The Status of Sterile Neutrino Dark Matter

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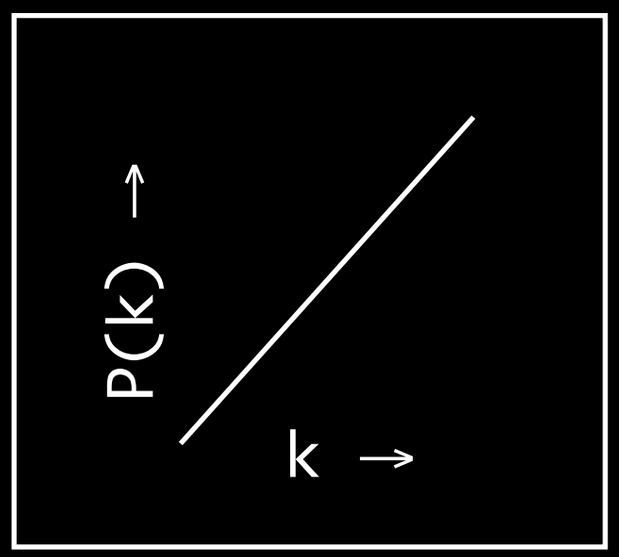
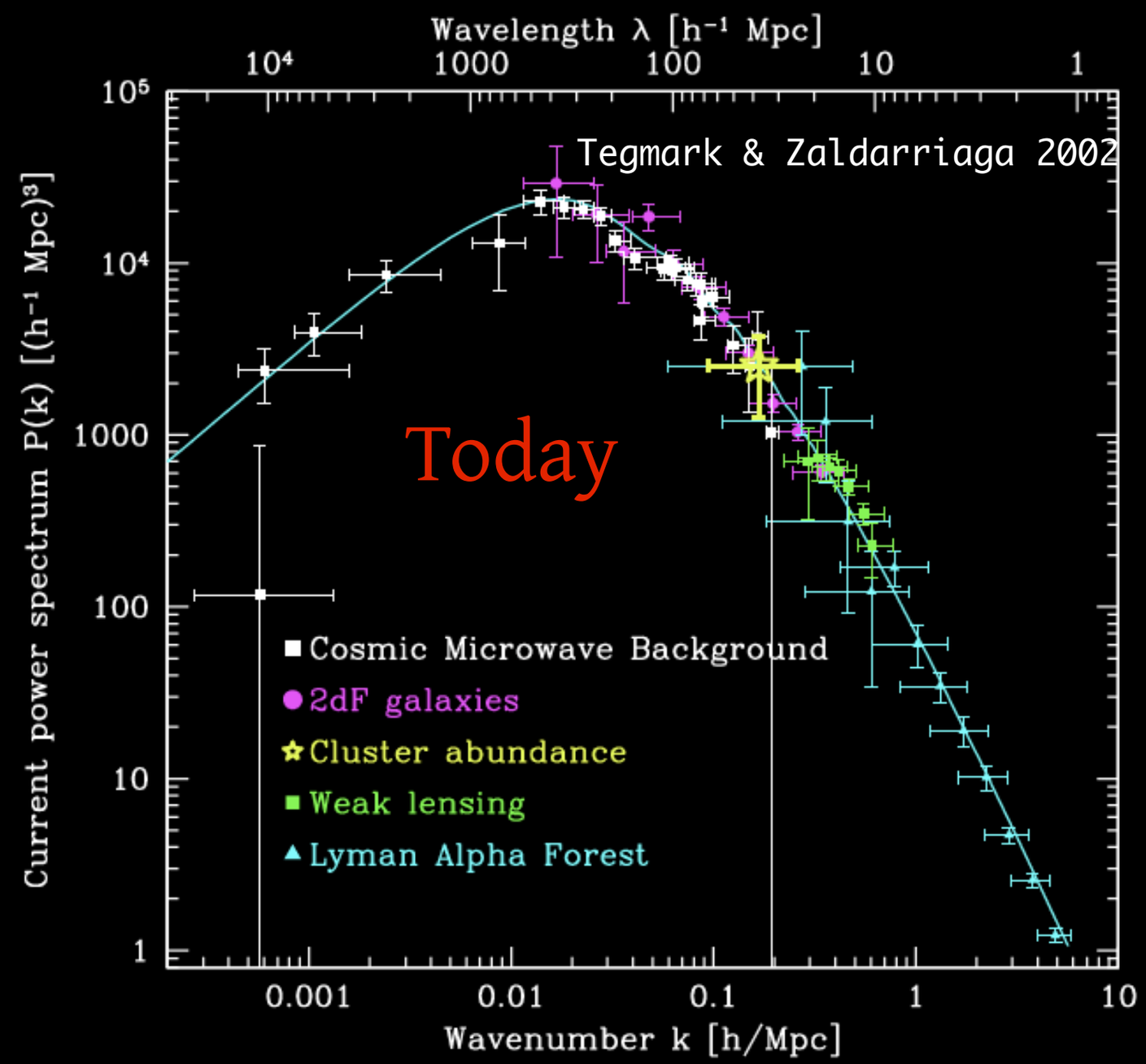
University of California, Irvine

Cosmic Frontiers - CF3 Session
March 7, 2013

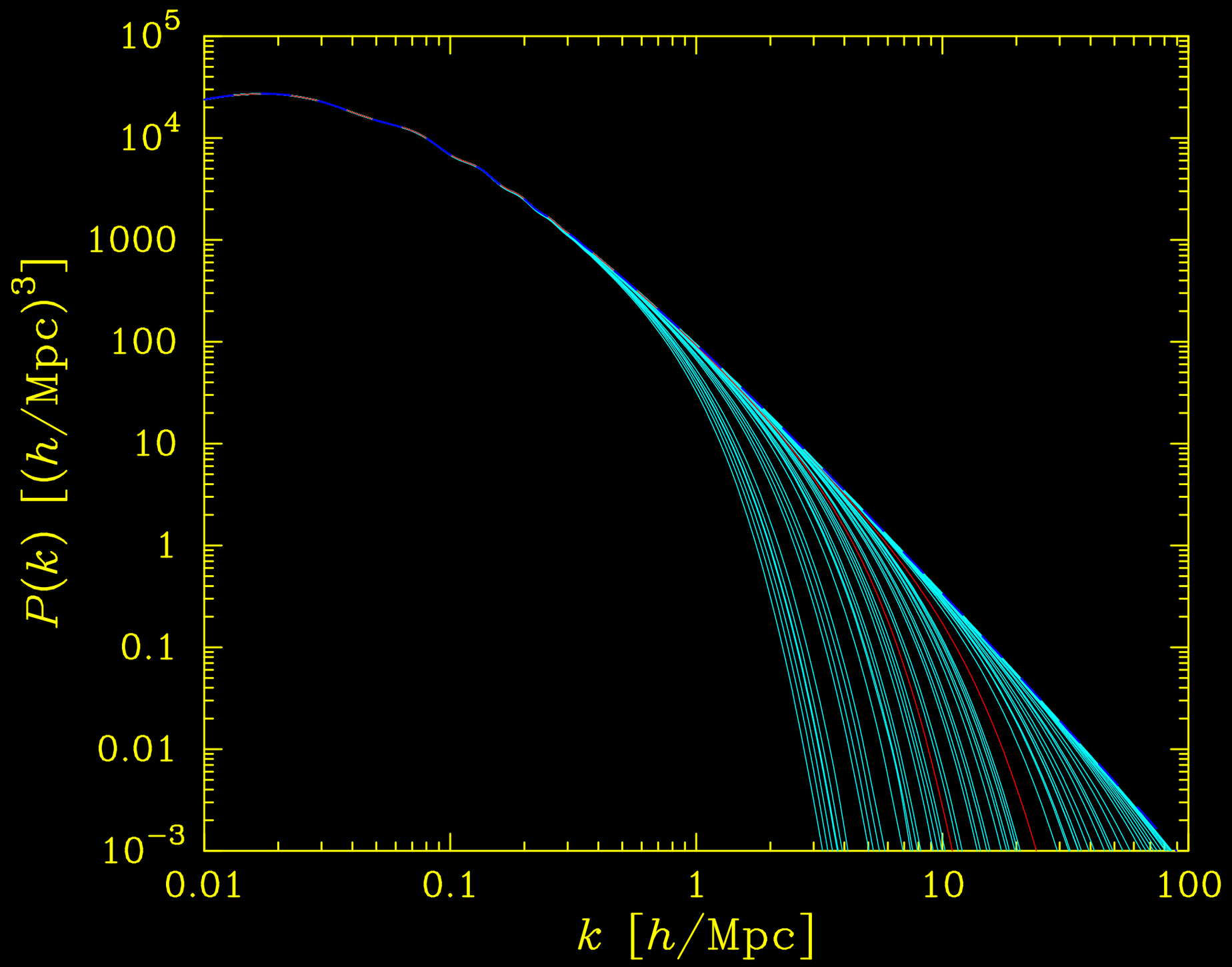
Large Scale Structure and The Matter Power Spectrum

Inflation





How far into the small-scale regime can we measure?



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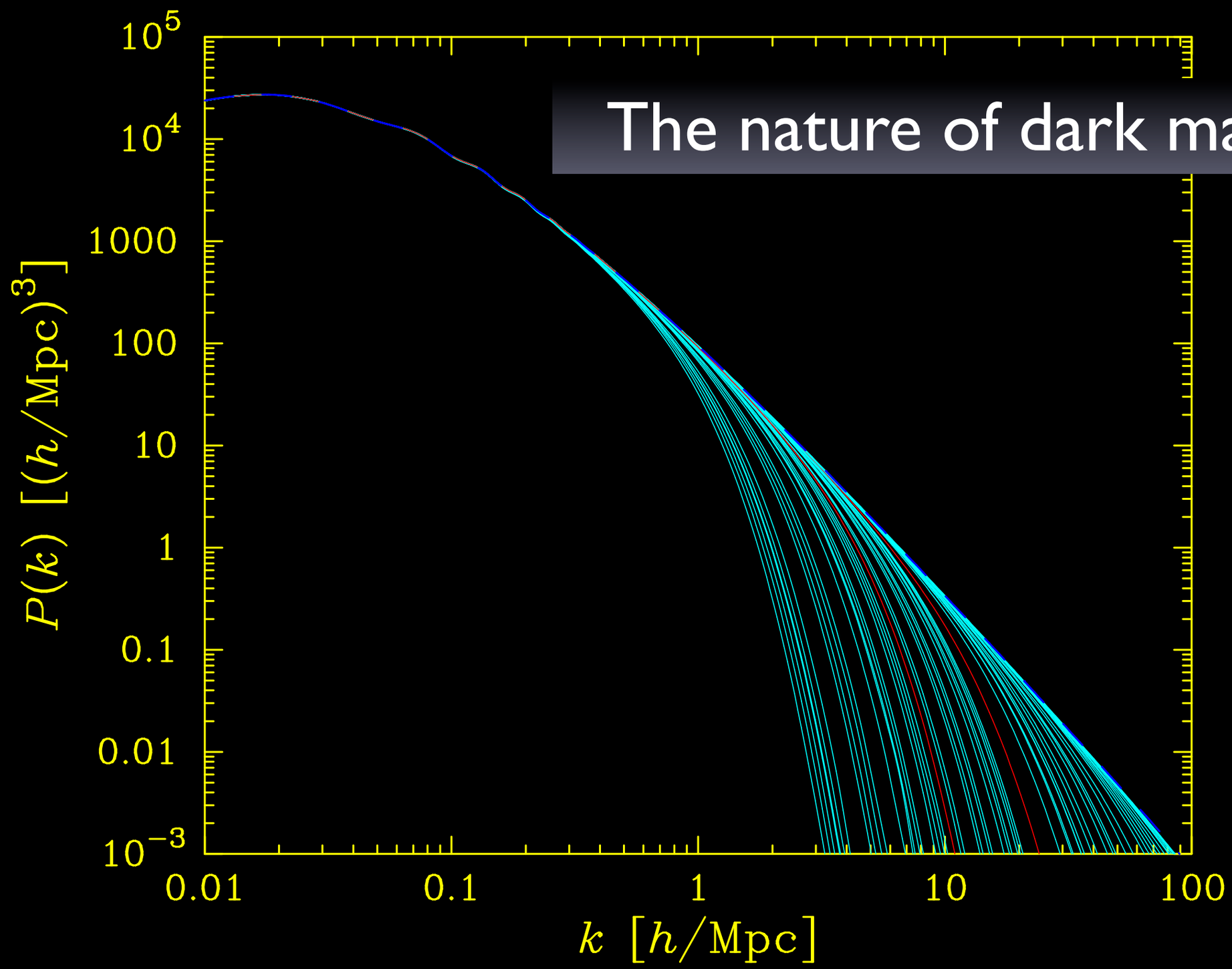

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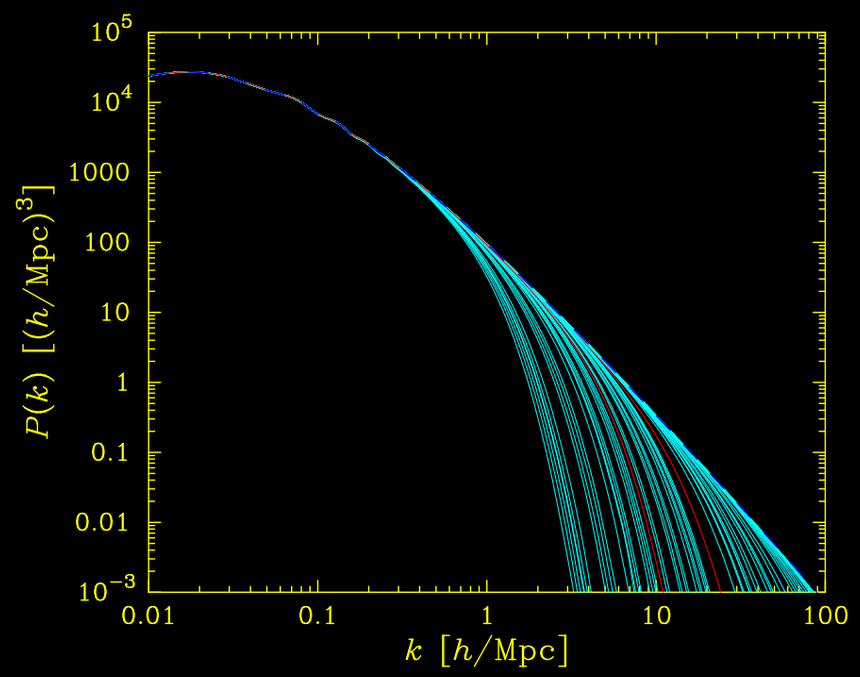

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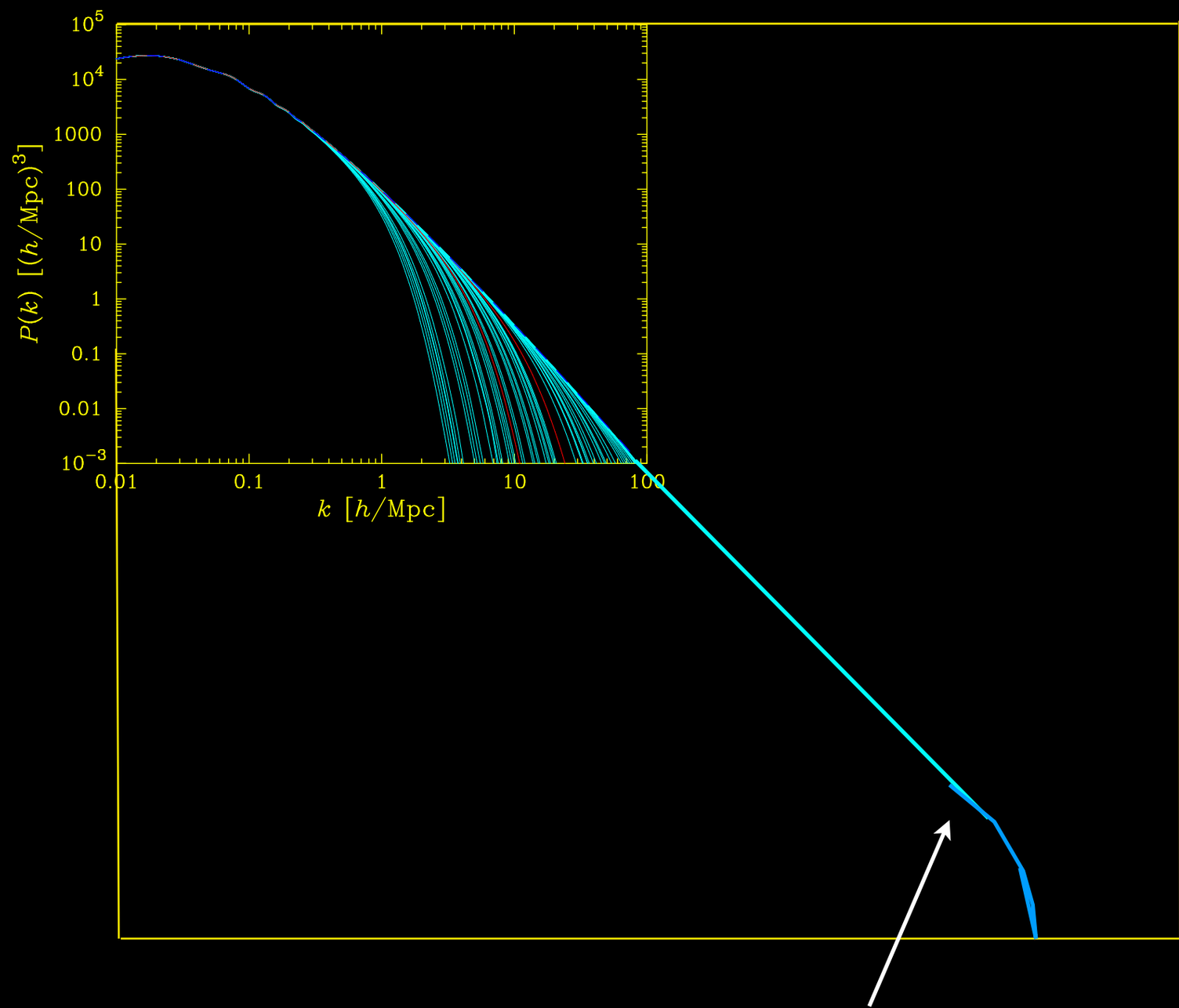

WIMP CDM

$k_c \sim 10^6\ h/\mathrm{Mpc}$

(Zaldarriaga & Loeb 2006)

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Dark matter comes out of the cold

By Jonathan Amos
BBC News science reporter

Astronomers have for the first time put some real numbers on the physical characteristics of dark matter.

The British team used 23 nights of observing time on the VLT

This strange material that dominates the Universe but which is invisible to current telescope technology is one of the great enigmas of modern science.

That it exists is one of the few things on which researchers have been certain.

But now an Institute of Astronomy, Cambridge, team has at last been able to place limits on how it is packed in space and measure its "temperature".

"It's the first clue of what this stuff might be," said Professor Gerry Gilmore. "For the first time ever, we're actually dealing with its physics," he told the BBC News website.

Science understands a great deal about what it terms baryonic matter - the "normal" matter which makes up the stars, planets and people - but it has struggled to comprehend the main material from which the cosmos is constructed.

Problems in Cold Dark Matter?

- Halo Substructure:
  satellite galaxies and sub-halos
  (Klypin et al 1999; Moore et al 1999)
- Halo Cores and Densities:
  (Zentner & Bullock 2003; Gilmore et al, 2003;
  Boylan-Kolchin et al. 2011; Parry et al. 2011)
- Void Galaxy abundances
  (Peebles 2001)
- Angular Momentum Problem
  (Navarro & Benz 1991;
  Sommer-Larsen & Dolgov 2001)
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Is the power spectrum different *at small scales*?

