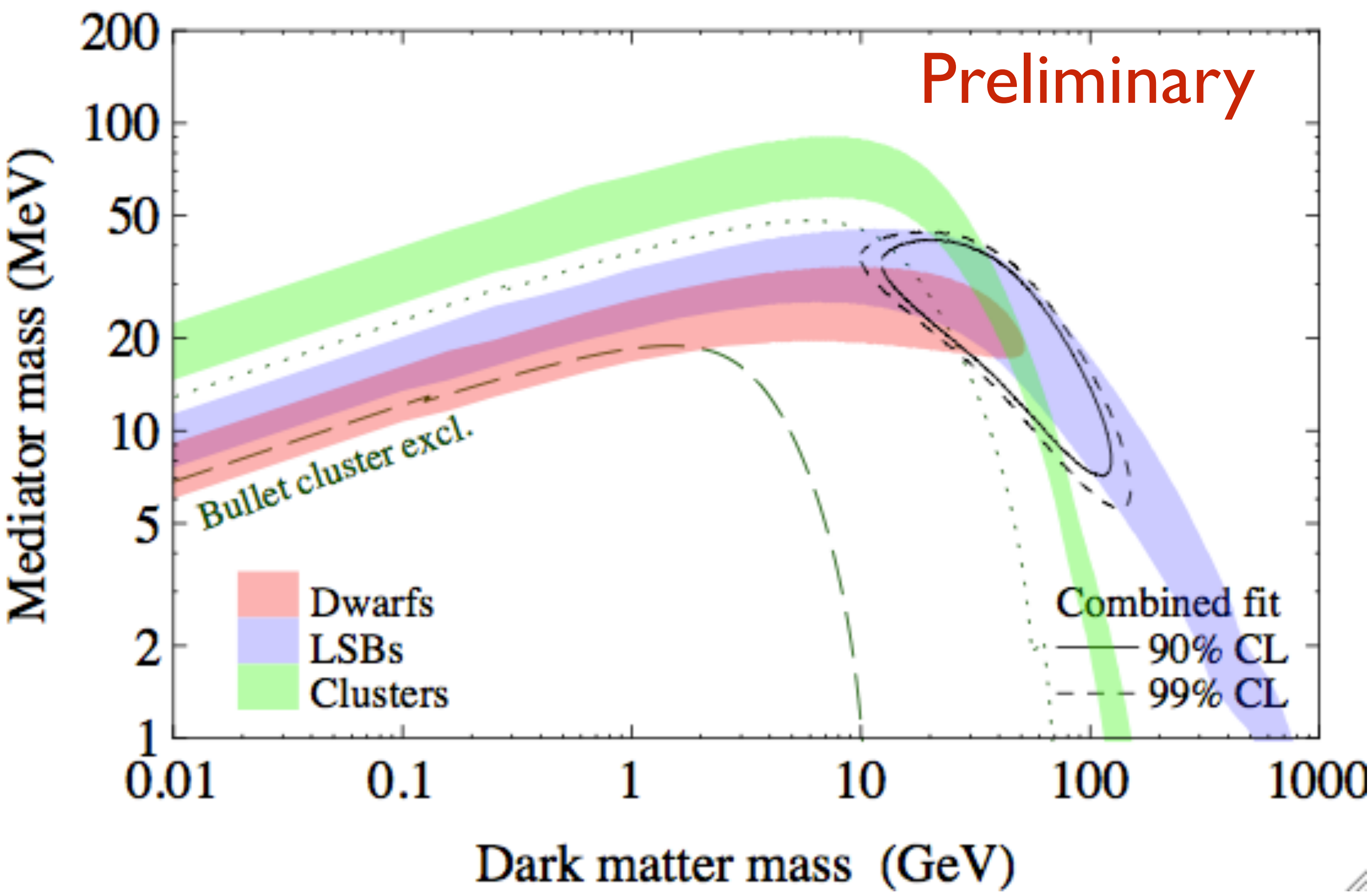
σ~1/v

Constant σ is disfavored!

