Title: The Alleged Small-Scale Problems of LambdaCDM

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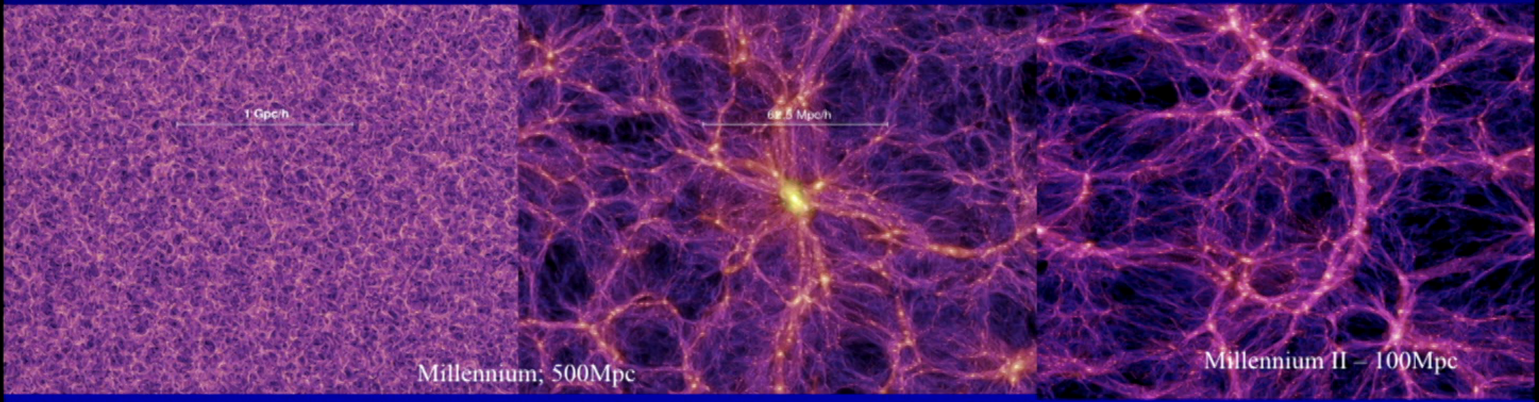
Abstract: <p>The Lambda Cold Dark Matter framework successfully accounts for observational constraints on large (> 1 Mpc) scales, from the clustering of galaxies to the angular dependence of the Cosmic Microwave Background to the structure and matter content of galaxy clusters. On the scale of individual galaxies and, in particular, of dwarf systems much fainter than the Milky Way, a number of apparent conflicts with LCDM expectations have been reported. These have prompted the consideration of a number of radical modifications to LCDM, such as the possibility that dark matter might be "self-interacting", or that it might not be â€œcoldâ€•. I will review the status of these alleged problems and will report on recent work that reevaluates the observational evidence and reexamines the role of systematic uncertainties in the comparison between observation and model predictions. In particular, I will propose a possible resolution to the â€œcusp vs coreâ€• problem that requires no cores; an explanation for the mass discrepancy-acceleration relation that requires no changes to LCDM halos; and a plausible tidal origin for the enigmatic population of galaxies inhabiting â€œextremely coldâ€• dark matter halos, such as the recently discovered Crater 2 satellite.</p>

The Clustering of Dark Matter

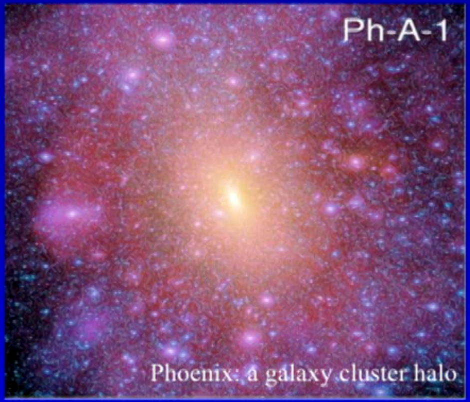
The Millennium Simulation Series



Millennium; 500Mpc

Millennium II – 100Mpc

Aquarius: a galaxy halo



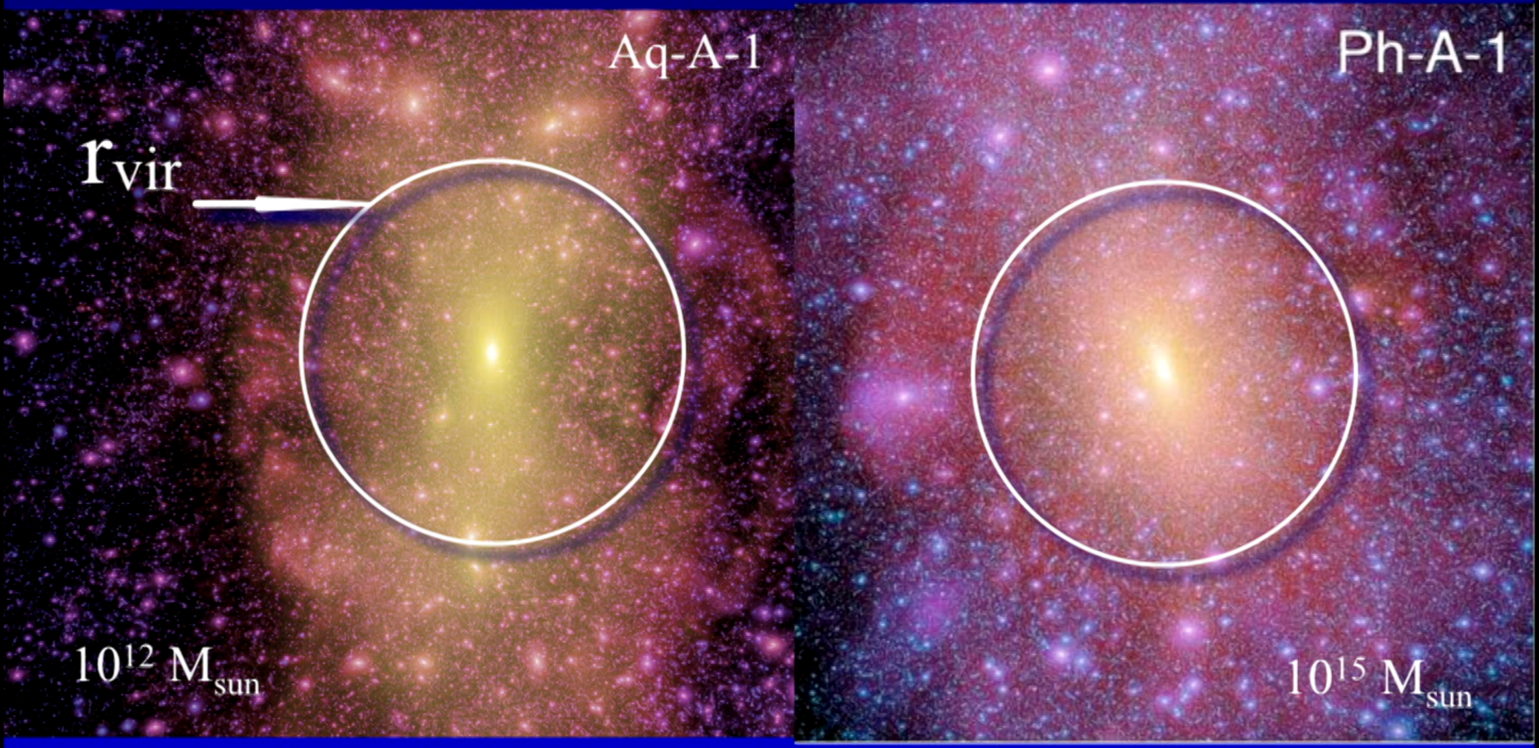
Phoenix: a galaxy cluster halo

Simulations have enabled a full characterization of the (hierarchical) clustering of cold dark matter on large and small scales.

Spinger et al 2005, Boylan-Kolchin et al 2009, Angulo et al 2012

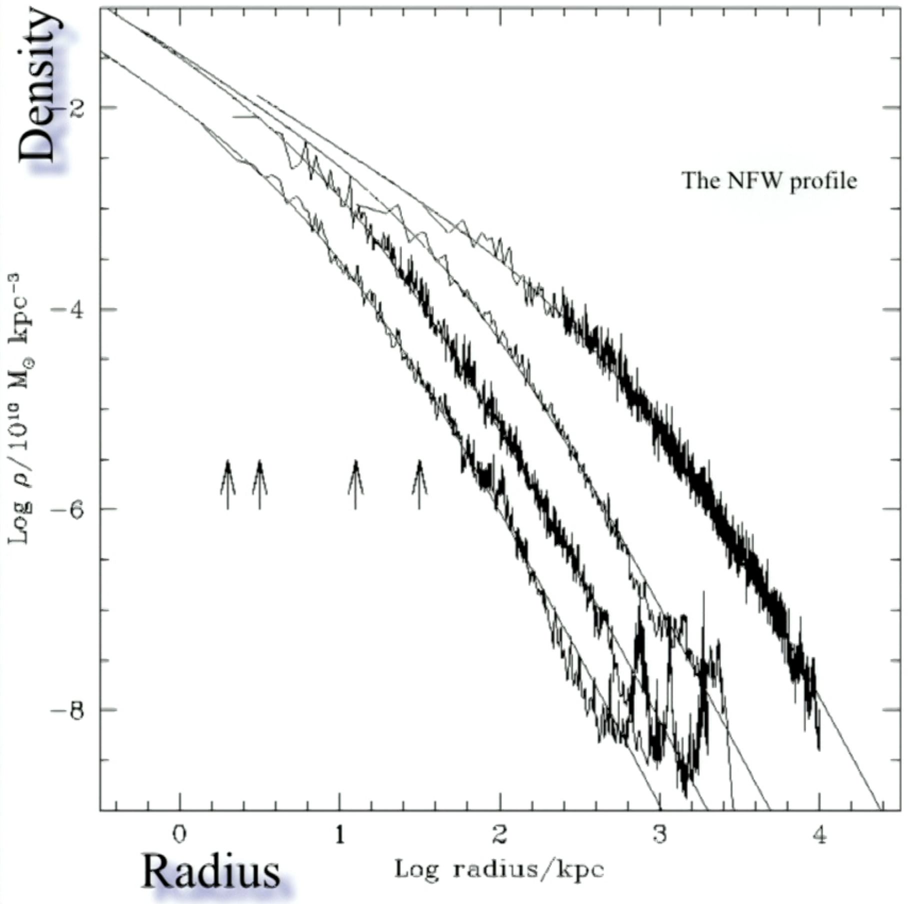
VIRGO

The self-similar nature of LCDM halos



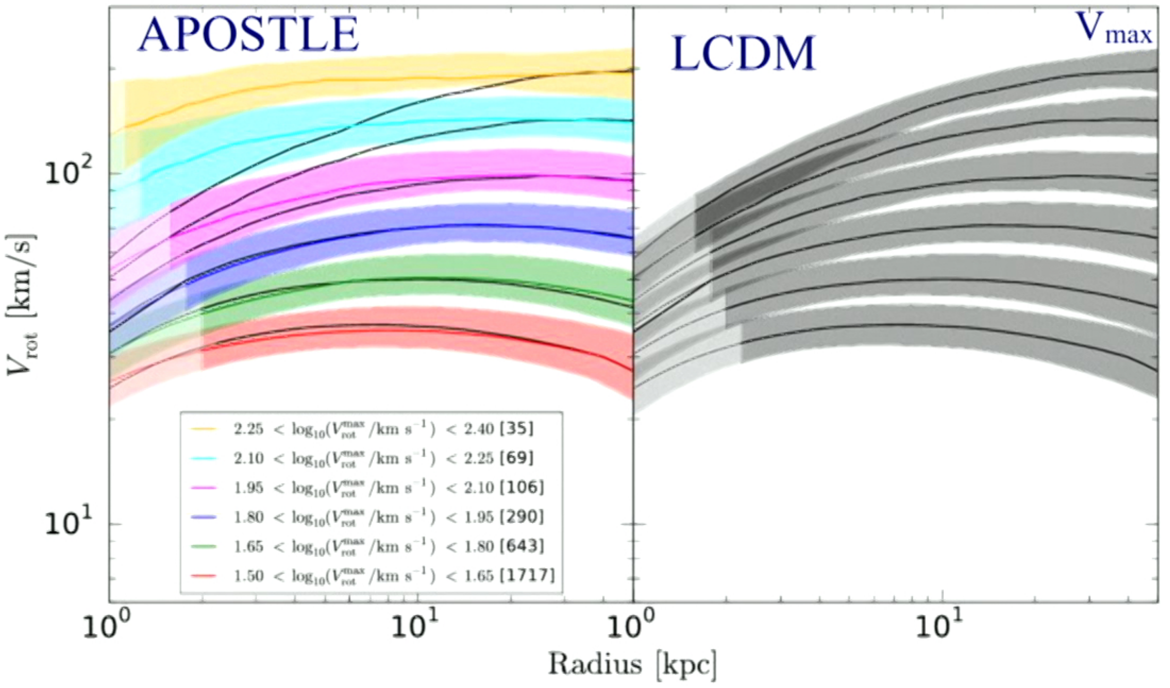
DM halos:
we can count them, and we know their structure

The Mass Profile of Cold Dark Matter halos



- The shape of the mass profiles of dark mater halos is roughly independent of halo mass and cosmological parameters
- Density profiles are "**cuspy**" and clearly differ from power laws
- Well reproduced by scaling a simple formula $\rho/\rho_{crit}=\delta_c/[(r/r_s)(1+r/r_s)^2]$
- Curves do not cross
- DM is "colder" near the center.

LCDM predicted circular velocity profiles

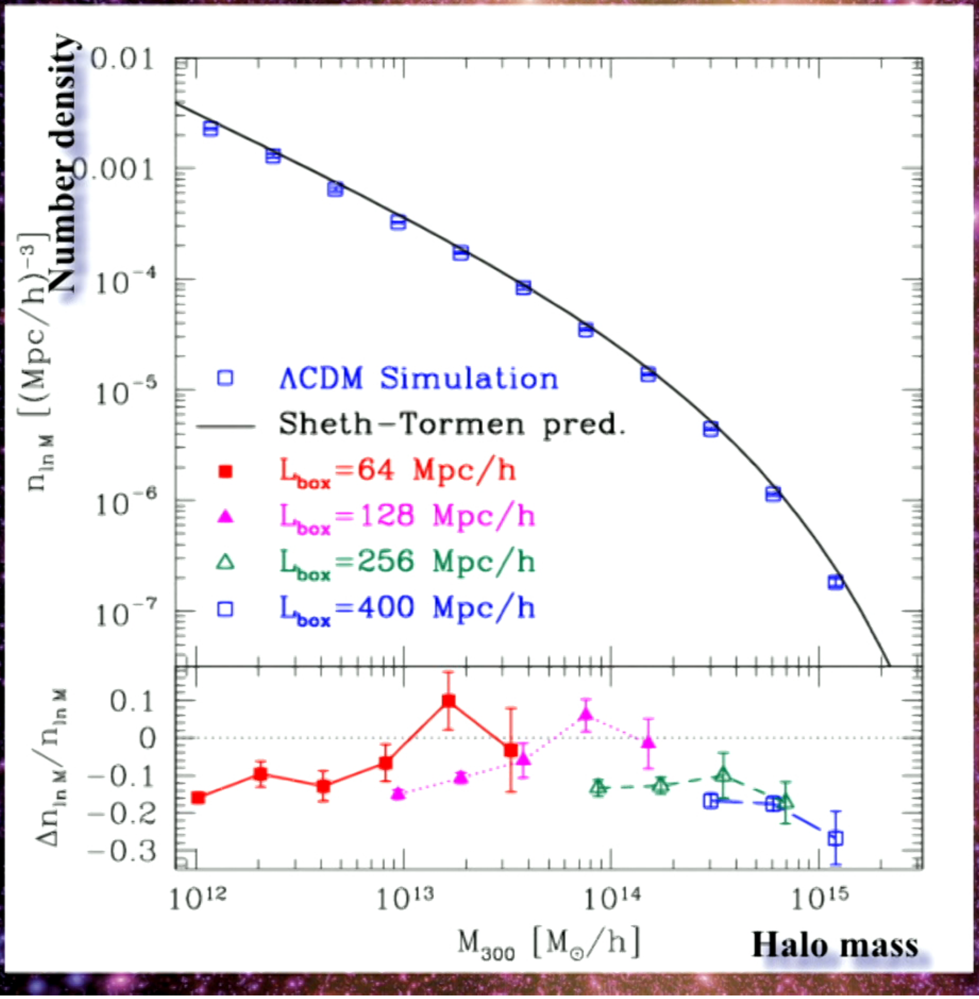


- CDM predicts a **single** mass/ circular velocity profile for a given velocity scale

- Vmax is another way of specifying the mass of the system

Oman+15

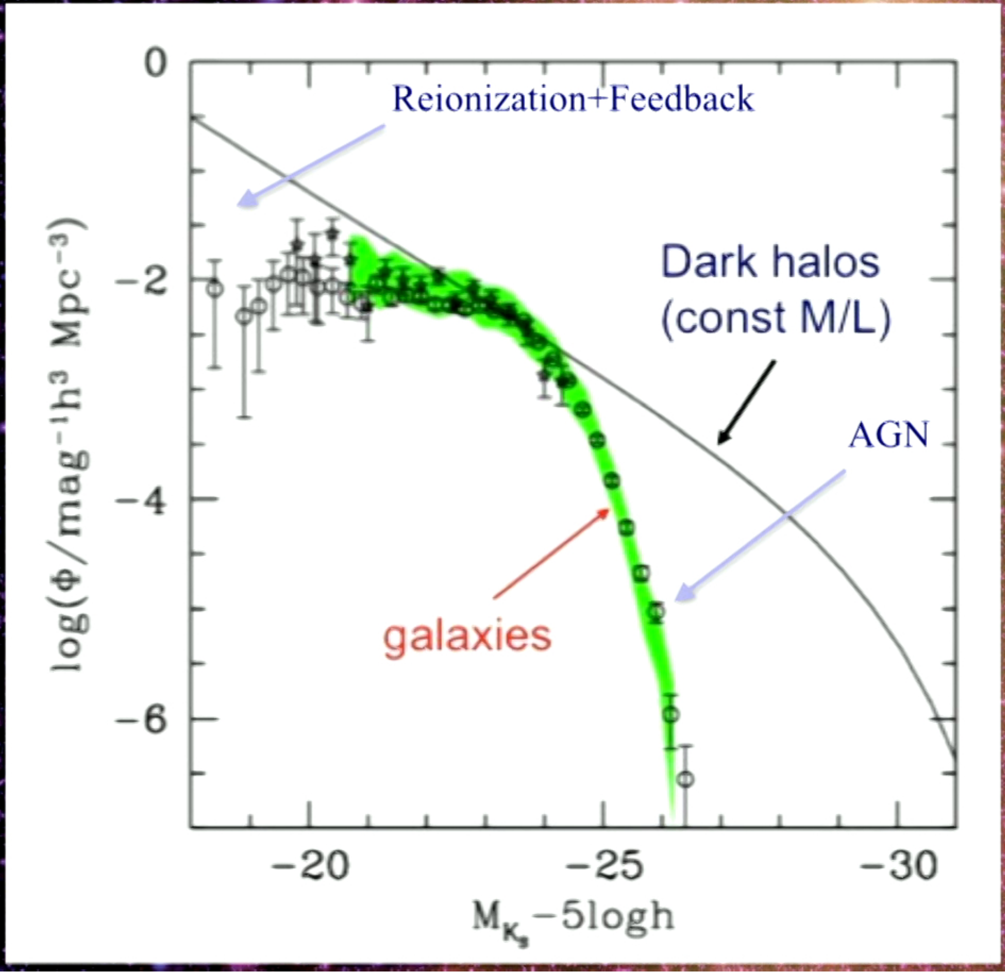
CDM halo mass function



- CDM halo mass function is now well understood in all mass scales relevant to galaxy formation.

