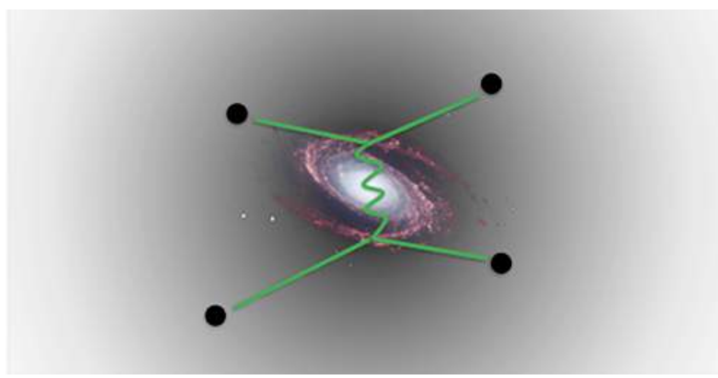
Standard Structure Formation in CDM: Successes & Failures

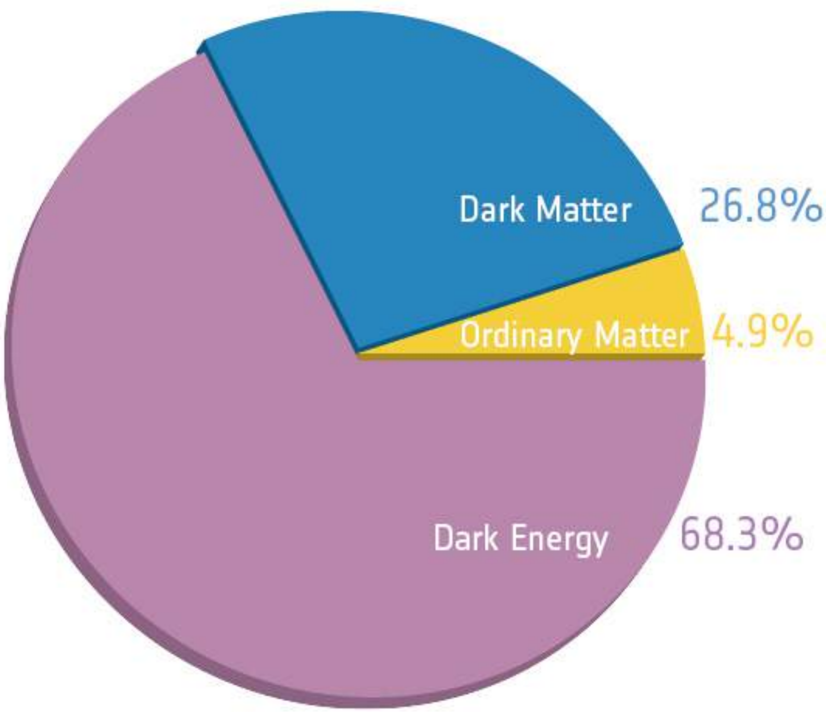
Hai-Bo Yu
University of California, Riverside



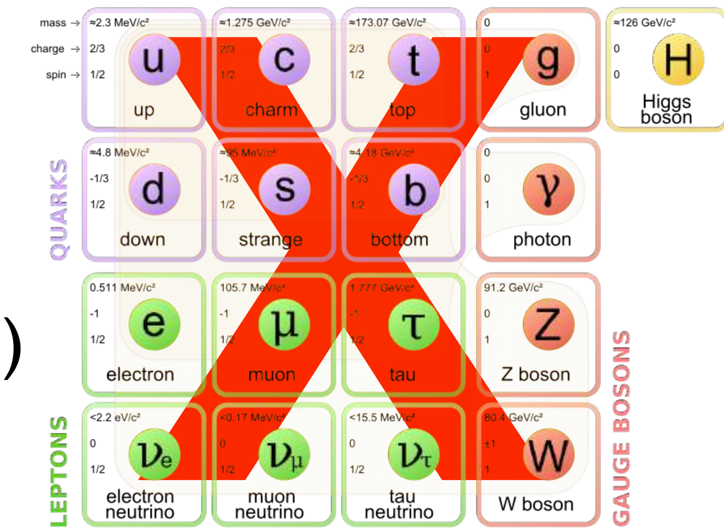
SIDM Workshop, Niels Bohr Institute, July 31-August 4, 2017

Review for Physics Reports: Sean Tulin, HBY (2017)

The Standard Model of Cosmology



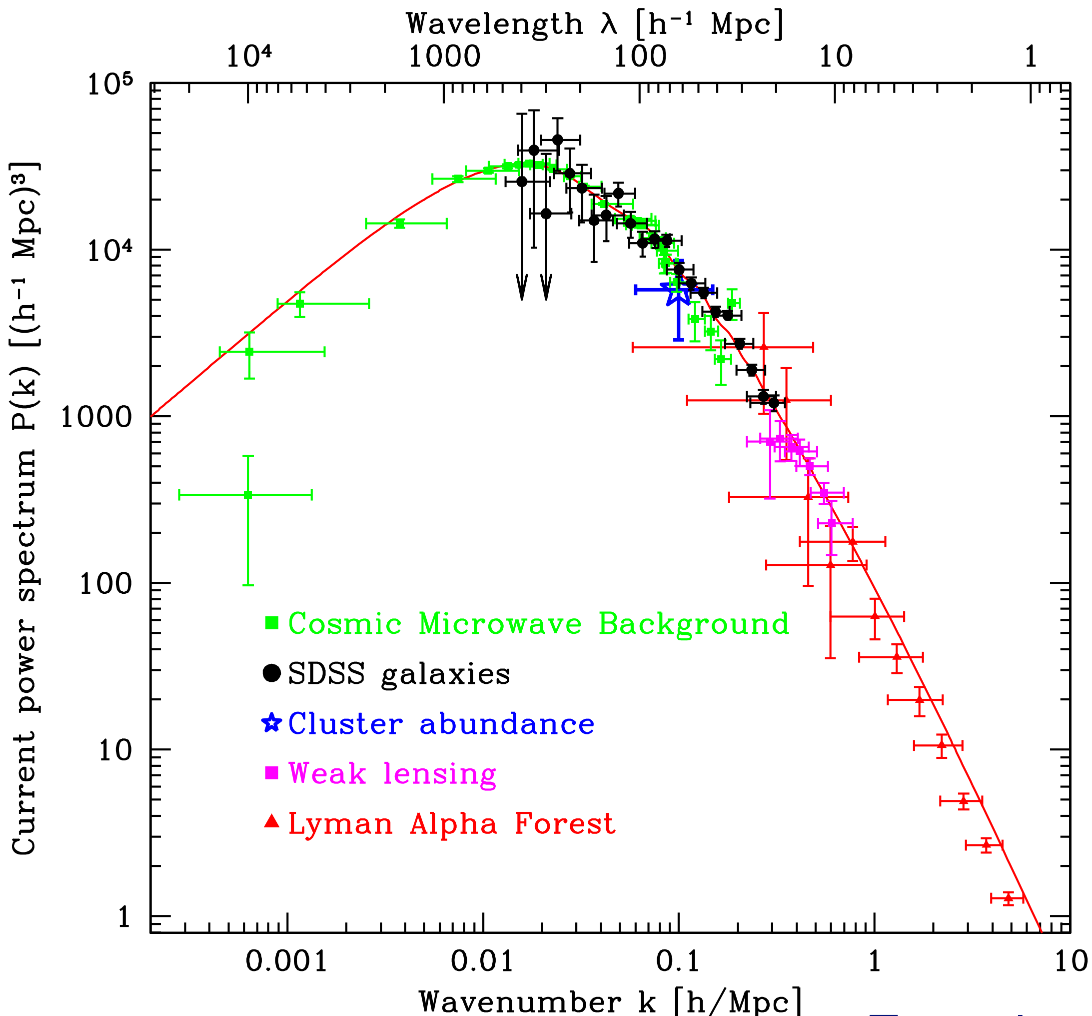
dark
cold (warm)
long-lived



- Introduce a new particle (X) and assume it is cold and collisionless: CDM
- Possible connections to BSM new physics: WIMPs, axions…

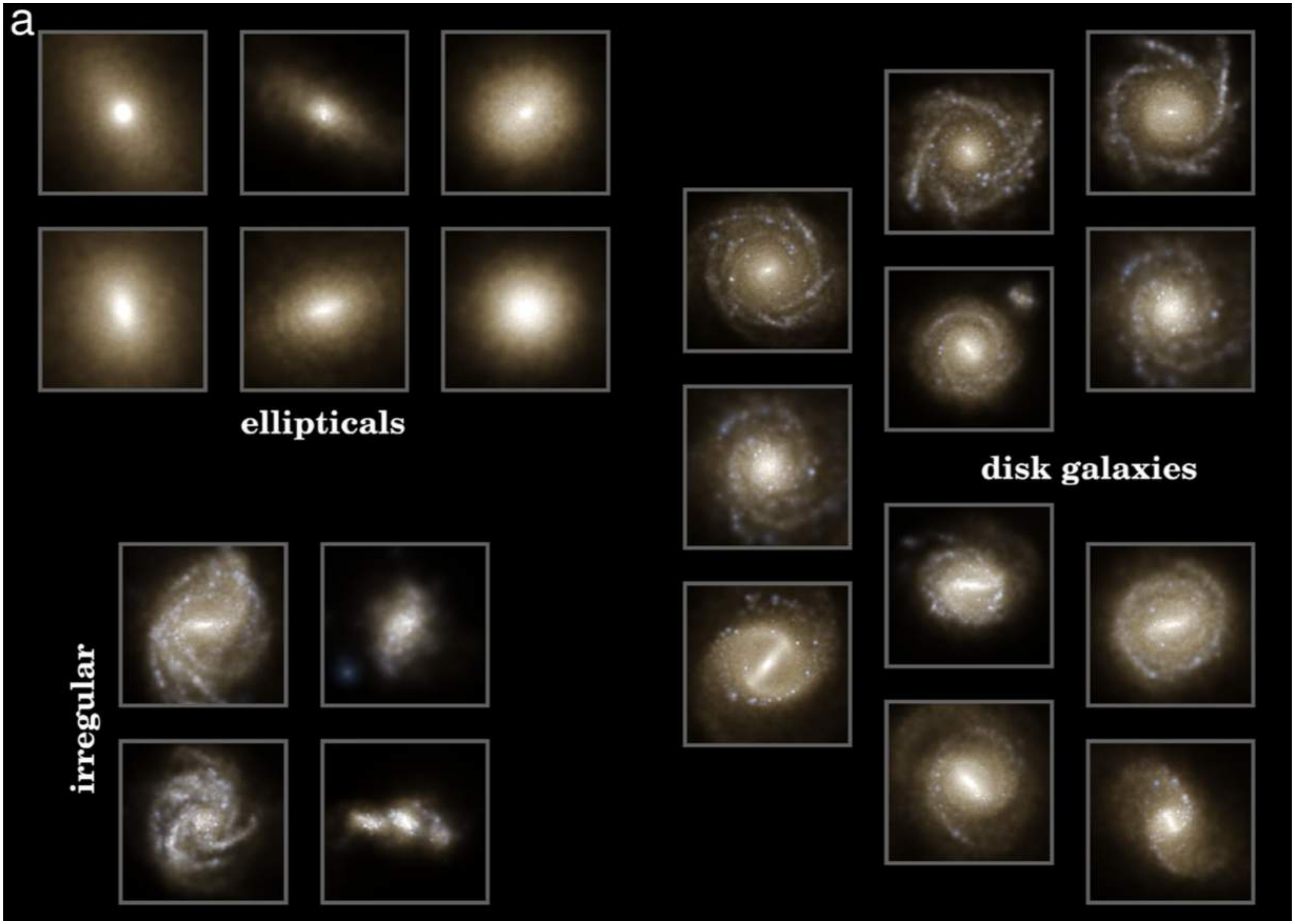
ΛCDM on Large Scales

- works very well, >O(100) kpc



Tegmark et al. (2004)

ΛCDM on Galactic Scales



Illustris Project, Vogelsberger et al. (2014)

Produce a variety of galaxy types consistent with observations

Small-Scale Issues

- Crisis on small scales: galactic scales, <10-100 kpc

  Core vs. Cusp
  Diversity
  Missing Satellites
  Too-Big-To-Fail

- Solutions

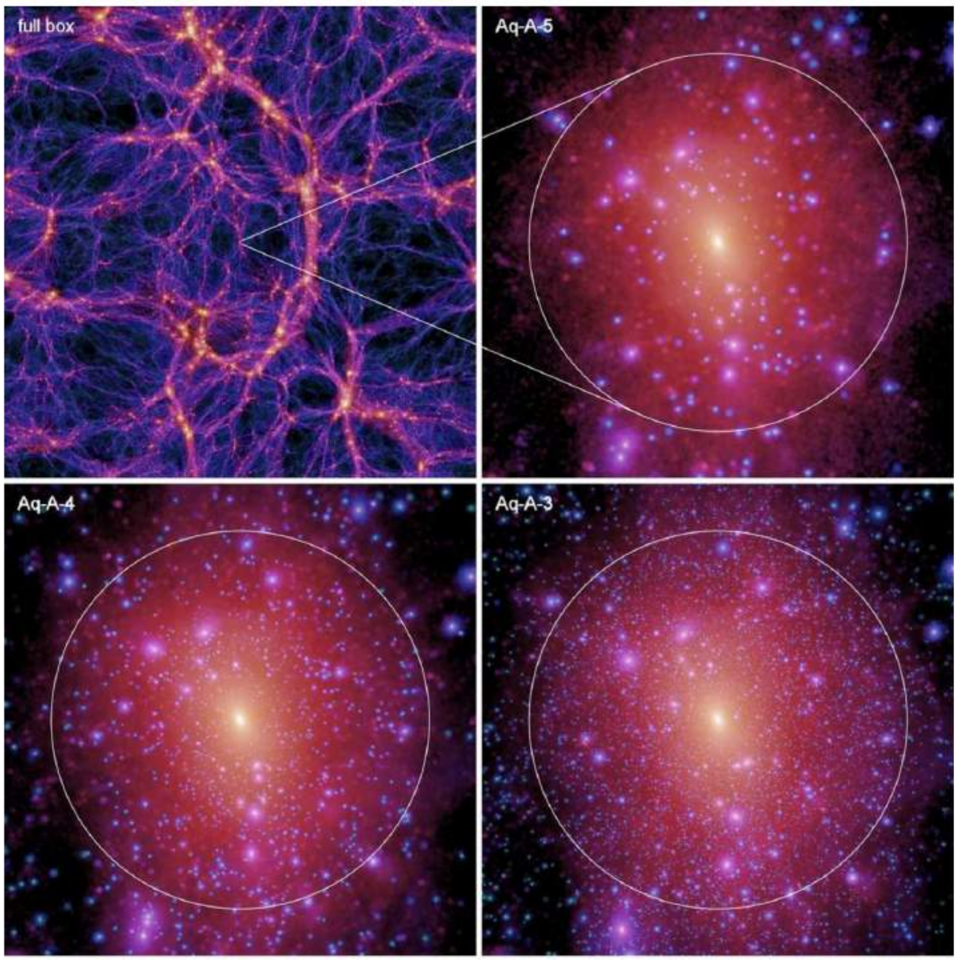
  Observational limitation

  Baryon physics (see Andrew Pontzen's talk)

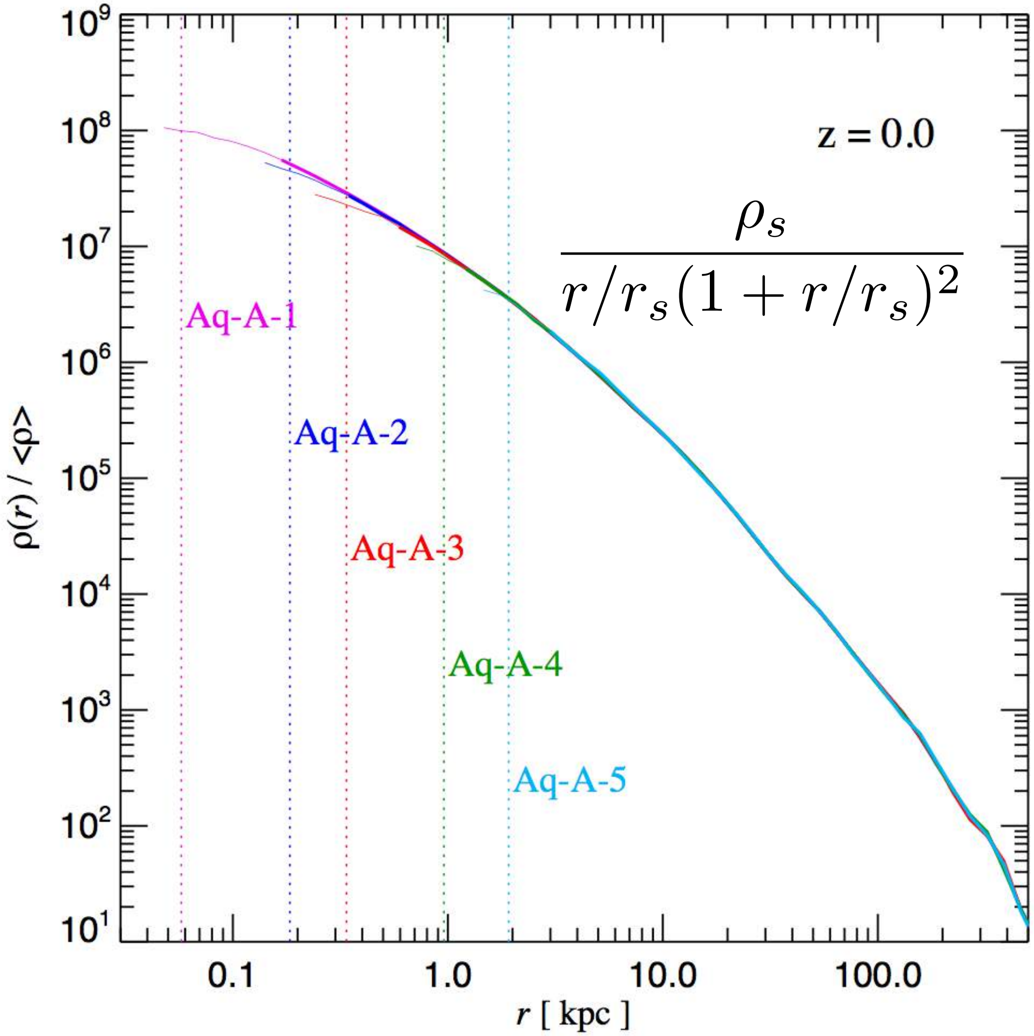
  New physics (the focus of this talk, SIDM)

see Tulin, HBY (2017) for a review

ΛCDM Predictions on Small Scales



Aquarius Project, Springel et al. (2008)



the Navarro-Frenk-White (NFW) profile (1996)

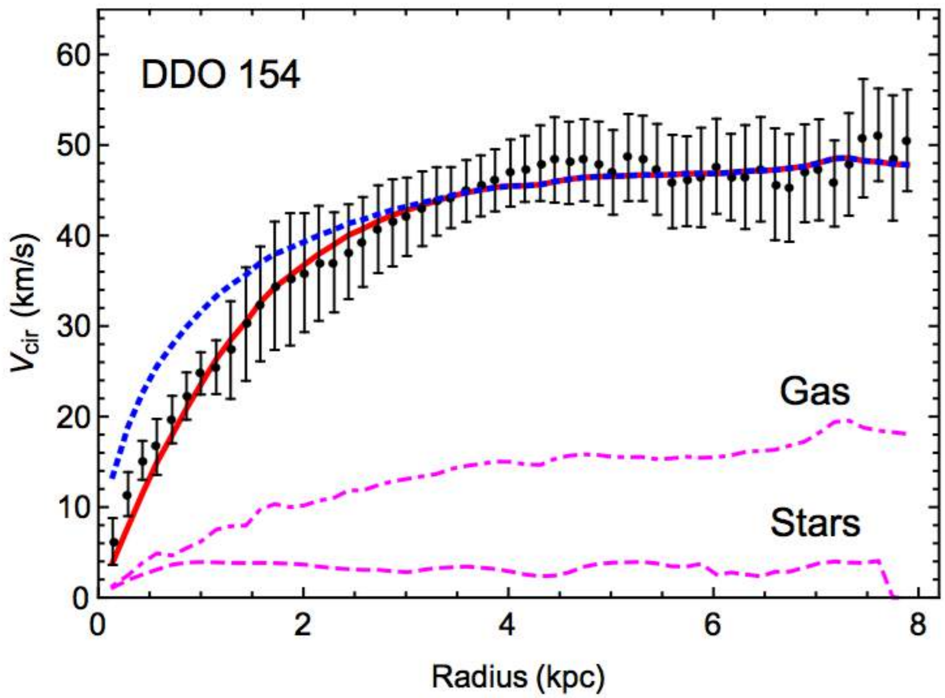
A lot of substructure, a universal density profile, ρ_s and r_s are correlated

