Cosmological effects of Late Forming Dark Matter

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The WIMP Miracle

Particles falling out of thermal equilibrium with the hot dense plasma of the early universe.

$$\Omega_\chi \propto \frac{1}{<\sigma v>} \sim \frac{m_\chi^2}{g_\chi^4}$$

For $m_{weak} \sim 100$ GeV and $g_{weak} \sim 0.6$

We have $\Omega_\chi \approx 0.1$ ← WIMP MIRACLE

A measure of relic dark matter density at present --> a golden opportunity to solve two problems in one go

Most Preferred candidate : **WIMP**: Describes the large scale features very well

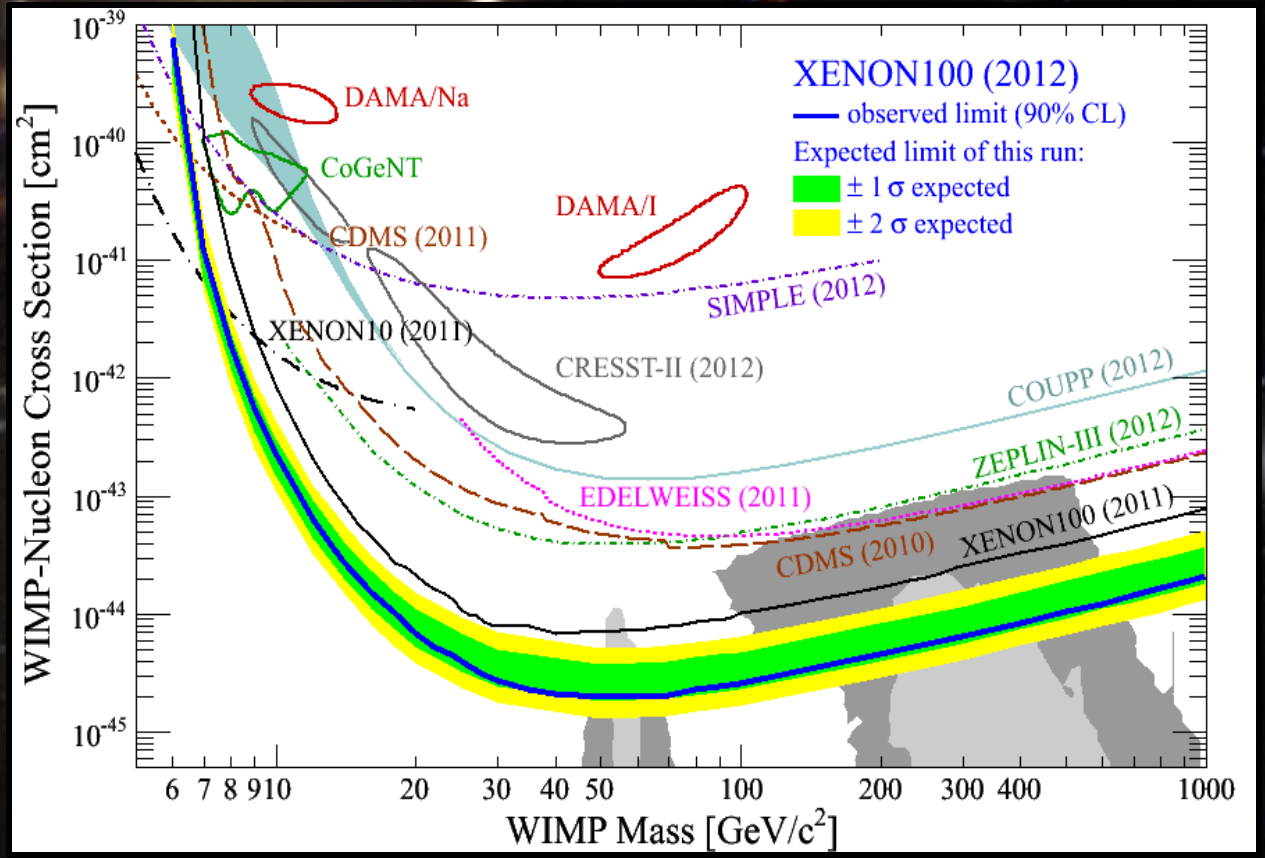
START HUNTING FOR WIMP!

Direct:

XENON100,CDMS-II,DAMA

Indirect:

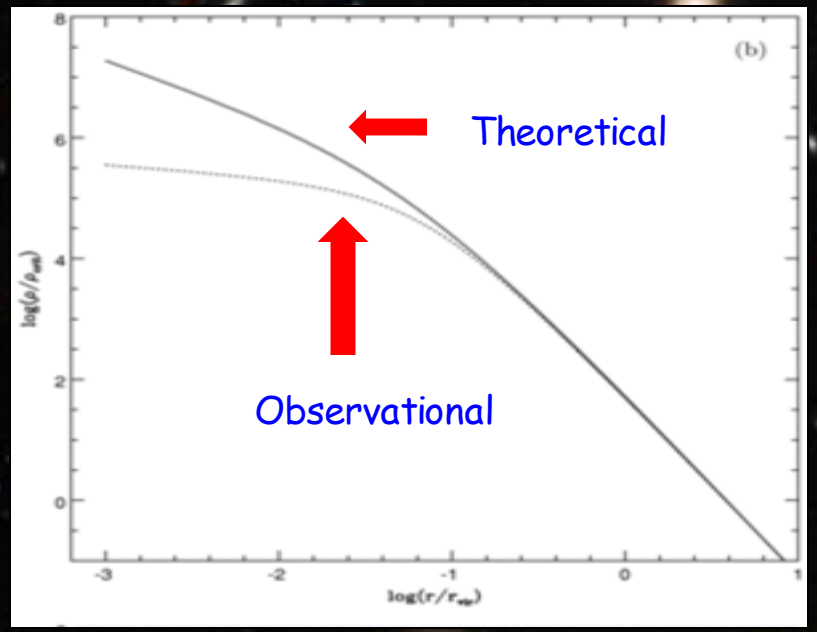
PAMELA, FermiLAT



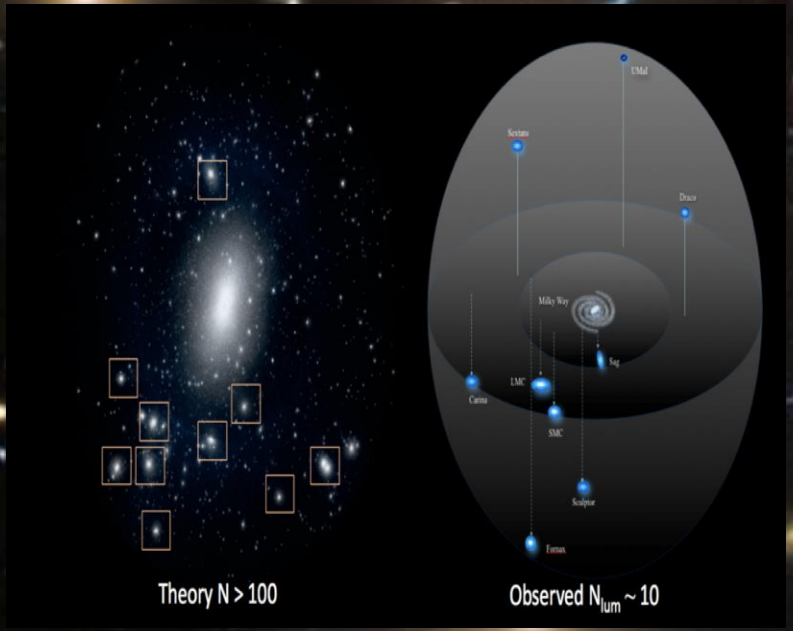
THE RESULTS ARE IN CONFLICT WITH EACH OTHER!! (Hooper JCAP09(2013)035)

More problems with WIMPS!

Core cusp problem
(De Blok; Arxiv :0910.3538v2)



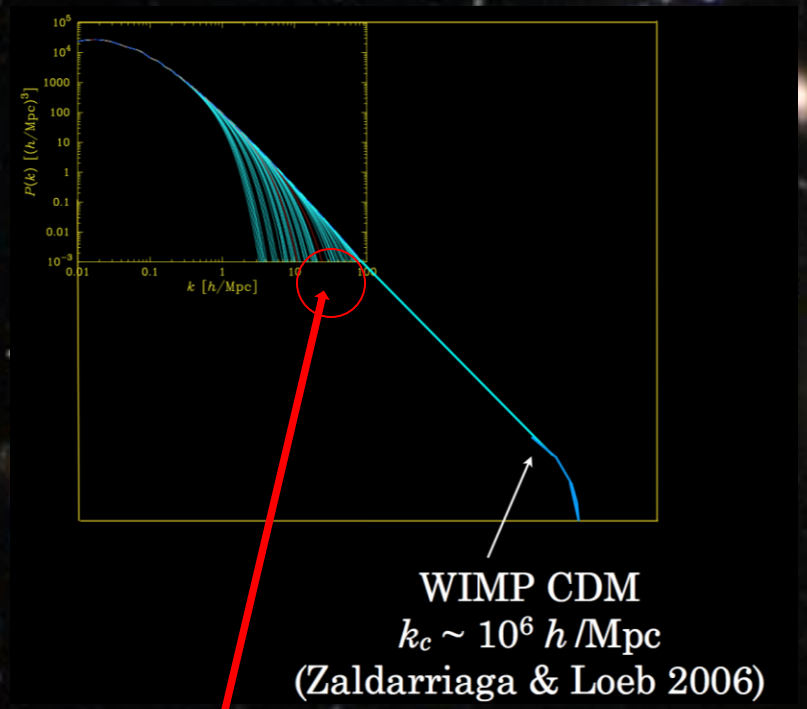
The Missing Satellite Problem
(Klypin et all ApJ 524,L19, 1999)



Too big to fail Problem
(Boylan-Kochlin et al 2011)

Most massive subhaloes of Milky Way are too dense to host it's bright satellites

Time to look for non-WIMP candidates ?



