Dark matter halos: cores or cusps?

Carlos S. Frenk
Institute for Computational Cosmology, Durham

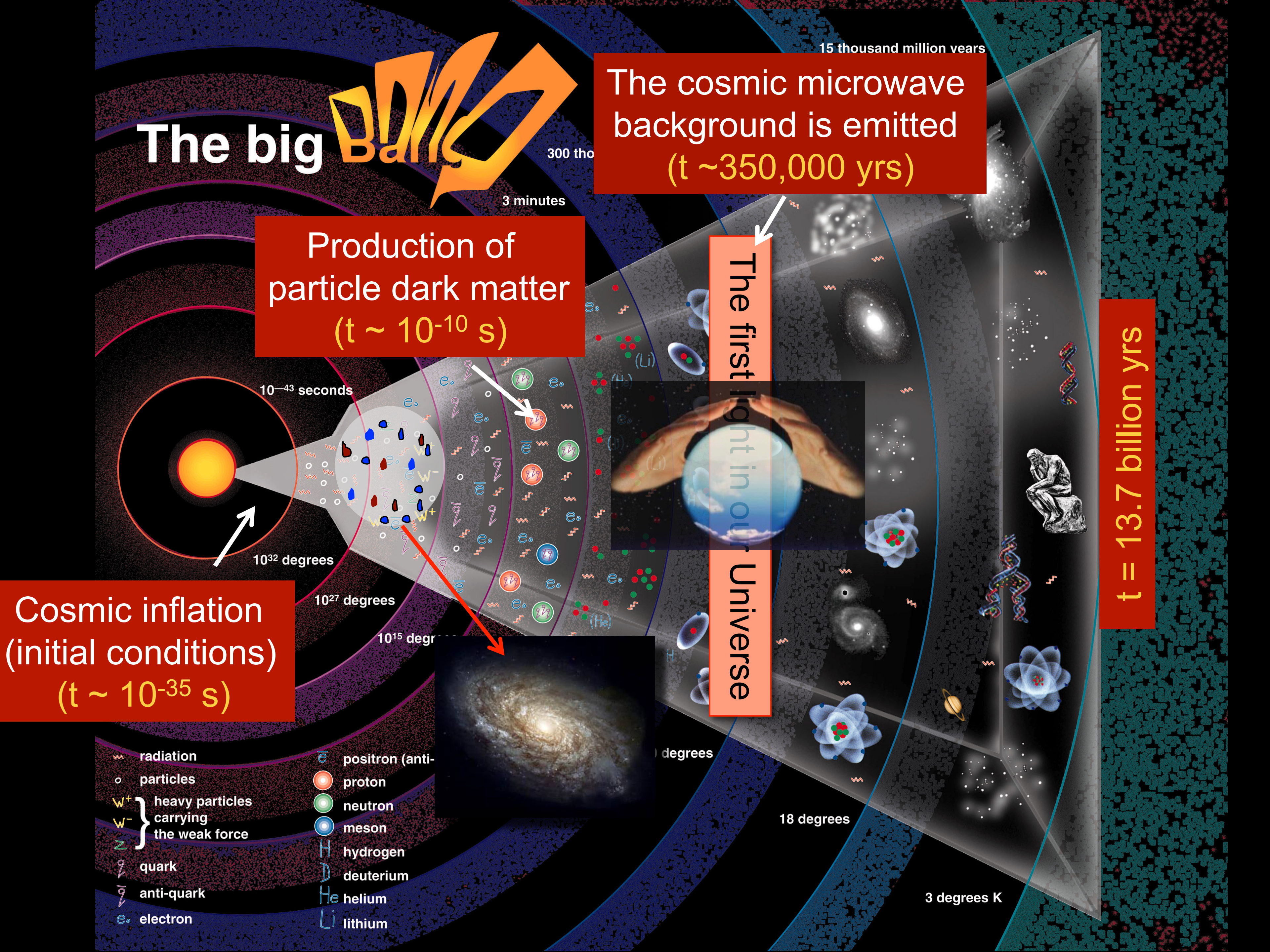
A challenge to cold dark matter?

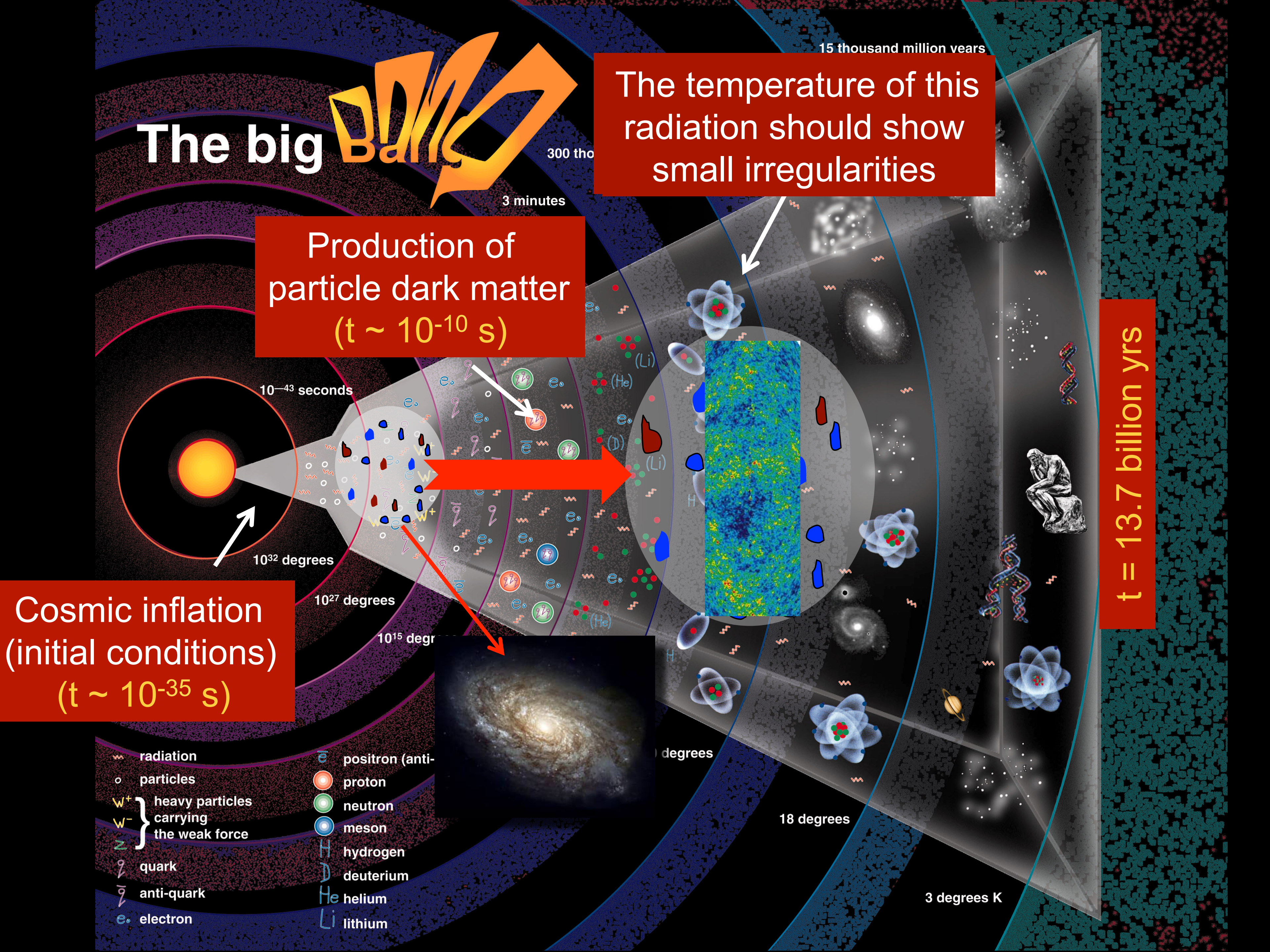
University of Durham

The ΛCDM model of cosmogony

Cosmological constant

Cold dark matter


The big Bang
The cosmic microwave background is emitted (t ~350,000 yrs)
Production of particle dark matter (t ~ 10^-10 s)
Cosmic inflation (initial conditions) (t ~ 10^-35 s)
The first light in our Universe
t = 13.7 billion yrs
15 thousand million years
300 tho
3 minutes
10—43 seconds
1032 degrees
1027 degrees
1015 degr
degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-
proton
neutron
meson
hydrogen
deuterium
helium
lithium



The big Bang
15 thousand million years
300 tho
3 minutes
The temperature of this radiation should show small irregularities
Production of particle dark matter ($t \sim 10^{-10}$ s)
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degr
degrees
18 degrees
3 degrees K
Cosmic inflation (initial conditions) ($t \sim 10^{-35}$ s)
$t = 13.7$ billion yrs
radiation
particles
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helium
lithium

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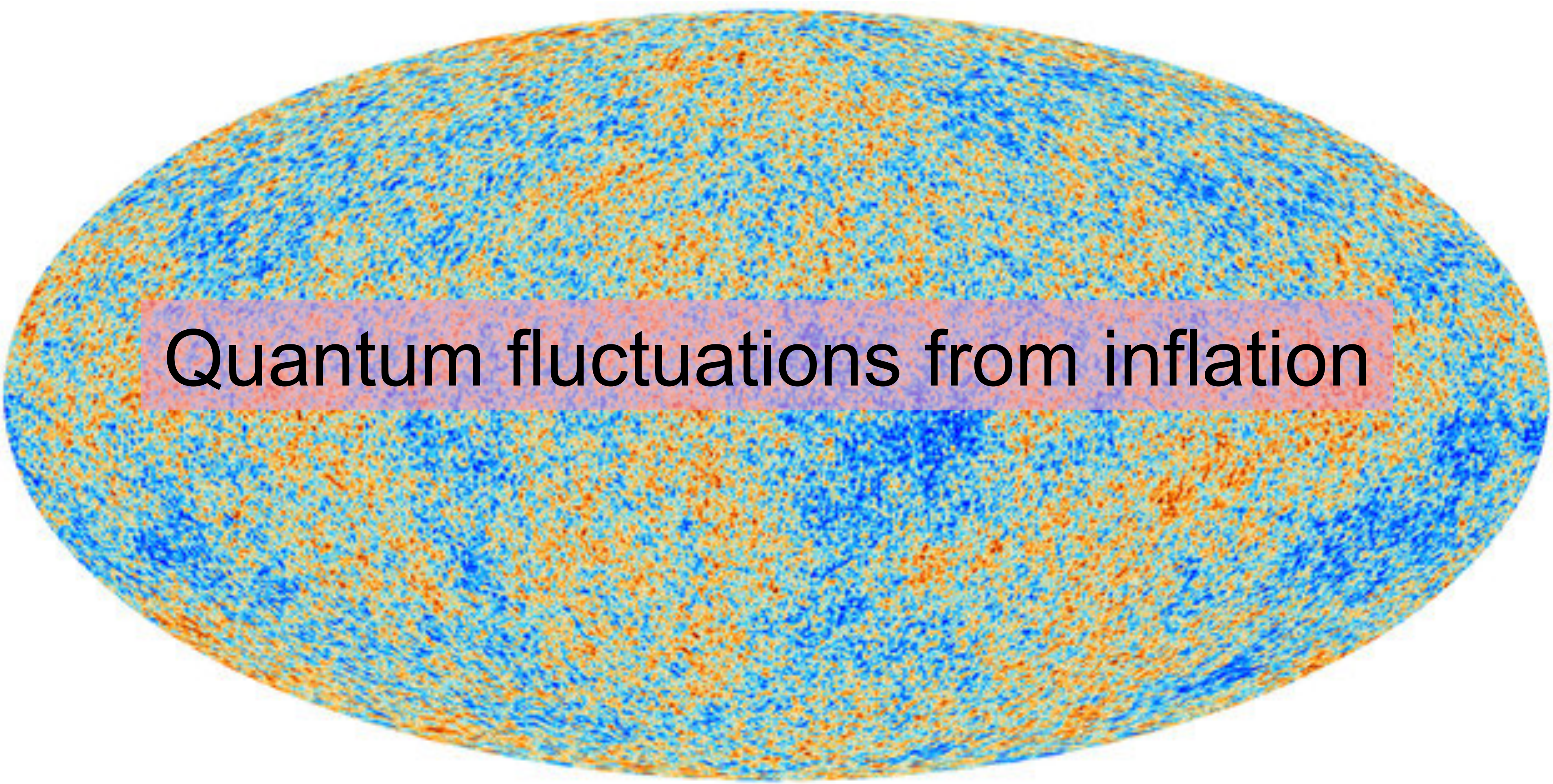
The initial conditions for galaxy formation



Planck satellite

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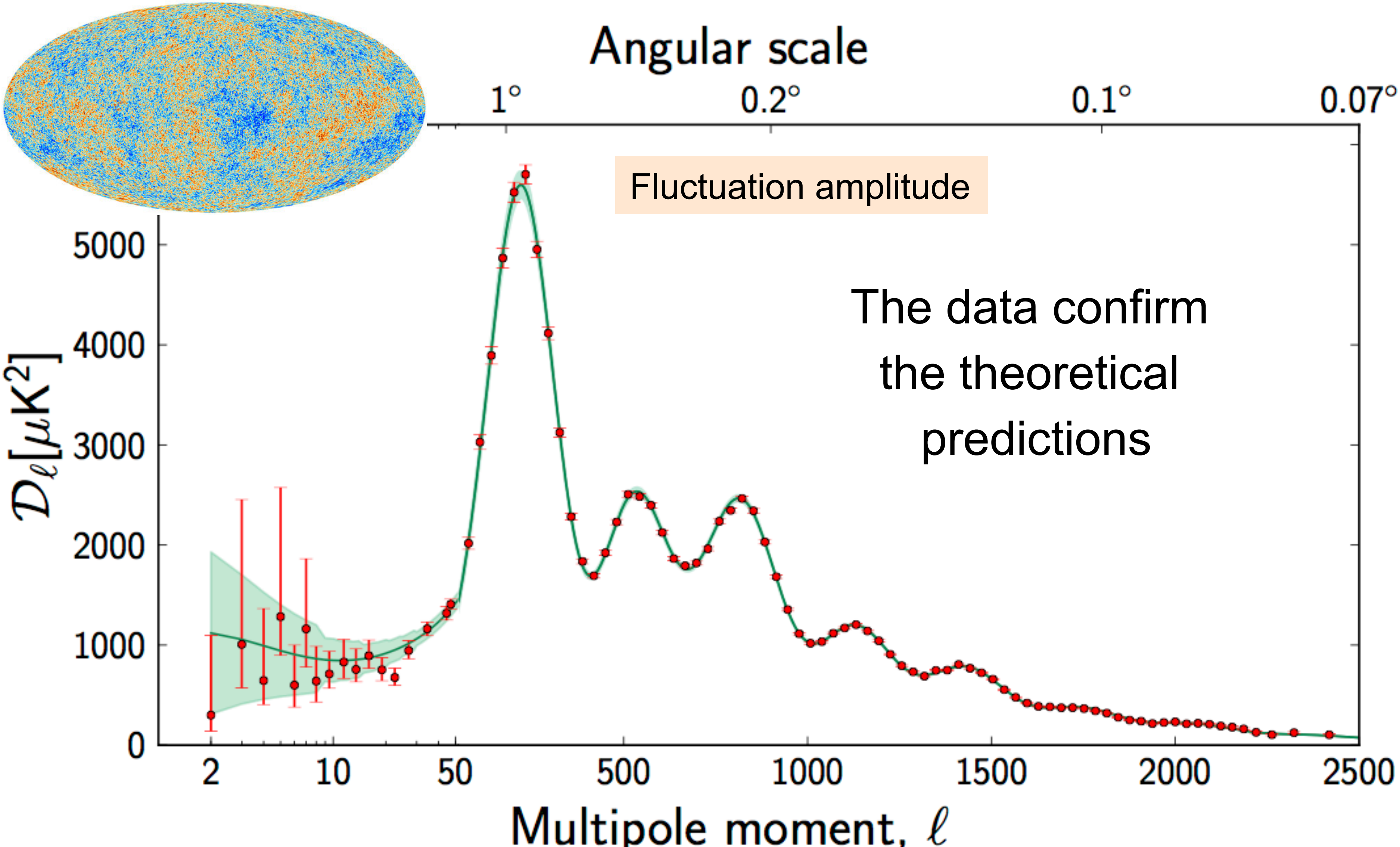
Planck: CMB temperature anisotropies



The data confirm the theoretical predictions

Planck coll. 2015

Institute for Computational Cosmology

Univer

The six parameters of minimal ΛCDM model

	Planck+WP	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$

6 mdoel parameters

A 40σ detection of non-baryonic dark matter using only z=1000 data!

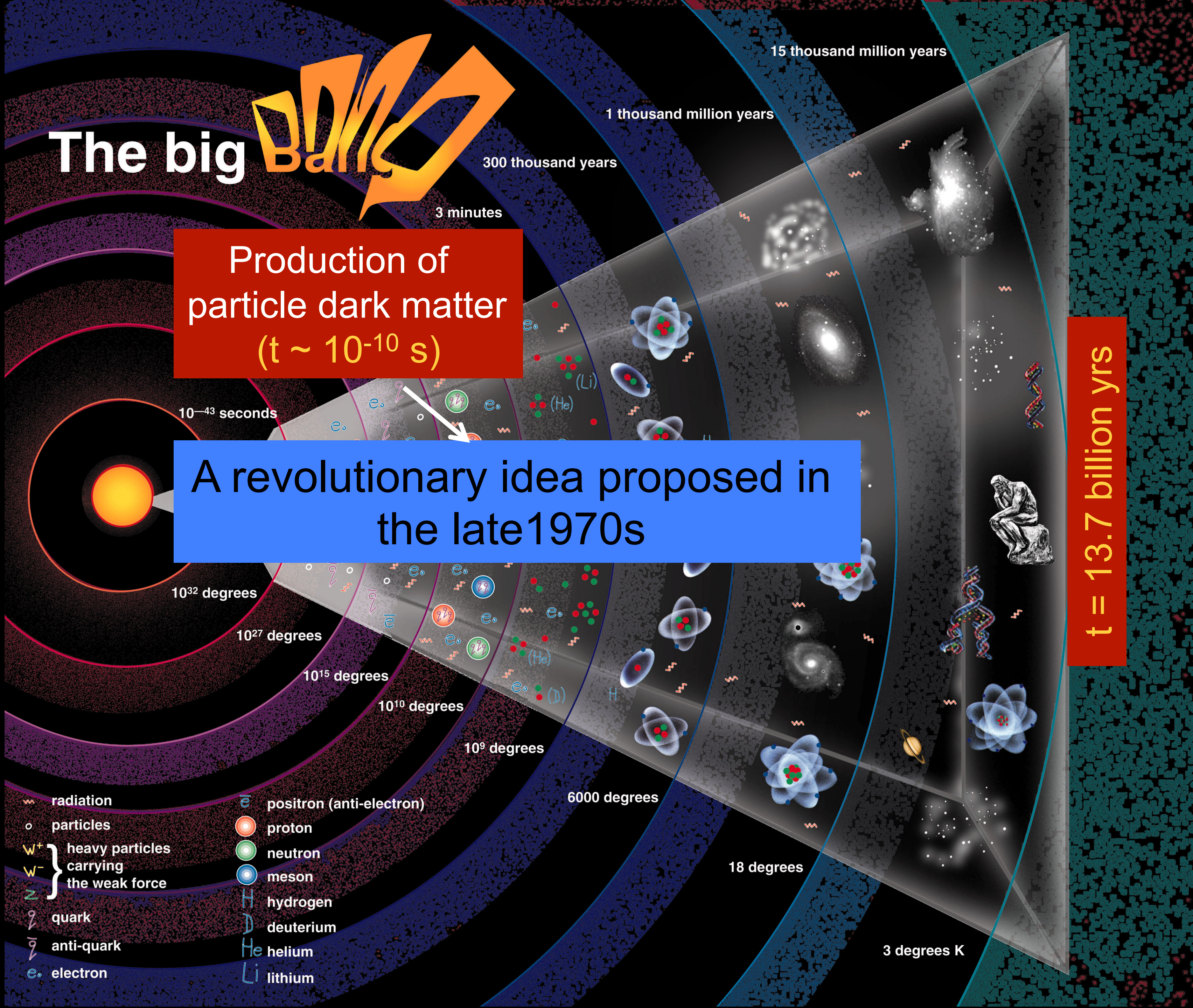
Planck collaboration ‘13

Institute for Computational Cosmology

Production of particle dark matter ($t \sim 10^{-10}$ s)

A revolutionary idea proposed in the late1970s

$t = 13.7$ billion yrs



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Non-baryonic dark matter candidates

From the early 1980s:

Type	example	mass
hot	neutrino	few tens of eV
warm	sterile ν	keV-MeV
cold	axion neutralino	10^{-5}eV - 100 GeV

These possibilites can be tested with astrophysics

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The dark matter power spectrum

Free streaming →

$\lambda_{cut} \propto m_x^{-1}$

for thermal relic

m_{CDM} ~ 100GeV

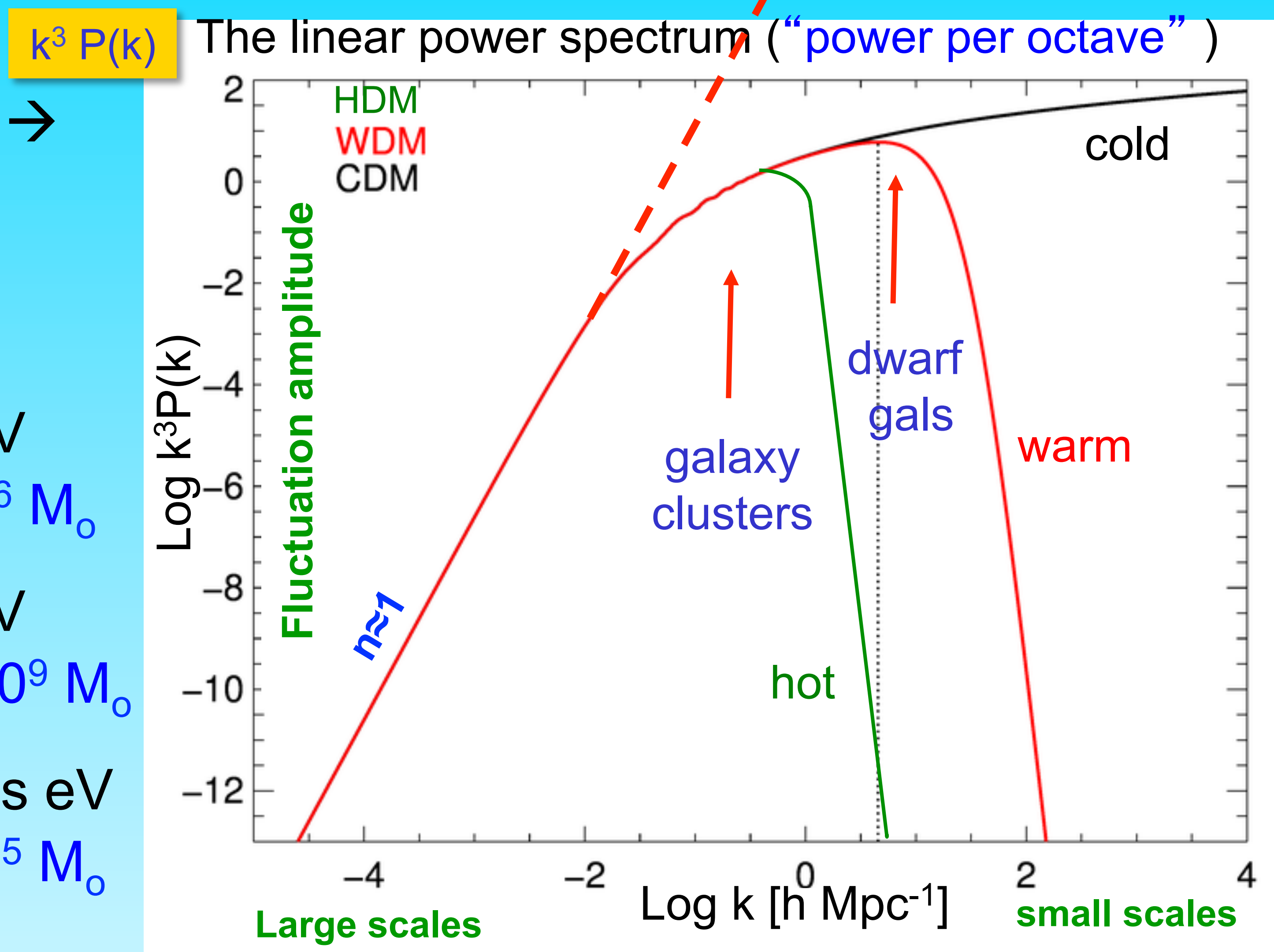
susy; M_{cut} ~ 10^{-6} M_o

m_{WDM} ~ few keV

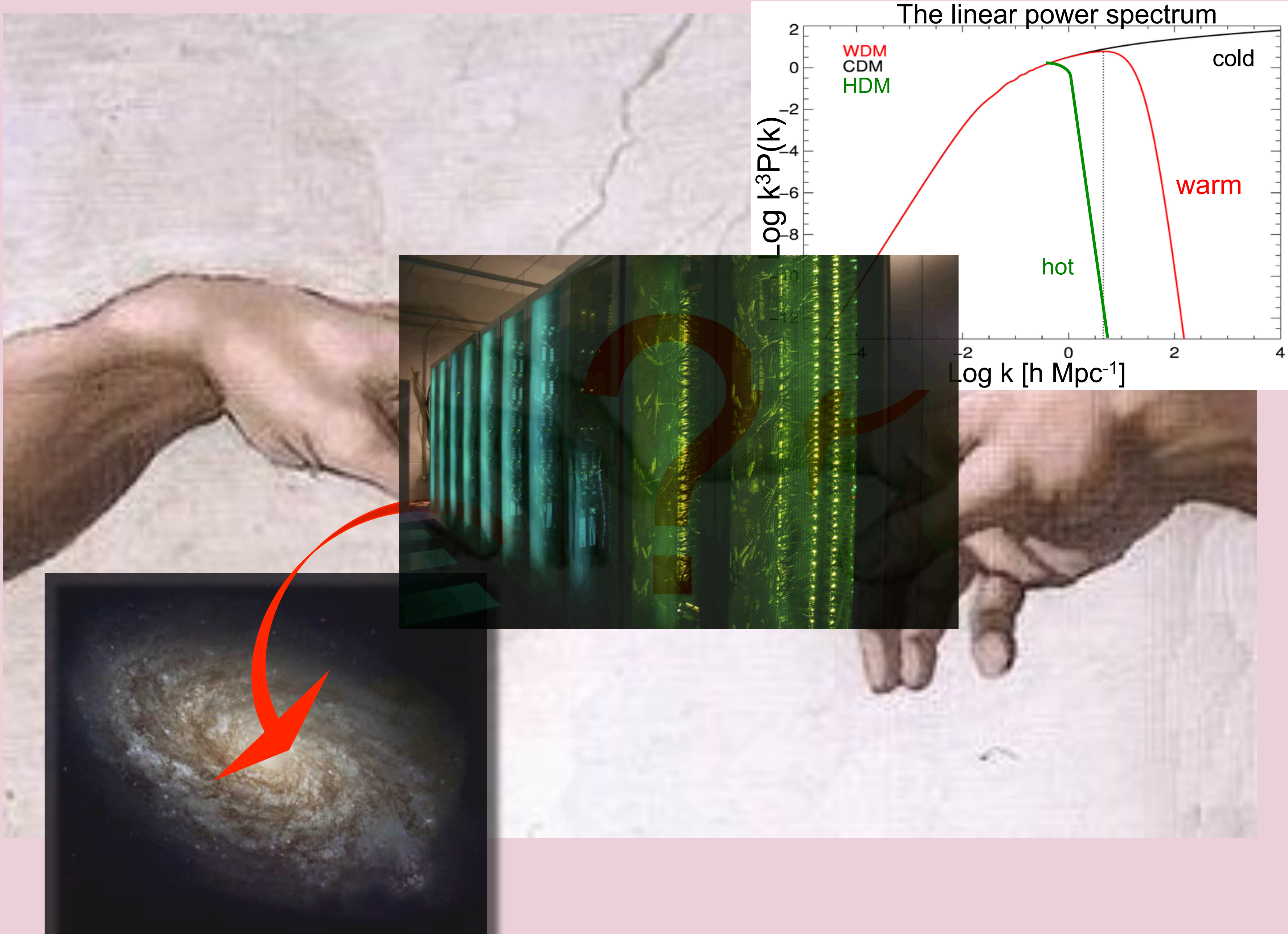
sterile ν; M_{cut}~10^9 M_o

m_{HDM} ~ few tens eV

light ν; M_{cut}~10^{15} M_o



Non-linear evolution



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Non-linear evolution: simulations