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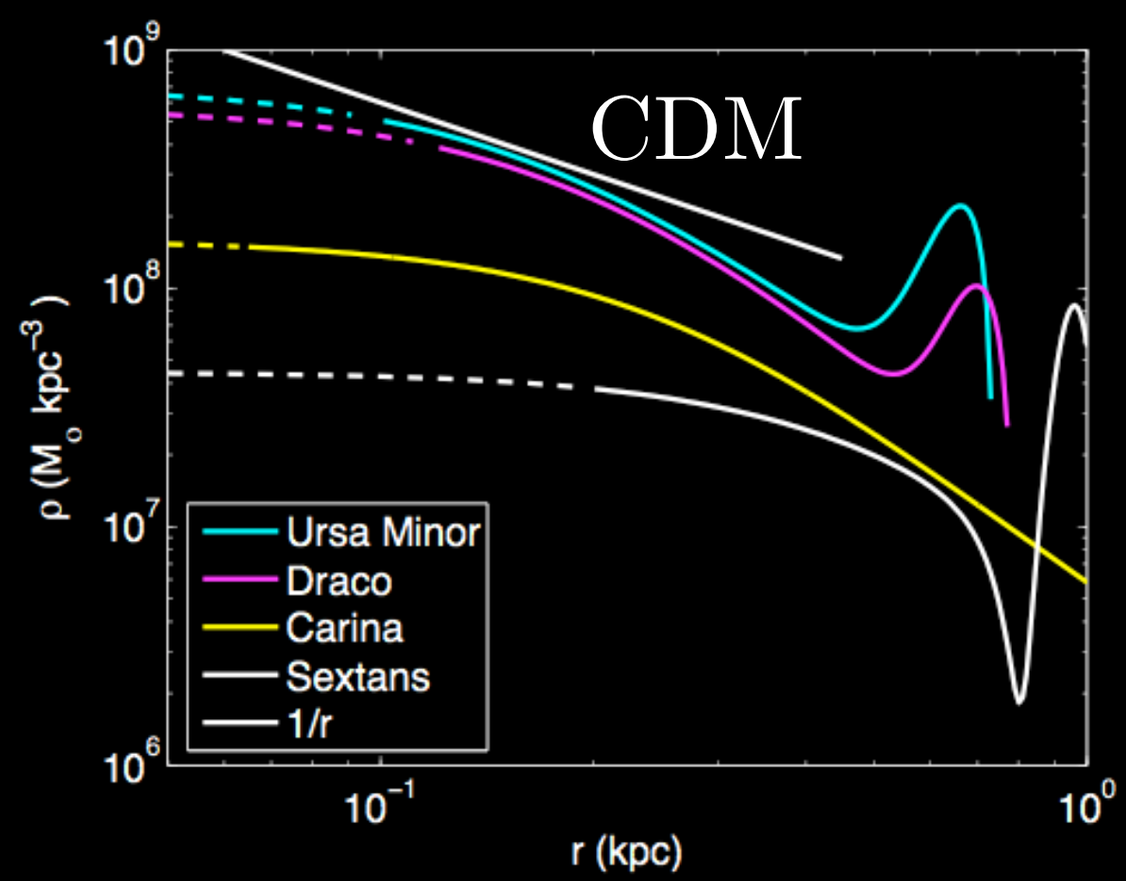
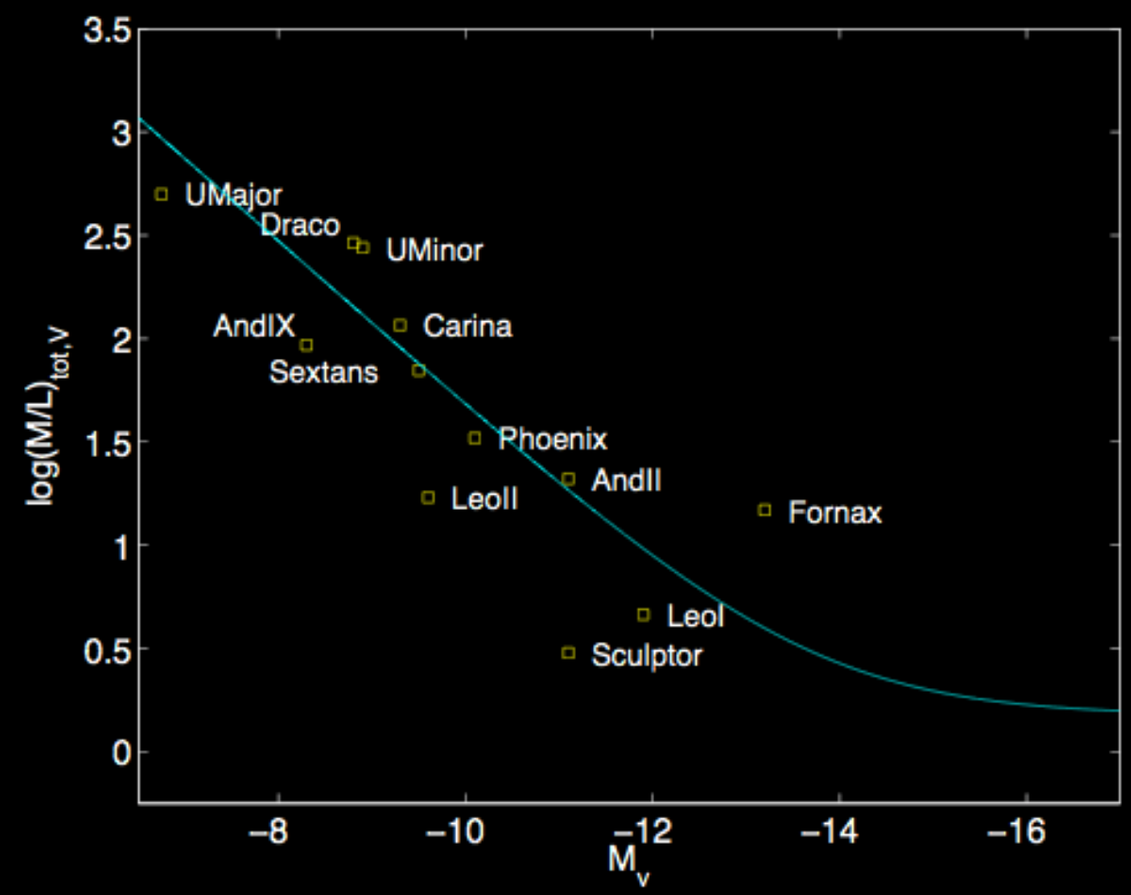
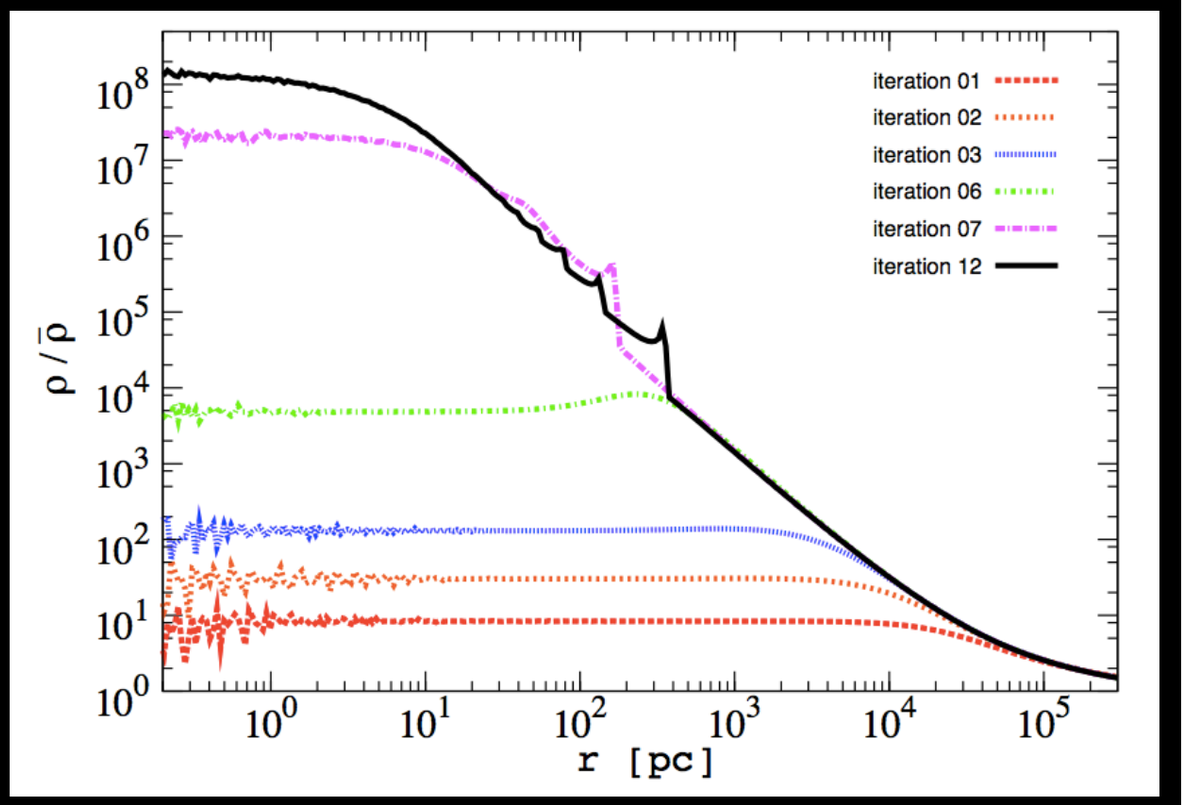
Dwarf Spheroidal Density Profiles from Radial Stellar Velocity Dispersion

- All dwarf spheroidals studied are consistent with NFW and cored profiles, except for UMi, “only consistent with cored profile” [Gilmore et al.,astro-ph/0608528]
- Constant core mass within stellar profile

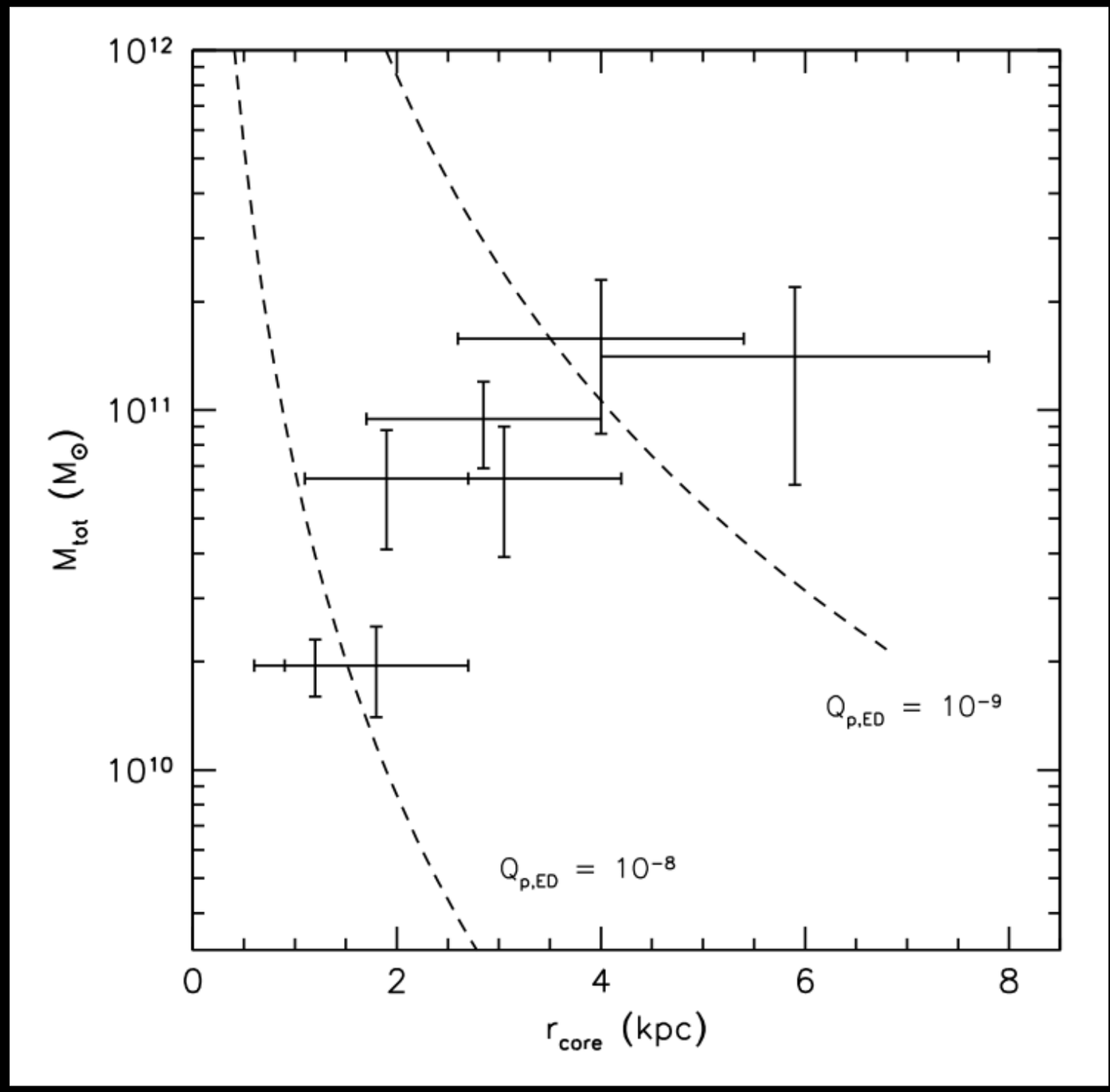




WDM Does *Not* Produce Cores!



Dalal & Villaescusa-Navarro 2010



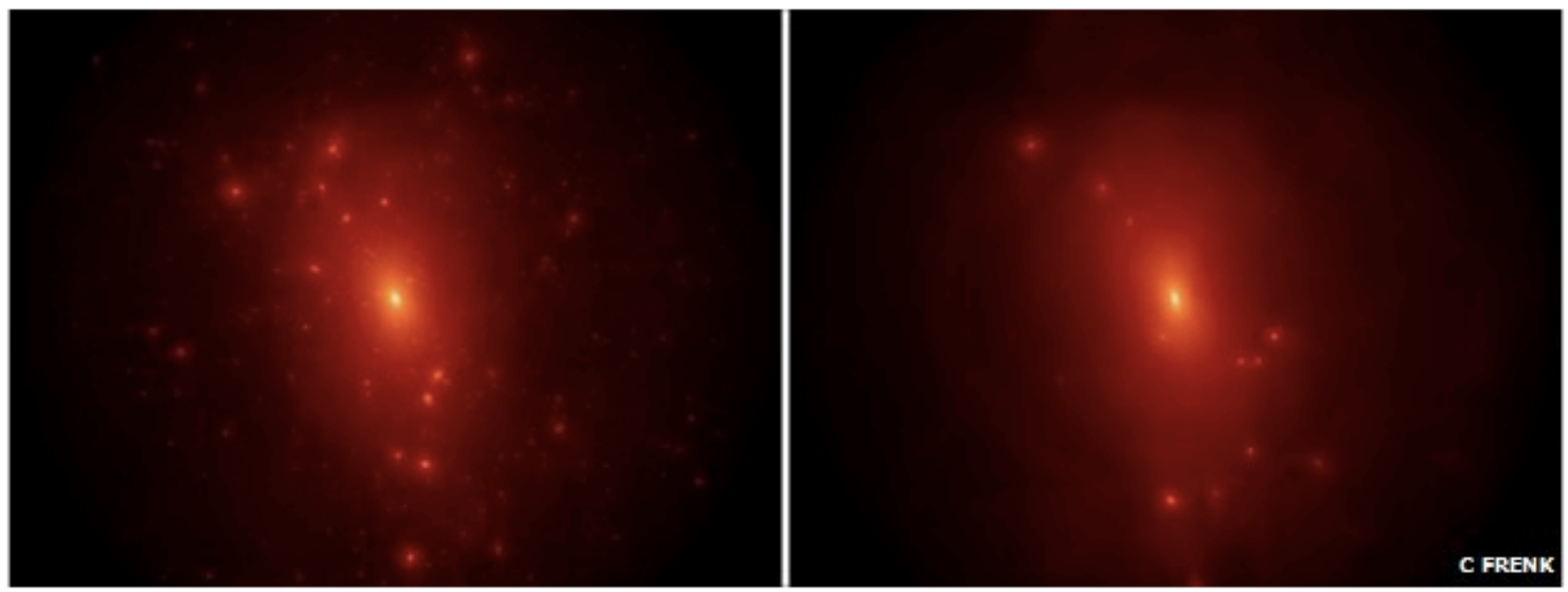
Kuzio de Naray et al 2009

16 September 2011 Last updated at 13:47 ET

6,051 Share

Dwarf galaxies suggest dark matter theory may be wrong

By Leila Battison
Science reporter, Bradford



Dwarf galaxies around the Milky Way are less dense than they should be if they held cold dark matter

Scientists' predictions about the mysterious dark matter purported to make up most of the mass of the Universe may have to be revised.

Research on dwarf galaxies suggests they cannot form in the way they do if dark matter exists in the form that the most common model requires it to.

That may mean that the Large Hadron Collider will not be able to spot it.

Leading cosmologist Carlos Frenk spoke of the "disturbing" developments

Related Stories

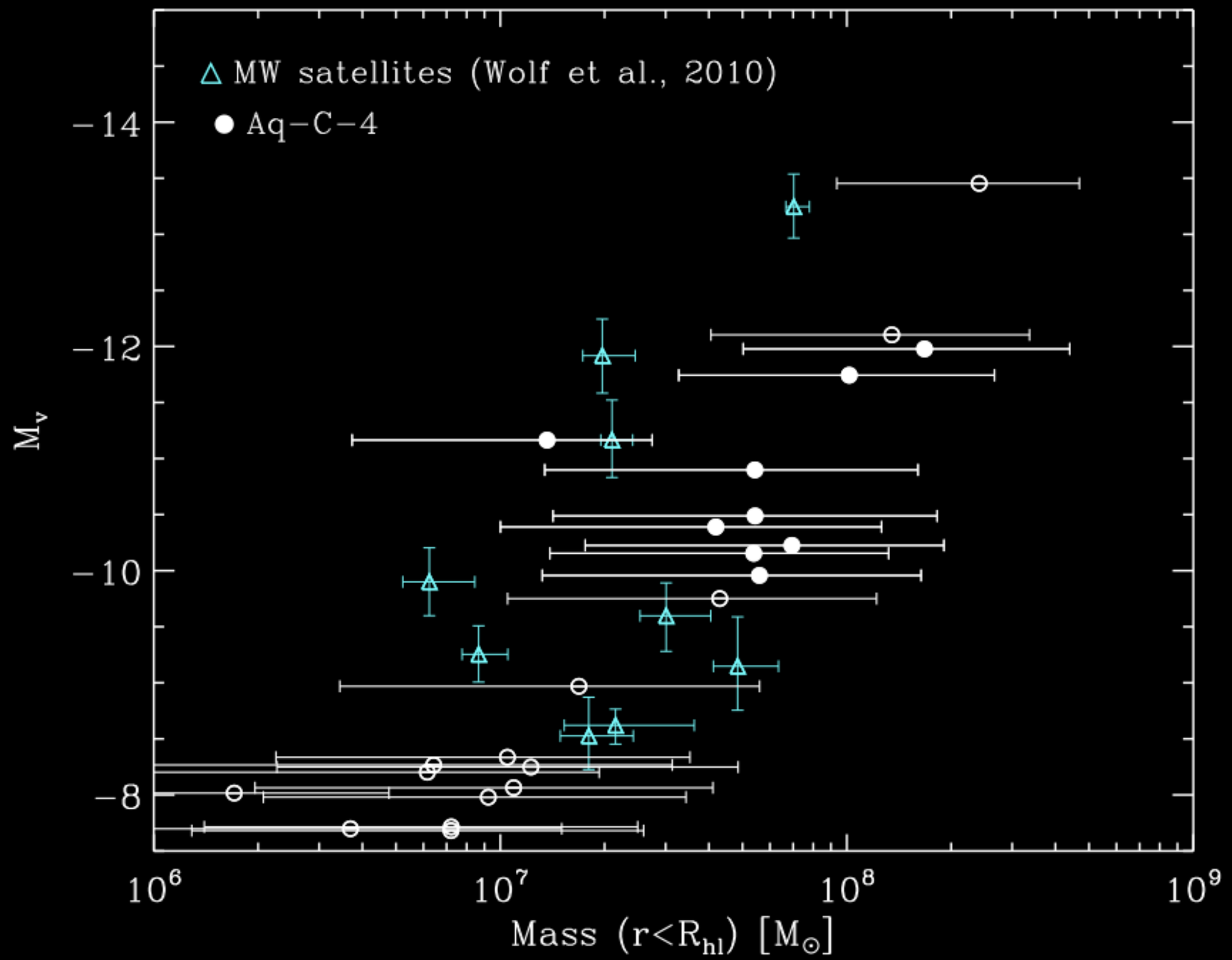
Dark matter hunters see 67 hints

Is LHC closing in on elusive Higgs particle?

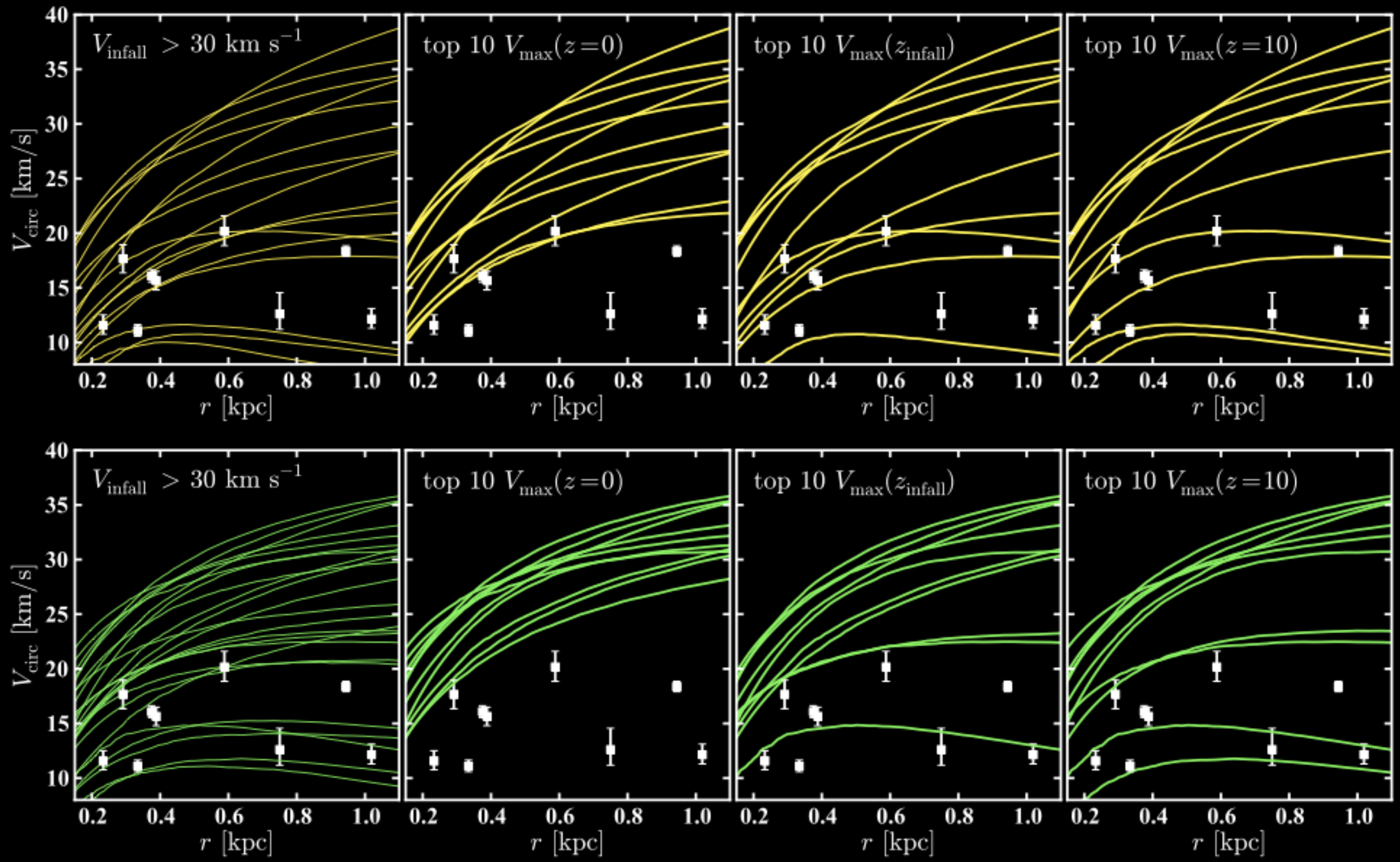
'Filaments' hold dark matter test

Low Central Densities in Dwarfs

(Parry, Eke, Frenk, Okamoto 2011)

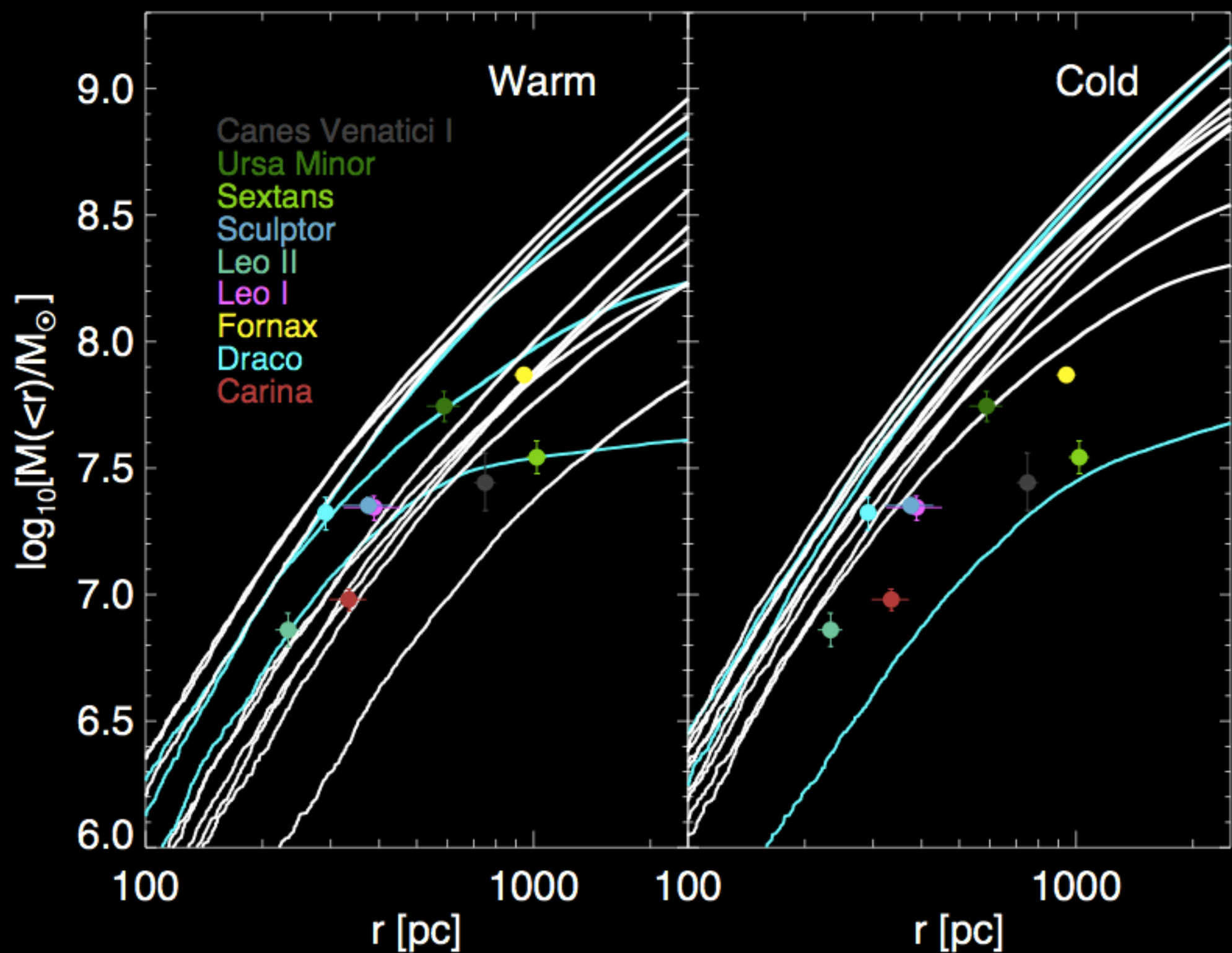


Dark Matter V_{circ} / Central Concentrations are Much Too Low... The Subhalos are "Too Big Too Fail"