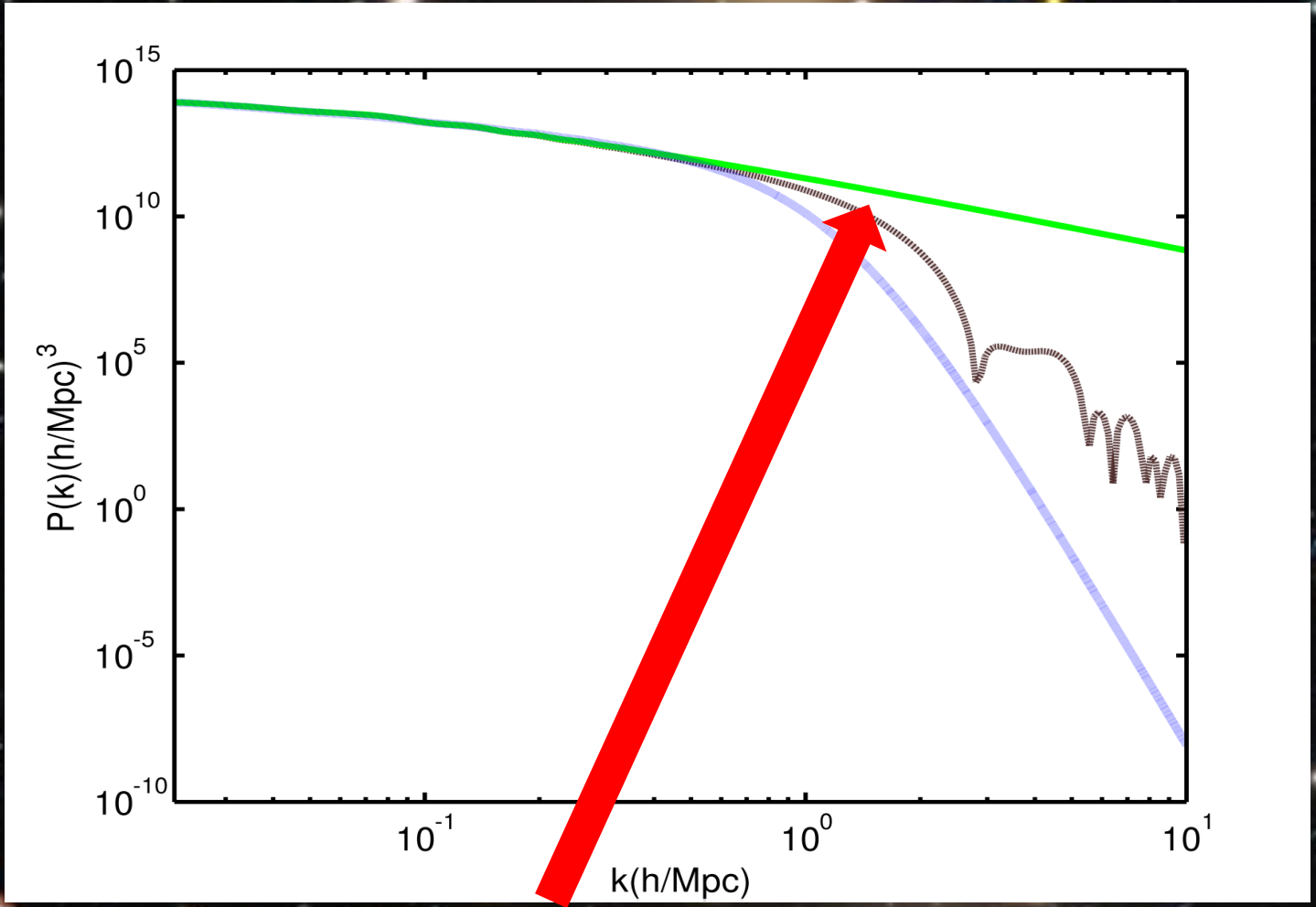
Break in power due to free streaming

Problems with WDM

WDM with mass ~ keV → too few subhaloes (Polisensky Ricotti 2011)

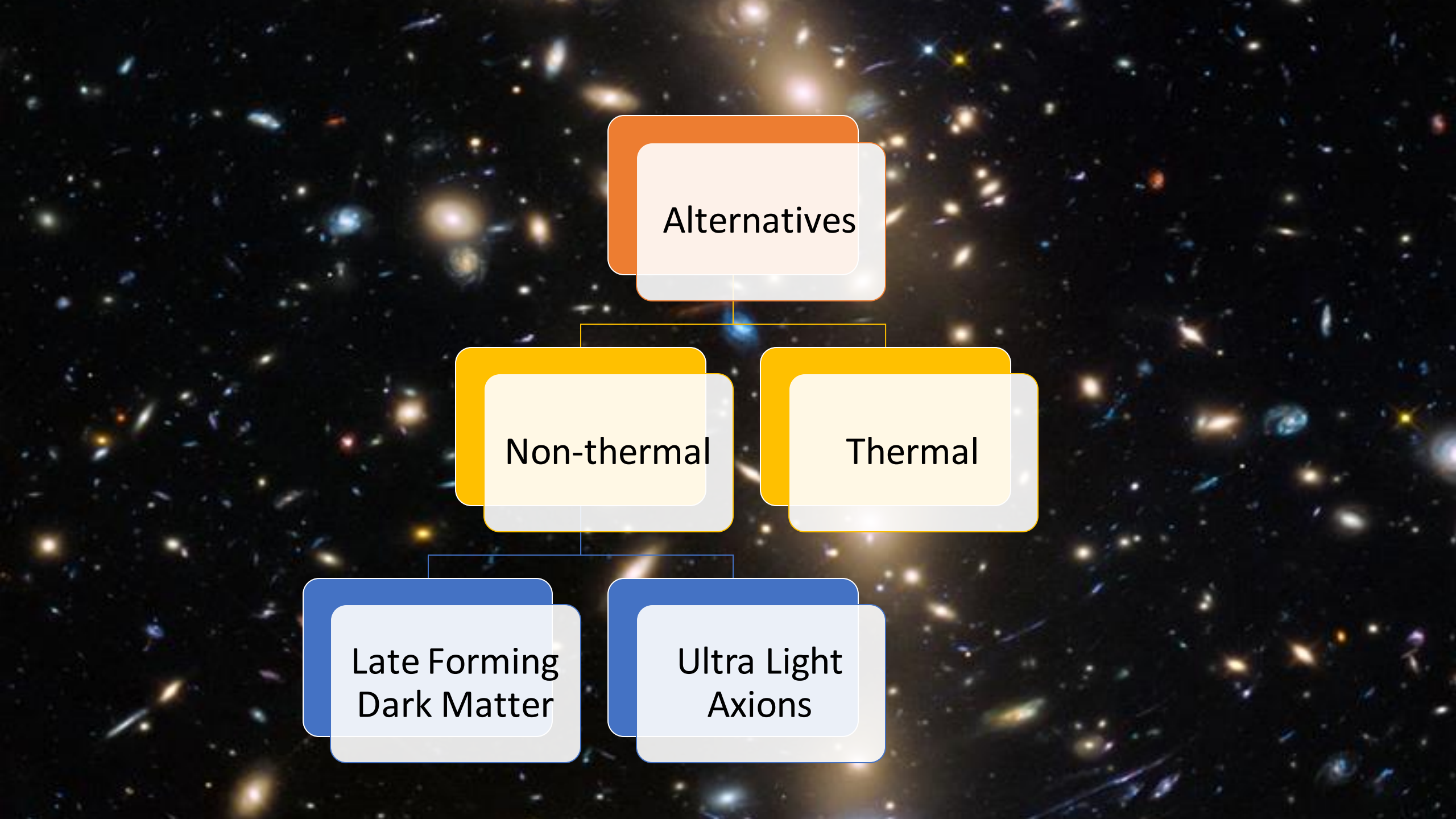
Lyman-α forest flux power spectrum combined with hydrodynamical simulation (Viel et al 2013) → $m_{WDM} \geq 3.3$keV

Cusp-core problem is partially solved for $m_{WDM} \sim 0.1$keV (Maccio et al 2012) where the "too big too fail" problem is best solved at $m_{WDM} \sim 1.5$-2 keV (Lovell et al 2012)



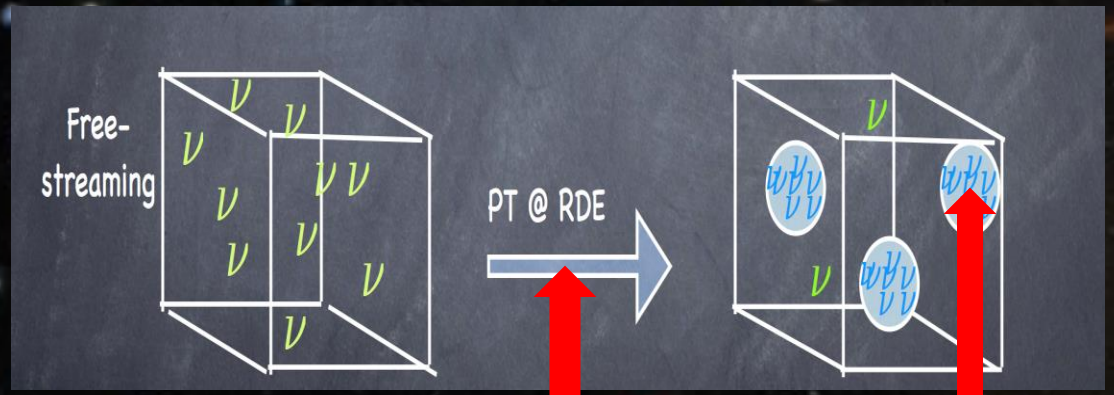
Break in power: but not too much

Late Forming Dark Matter comes into play


Alternatives
Non-thermal
Thermal
Late Forming Dark Matter
Ultra Light Axions

Theoretical models of LFDM:

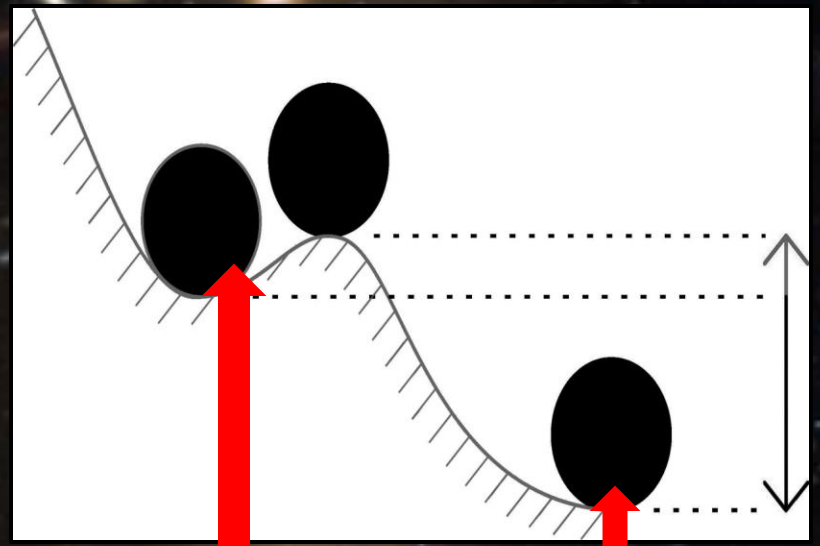
Fermionic : Das JPCS(2012)



Transition happens at $z=z_f$

Nuggets behave as dark matter

Scalar: scalar field tightly coupled with massless neutrino (Das,Weiner PRD 2011)