Initial conditions + assumption about content of Universe

Relevant equations:

Collisionless Boltzmann;
Poisson; Friedmann eqns;
Radiative hydrodynamics
Subgrid astrophysics

How to make a virtual universe

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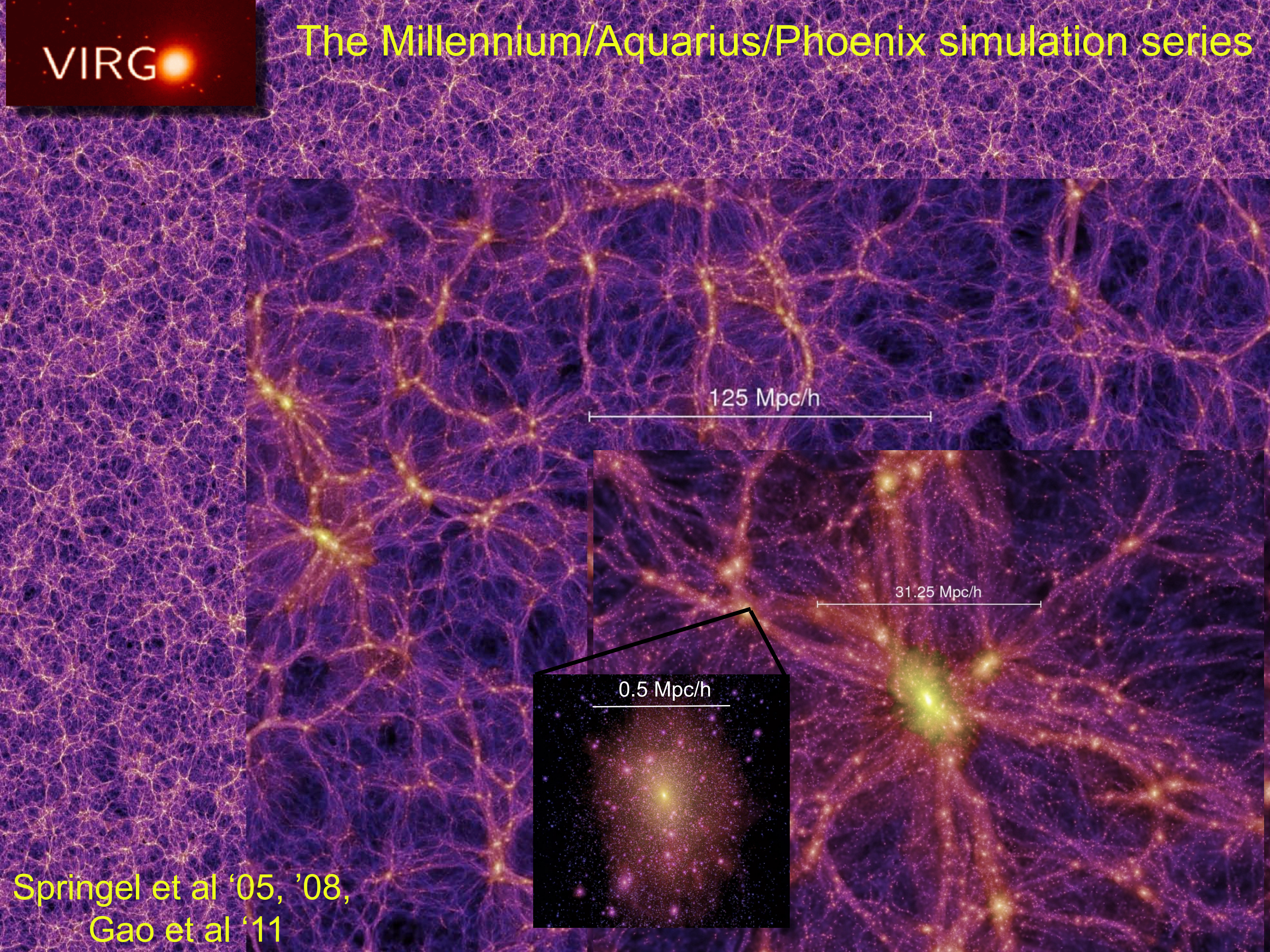
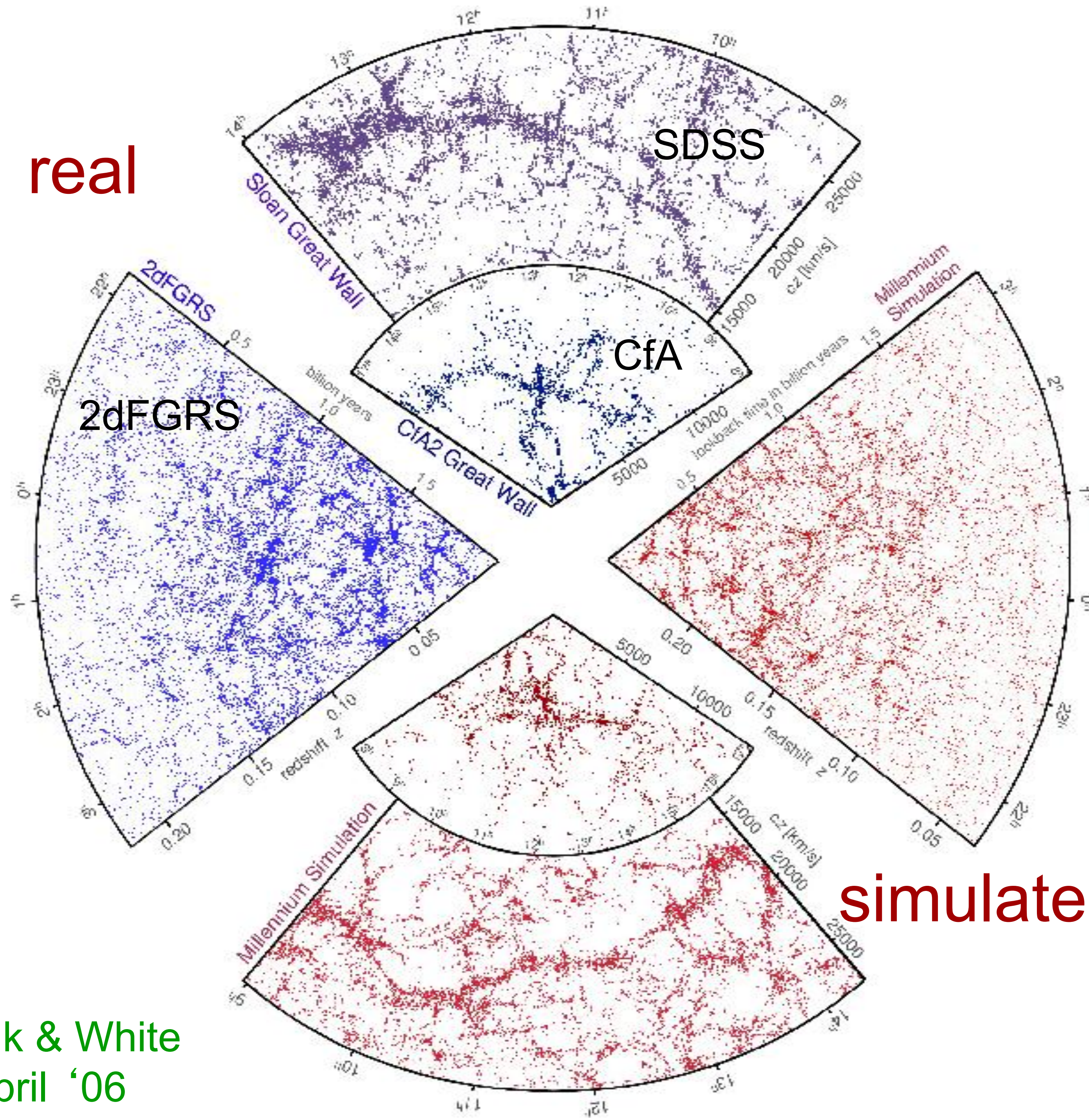
The Millennium/Aquarius/Phoenix simulation series



Springel et al ‘05, ’08,
Gao et al ‘11

real



simulated

Springel, Frenk & White
Nature, April ‘06

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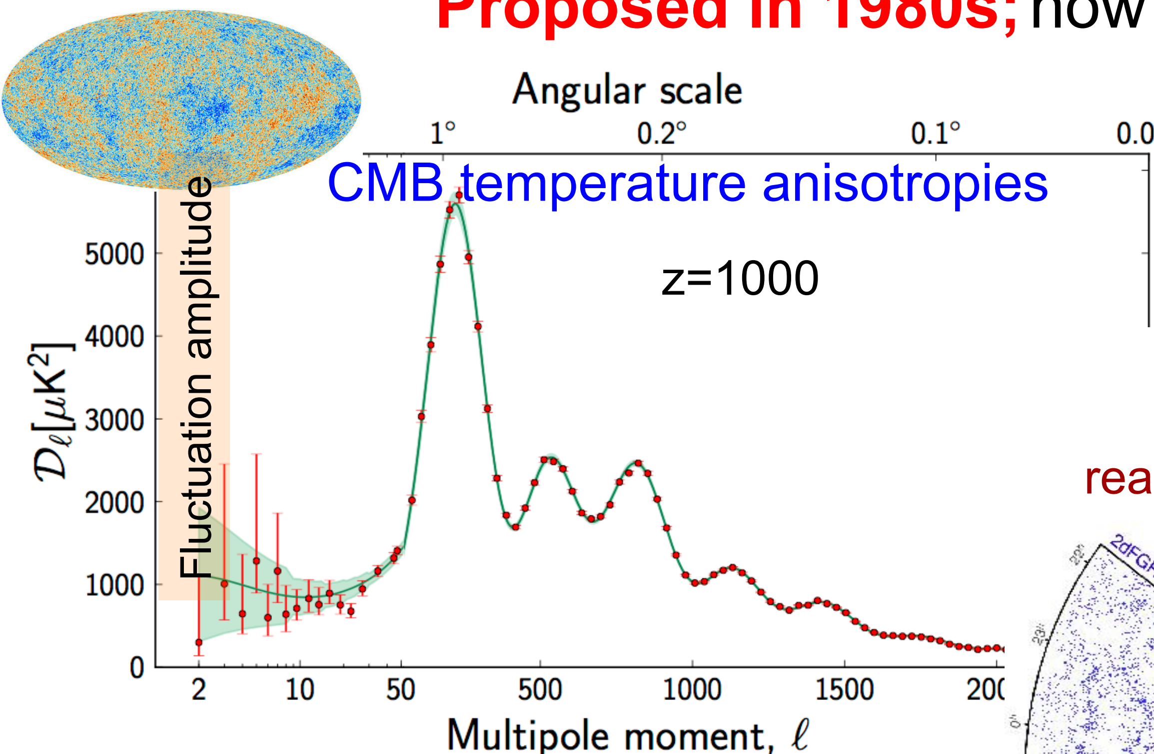
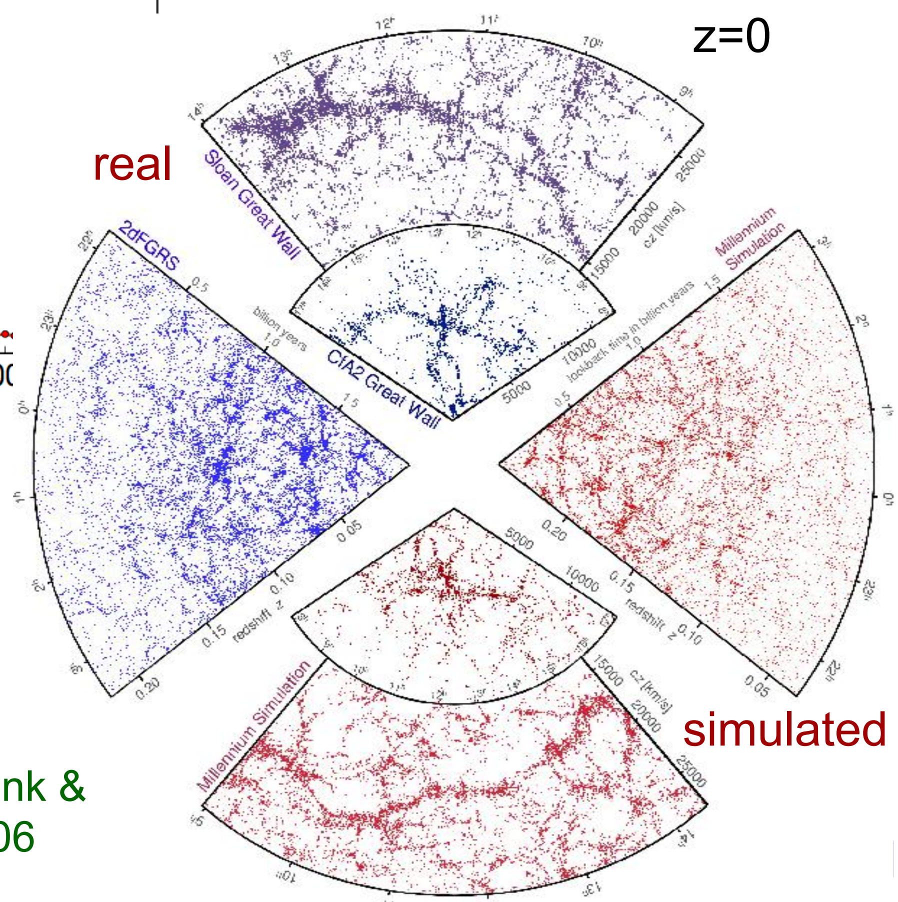
The ΛCDM model of cosmogony

Proposed in 1980s; now empirically supported by:



Planck coll. 2015

Galaxy clustering



Springel, Frenk & White 2006

ICC
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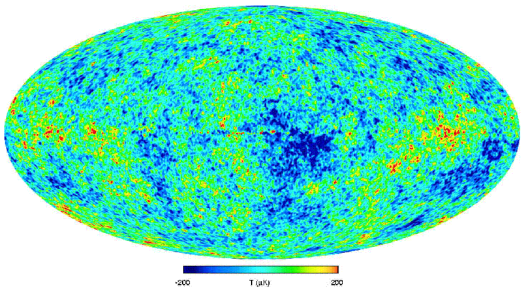
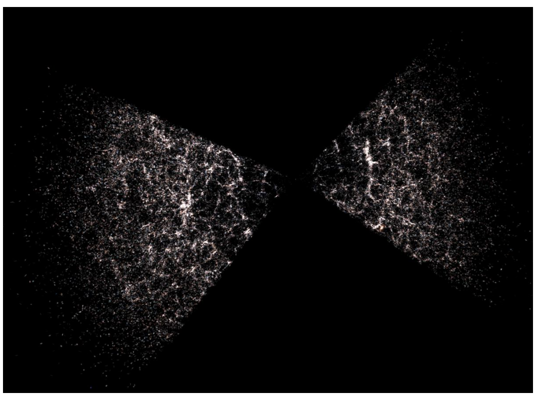
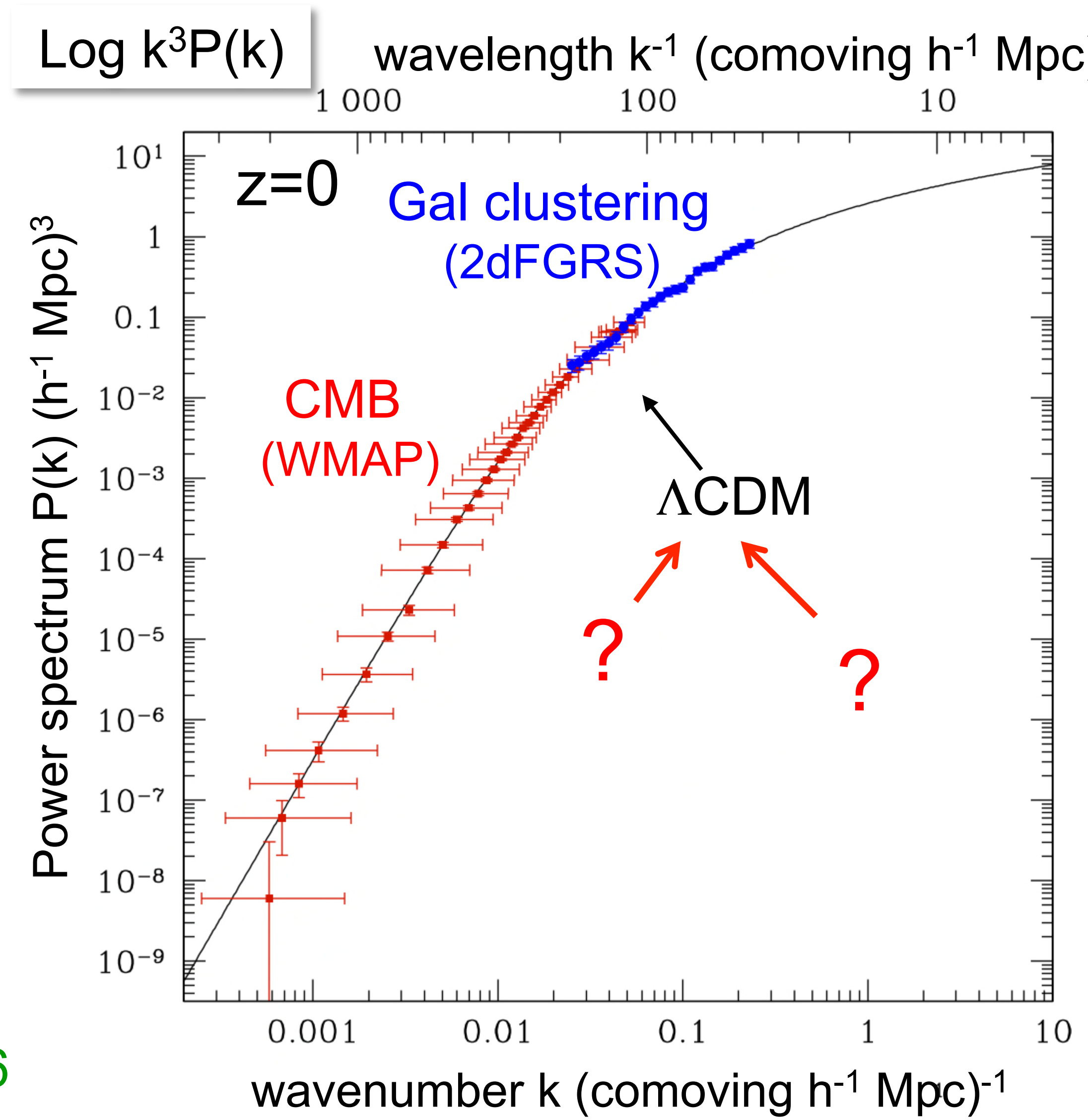
The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



z~0



⇒ ΛCDM provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06

ICC University of Durham

The cosmic power spectrum: from the CMB to the 2dFGRS

Free streaming →

$\lambda_{cut} \propto m_x^{-1}$

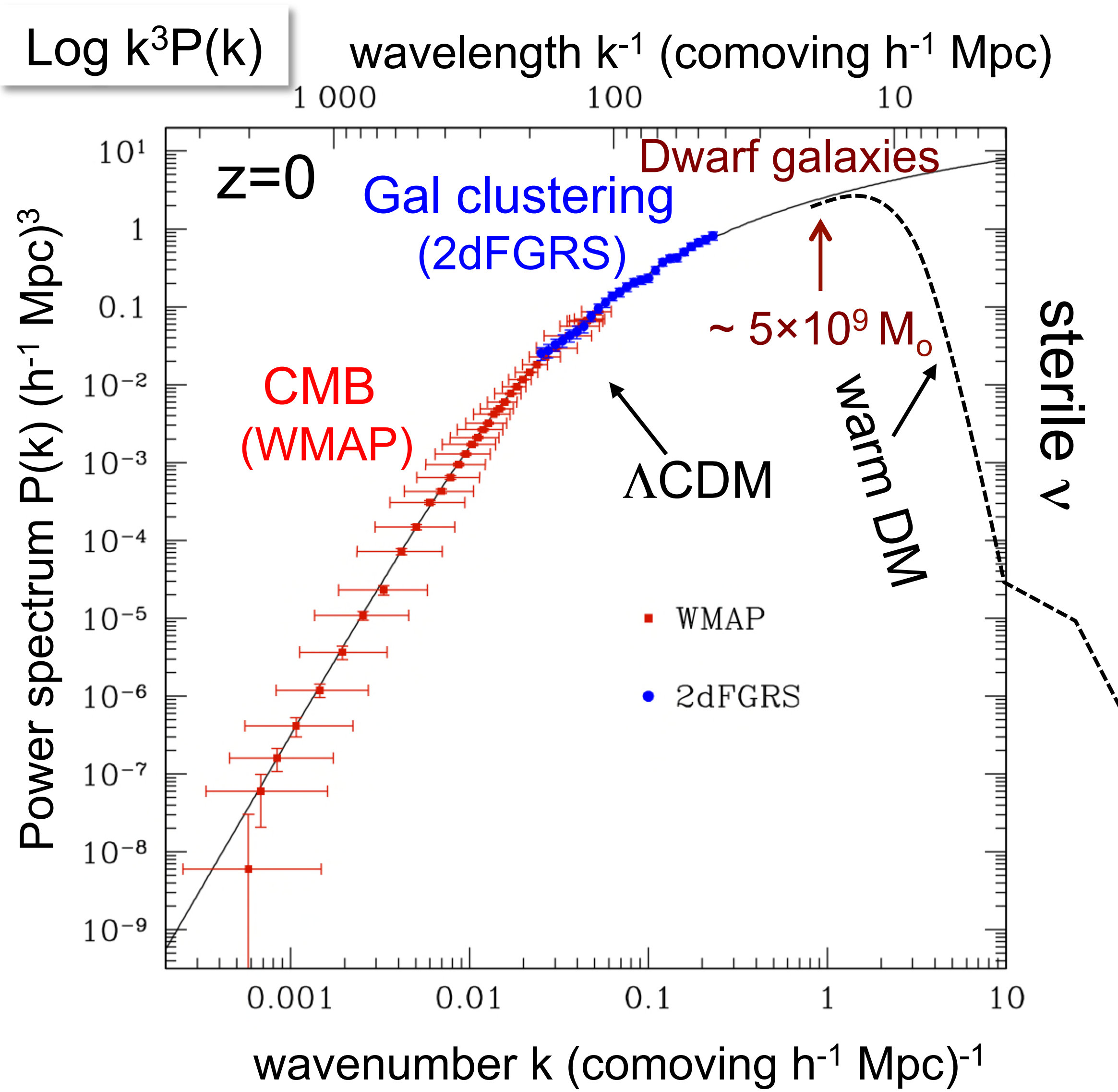
for thermal relic

$m_{CDM} \sim 100GeV$

susy; $M_{cut} \sim 10^{-6} M_o$

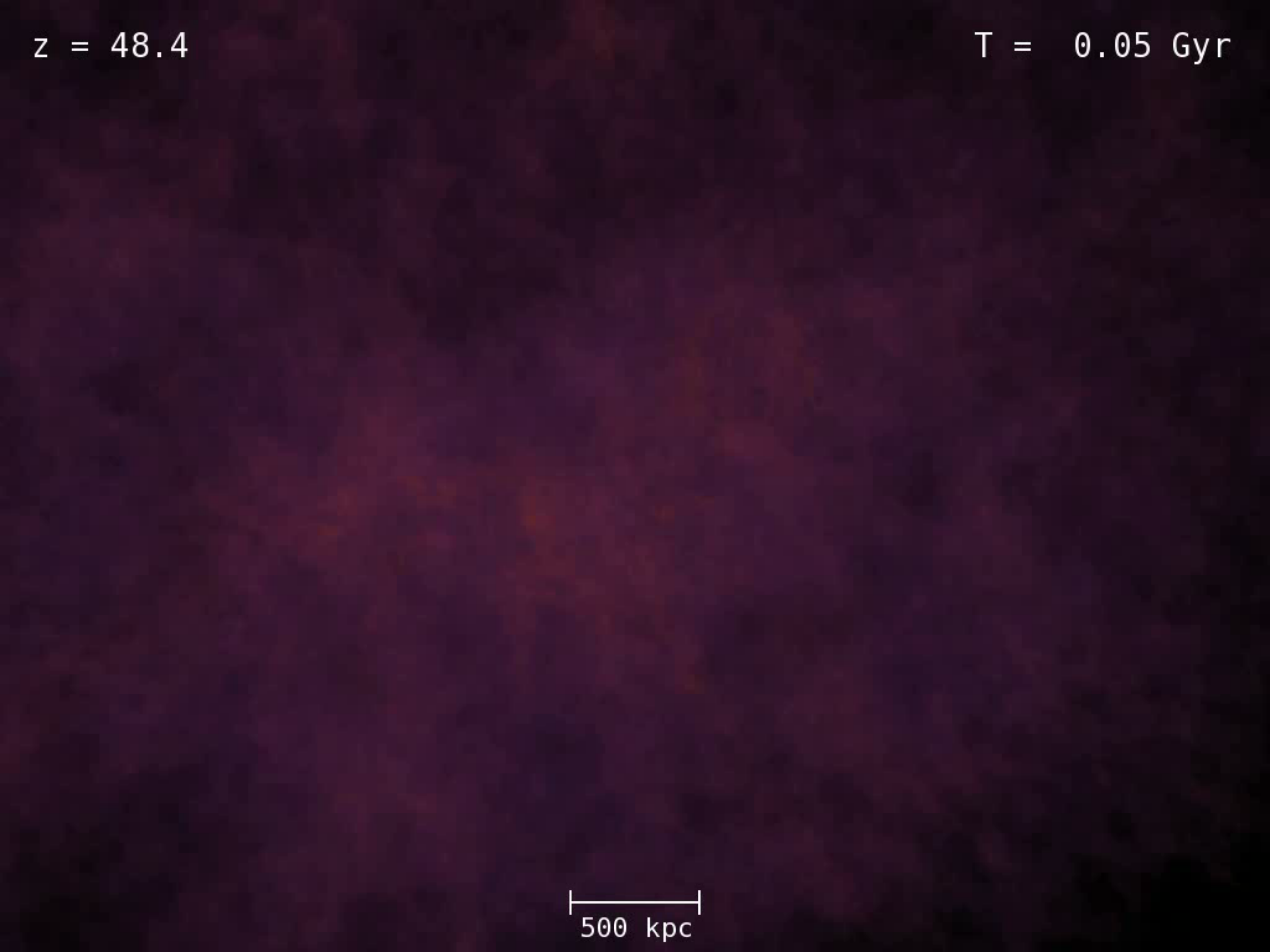
$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9 M_o$



