Galaxy formation on subgalactic scales

Carlos S. Frenk
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University of Durham

Dark matter halos: cores or cusps?

The new Ogden Centre at Durham

Dark matter halos: cores or cusps?

Two myths

- The DM halos of dwarf galaxies have central cores
- Hydro simulations of dwarfs produce cores if they have bursty star formation

Dark matter halos: cores or cusps?

Two myths

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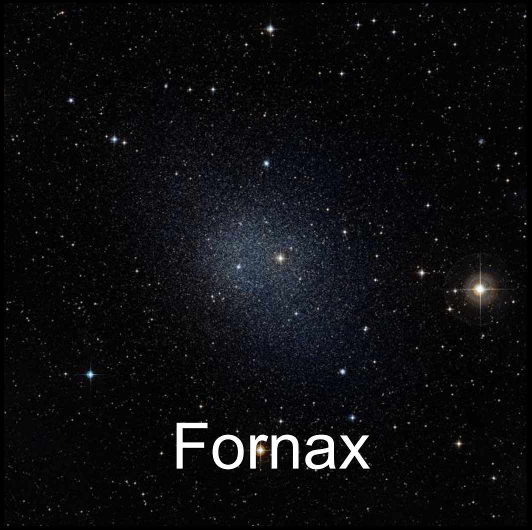
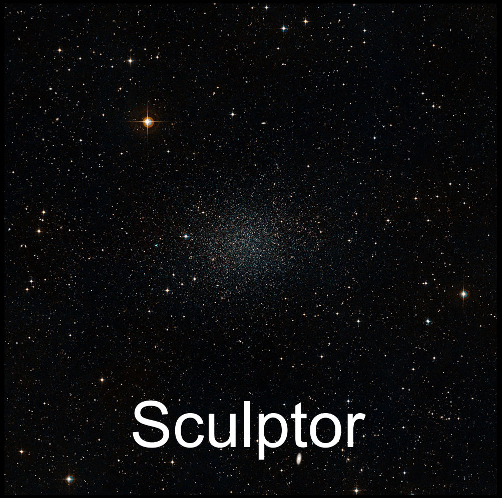
Cores in real dwarf galaxies






Sextans

Carina


Sagittarius

The DM halos of dwarf spheroidals

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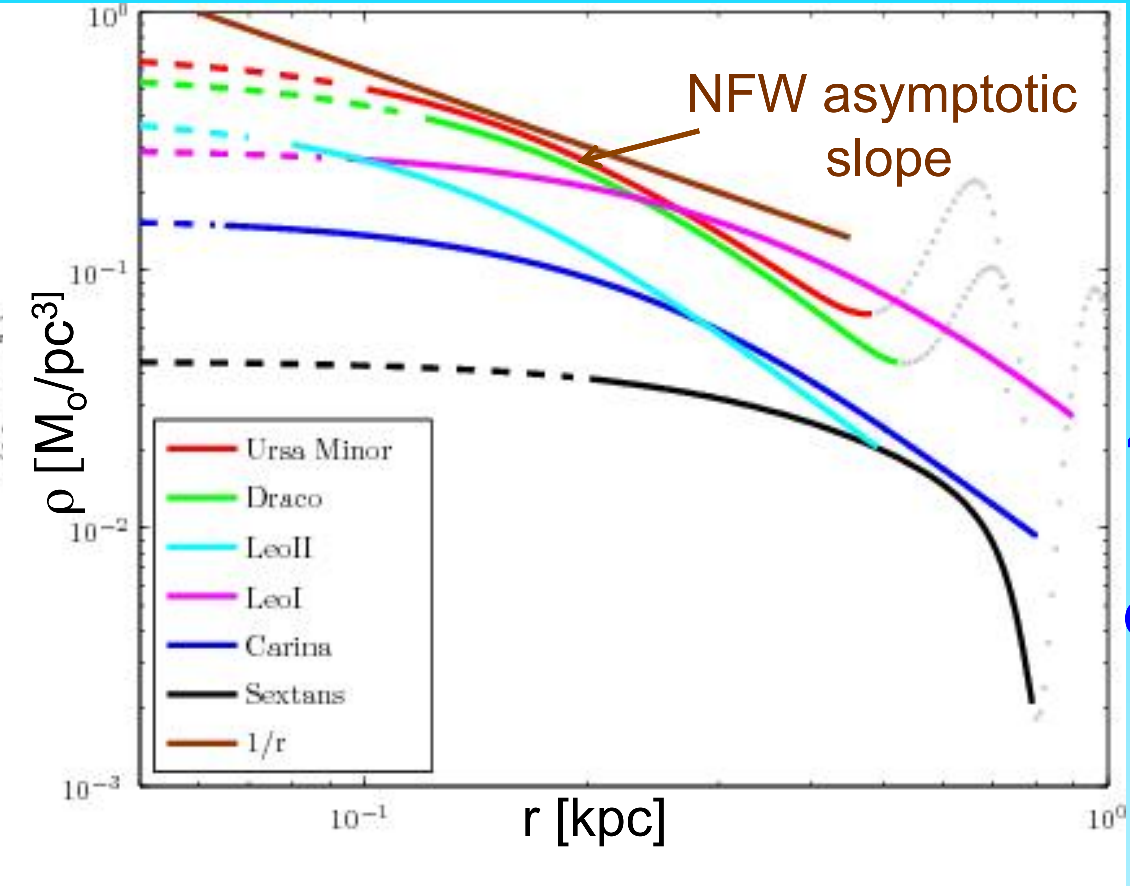

Gilmore etal '07

Inferred density profiles for 6 dwarf spheroidals

"…dark matter forms cored mass distributions, with a core scale length of greater than about 100pc…"

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Fits assuming NFW →

Dwarf sphs: cores or cusps?

Jeans eqn:

$$\frac{GM(r)}{r} = -\sigma_r^2\left[\frac{d\ln\rho_*}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right]$$

from Aquarius sim

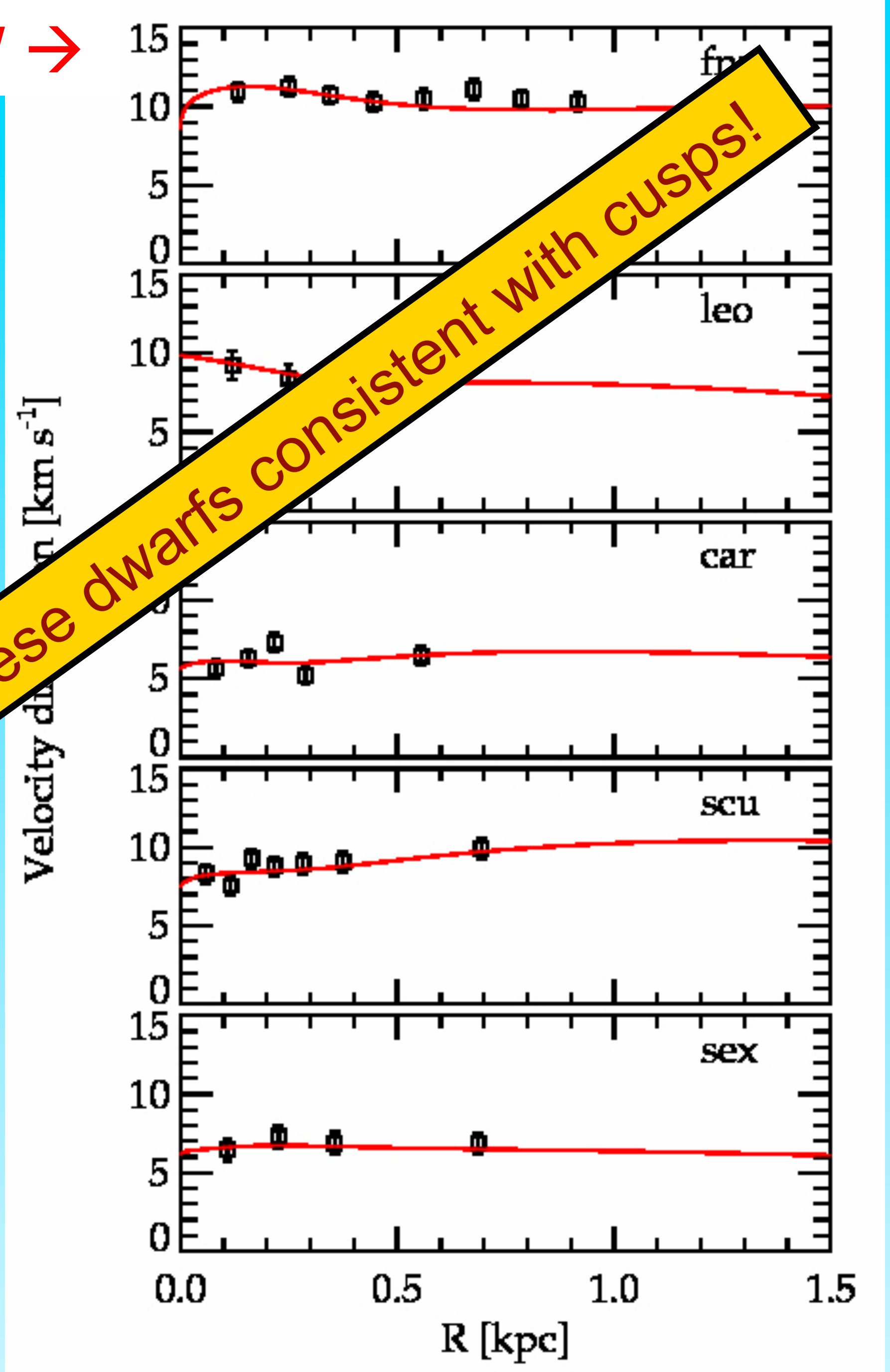
Cuspy!

vel. an... py

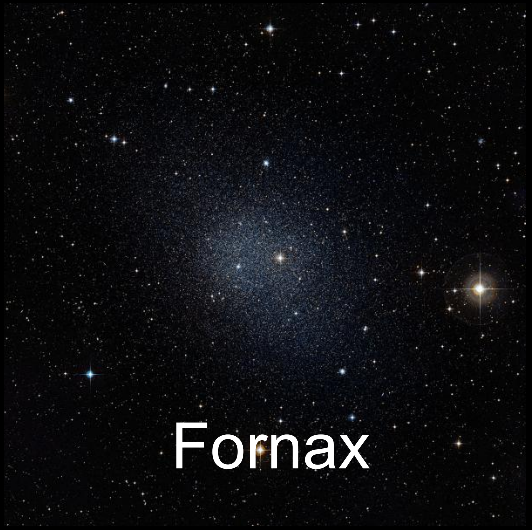
- Assume isotropi... ts
- Solve for σ...
- Com... with observed σ_r (r)
- ... best fit” subhalo

Strigari, Frenk & White ‘10

Photometric and kinematical data for these dwarfs consistent with cusps!



Dwarf galaxies around the Milky Way



Sextans

Carina

Sagittarius

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The DM halo of the Sculptor dwarf

University of Durham

Sculptor has two stellar pops:

(i) centrally concentrated, high [Fe/H]

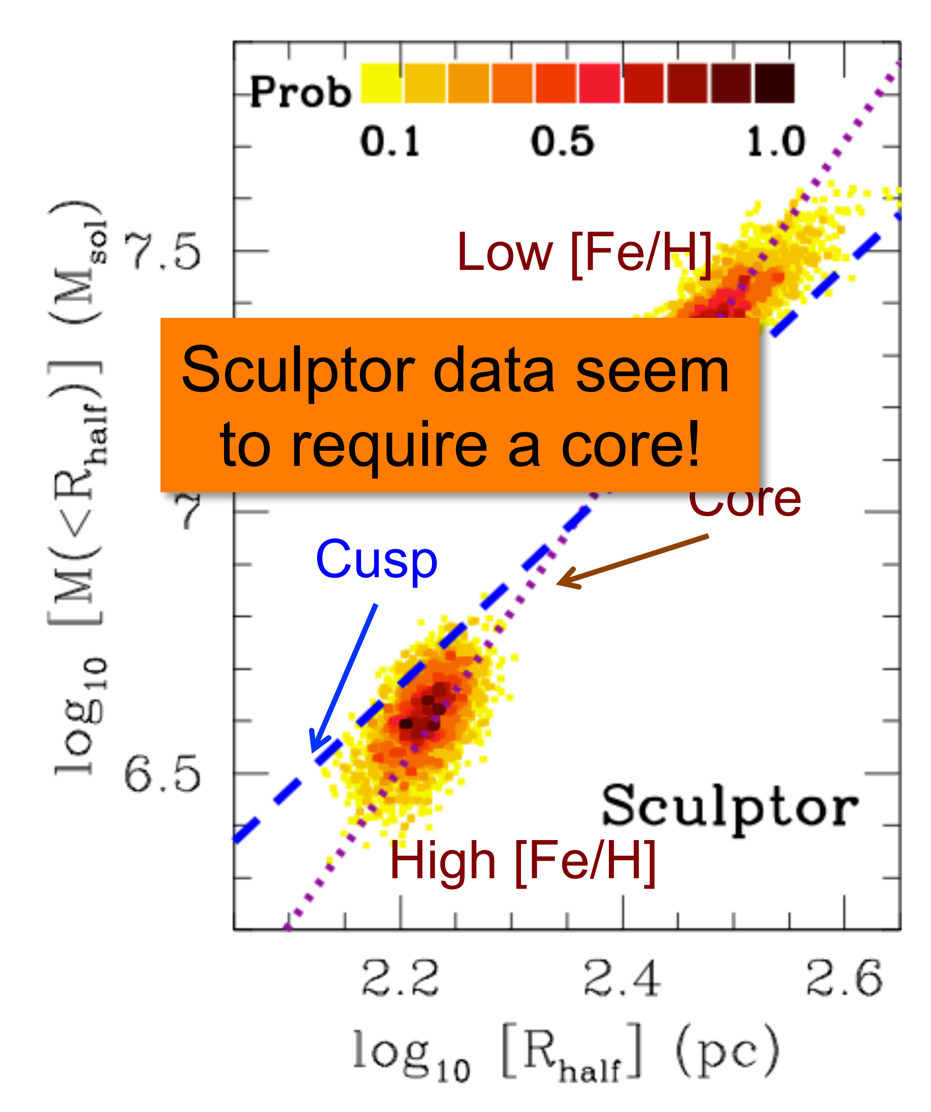
(ii) extended, low [Fe/H]

$$M(<r) = \mu \frac{r<\sigma_{los}^{2}>}{G}$$

$r=r_{1/2}$

Walker '10; Wolf et al '10→

if $r=r_{1/2}$, $\mu=2.5$, independently of model assumptions!



Sculptor data seem to require a core!

Walker & Peñarrubia '11

The DM halo of the Sculptor dwarf

University of Durham

Strigari, Frenk & White '15

Distribution function analysis of 2 metallicity pop. data of Battaglia et al.

Assume pops in equil. in NFW halo: $$\rho(r) = \frac{\rho_s}{x(1+x)^2}$$

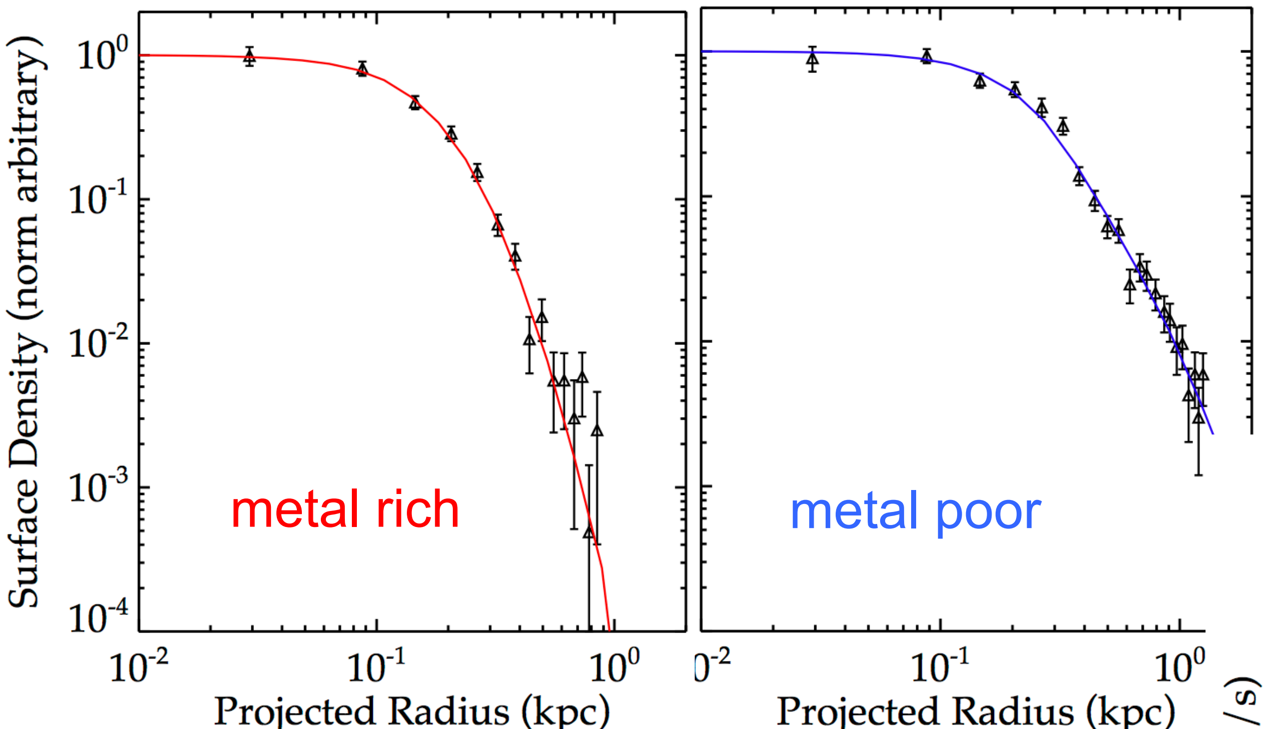
For each population: $$f(E,J) = g(J)h(E),$$

Parametrize: $$g(J) = \left[\left(\frac{J}{J_\beta}\right)^{\frac{b_0}{\alpha}} + \left(\frac{J}{J_\beta}\right)^{\frac{b_1}{\alpha}}\right]^{\alpha}$$

$$h(E) = \begin{cases} NE^a(E^q + E_c^q)^{d/q}(\Phi_{lim} - E)^e & \text{for } E < \Phi_{lim} \\ 0 & \text{for} E \geq \Phi_{lim}, \end{cases}$$

