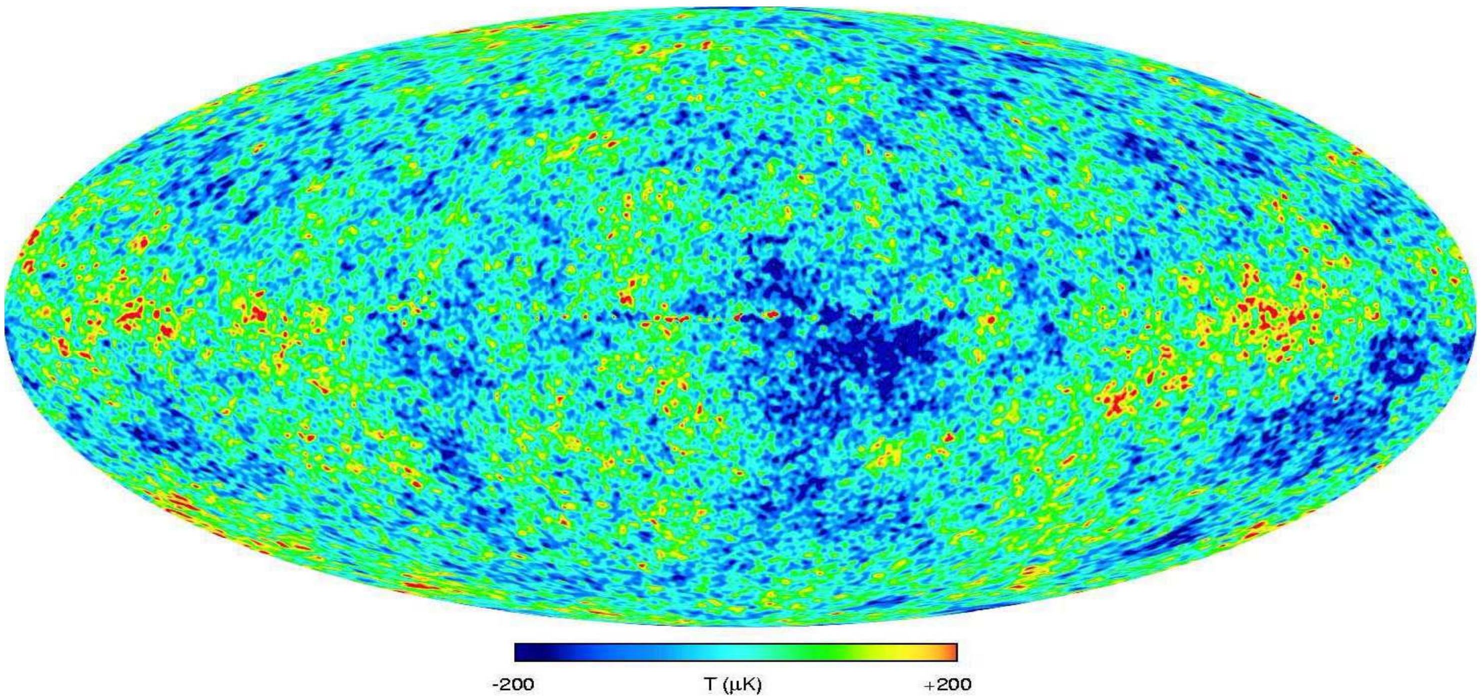
Rome, MG 15 : JPO

2 July, '18

Ultra Light Scalars as Cosmological Dark Matter: Explanation of *Small* Scale

Structure



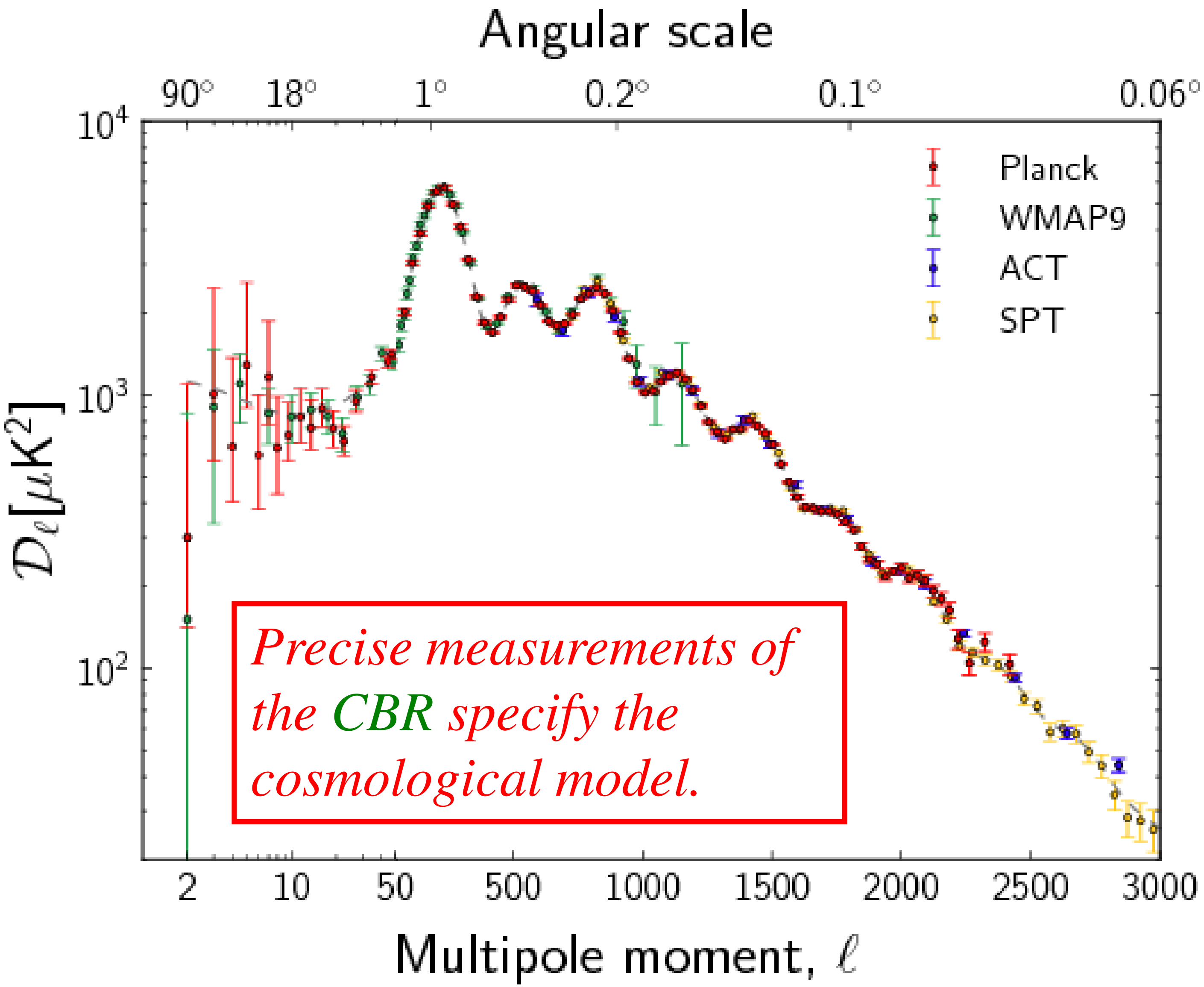
We have a standard model of cosmology and structure formation

- Three components
  - Dark matter: standard model, cold particles ~ GeV
  - Dark energy: standard is Einstein Lambda
  - Baryons: standard from light element nucleo-synthesis
- Spectrum of power law gaussian perturbations of very low amplitude: $P(k) \sim k^{-1}$
- Gravitationally induced growth of structure
- Produces cuspy (NFW) "halos" with fractal subhalos
- Add hydrodynamics and atomic physics

Does it work?