The density structure of dark matter halos

→ a fundamental prediction of cold dark matter


z = 48.4
T = 0.05 Gyr
500 kpc

ICC

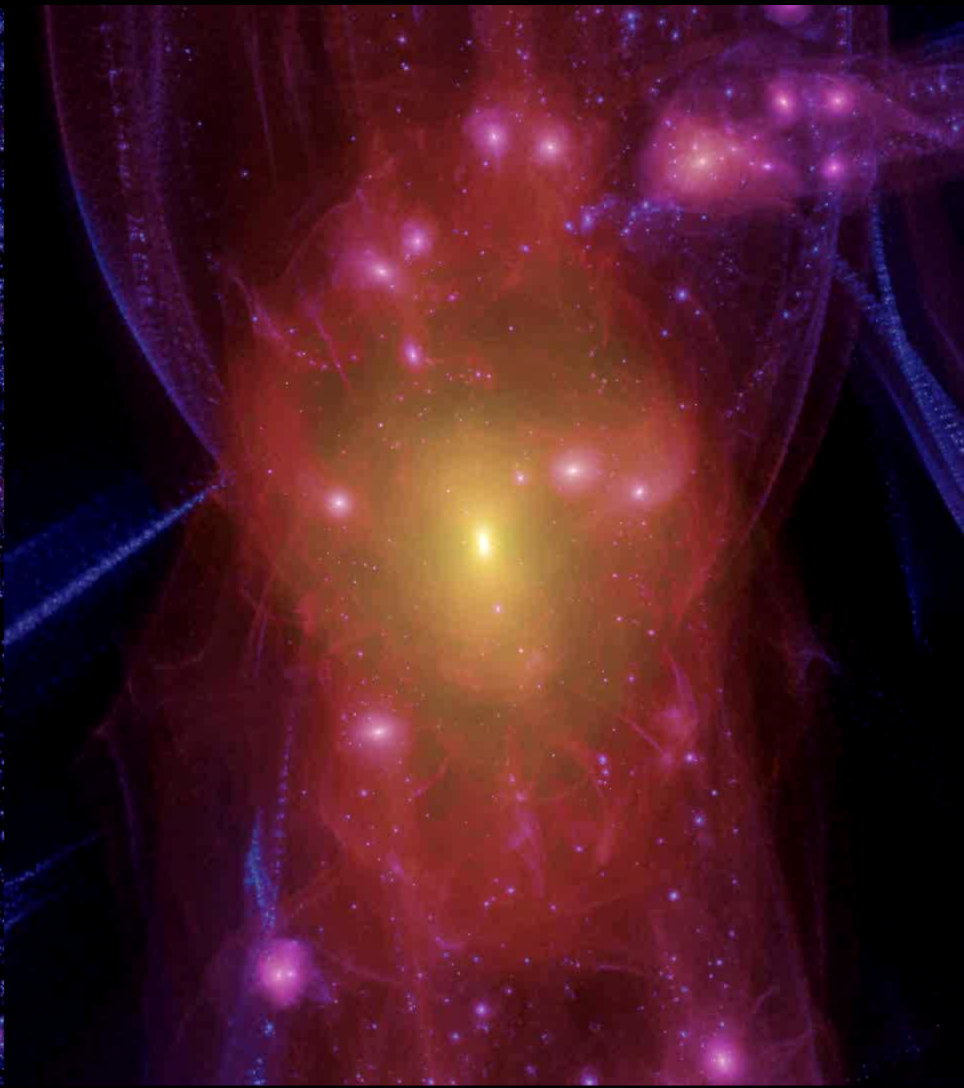
Cold Dark Matter | Warm Dark Matter

13.4 billion years ago

Institute for Computational Cosmology

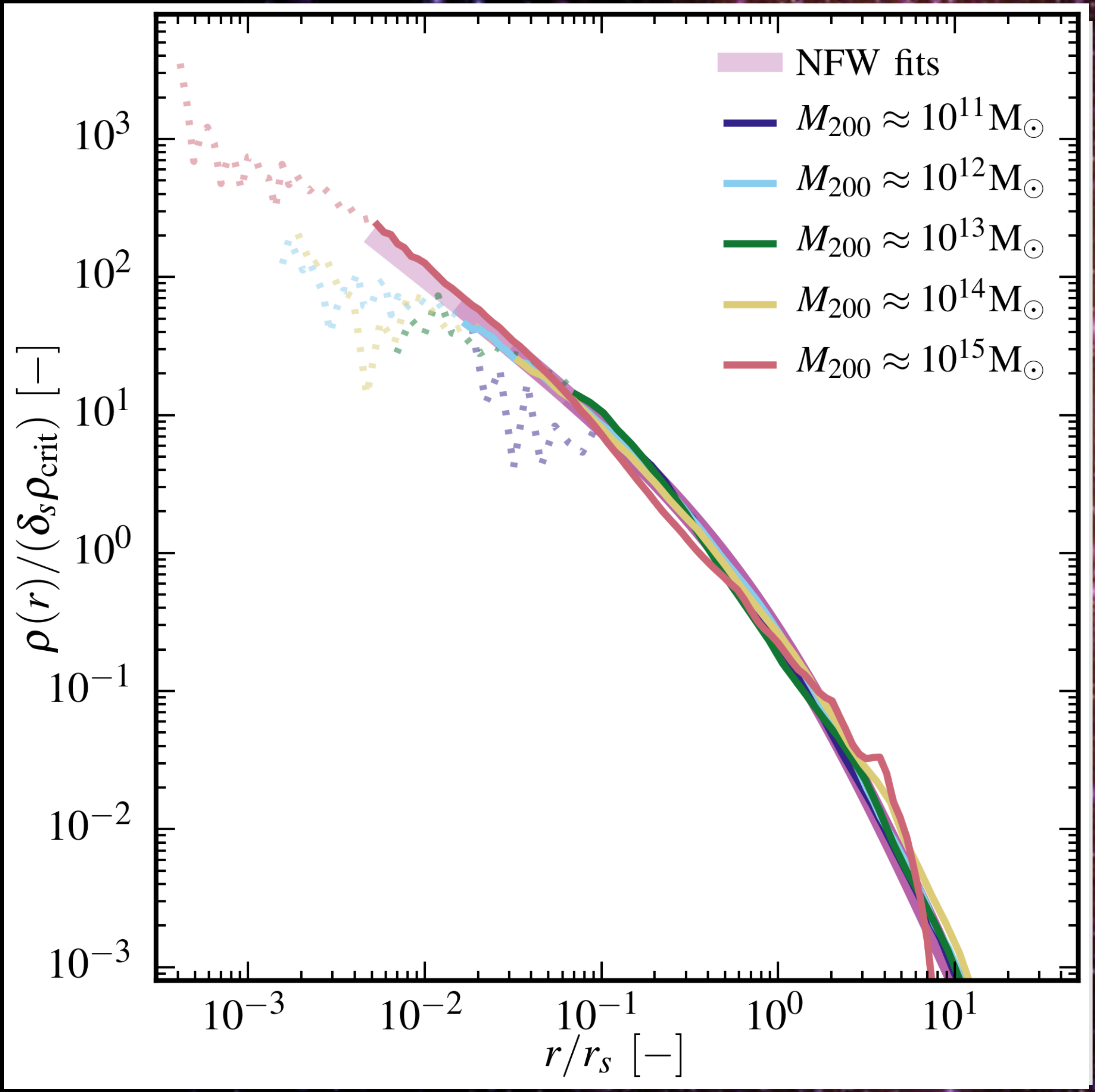
cold dark matter

warm dark matter



Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12

The Density Profile of Cold Dark Matter Halos



Shape of halo profiles ~independent of halo mass & cosmological parameters

Density profiles are "cuspy" - no `core' near the centre

Fitted by simple formula:

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

(Navarro, Frenk & White '97)

More massive halos and halos that form earlier have higher densities (bigger δ)

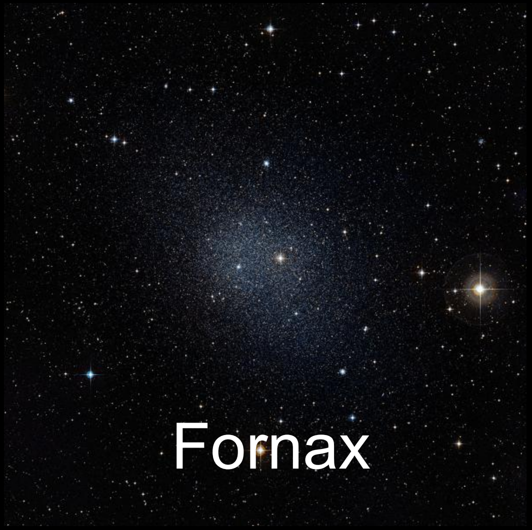
Dark matter halos: cores or cusps?

A myth

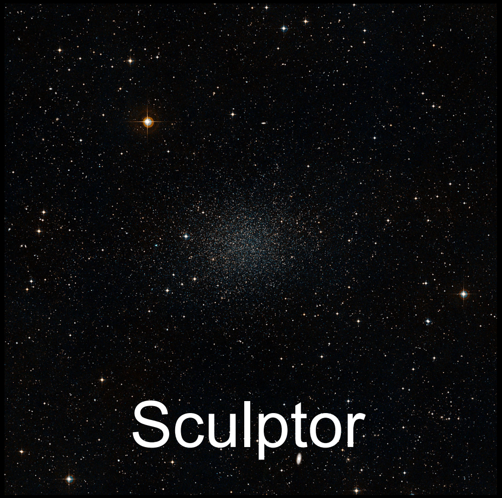
The DM halos of dwarf galaxies have central cores

A challenge for CDM?

Cores in real dwarf galaxies



Fornax



Sculptor

Leo I

Sextans

Carina

Sagittarius

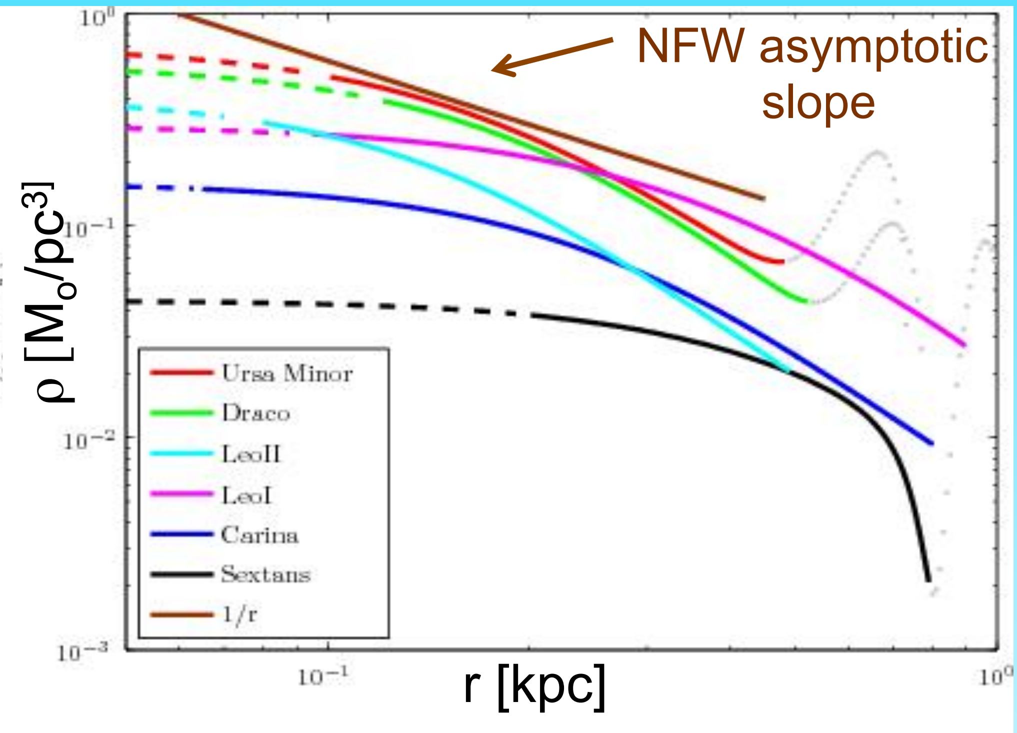
University of Durham

The DM halos of dwarf spheroidals

THE ASTROPHYSICAL JOURNAL, 663:948–959, 2007 July 10

THE OBSERVED PROPERTIES OF DARK MATTER ON SMALL SPATIAL SCALES

GERARD GILMORE,[1] MARK I. WILKINSON,[1,2] ROSEMARY F. G. WYSE,[3] JAN T. KLEYNA,[4] ANDREAS KOCH,[5,6]
N. WYN EVANS,[1] AND EVA K. GREBEL[6,7]



Inferred density profiles for 6 dwarf spheroidals

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

"…(keV) sterile neutrino particles have been discussed as relevant in just the spatial and density range we have derived here."

Density profiles of WDM halos

WDM particles have significant thermal velocities at early times

Since the phase-space density cannot increase, this should produce a nearly uniform density core

University of Durham

Core radii in WDM halos

The thermal velocities of WDM particles induce cores

Liouville's theorem → upper bound on fine-grained ph. space den.

$$f_{FD} = \frac{g m_x^4}{2(2\pi\hbar)^3}.$$

Shao, Gao, Theuns, Frenk '13

Maccio et al.'12

University of Durham

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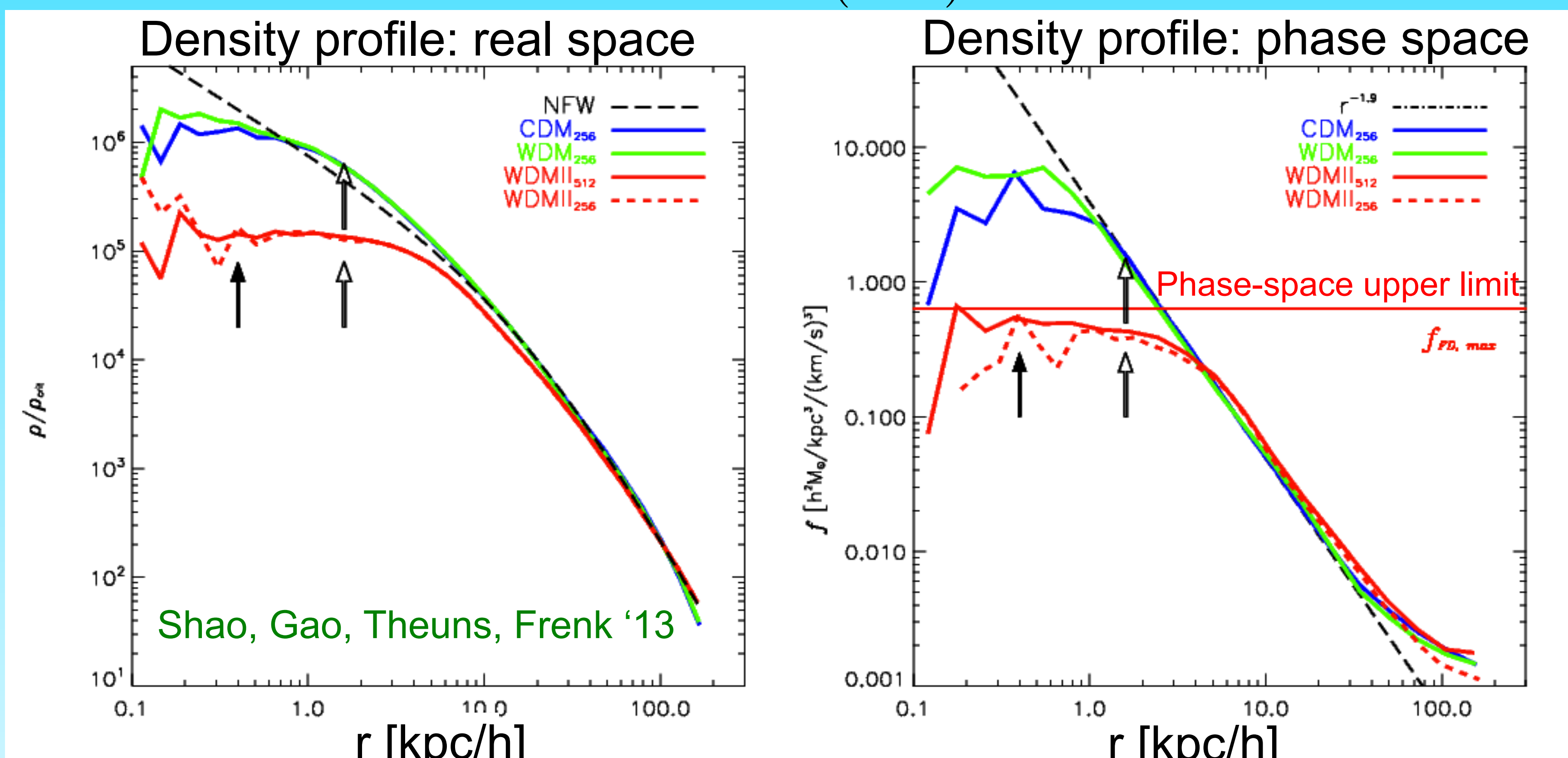


Core radii in WDM halos

University of Durham

The thermal velocities of WDM particles induce cores

Liouville's theorem → upper bound on fine-grained ph. space den.

$$f_{FD} = \frac{g m_x^4}{2(2\pi\hbar)^3}.$$

By requiring $f = f_{FD}$

$$m_x^4 = \frac{6(2\pi\hbar)^3}{(2\pi)^{5/2} g G \sigma r_h^2}$$

Shao, Gao, Theuns, Frenk ' 13

University of Durham

Core radii in WDM halos

The thermal velocities of WDM particles induce cores

Liouville's theorem → upper bound on fine-grained ph. space den.

$$f_{FD} = \frac{g m_x^4}{2(2\pi\hbar)^3}.$$

Phase space arguments →

$$r_c = \frac{pc}{\left(\frac{m_x c^2}{8.2keV}\right)^2 \left(\frac{\sigma}{km/s}\right)^{1/2} \left(\frac{g}{2}\right)^{1/2}}$$

core radius

For m_{WDM} > 1.5 keV, the core radii in WDM models are of 10 times smaller than the values inferred by Gilmore et al. !

→ core radii in dwarfs NOT relevant in WDM models

Shao, Gao, Theuns, Frenk '13
see also Maccio et al '12

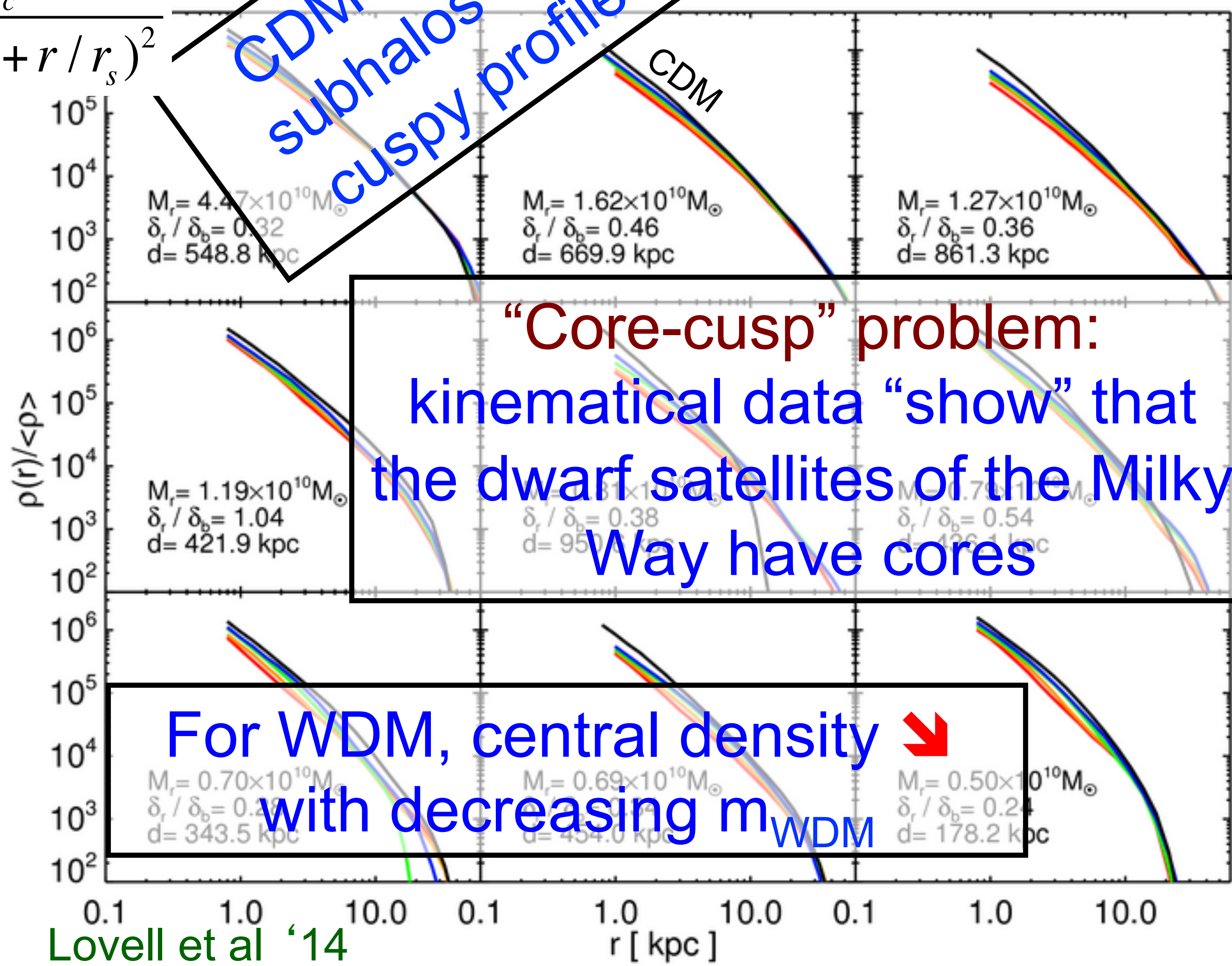
The core-cusp problem

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

CDM & WDM subhalos have cuspy profiles

WDM

- 2.3 keV
- 2.0 keV
- 1.6 keV
- 1.4 keV



"Core-cusp" problem: kinematical data "show" that the dwarf satellites of the Milky Way have cores

For WDM, central density ↘ with decreasing m_{WDM}

Lovell et al '14

The DM halos of dwarf spheroidals

University of Durham

The Astrophysical Journal, 663:948–959, 2007 July 10

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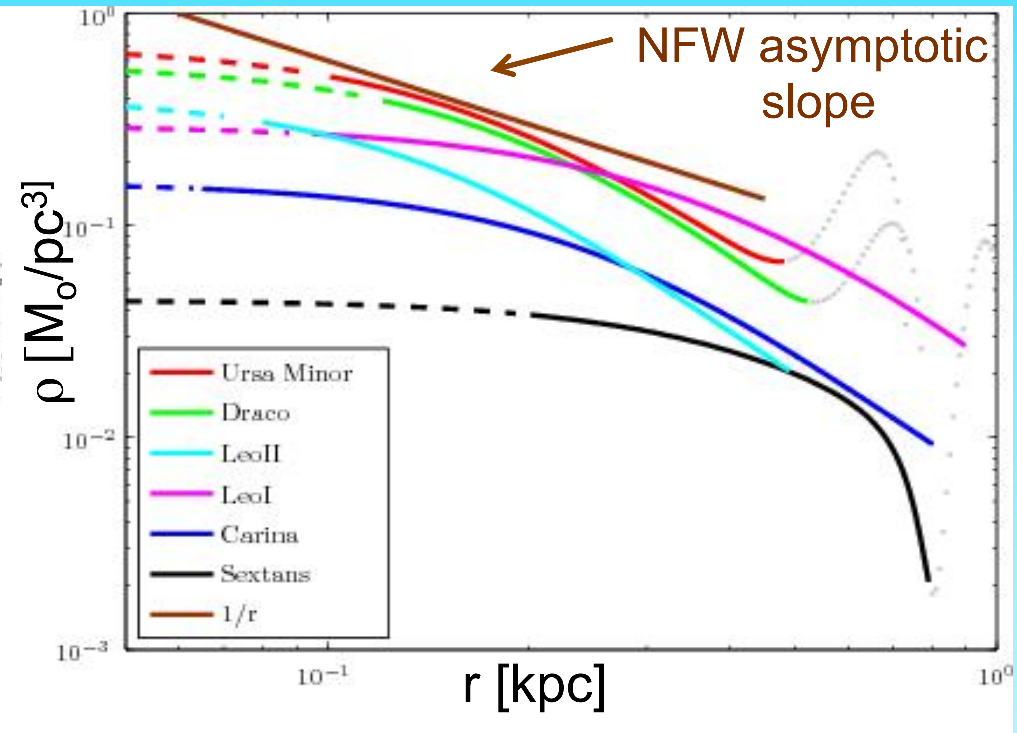
Gerard Gilmore,[1] Mark I. Wilkinson,[1,2] Rosemary F. G. Wyse,[3] Jan T. Kleyna,[4] Andreas Koch,[5,6] N. Wyn Evans,[1] and Eva K. Grebel[6,7]



Inferred density profiles for 6 dwarf spheroidals

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"…(keV) sterile neutrino particles have been discussed as relevant in just the spatial and density range we have derived here."

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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

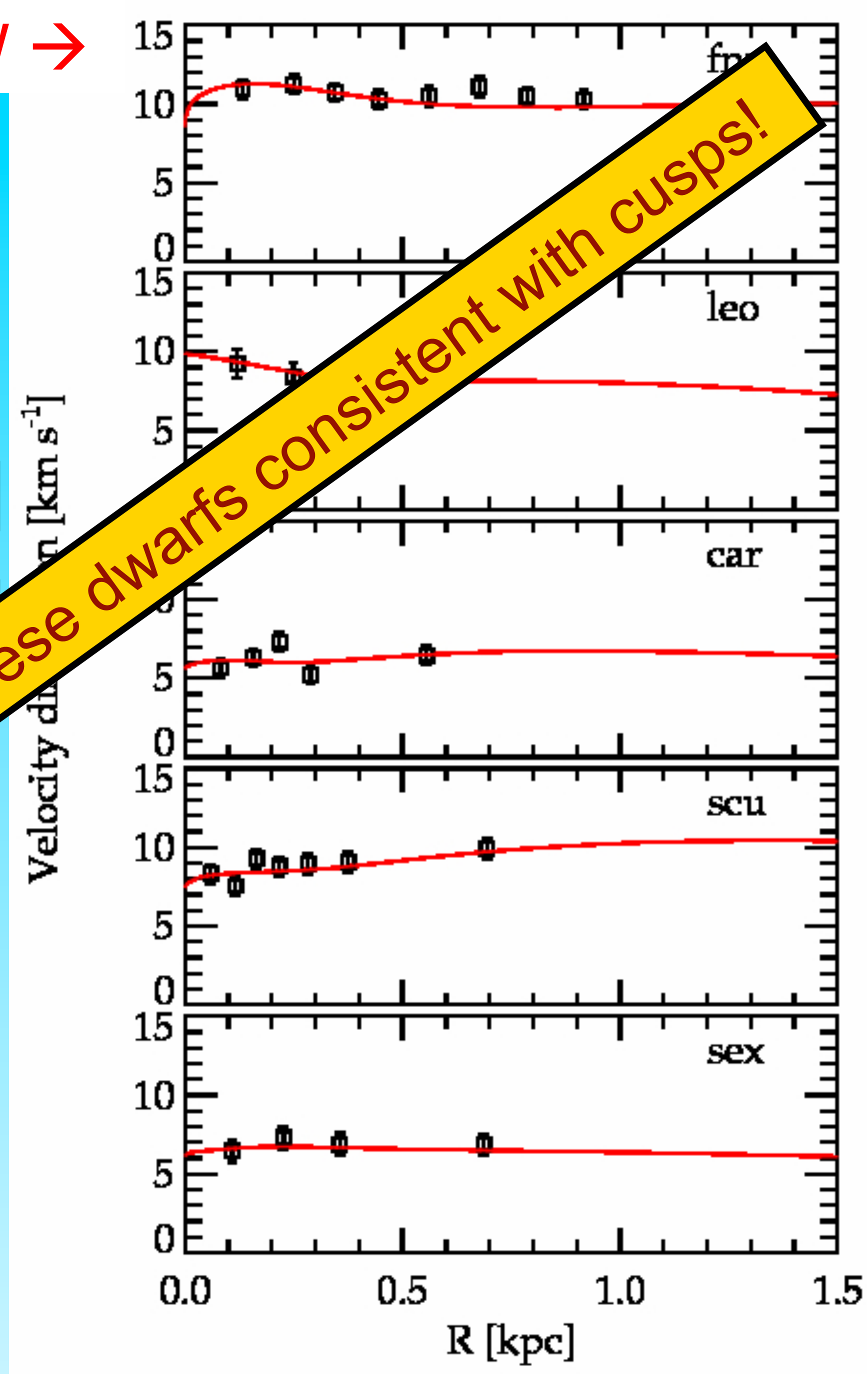
Cuspy!

vel. an… py

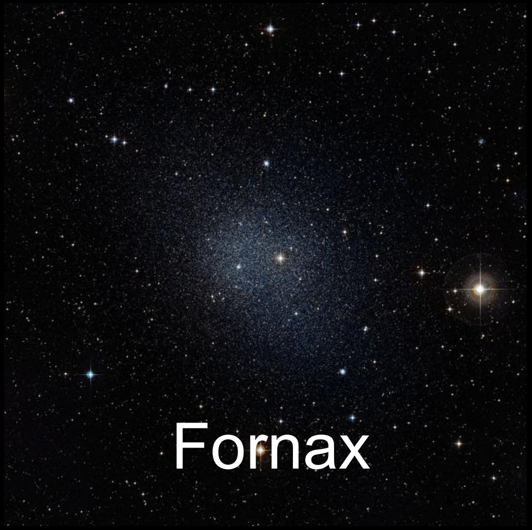
- Assume isotrop… …ts
- Solve for σ…
- Com… with observed σ_r (r)
- … best fit" subhalo

Photometric and kinematical data for these dwarfs consistent with cusps!