Find best-fit parameters using MCMC

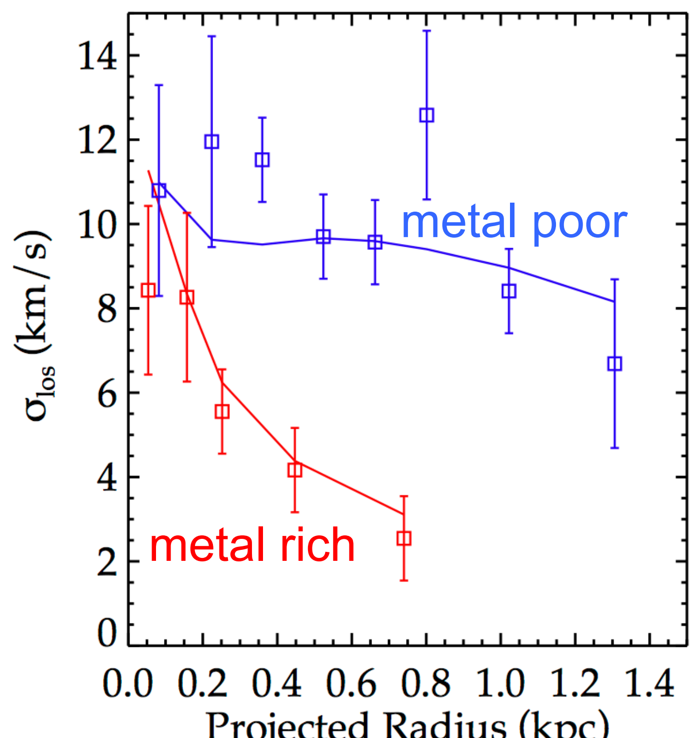
The DM halo of the Sculptor dwarf



Surface density

Distribution function analysis

Velocity dispersion

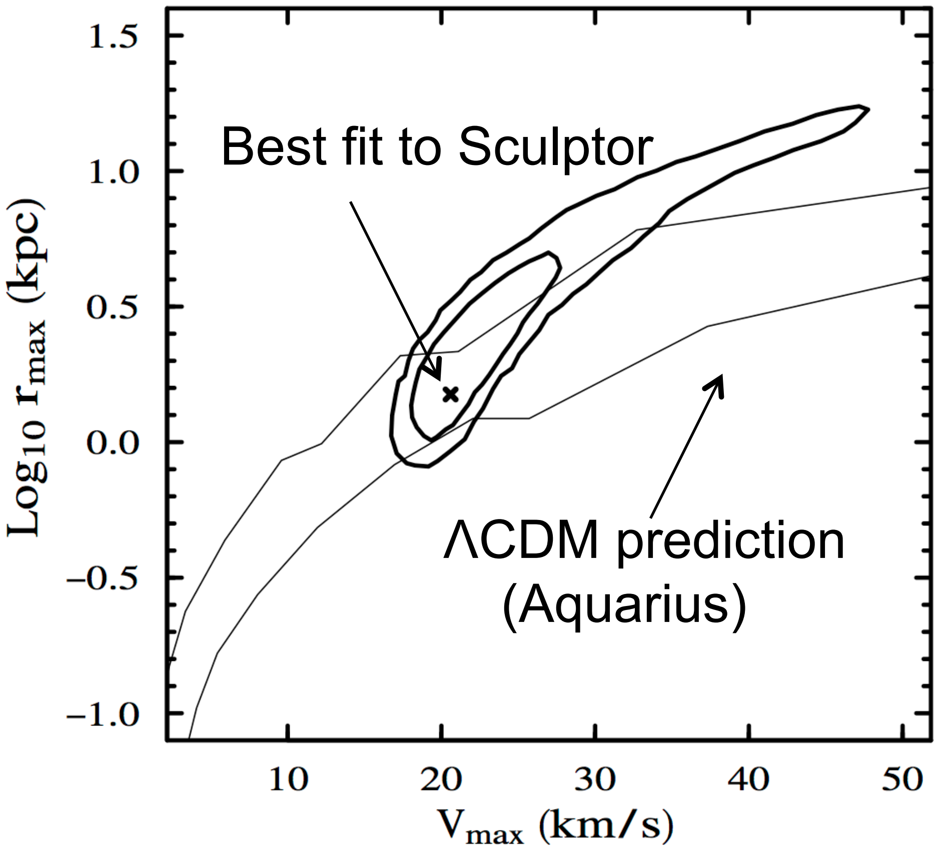


Data consistent with two populations in equilibrium in NFW halo

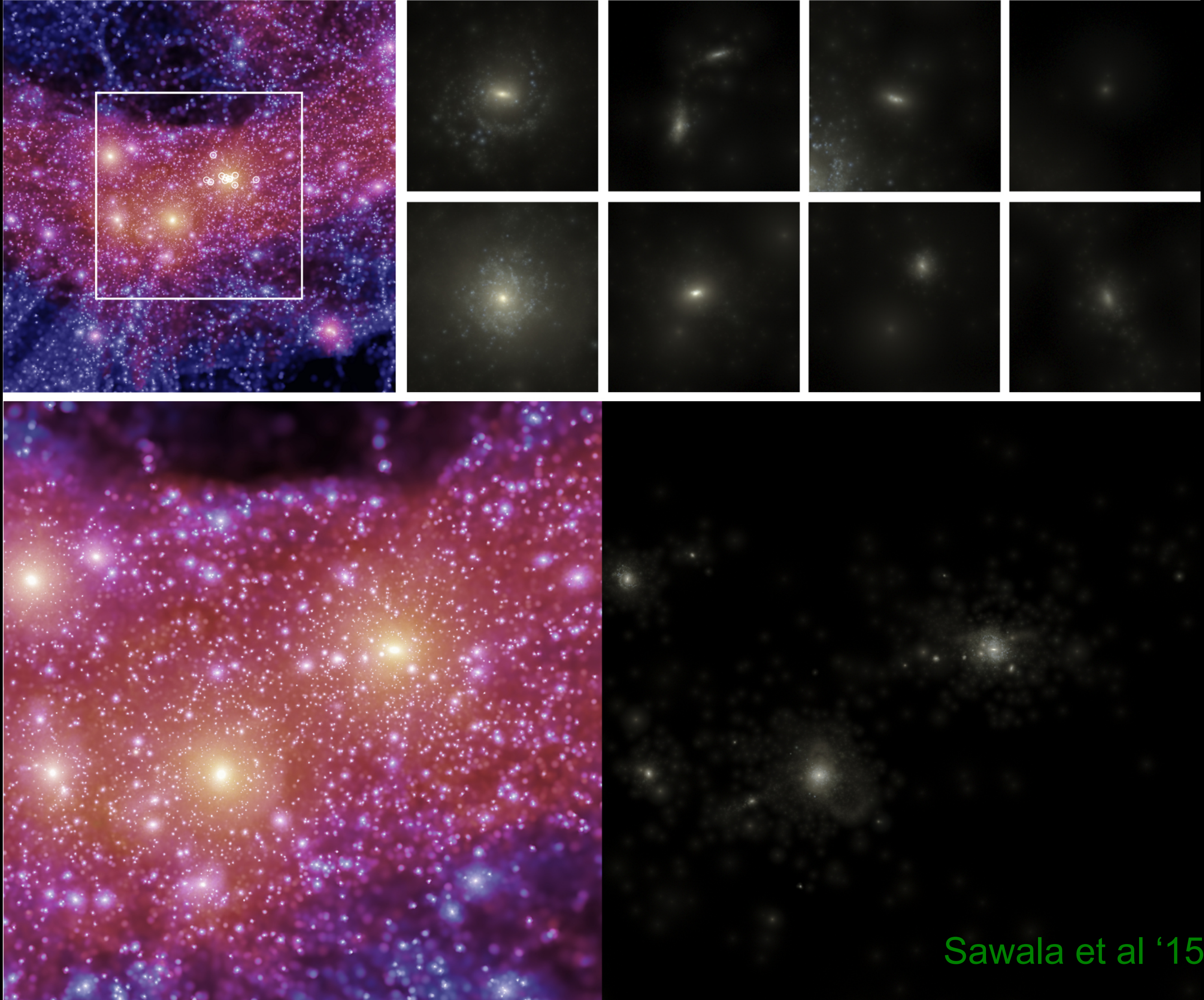
Strigari, Frenk & White '15

The DM halo of the Sculptor dwarf

NFW best-fit parameters as expected in ΛCDM



Strigari, Frenk & White '14



Sawala et al '15

Apostle: satellites w. 2-metalicity pops

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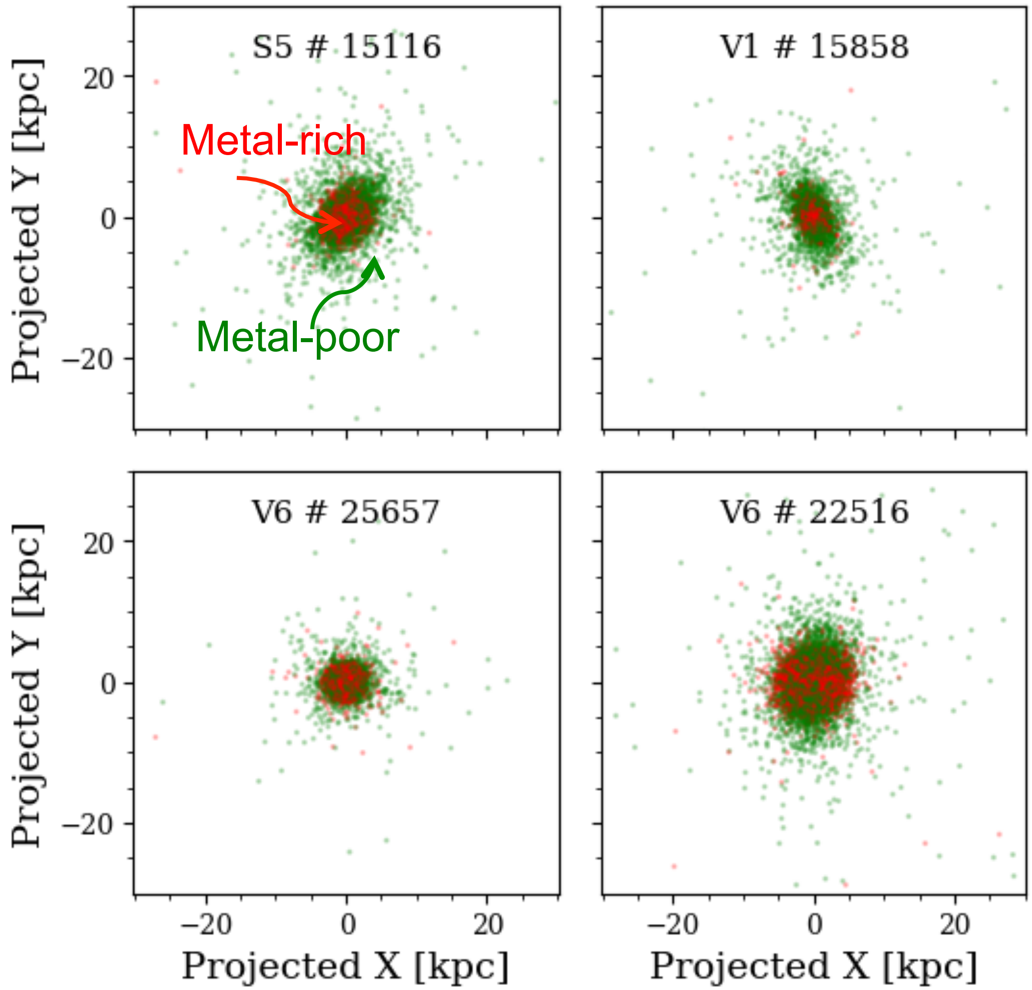
Two-metallicity, kinematically distinct populations form in some Apostle dwarfs

The stellar populations are not spherical and the shapes of the two can be different



Genina, Benitez-Llambay CSF + '17

The DM halo of the Sculptor dwarf

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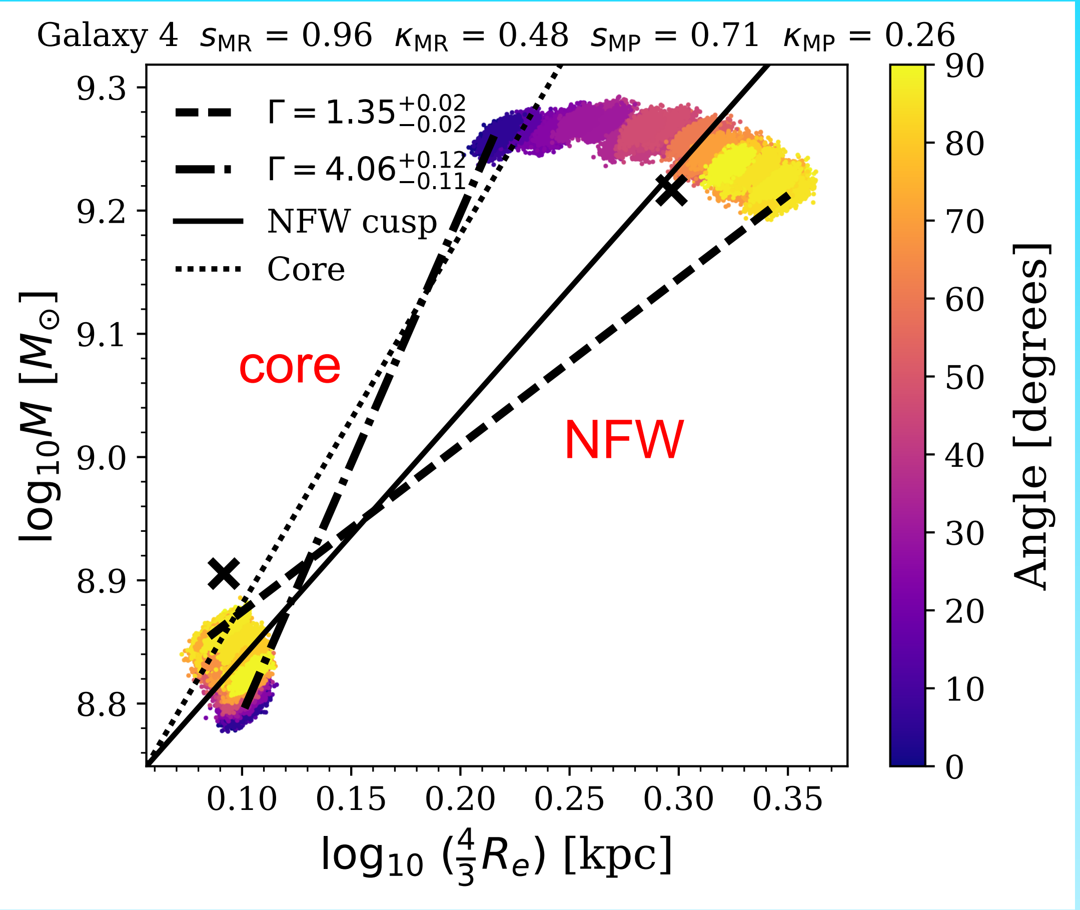
$$M(<r) = \mu \frac{r < \sigma_{los}^{2} >}{G}$$

Key assumption of mass estimator:

spherical symmetry

Most satellites in apostle are elongated!

View galaxy from different directions



You can infer any slope, from NFW to core depending on viewing angle!

Genina, Benitez-Llambay, CSF + ‘17

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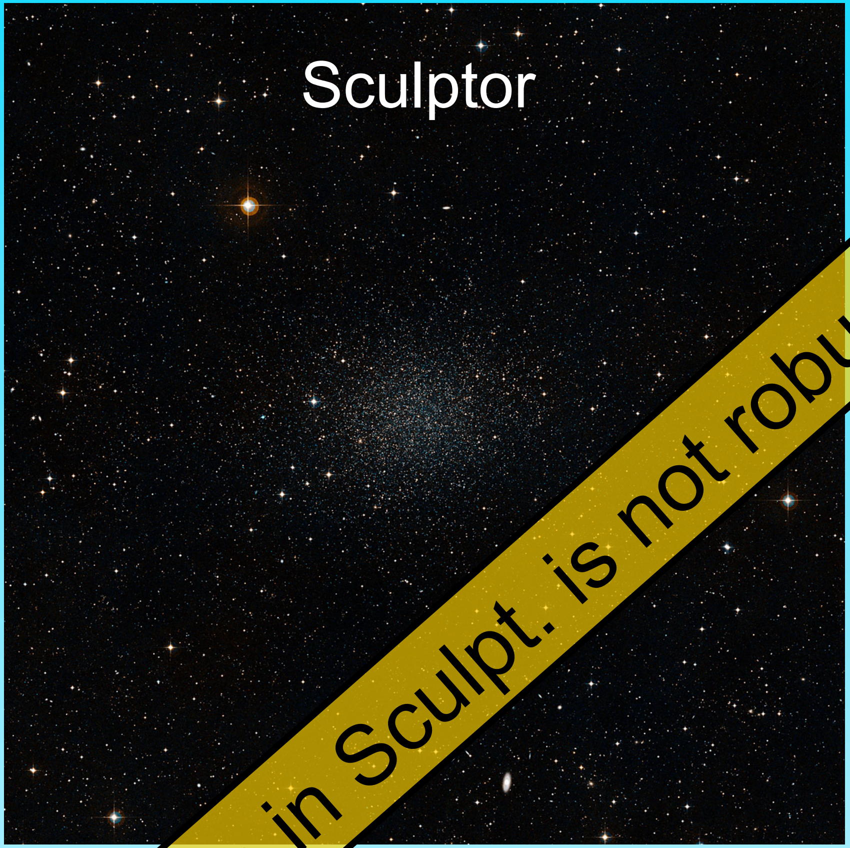
The DM halo of the Sculptor dwarf

$$M(<r) = \mu \frac{r < \sigma_{los}^{2} >}{G}$$



Key assumption of mass estimator:

spherical symmetry

Is Sculptor spherical?

