Theory: dark matter models from the astro theory point of view

with slides from: Manoj Kaplinghat (UC Irvine)

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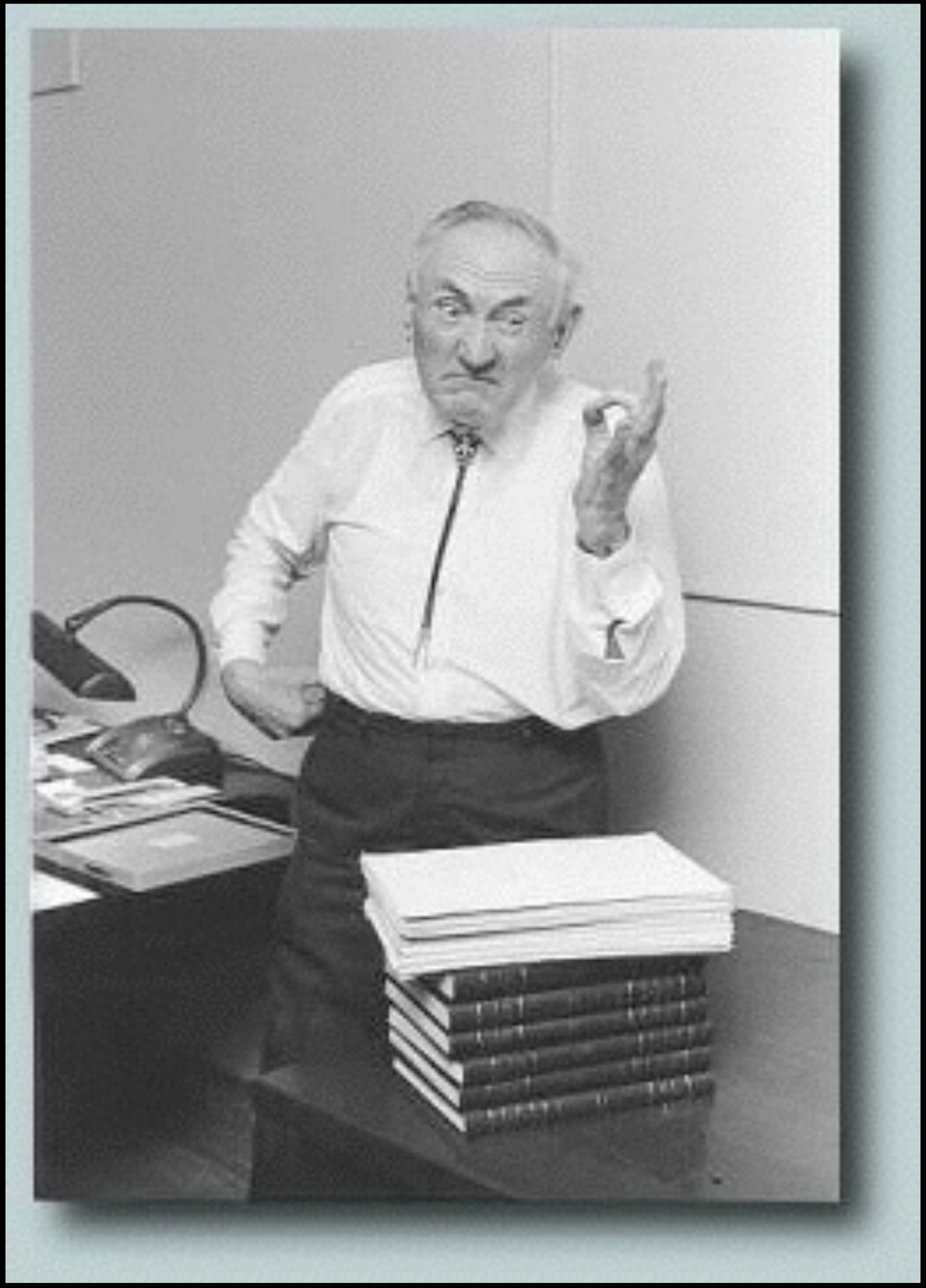
Colegio de Física Fundamental e Interdiciplinaria de las Américas
PIRE Worksop

The Cosmological Dark Matter Problem

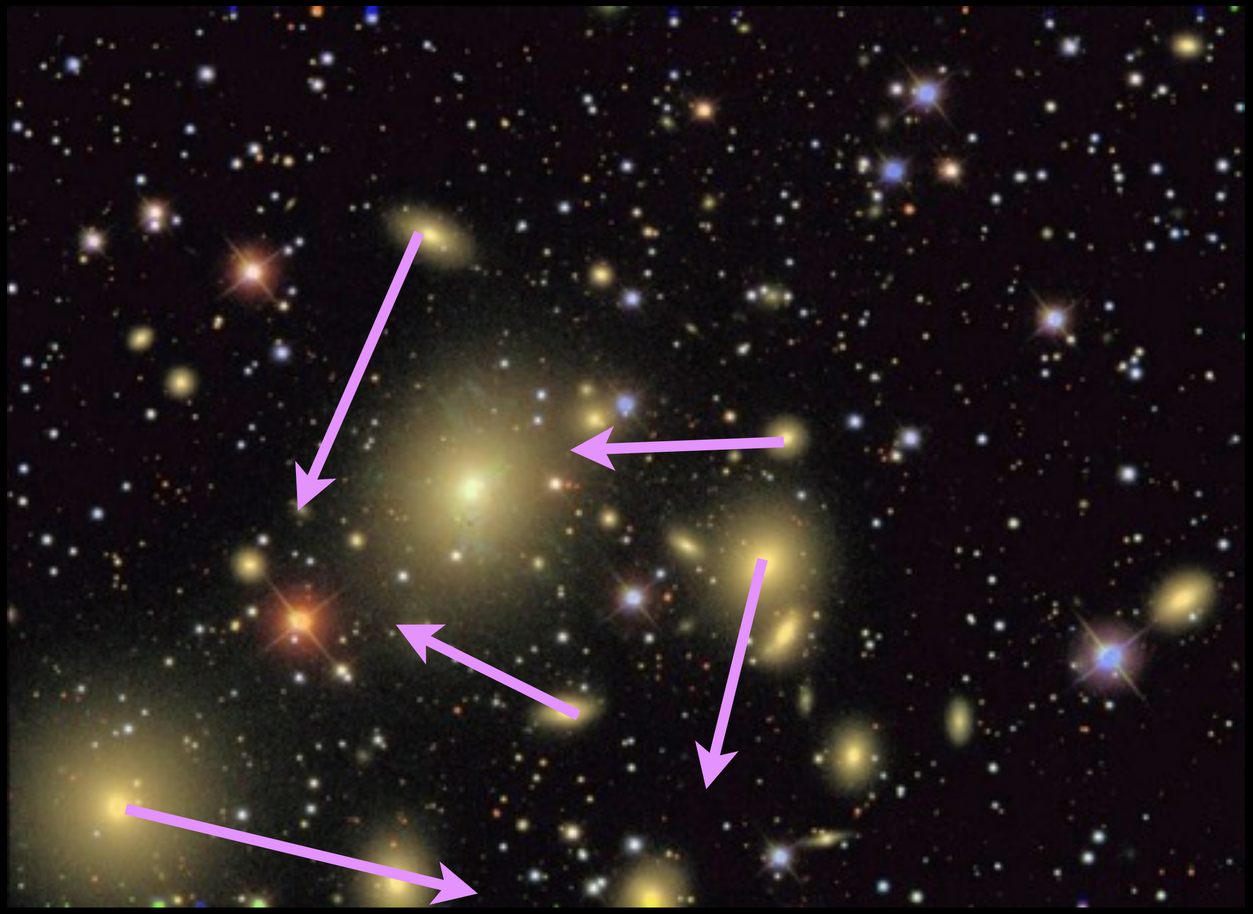


First indications: velocity of galaxies in a cluster

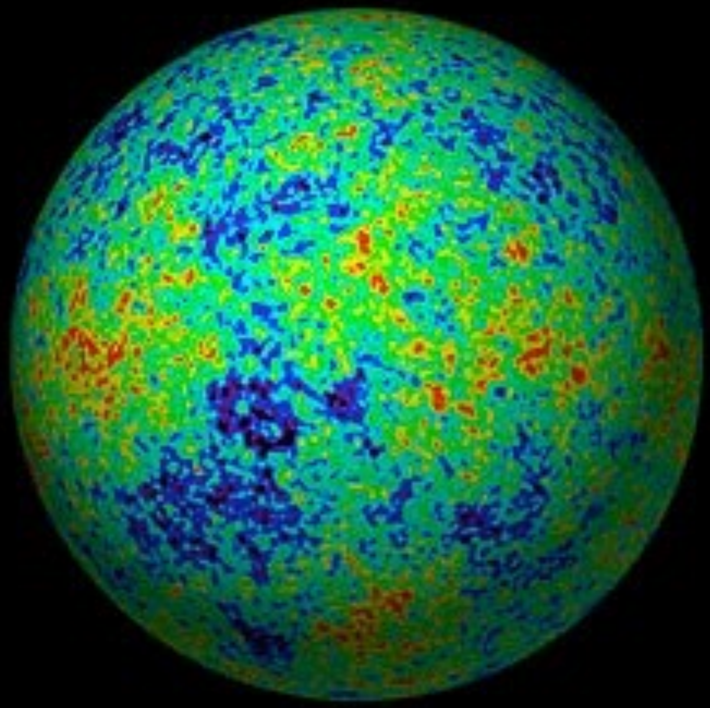
$$GM = \langle v^2 \rangle r_{1/2} \alpha^{-1}$$

$$\Rightarrow M \gg M_{\rm stars} + M_{\rm gas}$$

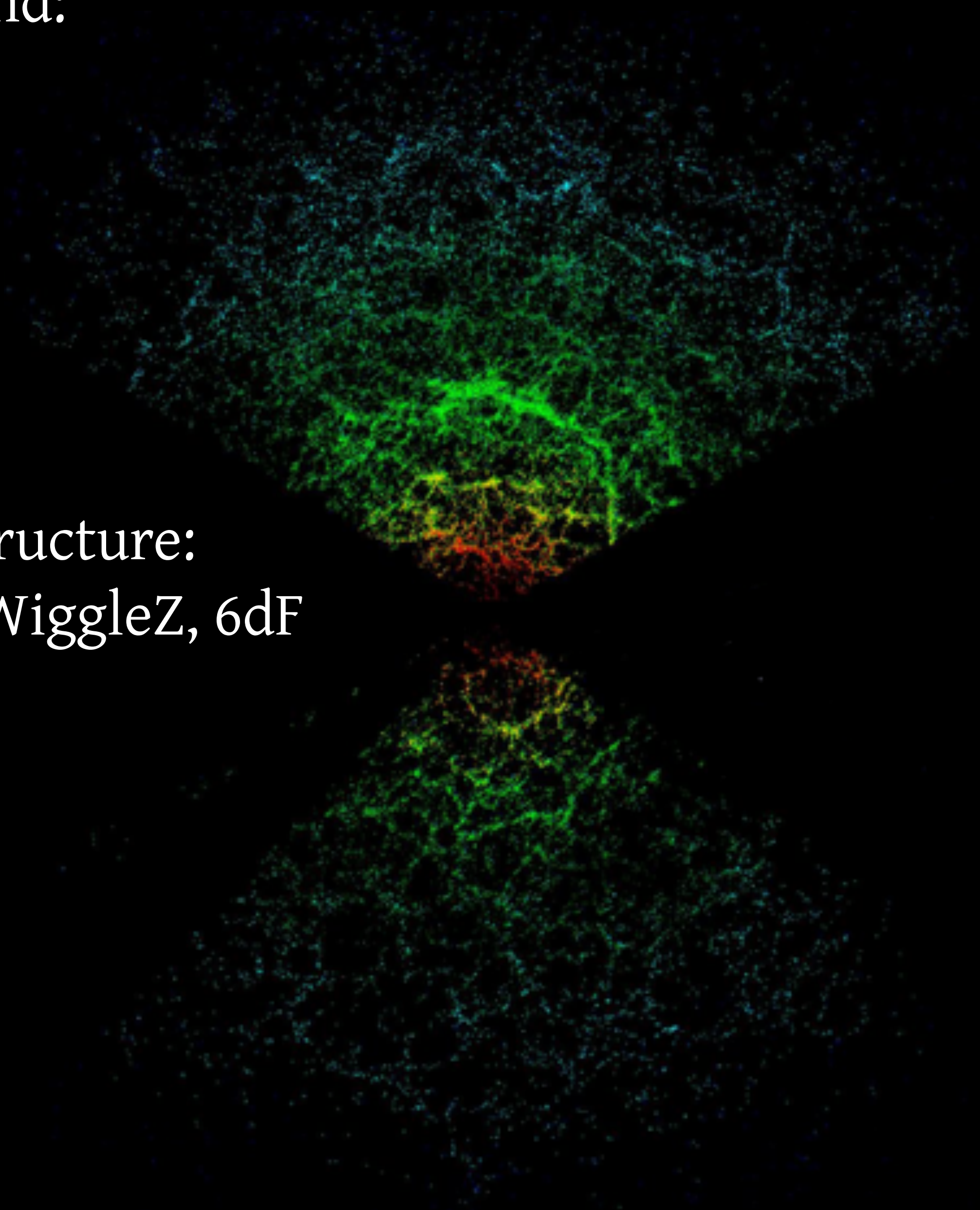
Zwicky (1933):
the “dunkel-materiel”/ the “dark matter”



Dark Matter Today: from large scale cosmology



Cosmic Microwave Background:
Planck, SPT, ACT, PolarBEAR

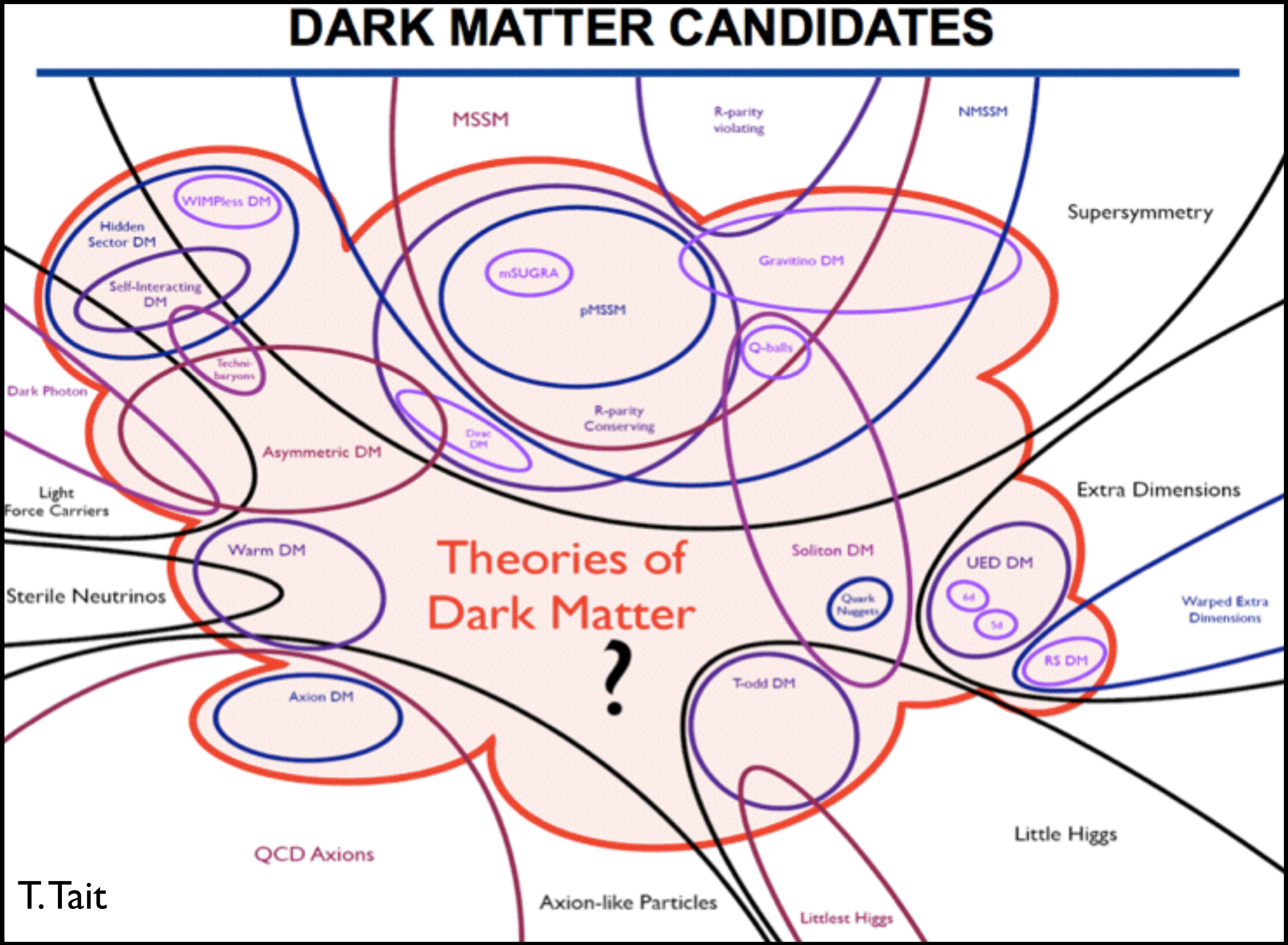


Large Scale Structure:
SDSS (BOSS), WiggleZ, 6dF

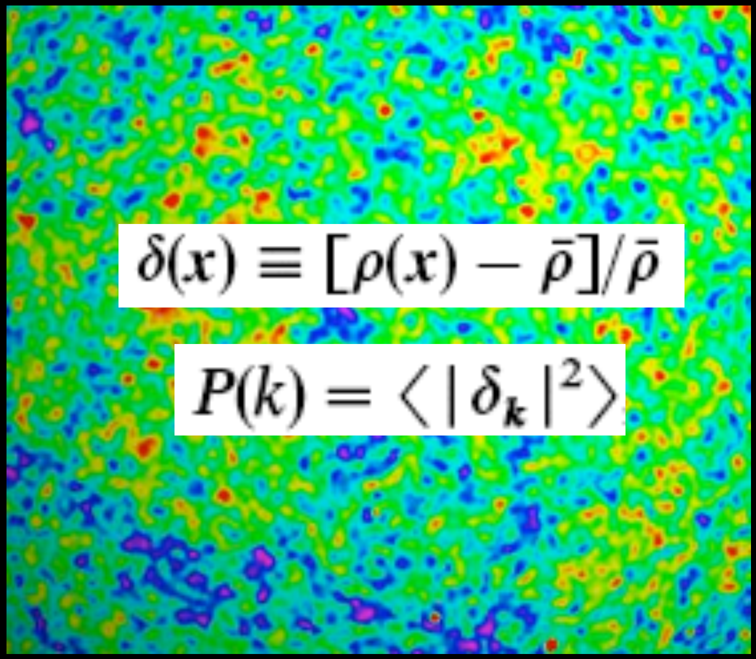
$$\Omega_{\rm DM} \equiv \frac{\rho_{\rm DM}}{\rho_{\rm crit}} = 0.259 \pm 0.002$$

Planck 2015 + BAO + SNe + H_0
(Planck Collab. 2015)

What is dark matter?



Large Scale Structure: the cosmological density perturbation spectrum



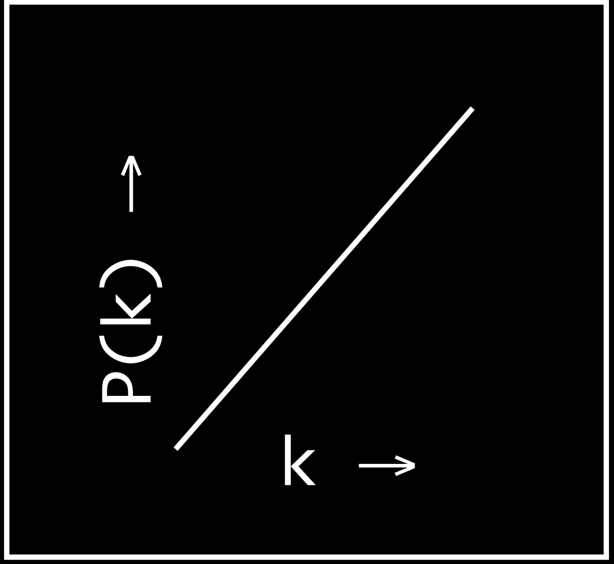
- Power spectrum of cosmological density fluctuations

$$P(k) = \langle |\delta_k|^2 \rangle$$

- Primordial Harrison-Zeldovich: from scale invariance

$$P(k) \propto k$$

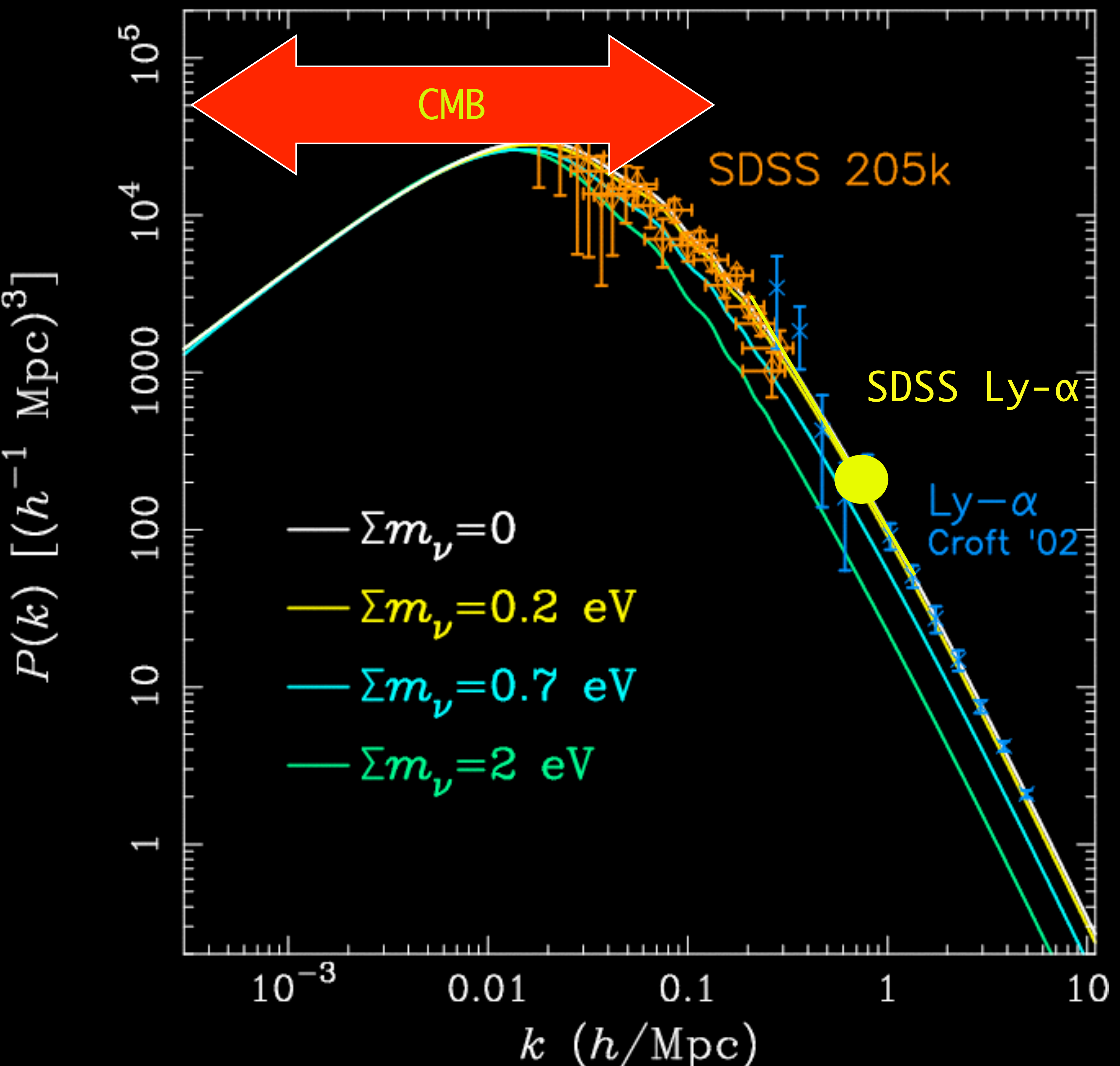
  – Natural solution to perturbation spectrum: self-similar evolution



