Focusing on Warm Dark Matter with Lensed High-Redshift Galaxies

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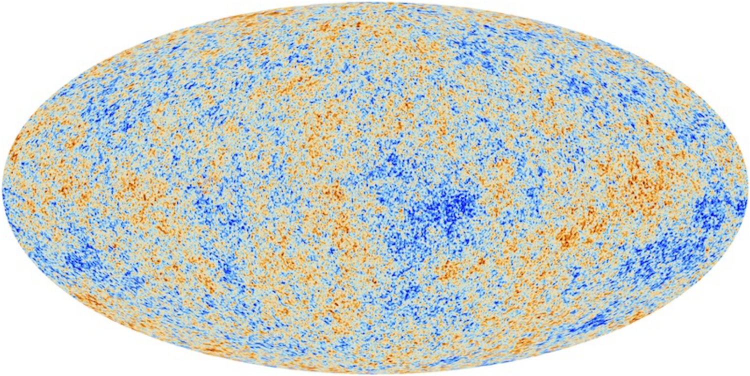
Summary

The LCDM: Key Successes and Limitations

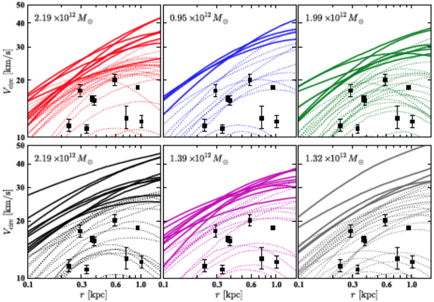
The Concordance LCDM has been remarkably successful in predicting the matter distribution on large scales: CMB, cluster abundances, galaxy clustering and the cosmic web.



Observations of low-redshift galaxies have suggested that the CDM predicts too much power on small scales.

Problems with the Small Scales

- Number of satellite galaxies in Milky Way (*Klypin et al. 1999*) and in the field (*Papastergis et al. 2011, Ferrero et al. 2012*) is too low
- CDM simulations result in a population of massive, concentrated Galactic sub-halos that are inconsistent with kinematic observations of the bright Milky Way satellites (*Boylan-Kolchin et al. 2012*)
- Inner profiles of dwarf galaxies are too shallow compared with CDM predictions (*Maccio et al. 2012*)



Possible Solutions to the Small Scale Problem

Baryonic Feedback

- Baryonic feedback caused by supernovae explosions and heating due to the UV background may suppress the baryonic content of low-mass halos and make their inner profile shallower (*Governato et al. 2007, Busha et al. 2010*).
- It is not clear if baryonic feedback provides a satisfactory match to all observations, even when arbitrarily tuned (*Boylan-Kolchin et al. 2012, Teyssier et al. 2013*).

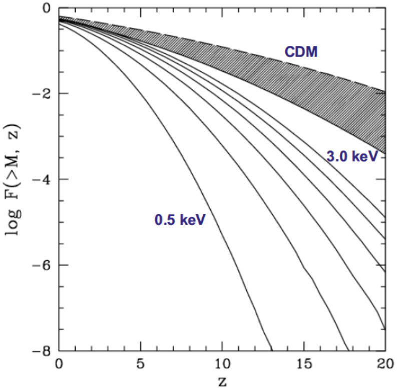
Warm Dark Matter

- An alternative explanation might be found if dark matter consisted of lower mass ($\sim keV$) particles, so-called Warm Dark Matter (*Blumenthal et al. 1982*).
- Small scale structure is dramatically suppressed in WDM models, due to the effect of free-streaming and velocity dispersion. These models may provide a better match to local galaxies.

High-z Observations for the WDM

The most powerful test-bed for these scenarios is the high-redshift Universe: structure formation in WDM models is exponentially suppressed on small scales.

The mere presence of a galaxy at high redshift ($z > 10$) can set strong lower limits on the WDM particle mass (*Mesinger et al. 2005*).



Current Constraints from the High-z Universe

Constraints affected by degeneracy with Astrophysics:

- Lyman alpha forest: $m_x > 3\,keV$ (*Viel et al. 2008*)
- Reproducing stellar mass function and Tully-Fisher relation: $m_x > 0.75\,keV$ (*Kang et al. 2013*)
- Observation of dwarf spheroidal galaxies: $m_x \geq 1.0\,keV$ *(de Vega & Sanchez 2010)*
- Reionization occurring by $z \sim 6$: $m_x > 1\,keV$ (*Barkana et al. 2001*)
- Swift GRB distributions: $m_x > 1.5\,keV$ (*de Souza et al. 2013*). This method is in general very robust and less affected than the previous ones by degeneracy with Astrophysics.