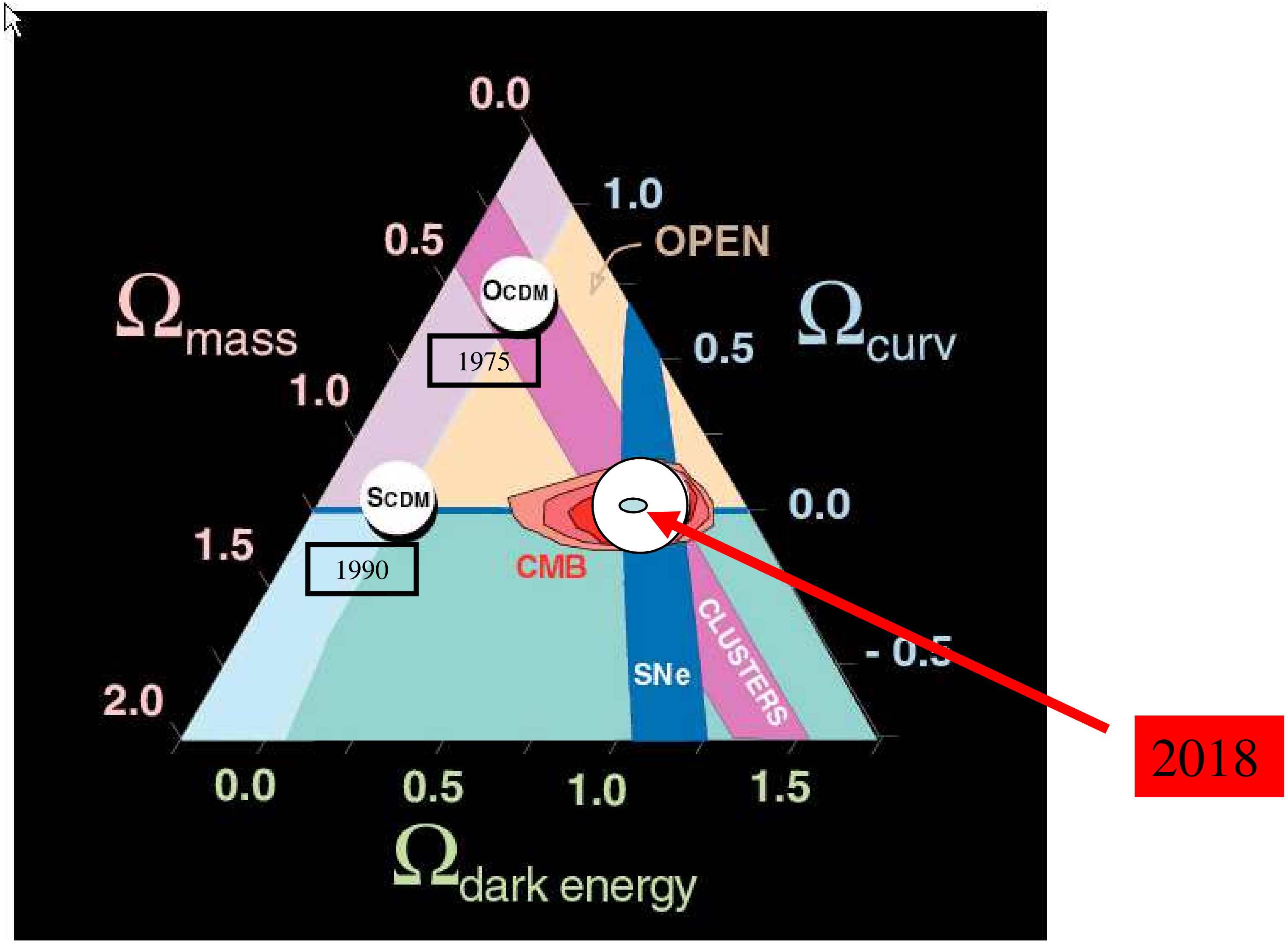
- CBR, microwave background comes out right.
- Size, mass and formation epoch of galaxies comes out roughly right.
- Galaxy distribution, clusters and voids come out right.
- Intergalactic medium comes out right.
- +++++++++++++++++++++++++++++++
- *What is the problem? Details, important details.*

CBR Spectrum – Planck and all



Precise measurements of the CBR specify the cosmological model.

Where we are now….



In Detail: Representative Current Cosmological Model (prior: ΛCDM)

- Ω_{tot} = 1 (assumption) [=1.010 +0.016]
- Ω_{cdm} = 0.241 ± 0.009
- Ω_{baryon} = 0.047 ± 0.001
- Ω_{lambda} = 0.71 ± 0.01
- n = 0.97 ± 0.01
- H_0 = 69.3 ± 0.9 km/s/Mpc
- σ_8 = 0.83 ± 0.02
- τ_{scat} =0.088 ± 0.013

; Spergel *et al* (WMAP9)

"precision cosmology"??

A More Critical Look at the Low Red-Shift Tests:

But…	$10^3 > Z > 6$	$6 > Z > 0.5$	$0.5 > Z$
Photons	CBR ▤▤	SZ ▤▤	Rdio Lns ▤
Baryons	CBR ▤▤	GalForm ▤	LEN ▤▤
Dark Matter	CBR ▤▤	StrGrth ▤▤	HlsClstrs▤▤
Dark Energy	CBR▤▤	SN ▤	Ages,BAO etc ▤
λ > 20Mpc/h	CBR ▤▤	Clstrs2pt▤▤	SDSS ▤▤
20 > λ >1	CBR ▤?	Cltrs,LyA, StrGrth ▤▤	GrLensing▤
1 > λ	????xx?	X▤??	XXX???

FIRST:
Let us look at observed galaxy properties: dwarf spheroidals are a separate low density sequence and the lower the mass the lower the density (Kormendy, 2015 data)

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Elliptical

Dwarf Spher.