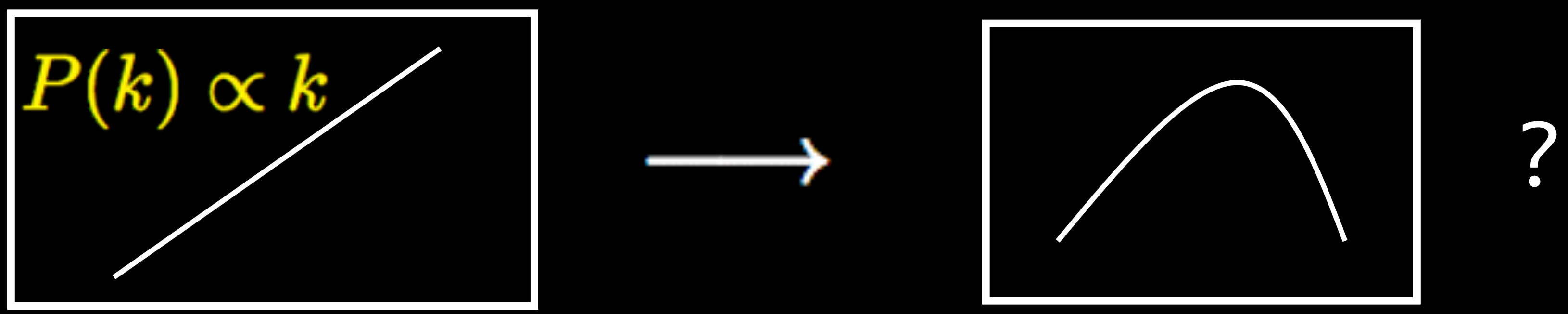
- Predicted by inflation

$$P(k) \propto k^n \qquad n \lesssim 1$$

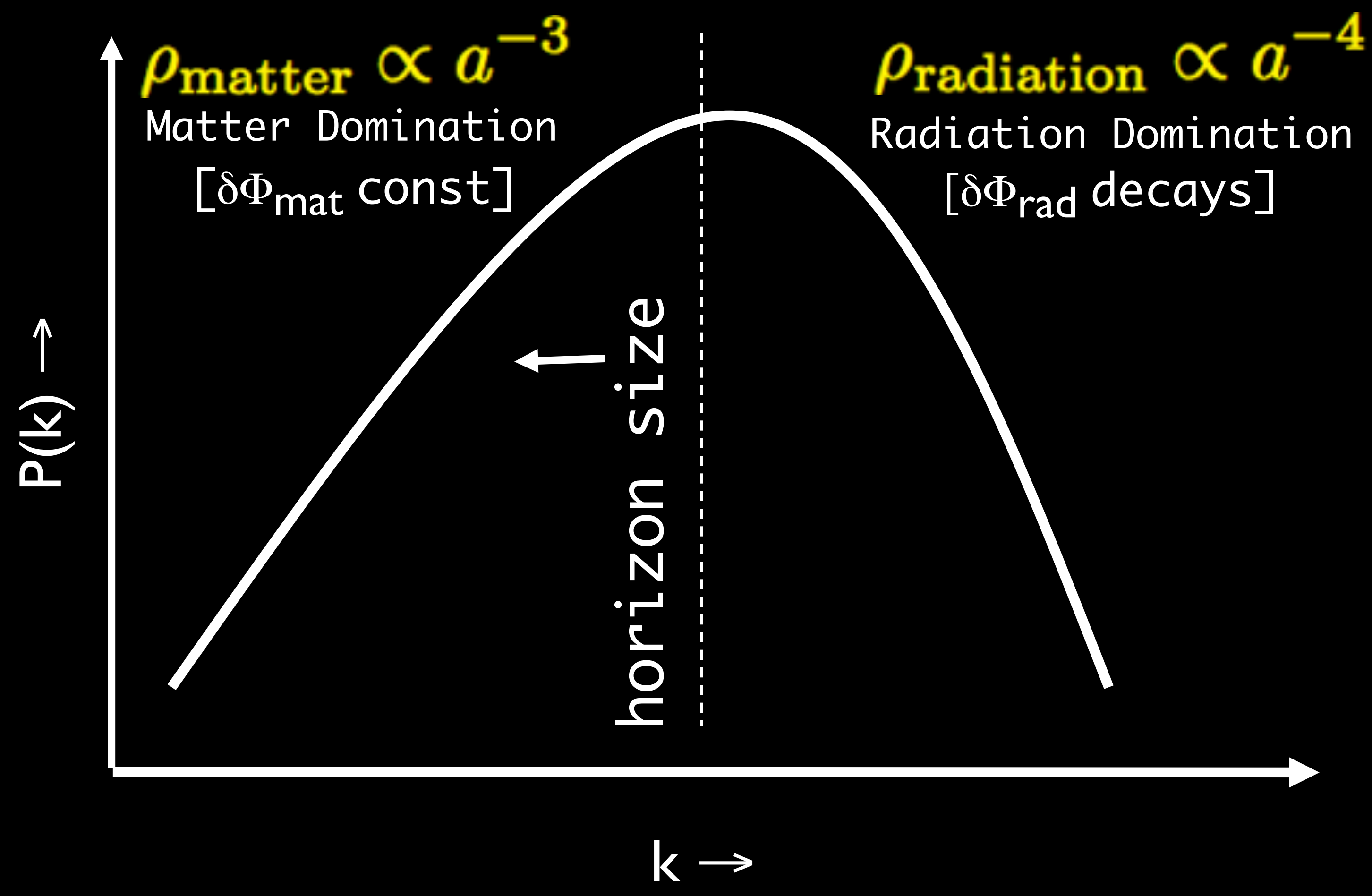
Measuring Large Scale Structure $P(k)$

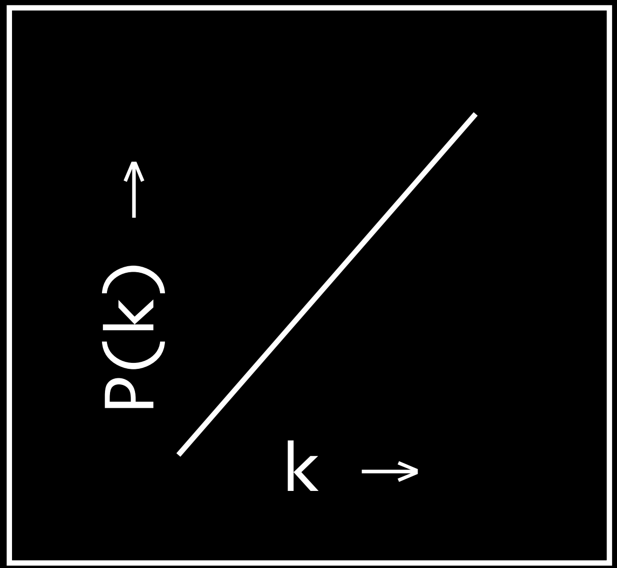


The Cosmological Matter Power Spectrum



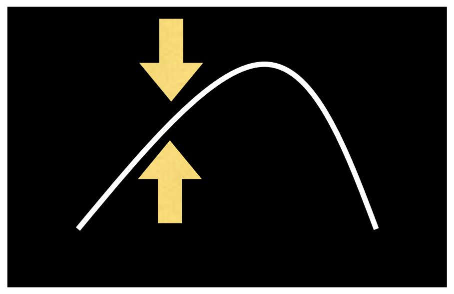
Perturbations enter horizon:





The Primordial Spectrum: CMB gives a Precision Determination at Large Scales

$$P(k) = Ak^n$$



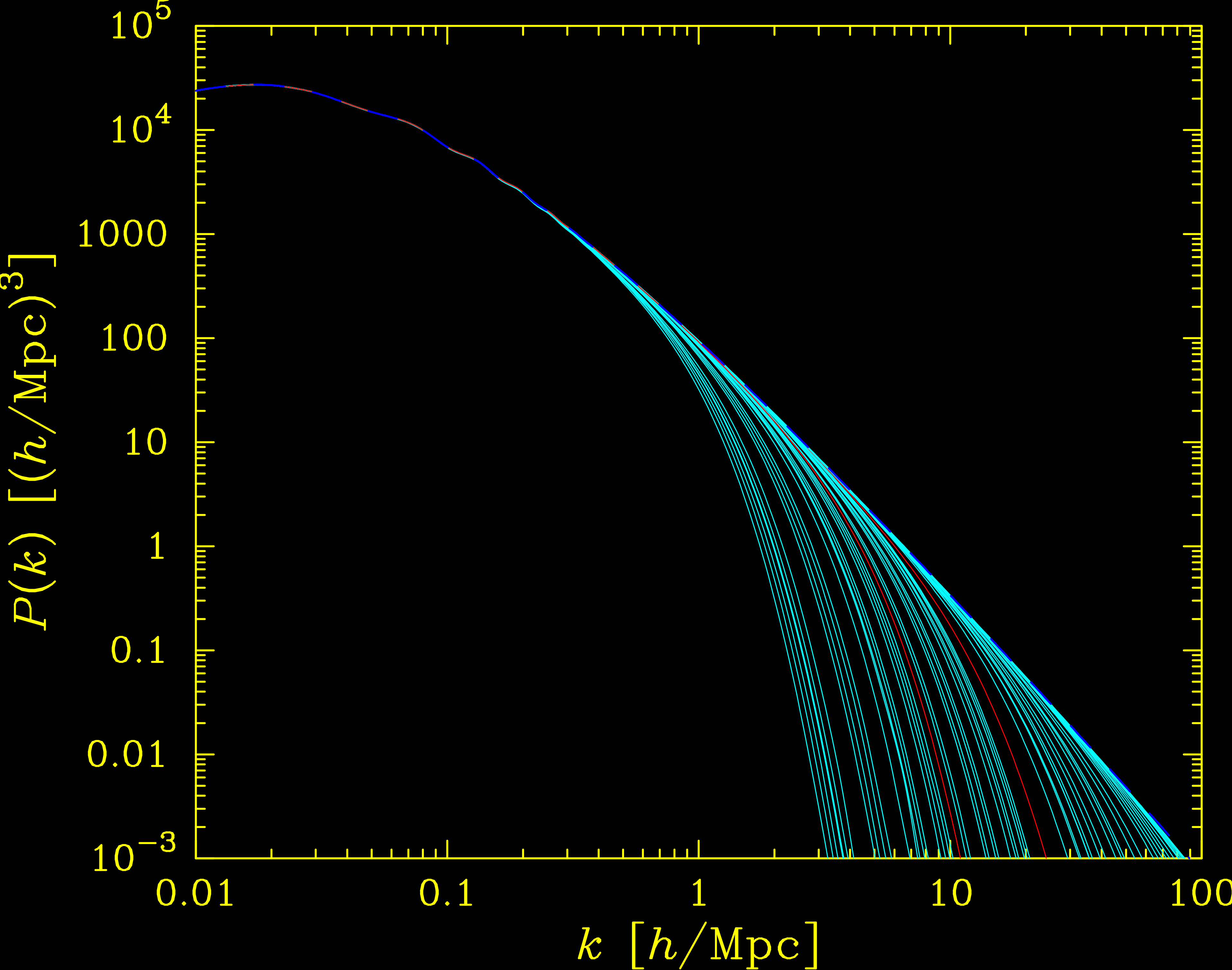
Planck Collaboration 2015:

$$\ln\left(10^{10}A\right) = 3.094 \pm 0.034 \qquad (1.1\%)$$

$$n = 0.9645 \pm 0.0049 \qquad (0.51\%)$$

Perturbation Evolution

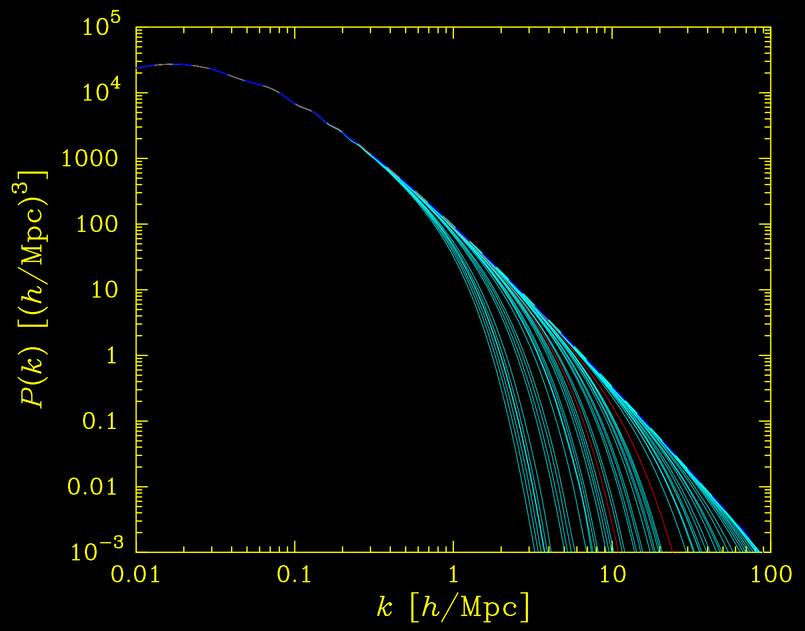
How warm is too warm?



Abazajian astro-ph/0511630

CDM has a natural cutoff

kinetic coupling until T ~ 1 MeV



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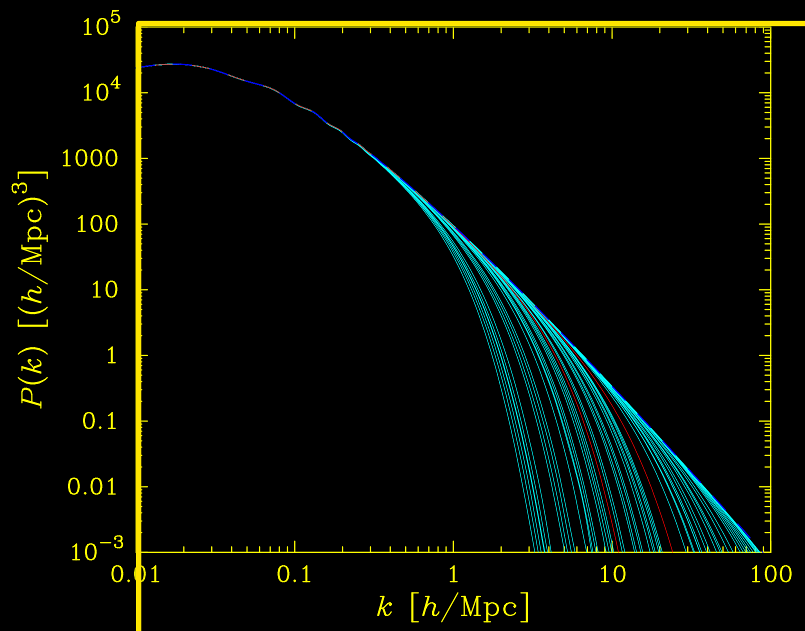

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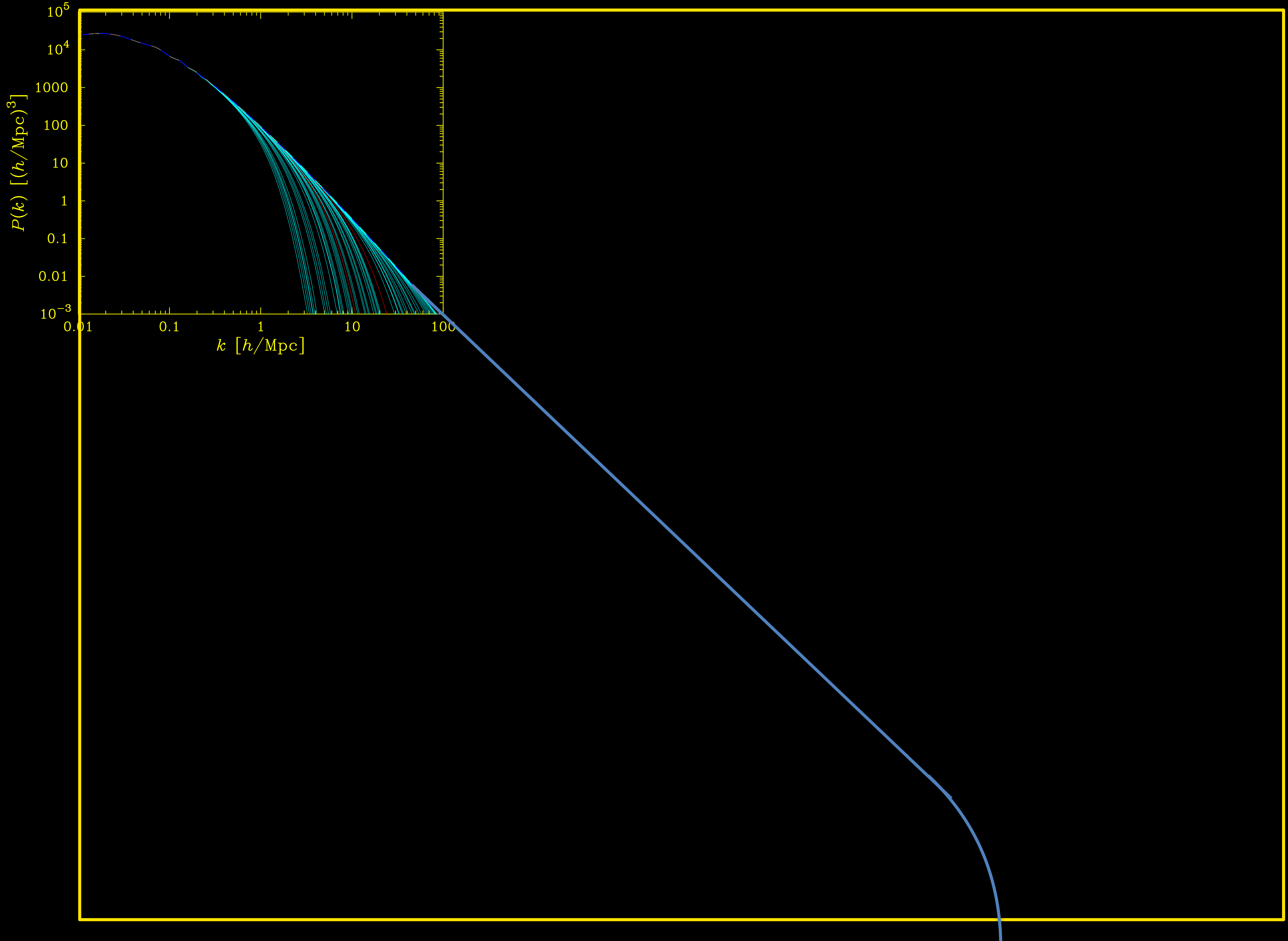
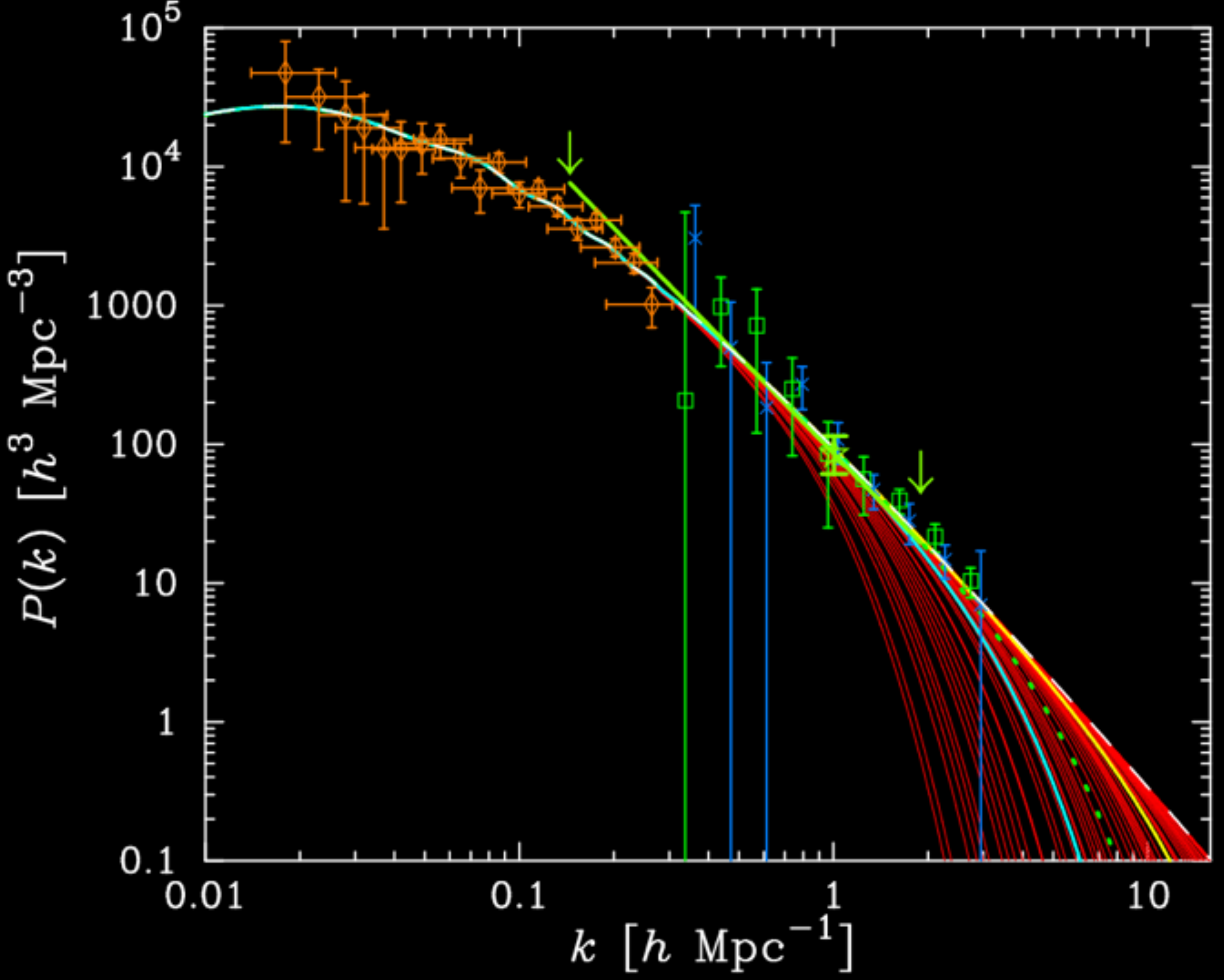


Lower Bounds on Mass:
Suppression of Small-Scale Structure



- SDSS 3D P(k) Main Galaxies (Tegmark et al 2003)
- SDSS Lyman-alpha forest (McDonald et al 2005)
- High-Resolution Lyman-alpha forest (Viel, Haehnelt & Springel 2004)
- CMB: WMAP, ACBAR, CBI, VSA, BooMERANG-2K2

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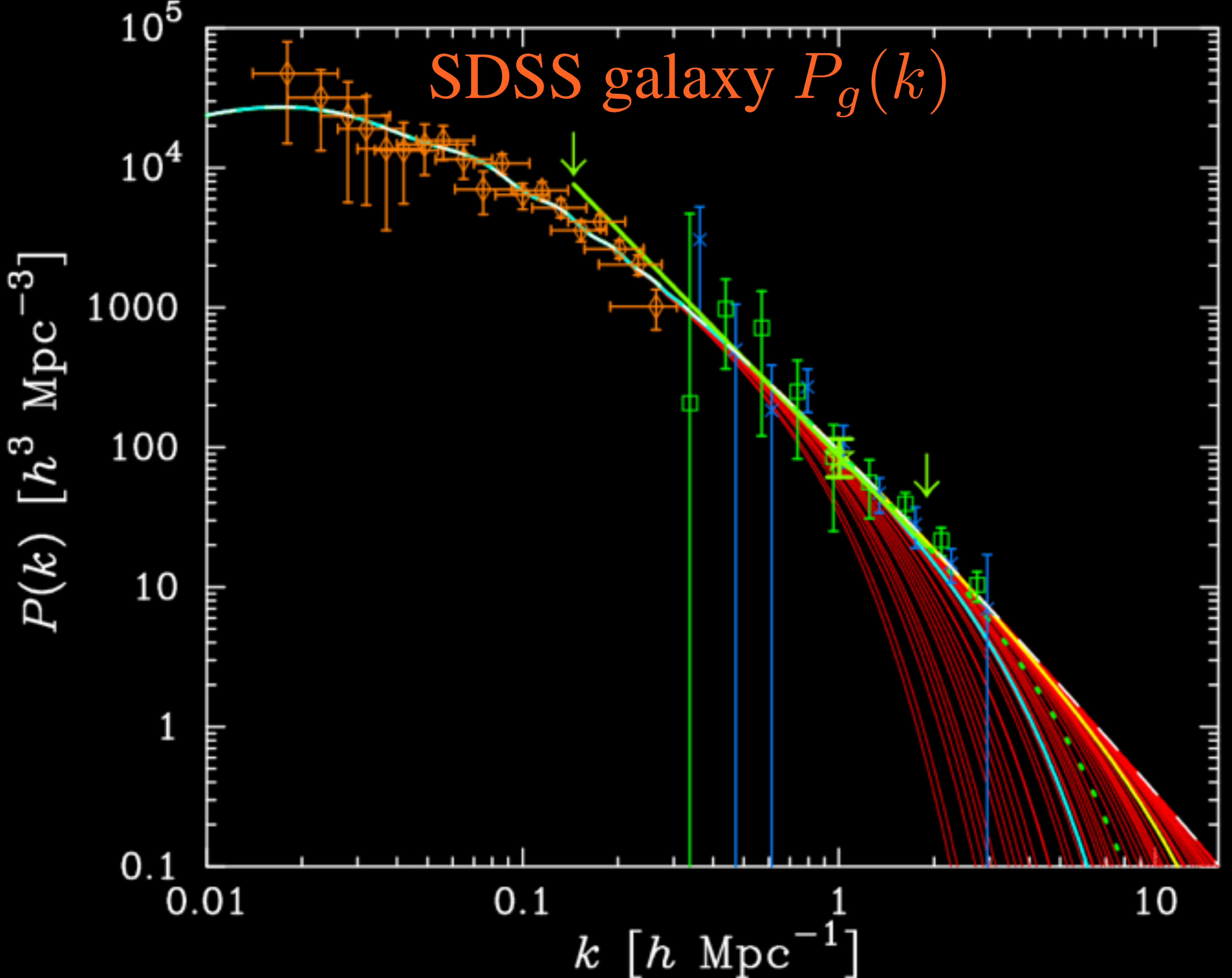