WP11 core in Sculpt. is not robust

Genina, CSF et al '17

Many nearby galaxies now have hi-res 2D HI velocity fields → ideal for infering potential

Assume: gas is in centrifugal equilibrium on approximately circular orbits

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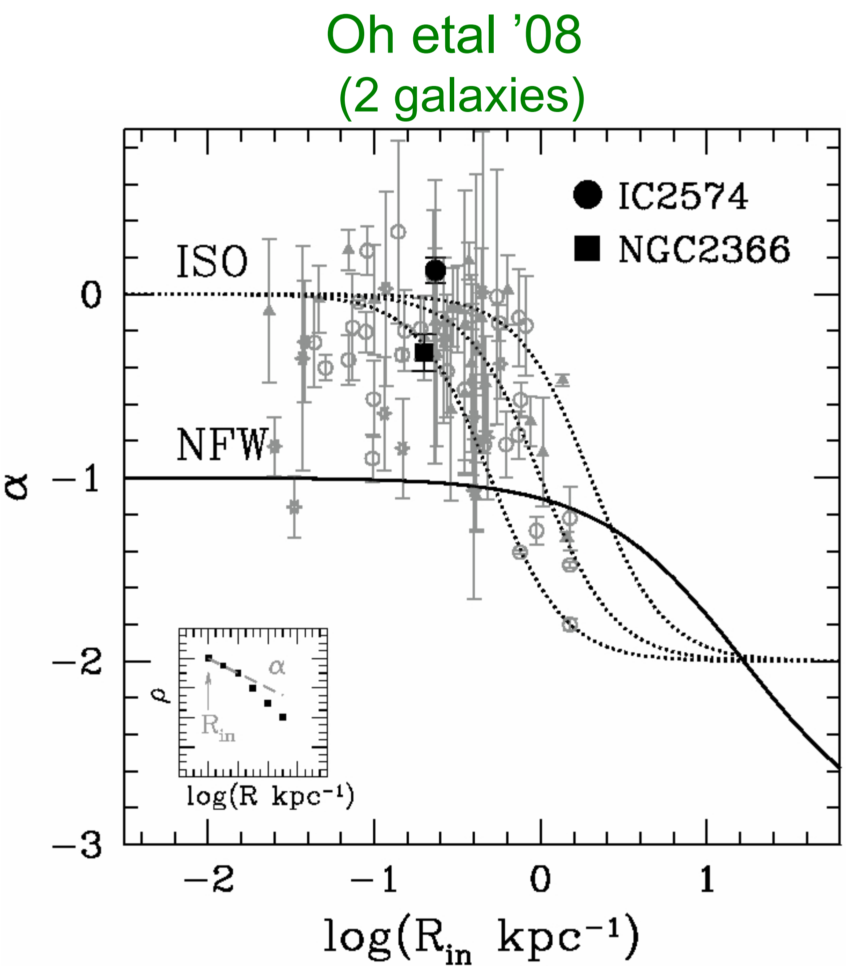
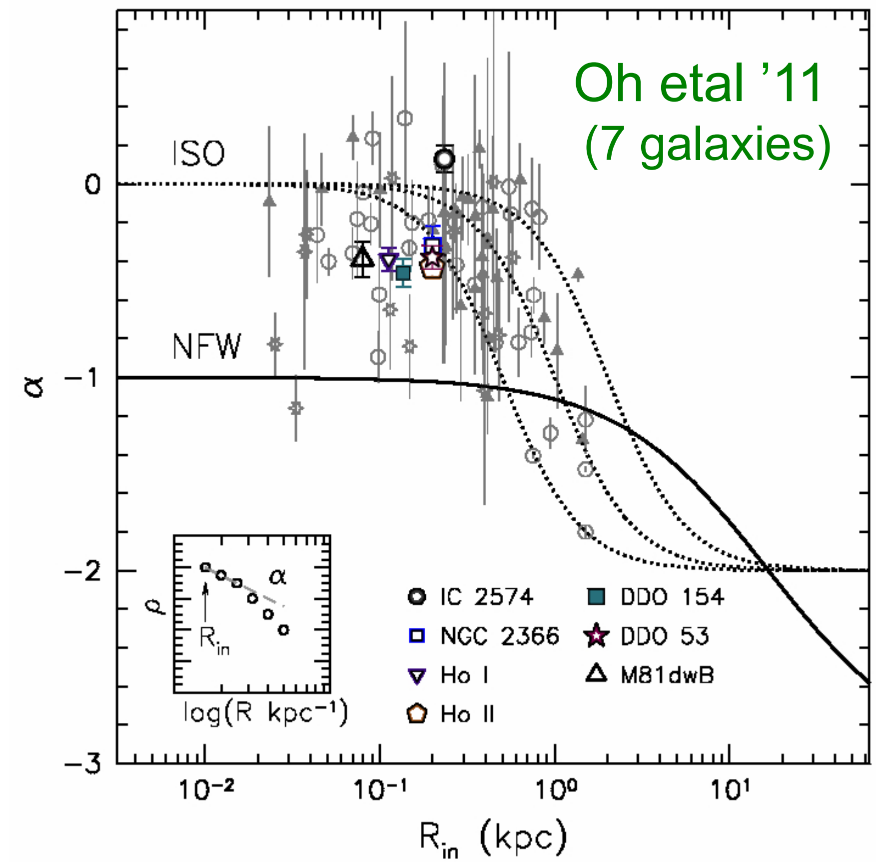
THINGS HI rotn curves of dwarfs





$$\rho(r) \propto r^{\alpha}(1 + r/r_s)^{\beta}$$

"We find discrepancies between the derived dark matter distributions … and those of CDM simulations, even after corrections for non-circular motions ..."

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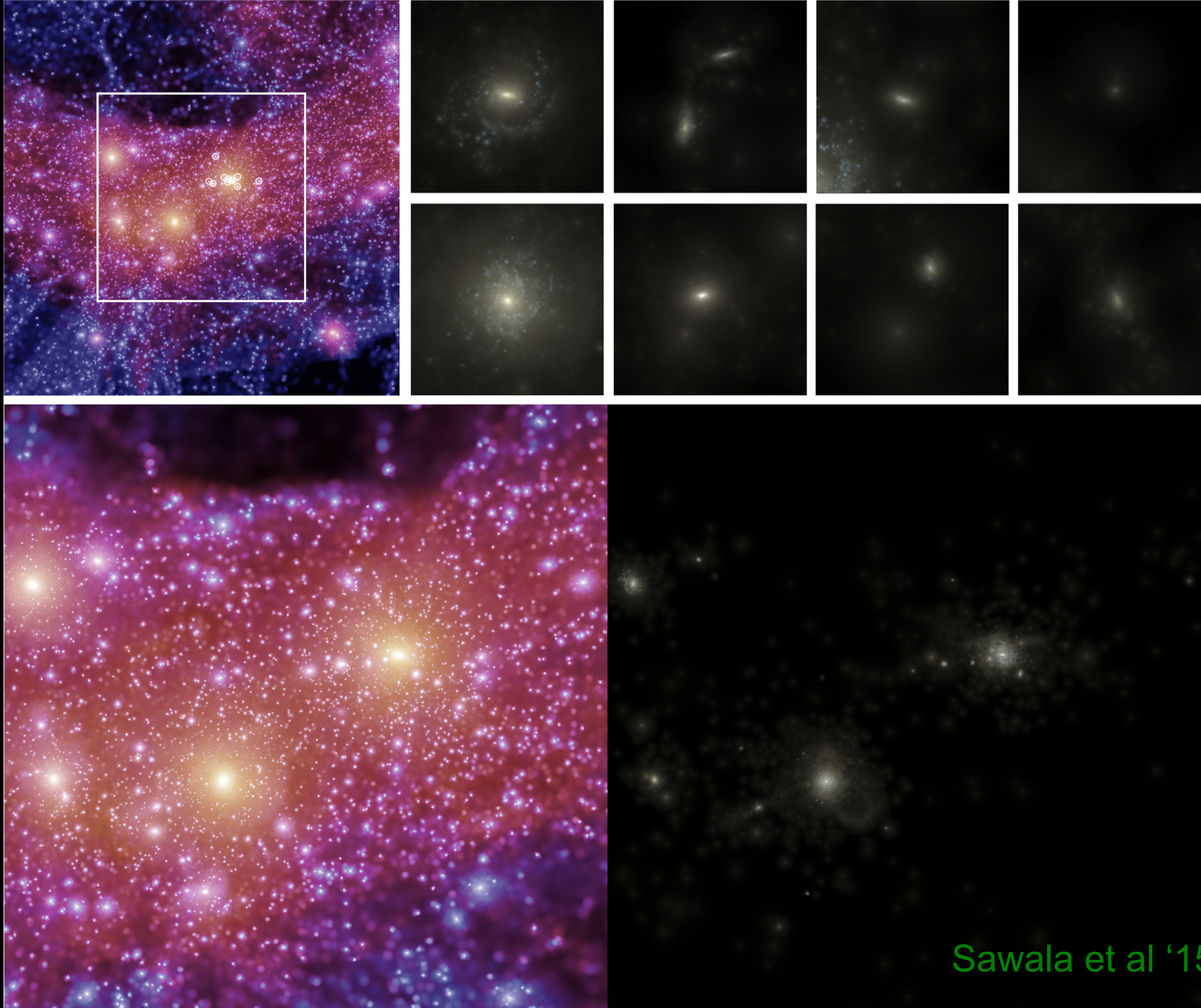
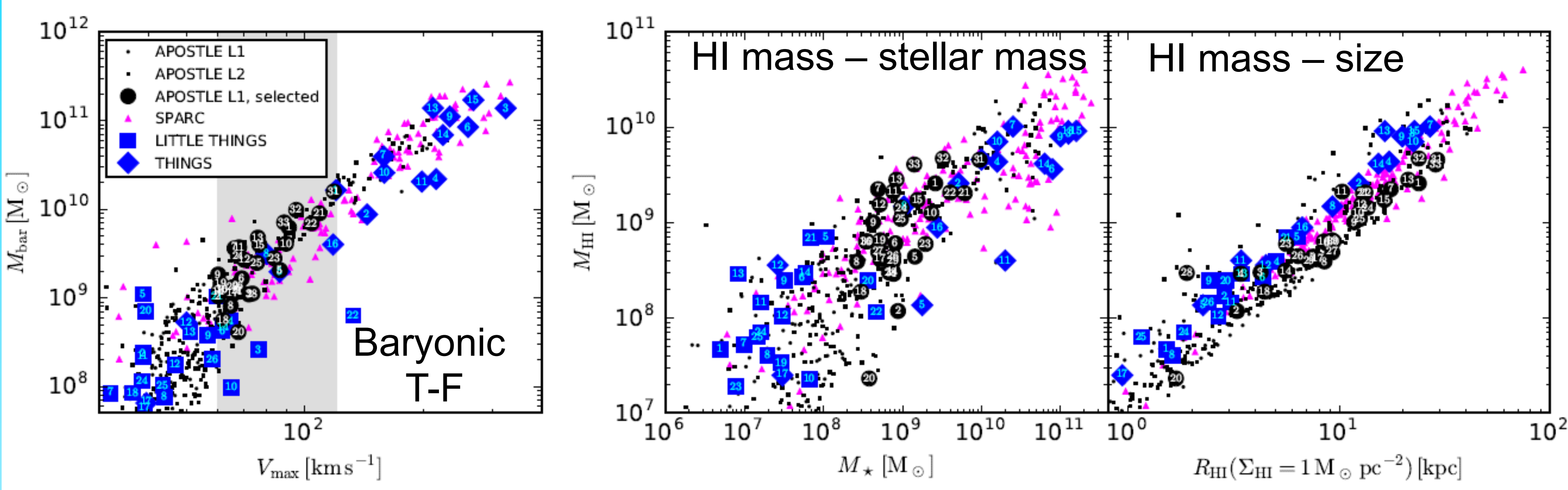


Sawala et al ‘15

University of Durham

HI properties of APOSTLE dwarfs

60 km/s $< V_{max} <$ 120 km/s



Scaling relations between baryon mass, halo mass, stellar mass, HI mass and HI size in APOSTLE match those in the THINGS and Little THINGS surveys

Oman, Marasco, Navarro, CSF, Schaye, Benitez-Llambay '17

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Analysis of 2D velocity fields

University of Durham

2D velocity field → V_c (r) (rotn curve); in dynamical equilibrium: $V_c = \sqrt{\frac{GM(<r)}{r}}$

Tilted-ring model corrected for asymmetric drift

- ^{3D}BAROLO fit

University of Durham

Analysis of 2D velocity fields

2D velocity field → V_c (r) (rotn curve); in dynamical equilibrium: $V_c = \sqrt{\frac{GM(<r)}{r}}$

Tilted-ring model corrected for asymmetric drift

^{3D}BAROLO fit

Let's apply this to APOSTLE galaxies by making a mock 2D velocity field data cube and analysing it just as the real data

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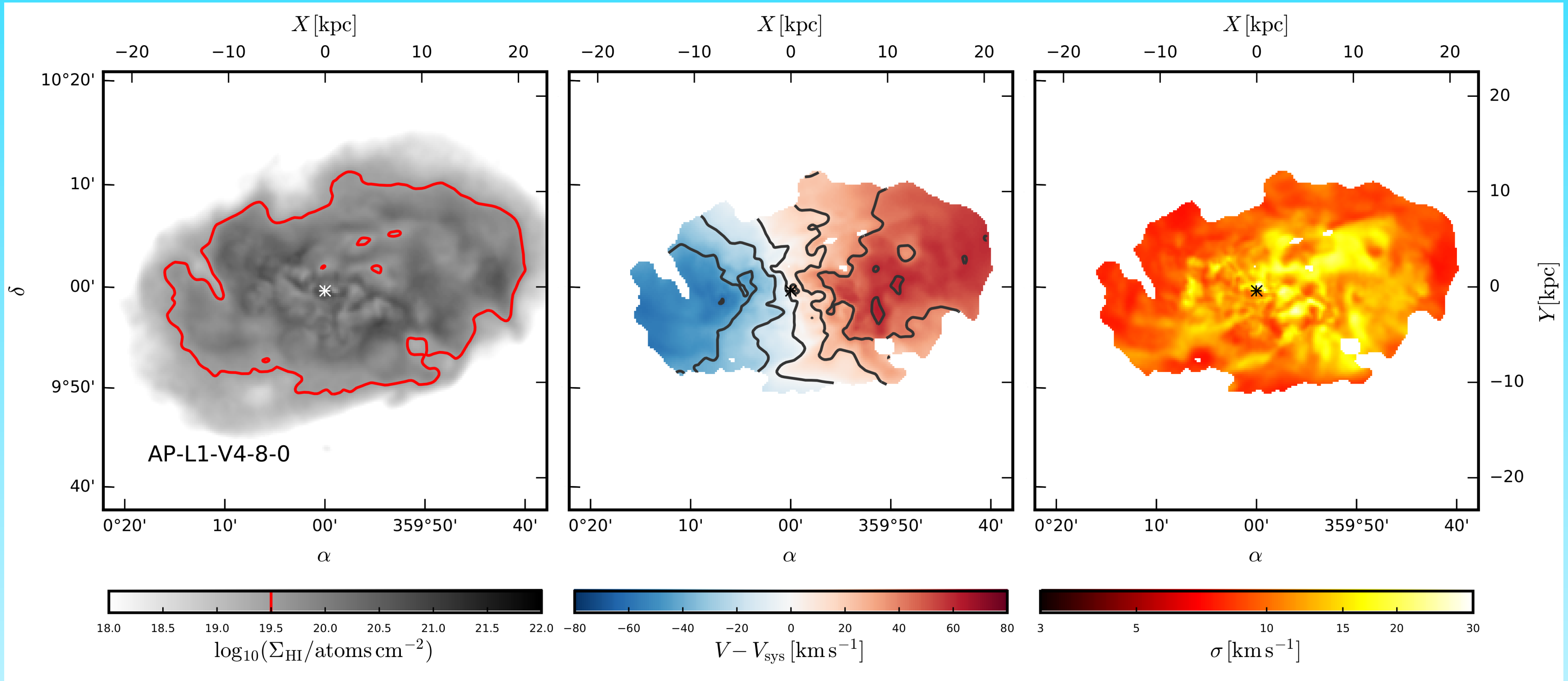
Synthetic HI observations of curves of an APOSTLE dwarf

HI surface density | Mean velocity | Velocity dispersion



Oman+ '17

Institute for Computational Cosmology

University of Durham

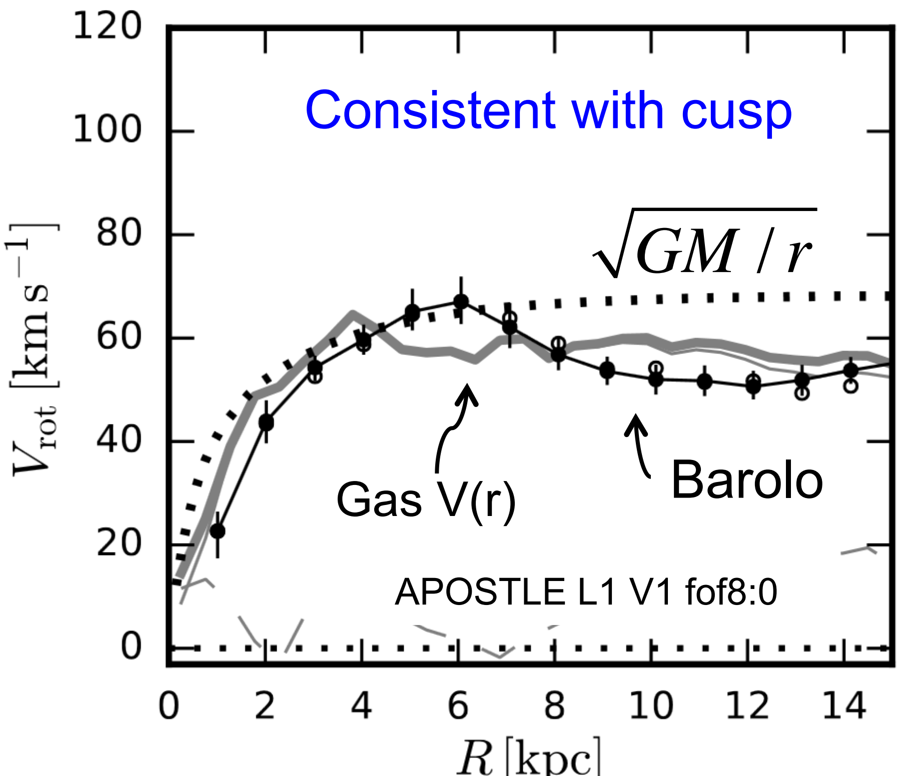
Rotation curves of 2 APOSTLE dwarfs

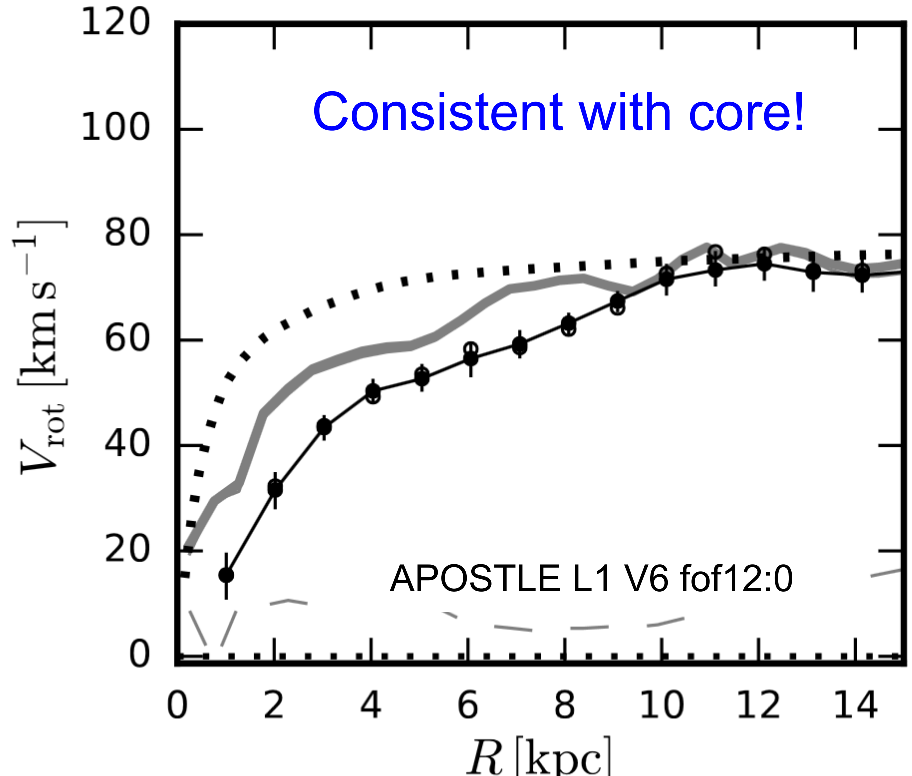
APOSTLE galaxies all have NFW cusps

2D velocity field → V_c (r) (rotn curve); in dynamical equilibrium: $V_c = \sqrt{\frac{GM(<r)}{r}}$

