Constraints on dark matter scenarios from measurements of the galaxy luminosity function at high-z

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Publications:

PSC et al. (2017), arXiv:1611.05892
Carucci & PSC, in preparation
Carucci & PSC (2017), arXiv:1706.09462

Mainz, ``Tensions in the LCDM paradigm'', 14-18 May 2018

Observatoire de Paris – Meudon Campus

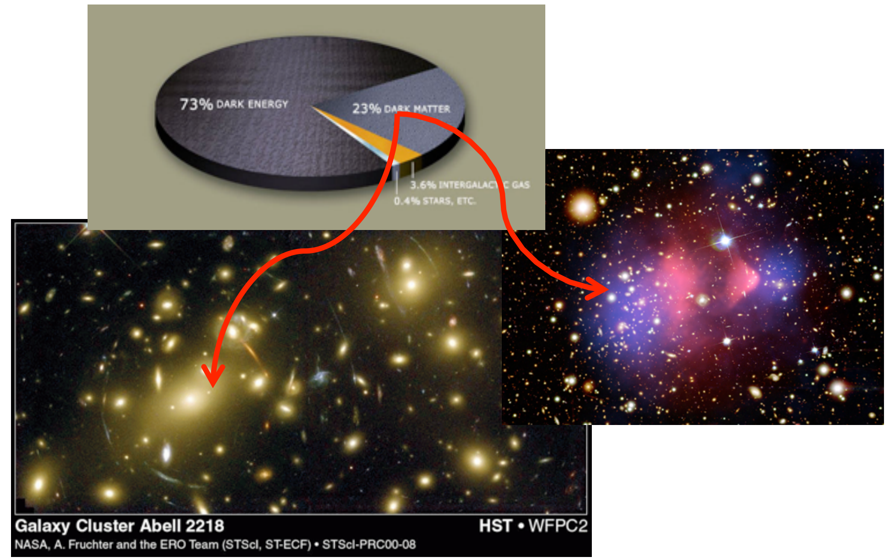
Outline

- Motivations
- High-z Galaxy Luminosity Function
- N-body Simulations & Numerical Systematics
- Statistical Halo-Galaxy Model
- DM Model Constraints & Astrophysical Implications

Standard DM paradigm

Dark Matter:

- Foster matter clustering
- Resides in virialized clumps

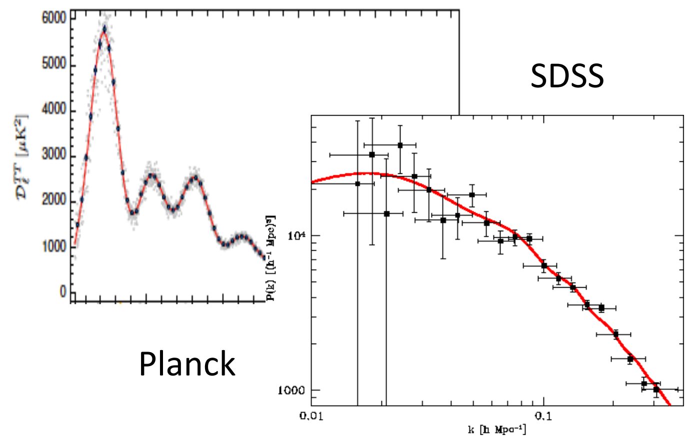


Halos:

- Building blocks of cosmic structure formation
- Shape baryon distribution

Large Scales:

- Successful Description CMB spectra
- Clustering of Matter from galaxy surveys
- Bottom-Up Evolution -> Certainly no HDM



Cold Dark Matter Paradigm

- WIMP miracle

Small Scales & Beyond CDM

CDM Anomalies:

- Core vs Cusp Profiles
- Missing Satellites
- Too-big-too fail

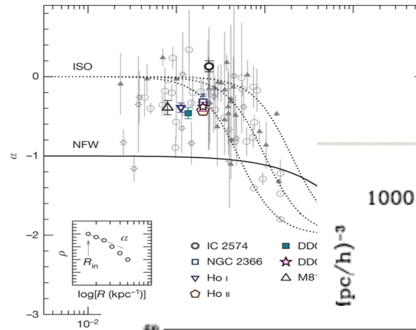
Non-DM Physics Explanations:

- Baryonic Feedback
- Observational Selection Effects
- Uncertainties of Milky-Way Mass

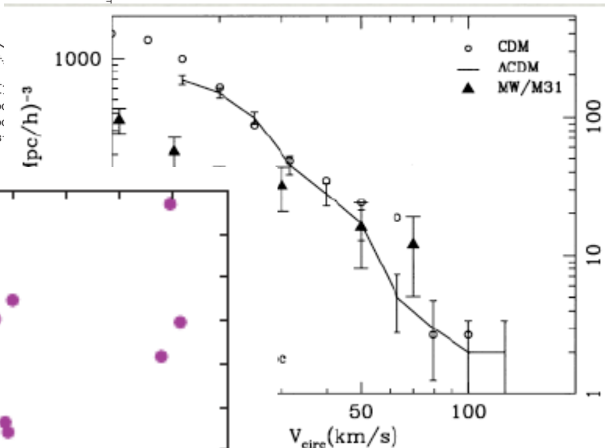
DM Direct Searches:

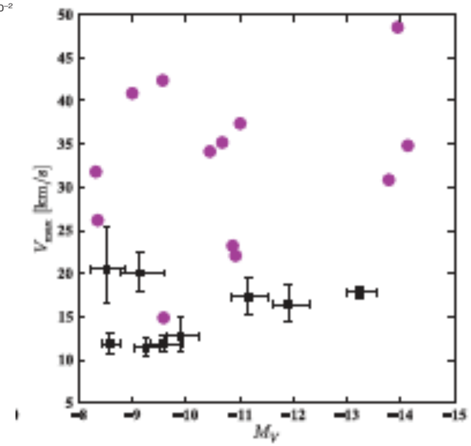
- Negative or Contrasting Results
- No signal at LHC

Pontzen & Governato 2014



Klypin et al. 1999



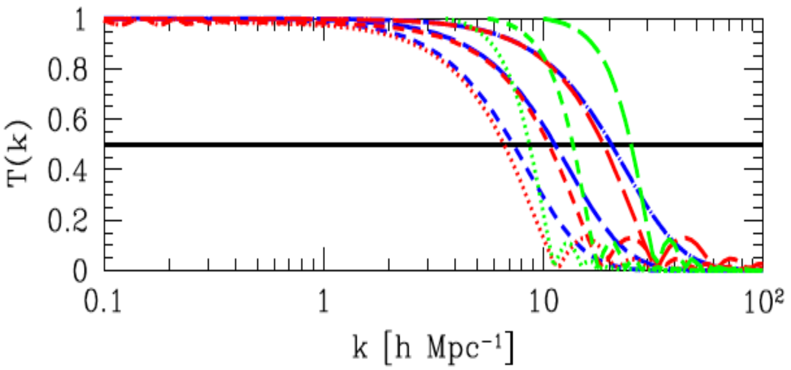


Boylan-Kolchin et al. 2012

Non-CDM Candidates

Warm Dark Matter

- Thermal Relic , $m_{WDM} \approx$ keV
- Free-Stream ≤ 100 kpc
- Small-Scale Power Spectrum Cut-off



Self-Interacting DM

Spergel & Steinhardt 2000

- DM scattering cross-section (velocity in/dependent)
- Interaction with radiation

Ultra-Light Axions and Late-Forming DM

- ULA: Axion field transition from vacuum to matter (w=-1 -> w=0)

see review Marsh (2015)

- LFDM: Before matter/radiation equality, decay of scalar field coupled to radiation (w ≈ 1/3 -> w=0)

Fardon, Nelson, Weiner 2006; Das & Weiner 2011

Non-CDM Observational Consequences

Warm Dark Matter

- m_{WDM} < 0.1 keV to core the DM profiles e.g. Maccio et al. 2012
- 1.5 < m_{WDM} [keV] < 2 to solve too-big-to-fail Lowell et al. 2012, 2014
- m_{WDM} > 3.3 keV from Lyman-α power spectrum a z>2 Viel et al. 2012

Self-Interacting DM

- Lower density sub-halos and core profiles Vogelsberger et al. 2012; Zavala et al. 2013
- Low mass halo abundances unaltered

Axion DM

- CMB anisotropy and large scale galaxy clustering analysis: $m > 10^{-24}$ eV

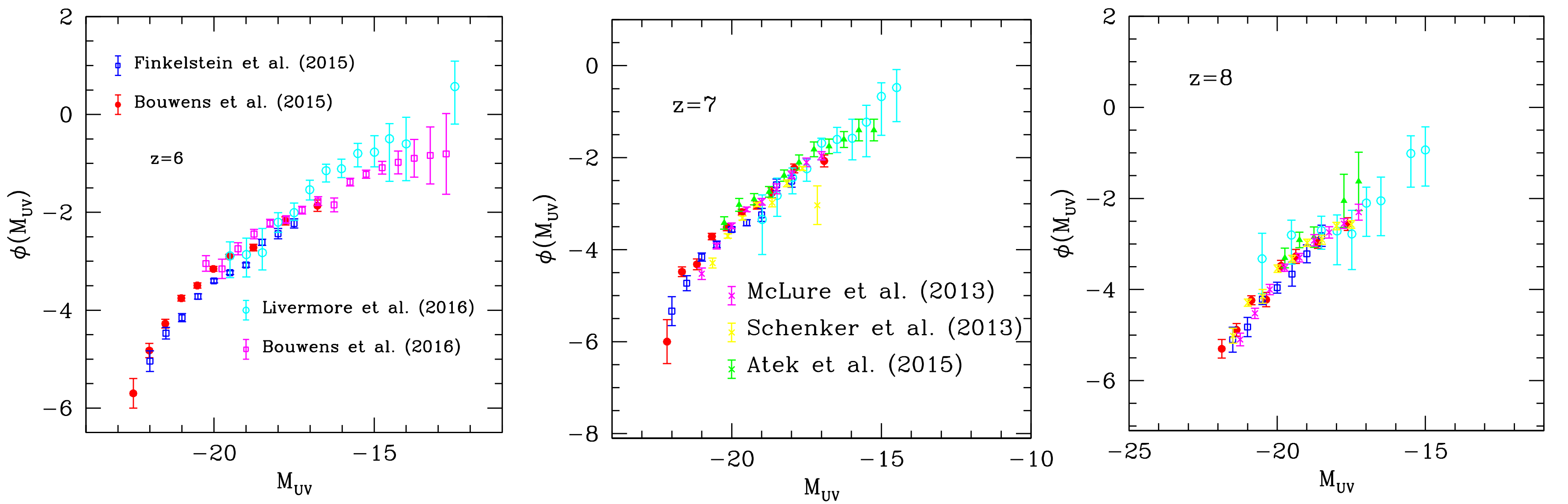
Hlozek et al. 2015

High-z Galaxy Luminosity Function

- Test for galaxy formation models
- Linked to Cosmic Reionization Scenarios
- Probe low-mass end HMF evolution

Fast evolving field

- Deep surveys *(Hubble Deep Field)*
- Cluster Gravitational Lensing (*Hubble Frontier Fields*)



High-z LF vs DM

Galaxy Number Density:

- m_{WDM}> 1 keV (CLASH at z = 10)

Pacucci, Mesinger & Haiman (2013)

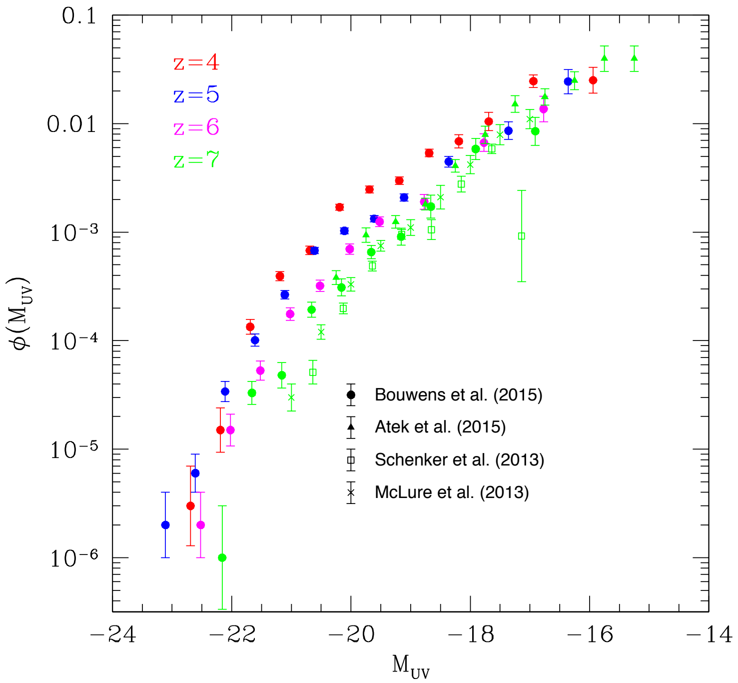
- m_{WDM}> 2.9 keV (HFF at z =6)