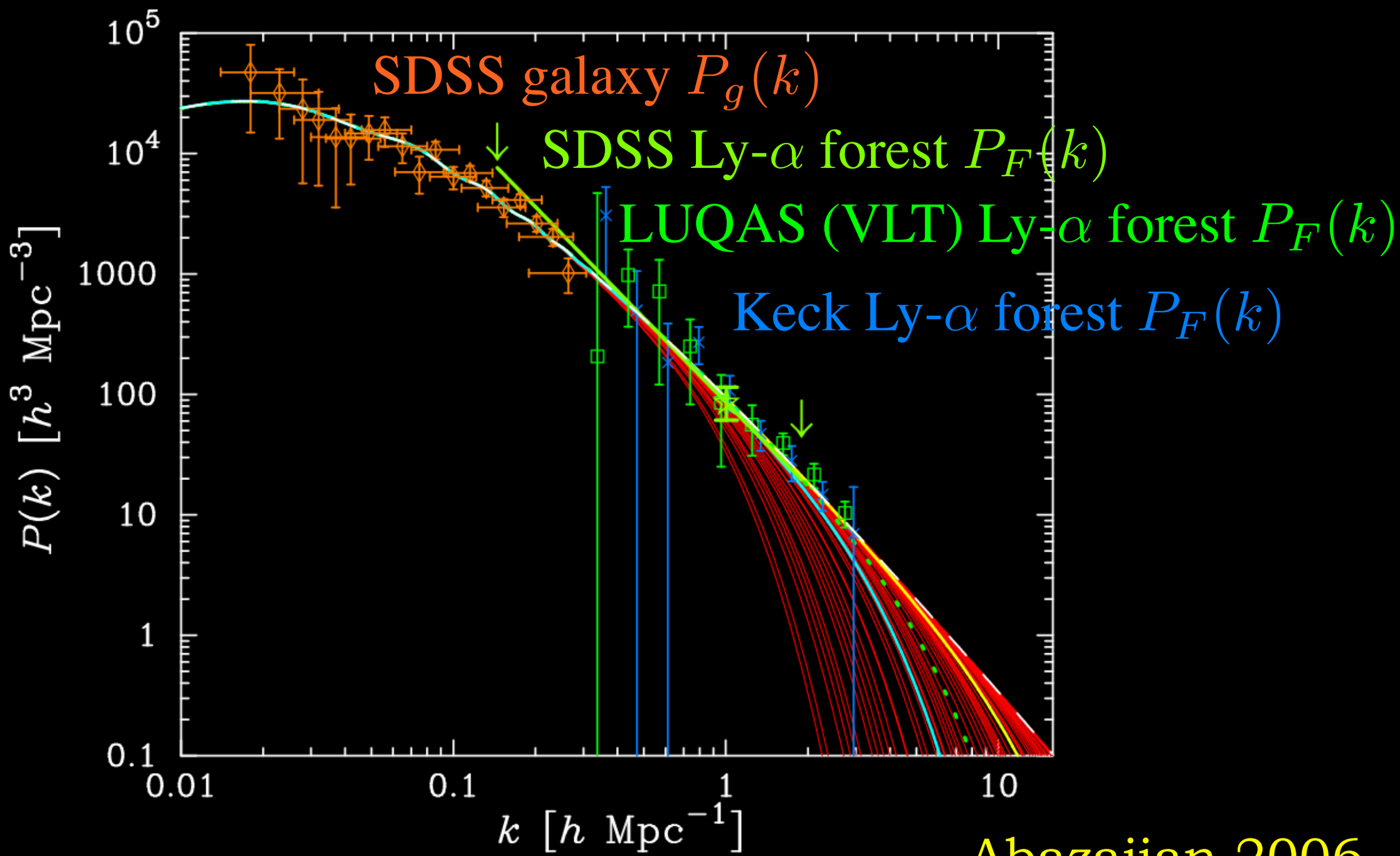
Boylan-Kolchin, Bullock, Kaplinghat 2011

WDM Solution to "Too Big To Fail"?



Lovell et al. 2010

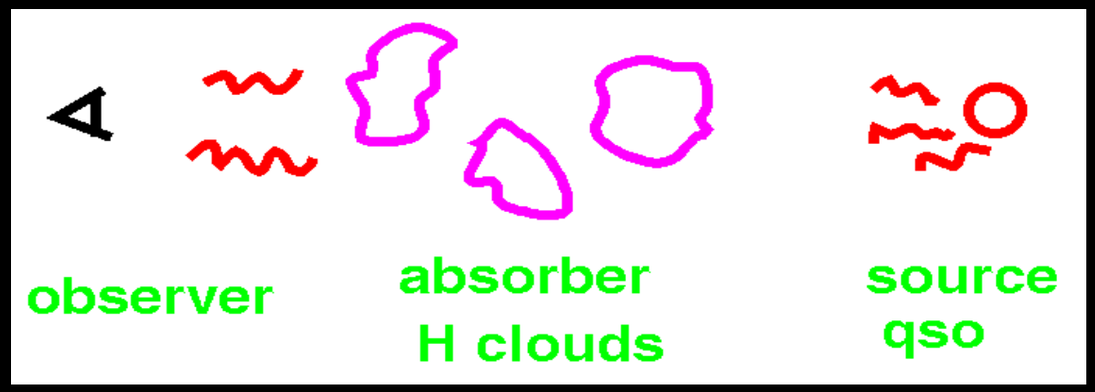
Where does the CDM ansatz fail?

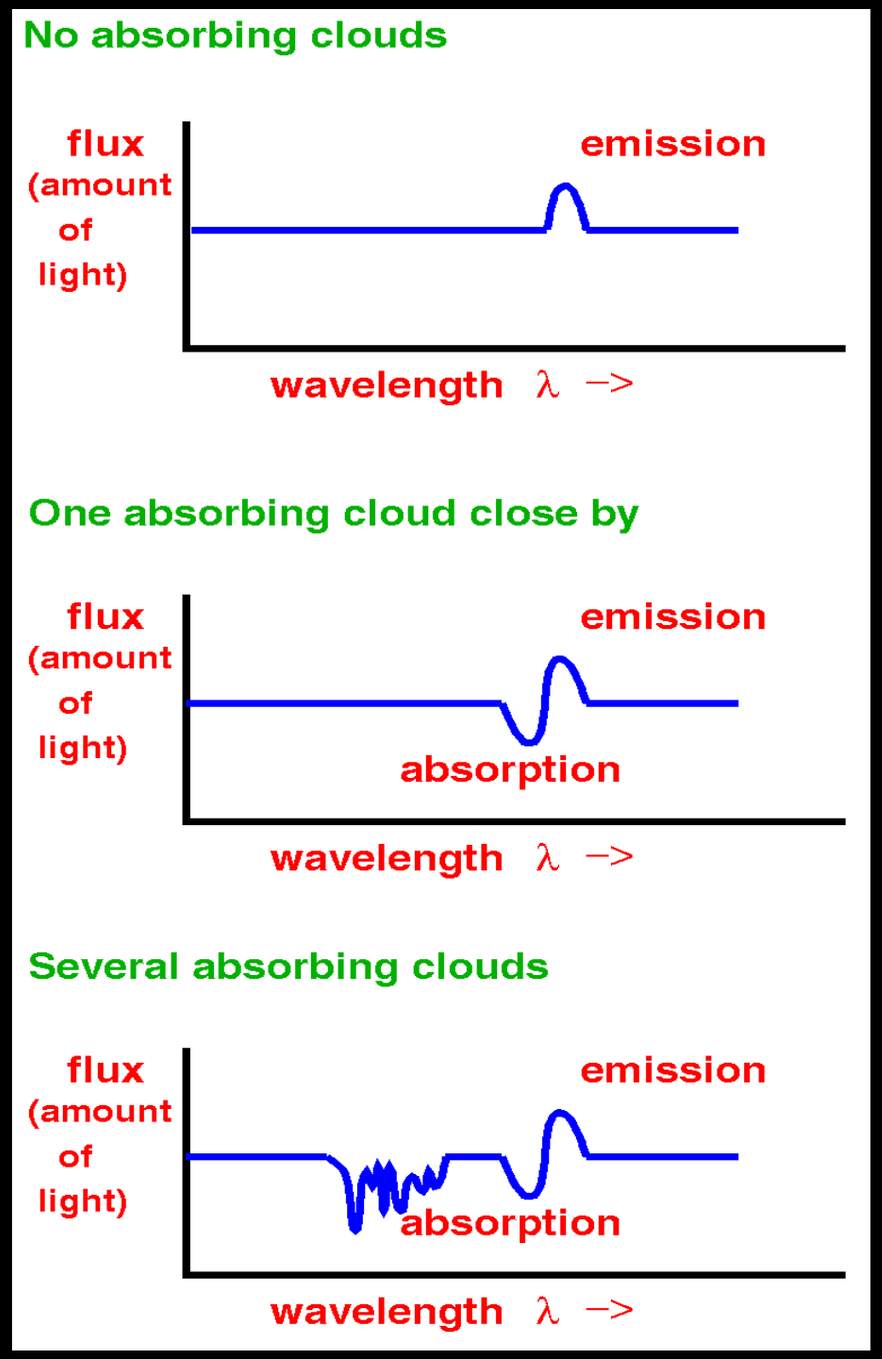


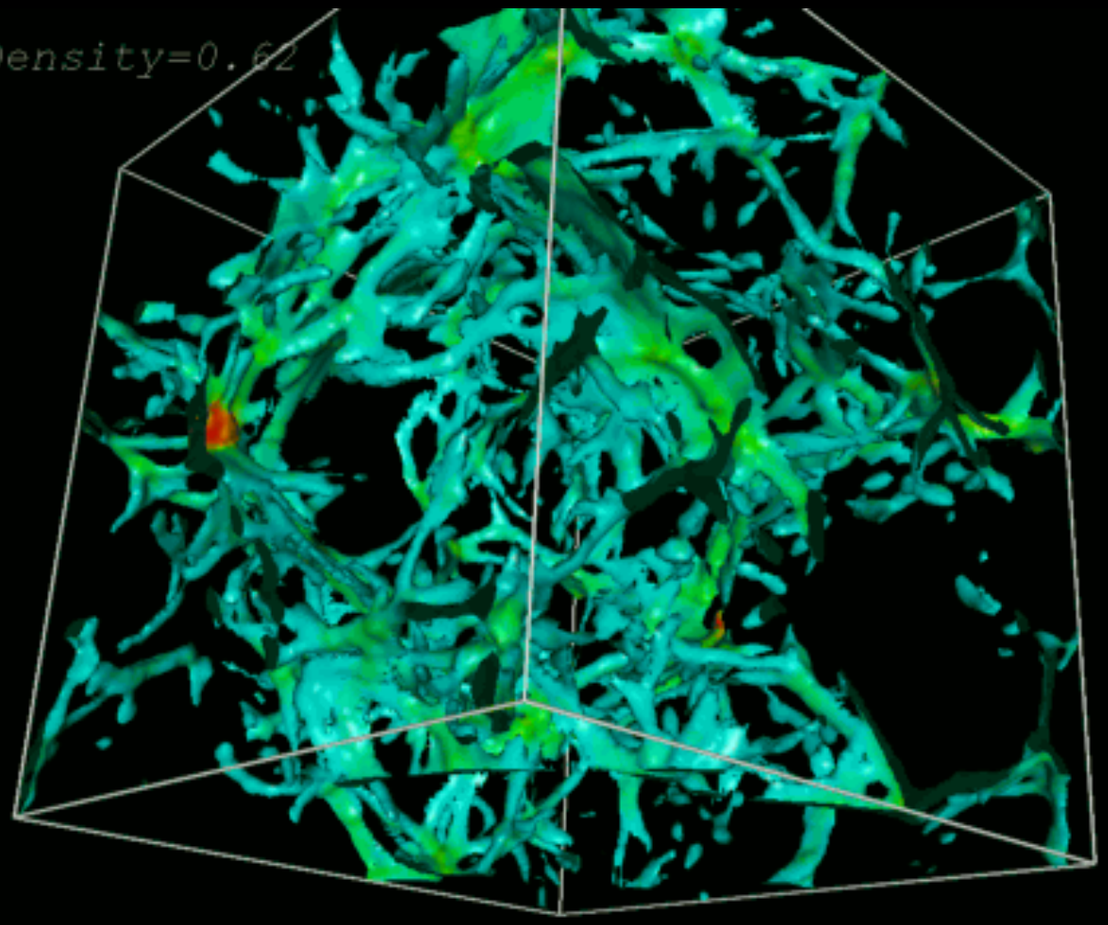
Abazajian 2006

- 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

Lyman-α forest: Powerful & Challenging







J. Shalf, Y. Zhang (UIUC) et al., GCCC

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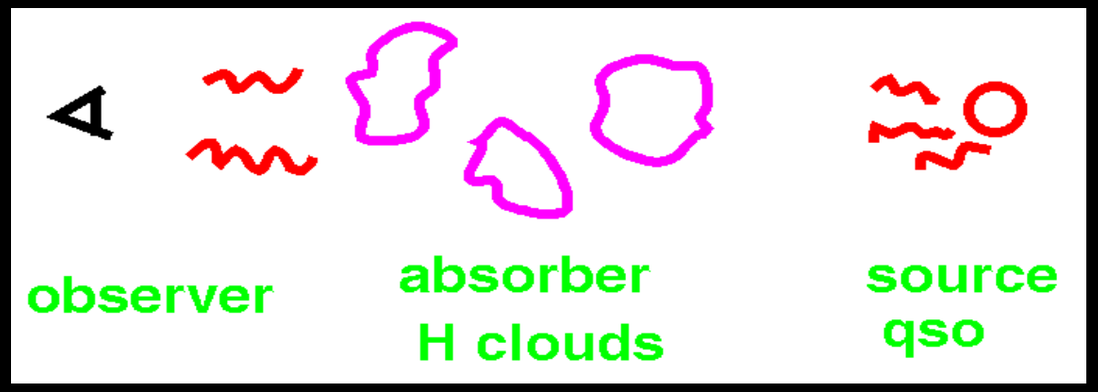
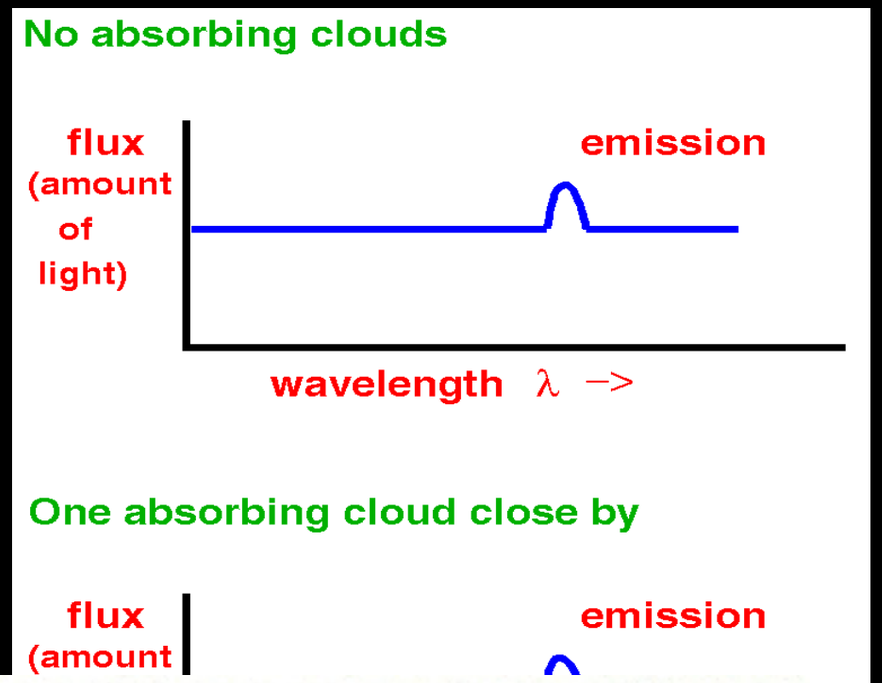
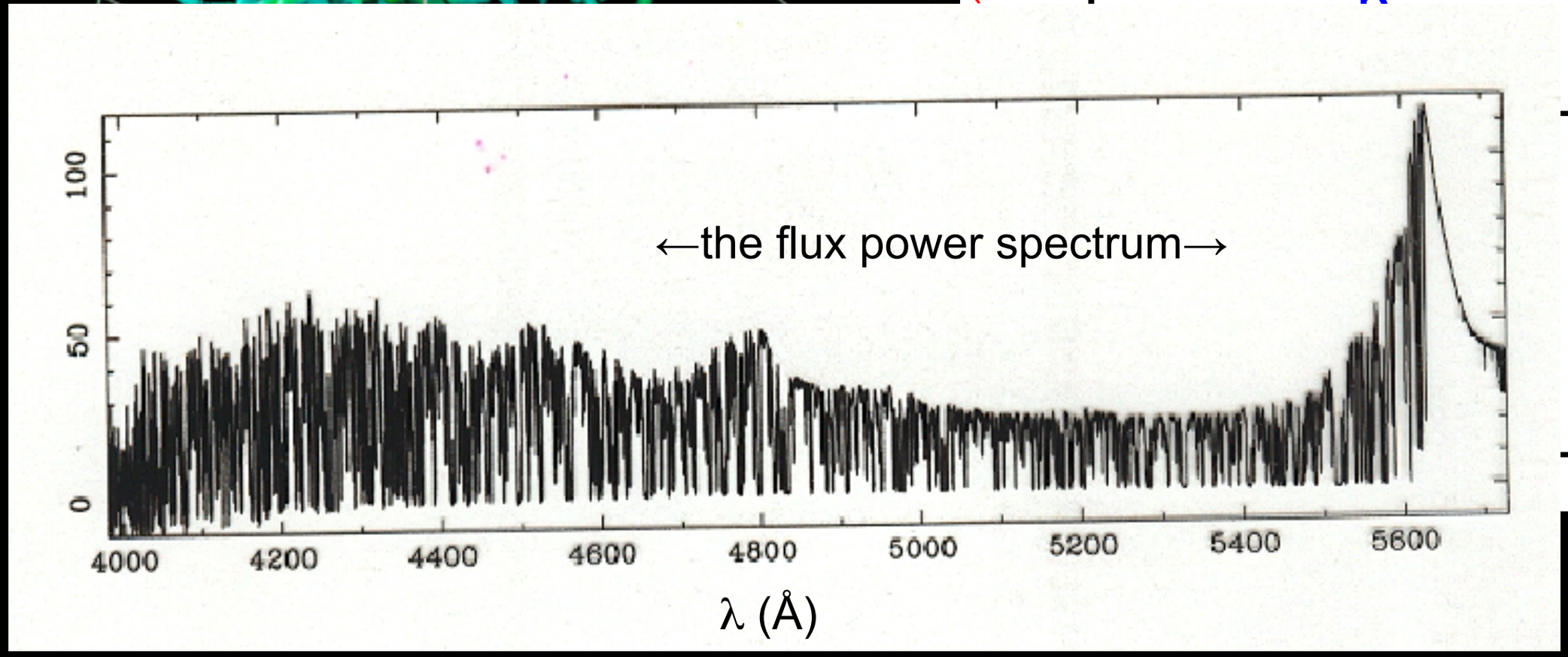
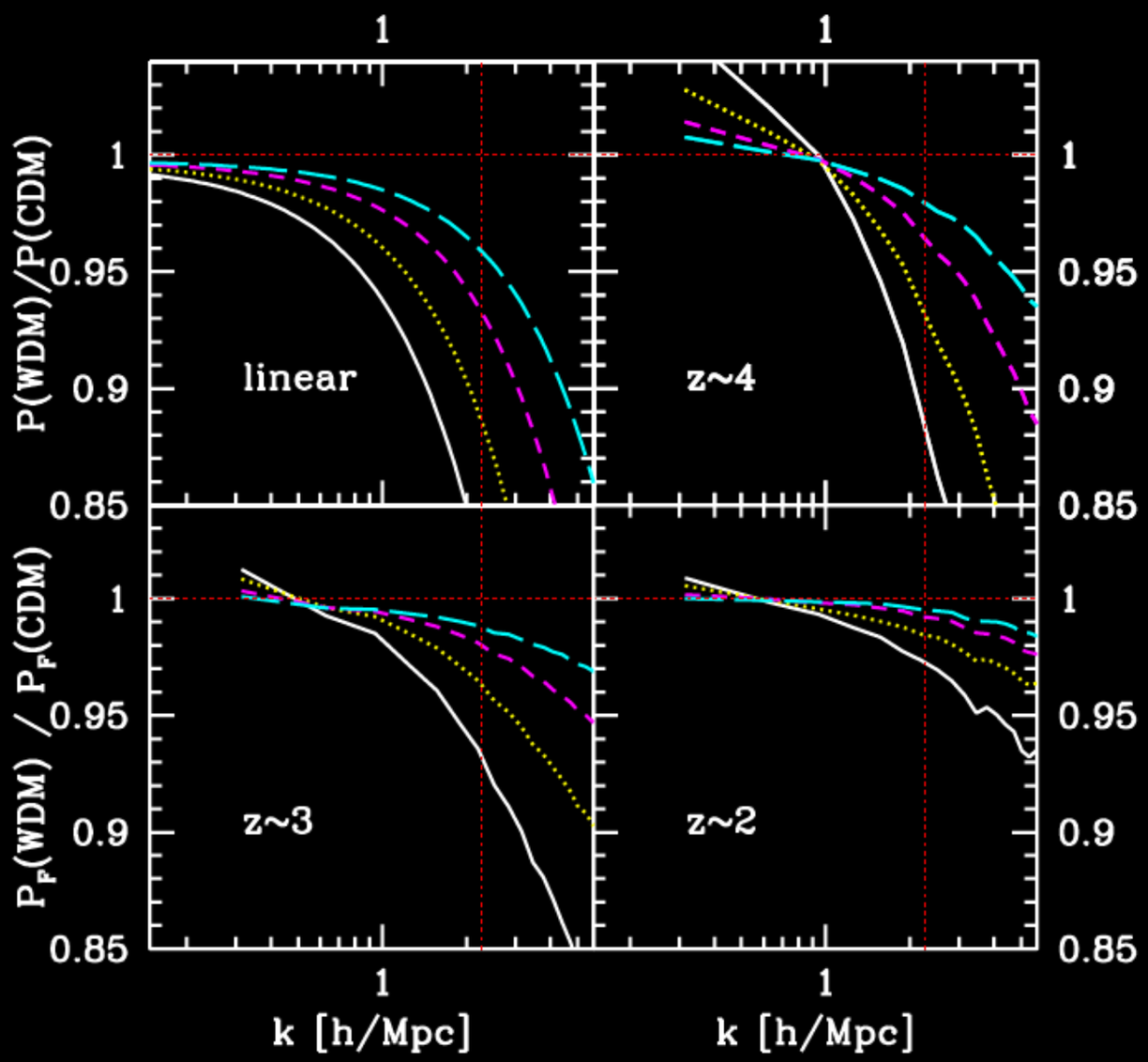
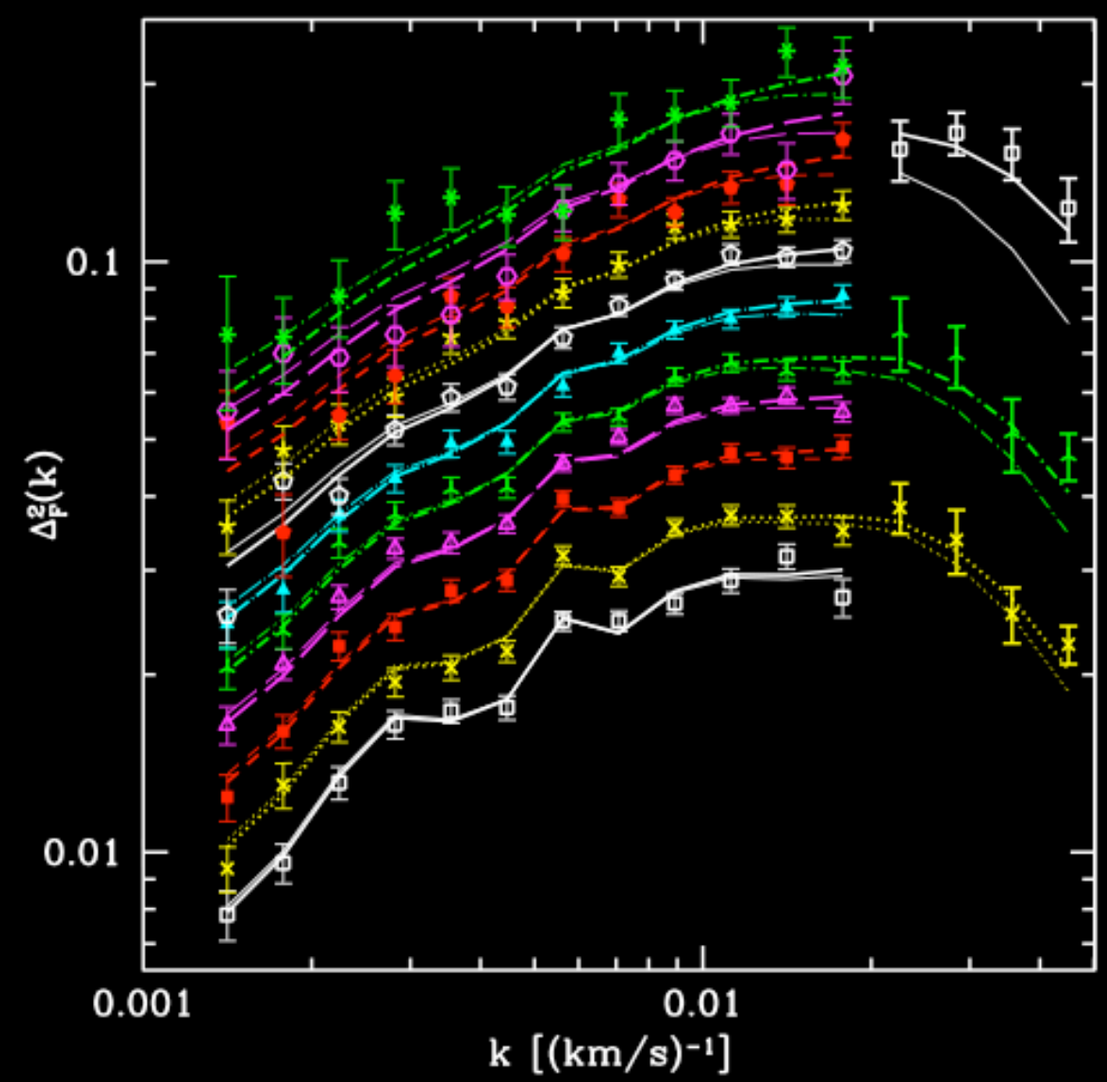






