Mapping Dark Matter in Galaxies Large and Small

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CARNEGIE SCIENCE

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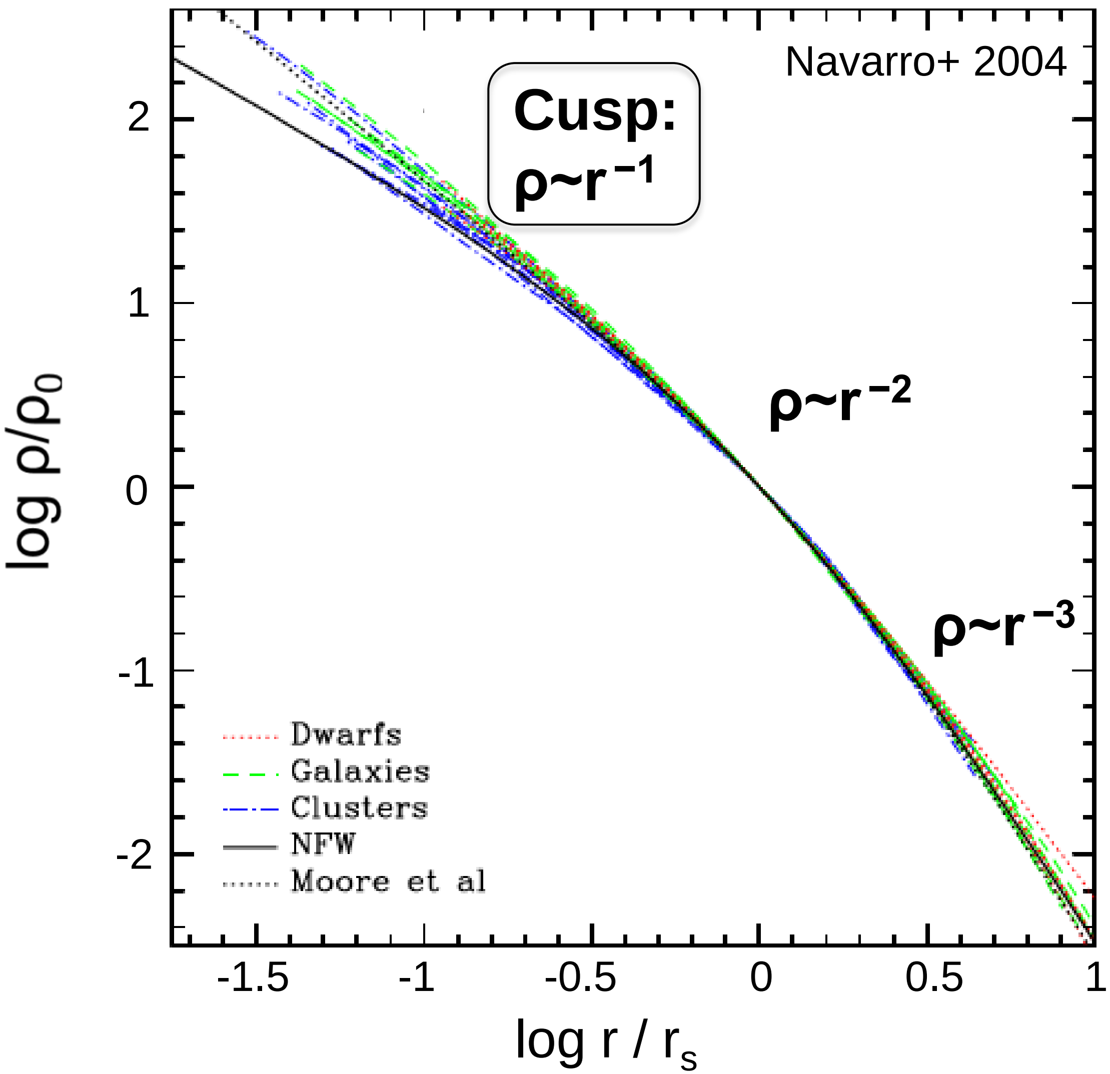
Paths for constraining DM through astrophysics

- Dwarf galaxies in the Local Group
- Abundance of early galaxies
- Small-scale structure in the intergalactic medium
- Dark subhalos detected by lensing or streams
- Dark matter density profiles
- Colliding clusters
- Shapes of dark matter halos
- CMB
- …

Halo structure in collisionless CDM



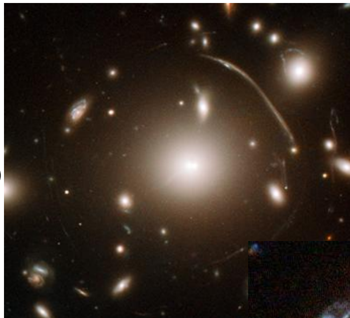
"Standard" LCDM predicts:

- Distribution of densities for halos of a given mass (mass—concentration relation)
- Shape of density profile is (nearly) universal, the famous NFW profile

(Note: not yet including effects of baryons)

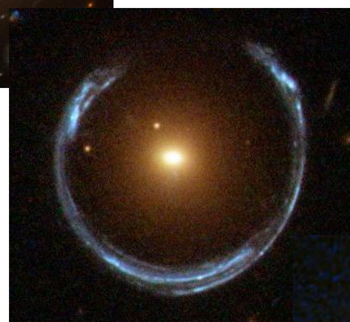
Dark matter density profiles: Clusters to dwarfs