Menci et al. (2016)

Does not need to specify M_{UV}-M_h but not free of other caveats

- m_{WDM} > 0.8 keV (at mag limit HUDF data) using HAM of LCDM

Schultz et al. (2014)



Luminosity Function:

- m_{Ψ} > 10^{-22} eV from HAM assuming parametrized L_{UV}(M) relation

Schive et al. (2016)

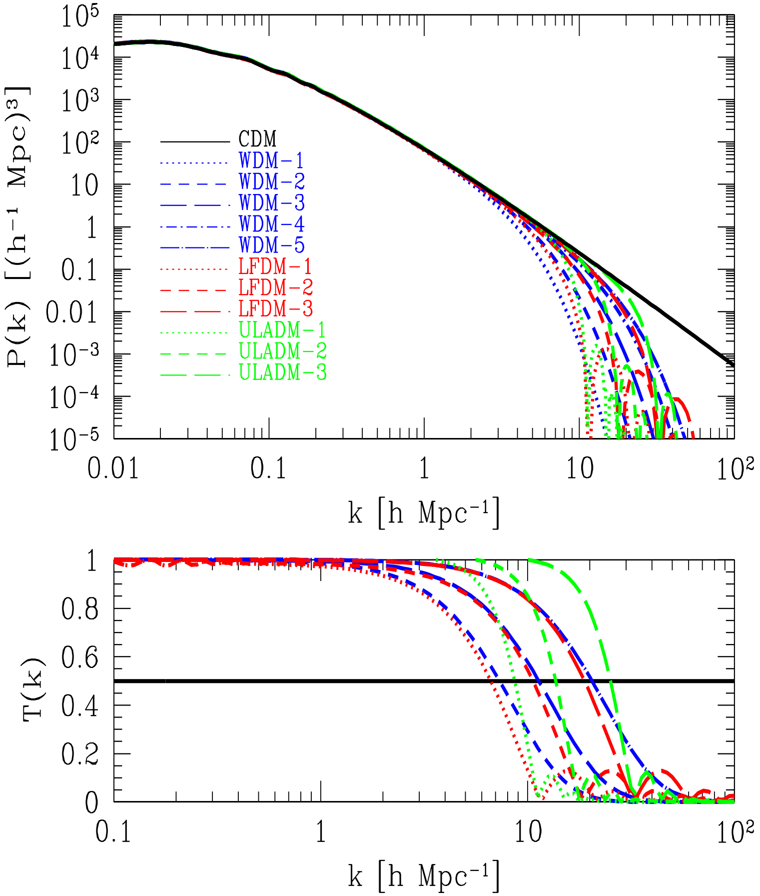
N-body Simulations

Models:

- **WDM**: m_{WDM} = 0.7, 1.0, 1.5, 2.0, 2.4 keV
- **LFDM**: z_t = 5, 8 ,15 × 10^5
- **ULADM**: m_{ULA} = 1.6, 4.2, 15.4 × 10^{-22} eV

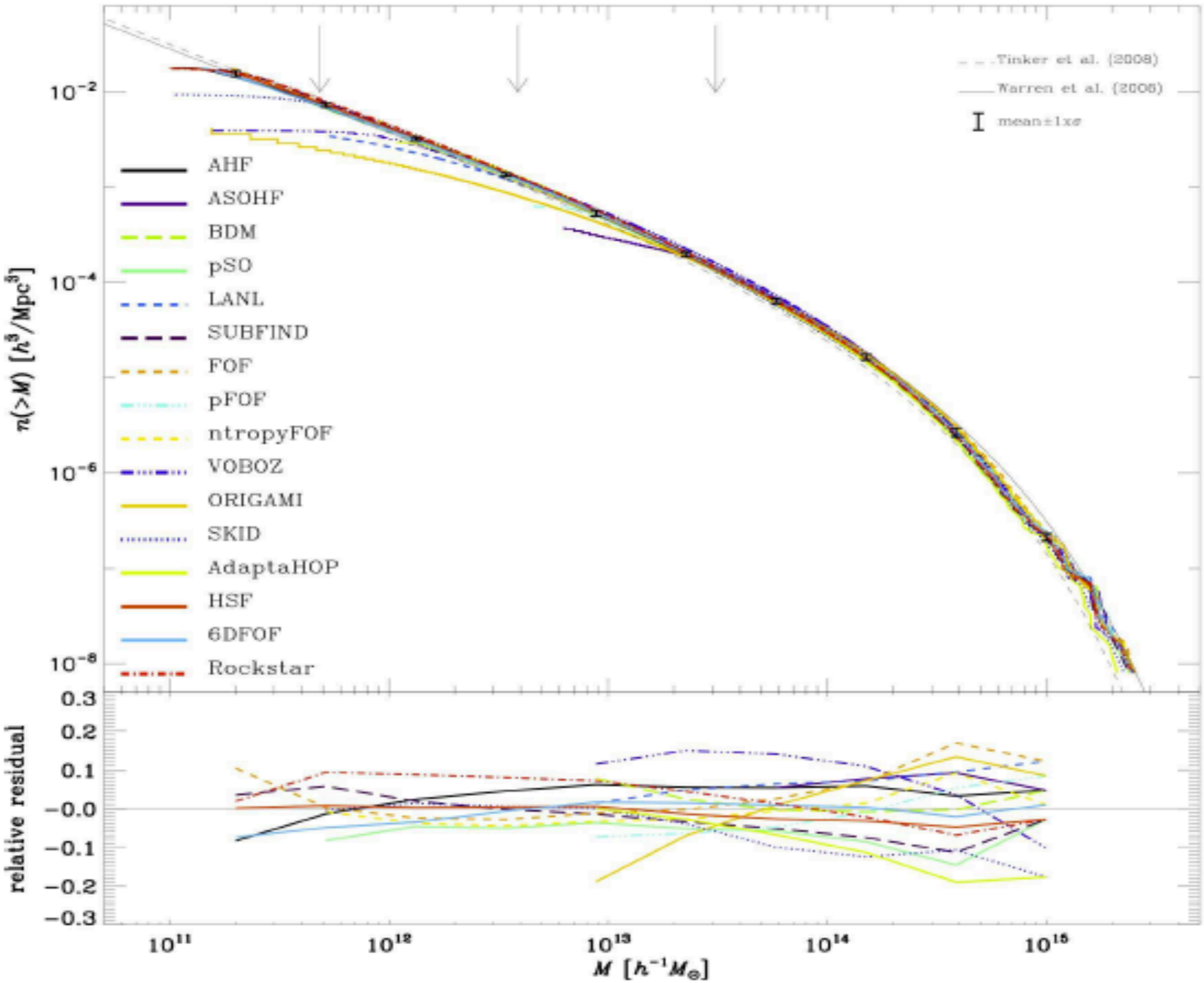
Runs:

- RAMSES
- L_{box} = 27.5 Mpc/h
- $N_p = 1024^3$ ($m_p = 1.6 \times 10^6\ M_\odot/h$)



Why can we use N-body?

pFoF Halo Finder

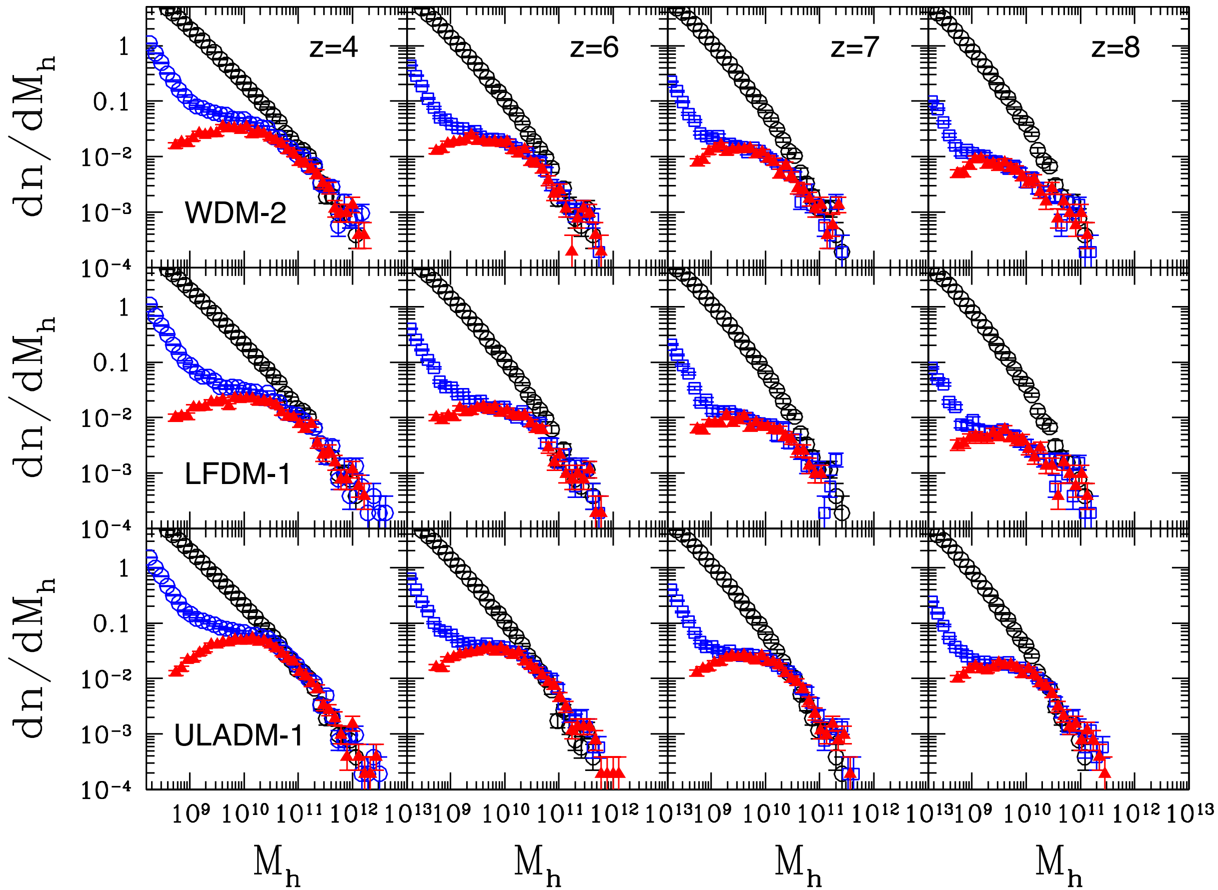


Knebe et al. (2011)

DM model halo catalogs

Initial Catalogs:

- FoF halos
- $N_h > 100$
- lots of spurious halos



Selections:

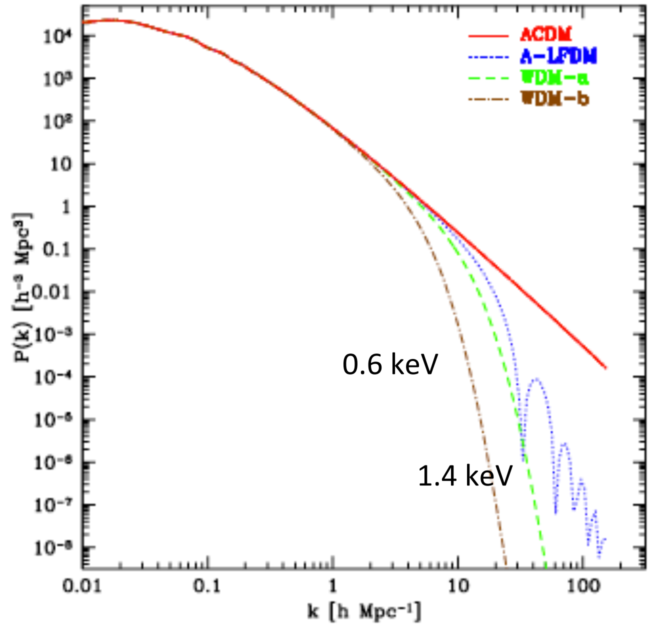
- $N_h > 300$
- only halos with $0 < \eta = 2K/E < 1.5$

