Predictions from ΛCDM cosmological simulations

Carlos S. Frenk
Institute for Computational Cosmology, Durham

… (mostly) for low-surface brightness dwarf galaxies in the local universe

Carlos S. Frenk
Institute for Computational Cosmology, Durham

VIRGO

ΛCDM initial conditions

"Evolution and assembly of galaxies and their environment"

THE EAGLE PROJECT

Virgo Consortium

Durham: Richard Bower, Michelle Furlong, Carlos Frenk, Matthieu Schaller, James Trayford, Yelti Rosas-Guevara, Tom Theuns, Yan Qu, John Helly, Adrian Jenkins.

Leiden: Rob Crain, Joop Schaye.

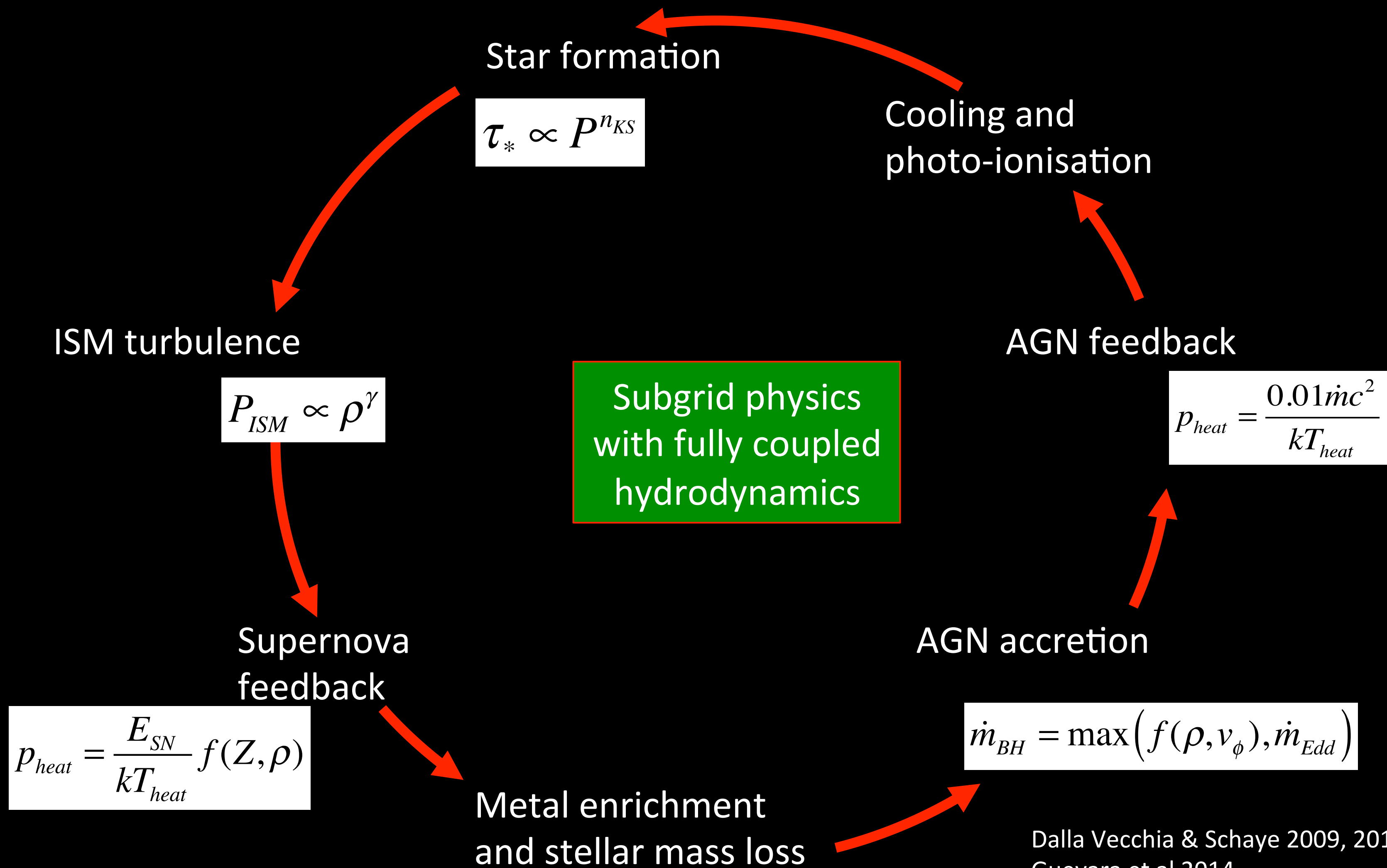
Other: Claudio Dalla Vecchia, Ian McCarthy, Craig Booth…

icc.dur.ac.uk/Eagle

Durham University VIRGO ICC DiRAC PRACE

The EAGLE simulation is a project by the Virgo Consortium.
Images courtesy of Richard Bower.

