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EDECS
Exploring Dark Energy Cosmic Structures

Non-Linear Small Scale Structure Formation in Non-Standard Dark Matter Cosmologies

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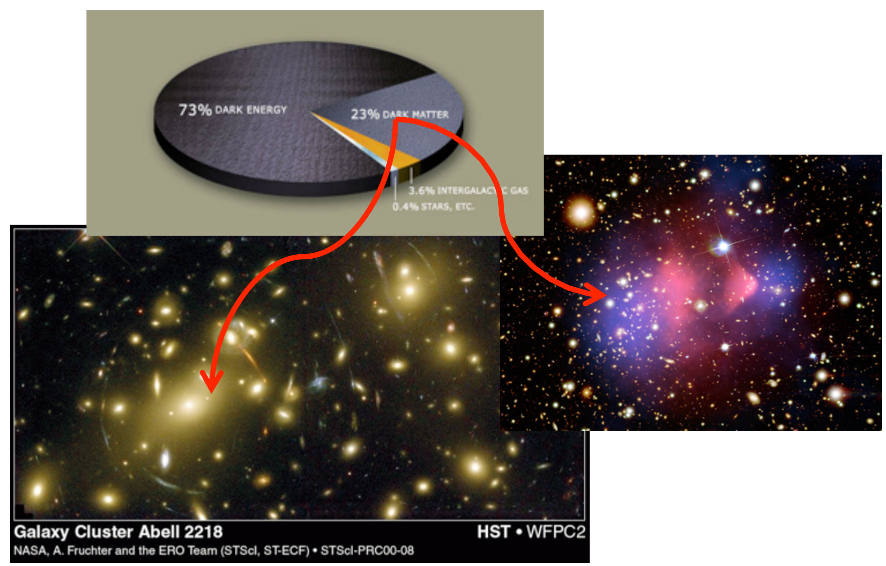
Standard Cosmological Scenario

Dark Matter:

- Gravitational Collapse Initial Fluctuations
- Foster matter clustering
- Resides in virialized clumps



Halos:

- Building blocks of cosmic structure formation
- Shape baryon distribution & formation of visible structures

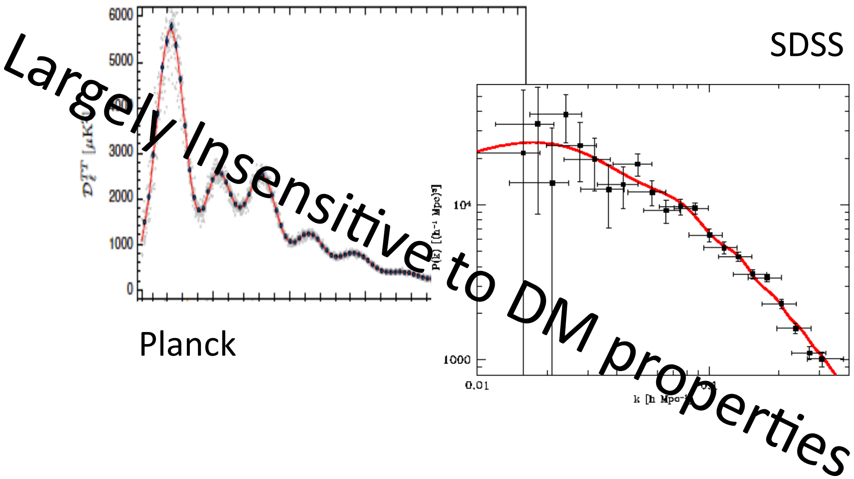
CDM Paradigm

Theoretical Bias:

- WIMP hypothesis/Neutralino

Large Scales

- Successful Description CMB spectra
- Clustering of Matter from galaxy surveys



Minimal Scenario - LCDM

- 6 parameter models: H_0, $\Omega_m(1-\Omega_\Lambda)$, Ω_b, σ_8, n_s, τ
- Censored Comments

Small Scales & Beyond CDM

DM Direct Searches:

- Negative/Contrasting Results
- No signal at LHC

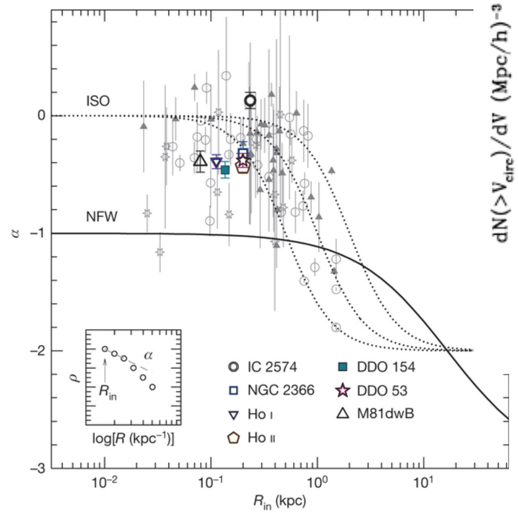
CDM anomalies :

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

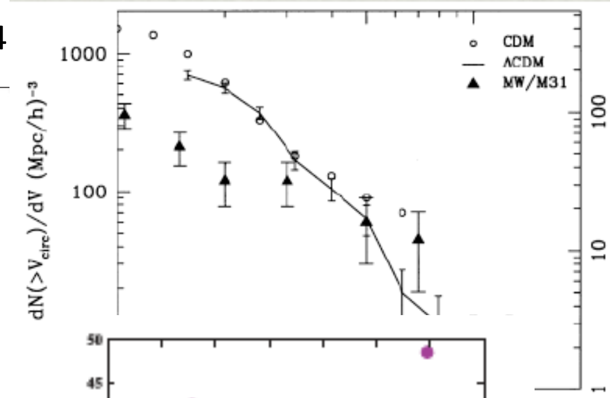
Complex Physics:

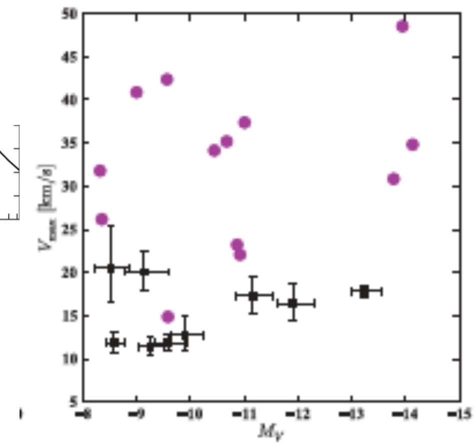
- Baryonic Feedback
- Observational Selection Effects
- Uncertainties of Milky-Way Mass

Pontzen & Governato 2014



Klypin et al. 1999



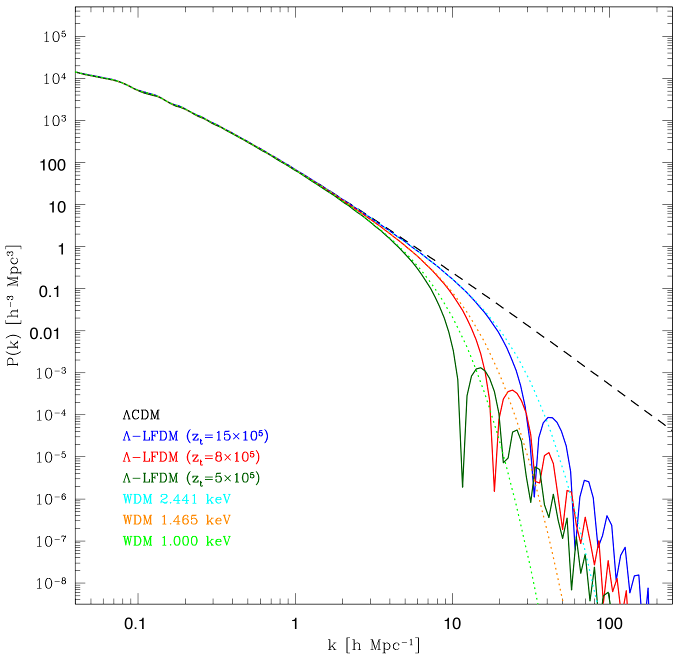


Boylan-Kolchin et al. 2012

Alternative Scenarios

Warm Dark Matter

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



Self-Interacting DM

- DM scattering cross-section
- Interaction with radiation

Late Forming DM & Ultra-Light Axions

- LFDM: Before matter/radiation equality, decay of scalar field coupled to relativistic particles ($w \approx 1/3$ -> $w=0$)
- ULA: Axion field transition from vacuum to matter ($w=-1$ -> $w=0$)