Artificial Halos

Discretization Effect

- Sampling Poisson Noise ($k > k_{cut\text{-}off}$)
- Spurious Numerical Halos

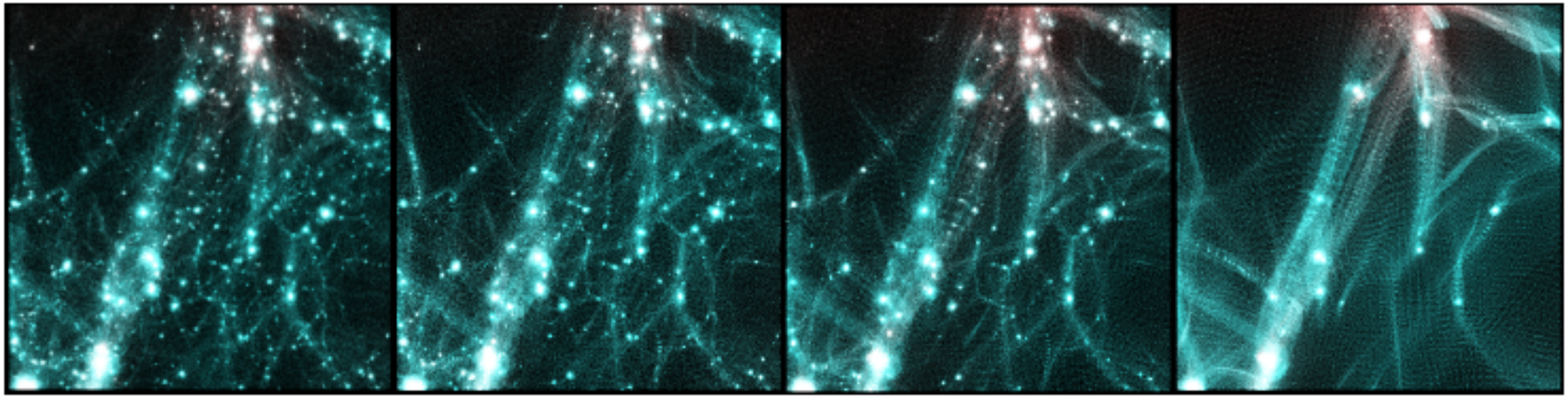
Gotz & Sommer-Larsen 2002, 2003; Wang & White 2007



Example

RAMSES AMR

- $N_p = 512^3$
- $L_{box} = 27.5$ Mpc h^{-1}
- $m_p \sim 10^7$ M_{sun} h^{-1}
- $dx_{coarse} \sim 54$ kpc h^{-1}



Spurious Halo Contamination

Halo Mass Function

- $N_{h\text{-}particles} > 100$
- Upturn at $M<M_*$
- Simulation Dependent Slope

Proposed Cures

- Mass Cut: $M_{min} = 10.1\ \rho\ d\ k_p^{-2}$

  Wang & White 2007

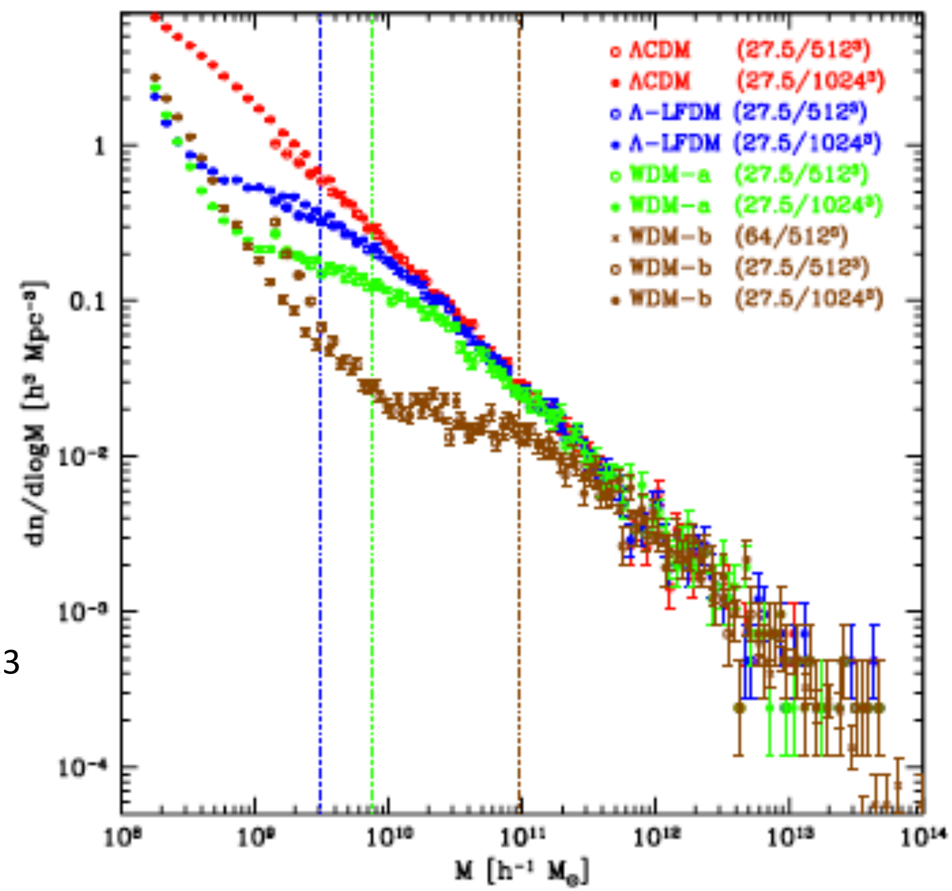
- Select Unflatten Proto-Halos in Initial Lagrangian Patch & Apply Mass Cut Lowell et al. 2012

- Visual Inspection Angulo, Hahn, Abel 2013

- Tessellation 6-d phase-space folding (reduce but dosn't solve)

  Hahn, Abel, Kaehler 2013

- $N_p=1024^3$
- L_{box}= 27.5 Mpc h^{-1}
- m_p~ 10^6 M_{sun} h^{-1}
- dx_{coarse}~ 26 kpc h^{-1}



Agarwal & Corasaniti 2015

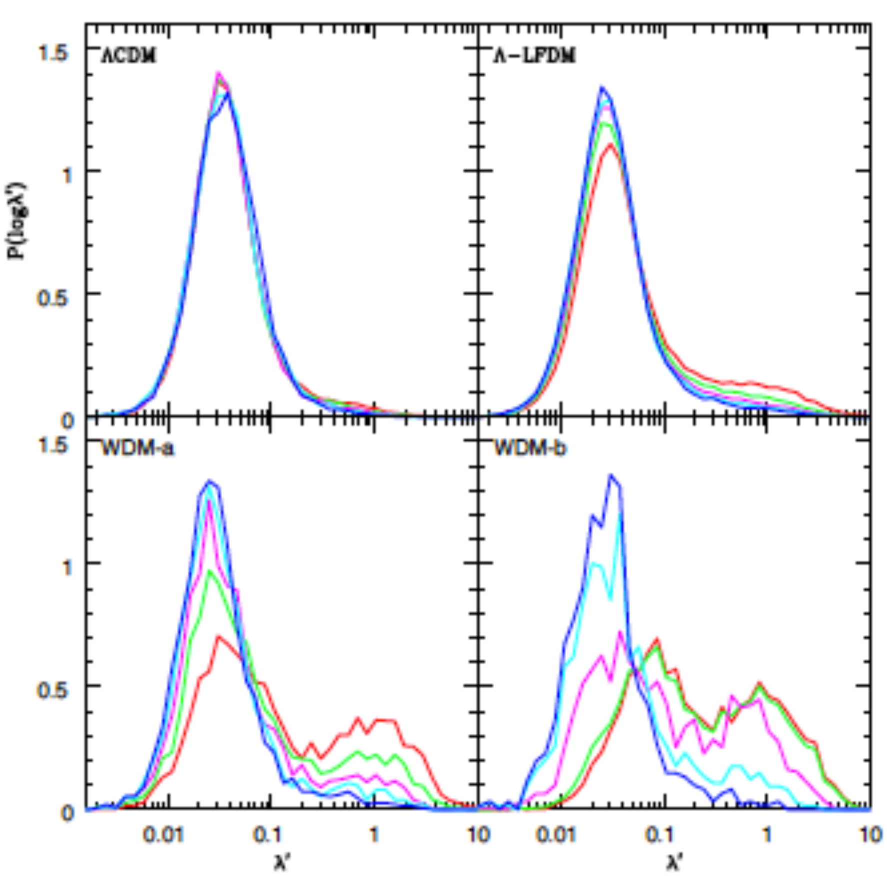
Structural Properties of Halos

Agarwal & Corasaniti 2015

Halo Spin

- Spin parameter $\lambda' = \frac{J}{\sqrt{2}MVR}$
- $V = \sqrt{(GM/R)}$
- 8 bins: $4 < M[10^9\ M_{sun}\ h^{-1}] < 8$

- CDM: log-normal & mass independent
- non-CDM: deviations from lognormality/bimodality and mass dependent
- spurious halos have large spins



Structural Properties of Halos

Halo Shape

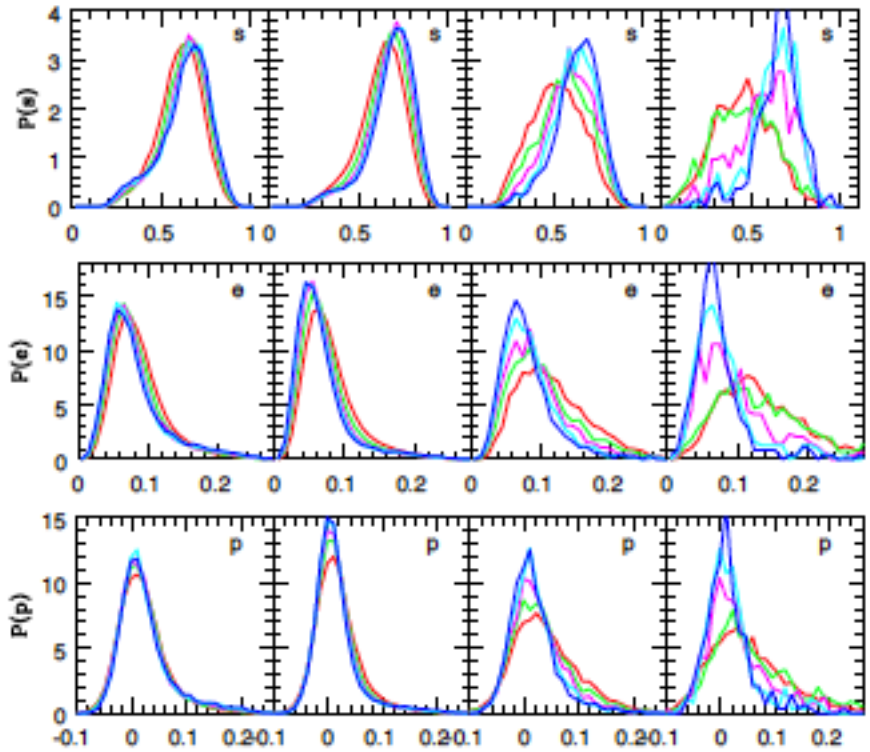
- Symmetric Mass Distribution Tensor

$$M_{\alpha\beta} = \frac{m_p}{M} \sum_{i=1}^{N_h} (r_{\alpha,i} - r_{\alpha,c})(r_{\beta,i} - r_{\beta,c})$$

- sphericity, ellipticity & prolatness

- CDM: mass independent & elliptical halos

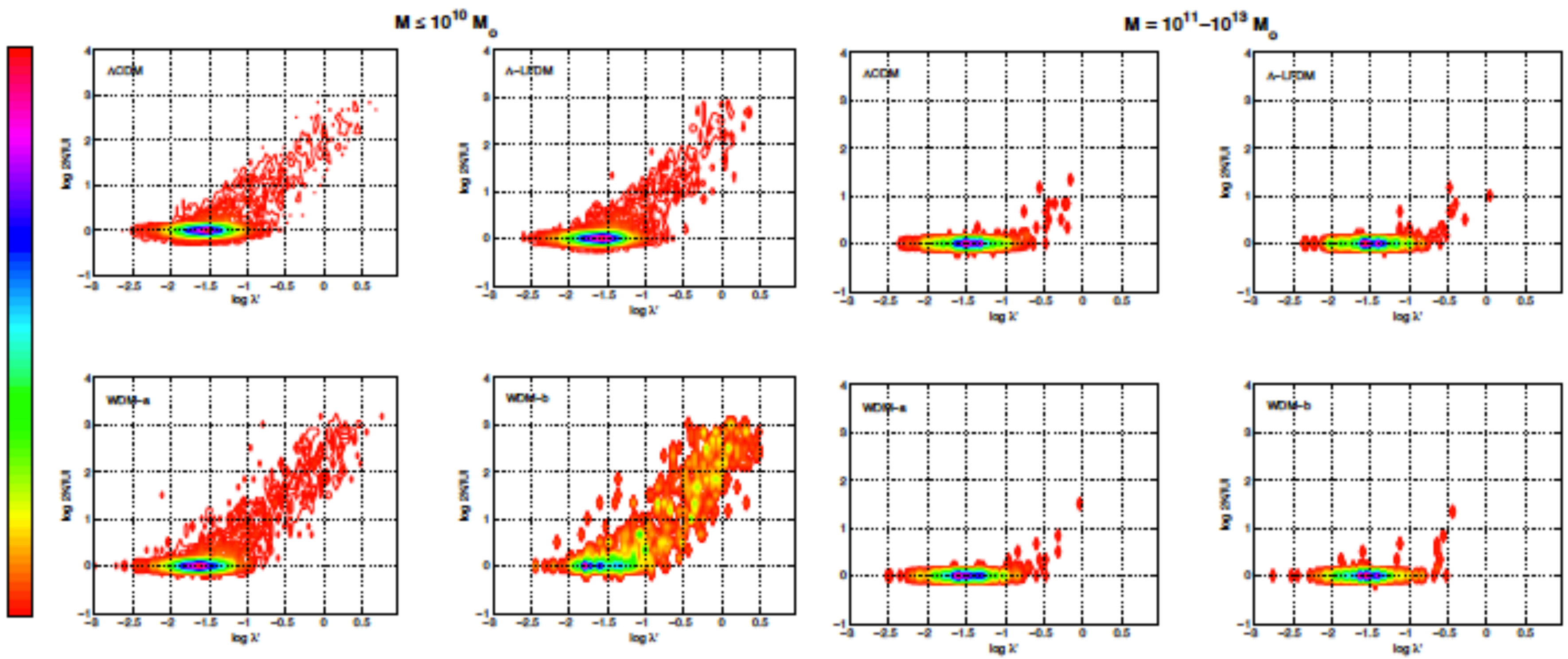
- non-CDM: mass dependent & highly non-spherical (elliptical & prolate, i.e. alignment with filaments)