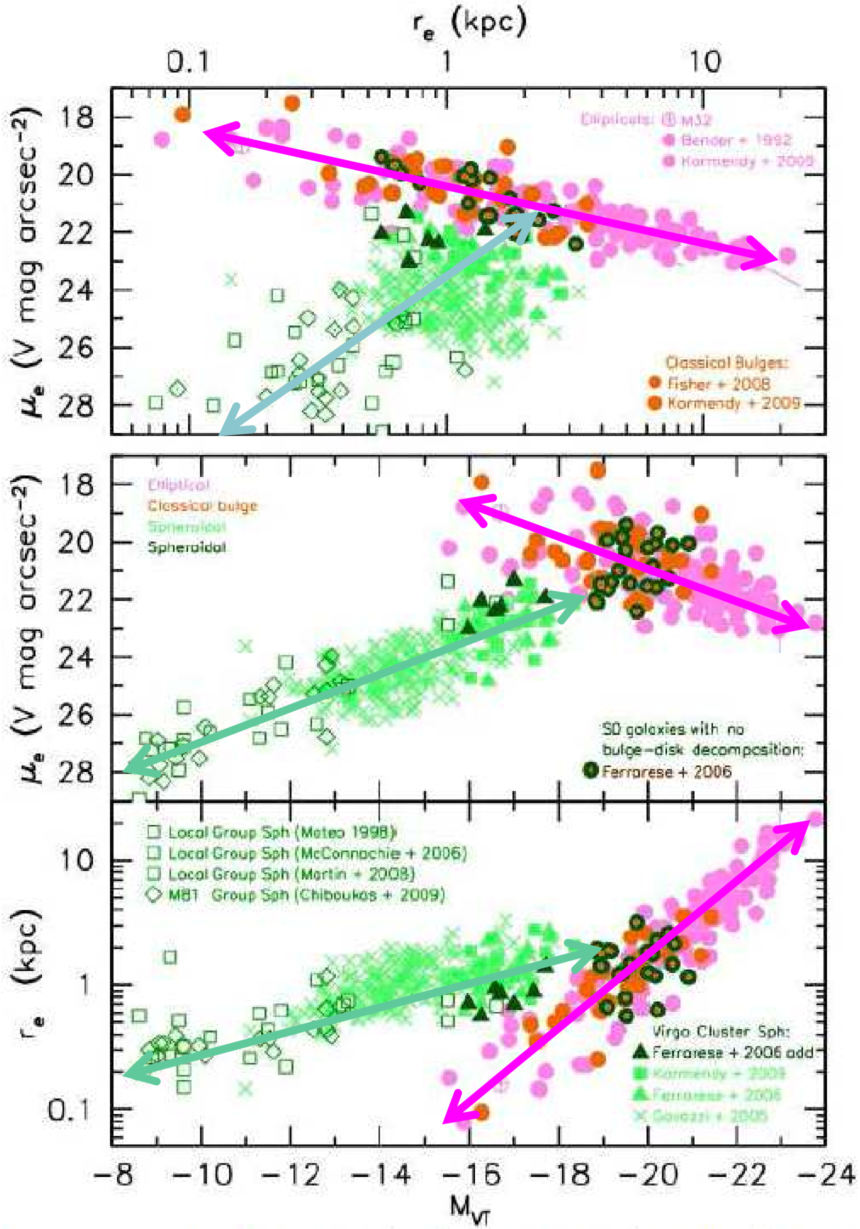


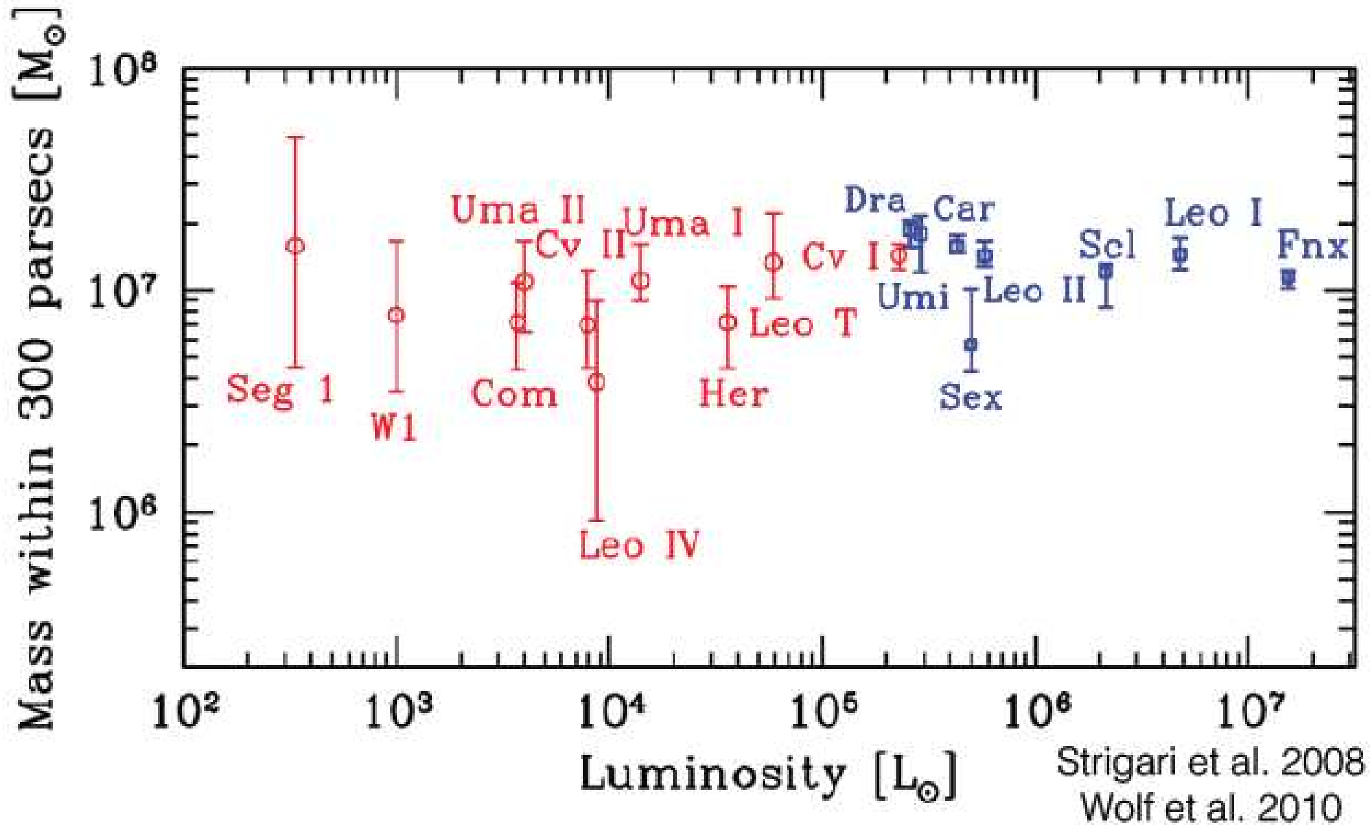
Fig. 2 – Global parameter correlations for ellipticals (pink), classical bulges (light brown), and spheroidals (light green) from Kormendy et al. (2009: KFCB) and from Kormendy (2009). Local Group Sphs have been updated and M 81 Group Sphs have been added. The bottom panels show effective radius r_e and surface brightness μ_e at the effective radius versus galaxy absolute magnitude. The top panel is the $\mu_e - r_e$ or Kormendy (1977b) relation, which shows the fundamental plane

Let us now look at low mass galaxies in the local group

Occupy halos of similar mass:

~3 x 10^9 $M_\odot$

Strigari, Coral Wheeler, 2015



Let us look at the "problems" at small scales

- Absence of DM cusps in Dwarf Spheroidal Galaxies?
- Orbiting GCs in Dwarf Spheroidal Galaxies?
- Mass cutoff for low mass Galaxies?
- Wrong red-shift evolution of low mass Galaxies?
- +++++++++++++++++
- Lack of substructure found in MW halo from study of stellar streams?
- No good explanation for disk thickening with time?
- Lack of gravitational lensing from halo substructures?