Tilted-ring model corrected for asymmetric drift

● ^{3D}BAROLO fit



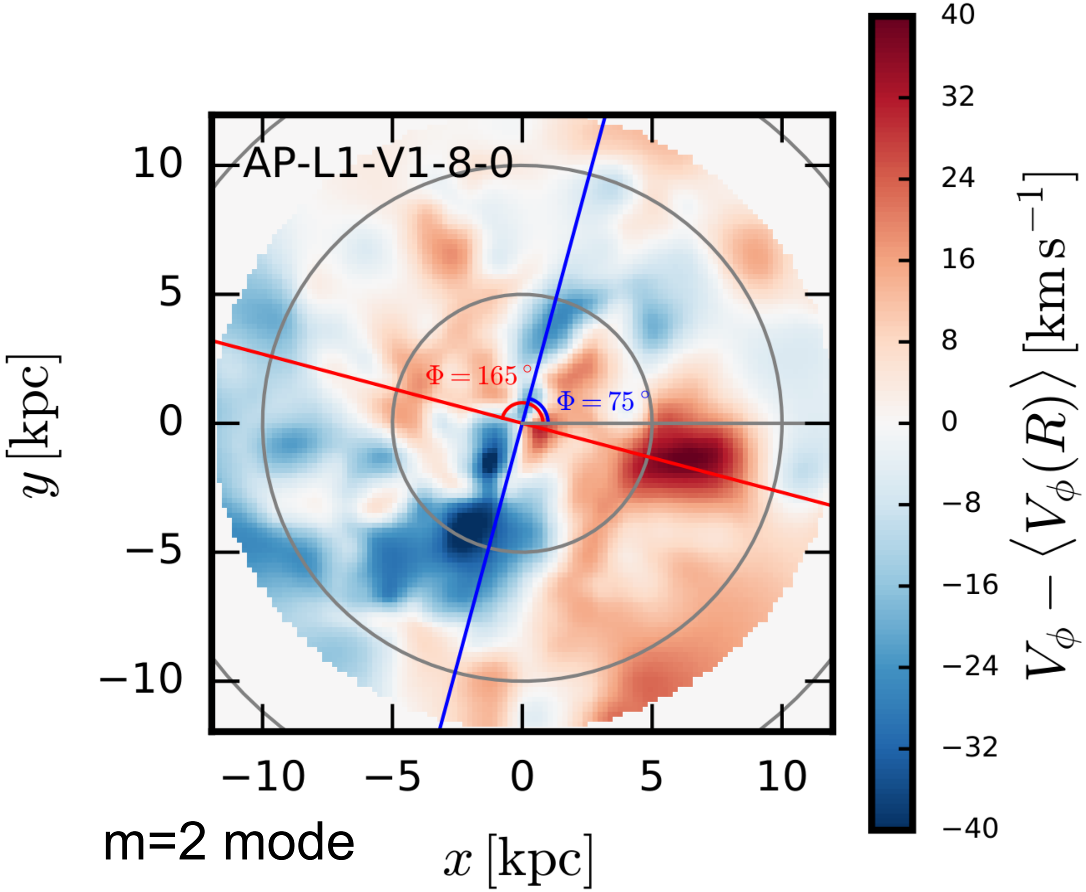


Oman et al '17; Marasco et al '17

University of Durham

Non-circular motions

Residual azimuthal velocities (after subtracting mean v(r))

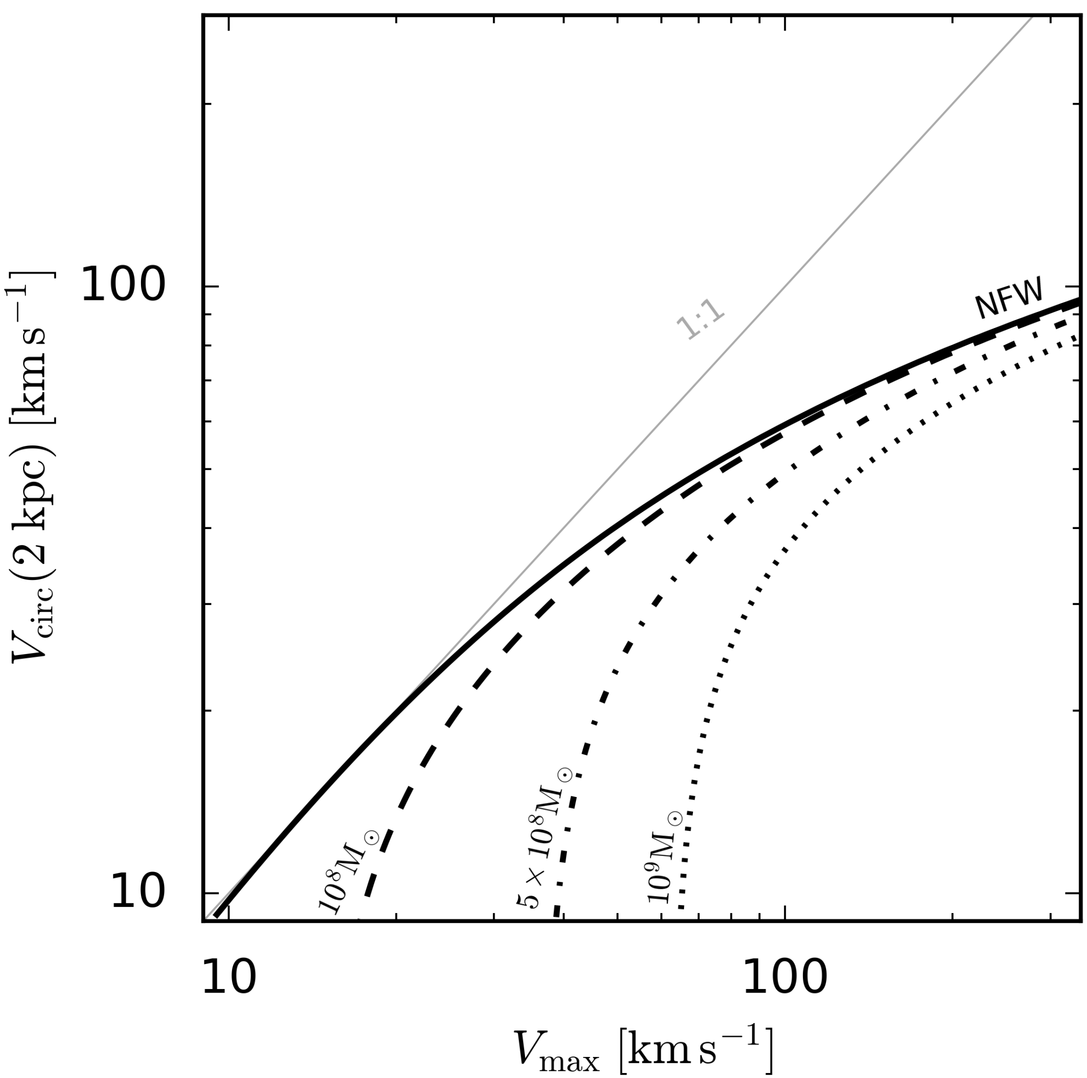


m=2 mode

Synthetic data cubes from simulated galaxies , analyzed as the data (with ^{3D}Barolo tilted ring code) often imply cores … where there are cusps