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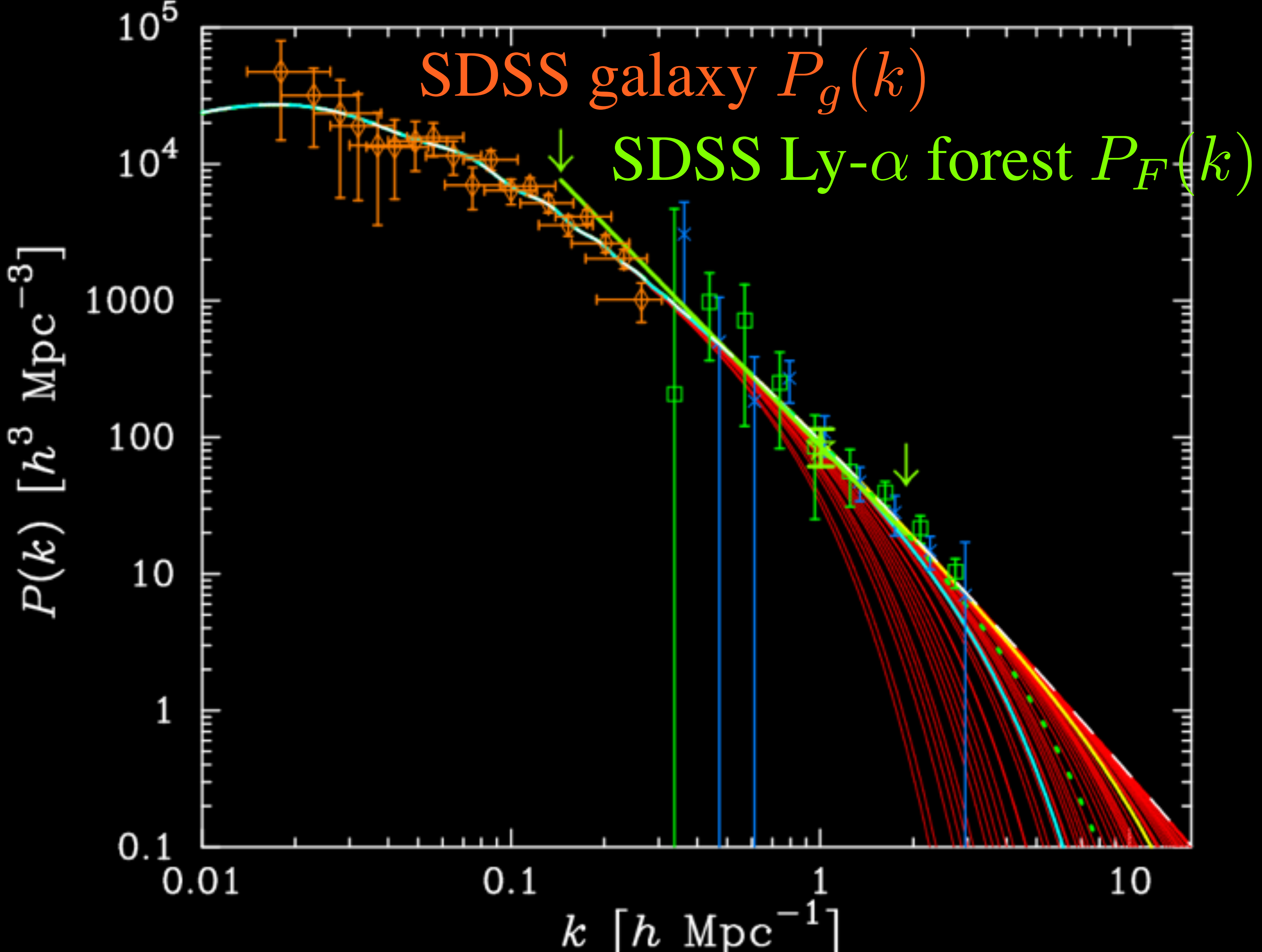

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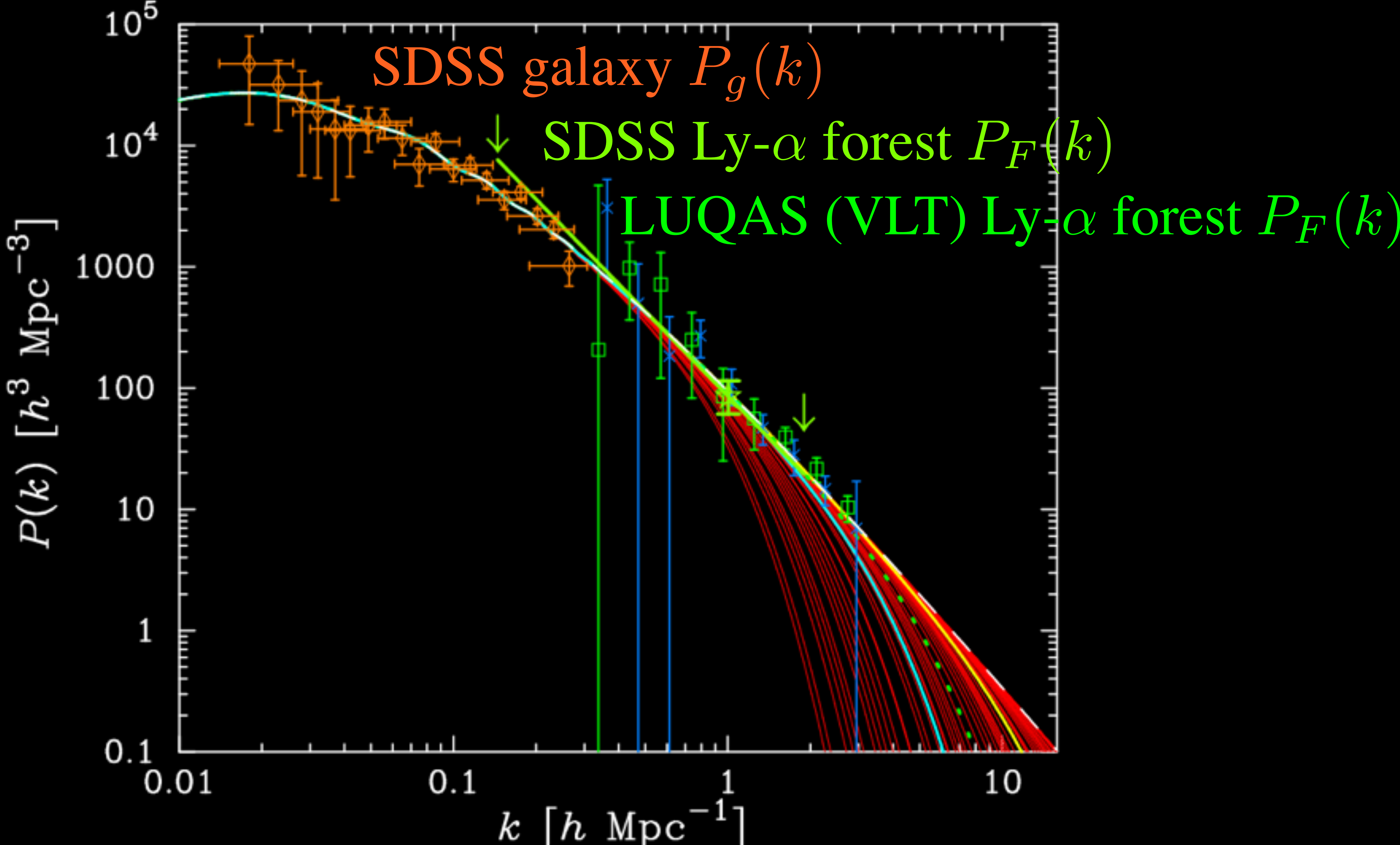

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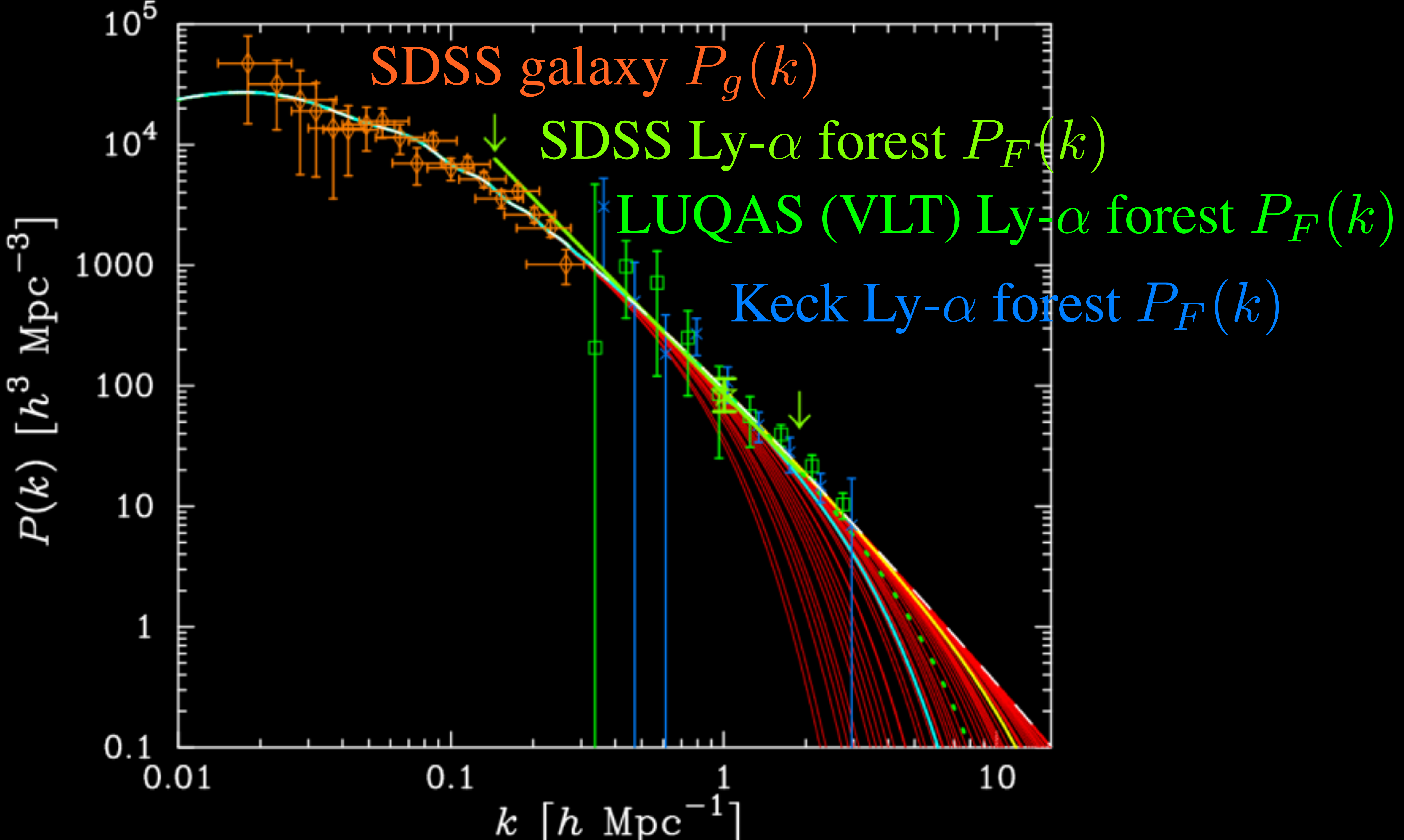

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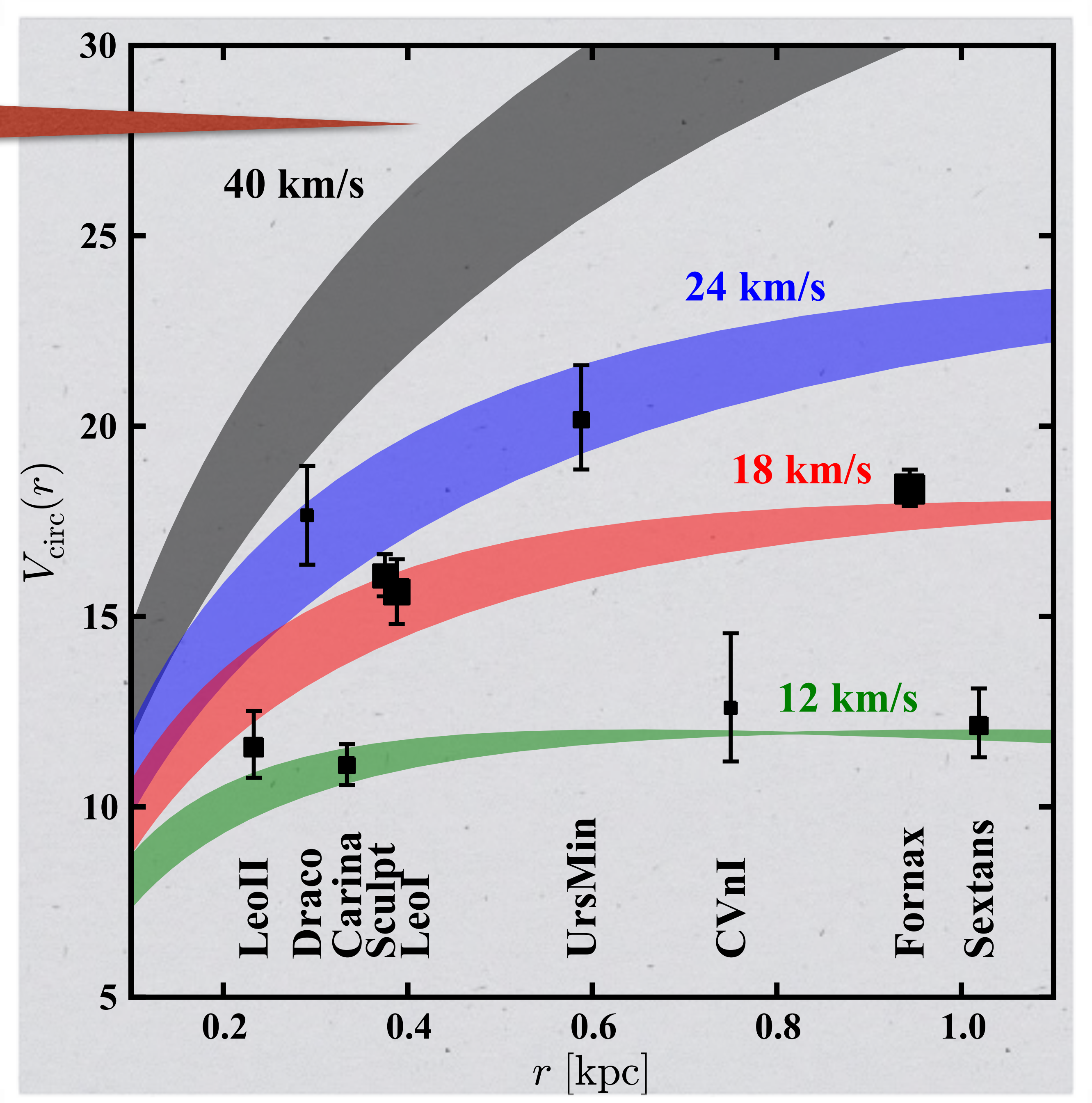
Too big to fail? The most massive apparently don’t light up...

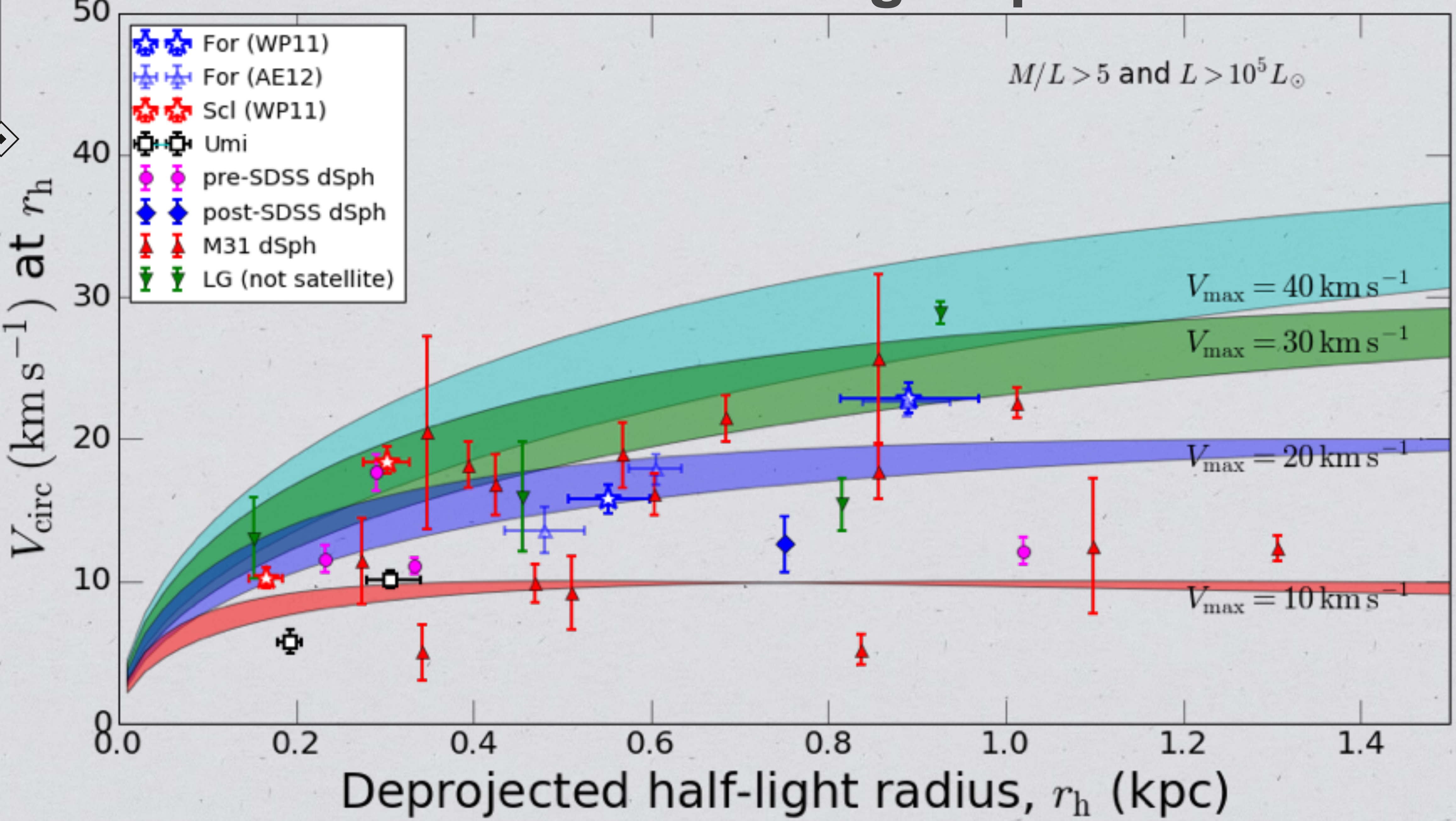
Where are these denser satellites?



Not dependent on resolving about core/cusp

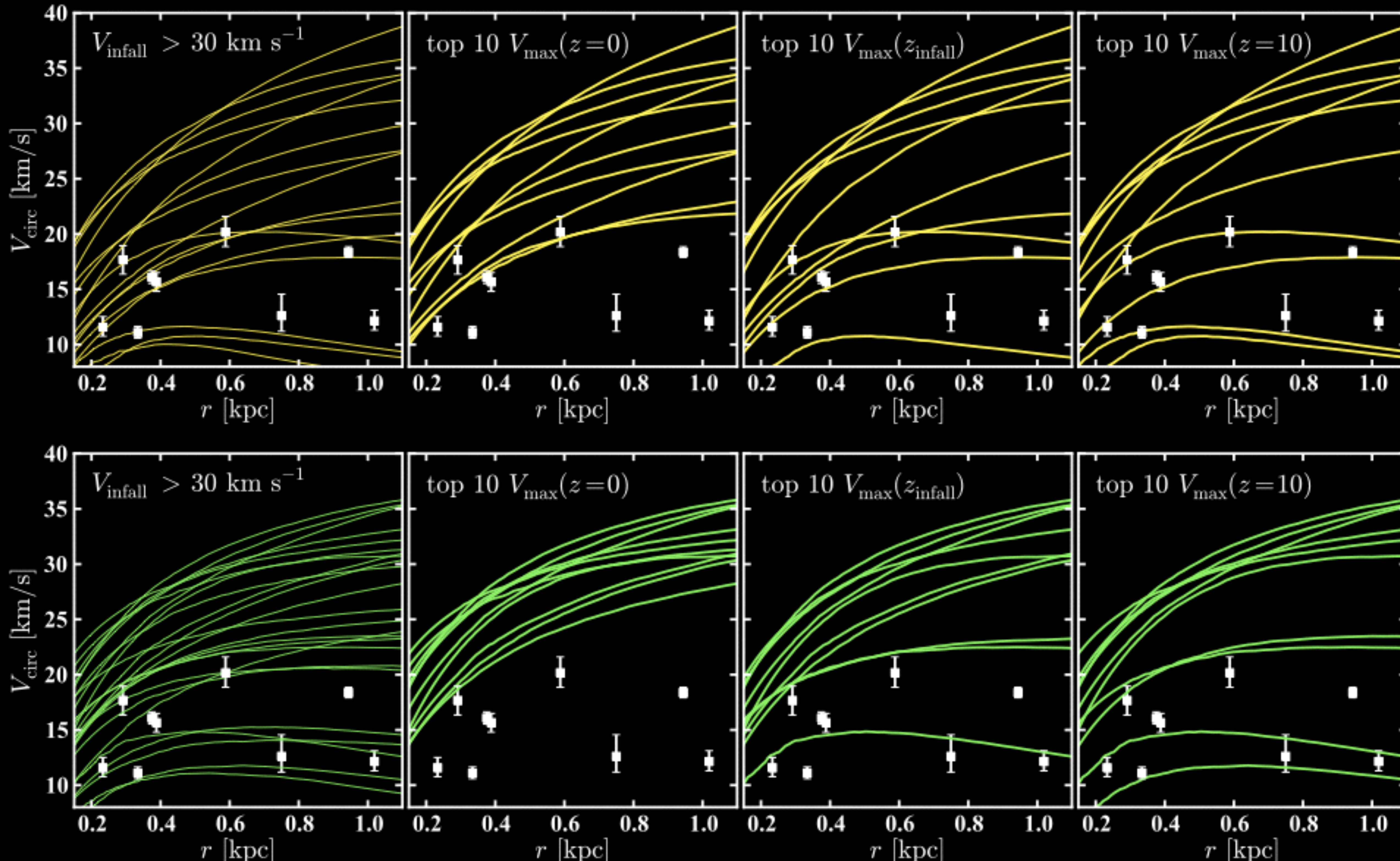
Boylan-Kolchin, Bullock, Kaplinghat 2011, 2012

TBTF in the local group



Generic issue in the Local Group (M31, MW and in between)
[Tollerud + 2014, Kirby + 2014, Garrison-Kimmel + 2014]

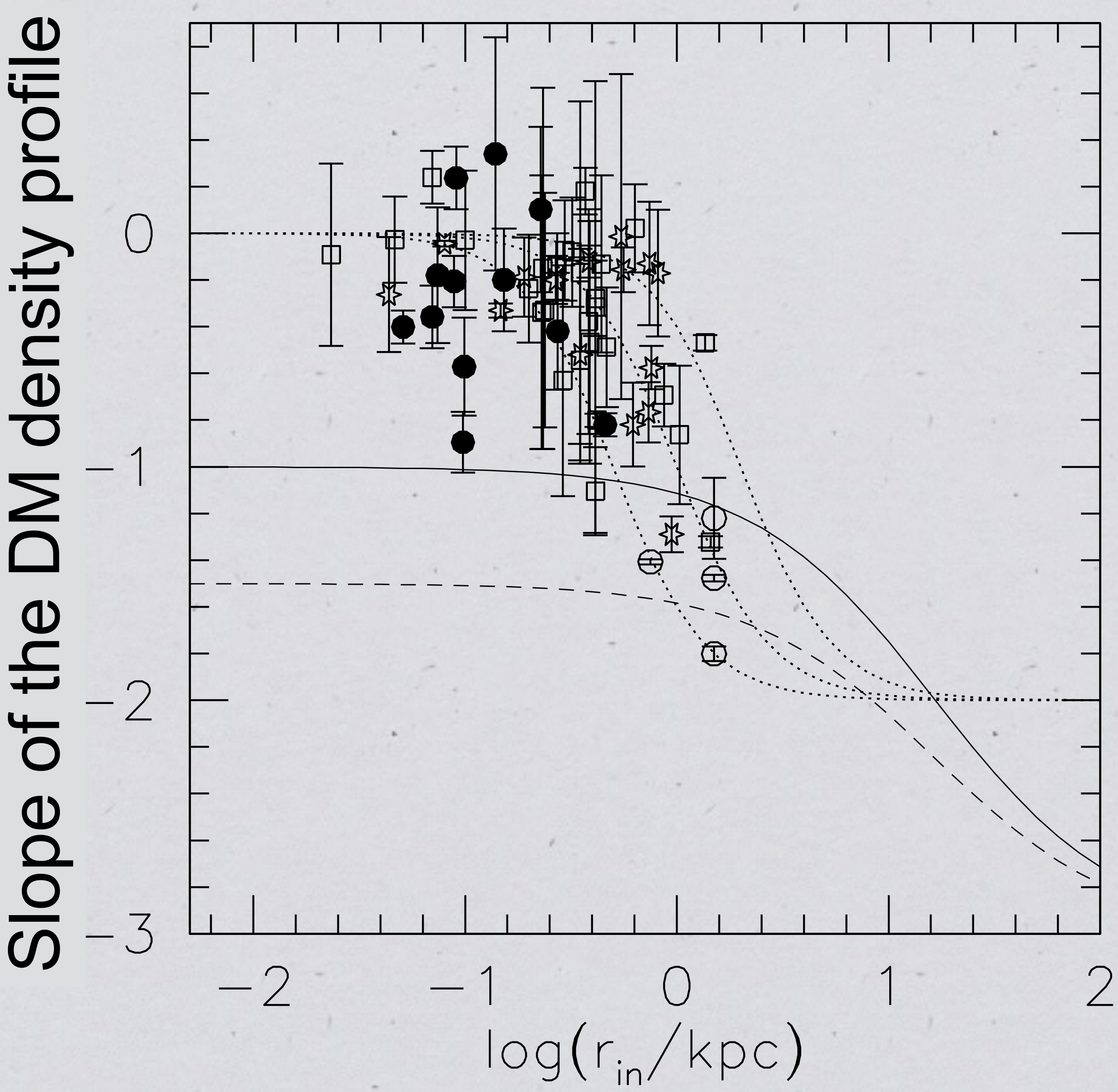
Observed Dwarf Galaxy Concentrations are Much Too Low, While CDM Subhalos are "Too Big Too Fail"