Schmidt et al 2009

CDM halo mass function vs galaxy luminosity function



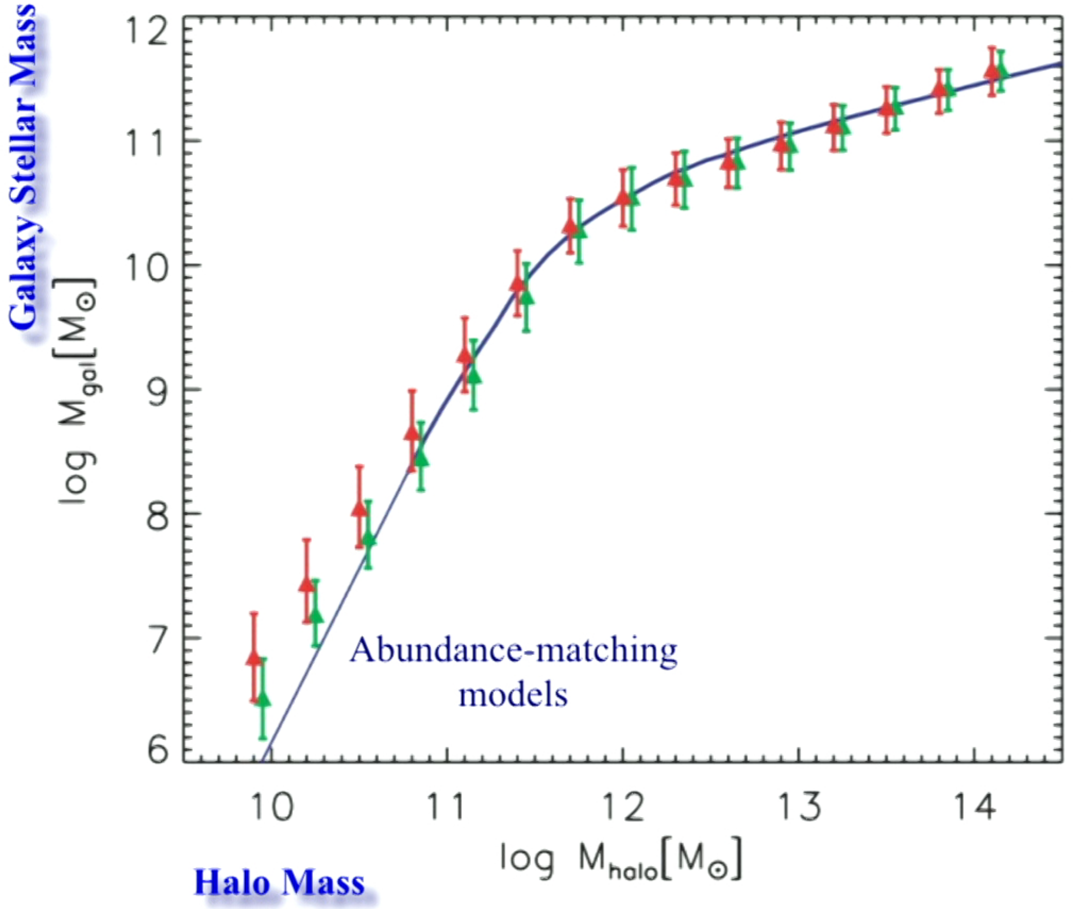
- CDM halo mass function *much steeper* than the galaxy luminosity function at the faint end

- Reconciling the two requires a highly non-linear dependence between galaxy and halo mass

- At low masses reionization, as well as feedback from evolving stars, are thought to be responsible

- Most dwarf galaxies live in halos of the same mass. Galaxy formation efficiency should decline in low mass halos

Abundance Matching: Galaxy Stellar Mass vs Halo Mass



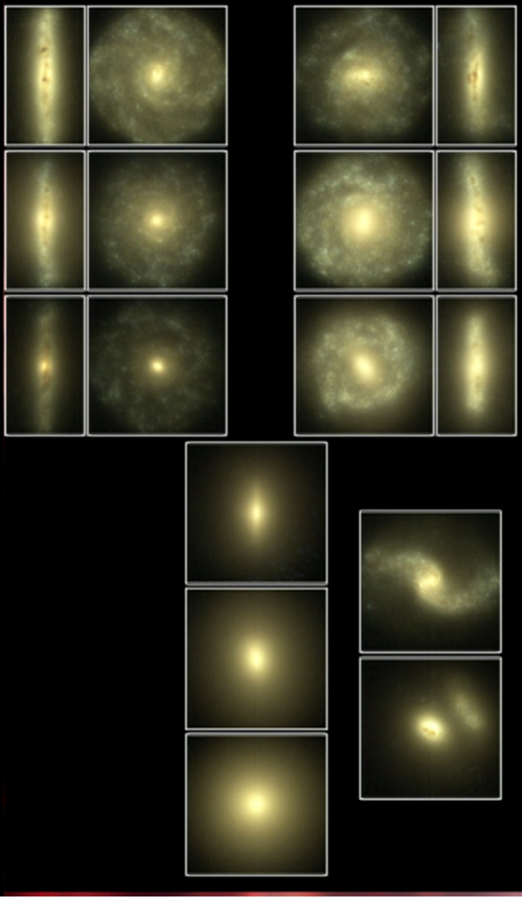
- Galaxy formation efficiencies are very low, peak at 15% for Milky Way-like galaxies
- Steep dependence at low halo mass--a fundamental result of galaxy formation models.
- Most dwarfs form in halos of similar mass and hence similar properties—-what is the origin of their diversity then?
- Very few luminous galaxies should form in halos with mass below a “threshold” of 10^{10} M_{sun}

Guo et al 2011

The Eagle simulations

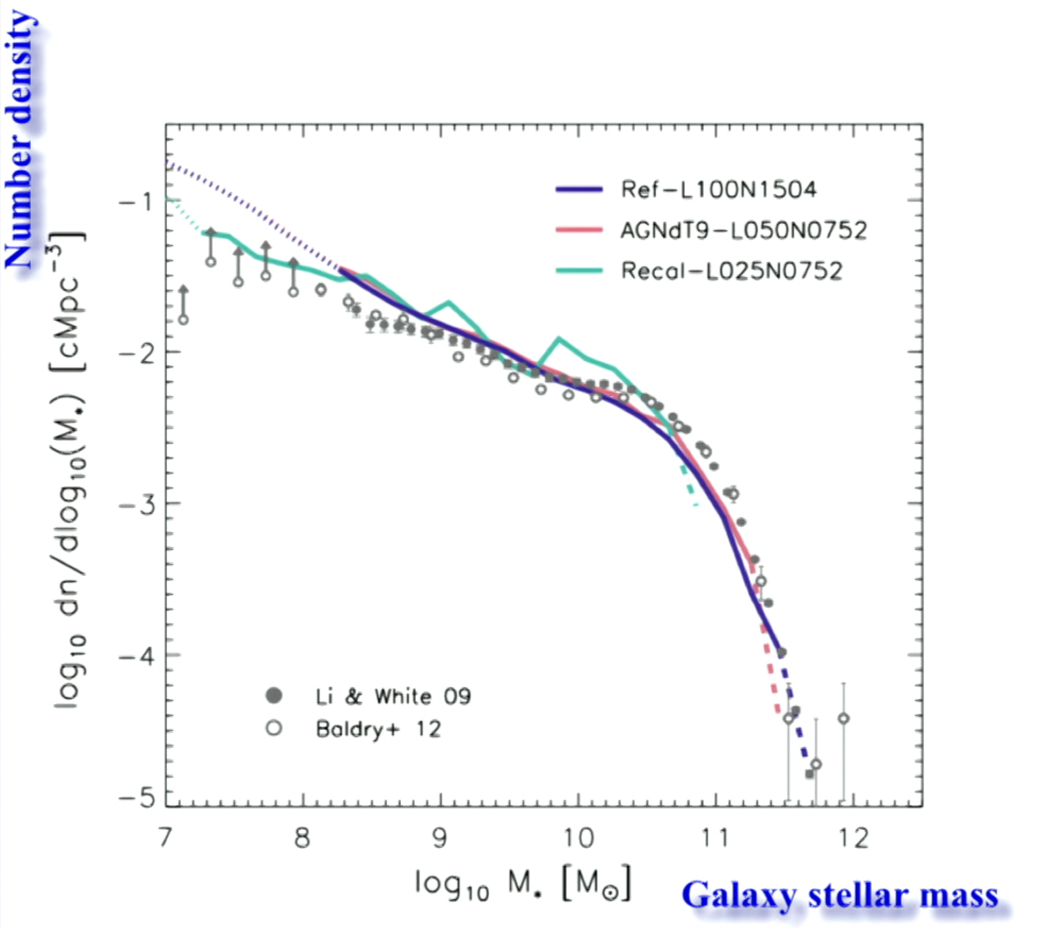
EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

A project of the Virgo Consortium



- Large hydrodynamical simulations of cosmologically representative volumes (~100 Mpc box) have recently been completed

EAGLE Galaxy Stellar Mass Function



- Recent simulations have been able to include reionization and feedback effects to reproduce the galaxy stellar mass function down to galaxies of $M_* \sim 10^8$ solar masses in stars

- They also match reasonably well other properties of the observed galaxy population

- Does this success extend to the faintest dwarfs?

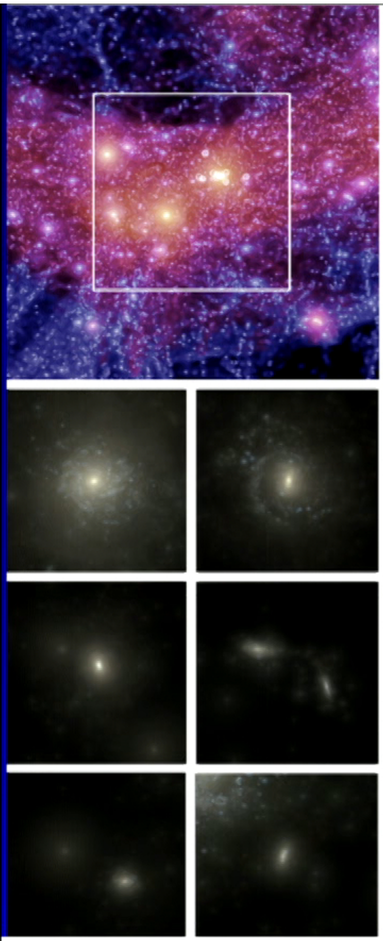
Schaye et al 2015

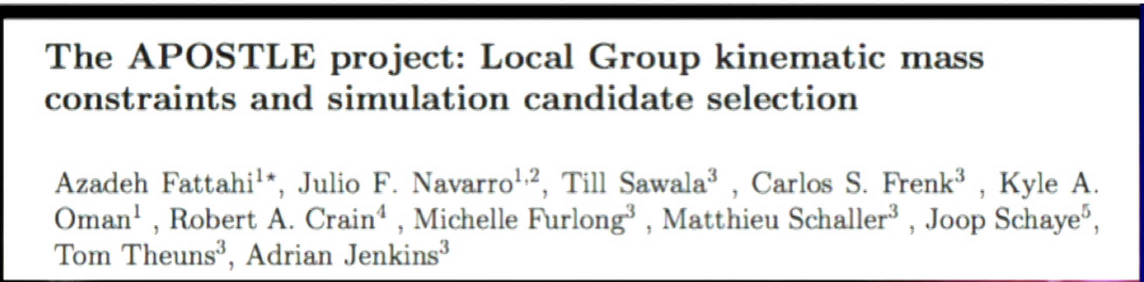
Cosmological Puzzles from Dwarf Galaxies

- Observations of dwarfs have revealed a number of challenges when compared to dark matter-only LCDM simulations
- Dwarf Galaxy puzzles
  - Dwarf galaxy diversity
  - Rotation curves or “cusp vs core” problem
  - “Missing dark matter” galaxies
  - The mass discrepancy-acceleration relation
  - The “cold feeble giant” problem: satellites in “extremely cold halos”
- Local Group puzzles
  - ”Missing satellites” problem
  - “Too big to fail” problem
  - “Satellite alignment” problem

APOSTLE blessings: cures for the LCDM small scale ailments

A Project of Simulations of the Local Environment



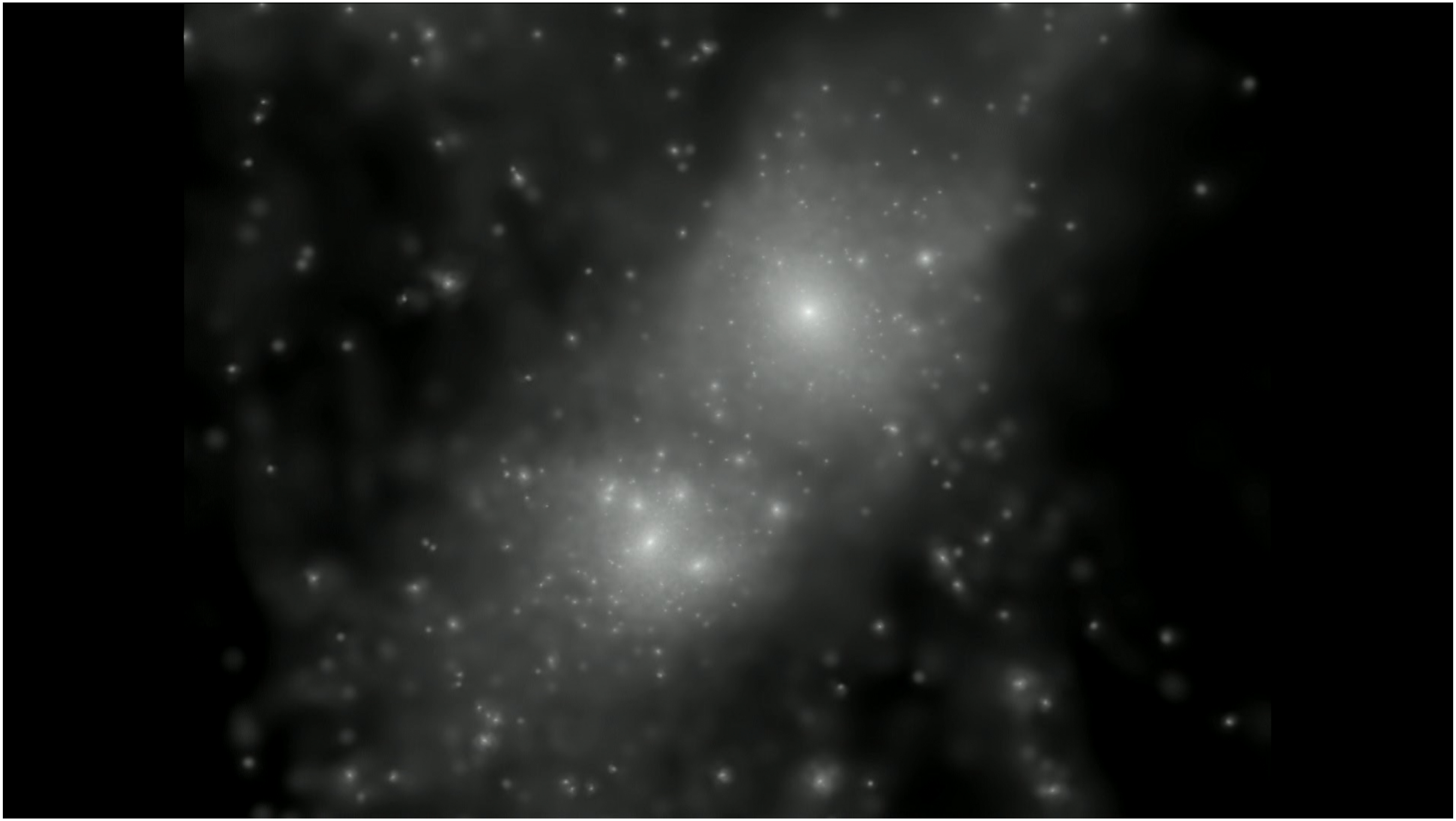


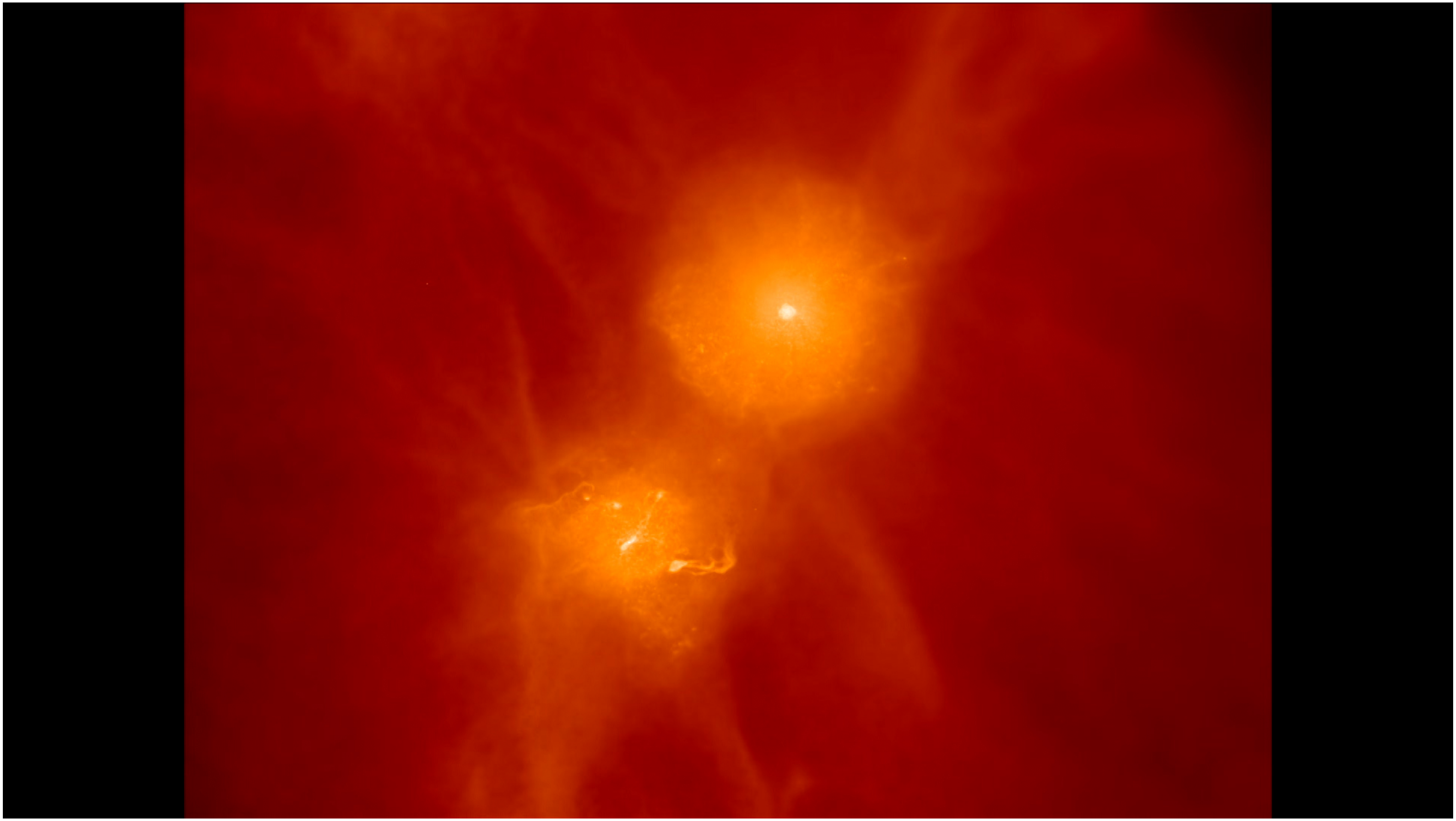
The APOSTLE project: Local Group kinematic mass constraints and simulation candidate selection