Observational Constraints

CUM GRANO SALIS

Warm Dark Matter*

- m_{WDM} < 0.1 keV to core the profiles — e.g. Maccio et al. 2012
- 1.5 < m_{WDM} [keV] < 2 ve too-big-to-fail — Lowell et al. 2012, 2014
- m_{WDM} > 3.3 ke 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

Late Forming DM

- Evade Lyman-alpha constraints (z_t>5 10^5) — Agarwal, Corasaniti, Das & Rasera 2015
- Suppressed halo abundances
- Flatter profiles than LCDM (not cored)

N-body Simulations

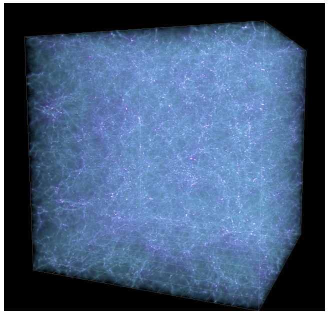
Monte Carlo Method

- Macro-particle sampling DM field
- Initial Conditions:
  - WDM thermal velocities negligible (?)
  - LFDM effectively collision-less
- Numerical integration trajectories

$$\frac{d\vec{p}_i}{da} = -\frac{\nabla\Phi}{\dot{a}}, \quad \frac{d\vec{x}_i}{da} = \frac{\vec{p}}{\dot{a}a^2}, \quad i = 1, N$$

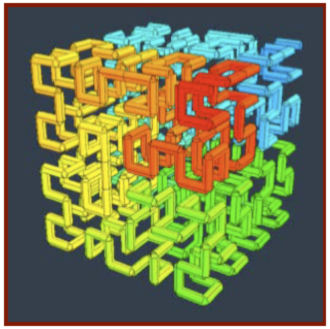
$$\nabla^2\Phi = 4\pi G a^2 \bar{\rho}_m \delta_m$$

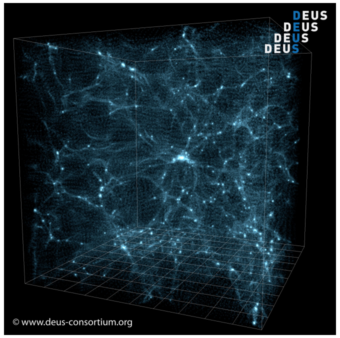
- Analyze final macro-particle distribution



Initial Conditions
- ZA displacements from input P(k)

N-body Solver
- AMR, TreePM, etc.





Simulation Characteristics

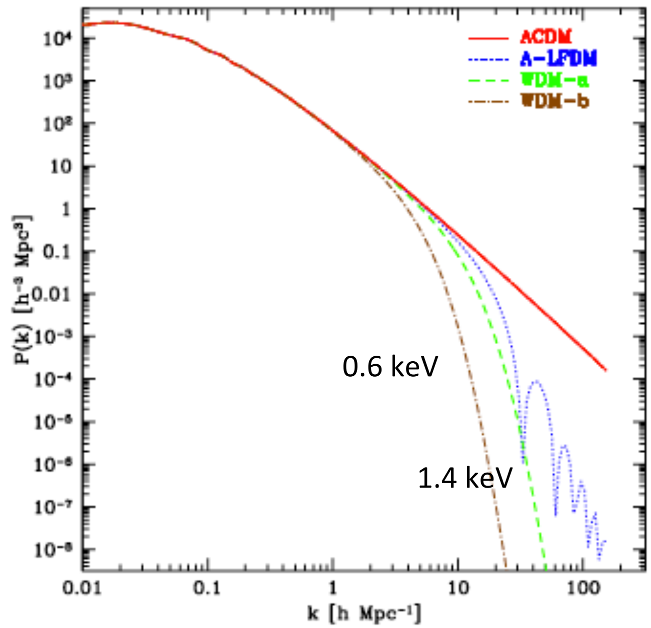
- Gravity Solver
- Cosmological Volume L_{box}^3
- Mass Resolution $m_p = \rho_c \Omega_m L_{box}^3 / \mathrm{N}_p$
- Spatial Resolution Δx

Artificial Fragmentation (Mass Segregation)

Discretization Effect

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

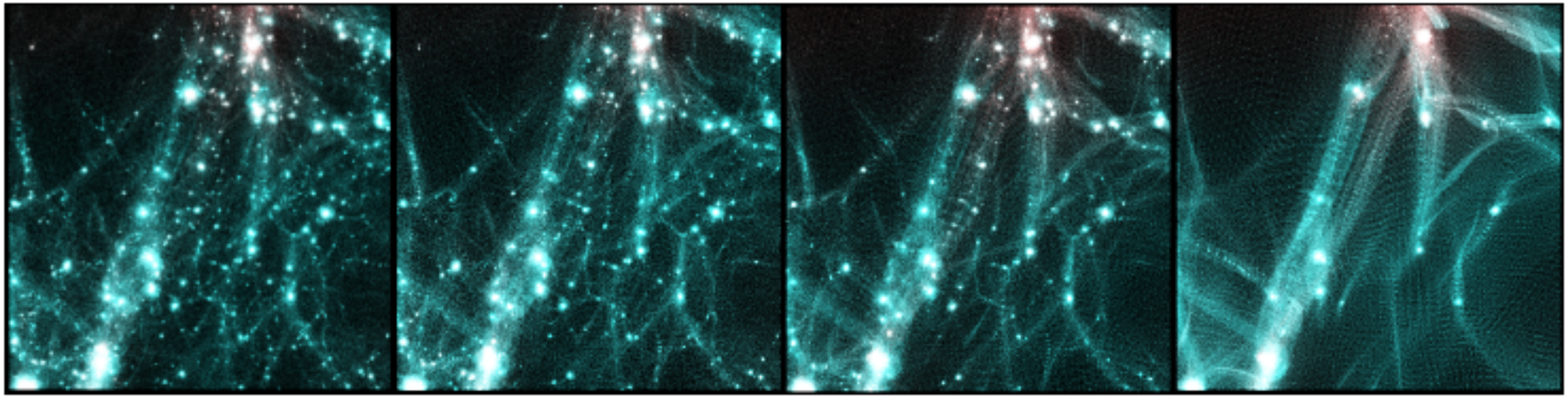
Gotz & Sommer-Larsen 2002, 2003; Wang & White 2007