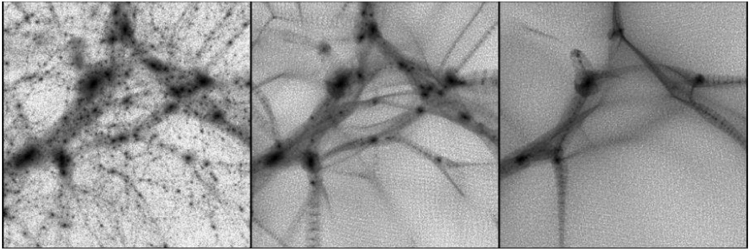
Our method is completely independent of the physics of the baryons

WDM Free-Streaming Effect

Particle free-streaming smears out small scale structure, altering the effective transfer function of the matter power spectrum.

Free-streaming scale for a thermal relic (*Bode et al. 2001*):

$$R_{\mathrm{fs}} \approx 0.31 \left(\frac{\Omega_x}{0.3}\right)^{0.15} \left(\frac{h}{0.65}\right)^{1.3} \left(\frac{\mathrm{keV}}{m_x}\right)^{1.15} \frac{\mathrm{Mpc}}{h}$$



Modification of the matter power spectrum:

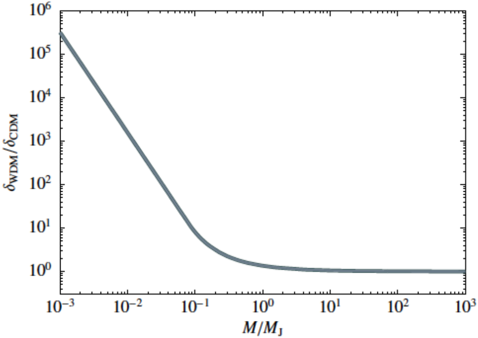
$$P_{\mathrm{WDM}}(k) = P_{\mathrm{CDM}}(k) \left[1 + (\epsilon k)^{2\mu}\right]^{-5\mu}$$

WDM Velocity Dispersion Effect

The stochastic residual velocity dispersion of particles prevents the growth of early perturbations below a WDM Jeans scale, acting as an effective pressure term (Barkana et al. 2001)

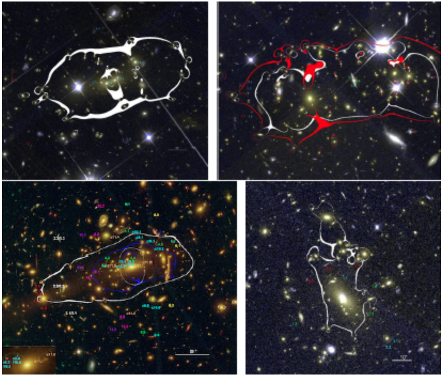
$$M_{\rm WDM} \sim 3.06 \times 10^8 \left(\frac{\Omega_x h^2}{0.15}\right)^{1/2} \left(\frac{m_x}{\rm keV}\right)^{-4} \times \left(\frac{1+z_{\rm eq}}{3000}\right)^{1.5} \left(\frac{g_x}{1.5}\right)^{-1} {\rm M}_\odot$$

WDM pressure effect incorporated by raising $\delta_c(M, z)$:



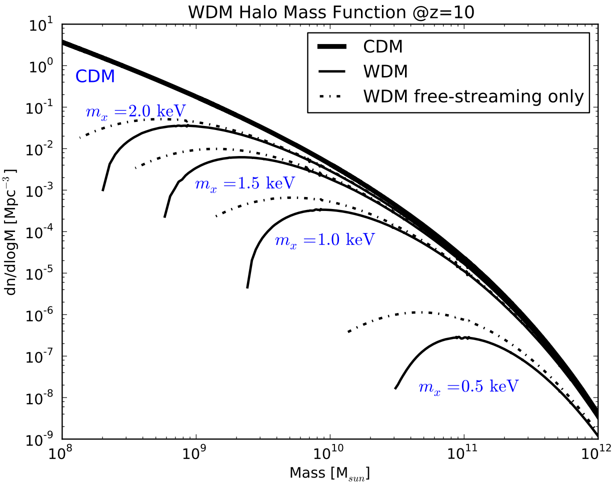
Our Estimate is Independent of Astrophysical Degeneracies

CLASH: Cluster Lensing And Supernova survey with Hubble



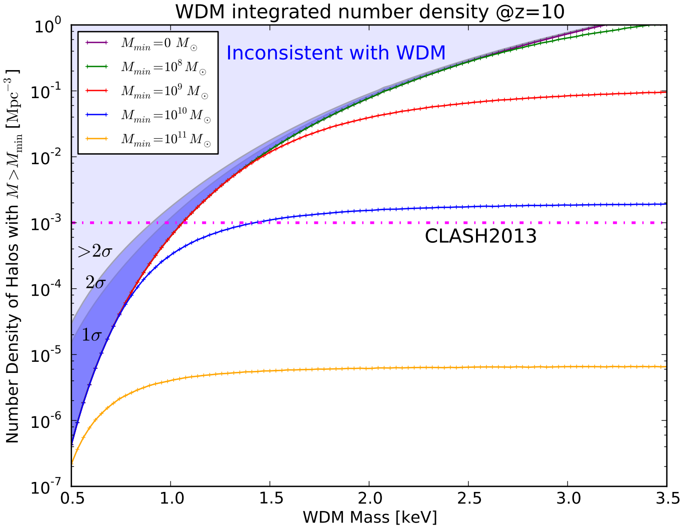
Object ID	μ	$V_{eff}(\mu)$ [Mpc^3]
MACS1149-JD	*15*	~ 700
MACS0647-JD	*8*	~ 2000