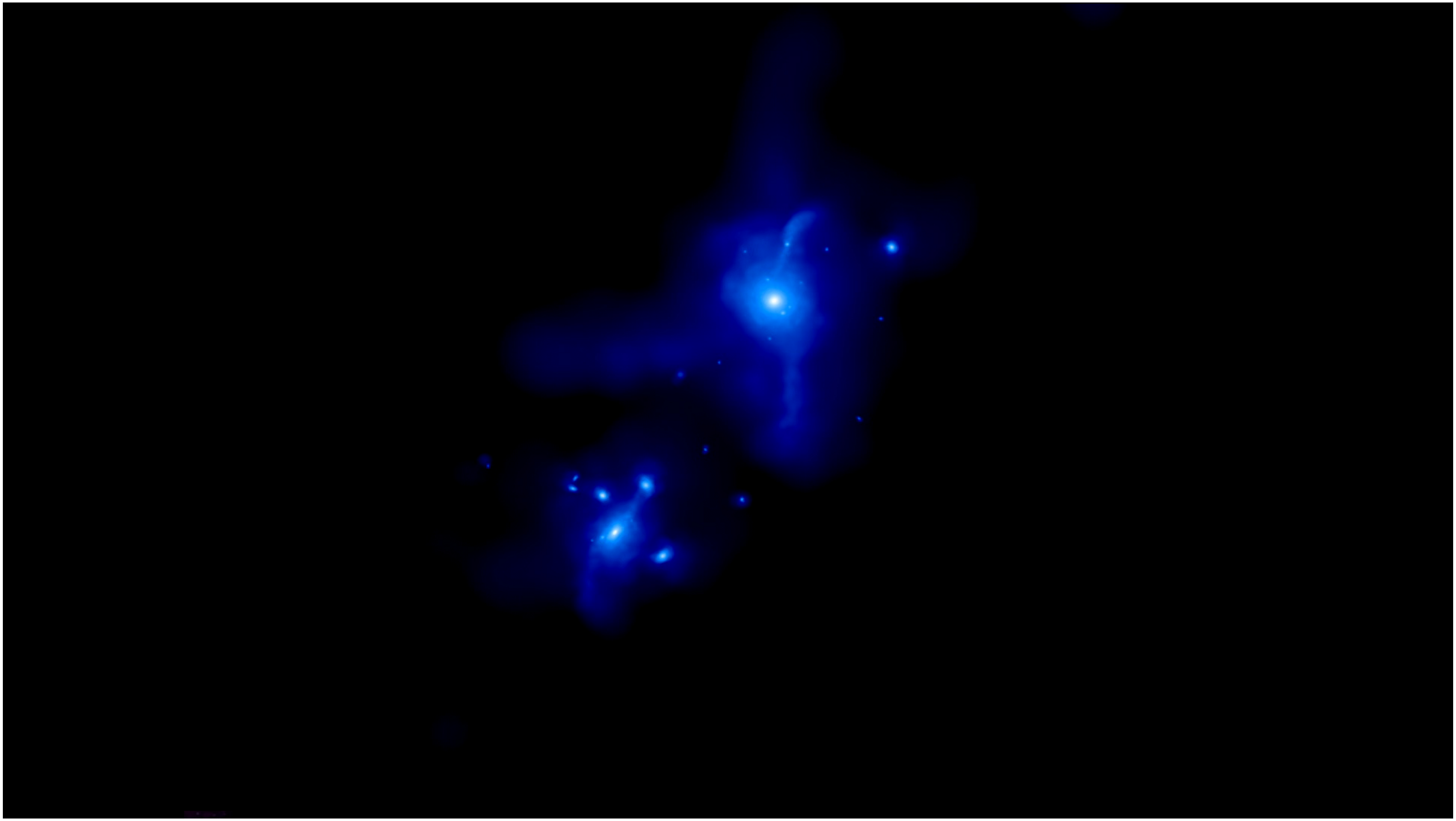
Azadeh Fattahi[1*], Julio F. Navarro[1,2], Till Sawala[3] , Carlos S. Frenk[3] , Kyle A. Oman[1] , Robert A. Crain[4] , Michelle Furlong[3] , Matthieu Schaller[3] , Joop Schaye[5], Tom Theuns[3], Adrian Jenkins[3]

Sawala+14, Fattahi+15

- Twelve LG candidates have been re-simulated using the *same* code used for the EAGLE project
- Any success on LG scales does not come at the expense of failures on large scales



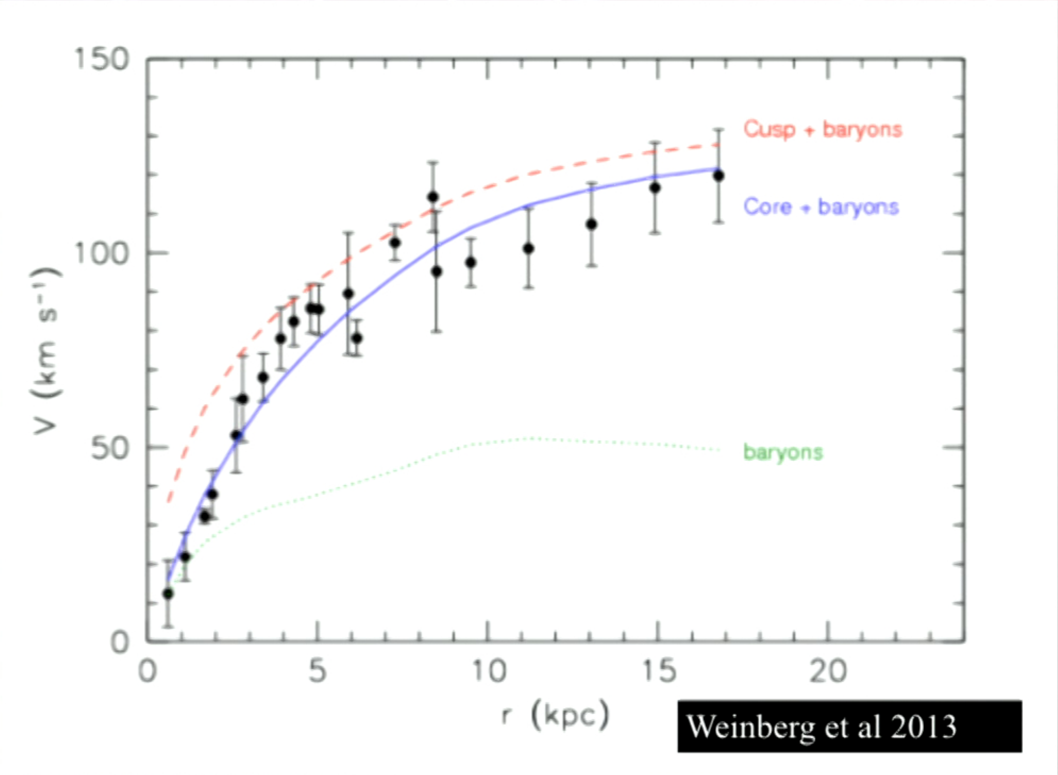




Rotation c

Rotation curves of dwarf galaxies : the "cusp vs core" problem

The rotation curve problem

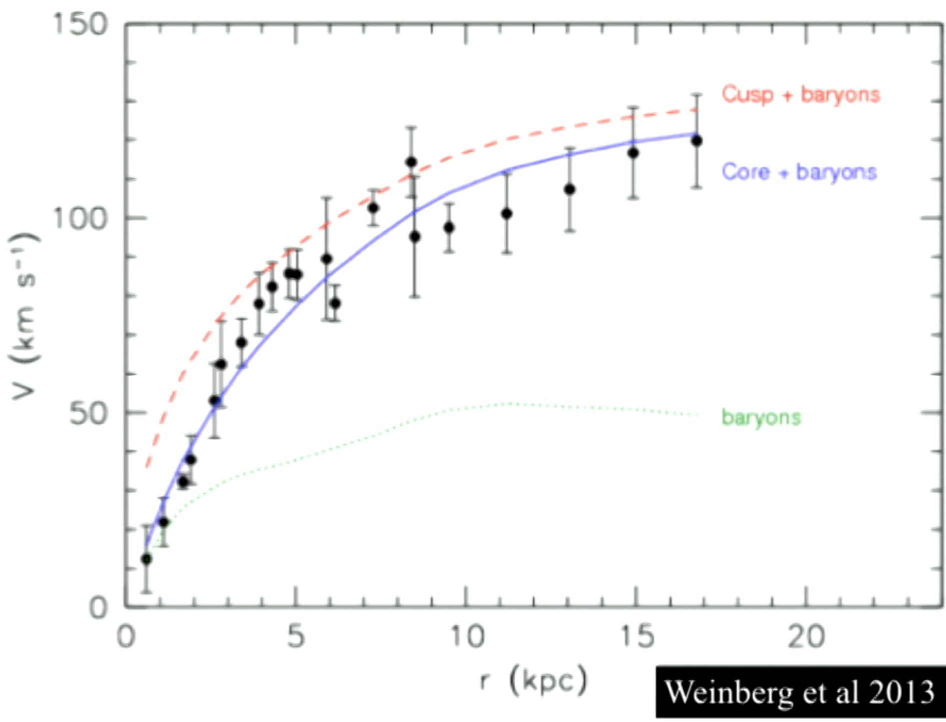


Weinberg et al 2013

A constant density "core" is at odds with the predicted cuspy profiles has been predicated for a number of dwarf galaxies on the basis of rotation curves of disk galaxies.

The evidence relies on the interpretation of the innermost regions of rotation curves, where observations are most challenging

The rotation curve problem



Weinberg et al 2013

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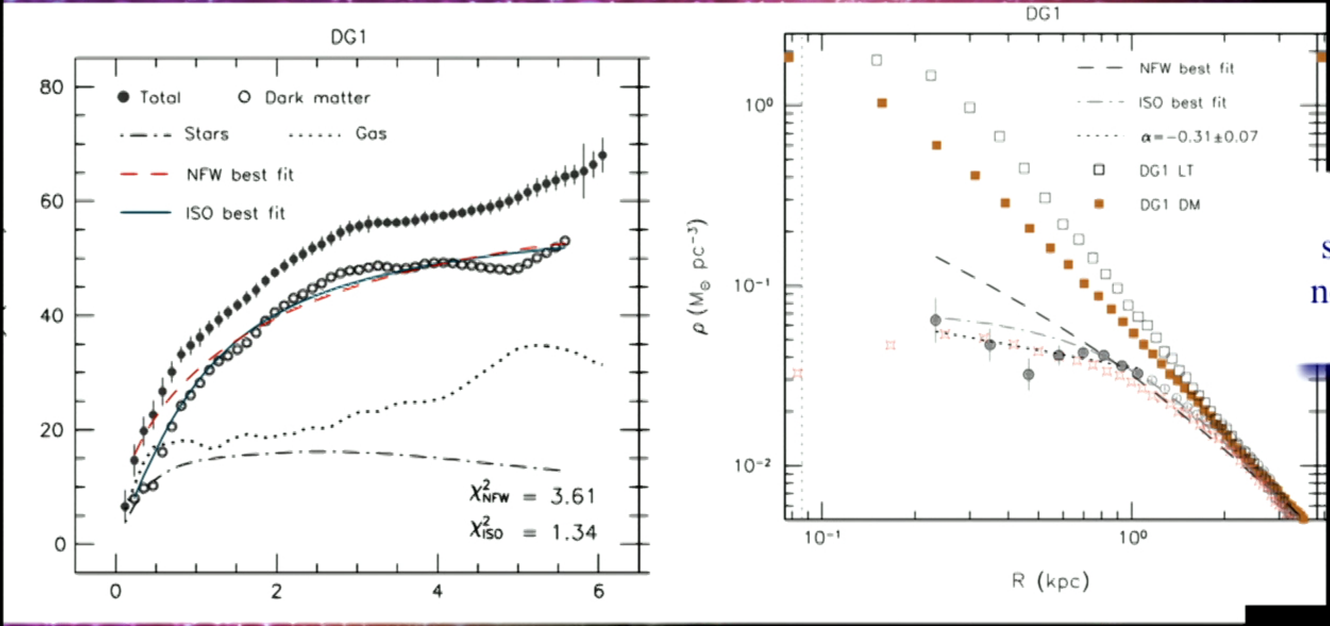
The evidence relies on the interpretation of the innermost regions of rotation curves, where observations are most challenging

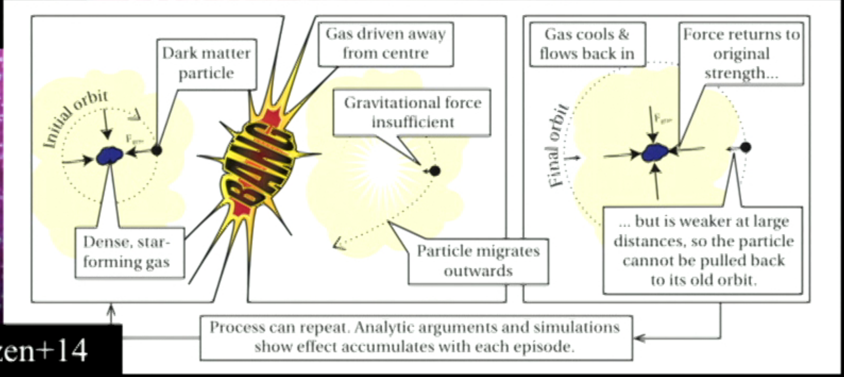
> "A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."—Max Planck

Baryon-induced cores



Some simulations now produce “cores”