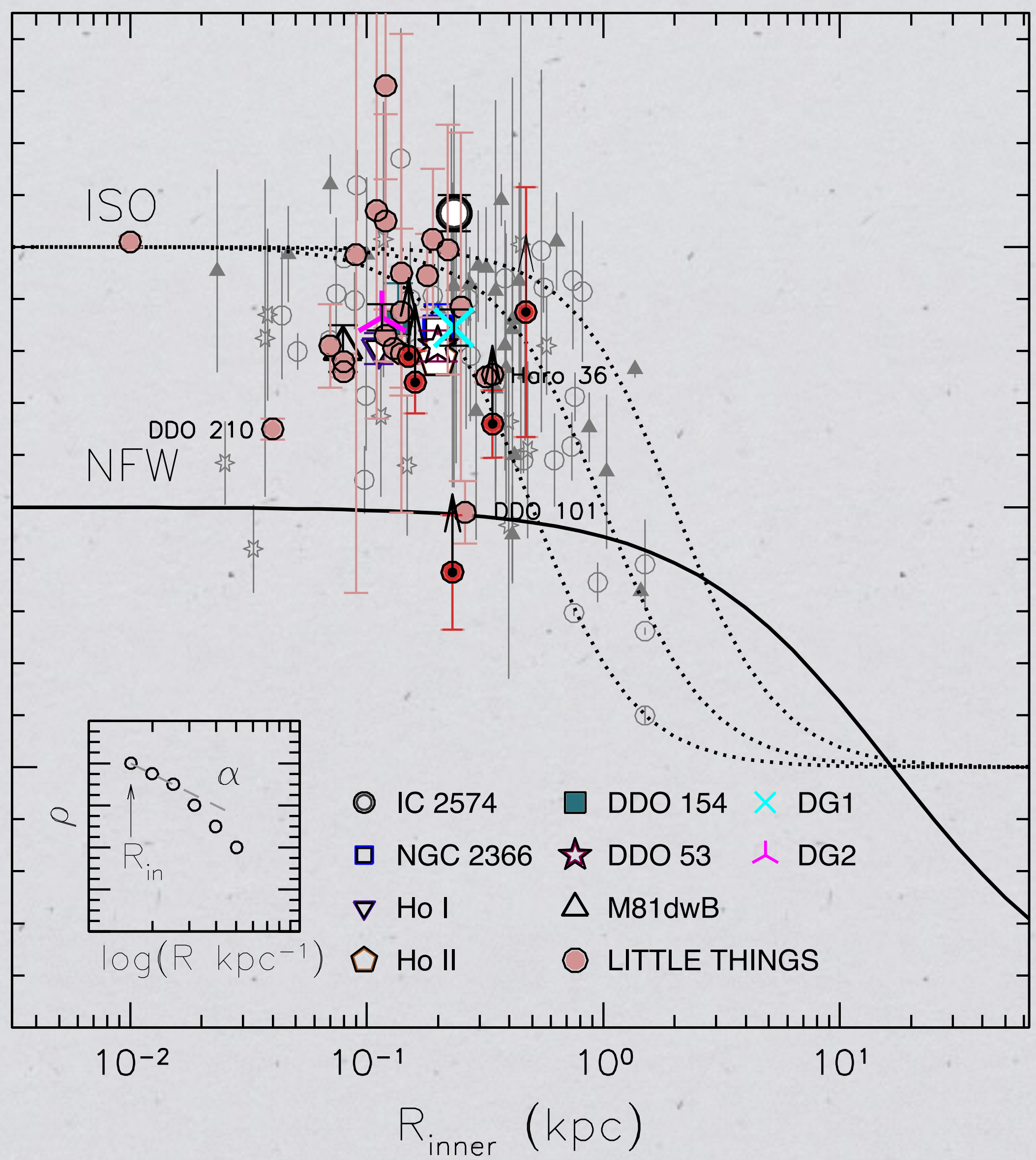
Boylan-Kolchin et al. 2011, 2012

Cusp/Core: dwarf galaxies
to clusters of galaxies

Cores in dwarf galaxies

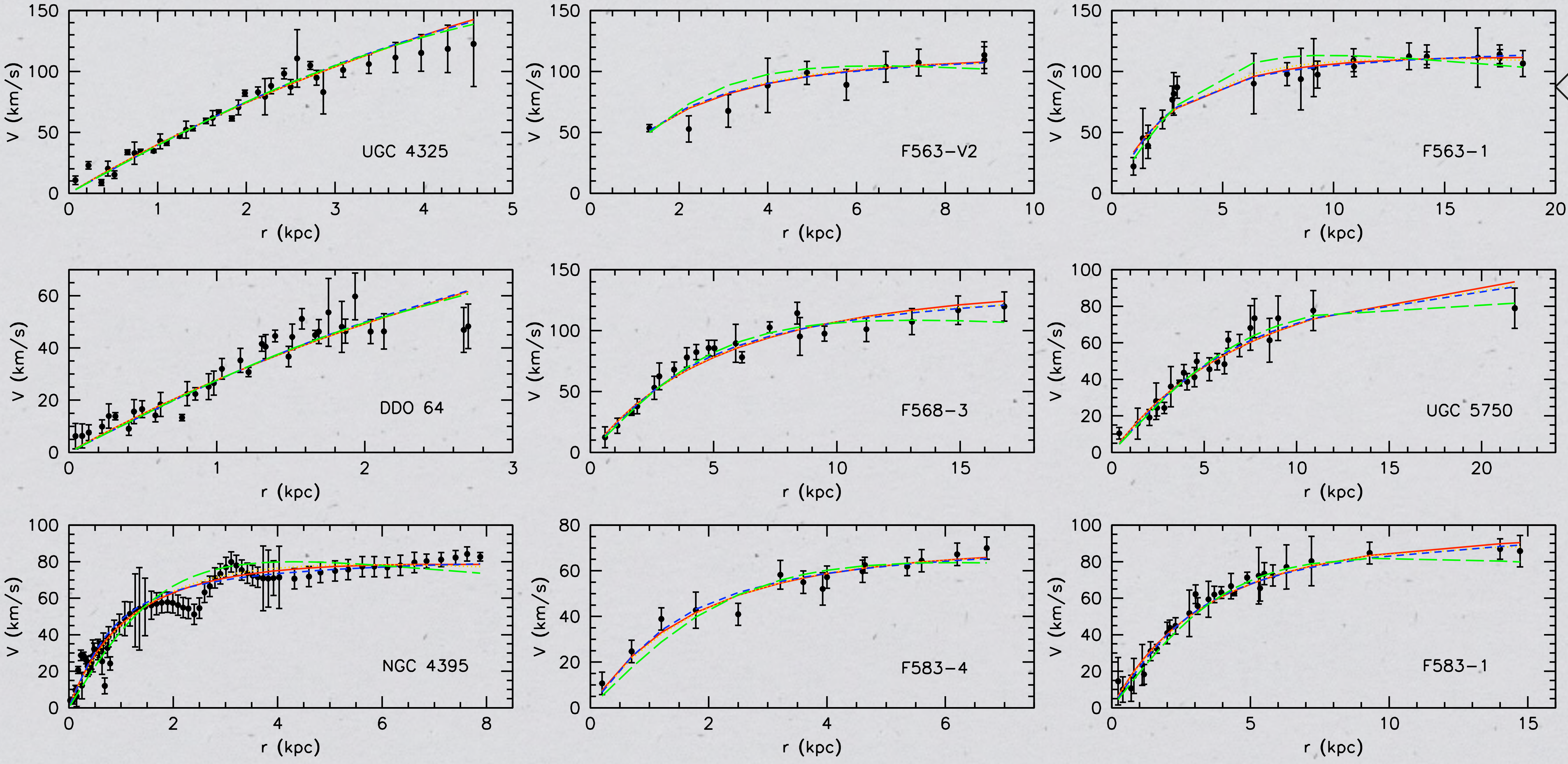


deBlok and Bosma, 2002



LITTLE THINGS, Oh et al 2015

Cores in more massive (LSB) galaxies



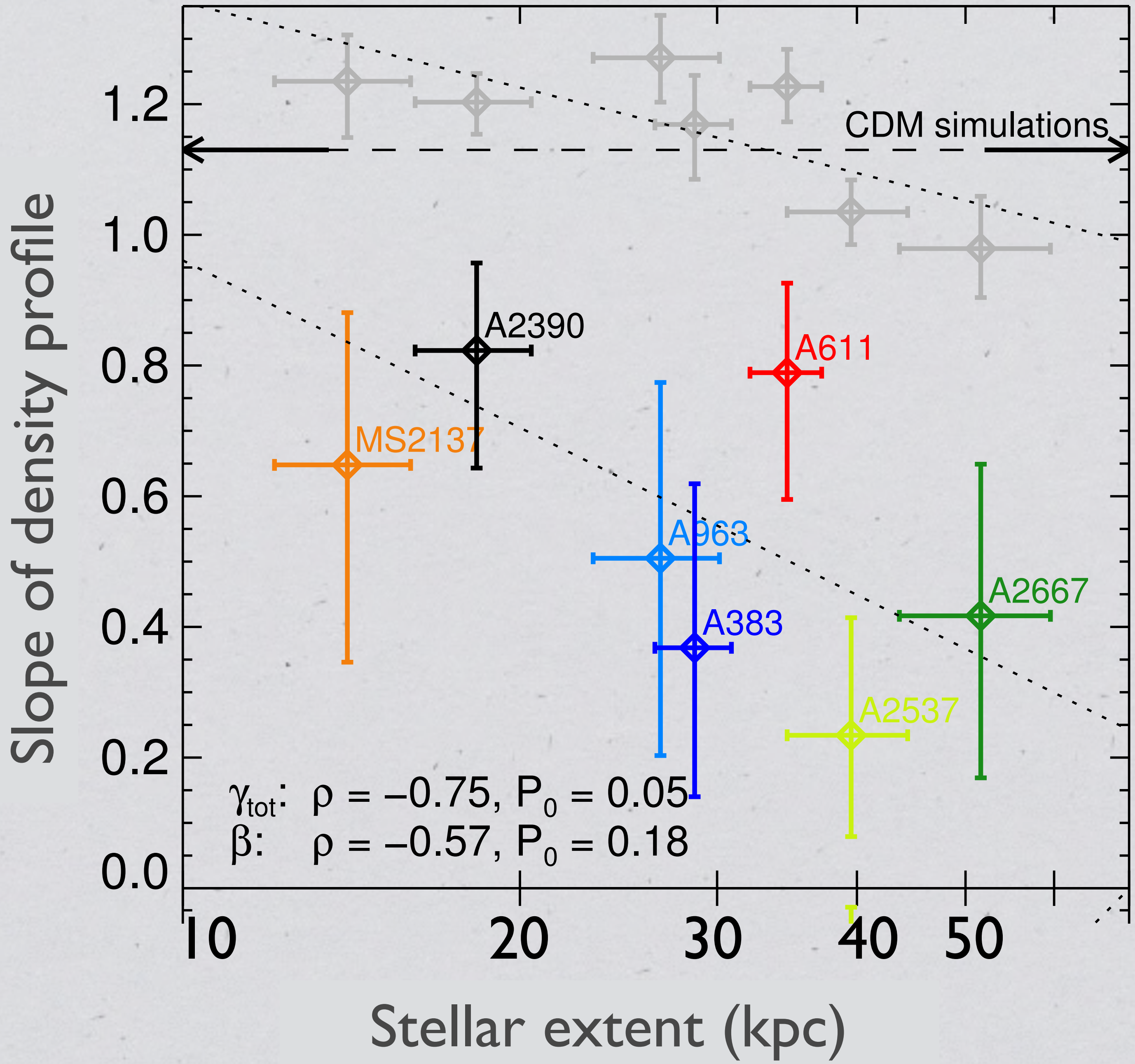
Note the linear rise in rotation velocity at small radii for all galaxies => constant density cores

Kuzio de Naray, McGaugh, de Blok, Bosma 2005, 2006

Cores of clusters of galaxies

Weak lensing, strong lensing and BCG stellar kinematics used

Masses ~ 10^{15} M_{sun}



Newman et al 2012

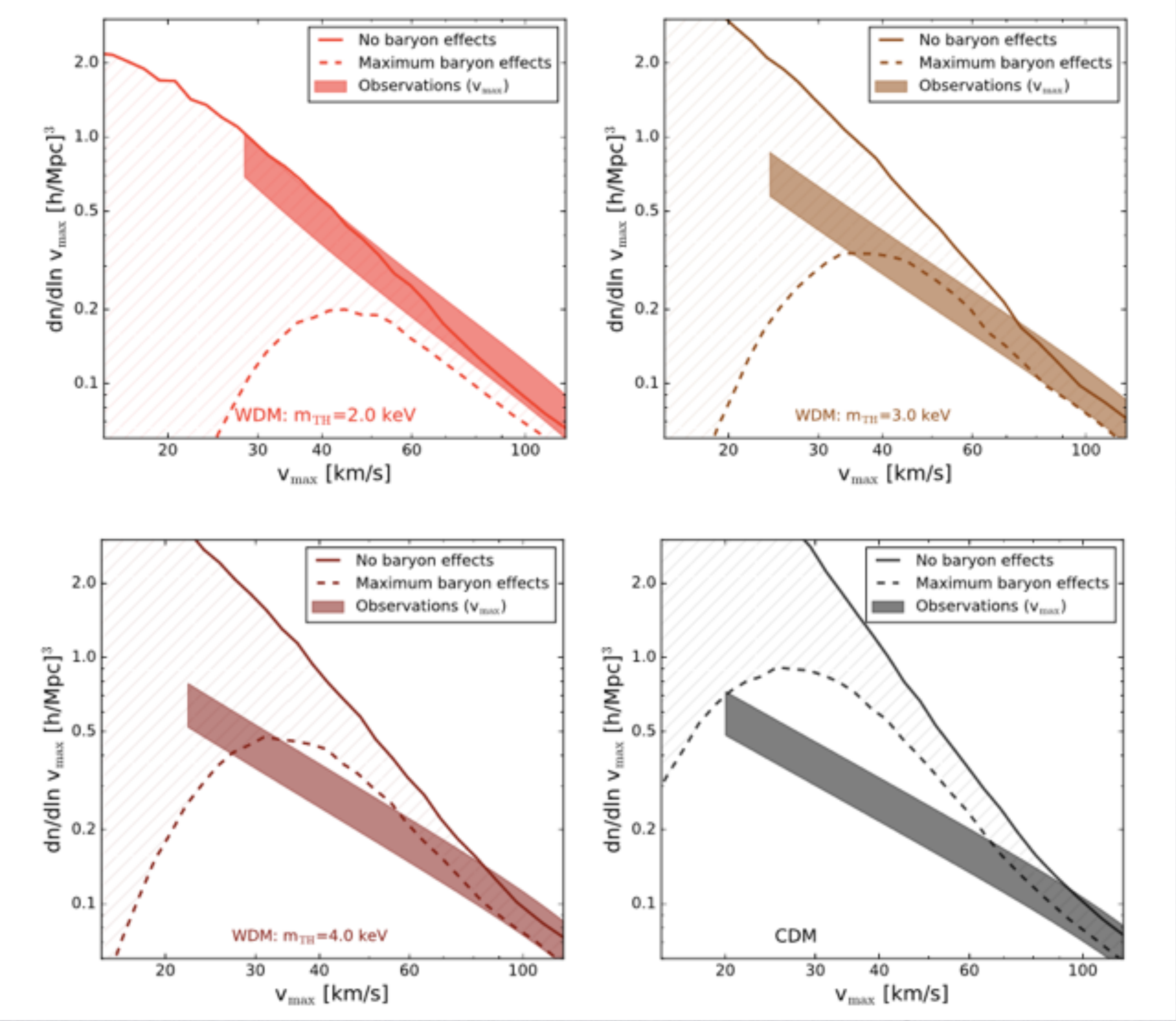
Dark matter densities in the inner regions of galaxies

	Scales of interest (distance from center of galaxy)	Cores (region of roughly constant density)	Lower densities than predicted by CDM-only simulations
Clusters of galaxies (10^{14}-10^{15} M_{sun})	5-50 kpc	Not clear	Yes
Large spirals and ellipticals (10^{12}-10^{13} M_{sun})	1-20 kpc	Not required	No evidence
Dwarf galaxies; Low surface brightness galaxies (10^{10}-10^{12} M_{sun})	0.5-5 kpc	Yes	Yes
Dwarf galaxies within the Milky Way (satellites) (10^{9}-10^{10} M_{sun})	0.3-1 kpc	? (See Walker and Penarrubia and Strigari et al)	Yes