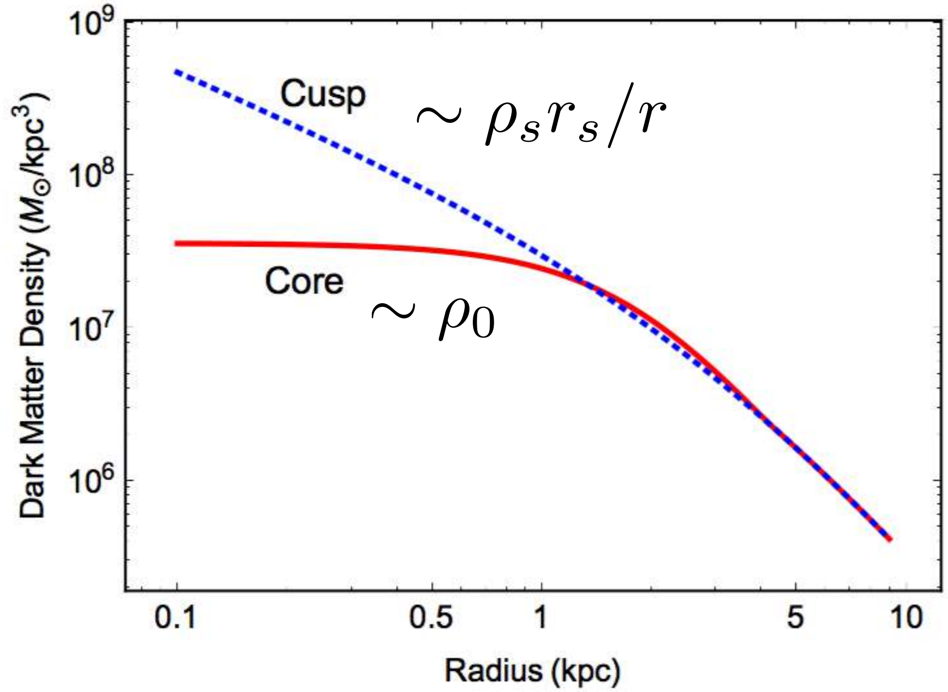
(the halo concentration-mass relation)

CDM-only cosmological simulations

Core vs. Cusp Problem

- DM-dominated systems (dwarfs, LSBs)





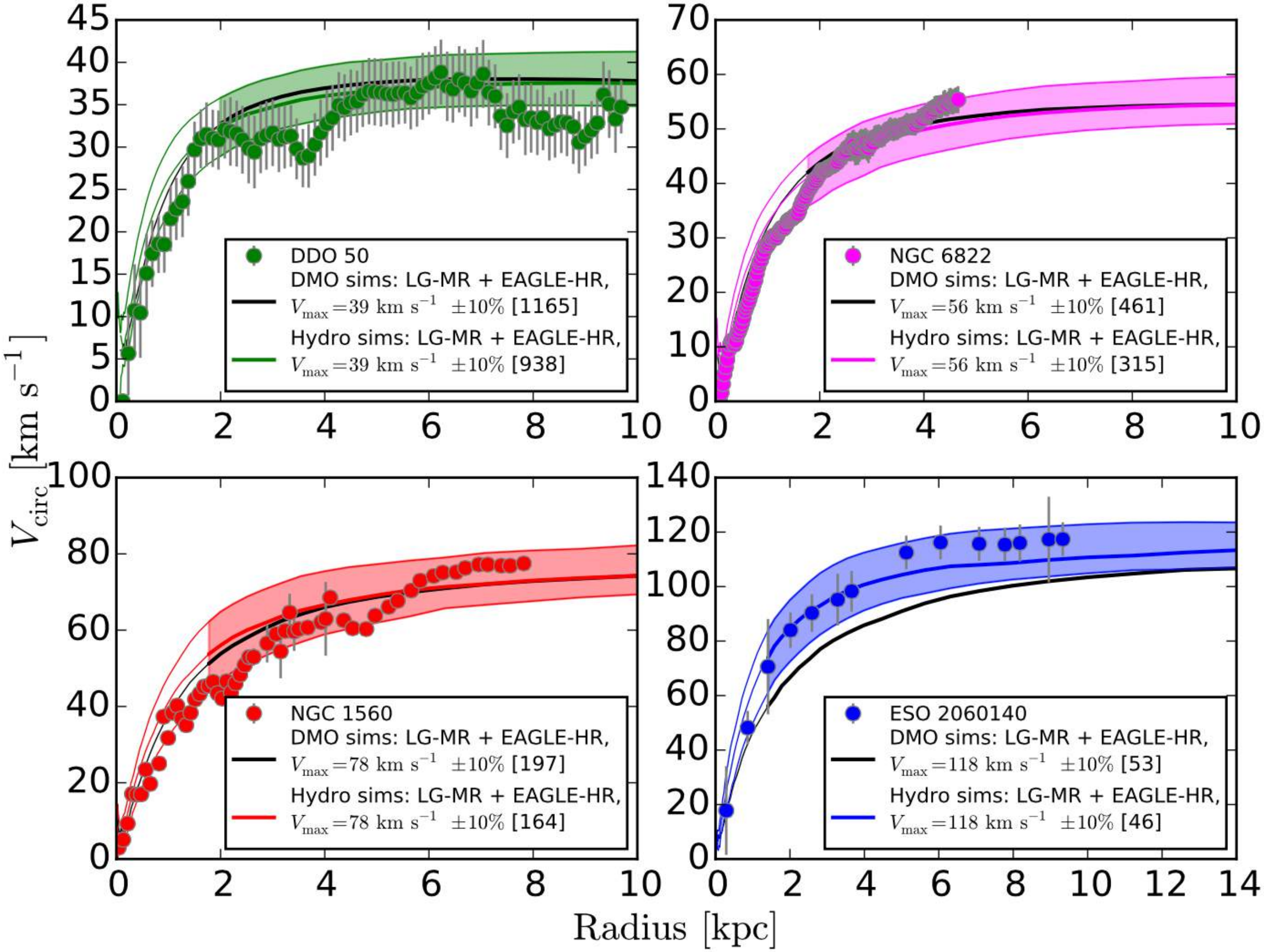
$$\frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

Tulin, HBY (2017)

Many dwarf galaxies prefer a shallow density core, instead of a steep density cusp

Flores, Primack (1994), Moore (1994)

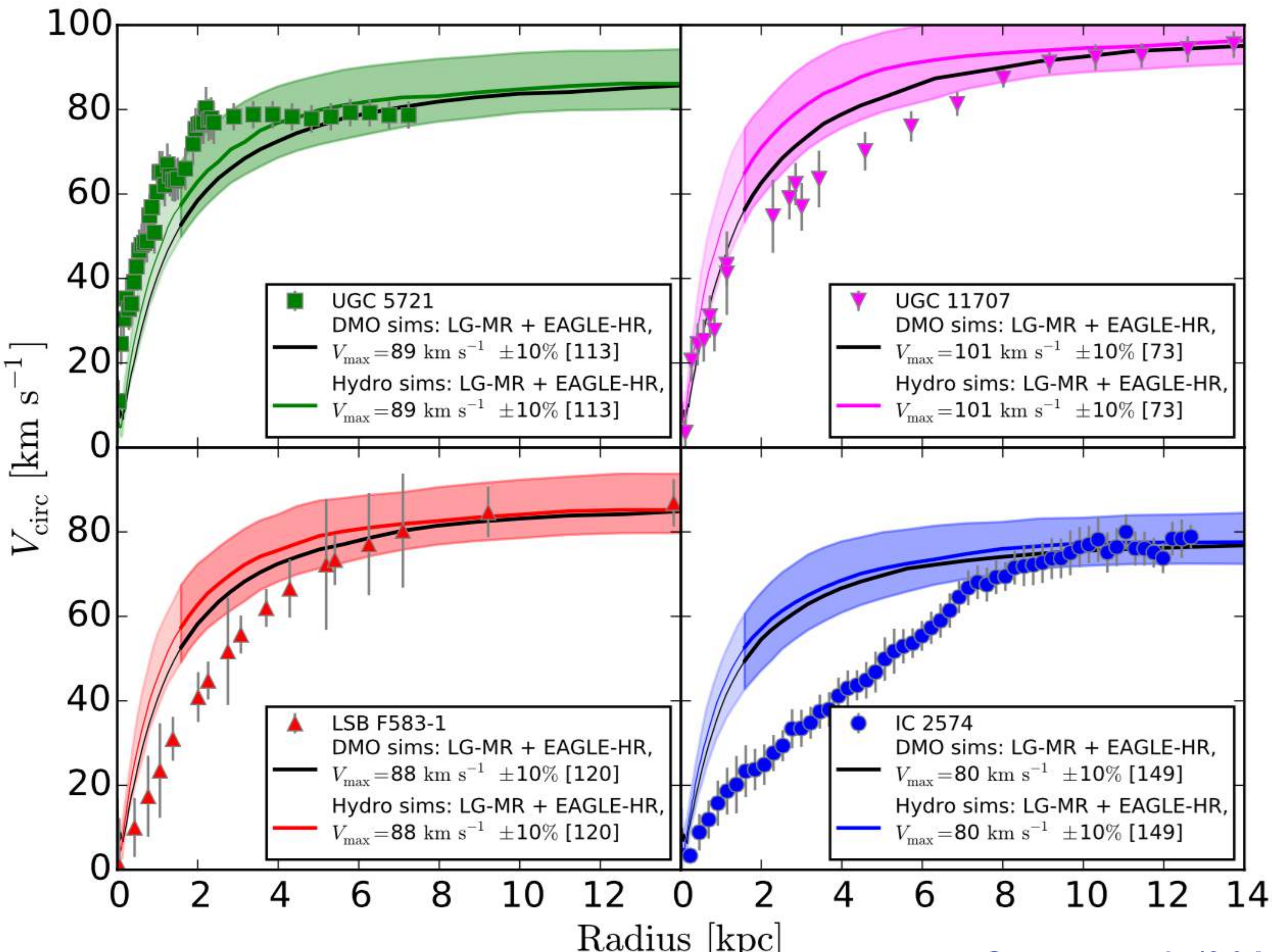
The Diversity Problem



Colored bands: hydrodynamic simulations of ΛCDM

Oman et al. (2015)

The Diversity Problem



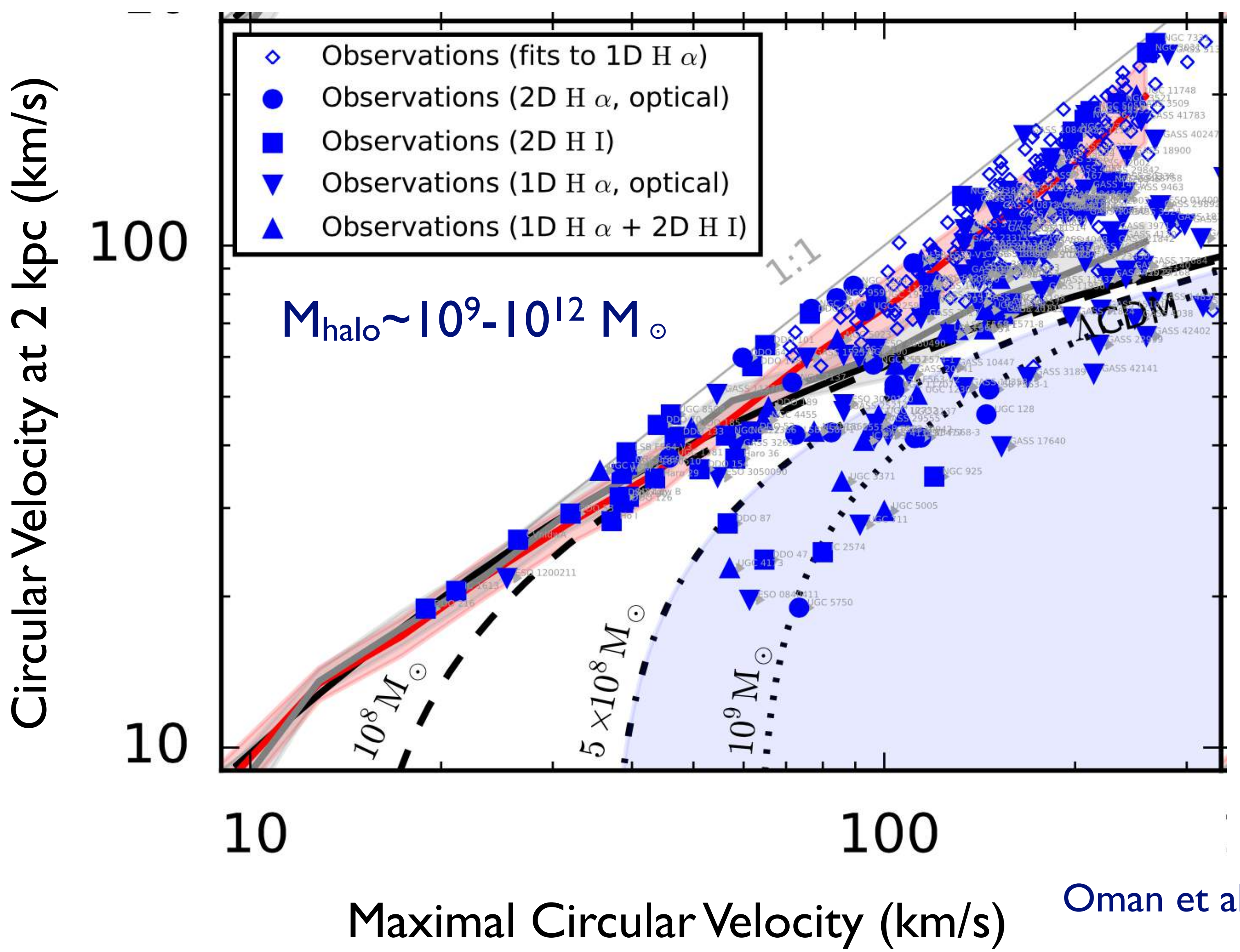
All galaxies have the same Vmax!

Oman et al. (2015)

Colored bands: hydrodynamic simulations of ΛCDM

See also Kuzio de Naray, Martinez, Bullock, Kaplinghat (2009)

A Big Challenge for ΛCDM



Oman et al. (2015)

V_{circ}(2kpc) has a factor of 3-4 scatter for fixed V_{max}

Mon. Not. R. Astron. Soc. **000**, 000–000 (0000)   Printed 10 July 2015   (MN LaTeX style file v2.2)

The unexpected diversity of dwarf galaxy rotation curves

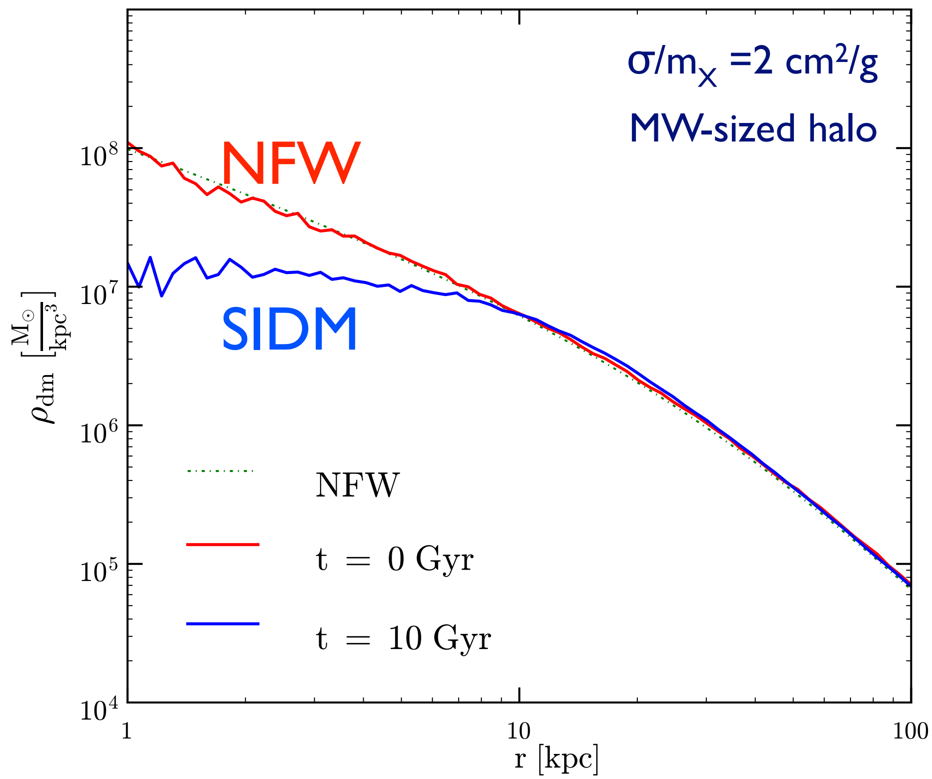
Kyle A. Oman[1,⋆], Julio F. Navarro[1,2], Azadeh Fattahi[1], Carlos S. Frenk[3], Till Sawala[3], Simon D. M. White[4], Richard Bower[3], Robert A. Crain[5], Michelle Furlong[3], Matthieu Schaller[3], Joop Schaye[6], Tom Theuns[3]

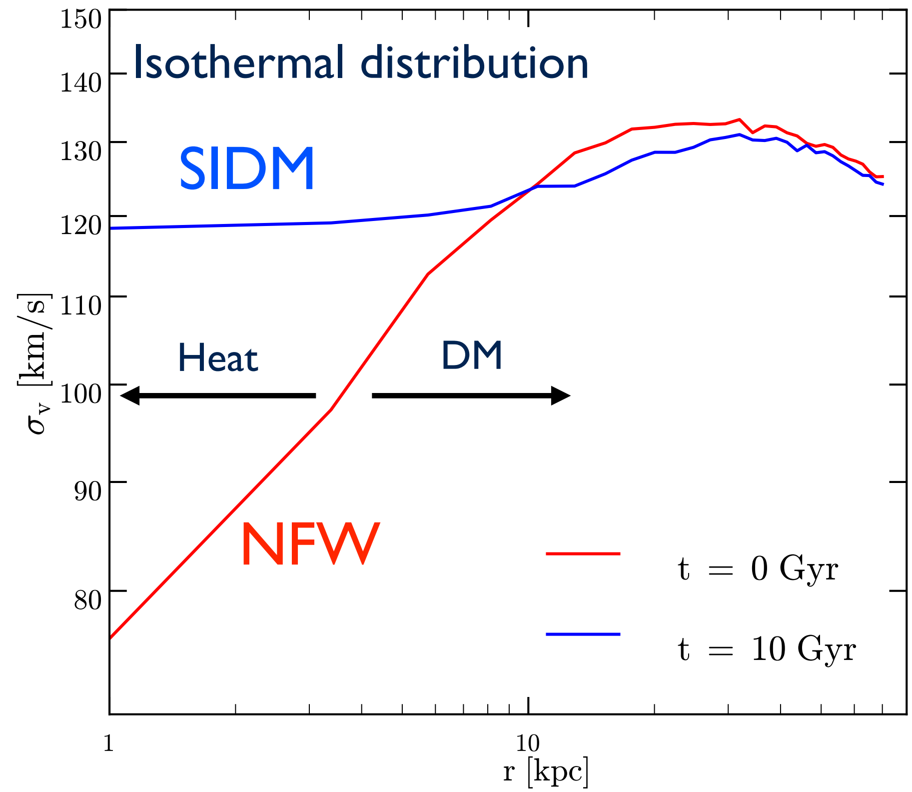
[1] *Department of Physics & Astronomy, University of Victoria, Victoria, BC, V8P 5C2, Canada*
[2] *Senior CIfAR Fellow*
[3] *Institute for Computational Cosmology, Department of Physics, University of Durham, South Road, Durham DH1 3LE, United Kingdom*
[4] *Max-Planck Institute for Astrophysics, Garching, Germany*
[5] *Astrophysics Research Institute, Liverpool John Moores University, IC2, Liverpool Science Park, 146 Brownlow Hill, Liverpool, L3 5RF, United Kingdom*
[6] *Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, the Netherlands*