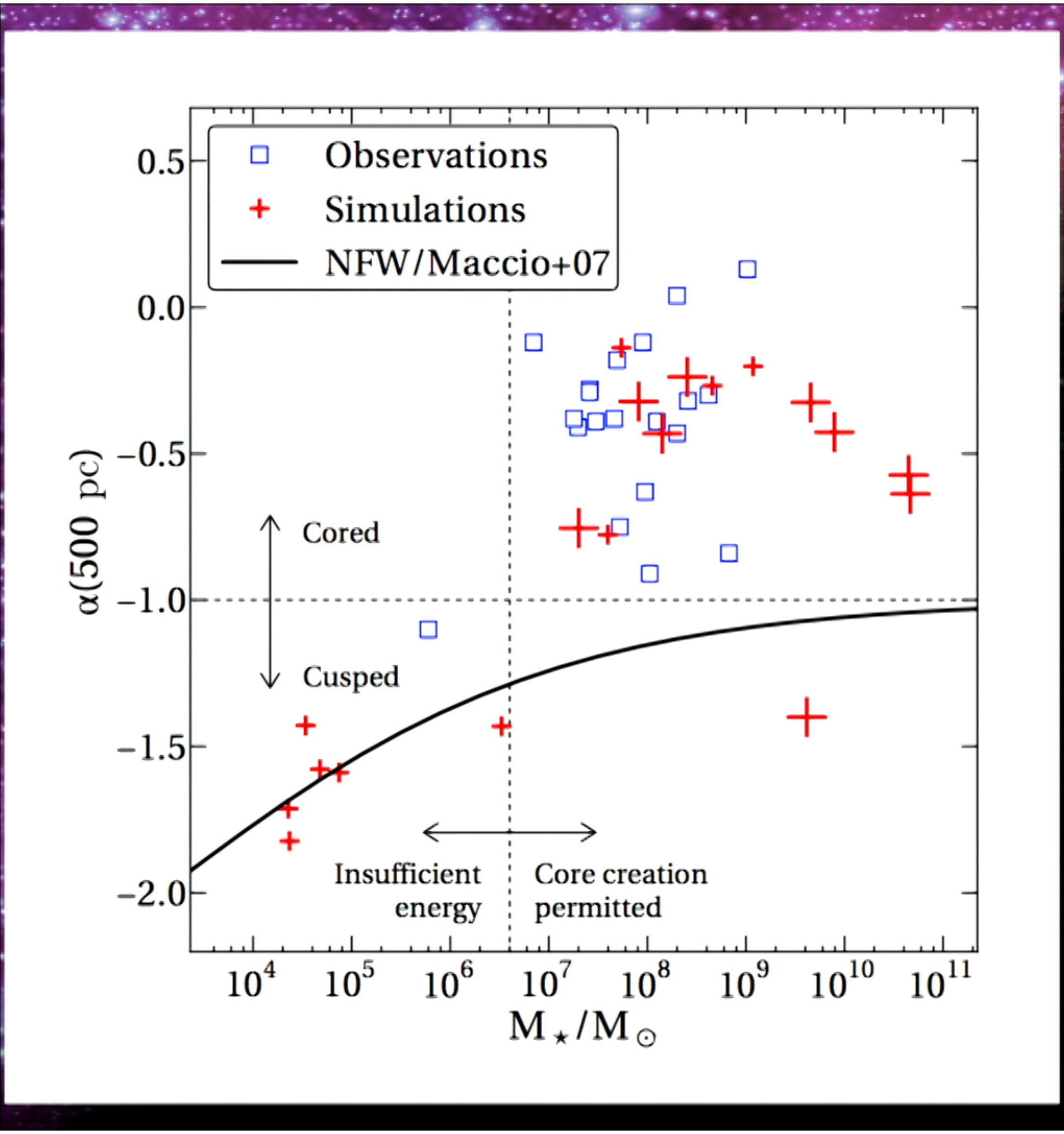
Oh+11



Pontzen+14

- The effect, however, is small, and mainly noticeable at the center

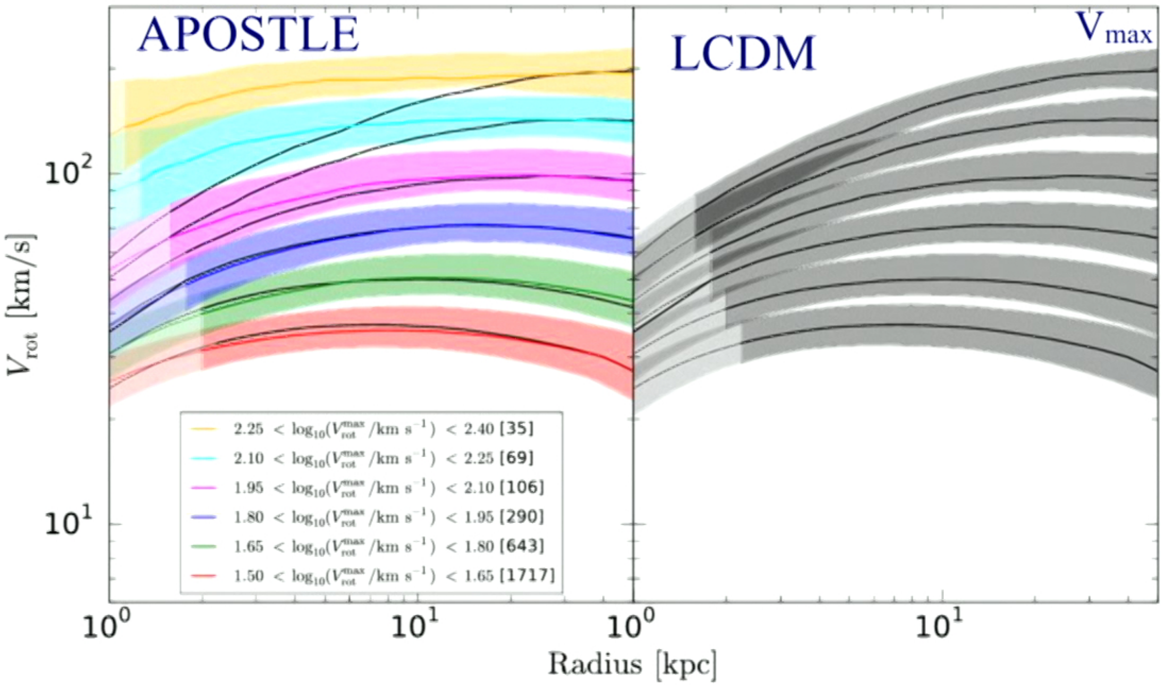
The rotation curve problem



- The comparison between data and simulations have focussed on the very inner regions (500 pc!) of a galaxy, where observations are very difficult…

Pontzen'14

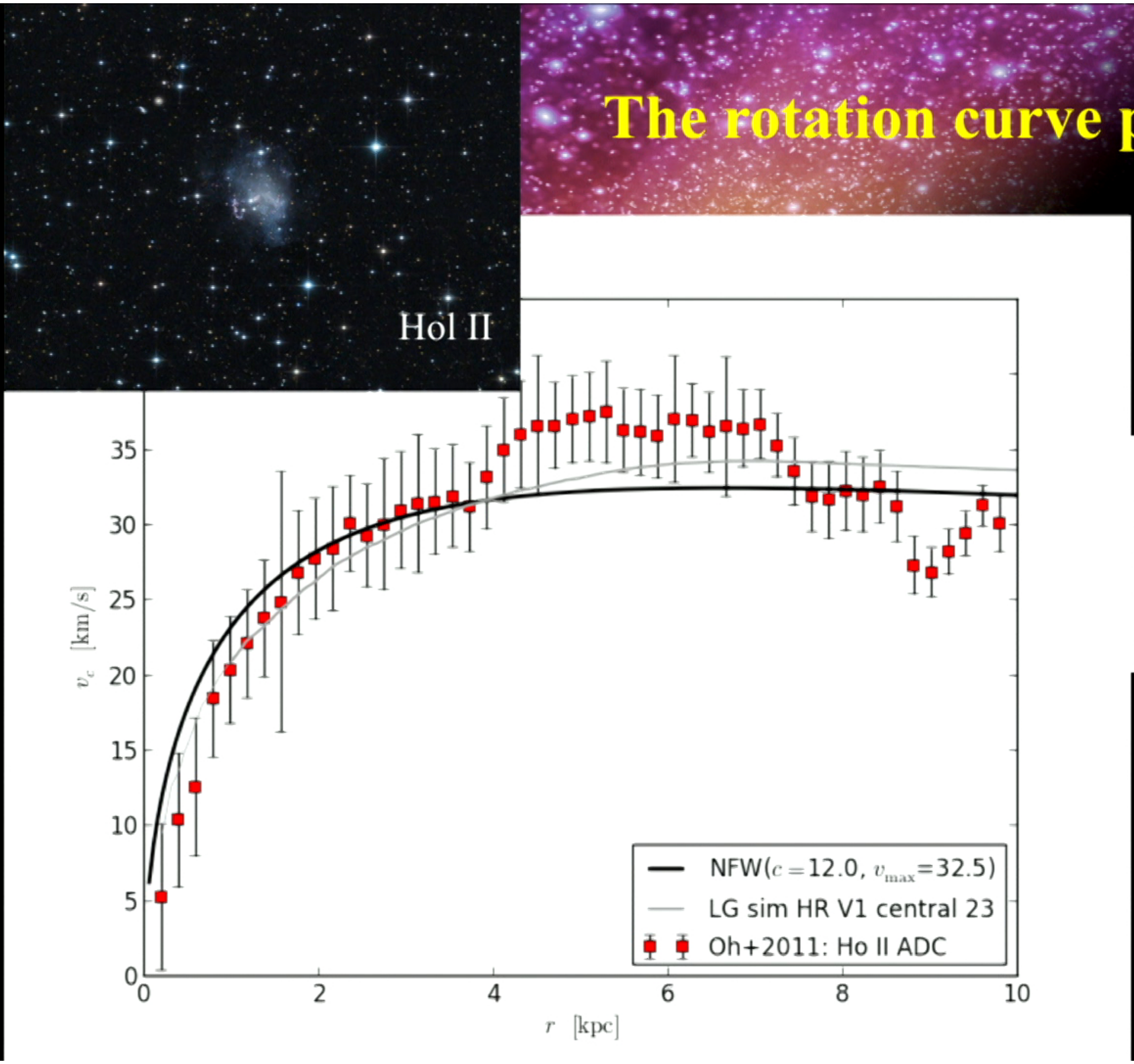
LCDM predicted circular velocity profiles



- CDM predicts a **single** mass/ circular velocity profile for a given velocity scale

Oman+15

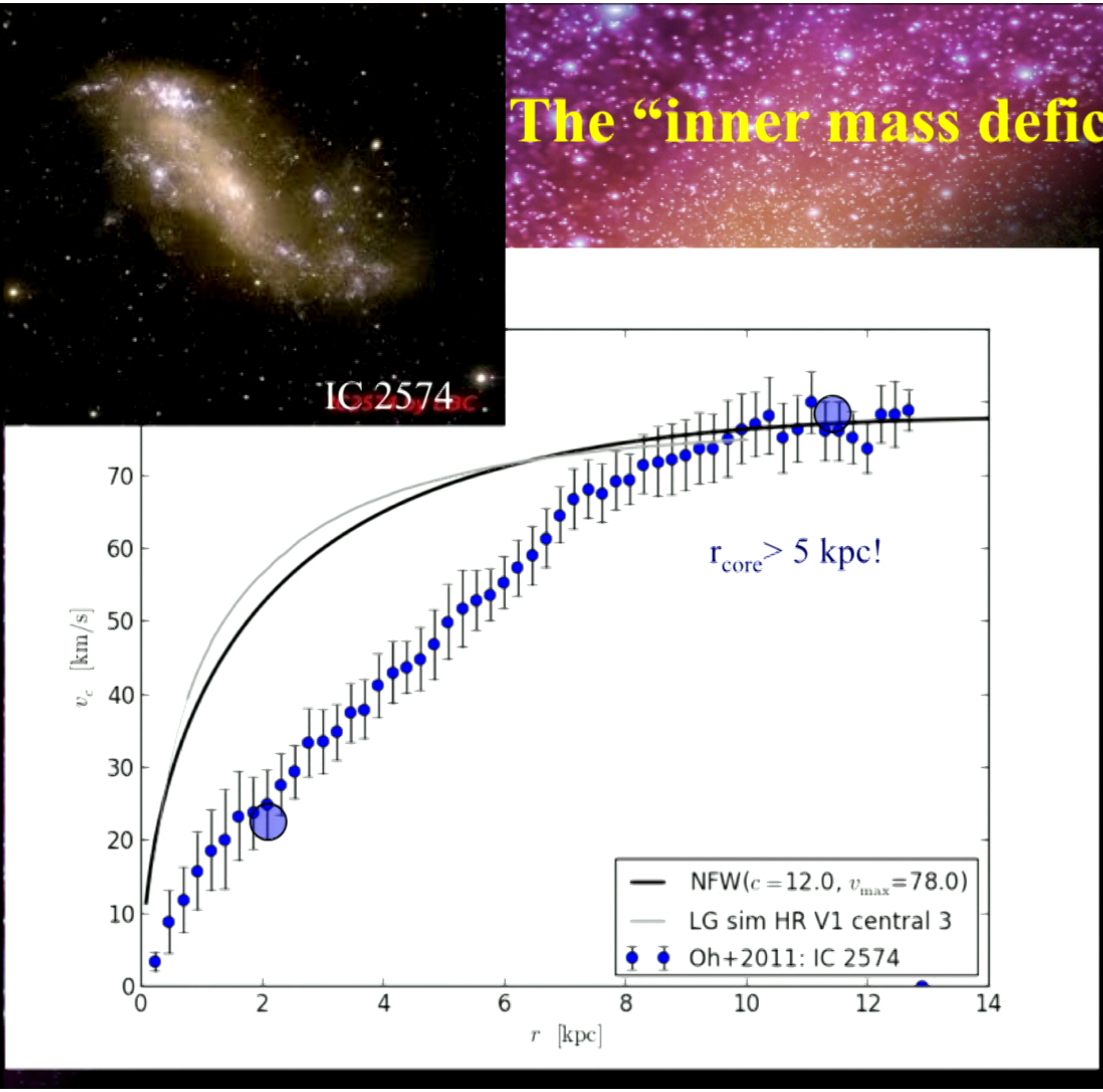
The rotation curve problem



- Some galaxies have rotation curves that agree with simulation predictions

Oman+15

The “inner mass deficit” problem



$r_{core} > 5$ kpc!

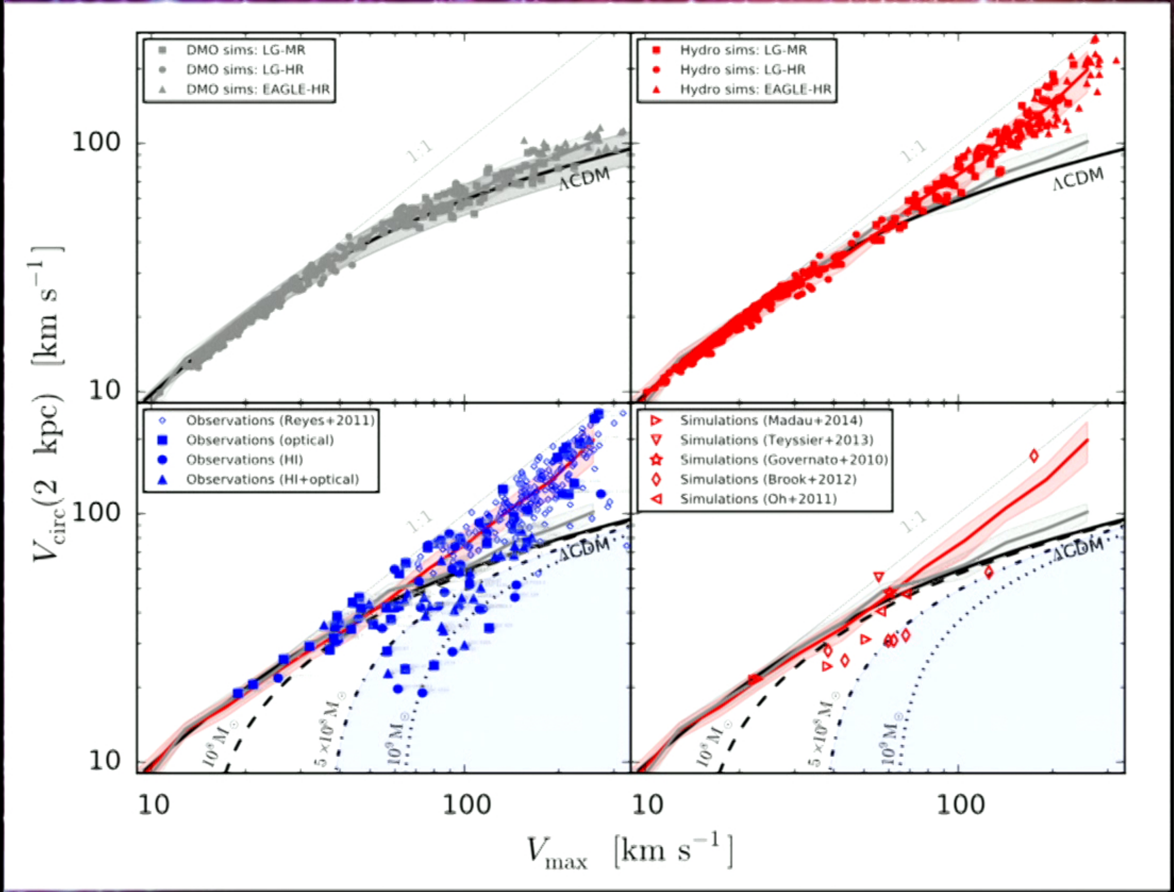
- Some galaxies have rotation curves that differ from simulation predictions

- Others do not

- The cusp vs core problem is best thought of as an “inner mass deficit” problem

Oman+15

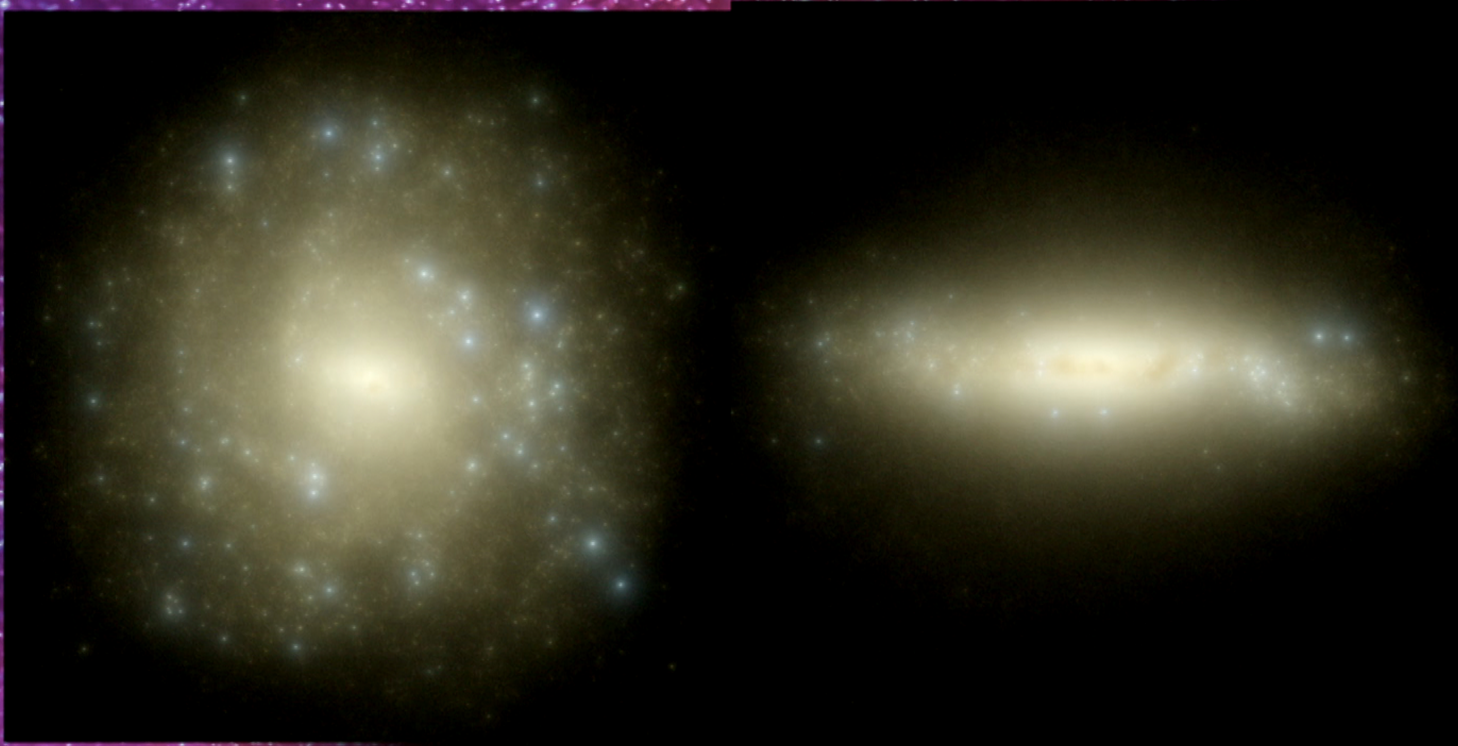
“Cores” as an inner mass deficit problem



- •Dwarf galaxies have a wide diversity of rotation curves
- •Some galaxies are consistent with CDM, others are not
- •“Cores” seem present in galaxies up to ~200 km/s
- •Some core radii are larger than simulations can produce
- •Is the interpretation of the data reliable?