Lyman-alpha Forest Constraints on CDM





$m_s > 14$ keV Seljak et al 2006: WMAP1 + SDSS Pg(k) + Lya + HR

$\lambda_{FS} < 54$ kpc $M_{FS} < 10^7$ M_{sun} (Abazajian & Koushiappas 2006)

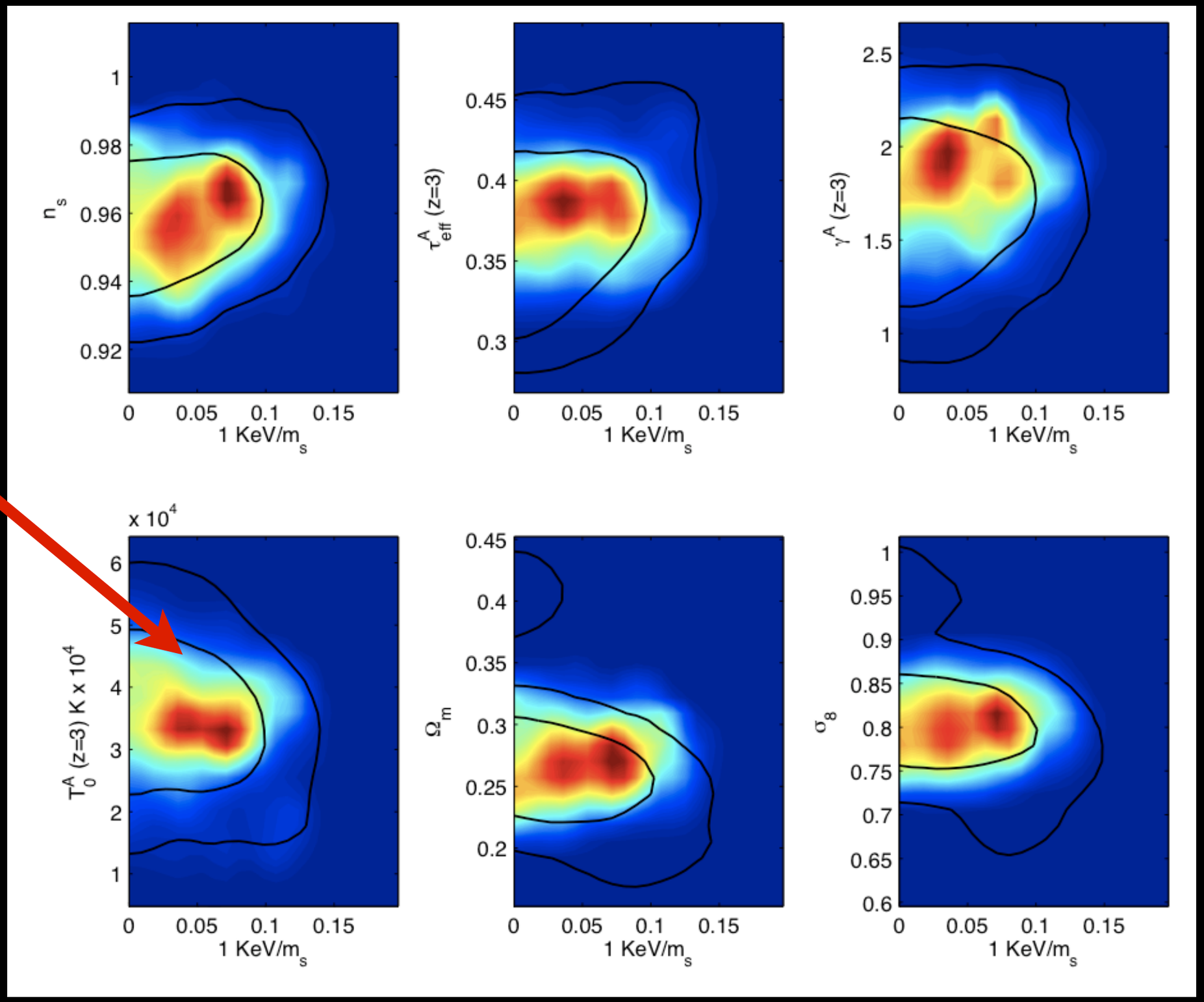
$m_s > 8$ keV(99%CL) (SDSS P_F(k) + VLT data; Boyarsky et al 2009)

$m_s > 2$ keV (99%CL) "Cool DM"

SDSS Ly-α Constraints: Viel et al 2006 (*unpublished*)

WDM analysis

Very high T_0 ~35000 K



Turning an astrophysical signal into a constraint: The Dwarf galaxy count in the Milky Way

TABLE II. Summary of known Milky Way satellites.

Name	*dist* [kpc]	σ_{star} [km/s]	M_V	References
Classical (pre-SDSS)				
Sagittar	24 ± 2	11.4 ± 0.7	-13.4	[72]
LMC	49 ± 2	-	-18.4	[72]
SMC	58 ± 2	-	-17.0	[72]
Ursa Minor	66 ± 3	9.3 ± 1.8	-8.9	[72]
Draco	79 ± 4	9.5 ± 1.6	-8.8	[72]
Sculptor	79 ± 4	6.6 ± 0.7	-11.1	[72]
Sextans	86 ± 4	6.6 ± 0.7	-9.5	[72]
Carina	94 ± 5	6.8 ± 1.6	-9.3	[72]
Fornax	138 ± 8	10.5 ± 1.5	-13.2	[72]
Leo II	205 ± 12	6.7 ± 1.1	-9.6	[72]
Leo I	270 ± 30	8.8 ± 0.9	-11.9	[72]
Phoenix	405 ± 15	-	-10.1	[72]
SDSS discovered				
Segue I	23 ± 2	4.3 ± 1.2	-1.5	[73]
Ursa Major II	30 ± 5	6.7 ± 1.4	-3.8	[74, 75]
Segue II	~ 35	3.4 ± 2.0	-2.5	[76]
Willman I	38 ± 7	$4.3^{+2.3}_{-1.3}$	-2.5	[74, 77]
Coma Berenics	44 ± 4	4.6 ± 0.8	-3.7	[75, 78]
Bootes II	60 ± 10	-	-3.1	[79]
Bootes I	62 ± 3	$6.5^{+2.0}_{-1.4}$	-5.8	[74]
Pisces I	80 ± 14	-	-	[80, 81]
Ursa Major I	106^{+9}_{-8}	7.6 ± 1.0	-5.6	[75]
Hercules	140^{+13}_{-12}	5.1 ± 0.9	-6.0	[75, 78]
Canes Venatici II	150^{+15}_{-14}	4.6 ± 1.0	-4.8	[75, 78]
Leo IV	160^{+15}_{-14}	3.3 ± 1.7	-5.8	[75, 78]
Leo V	175 ± 9	2.4 ± 1.8	-5.2	[82, 83]
Pisces II	~ 180	-	-5.0	[84]
Canes Venatici I	220^{+25}_{-16}	7.6 ± 0.4	-7.9	[75, 85]
Leo T	~ 420	7.5 ± 1.6	-7.1	[75, 86]

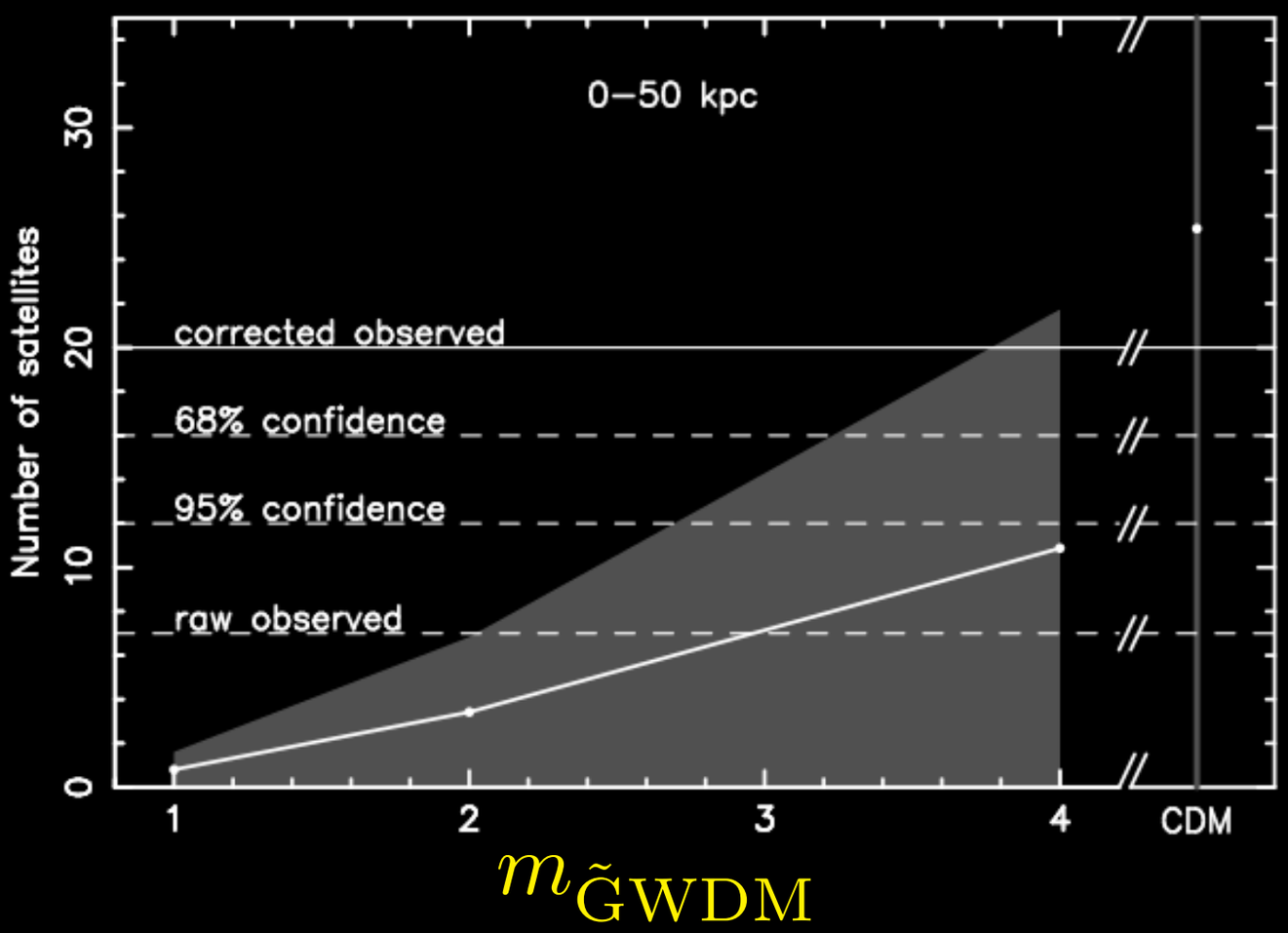
- Eventually, WDM is too much of a good thing, oversupression of the dwarf galaxy scale
- SDSS has found a large population of new dwarf galaxies in the MW local group

$$m_{\tilde{G}} \gtrsim 2 \text{ keV}$$

$$m_s \gtrsim 10 \text{ keV}$$

Polisensky & Ricotti (2011)

Turning an astrophysical signal into a constraint: The Dwarf galaxy count in the Milky Way



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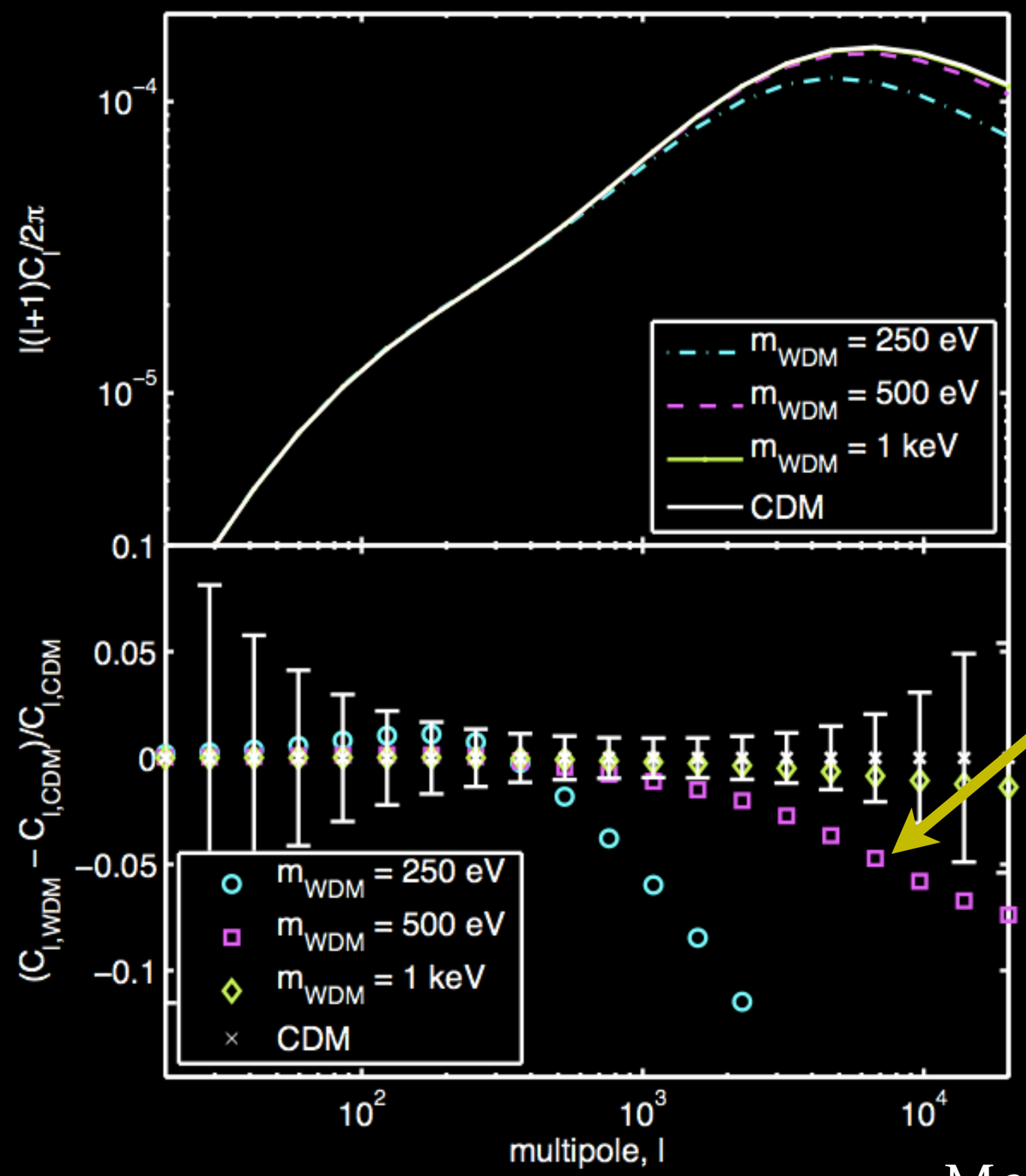
Weak Lensing Measures of the Nonlinear Regime



Great sensitivity to the effects of WDM

Markovic et al 2011

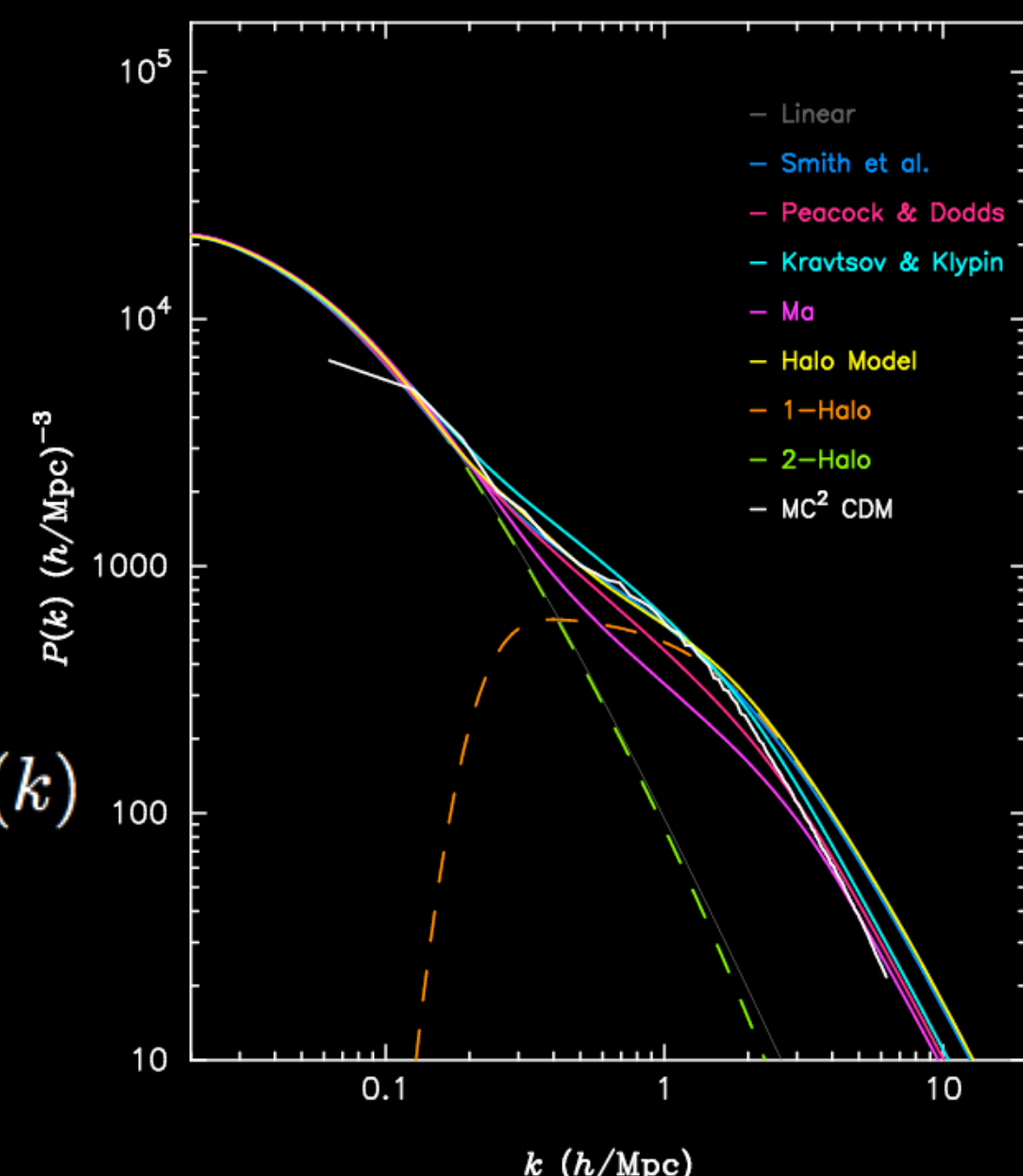
Modeling nonlinear clustering: The full halo model in WDM

$$P(k) = P_{1h}(k) + P_{2h}(k) + P_{ss}(k) + P_{sh}(k)$$

$$P^{1h}(k) = \int dM \frac{dn}{dM} \left(\frac{M}{\bar{\rho}}\right)^2 |u(k \mid M)|^2$$

$$P^{2h}(k) = \int dM_1 \frac{dn}{dM_1} \frac{M_1}{\bar{\rho}} u(k \mid M_1) \times \int dM_2 \frac{dn}{dM_2} \frac{M_2}{\bar{\rho}} u(k \mid M_2) \times P_{hh}(k \mid M_1, M_2).$$

