The Self-Interacting Dark Matter Paradigm

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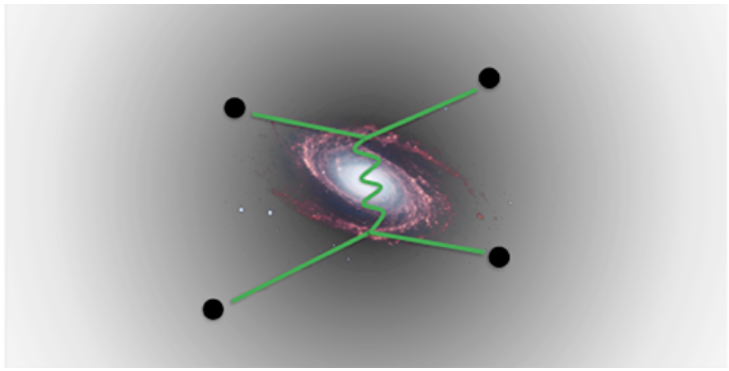
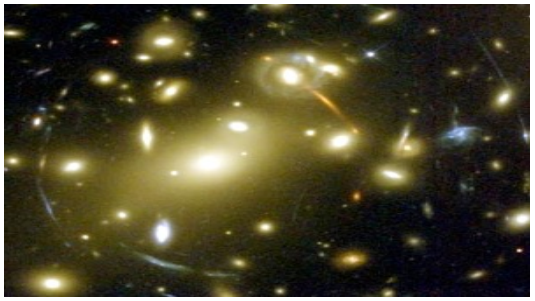
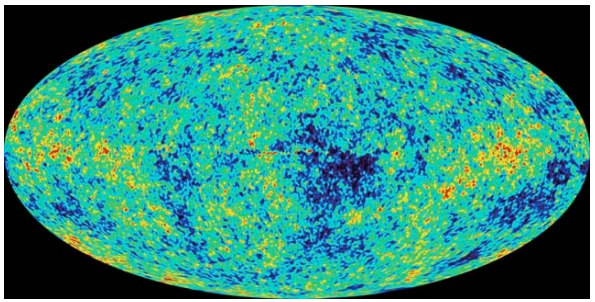


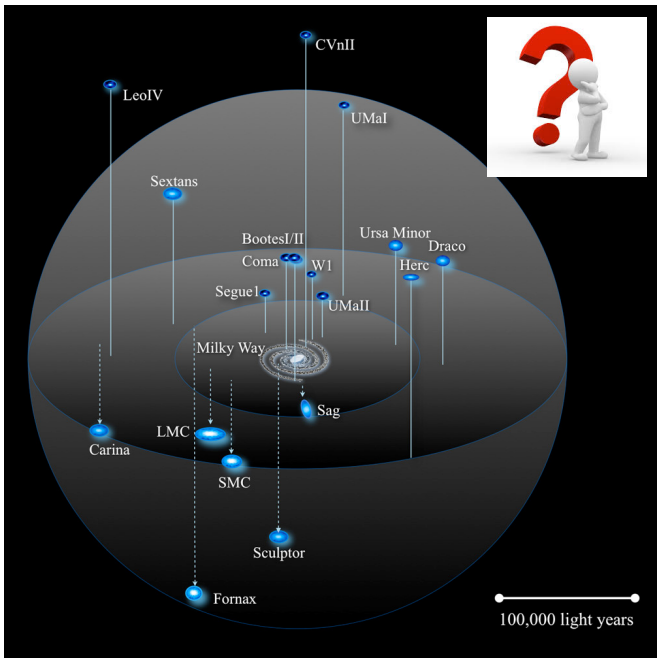
Mitchell Workshop, TAMU, May 23-26, 2016

Cold Dark Matter

- Large scales: very well

- Small scales (dwarf galaxies, galaxies, galaxy clusters): ?



- Core VS. Cusp problem

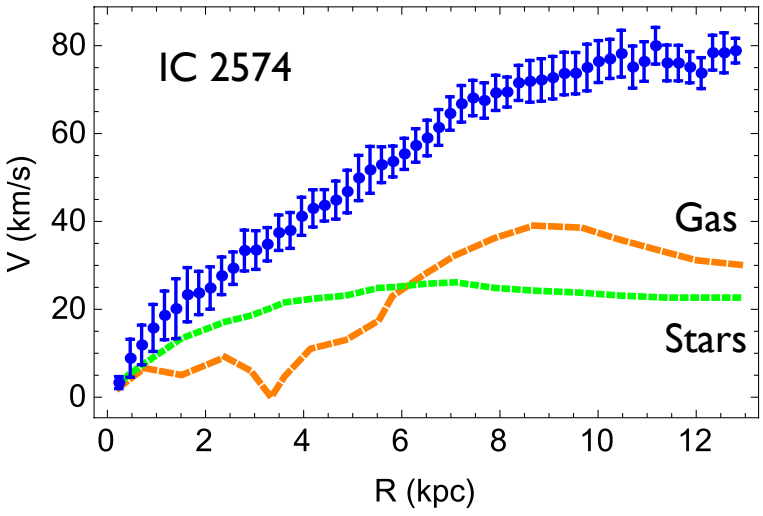
  Flores, Primack (1994), Moore (1994)

- Too-big-to-fail problem

  Boylan-Kolchin, Bullock, Kaplinghat (2011)

Core VS. Cusp Problem

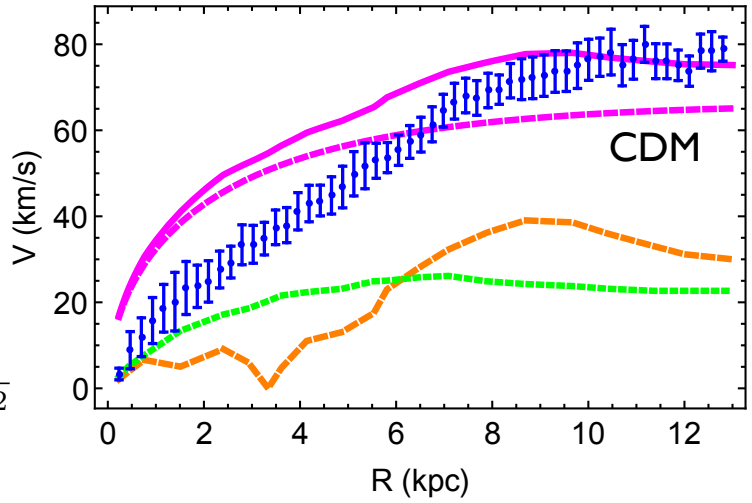
- DM-dominated systems (dwarfs, LSBs) from THINGS Oh+(2011)