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

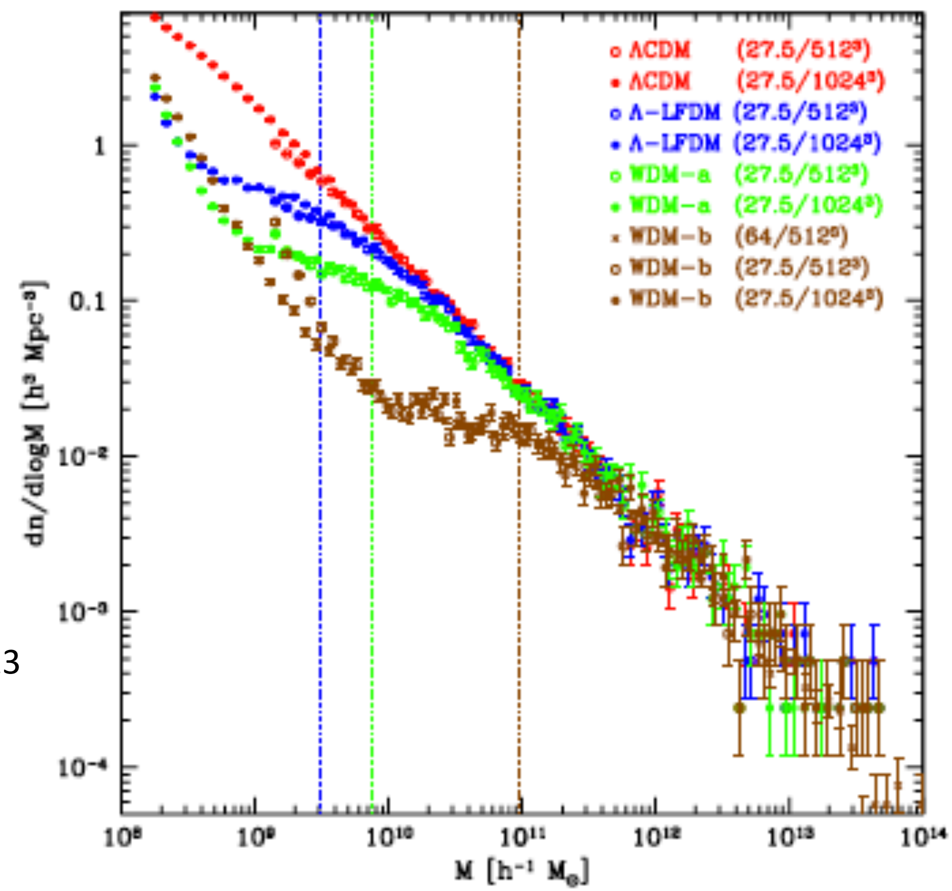
Halo Mass Function

- $N_{h\text{-}particles} > 100$
- 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}
- $m_p \sim 10^6\ M_{sun}\ h^{-1}$
- $dx_{coarse} \sim 26$ kpc h^{-1}