$$P_{hh}(k \mid M_1, M_2) \approx b_1(M_1)\, b_2(M_2)\, P_{lin}(k)$$

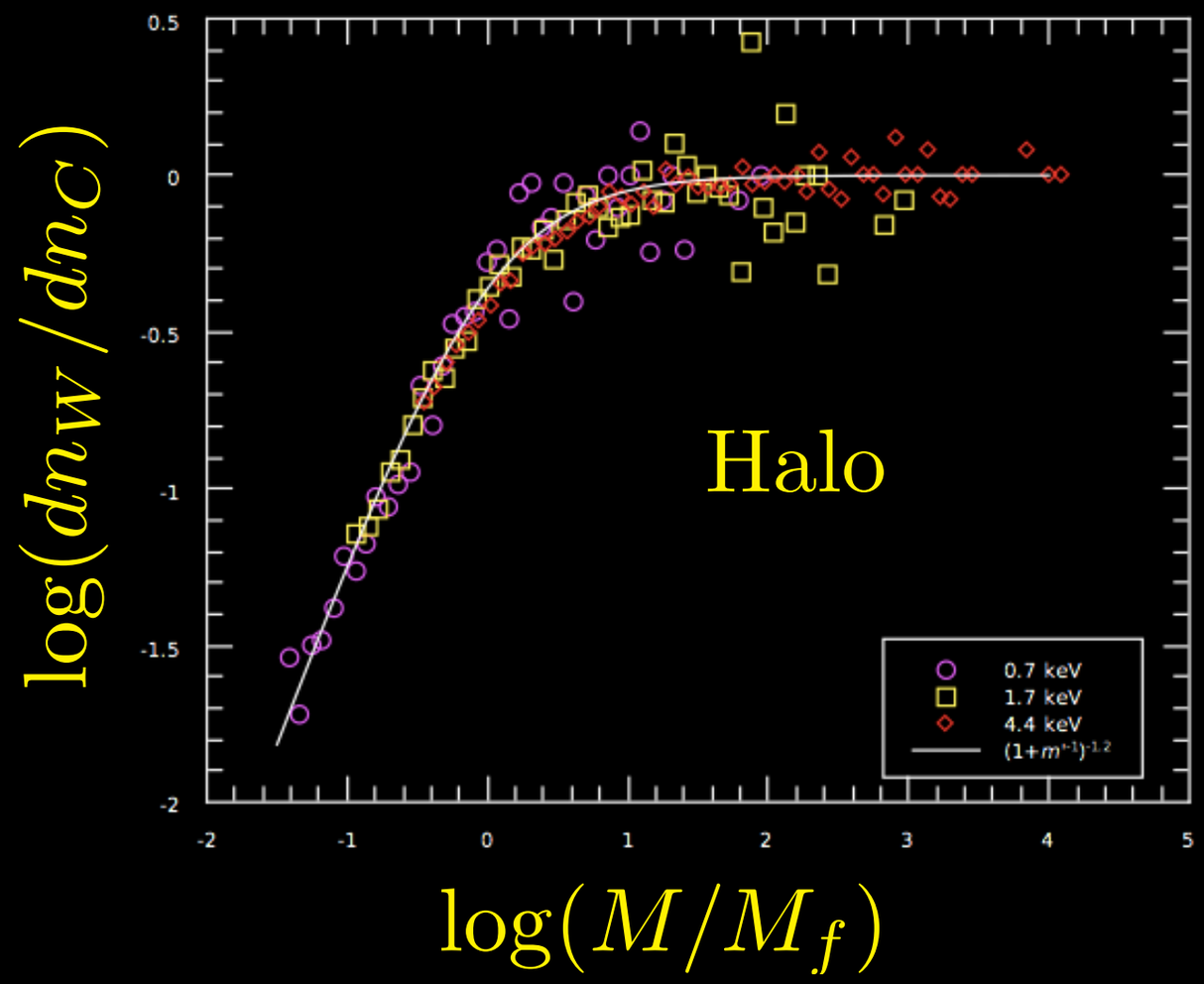


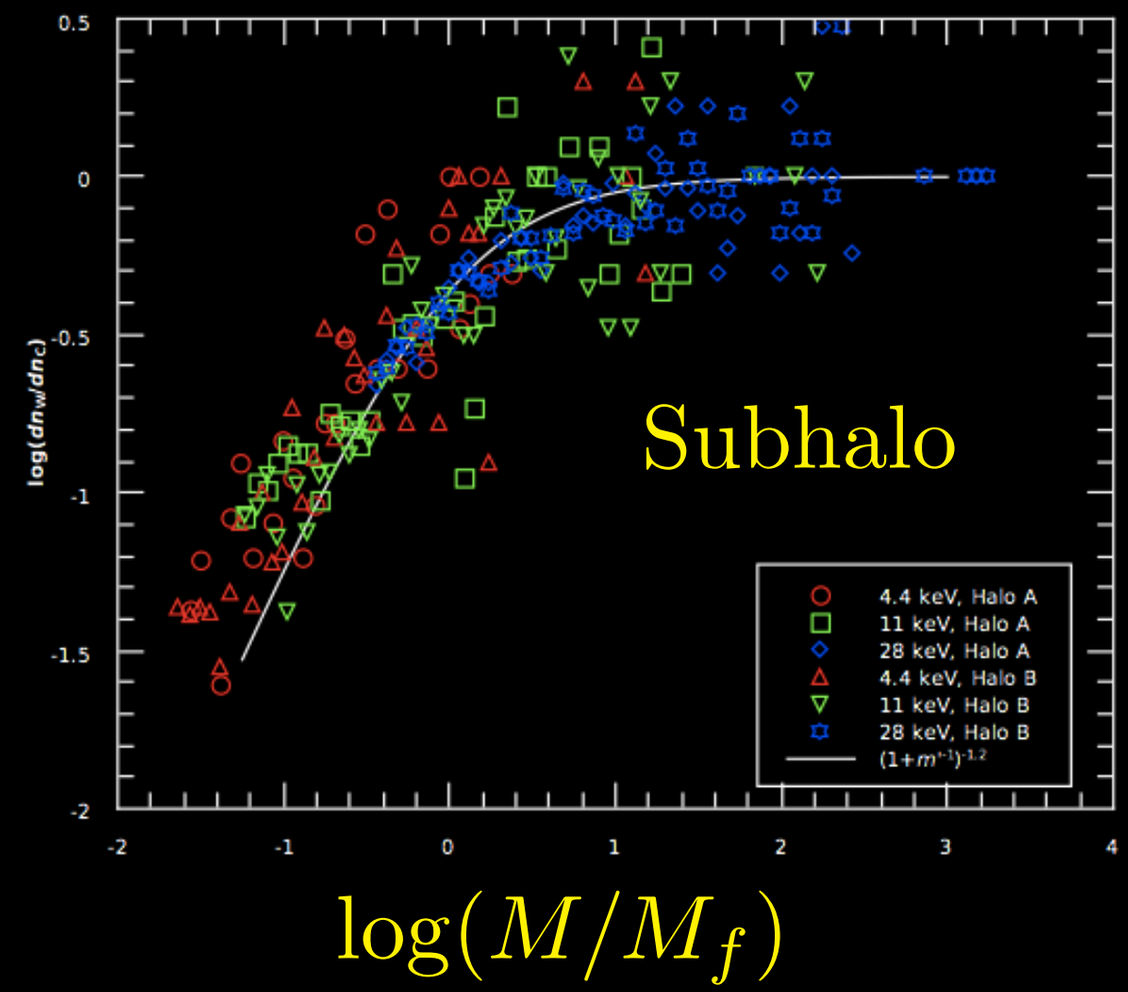
Substructure within 1 halo:

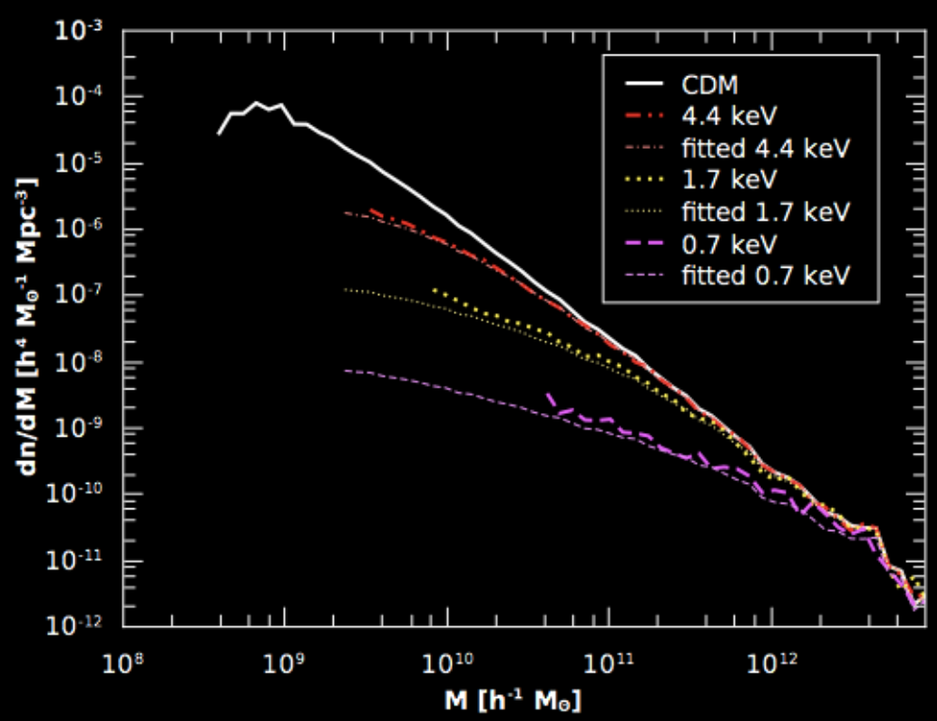
$$P_{1h} = P_{ss} + P_{sc} + P_{1c} + P_{2c}$$

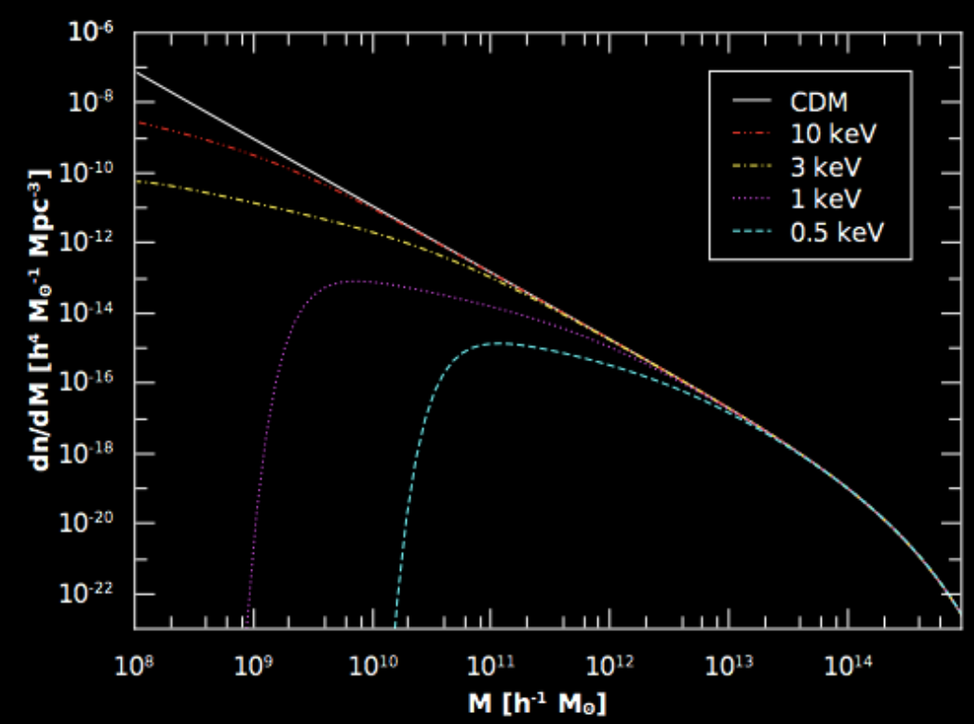
Dunstan, Abazajian, Polisensky & Ricotti 2011