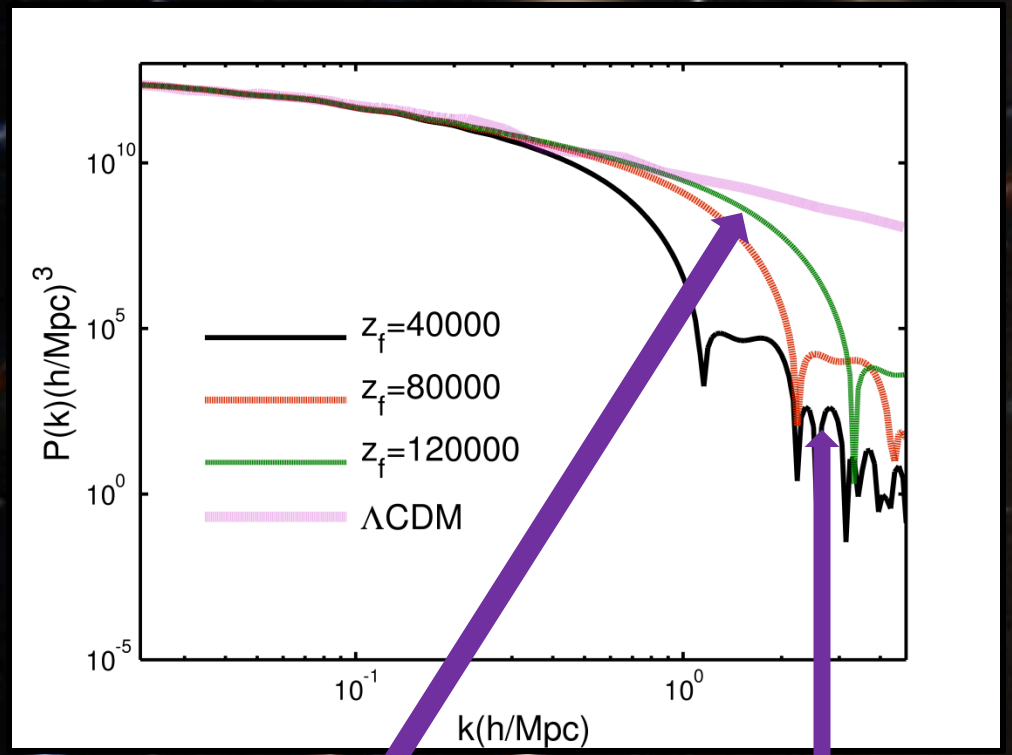
Behaves as dark energy

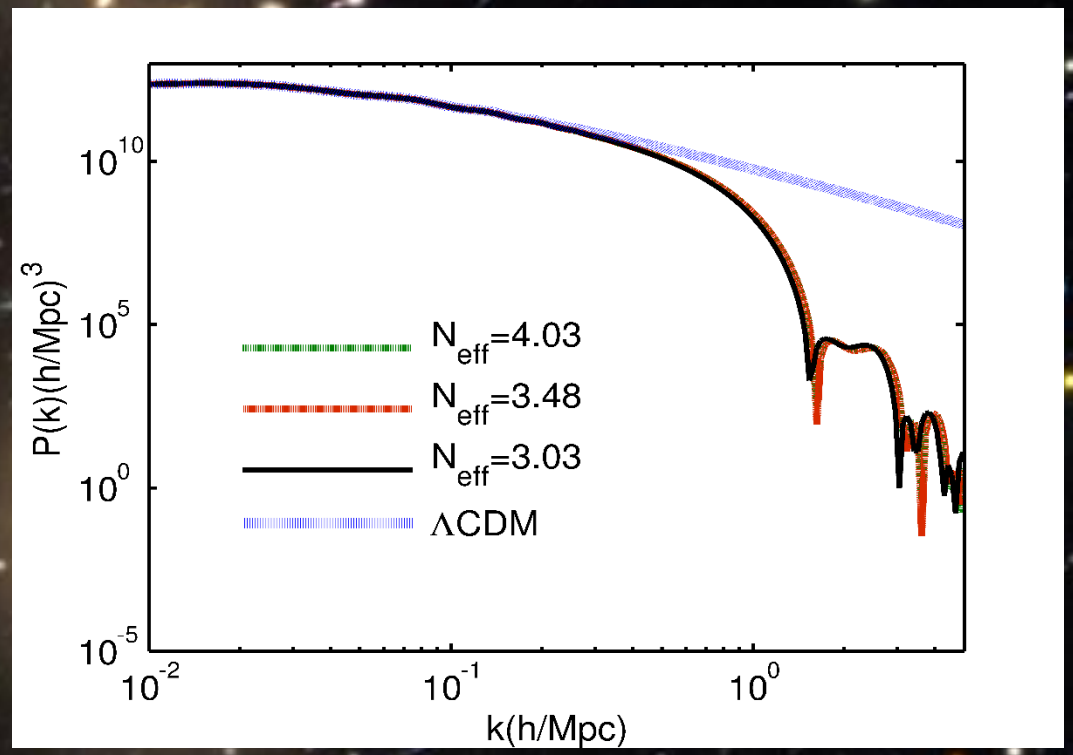
w=0, behaves as dark matter

Equation of state

$$w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$

2 parameters of interest : z_f, N_{eff}





Sharp break in power

Oscillations

Scales of the problem :

1) Affected by N_{eff} : $k \sim 10^{-2}$

2) Smaller scales → $k > 0.1$ → carries the signature of z_f

NEED OBSERVATIONAL DATA FOR BOTH SCALES!

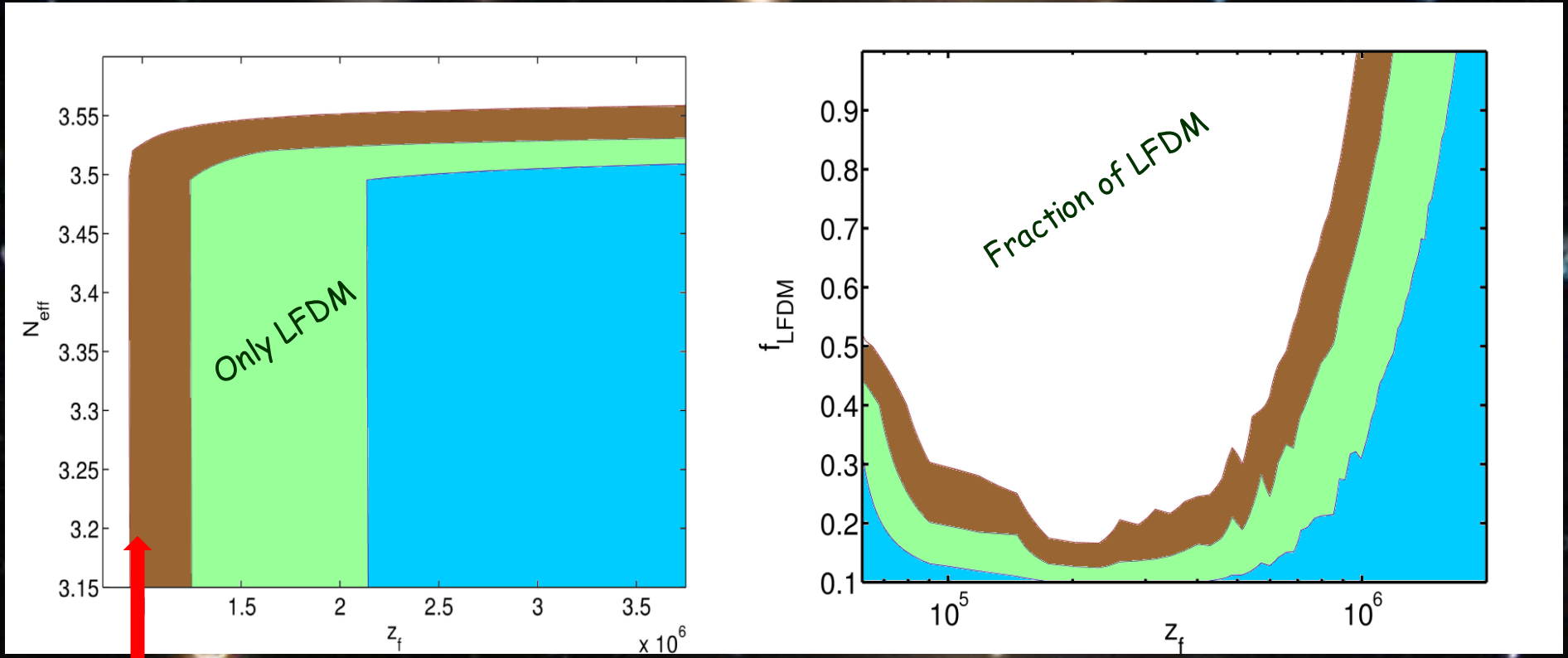
SDSS DR7

Lyman-a(Tegmark et all 2004)

χ^2 analysis → marginalization over irrelevant parameters

PRIMARY RESULTS (AS, Das, Sethi JCAP 03(004)2015)

Limits on z_f : Using reconstructed Lyman-α power spectrum from Tegmark et al 2004