Agarwal & Corasaniti 2015

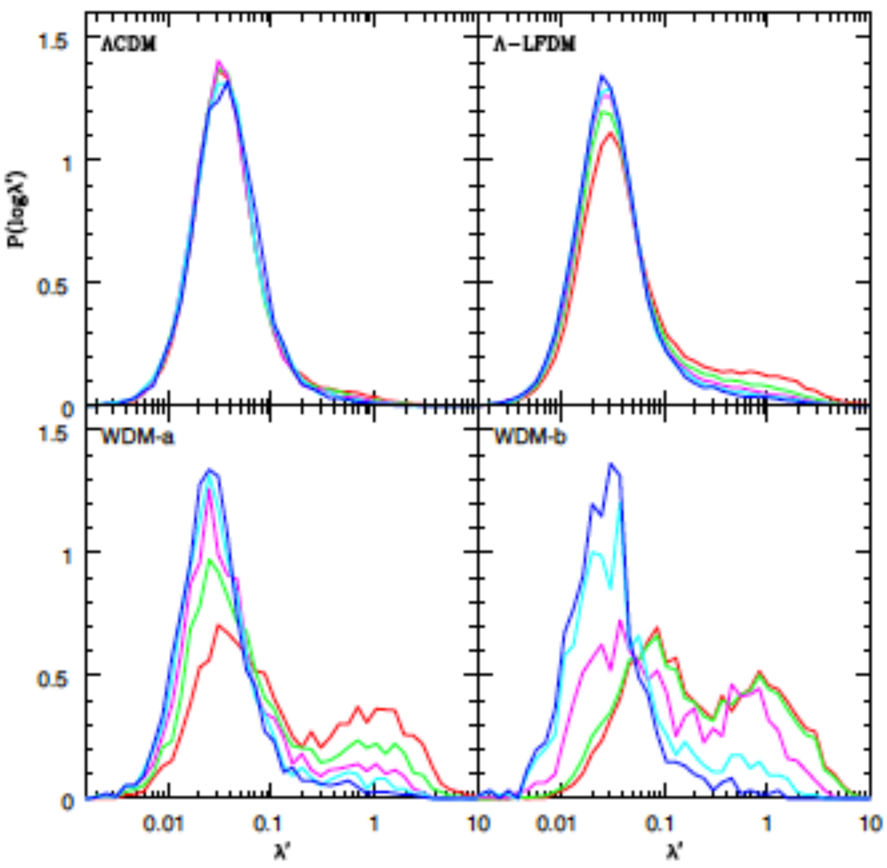
Structural Properties of Halos

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

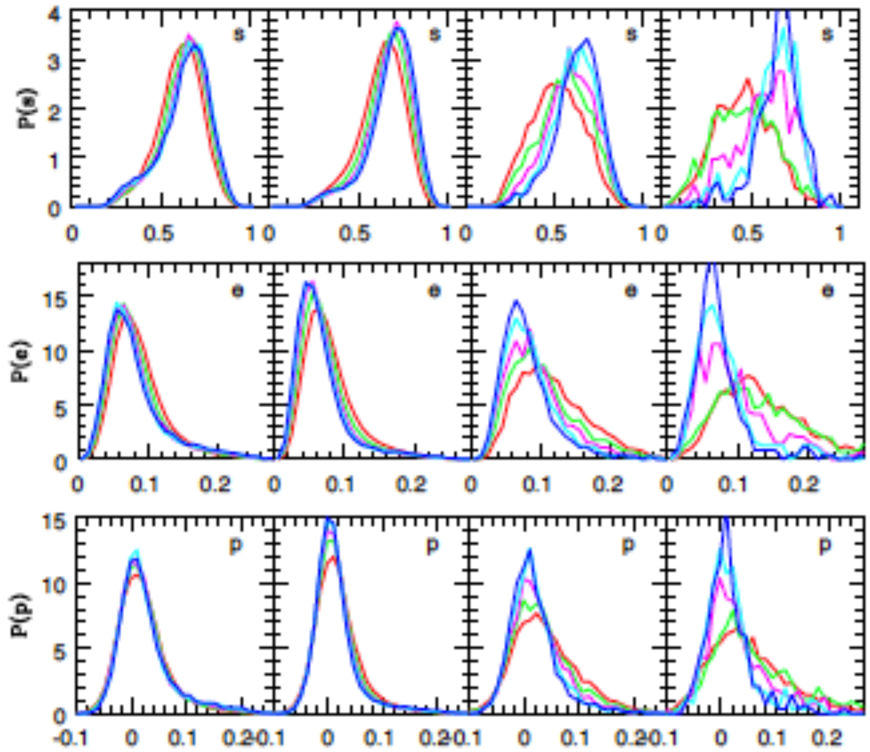
- Symmetric Mass Distribution Tensor

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

- sphericity, ellipticity & prolatness

- CDM: mass independent & elliptical halos

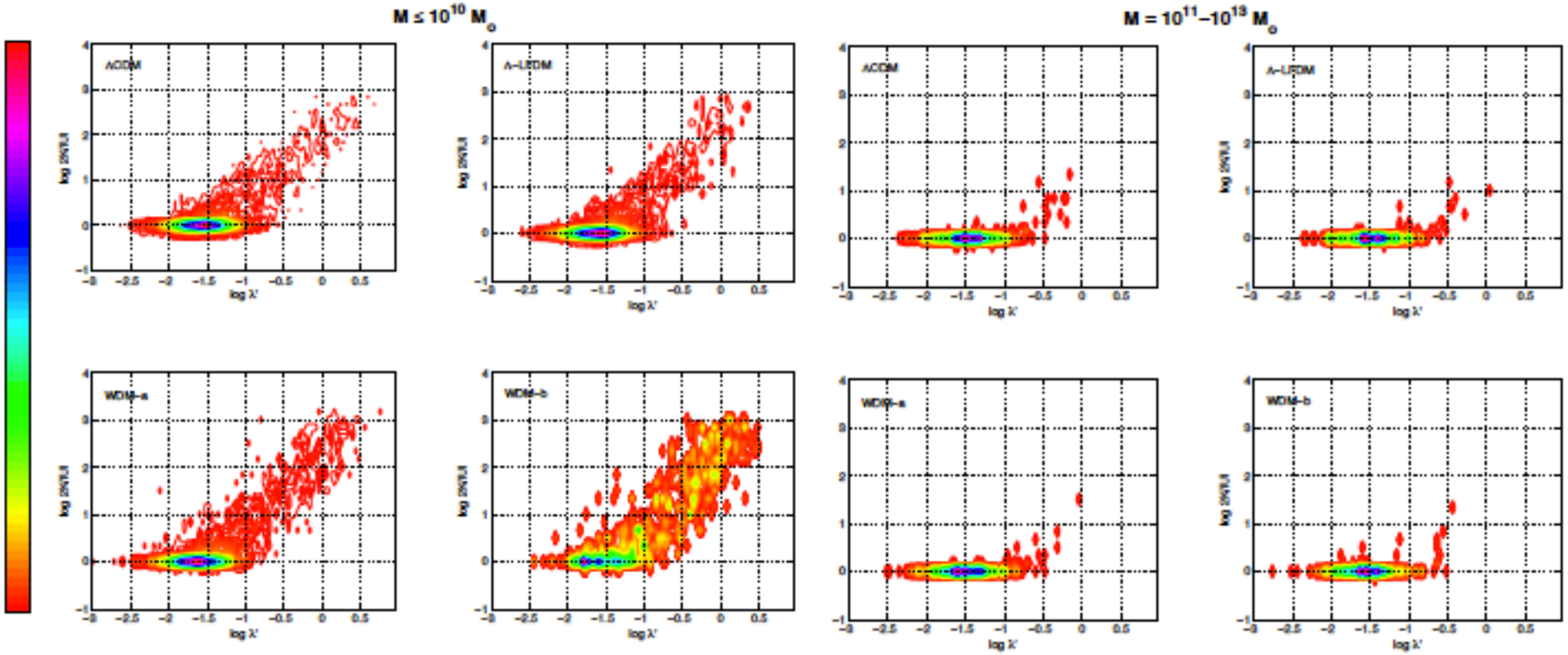
- non-CDM: mass dependent & highly non-spherical (elliptical & prolate, i.e. alignment with filaments)



Halo Dynamical State

Virial Condition

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



Virial State Selection

Removing Spurious Halos

- $0 < \eta = 2K/|E| < 1.5$

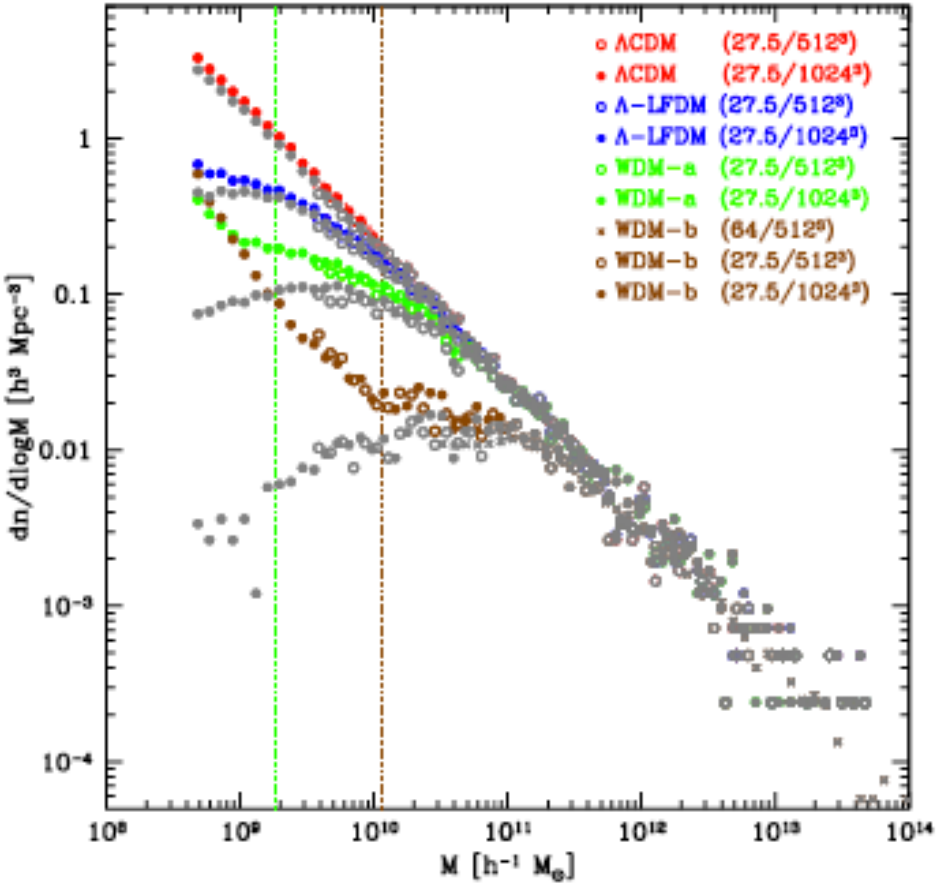
- recover halo triaxial distribution

- recover spin log-normality

- recover suppressed mass function at low mass (mass resolution convergence)

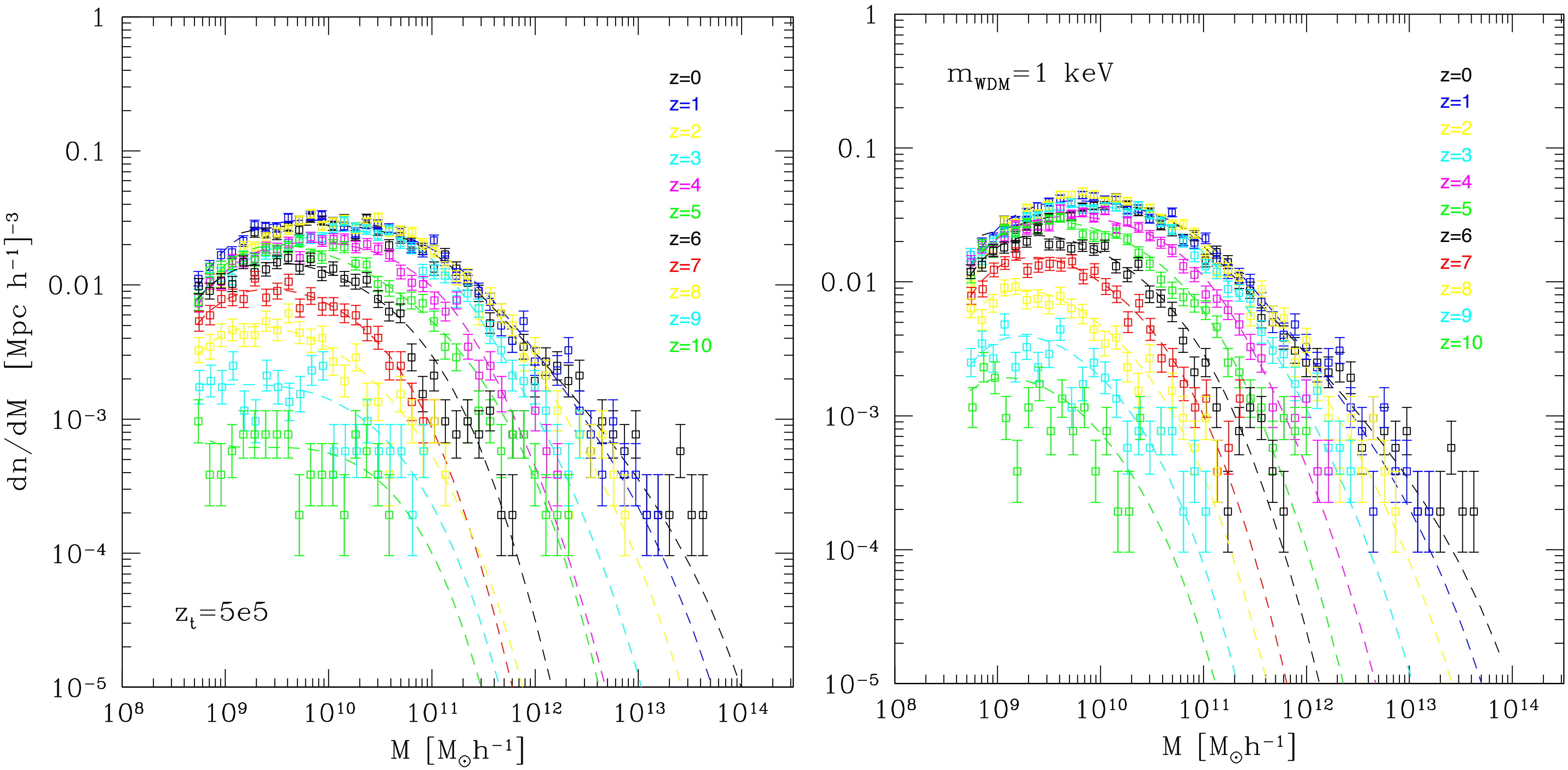
- spurious halos still present with simple mass-cut at M_{min}