Oman+ '17

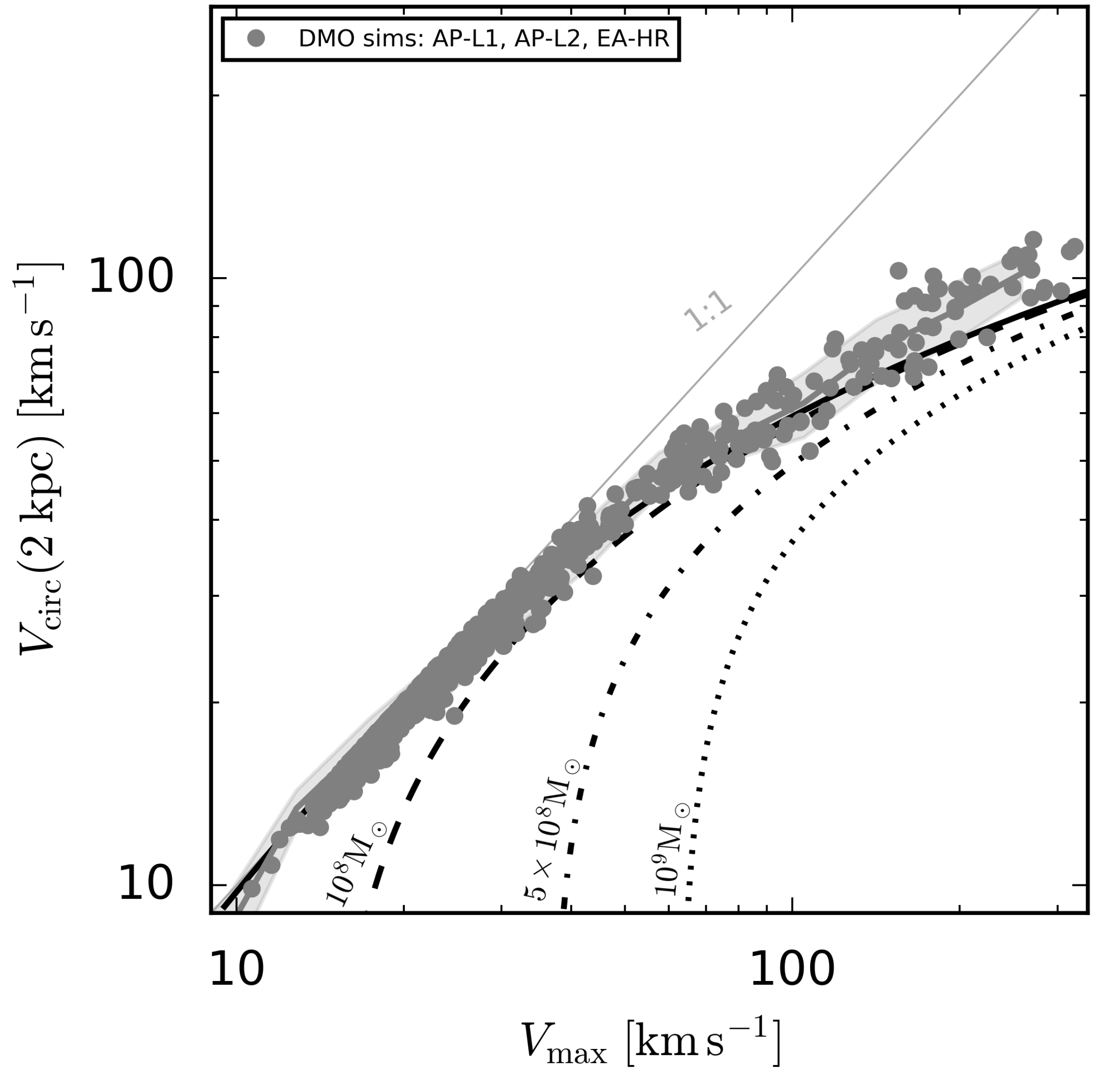
The diversity of rotation curves



Oman+ '17

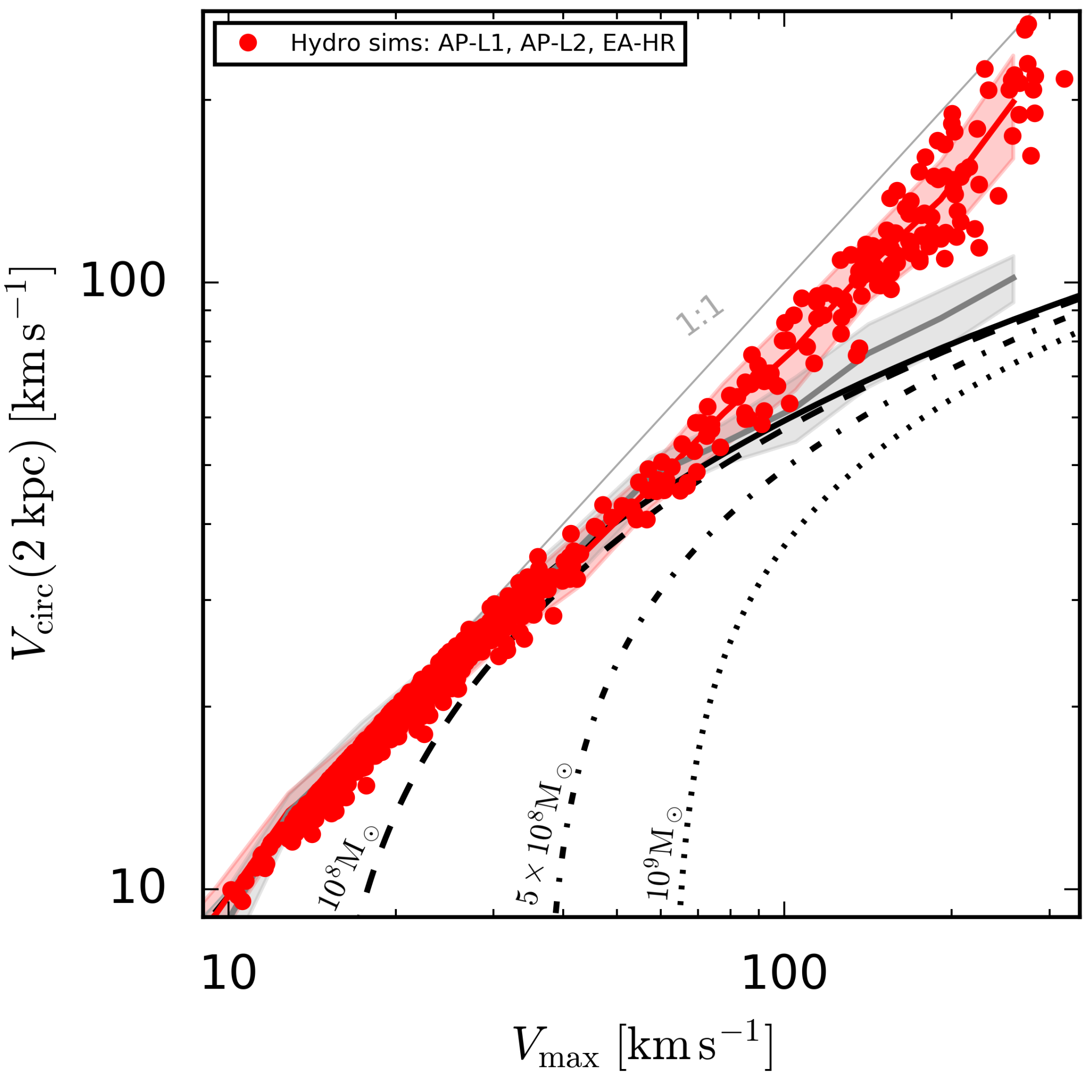
The diversity of rotation curves

University of Durham



Oman+ '17

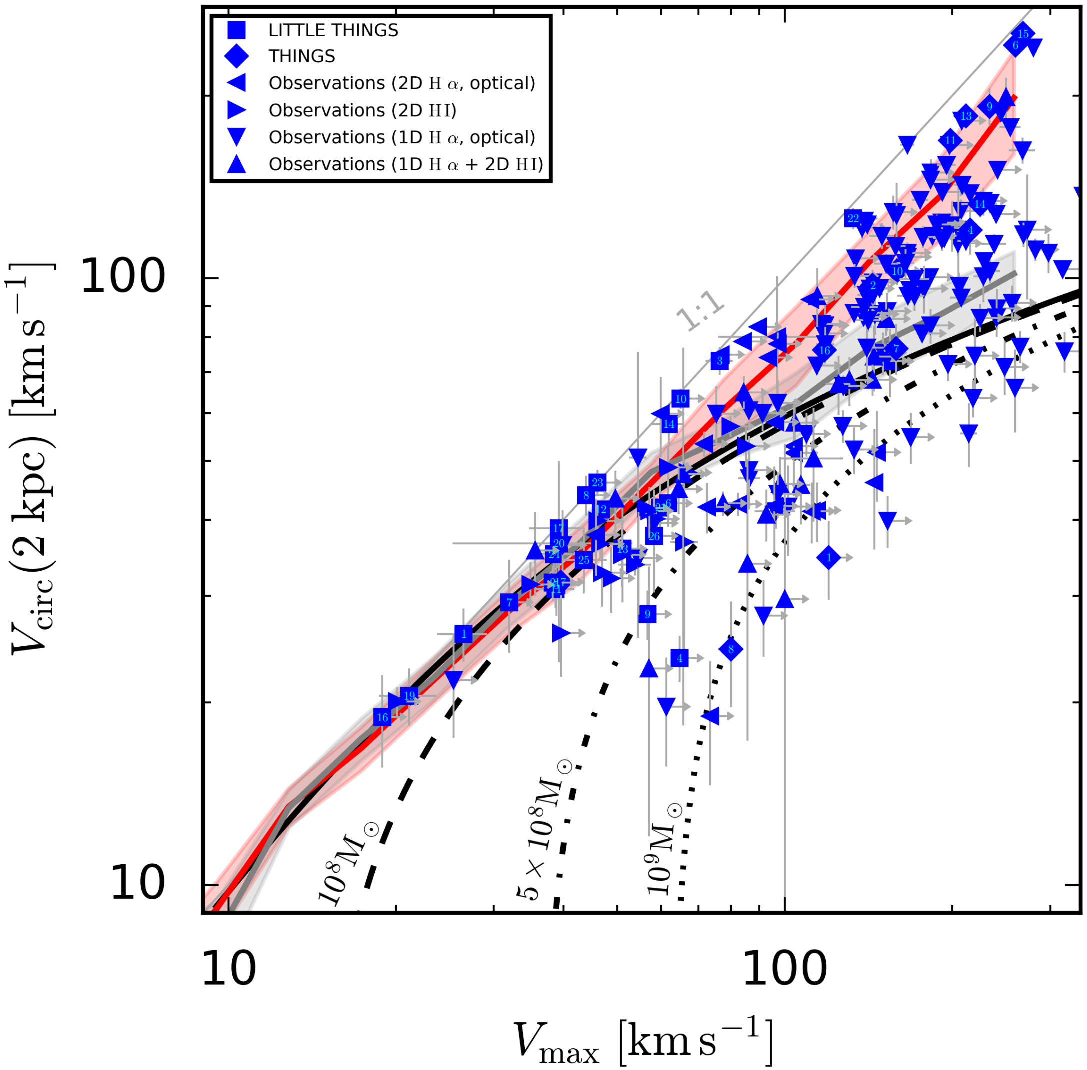
The diversity of rotation curves



Oman+ '17

University of Durham

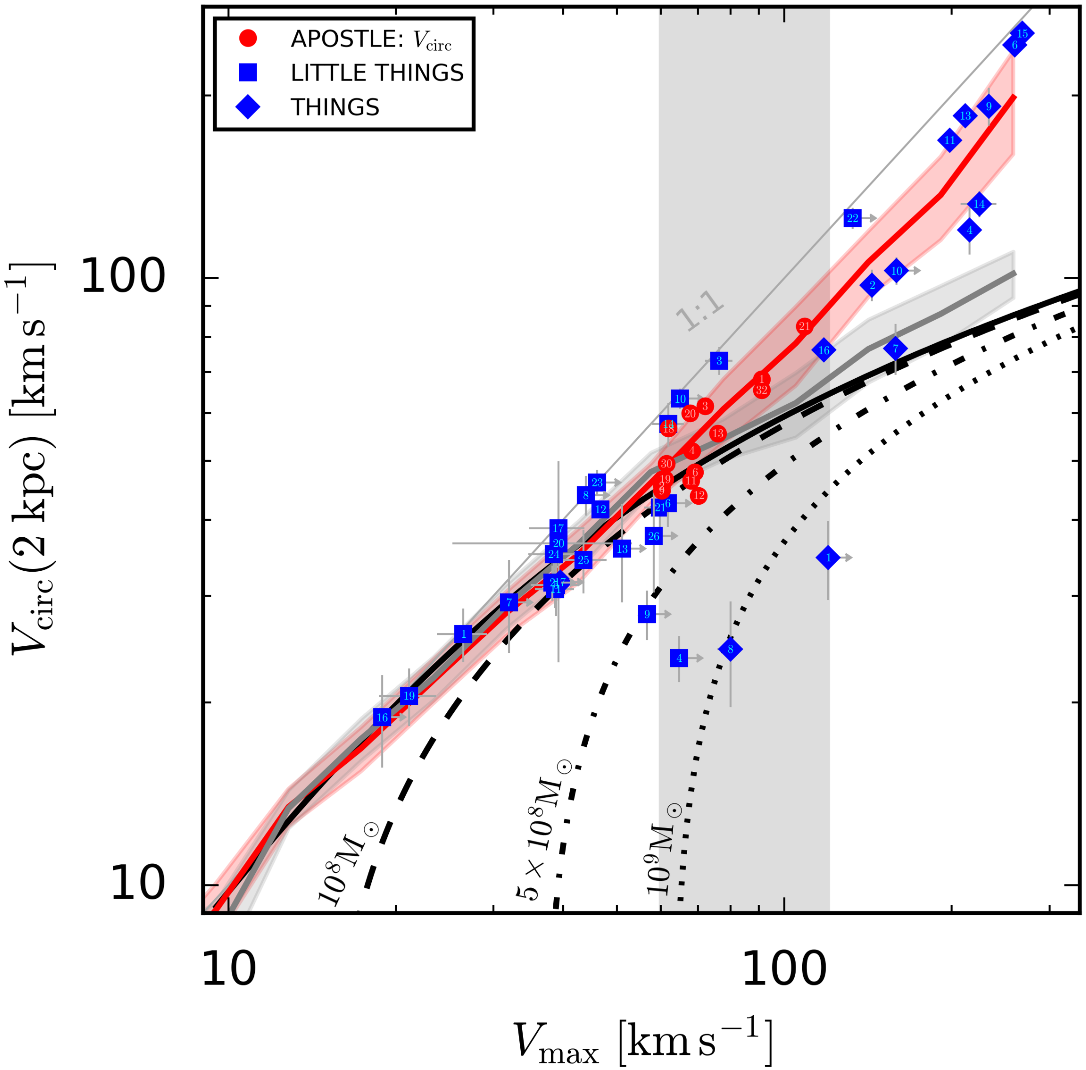
The diversity of rotation curves



Oman+ '17

Institute for Computational Cosmology

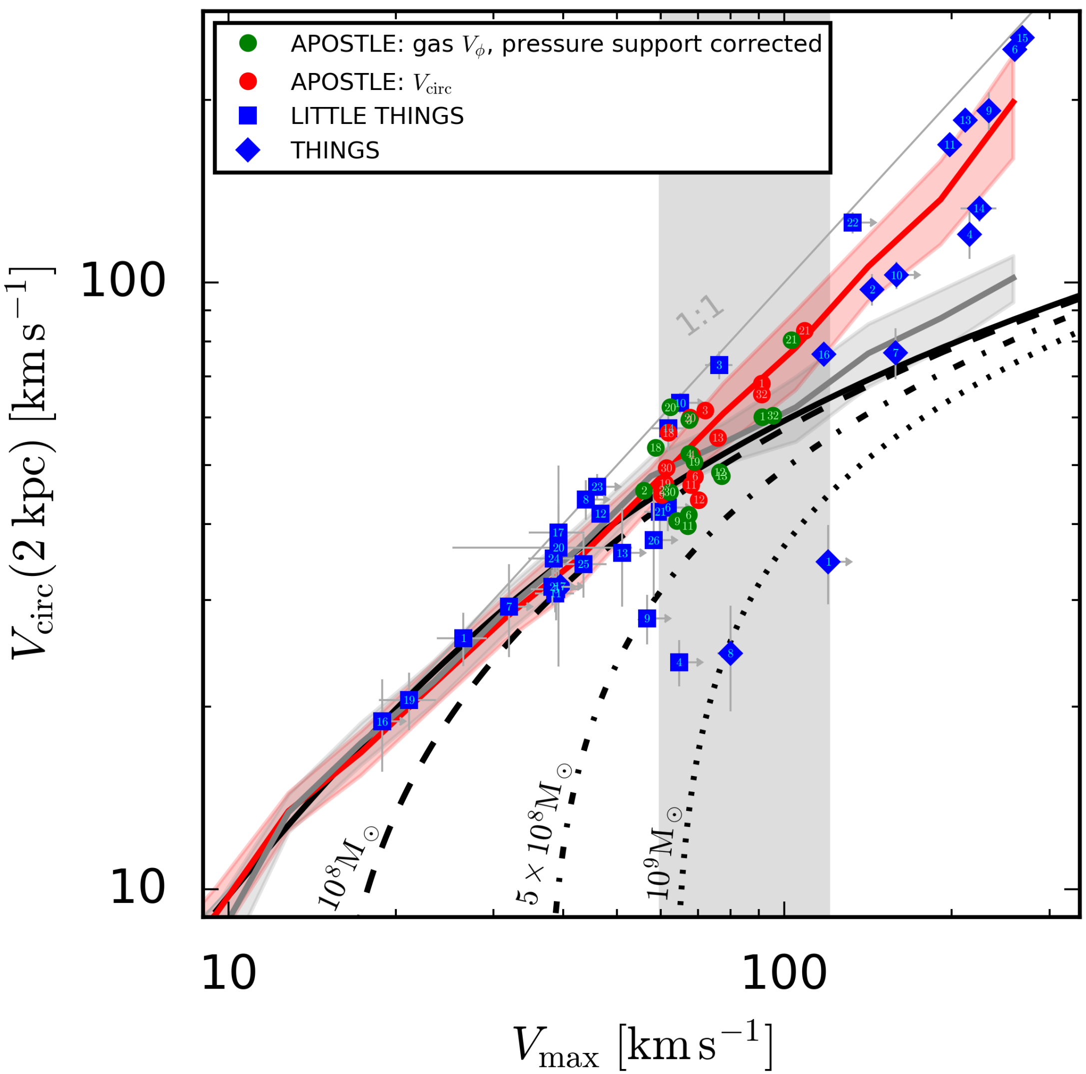
The diversity of rotation curves



Oman+ '17

University of Durham

The diversity of rotation curves

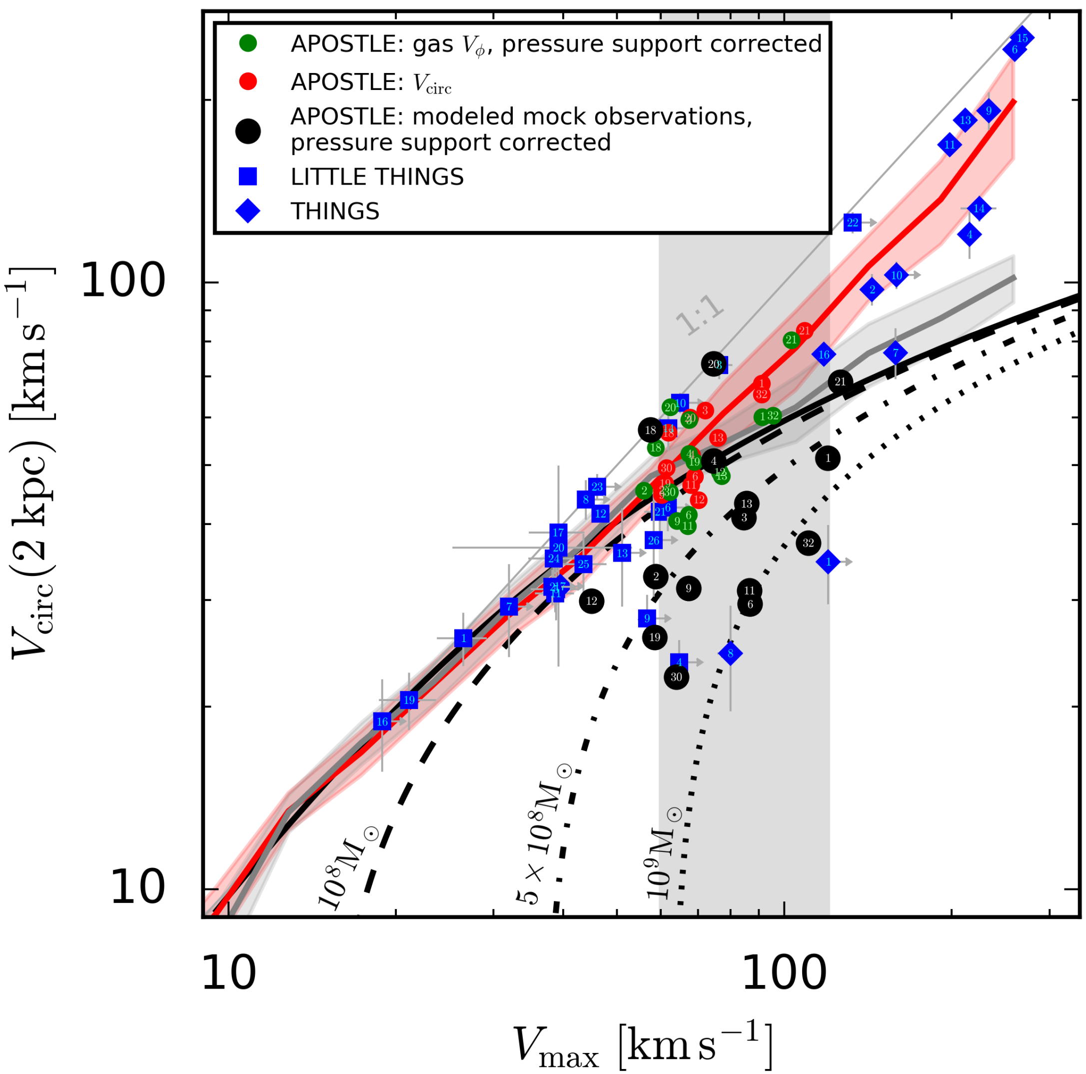


Oman+ '17

Institute for Computational Cosmology

The diversity of rotation curves

University of Durham



Oman+ ‘17

Institute for Computational Cosmology

Dark matter halos: cores or cusps?

Two myths

- The DM halos of dwarf galaxies have central cores
- Hydro simulations of dwarfs produce cores if they have bursty star formation

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Dark matter halos: cores or cusps?

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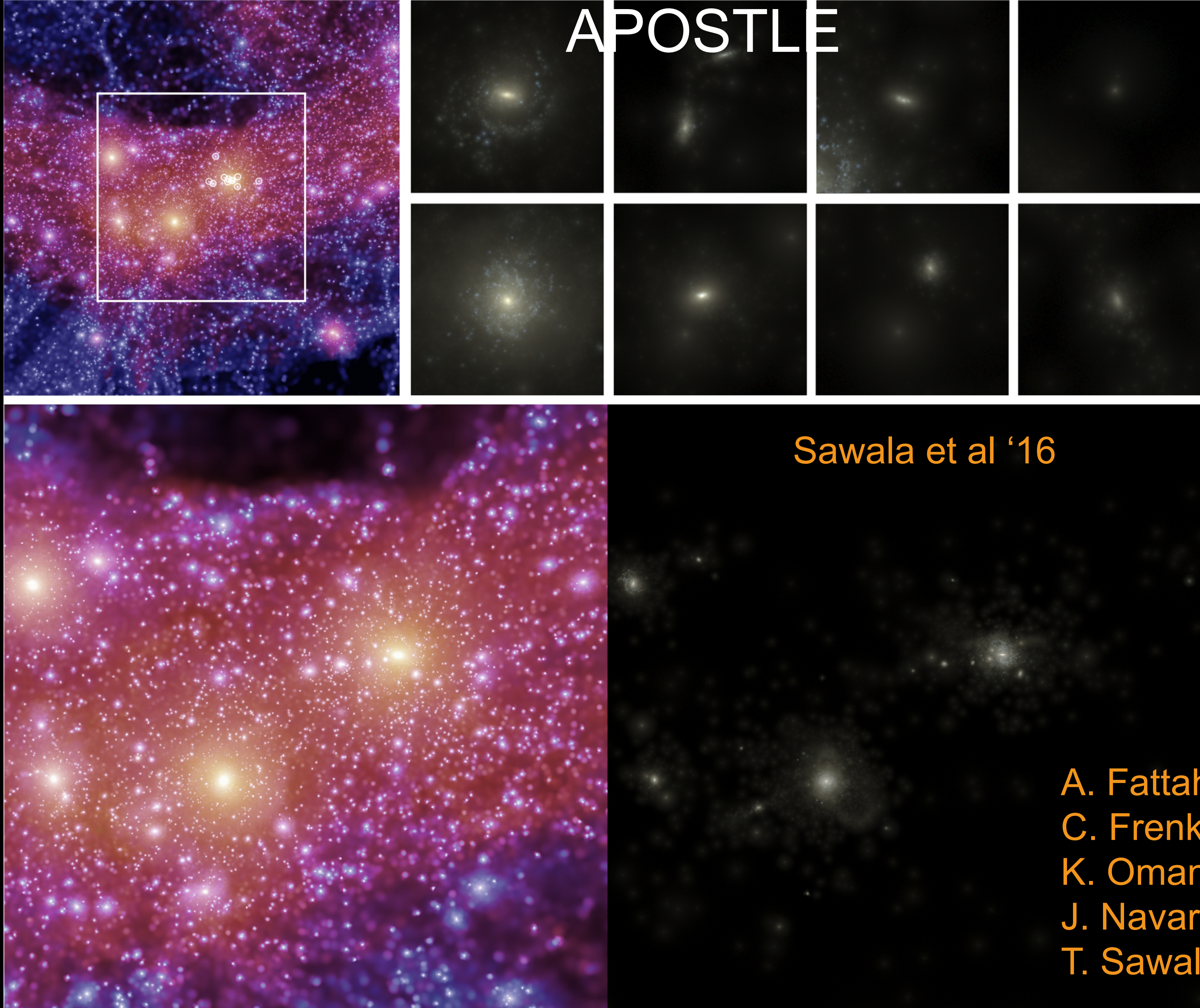
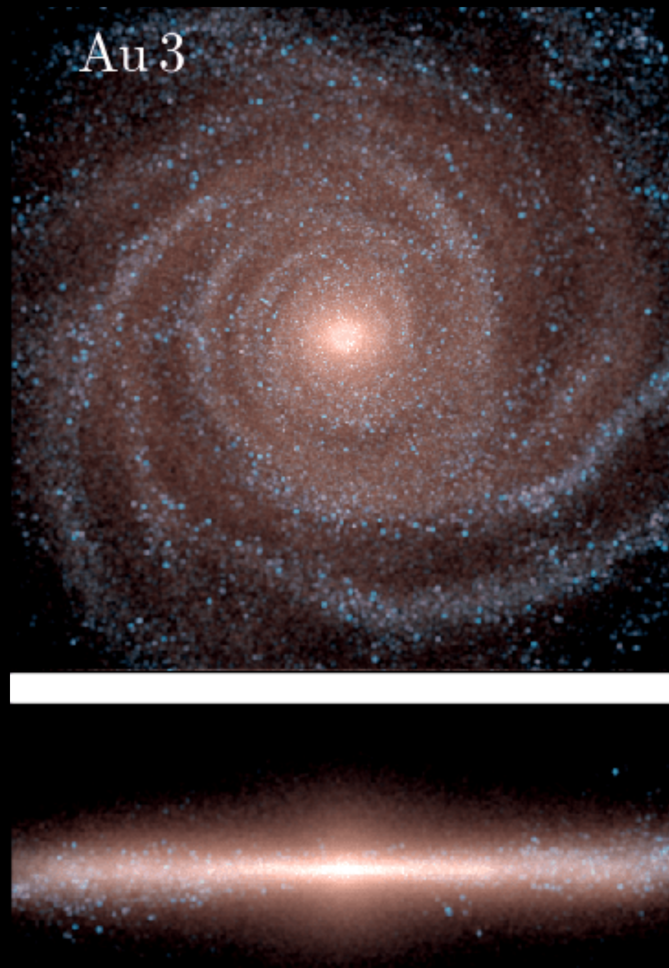