Subgrid modules in EAGLE

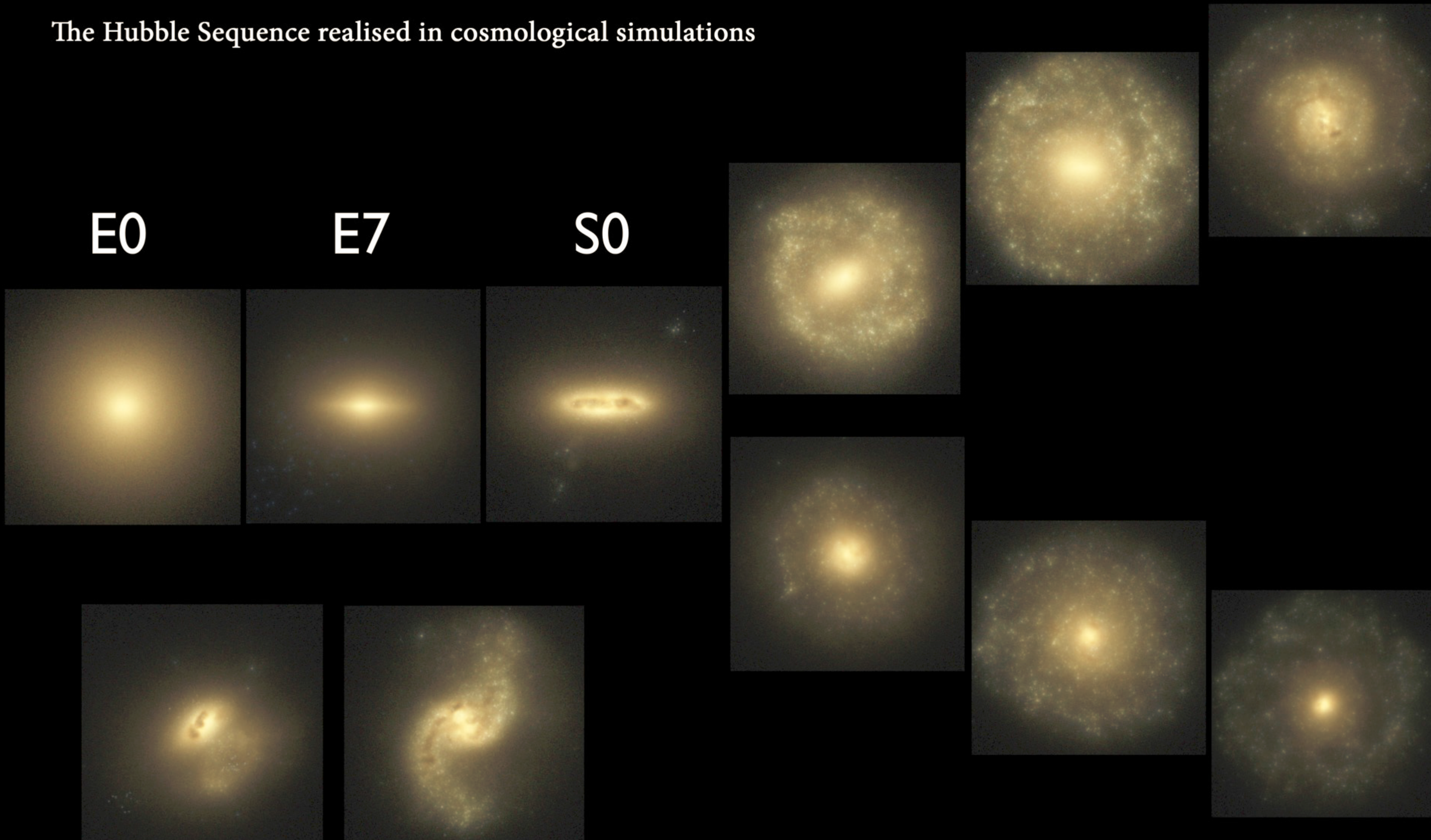


Dalla Vecchia & Schaye 2009, 2012; Roasas-Guevara et al 2014

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

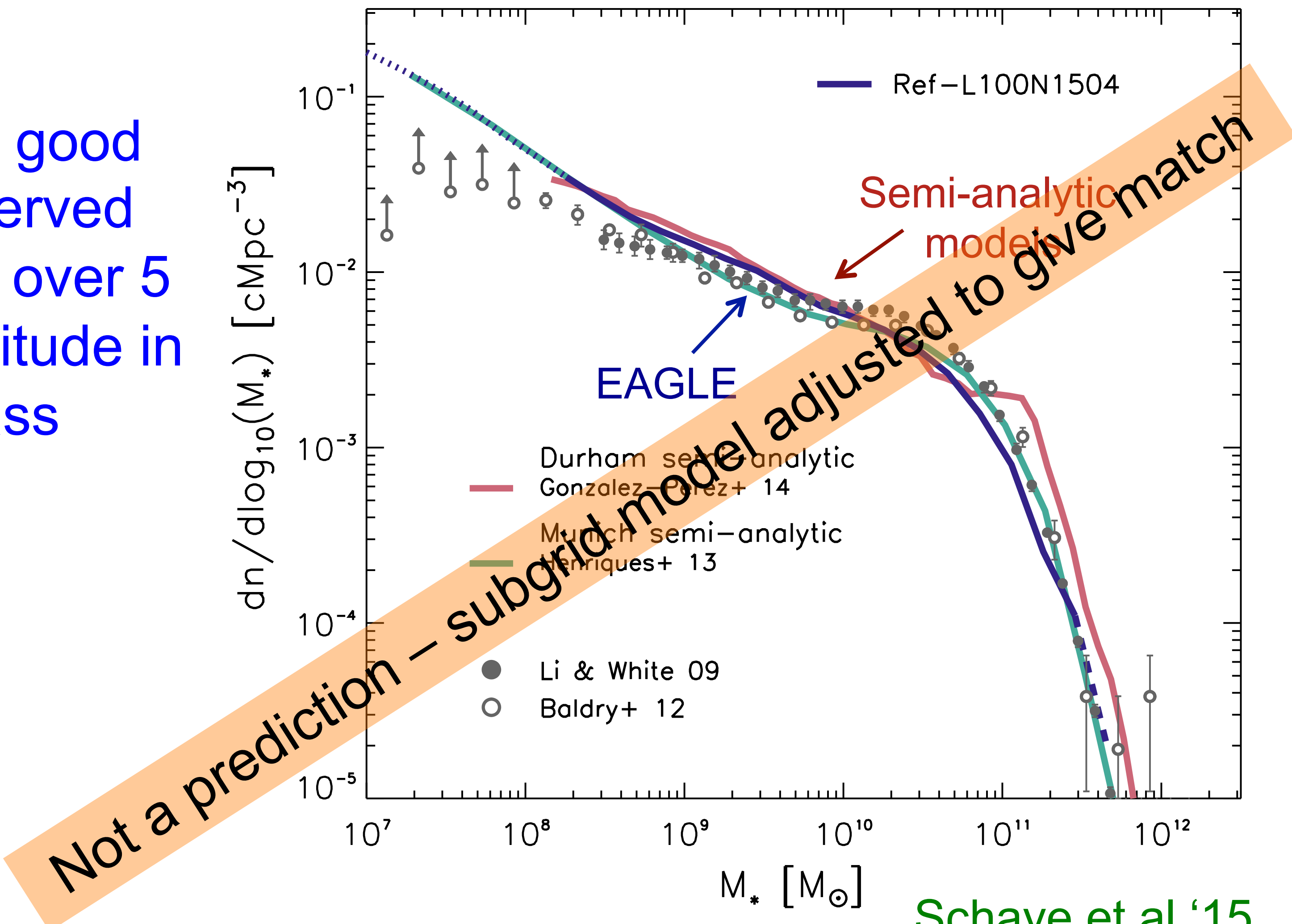
The Hubble Sequence realised in cosmological simulations



Trayford et al ‘14

Galaxy stellar mass function

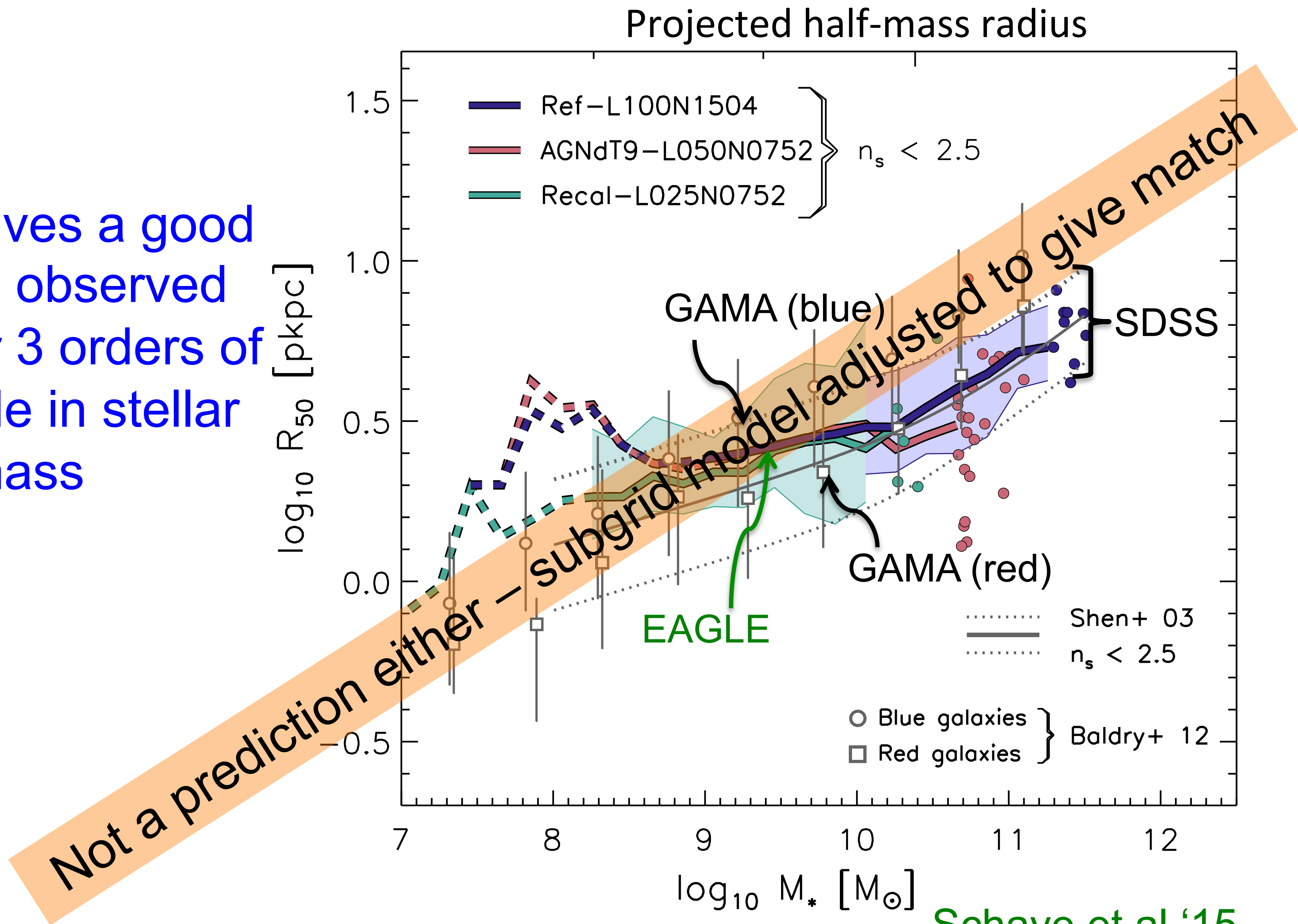
Eagle gives a good match to observed stellar mass fn over 5 orders of magnitude in stellar mass



Schaye et al ‘15

Galaxy sizes

EAGLE gives a good match to observed sizes over 3 orders of magnitude in stellar mass



Schaye et al '15

http://icc.dur.ac.uk/Eagle/database.php

A Project Of Simulations of The Local Environment (APOSTLE)

Carlos S. Frenk
Institute for Computational Cosmology, Durham

VIRGO

APOSTLE EAGLE full hydro simulations

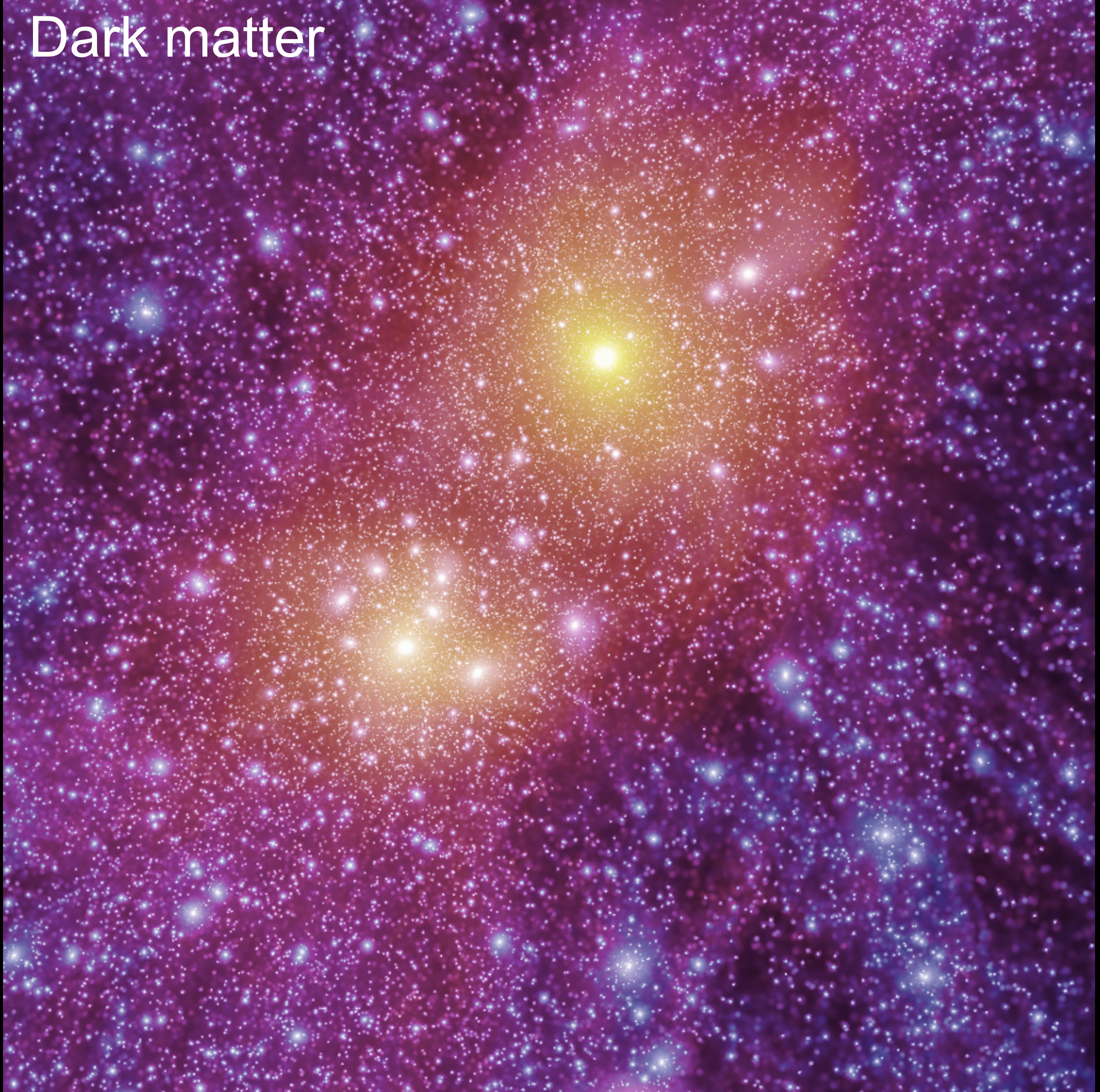
Local Group

CDM & WDM

Sawala et al ’15

Fattahi et al ’15

Lovell et al’ 16



Most subhalos never make a galaxy!