Strigari, Frenk & White '10



Dwarf galaxies around the Milky Way



Sextans

Carina

Sagittarius

The DM halo of the Sculptor dwarf

University of Durham

Sculptor has two stellar pops:

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

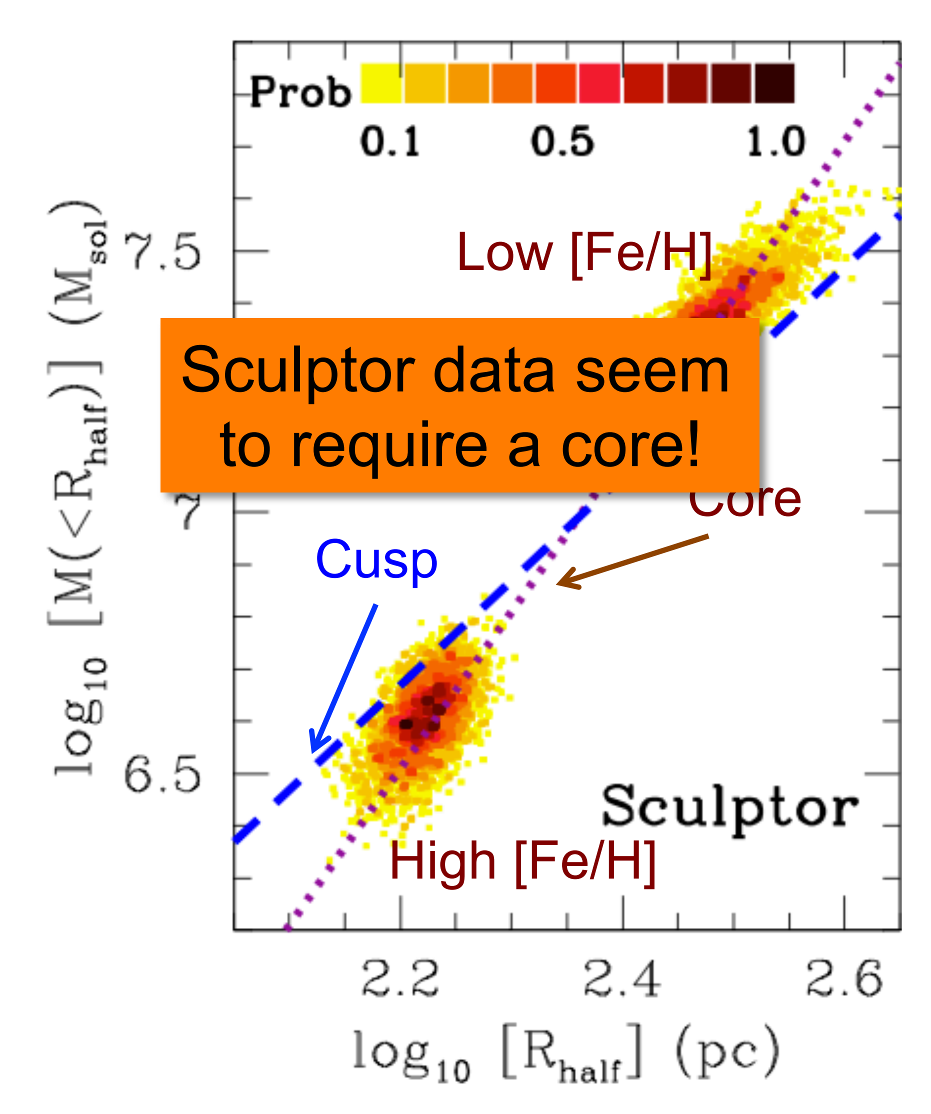
(ii) extended, low [Fe/H]

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

$r=r_{1/2}$

Walker '10; Wolf et al '10→

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

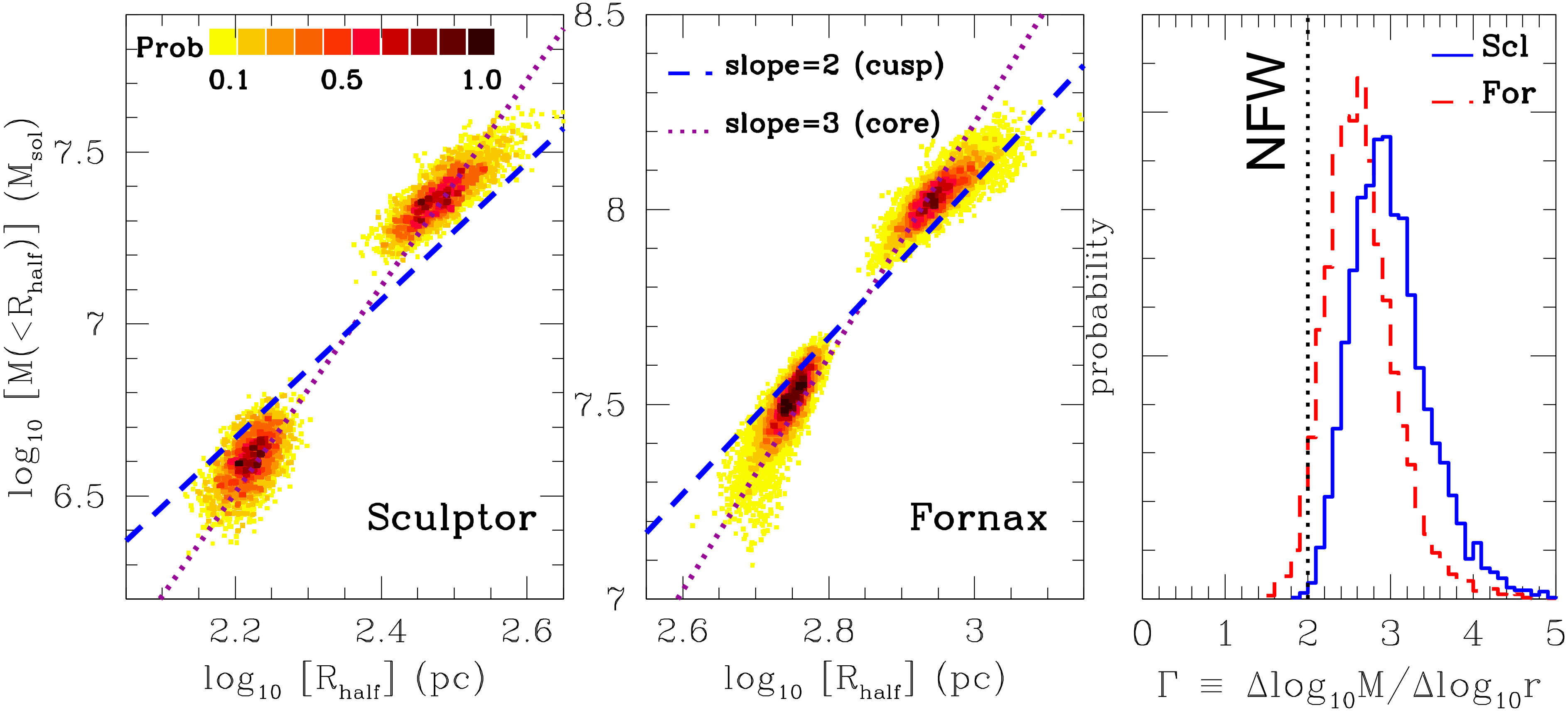


Walker & Peñarrubia '11

University of Durham

Cusps in Sculptor and Fornax

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



NFW ruled out at { >96% Fornax, >99% Sculptor

Walker & Peñarrubia (2011)

Institute for Computational Cosmology

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: $$f(E,J) = g(J)h(E),$$

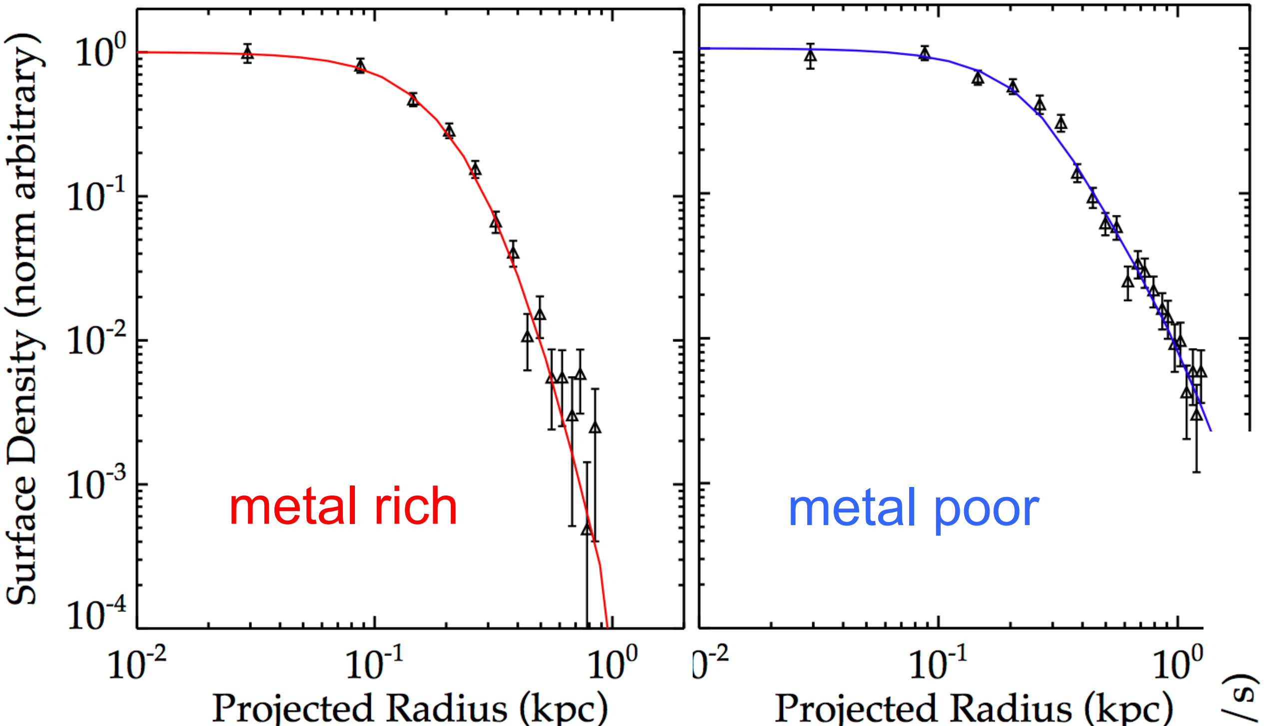
Parametrize: $$g(J) = \left[\left(\frac{J}{J_\beta}\right)^{\frac{b_0}{\alpha}} + \left(\frac{J}{J_\beta}\right)^{\frac{b_1}{\alpha}}\right]^{\alpha}$$

