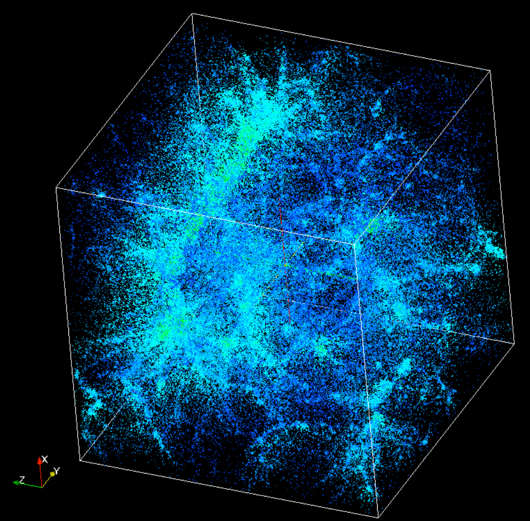
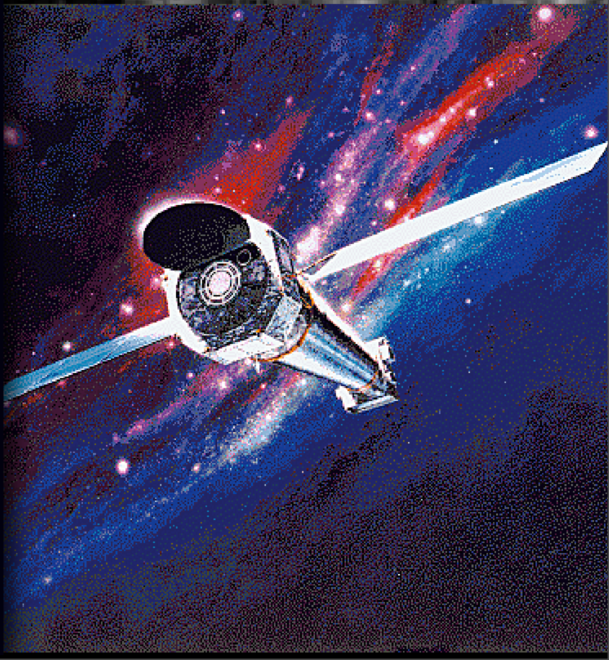
Detecting Dark Matter in the X-ray