Because:

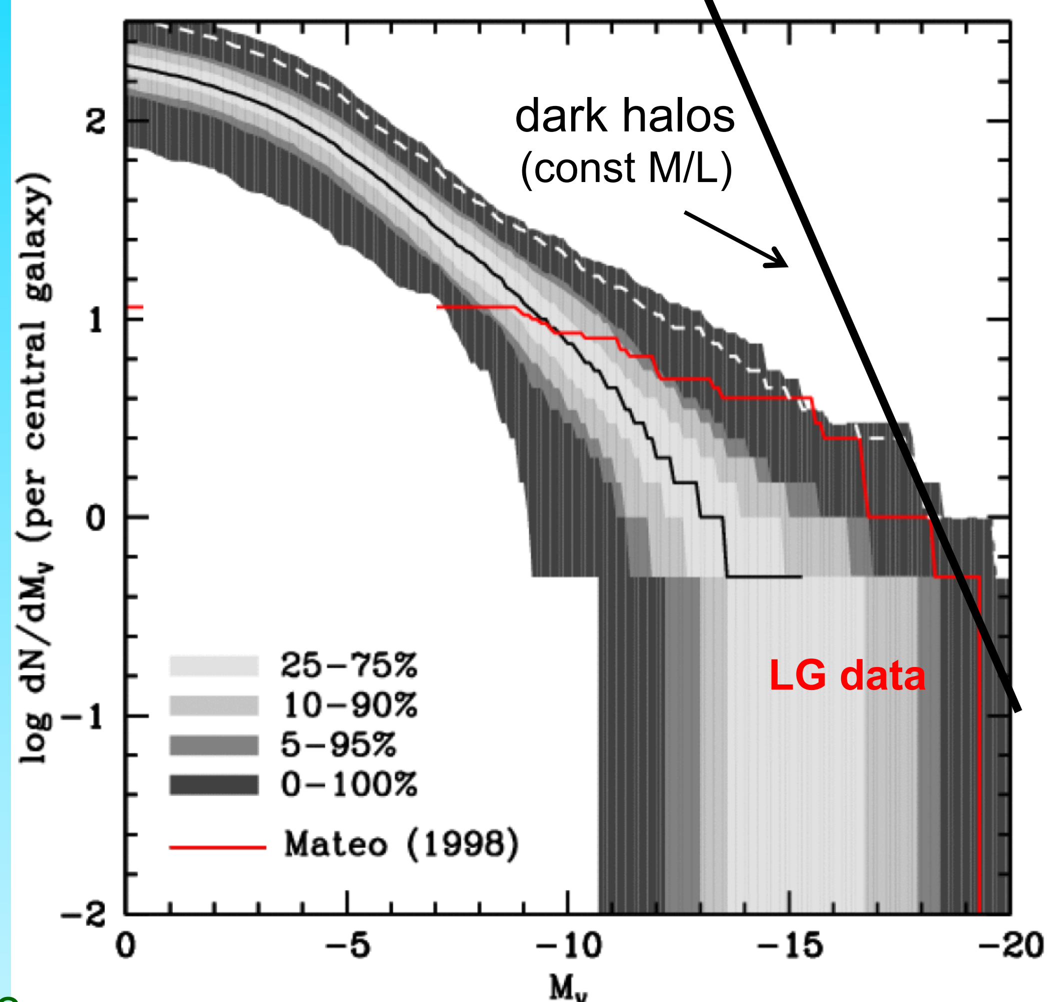
- Reionization heats gas to ~10^4K, preventing it from cooling and forming stars in small halos
- Supernovae feedback expels any residual gas

Luminosity Function of Local Group Satellites

- Median model → correct abund. of sats brighter than M_V=-9 and V_{cir} > 12 km/s

- Model predicts many, as yet undiscovered, faint satellites

- LMC/SMC should be rare (~2% of cases)



Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman et al '93, Bullock et al '00)

Luminosity Function of Local Group Satellites

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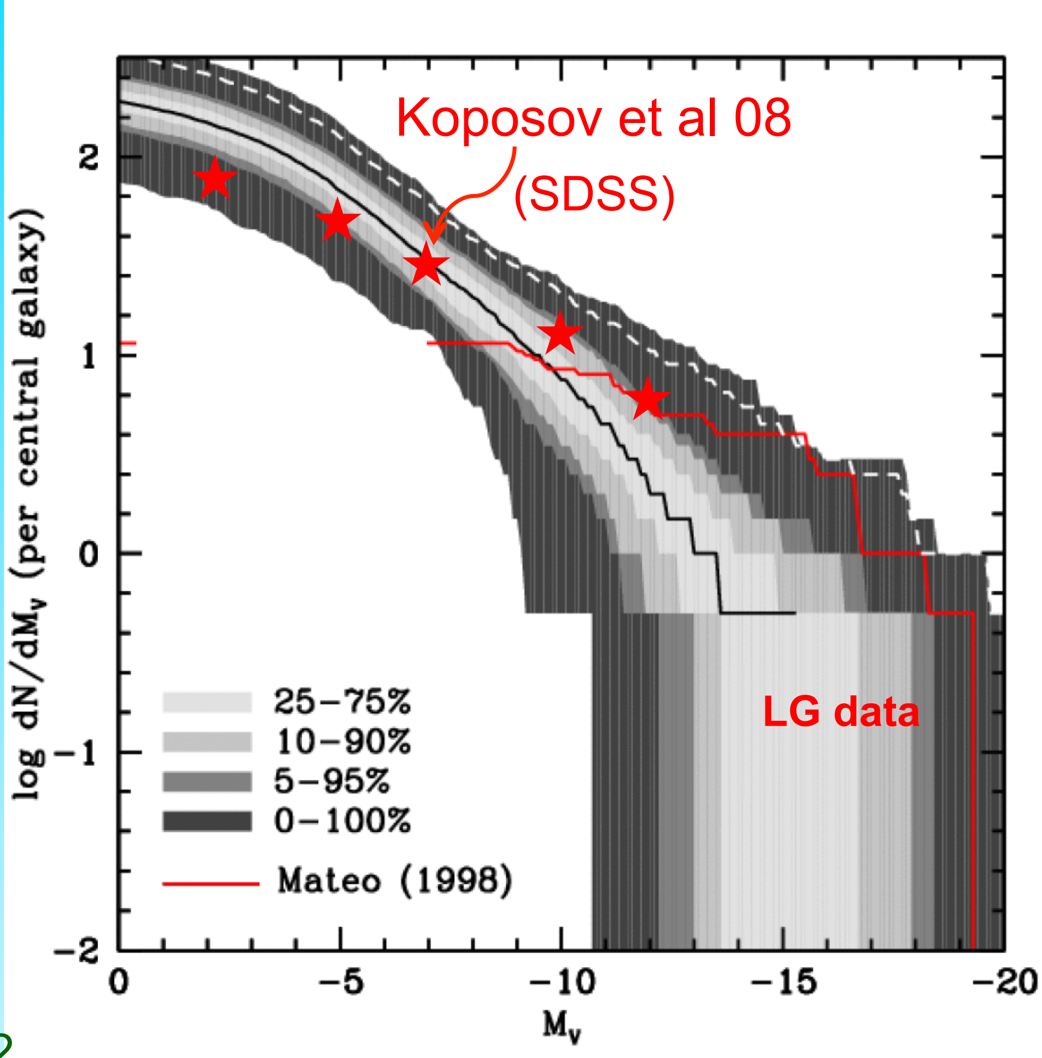

Benson, Frenk, Lacey, Baugh & Cole '02
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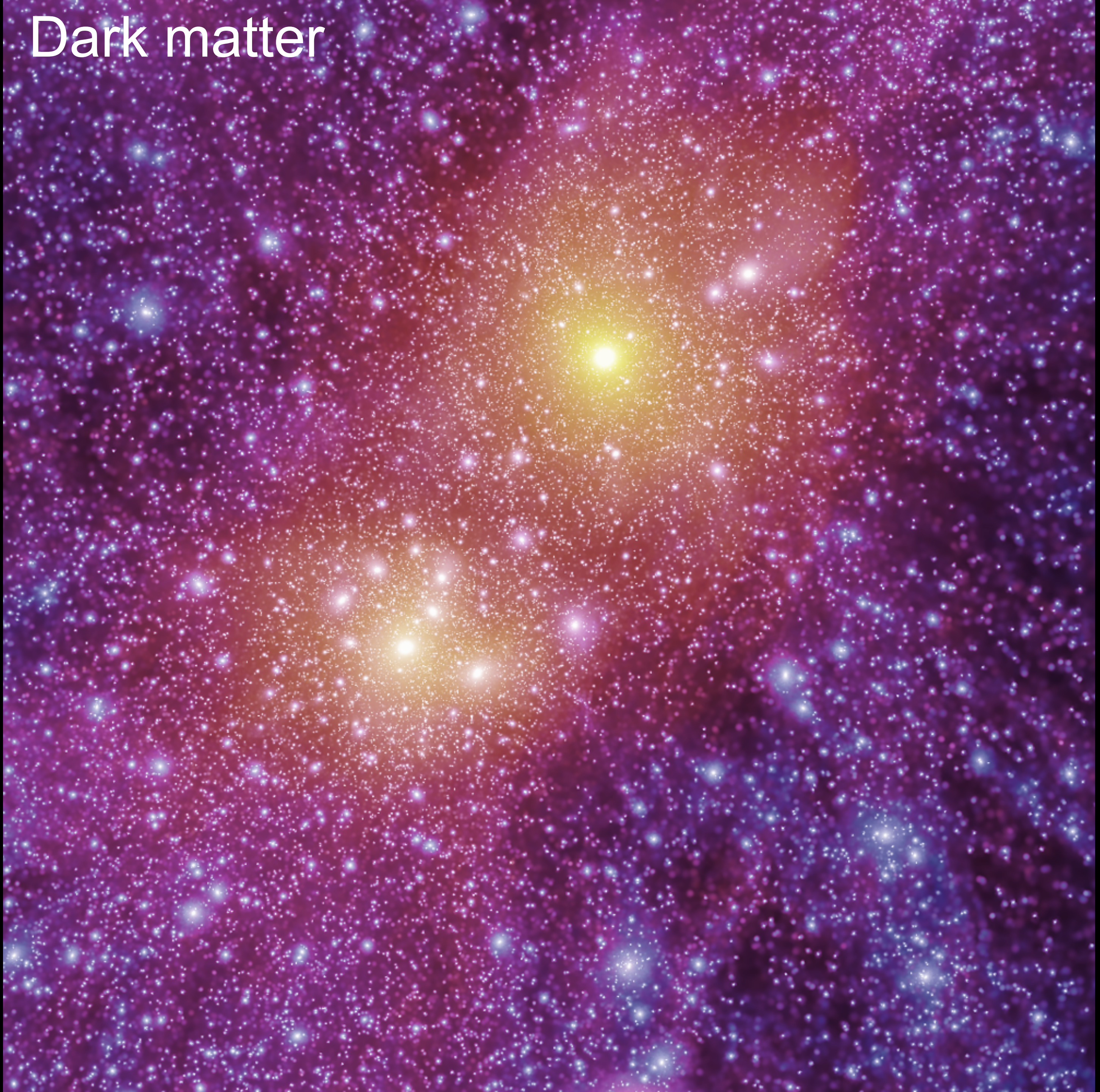
VIRGO