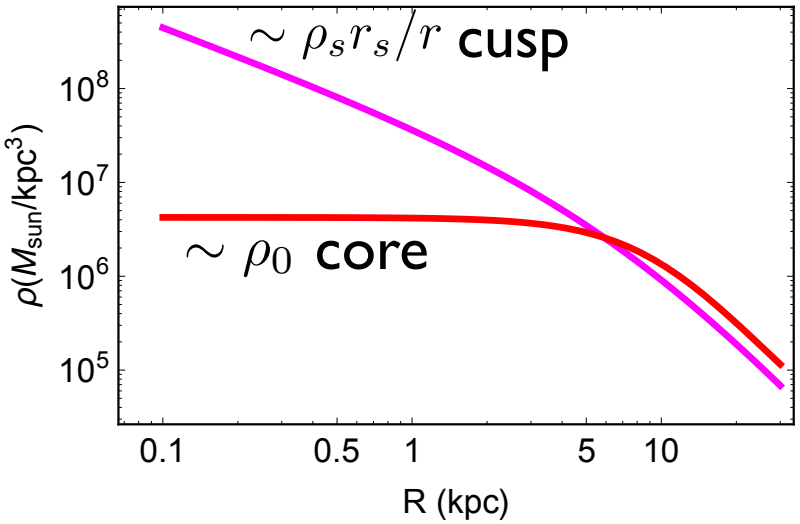


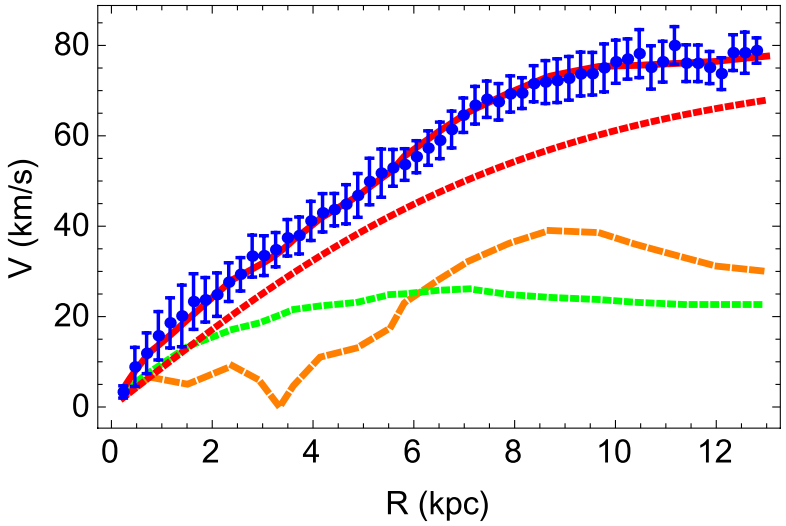
NFW

$$\frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

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



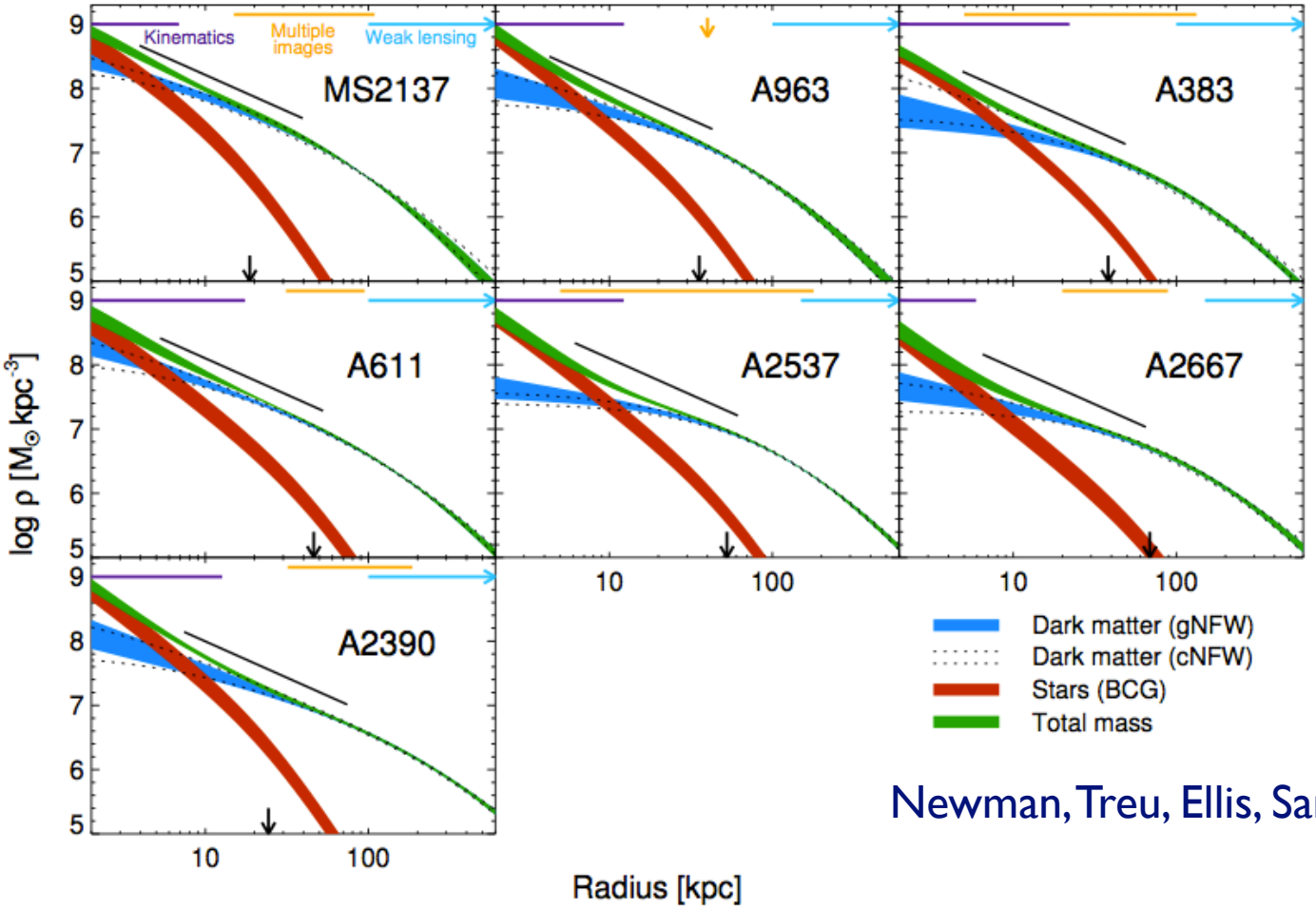


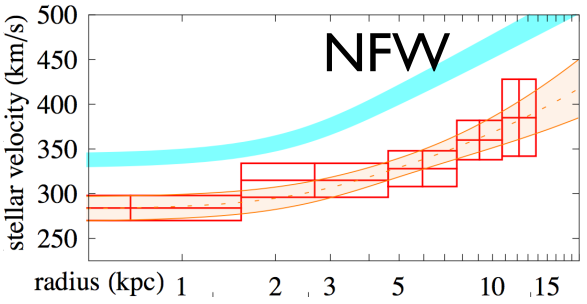


- CDM halos too dense in the inner regions

Even Galaxy Clusters

- Seven well-resolved galaxy clusters



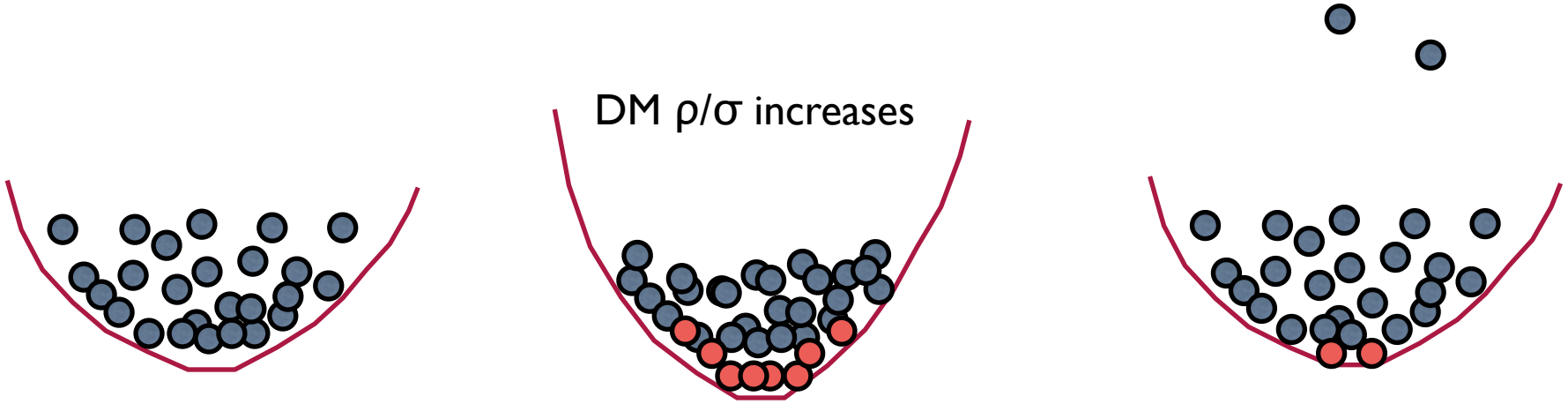


Newman, Treu, Ellis, Sand (2013)

- Remove DM from the central region of halos

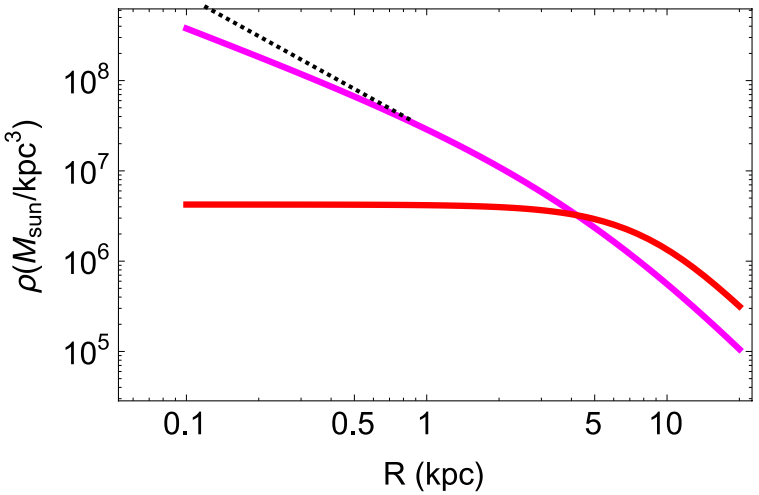
Baryon Physics?