Testing WDM vs CDM with Velocity Function

Schneider+ 1611.09362

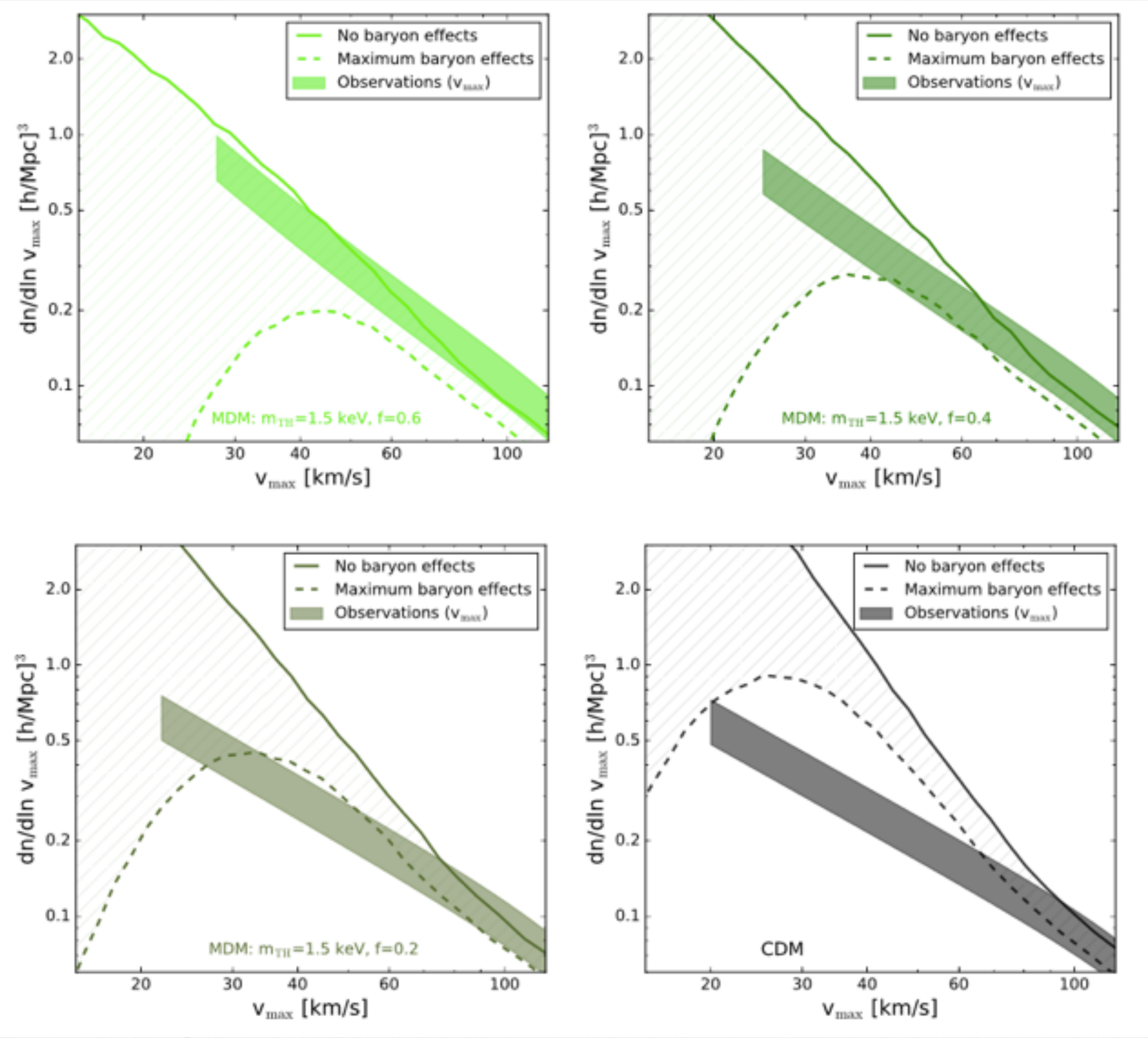
Warm Dark Matter



Testing CDM & fractional WDM with Velocity Function

Schneider+ 1611.09362

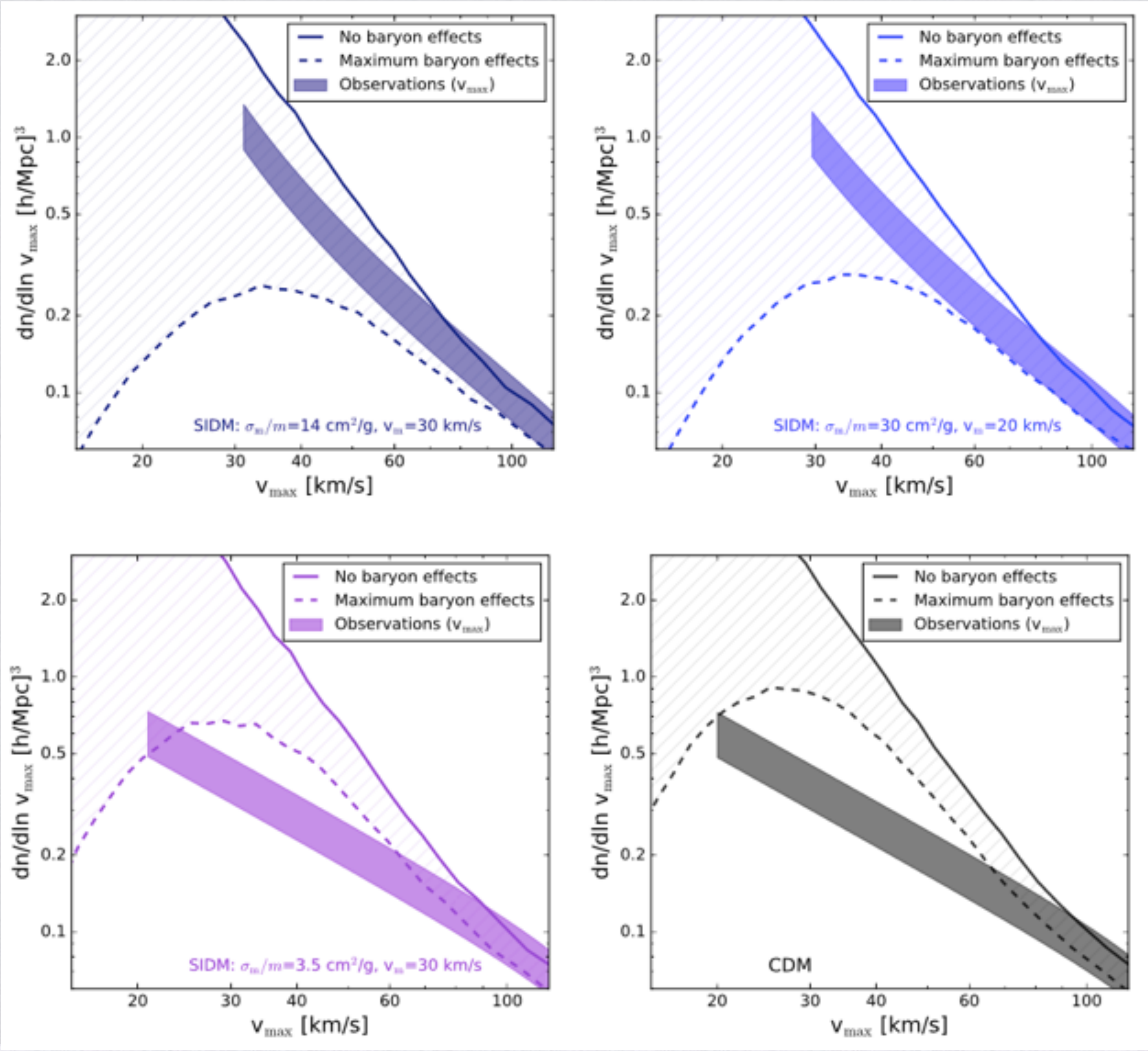
Fractional Warm Dark Matter



Testing SIDM with Velocity Function

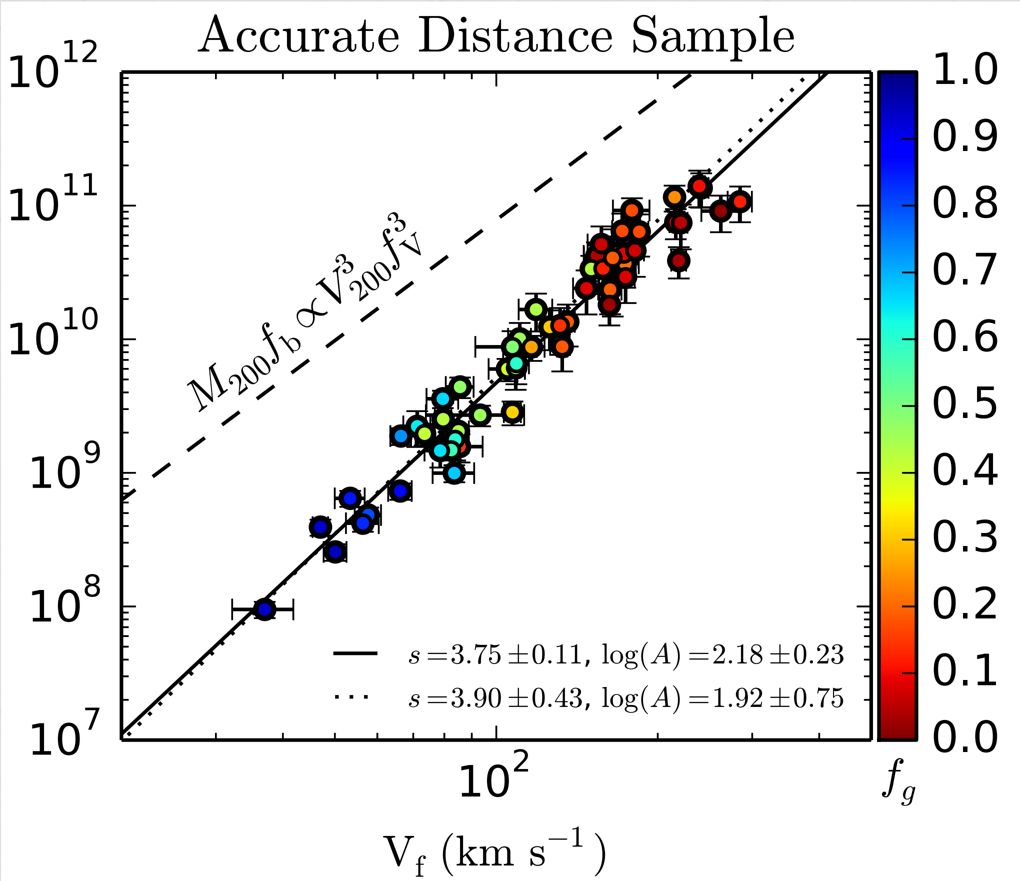
Schneider+ 1611.09362

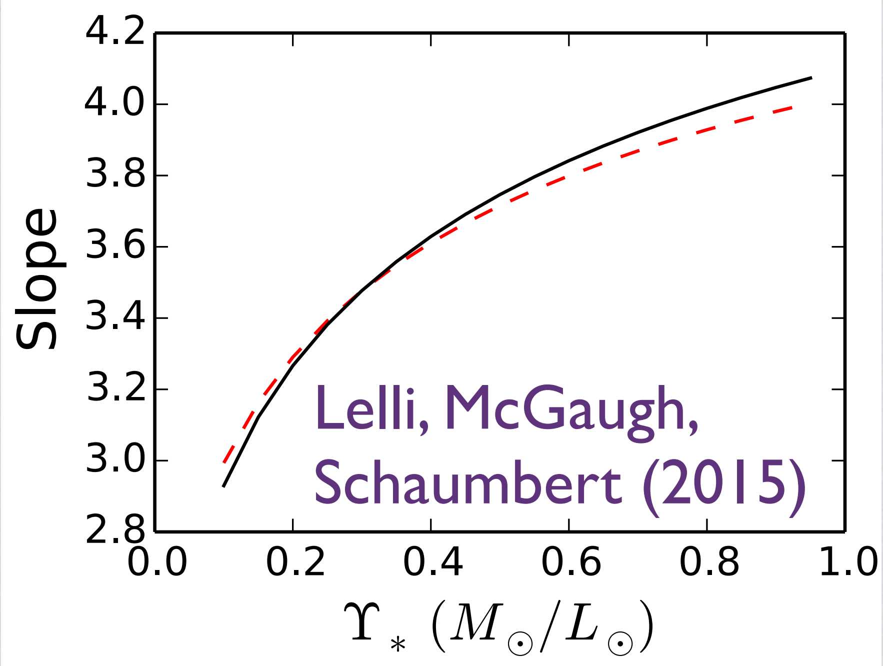
Self-Interacting Dark Matter



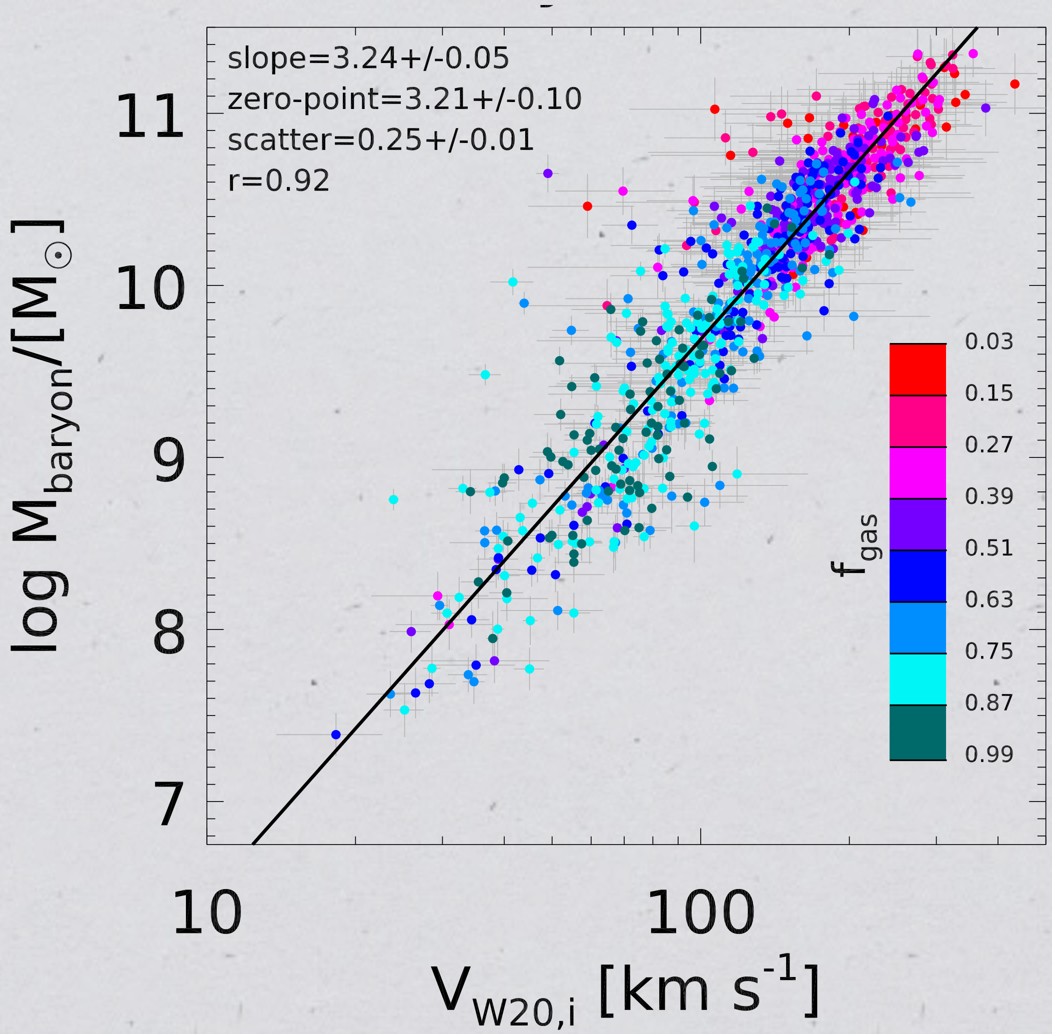
Rotation curves: Diversity, uniformity and correlations

Correlations: Tully-Fisher relations





Lelli, McGaugh, Schaumbert (2015)

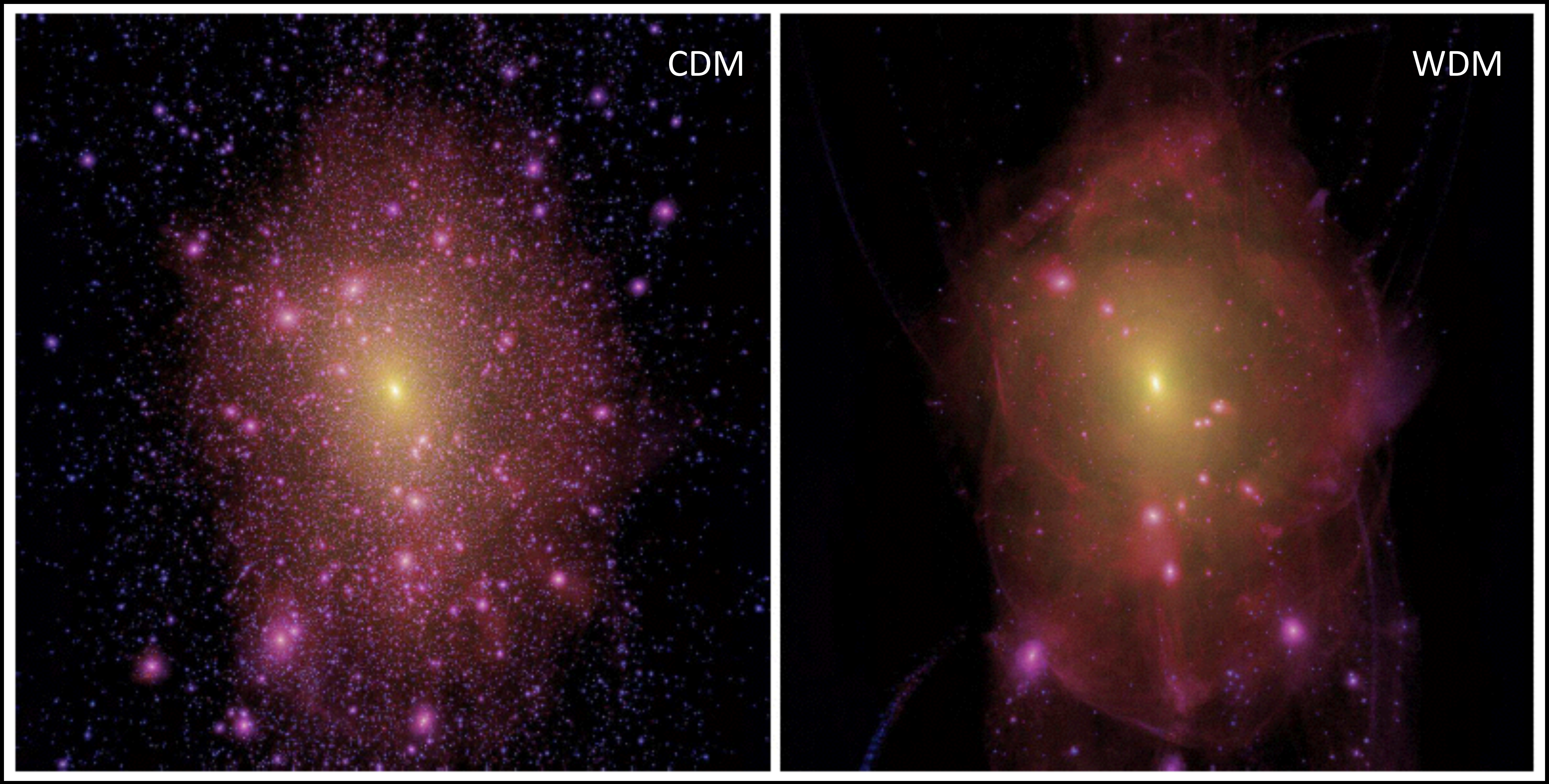


Bradford, Geha, van den Bosch (2016)

Also see Papastergis, Adams and Hulst (2016)

Warm dark matter as a solution of the small-scale puzzles

Warm dark matter structures



Lovell et al, MNRAS (2012)
Based on a resonant sterile neutrino model

What is the relationship between particle mass and warm dark matter free streaming scale?

WDM Particle Mass: Sterile Neutrinos vs "Thermal" WDM

$$m_{\tilde{g}} = 0.326\ \mathrm{keV}\left(\frac{m_s}{1\ \mathrm{keV}}\right)^{3/4}\left(\frac{\Omega_{\mathrm{DM}}}{0.12}\right)^{1/4}$$

$$m_{\tilde{g}} = 2\ \mathrm{keV} \Rightarrow m_{s,\mathrm{DW}} = 11.2\ \mathrm{keV}$$

$$(m_{\mathrm{SF}} < m_{\mathrm{DW}})$$

WDM Particle Mass: Sterile Neutrinos vs "Thermal" WDM

- "Thermal" WDM is frozen-out early, then abundance is set by disappearance of degrees of freedom. That is, there is a heating up of plasma after freezout to reduce WDM abundance to match Ωdm.
  - Cools the DM relative to plasma (photons & neutrinos)
- Dodelson-Widrow Sterile Neutrinos have neutrino velocity "thermal" distribution: they are warmer than gravitinos

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$$m_{\tilde{g}} = 2\ \mathrm{keV} \Rightarrow m_{s,\mathrm{DW}} = 11.2\ \mathrm{keV}$$

- Shi-Fuller Sterile Neutrinos are *colder* versions of Dodelson-Widrow neutrinos $(m_{\mathrm{SF}} < m_{\mathrm{DW}})$

Sterile Neutrino Dark Matter Production

$$\Gamma(\nu_\alpha \to \nu_s) \sim \frac{\Gamma_\alpha(p)\Delta^2(p)\sin^2 2\theta}{\Delta^2(p)\sin^2 2\theta + D^2(p) + [\Delta(p)\cos 2\theta - V^L(p) - V^T(p)]^2}$$

Sterile Neutrino Dark Matter Production

$$\Gamma_\alpha(p) \sim G_F^2 p T^4 \sim T^5$$

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$$D(p)^2 \sim T^{10}$$

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$$H^2 = \frac{8\pi}{3} G\rho \sim T^4$$

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$$\frac{\Gamma}{H} \sim \begin{cases} T^{-9} & \text{High } T \\ T^3 & \text{Low } T \end{cases}$$

Sterile Neutrino Dark Matter Production

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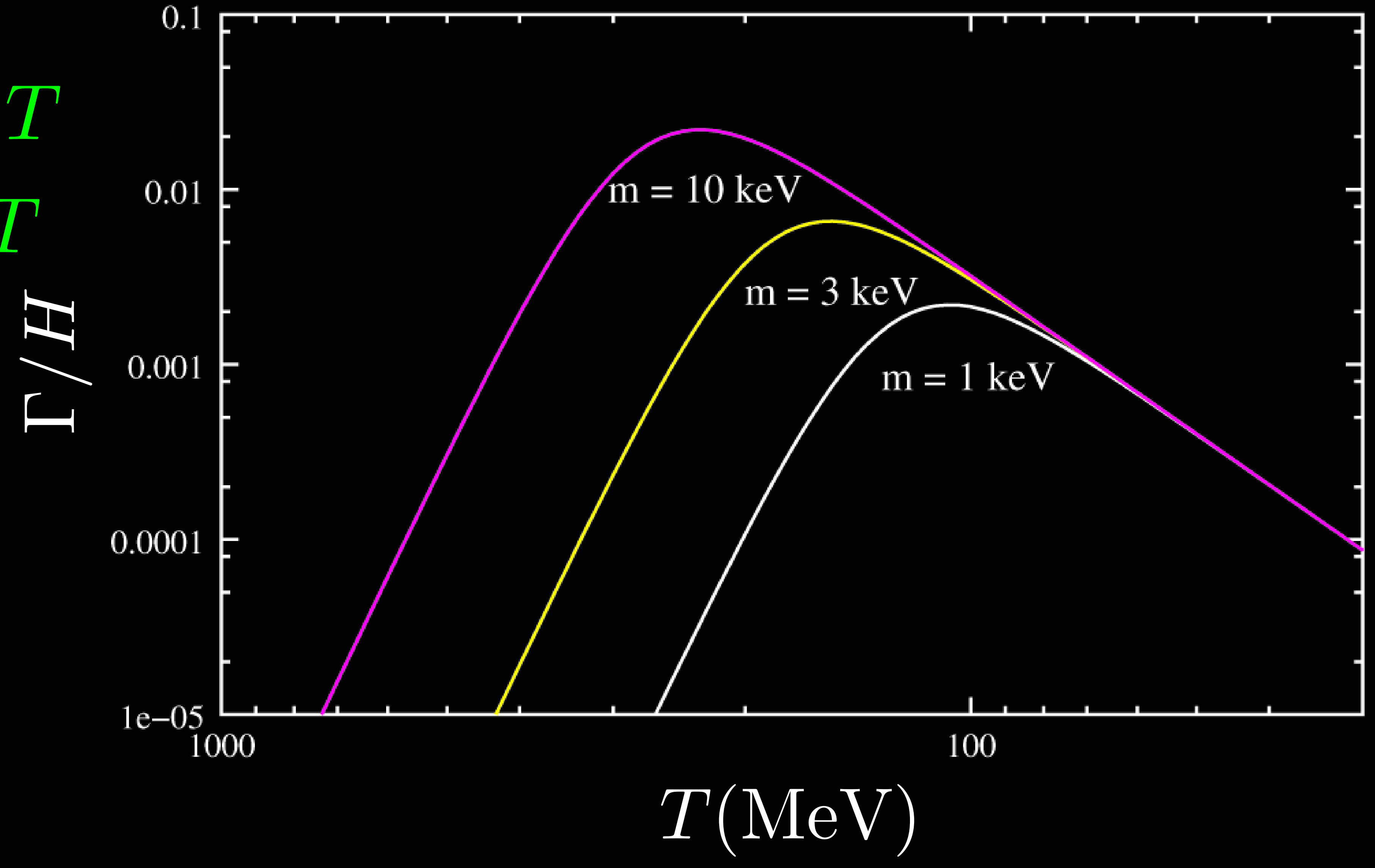

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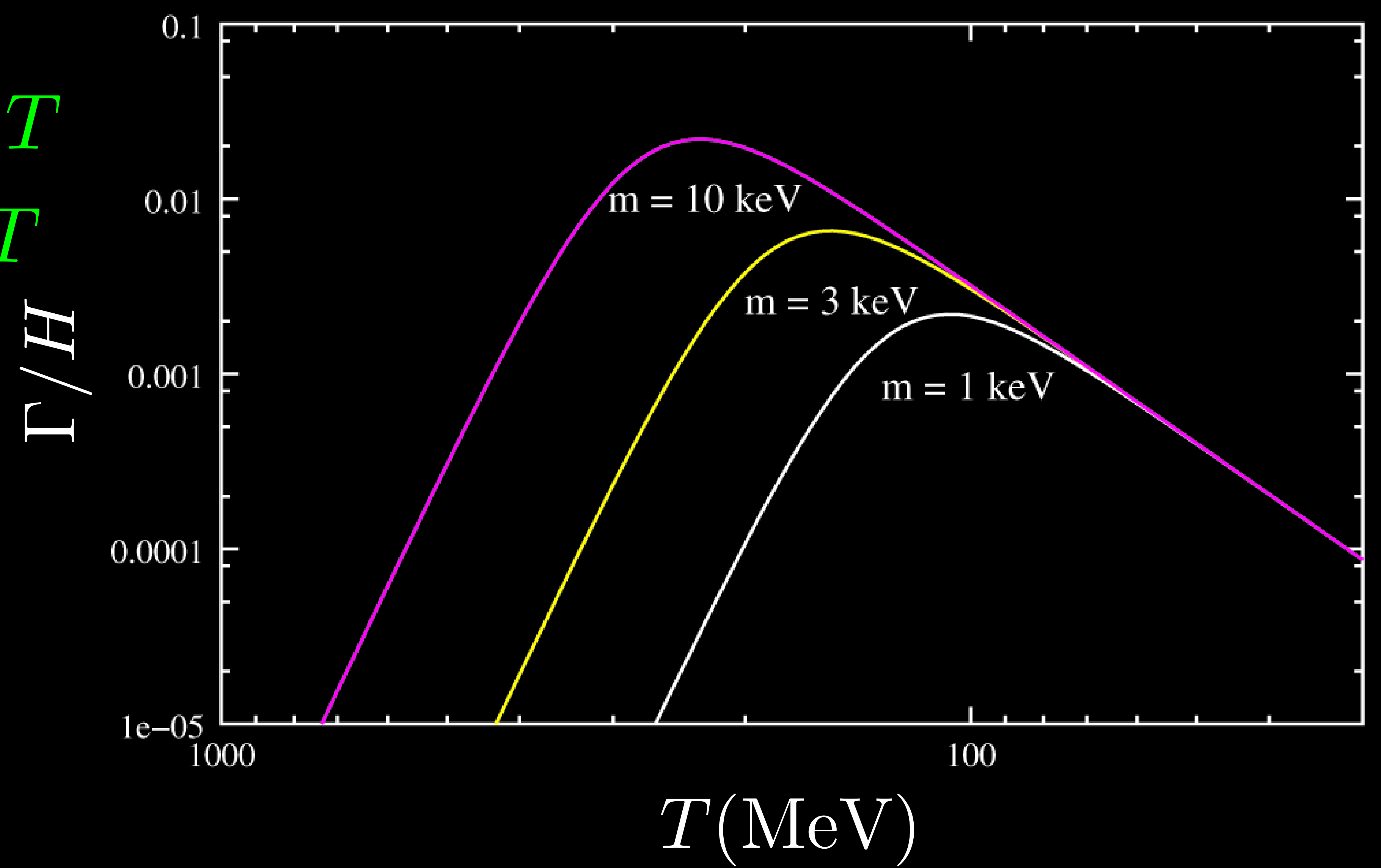
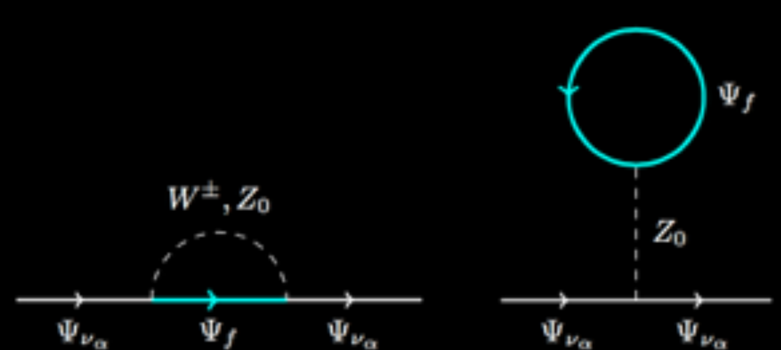
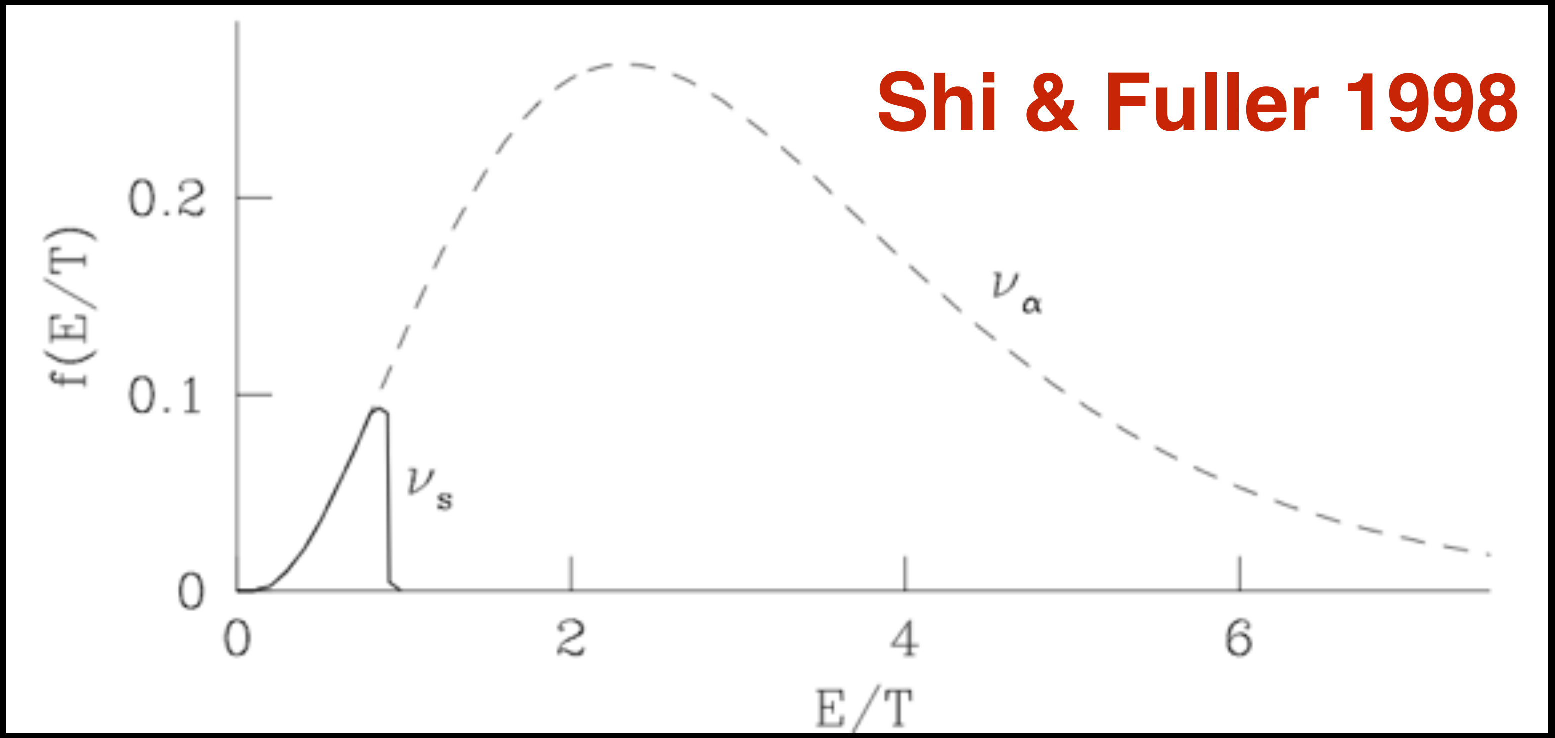


Never in Equilibrium!!