- mass range larger than mass cut



Evolution of HMF in NDM models

Corasaniti et al. in preparation



- Low mass end saturates at z < 3
- Fitting function:

$$\left(\frac{dn}{d\ln M}\right)_{NDM} = 10^{A_0 + A_1 M}\left(\frac{dn}{d\ln M}\right)_{LCDM}\left[1 - e^{-\frac{M}{m_*}}\right]^{-\alpha}$$

Abundance of Field Dwarf-Galaxies z=0

Velocity Function

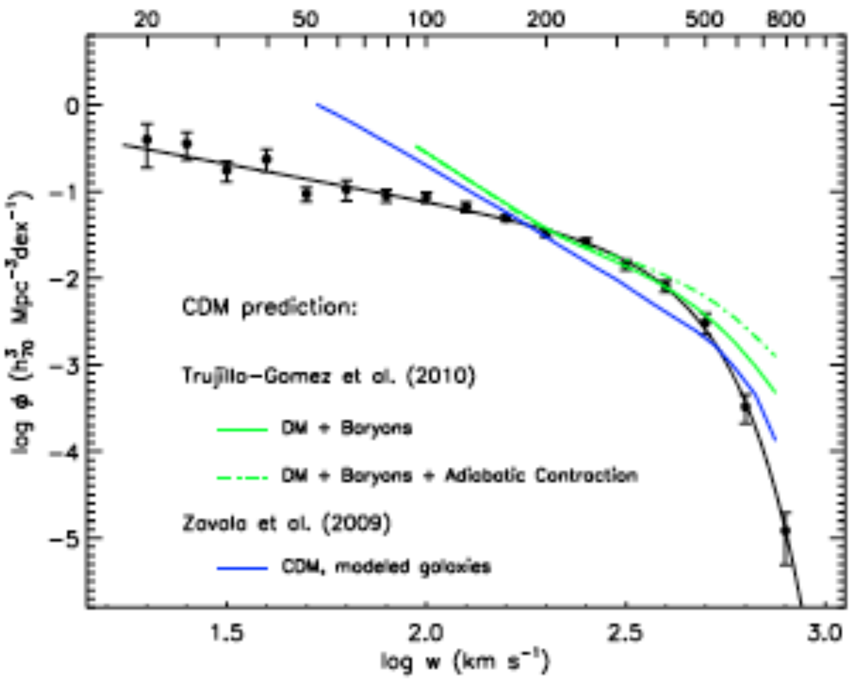
- Abundance of galaxies with given circular velocity
- More sensitive to halo dynamics than gas physics
- Mostly individual halos rather than satellite

Caveats

Theory: circular velocity / Observations: line-of-sight velocity

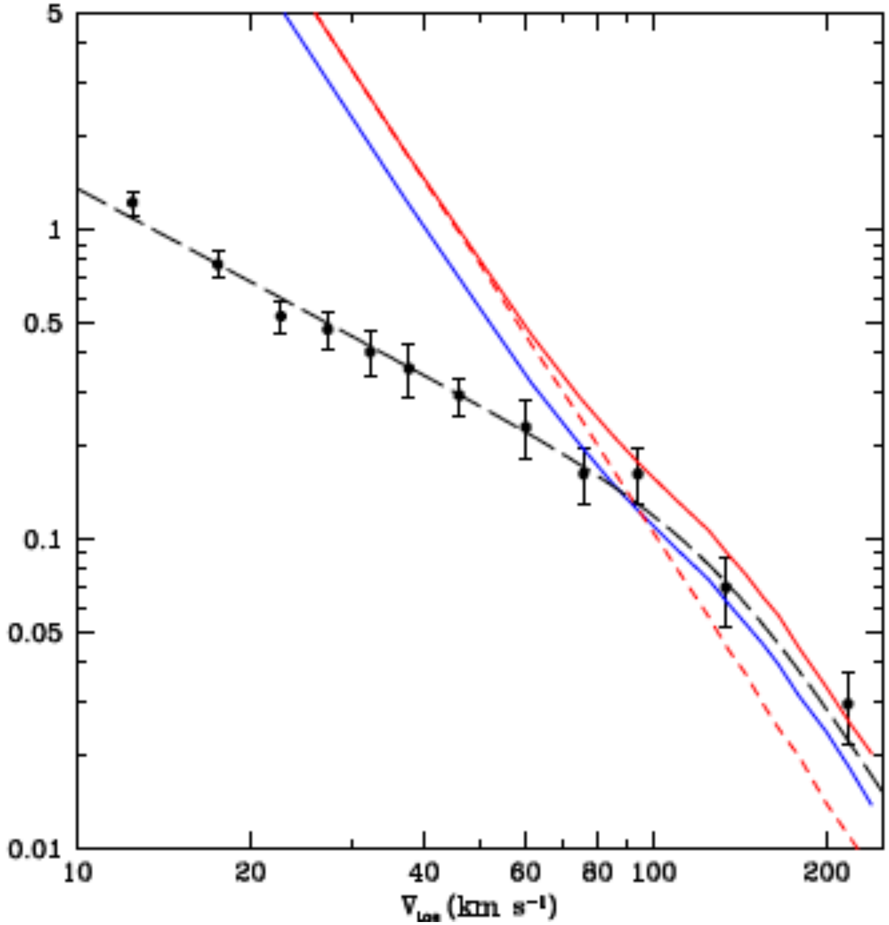
- Inclination effect
- Baryons at high-velocity end
- Selection