10^{15} $M_\odot$



Galaxy clusters

10^{14} $M_\odot$



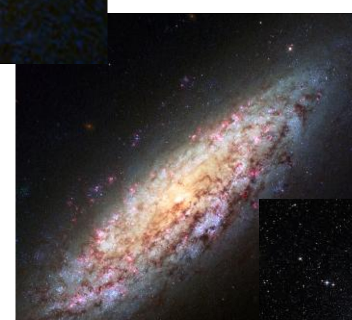
Galaxy groups

10^{13} $M_\odot$

Massive galaxies

…

10^{11} $M_\odot$



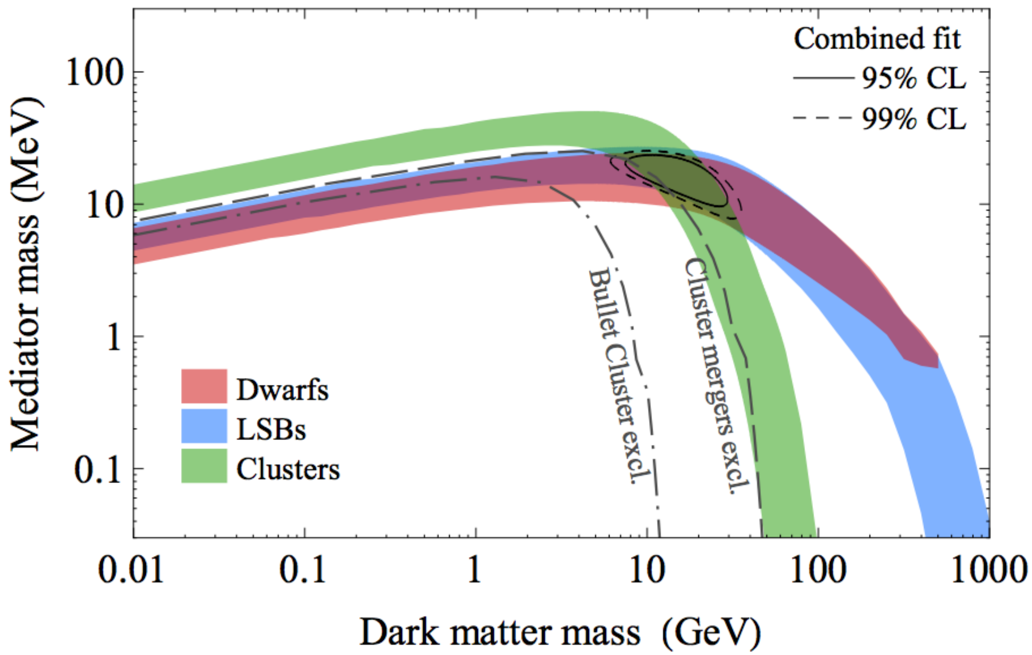
Low-mass disks

…

$<10^{9}$ $M_\odot$

Dwarf spheroidals
(not this talk)

The utility of density profiles for constraining DM



Kaplinghat, Tulin & Yu 2016

Observations of the inner regions of DM halos over a wide mass range can constrain particle models (see dark photon model above).

→ Motivates need to understand more than lowest-mass systems

Constraining DM: Three levels of inference

- Measuring total mass distribution
- Subtracting baryons

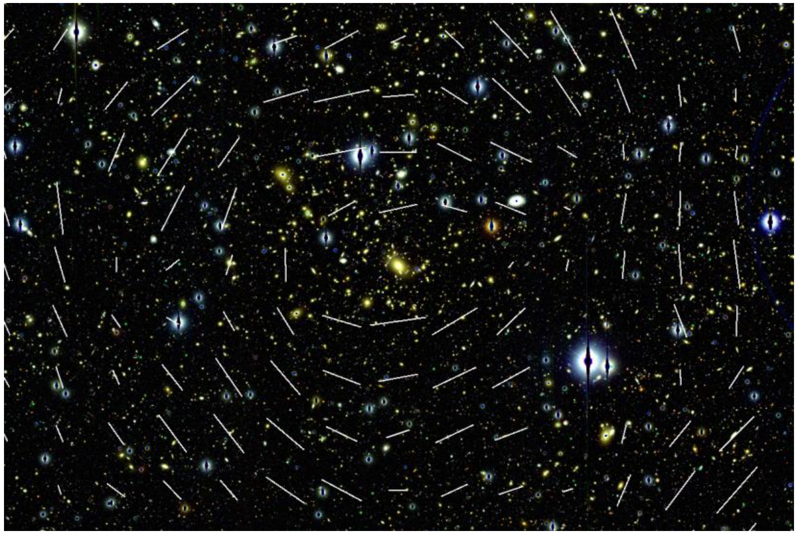
  Negligible only in lowest-mass galaxies

- Interpreting the dark matter profile

  Often (not always) observe lower central densities and/or shallower inner density slopes than NFW, i.e. “cores”

  Signs of additional DM physics?
  Or rearrangement of DM by baryonic processes?
  How can we tell the difference?

Galaxy clusters (~10^{15} $M_\odot$): Tools of the trade



Weak gravitational lensing
(~100 kpc – 3 Mpc)

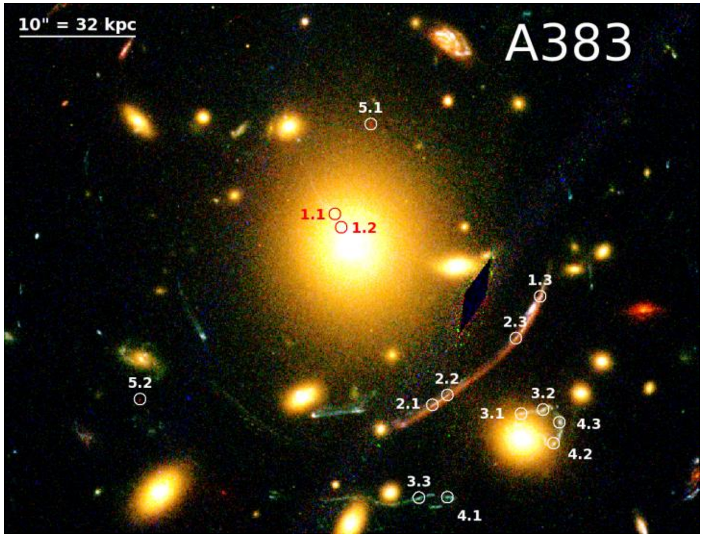
Small, systematic distortions in the shapes of all sources behind the cluster.

X-rays
(~30 kpc – 500 kpc)

X-ray emission from hot gas assumed to be near hydrostatic equilibrium.

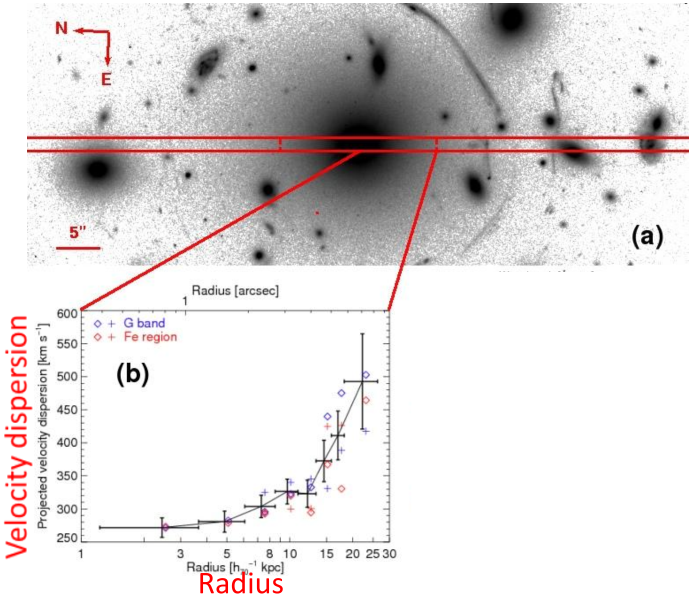
Many observables are available that probe the mass distribution over factor 10^3 in radius.

Galaxy clusters (~10^{15} $M_\odot$): Tools of the trade



Strong gravitational lensing
(~10 kpc – 100 kpc)

Multiple images of one or more galaxies behind the cluster; gives geometric constraints on inner mass distribution.