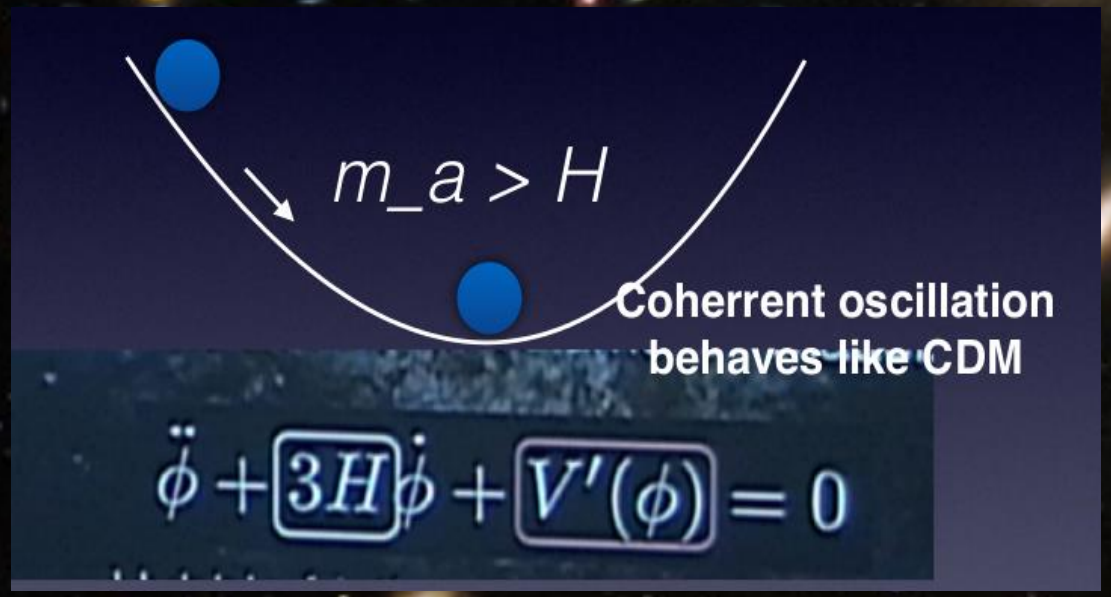


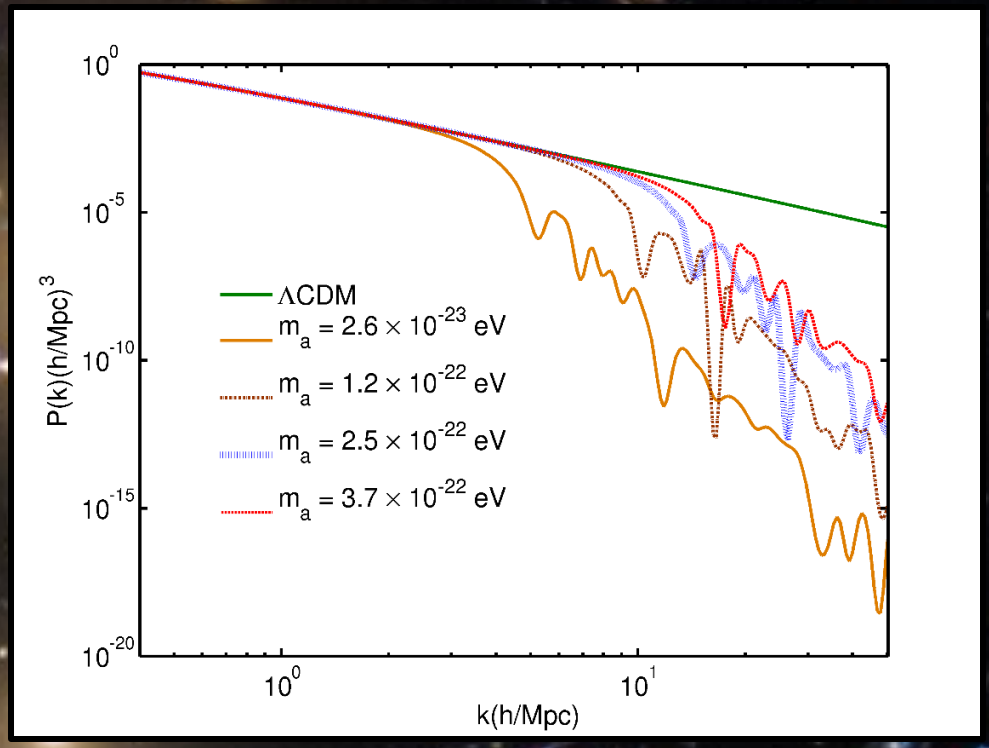
$z_f \sim 0.98 \times 10^5$

Ultra Light Axions

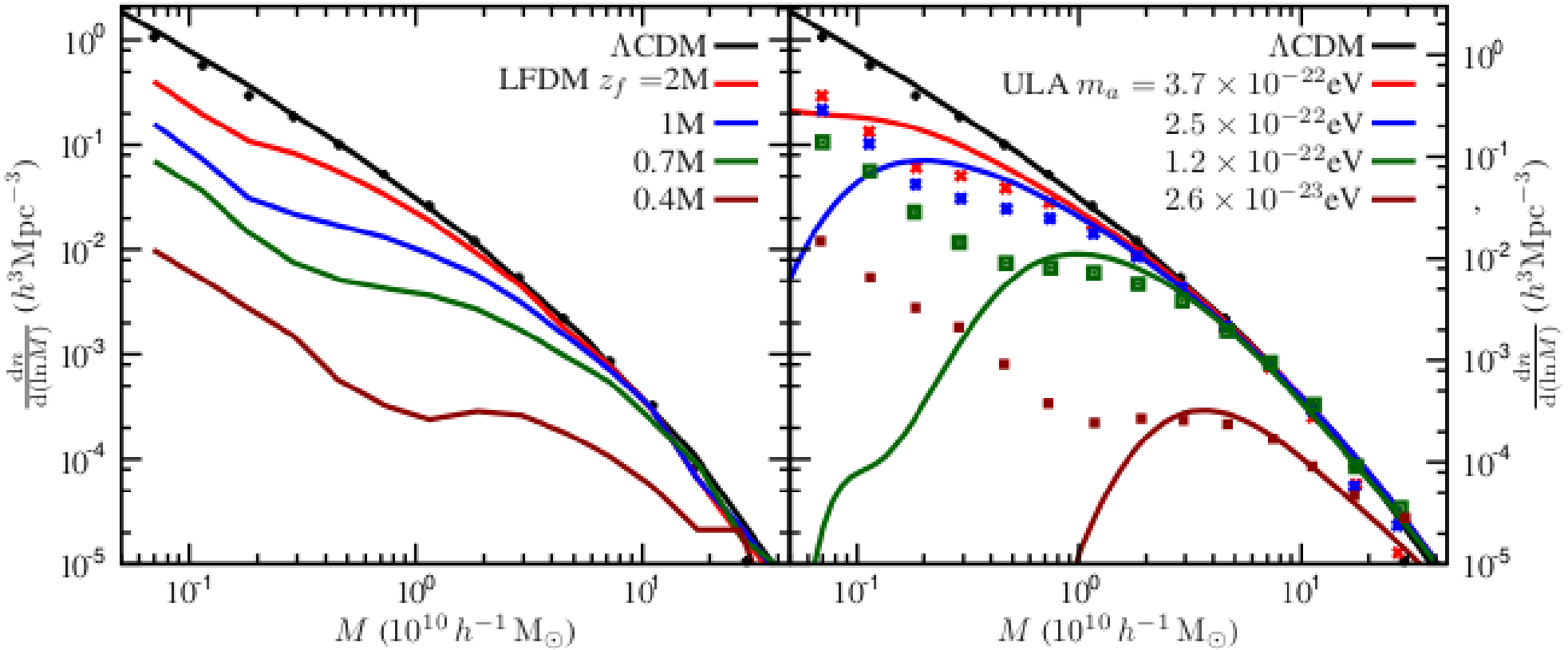
Forms in the early universe by symmetry breaking and obtains it's initial condition (Marsh et al PRD 2010)