APOSTLE
Sawala et al '16
A. Fattahi
C. Frenk
K. Oman
J. Navarro
T. Sawala

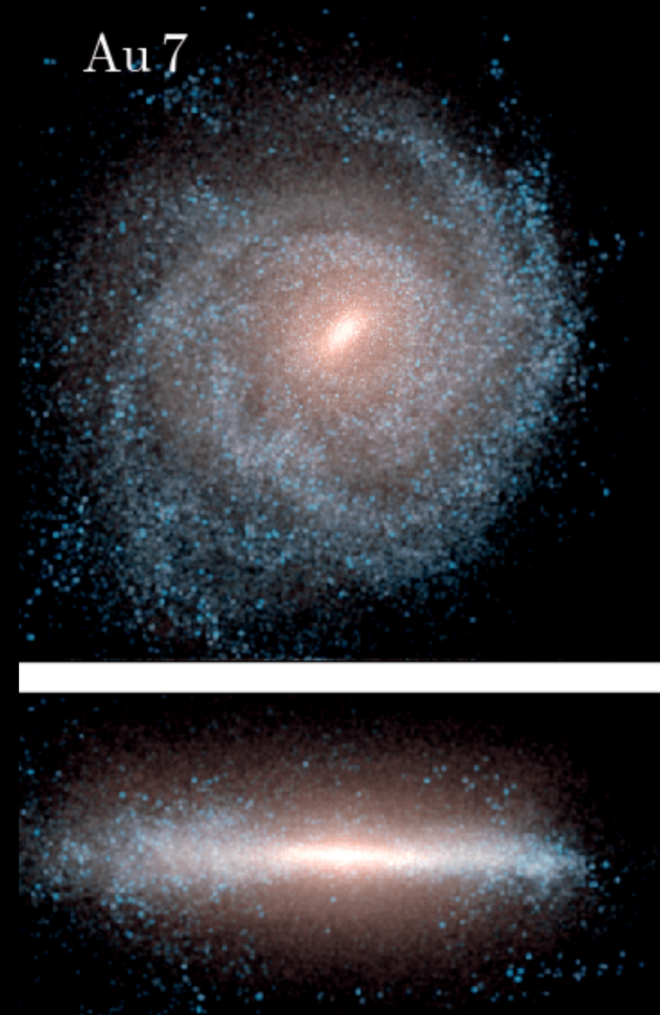
The Auriga MW-like galaxies

Grand et al ‘16

30 very high res Arepo sims

6 even higher res sims

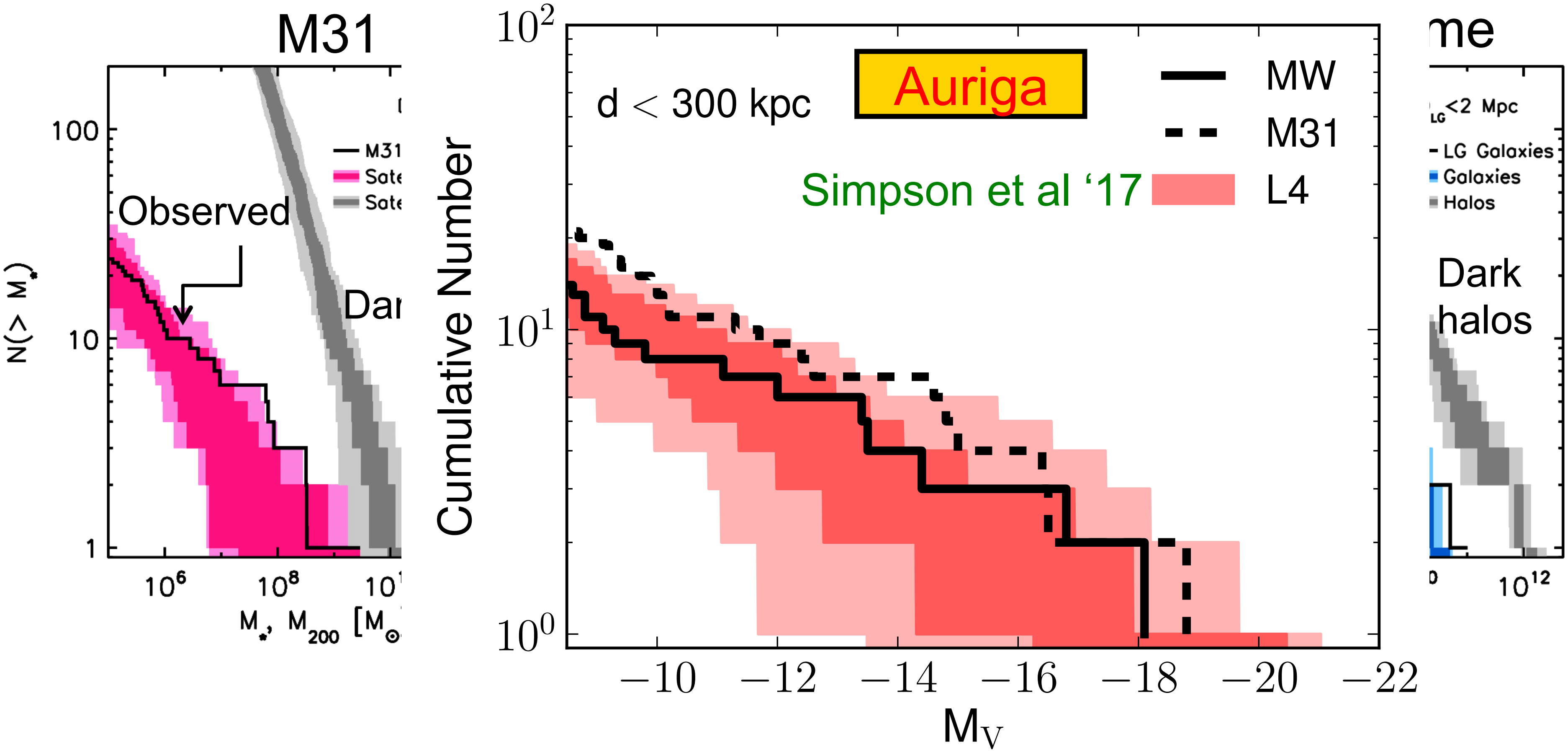




D. Campbell
C. Frenk
F. Gomez
R. Grand
A. Jenkins
F. Marinacci
R. Pakmor
V. Springel
S. White

APOSTLE Local Group simulation

University of Durham



Sawala, CSF et al '16

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Apostle and Auriga dwarfs

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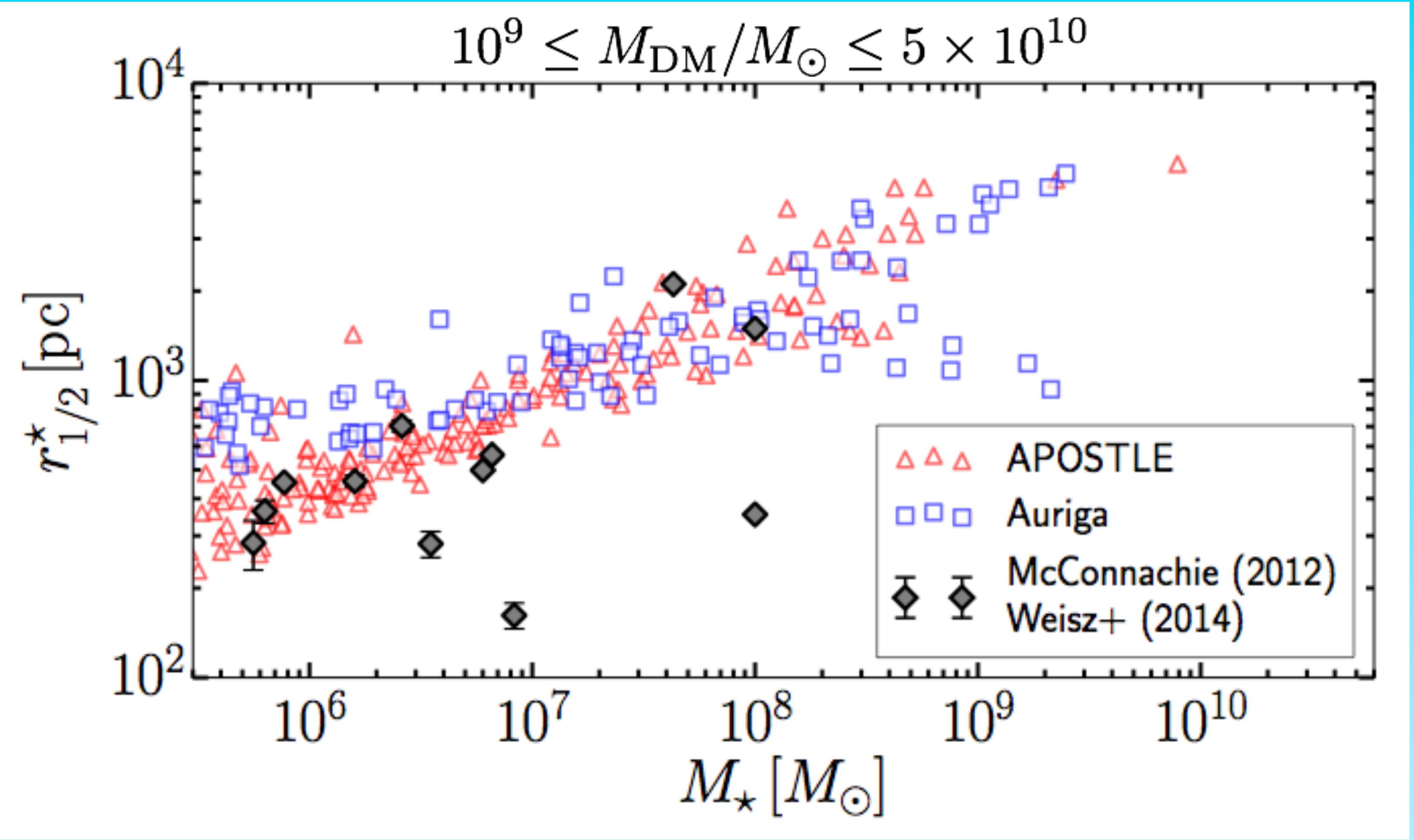
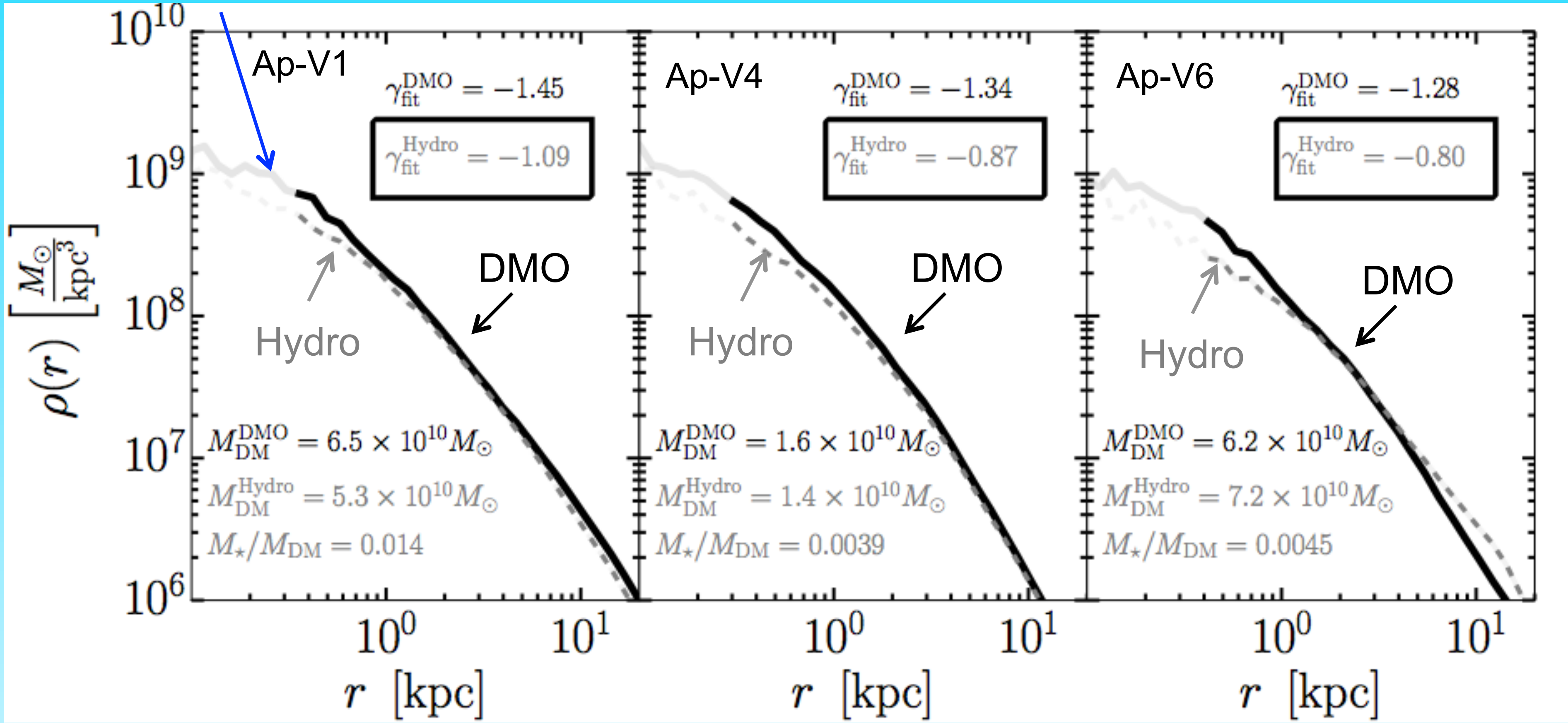


Size – stellar mass relation for (isolated) dwarfs in APOSTLE & Auriga roughly consistent with observed Local Group dwarfs

Dark matter density profiles of Apostle dwarfs - cusps

converged above ~ 400 pc

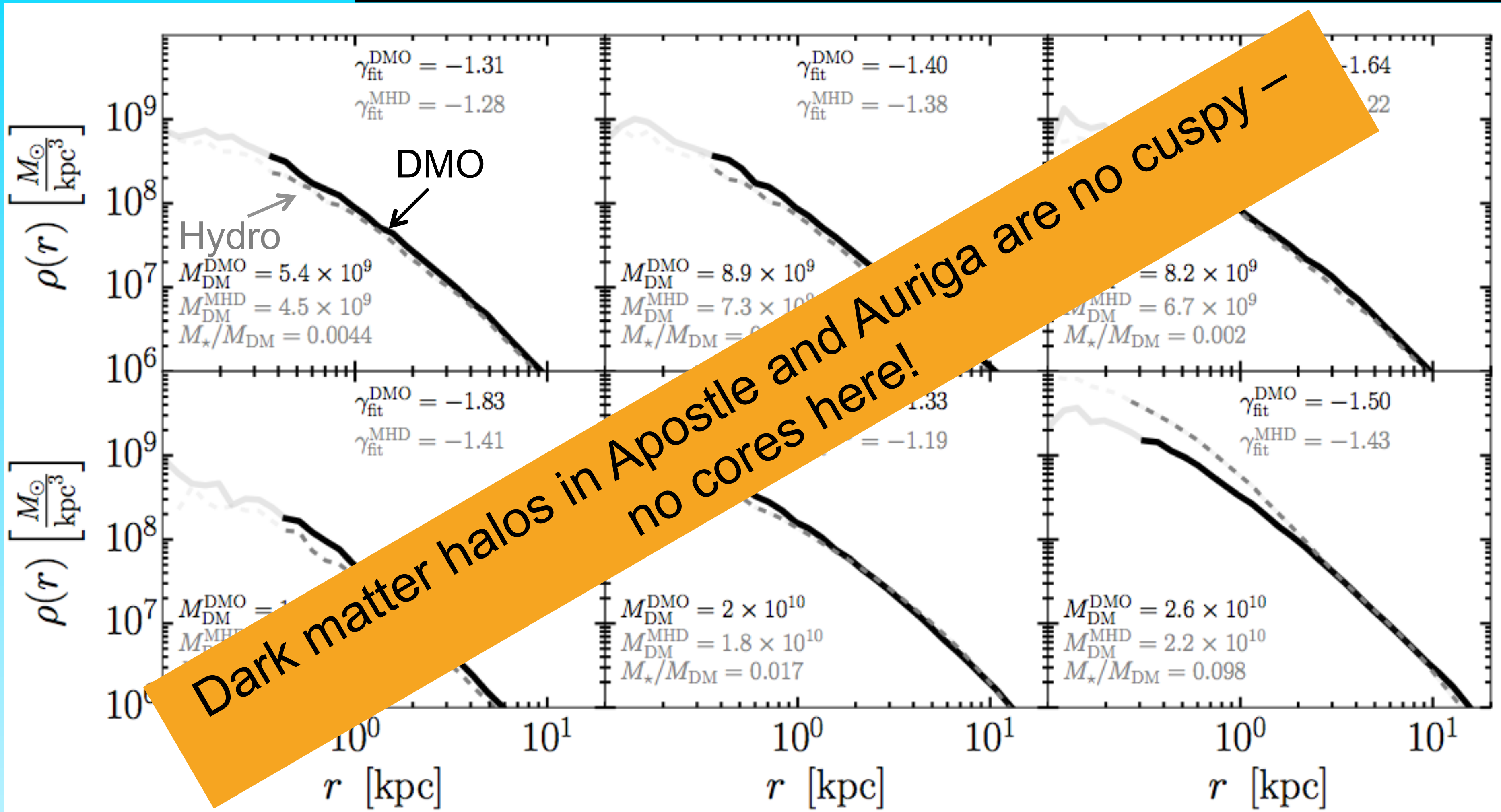
Shallowest profiles



Bose, CSF et al ‘18

University of Durham

Dark matter density profiles of Auriga dwarfs - cusps



Shallowest inner asymptotic slope of the DM density profile in either Auriga or APOSTLE is ~ -0.80. → No evidence for cores

Star formation rates of Apostle and Auriga dwarfs

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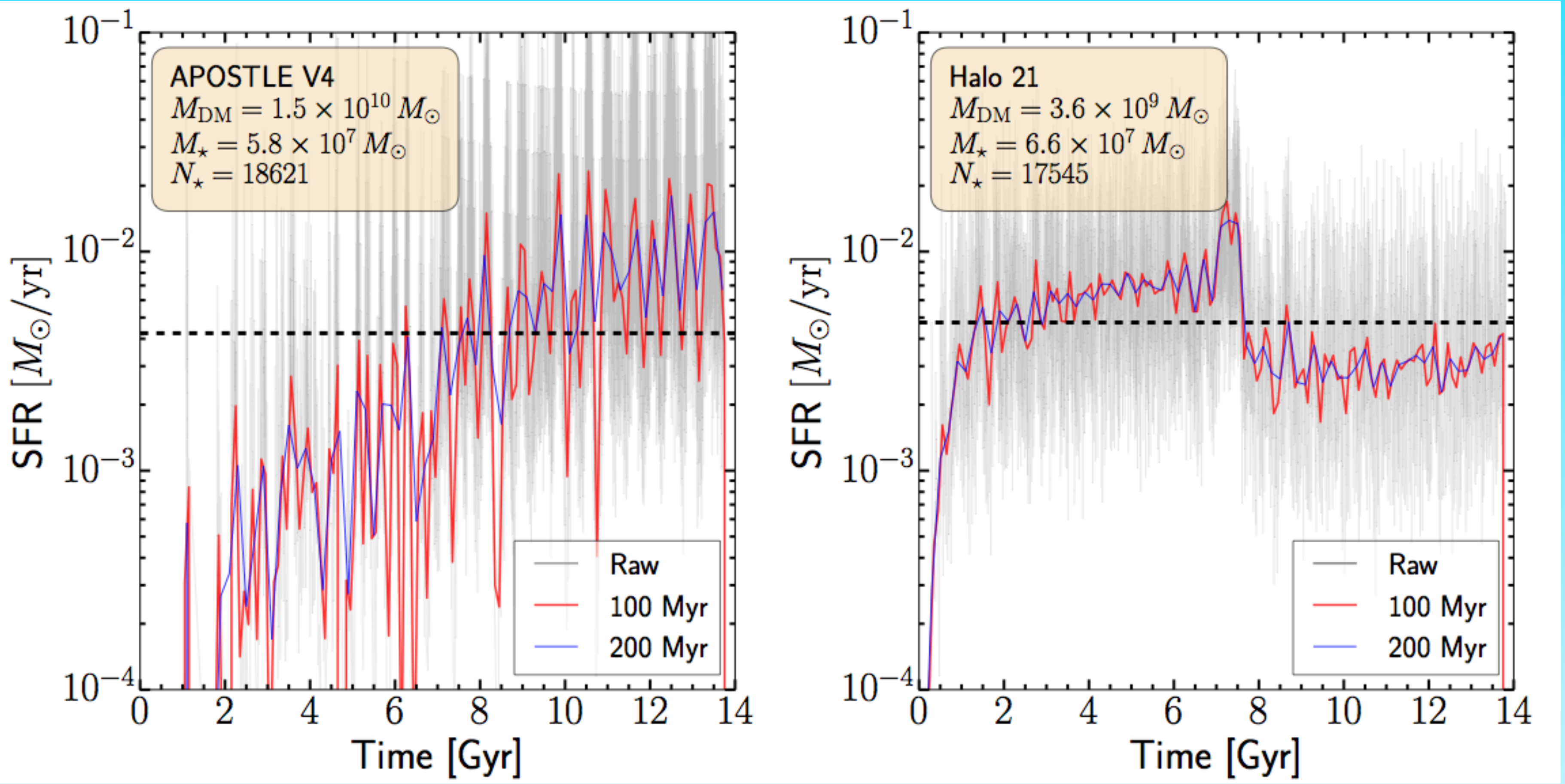
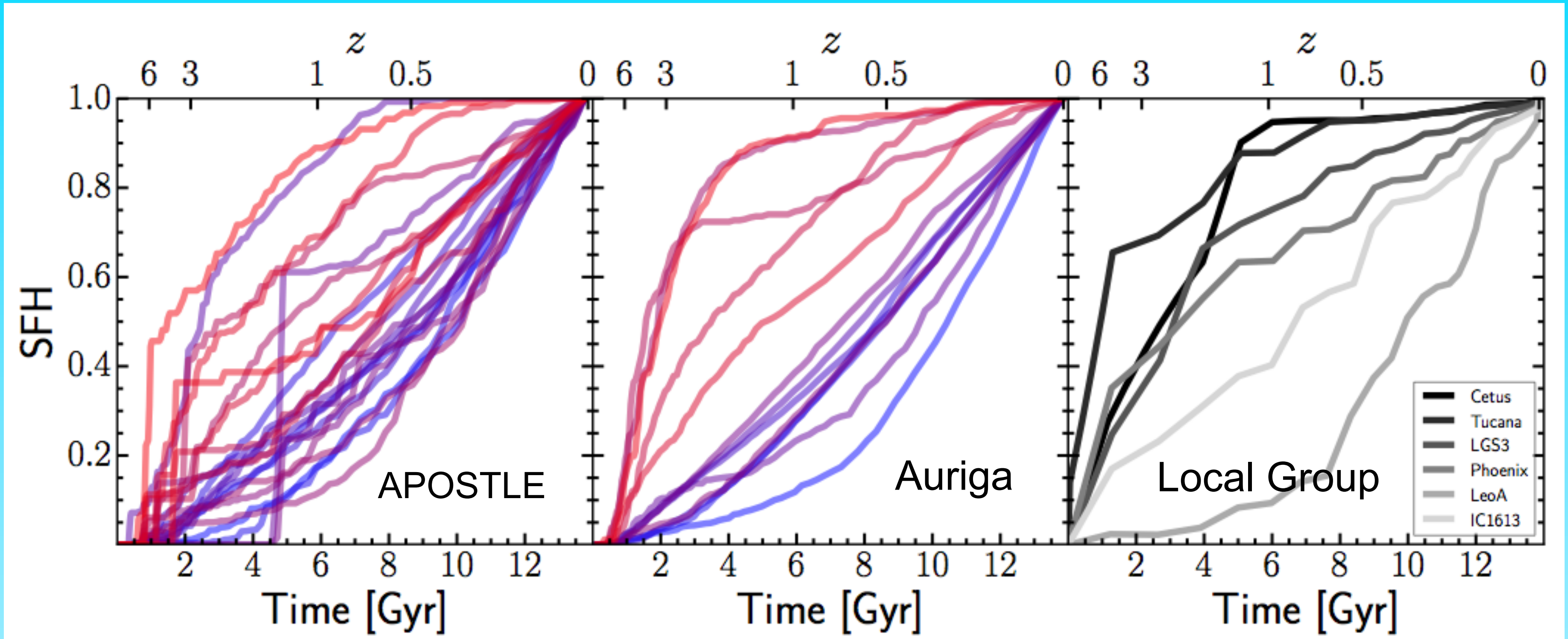
SFR in Apostle and Auriga are bursty!