Bullet Cluster: σ <1 cm^2/g

Measuring Dark Matter Mass

- Self-scattering kinematics determines SIDM mass



m_X v VS. m_ϕ

If m_X too large, $\sigma \sim 1/v^4$
σ too small for clusters

If m_X too small, $\sigma \sim$ const
σ too large for clusters

Mild dependence on α_X

$\alpha_X = 0.01$
m_X: ~10-200 GeV, m_ϕ: ~5-40 MeV

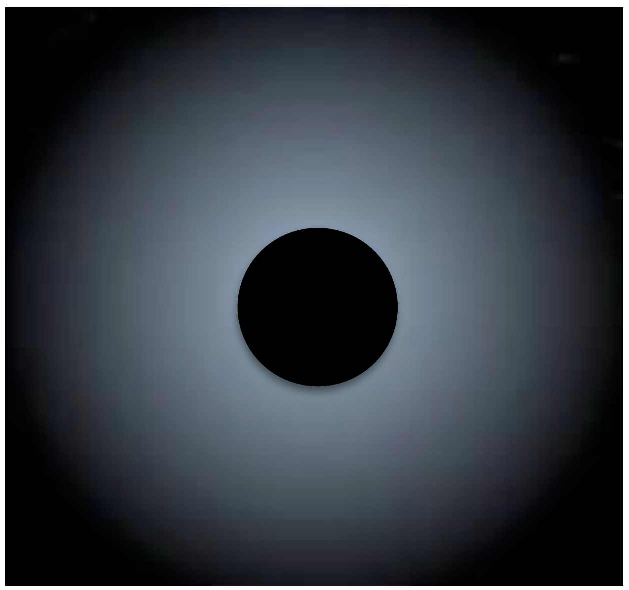
$$\sigma \sim \alpha_X^2 m_X^2 / m_\phi^4$$

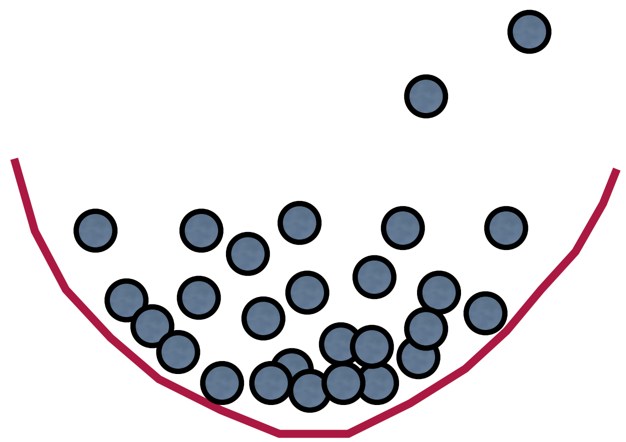
Kaplinghat, Tulin, HBY (in preparation)

Idea 2: Tying SIDM to Baryons

- SIDM: equilibrium

ideal gas with gravity





$$p = k_B T \rho / m$$

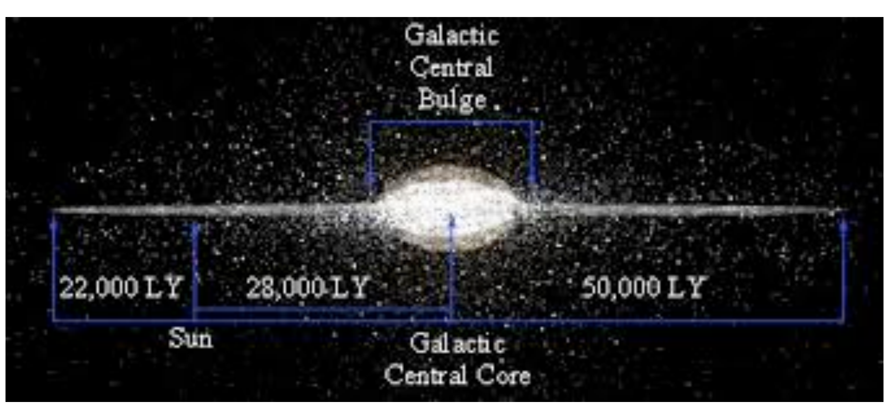
$$\boldsymbol{\nabla} p = -\rho \boldsymbol{\nabla} \Phi$$

$$\nabla^2 \Phi = 4\pi G(\rho + \rho_B)$$

- If $\Phi \sim \Phi_B$, SIDM follows the stellar distribution!