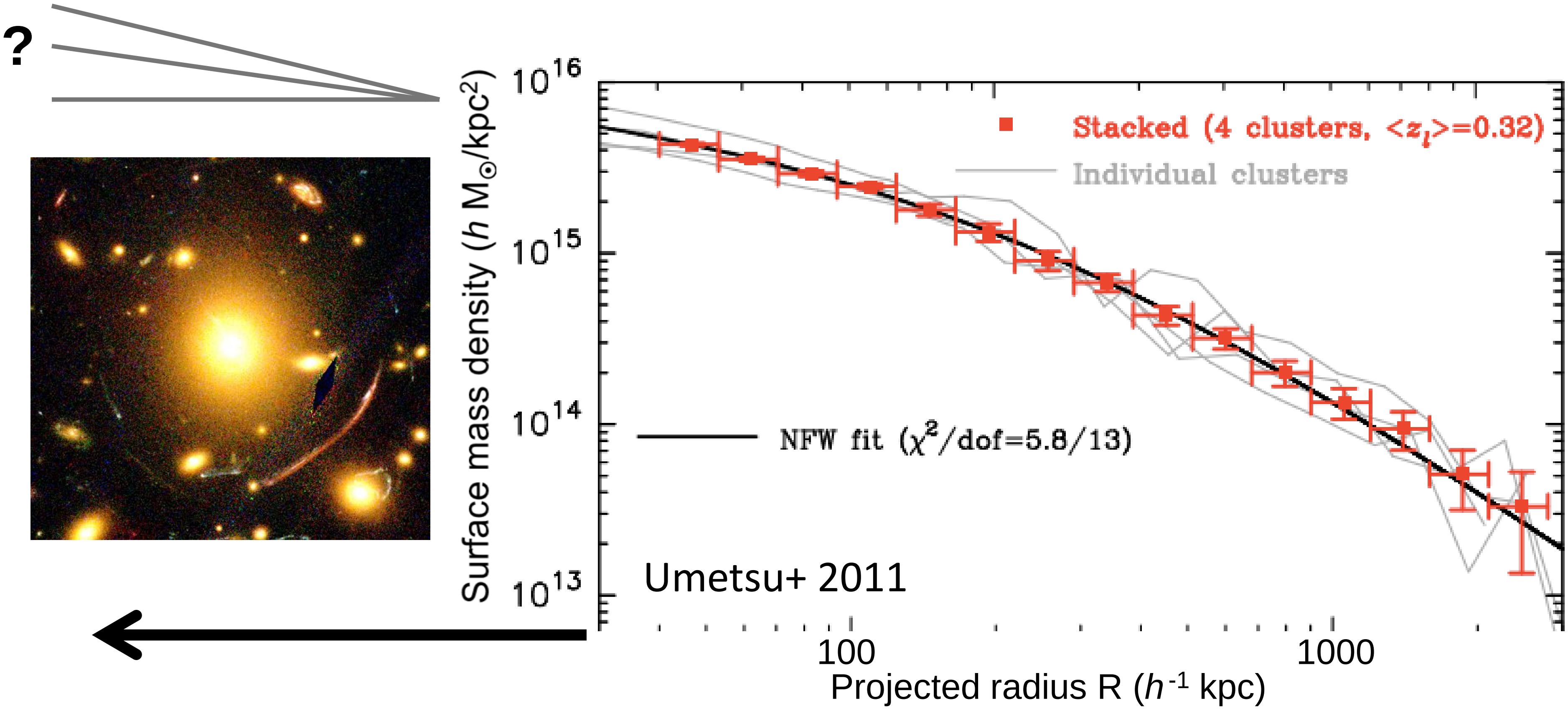


Stellar dynamics
(~3 kpc – 20 kpc)

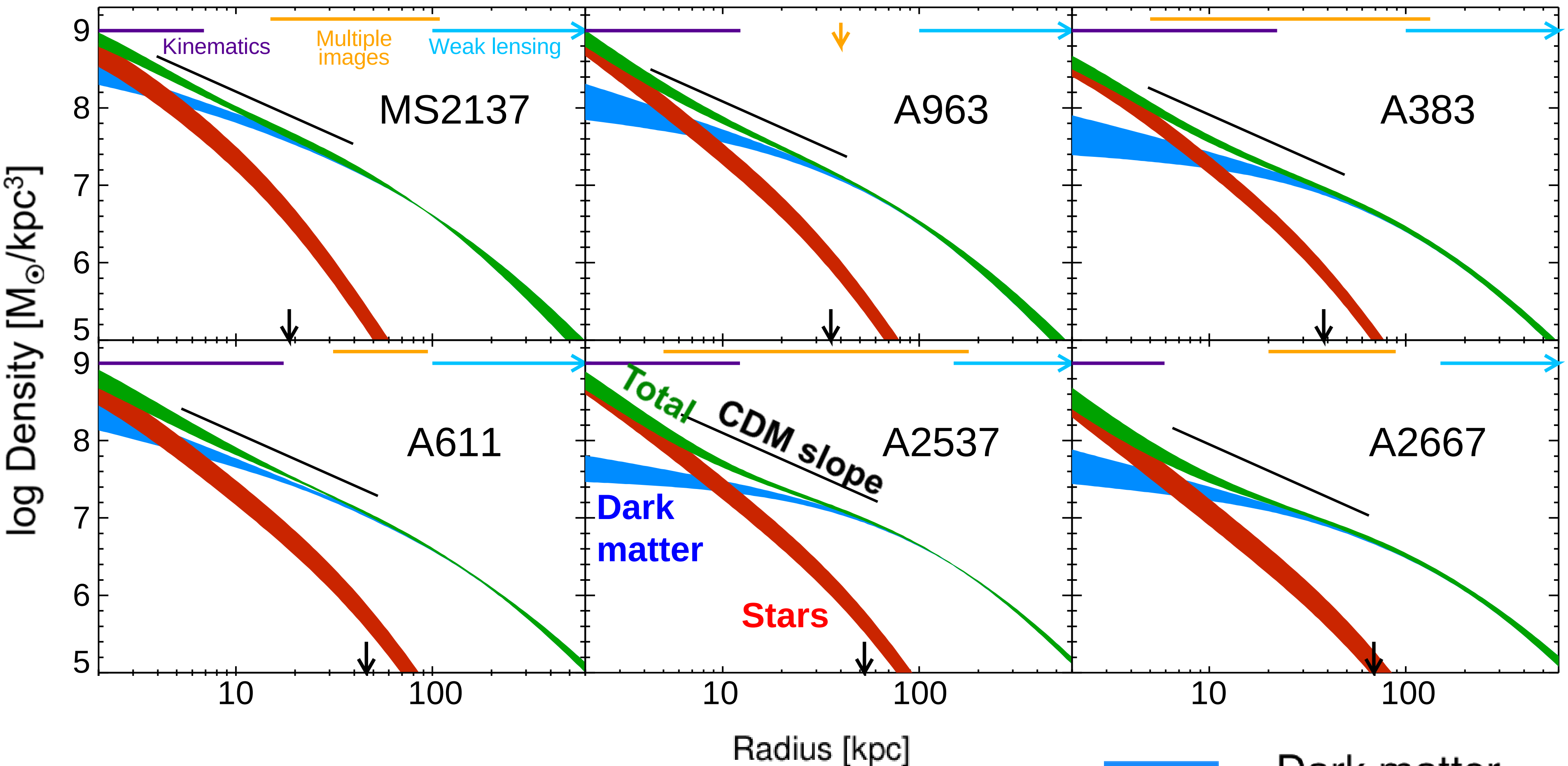
Internal motions (velocity dispersions) of stars in the central giant galaxy.