Bose, CSF et al ‘18

Diversity of star formation histories

University of Durham



Skillman+ '14

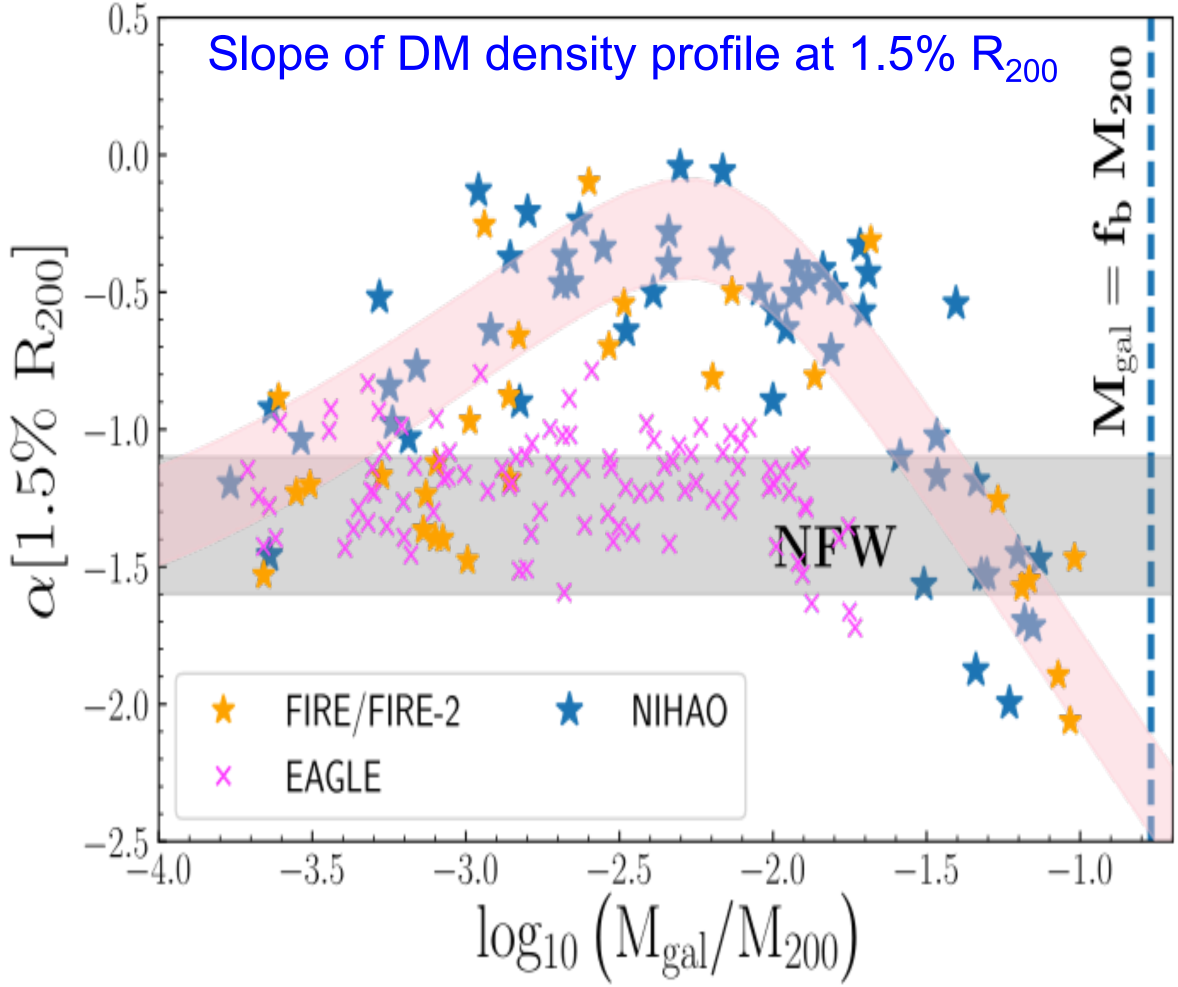
Isolated dwarfs in APOSTLE and Auriga have a diversity SFHs: they undergo early, late, or ~uniform star formation

Yet – they have no density cores

Bose, CSF et al '18

Cores or cusps in simulations of dwarfs

Benitez-LLambay, CSF, Ludlow, Navarro, Schaller ‘18



See e.g. Tollet et al. (2016), Hopkins et al. (2017), Di Cintio et al. (2014)

Simulations with codes such as FIRE / FIRE-2 or GASOLINE produce a reduction in the central density due to baryonic effects

1) Such baryonic effects seem not to be present in EAGLE and Auriga

2) Physics or numerical effects?

The physics of core formation

Cusps → cores

Perturb central halo region by growing a galaxy adiabatically and removing it suddenly (Navarro, Eke & Frenk '96)

Cores may also form by repeated fluctuations in central potential (e.g. by SN explosions) (Pontzen & Governato '12,'14; Bullock & Boylan-Kolchin '17)

Navarro, Eke & Frenk (1996)

The cores of dwarf galaxy haloes L75

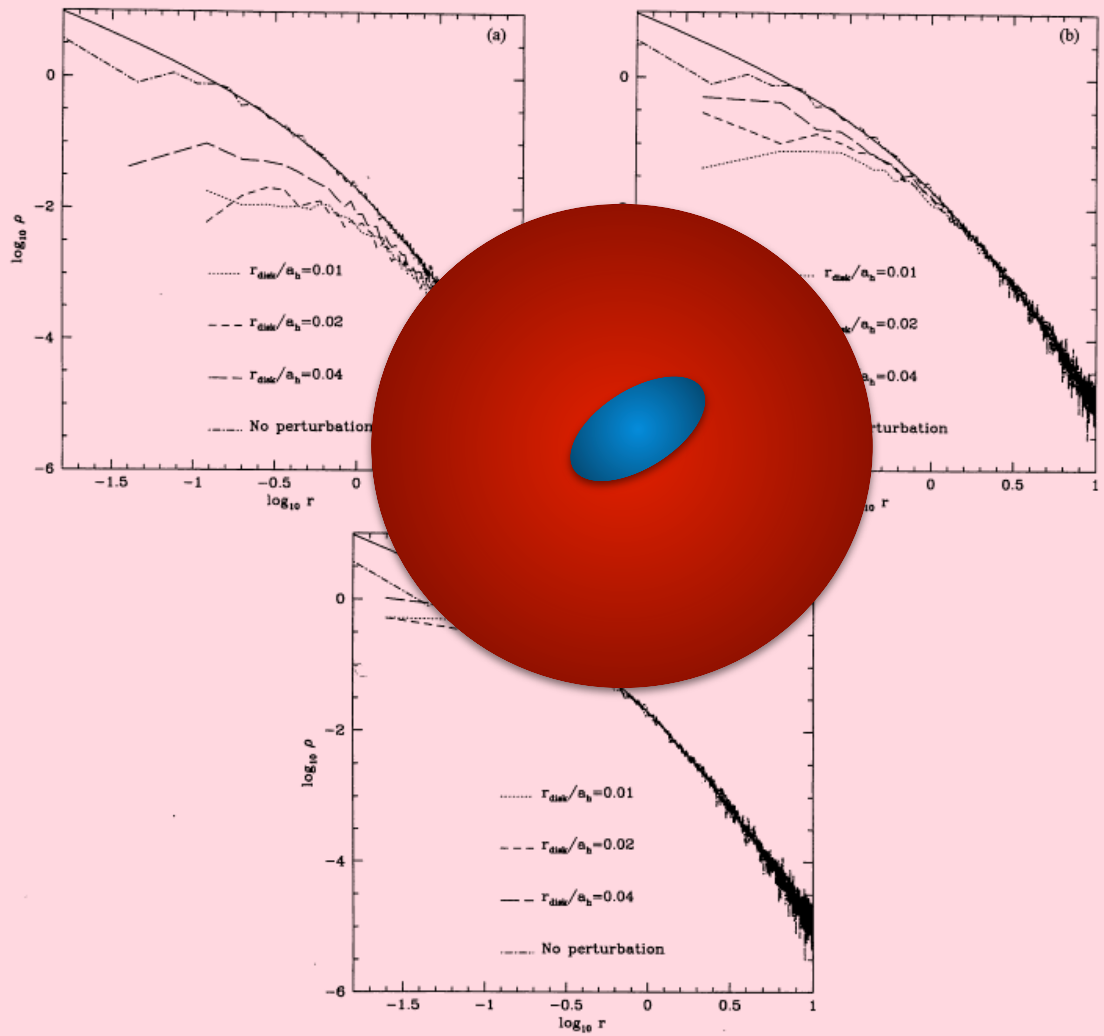
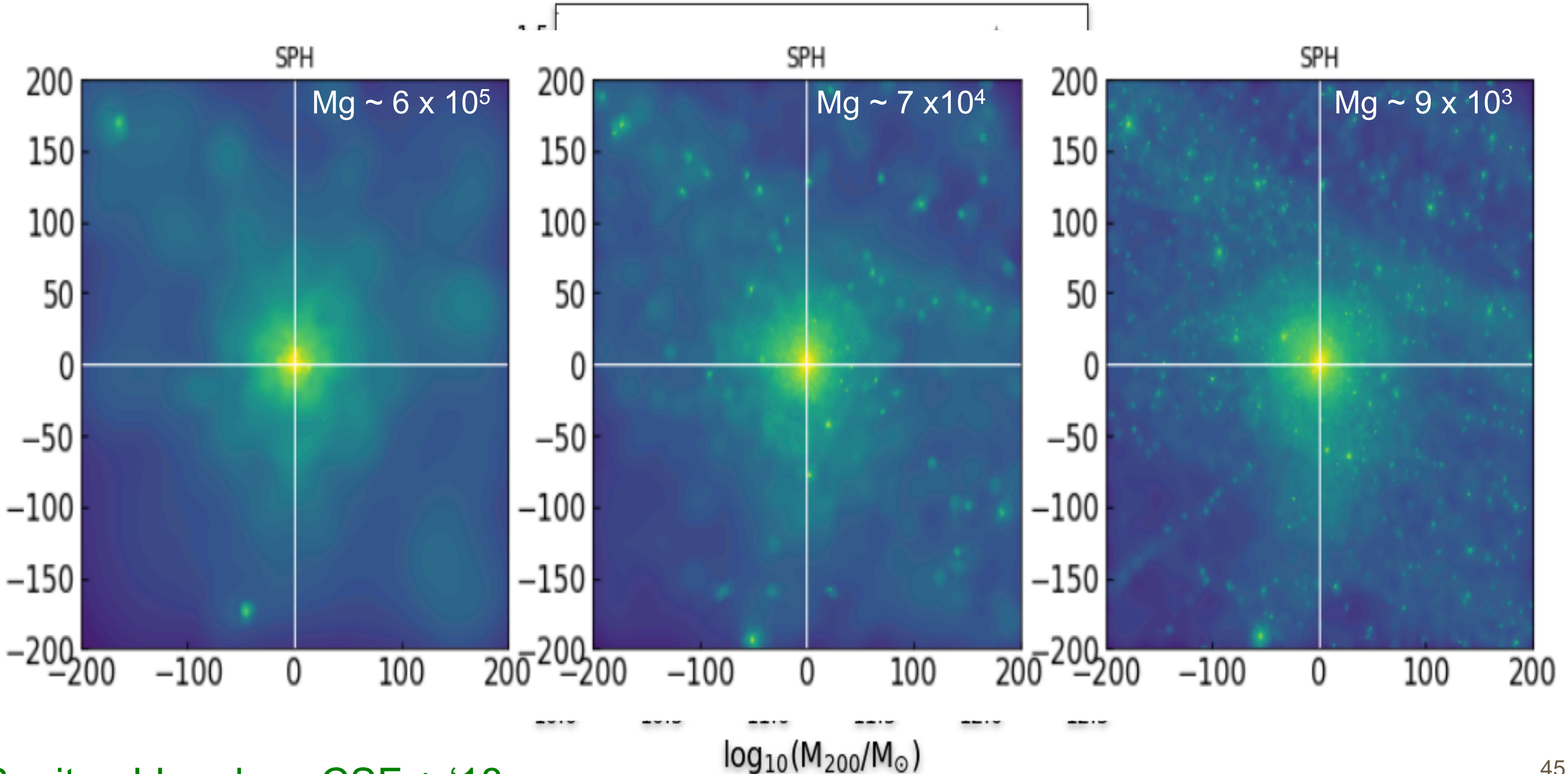


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t = 200$. (a) $M_{disc} = 0.2$. (b) $M_{disc} = 0.1$. (c) $M_{disc} = 0.05$.

Why does EAGLE not form cores?

Simulated 12 Mpc cube cosmological volume (Mgas ~ 6.3 x 10^5 M_o), identified isolated dwarfs in wide range of masses and resimulated them at higher resolution.



Benitez-LLambay, CSF + '18

Core formation

In the absence of a treatment of the (multi-phase) interstellar medium, need a “subgrid” model for star formation

In Eagle stars form from (cooling) gas that reaches a density higher than ρ_{th} (and T~10^4 K)