Kev Abazajian

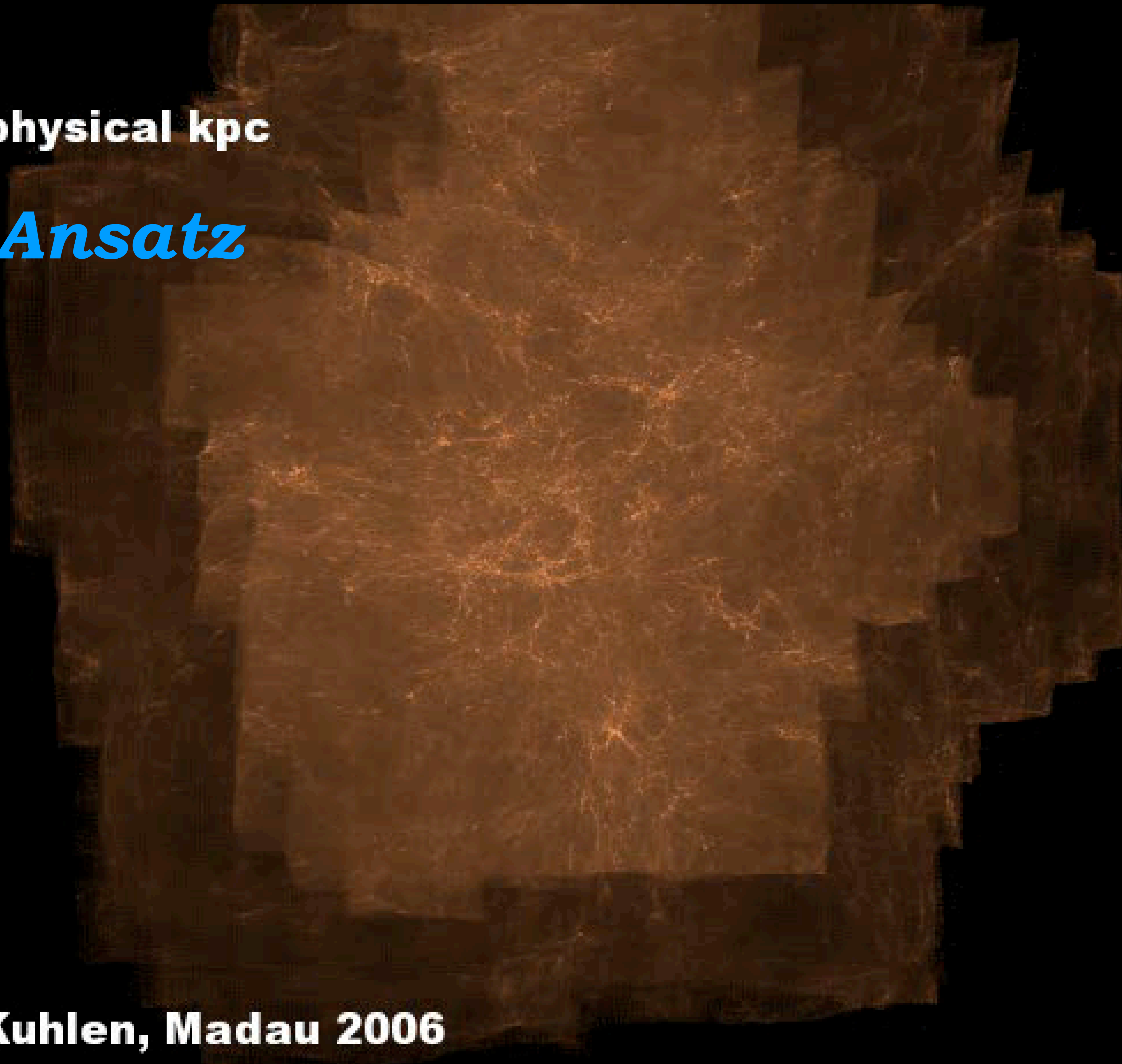
University of Maryland

Quantum 2 Cosmos 3:
Airlie Center, July 8, 2008

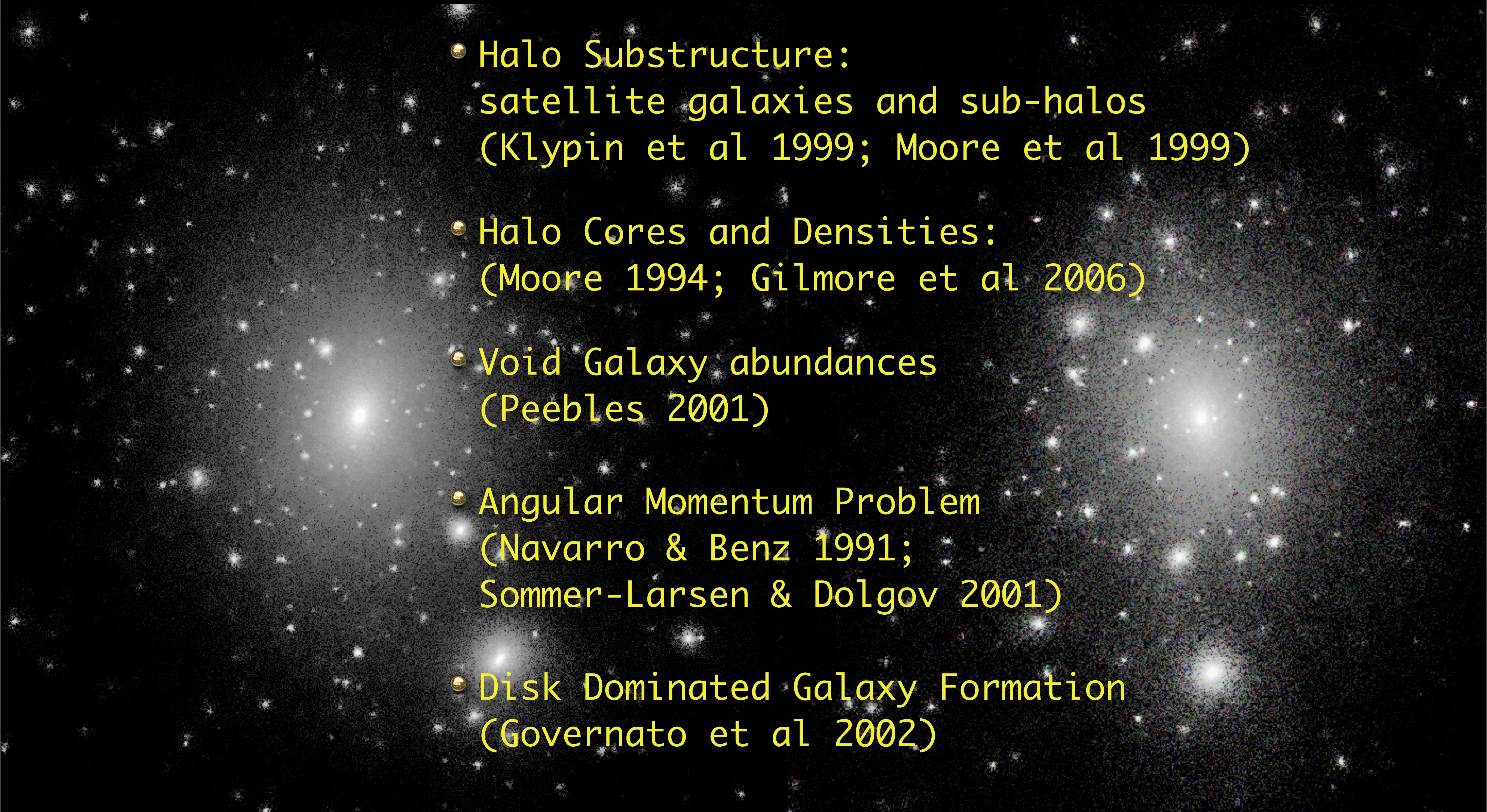




The CDM ***Ansatz***



Problems in Cold Dark Matter?