Many observables are available that probe the mass distribution over factor 10^3 in radius.

Collisionless CDM predictions are verified at "large" radii



Lensing studies have shown that on scales larger than the central galaxy, the canonical CDM profile is accurately followed in massive galaxy clusters.

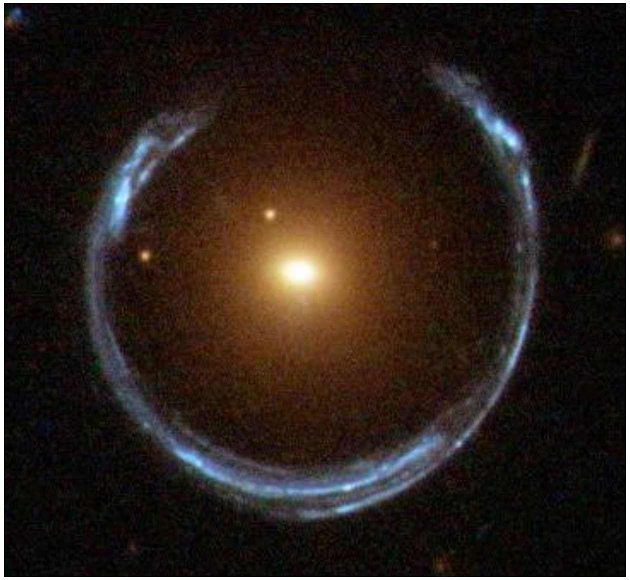


In cluster cores we find β=0.50+-0.17 cf. β=1 cusp for collisionless CDM.

Corresponds to "missing" ~half of DM within ~15 kpc, or about 1% of the virial radius of the cluster.

ABN+ 2013a,b

Galaxy groups (10^{14} $M_\odot$)



Is the low central DM density particular to clusters (massive halos)?

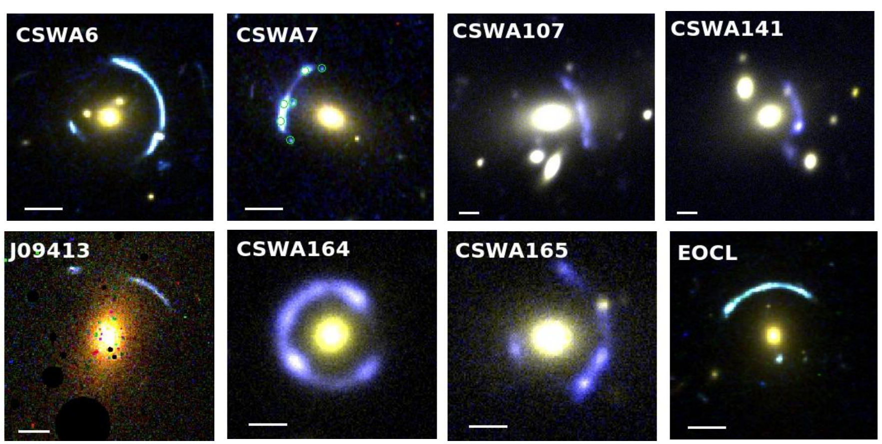
Similar techniques can be applied to galaxy groups (halos of 10^{14} $M_\odot$) that act as strong lenses:

strong lensing

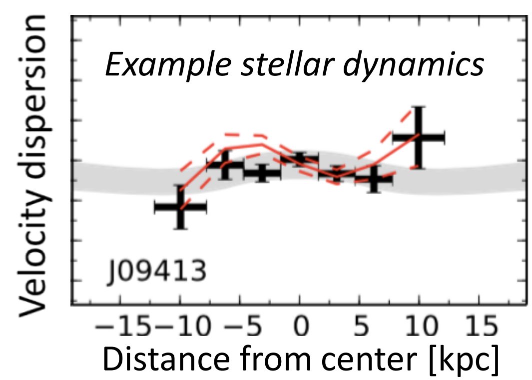
satellite kinematics / weak lensing

stellar kinematics

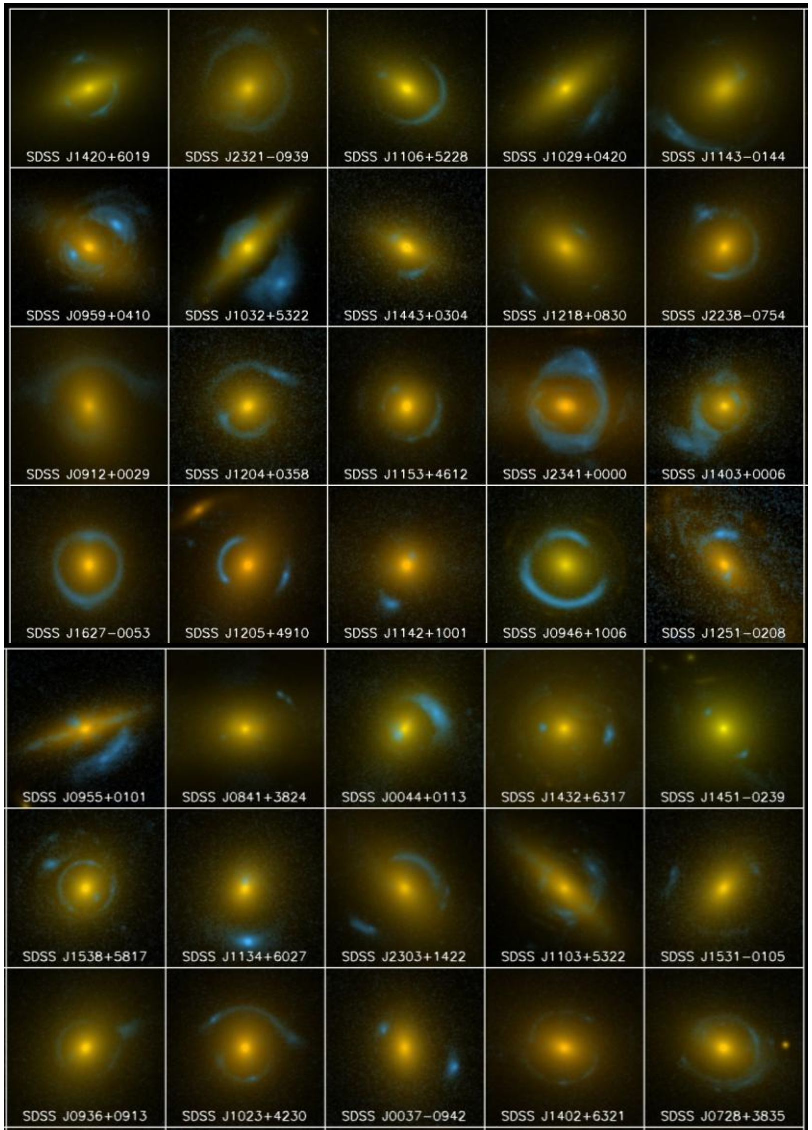
ABN+ 2015, Spiniello+ 2011, Deason+ 2013



ABN+ 2015



Individual massive galaxy lenses (10^{13} $M_\odot$)