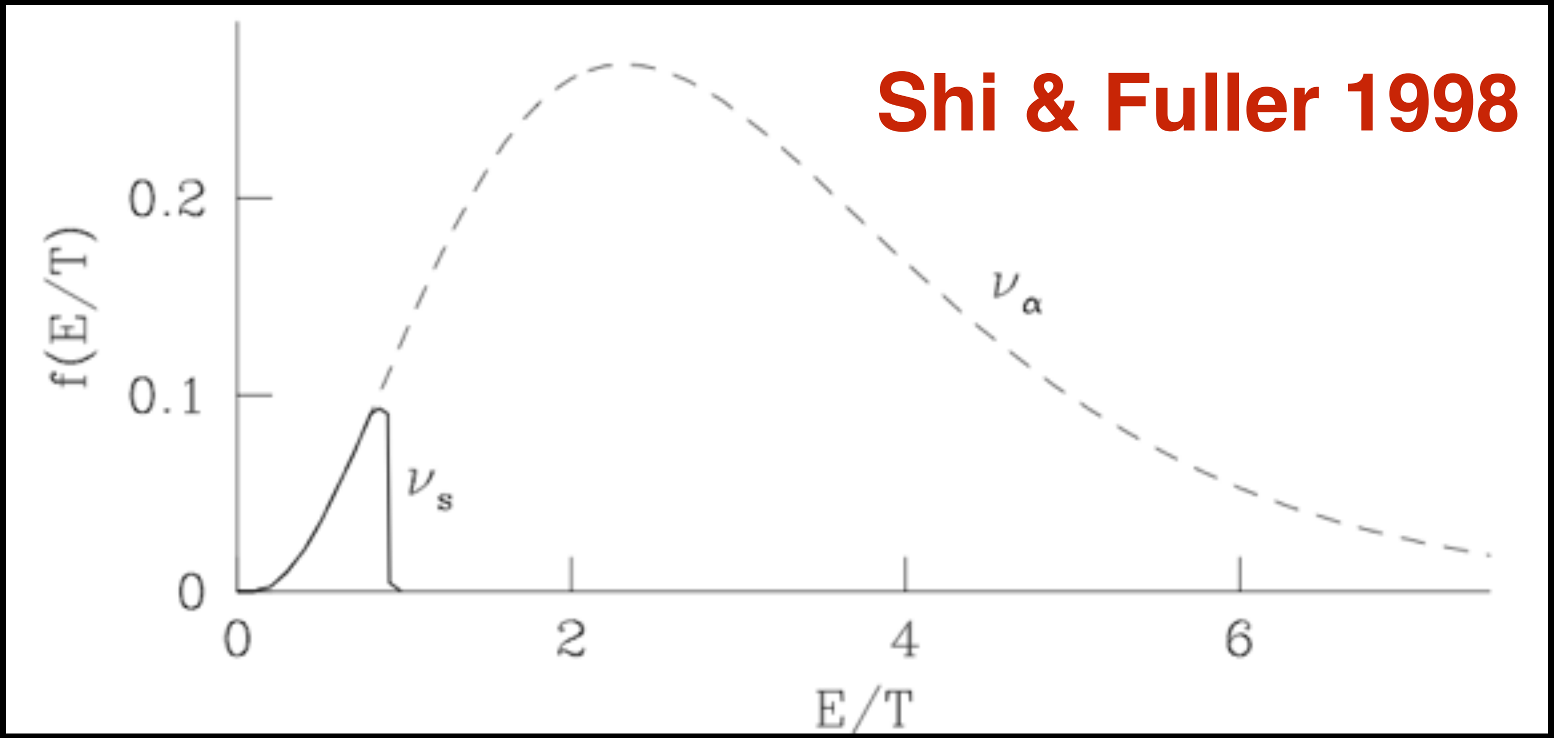
Resonant Production



Matter (thermal) mixing angle:

$$\sin^2 2\theta_m = \frac{\Delta^2(p)\sin^2 2\theta}{\Delta^2(p)\sin^2 2\theta + [\Delta(p)\cos 2\theta - V^D - V^T(p)]^2}$$

Resonant Production



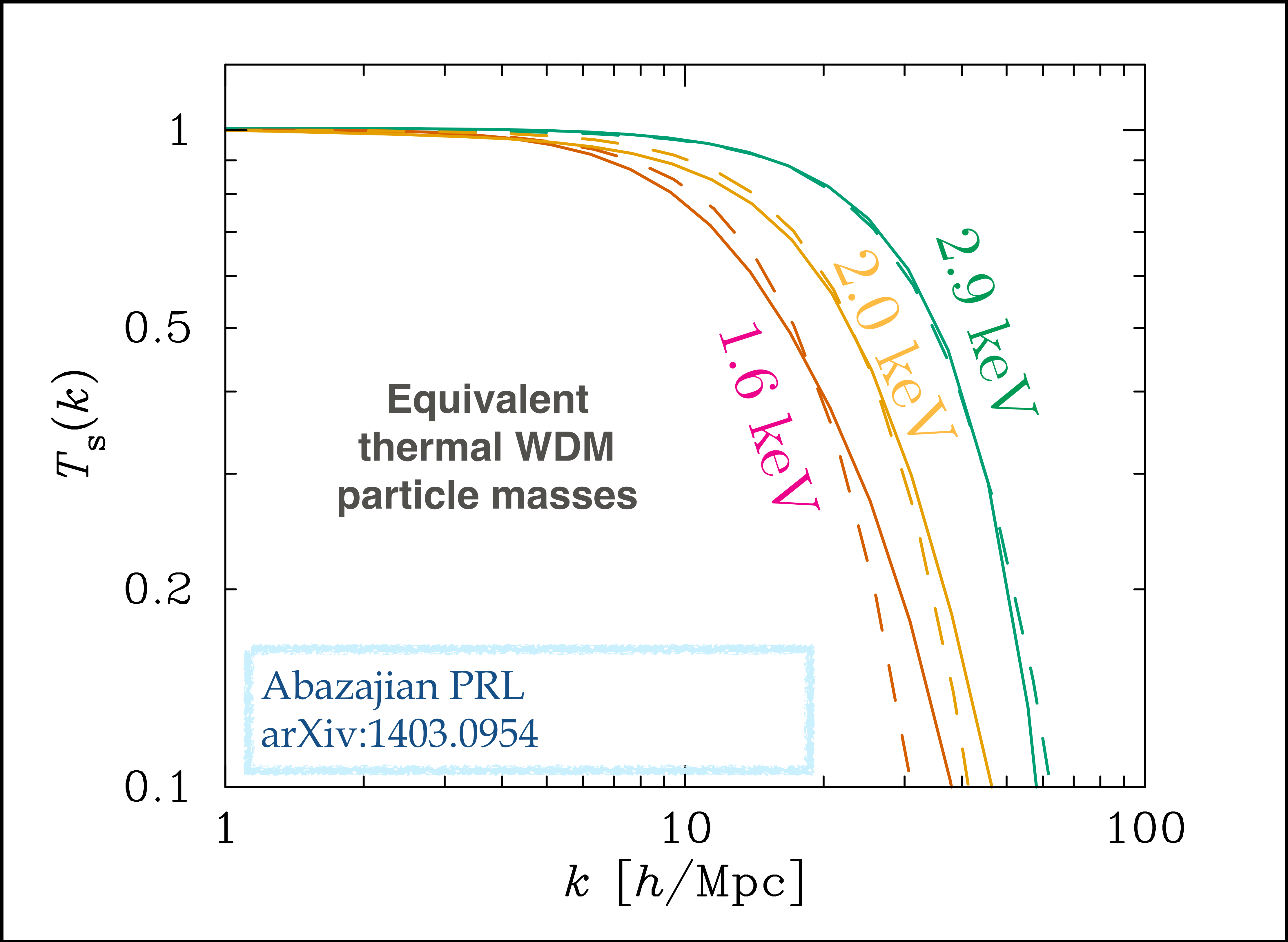
Matter (thermal) mixing angle:

$$\sin^2 2\theta_m = \frac{\Delta^2(p)\sin^2 2\theta}{\Delta^2(p)\sin^2 2\theta + [\Delta(p)\cos 2\theta - V^D - V^T(p)]^2}$$

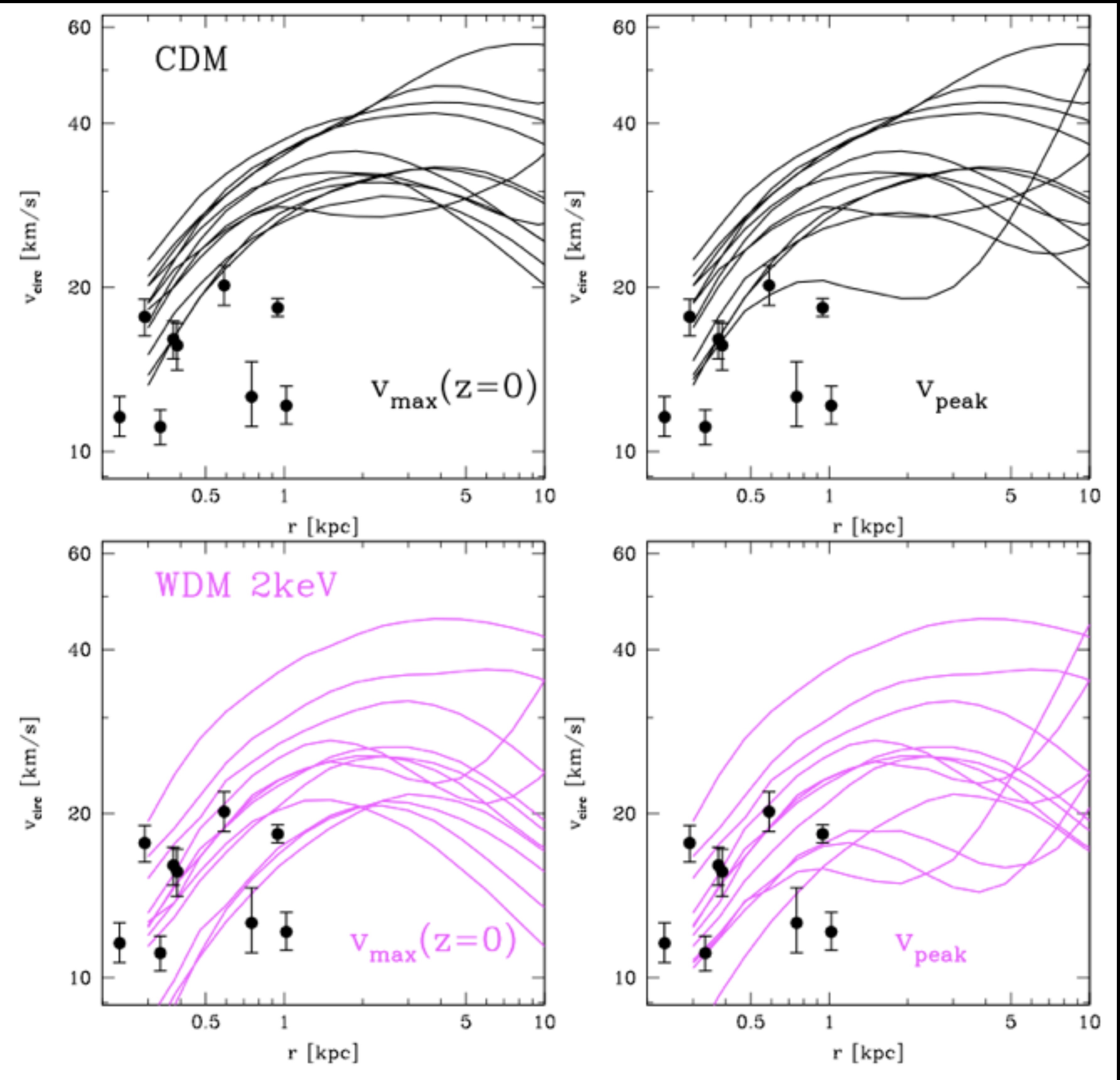
$$\Rightarrow \qquad \epsilon_{\rm res} \approx \frac{\delta m^2}{(8\sqrt{2}\zeta(3)/\pi^2)G_{\rm F}T^4 L}$$

$$\approx 3.65\left(\frac{\delta m^2}{(7\,\mathrm{keV})^2}\right)\left(\frac{10^{-3}}{L}\right)\left(\frac{170\,\mathrm{MeV}}{T}\right)^4$$

7 keV Resonant Sterile Neutrino: Free streaming cutoff is very different, even for the same particle mass



WDM Solution to TBTF?



Anderhalden et al.
arXiv:1212.2967

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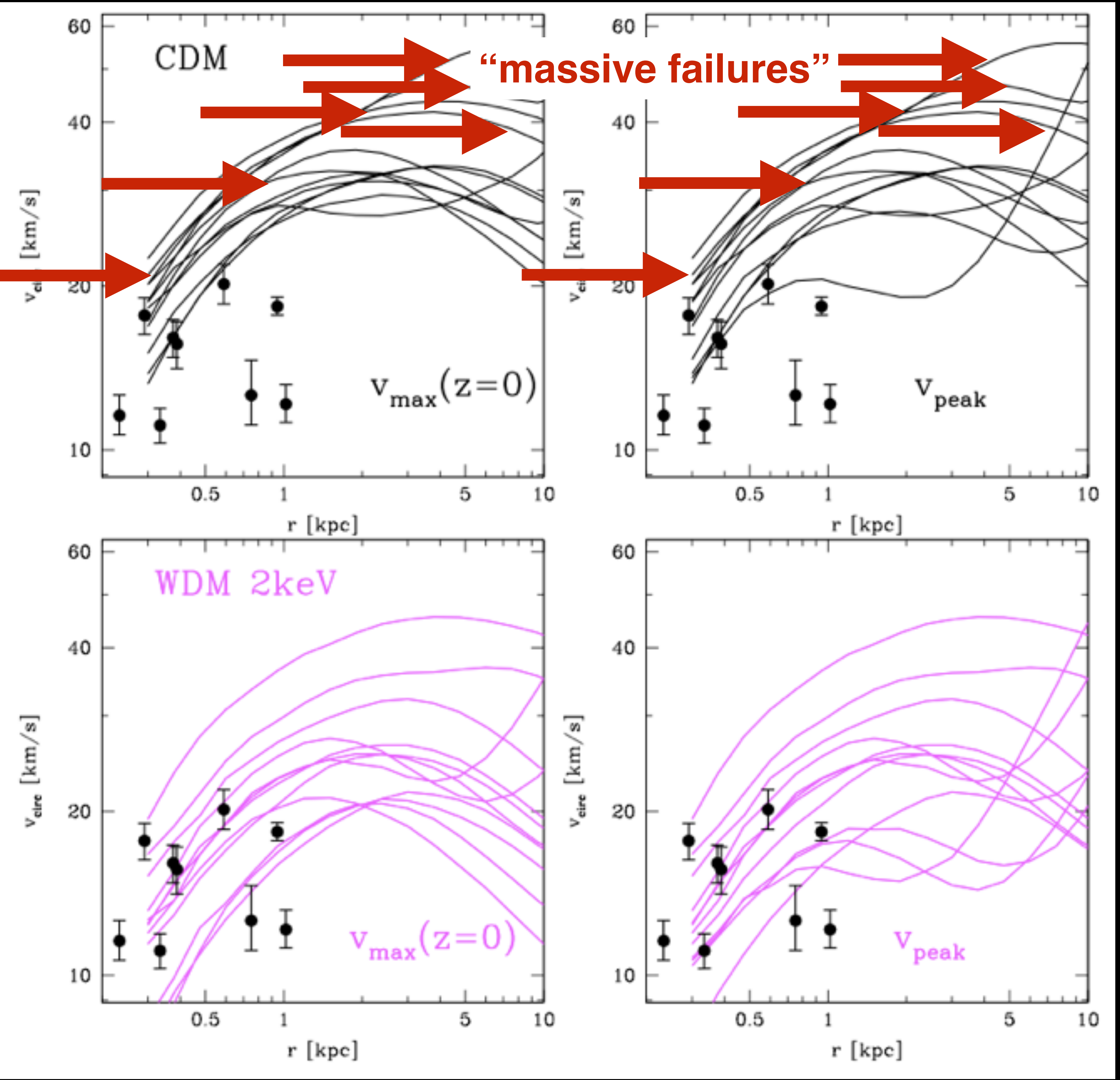

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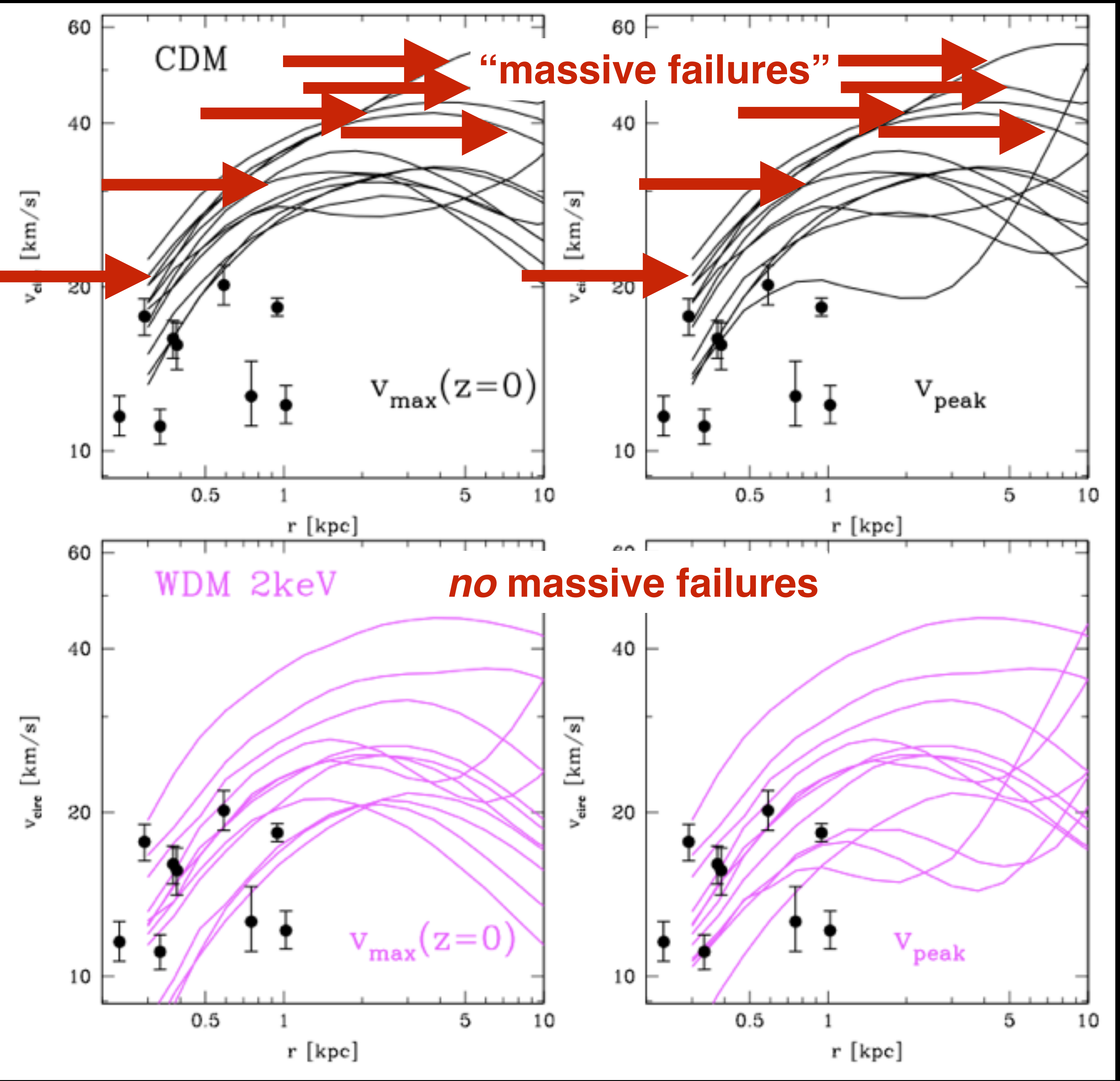

Anderhalden et al.
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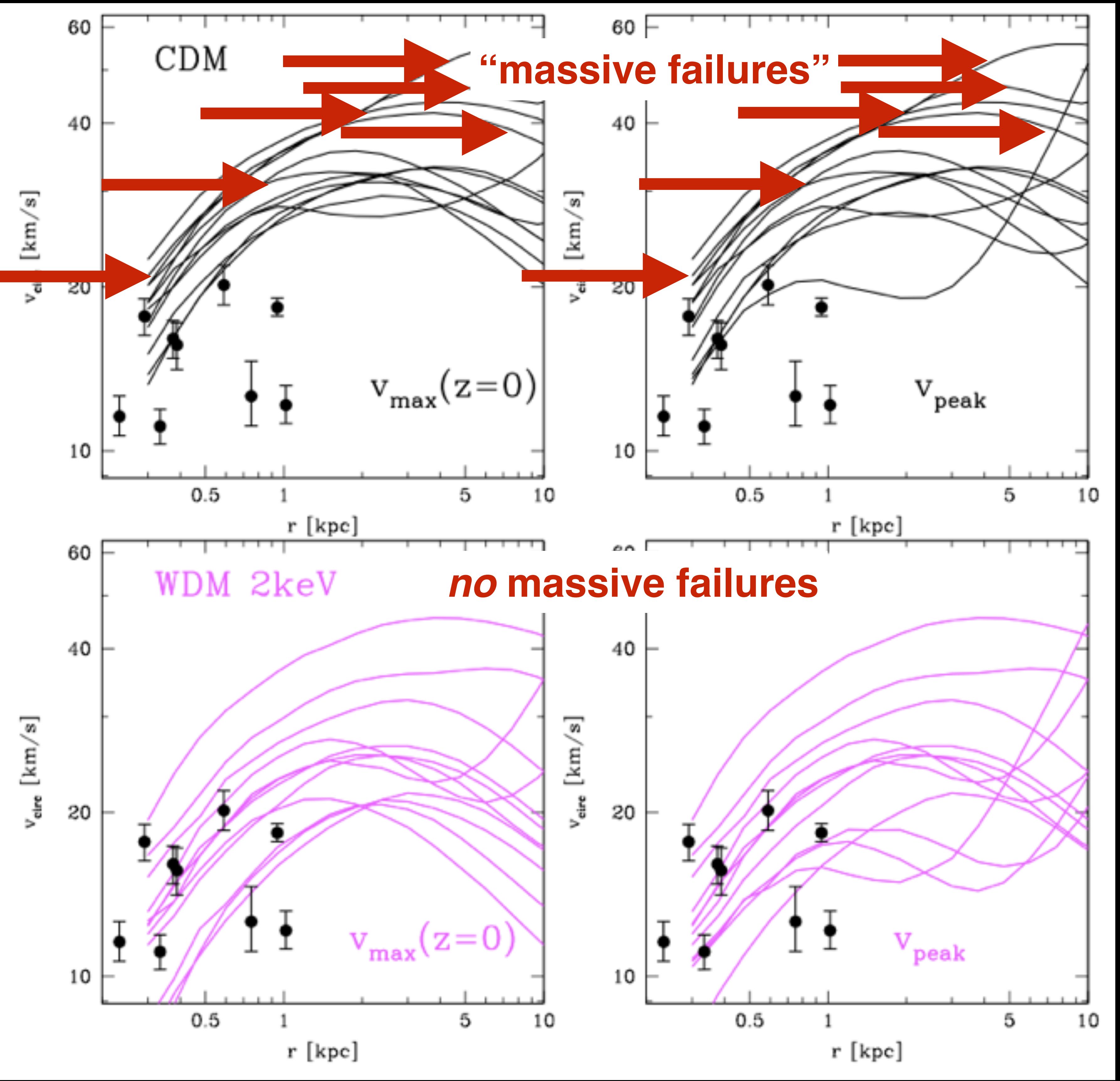


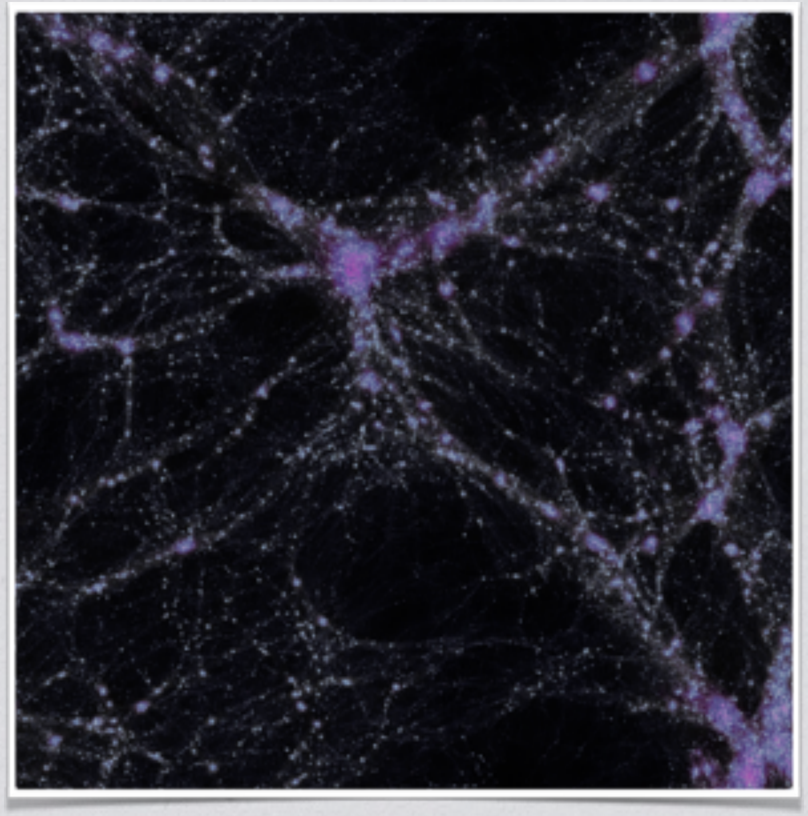
Anderhalden et al. arXiv:1212.2967

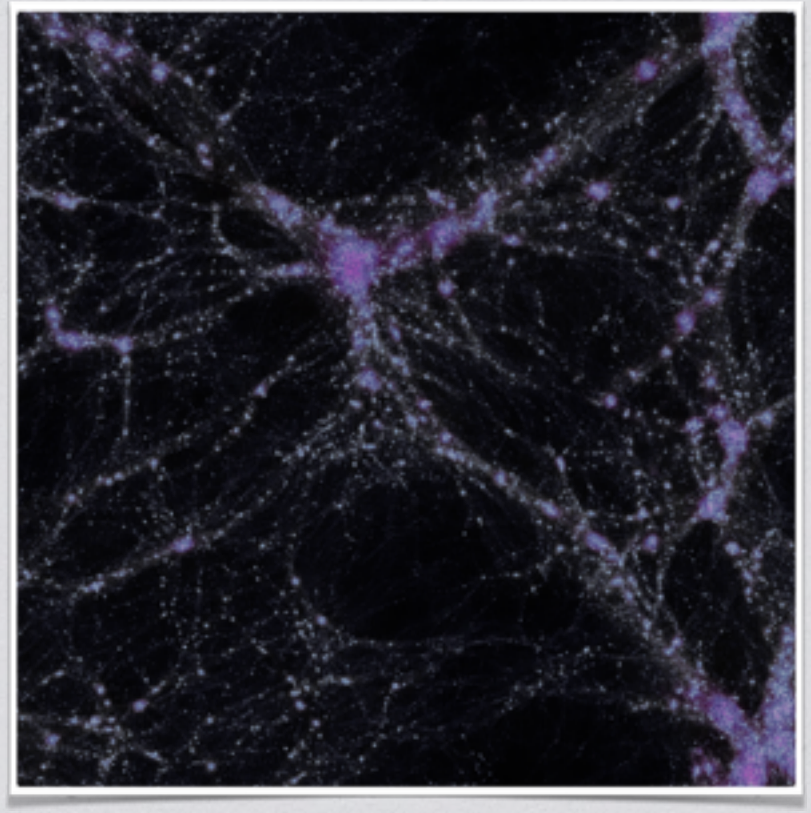
“It seems that only the pure WDM model with a 2 keV [thermal] particle is able to match the all observations” of the Milky Way Satellites: “the total satellite abundance, their radial distribution and their mass profile” (or TBTF)

Self-interacting dark matter as a solution of the small-scale puzzles

SIDM = CDM (almost)

SIDM looks the same as CDM on large scales, so it passes all the cosmological tests. It modifies the inner part of halos [Spergel and Steinhardt 2000].