The diversity is expected if dark matter has strong self-interactions

Self-Interacting Dark Matter

- Self-interactions thermalize the inner halo





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

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

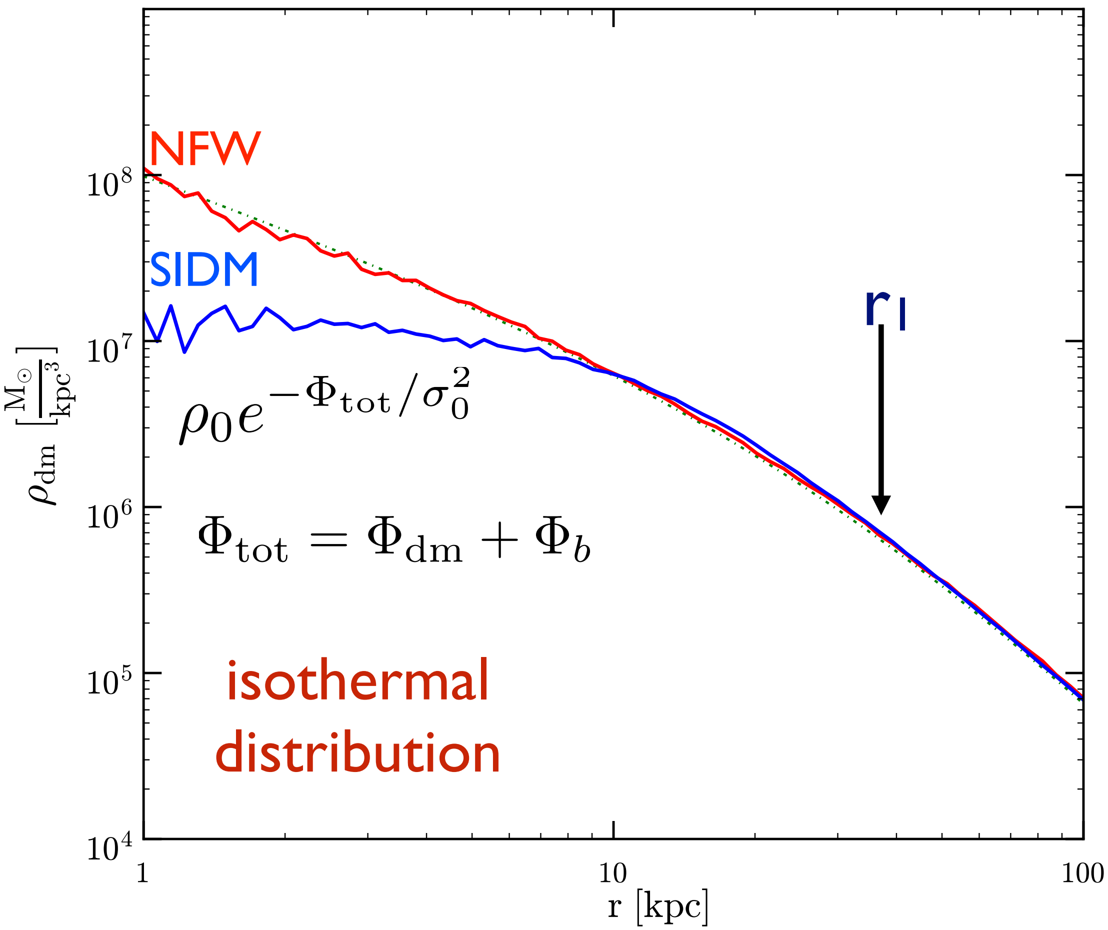
Spergel, Steinhardt (1999)

From Huo

see Tulin, HBY (2017) for a review

Modelling SIDM Halos

- An analytical SIDM halo model



$$\text{rate} \times \text{time} \approx \frac{\langle \sigma v \rangle}{m} \rho(r_1)\, t_{age} \approx 1$$

$$\rho(r) = \begin{cases} \rho_{iso}(r), & r < r_1 \\ \rho_{NFW}(r), & r > r_1 \end{cases}$$

Matching conditions:

$$\rho_{iso}(r_1) = \rho_{NFW}(r_1)$$
$$M_{iso}(r_1) = M_{NFW}(r_1)$$

$$(\rho_0, \sigma_0) \leftrightarrow (\rho_s, r_s)$$

Ideal gas: PV=nRT

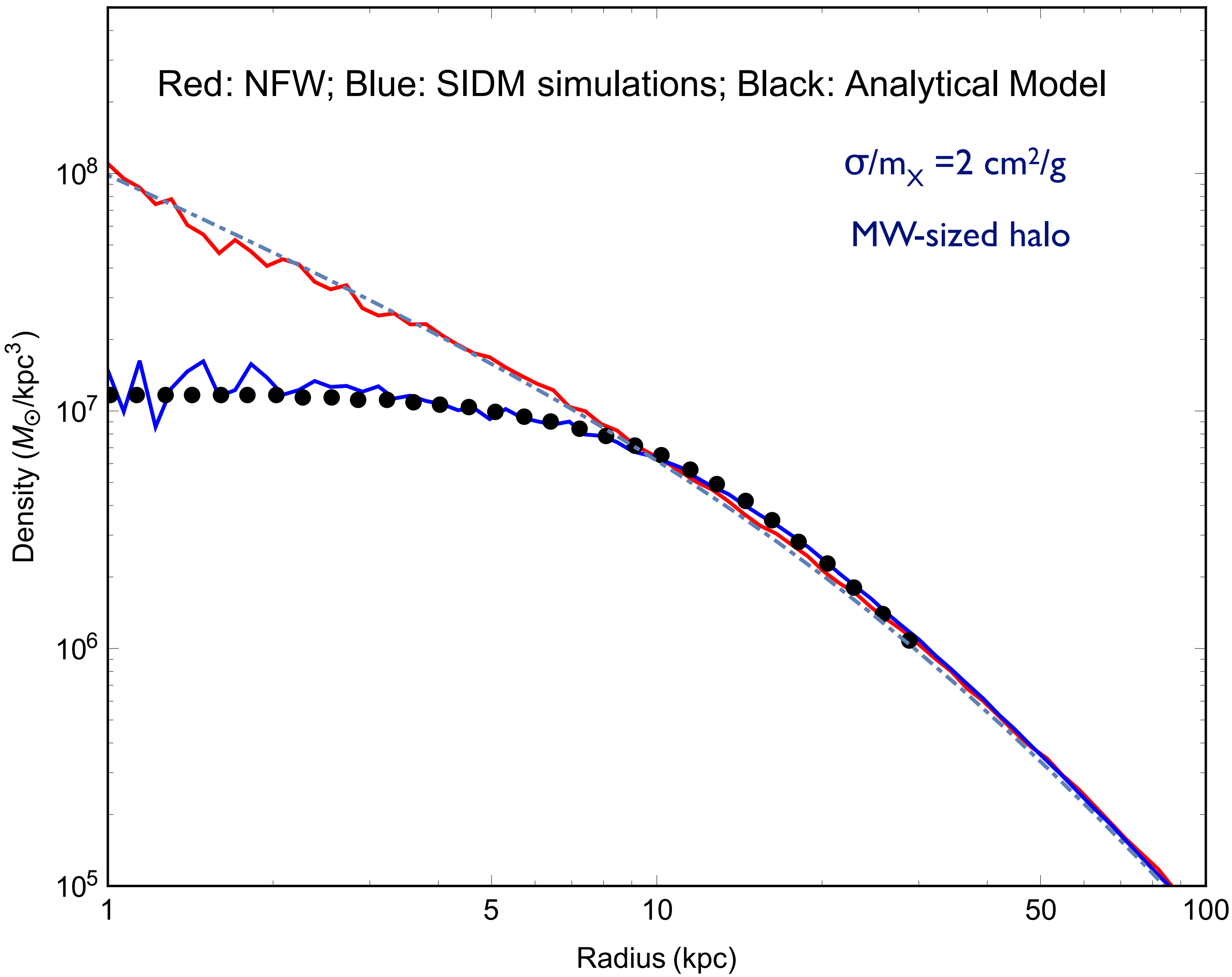
$$\frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

with Kaplinghat, Tulin (2015)

with Kamada, Kaplinghat, Pace (2016)

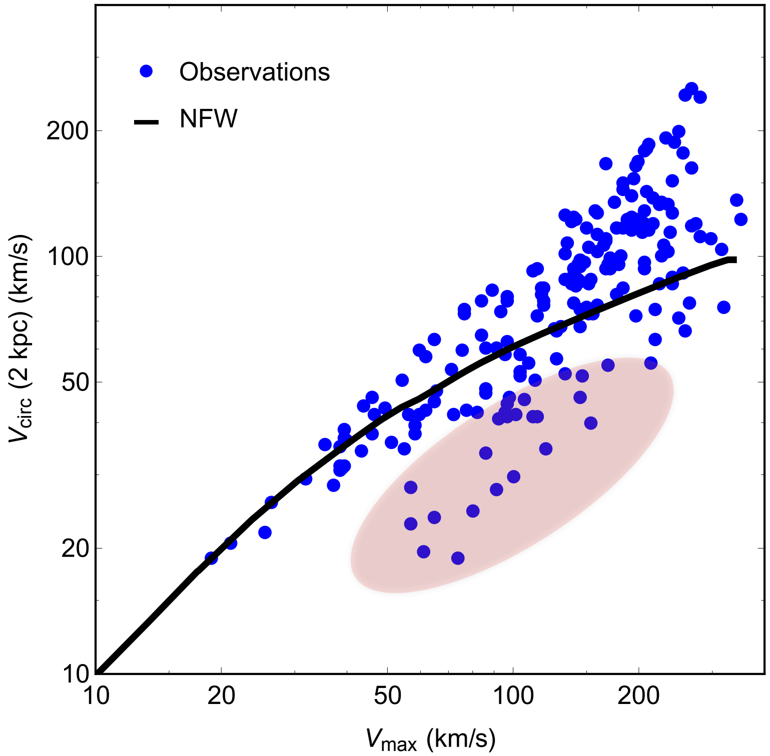
Modelling SIDM Halos

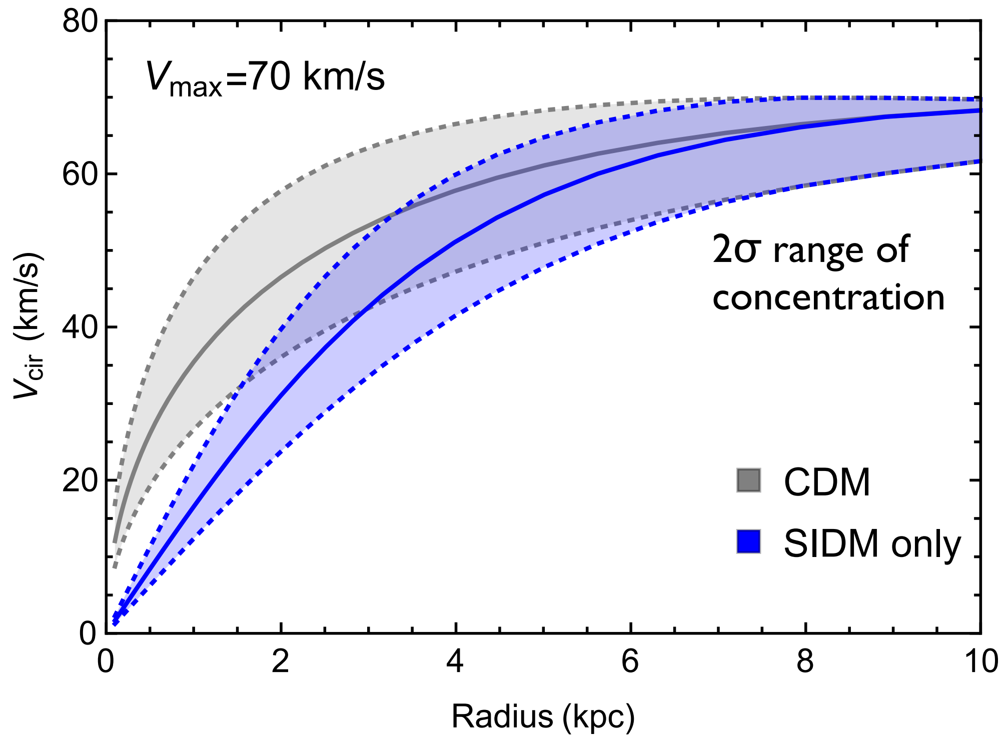
- The model works well remarkably



Addressing the Diversity Problem

- DM self-interactions thermalize the inner halo





DM-dominated galaxies: Lower the central density and the circular velocity

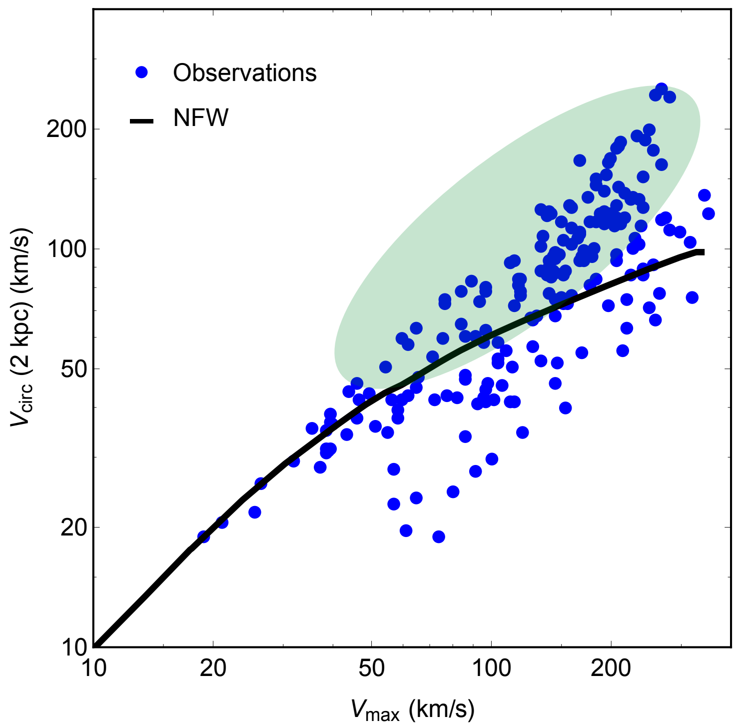
Isothermal distribution

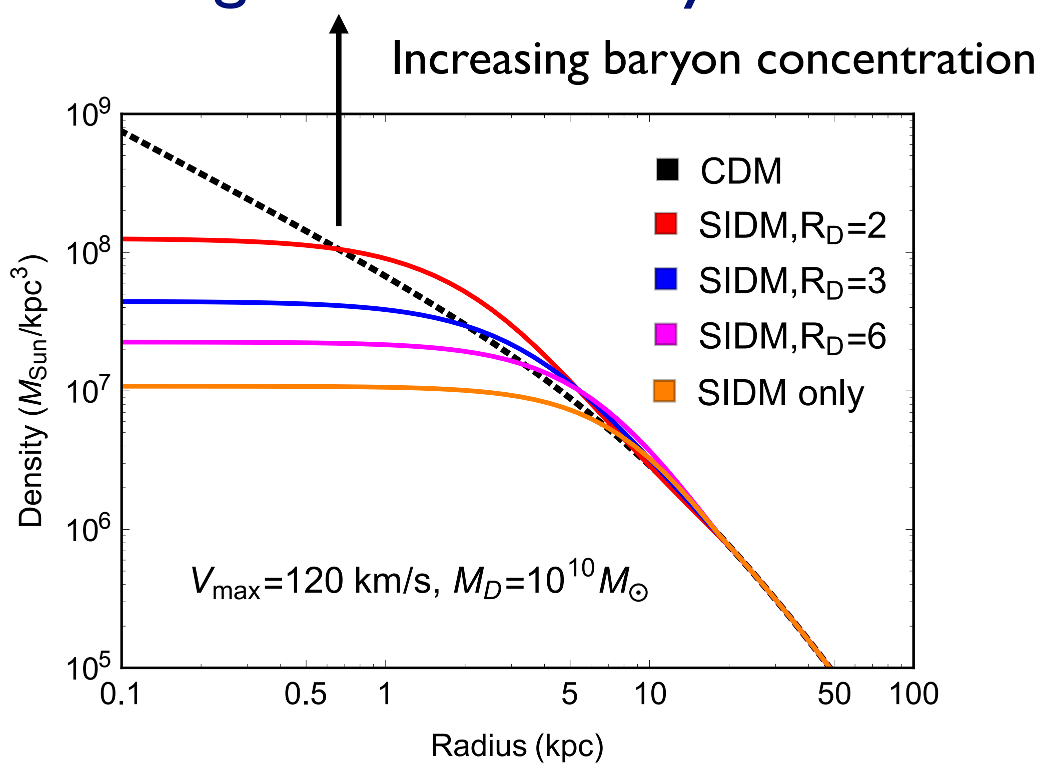
$$\rho_X \sim e^{-\Phi_{\rm tot}/\sigma_0^2} \sim e^{-\Phi_X/\sigma_0^2}$$

with Kamada, Kaplinghat, Pace (2016)

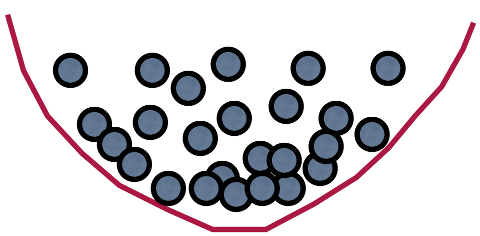
High Luminous Galaxies

- DM self-interactions tie DM together with baryons





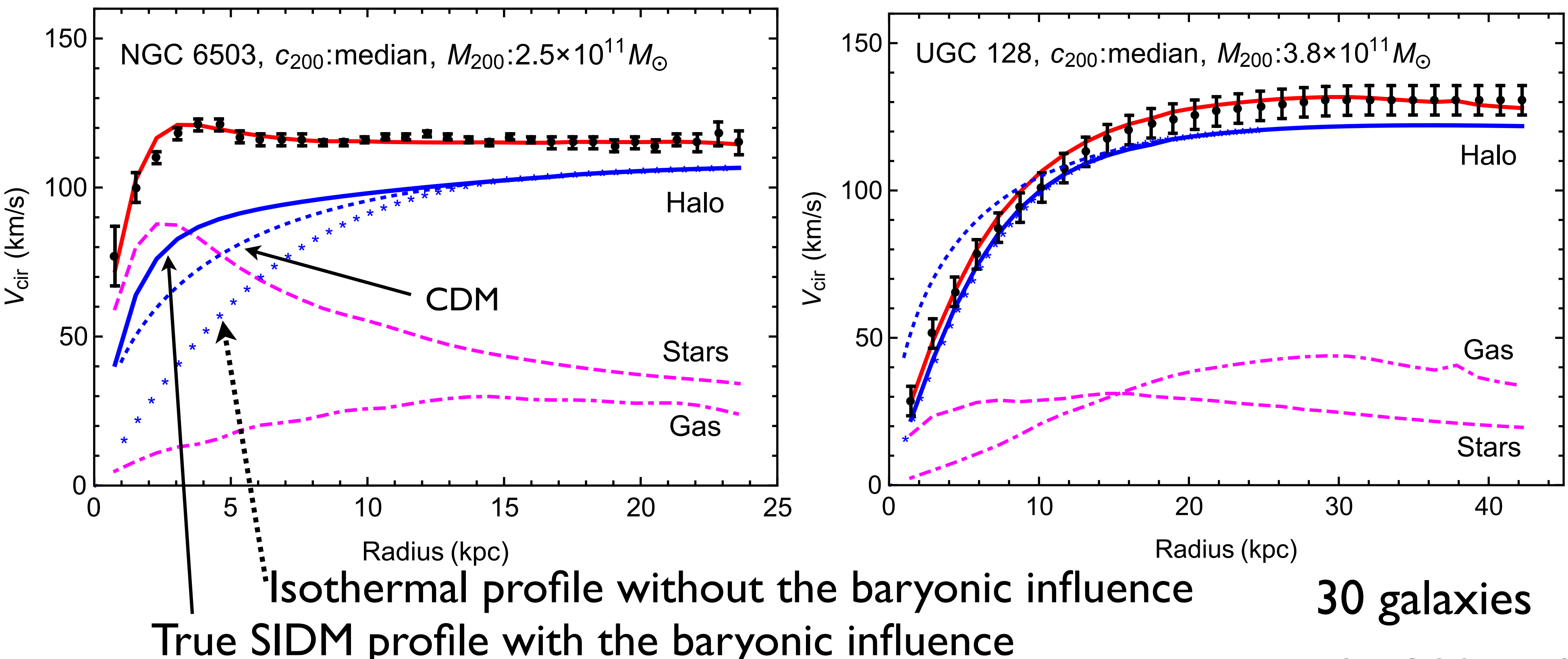
Thermalization leads to higher DM density due to the baryonic influence



$$\rho_X \sim e^{-\Phi_{\rm tot}/\sigma_0^2} \sim e^{-\Phi_{\rm B}/\sigma_0^2}$$

with Kamada, Kaplinghat, Pace (2016)
with Kaplinghat, Keeley, Linden (2013)
with Kaplinghat, Linden (2013)