SLACS survey Bolton, Koopmans, Treu, Gavazzi, Moustakis, Burles

Many (>100) galaxy strong lenses are known, but:

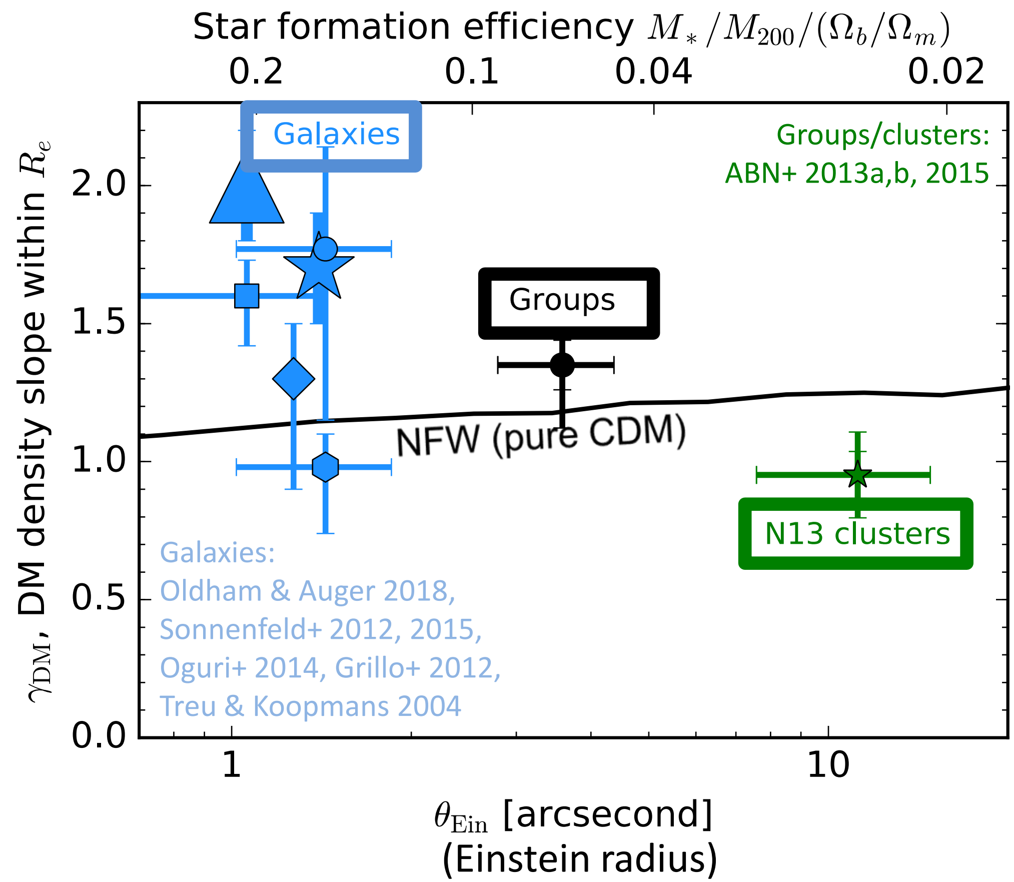
There are fewer observational constraints per system

Galaxies are baryon-rich within the strong lensing zone

→ Hard to measure DM slope, but possible in special cases or using sophisticated lens modeling

e.g. Sonnenfeld+ 2012, Oldham+ 2018

Constraints on inner DM profiles of massive halos



Clusters are the only systems with evidence for ***shallow*** dark matter slopes.
Groups are compatible with an ***unmodified*** NFW profile.
Galaxies are uncertain but probably have ***steeper*** than NFW slopes.

Dark matter profiles seem to vary systematically in the inner regions of massive galaxies.

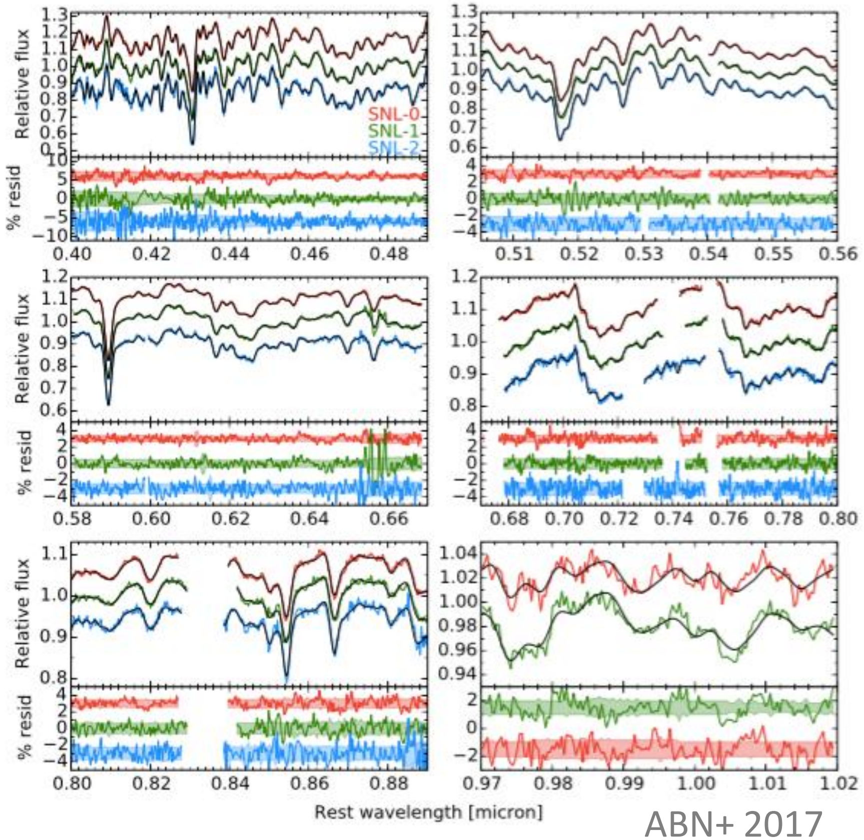
Can this be understood within “standard” LCDM?

With self-interacting DM (SIDM)?

Caveats in measurements & future improvements

- Measuring total mass distribution
  - Leading uncertainty is stellar orbits (anisotropy); can likely measure

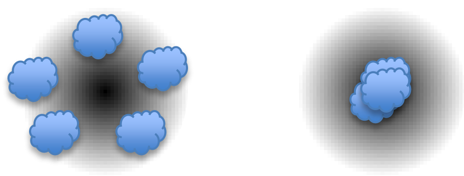
- Subtracting stellar mass
  - "Holy grail": Convert light to mass independent of gravitational probes
  - New spectroscopic techniques are able to probe faint, low-mass stars that may dominate the stellar mass
    e.g. Conroy & van Dokkum 2012
  - Remarkably, basic agreement among independent methods, *but* also scatter & variations that are not understood
    e.g. Treu+ 2010, Cappellari+ 2013, ABN+ 2017, Oldham+ 2018



ABN+ 2017

Baryon-based explanations

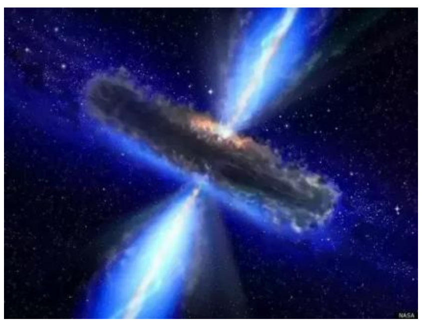
Adiabatic contraction



Gas cools and condenses in halo center. Conserving specific angular momentum $\Rightarrow \; rM(<r) = \text{const}$
Increases central density.