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

Find best-fit parameters using MCMC

University of Durham

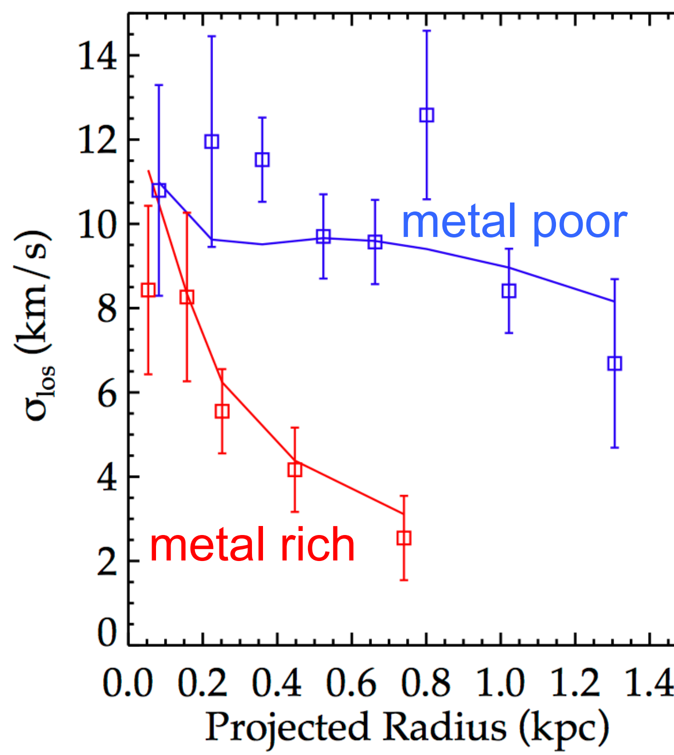
The DM halo of the Sculptor dwarf



Surface density

Distribution function analysis

Velocity dispersion



Data consistent with two populations in equilibrium in NFW halo

Strigari, Frenk & White ‘15

VIRGO

icc.dur.ac.uk/Eagle

“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…

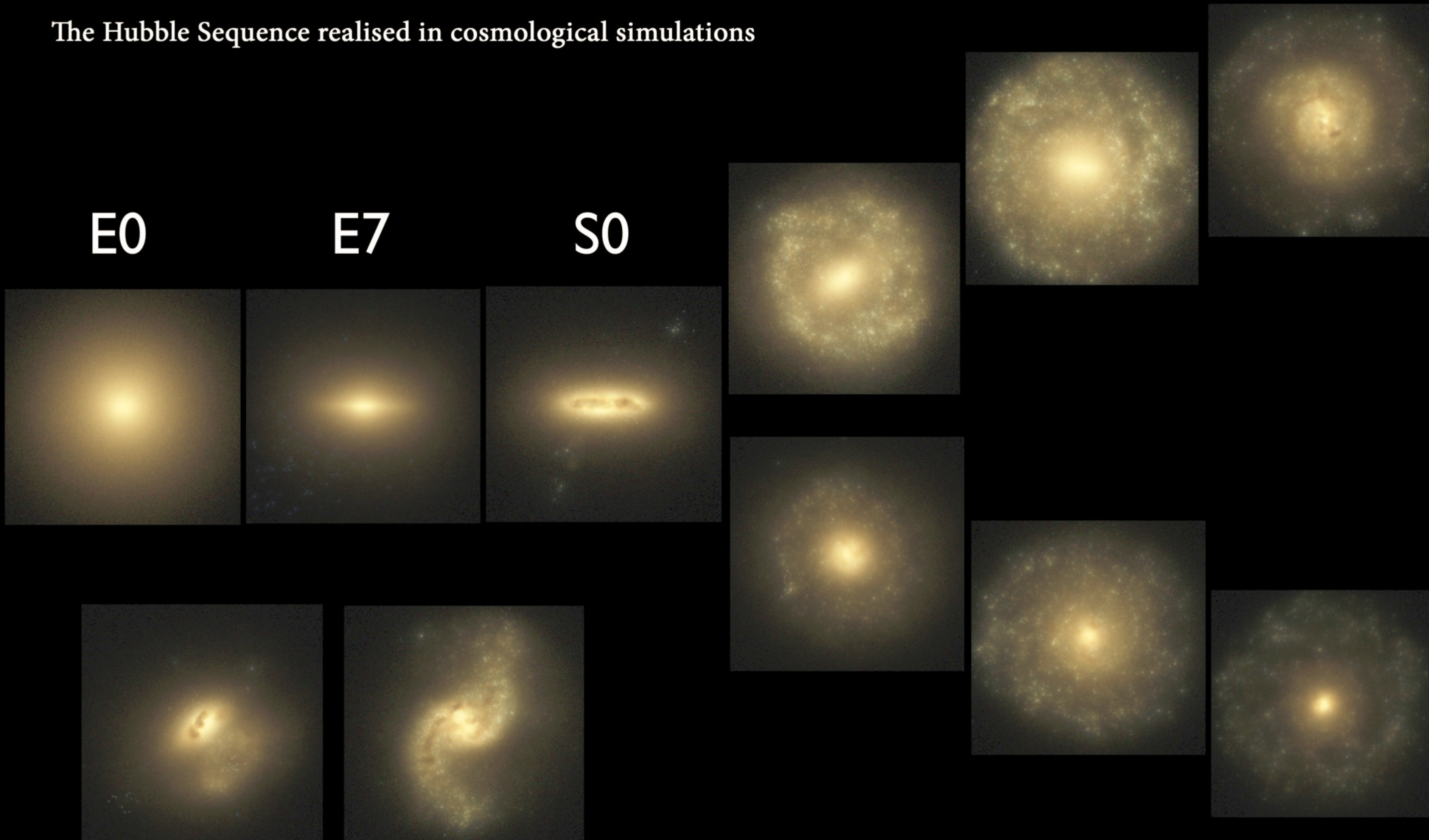
Durham University VIRGO ICC DiRAC PRACE

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

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

The Hubble Sequence realised in cosmological simulations



Trayford et al '15

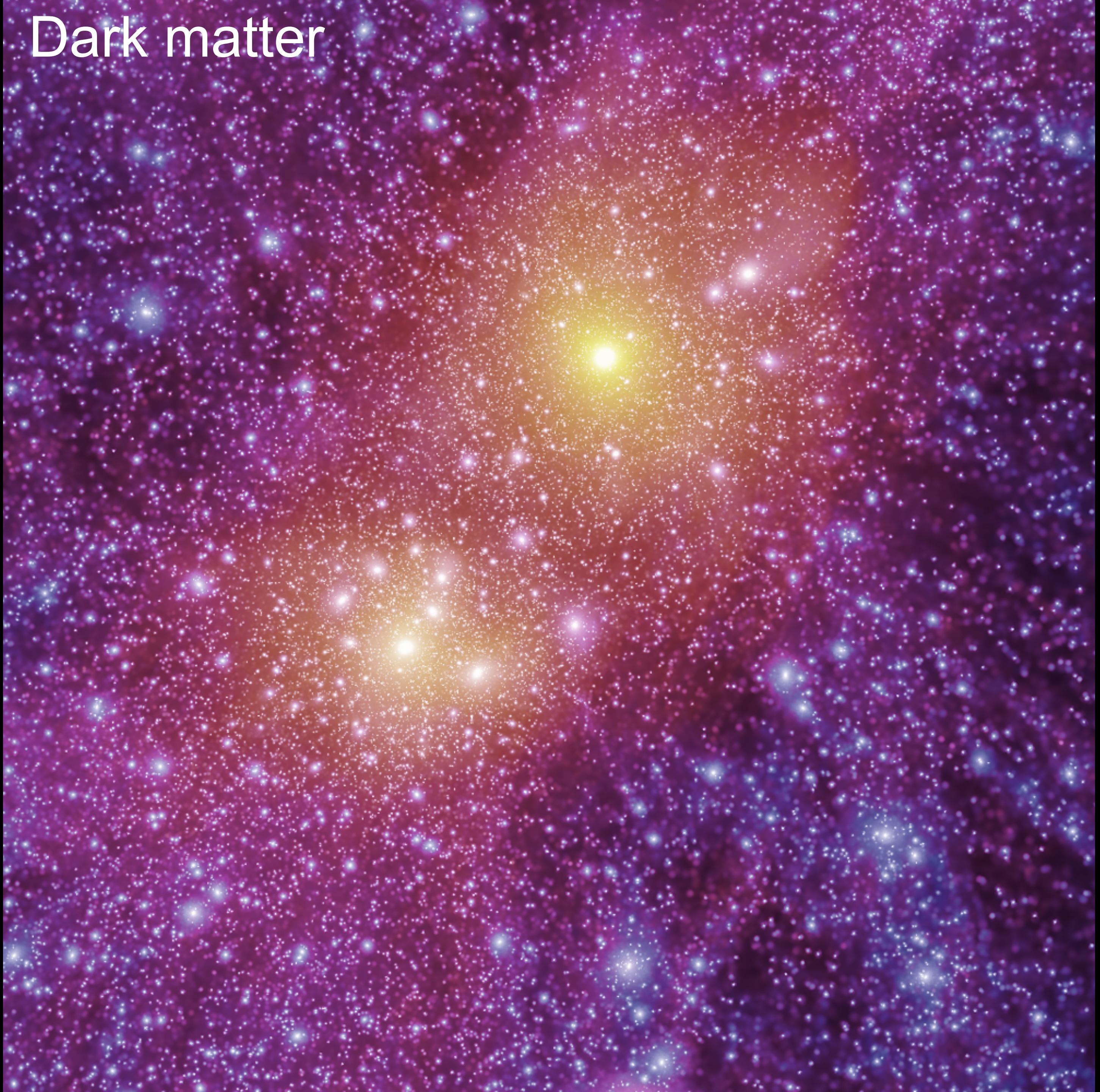
VIRGO

APOSTLE EAGLE full hydro simulations

Local Group

CDM

Sawala et al '16



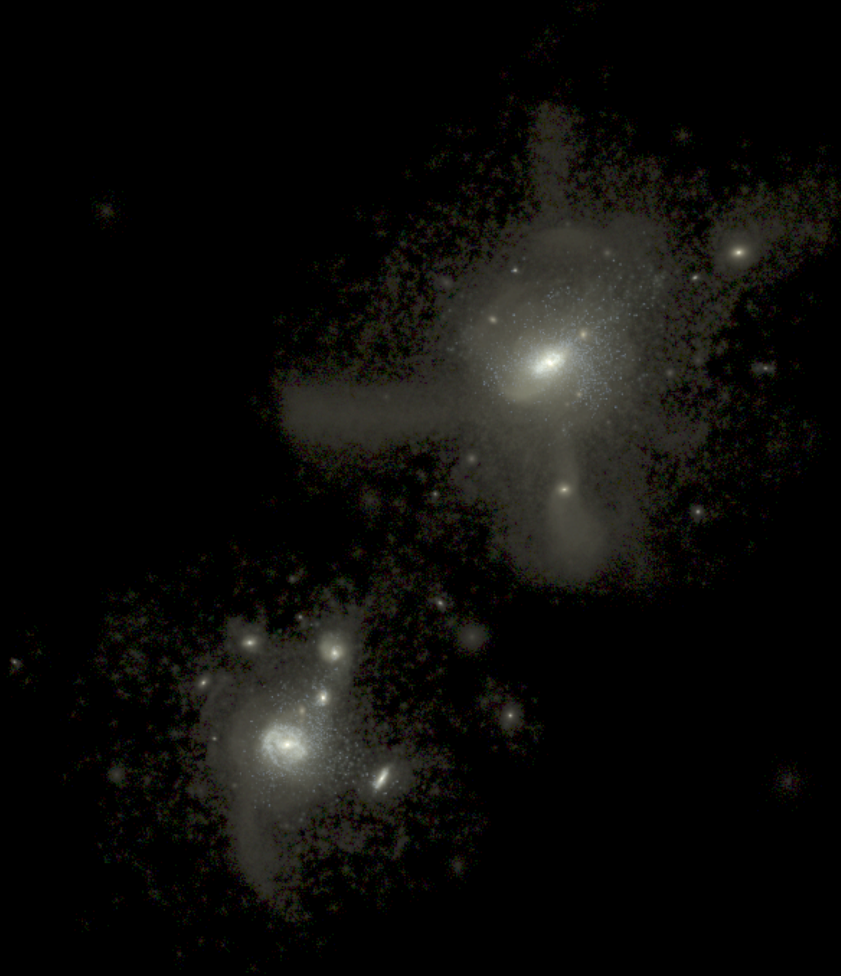
VIRGO

Stars

APOSTLE EAGLE full hydro simulations

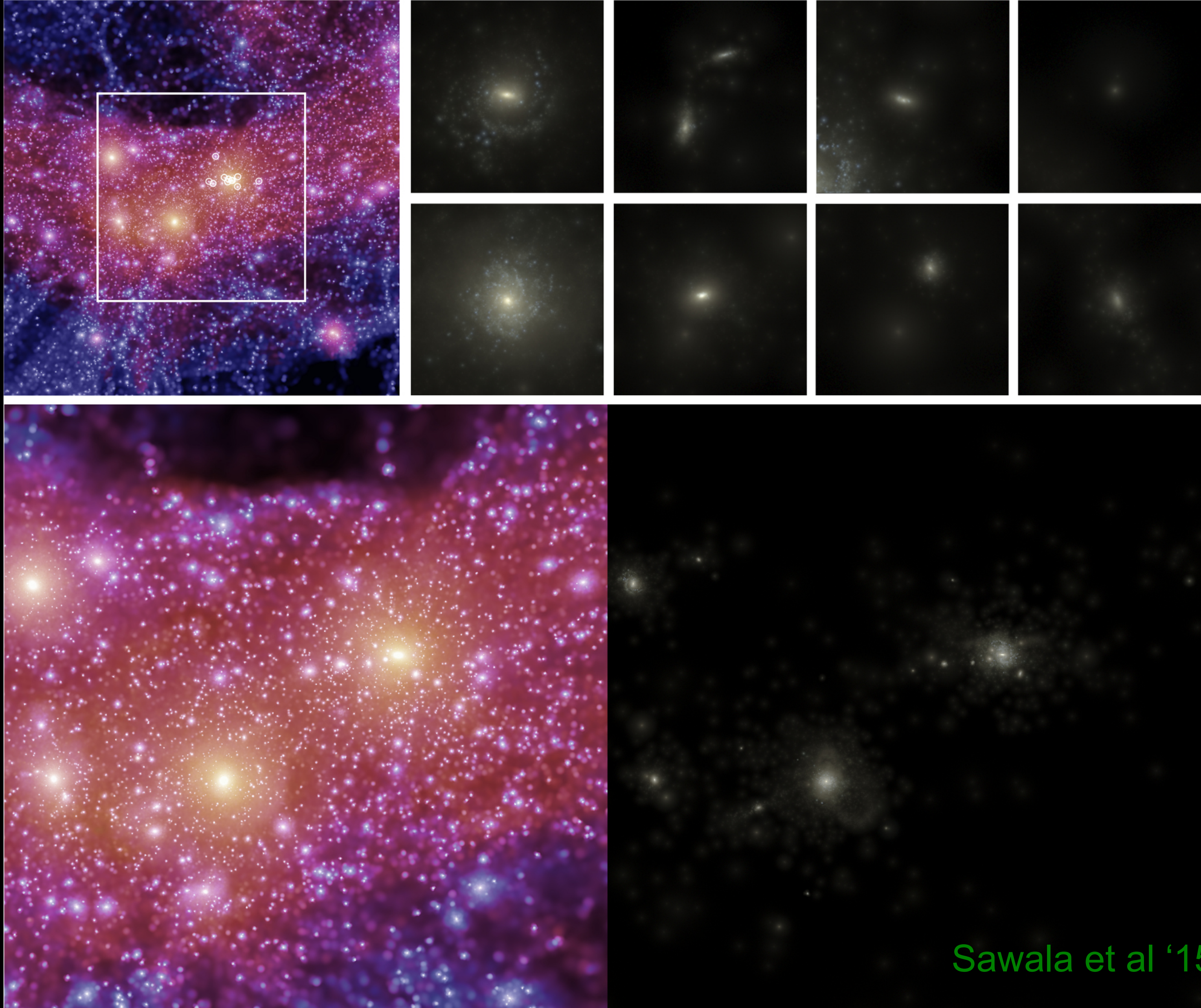
Local Group

CDM



Far fewer satellite galaxies than CDM halos

Sawala et al ‘16



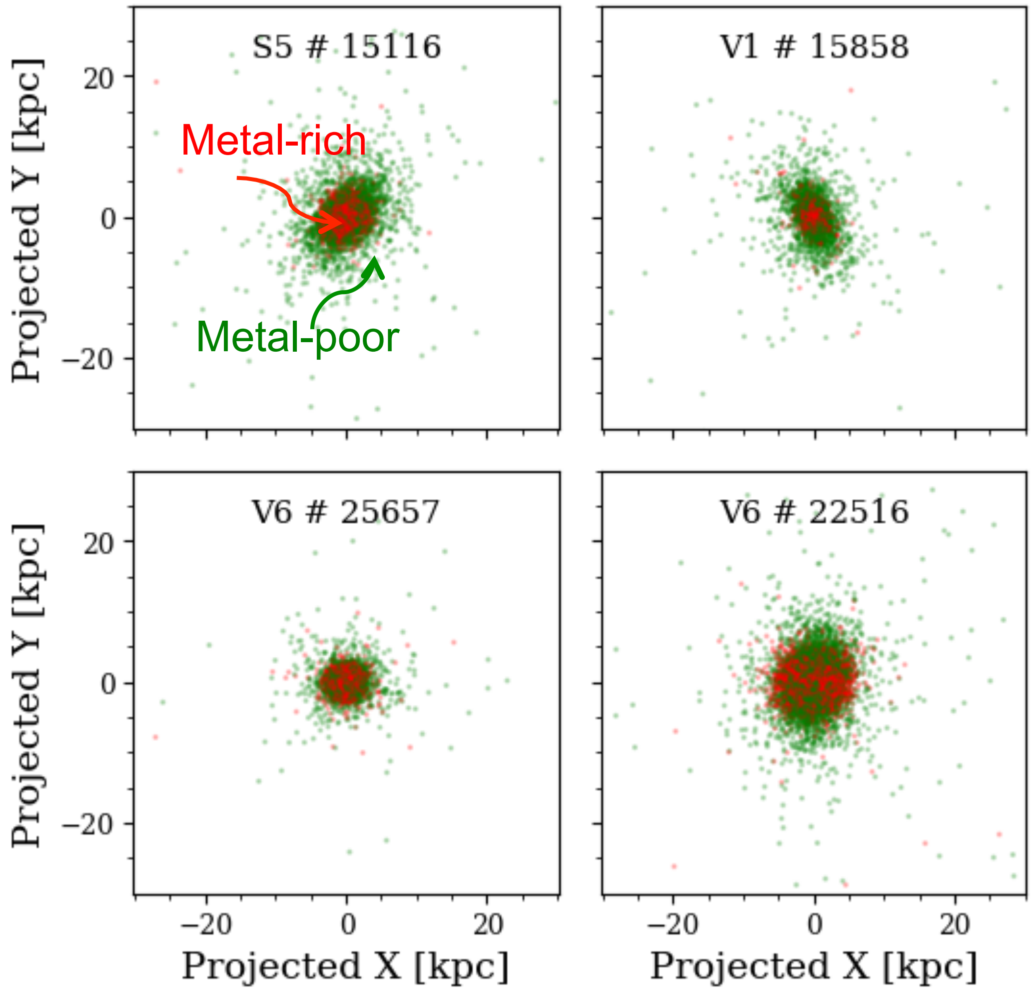
Sawala et al ‘15

Apostle: satellites w. 2-metalicity pops

University of Durham

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

University of Durham

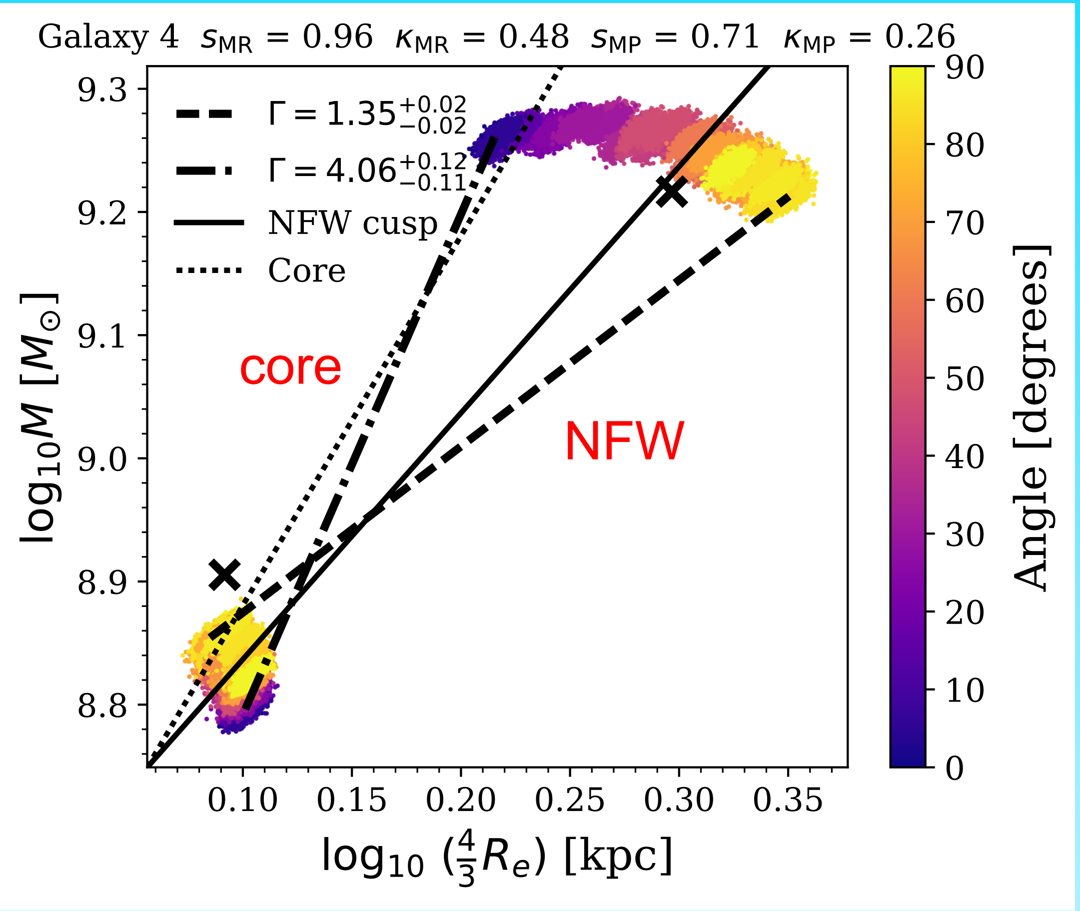
$$M(<r) = \mu \frac{r < \sigma_{los}^{\;2} >}{G}$$

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

University of Durham

The DM halo of the Sculptor dwarf

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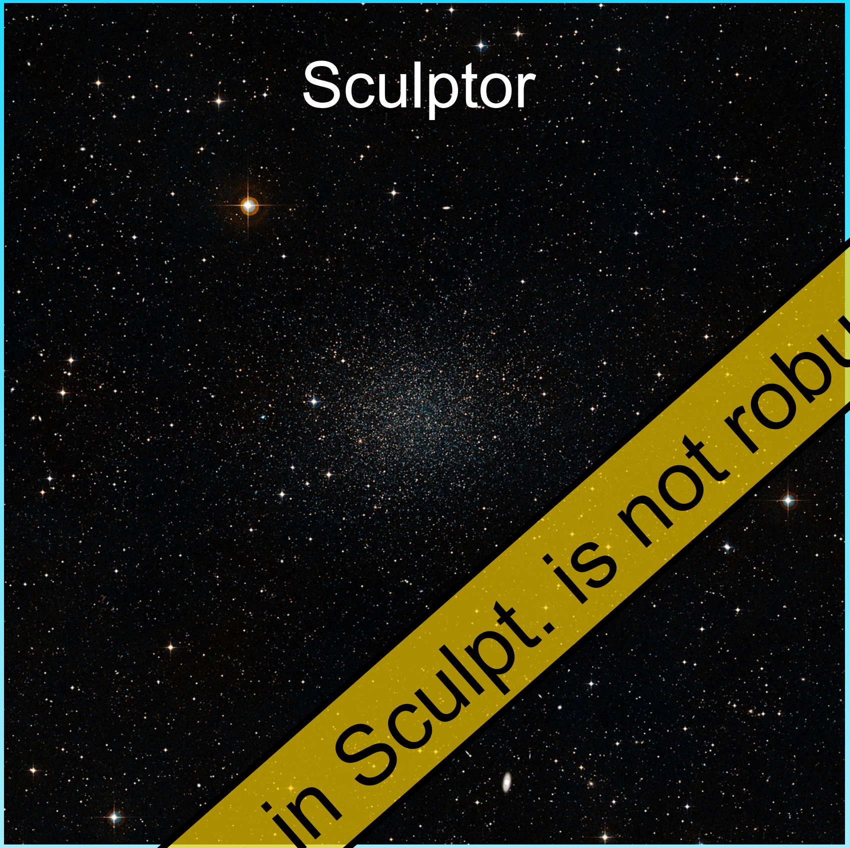
Key assumption of mass estimator:

spherical symmetry

Is Sculptor spherical?



WP11 core in Sculpt. is not robust

Genina, CSF et al ‘17

Institute for Computational Cosmology

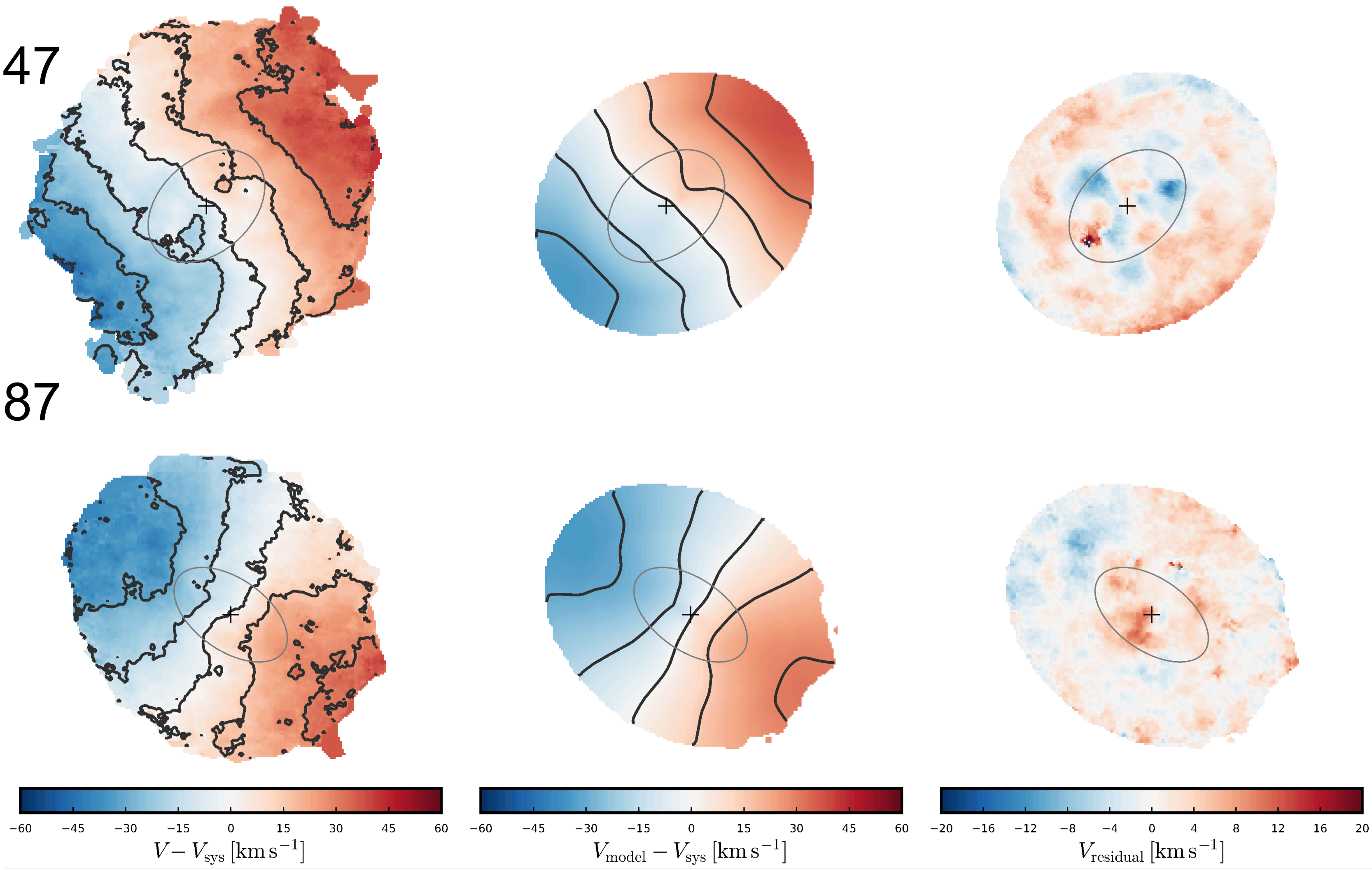
Many nearby galaxies now have hi-res 2D HI velocity fields → ideal for infering potential

Assume: gas is in centrifugal equilibrium on approximately circular orbits

2D HI velocity data for local dwarfs

DDO 47

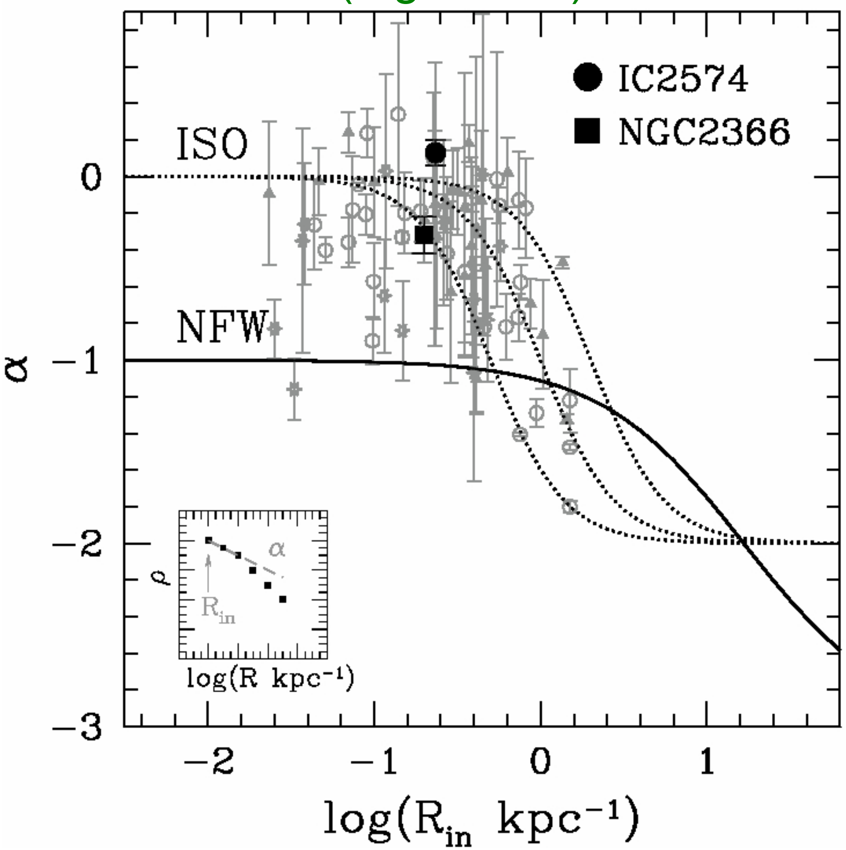
DDO 87



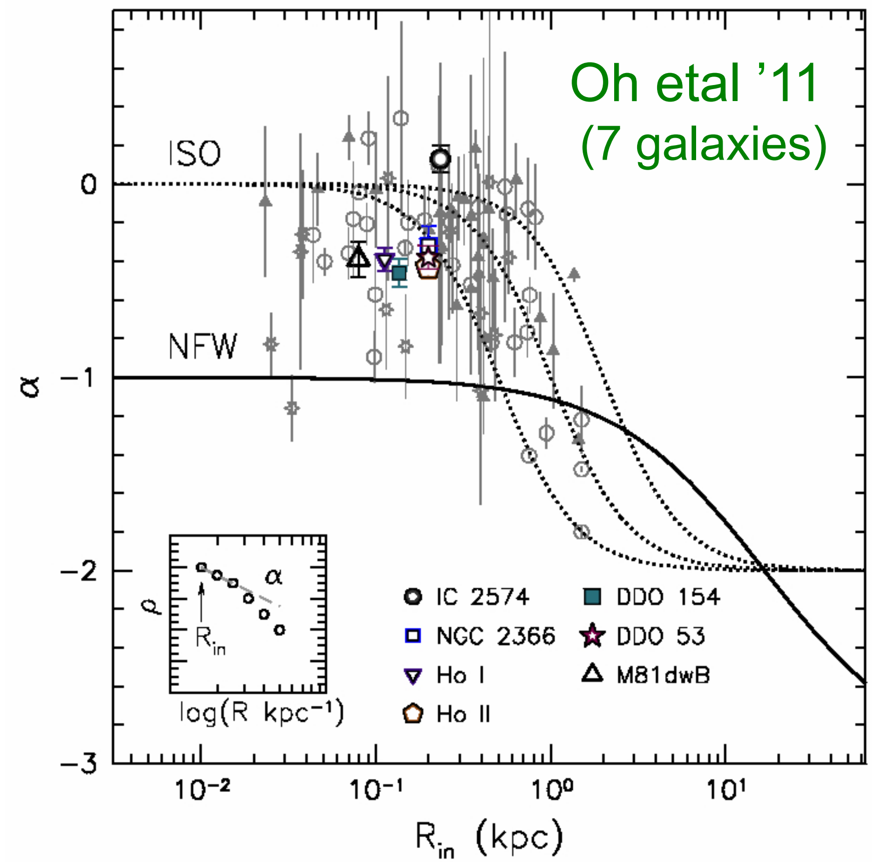
THINGS HI rotn curves of dwarfs

University of Durham

Oh etal ’08
(2 galaxies)