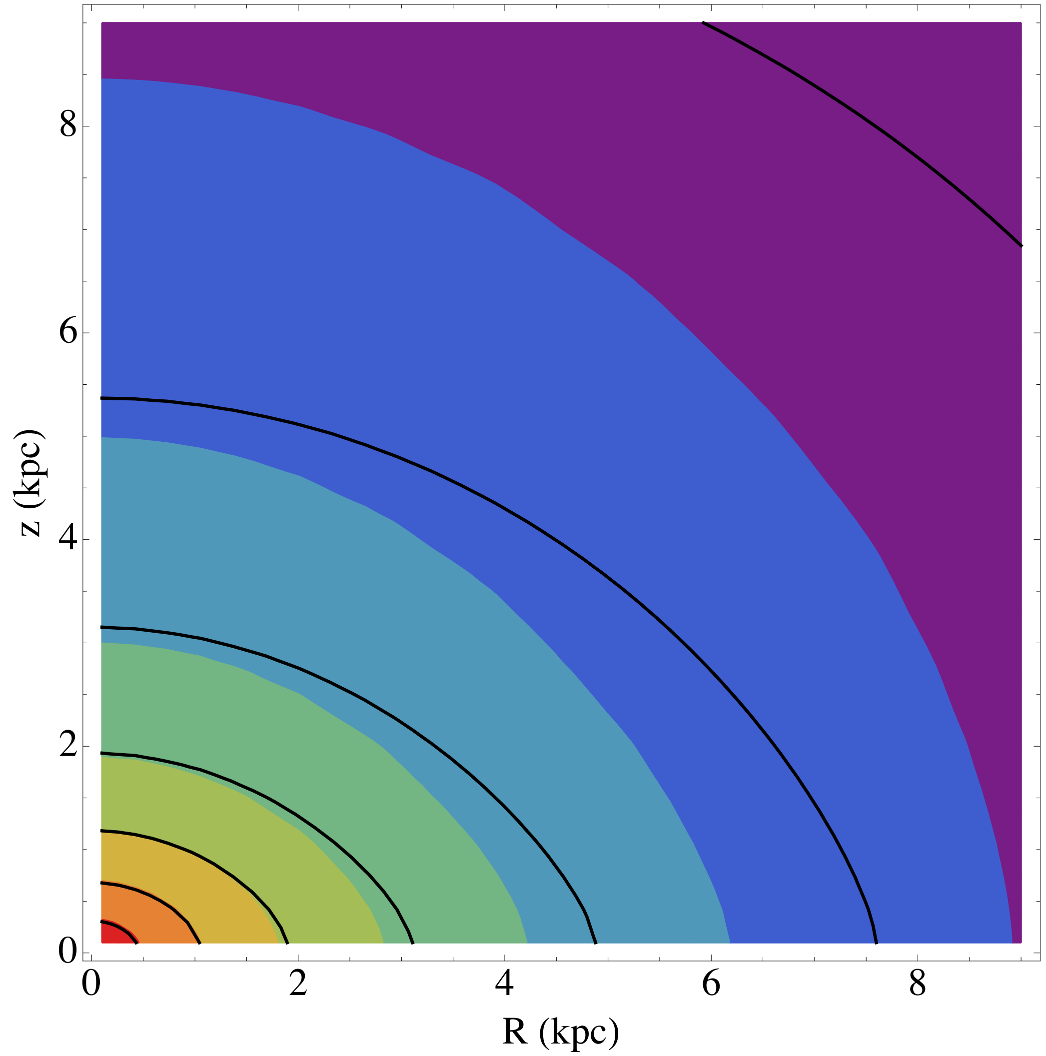
$$\nabla^2 \Phi = 4\pi G(\rho + \rho_B)$$