Halo Mass Functions in CDM and WDM

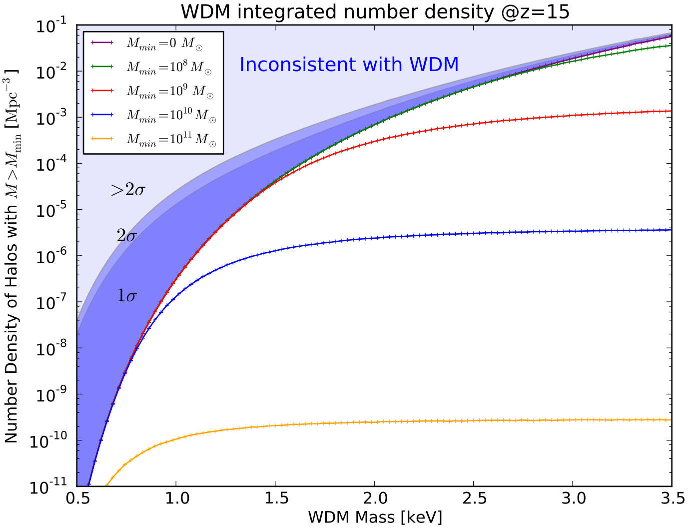


Lensed galaxies provide a special view over the high-z mass functions

A Lower Limit for the WDM Particle Mass



Constraints from Higher Redshift Observations

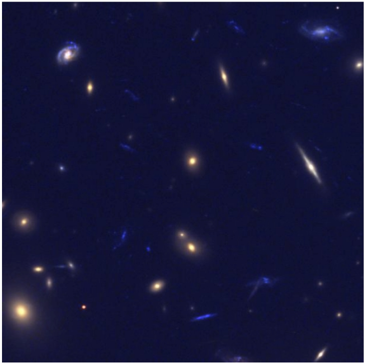


Future Potential

- Results can be updated when the final CLASH number density becomes known.
- Deeper cluster surveys can improve on the number density by detecting even fainter galaxies (like the HST Frontier Fields).
- More robust constraints can be obtained by modeling the redshift evolution of the mass functions across the lensing volume of each cluster.
- Tighter constraints on the WDM particle mass can be obtained at the cost of including astrophysical uncertainties. This involves a modeling of the mass-luminosity relations in halos, which is general very uncertain.

The Frontier Fields

- Targeting 6 lensing clusters.
- Reaching 3 magnitudes deeper and revealing galaxies populations $\sim 10 - 100$ times fainter than CLASH.
- Probing larger volumes than CLASH, decreasing the observational uncertainty.
- Expected conclusion of observations: July 2015.



		2013			2014												2015						
	Progress	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
ABELL-2744	54.3%	WFC3	WFC3						ACS	ACS	ACS												
ABELL-2744-HFFPAR	54.3%	ACS	ACS						WFC3	WFC3	WFC3												
MACSJ0416.1-2403	50.0%				ACS	ACS						WFC3	WFC3										
MACSJ0416.1-2403-HFFPAR	50.0%				WFC3	WFC3						ACS	ACS										
MACSJ0717.5+3745	1.4%	ACS											ACS	ACS	ACS			WFC3	WFC3	WFC3	WFC3		
MACSJ0717.5+3745-HFFPAR	1.4%	WFC3											WFC3	WFC3	WFC3			ACS	ACS	ACS	ACS		
MACSJ1149.5+2223	2.9%		WFC3					ACS							WFC3	WFC3	WFC3	WFC3		ACS	ACS	ACS	ACS
MACSJ1149.5+2223-HFFPAR	2.9%		ACS					WFC3							ACS	ACS	ACS	ACS		WFC3	WFC3	WFC3	WFC3

Conclusions

- Structure formation in WDM models is dramatically suppressed at small-scales.
- This leads to a dramatic difference between halo abundances in CDM and WDM models at the high-z, with the Universe becoming increasingly empty as the WDM particle mass is decreased.
- In our work we illustrated how the high implied abundances of lensed galaxies at $z \sim 10$ can be used to set robust constraints on m_x.
- Using two $z \sim 10$ galaxies observed to date by CLASH, we set lower limits of $m_x > 1\,(0.9)$ *keV* at 68% (95%) C.L..
- **This limit is the first constraint on m_x strictly independent of any astrophysical degeneracies.**