Rocha et al 2012

In its simplest incarnation, SIDM has one extra parameter: scattering cross section over mass.

Brief history of SIDM

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Proposals motivated by small-scale issues [Spergel and Steinhardt 2000, Firmani et al 2000]. Related early work on mirror dark matter [Mohapatra, Nussinov, Teplitz 2001; Foot, Volkas 2004]. See also Carlson, Machacek and Hall (1992).

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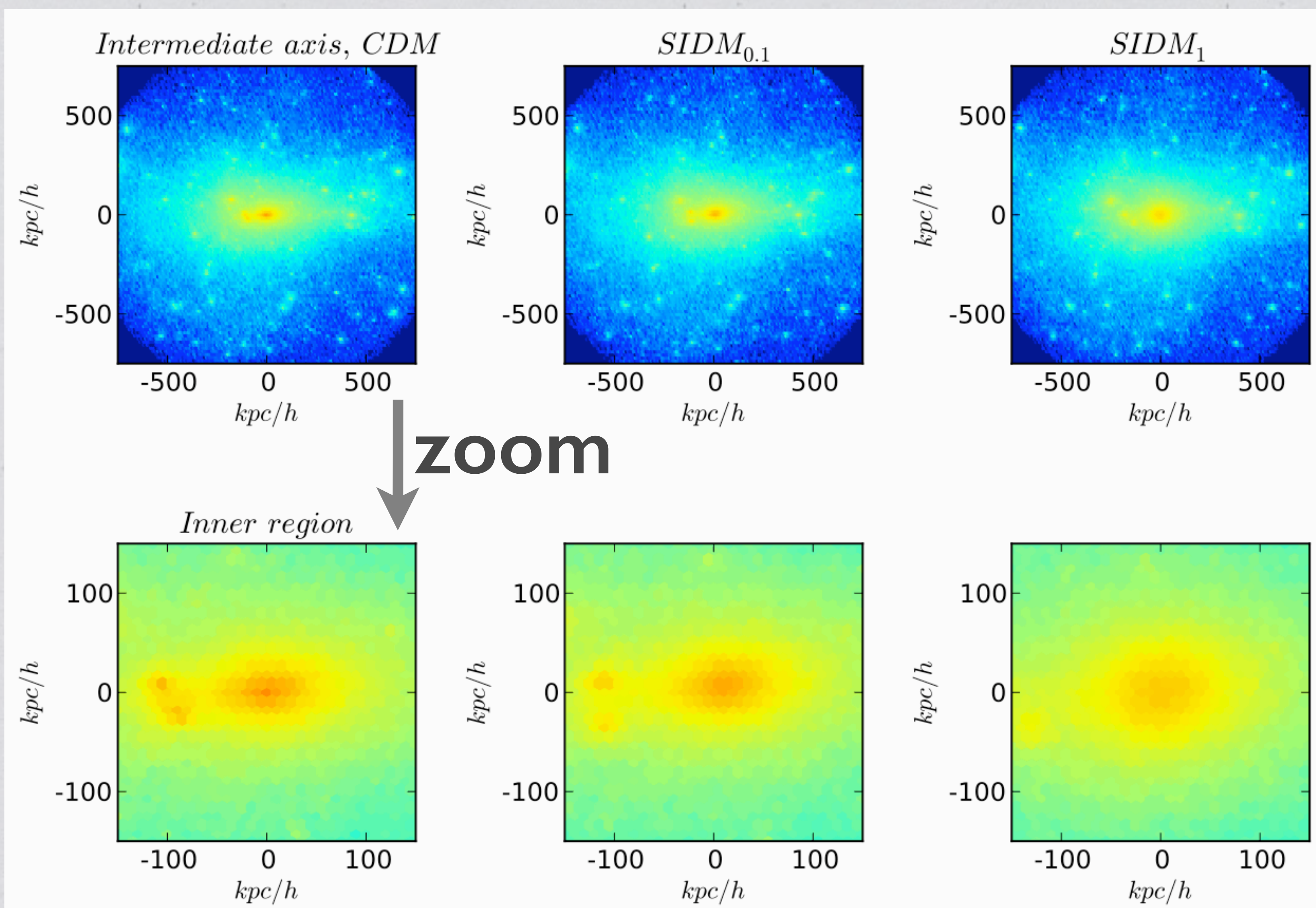
Recent revival of SIDM motivated partly by model building:
Ackerman, Buckley, Carroll, Kamionkowski (2008), Feng, Kaplinghat, Yu, Tu (2009), Feng, Kaplinghat, Yu 2010, Loeb and Weiner 2011

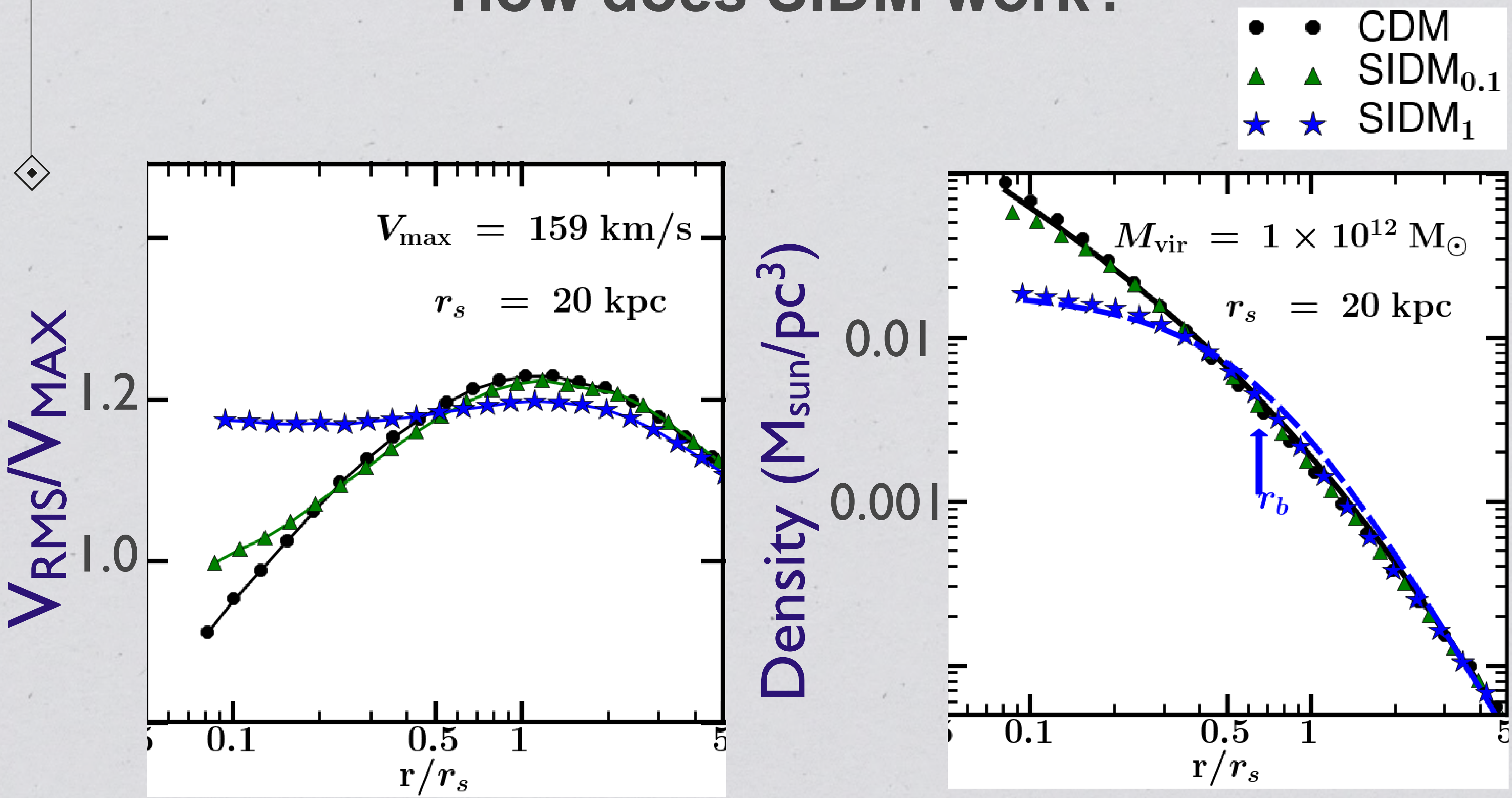
Cluster halo shape constraints



Constraints using shapes of LoCuSS clusters (Richards et al 2010) not better than about 1 cm^2/g.

Peter, Rocha, Bullock, Kaplinghat 2012

How does SIDM work?



Rocha et al 2012

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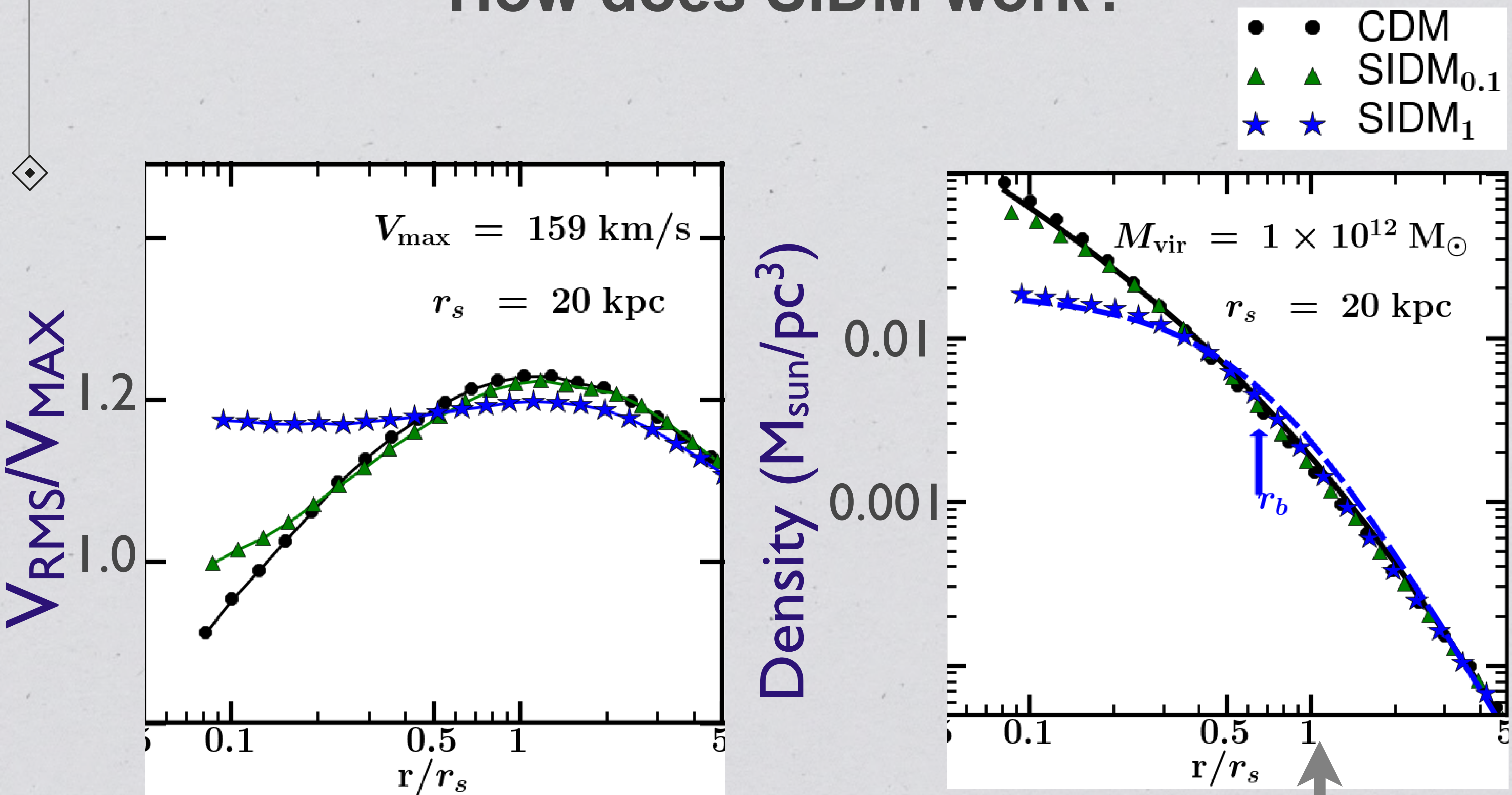
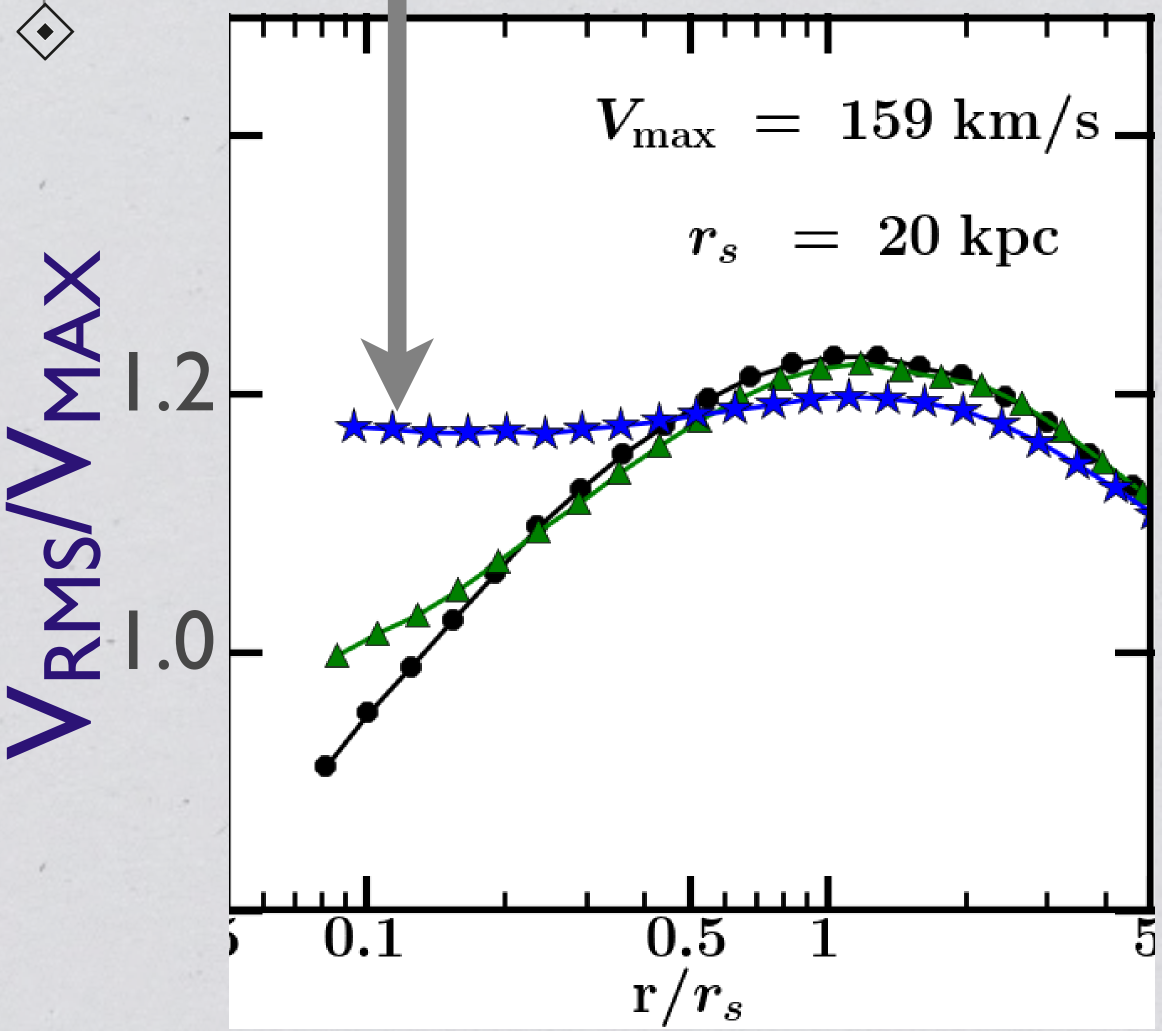


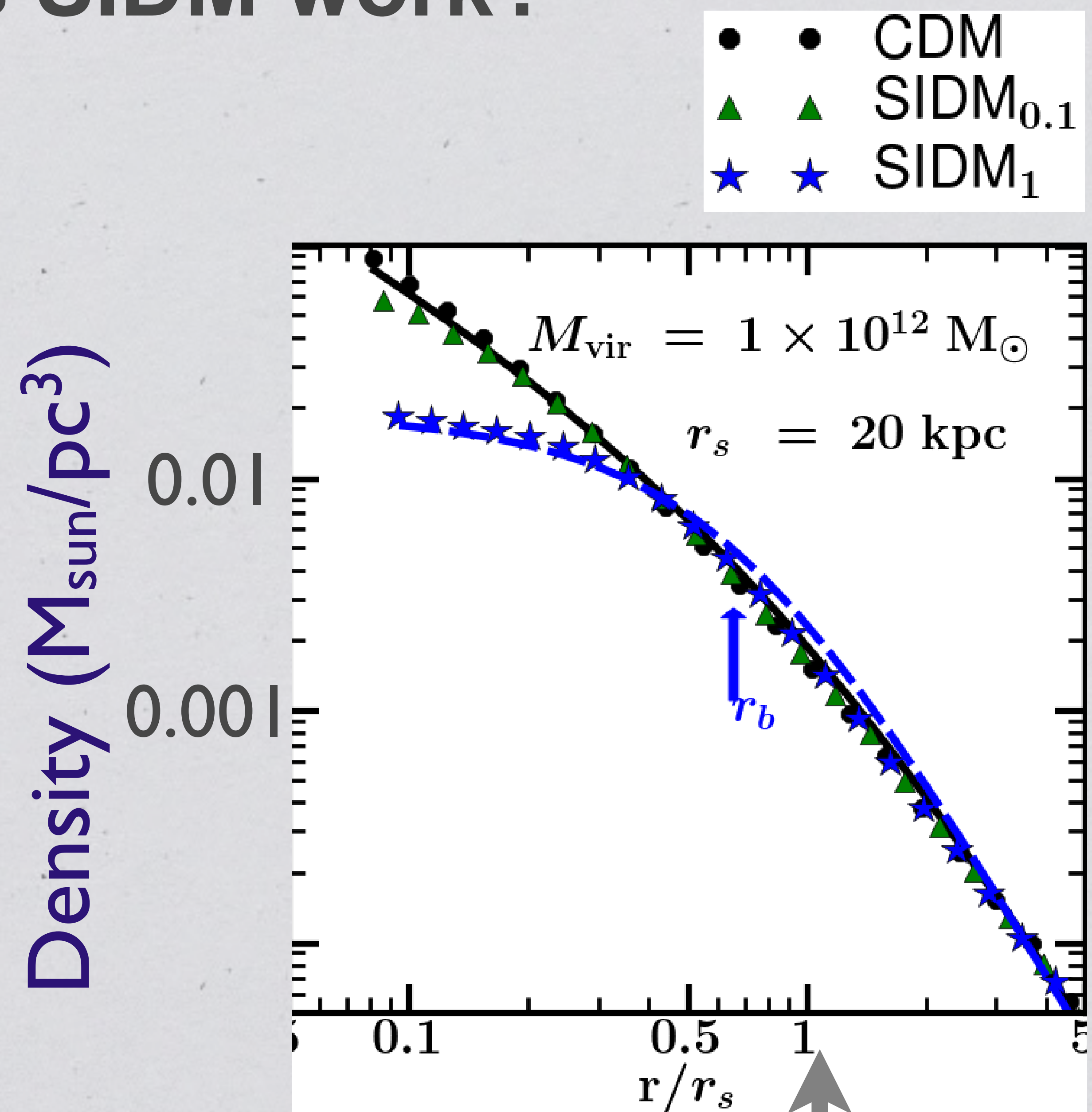
One interaction on average over halo age

Rocha et al 2012

How does SIDM work?

Isothermal





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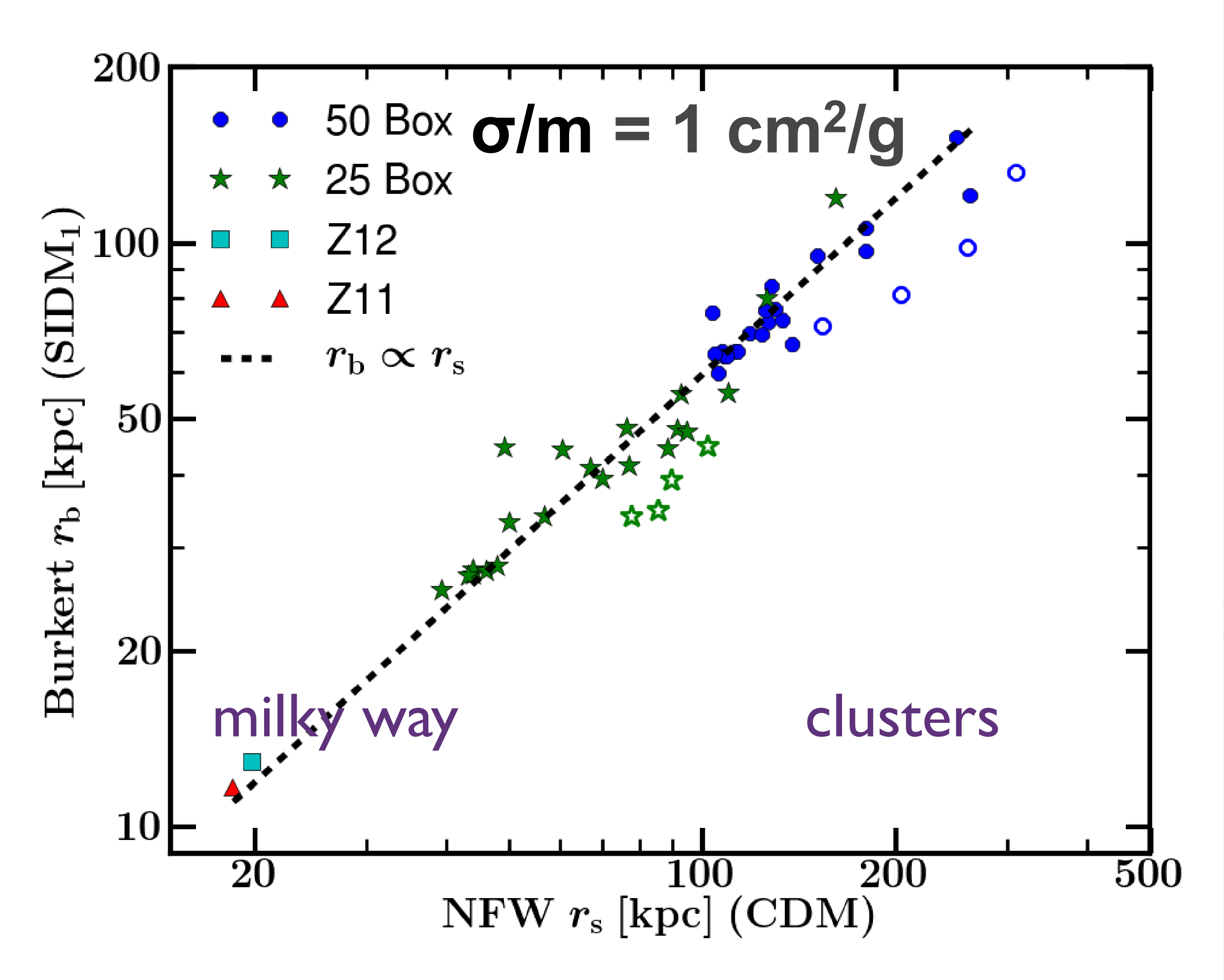
Rocha et al 2012

SIDM solution: core sizes

Outside this core radius, solution is CDM-like.