CDM Overabundance

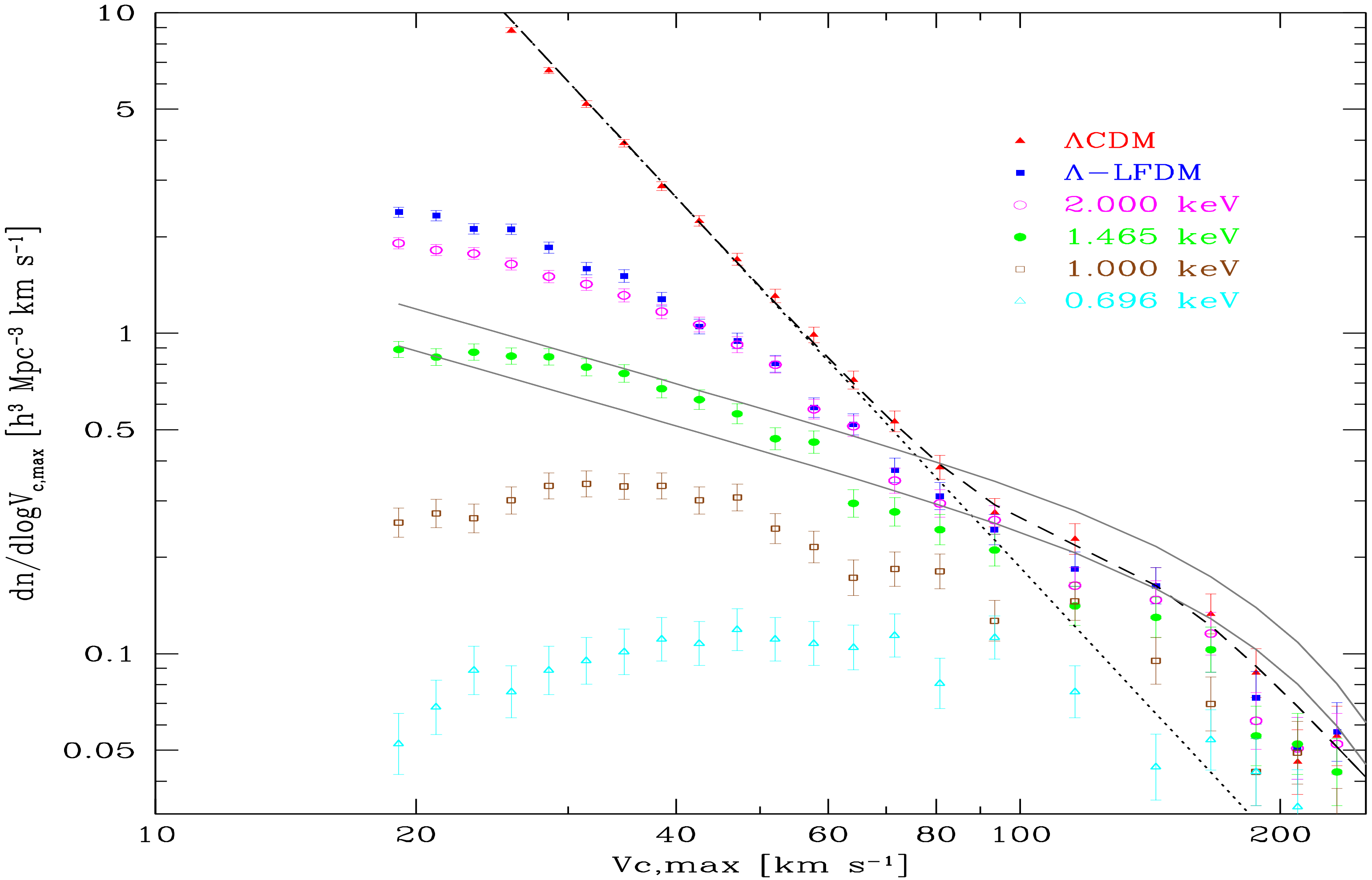


Papastergis et al. 2011

Klypin et al. 2015



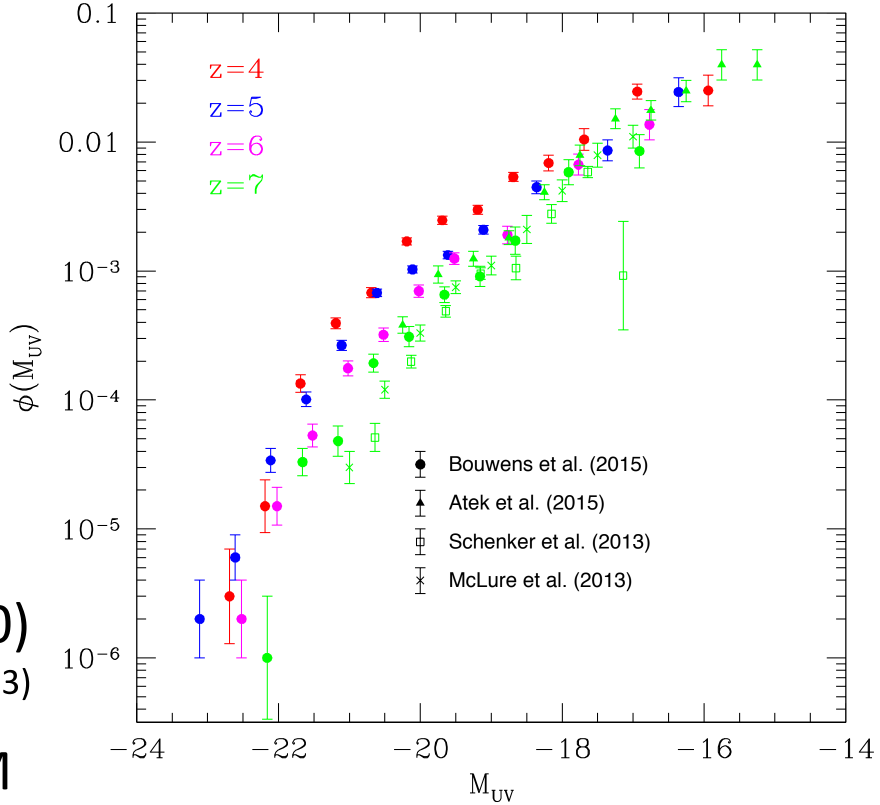
Velocity Function



High-Redshift Universe

Galaxy Luminosity Function

- Probe low mass end HMF evolution
- Depends on galaxy formation
- Several estimates at z > 4



Constraints on NDM

- m_{WDM}> 1 keV (CLASH gal. den. z = 10)

Pacucci, Mesinger & Haiman (2013)

- m_{WDM} > 0.8 keV from HAM of LCDM

Schultz et al. (2014)

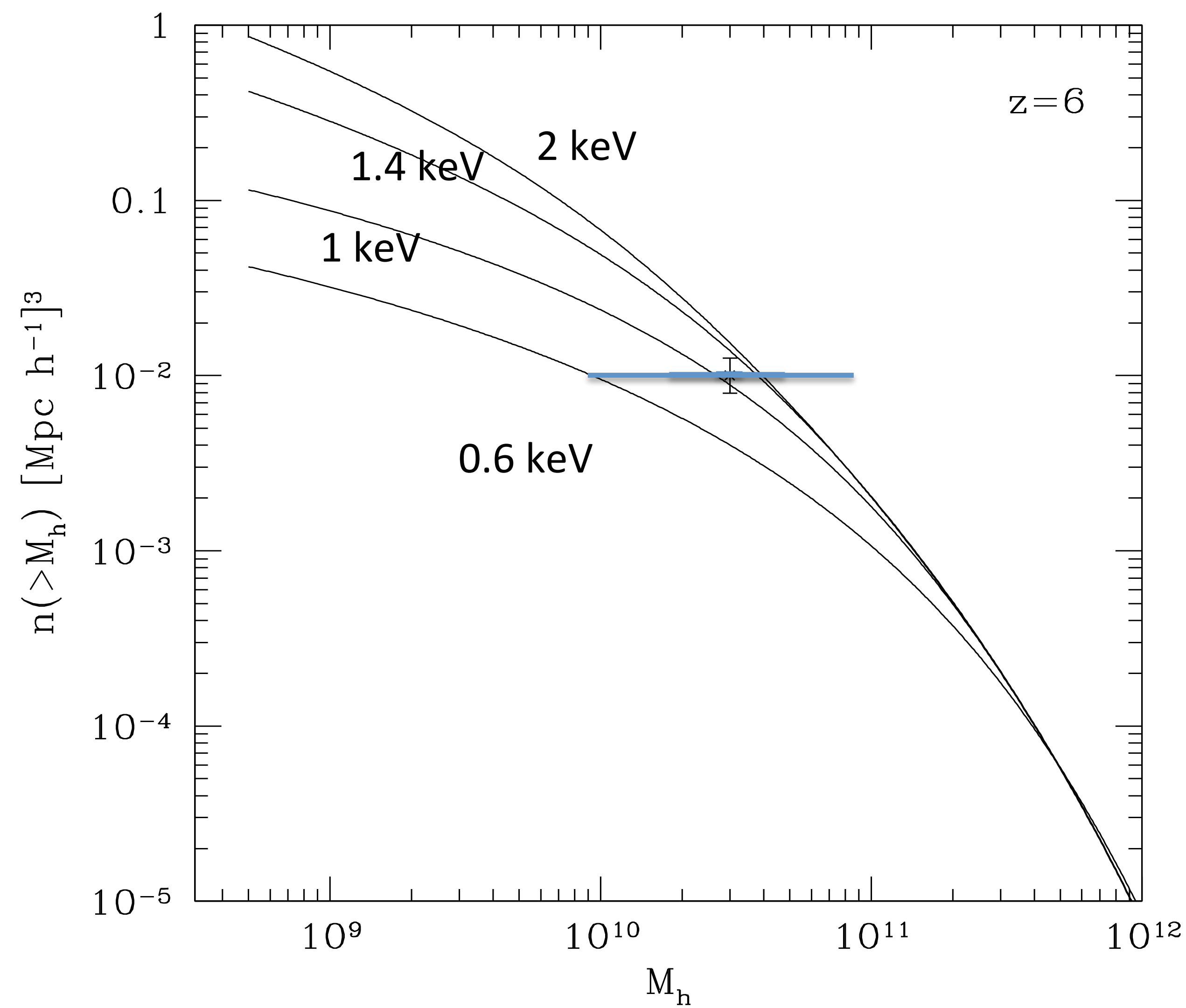
- m_{Ψ} > 10^{-22} eV from HAM assuming parametrize $L_{UV}(M)$ relation