- Violent baryonic feedback process



Baryonic Infall

Supernova Explosion



Blumenthal, Flores, Primack (1986)

gravitational binding energy VS.
energy injection from supernovae

only works $r<r_*$

Navarro, Eke, Frenk (1996)

Baryon Physics?

- Violent baryonic feedback process

See Andrew Pace's talk

depends on the stellar mass
Governato+ (2012)

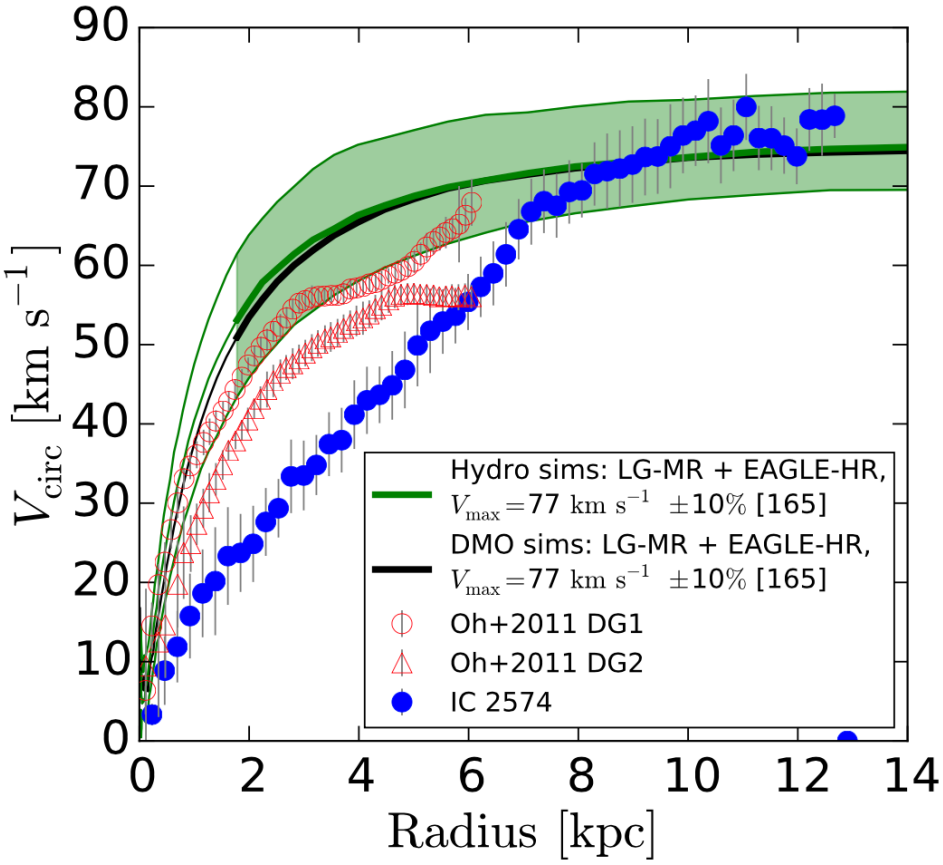
depends on when it occurs
Onorbe+(2015)

galaxies with cores larger than r_*
Papastergis, Shankar (2015)

depends on the recipe of hydrodynamical simulations!

Other group did not see the effect
Oman+ (2015) ("NFW" group)

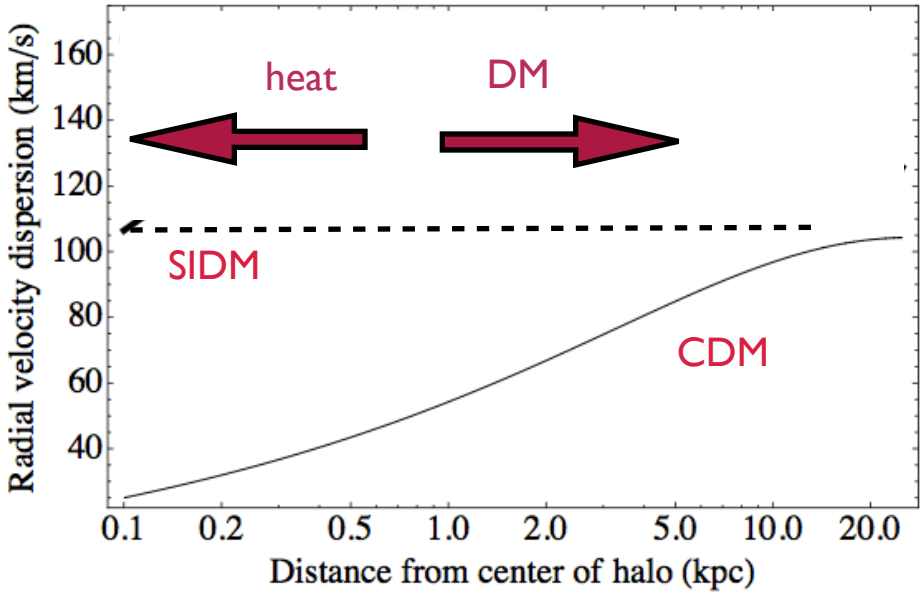
We are still debating!

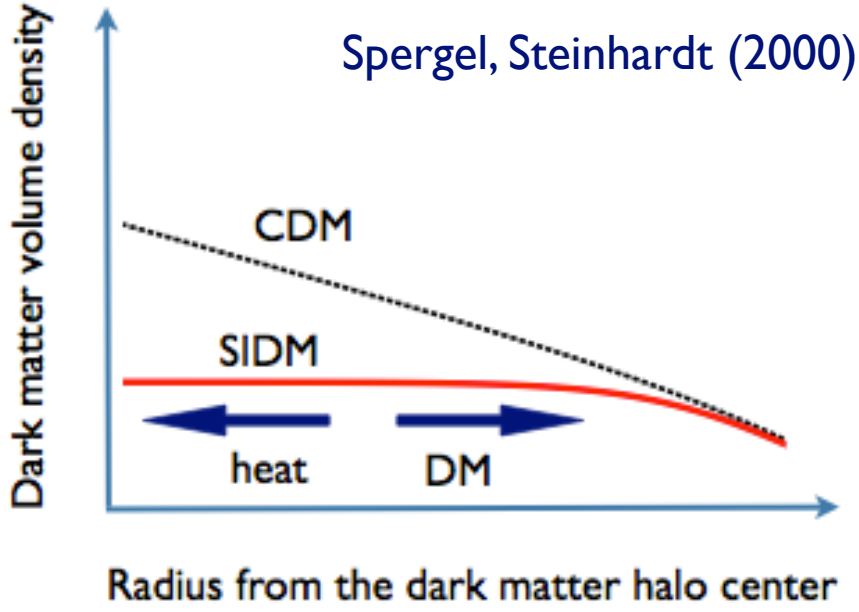


Oman+ (2015)

Dark Matter Physics?

- Self-interactions can reduce the central DM density





Recent simulations: Irvine group, MIT group

$\sigma/m_X \sim 1\ \mathrm{cm}^2/\mathrm{g}$

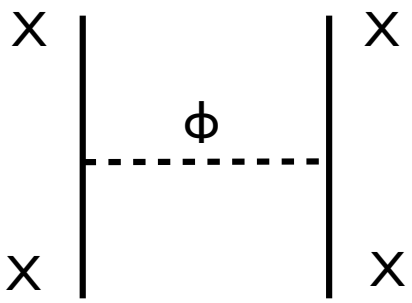
$$\Gamma \simeq n\sigma v = (\rho/m_X)\sigma v \sim H_0$$