Core radius



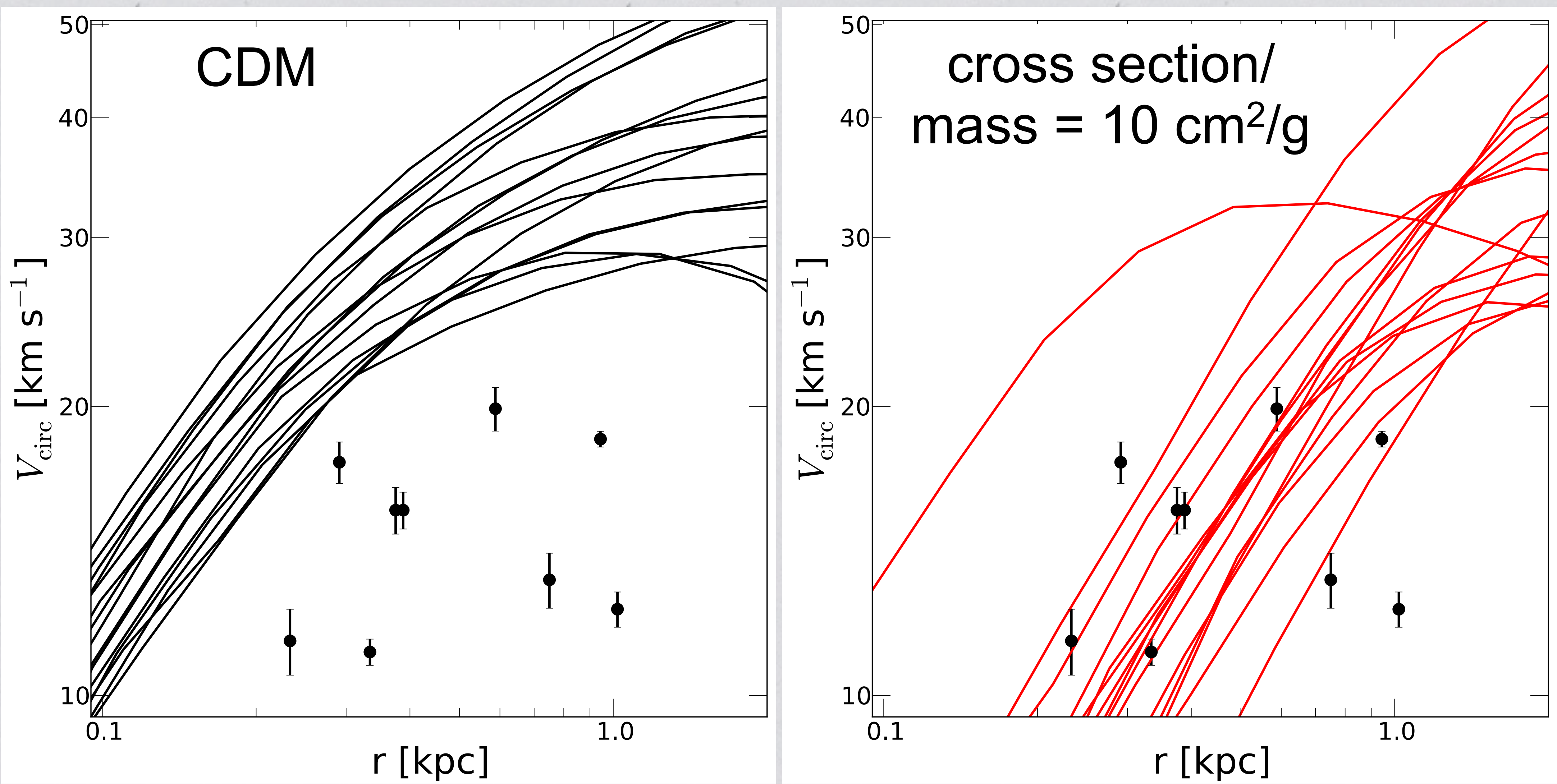
Core size ~ 0.5 r_s, large enough to explain spiral and dwarf galaxy observations.

ρ_{core} α $1/V_{max}$

Rocha et al (2012)
Elbert et al (2015)

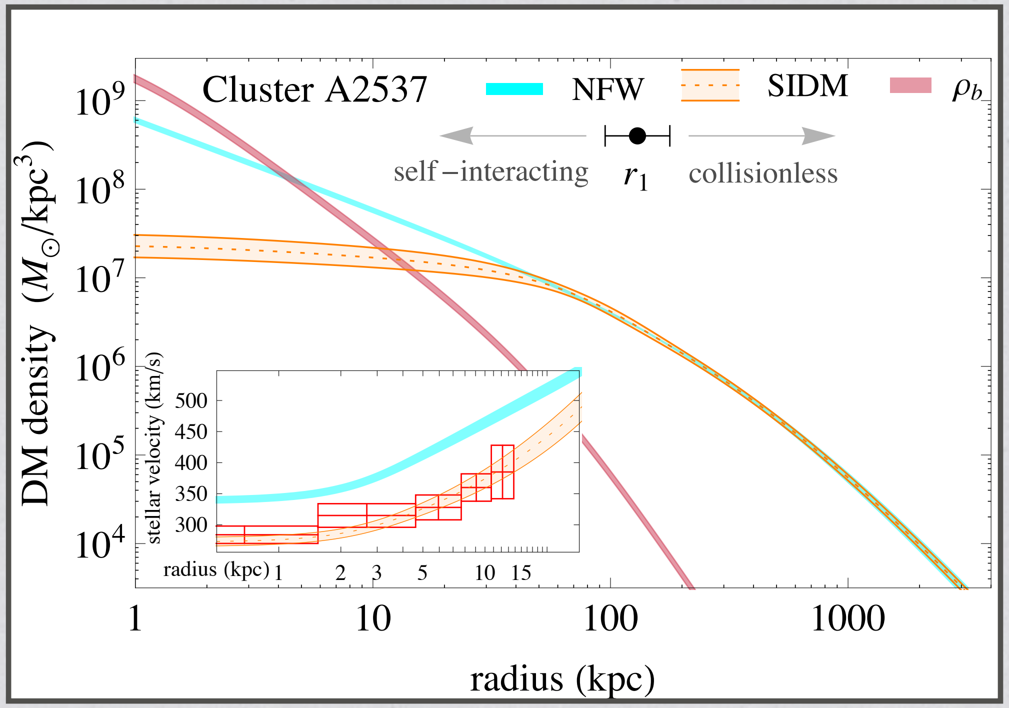
Similar results from Fry et al (2015)

SIDM solution for satellites



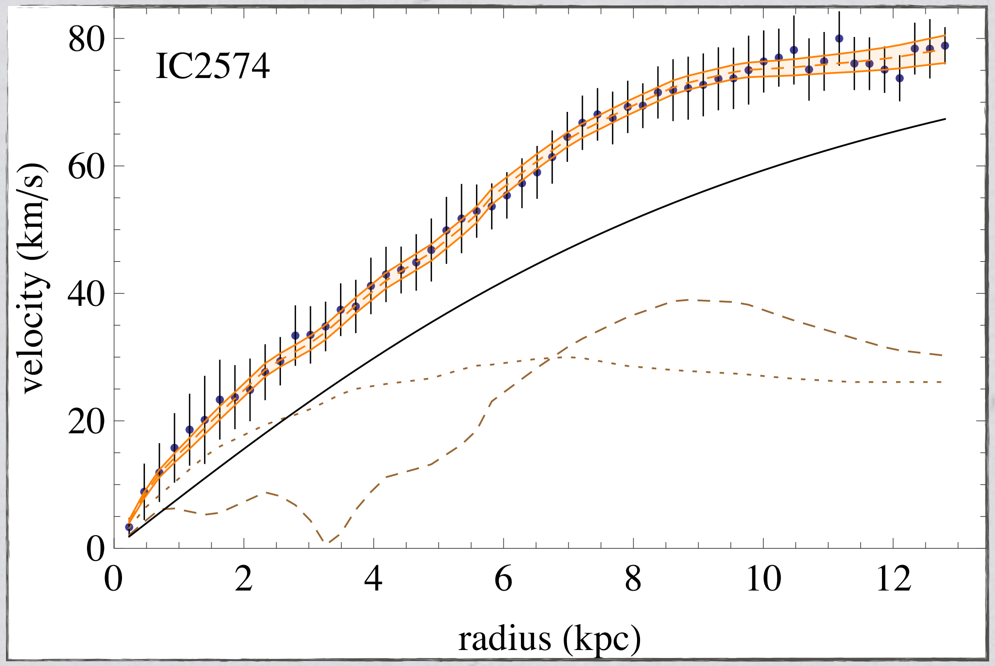
TBTF problem can be solved with the production of large cores [Vogelsberger, Zavala and Loeb 2012, Vogelsberger, Zavala and Walker 2012]

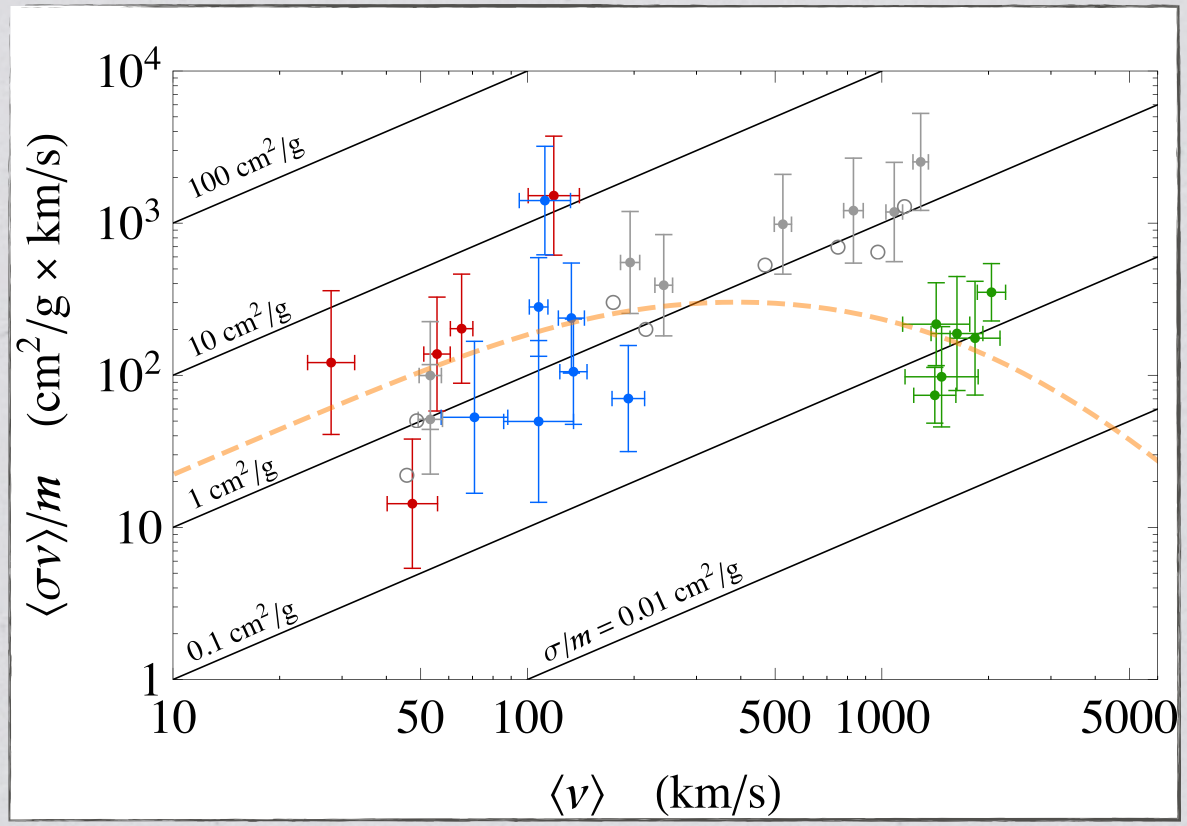
SIDM fits to galaxies and clusters



$$\rho(r) = \begin{cases} \rho_{\rm iso}(r)\,, & r < r_1 \\ \rho_{\rm NFW}(r)\,, & r > r_1 \end{cases}$$

$$\text{rate} \times \text{time} \approx \frac{\langle \sigma v \rangle}{m} \rho(r_1)\, t_{\rm age} \approx 1$$

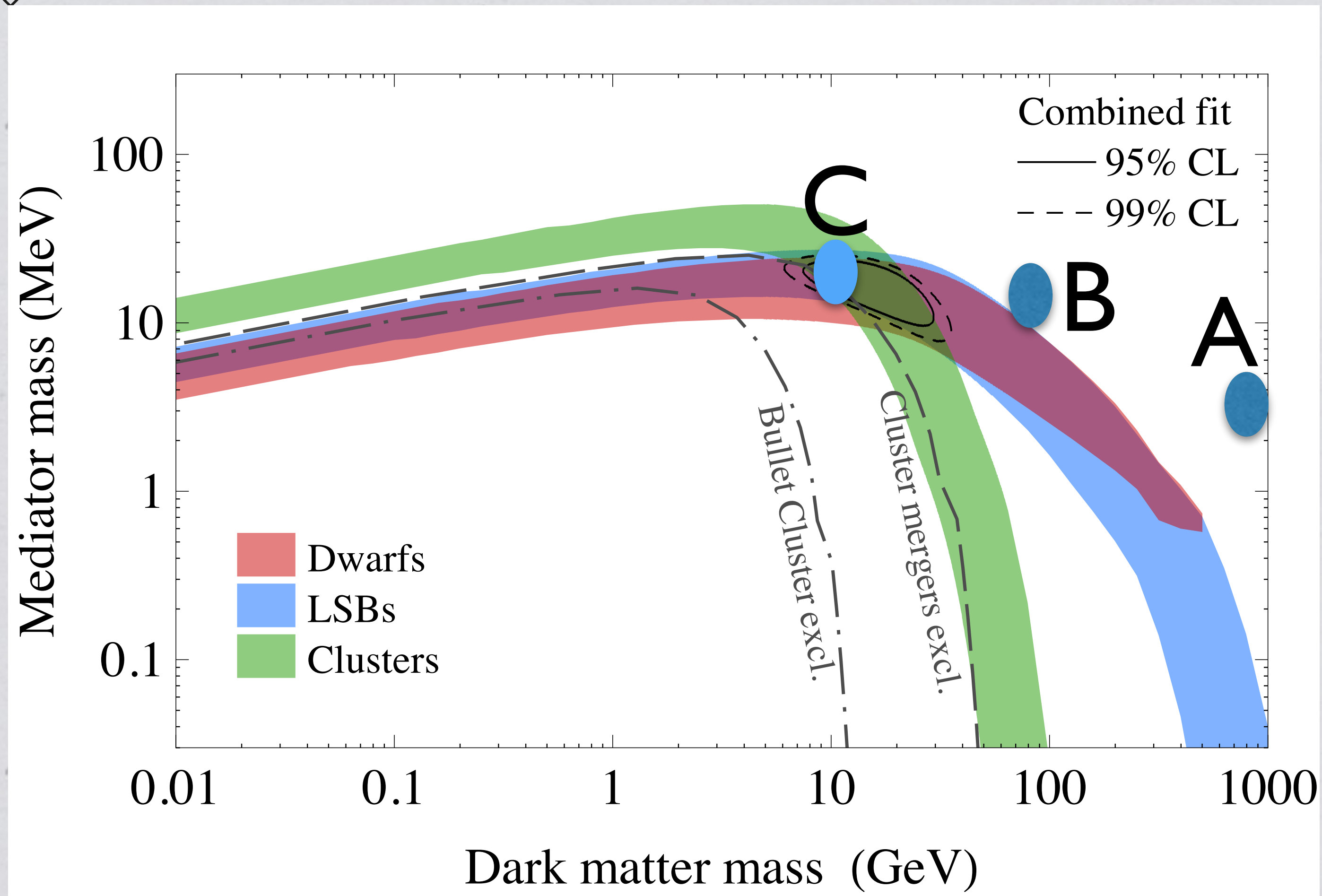




Diversity in cores ~ c(M) relation

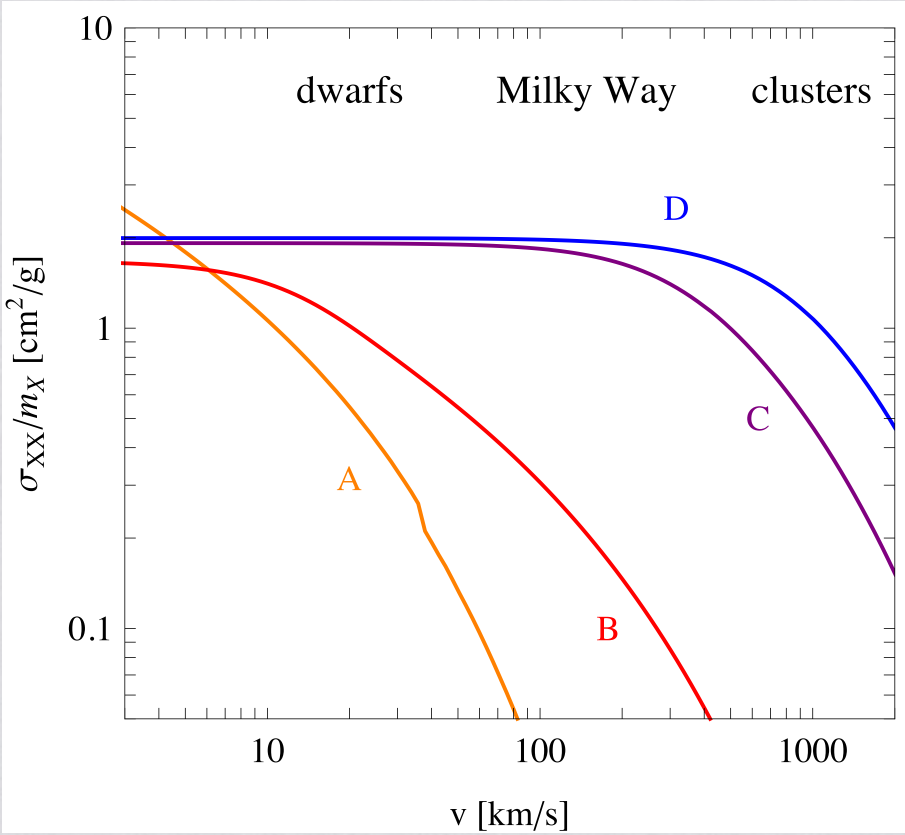
Kaplinghat, Tulin and Yu, 2015

A consistent SIDM solution requires a mild velocity dependence!



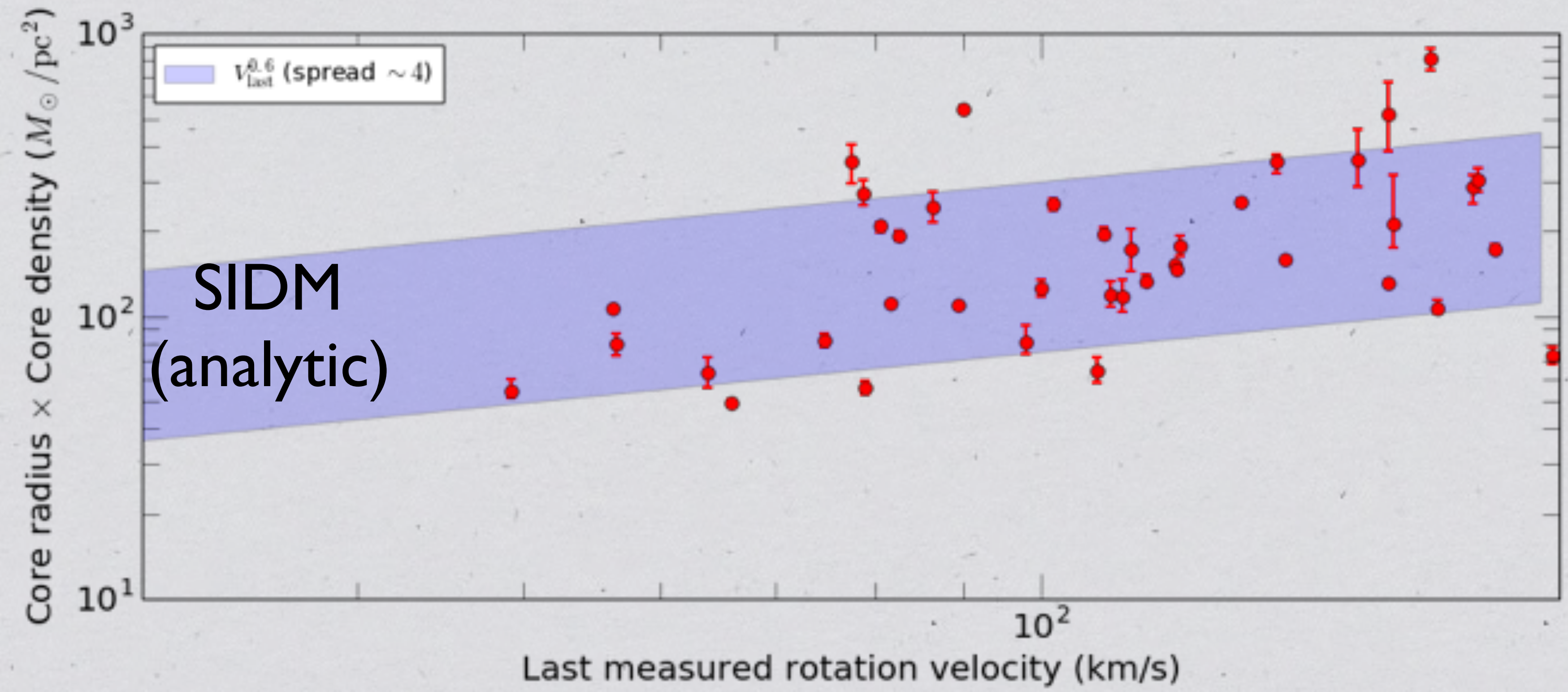
$$\mathcal{L} = g_\chi \bar{\chi}\gamma^\mu \chi \phi_\mu + m_\chi \bar{\chi}\chi + m_\phi^2 \phi^\mu \phi_\mu$$

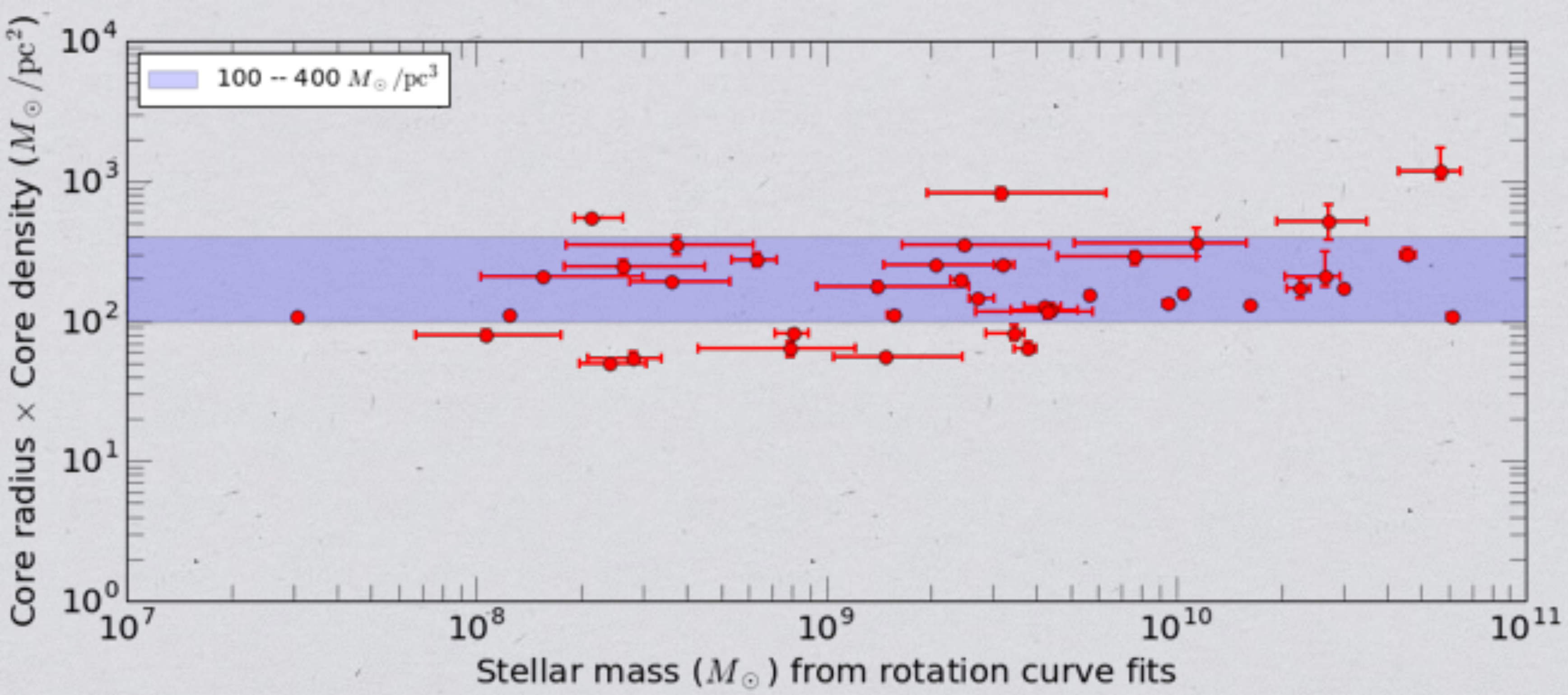
$$V = \pm \frac{\alpha_x}{r} \exp\left(-m_\phi r\right)$$



Kaplinghat, Tulin and Yu, 2015

Uniformity of DM (cored) profiles





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  - Fuzzy DM
    (though significantly ruled out by Menci+ 2017)