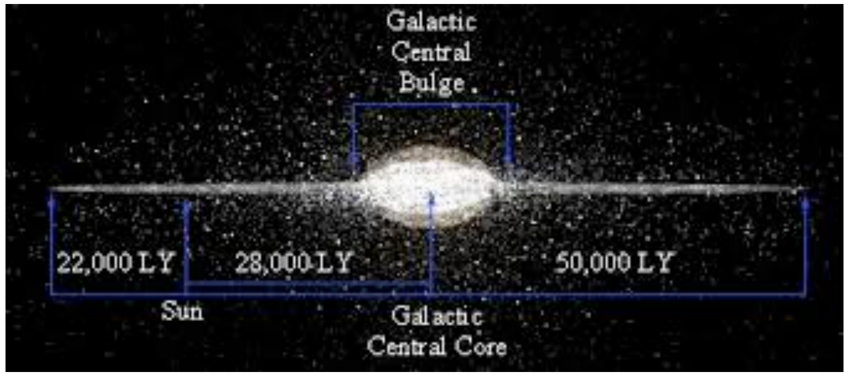
neglect

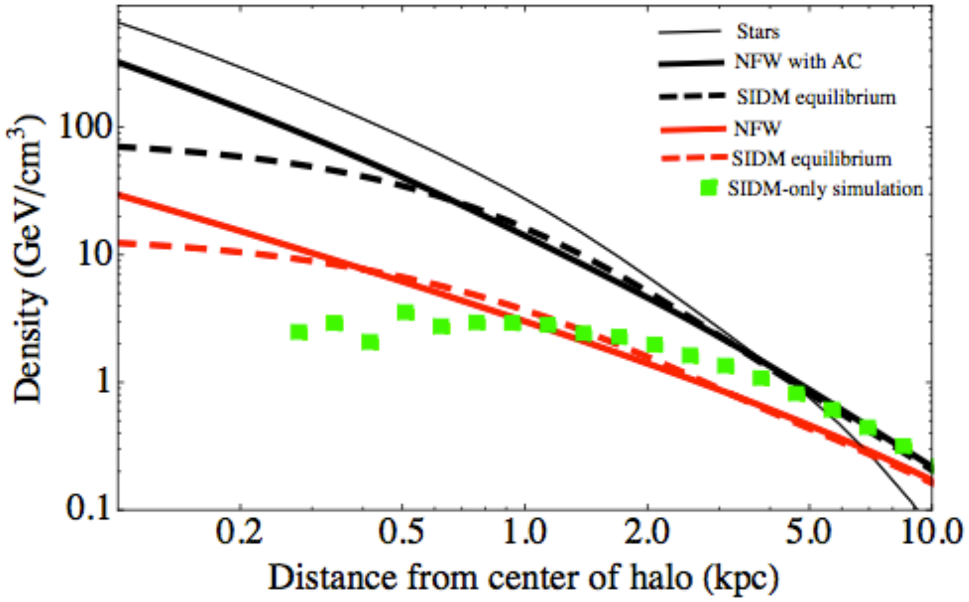


Halo Morphology: Milky Way

- SIDM particles follow the stellar distribution





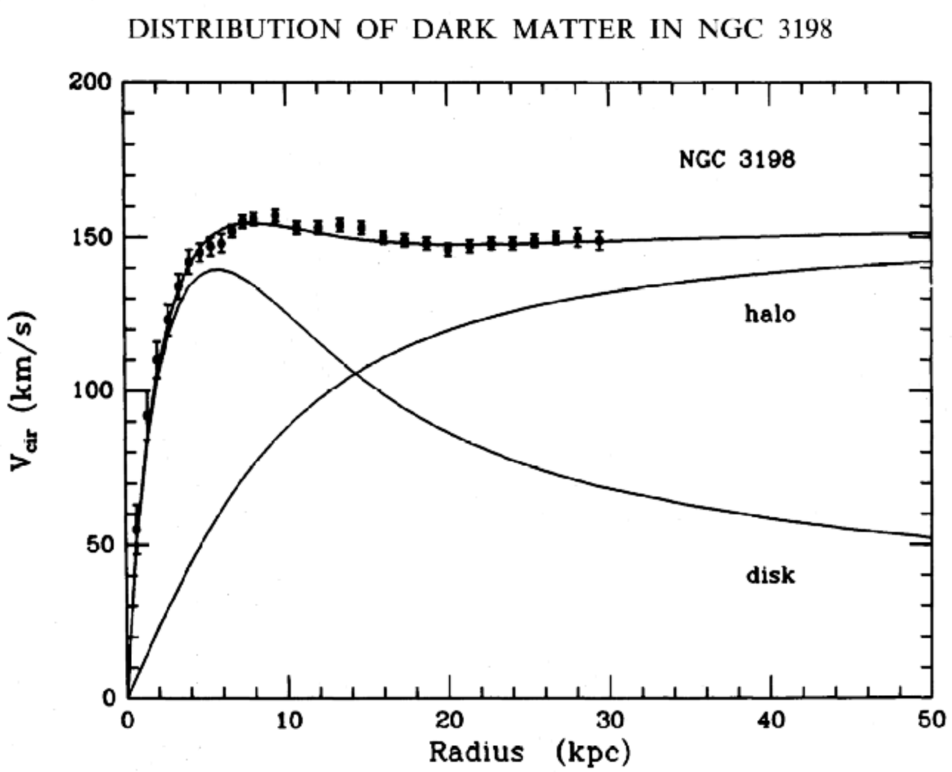