APOSTLE
EAGLE full
hydro
simulations

Local Group

CDM

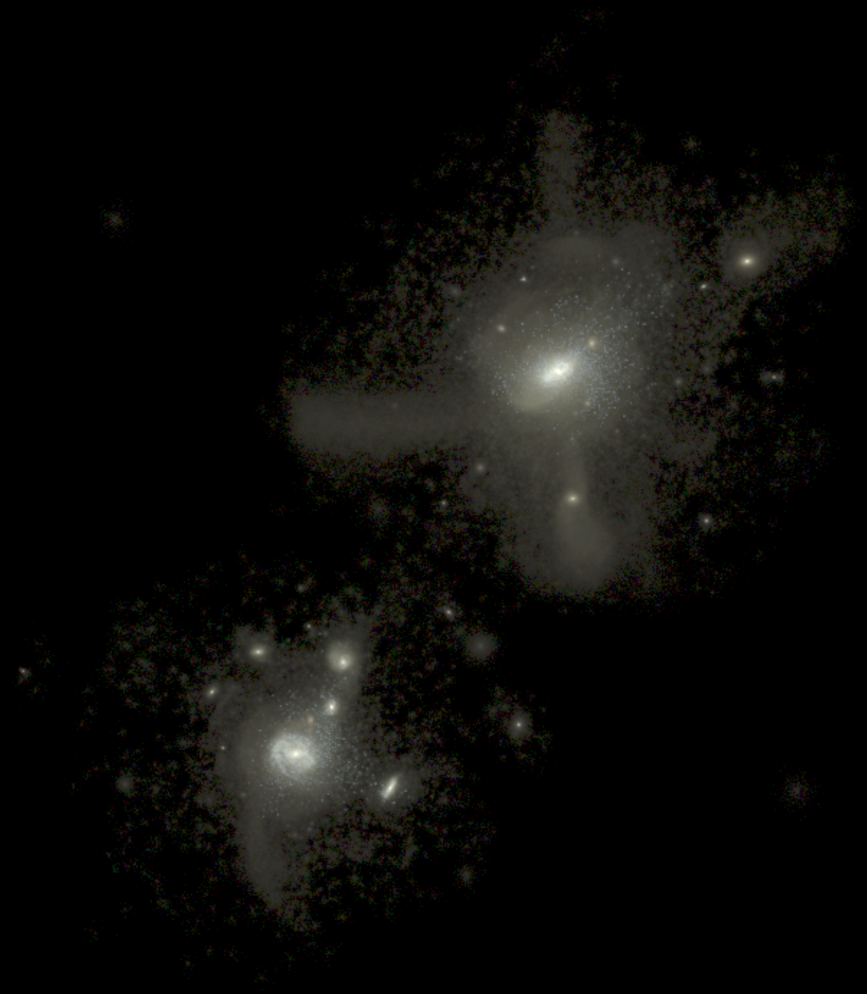
Sawala et al ‘15



Stars

APOSTLE EAGLE full hydro simulations

Local Group



Far fewer satellite galaxies than CDM halos

Sawala et al ‘15

EAGLE Local Group simulation

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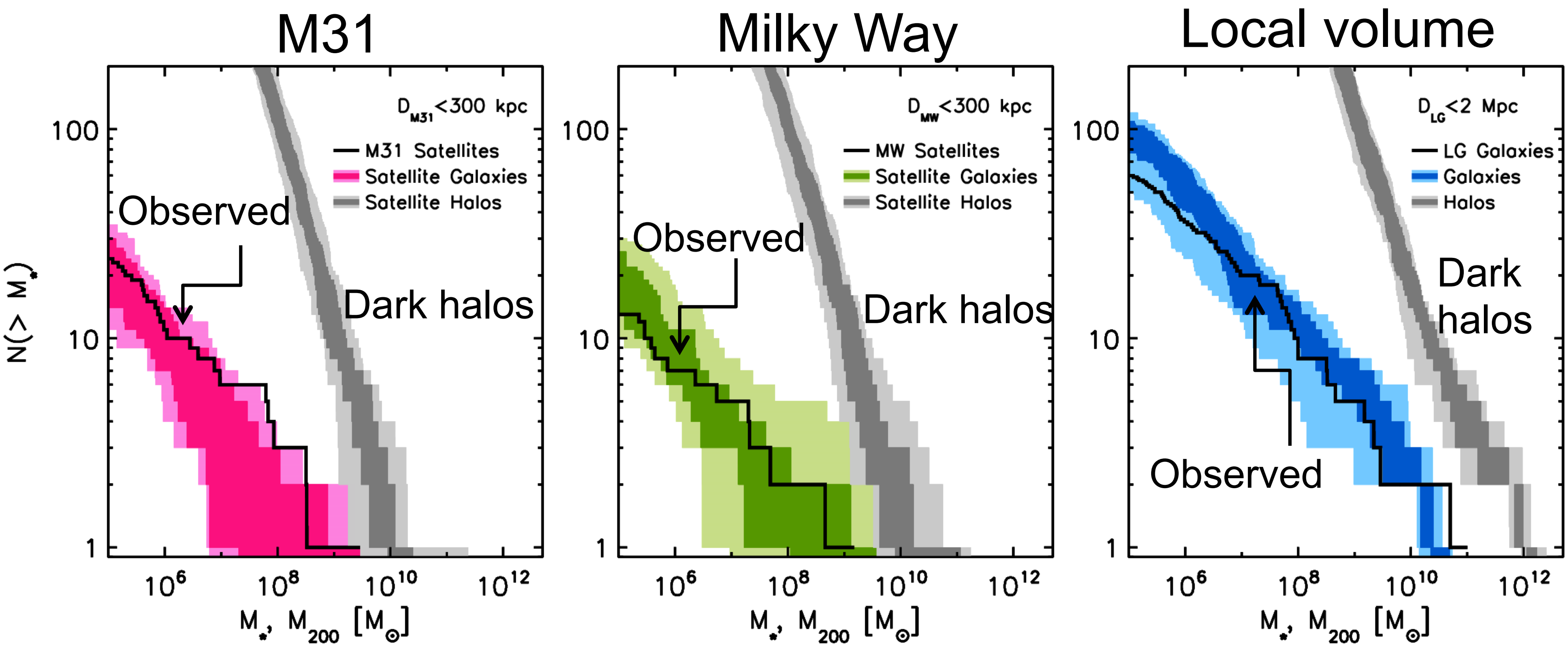
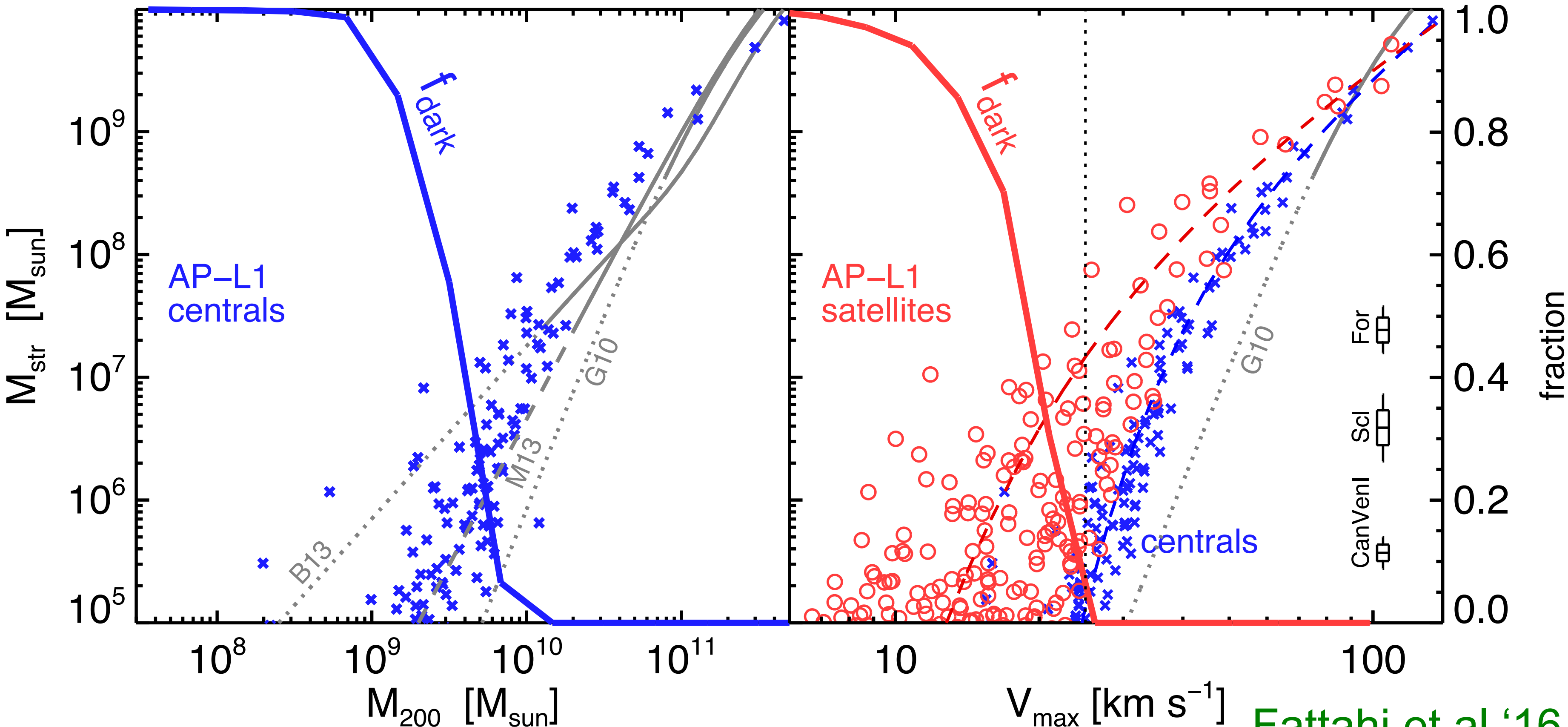


Sawala et al '15

Fraction of dark subhalos

$$V_c = \sqrt{\frac{GM}{r}} \qquad V_{max} = \max V_c$$



Fattahi et al ‘16

All halos of mass < $10^9 M_o$ or V_{max} < 7 km/s are dark

Is there a "missing satellite problem" in CDM?