Halo Dynamical State

Virial Condition

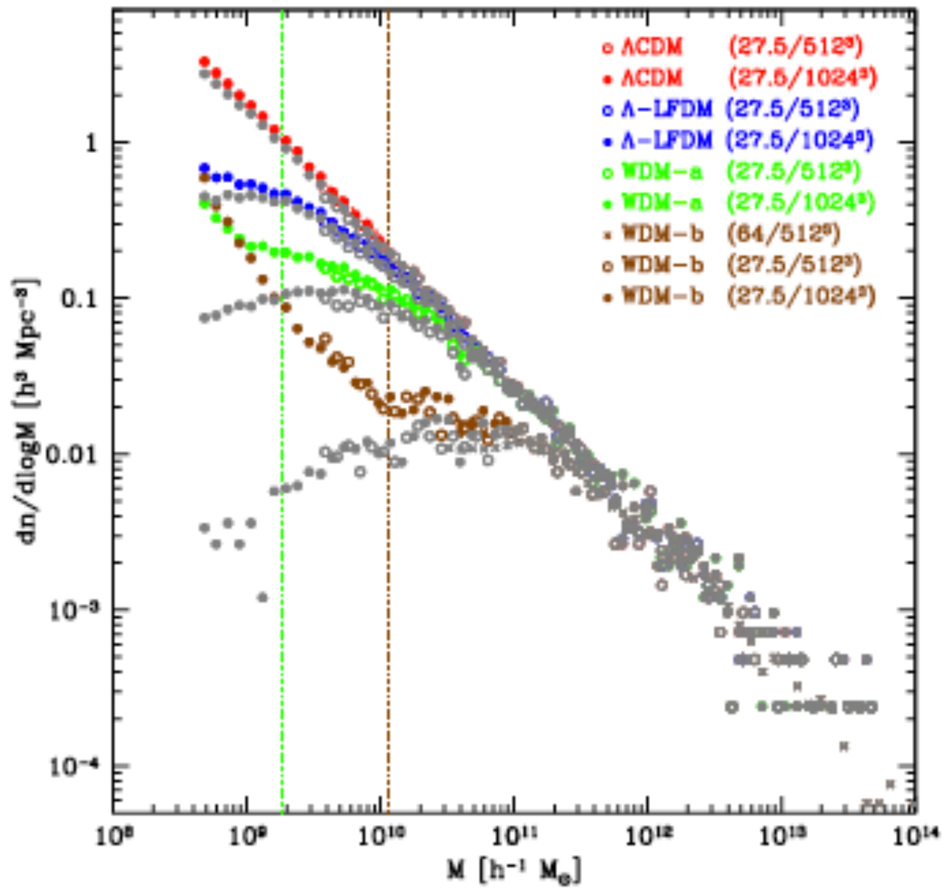
- proxy: $\eta = 2K/|E|$
- correlation λ'-η for $\eta > 1$



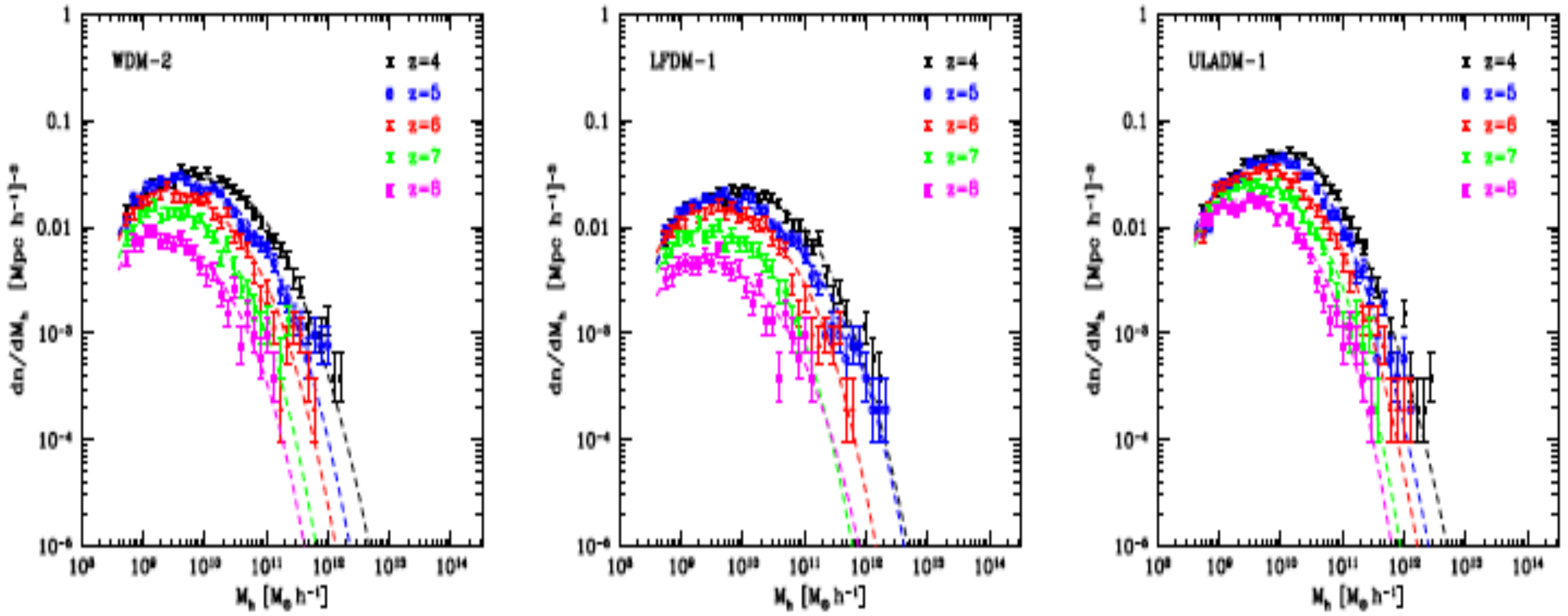
Virial State Selection

Removing Spurious Halos

- $0 < \eta = 2K/|E| < 1.5$
- recover halo triaxial distribution
- recover spin log-normality
- recover suppressed mass function at low mass (mass resolution convergence)
- spurious halos still present with simple mass-cut at M_{min}
- mass range larger than mass cut



Evolution of HMF in NDM models



Calibrated Analytical Formula

$$\frac{dn}{d\mathrm{M_h}} = 10^{\alpha+\beta\frac{\mathrm{M_*}}{\mathrm{M_h}}}\left(1 - e^{-\frac{\mathrm{M_h}}{\mathrm{M_*}}}\right)^{\gamma}\frac{dn}{d\mathrm{M_h}}\bigg|_{\mathrm{CDM}}$$

Predicting LF at z > 5

From HMF to GLF:

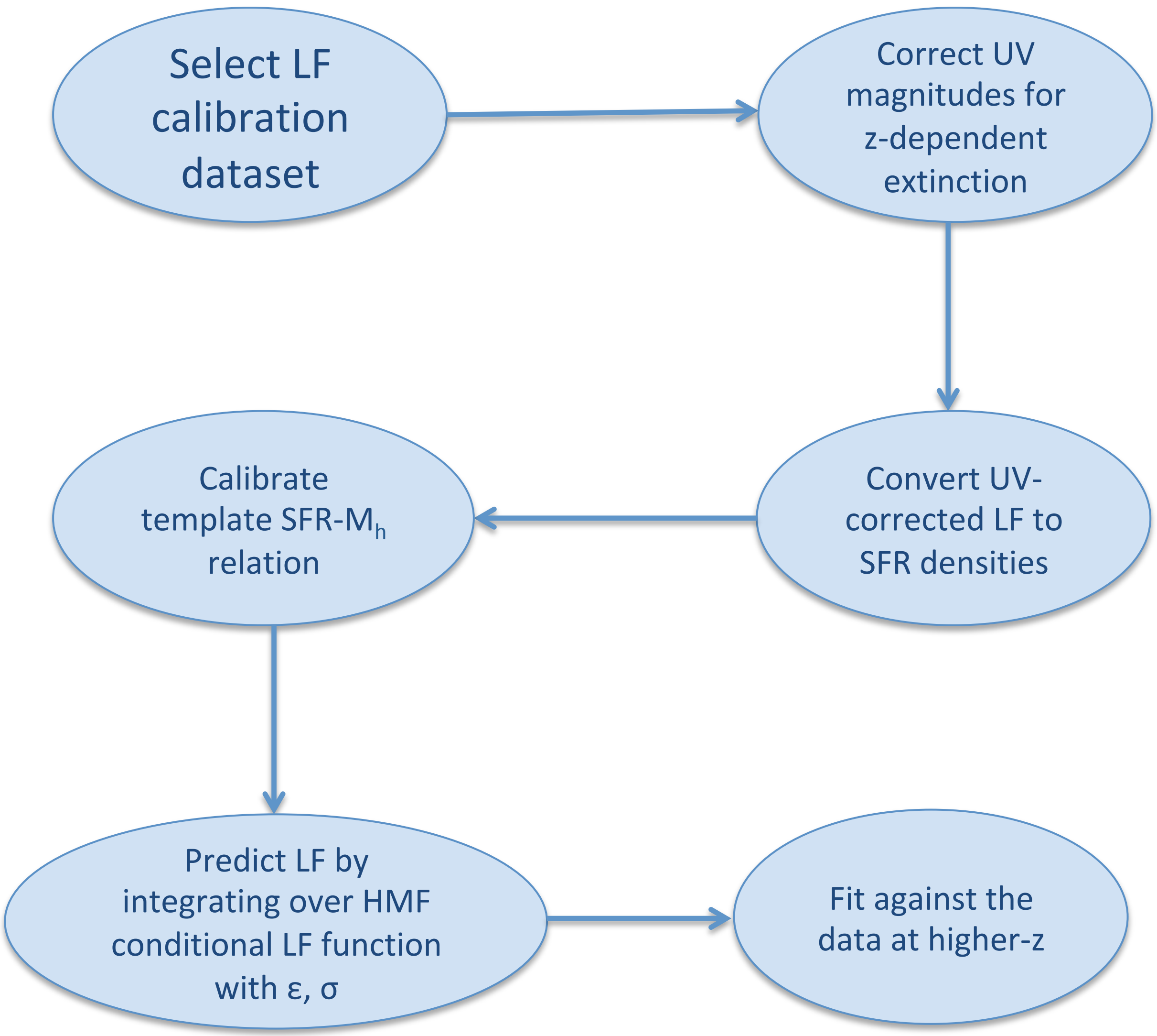
- Must assume: M_{UV} - M_h

- Infer from ensemble averaging using HAM (e.g. Mashian et al. 2016)
- Calibrate SFR(M) model using single dataset at given z (e.g. Mason et al. 2015)
- Parametrize and derive parameters from LF data fitting (e.g. Schive et al. 2016)

What can we do to..