Halo and Subhalo Mass Functions

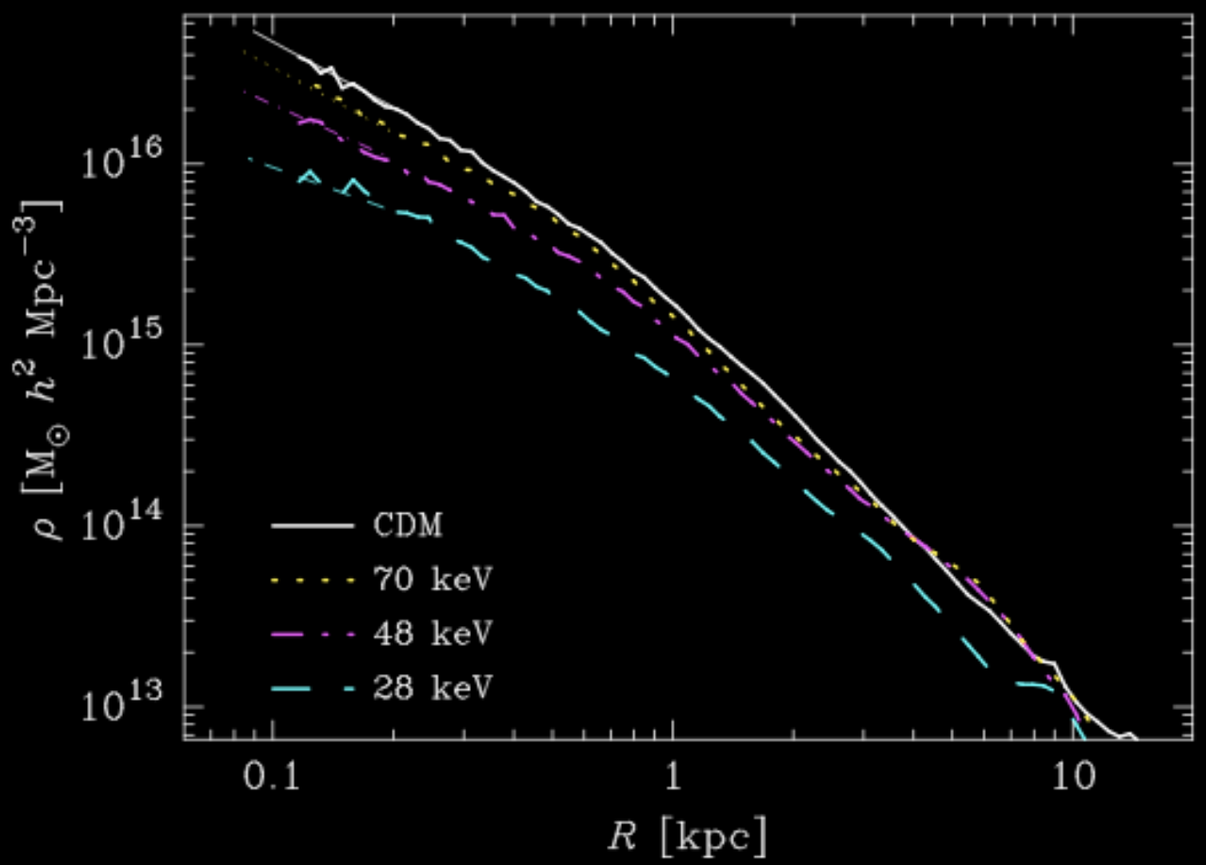


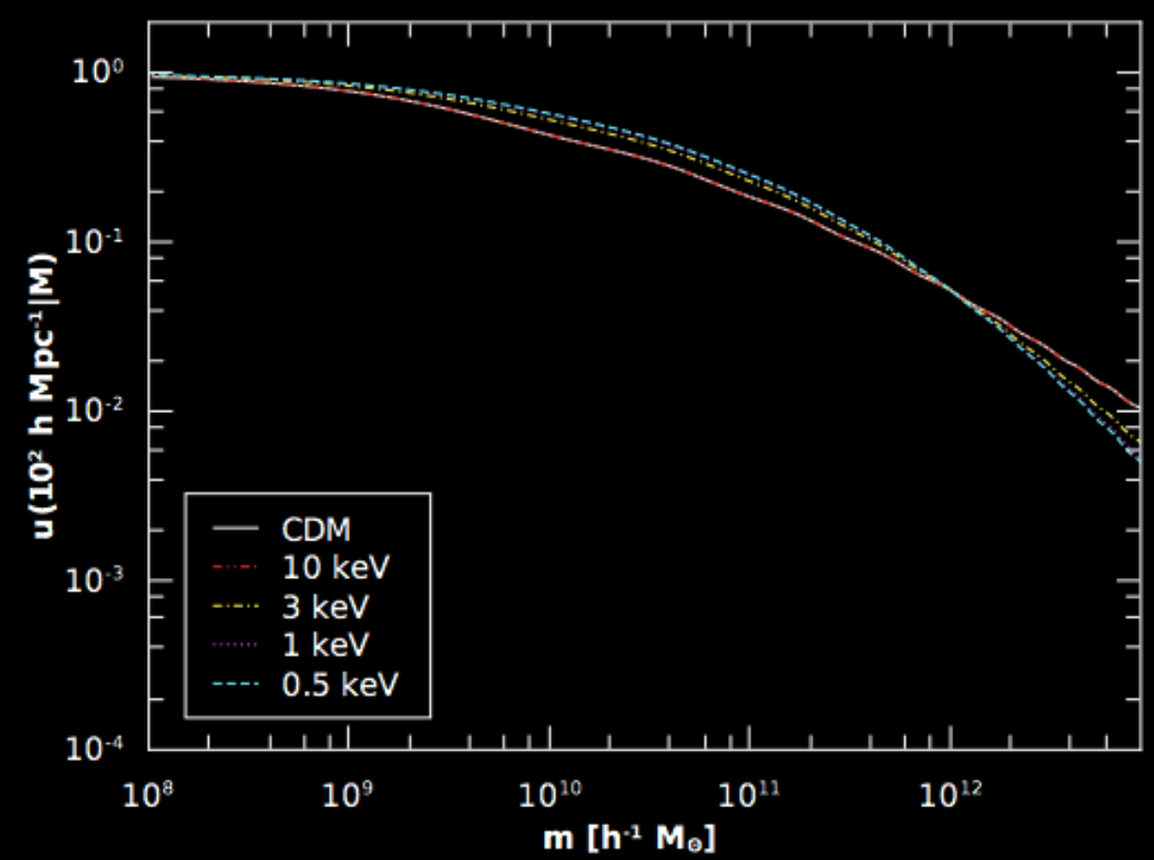


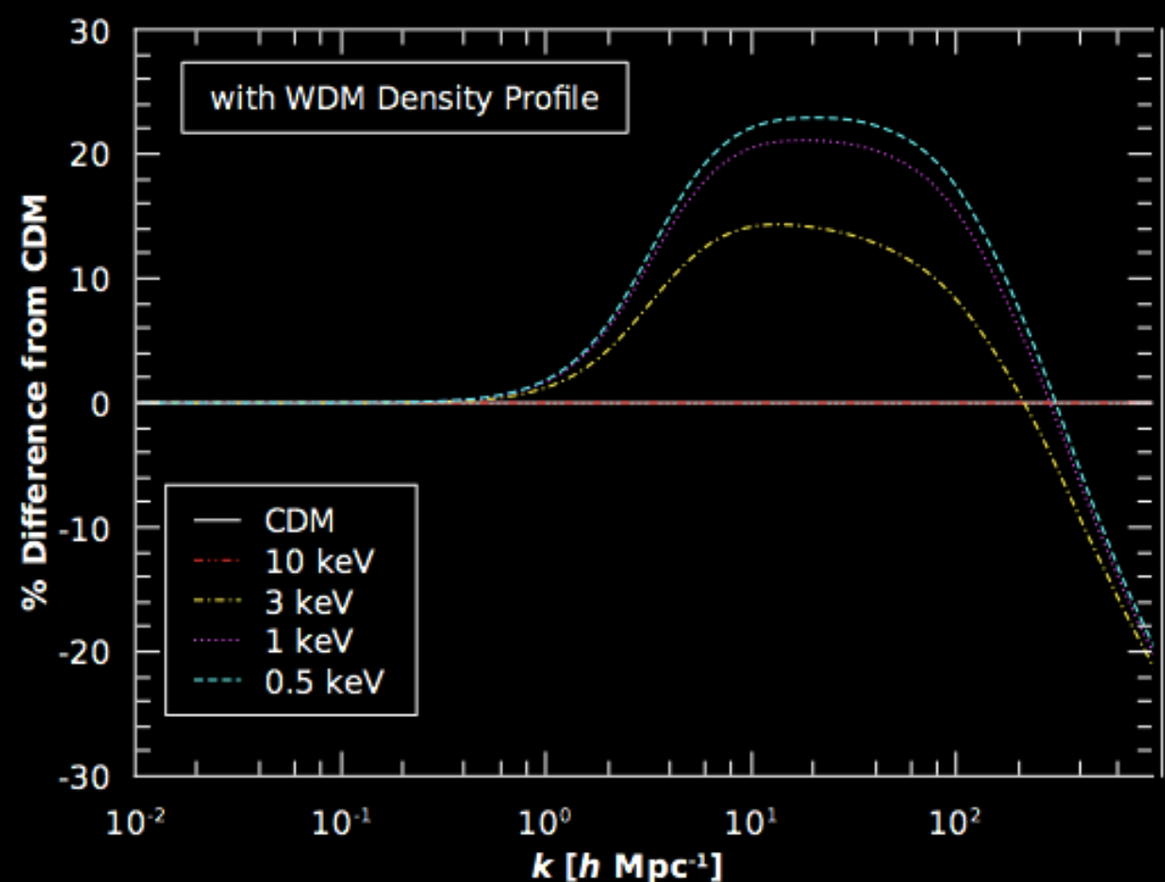




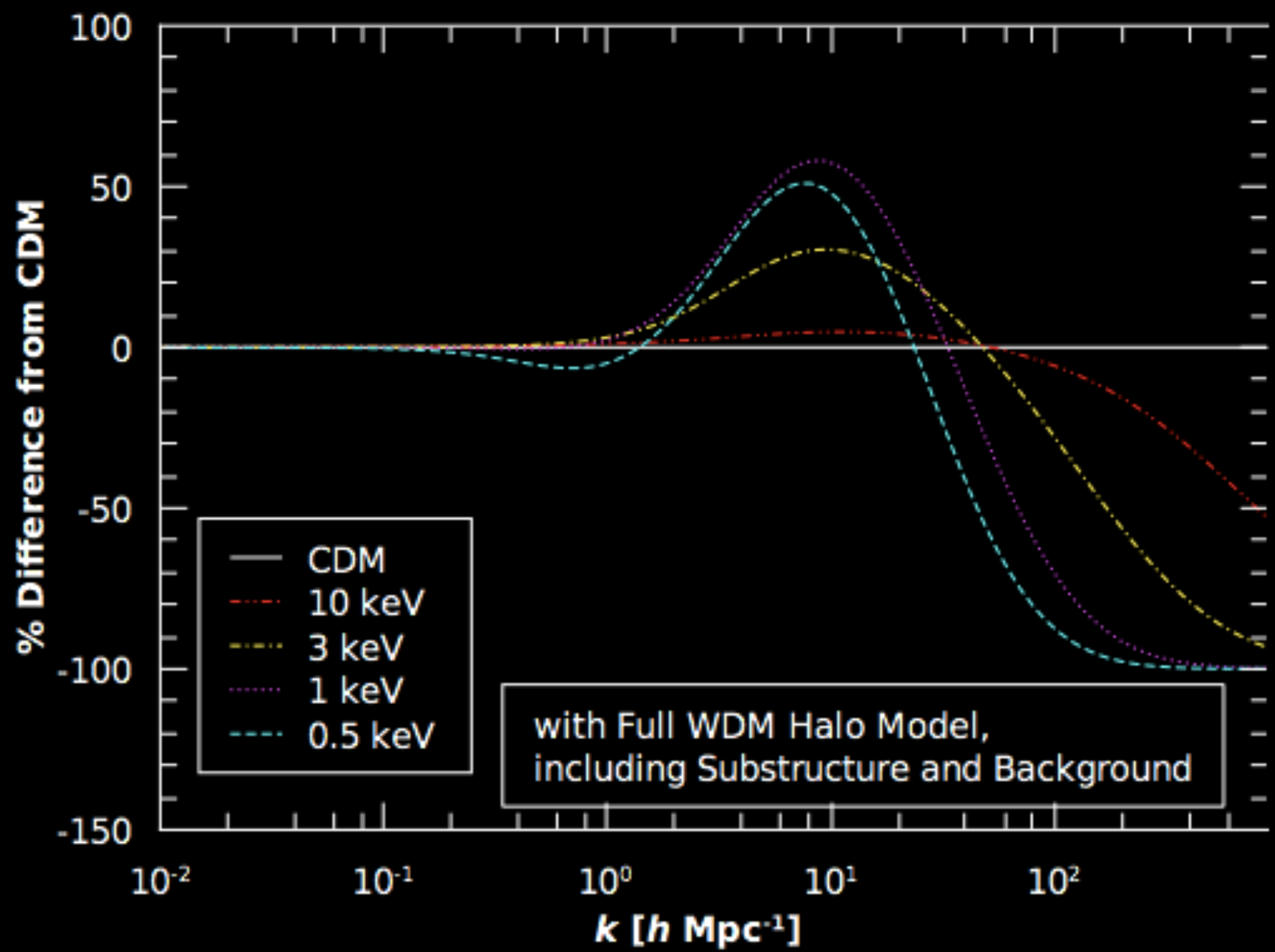
Halo Profile Effects



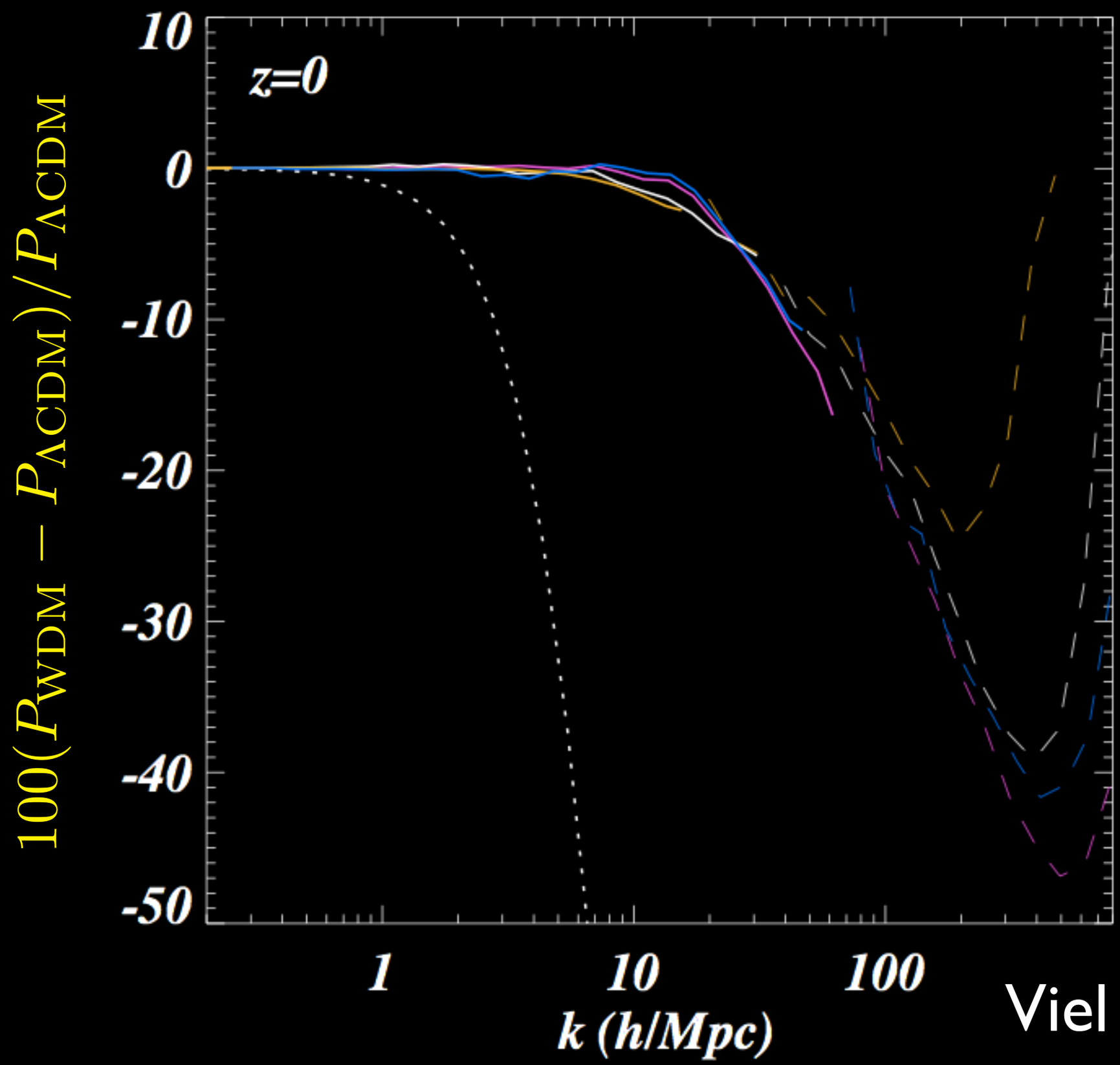




Results on the Full Nonlinear Effects from the Halo Model

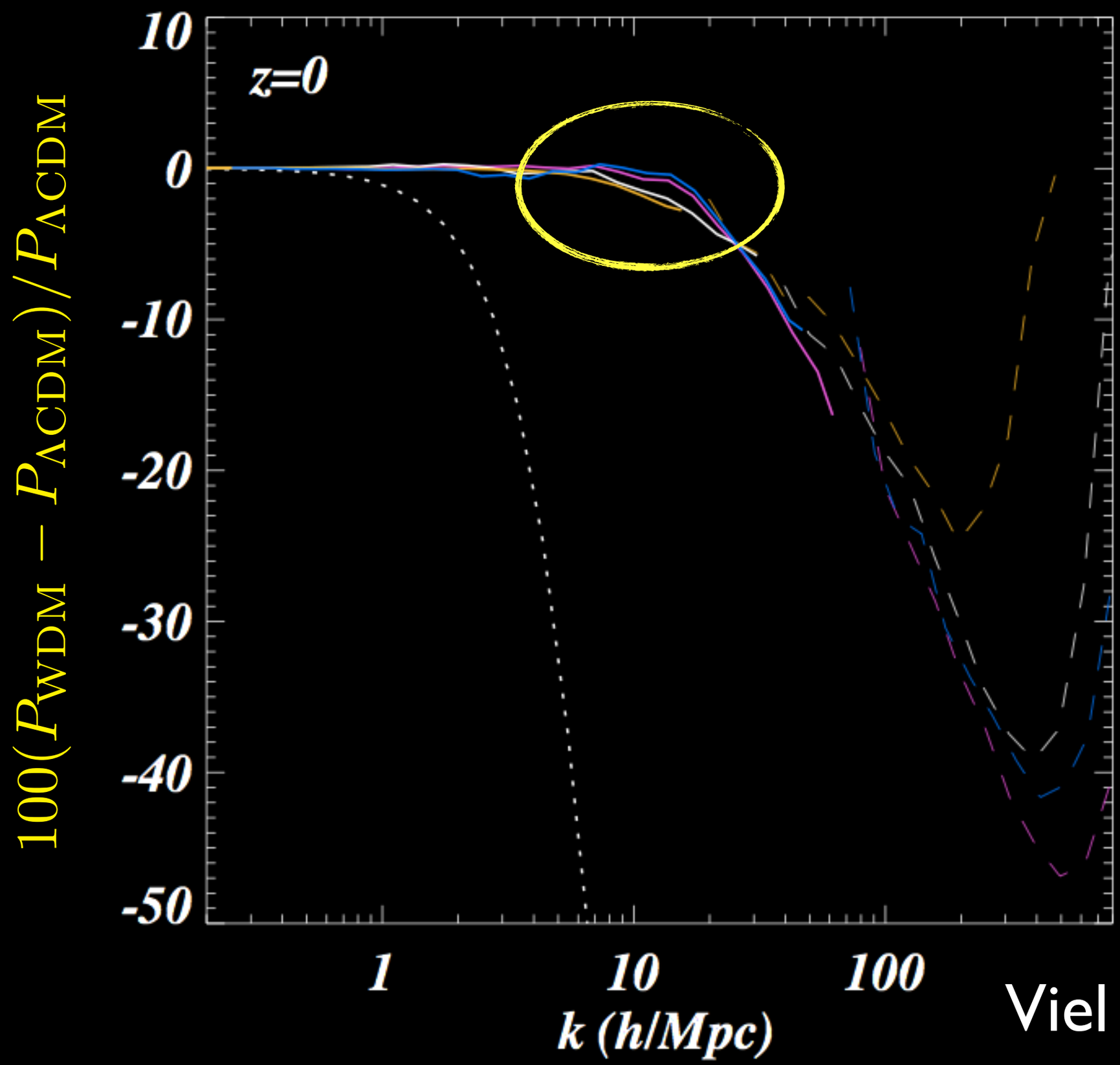


Numerical Power Spectrum Results



Viel et al 2011

Numerical Power Spectrum Results



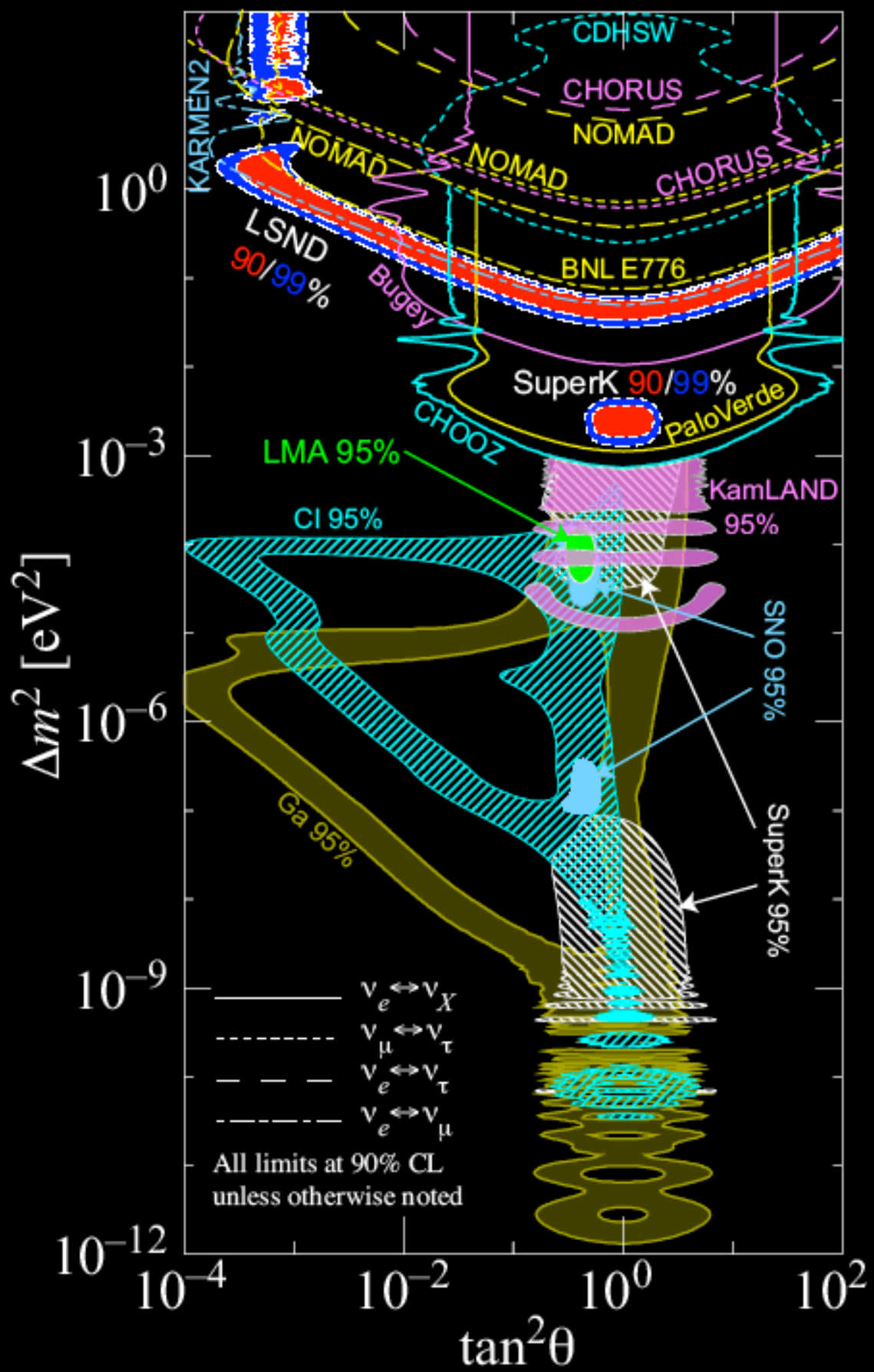
Viel et al 2011

Particle Physics of Sterile Neutrinos

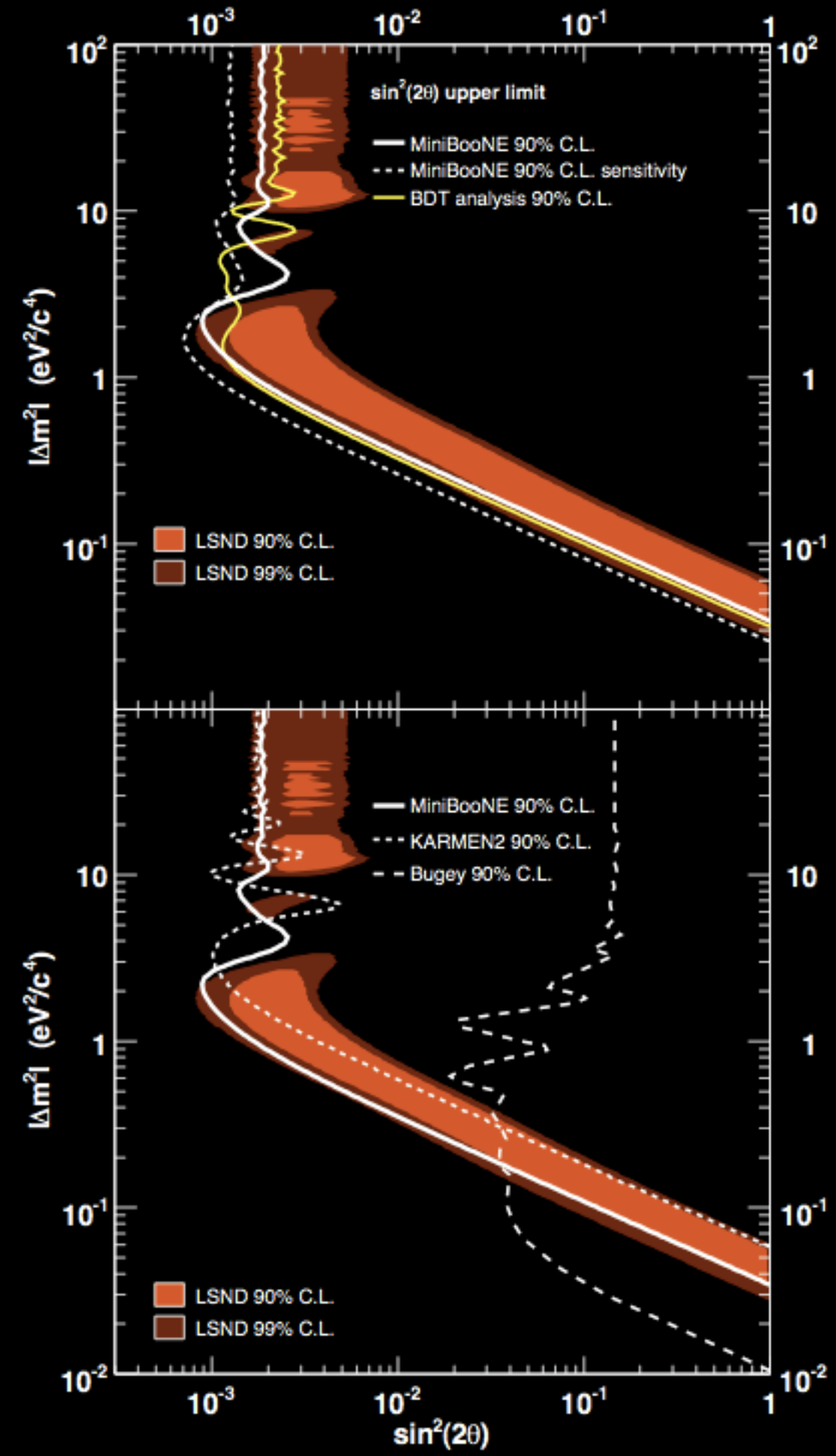
Sterile Neutrinos

Beyond the Standard Model of Particle Physics

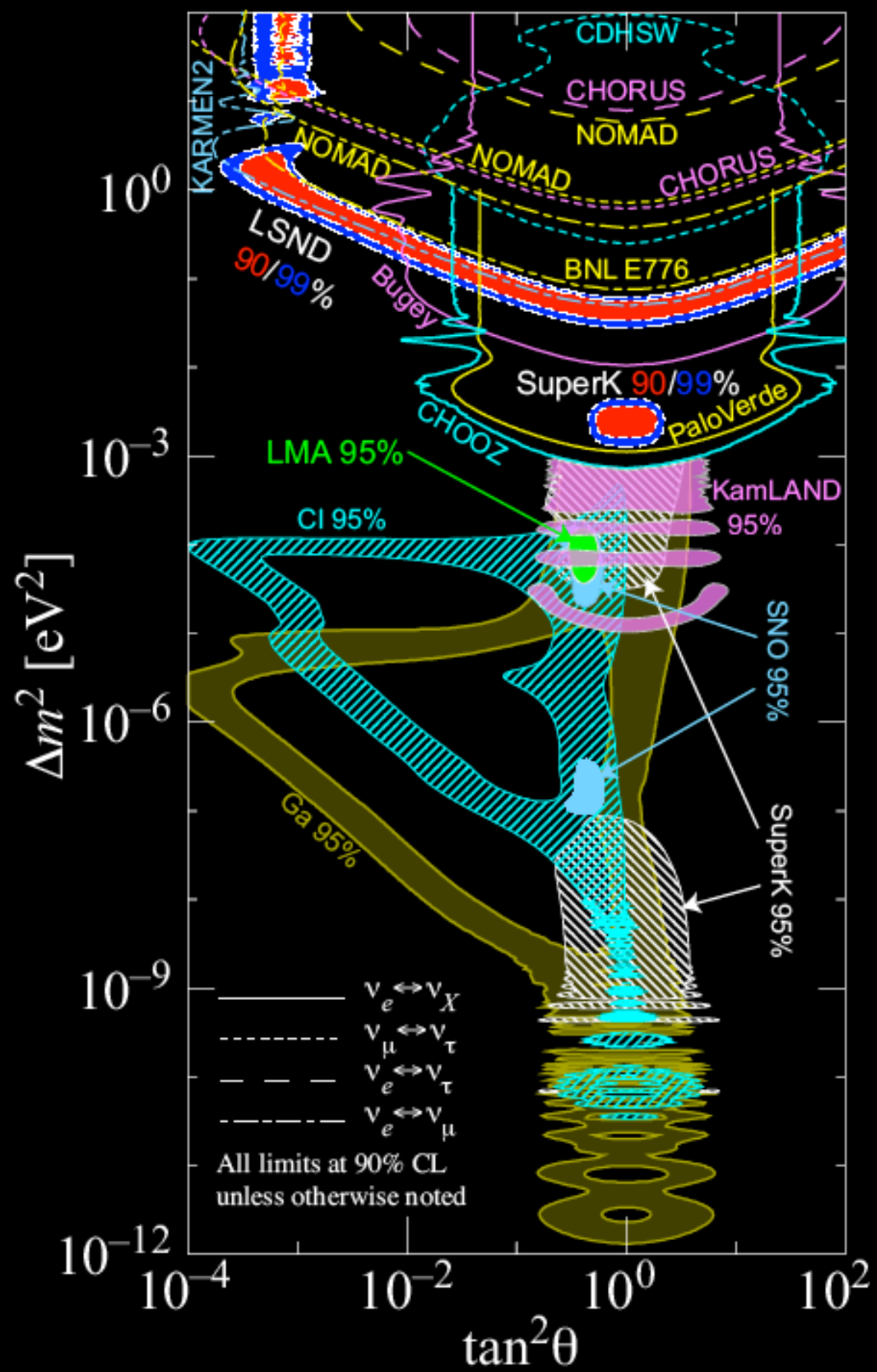
- ν_s Phenomenological Insertion of Majorana & Dirac Mass Terms of Comparable Magnitude (atmos. & solar) (e.g. νMSM Asaka et al 2006)
- ν_s Left-Right Symmetric Models (Pati & Salam 1974; Mohapatra & Pati 1975)
- ν_s Higher Dimensional Operators in String-Inspired models (Langacker 1998)
- ν_s Bulk Fermions in Large Extra Dimensions (ADD; Dvali & Smirnov 2000)
- ν_s Axino in R-parity Violating Minimal Supersymmetric Models (Chun & Kim 1999)



PDG, RPP 2004



Aguilar-Arevalo 2007 [MiniBooNE]



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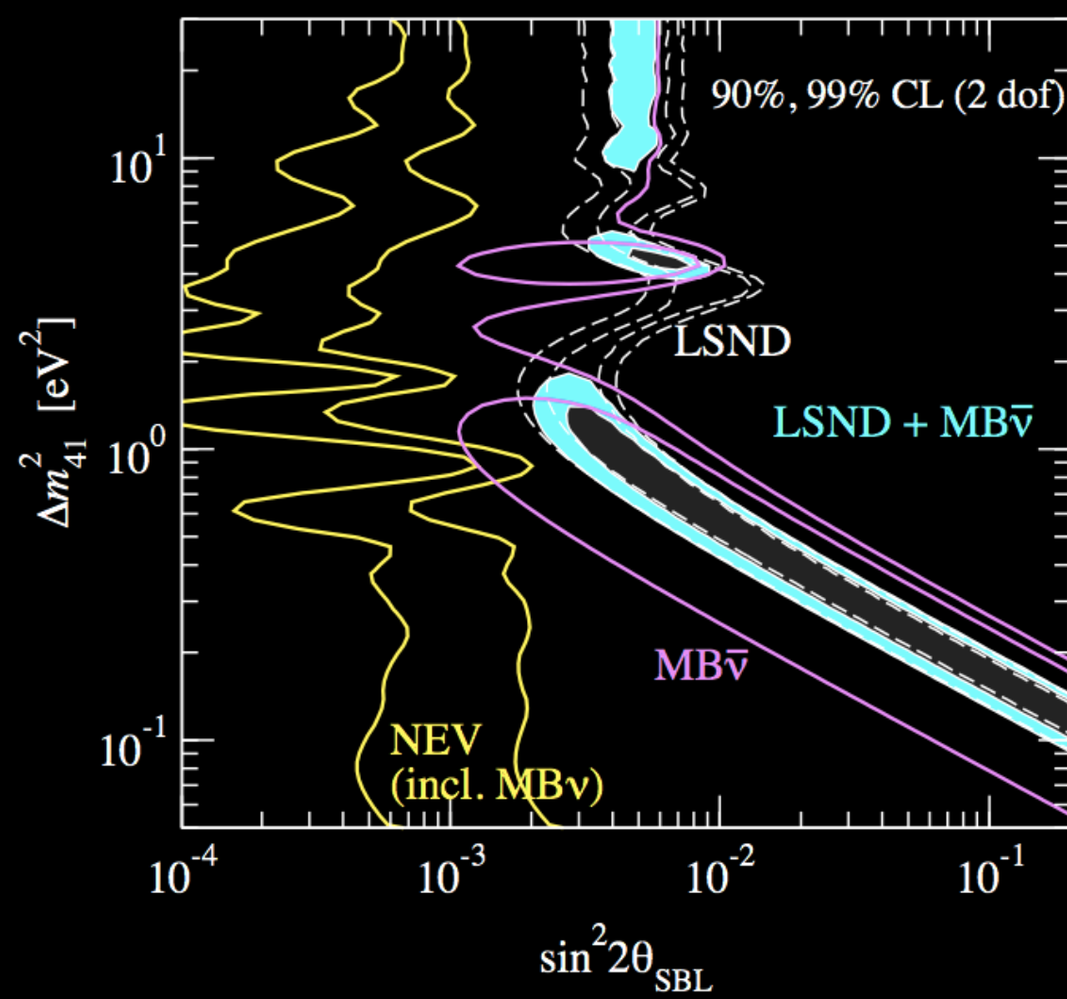
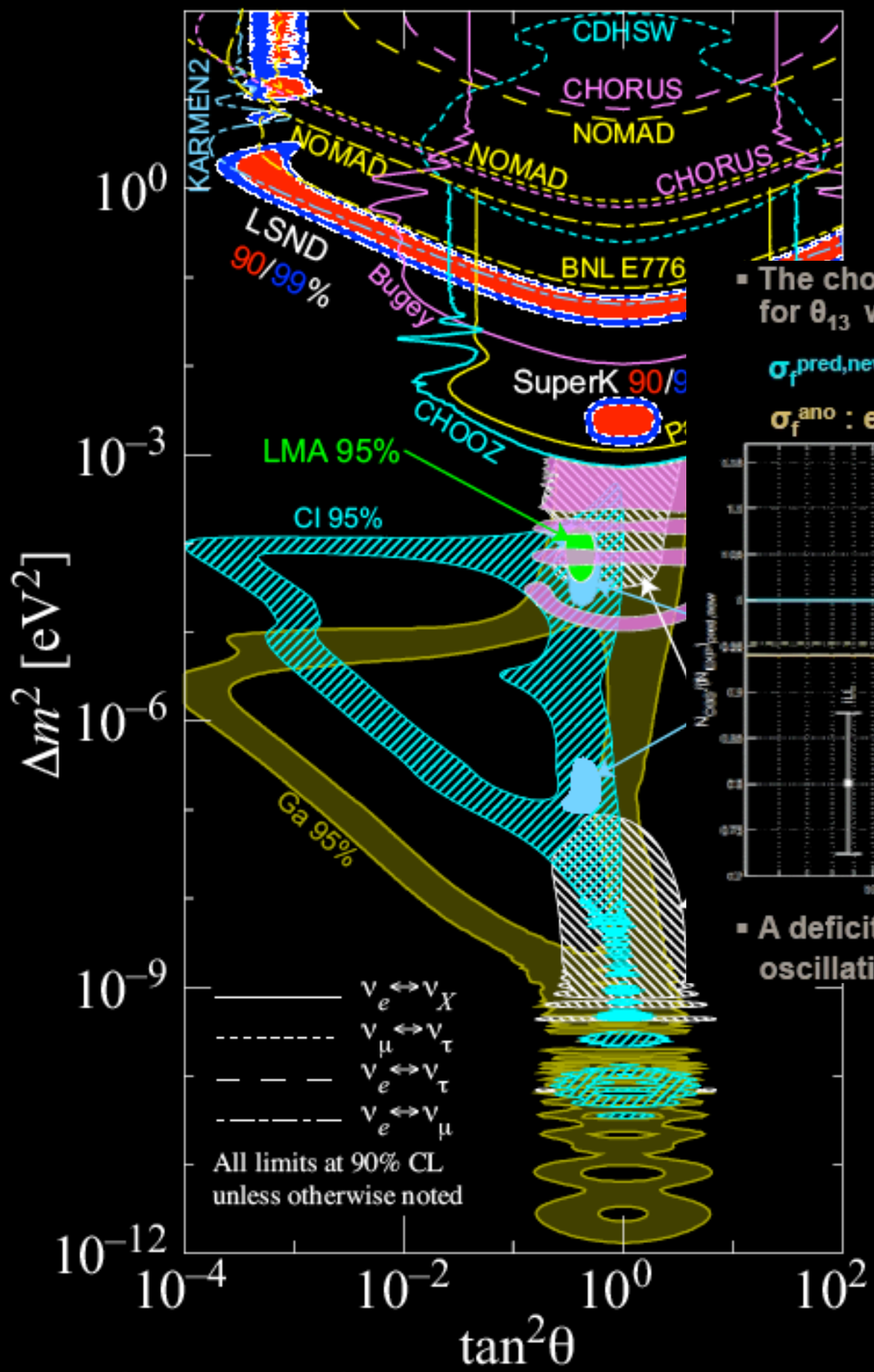