Schive et al. (2016)

Cumulative Number Density

How reliable?

- DM Halo mass is highly uncertain



Abundance Matching

Empirical Approach:

$$\int_{M} d\tilde{M} \; \frac{dn}{d\tilde{M}} = \int_{M_{UV}} d\tilde{M}_{UV} \phi(\tilde{M}_{UV})$$

- Rely on approximate analytical form of HMF
- Extrapolate LCDM relation to NDM models
- Redshift evolution may be driven by extinction

What can we learn?

- **About galaxy formation in NDM models?**
- **What high-z can tell about NDM under minimal assumptions?**

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)

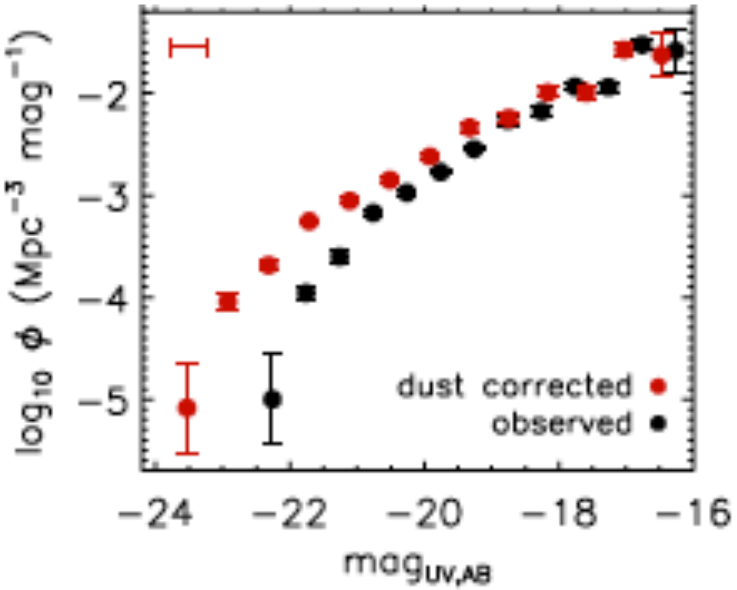
Extinction Correction

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

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)

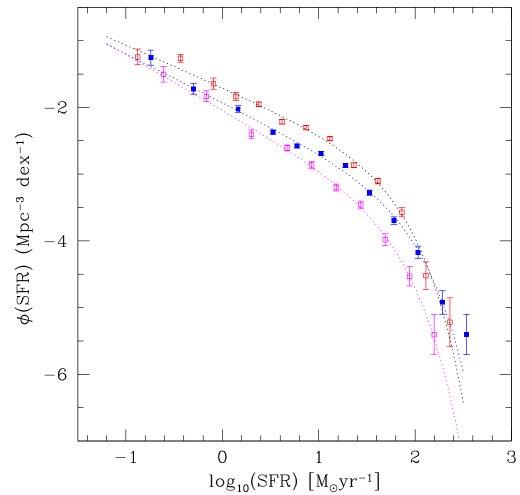


Smit et al. (2012)