- Account for z-evolution of M_{UV} – M_h due dust extinction
- Infer such relation from the data
- Deduce information on galaxy properties e.g. SFR(M_h)
- Learn about DM model dependencies

Empirical Approach



HAM & SFR

UV-Luminosity to SFR

- Account for dust extinction
- Convert M_{UV} corrected to SFR (Kennicut relation)
- Derive SFR-density functions (see Mashian, Oesch, Loeb 2015 for LCDM)

Extinction Correction

$$\langle A_{UV} \rangle = 4.43 + 0.79 \ln 10 \sigma_\beta^2 + 1.99 \langle \beta \rangle$$

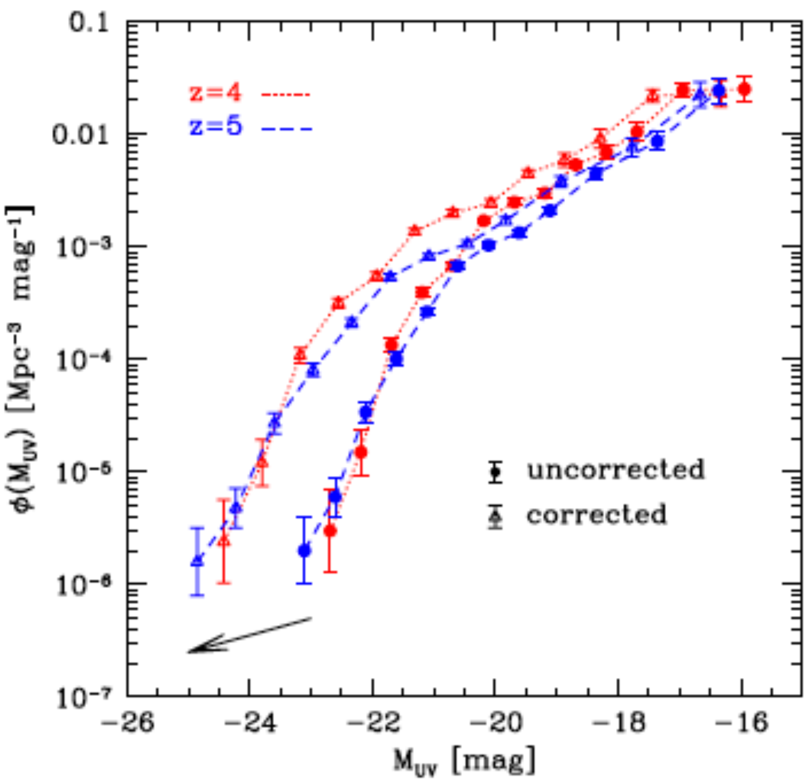
Meurer et al. (1999)

$$\langle \beta(M_{UV}, z) \rangle = \begin{cases} \left[\beta_{M_0}(z) - C\right] e^{\beta'(z) \frac{M_{UV} - M_0}{\beta_{M_0}(z) - C}} & M_{UV} \geq M_0 \\ \beta'(z)\left[M_{UV} - M_0\right] + \beta_{M_0}(z) & \end{cases}$$

Tacchella et al. (2013), Mason, Trenti & Treu (2015)

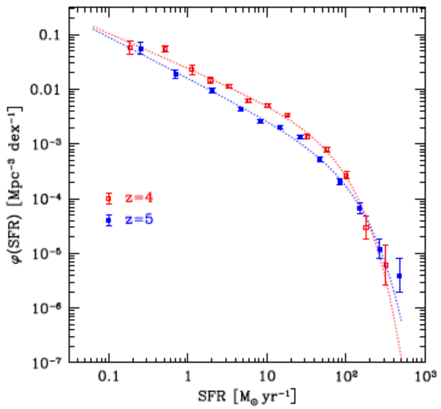
- Changes UV-mag bin size
- Shift toward higher luminosities

Smit et al. (2012)



Template Function SFR – M_h relation

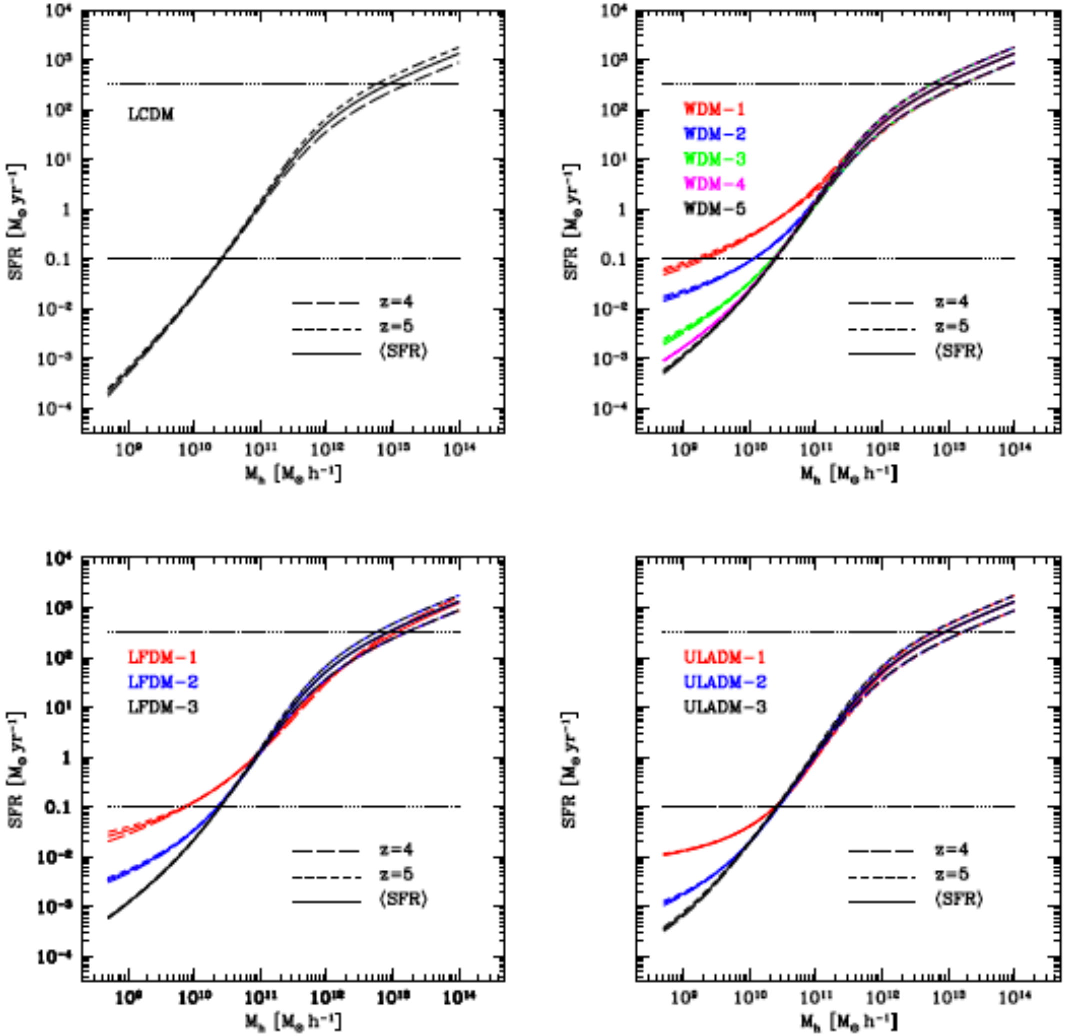
SFR density function



- Fit Φ(SFR) with Press-Schechter function

- HAM

$$\int_M d\tilde{M}_h \left(\frac{dn}{d\tilde{M}_h}\right)_{NDM} = \int_{SFR} dSFR' \;\phi(SFR')$$



Modeling Luminosity Function at z > 5

Average amplitude and intrinsic scatter SFR-M_h relation

- Compute

$$\phi(SFR,z) = \frac{1}{\sigma_{\rm int}^2 \sqrt{2\pi}\ SFR} \int dM_h \frac{dn}{dM_h}(M_h,z)\ e^{-\frac{\log_{10}^2\left[SFR/(\varepsilon \cdot \langle SFR(M_h)\rangle\right]}{2\sigma_{\rm int}^2}}$$

- Convert to UV luminosities
- Add extinction effect
- Estimate Φ (M_{UV})
- Fit against the data ε, σ_{int}

High-z LF data

Bright-end side of LF

Bouwens et al. (2015):

- 10,000 galaxies HST data
- subsample for dust model

Faint-end Slope

HFF observations:

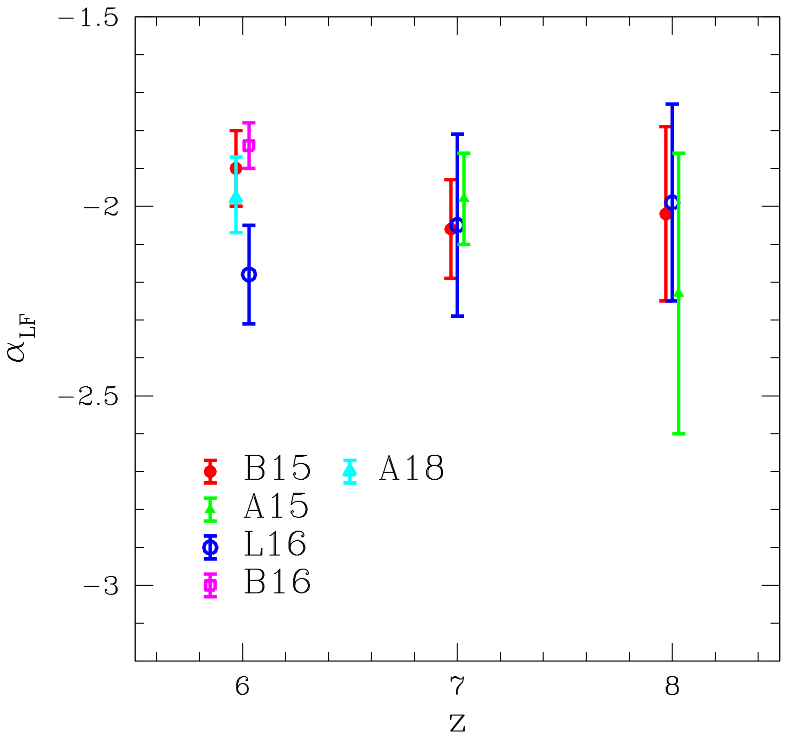
Atek et al. (2015)

Livermore et al. (2016)

Bouwens et al. (2016)

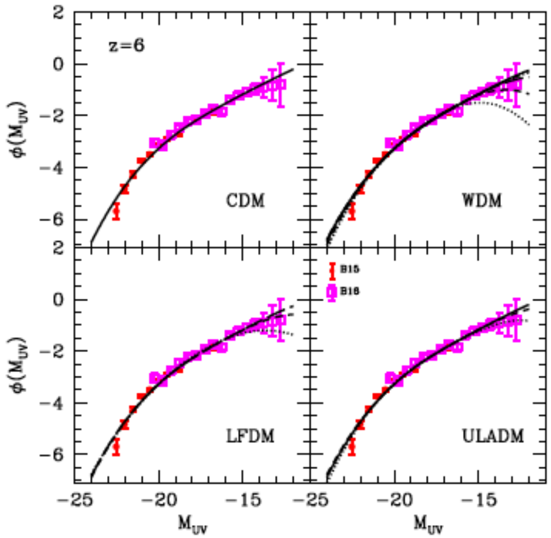
Our selected dataset

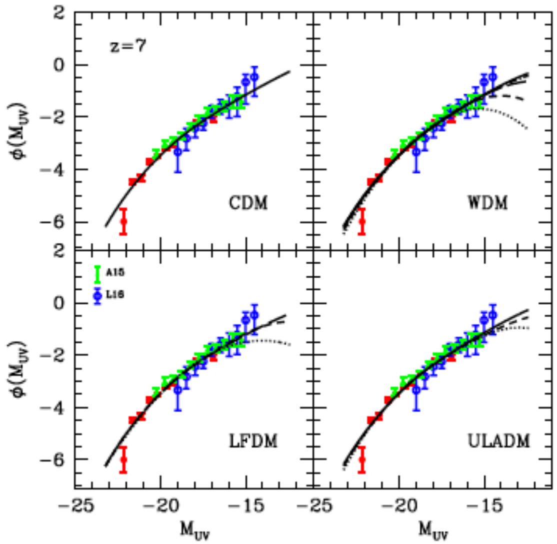
26 points at z=6 (B15+B16)
31 points at z=7 (B15+A15+L16)
22 points at z=8 (B15+A15+L16)