Aguilar-Arevalo 2010 [MiniBooNE]
Akhmedov & Schwetz 2011

Reactor Anomaly

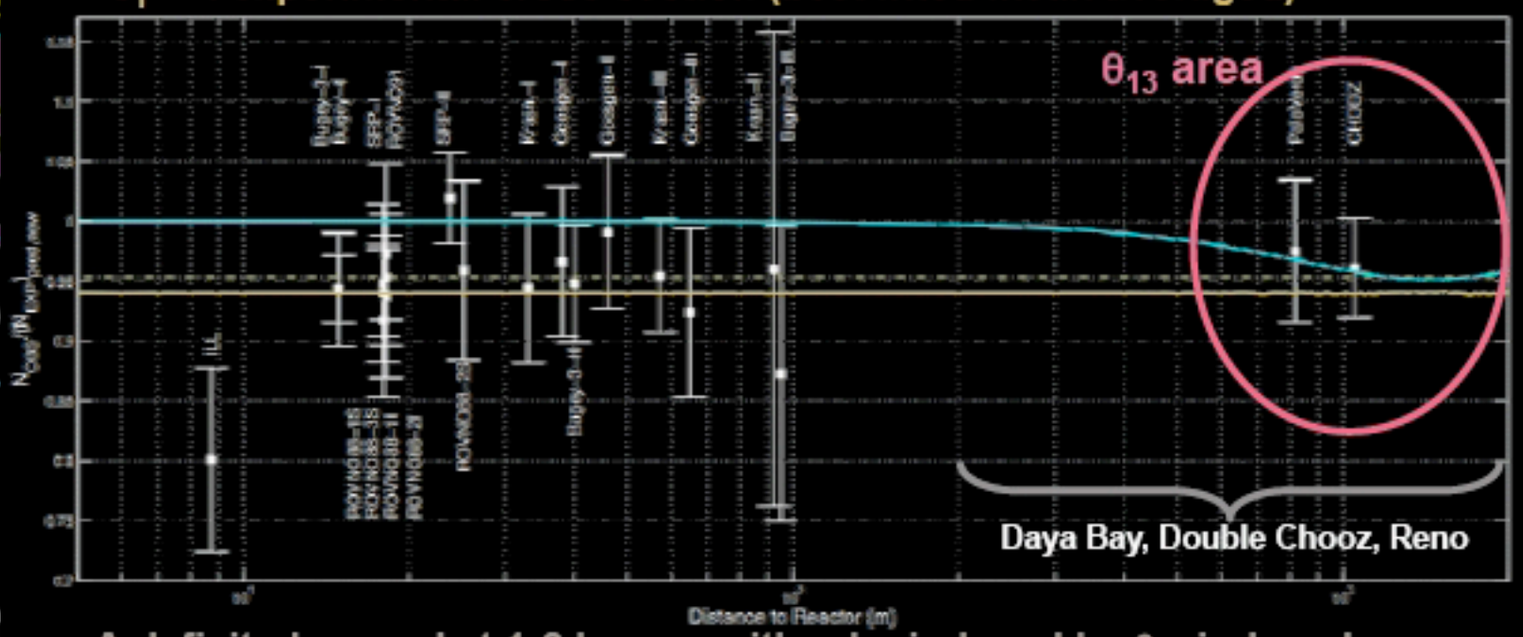


PDG, RPP 2004

- The choice of normalization is crucial for reactor experiments looking for θ_{13} without near detector

$\sigma_f^{pred,new}$: new prediction of the antineutrino fluxes

σ_f^{ano} : experimental cross section (best fitted mean averaged)



- A deficit observed at 1-2 km can either be induced by θ_{13} induced oscillation BUT also by other explanations (experimental, new ϕ, ...)

$\sin^2 2\theta_{SBL}$

Aguilar-Arevalo 2010 [MiniBooNE]
Akhmedov & Schwetz 2011

A Phenomenelogical Model

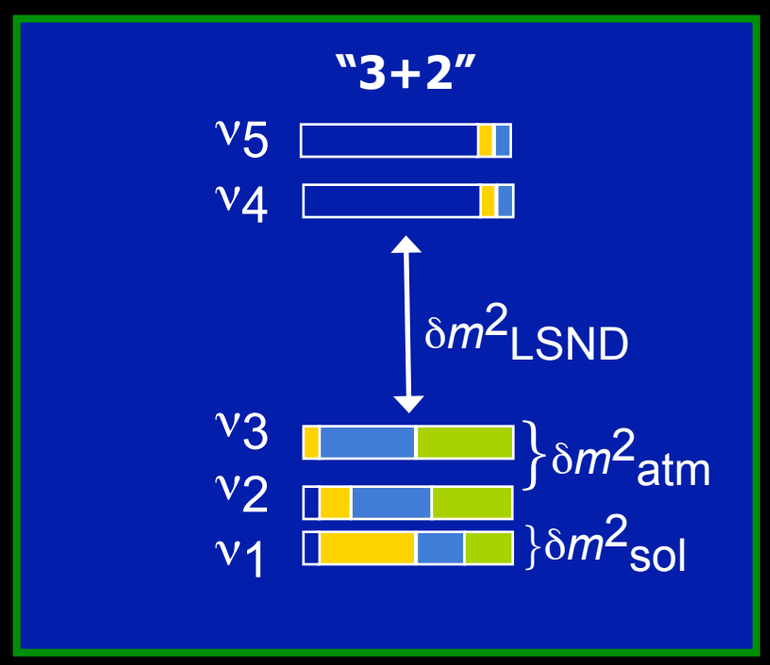
Sterile Neutrino Dark Matter

ν_6

$$|\nu_\alpha\rangle = \cos\theta|\nu_a\rangle + \sin\theta|\nu_b\rangle$$
$$|\nu_s\rangle = -\sin\theta|\nu_a\rangle + \cos\theta|\nu_b\rangle$$

~ 1 keV

$\sin^2 2\theta \sim 10^{-7}$



~ 1 eV

~ 0.01 eV

Sterile Neutrino Dark Matter Production

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

$$\Delta^2 \sim p^{-2} \sim T^{-2}$$

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

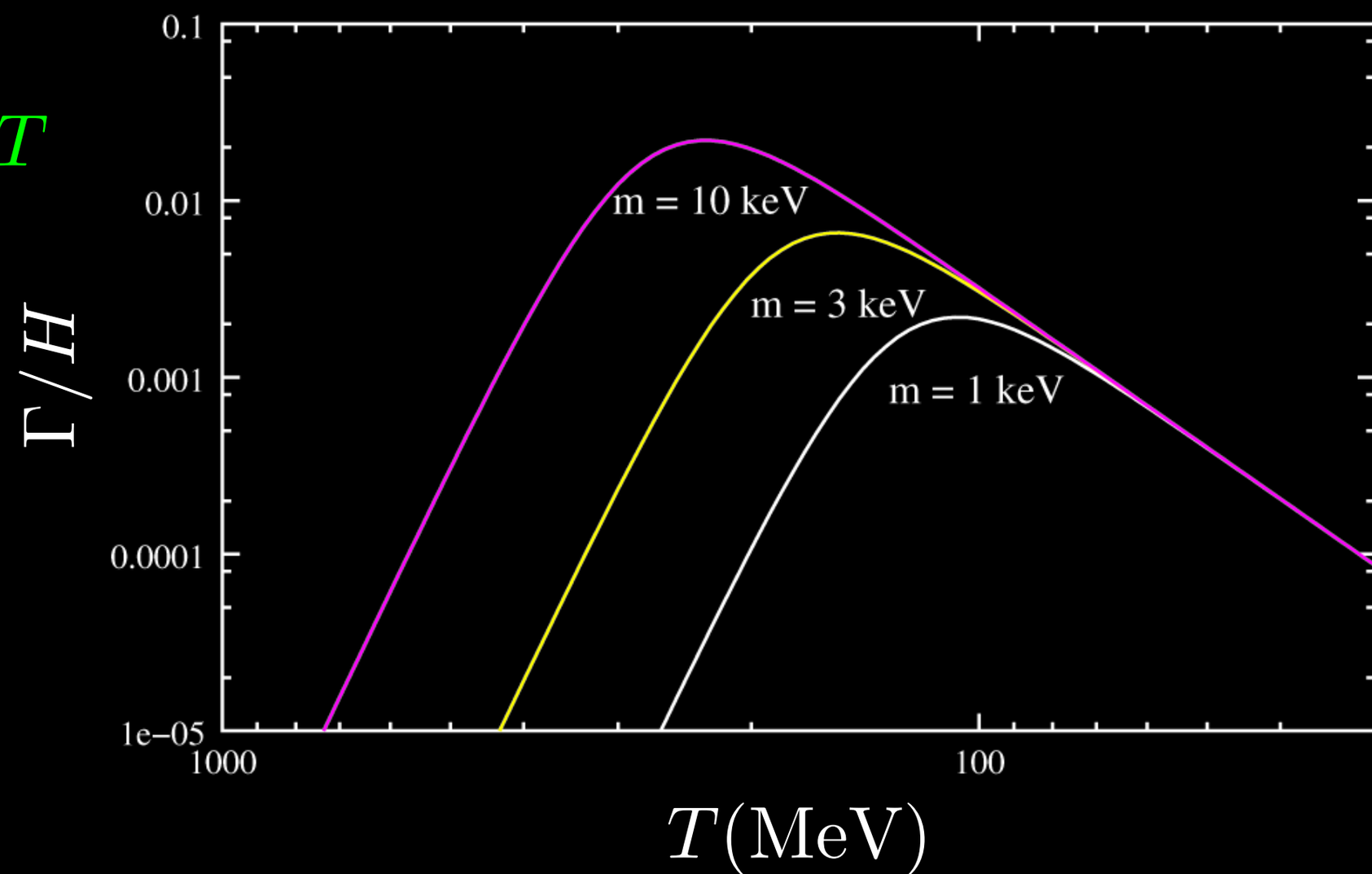
$$D(p)^2 \sim T^{10}$$

$$[V^T]^2 \sim T^{10}$$

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

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

Never in Equilibrium!!



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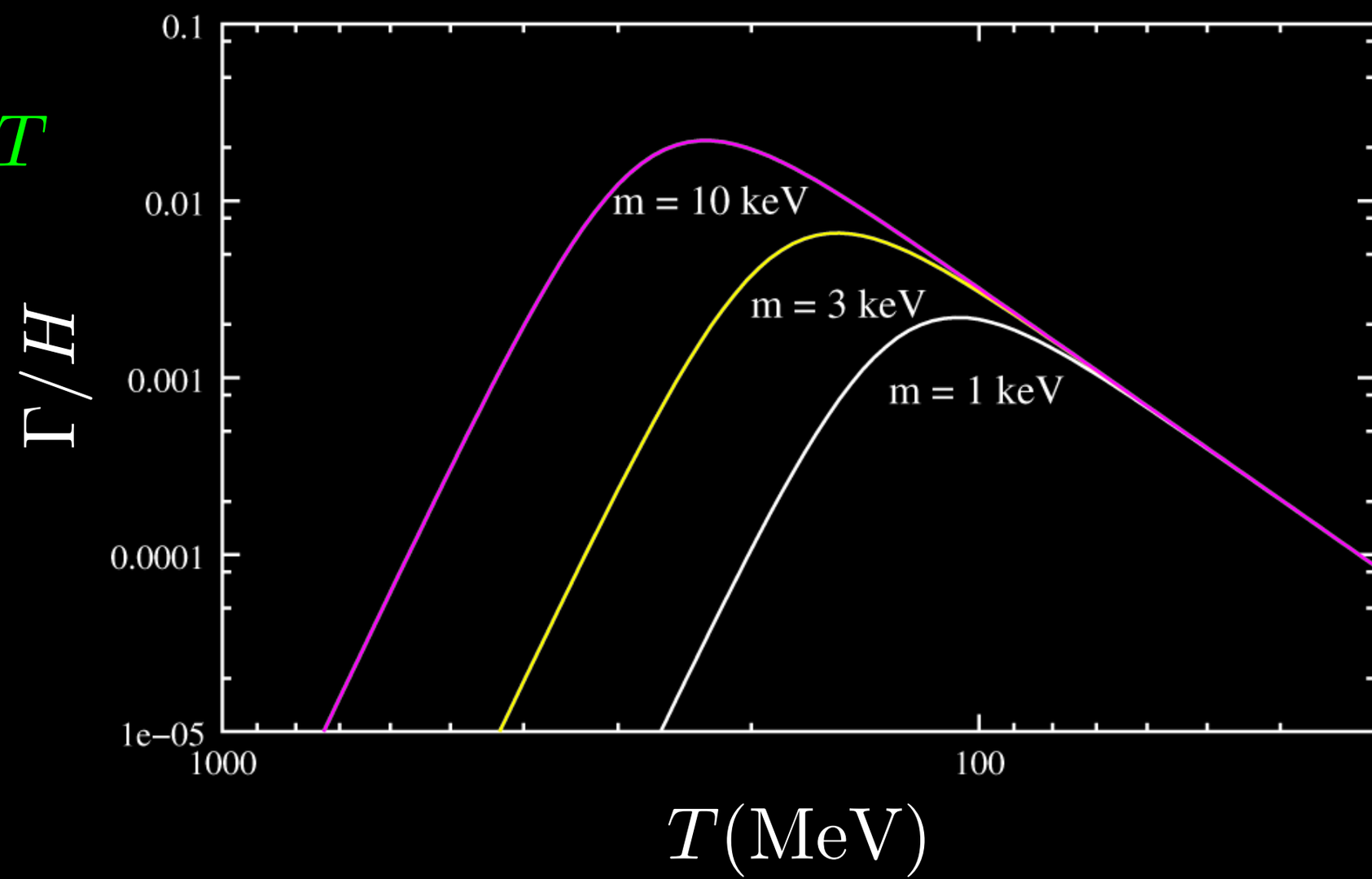
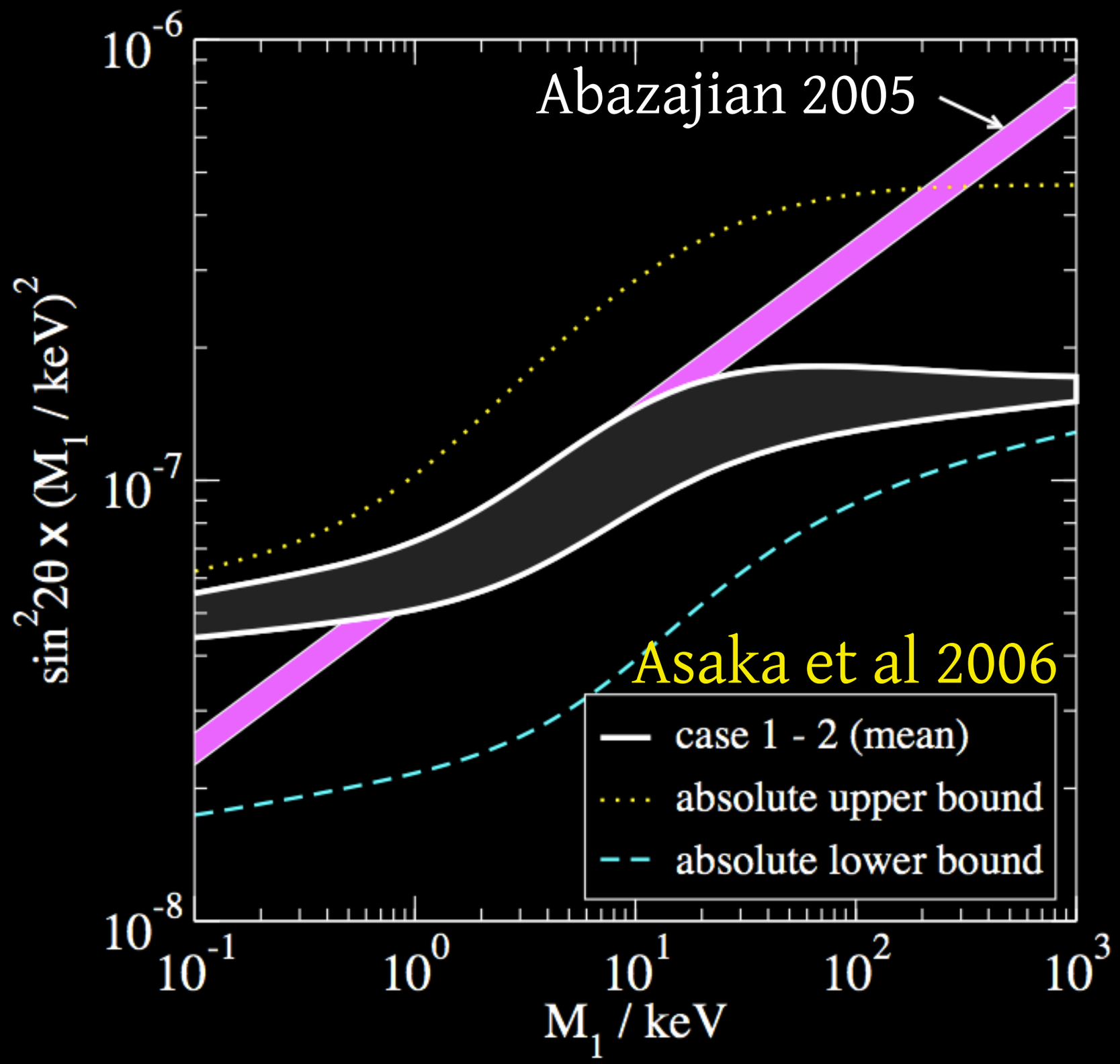
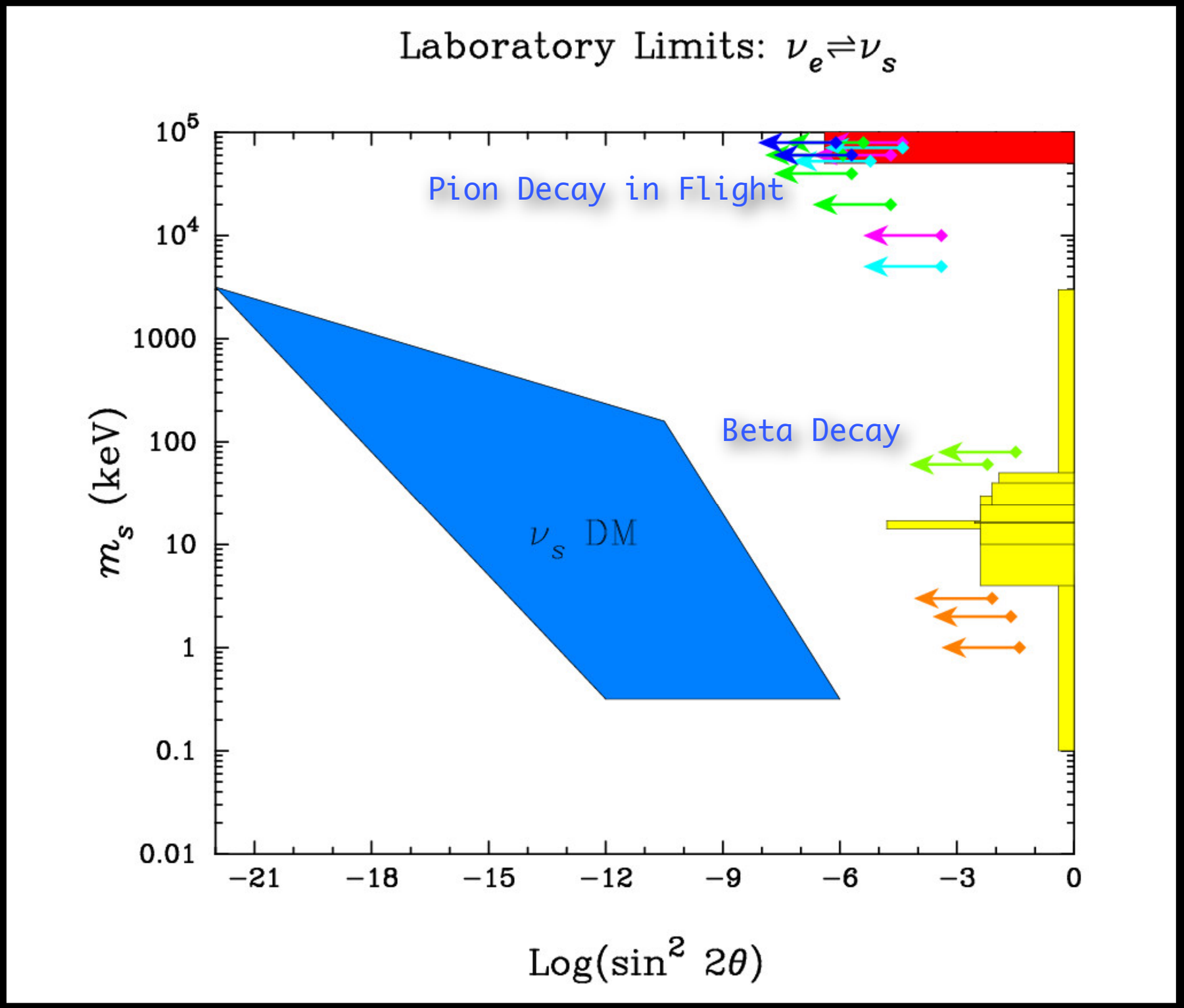


Calculations of Sterile Neutrino Dark Matter Production Affected by QCD Transition