Solving the Diversity Problem



30 galaxies

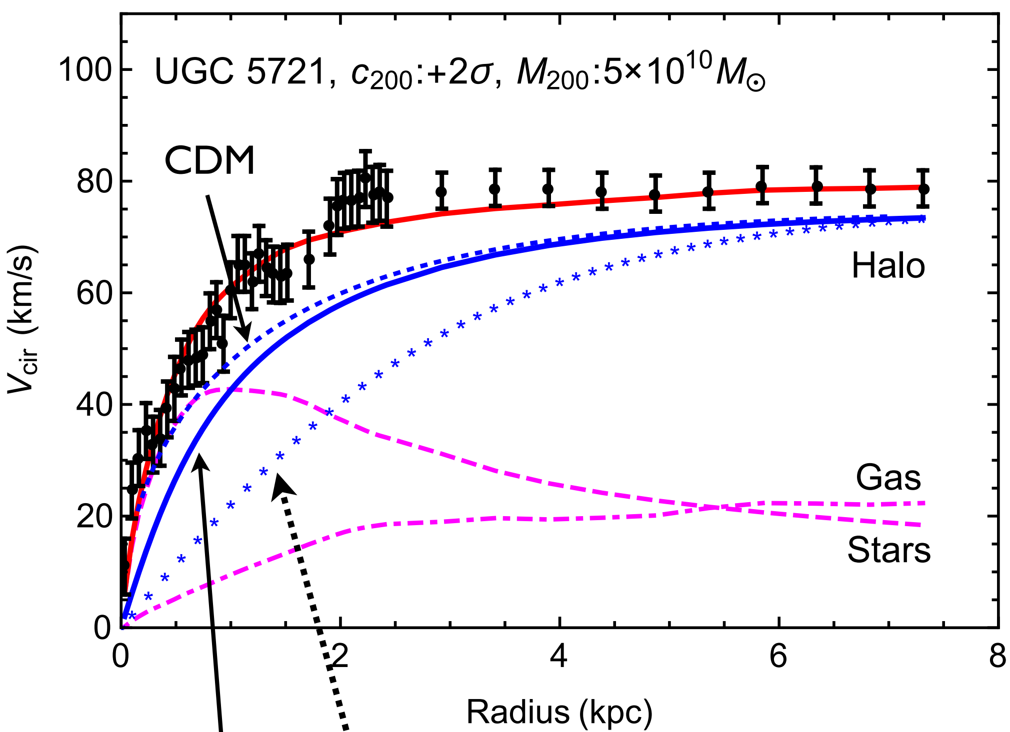
V_{max}~25-300 km/s

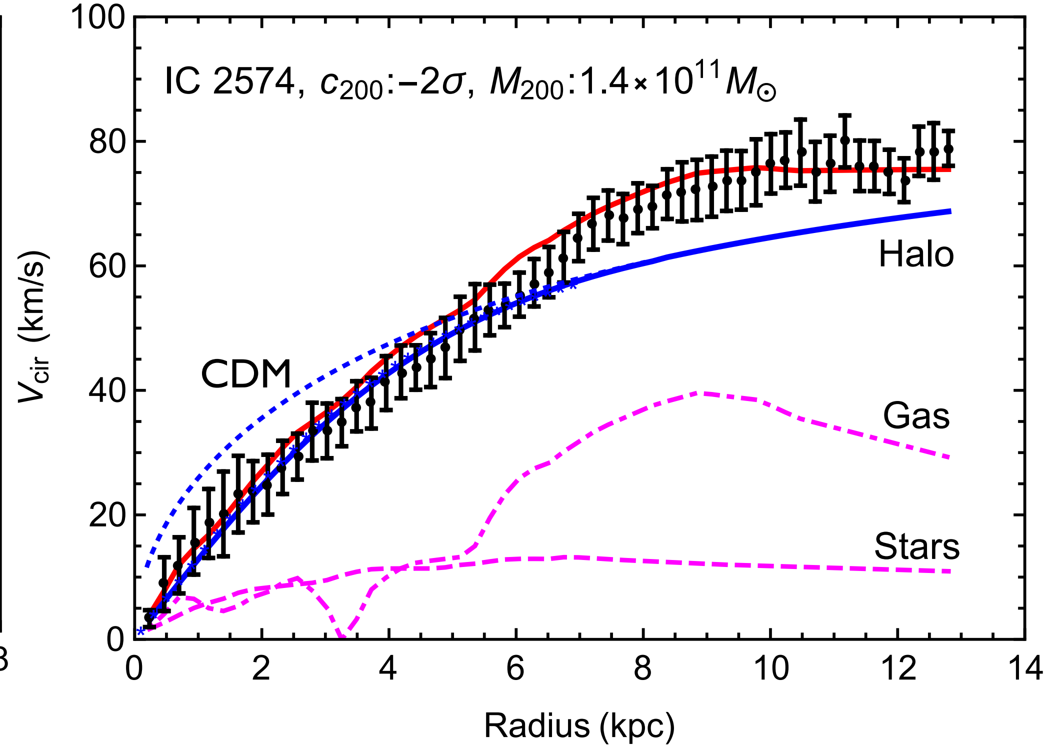
- DM self-interactions thermalize the inner halo together with baryons

High luminous galaxies (NGC 6503): small and dense core
Low luminous galaxies (UGC 128): large and shallow core

with Kamada, Kaplinghat, Pace (2016)

Solving the Diversity Problem





Isothermal profile without the baryonic influence

True SIDM profile with the baryonic influence

30 galaxies

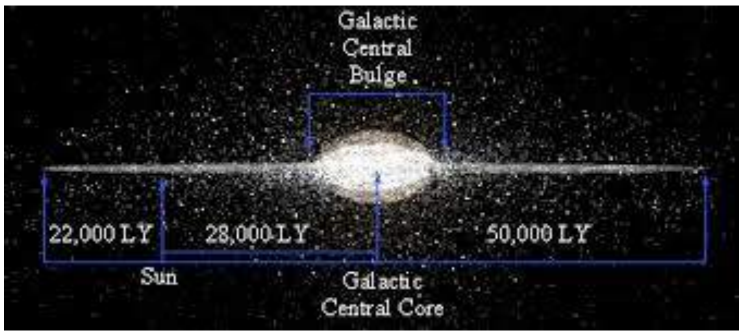
V_{max}~25-300 km/s

- Scatter in the halo concentration-mass relation
- Baryon distribution
- DM self-interactions thermalize the inner halo and correlate DM and baryon distributions

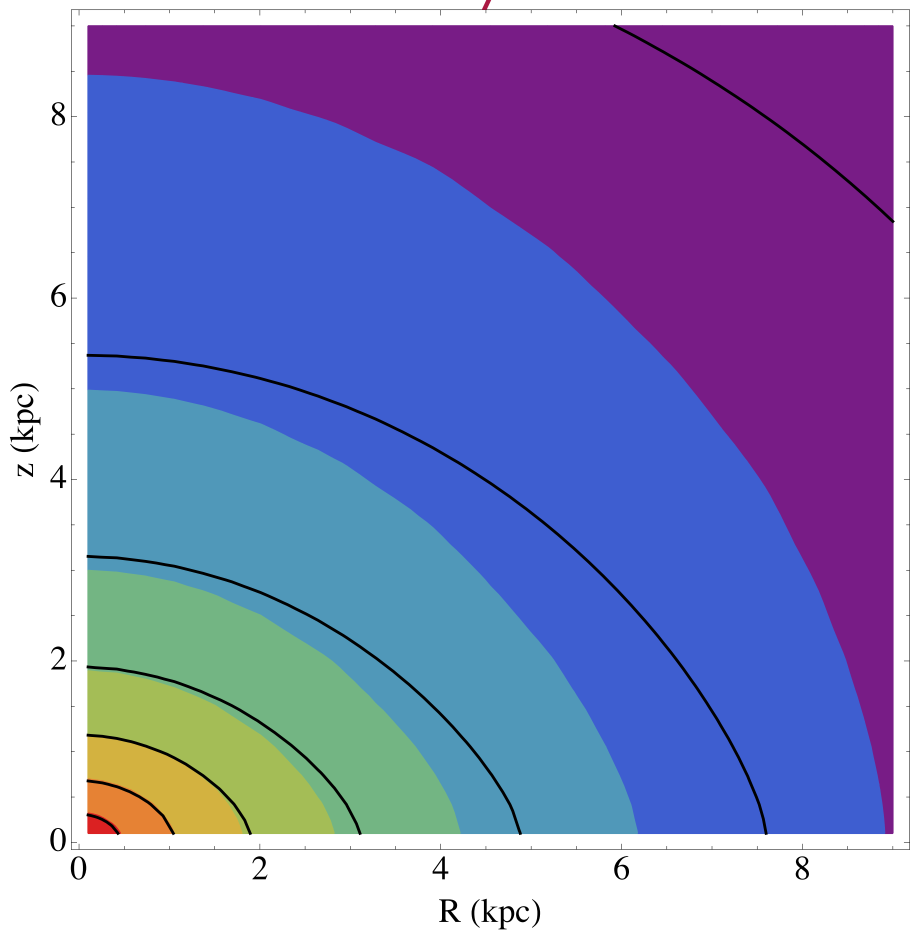
with Kamada, Kaplinghat, Pace (2016)

Tying SIDM to Baryons

- SIDM may follow the stellar distribution; halo morphology



SIDM density contour

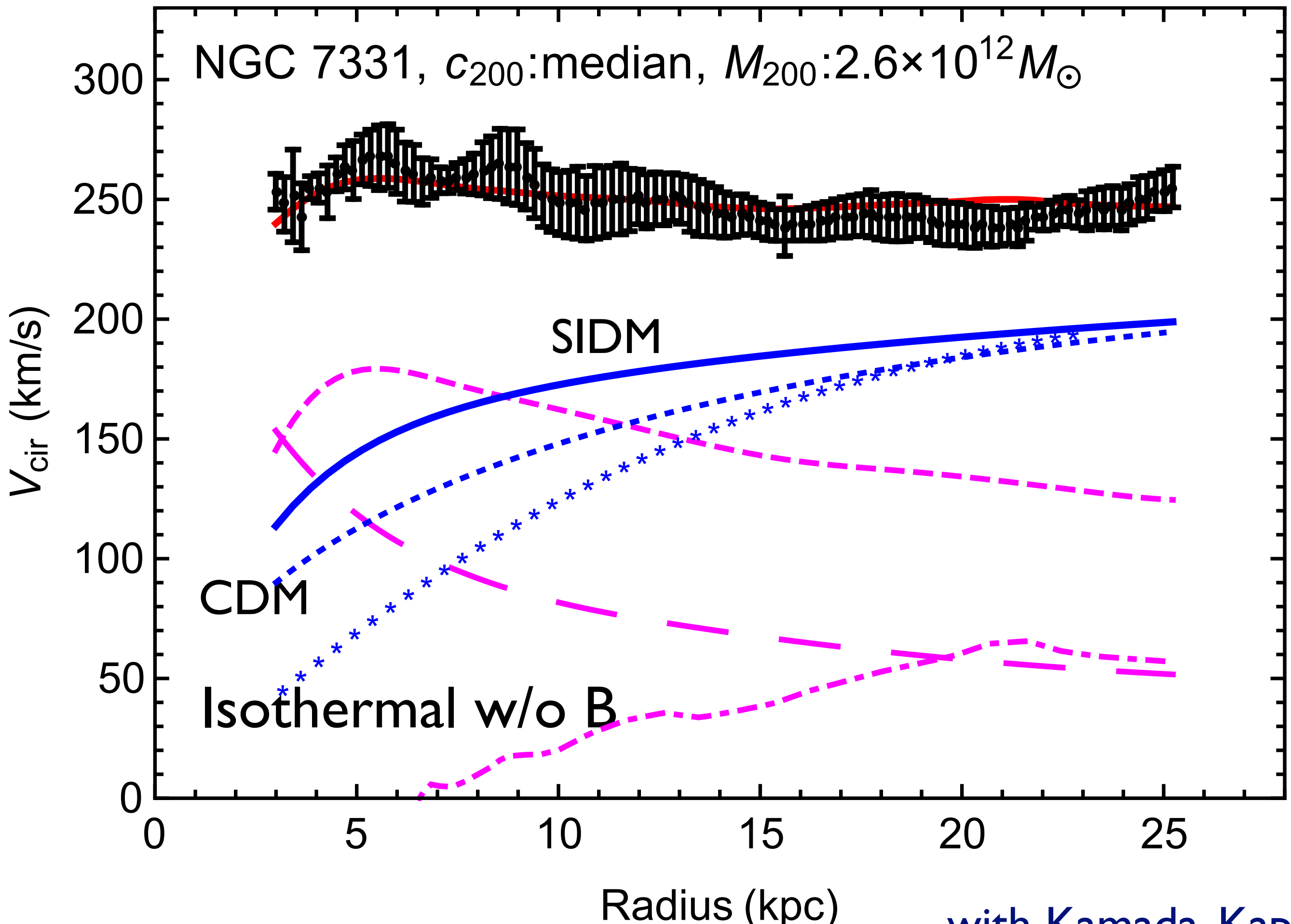


with Kaplinghat, Keeley, Linden (2013)

Correlation between the stellar distribution and the SIDM distribution

Disk-Halo Conspiracy

- Why is the rotation curve so flat in massive galaxies?

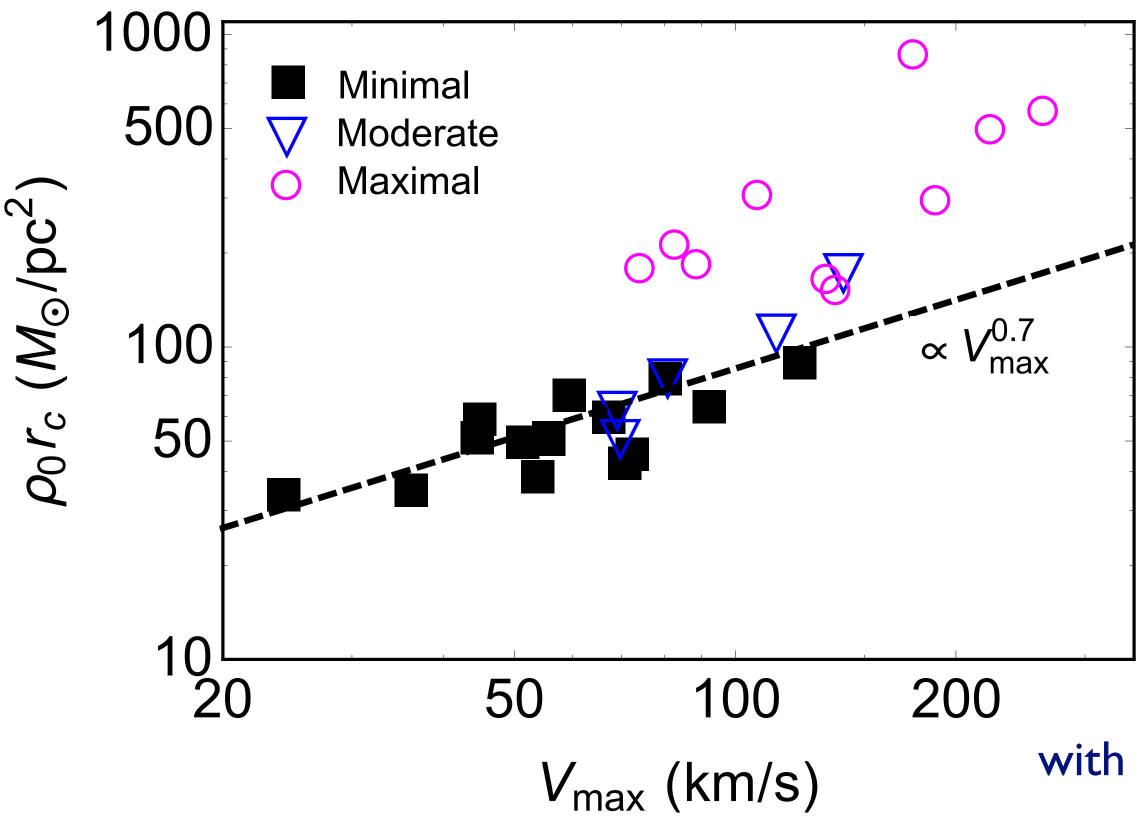


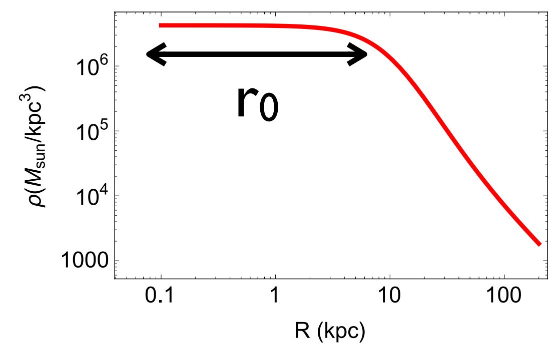
with Kamada, Kaplinghat, Pace (2016)

SIDM: isothermal distribution with baryons~$1/r^2$

Uniformity

- (Almost) constant DM halo surface density





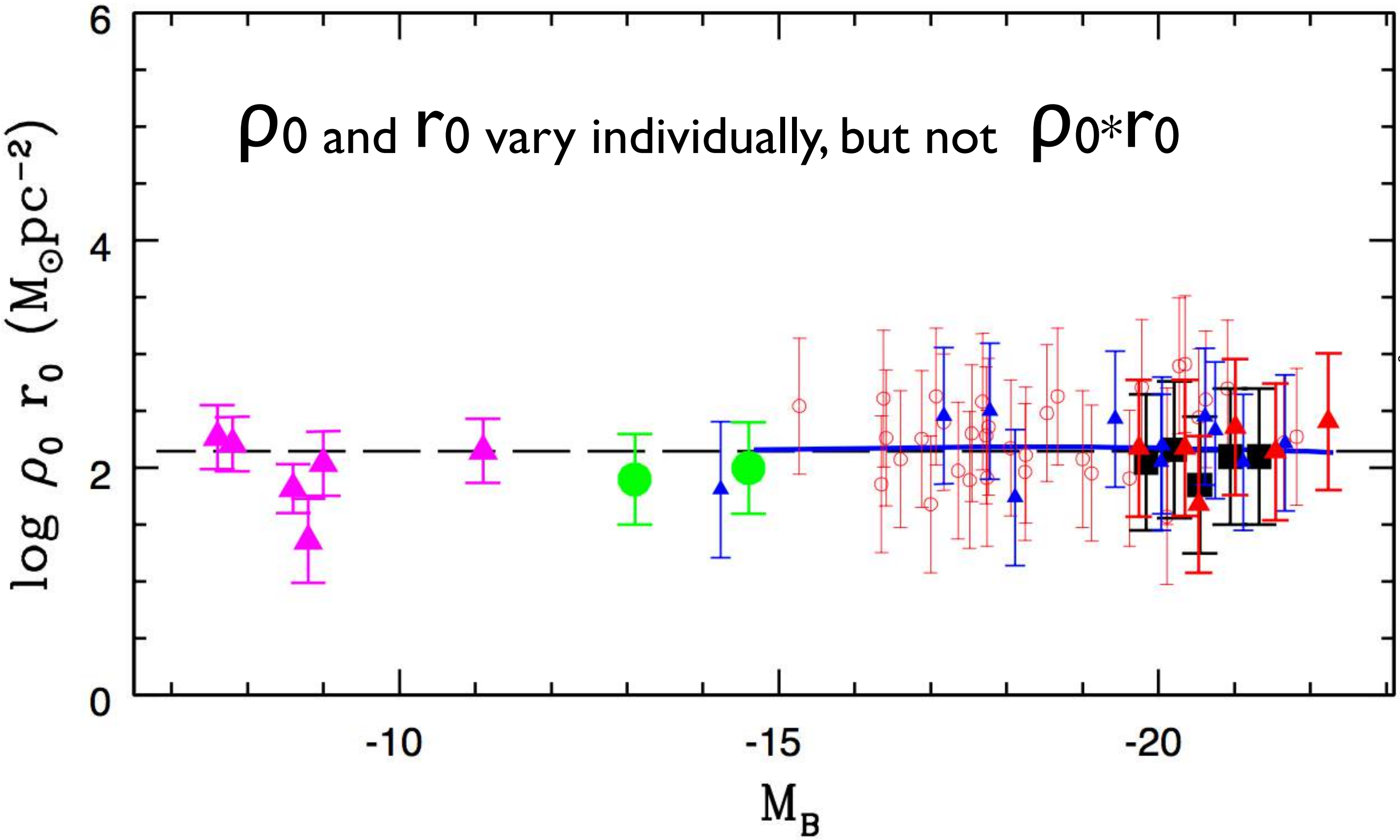
$$\rho(r_0) = \rho_0/2$$

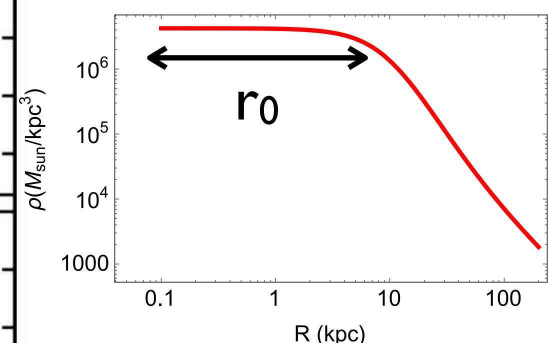
with Kamada, Kaplinghat, Pace (2016)