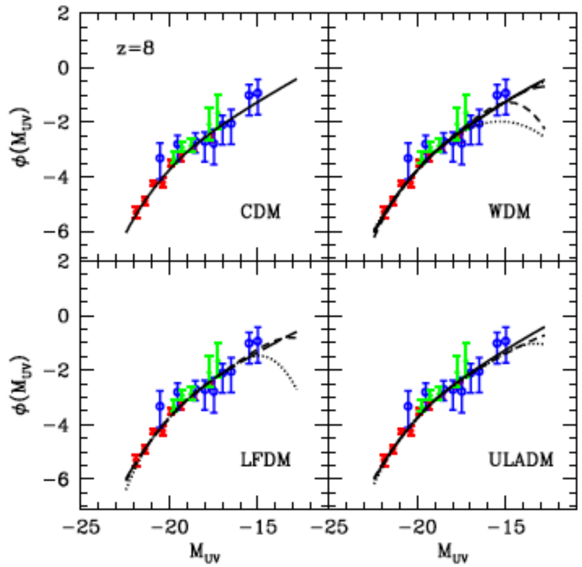


Sensitivity to lens model magnification systematics

DM models goodness-of-fit







Model	$\log_{10}\varepsilon_{SFR}^{z=6}$	$\log_{10}\sigma_{SFR}^{z=6}$	$\chi^2_{z=6}$	$\log_{10}\varepsilon_{SFR}^{z=7}$	$\log_{10}\sigma_{SFR}^{z=7}$	$\chi^2_{z=7}$	$\log_{10}\varepsilon_{SFR}^{z=8}$	$\log_{10}\sigma_{SFR}^{z=8}$	$\chi^2_{z=8}$	χ^2_{tot}
CDM	−0.80	−0.23	21.5	−0.52	−0.23	27.6	−0.18	−0.39	15.8	**64.9**
WDM-1	−0.78	−0.26	87.7	−0.60	−0.25	57.4	−0.58	−0.24	23.8	168.9
WDM-2	−0.79	−0.25	22.4	−0.53	−0.24	31.6	−0.12	−0.47	17.5	71.5
WDM-3	−0.83	−0.22	20.5	−0.54	−0.23	28.1	−0.23	−0.37	15.7	**64.3**
WDM-4	−0.90	−0.20	21.7	−0.60	−0.21	27.8	−0.28	−0.35	15.9	65.4
WDM-5	−0.85	−0.21	22.0	−0.60	−0.21	27.1	−0.26	−0.36	15.8	64.9
LFDM-1	−0.92	−0.17	37.2	−0.73	−0.14	45.0	−0.29	−0.50	16.6	98.8
LFDM-2	−0.83	−0.23	20.1	−0.53	−0.23	28.3	−0.22	−0.38	15.6	**64.0**
LFDM-3	−0.85	−0.22	21.7	−0.73	−0.20	30.5	−0.49	−0.29	16.2	68.4
ULADM-1	−0.91	−0.24	21.3	−0.69	−0.24	33.6	−0.48	−0.36	14.9	69.8
ULADM-2	−0.89	−0.20	21.5	−0.78	−0.19	31.4	−0.59	−0.26	16.5	69.4
ULADM-3	−0.81	−0.23	21.9	−0.60	−0.21	27.3	−0.29	−0.34	15.9	**65.1**

WDM:

$m_{WDM} \geq 1.5$ keV

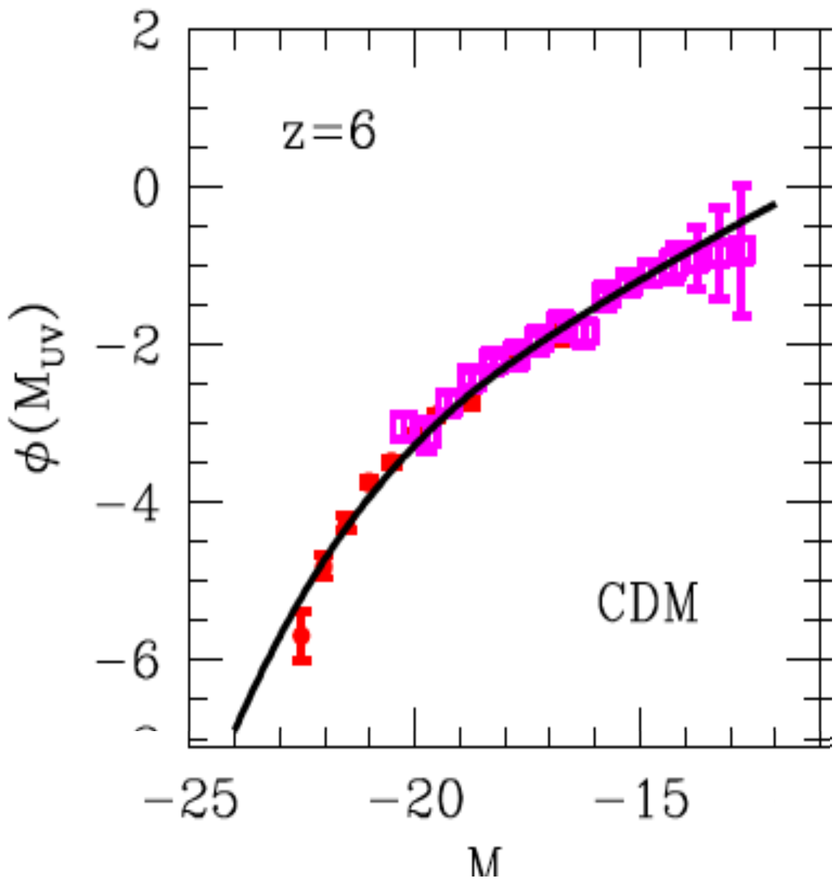
LFDM:

$z_t \geq 8 \times 10^5$

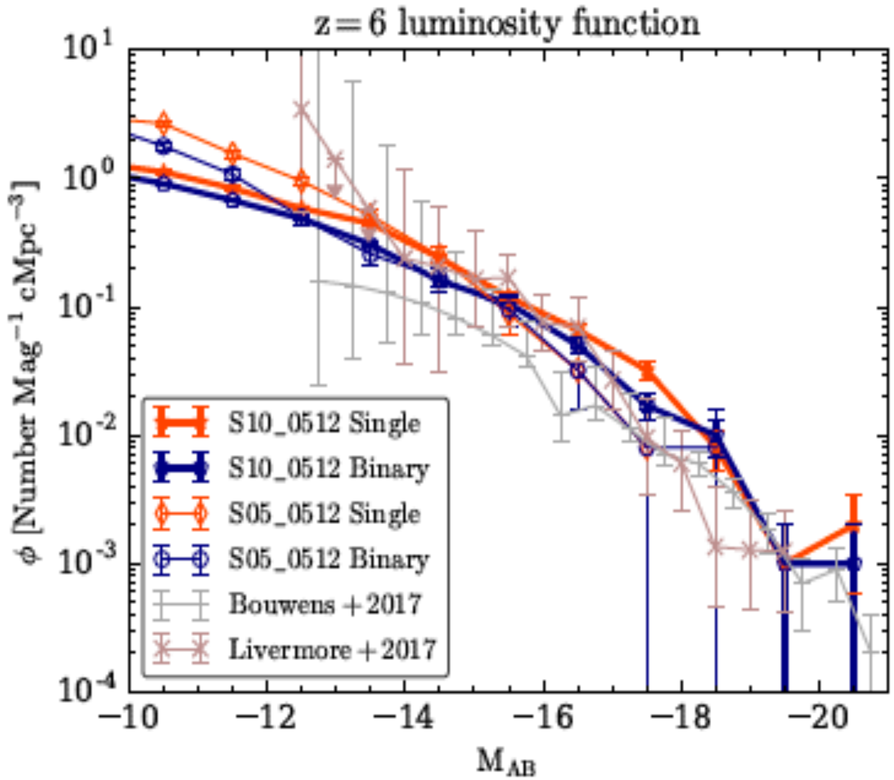
ULADM:

$m_{ULA} \geq 1.6\times10^{-22}$ eV

LCDM comparison to Sphinx Simulations



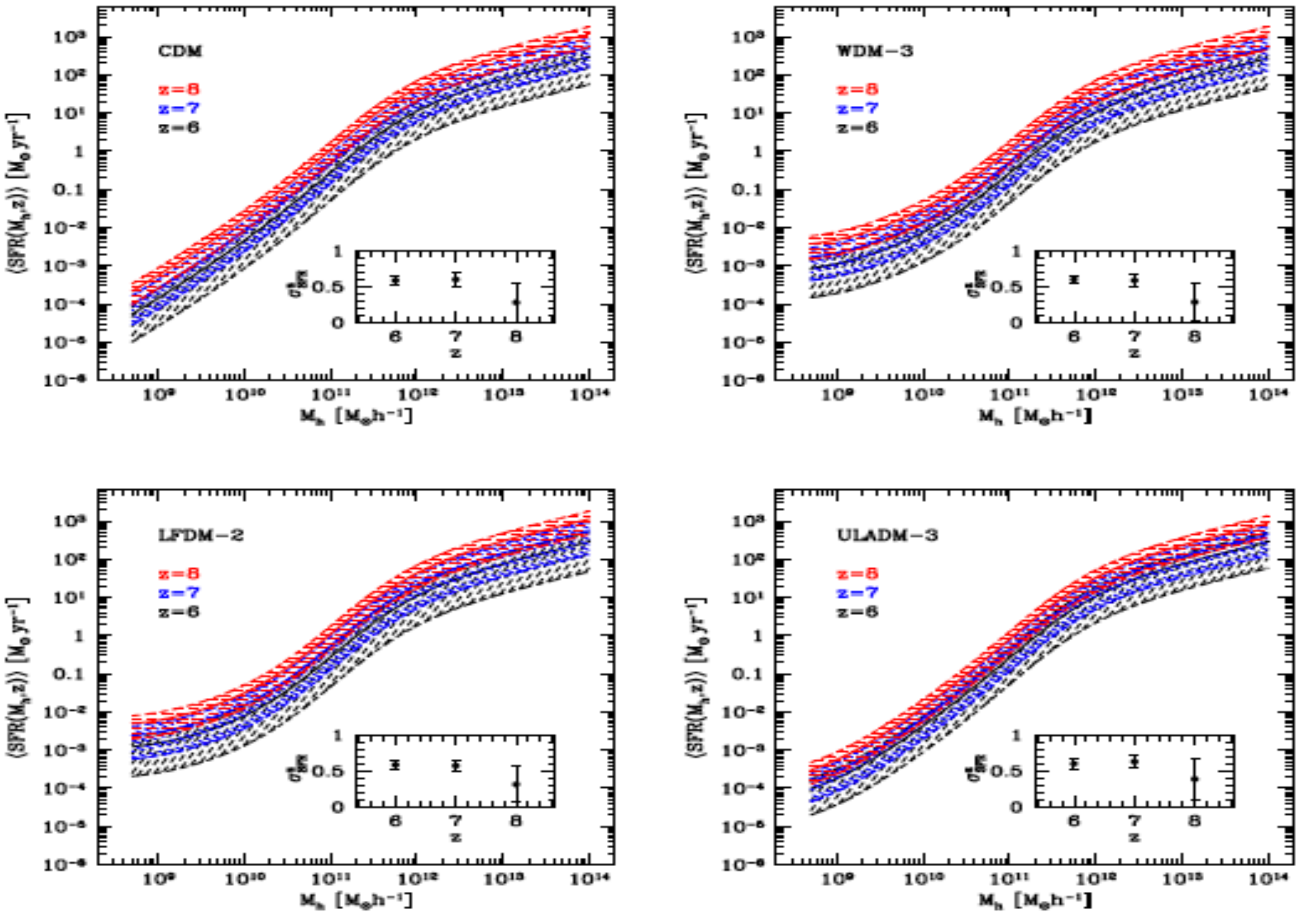
Radiation-Hydrodynamics
Simulation Suite



Rosdahl et al. (2018)

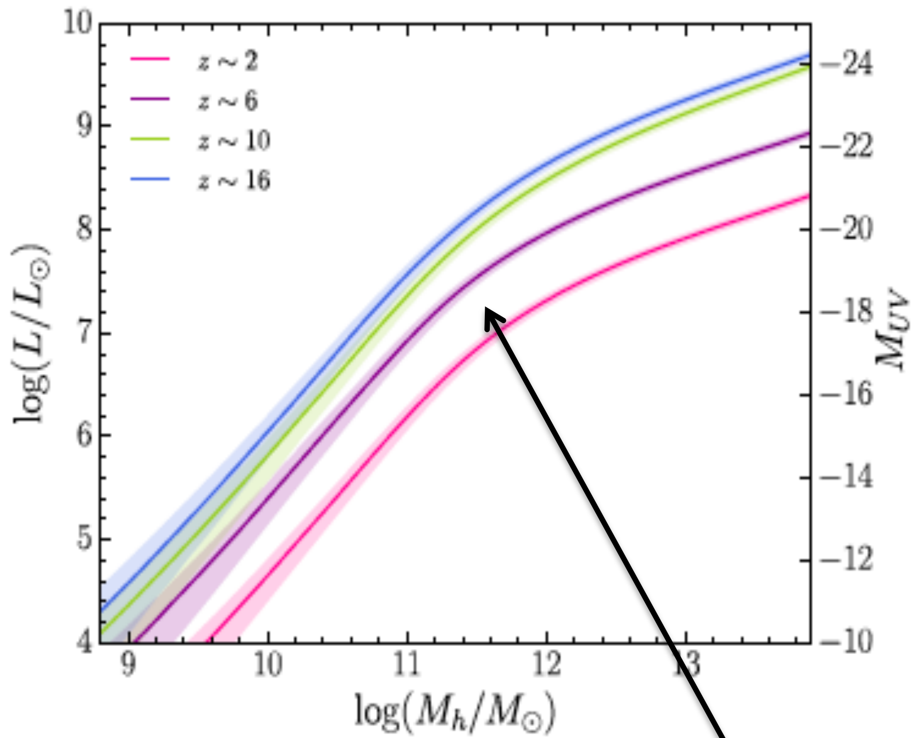
- Consistent LF "predictions"
- Disagreement on the choice of x-axis orientation