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

Bullet Cluster: $<1\ \mathrm{cm}^2/\mathrm{g}$

NOT a WIMP: $\sigma \sim 10^{-38}\ \mathrm{cm}^2\,(m_X/100\ \mathrm{GeV})$

SIDM Particle Physics

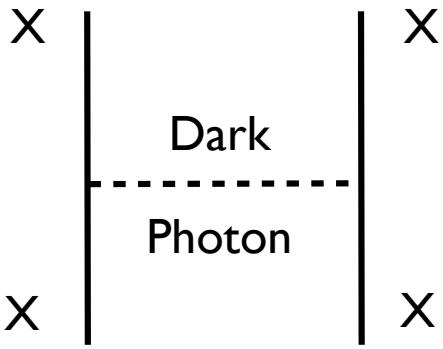


- SIDM indicates light mediators

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

in the perturbative and small velocity limit

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

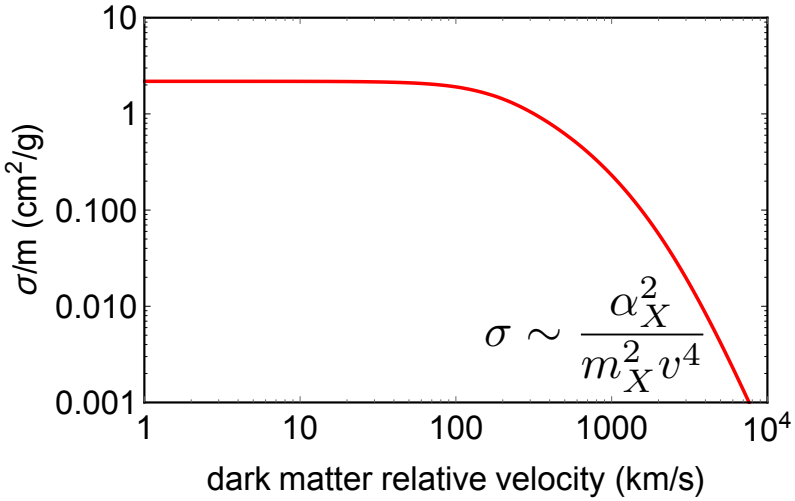


$$V(r) = \pm \frac{\alpha_X}{r} e^{-m_\phi r}$$

$m_X v >> m_\phi$ Rutherford limit

$m_X v << m_\phi$ contact interaction

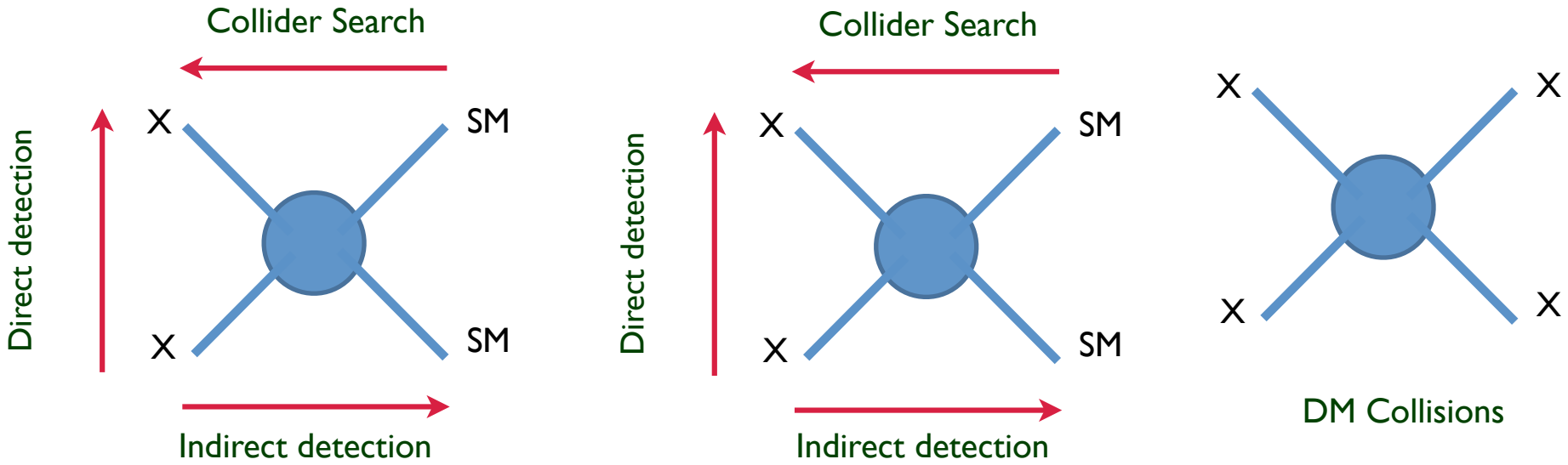
Bullet Cluster: <1 cm^2/g



Feng, Kaplinghat, Tu, HBY (2008); Feng, Kaplinghat, HBY (2009); Buckley, Fox (2009), Loeb, Weiner (2010); Tulin, HBY, Zurek (2012) (2013)

The SIDM Paradigm

- The SIDM paradigm is predictive



the WIMP paradigm

the SIDM paradigm

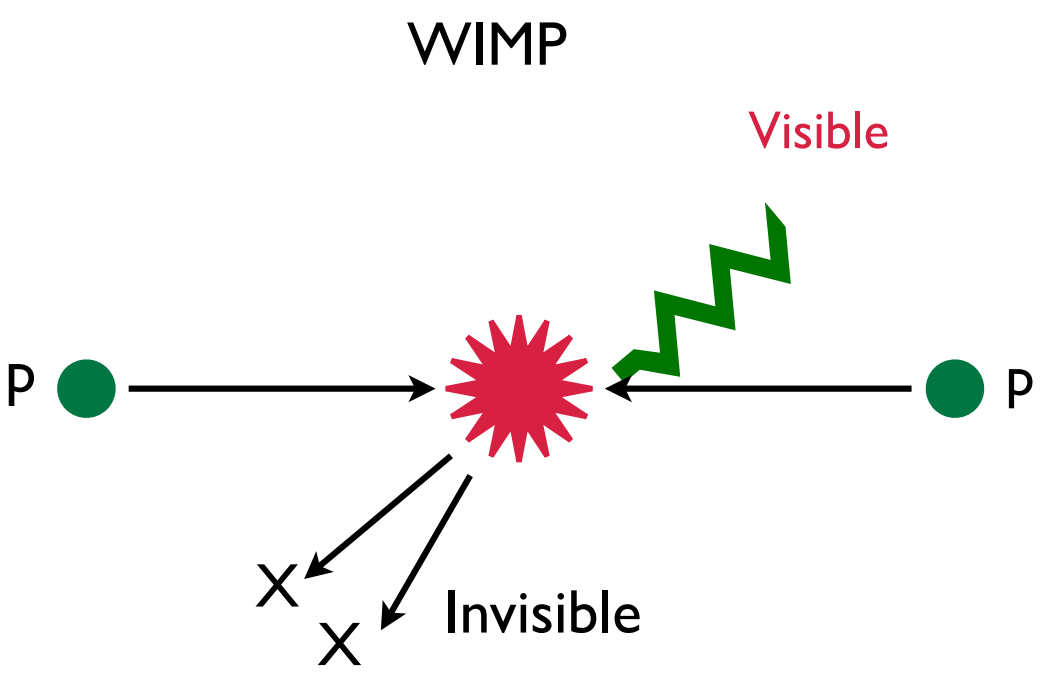
Collider search: Bjorken, Essig, Schuster, Toro (2009); Bai, Rajaraman (2011), Daci, De Bruyn, Lowette, Tytgat, Zaldivar (2015); An, Echenard, Pospelov, Zhang (2015); Tsai, Wang, Zhao (2015)

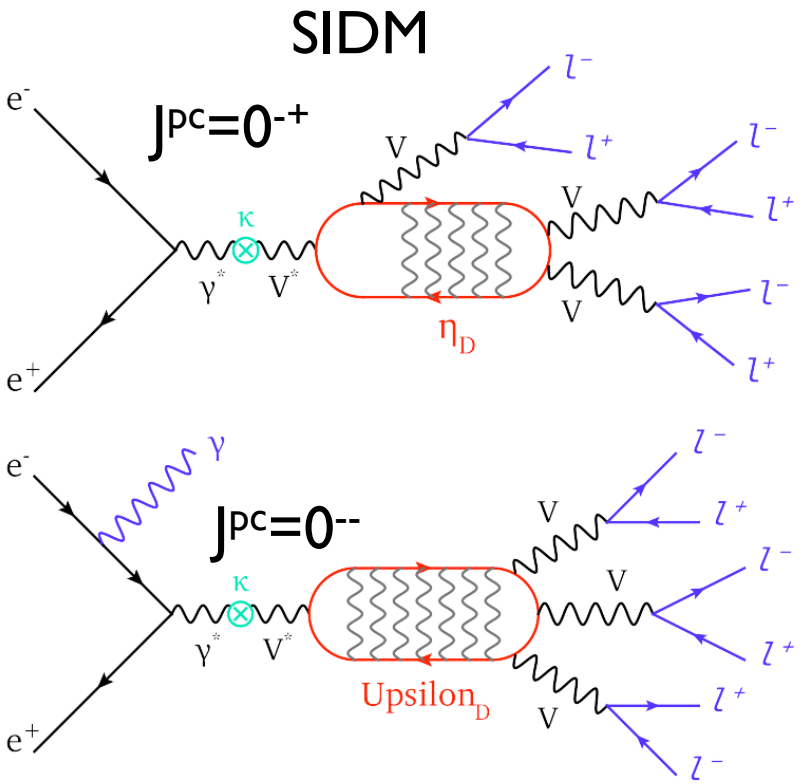
Indirect search: Boddy+ (2014); Kaplinghat, Linden, HBY (2015); Feng, Smolinsky, Tanedo (2015,2016)