An Alternative to Standard (*eg* WIMP) DM: *Fuzzy Dark Matter*

- Lam Hui, JPO, Scott Tremaine & Edward Witten

Phys Rev D 95, 043541 (2017)

- Ultra light bosons – axions w mass ~10^{-22} eV
- Quantum limit: $\hbar = m * v * \lambda$ implies large size when v is small: $M * R = (\hbar^2/(G * m^2))$
- Coupled with VT and cosmological formation gives a minimum halo mass *vs* redshift.
- Can explain dwarf spheroidal results.
- Testable predictions of reduced substructure.

Abbreviated History

- Very prescient papers:
  - Ruffini & Bonazzola, 1969, Phys Rev
  - Baldeschi, Gelmini, Ruffini. 1983 Phys Rev L.

- Recent revival:

  Barkana, Broadhurst, Hu, Marsh, Schive, Spergel…(> 100 names).

  Review by D. Marsh Phys Rev, 643,1 (2016)

Mass-Radius relation at low mass end: from QM

- $v^2 = GM/R = \hbar^2/(m^2 R^2)$

  ➔ $M * R \geq = \hbar^2/(G * m^2)$

  – or

  $R \geq R_{min} = 1$ kpc * $(M/10^9 M_{solar})^{-1} * m_{-22}^{-2}$

Mass-Radius relation at low end: combine w cosmology to get mass limit!

- $\rho \geq 200\, \rho_{crit} = 600 * H^2/(8\, \pi\, G)$
- *and*

$$\rho \sim M/R^3 \sim M^4$$

$$\Rightarrow M \geq M_{min} = (H^2\, \hbar^6/(G^4 * m^6))^{1/4}$$

–or

$$M_{min} = 1.2\ 10^8\, M_{solar} * (1 + z)^{3/4} * m_{-22}{}^{-3/2}$$

And the halos have a different shape: no cusp.

Several papers show that the profiles match those of dwarf spheroidals better than does the standard NFW profile.

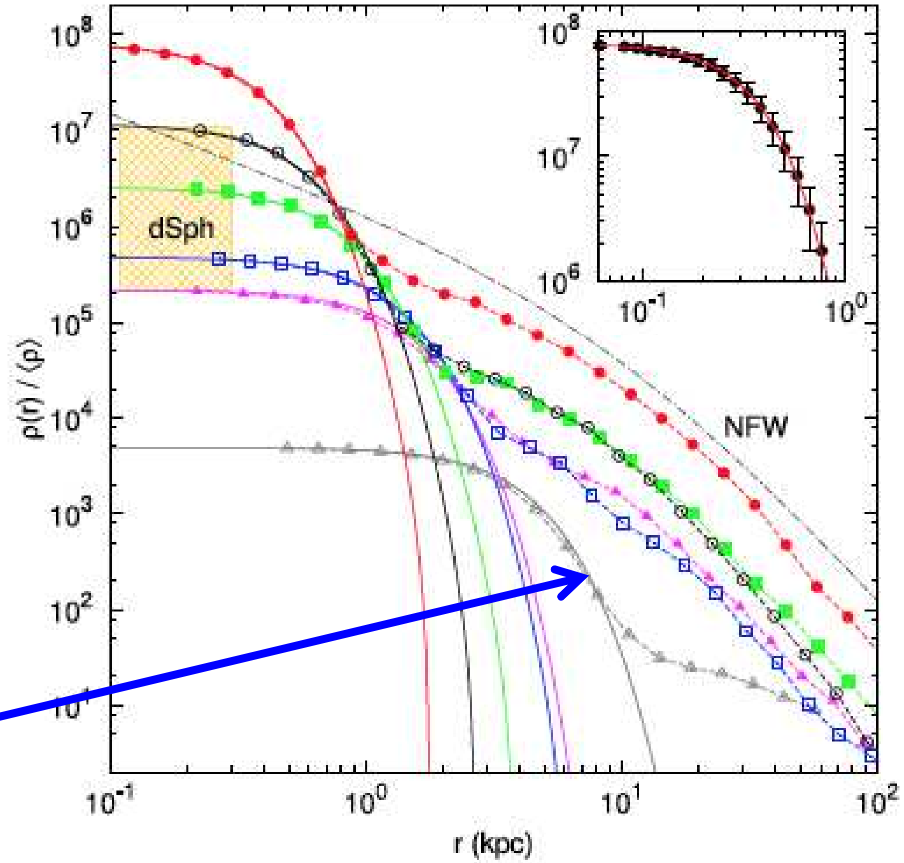


Figure 3: Radial density profiles of haloes formed in the ψDM model. Dashed lines with various sym-

Central soliton is extended in low mass galaxies. A signature.

Soliton structure

Note
“wavelets”