Oman+15

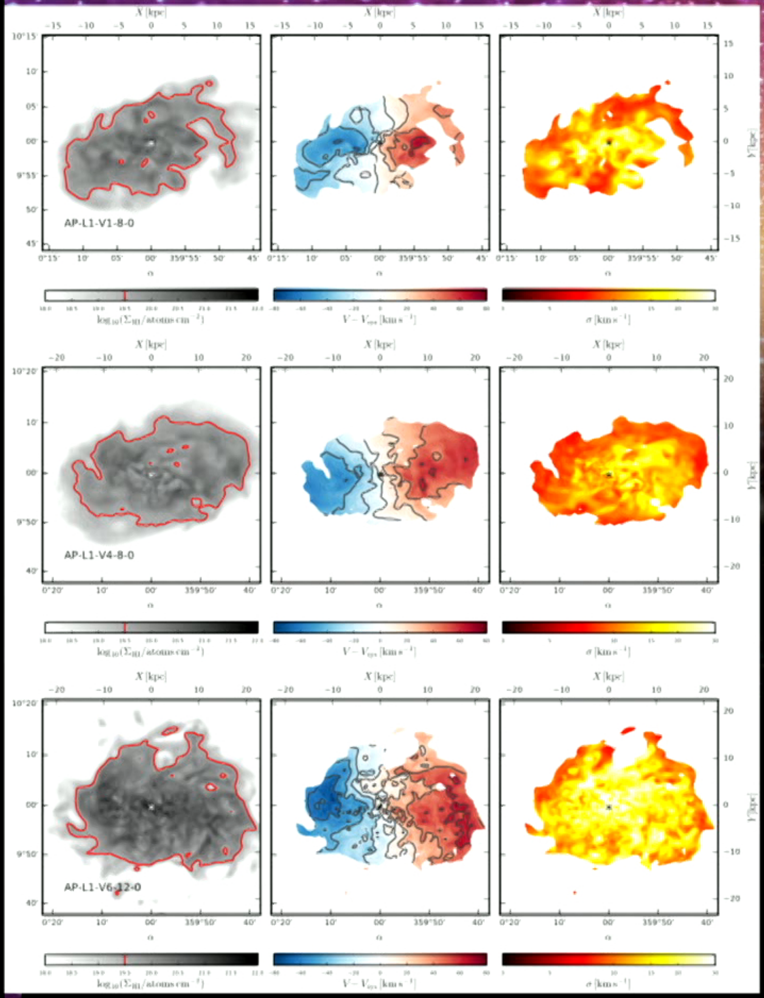
Rotation curves of APOSTLE galaxies



- HI velocity fields used to derive rotation curves using the same tools as in observations
- HI data cubes are built after assuming a favourable inclination and distance
- Rotation curves derived using BAROLO^{3D}, one of the latest version of "tilted-ring"models
- Procedure tested on galaxies from the THINGS and LITTLE THINGS datasets

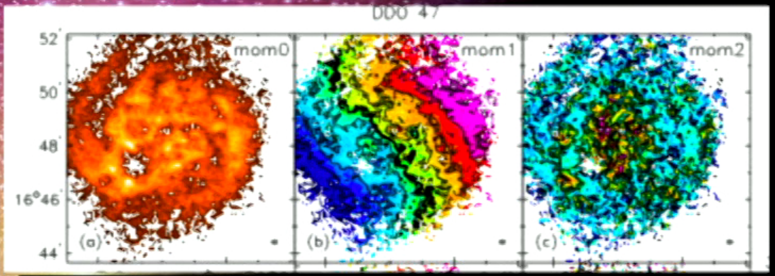
Oman+17

HI in APOSTLE

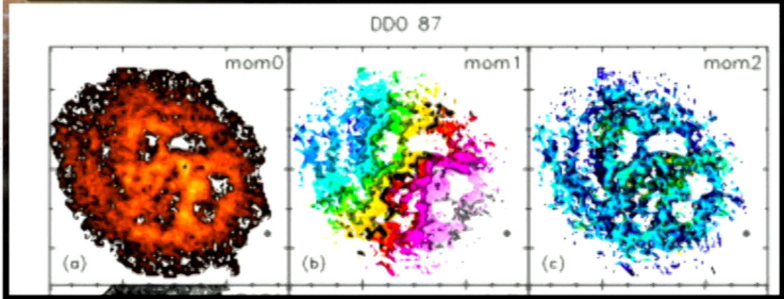


Oman+17

HI in LITTLE THINGS



HI Surface density Mean velocity rms velocity



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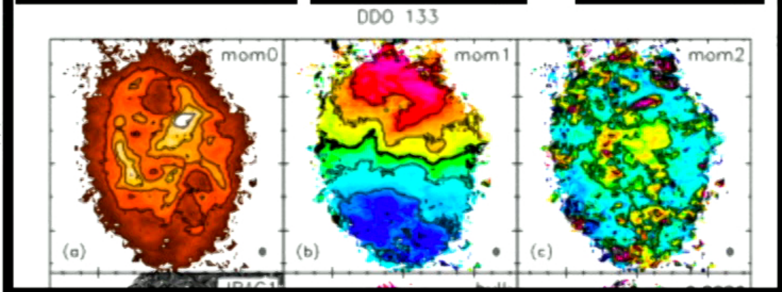
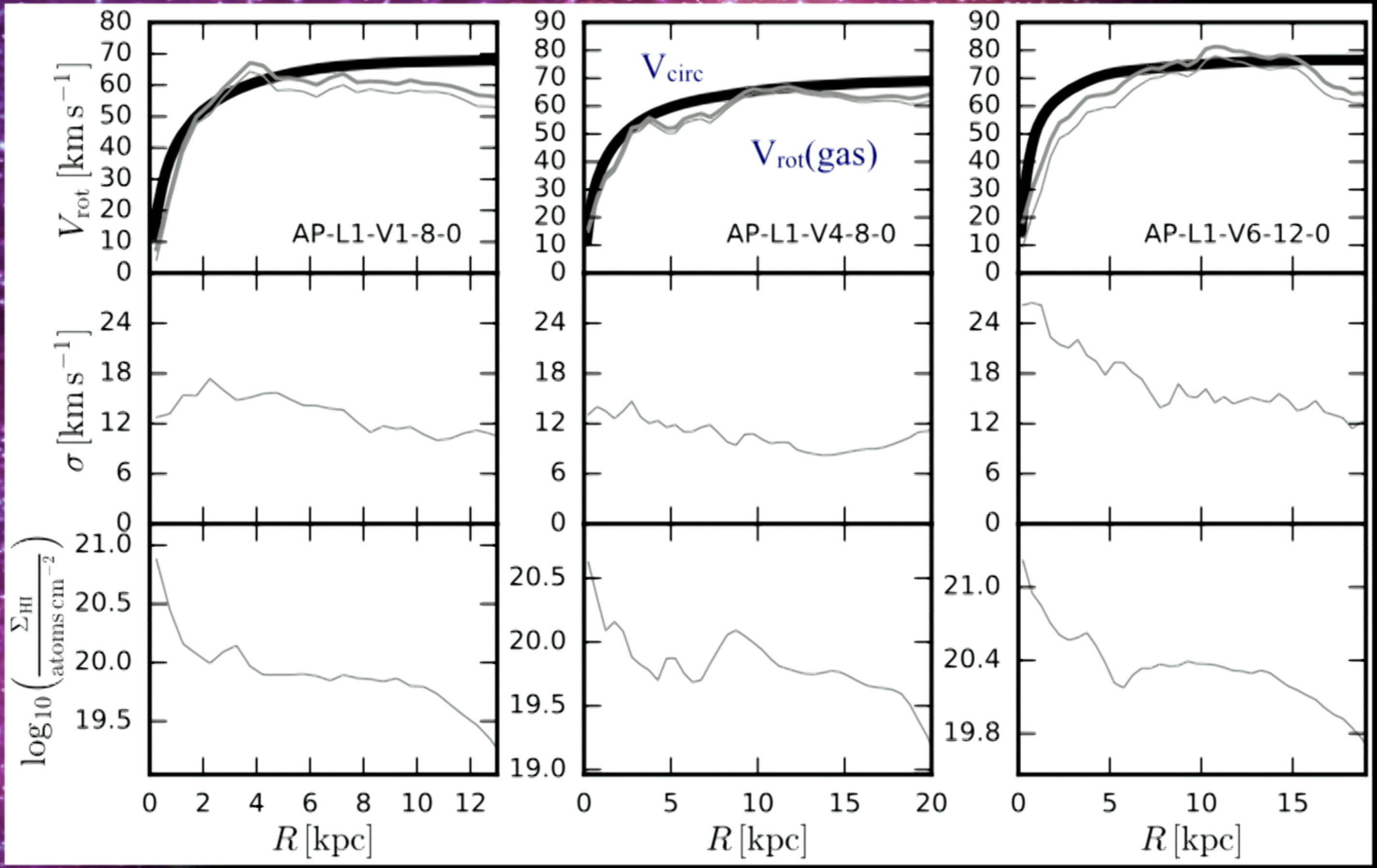


Oh+15

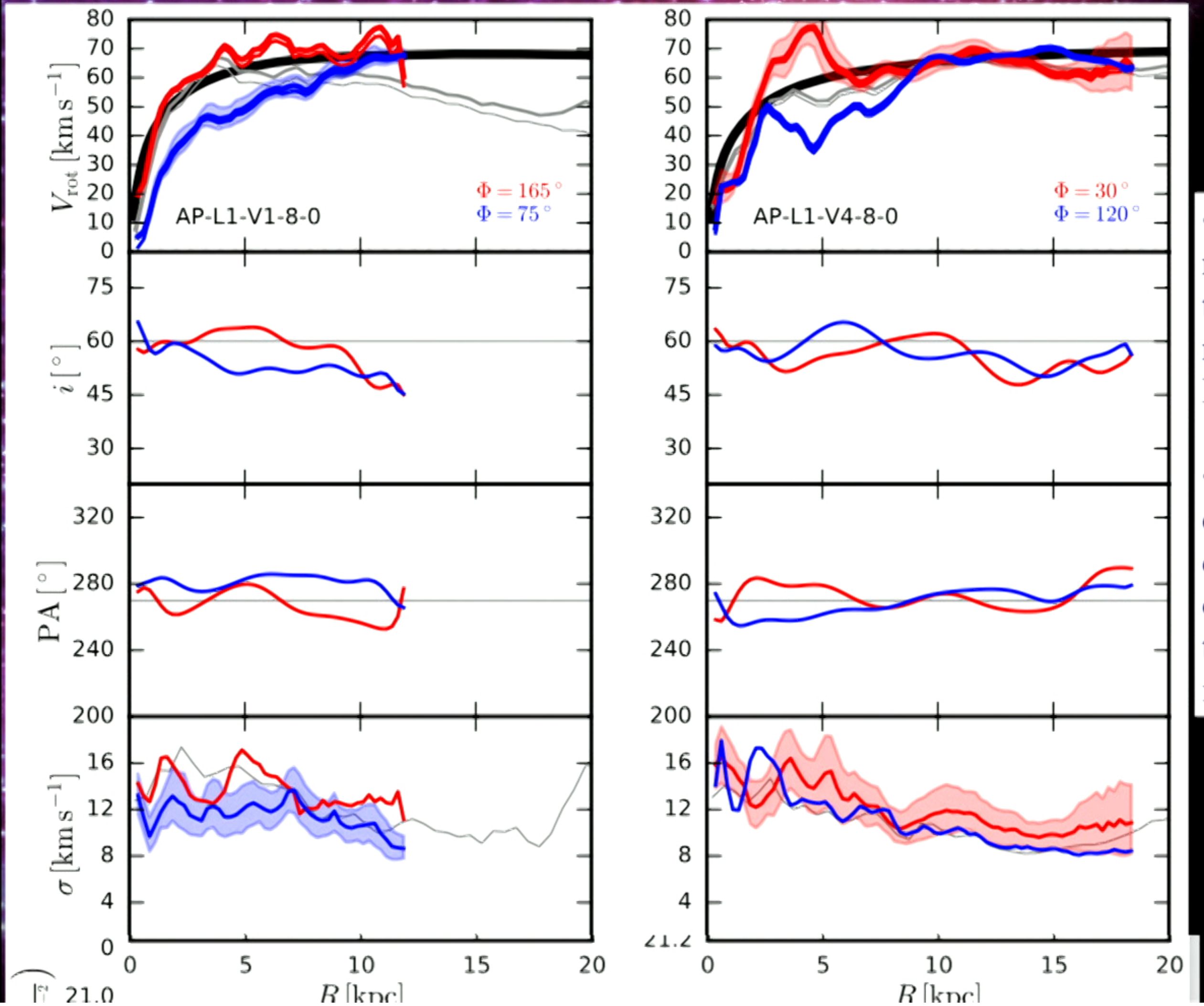
Gas rotation velocities of APOSTLE galaxies



- In most galaxies gas rotation traces the circular velocity fairly well

Oman+17

HI rotation curves of APOSTLE galaxies

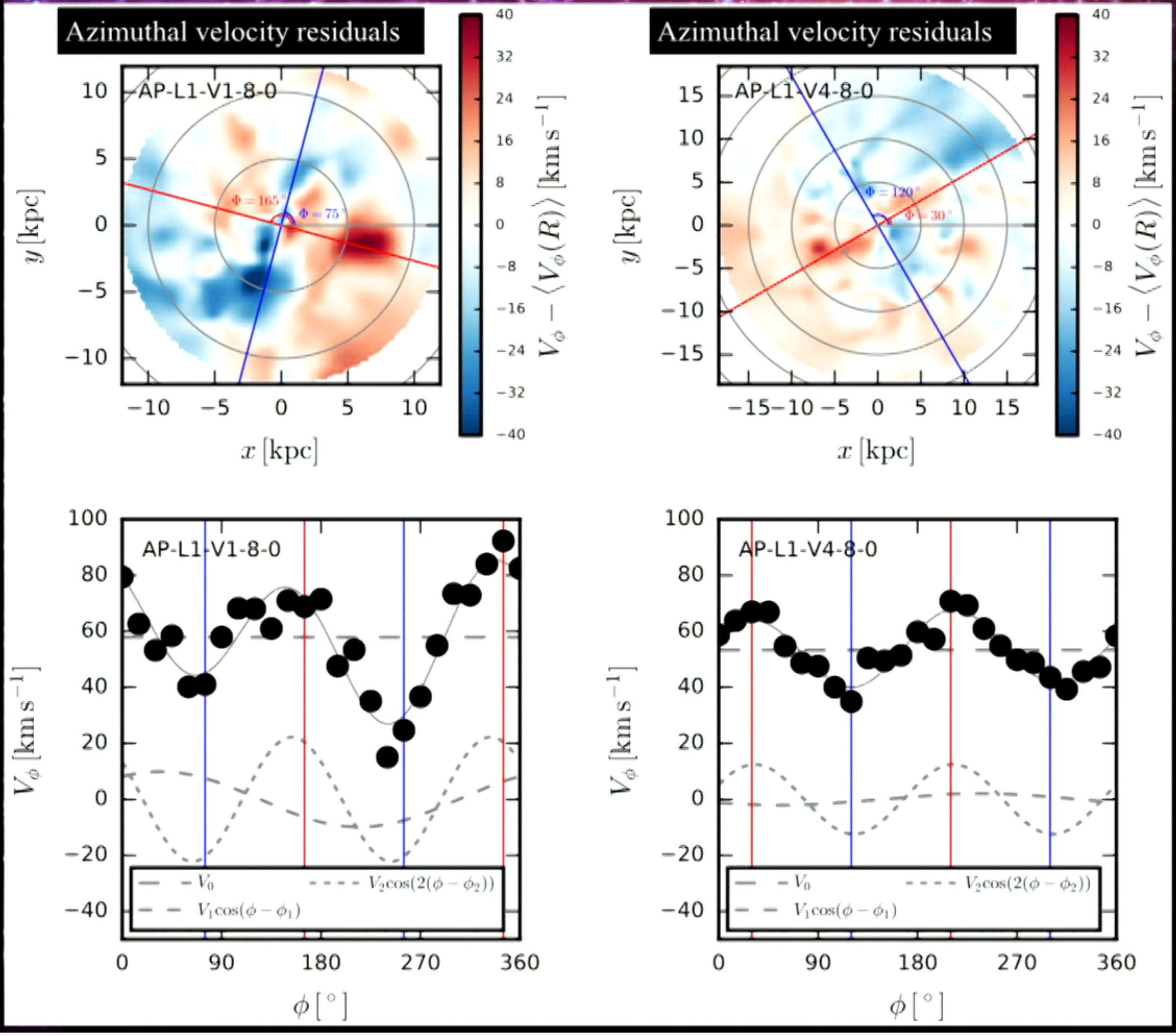


- Rotation curves recovered using the tilted-ring model of BAROLO^{3D}

- **Blue** and **red** correspond to two different orientations for the *same* inclination