No, when galaxy formation physics are folded in!

The core-cusp problem

Dark matter halos and subhalos in CDM have cuspy NFW profiles

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

ICC

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The core-cusp problem

2001

MASS DENSITY PROFILES OF LSB GALAXIES

W.J.G. de Blok[1]
Australia Telescope National Facility
PO Box 76, Epping NSW 1710, Australia
Stacy S. McGaugh
Department of Astronomy, University of Maryland
College Park, MD 20742-2421, USA
Albert Bosma
Observatoire de Marseille
2 Place Le Verrier
F-13248 Marseille Cedex 4, France

and

Vera C. Rubin
Department of Terrestrial Magnetism
Carnegie Institution of Washington
Washington, D. C. 20015, USA

Draft version February 1, 2008

ABSTRACT

We derive the mass density profiles of dark matter halos that are implied by high spatial resolution rotation curves of low surface brightness galaxies. We find that at small radii, the mass density distribution is dominated by a nearly constant density core with a core radius of a few kpc. For $\rho(r) \sim r^{\alpha}$, the distribution of inner slopes α is strongly peaked around $\alpha = -0.2$. This is significantly shallower than the cuspy $\alpha \leq -1$ halos found in CDM simulations. While the observed distribution of α does have a tail towards such extreme values, the derived value of α is found to depend on the spatial resolution of the rotation curves: $\alpha \approx -1$ is found only for the least well resolved galaxies. Even for these galaxies, our data are also consistent with constant density cores ($\alpha = 0$) of modest (~ 1 kpc) core radius, which can give the illusion of steep cusps when insufficiently resolved. Consequently, there is no clear evidence for a cuspy halo in any of the low surface brightness galaxies observed.

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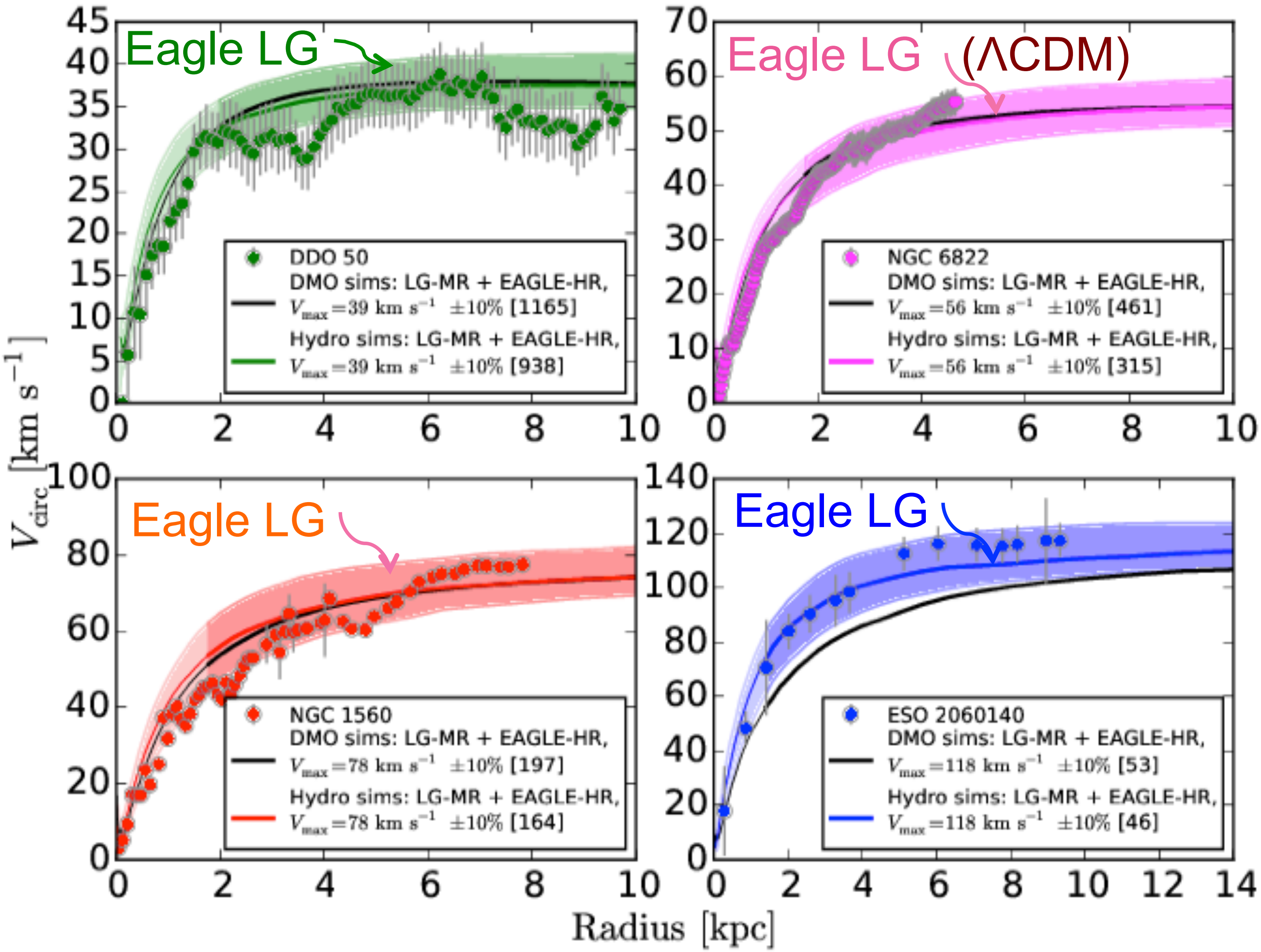
The diversity of gal rotation curves

Four rotation curves that are well fit by ΛCDM

(from dwarfs to ~L*)