Direct search: Del Nobile, Kaplinghat, HBY (2015)

SIDM at Colliders

- Striking collider signals





$p\bar{p} \rightarrow$ Monojet+Missing Energy

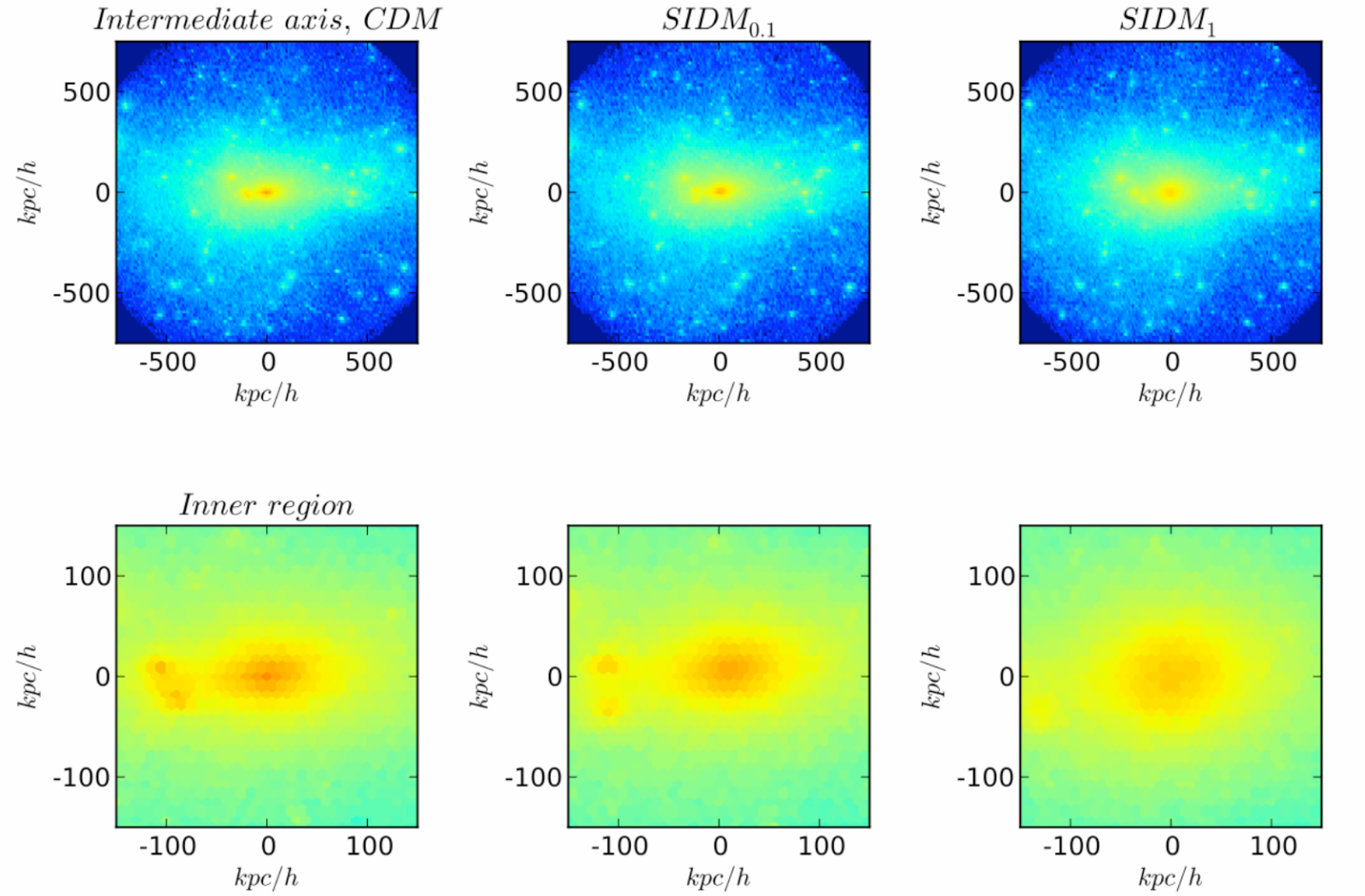
An, Echenard, Pospelov, Zhang (PRL 2015)

Tsai, Wang, Zhao (PRD 2015)

Focus on smoking-gun signatures, independent of DM-SM interactions

Idea 1: Halo Morphology

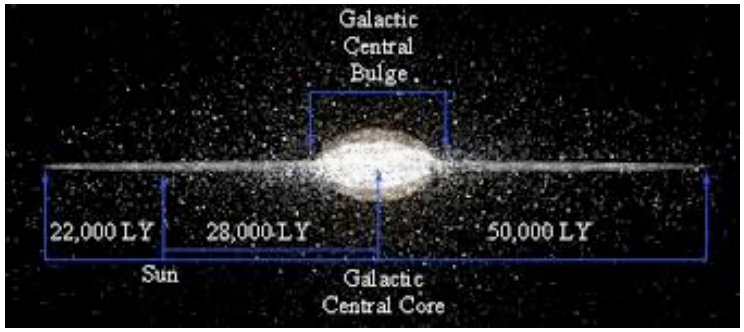
- SIDM halos are more spherically symmetric than CDM ones



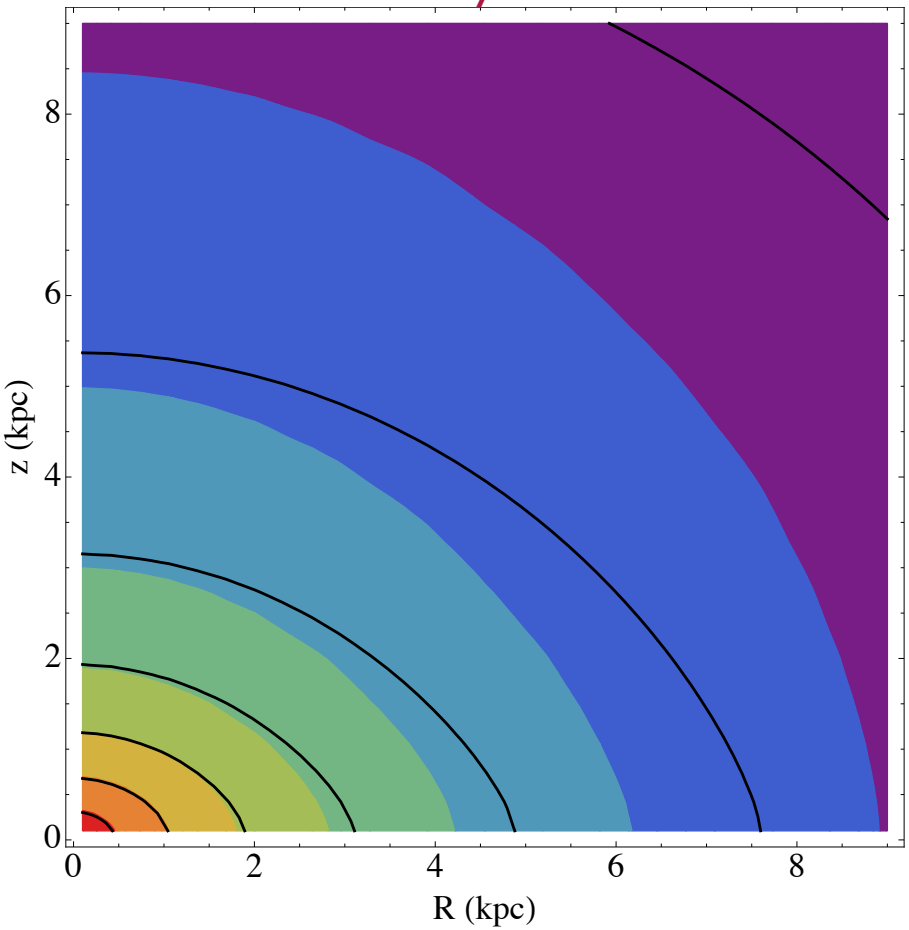
Peter+(2013)

Tying SIDM to Baryons

- SIDM may follow the stellar distribution; halo morphology



SIDM density contour

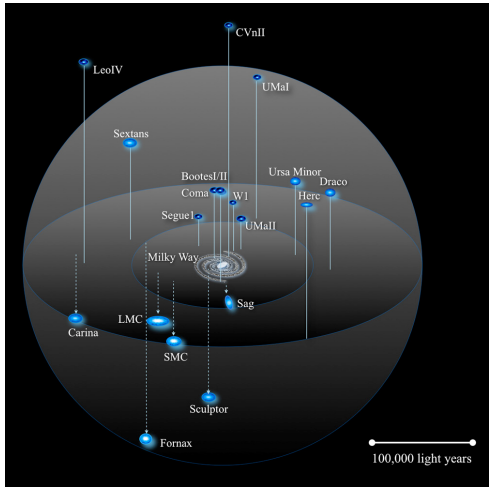


Kaplinghat, Linden, Keeley, HBY (PRL 2014)