Reflection of the halo concentration-mass relation in ΛCDM/ΛSIDM

See also Lin, Loeb (2015)

Uniformity





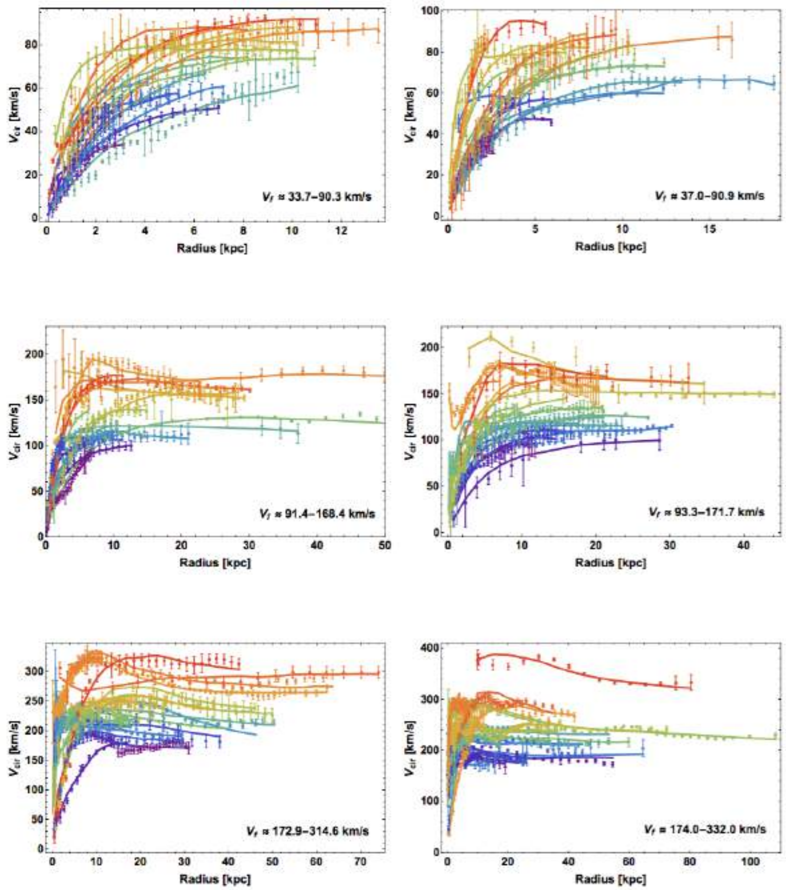
$$\rho(r_0) = \rho_0/2$$

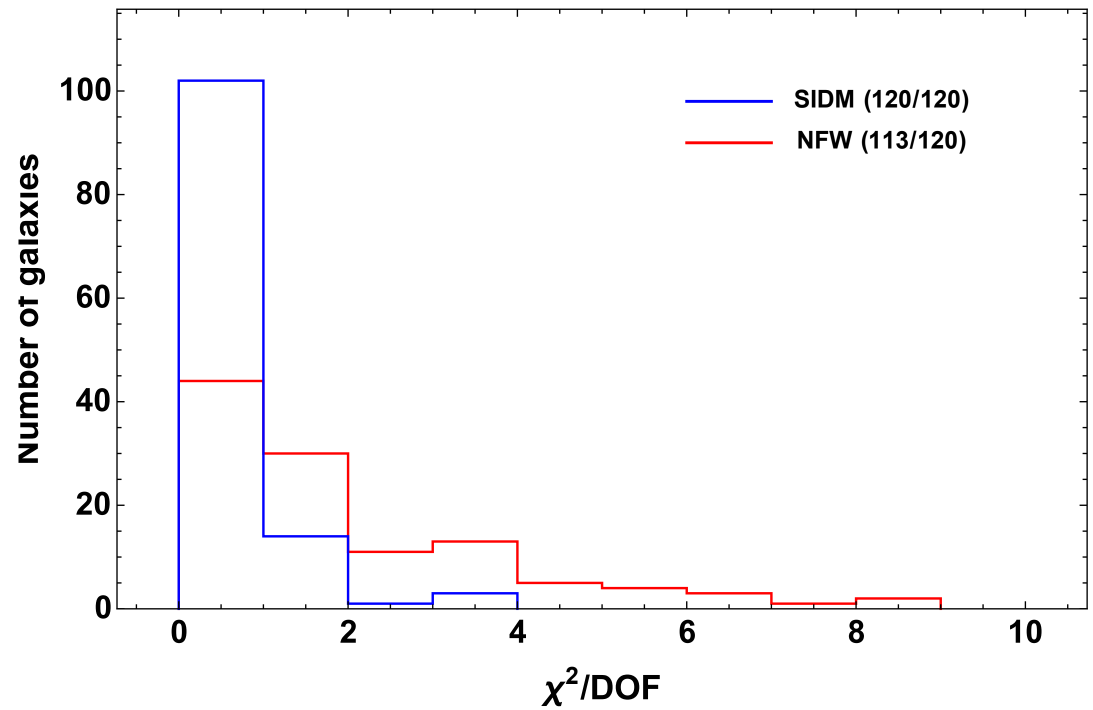
Donato+(2009)

Kormendy, Freeman (2004)

$$\rho(r) = \frac{\rho_0}{1 + (r/r_0)^2}$$

More Galaxies…

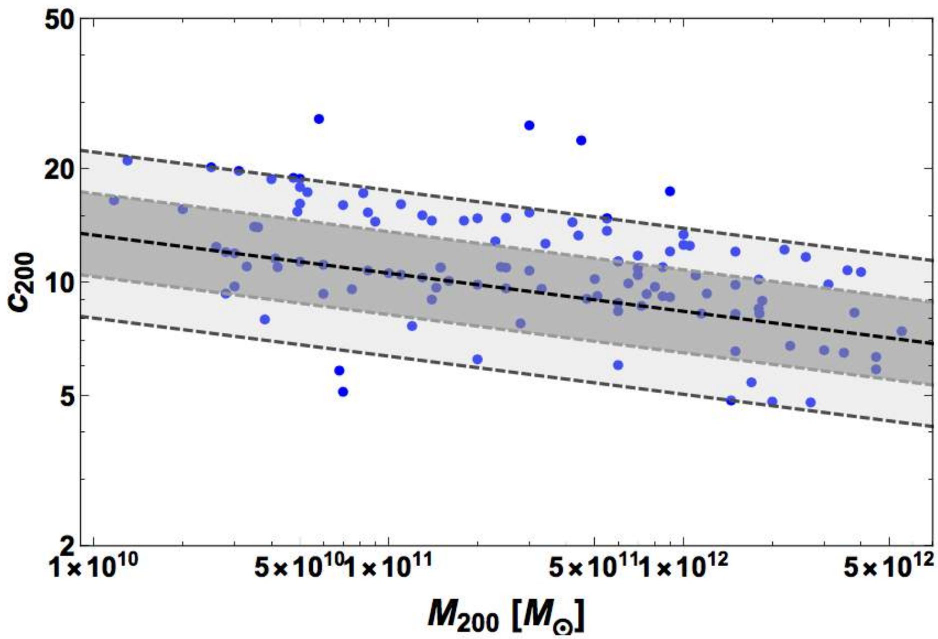


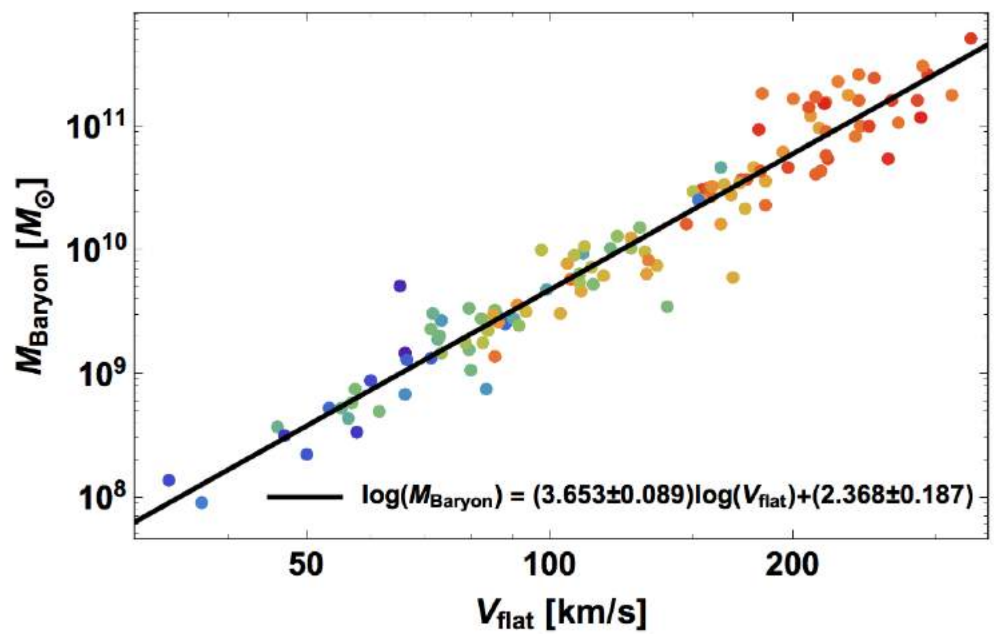


120 spiral galaxies with high-quality data

with Kaplinghat, Kwa, Ren (in prep)

More Galaxies…

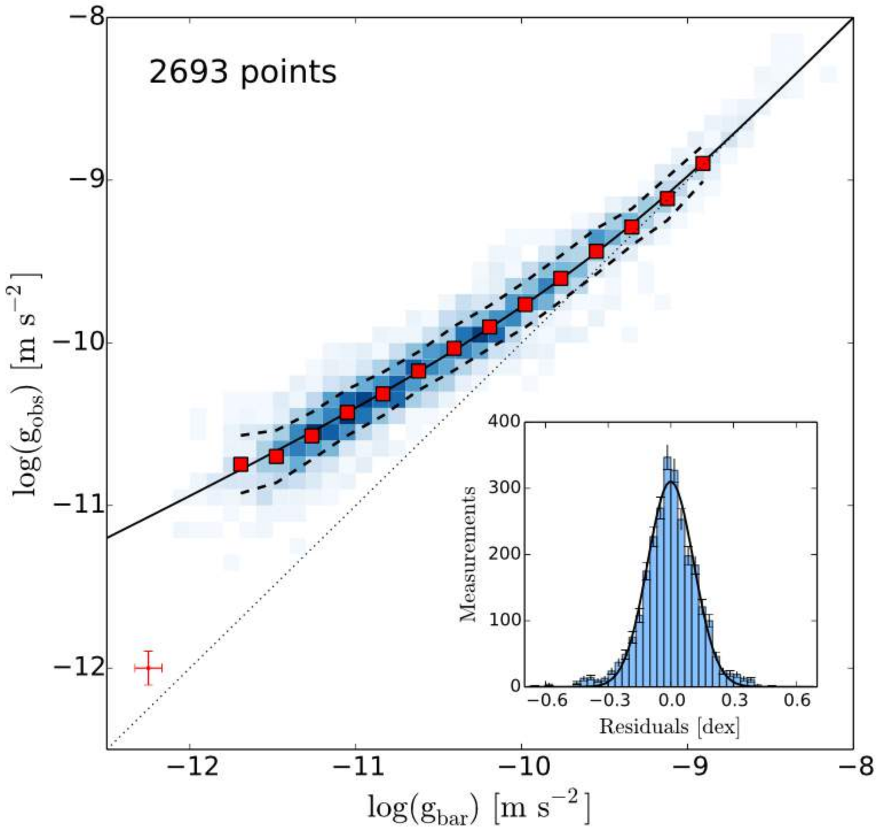




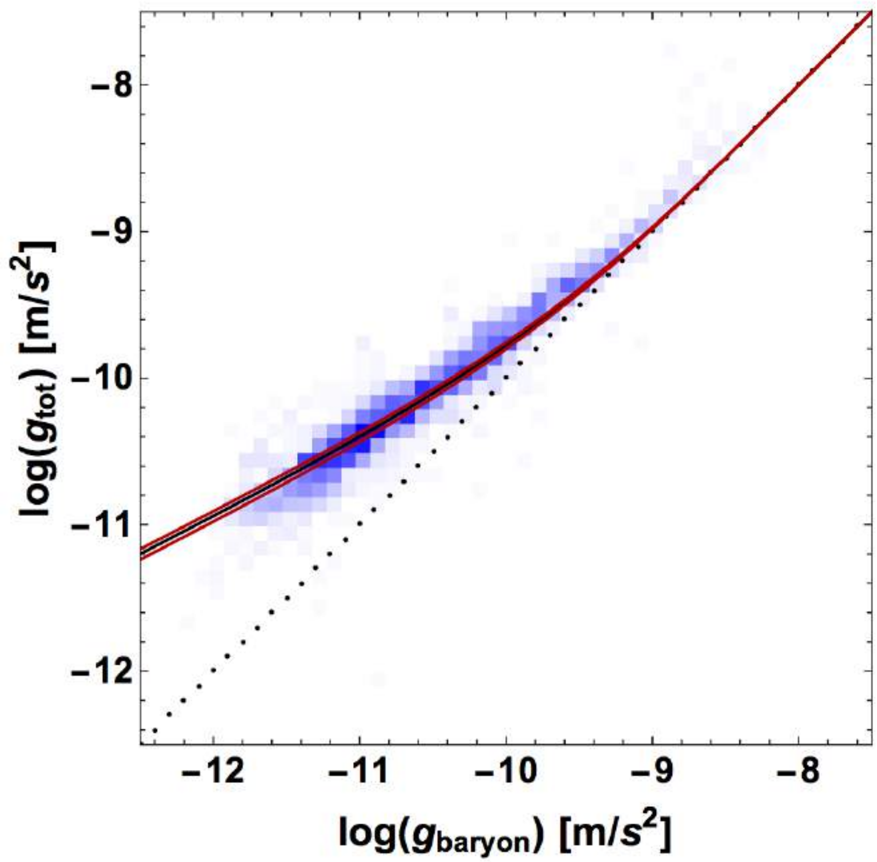
With Kaplinghat, Kwa, Ren (in prep)

- ~114/120 galaxies can be fitted within 2σ range of the halo concentration-mass relation predicted in ΛCDM cosmology (from Dutton, Maccio, 2014)
- The SIDM fits reproduce the Tully-Fisher relation

Radial Acceleration Relation



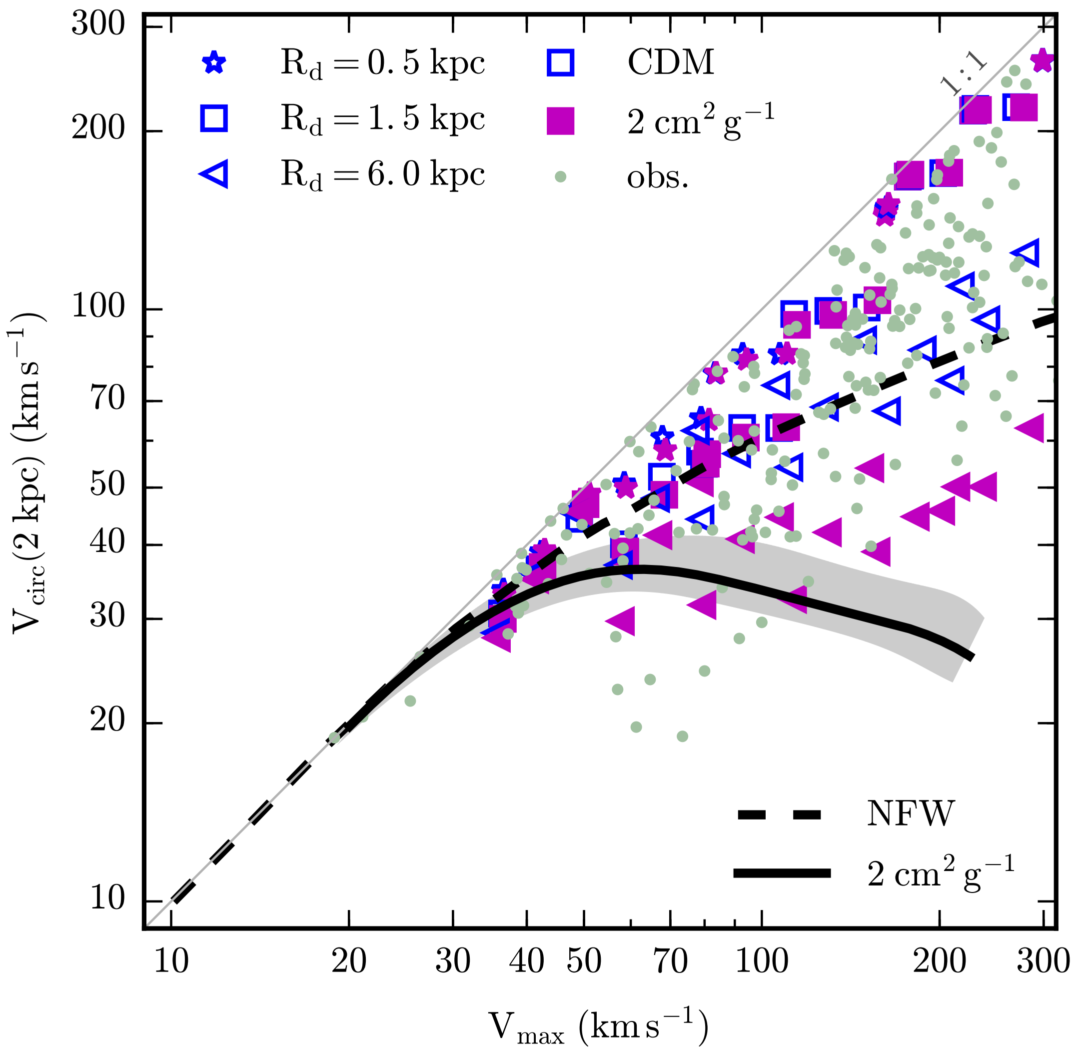
McGaugh, Lelli, Schombert (2016)