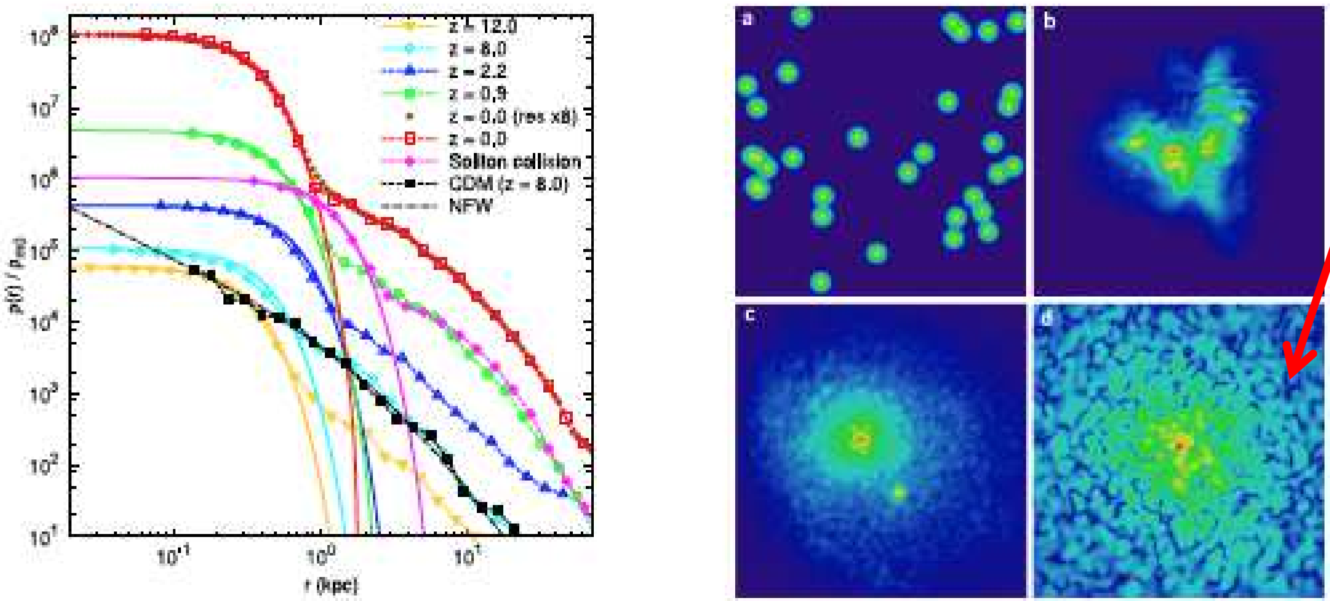
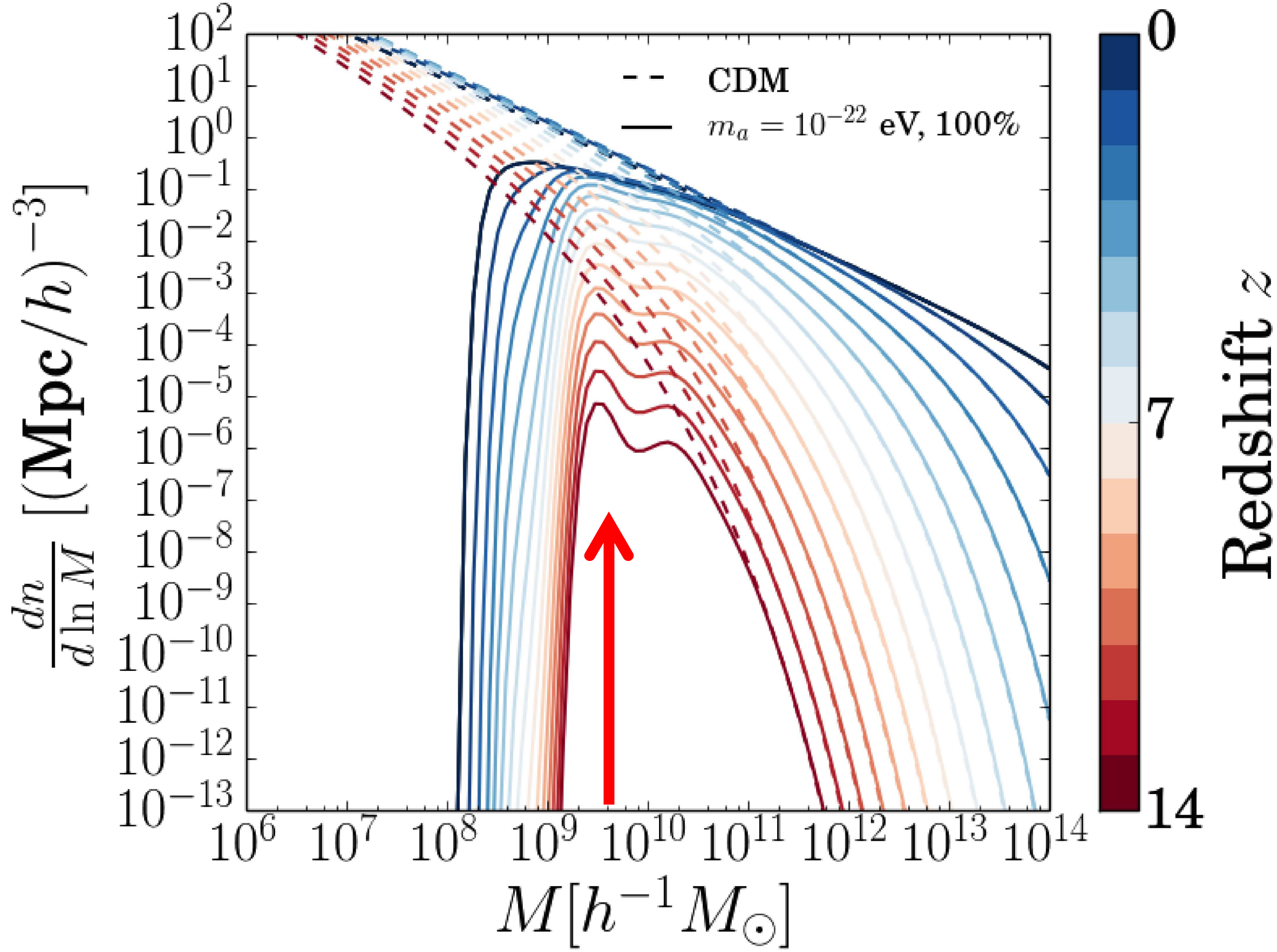


Figure 19: *Left Panel:* Halo density profiles from cosmological simulations of structure formation with a non-relativistic scalar field of mass $m_a = 8.1 \times 10^{-23}$ eV (equivalent to a ULA). There is a central soliton core, transitioning to an NFW profile at large radius, as Eq. (135). *Right Panel:* Understanding halo formation from soliton collision. The solitons virialize and leave behind a small, dense core, and a granular outer halo: (d) is a close up of (c) detailing this. Reproduced (with permission) from Ref. [182]. Copyright (2015) by The American Physical Society.

Mass Function of Halos Computed:

Bozek *et al* (2015)



High redshift luminosity functions are consistent w FDM if $m_{-22} > 1.2$.