$k_m \sim (m/10^{-33}eV)^{1/3}$ (100kms^{-1}/c) h Mpc^{-1}

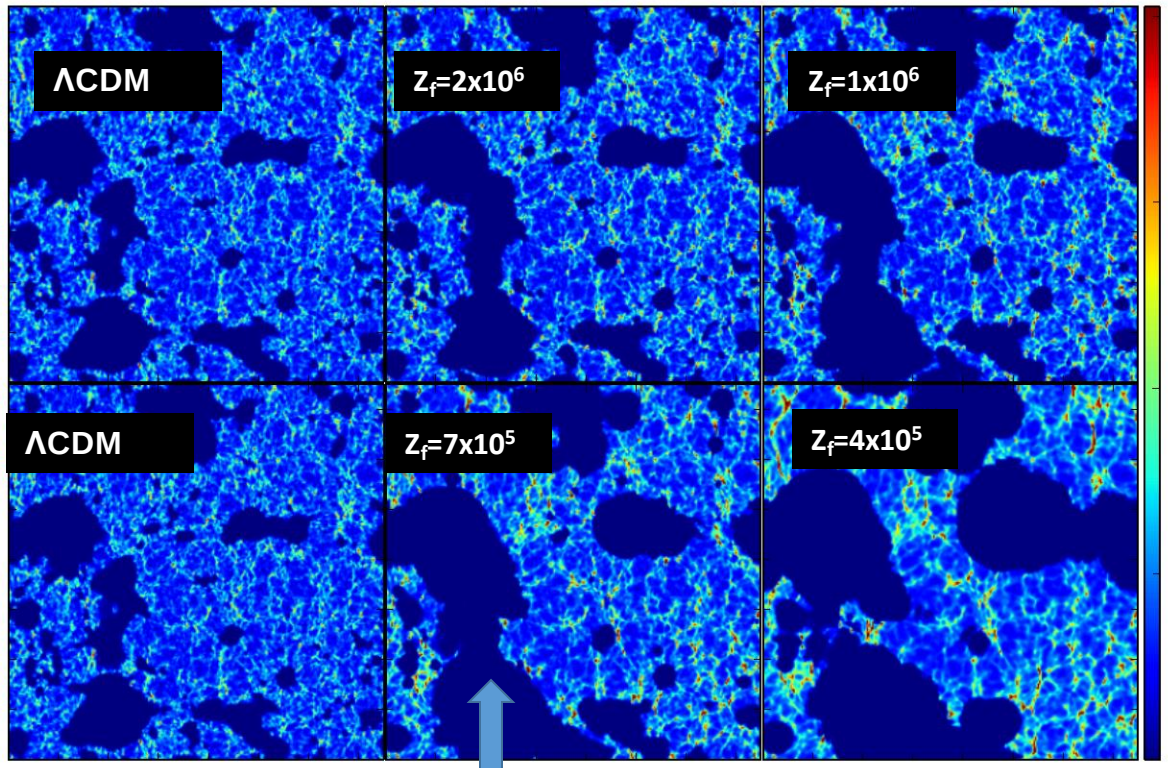


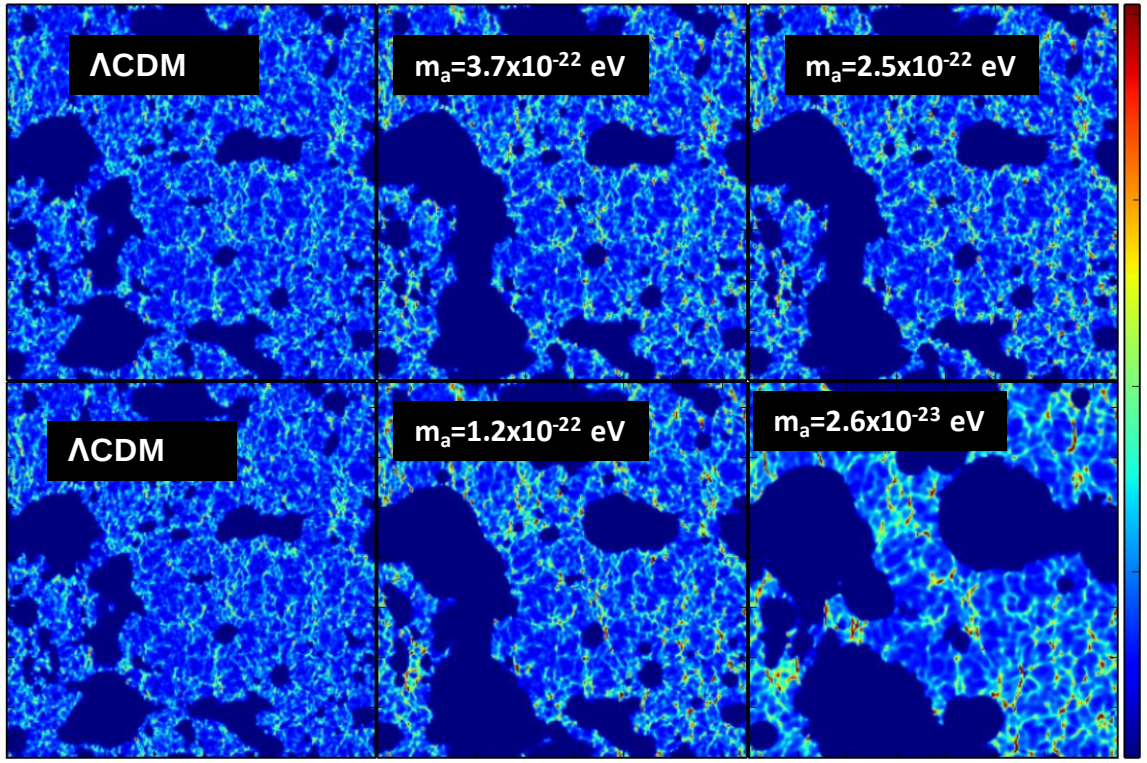


Observational probe I: Effects on mass function (AS, Mondal, Das, Sethi, Bharadwaj and Marsh arxiv 1512.03325)



Observational probe I: Effects on Re-ionization (Contd.)