Correlation between the stellar distribution and the SIDM distribution

Idea 2: Dark Matter "Colliders"

Dwarf galaxies

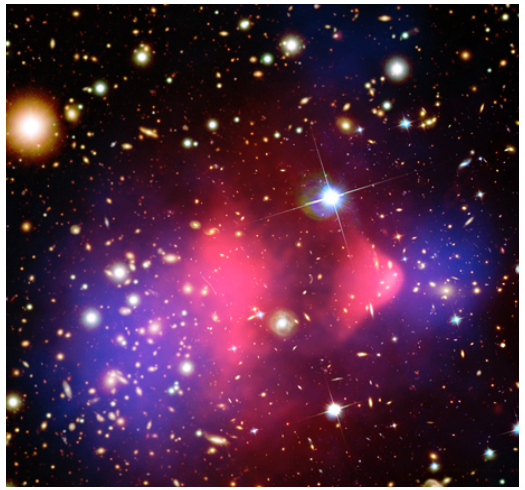


"B-factory" (v~30 km/s)

MW-size galaxies

"LEP" (v~200 km/s)

Clusters



"LHC" (v~1000 km/s)

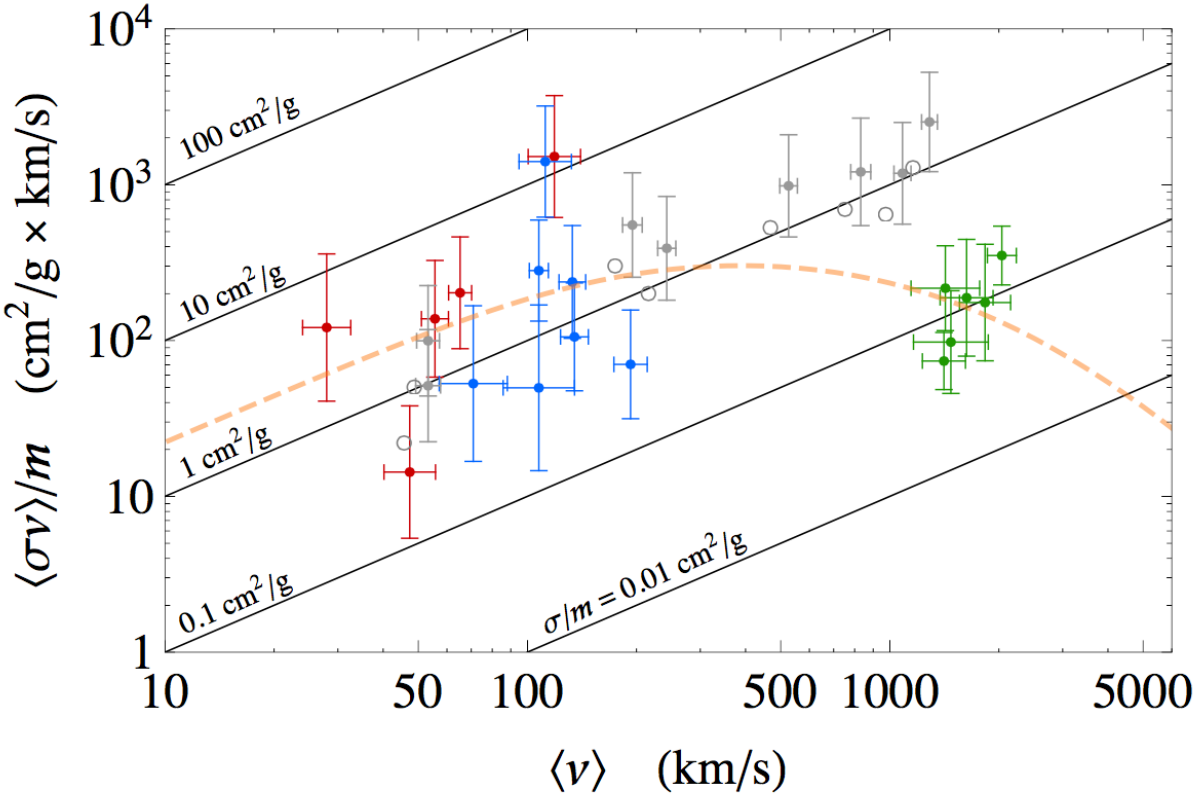
Observations on all scales

Self-scattering kinematics

Measure particle physics parameters σ_X, m_X, g_X

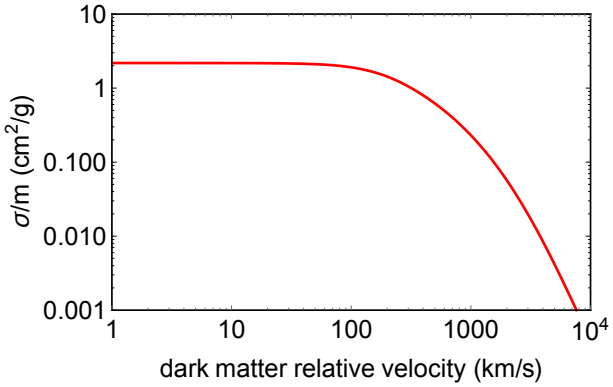
SIDM From Dwarfs to Clusters

- Consider 5 THINGS dwarfs (red), 7 LSBs (blue), 6 galaxy clusters (green)
- 8 simulated halos with σ/m=1 cm^2/g (gray) for calibration



Outliers:
Due to scatter in halo concentration

favors a mild v-dependence



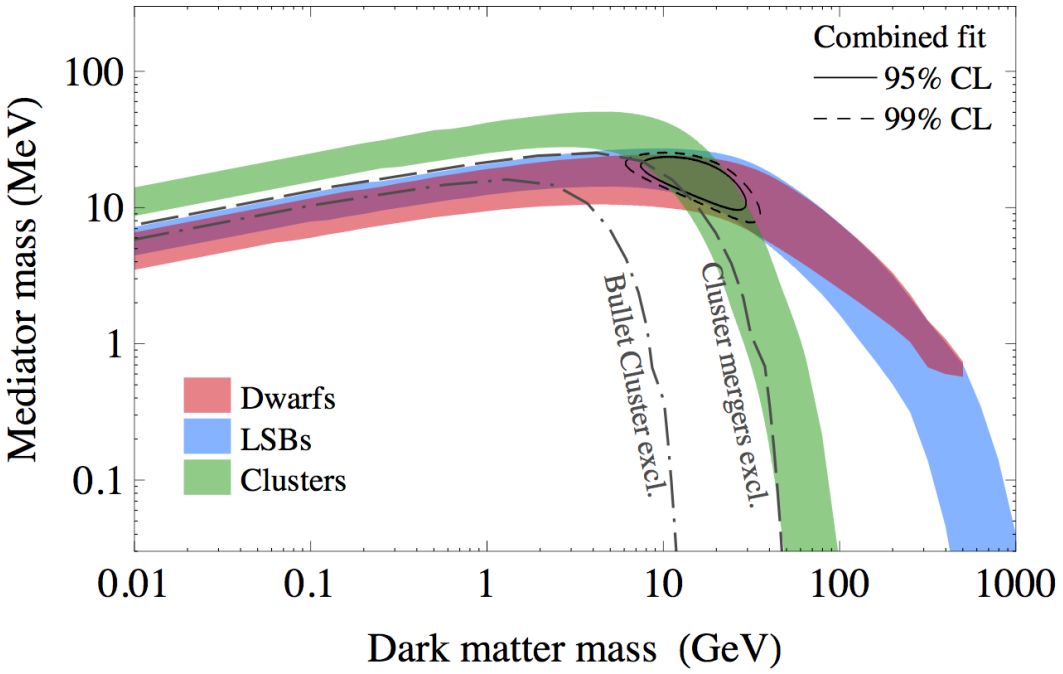
Galaxies: ~1–2 cm^2/g
Clusters: ~0.1 cm^2/g

Bullet Cluster: <1 cm^2/g

Kaplinghat, Tulin, HBY (PRL 2015)