Oman+17

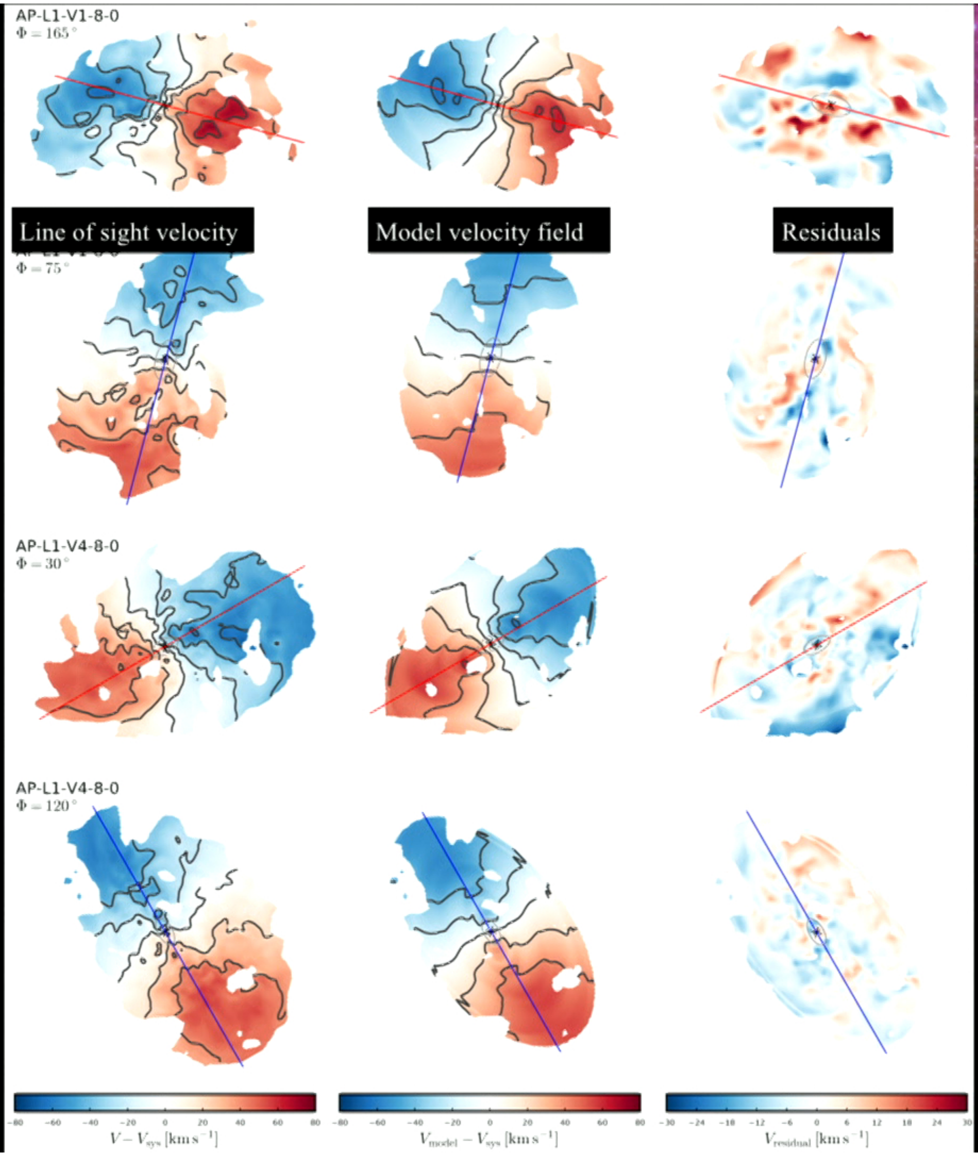
HI Velocity fields of APOSTLE galaxies



- The orientation dependence of the recovered rotation curves is due to non-circular motions in the galaxy plane

- Although the average V_ϕ is close to V_{circ}, there is a strong m=2 modulation in the velocity field

Oman+17

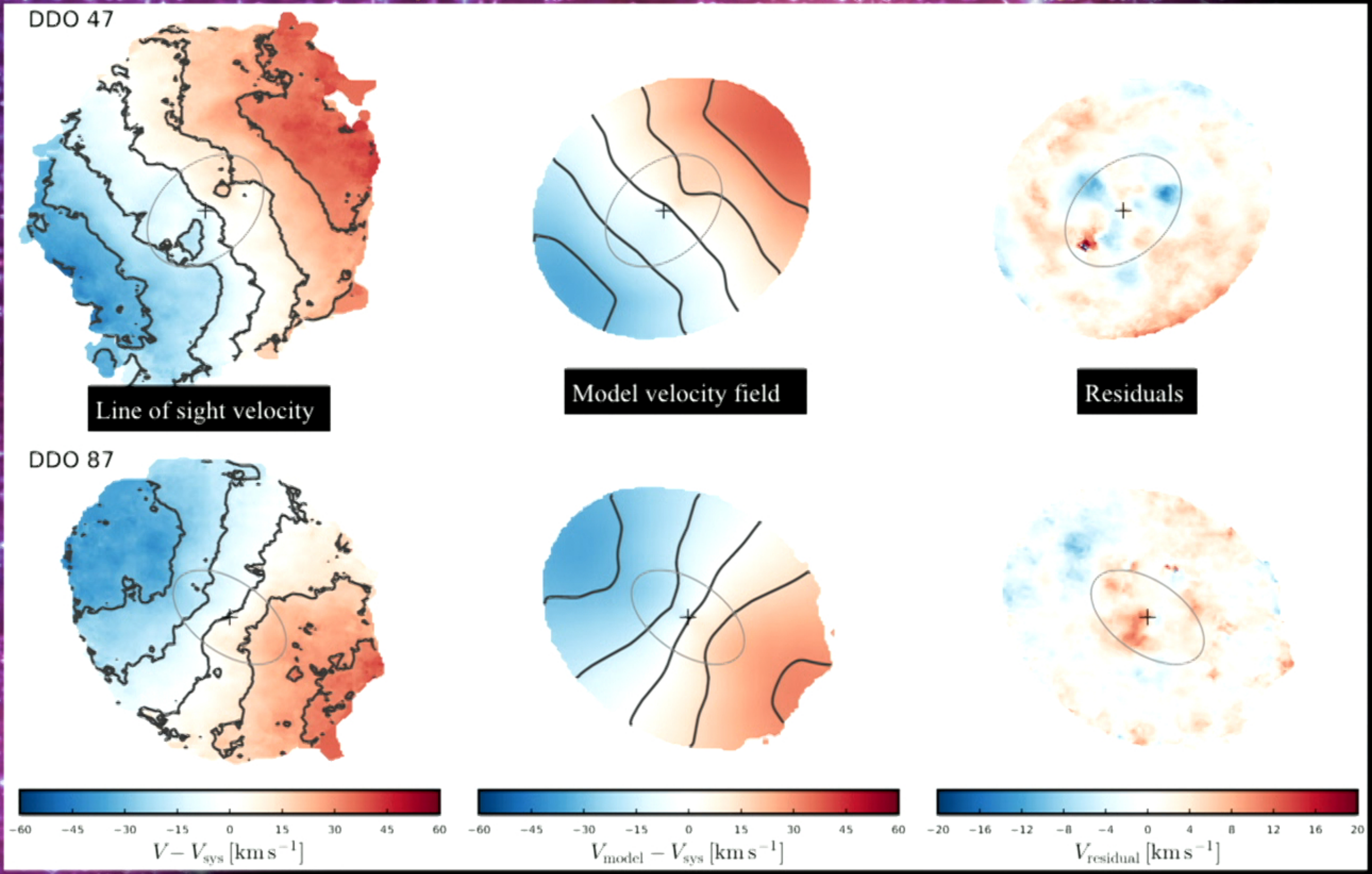


HI Line-of-sight velocity fields of APOSTLE galaxies

- In projection m=2 modes contribute to m=1 and m=3 modulations
- These are not obvious when subtracting the “best” tilted-ring model fit from the data
- They should still be recognizable in the most deviant cases

Oman+17

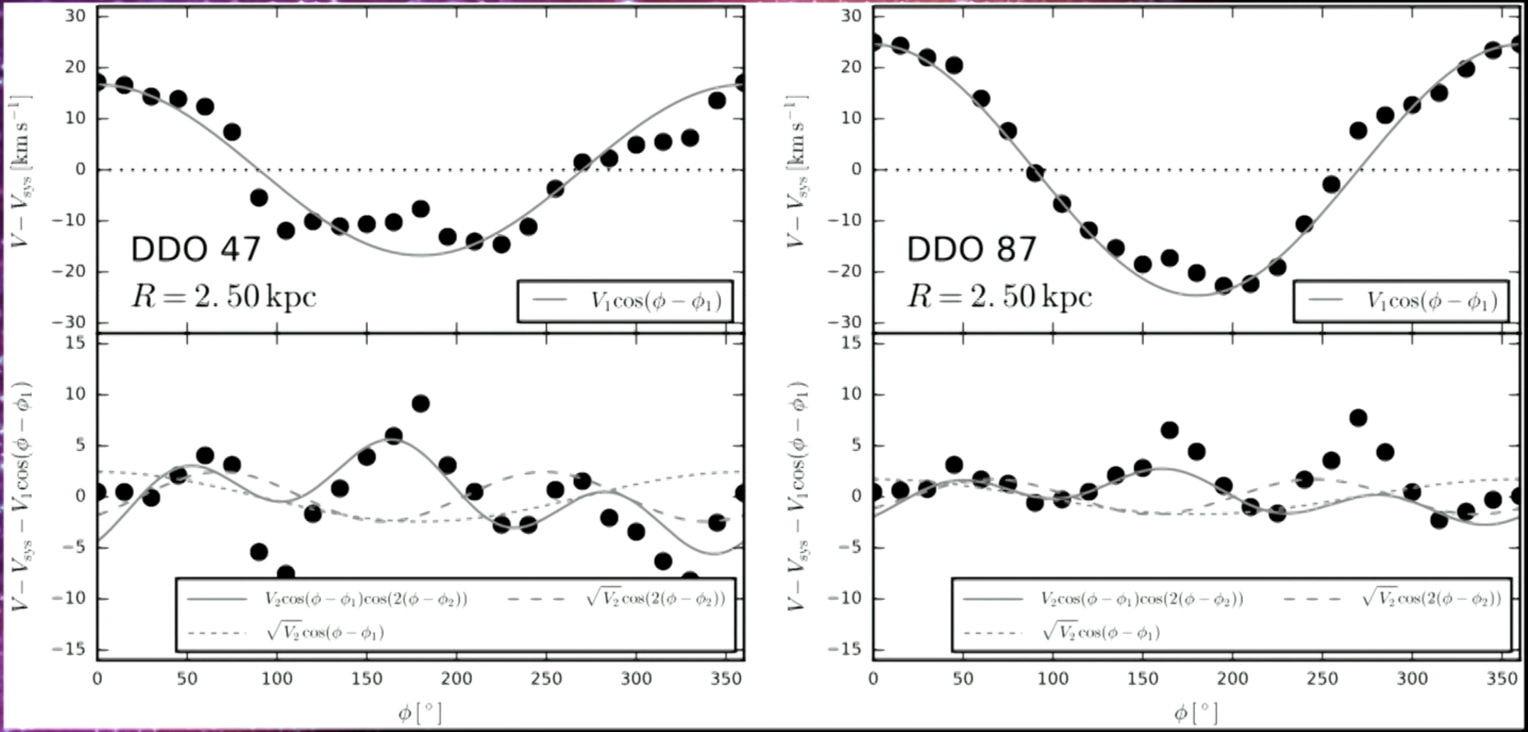
HI Velocity fields of LITTLE THINGS galaxies



- The m=3 mode is clearly present in two galaxies with slowly rising rotation curves reminiscent of constant density "cores"

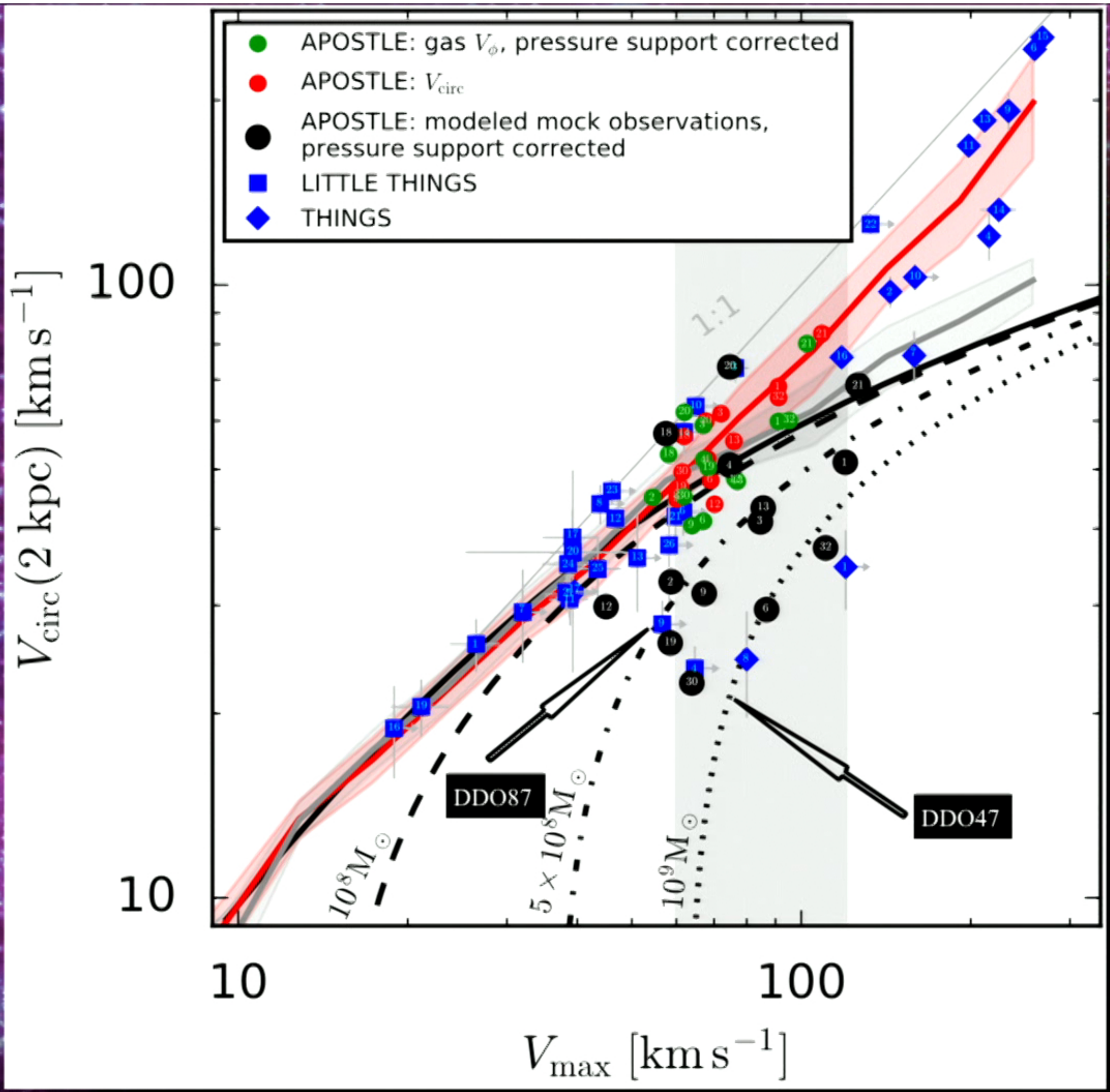
Oman+17

HI Velocity fields of LITTLE THINGS galaxies



- The azimuthal velocity around an ellipse of fixed radius confirms the m=3 mode pattern
- Amplitudes are <~10 km/s, roughly between 30% to 50% of the average rotation speed.

Oman+17



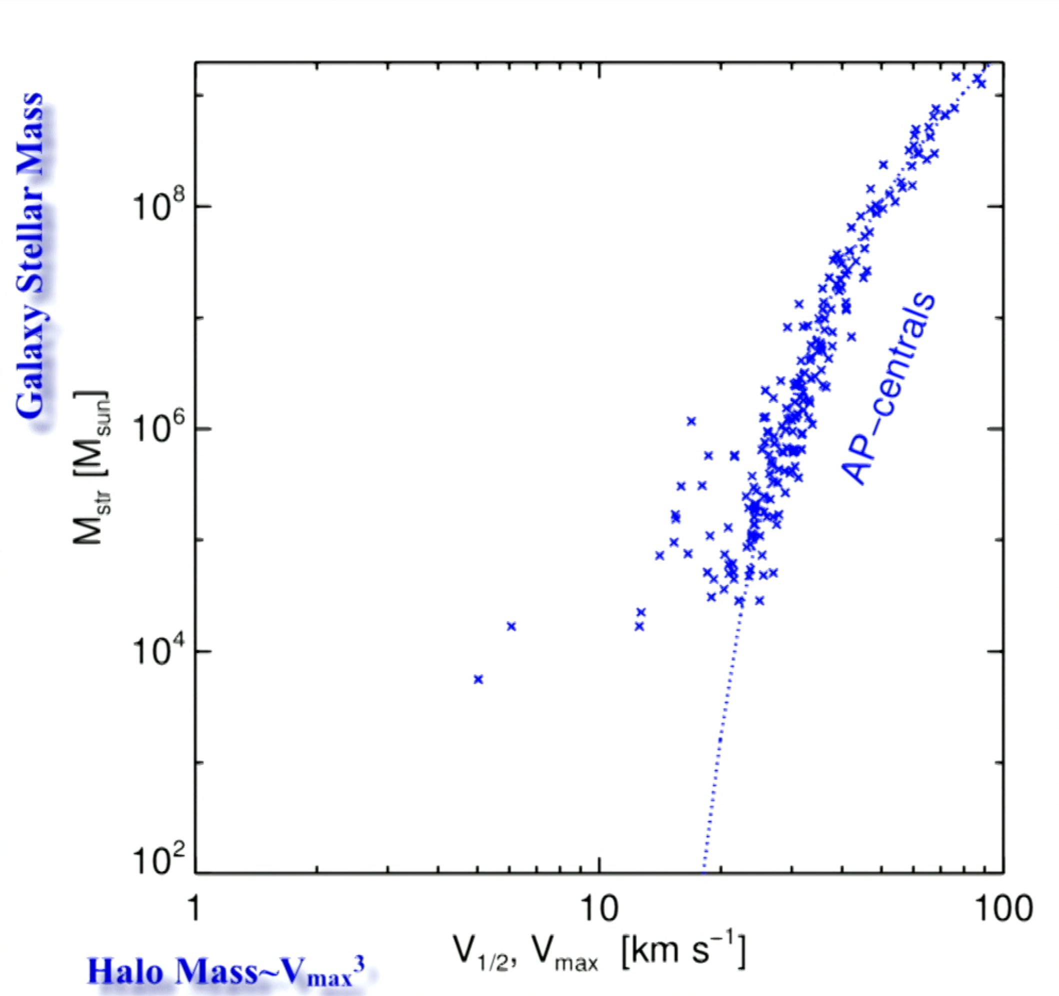
"Inner mass discrepancy" or non-circular motions?