(Schive *et al*, 2015)

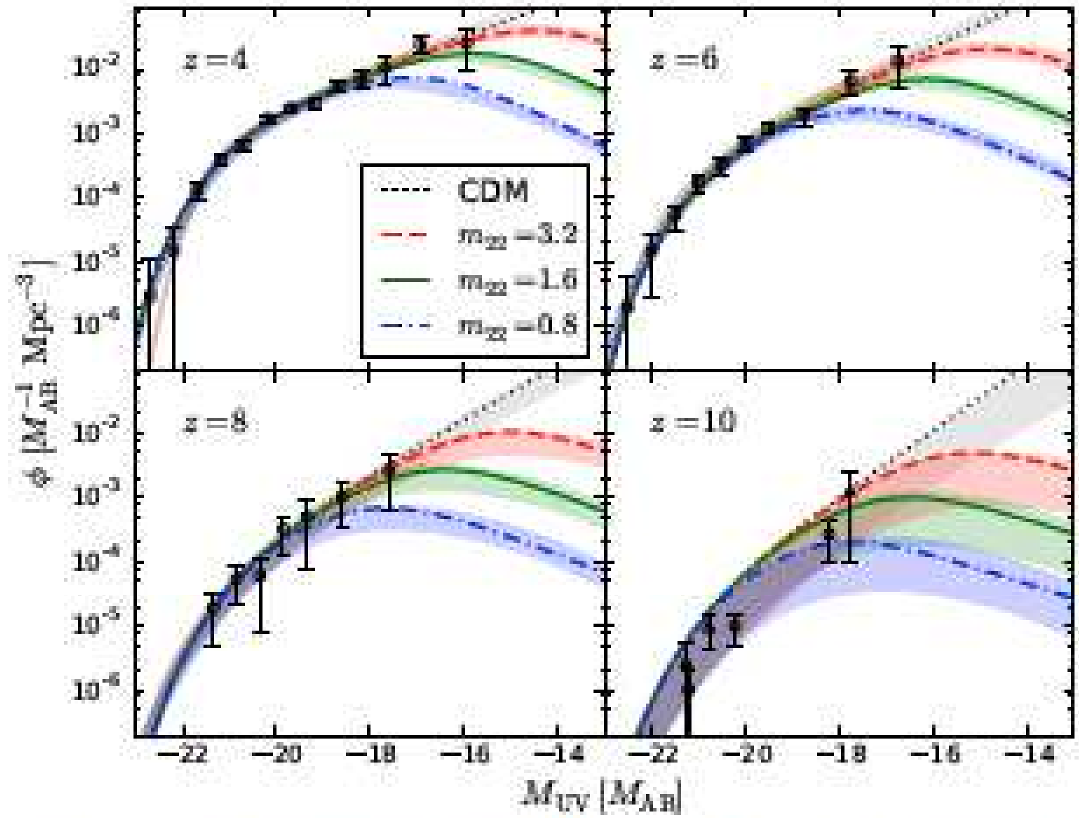


FIG. 7.— Luminosity function (LF) at $z = 4 - 10$ obtained by a single analytic formula similar to the Schechter function (Eqs. [11-13]; central lines). The shaded regions are the same as Fig. 6, showing the LF predicted by the conditional LF model within 2σ. Error bars show the observed LFs (2σ at $z = 4 - 8$ and 1σ at $z = 10$) of B15b (open circles) and Oesch et al. (2014, open triangles). The analytic formula well reproduces the conditional LF results at $z = 4 - 8$, while at $z = 10$ it slightly outnumbers the observed galaxies and is marginally consistent with the conditional LF model.

Recent E-print on high redshift

- **Magnification Bias of Distant Galaxies in the Hubble Frontier Fields: Testing Wave vs. Particle Dark Matter Predictions**
- Enoch Leung, Tom Broadhurst, Jeremy Lim, Jose M. Diego, Tzihong ChiuehHsi-Yu Schive, Rogier Windhorst
- (Submitted on 20 Jun 2018)
- Acting as powerful gravitational lenses, the strong lensing galaxy clusters of the deep {\it Hubble} Frontier Fields (HFF) program permit access to lower-luminosity galaxies lying at higher redshifts than hitherto possible. We analyzed the HFF to measure the volume density of Lyman-break galaxies at $z>4.75$ by identifying a complete and reliable sample up to $z\simeq10$. A marked deficit of such galaxies was uncovered in the highly magnified regions of the clusters relative to their outskirts, implying that the magnification of the sky area dominates over additional faint galaxies magnified above the flux limit. This negative magnification bias is consistent with a slow rollover at the faint end of the UV luminosity function, and indicates a preference for Bose-Einstein condensate dark matter with a light boson mass of mB$\simeq$10–22eV over standard cold dark matter.

But there are more stringent high redshift tests

- Does the universe re-ionize early enough ?
- Is the optical depth to electron scattering high enough? Recent Planck result $\tau = 0.053$ puts LCDM into difficulties.
- Is the Lyman alpha forest predicted correctly?
- Is the evolution of low mass galaxies consistent with observations?
- Are there too many massive gal at high z?

Re-ionization barely ok.