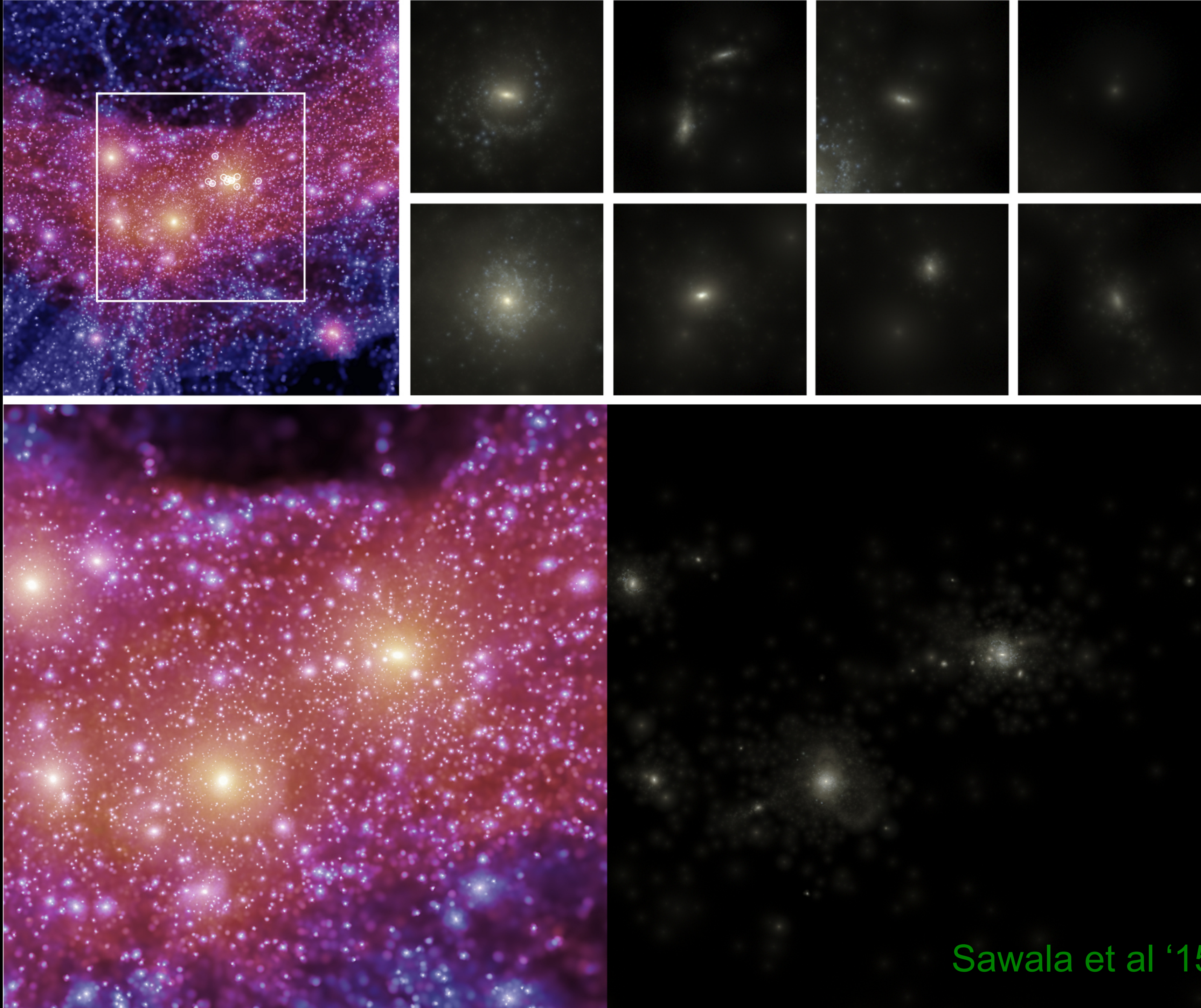


$$\rho(r) \propto r^{\alpha}(1 + r/r_s)^{\beta}$$



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

Institute for Computational Cosmology

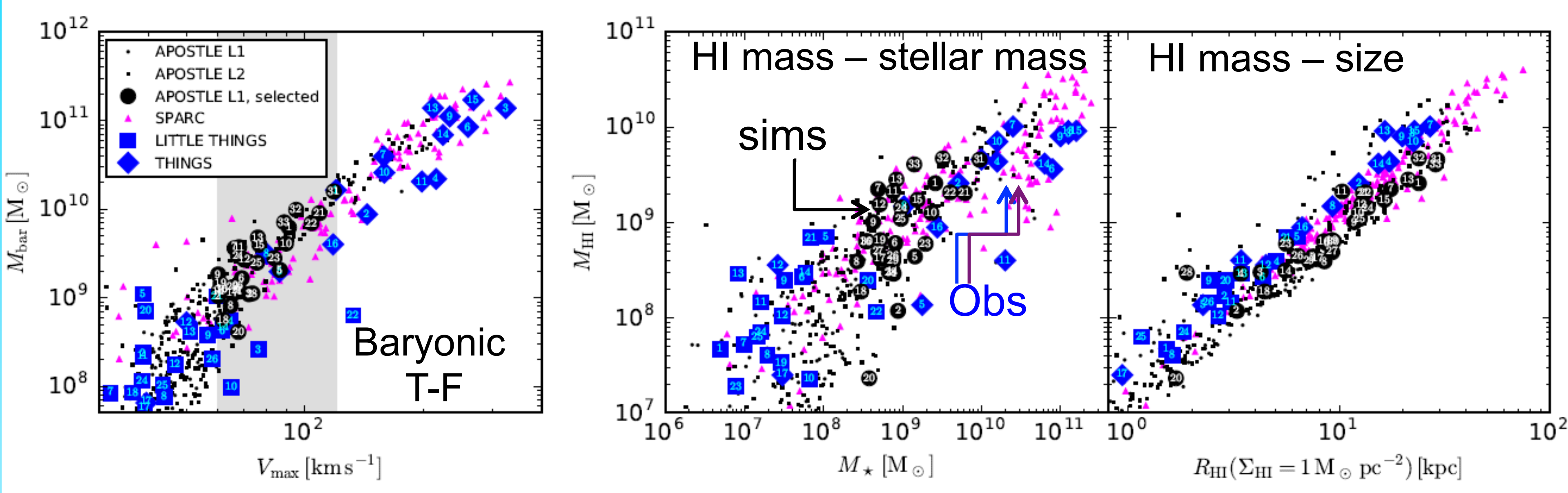


Sawala et al ‘15

HI properties of APOSTLE dwarfs

University of Durham

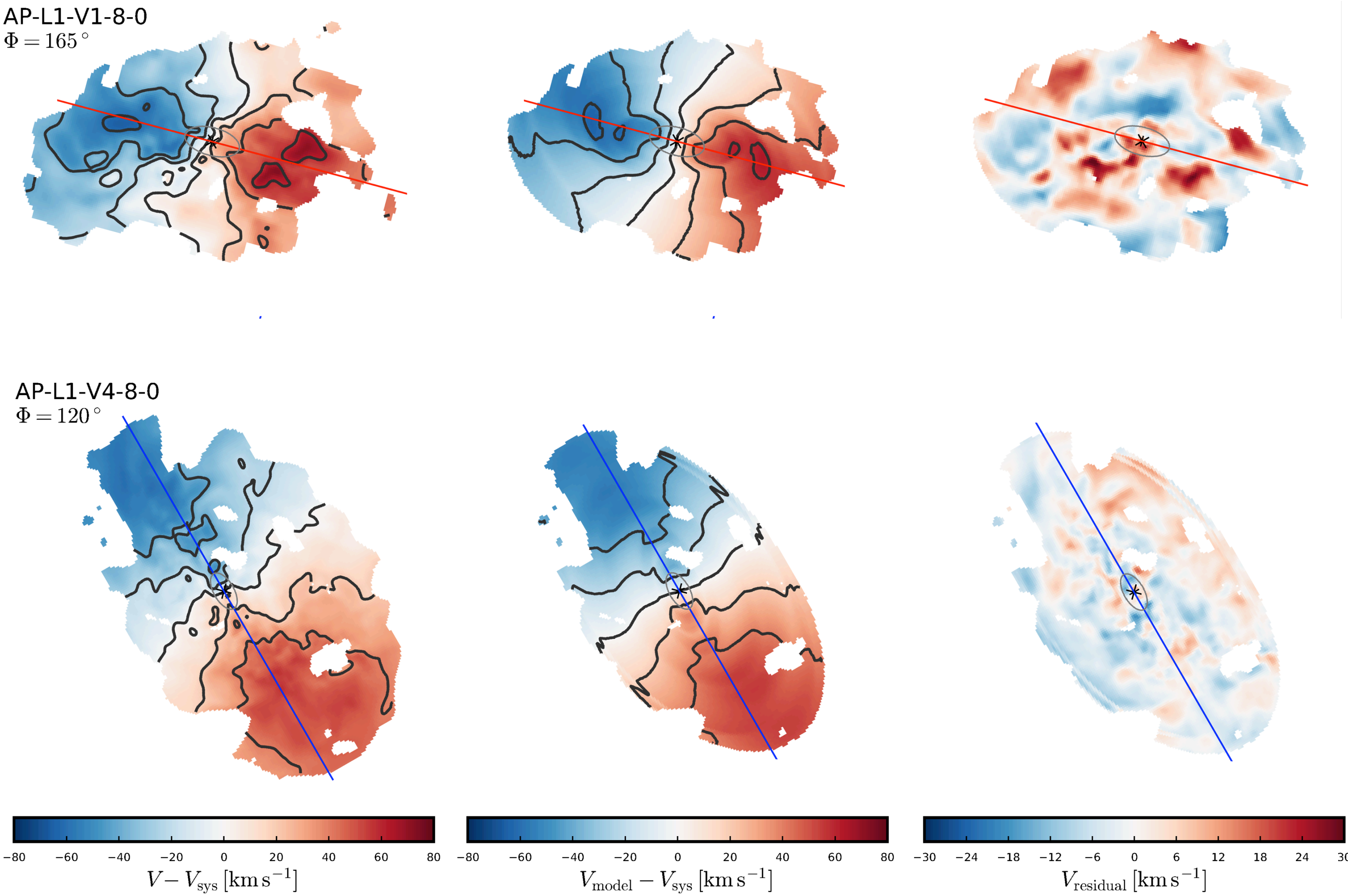
60 km/s <V_{max} < 120 km/s



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

2D velocity data for Apostle dwarfs



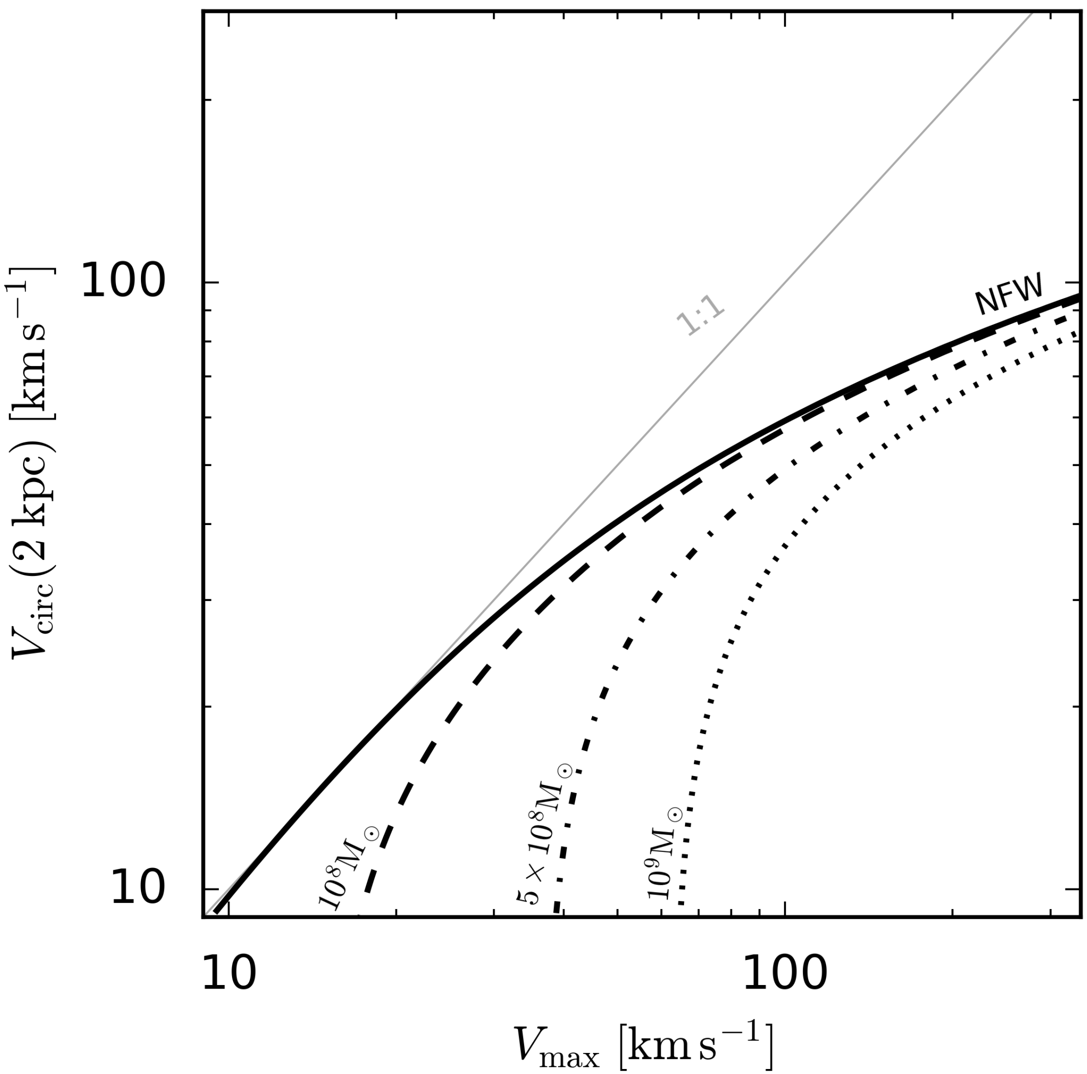
Oman, Marasco + 18

Predictions from CDM

The diversity of rotation curves

University of Durham

NFW

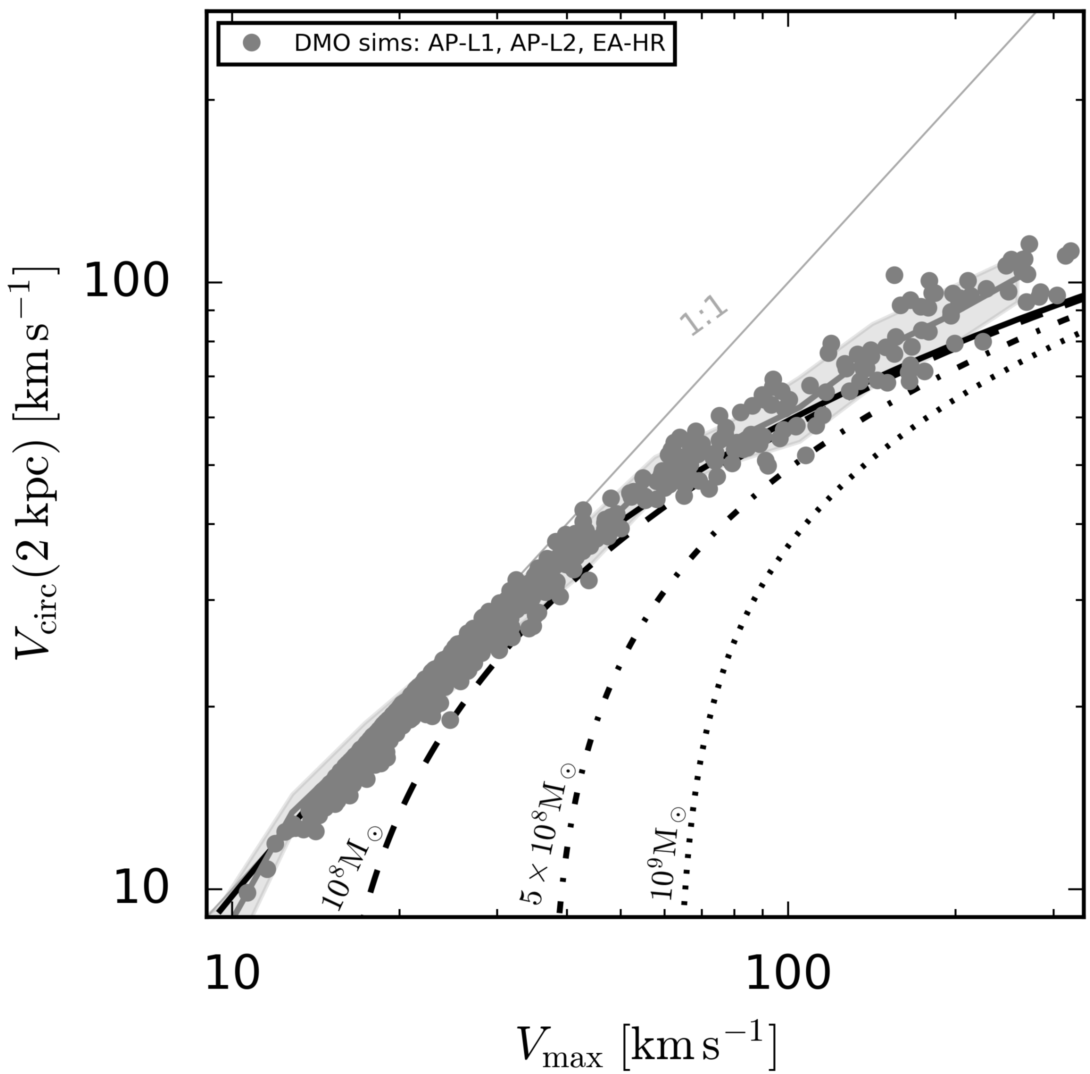


Oman+ '17

The diversity of rotation curves

University of Durham

N-body

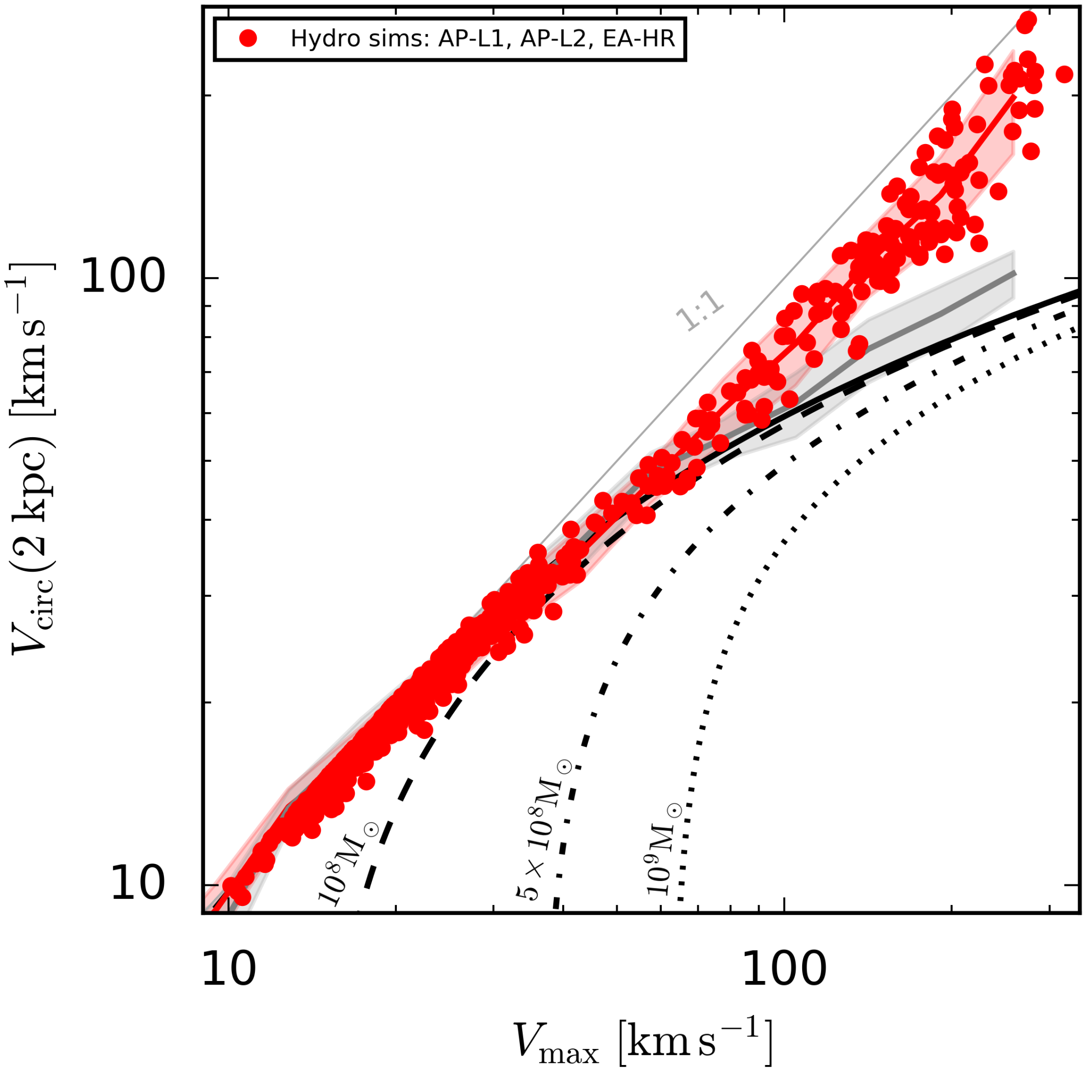


Oman+ '17

Institute for Computational Cosmology

The diversity of rotation curves

Hydro

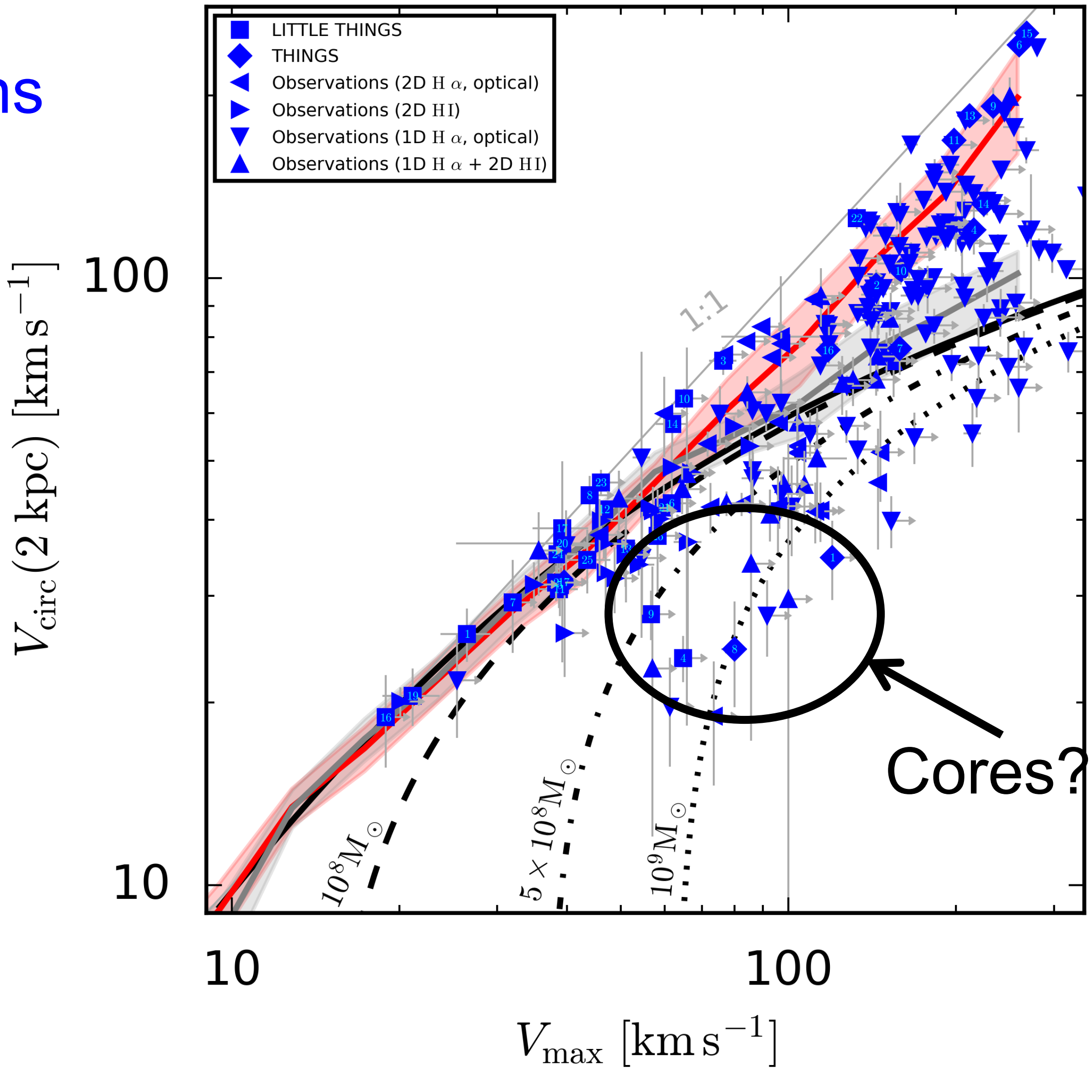


Oman+ ‘17

The diversity of rotation curves

University of Durham

Observations



Oman+ '17

Analysis of 2D velocity fields

University of Durham

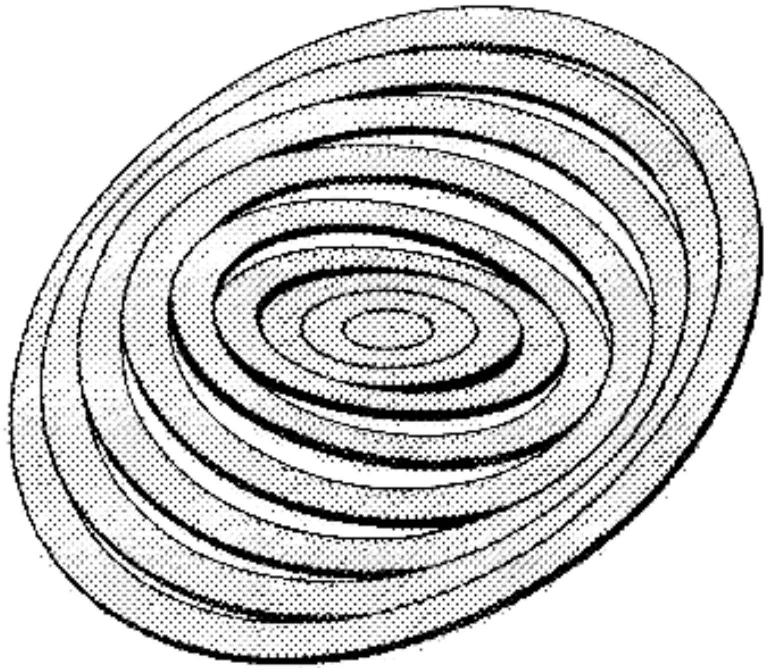
2D velocity field → V_c (r) (rotn curve); in dynamical equilibrium: $V_c = \sqrt{\frac{GM(<r)}{r}}$

Tilted-ring model corrected for asymmetric drift

• ^{3D}BAROLO fit

Tilted ring modelling

Model galaxy as a set of tilted rings and solve for the kinematics of each ring



Rogstad et al. (1974)

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

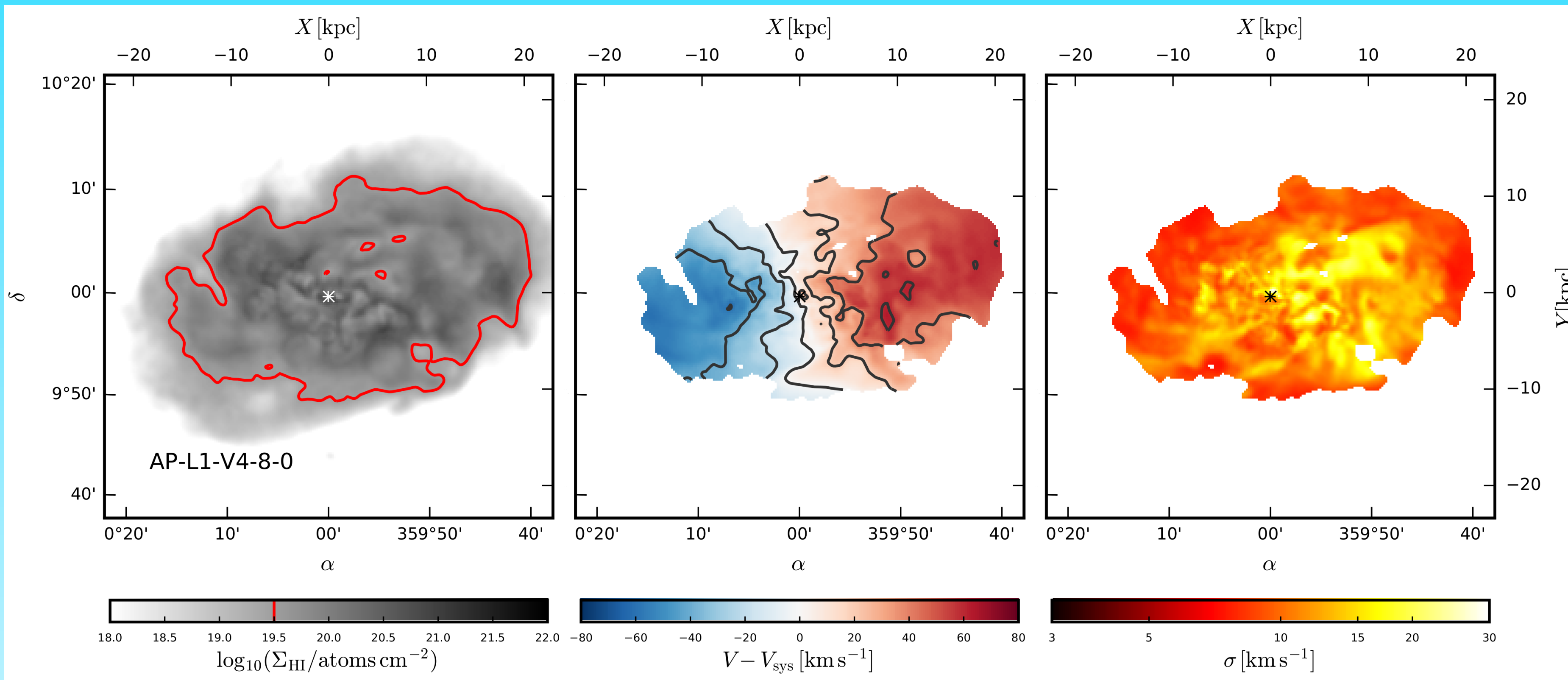
^{3D}BAROLO fit

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

University of Durham

Synthetic HI observations of curves of an APOSTLE dwarf

HI surface density | Mean velocity | Velocity dispersion



Oman+ '17

Institute for Computational Cosmology

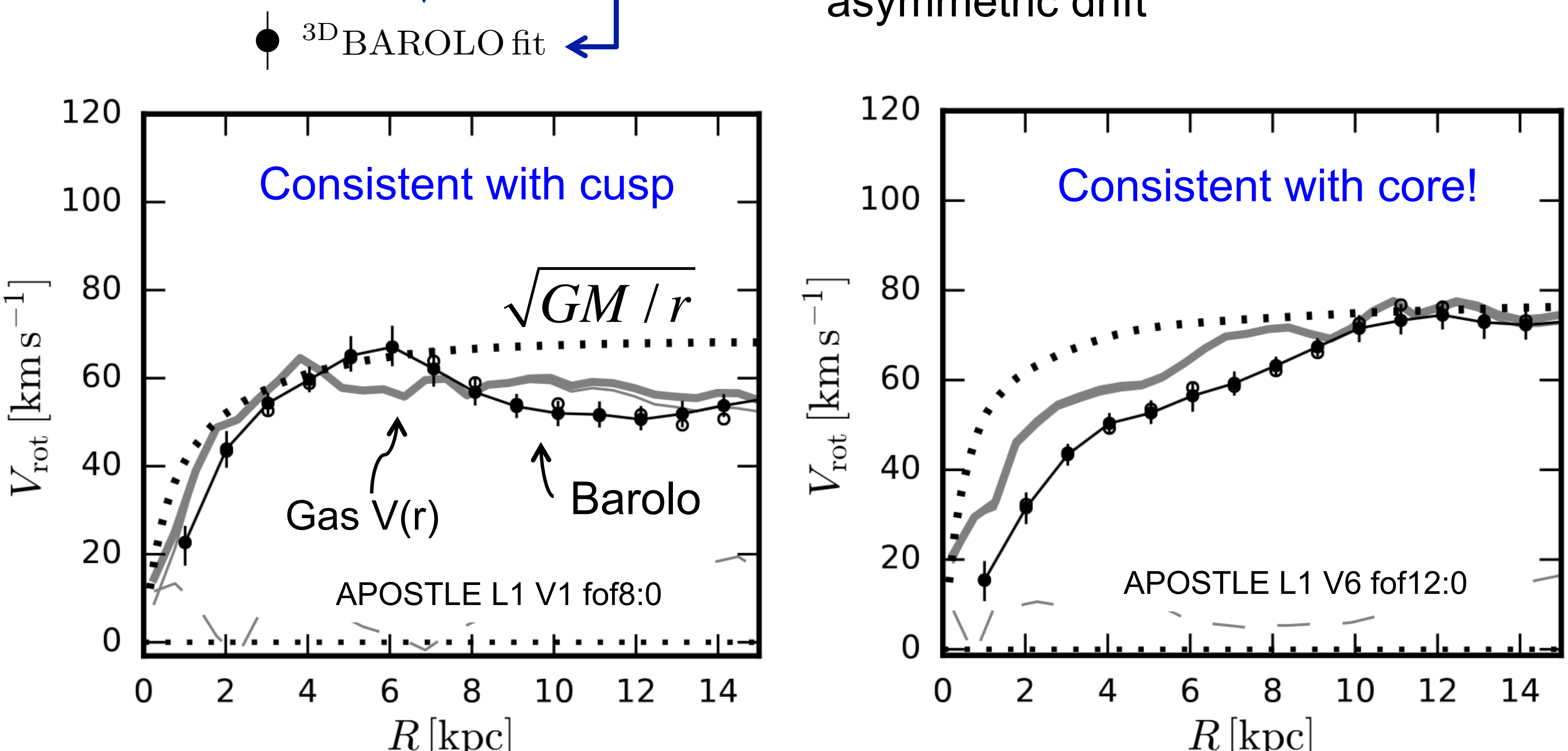
Rotation curves of 2 APOSTLE dwarfs

University of Durham

APOSTLE galaxies all have NFW cusps

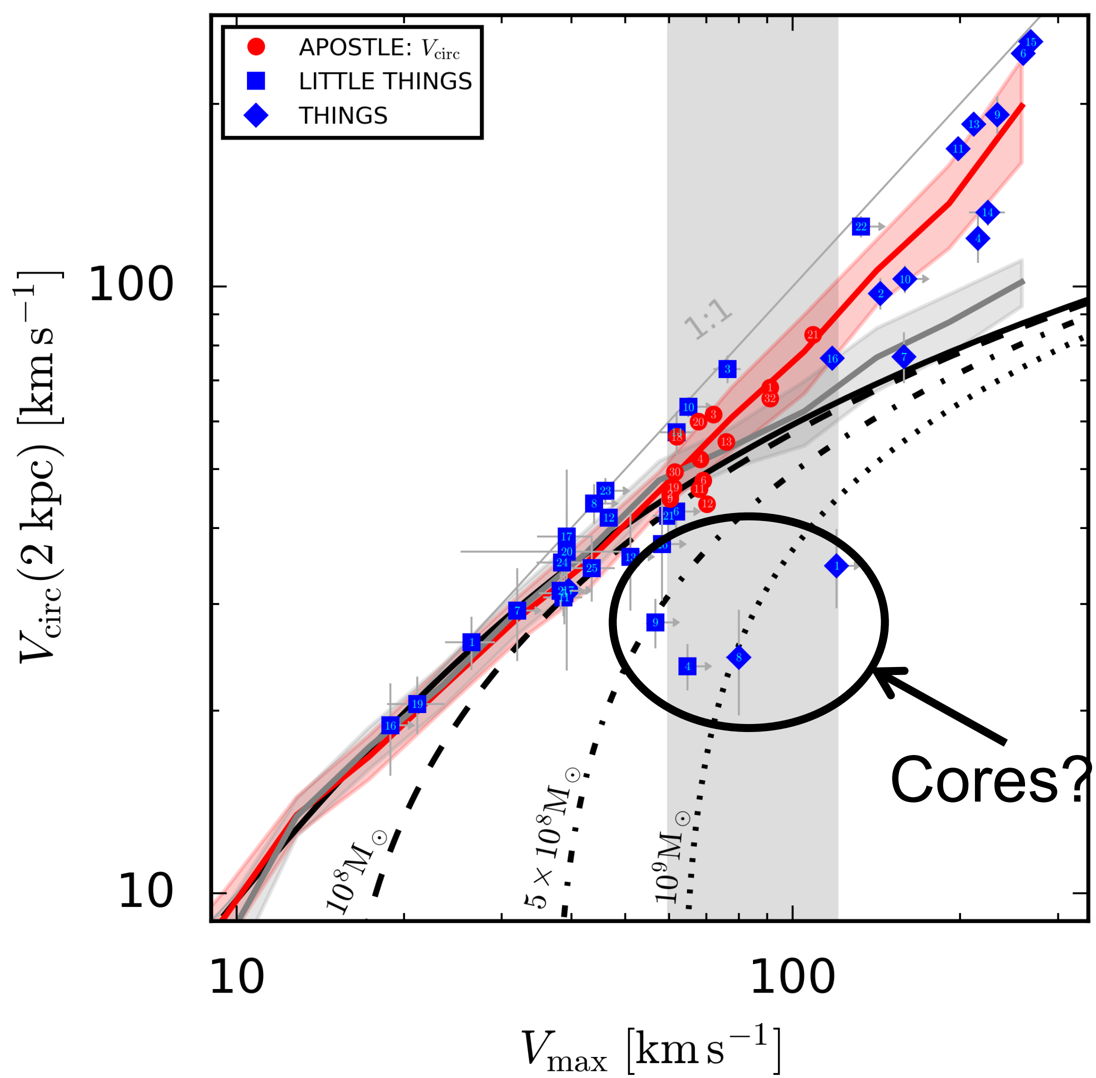
2D velocity field → V_c (r) (rotn curve); in dynamical equilibrium: $V_c = \sqrt{\frac{GM(<r)}{v}}$