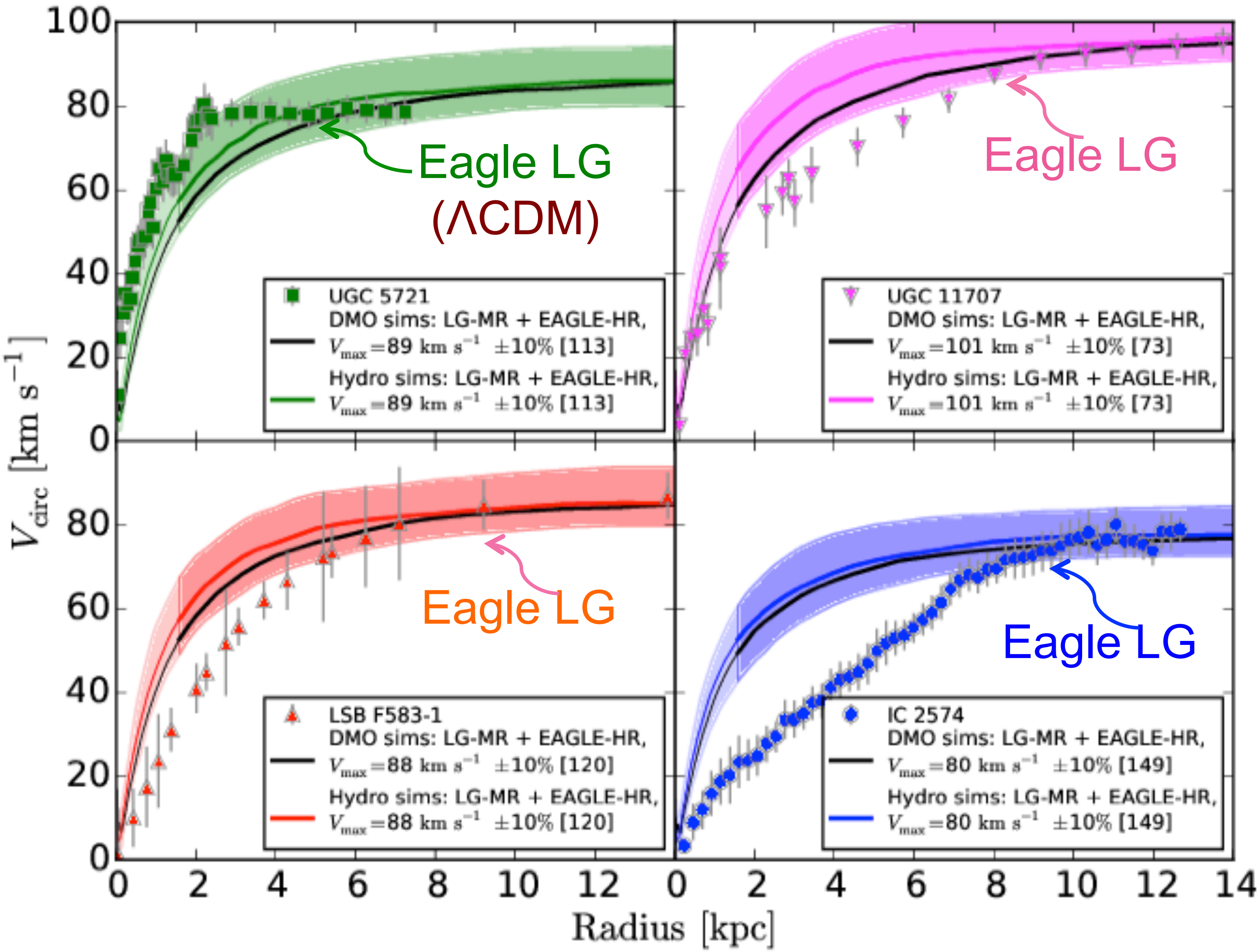


Oman, Navarro, Frenk et al. '15

The diversity of gal rotation curves

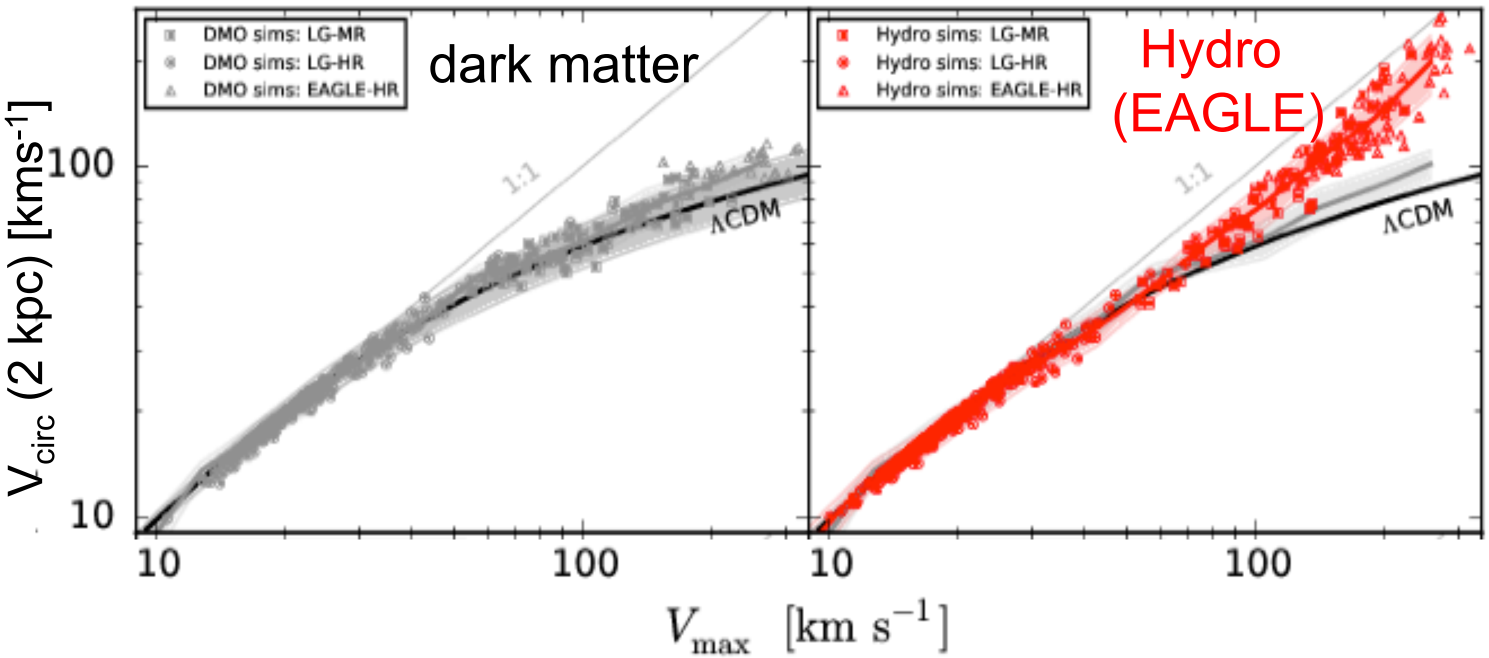
Four rotation curves that are NOT well fit by ΛCDM

(from dwarfs to ~L_*)



Oman et al. '15

The diversity of gal rotation curves



Oman et al. '15

The diversity of gal rotation curves

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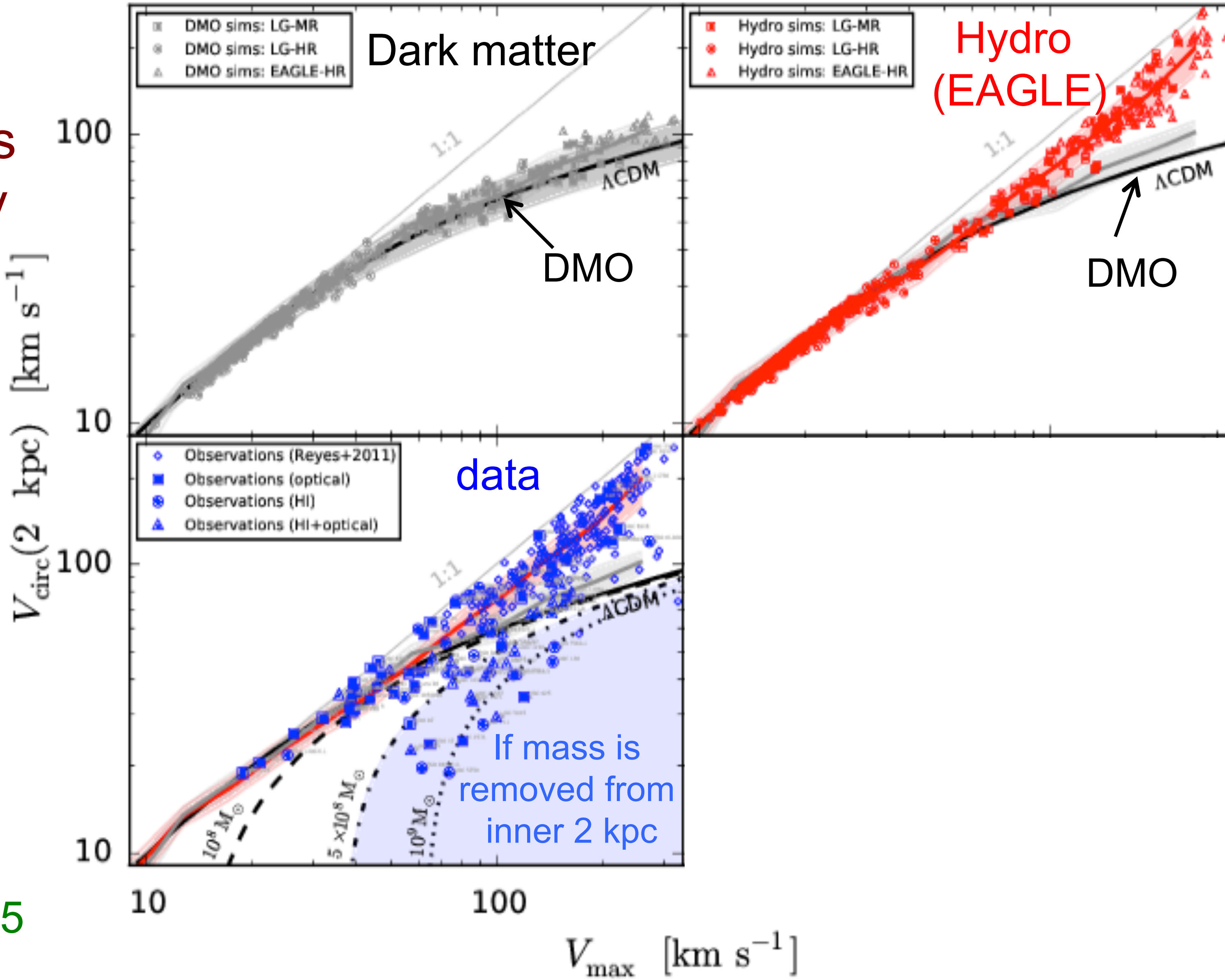
Most galaxies are well fit by EAGLE; others not fit by any simulation



Oman et al. '15

Are there baryon effects that could make cores but are not present in Eagle?

Mon. Not. R. Astron. Soc. **283**, L72–L78 (1996)

The cores of dwarf galaxy haloes

Julio F. Navarro,[1,2★] Vincent R. Eke[2] and Carlos S. Frenk[2]

[1]*Steward Observatory, The University of Arizona, Tucson, AZ 85721, USA*
[2]*Physics Department, University of Durham, South Road, Durham DH1 3LE*

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ABSTRACT

We use *N*-body simulations to examine the effects of mass outflows on the density profiles of cold dark matter (CDM) haloes surrounding dwarf galaxies. In particular, we investigate the consequences of supernova-driven winds that expel a large fraction of the baryonic component from a dwarf galaxy disc after a vigorous episode of star formation. We show that this sudden loss of mass leads to the formation of a core in the dark matter density profile, although the original halo is modelled by a coreless (Hernquist) profile. The core radius thus created is a sensitive function of the mass and radius of the baryonic disc being blown up. The loss of a disc with mass and size consistent with primordial nucleosynthesis constraints and angular momentum considerations imprints a core radius that is only a small fraction of the original scalelength of the halo. These small perturbations are, however, enough to reconcile the rotation curves of dwarf irregulars with the density profiles of haloes formed in the standard CDM scenario.