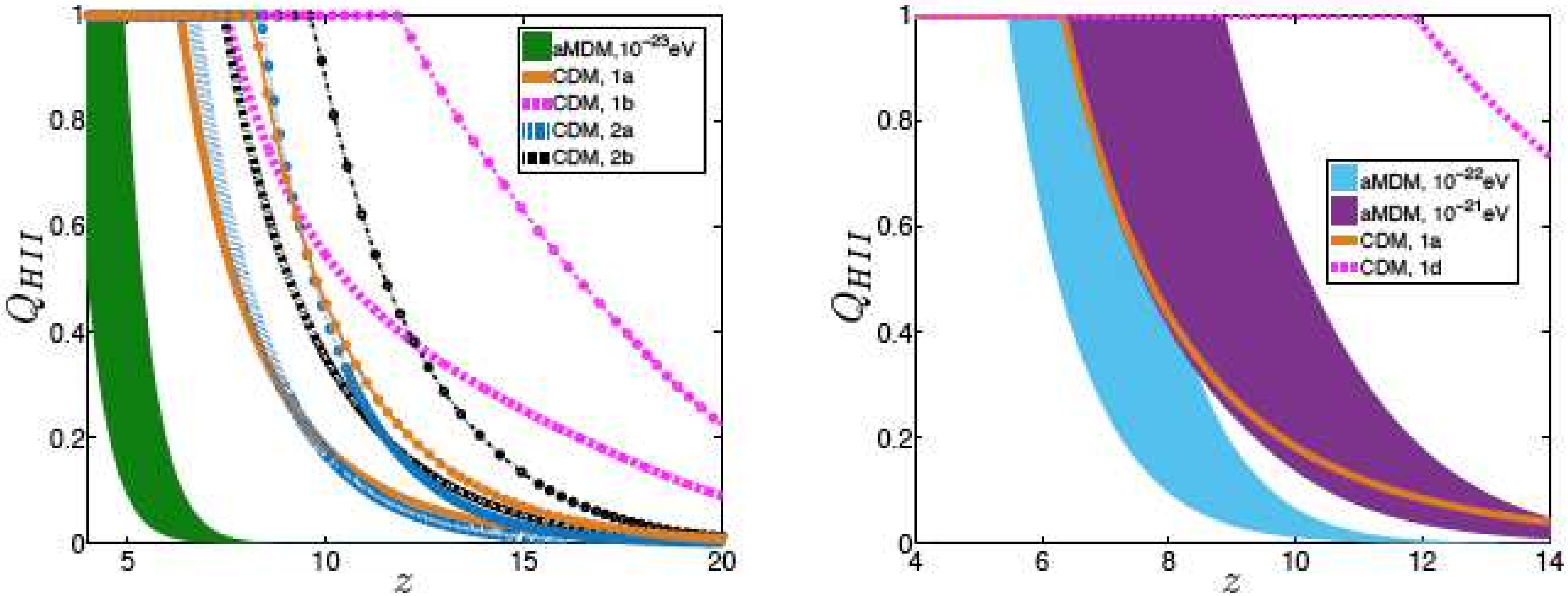


Figure 6. The reionization histories of the aMDM and CDM models. Left-hand panel: CDM '1a' (thick, solid orange), CDM '1b' (thick, dashed pink); CDM '1c' (thin, solid orange /circle markers); CDM '1d' (thin, dashed pink/circle markers); CDM '2a' (thick, dotted blue); CDM '2b' (thick, dash–dotted black); CDM '2c' (thin, dotted blue/circle markers); CDM '2d' (thin, dash–dotted black/circle markers). The full range of $m_a = 10^{-23}$ eV reionization histories are represented by the green patch. The $m_a = 10^{-23}$ eV aMDM models are unable to reionize the universe by $z = 5$. Right-hand panel: the full range of $m_a = 10^{-21}$ eV reionization histories are represented by the dark purple patch and the $m_a = 10^{-22}$ eV reionization histories are represented by the light blue patch. CDM models '1a' and '1d' are shown for reference (x-axis has a different scale in each panel). The $m_a = 10^{-22}$ eV aMDM model reionization histories complete reionization by $z = 6$ depending on the assumed reionization parameters. All models complete reionisaiton by $z = 5.5$. The reionization histories of the $m_a = 10^{-21}$ eV aMDM models complete reionization by $z = 6$.

Optical depth now ok.

New Planck result

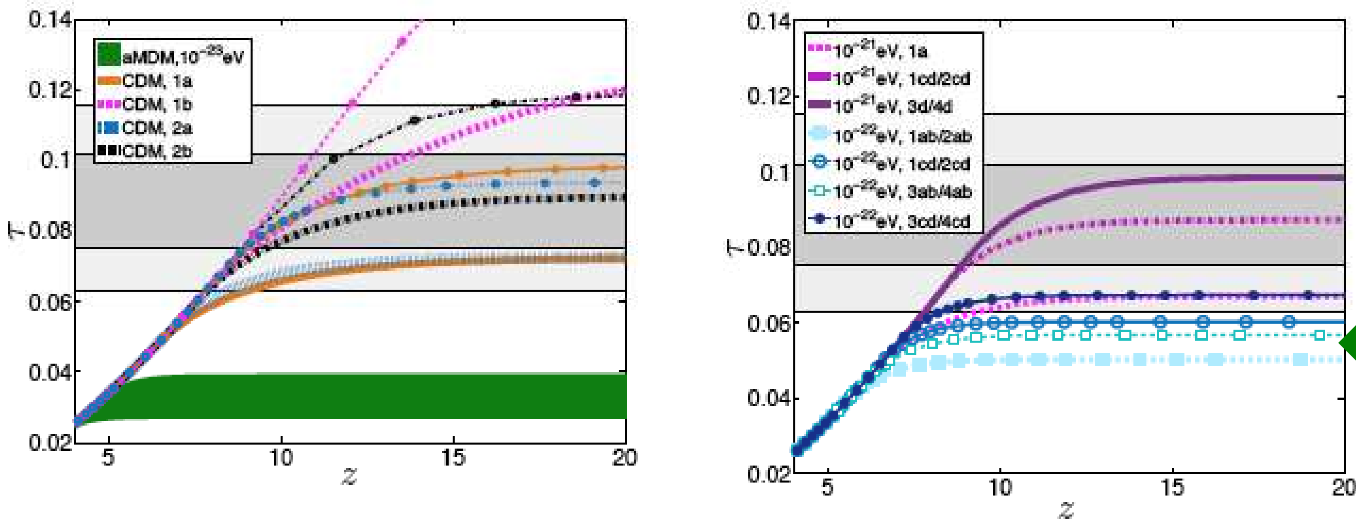


Figure 7. The CMB optical depth, τ, for the aMDM and CDM models. The grey (horizontal) bands in both panels are *Planck*+*WMAP* 68 per cent (1σ,dark grey) and 95.45 per cent (2σ,light grey) confidence levels. Left-hand panel: CDM '1a' (thick, solid orange), CDM '1b' (thick, dashed pink); CDM '1c' (thin, solid orange/circle markers); CDM '1d' (thin, dashed pink/circle markers); CDM '2a' (thick, dotted blue); CDM '2b' (thick, dash–dotted black); CDM '2c' (thin, dotted blue/circle markers); CDM '2d' (thin, dash–dotted black/circle markers). The full range of $m_a = 10^{-23}$ eV CMB optical depth values are represented by the shaded green patch. The $m_a = 10^{-23}$ eV aMDM model is excluded at greater than 99.99 per cent confidence. Right-hand panel: $m_a = 10^{-22}$ eV models '1ab/2ab' (dashed, light blue curve/filled square markers); $m_a = 10^{-22}$ eV models '1cd/2cd' (solid, blue/open circle); $m_a = 10^{-22}$ eV models '3ab/4ab' (dashed, cyan/open square); $m_a = 10^{-22}$ eV models '3cd/4cd' (solid, dark blue/filled circle); $m_a = 10^{-21}$ eV '1a' (dashed magenta); $m_a = 10^{-21}$ eV models '1cd/2cd' (dash–dotted purple); $m_a = 10^{-21}$ eV models '1cd/2cd' (solid dark purple). The $m_a = 10^{-22}$ eV aMDM model predictions for τ (right-hand panel) is in tension with *Planck*+*WMAP* constraints. Only the $m_a = 10^{-22}$ eV model with axions contributing only 50 per cent of the DM and with the most extreme reionization assumptions is consistent at 95.45 per cent (2σ) confidence. Less conservative models with larger DM fraction in axions are in more tension. The $m_a = 10^{-21}$ eV aMDM model τ predictions are all consistent with *Planck*+*WMAP* constraints and depend strongly on the reionization parameter assumptions.

Basic low redshift tests

- Cusp-core issue?
- Dwarf galaxy satellites?
- Dynamical friction in dwarf systems?
- Substructure in MW and other halos?
- Too big to fail problem?
- Sizes of small systems?
- Disk star heating by wavelets?

Cusp-Core issue in dwarf systems

Kyle A. Oman[1,*], Julio F. Navarro[1,2], Azadeh Fattahi[1], Carlos S. Frenk[3], Till Sawala[3], Simon D. M. White[4], Richard Bower[3], Robert A. Crain[5], Michelle Furlong[3], Matthieu Schaller[3], Joop Schaye[6], Tom Theuns[3]

"We conclude that one or more of the following statements must be true: (i) the dark matter is more complex than envisaged by any current model; (ii) current simulations fail to reproduce the diversity in the effects of baryons on the inner regions of dwarf galaxies; and/or (iii) the mass profiles of "inner mass deficit" galaxies inferred from kinematic data are incorrect."