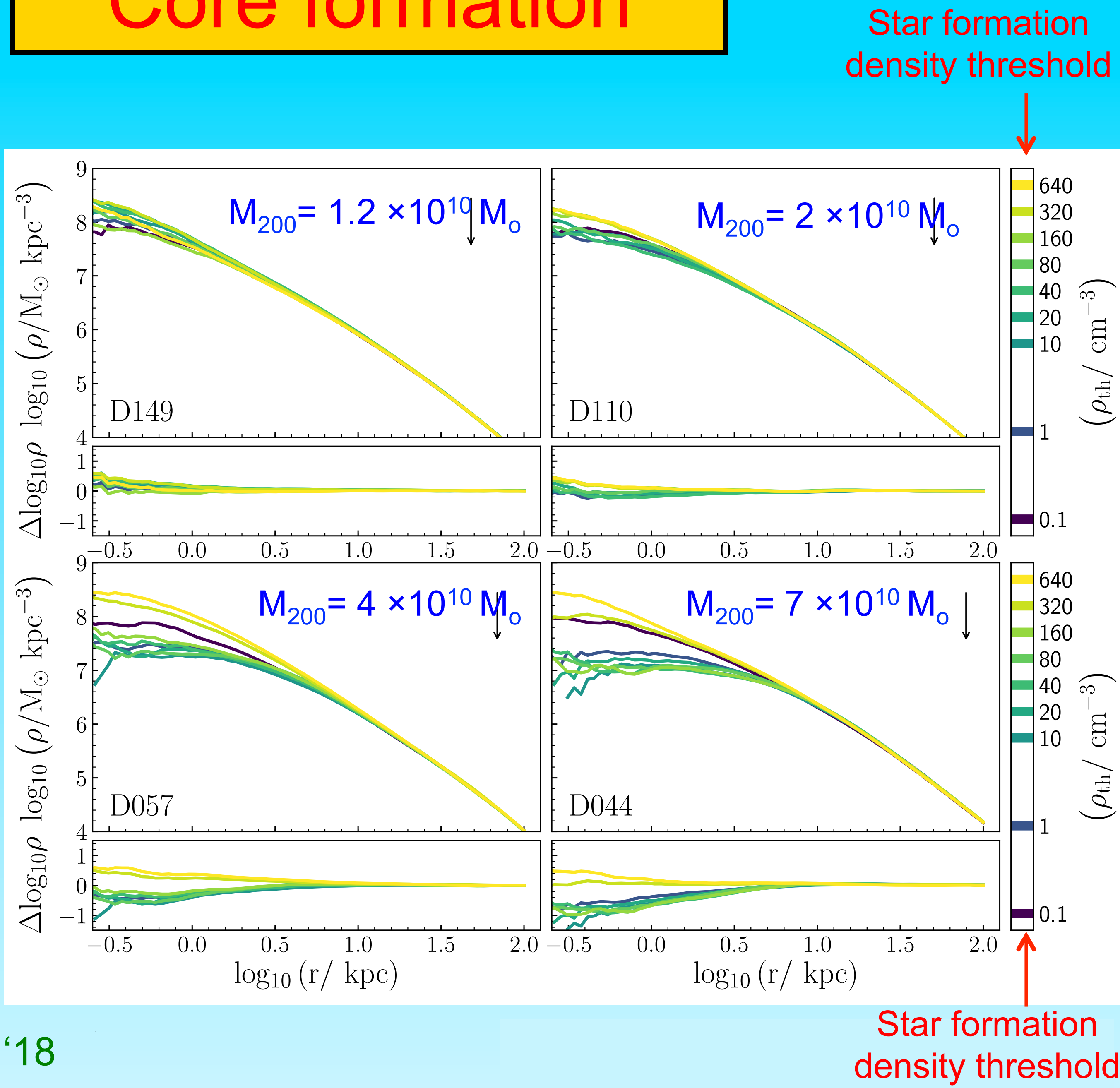
In Eagle ρ_{th}~0.1 cm^{-3}

For each resimulated dwarf, vary ρ_{th} from 0.1 - 10^4 cm^{-3}

Physically meaningless

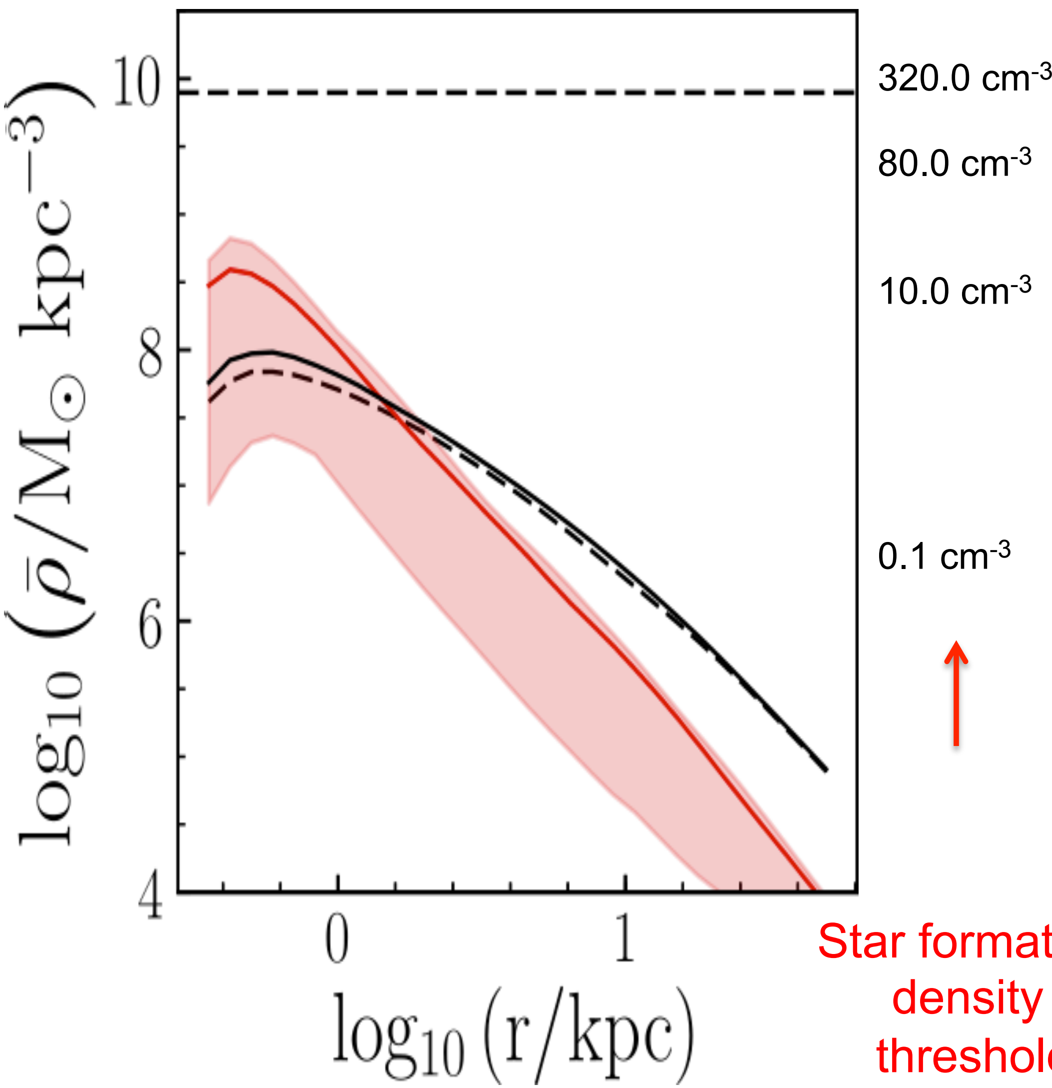
Core formation

- As density threshold for star formation increases, cores begin to form if galaxy is massive enough
- In small galaxies, cores are tiny (unresolved)
- If threshold is too high, no cores form – halo can become even cuspier

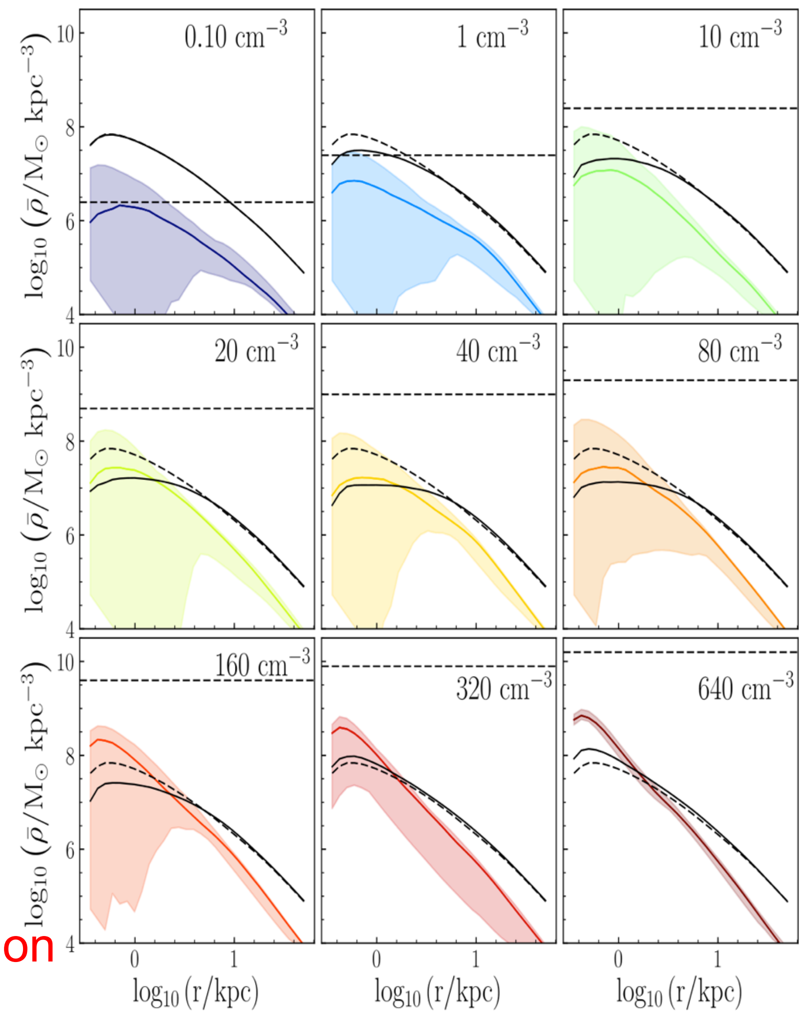


Benitez-LLambay, CSF + '18

Changing the density threshold for star formation

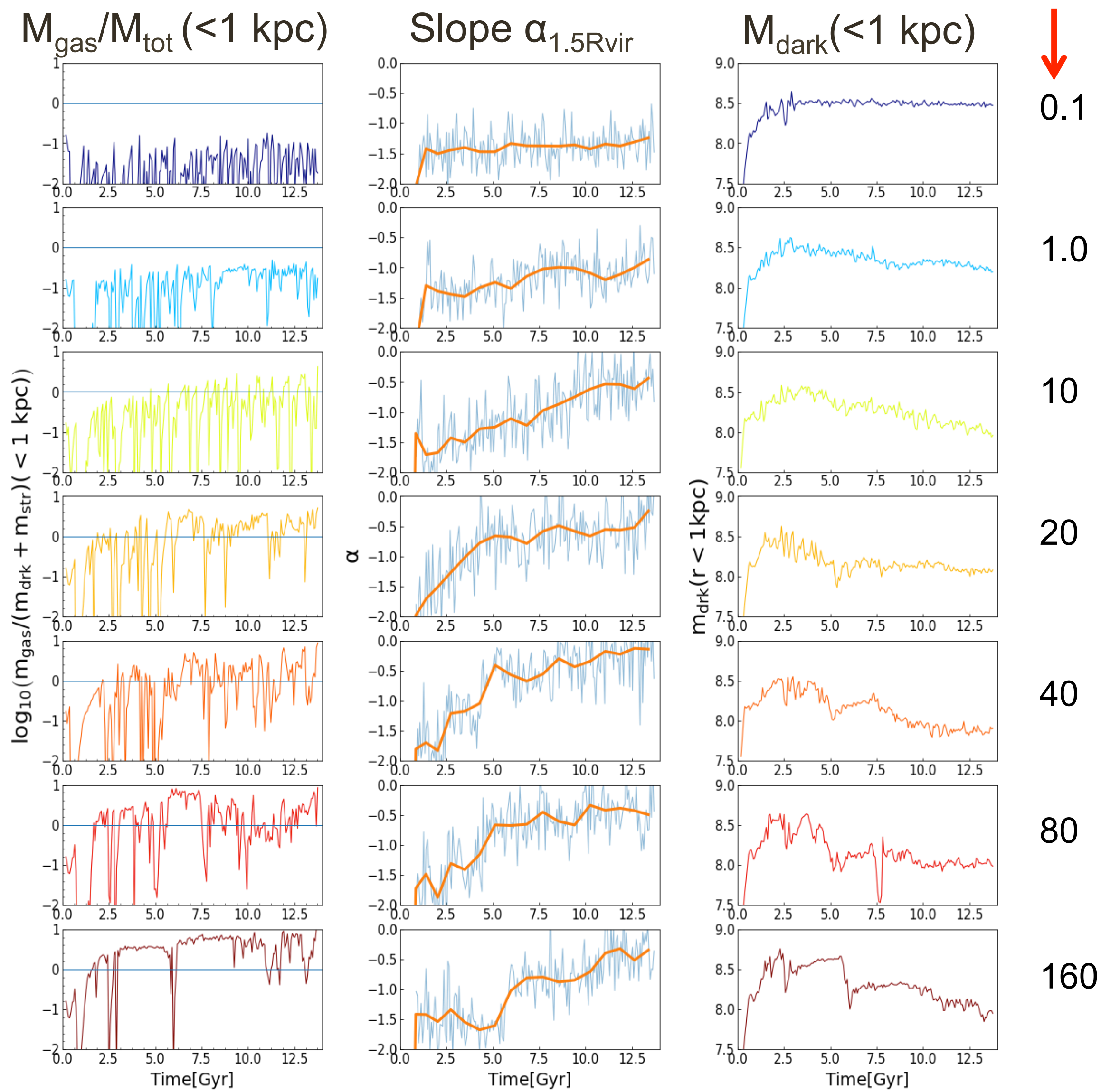


Star formation density threshold



How do cores form ?

SF density threshold



If baryons are irrelevant to gravitational potential, SN cannot affect central cusp

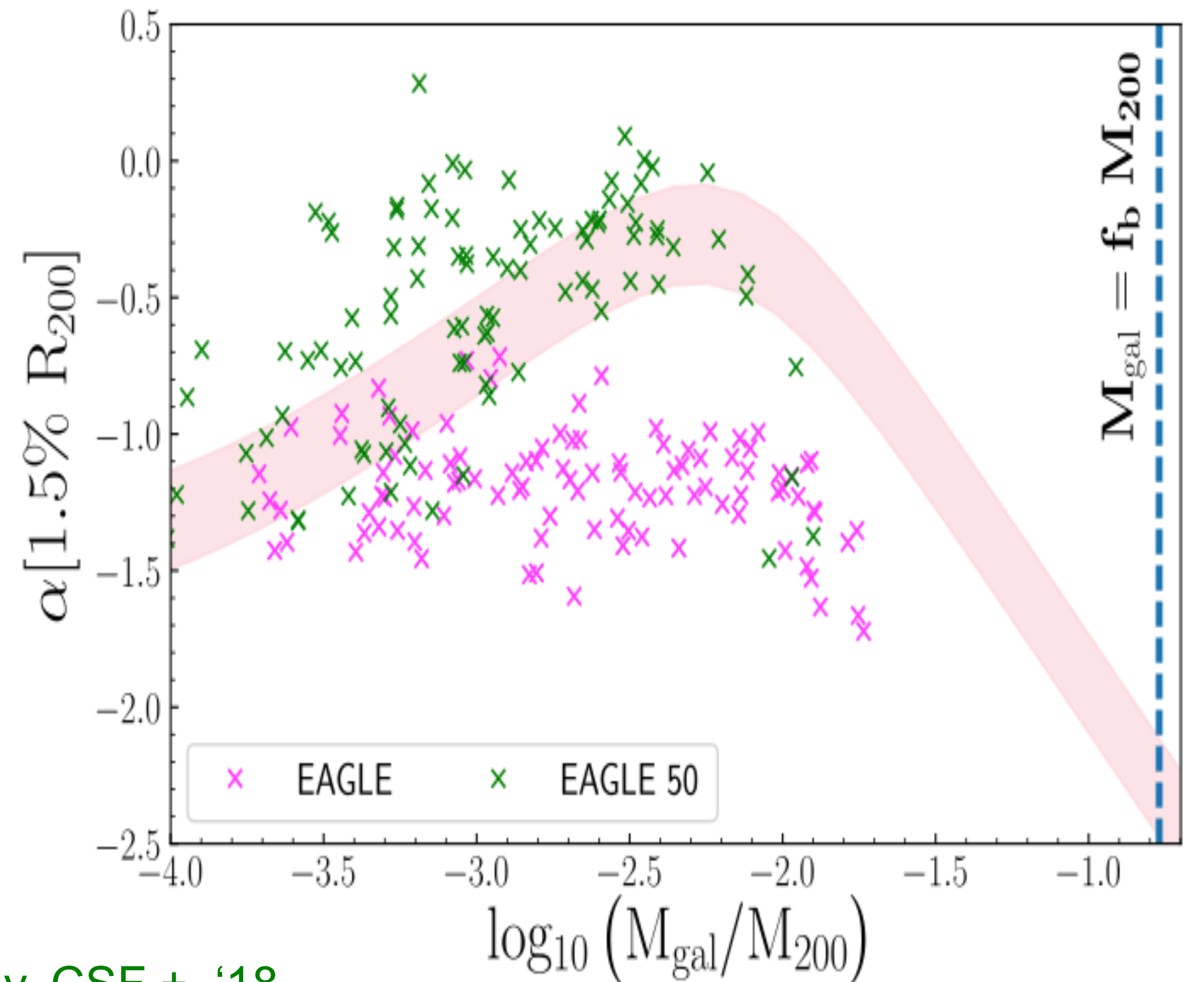
If gas marginally dominates potential, SN → secular evolution of inner halo slope.

If gas strongly dominant: core can form violently from single SN event

Benitez-LLambay, CSF + '18

EAGLE with cores

Cosmological volume (L=12 Mpc; m_{gas} ~ 7 x 10^4 M_o) using EAGLE RECAL model + SF density threshold of 50 particles / cm^3

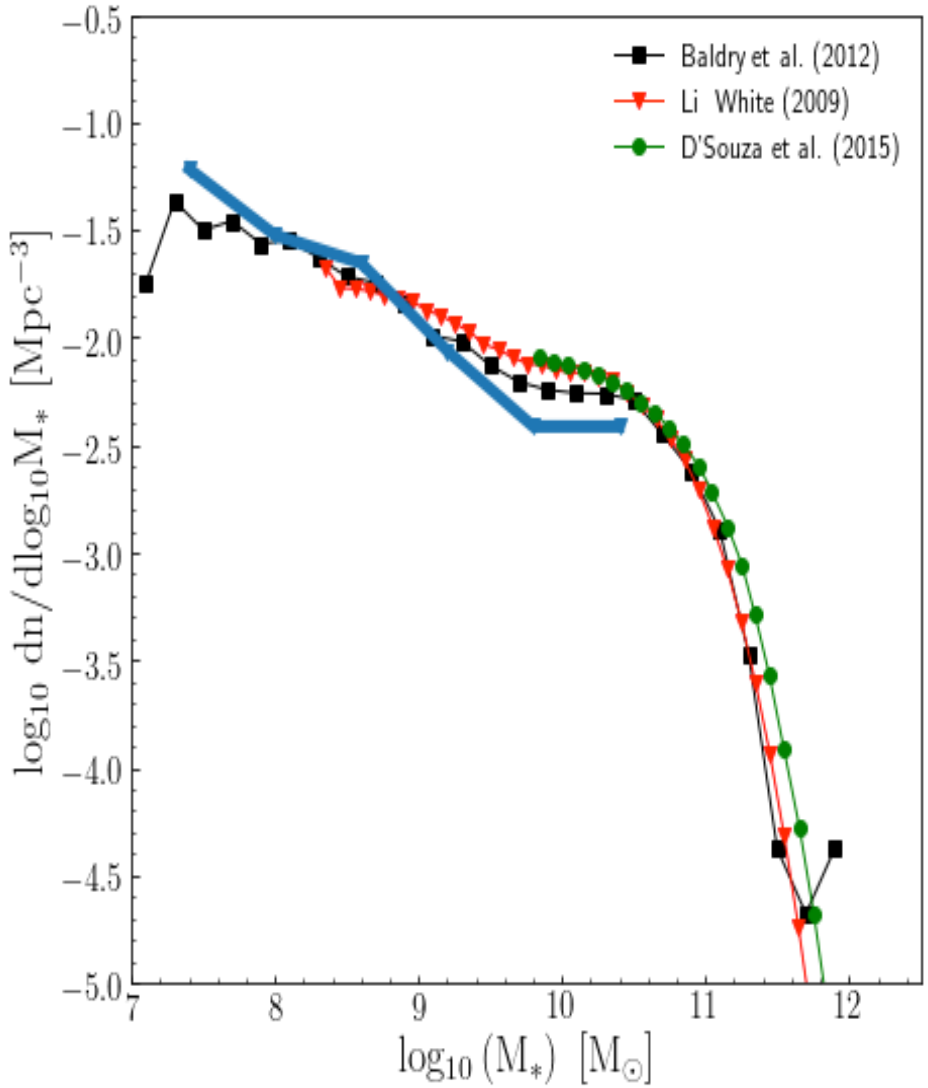


Benitez-LLambay, CSF + '18

Consequences for population of galaxies

Simulation with cores fails to match galaxy stellar mass fn.

New recalibration?



Benitez-LLambay, CSF + ‘18

Conclusions

- No evidence for cores in real dwarfs: cores and cusps are OK
- Neither Apostle nor Auriga make cores; yet their star formation is bursty & they have realistic star formation histories
- Can make cores in Eagle by raising density threshold for star formation
- Cores only form in a narrow range of halo masses
- Core sizes depend on subgrid SF threshold parameter
- … and also probably on many other factors