Baryon effects in the MW satellites

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Let gas cool and condense to the galactic centre

→ gas self-gravitating
→ star formation/burst

Rapid ejection of gas during starburst → a core in the halo dark matter density profile

Navarro, Eke, Frenk ‘96

Governato et al. ‘12
Pontzen & Governato ‘12
Brooks et al. ‘12

Navarro, Eke, Frenk ‘96

The cores of dwarf galaxy haloes L75

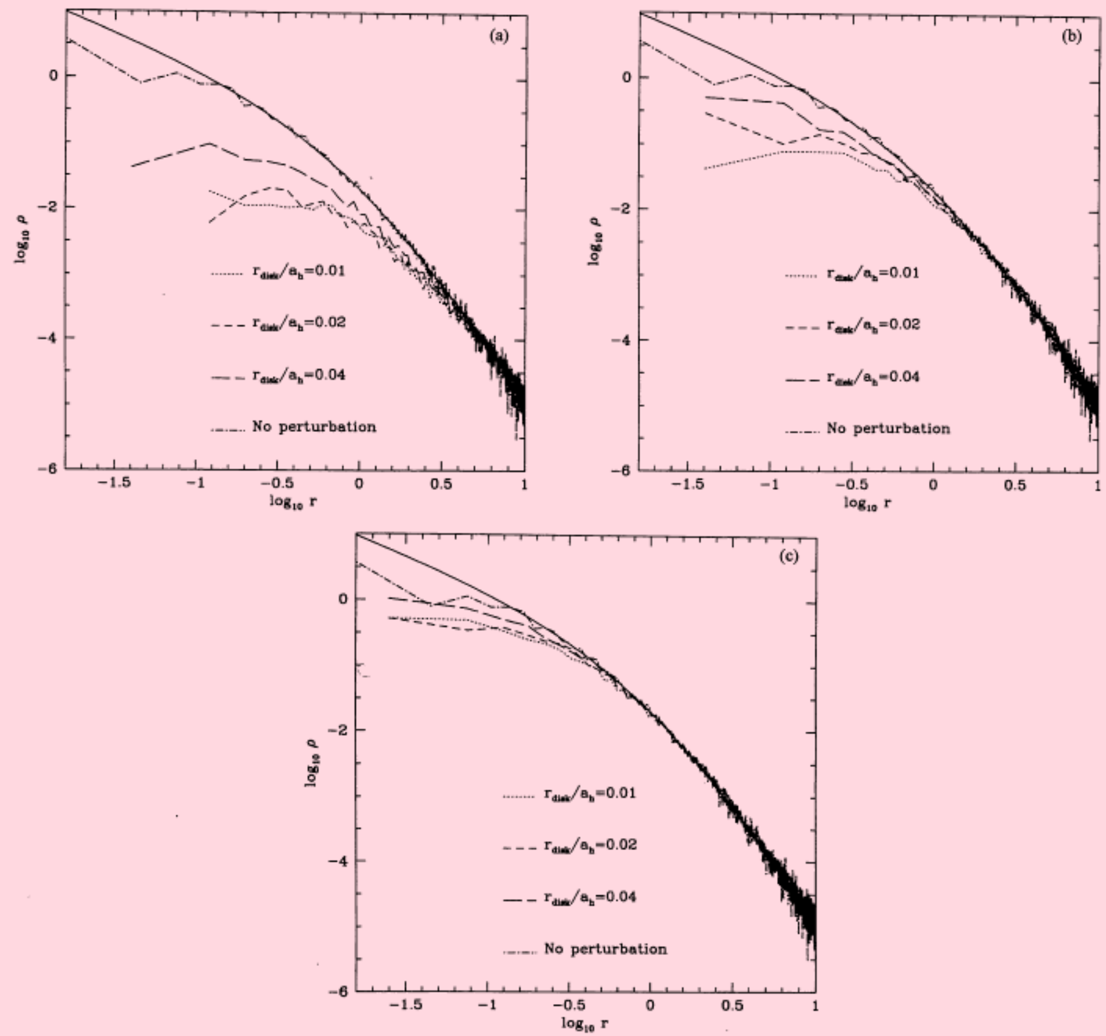

Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

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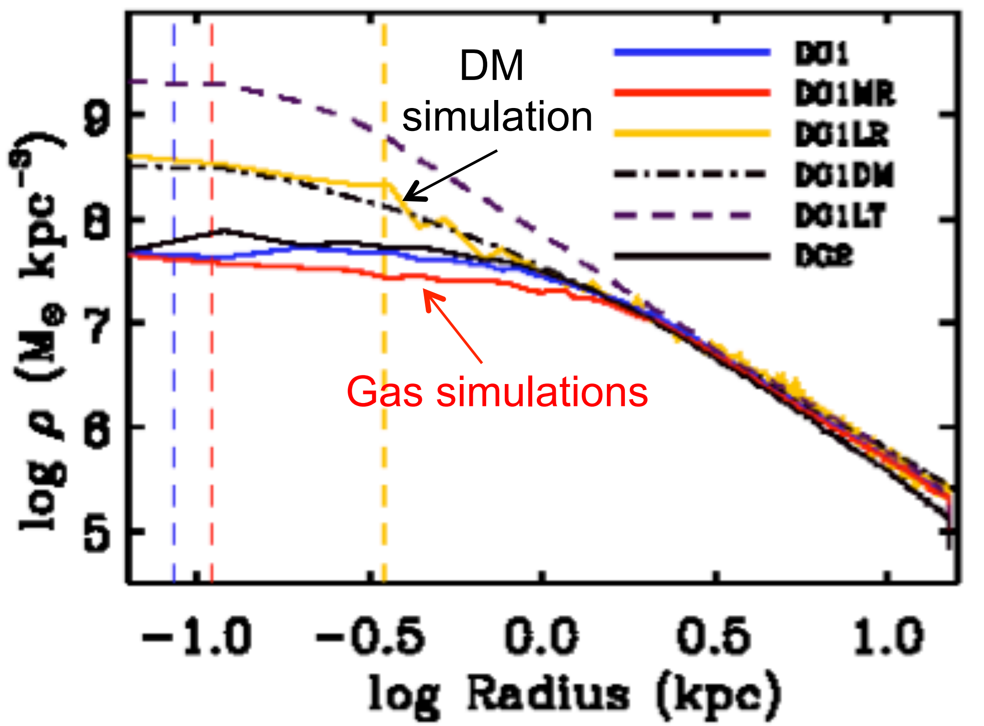
Cores in dwarf galaxy simulations

Governato et al. assume high density threshold for star formation

EAGLE does not

→ High threshold allows large gas mass to accumulate in centre

→ Sudden repeated removal of gas transfers binding energy



Governato et al. '10
Pontzen et al. '11

The diversity of gal rotation curves

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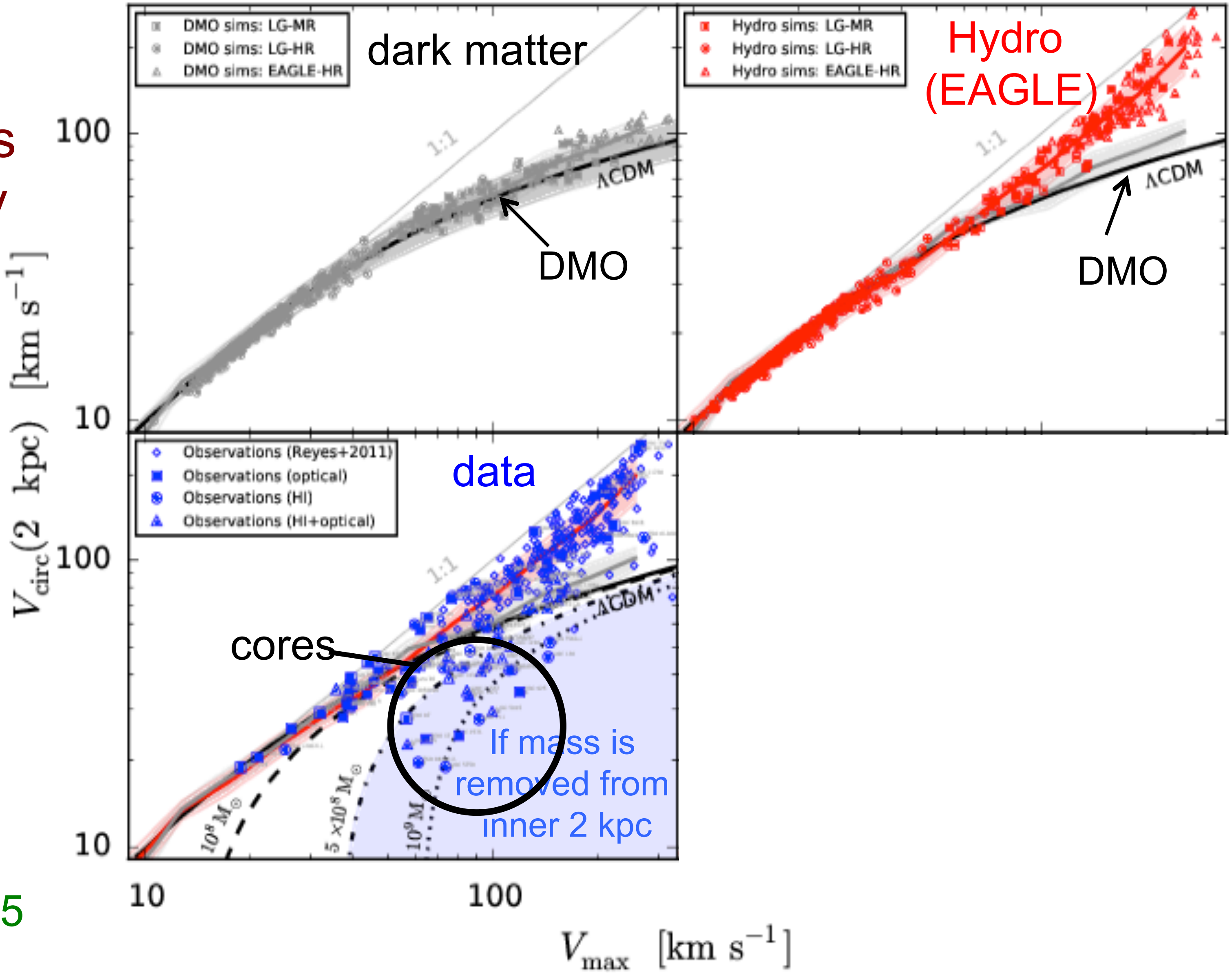
Most galaxies are well fit by EAGLE; others not fit by any simulation