- •Two galaxies that deviate from LCDM predictions have velocity estimates clearly affected by non-circular motions
- •Others may very well be affected too
- •The "cusp vs core" issue may have just be caused by systematic uncertainties associated with tilted-ring models

Oman+17

“Extremely cold” dwarf halos and the mass discrepancy-acceleration relation (MDAR)

Halo mass-stellar mass in APOSTLE/EAGLE



- Cosmic reionization imposes a sharp cutoff in the mass of halos that can host luminous galaxies
- This predicts that most faint galaxies are formed in halos of similar mass
- Faint dwarfs should have similar characteristic circular velocities

Fattahi+17

Crater 2: the cold feeble giant

Credit: Vassily Belokurov

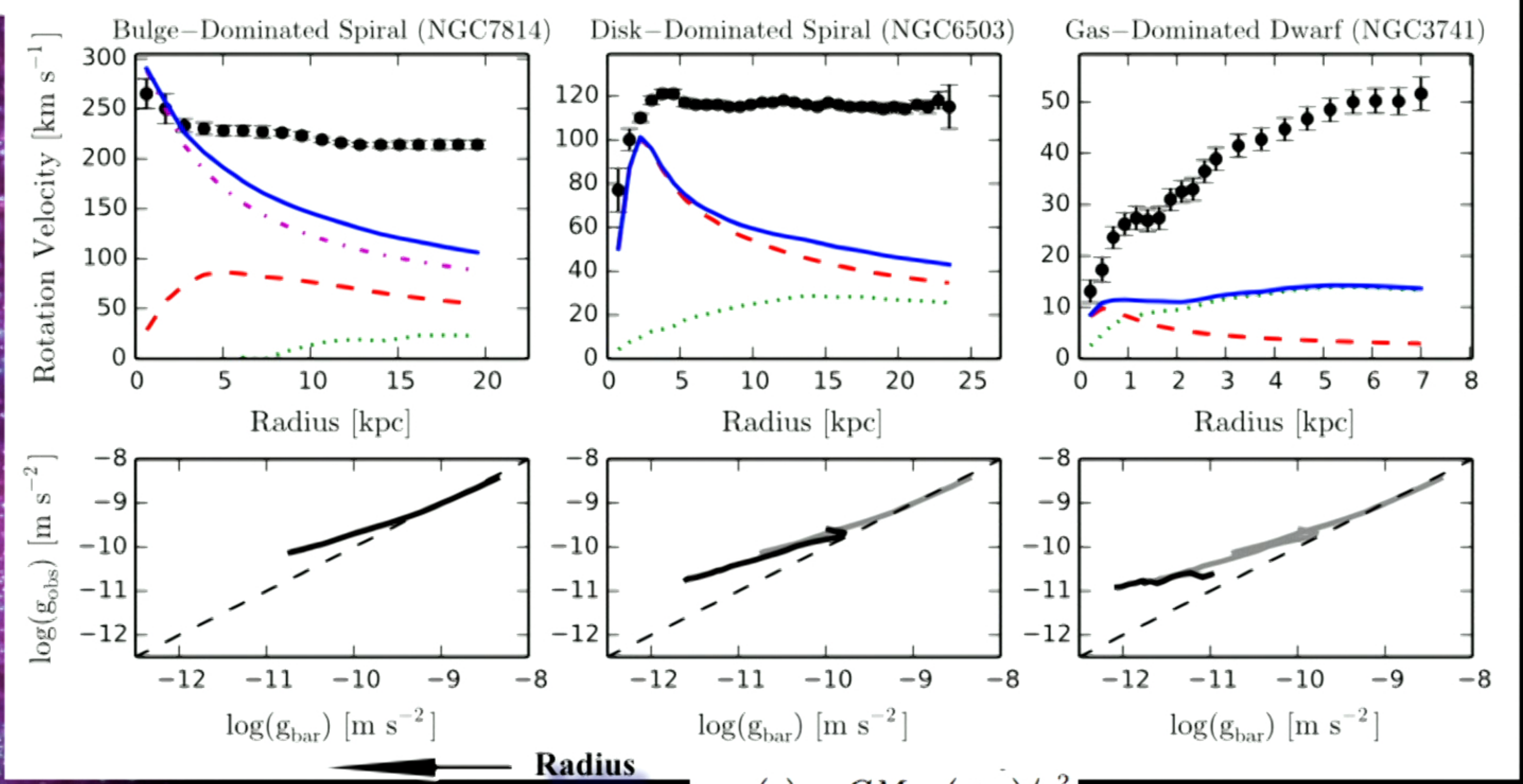
- Crater 2 is an unusual dwarf galaxy ($M_{star} \sim 10^5$ M_{sun}) because of its large size (~ 1 kpc) and extremely low velocity dispersion ($\sigma \sim 3$ km/s)
- Both properties are extremely unusual
- Galaxies this large tend to be much more luminous
- Galaxies this large should have much higher velocity dispersion.

Fattahi+17

The mass discrepancy-acceleration relation (MDAR)

Disk galaxy rotation velocities may be "predicted" from the distribution of luminous matter

$$g_{\rm obs} = \frac{V^2(R)}{R}$$



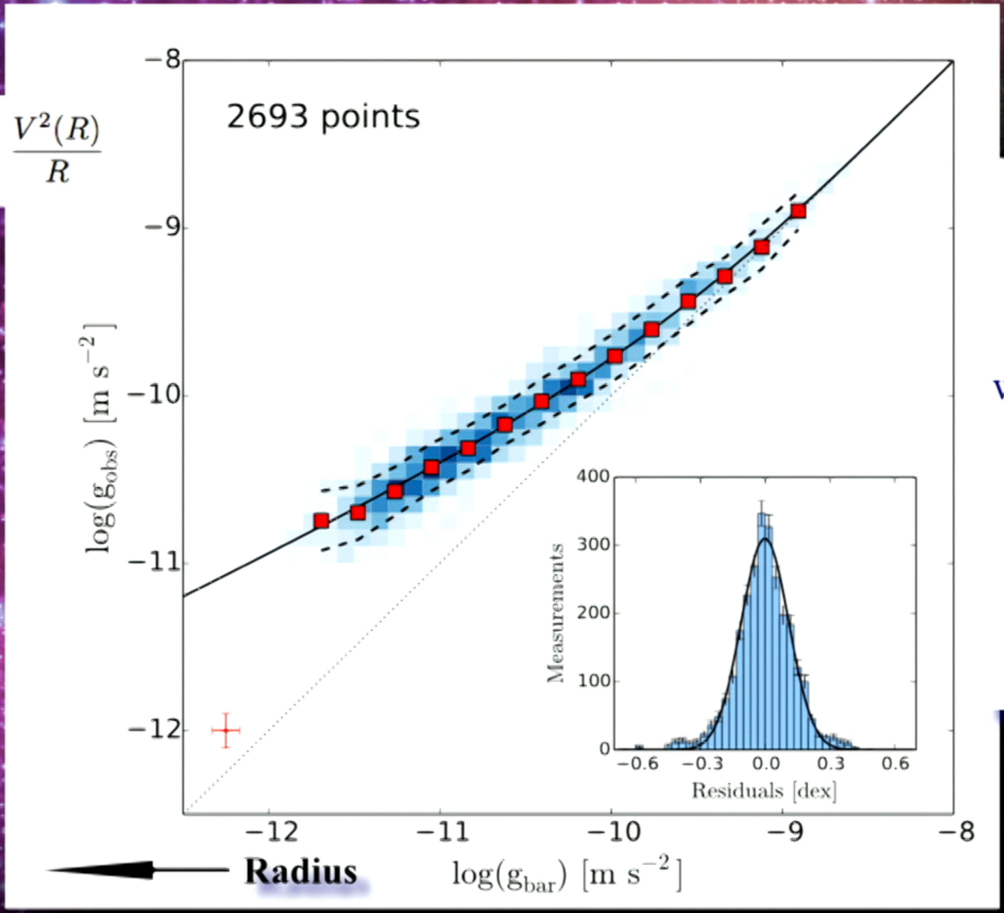
← **Radius**

$$g_{\rm bar}(r) = GM_{\rm bar}(< r)/r^2$$

McGaugh+16

The mass discrepancy-acceleration relation

$$g_{\rm obs} = \frac{V^2(R)}{R}$$



$$g_{\rm bar}(r) = GM_{\rm bar}(<r)/r^2$$

Two characteristic accelerations:

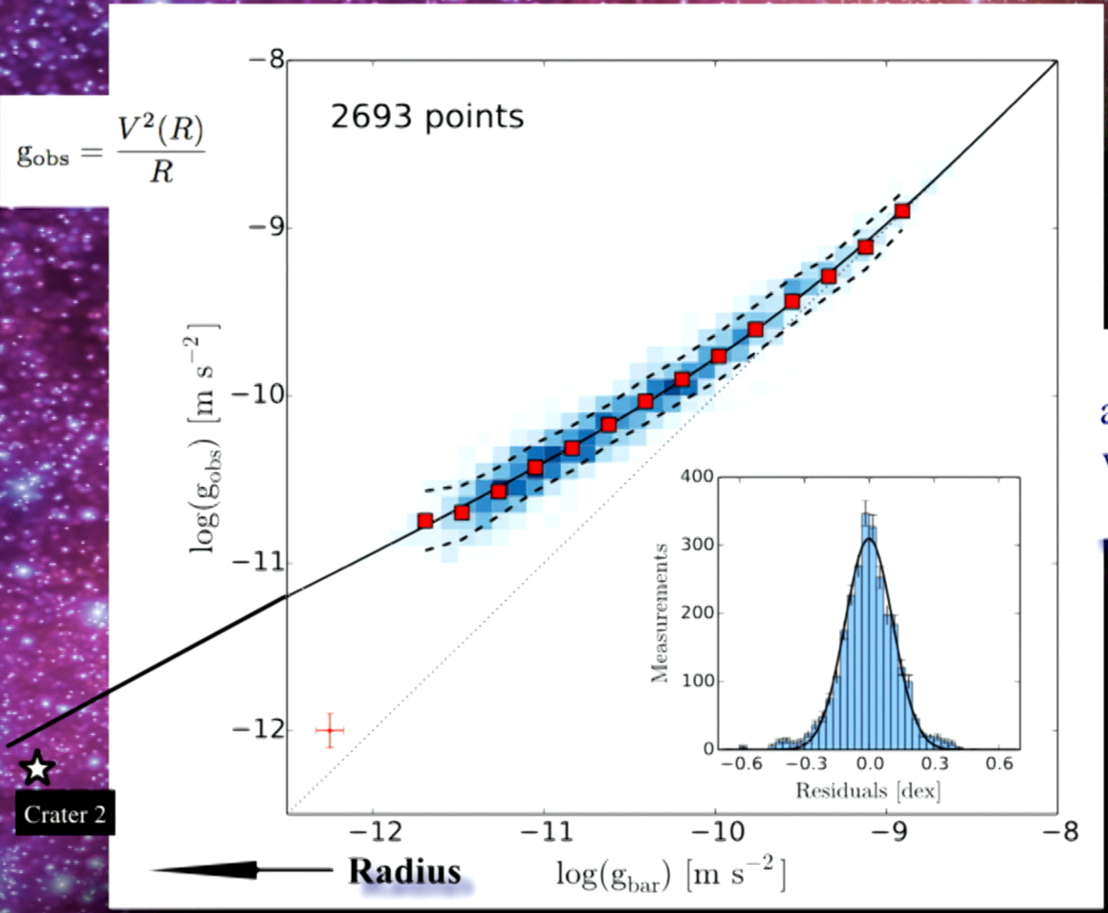
$a_0 \sim 10^{-10}$ m/s^2: above which there is little need for dark matter, and

$a_{\rm min} \sim 10^{-11}$ m/s^2: a "minimum" acceleration probed by galaxies

McGaugh+16

The mass discrepancy-acceleration relation

$$g_{\rm obs} = \frac{V^2(R)}{R}$$

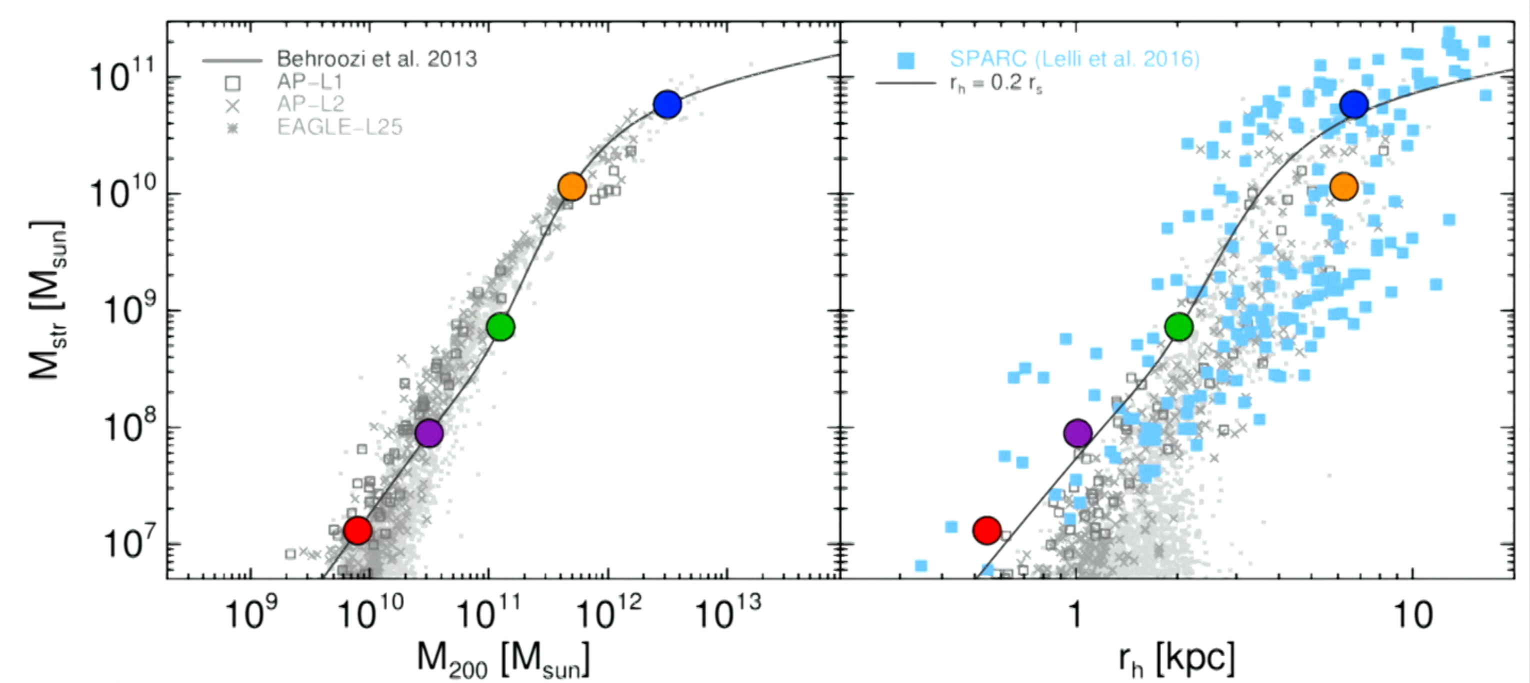


Crater 2 is well below amin and roughly aligns with an extrapolation of the MDAR

$$g_{\rm bar}(r) = GM_{\rm bar}(<r)/r^2$$

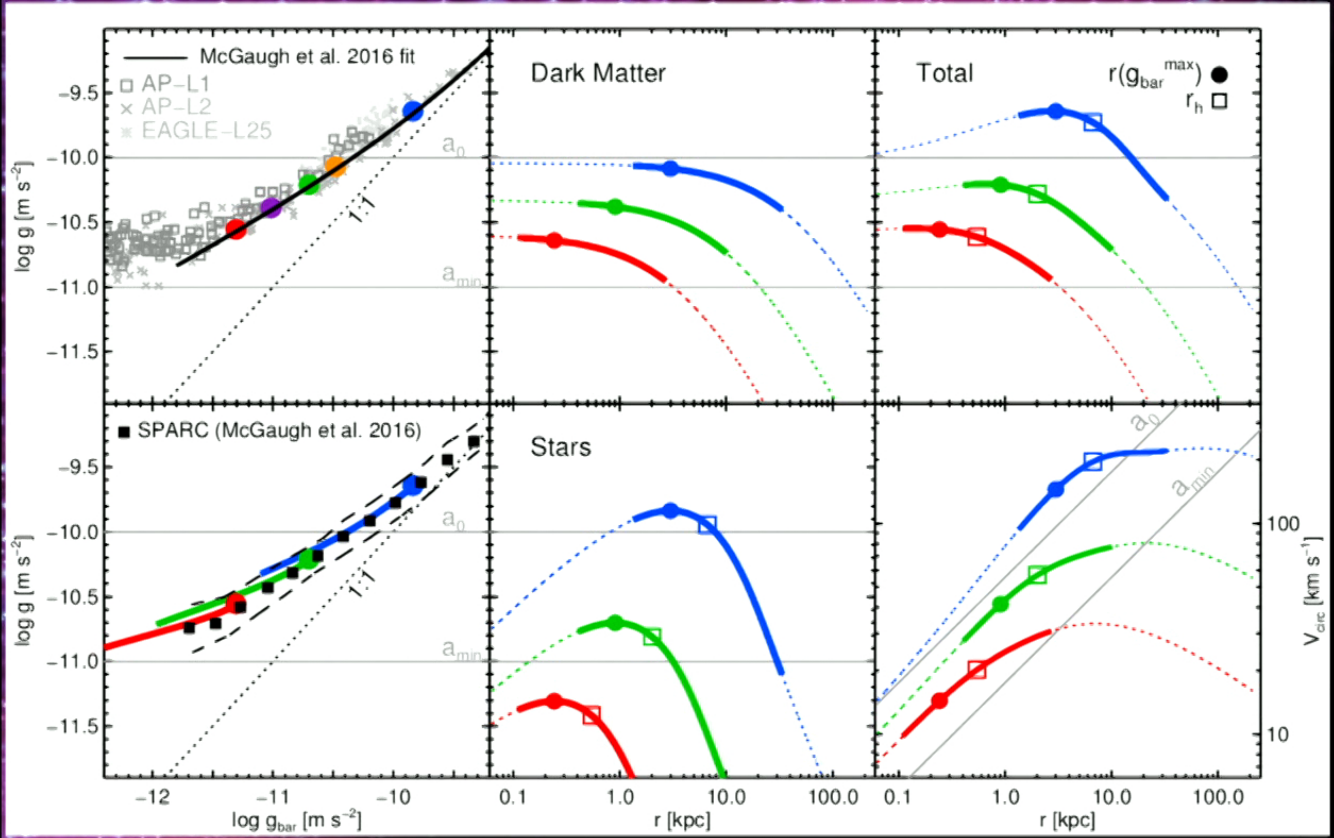
McGaugh+16

MDAR in LCDM



Every galaxy has a characteristic baryonic acceleration (“g_{bar}”) which depends on how its stellar mass and size correlate. This, together with the characteristic acceleration of the halo, which depends on its viral mass and concentration, imply a tight relation between g_{tot} and g_{bar} in LCDM