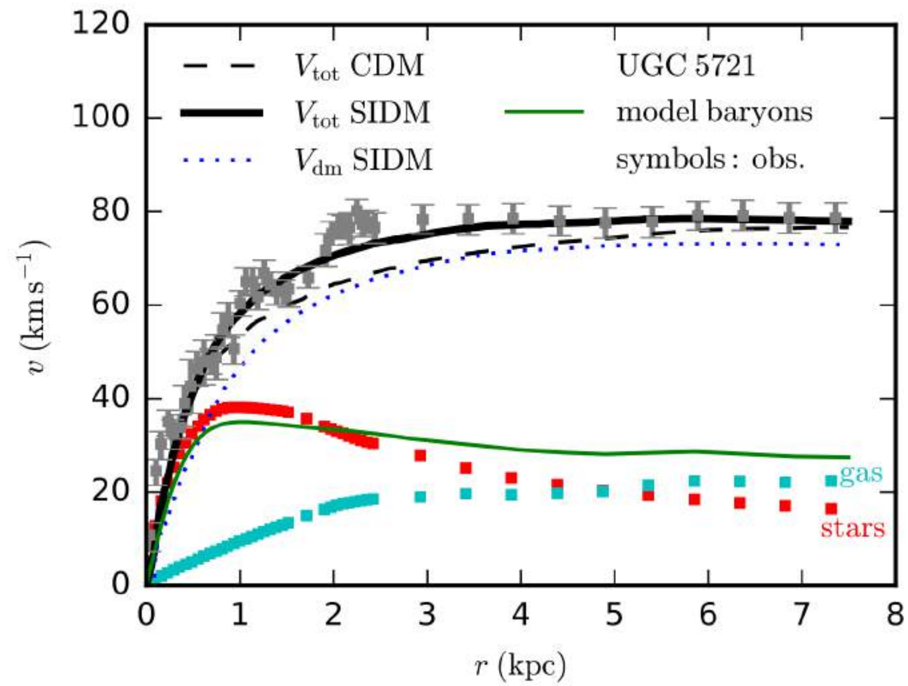


With Kaplinghat, Kwa, Ren (in prep)

The same SPARC data set

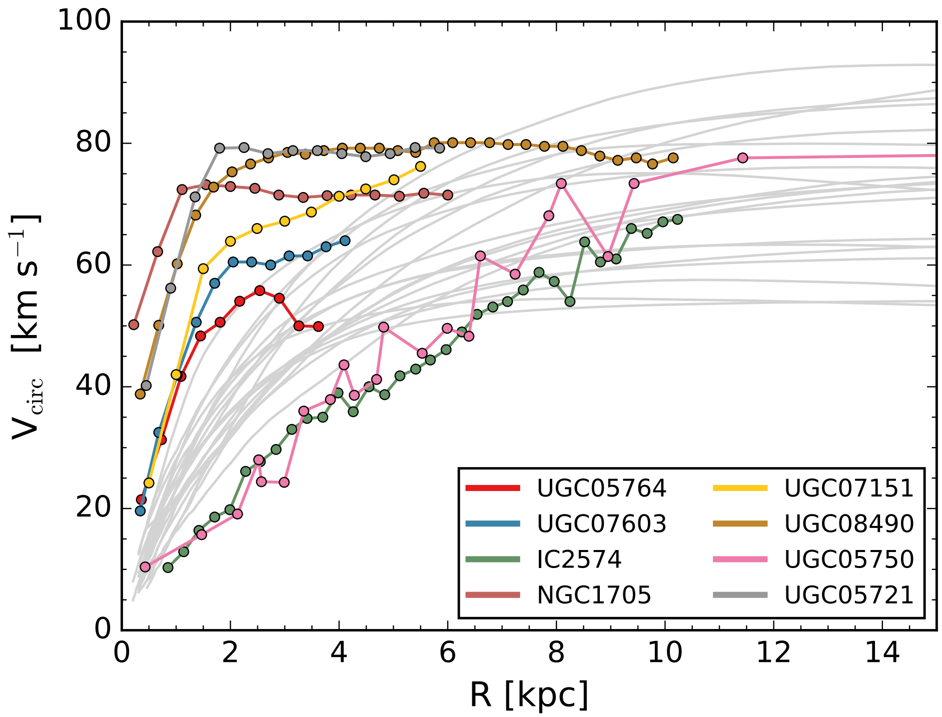
Simulations





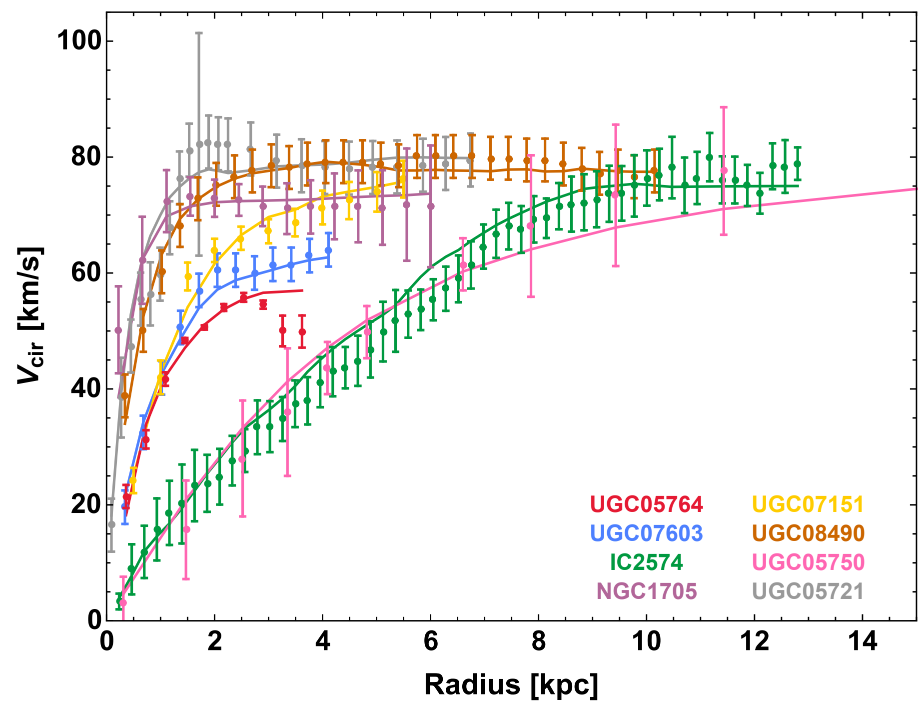
Controlled N-body simulations: with Creasey, Sameie, Sales, Vogelsberger, Zavala (2016)

Strong Feedback vs. SIDM



NIHAO simulations
strong feedback

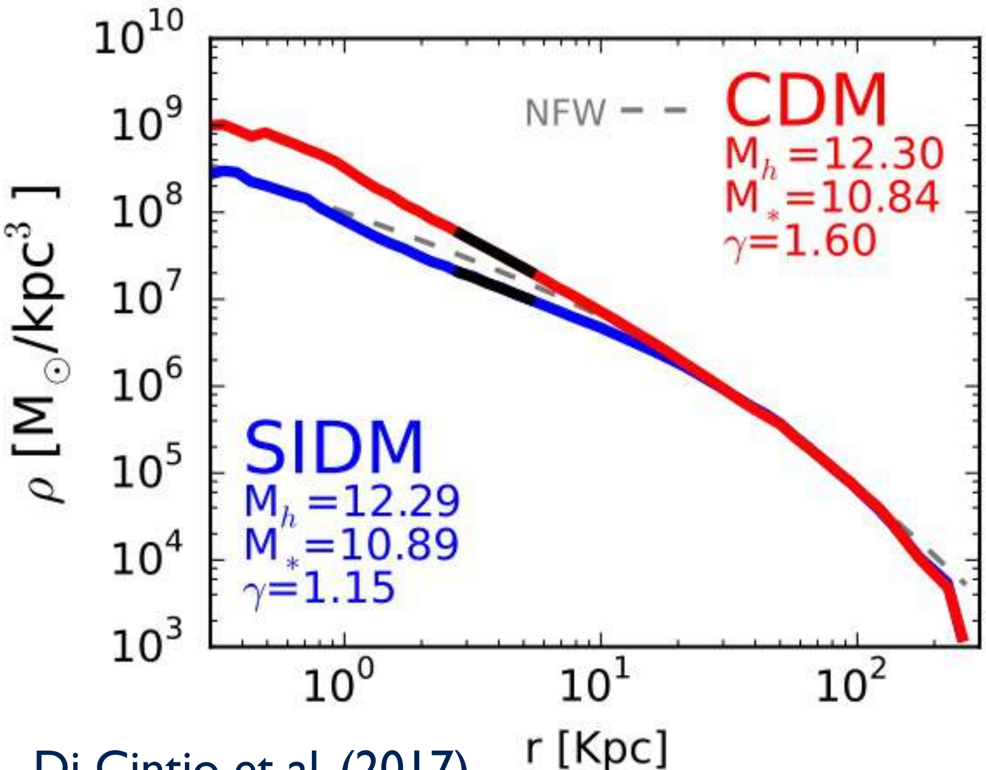
Santos-Santos et al. (2017)



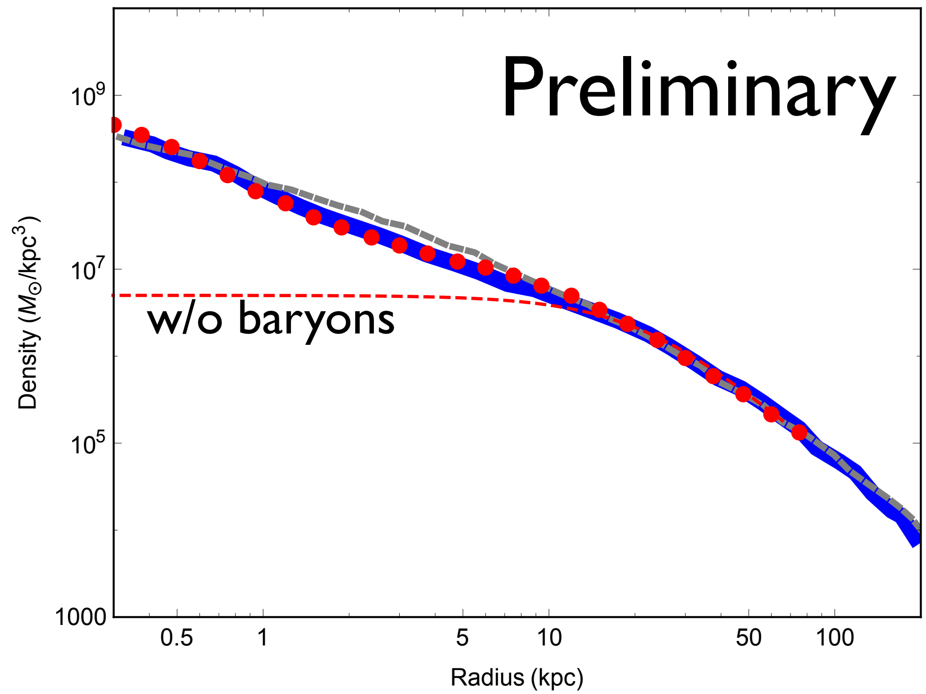
SIDM

with Kaplinghat, Kwa, Ren (in prep)

SIDM with Strong Feedback



Di Cintio et al. (2017)

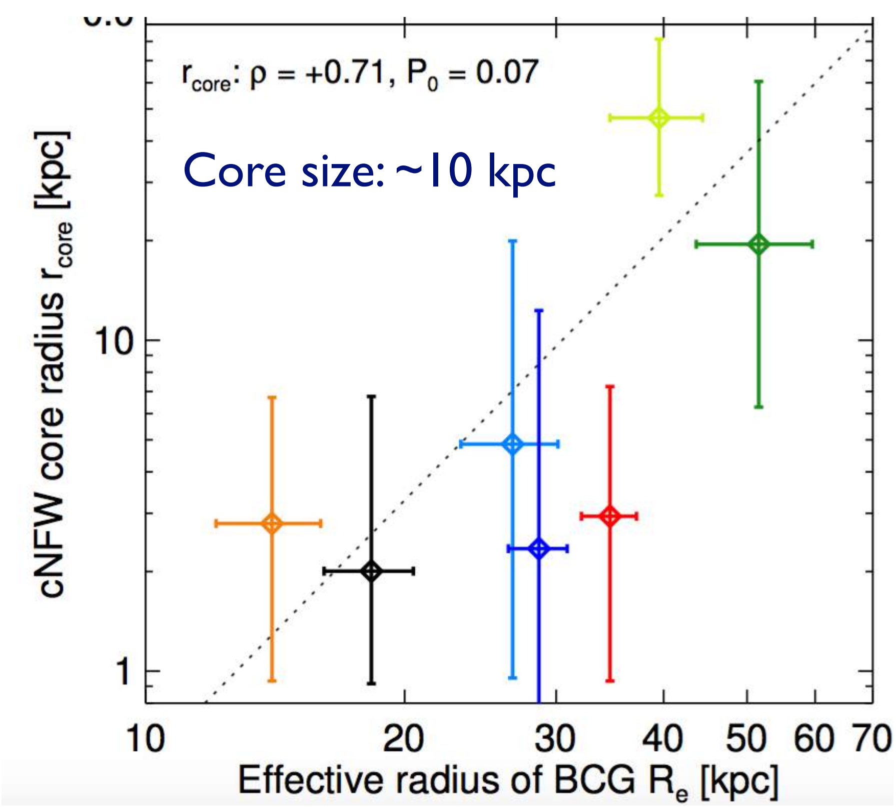


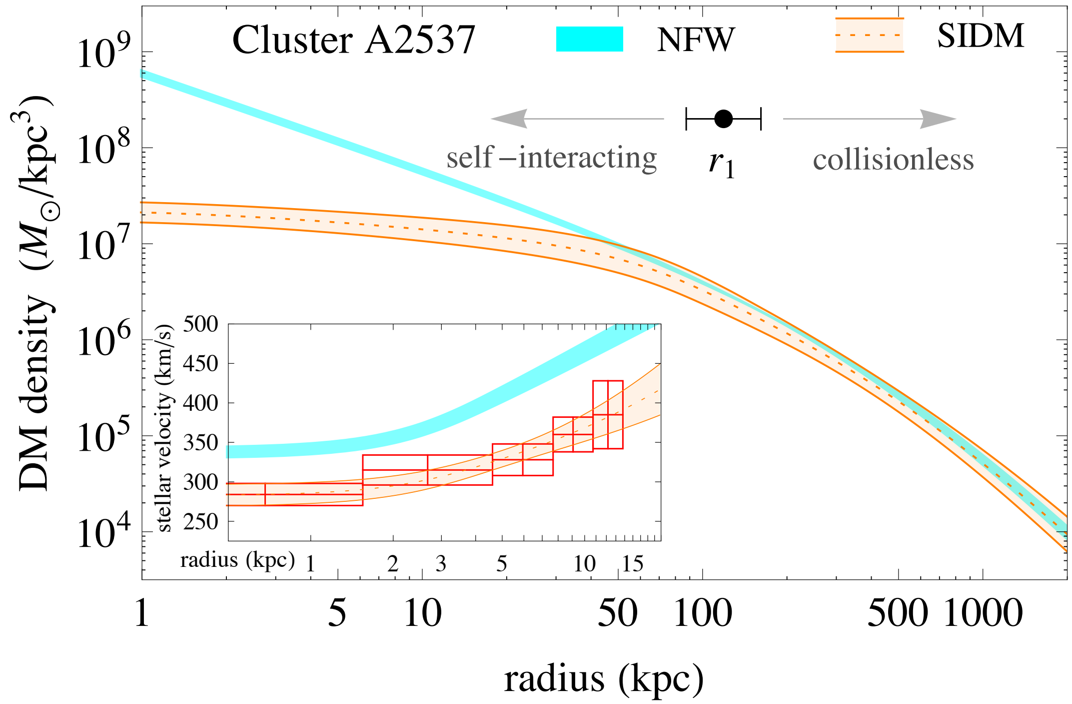
$$\rho_X \sim e^{-\Phi_{\rm tot}/\sigma_{\rm v0}^2}$$

red dots: thermal distribution w/ baryons

- The SIDM distribution is sensitive to the baryon distribution
- But, it is not sensitive to the formation history

Density Cores in Galaxy Clusters





Newman et al. (2013)

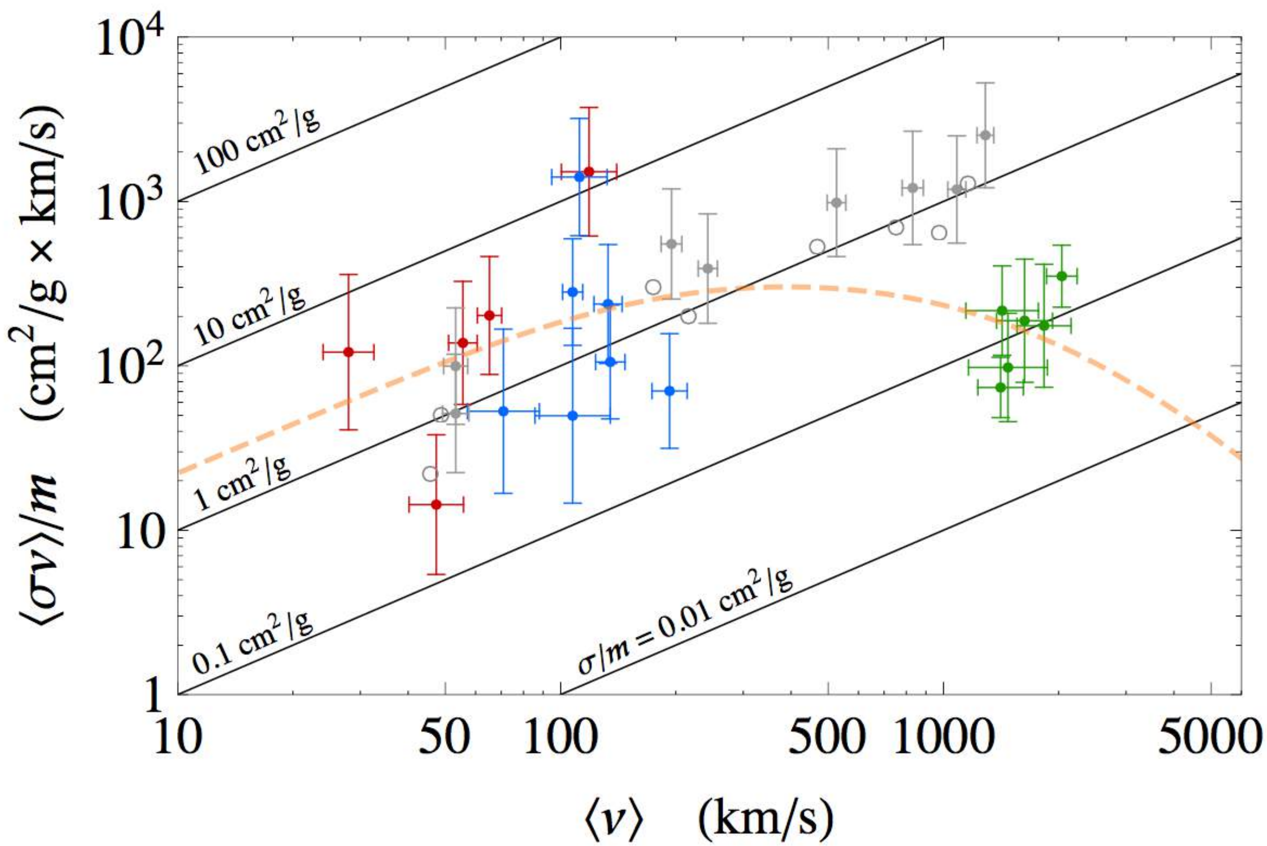
with Kaplinghat, Tulin (2015)

Clusters: M_{halo}~10^{14}-10^{15} $M_\odot$

Galaxies: M_{halo}~10^{9}-10^{12} $M_\odot$

SIDM from Dwarfs to Clusters

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



Galaxies: ~2-3 cm^2/g

Clusters: ~0.1 cm^2/g

Core size in clusters: ~10 kpc

If it were ~1 cm^2/g in clusters, the core size would be ~100 kpc

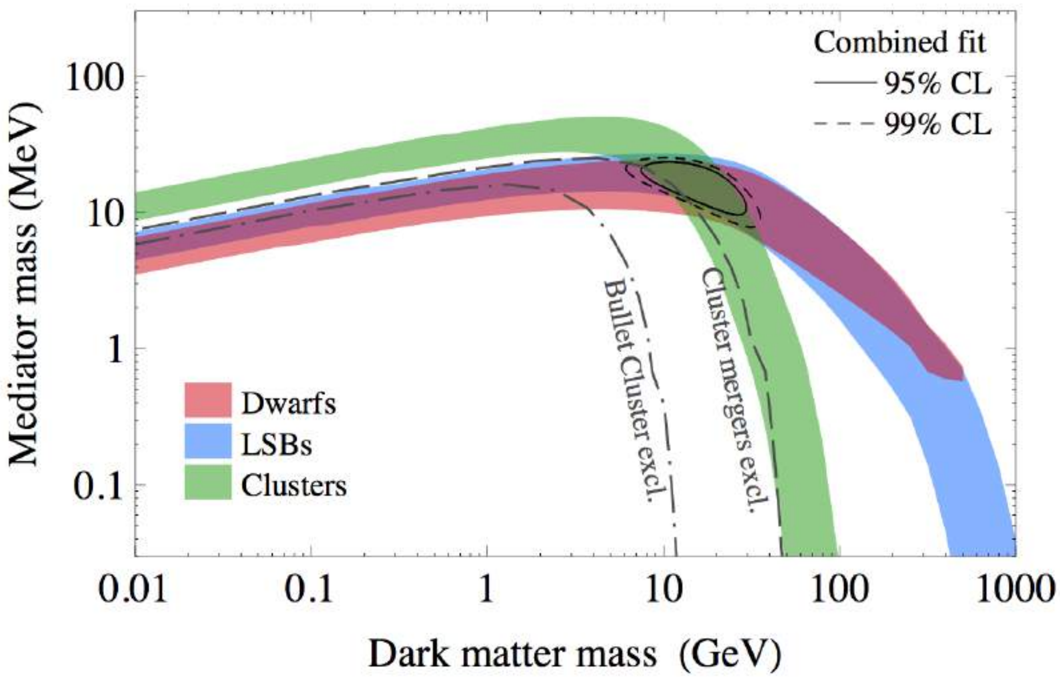
The strongest limit!