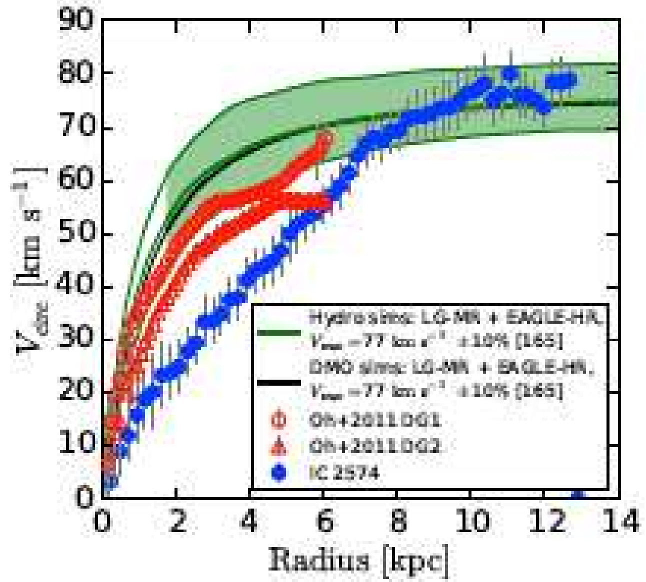
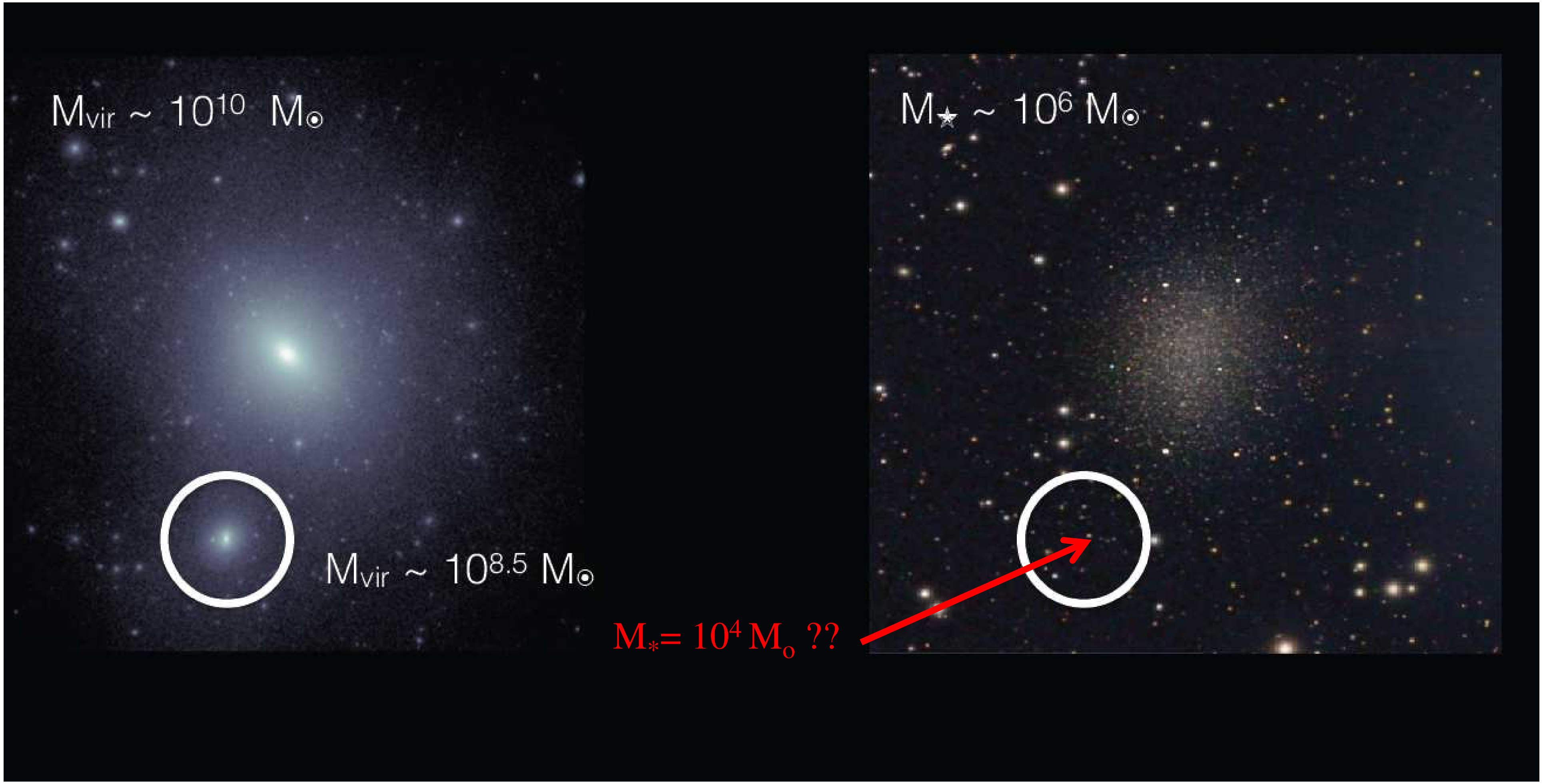


Figure 1. Rotation curves of IC 2574 (filled circles) and of the simulated galaxies DG1 (open circles) and DG2 (open triangles), taken from Oh et al. (2011). The green line shows the median circular velocity curve of all galaxies from our LG-MR and EAGLE-HR simulations (see §2.1) with $V_{max} = 77$ km s^{-1} ± 10 per cent, matching the value of V_{max} of IC 2574. The shaded area indicates the 10th–90th percentile range at each radius. The lines become thinner and the shading stops inside the average convergence radius, computed following the prescription of Power et al. (2003). The numbers in square brackets in the legend are the numbers of galaxies/haloes that contribute to that velocity bin. The solid black line is the median circular velocity profile of haloes of the same V_{max}, identified in our dark matter-only simulations.

And, typically, low mass satellites of dwarf galaxies are predicted to exist by standard theory:



Some Predictions

- No dynamical friction in small systems.
- No cusps in small systems.
- No sub-halos smaller than 10^8 M_{solar} at $z = 0$.
- By $z = 10$ minimum halo mass is 10^9 M_{solar}
  - and low mass galaxies form late.
- Wavelets put energy into stellar orbits.
- Gravitational lensing by intervening sub-halos is reduced.

Conclusion: Viable alternative to CDM

- *Proposal:* Bulk of DM is FDM: $m = 1.2 \times 10^{-22}$ eV.
- All large scale structure successes remain unchanged.
- Absence of direct detections to-date is understood.
- Absence of DM in globular clusters is understood.
- Anomalies in dwarf galaxies can be understood.
  - absence of dynamical friction
  - low inner rotation curves
  - absence of satellites
- Specific tests predicted, so hypothesis is falsifiable by experiments/observations underway.
- *Most critical potential inconsistency: Lyman-alpha forest.*