MDAR in LCDM



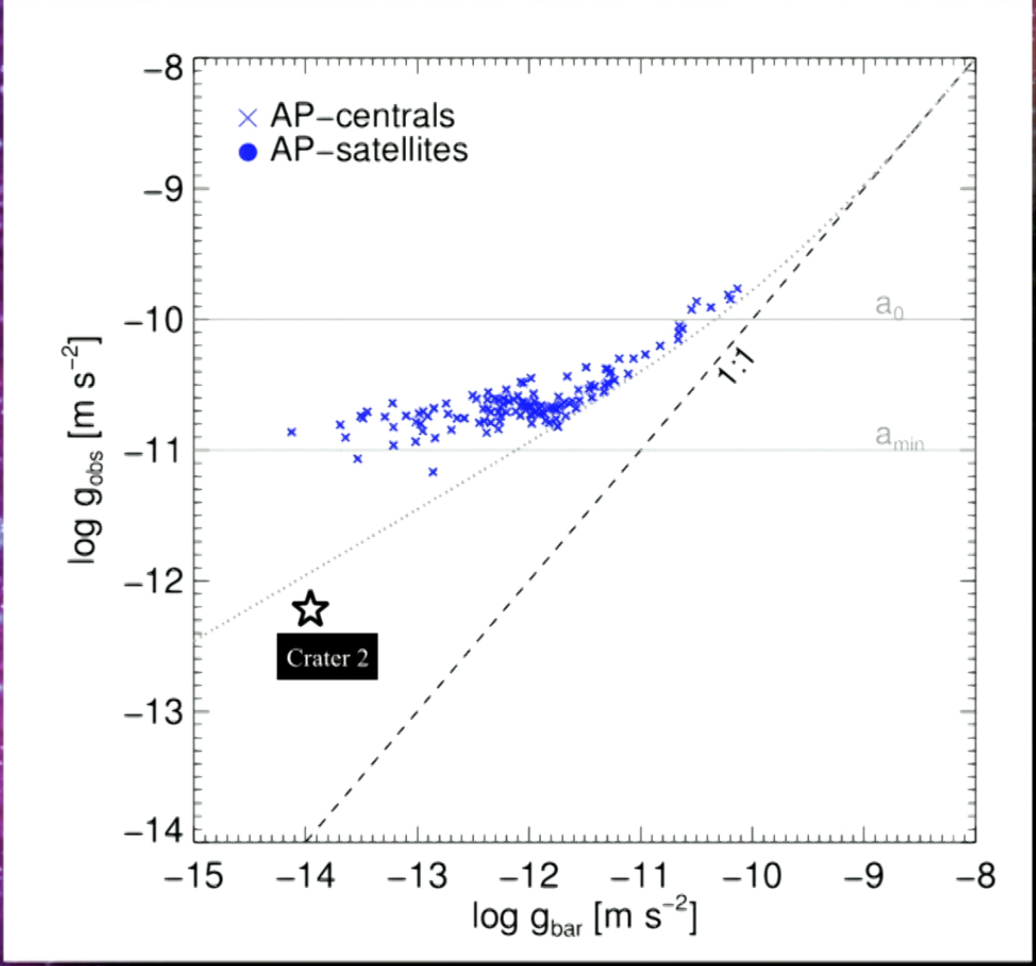
LCDM halos have a well-defined maximum central acceleration

$a_0 \sim 10^{-10}$ m/s^2 is the central acceleration of the most massive halo that may host a disk galaxy ($V_{max} \sim$ 200-300 km/s)

$a_{min} \sim 10^{-11}$ m/s^2: is the acceleration of the least massive halo able to host a luminous galaxy ($V_{max} \sim$20-30 km/s)

Navarro+16

Crater 2 and MDAR in LCDM



$g_{\rm bar}(r) = GM_{\rm bar}(< r)/r^2$

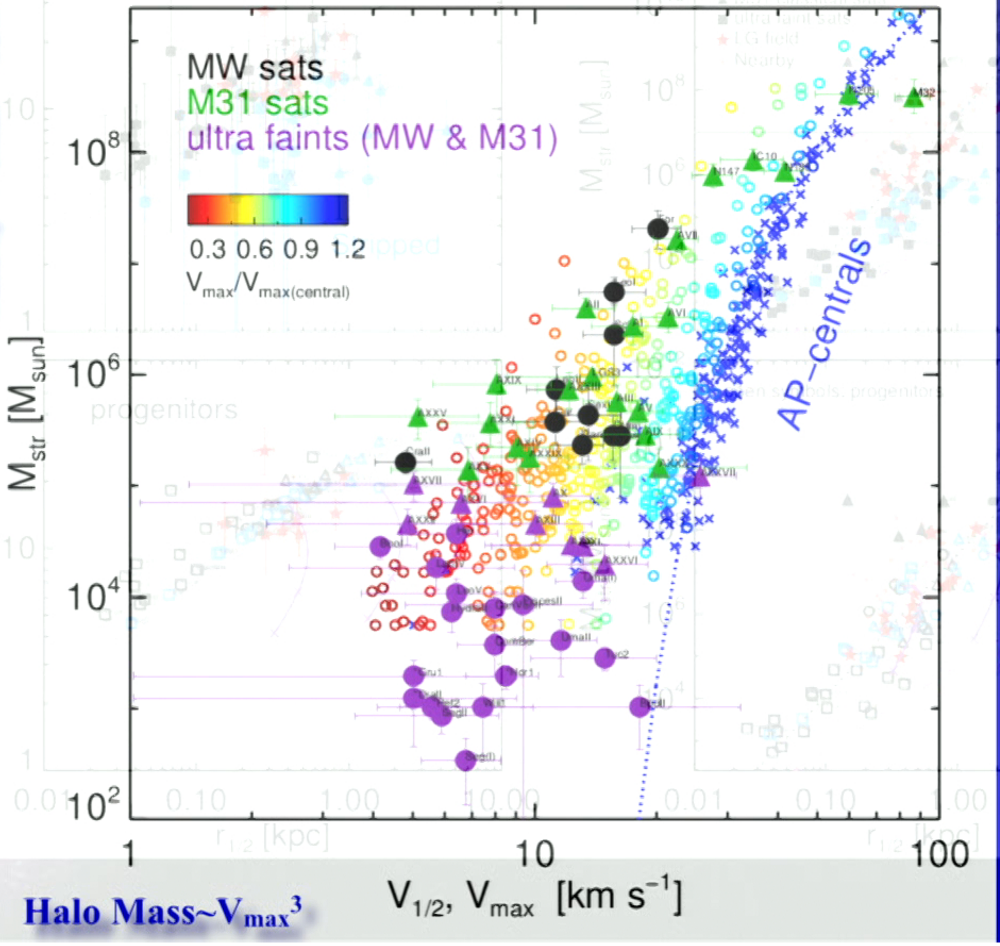
A further prediction of LCDM is that some *satellite* galaxies should deviate from the general trend and probe accelerations below $a_{\rm min}$.

This is because tidal stripping removes dark matter from satellites, reducing their central accelerations

Could Crater 2 be the remnant of a once much more luminous galaxy?

Fattahi+17

Halo mass-stellar mass in APOSTLE/EAGLE



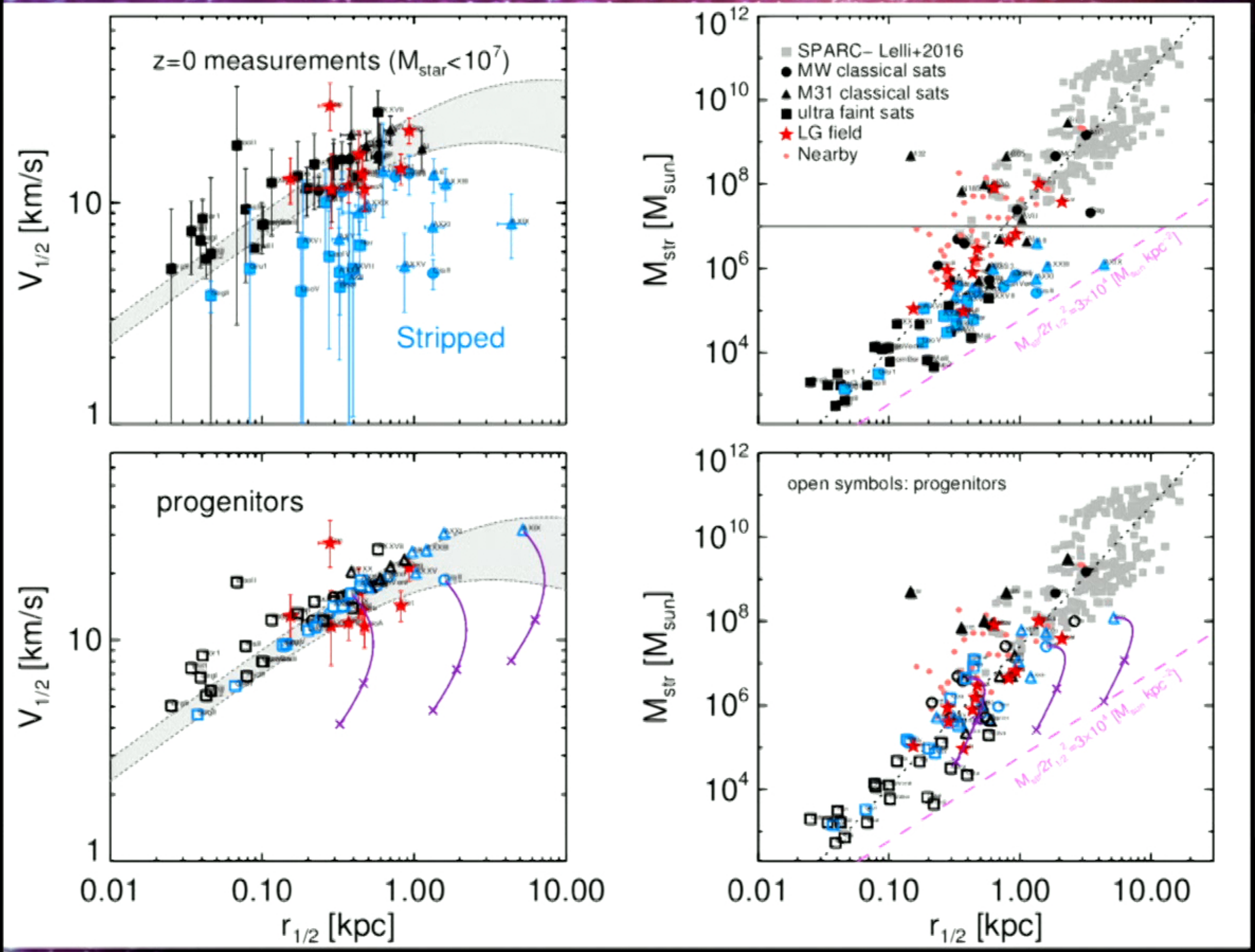
Galaxy Stellar Mass

Halo Mass~V_{max}^3

- Best data available are for nearby Local Group satellites
- Dwarf galaxies span a relatively wide range of circular velocities, but lower than predicted
- This is the source of many of the alleged problems for LCDM on the scale of dwarfs
- Offset may be due to (i) small size of dwarfs or (ii) the effects of tidal stripping

Fattahi+17

Tidal stripping and dwarf galaxy scaling laws



If stripping was not important there should be a strong correlation between radius and velocity for dwarf galaxies.

If stripping is the cause of the deviation from this prediction, we can use that to recover their progenitors

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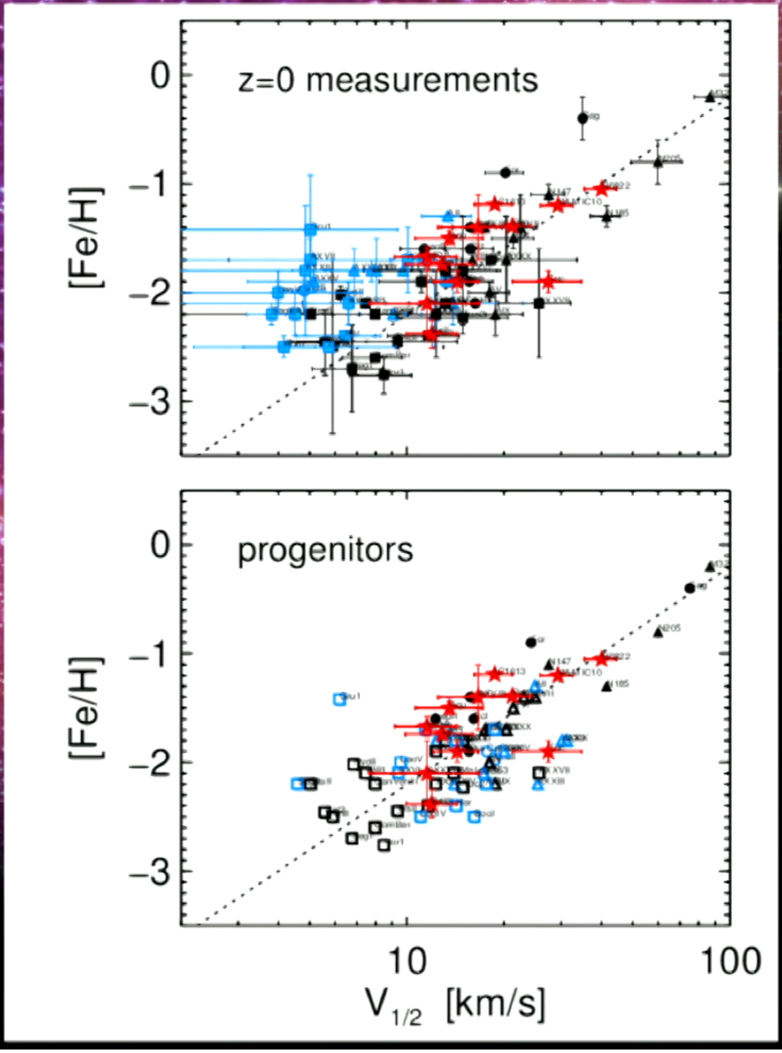
Tidal stripping and dwarf galaxy scaling laws



If stripping was not important there should be a strong correlation between radius and velocity for dwarf galaxies.

If stripping is the cause, we can use that to recover their progenitors

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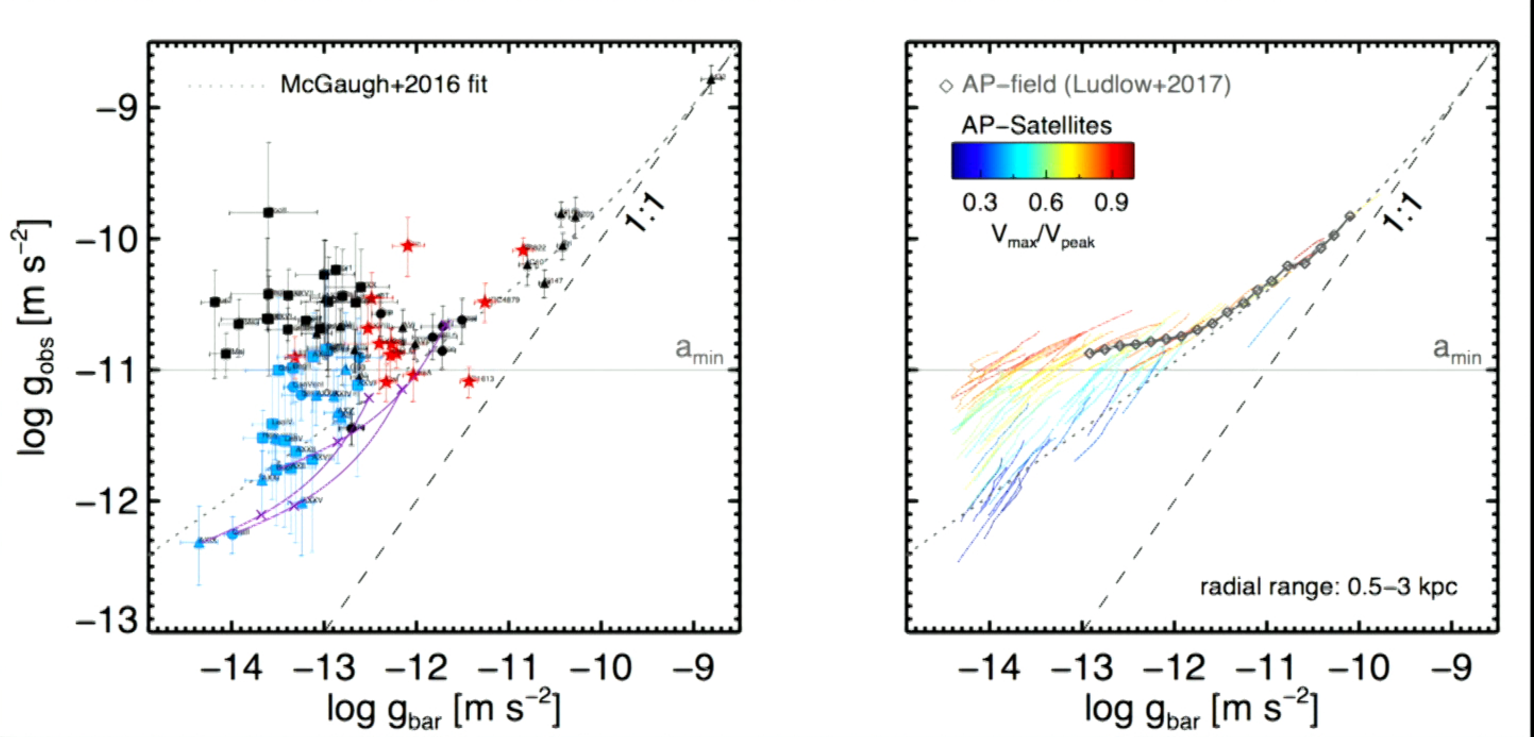
MDAR in LCDM



This large scatter at fixed g_{bar} is at odds with the predictions of alternative theories of gravity, like MOND

$g_{\rm bar}(r) = GM_{\rm bar}(<r)/r^2$

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