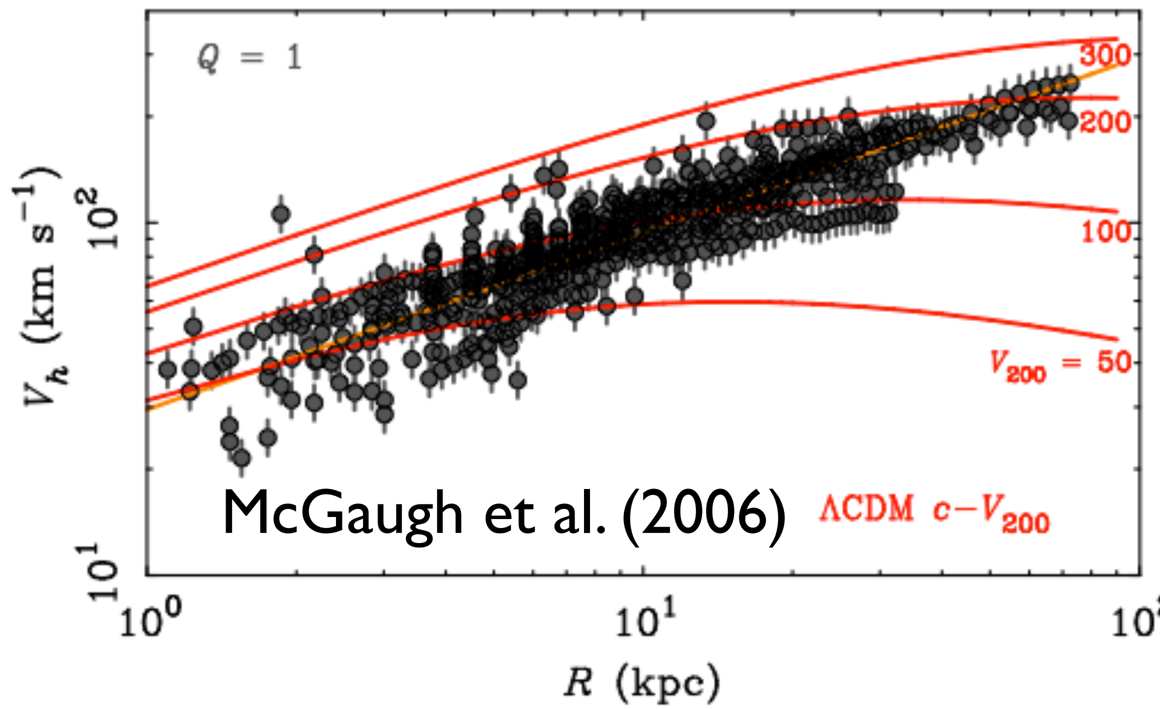
Constant density contours in cylindrical coordinates

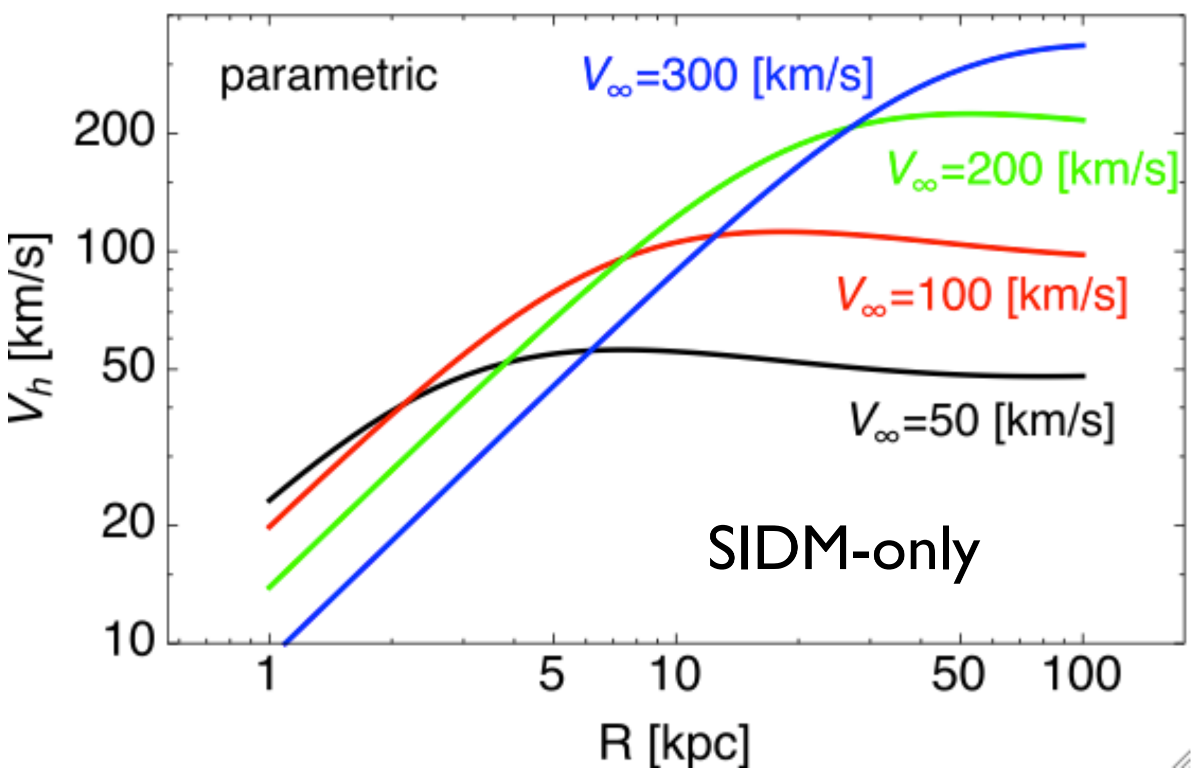
Kaplinghat, Linden, Keeley, HBY (2013) (PRL Editors' suggestion)