Star-Formation Rate Halo Mass Relation

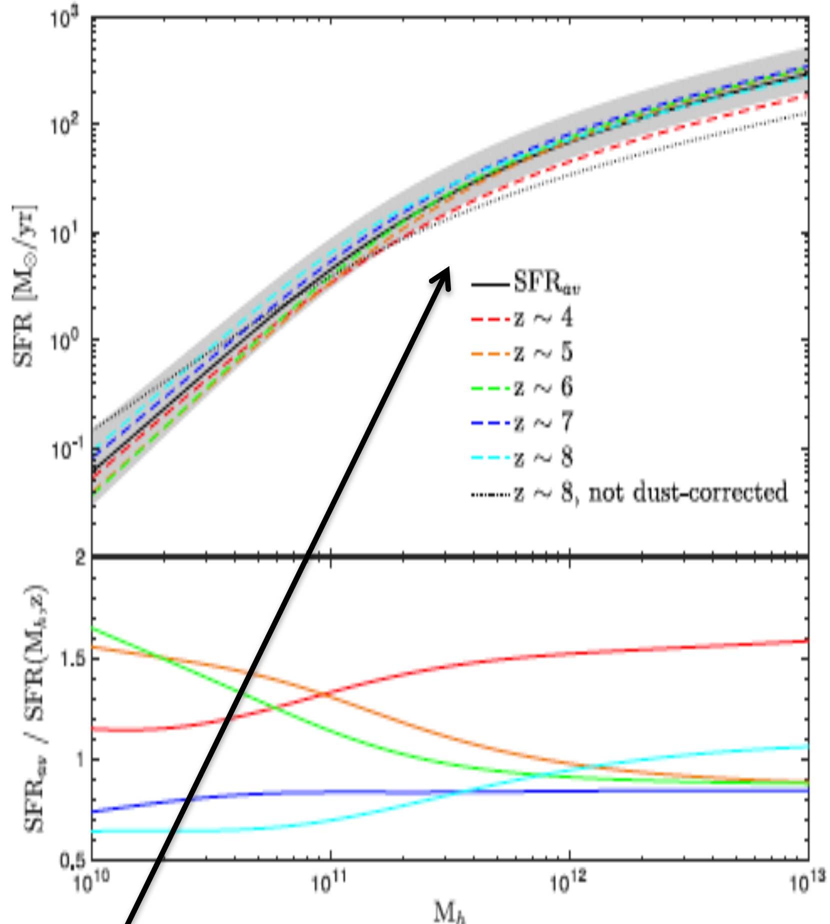


LCDM "prediction" consistency check

Different Empirical Models



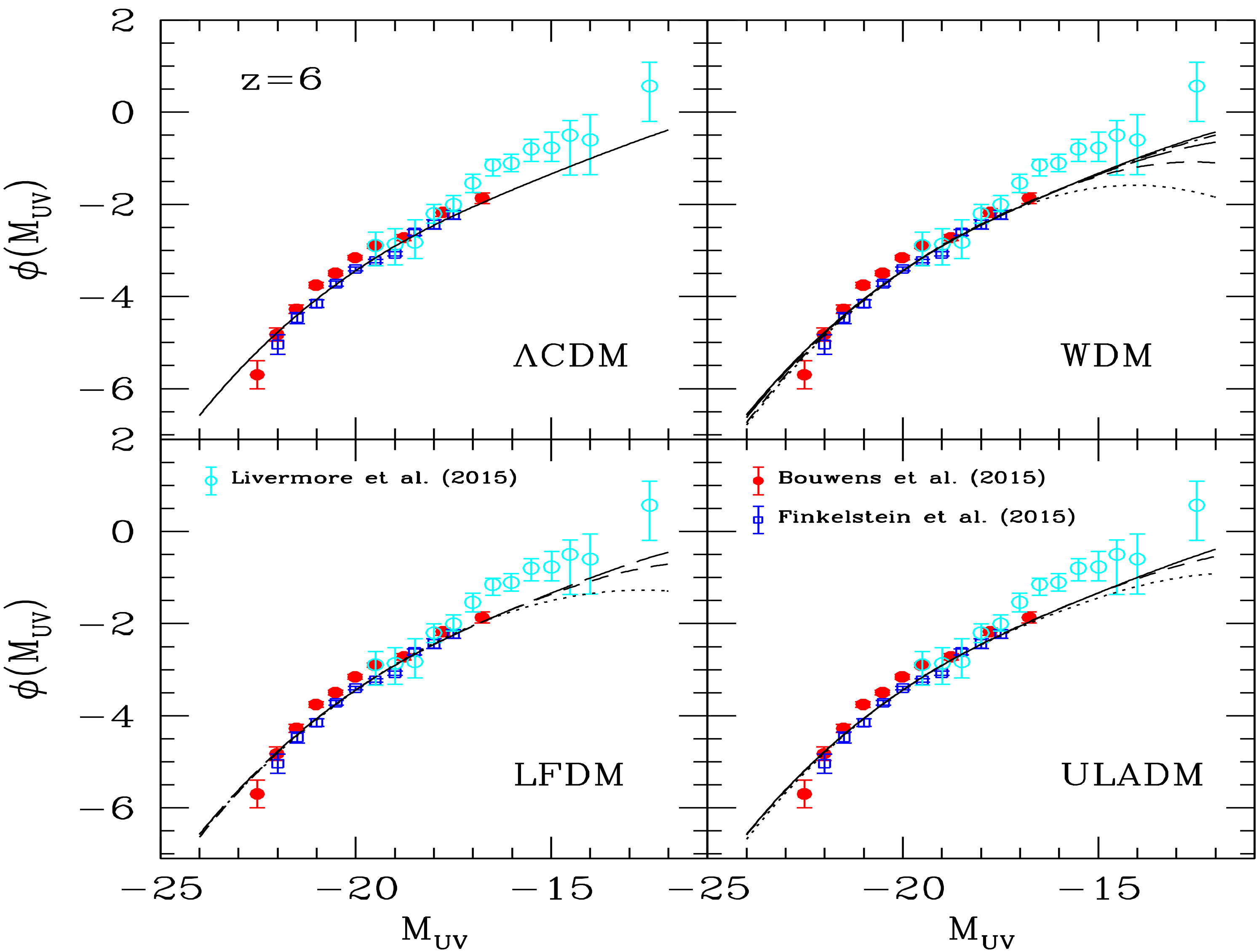
Mason, Trenti & Treu (2015)



Mashian, Oesch, Loeb (2015)

M_{*}~2 10^{11} M_{Sun}

If you like tensions: results from L16 at z=6



Cosmic Reionization Model

Kuhlen & Faucher-Giguere (2012)

Ionizing Emissivity Model

$$\dot{n}_{ion}^{com} = f_{esc} \int_{M_{\lim}}^{\infty} dM_{UV} \phi(M_{UV}) \gamma_{ion}(M_{UV})$$

Ionizing Luminosity

$$\gamma_{ion}(M_{UV}) = 2 \cdot 10^{25} \cdot 10^{0.4(51.63 - M_{UV})} \zeta_{ion} \quad [s^{-1}]$$

Volume Average Ionized Hydrogen Fraction

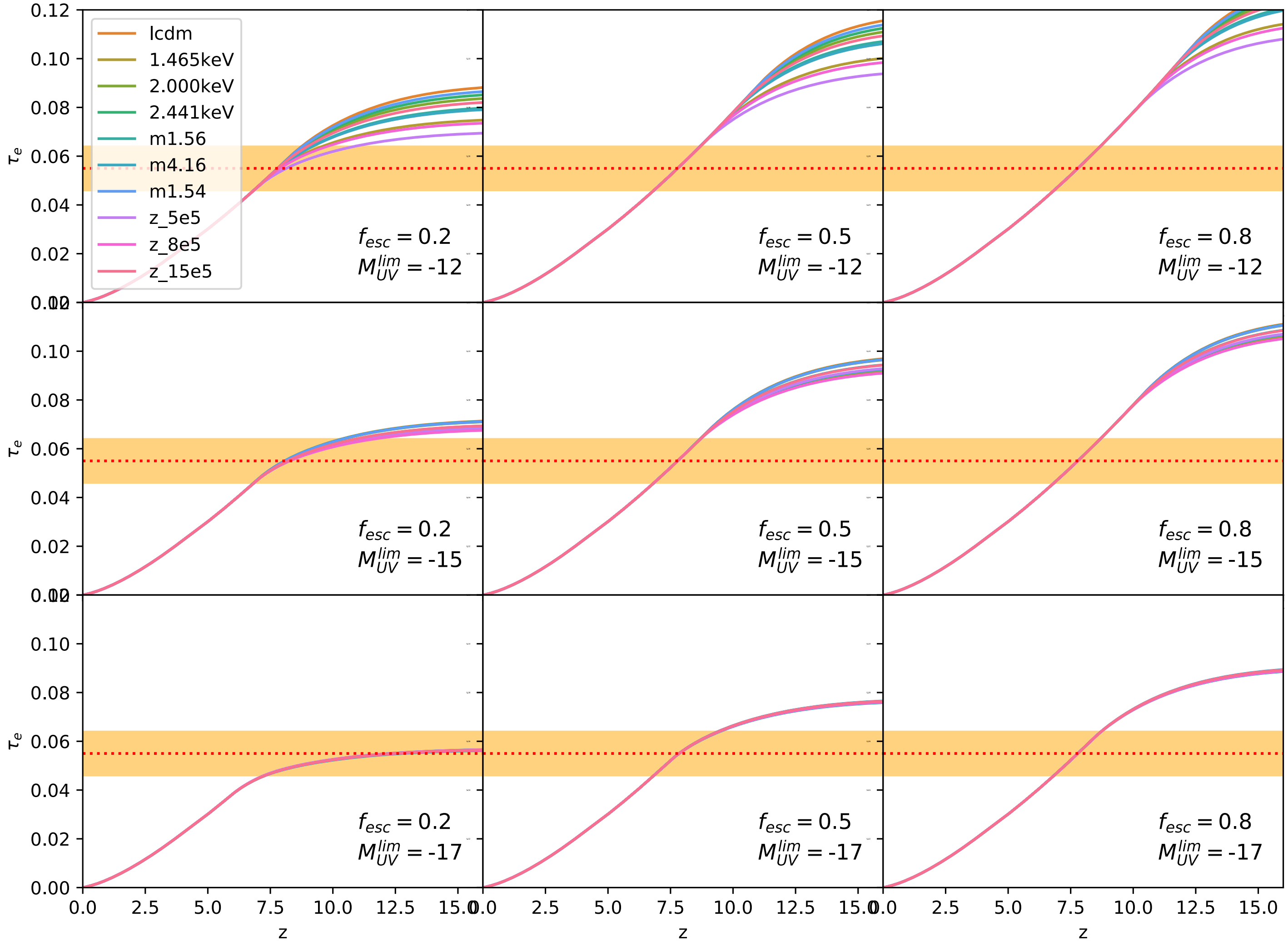
$$\frac{dQ_{HII}}{dt} = \frac{\dot{n}_{ion}^{com}}{\overline{n}_H} - \frac{Q_{HII}}{\overline{t}_{rec}}$$

$$\overline{t}_{rec} = 0.93 \left(\frac{C_{HII}}{3} \right)^{-1} \left(\frac{T_0}{2 \times 10^4 K} \right)^{0.7} \left(\frac{1+z}{7} \right)^{-3} \quad [\text{Gyr}]$$