Detecting keV Sterile Neutrinos: Laboratory limits



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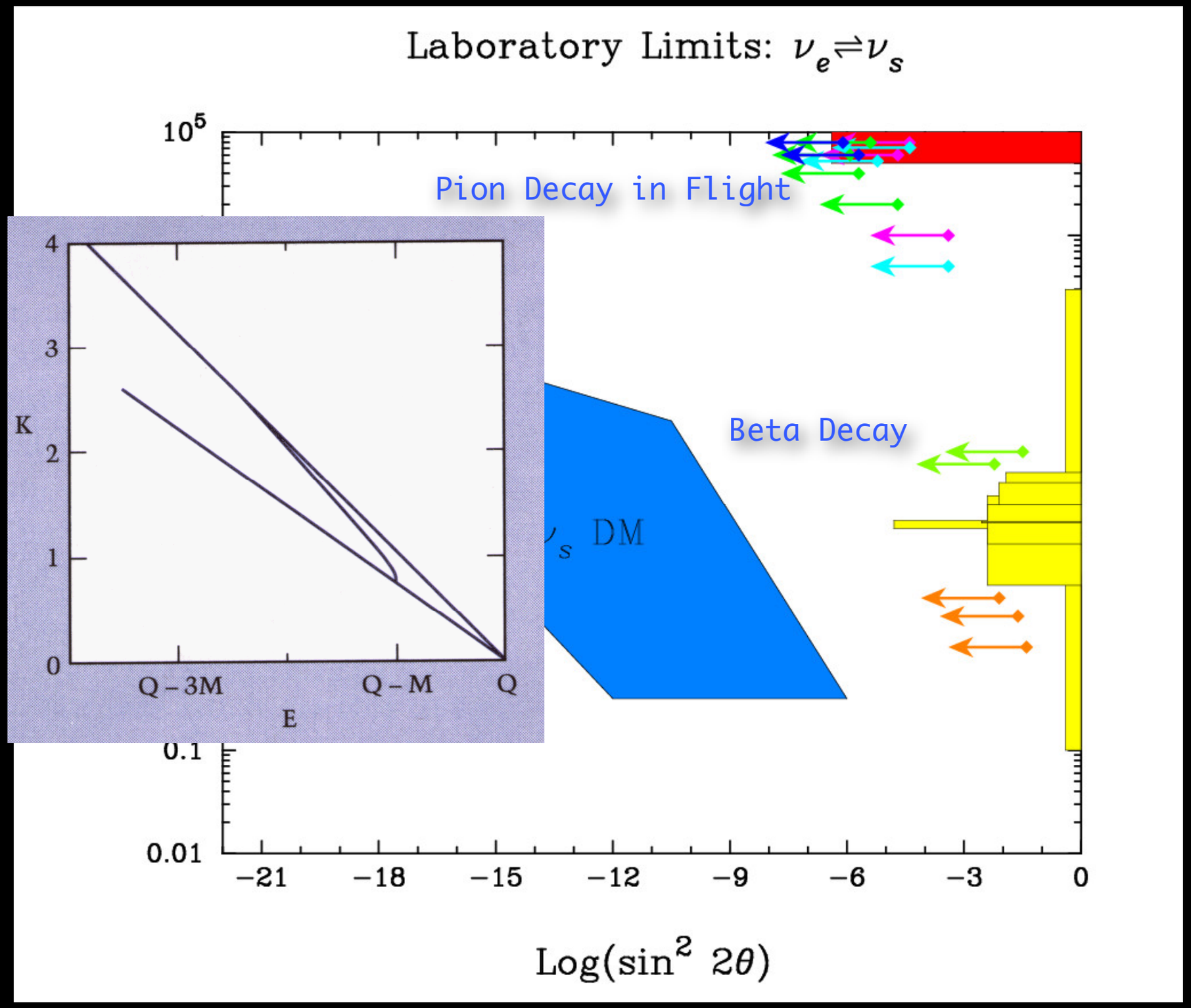
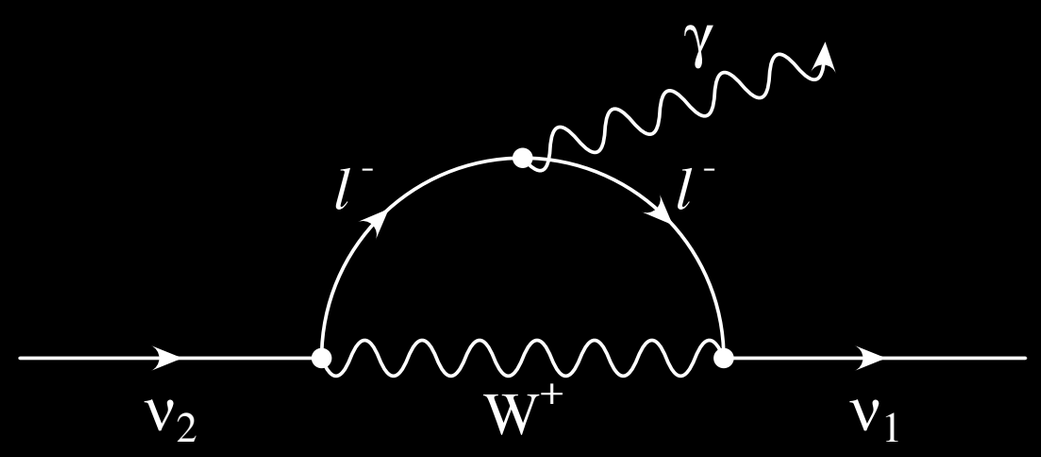


Radiative Decay in the X-ray

Pal & Wolfenstein 1981



$$\text{“}\nu_s\text{”} \longrightarrow \text{“}\nu_\alpha\text{”} + \gamma$$

$$E_\gamma = \frac{m_s}{2} \sim 1 \text{ keV}$$

$$\Gamma_\gamma = 6.8 \times 10^{-33} \text{ sec}^{-1} \left(\frac{\sin^2 2\theta}{10^{-10}}\right) \left(\frac{m_s}{1 \text{ keV}}\right)^5$$

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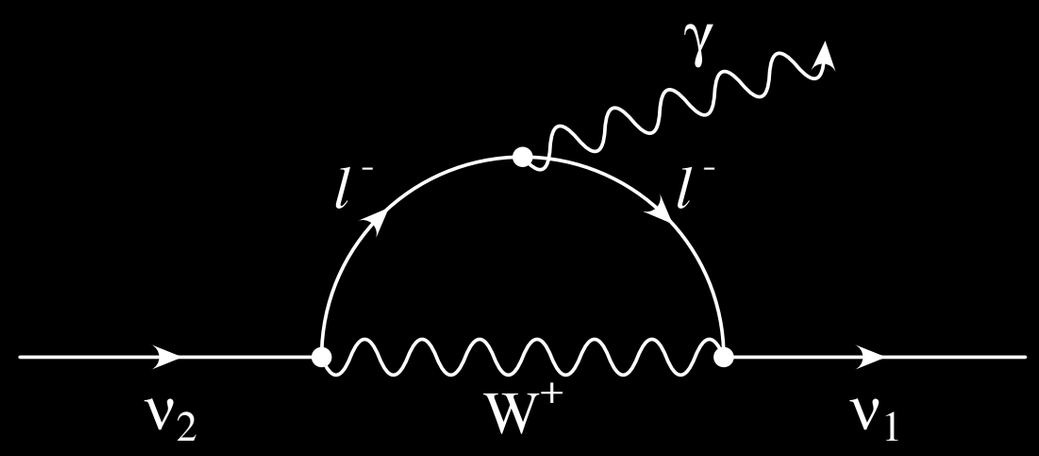

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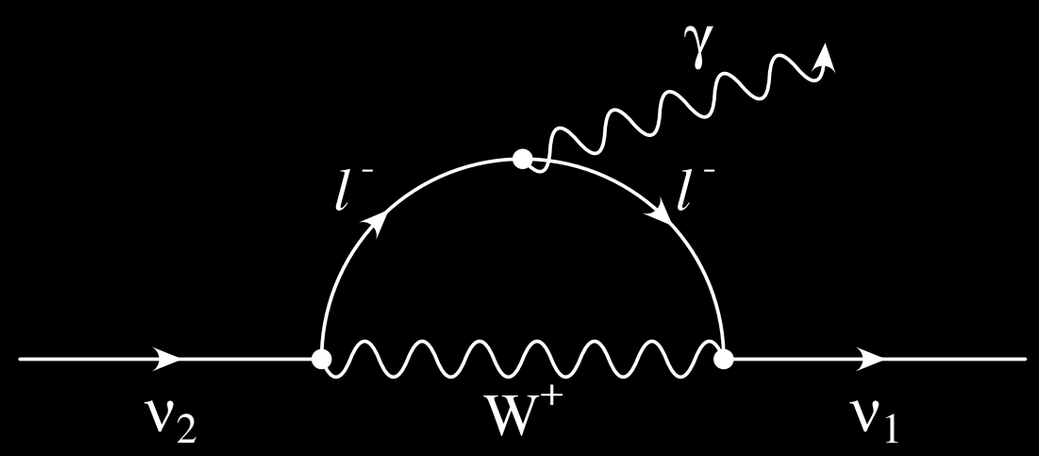

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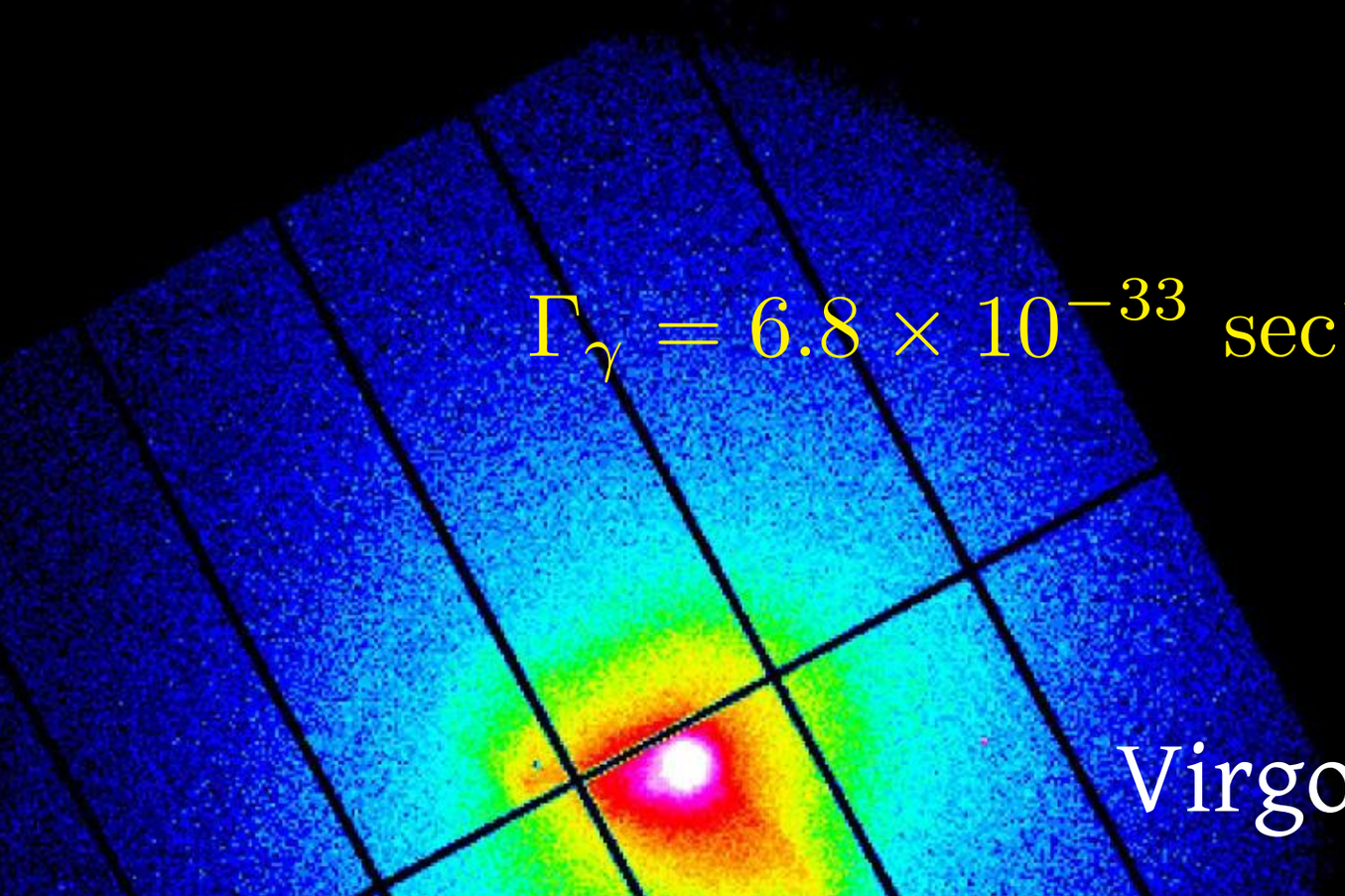
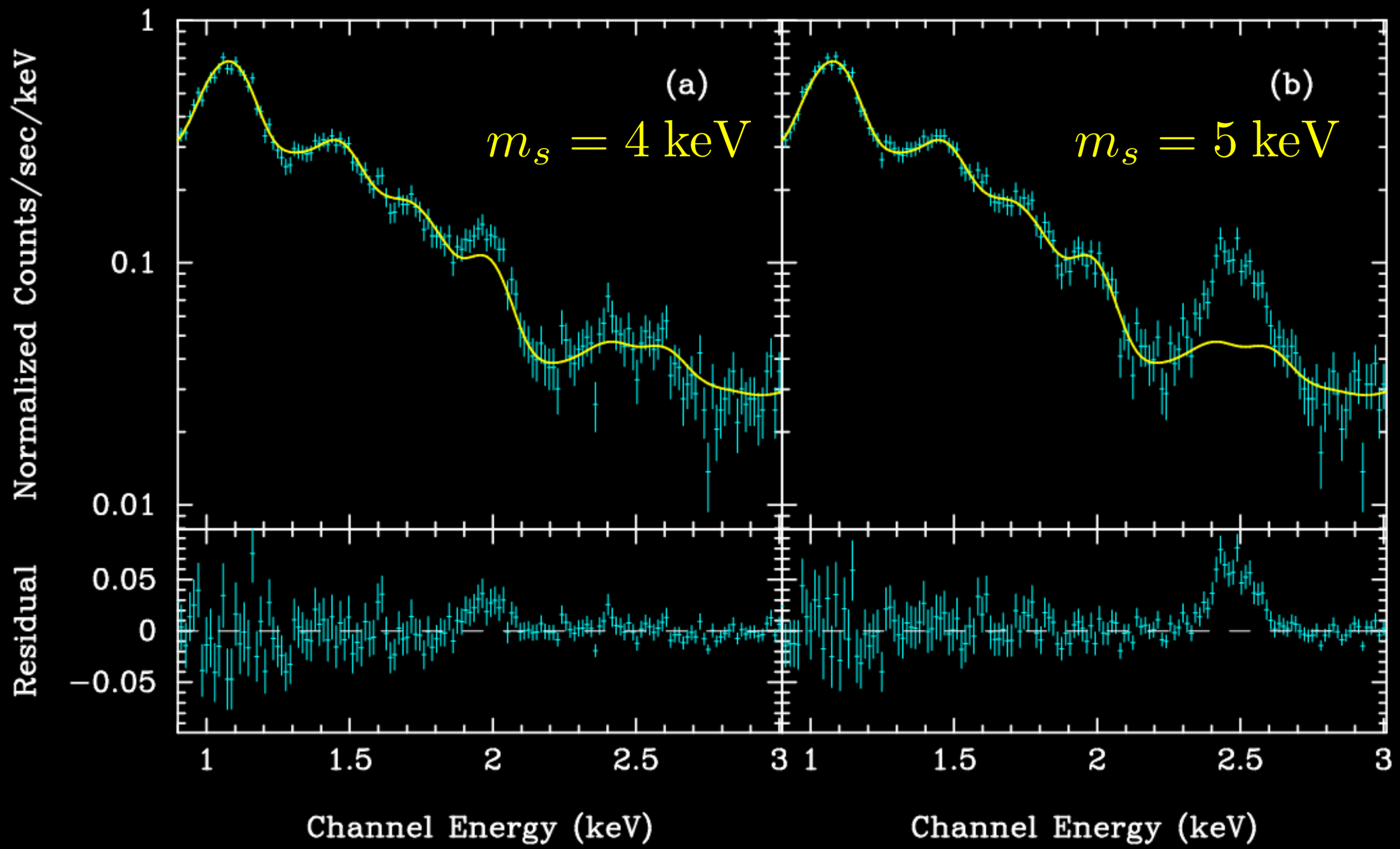


Virgo Cluster: 10^{70} DM particles

Upper Mass Limit:

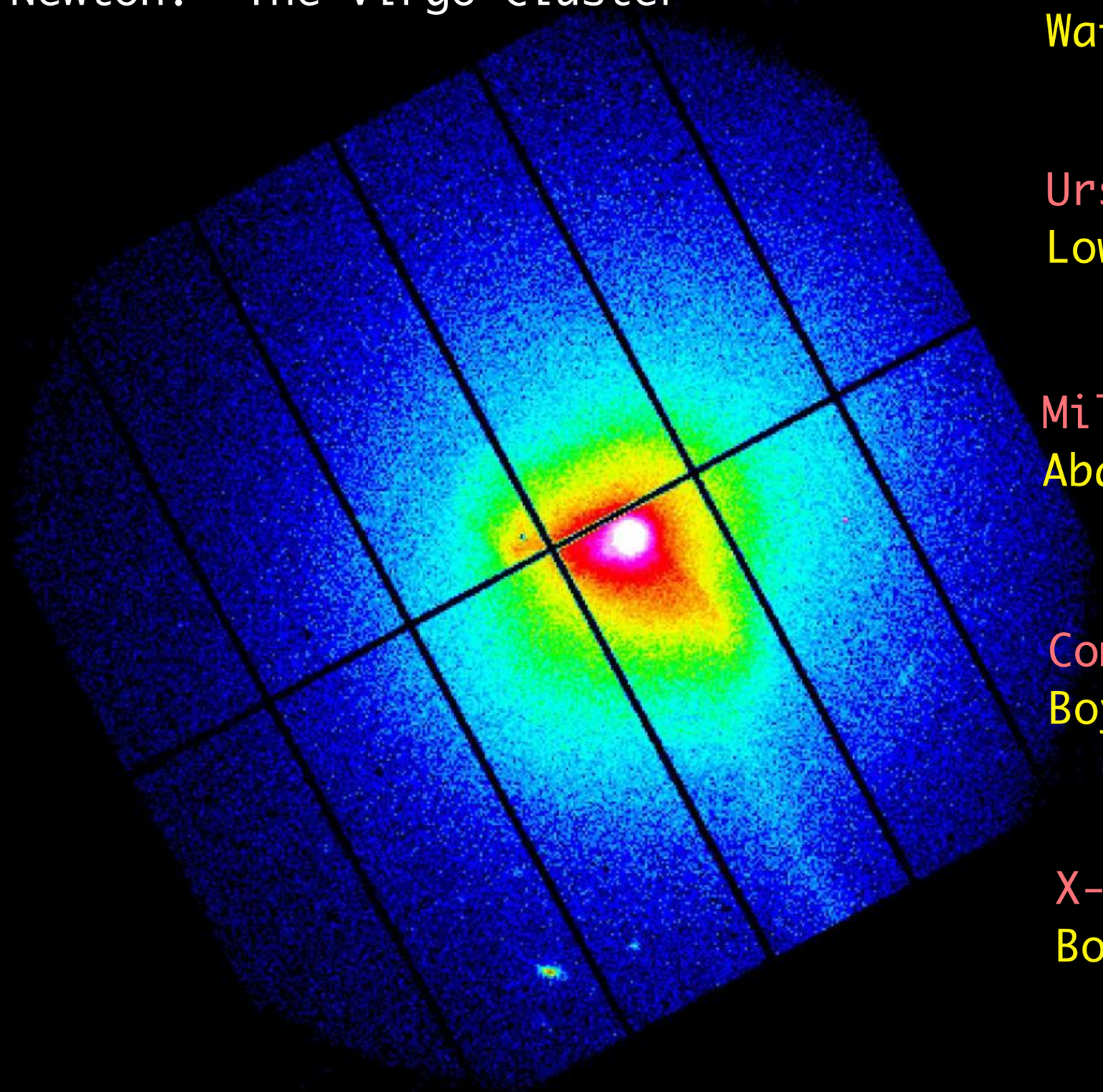
X-ray observations of Virgo



Abazajian, Fuller & Tucker 2001

X-ray Constraint Summary

XMM Newton: The Virgo Cluster



Andromeda Galaxy:
Watson et al. 2011

$$m_s < 2.2 \text{ keV}$$

Ursa Minor:
Lowenstein et al. 2008

$$m_s < 3.1 \text{ keV}$$

Milky Way in CXB:
Abazajian et al. 2006

$$m_s < 5.7 \text{ keV}$$

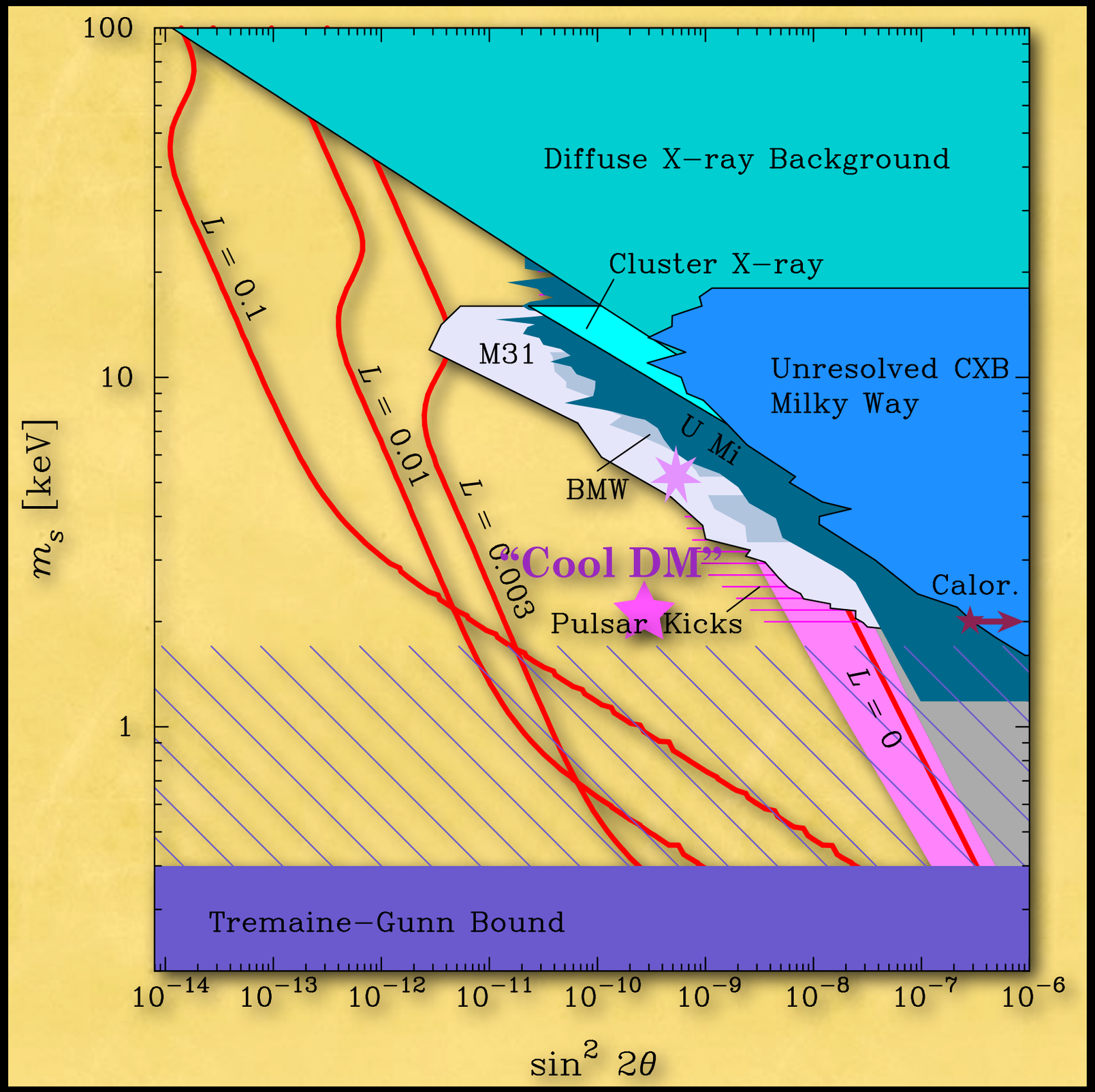
Coma + Virgo Clusters:
Boyarsky et al. 2006

$$m_s < 6.3 \text{ keV}$$

X-Ray Background:
Boyarsky et al. 2006

$$m_s < 8.9 \text{ keV}$$

Sterile Neutrino Dark Matter Parameter Space Summary



Abazajian 2012

Summary

Sterile Neutrino Dark Matter

- Warm Dark Matter has become the "standard alternate" cosmological structure formation scenario, as it may resolve many problems in structure formation, though stringent limits exist
- Sterile Neutrino Dark Matter is a natural, minimal WDM *and* CDM candidate
- Upcoming weak lensing and galaxy surveys can be sensitive to WDM effects in the mild to strongly nonlinear regime
- Lower-limits mass from the Lyman-alpha Forest are dependent on the thermal history of the universe, uncorrected noise in the SDSS spectrograph and uncertain
- Sterile Neutrino Dark Matter, in the standard production scenarios, is detectable or *potentially* excludable with the *IXO* satellite