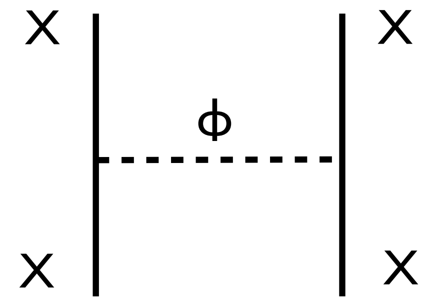
with Kaplinghat, Tulin (2015)

DM halos as particle colliders

Measuring Dark Matter Mass

- Self-scattering kinematics determines SIDM mass



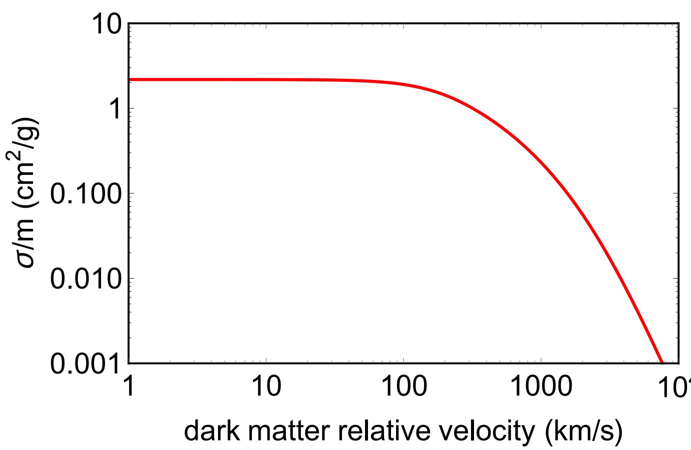


$$V(r) = \frac{\alpha_X}{r} e^{-m_\phi r}$$

α_X=1/137

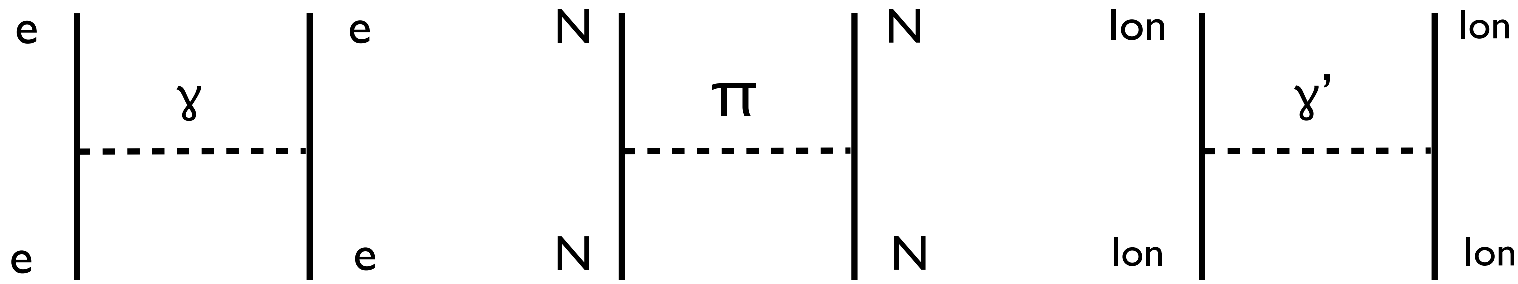
m_X: ~15 GeV, m_ϕ: ~17 MeV

with Kaplinghat, Tulin (2015)

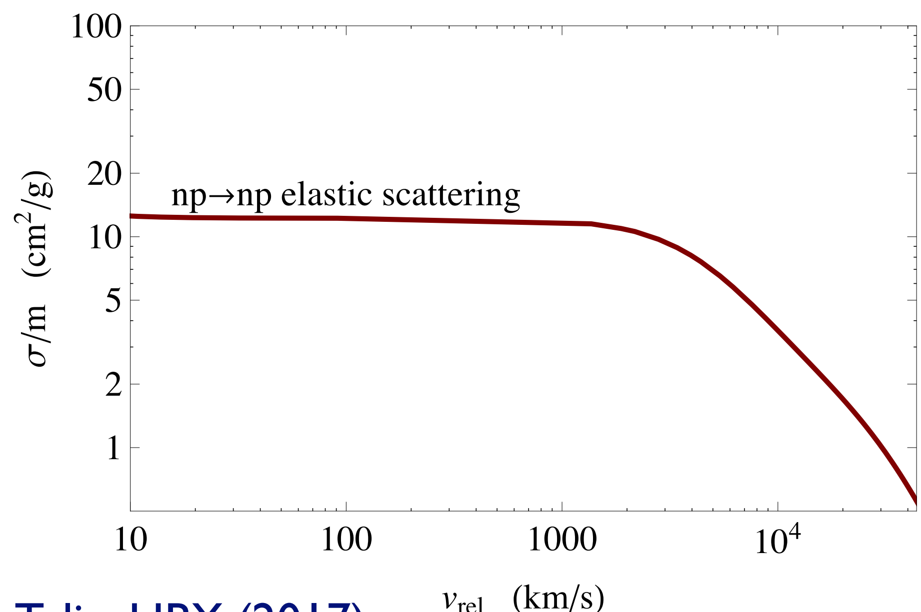


Particle Physics of SIDM

- Familiar examples in the visible sector



$$V(r) = \frac{\alpha_{\rm EM}}{r} \qquad V(r) = \frac{1}{r}e^{-m_\pi r} \qquad V(r) = \frac{\alpha_{\rm EM}}{r}e^{-m_D r}$$



Tulin, HBY (2017)

Data: Obloinsk et al. (2011)

Other examples: atomic DM, SU(N) composite DM…

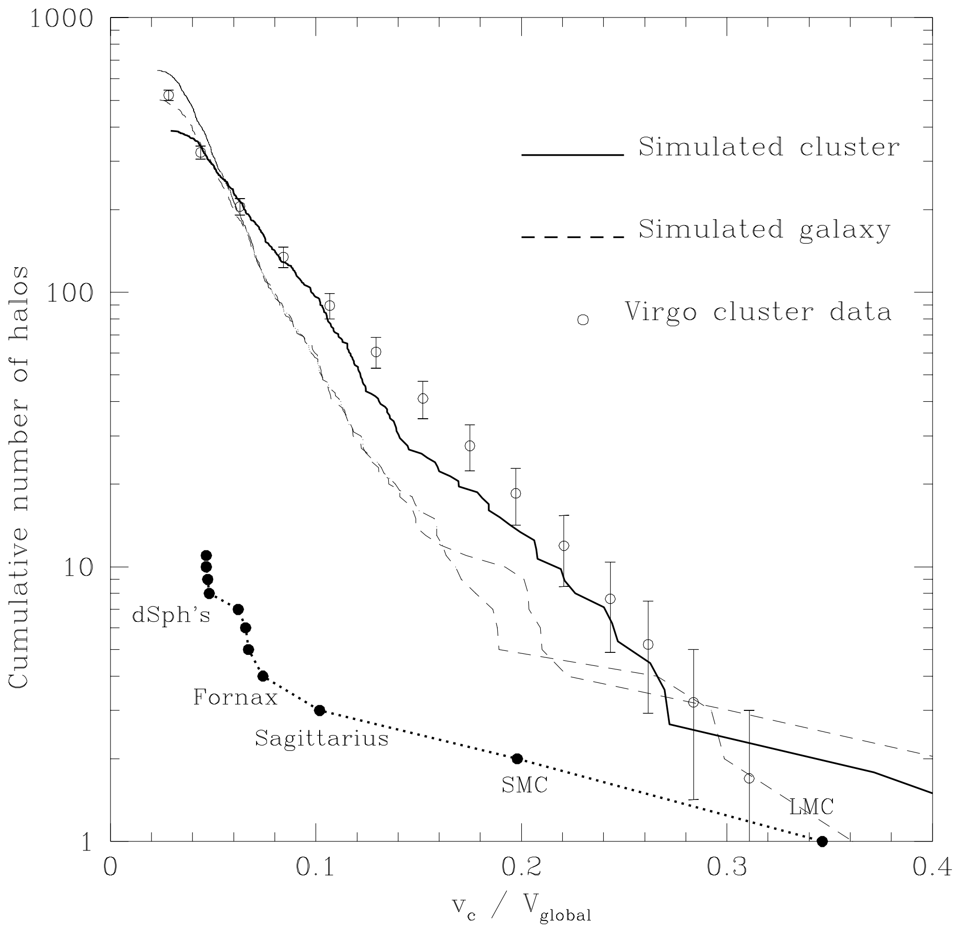
Need two scales to generate v-dependence

Small-Scale Issues

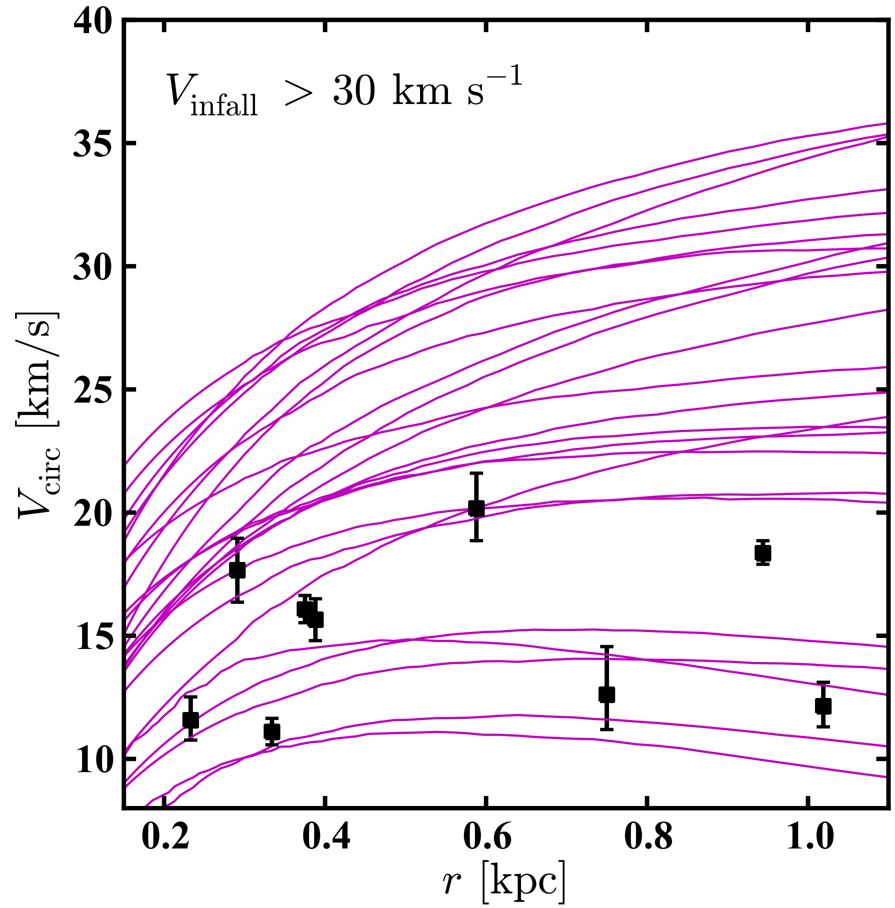
- Crisis on small scales: galactic scales, <10-100 kpc

  Core vs. Cusp
  Diversity
  Missing Satellites
  Too-Big-To-Fail

Missing Satellites & Too-Big-To-Fail



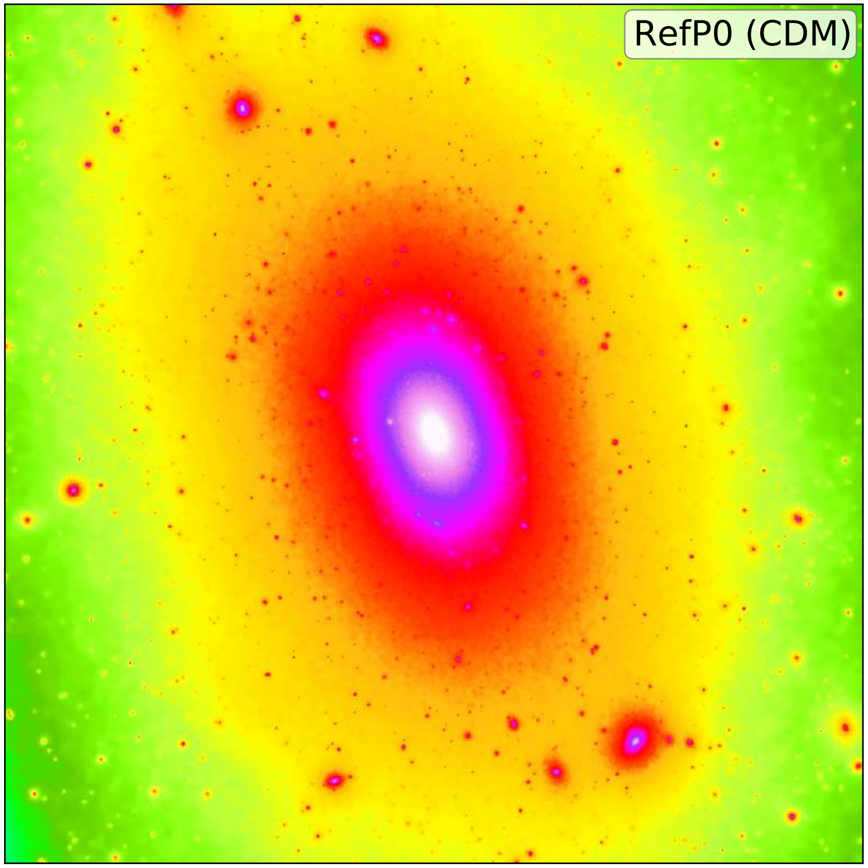
Moore et al. (1999)

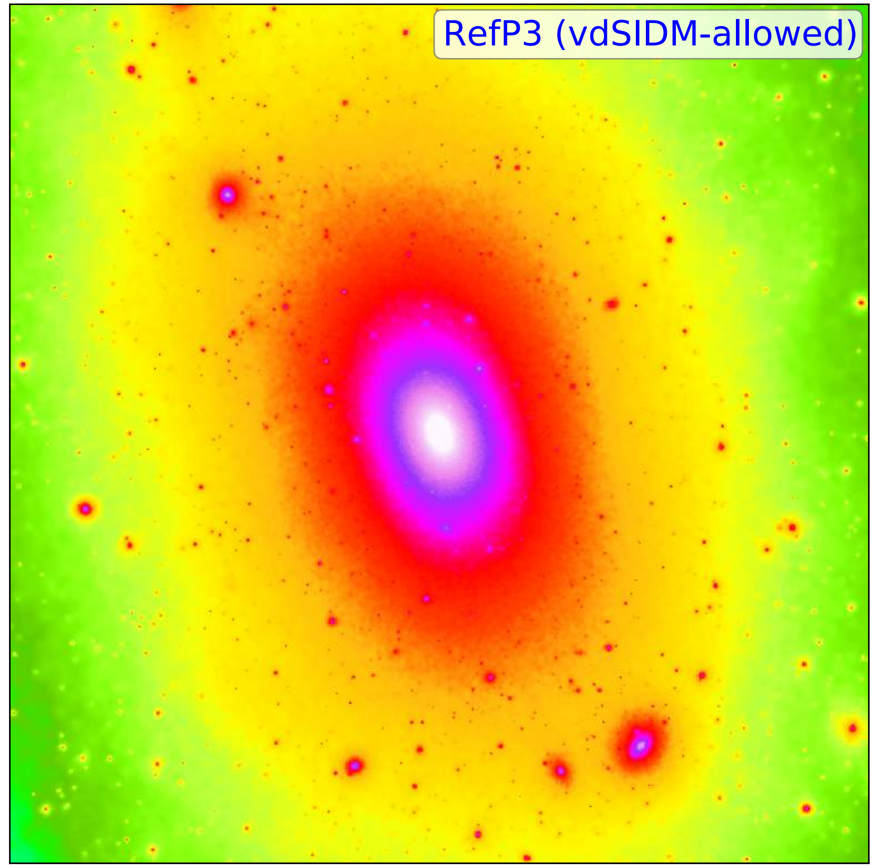


Boylan-Kolchin, Bullock, Kaplinghat (2011)

TBTF in the field: Zavala (2009), Ferrero et al. (2012), Papastergis et al. (2014), Klypin et al. (2015)

Subhalos in SIDM

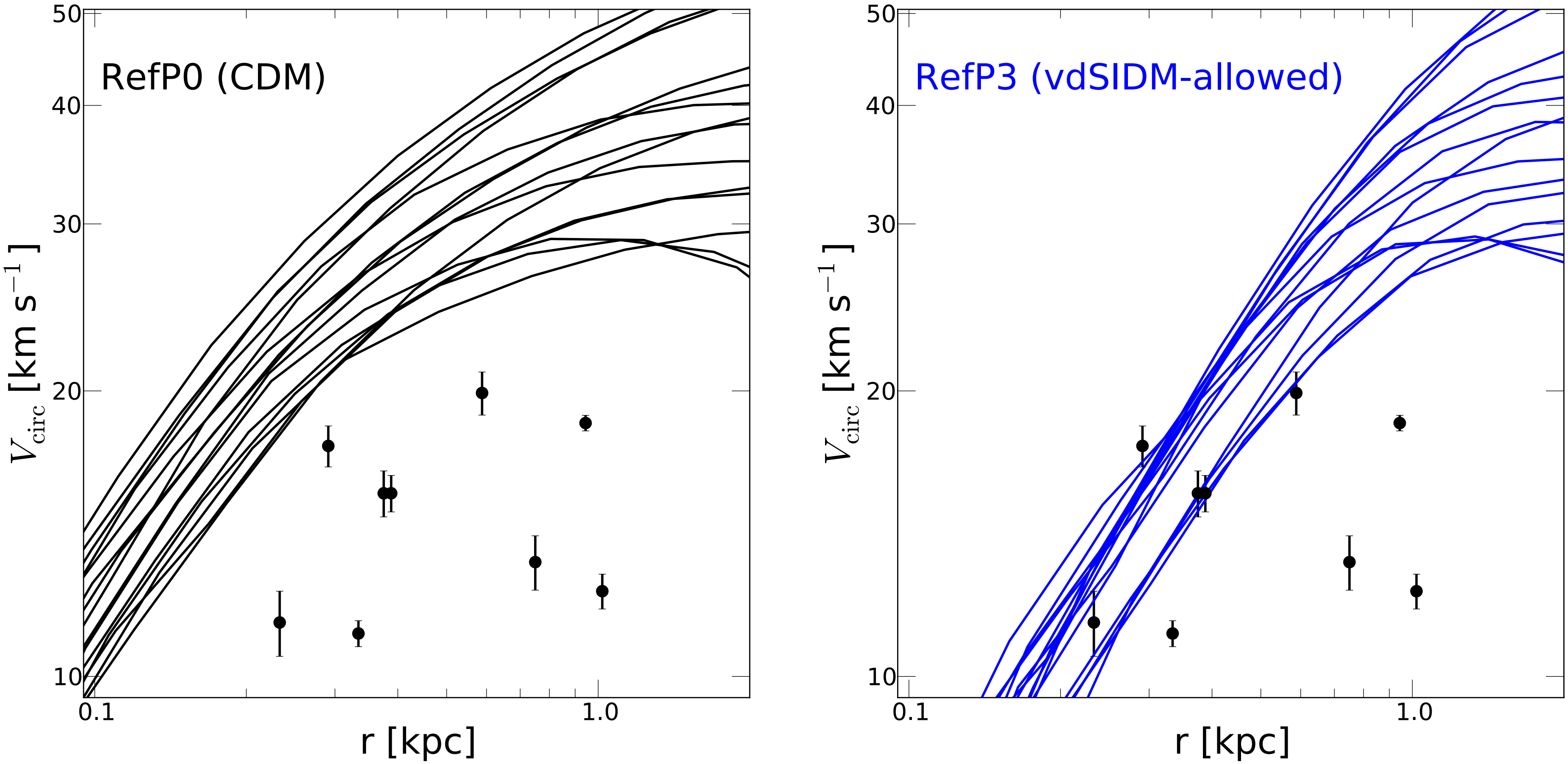




Vogelsberger, Zavala, Loeb (2010)