Tilted-ring model corrected for asymmetric drift



Oman et al '17; Marasco et al '17

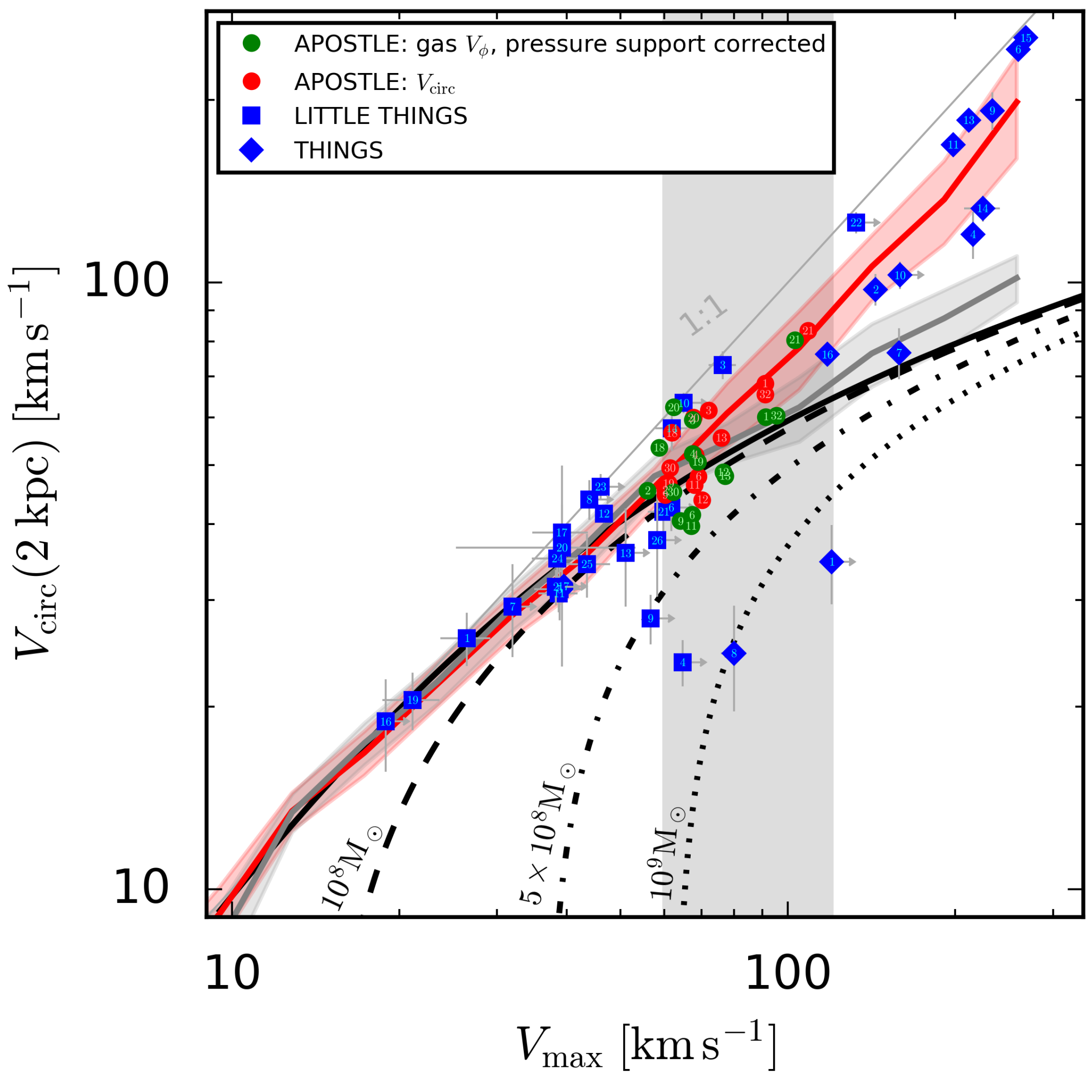
The diversity of rotation curves



Oman+ '17

The diversity of rotation curves

University of Durham

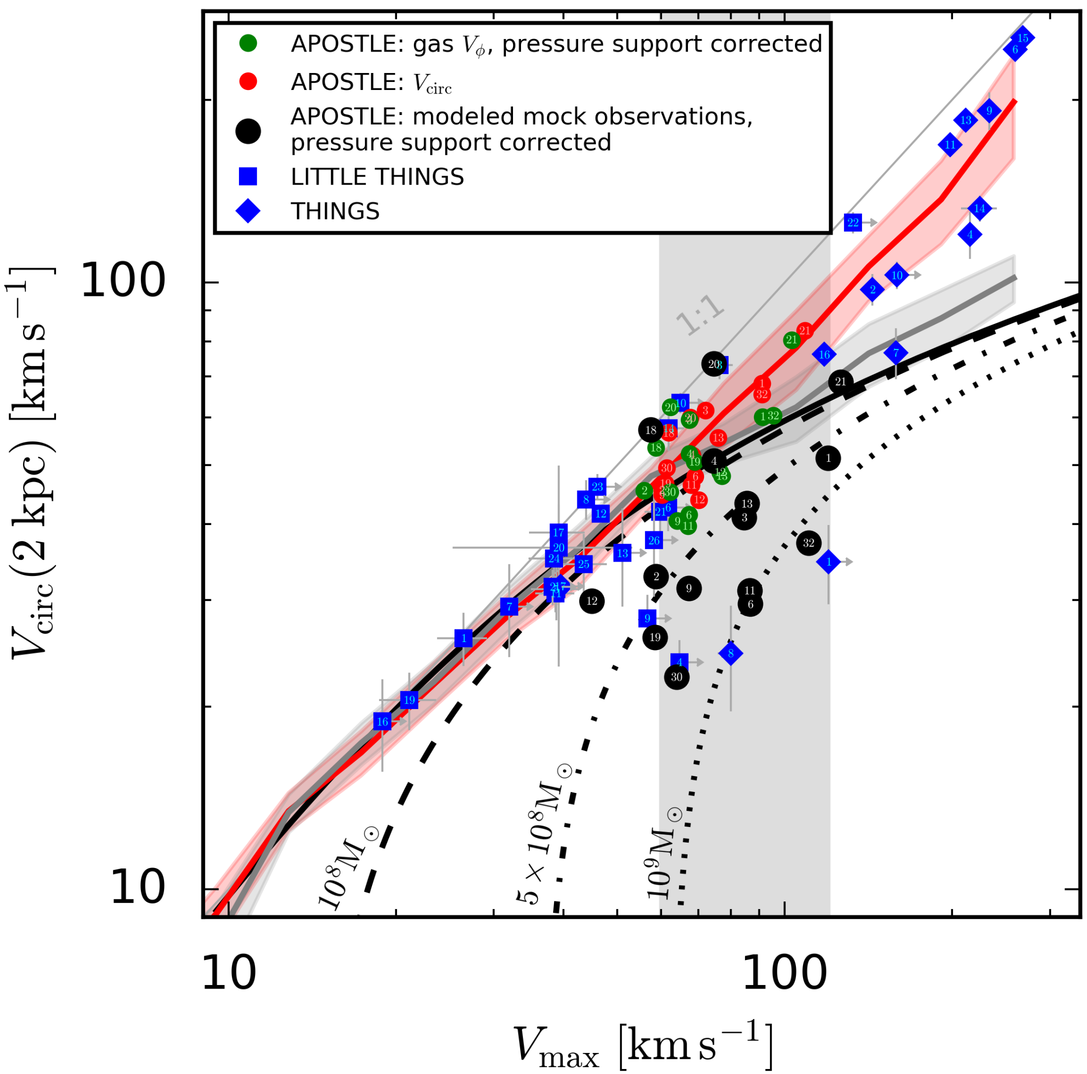


Oman+ '17

Institute for Computational Cosmology

The diversity of rotation curves

University of Durham



Oman+ '17

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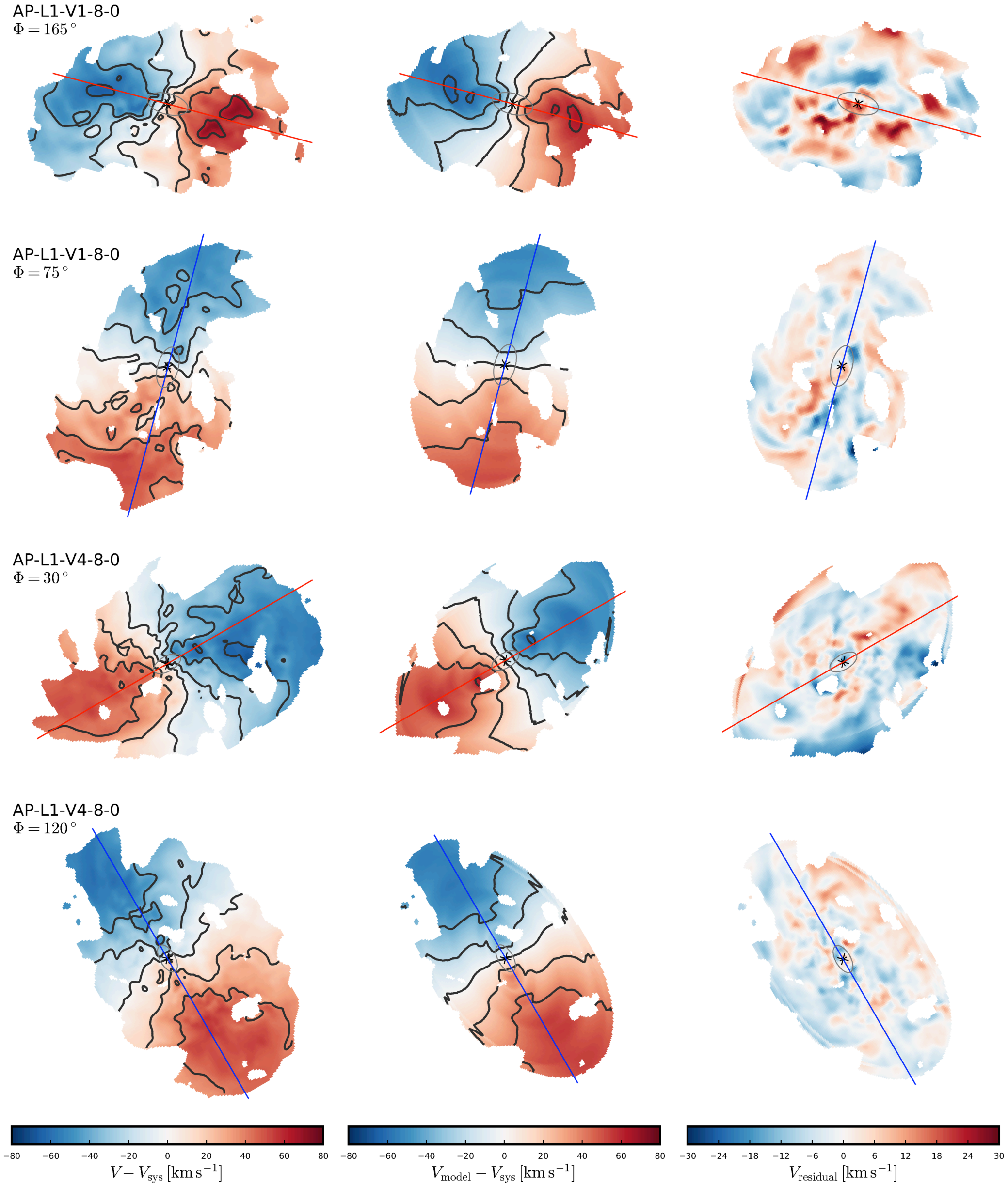
2D velocity data for Apostle dwarfs



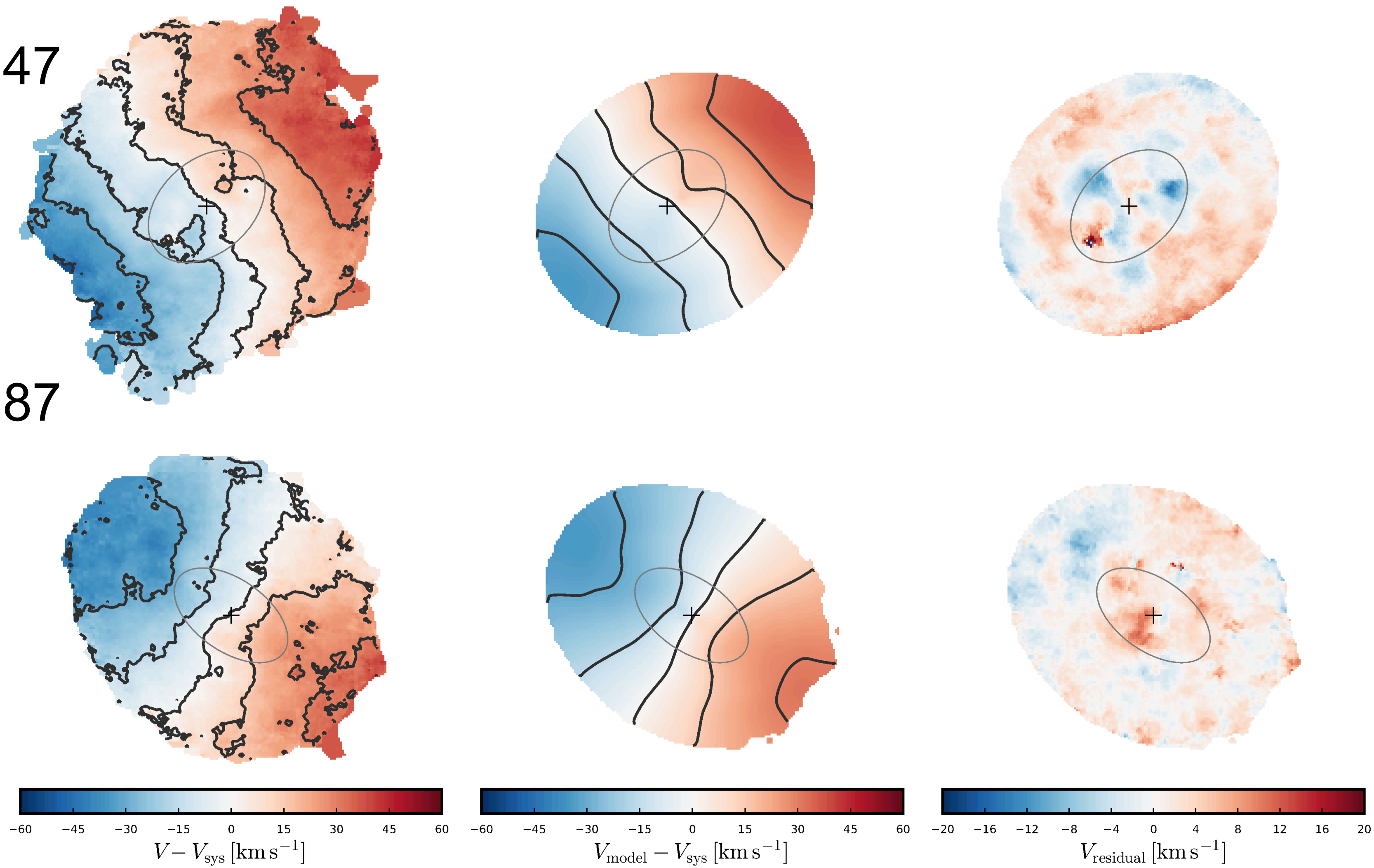
Oman, Marasco + 18

University of Durham

2D HI velocity data for local dwarfs

DDO 47

DDO 87



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Non-circular motions

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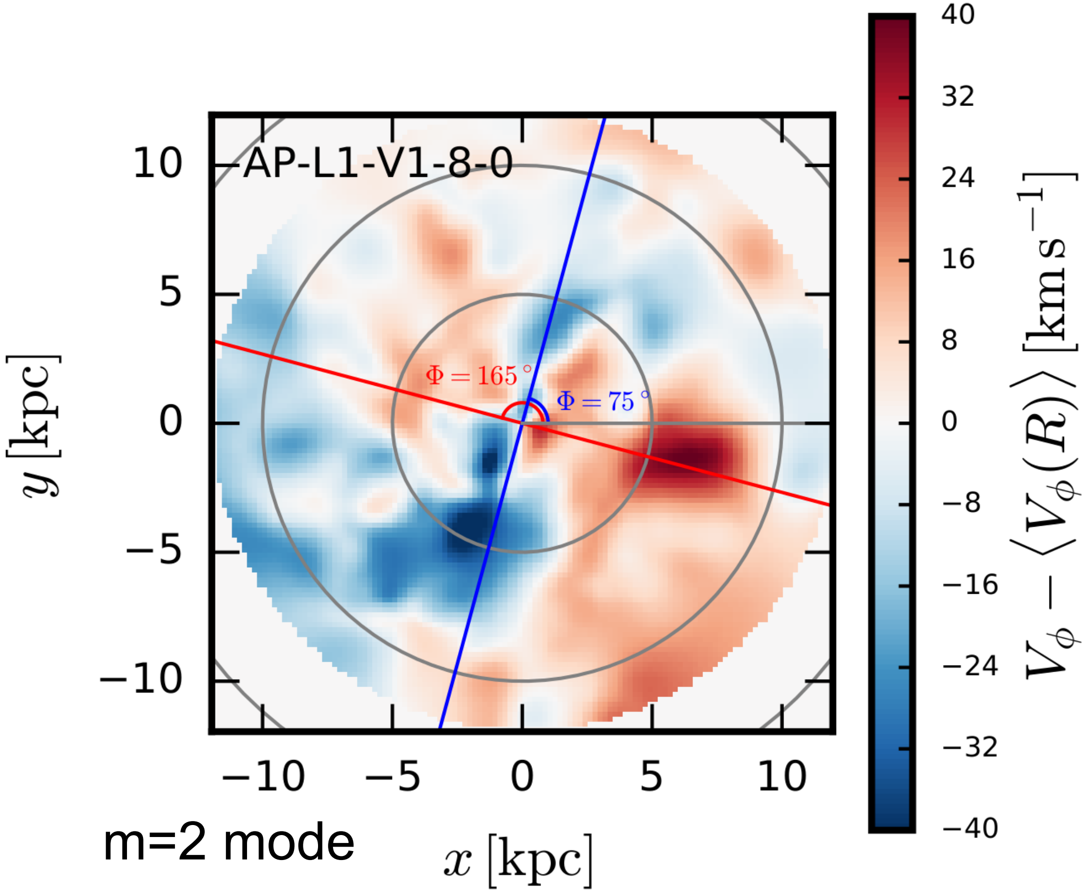
Residual azimuthal velocities (after subtracting mean v(r))



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+ '18

University of Durham

Dark matter halos: cores or cusps?

A myth:

The DM halos of dwarf galaxies have central cores

The facts:

Neither stellar dynamical data nor 2D HI velocity maps indicate the existence of cores

→ There is NO robust evidence for cores in galaxies

But, if cores we found to exist in galaxies, would this rule out CDM (& WDM)?

No!

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) (Read & Gilmore '05; Pontzen & Governato '12,'14; Bullock & Boylan-Kolchin '17)

Navarro, Eke & Frenk (1996)

The cores of dwarf galaxy haloes L75

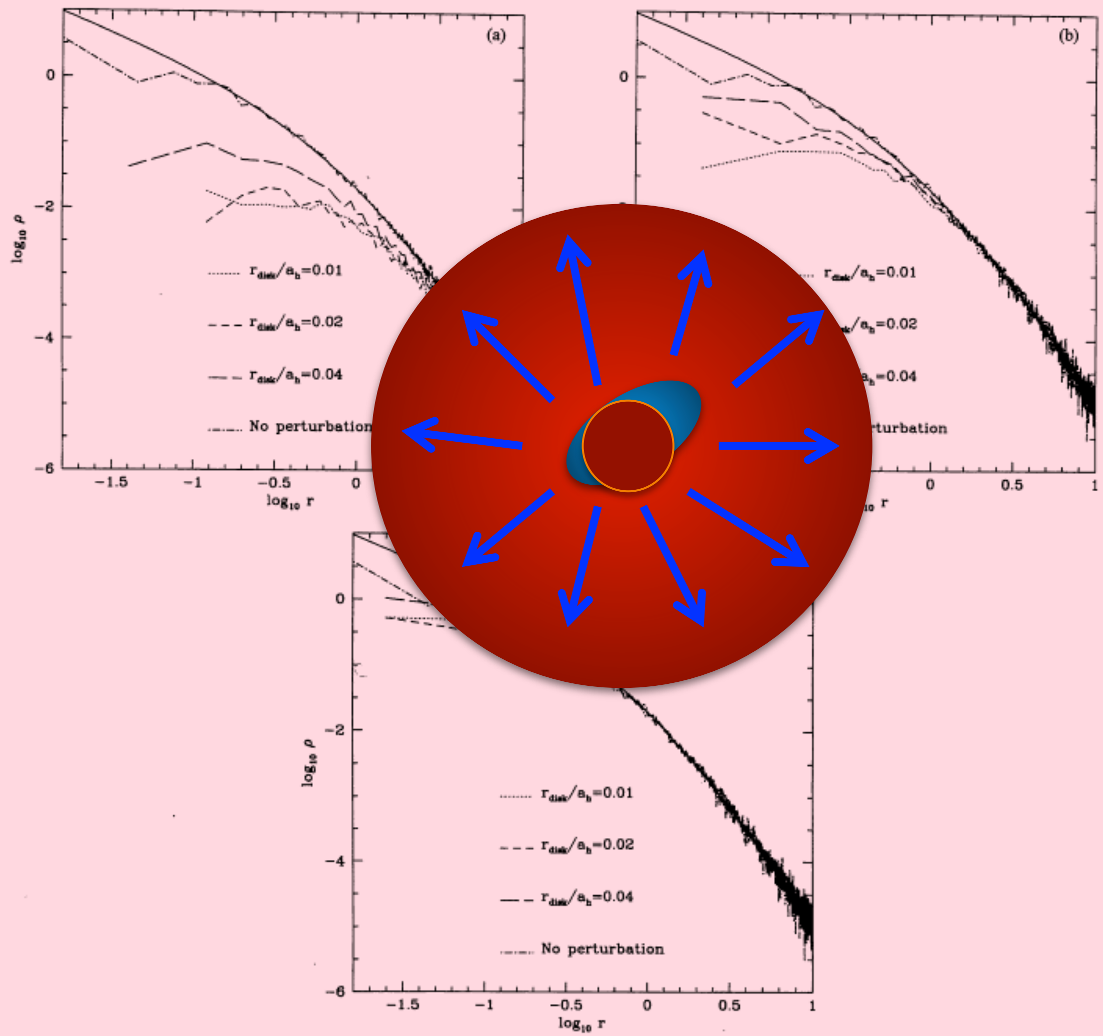


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

Cores in dwarf galaxy simulations

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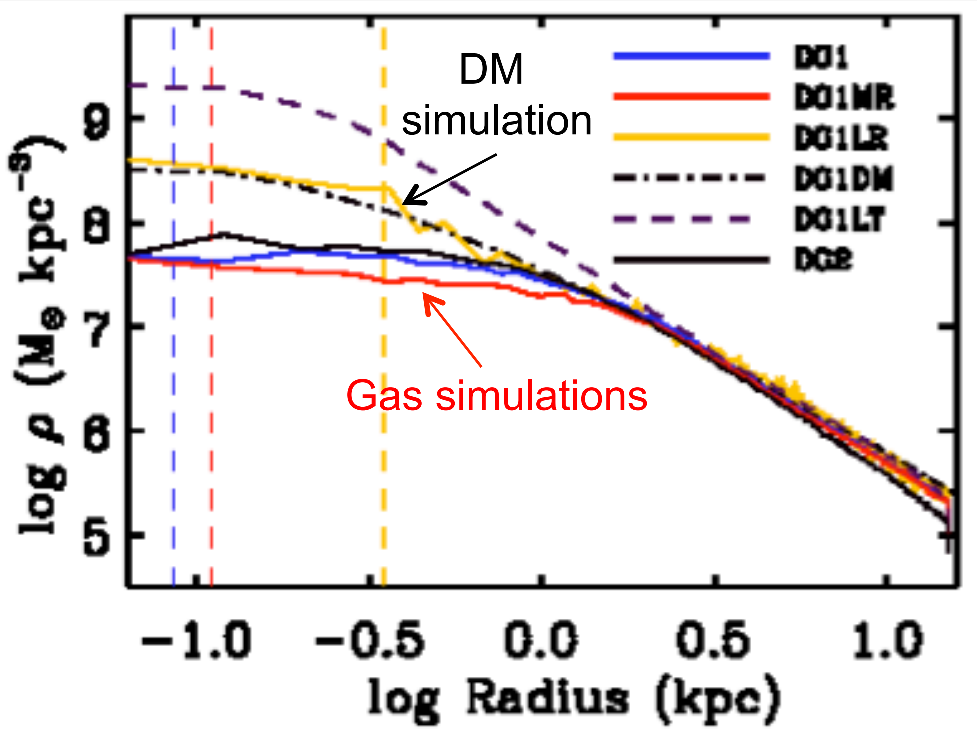
Governato et al. assume high density threshold for star formation