Barnes & White 1984; Blumenthal+ 1986;
Ryden & Gunn 1987; Gnedin+ 2004; …

Black hole feedback



The central supermassive black hole establishes a gas ejection / accretion cycle in forming clusters. Oscillations in the potential move DM outward.
Decreases central density.

Martizzi+ 2012, 2013; Peirani+ 2017; …

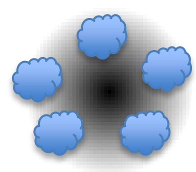
Gravitational heating

Infalling galaxies (& SMBHs) exert dynamical friction on the DM halo, heating and expanding the inner region.
Decreases central density.

El Zant+ 2001, 2004; Loeb & Peebles 2003; Nipoti+ 2004;
Lackner & Ostriker 2010; Laporte & White 2015; …

Baryon-based explanations

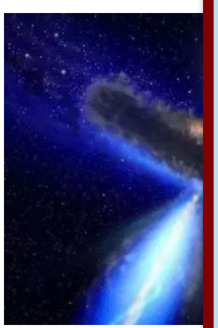
Adiabatic contraction



erving

84; Blumenthal+ 1986;
1987; Gnedin+ 2004; …

Black hol



a gas

2013; Peirani+ 2017; …

Gravitatio

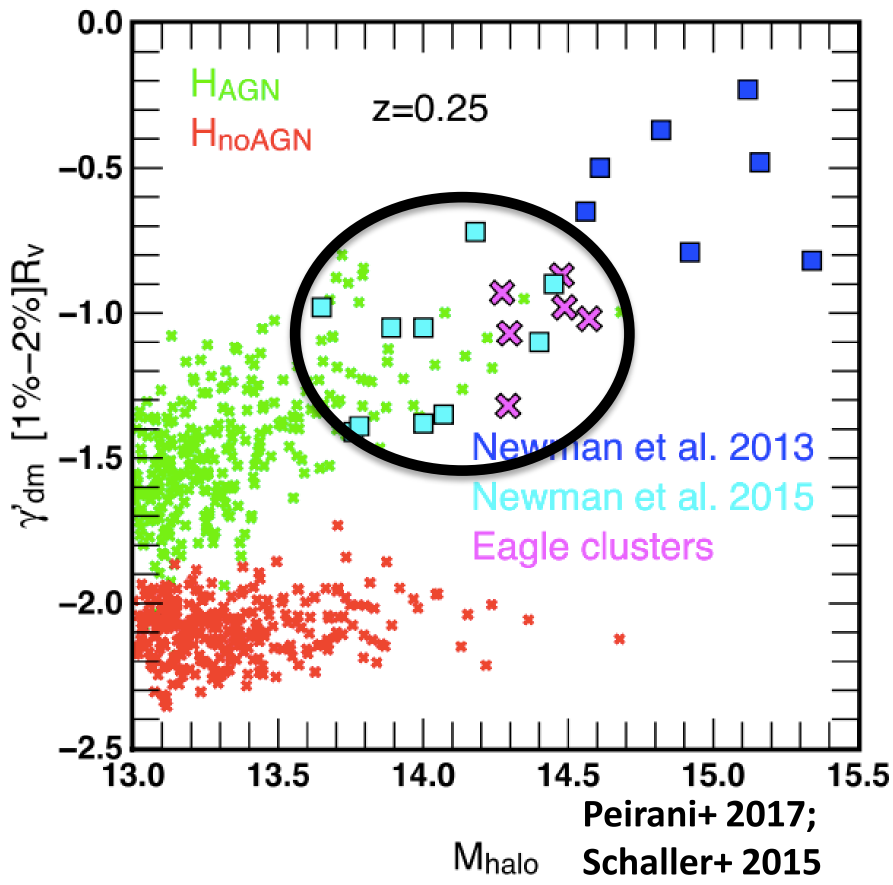
Net balance of these baryonic effects on the DM certainly varies with halo mass.

This could produce systematic variation in DM profiles within "standard" LCDM.

friction on the DM halo, heating and expanding the inner region. **Decreases** central density.

El Zant+ 2001, 2004; Loeb & Peebles 2003; Nipoti+ 2004;
Lackner & Ostriker 2010; Laporte & White 2015; …

Cosmological galaxy formation simulations within CDM



Peirani+ 2017; Schaller+ 2015

Good agreement at group masses between multiple simulations (e.g., EAGLE, Horizon-AGN) and observations. Simulated volumes are too small to contain massive clusters.

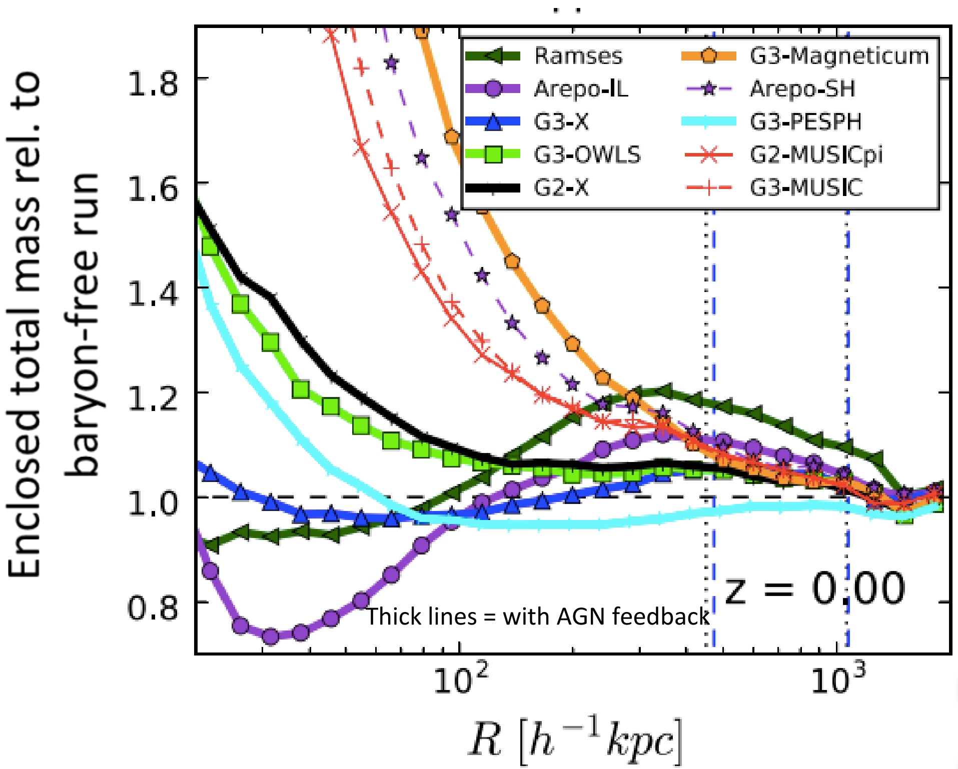
Massive cluster simulations in CDM with baryons