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

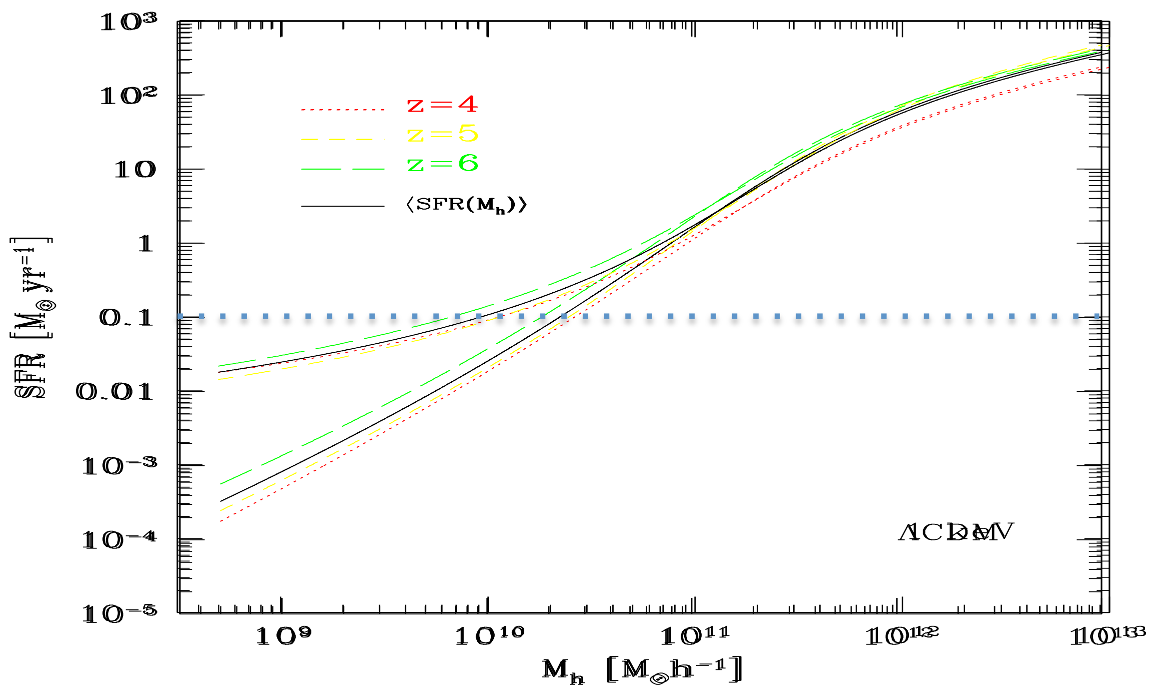
SFR density function

Φ(SFR) at 4<z<6



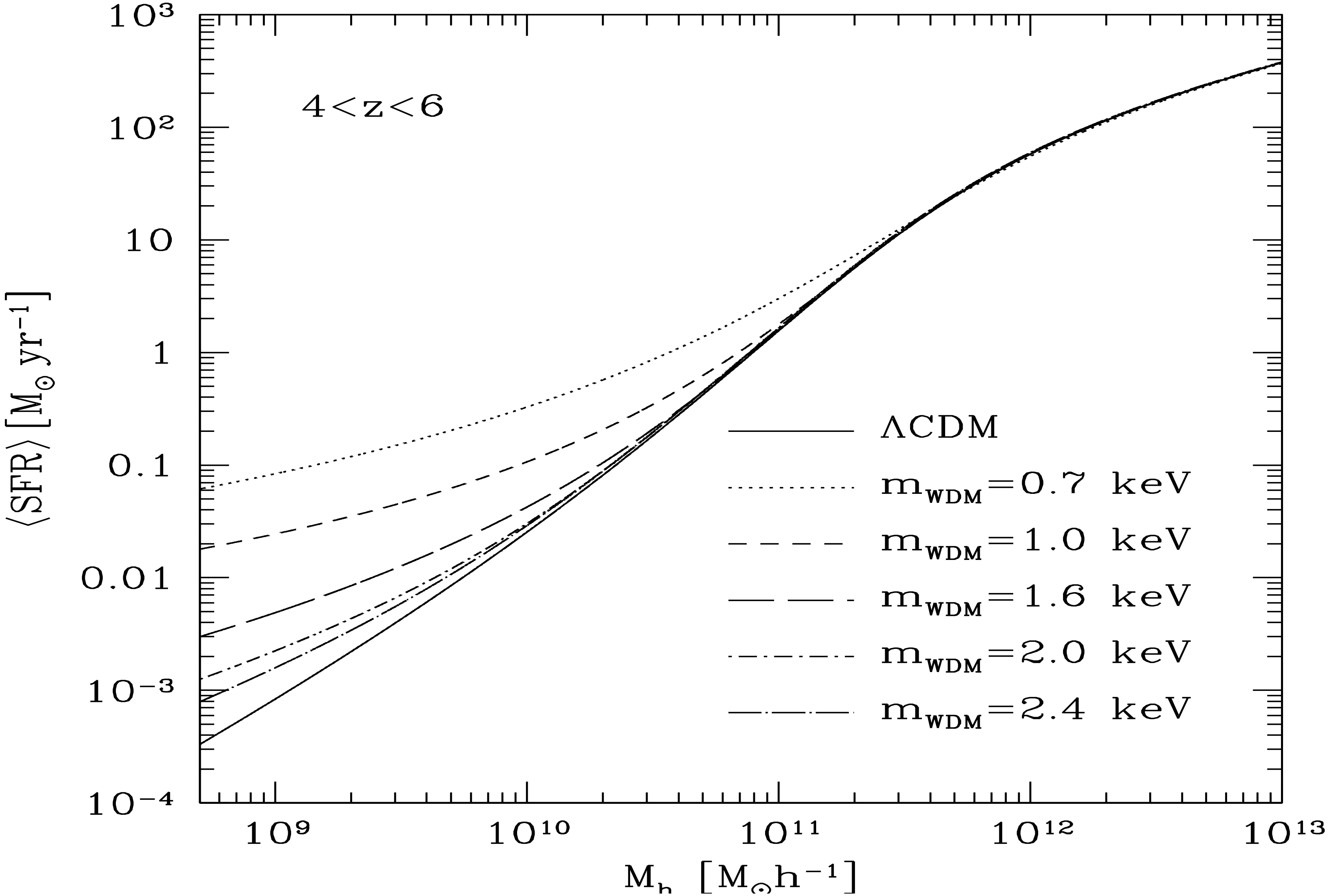
- Fit Φ(SFR) with Press-Schechter function
- HAM

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



- SFR-M_h evolves in amplitude
- Redshift average

Average SFR-M_h



Modeling Luminosity Function at z > 6

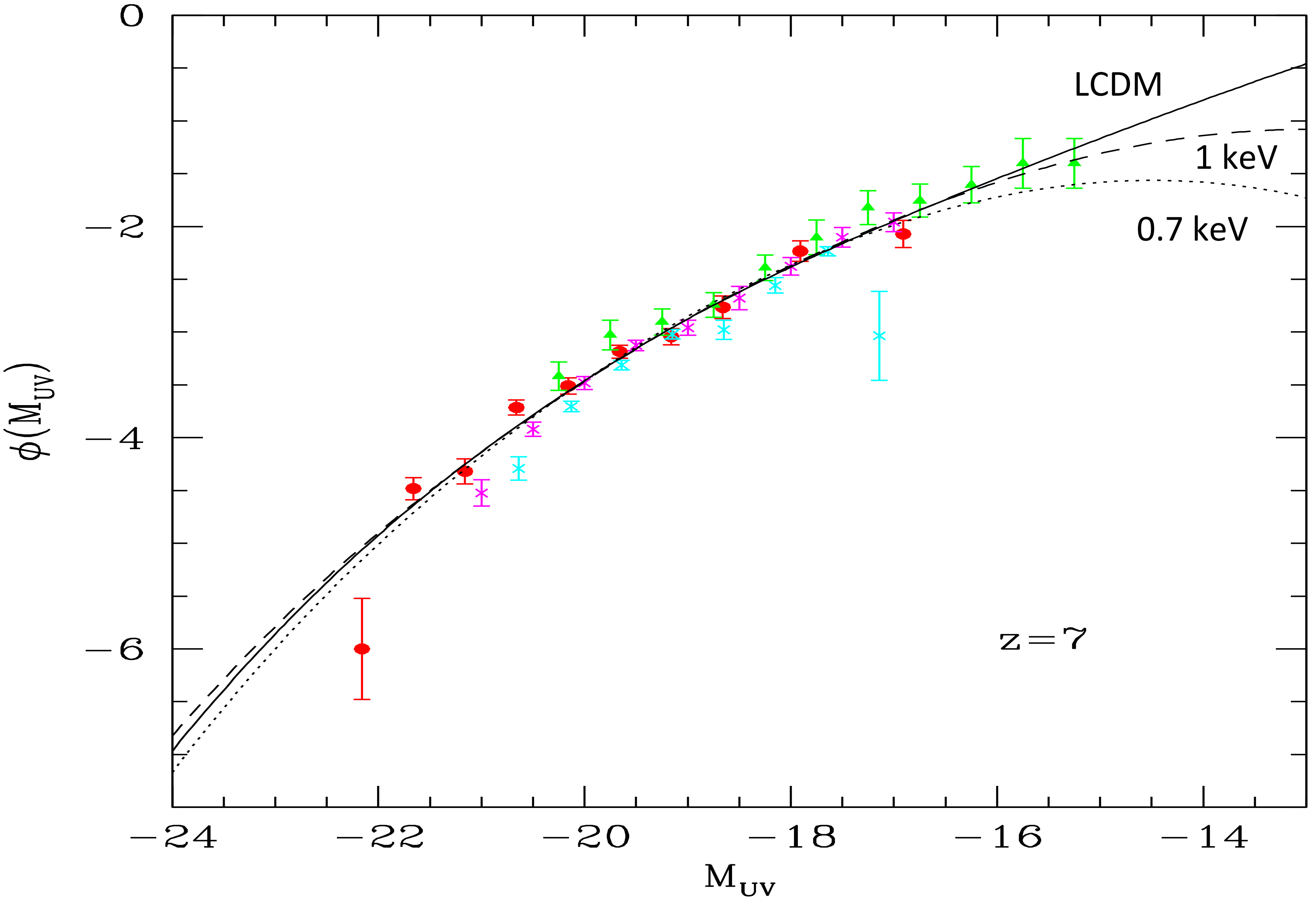
Intrinsic Scatter SFR-M_h relation

- 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}

Fitting Galaxy Luminosity Function at z > 6



Conclusions

- Small scale clustering of matter as probe of non-standard DM models (*free your mind*)

- Artificial fragmentation in simulation of models with suppressed spectrum at small scales needs to be accounted for (*be inquisitive*)

- Galaxy formation cannot occur in the same way in NCDM models (*question your believes*)

- Testing SFR halo mass relation can provide key insights (*truth arises more from error than confusion*)