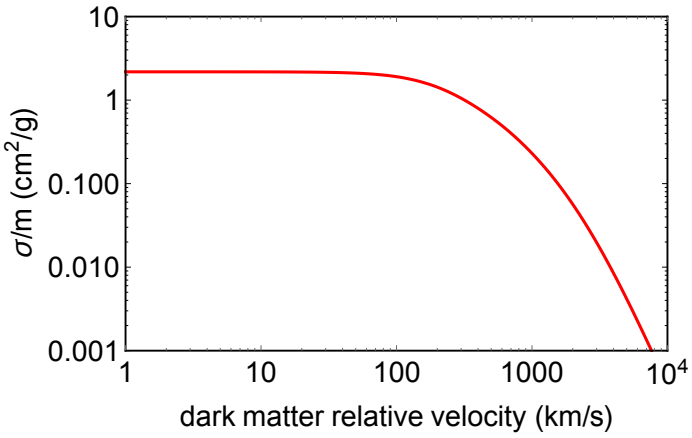
Measuring Dark Matter Mass

- Self-scattering kinematics determines SIDM mass



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

m_X v VS. m_ϕ 10^{-3} $m_X \sim m_\phi$



α_X=1/137

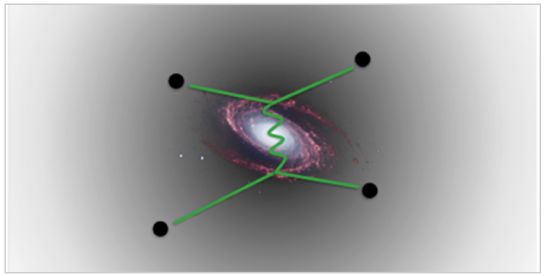
m_X: ~15 GeV, m_ϕ: ~15 MeV

Kaplinghat, Tulin, HBY (PRL 2015)

mild dependence on α_X

α_X=0.001–0.1

m_X: ~5-30 GeV



COSMOLOGY

Synopsis: A Little Empty Inside

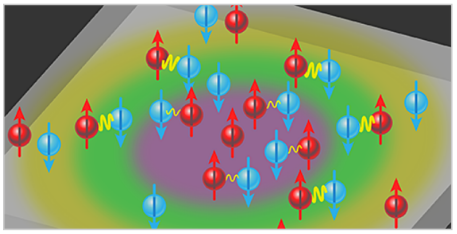
January 28, 2016

A new model has allowed researchers to test a theory for why the centers of dark matter halos are less dense than expected. **Read More »**

FEATURE

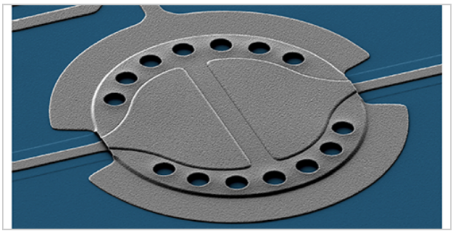
Q&A: Physics of the Animal World

January 28, 2016



ATOMIC AND MOLECULAR PHYSICS

Viewpoint: Journey from Classical to Quantum in Two Dimensions



QUANTUM PHYSICS

Synopsis: Tiny Oscillator Works as Photon Changing Room

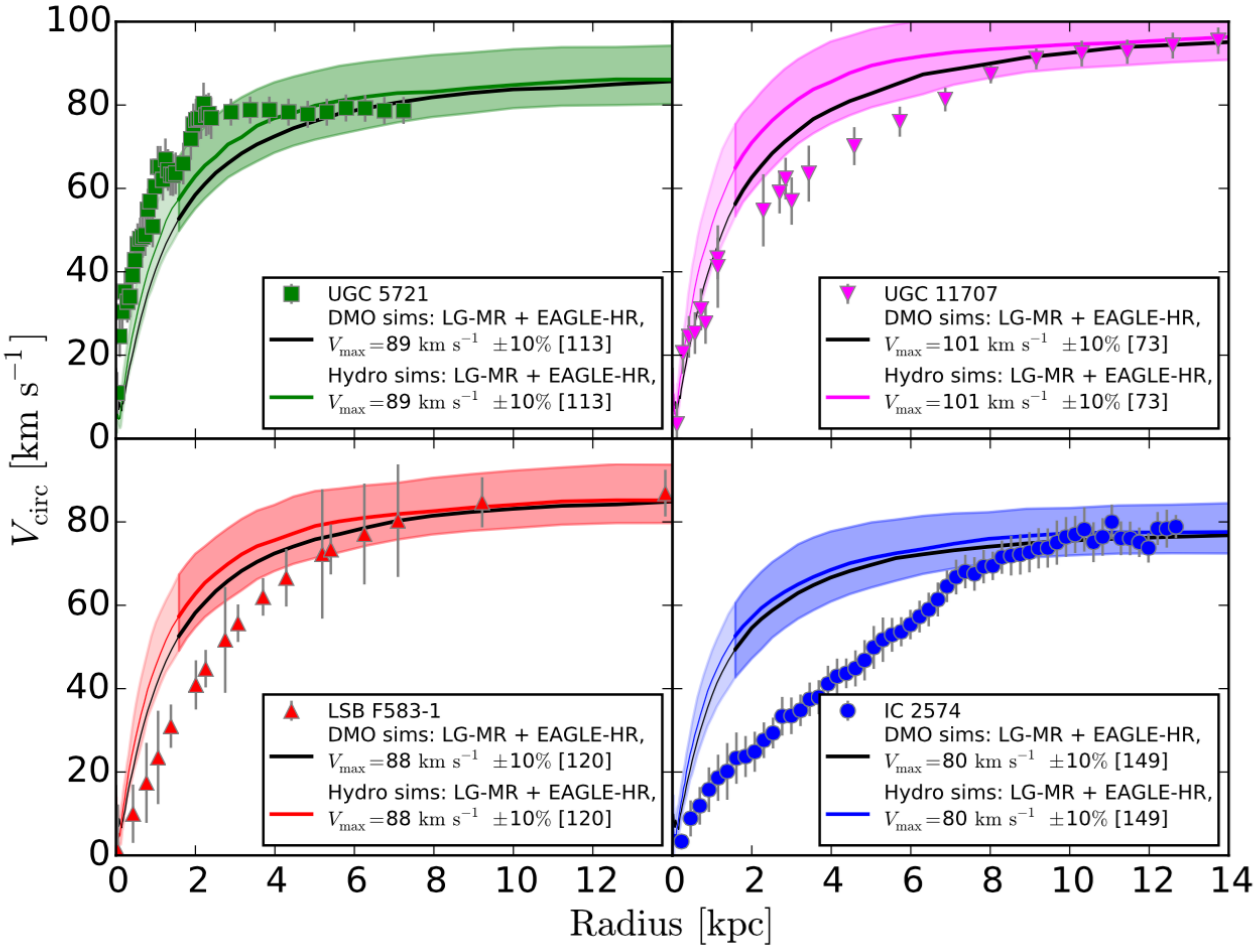
Summary

- It is time to think about new approaches to the dark matter problem
- CDM has serious issues on galactic scales
- The SIDM paradigm provides a solution with novel features
  - Direct, indirect, and collider signals
  - Tie dark matter to baryons
  - Measure dark matter mass via self-scattering kinematics