Compared to baryon-free simulation, central DM density is:

Lower
Laporte & White 2012
Martizzi+ 2013

Similar
e.g. Schaller+ 2015

Higher
e.g. Duffy+ 2010
Henson+ 2017



Cluster simulations with baryons & feedback do not consistently predict the inner mass distribution, even with same initial conditions

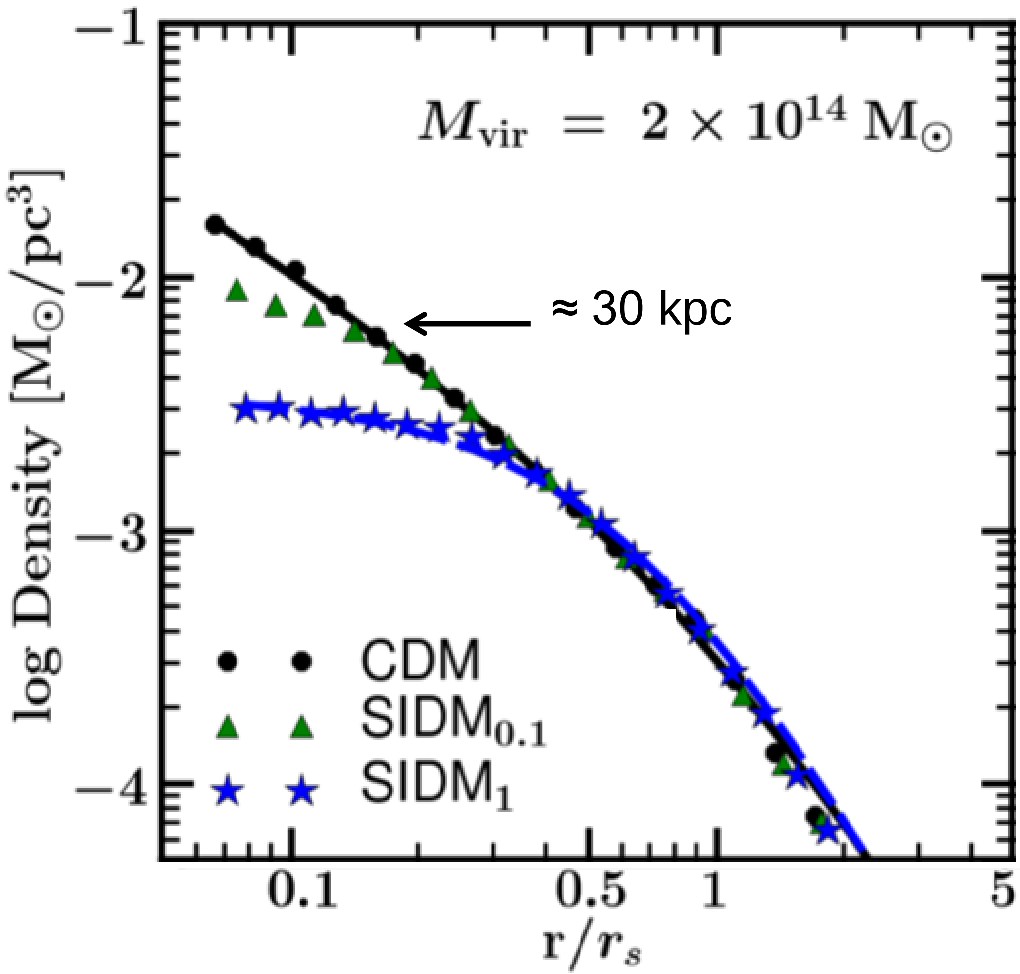
Cui+ 2016, nIFTY comparison project

Dark matter profiles in massive halos may be consistent with collisionless CDM + baryonic effects, but this is not convincingly shown either.

Is SIDM consistent with these data?

SIDM simulations of clusters

Rocha, Peter, Bullock, Kaplinghat et al 2013



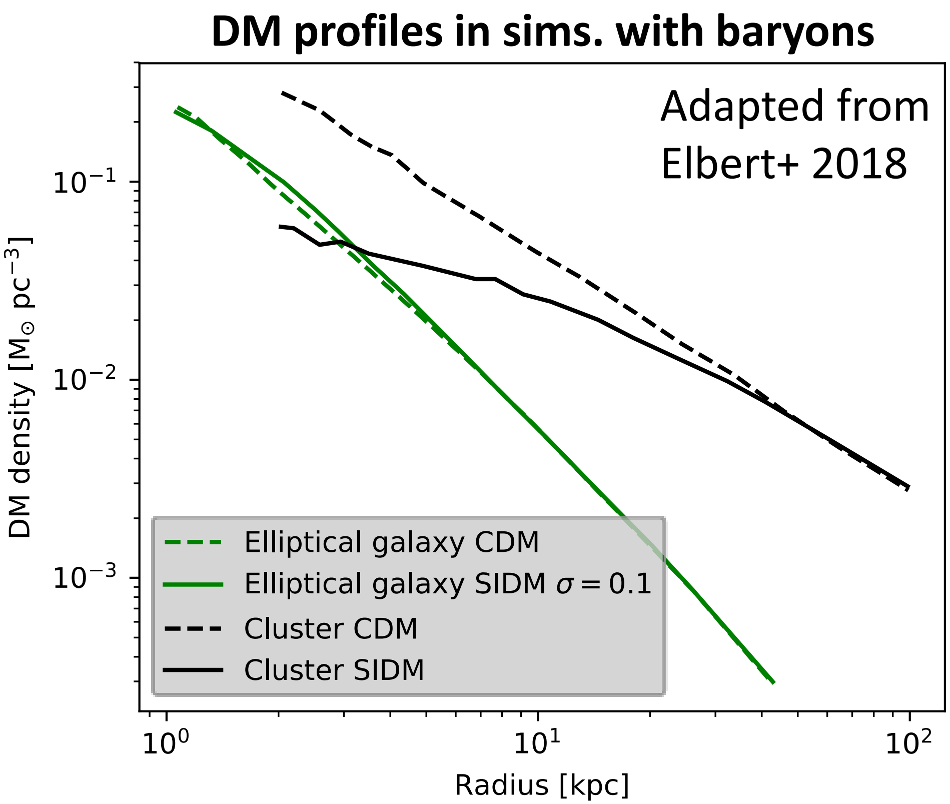
Self-interacting DM with

σ/m ~ 0.1 cm²/g
~ 0.2 barn/GeV

lowers density by a factor of ~2x at radii less than ~30 kpc—broadly consistent with cluster observations

Rocha+ 2013, Brinckmann+ 2017, Robertson+ 2017

SIDM with baryons



Is SIDM consistent with observed diversity in DM profiles?