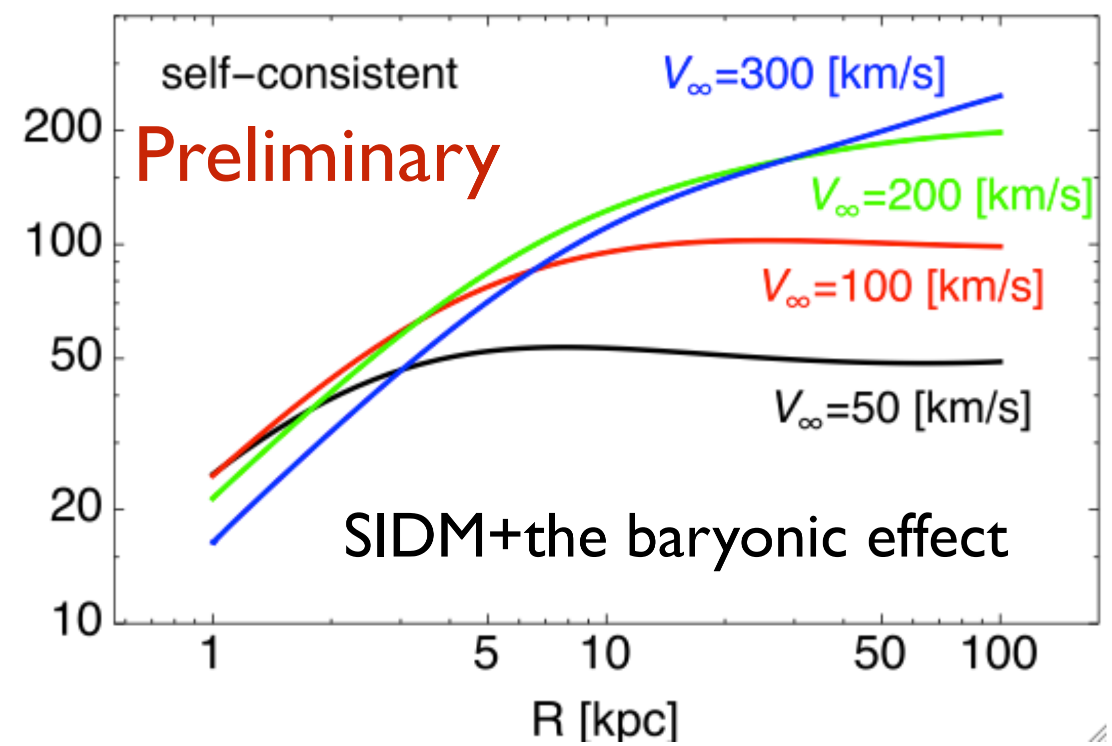
It has been confirmed by simulations

Idea 3: Rotation Curves









Kamada, Kaplinghat, HBY (in preparation)

Summary

- It is time to think about new approaches to the dark matter problem
- Observations have told us more than just Ω_m
- SIDM has novel features
  - Smoking-gun signatures in direct and indirect detection experiments
  - Measure dark matter mass via self-scattering kinematics
  - Tie dark matter to baryons
  - Explain the rotation curves of spiral galaxies better than CDM