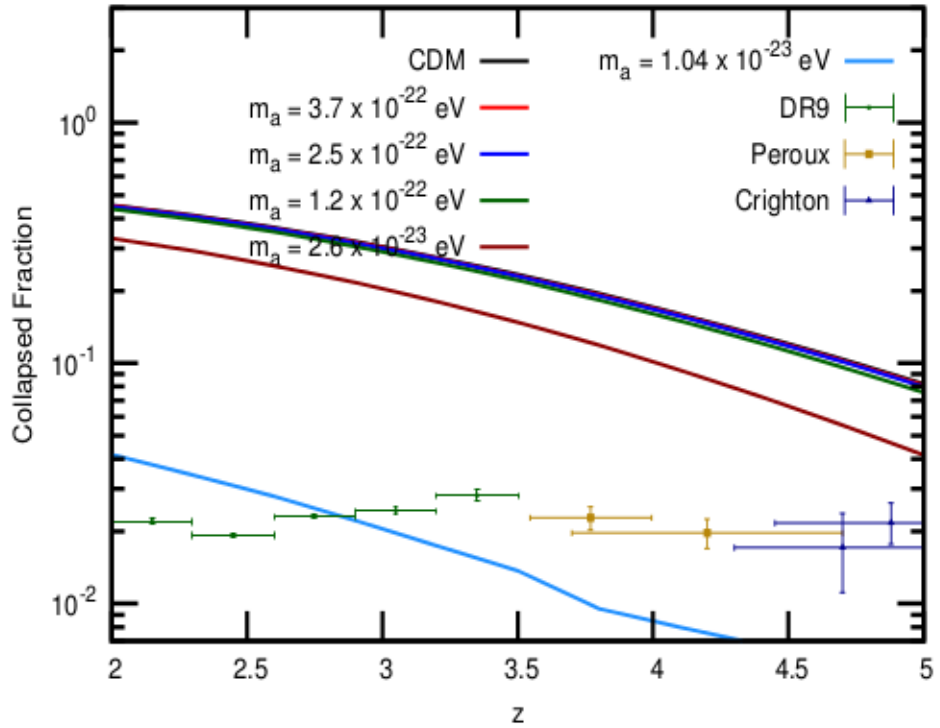
Number of ionized region is decreasing while their size is increasing

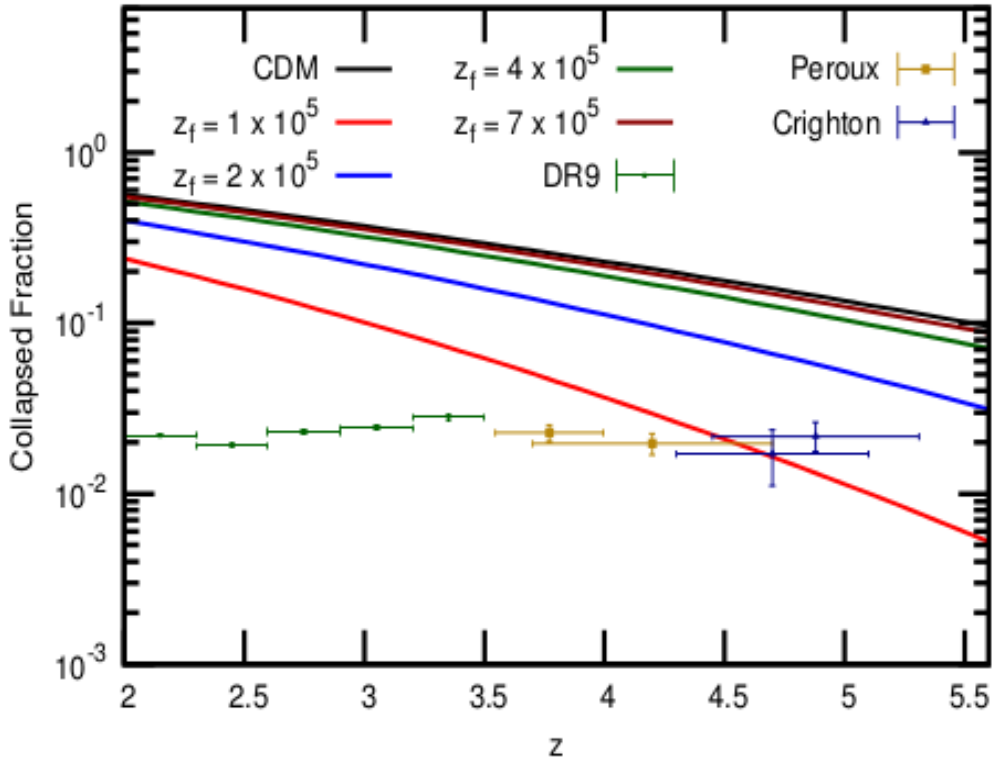
Results : Constraints on z_f and m_a : Subject to x_{HI} =0.5 at z=8

Model	Parameter	$N_{\rm ion}$	Reionization
CDM	[1, 51]	24	√
LFDM	$z_f = 2.0$M	47	√
	$z_f = 1.0$M	102	√
	$z_f = 0.7$M	212	√
	$z_f = 0.4$M	1230	×
	$z_f = 0.2$M	No Haloes	×
ULA DM	$m_a = 3.7 \times 10^{-22}$eV	61	√
	$m_a = 2.5 \times 10^{-22}$eV	75	√
	$m_a = 1.2 \times 10^{-22}$eV	134	√
	$m_a = 2.6 \times 10^{-23}$eV	965	×
	$m_a = 2.0 \times 10^{-23}$eV	No Haloes	×

Observational probe II: Effects on evolution of cosmic density of neutral hydrogen

For haloes with mass > 1×10^{10} Solar mass





Take home messages

- ✓Dark matter can form much later than assumed for ΛCDM cosmology . In this work two models are used LFDM and ULA dark matter.
- ✓Late formation of dark matter can cut the power at small scale but the amount of cut is lesser than WDM. Thus it can be a potential dark matter candidate to solve small scale problems simultaneously agreeing with large scale features.
- ✓Cutting power at small scale can have significant effect on reionization and the evolution cosmological gas density.
- ✓Analysis provide an upper bound on $z_f > 4 \times 10^5$ and $m_a > 2.6 \times 10^{-23}$ eV for getting $x_{HI} = 0.5$ at $z=8$, whereas evolution of collapsed gas fraction provides $z_f > 2 \times 10^5$ and $m_a > 10^{-23}$ eV.


THANK YOU!