Simulations show baryon contraction yields *similar density profiles* for CDM and SIDM in galaxies, but clusters retain *different profiles*
Elbert+ 2018, Robertson+ 2017

SIDM profiles are correlated with the baryons following the equilibrium model   Kaplinghat+ 2014

Galaxy → group → cluster lenses show
steeper → equal → shallower DM profiles relative to pure LCDM

Can be interpreted from very different (simplified) perspectives:

“Standard” CDM + Baryons

Most massive halos experience more gravitational heating and AGN feedback, overwhelming baryon contraction and lowering the inner DM density

SIDM + Baryons

More massive halos are less baryon dominated → SIDM is not thermalized within a deepened potential, so its characteristic density core is retained

How to disentangle these possibilities?

- Baryon-DM correlations expected in both scenarios, but probably differ in detail
  - Does SIDM equilibrium calculation explain group & cluster data? (Sean Tulin)
- Need to understand feedback in massive SIDM halos better
  - Only two cluster hydro.+feedback simulations with SIDM Robertson+ 2017
- Complimentary astrophysical probes
  - halo shapes Peter+ 2013
  - merging clusters: DM-baryon offsets, BCG miscentering Kim+ 2017
  - low-mass galaxies

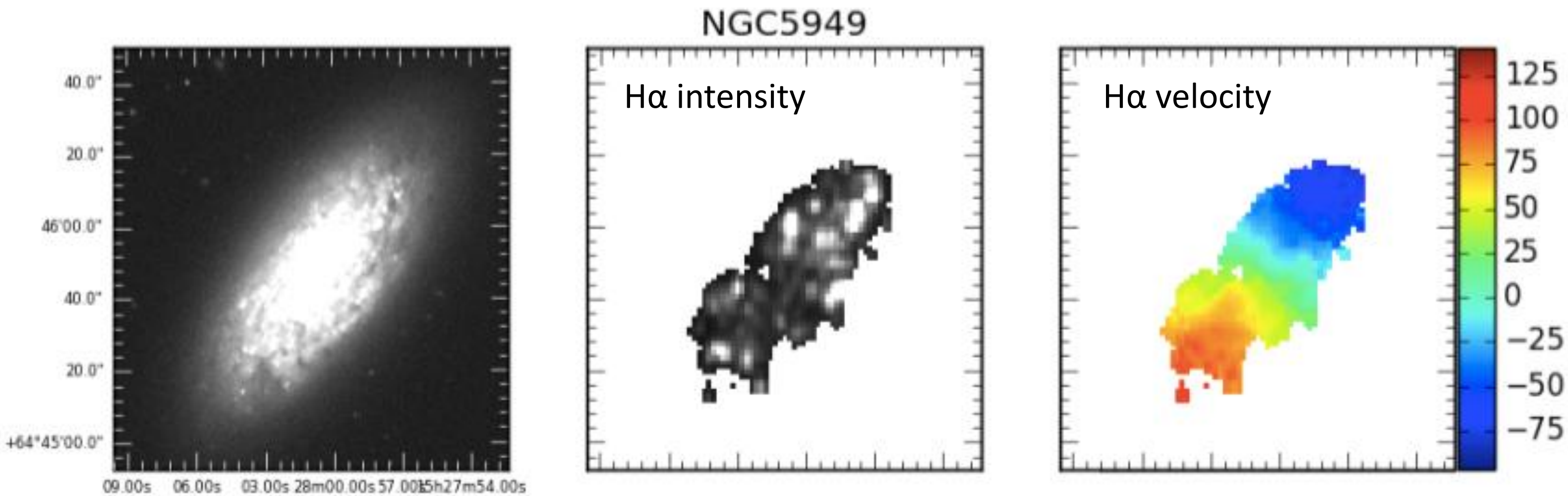
Dark Matter in Dwarf Galaxies Survey

Palomar 200”
Cosmic Web Imager
High-resolution Hα kinematics

CARMA
Molecular gas kinematics

A new survey of high-resolution gas kinematics in a sample of 26 dwarf galaxies (V_{max} ~ 60-120 km/s) within 30 Mpc.

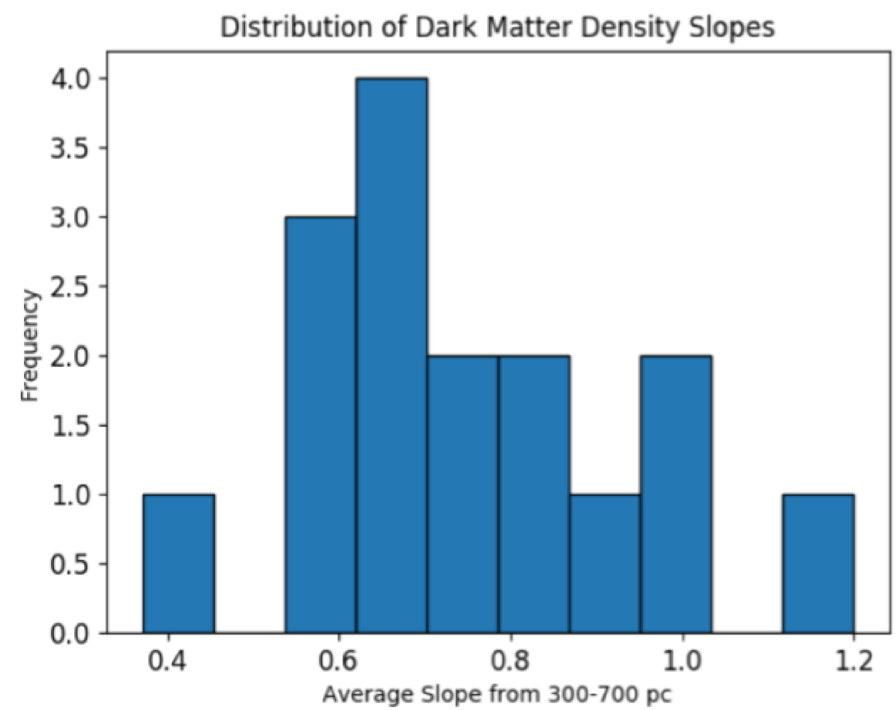
Nicole Relatores thesis (Carnegie/USC), ABN and Josh Simon (Carnegie), Phuongmai Truong and Leo Blitz (Berkeley), Richard Ellis (UCL), Chris Martin and CWI team (Caltech)



Mean inner DM slope β=0.7 $[r_{\mathrm{DM}}\ \mu\ r^{-b}]$
but *range* of DM profiles

Similar to some studies (e.g., Adams+ 2014, Simon+ 2005), steeper than others (e.g., Oh+ 2011, 2015, de Blok+ 2001)

Next step: Correlate with galaxy properties / baryon distribution, compare to predictions from feedback models and SIDM



Summary

- Some, but not all, massive dark matter halos seems to have a low central density or "core" relative to pure collisionless CDM
- There is tentative evidence for a trend between the inner DM profile and halo mass or a related property (e.g., baryon fraction)
- Such a trend could arise either from baryonic feedback effects or from collisional DM models
- Areas for progress in disentangling these possibilities:
  - Absolute masses of stellar populations from non-gravitational probes
  - Better measurements of correlations of DM profiles with baryons
  - Better theoretical understanding of feedback in massive halos in both CDM & SIDM