DM self-scattering itself does not reduce the number of massive subhalos significantly for $\sigma/m_X \sim 1\ cm^2/g$

SIDM Solution to TBTF



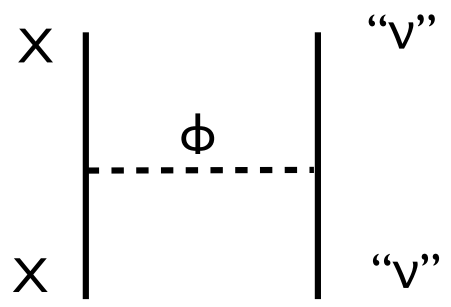
Vogelsberger, Zavala, Loeb (2012)

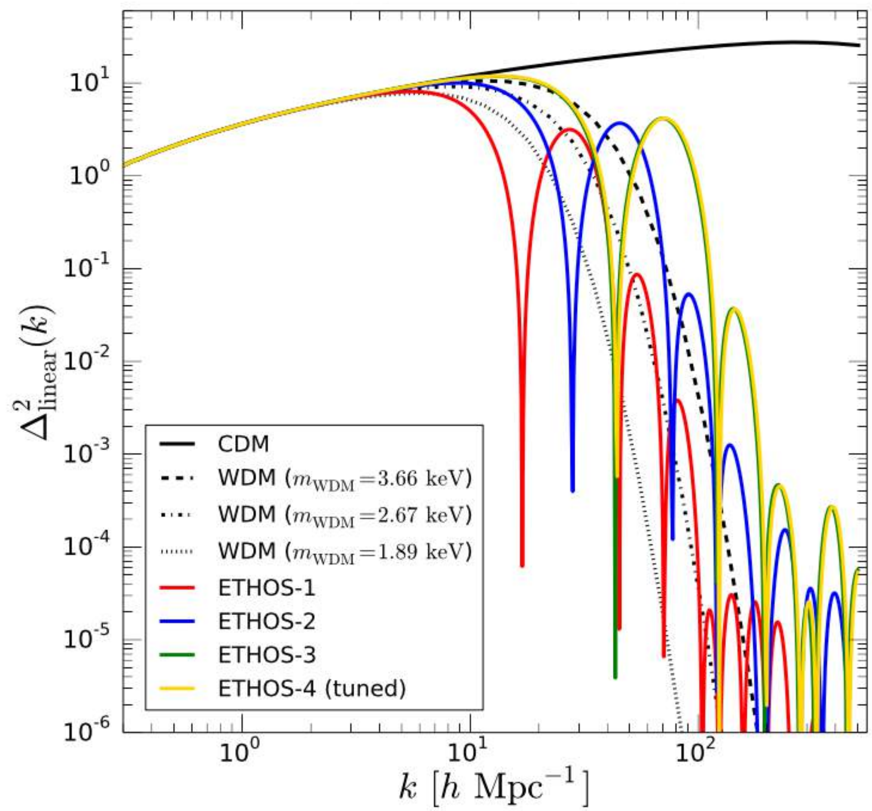
DM self-interactions reduce the total DM mass in the central regions

See Mauro Valli's talk in this session

Dark Acoustic Oscillation

- Roles of dark radiation, damped SIDM power spectrum





The ETHOS collaboration (2015)

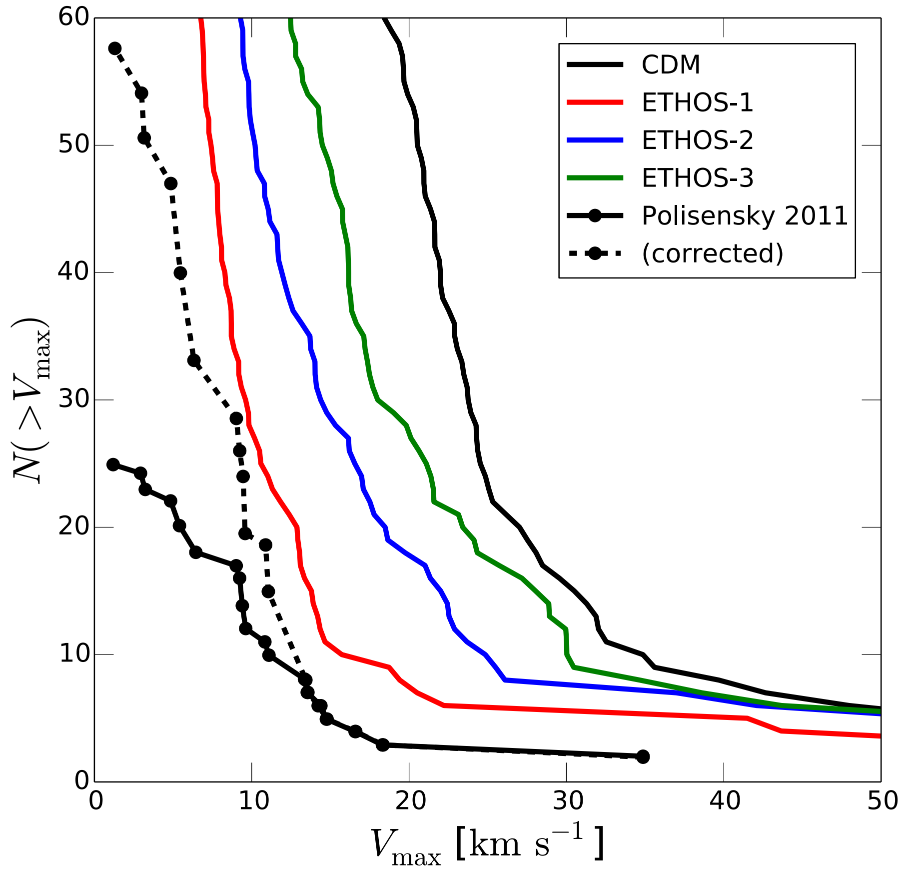
It may provide a mechanism to solve the MS problem.

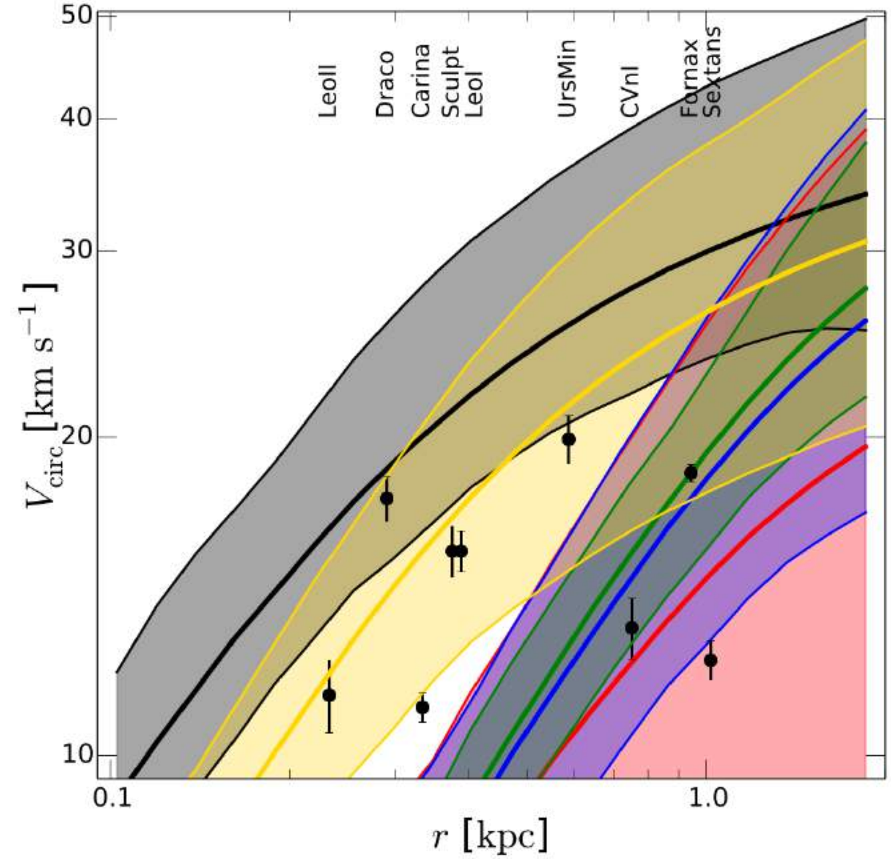
Boehm, Fayet, Schaeffer (2000); Boehm, Riazuelo, Hansen, Schaeffer (2002);
van Den Aarssen, Bringmann, Pfrommer (2012);
Cyr-Racine et al. (2015)…

- Such coupling is naturally expected in SIDM

SIDM: m_ϕ~10 MeV, T_{kd}~1 keV; CDM (WIMP): m_ϕ~1 TeV, T_{kd}~30 MeV

Damped Power Spectrum



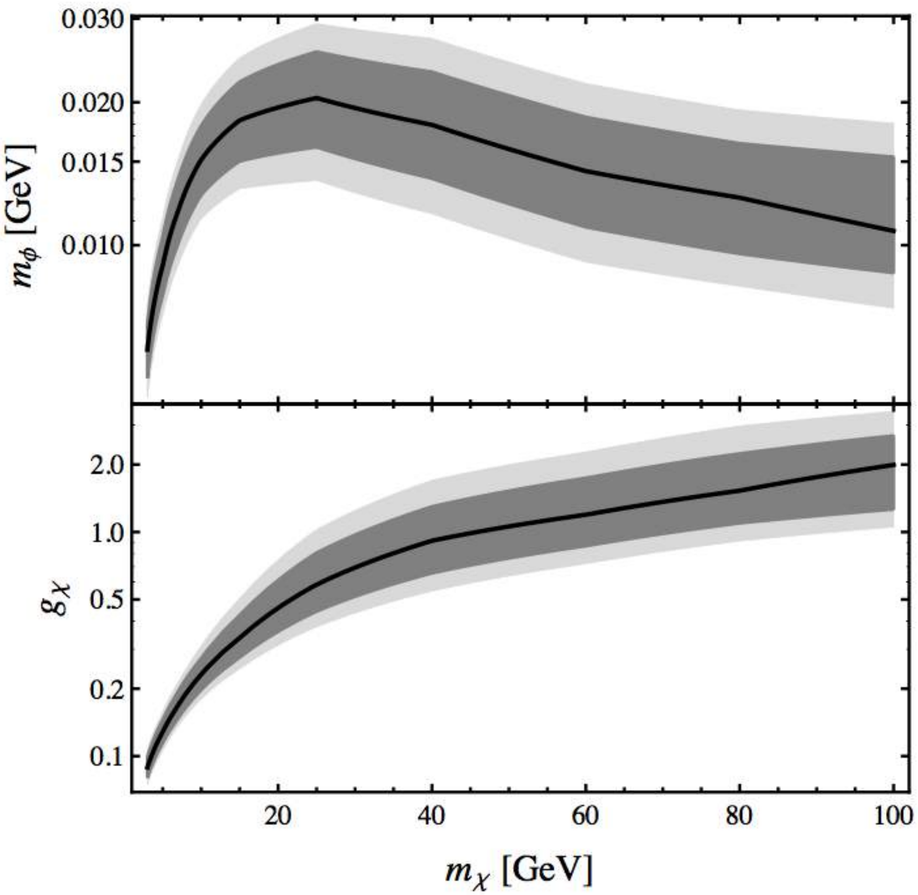


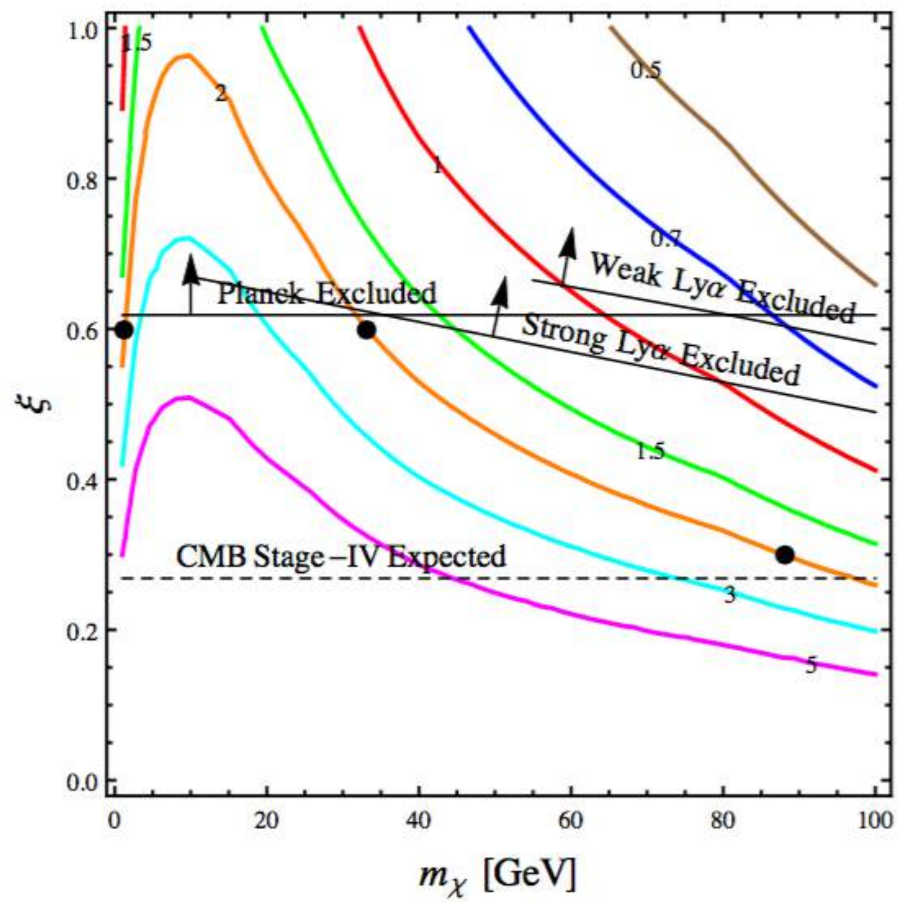
The ETHOS collaboration (2015)

See also Boehm et al., (2014), Schewtschenko et al. (2015)

- The combined effect due to DM self-scattering and damping can be important
- Damping itself could be dominant in solving the TBTF problem
- The damping effect creates large scatter in the central density, favored by the observations

A Unified Model





σ/m_χ ~ 2 cm^2/g (dwarfs), 0.1 cm^2/g (clusters)

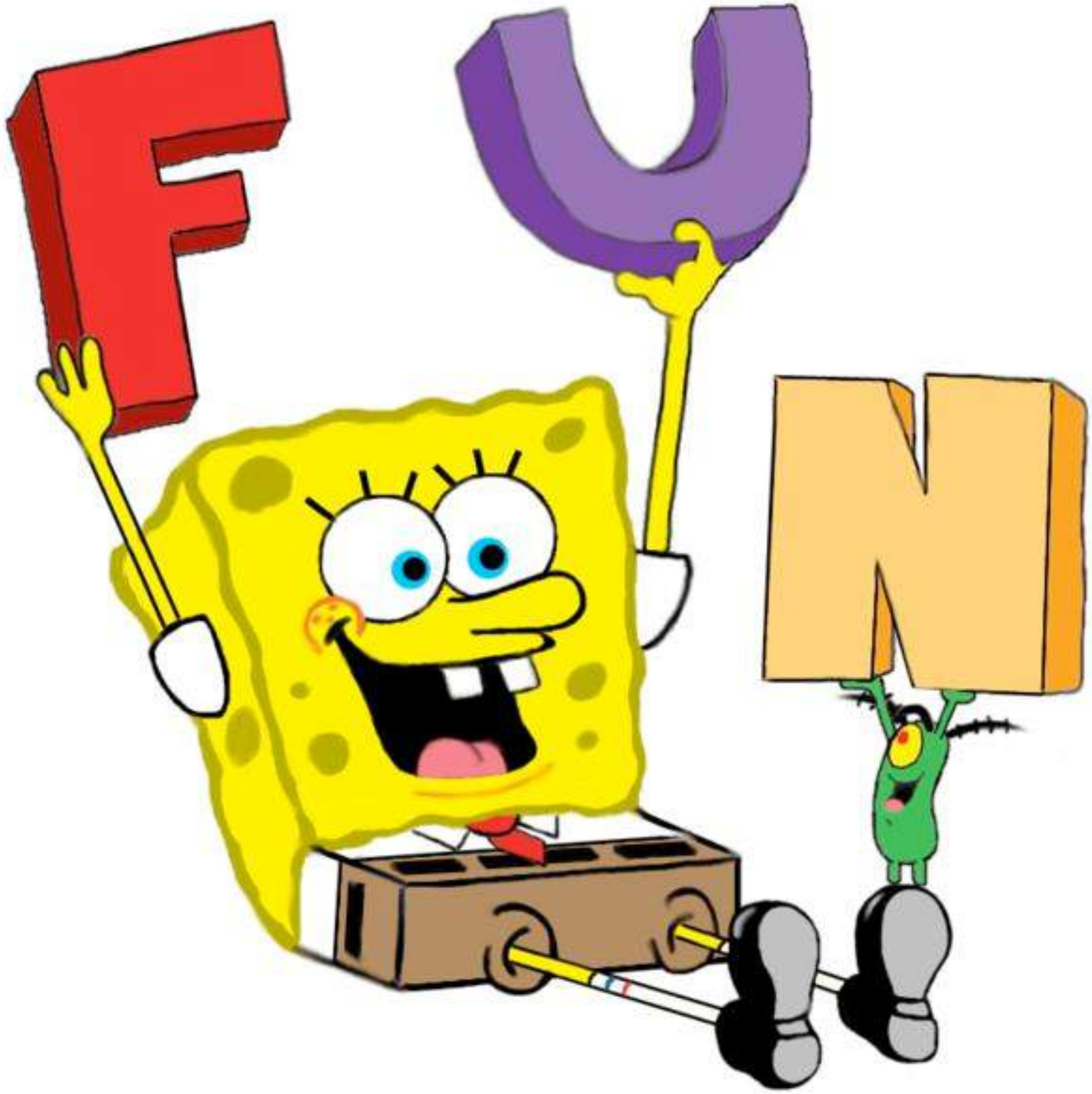
For given m_χ, we can fix g_χ and m_ϕ,

With Huo, Kaplinghat (in prep)

Summary

- It is time to think about new approaches to the dark matter problem
- SIDM is a compelling alternative to CDM
- It explains the diverse rotation curves of spiral galaxies
- It has other novel features: damped power spectrum, addressing MS and TBTF problems

We will hear more in this workshop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