Go beyond the small-scale issues

Diversity

- Puzzle 1: The diversity of spiral galaxies

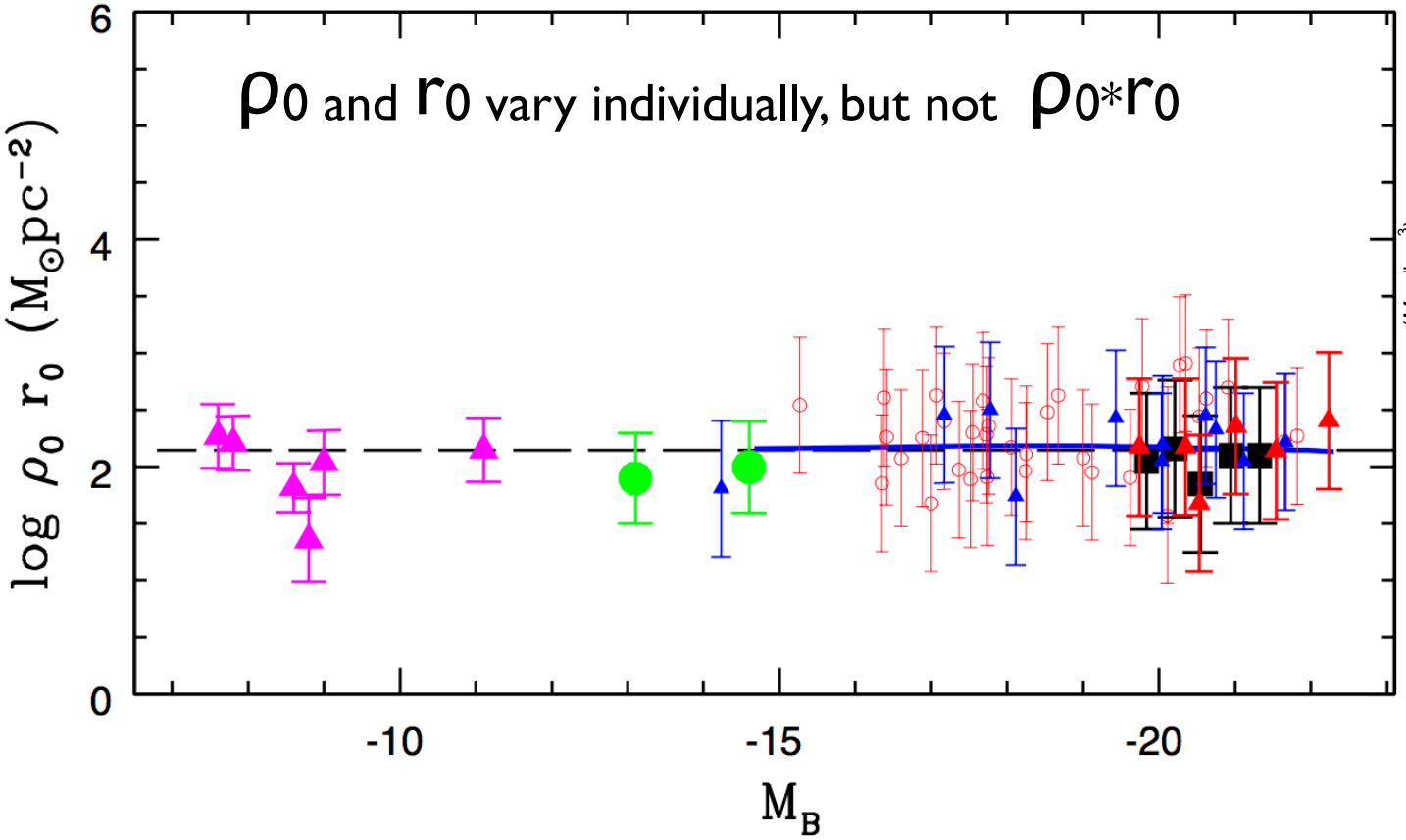


Oman+ (2015)

de Naray, Martinez, Bullock, Kaplinghat (2009)

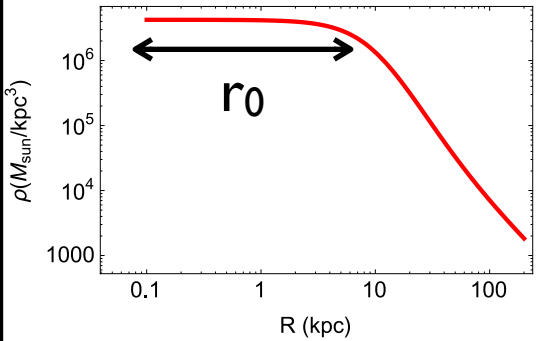
Uniformity

- Puzzle 2: Nearly constant DM halo surface density



Donato+(2009)

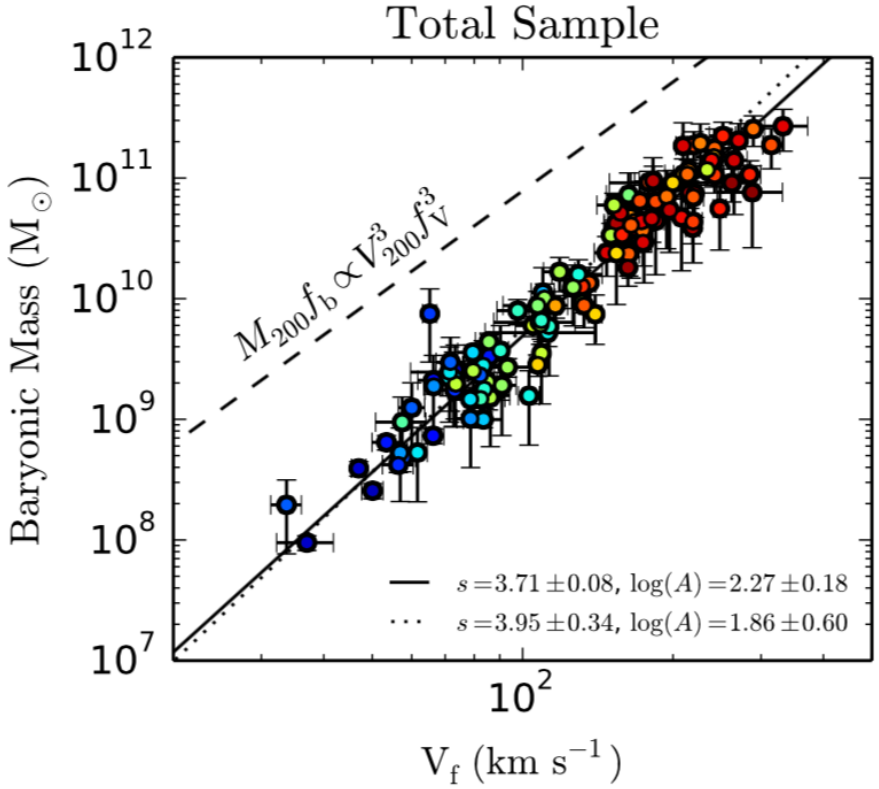
Kormendy, Freeman (2004)

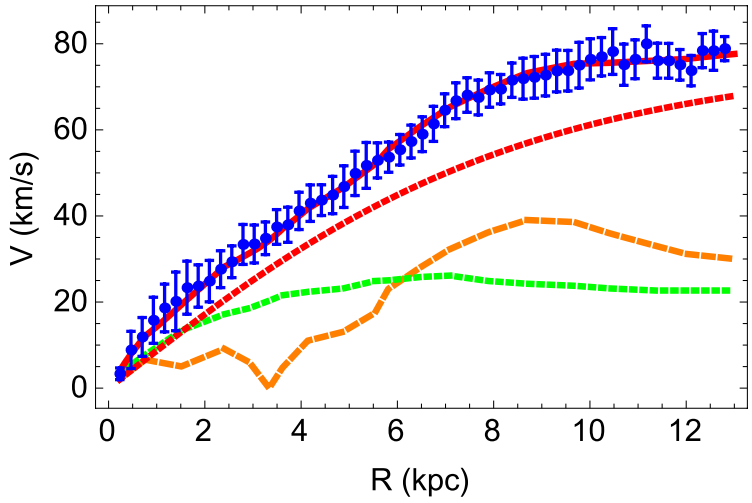


$$\rho(r_0) = \rho_0/2$$

Baryon-Halo Conspiracy

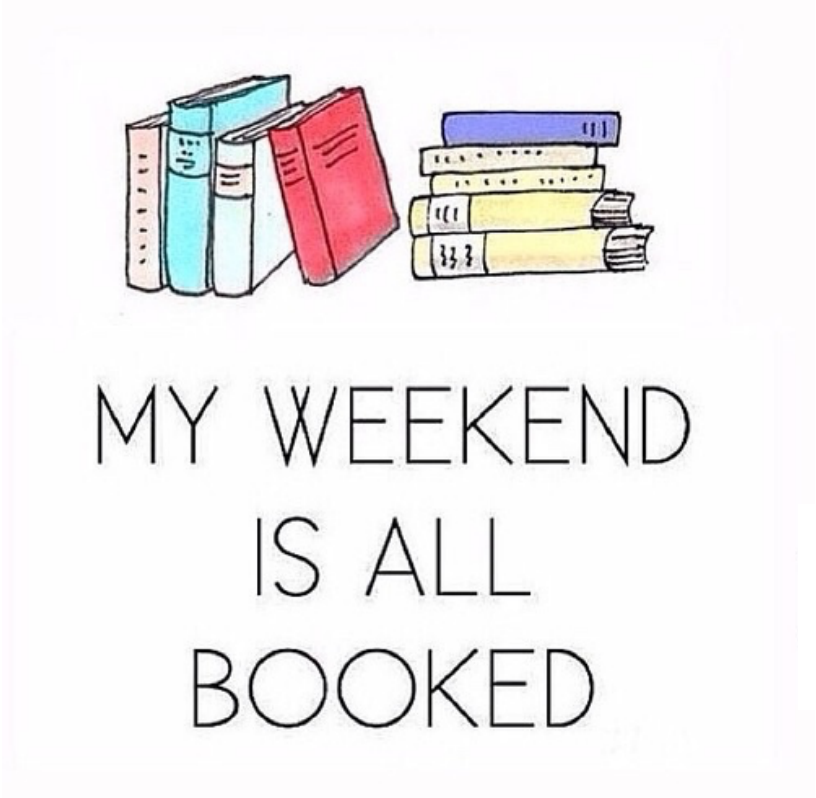
- Puzzle 3: The baryonic Tully-Fisher relation





Lelli, McGaugh, Schombert (2016)

Stay Tuned!



Thank You