Oman et al. '15

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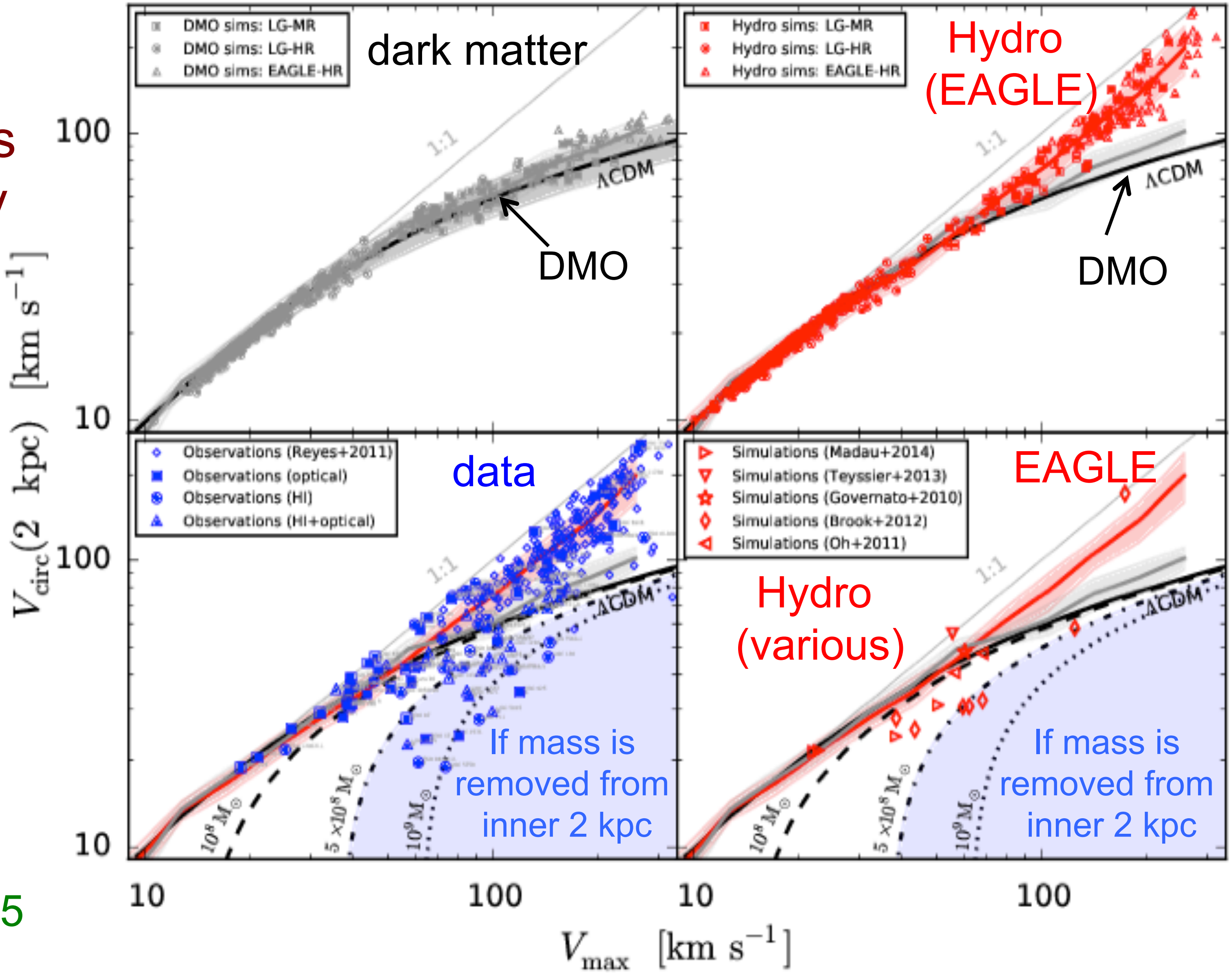


Oman et al. '15

Rotation curves of 2 APOSTLE dwarfs

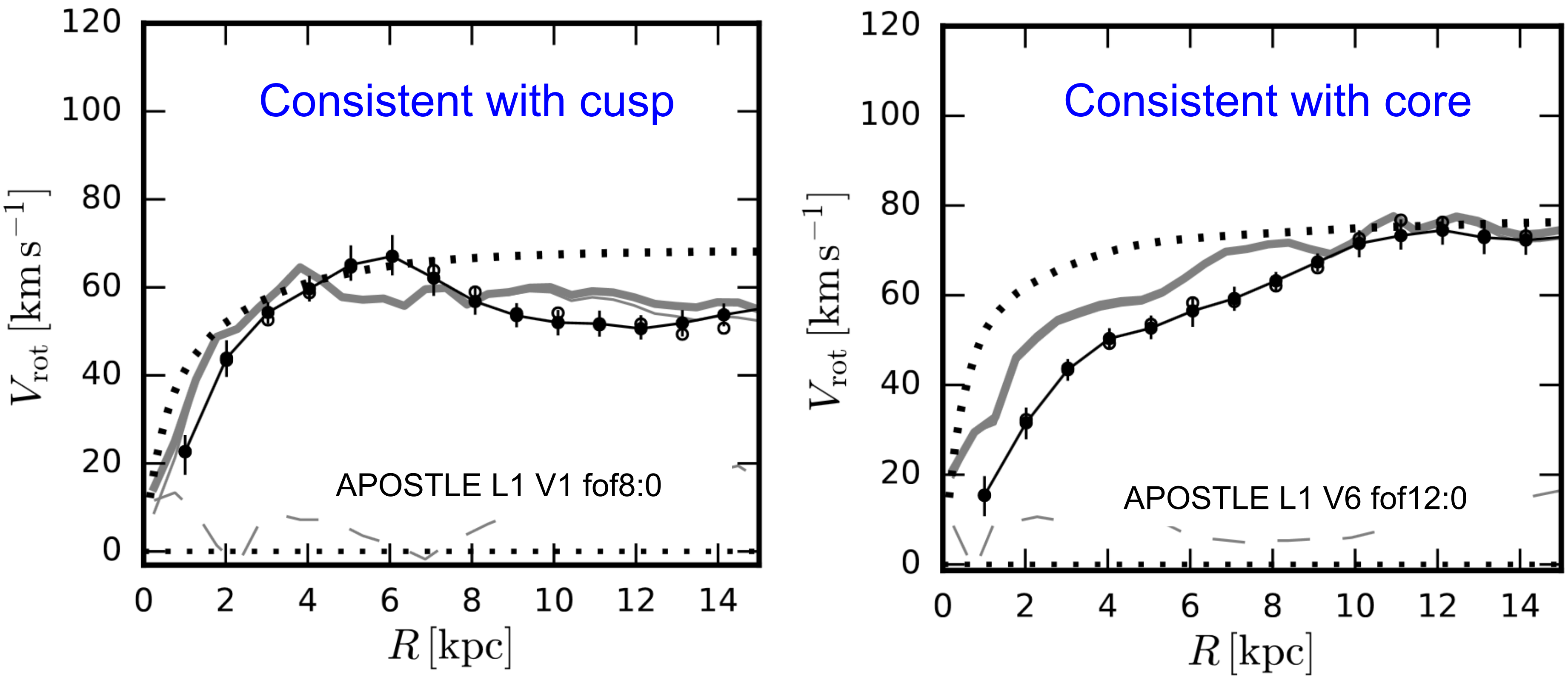
APOSTLE galaxies all have NFW cusps

Tilted-ring model corrected for asymmetric drift

$$V_c = \sqrt{\frac{GM(<r)}{r}}$$

gas $V_\phi(r)$

^{3D}BAROLO fit



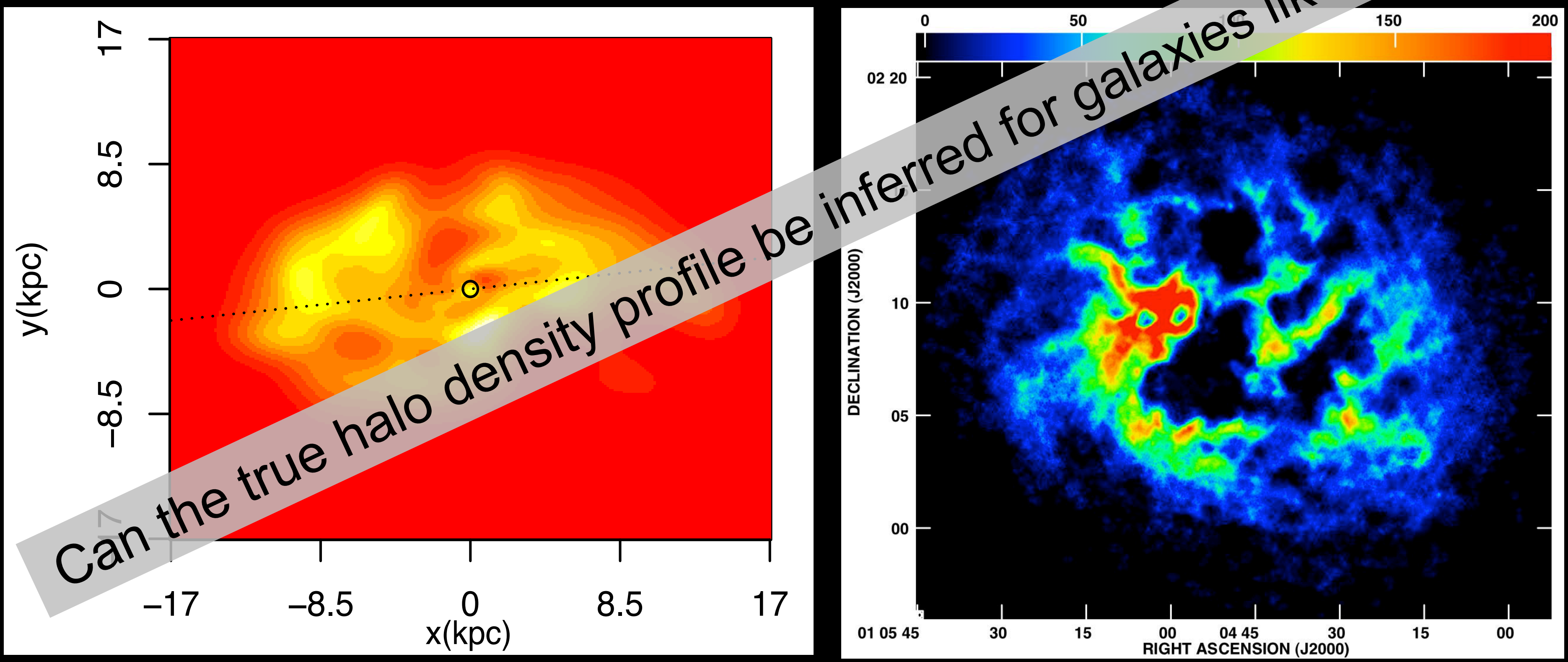
Oman, Marasco, et al '17

Rotation curves of APOSTLE dwarfs

Holes in APOSTLE due to supernovae explosions

APOSTLE dwarf

IC 1613 Little THINGS



Can the true halo density profile be inferred for galaxies like these?

Hague et al '16

Conclusions

- EAGLE/APOSTLE produces:
  - a galaxy population with correct mass function/size distribution
  - the correct MW and M31 satellite luminosiy functions
  - no galaxies in halos of $M<10^9M_o$
  - no cores in halos of any galaxies (including dwarfs)
- Cores in halos can be produced by non-EAGLE baryon effects
- Cores can be incorrectly inferred from 2D gas kinematical data because of non-circular motions