Optical Depth

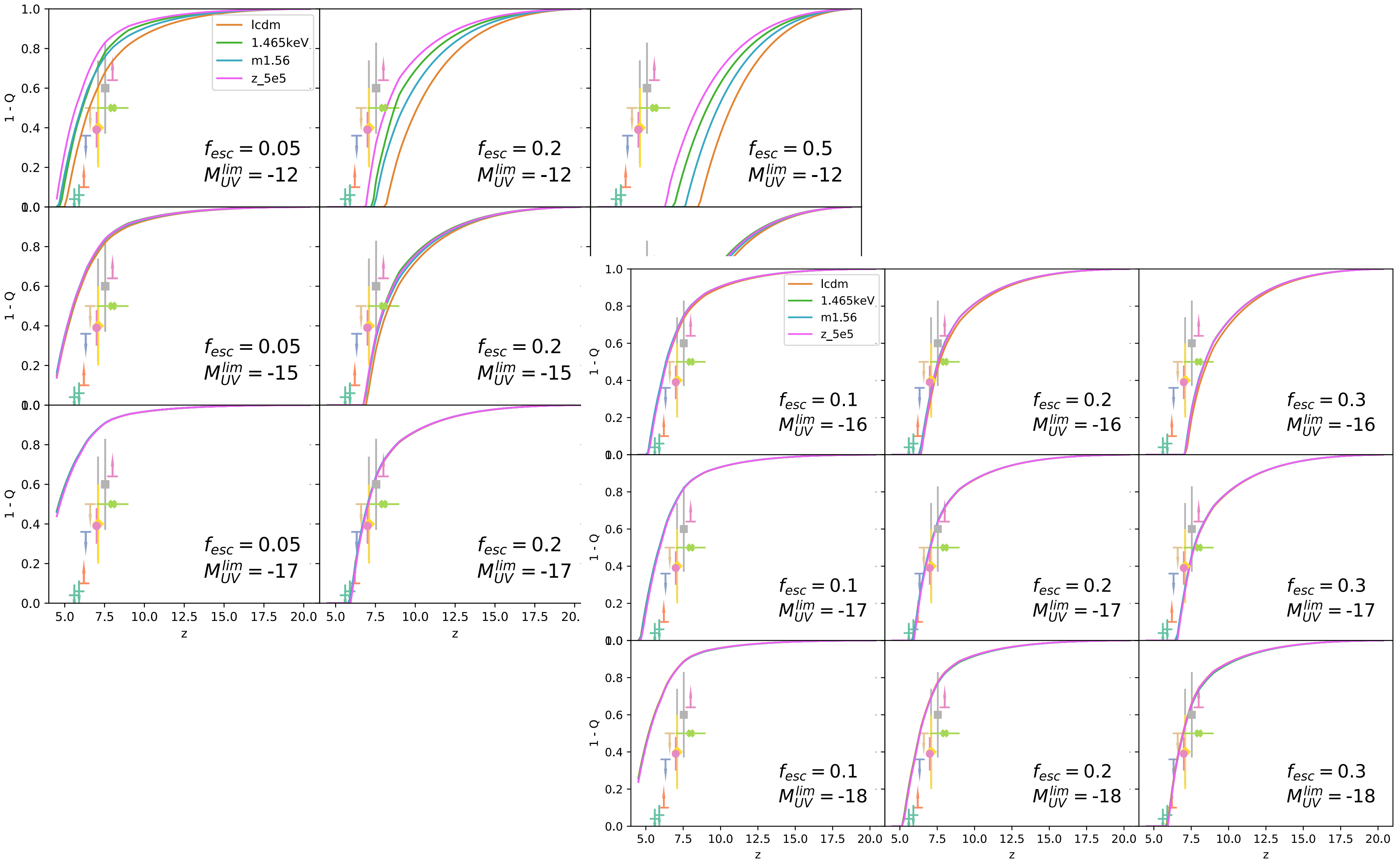
$$\tau_e = \int_0^{\infty} dz \frac{c(1+z)^2}{H(z)} Q_{\rm HII}(z)\, \sigma_T\, \bar{n}_H\, (1 + \eta Y/4X),$$

Planck Limits: f_{esc} vs M_{lim} DM Model Degeneracy



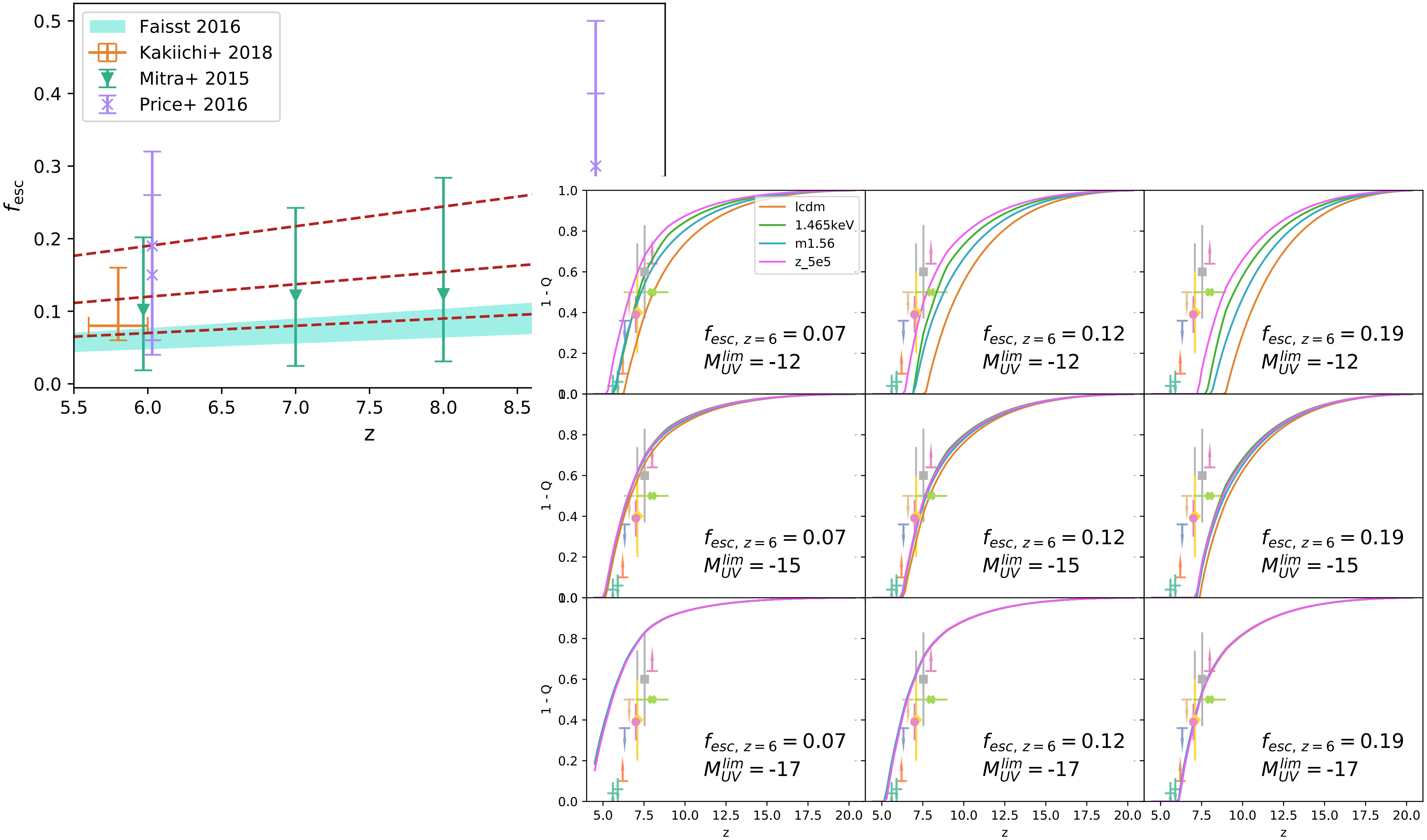
Carucci & PSC (in preparation)

Ionized Hydrogen Fraction



Carucci & PSC (in preparation)

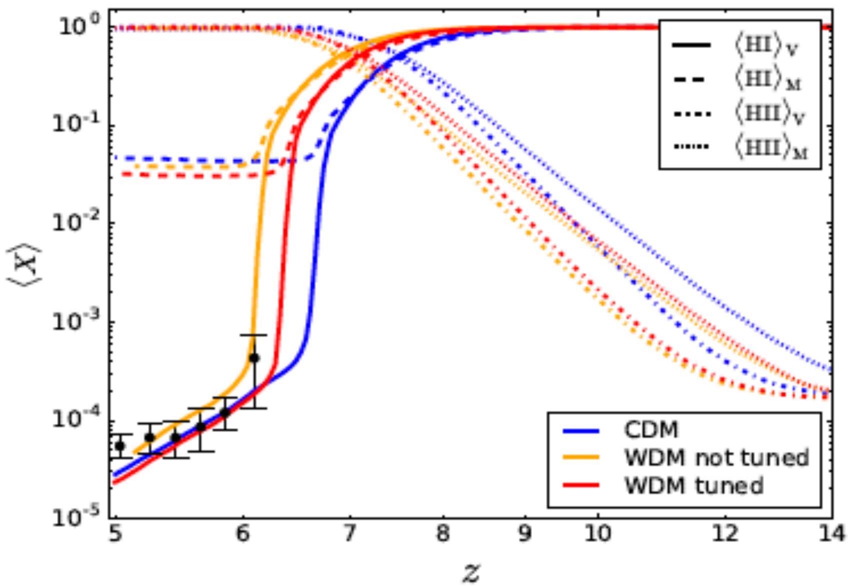
Impact of $f_{esc}(z)$



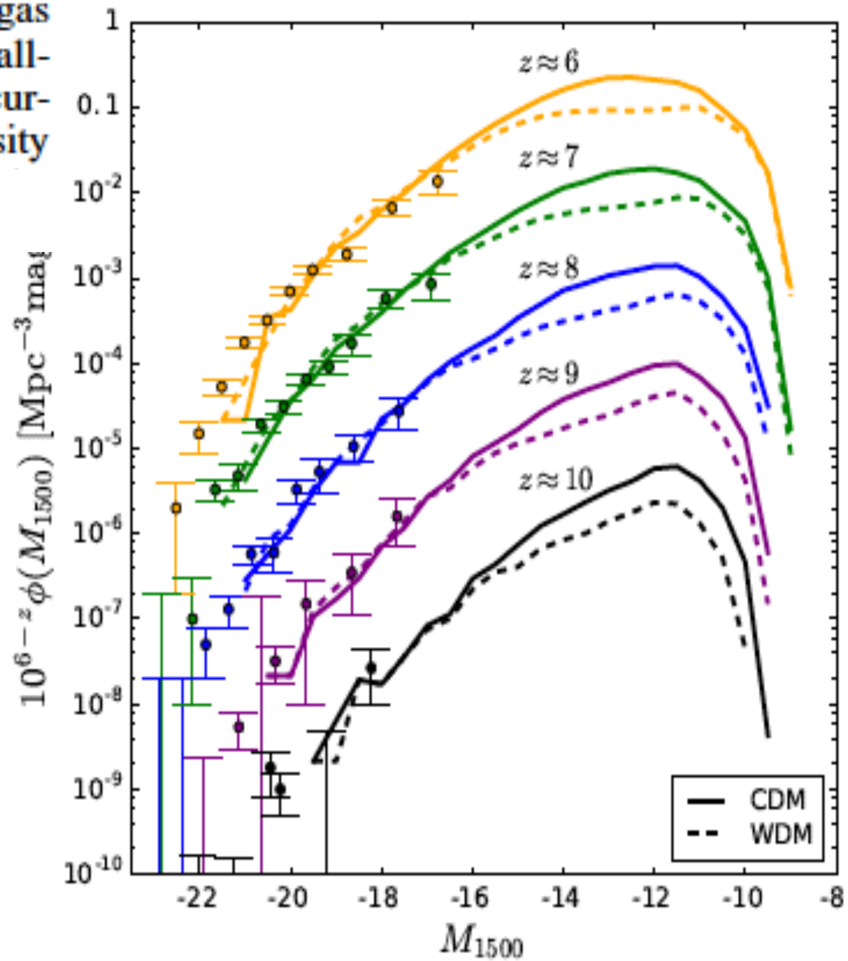
Carucci & PSC (in preparation)

WDM – Reionization Simulations

We have shown that the lack of small scale power in WDM cosmology (relative to the equivalent CDM case) due to the non-negligible free-streaming length of WDM particle considerably delays the reionization processes. However, a higher star formation efficiency (or, equivalently, a lower gas depletion time) compensates for the WDM-suppressed small-scale structure, leading to nearly identical (within the currently observationally constrained range) galaxy luminosity functions in the CDM and WDM cases.



Villanueva-Domingo, Gnedin, Mena (2017)



Conclusions

• Galaxy formation cannot occur in the same way in CDM and non-standard DM models if they reproduce LF data

• Testing SFR-halo mass relation at low halo masses can provide key insights on DM models

• Faint-end LF sensitive to DM halo abundance, location of turnover signature of DM physics (or minimum mass star forming halo?)

• Implications for reionization models degenerate with astrophysical processes

• What's next?

Alternative Cosmology Baryon Astrophysics Runs (ACBAR)