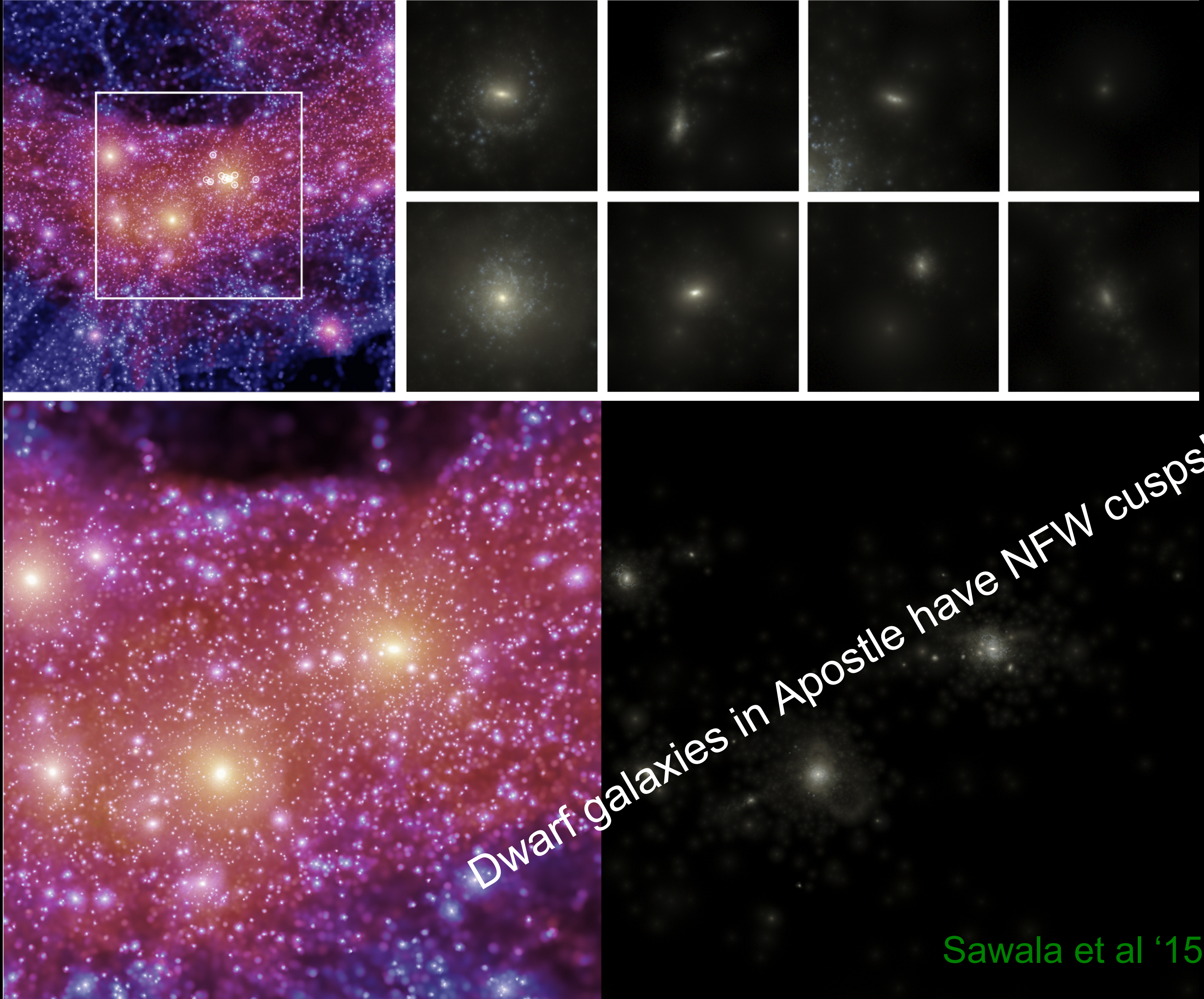
EAGLE does not

→ High threshold allows large gas mass to accumulate in centre

→ Sudden repeated removal of gas transfers binding energy



Governato et al. '12
Pontzen et al. '12

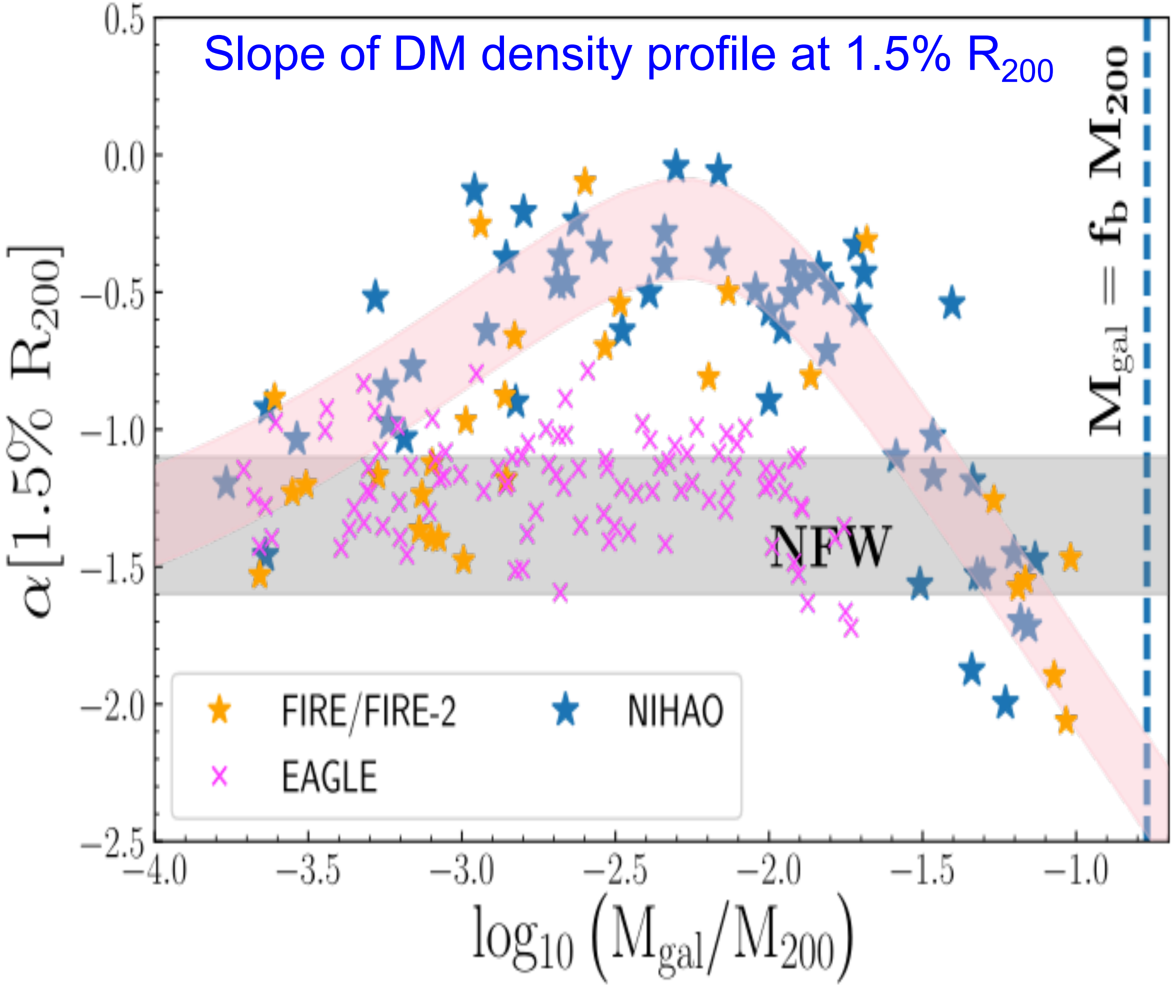


Sawala et al '15

Cores or cusps in simulations of dwarfs

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

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



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?

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

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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

Cores or cusps in simulations?

Key parameter: gas density threshold for star formation

High density → NEF mechanism

Low density → not enough central gas density to perturb DM

Core formation

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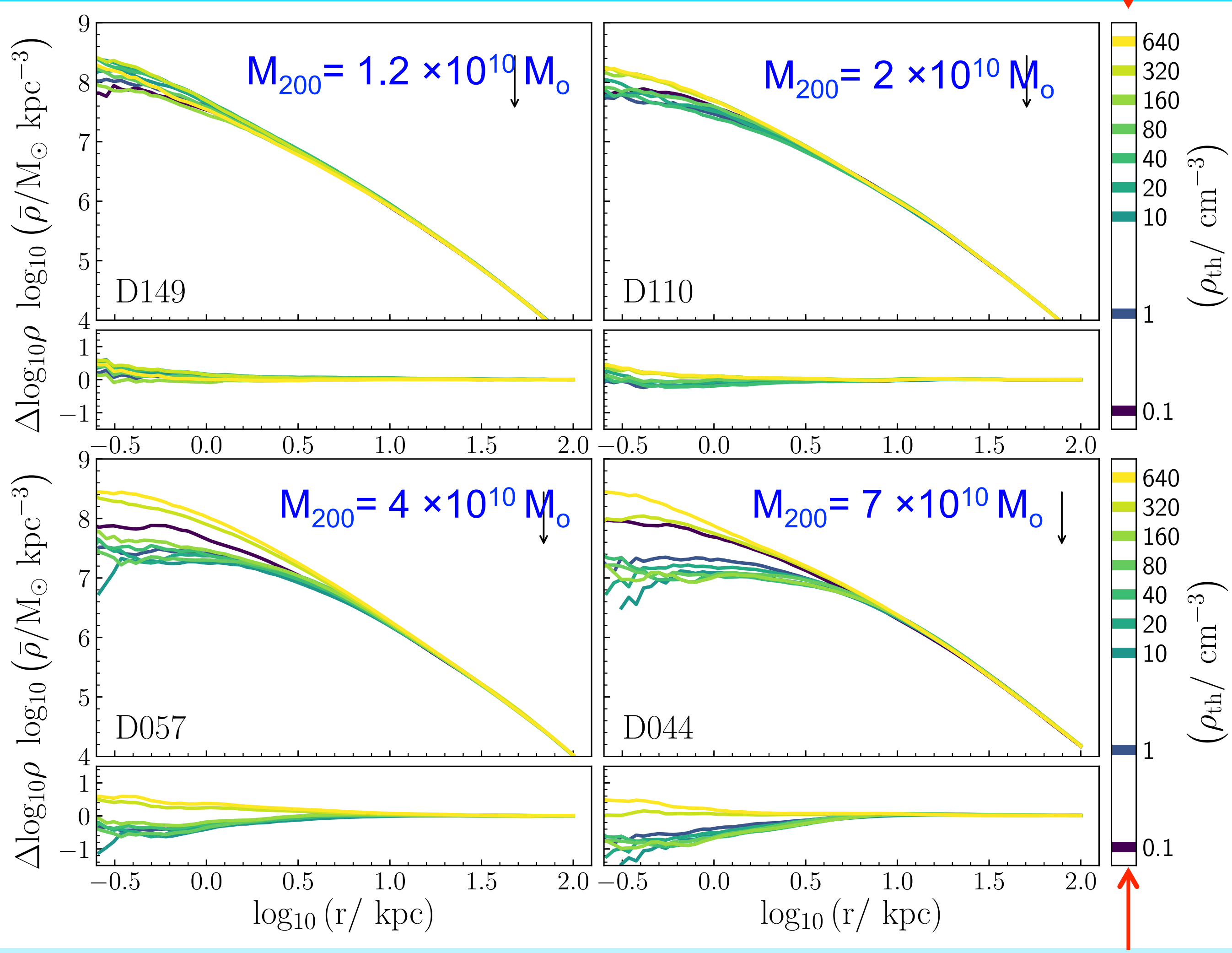
- As density threshold for star formation increases, cores begin to form if galaxy is massive enough
- In small galaxies, cores are tiny (unresolved)
- If threshold is too high, no cores form – halo can become even cuspier

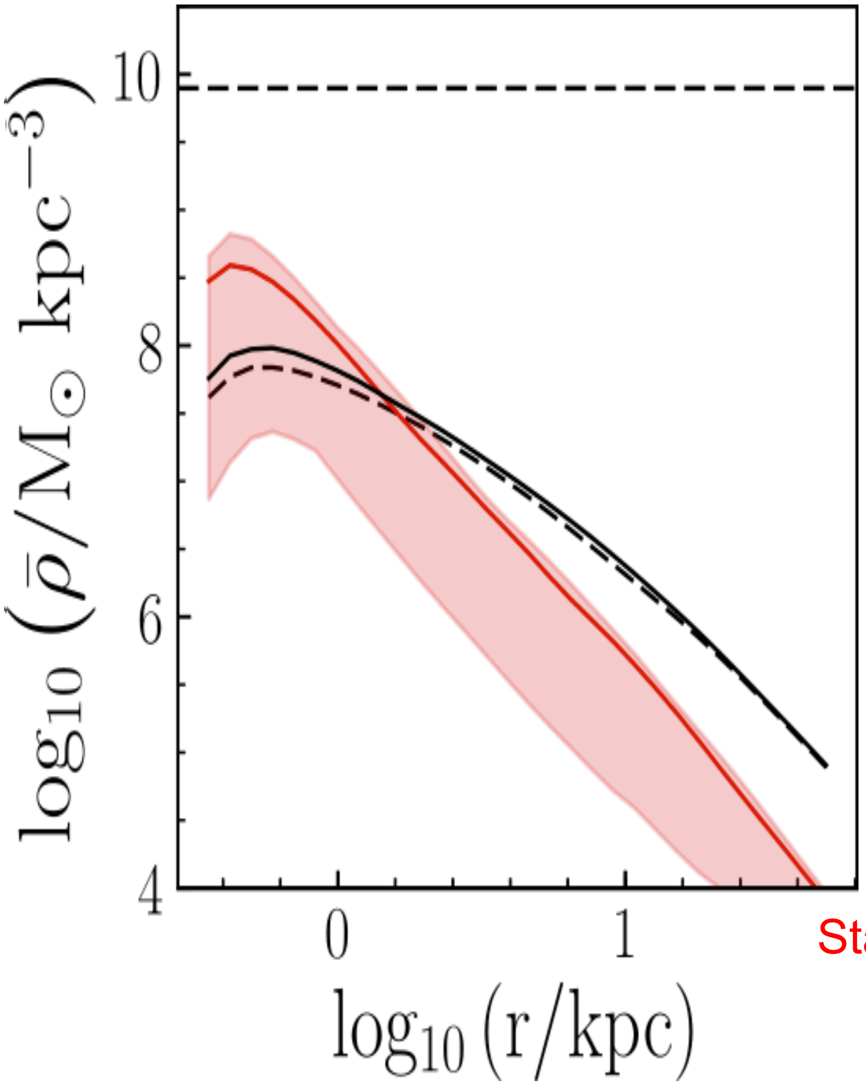
Star formation density threshold



Star formation density threshold

Benitez-LLambay, CSF + '18

Changing the density threshold for star formation



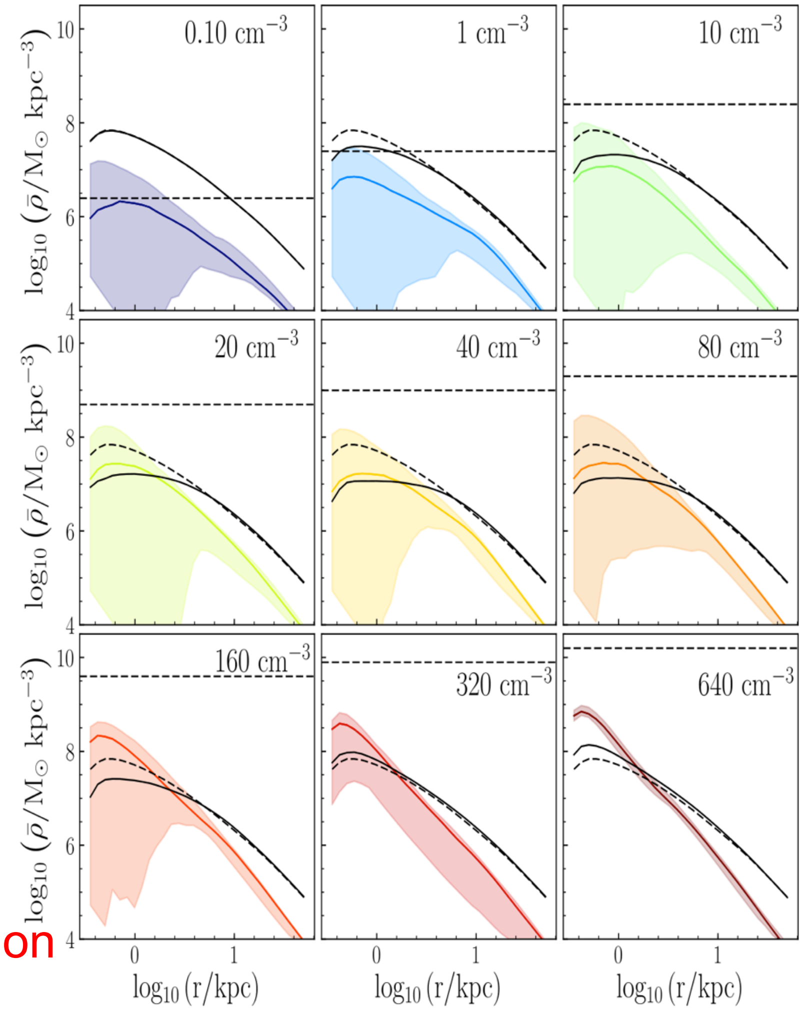
320.0 cm^{-3}

80.0 cm^{-3}

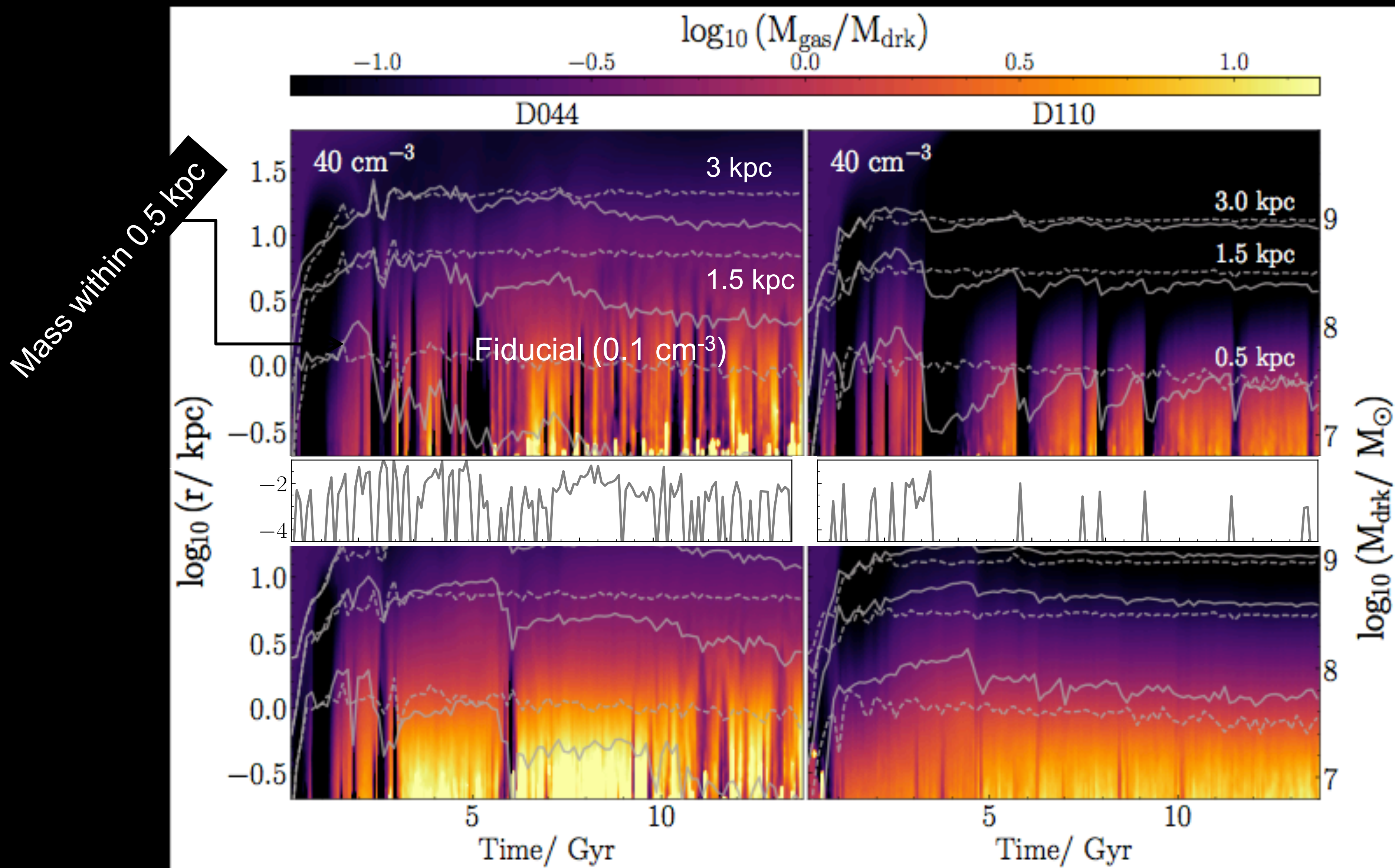
10.0 cm^{-3}

0.1 cm^{-3}

Star formation density threshold



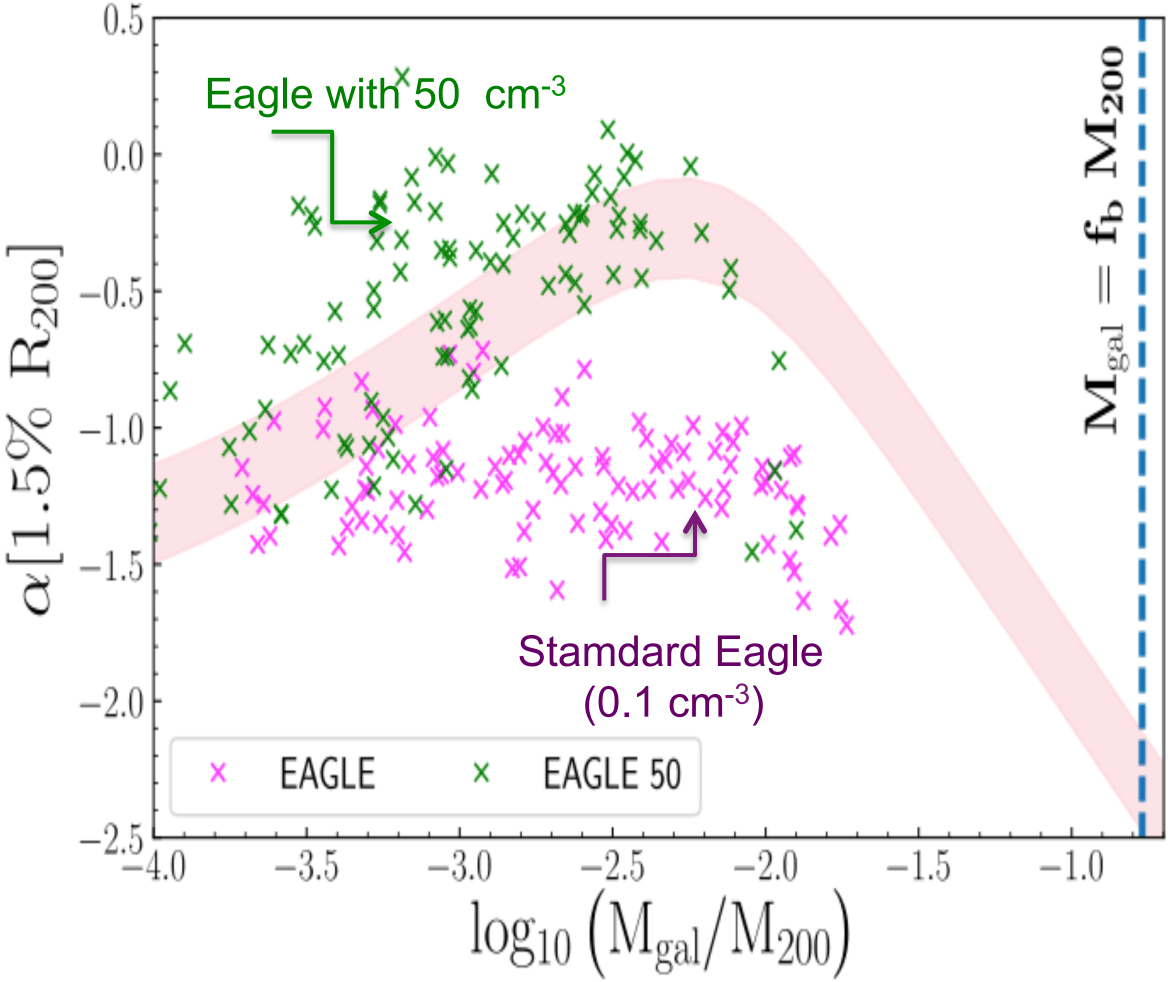
Cores or cusps in simulations?



Eagle with cores

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

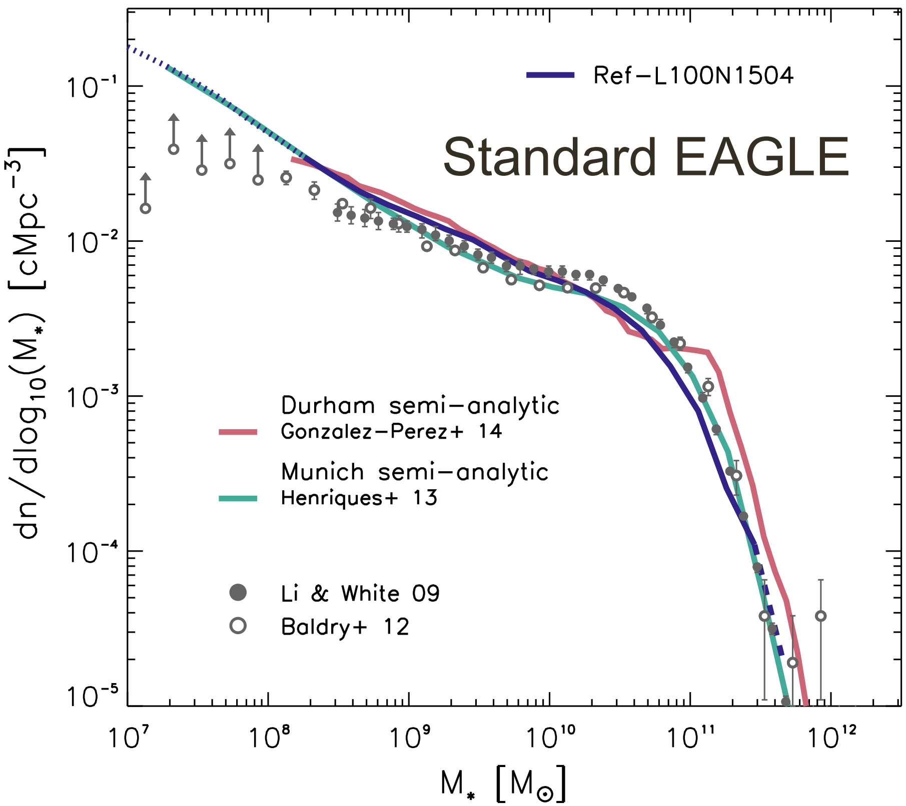
Cores form only on limited range of halo masses (or M_{gal}/M_{halo})



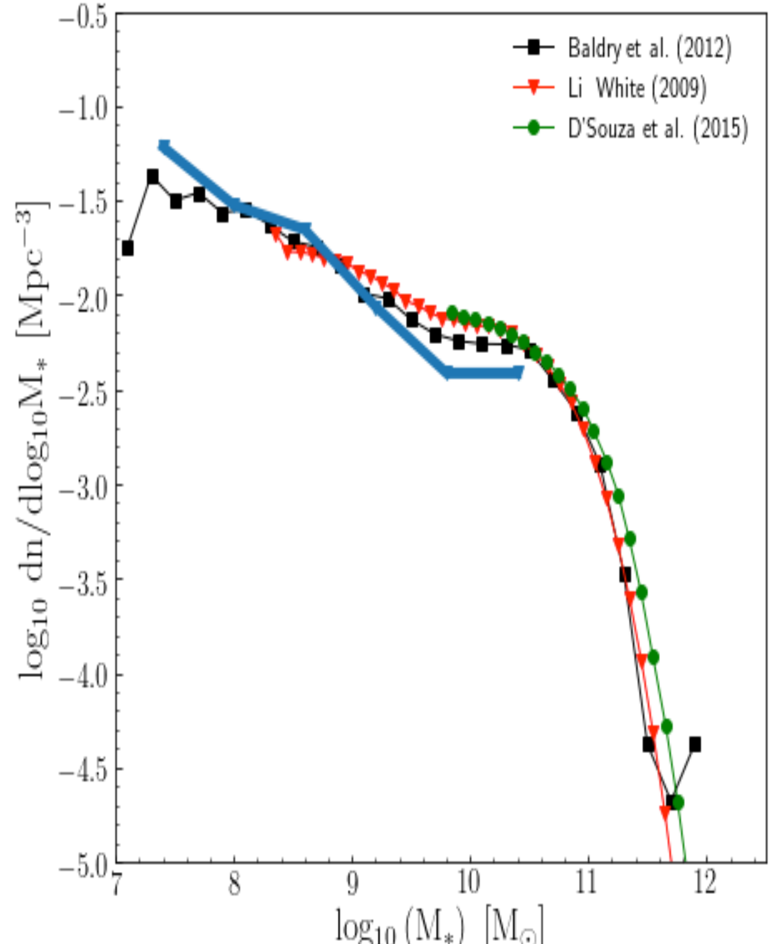
Benitez-LLambay, CSF + ‘18

The galaxy stellar mass function

Standard EAGLE: good match to data



Eagle with cores: poor match to data



Simulation with cores fails to match galaxy stellar mass fn.

New recalibration?

Benitez-LLambay, CSF + ‘18

Conclusions

- Stellar dynamics and HI rotation curves of real dwarfs

  → No evidence for cores: cores and cusps are OK

- N-body simulations → cusps in CDM halos
- Cores in viable WDM models are tiny
- Cores can be formed in CDM by baryon effects

  → Key parameter: density threshold for star formation

- Core sizes depend on subgrid SF threshold parameter

… and also probably on many other factors

- Cores only form in a narrow range of halo masses