- Halo Substructure:
  satellite galaxies and sub-halos
  (Klypin et al 1999; Moore et al 1999)

- Halo Cores and Densities:
  (Moore 1994; Gilmore et al 2006)

- Void Galaxy abundances
  (Peebles 2001)

- Angular Momentum Problem
  (Navarro & Benz 1991;
  Sommer-Larsen & Dolgov 2001)

- Disk Dominated Galaxy Formation
  (Governato et al 2002)

Problems in Cold Dark Matter?

- Halo Substructure:
  satellite galaxies and sub-halos
  (Klypin et al 1999; Moore et al 1999)
- Halo Cores and Densities:
  (Moore 1994; Gilmore et al 2006)
- Void Galaxy abundances
  (Peebles 2001)
- Angular Momentum Problem
  (Navarro & Benz 1991;
  Sommer-Larsen & Dolgov 2001)
- Disk Dominated Galaxy Formation
  (Governato et al 2002)

Is the Dark Matter *slightly Warm*?

Last Updated: Sunday, 5 February 2006, 23:25 GMT

E-mail this to a friend   Printable version

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".

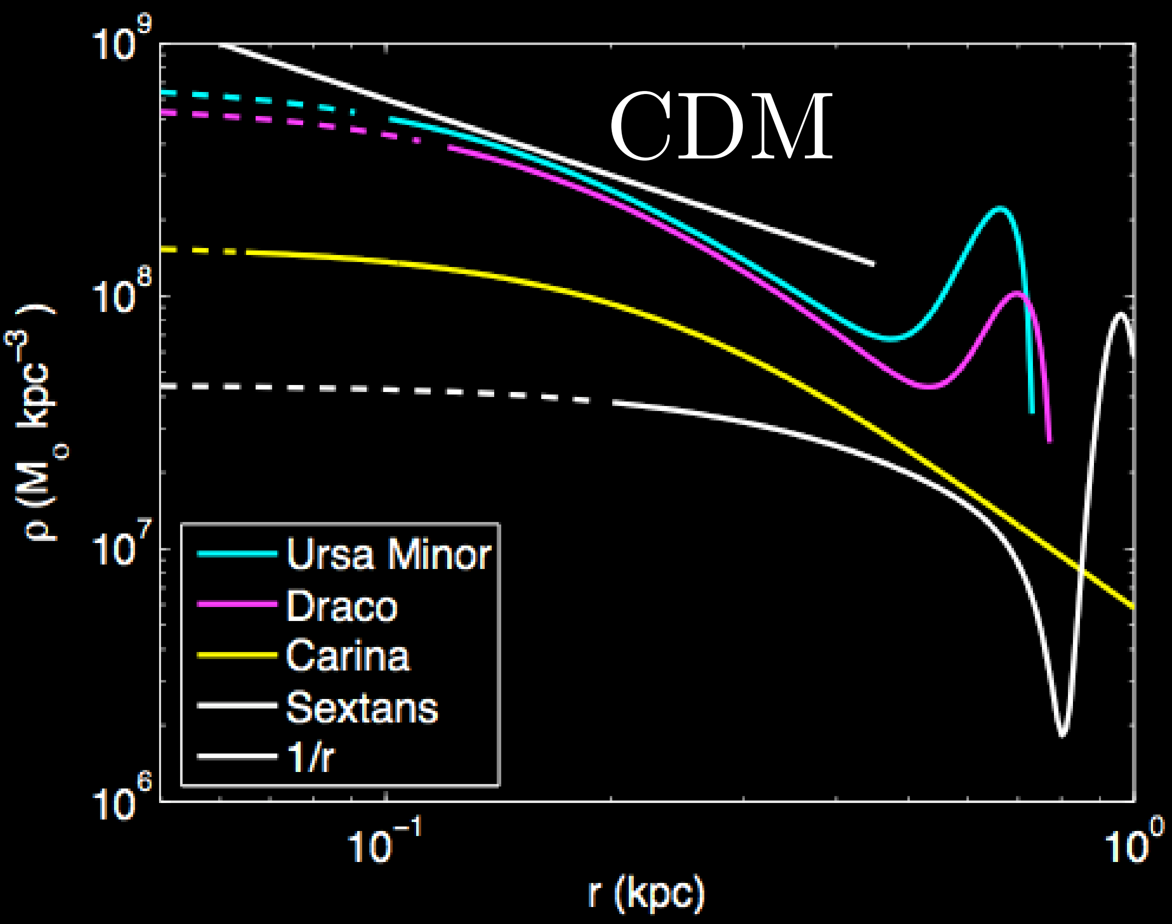
"It's the first clue of what this stuff might be," said Professor Gerry Gilmore. "For the first time ever, we're actually dealing with its physics," he told the BBC News website.

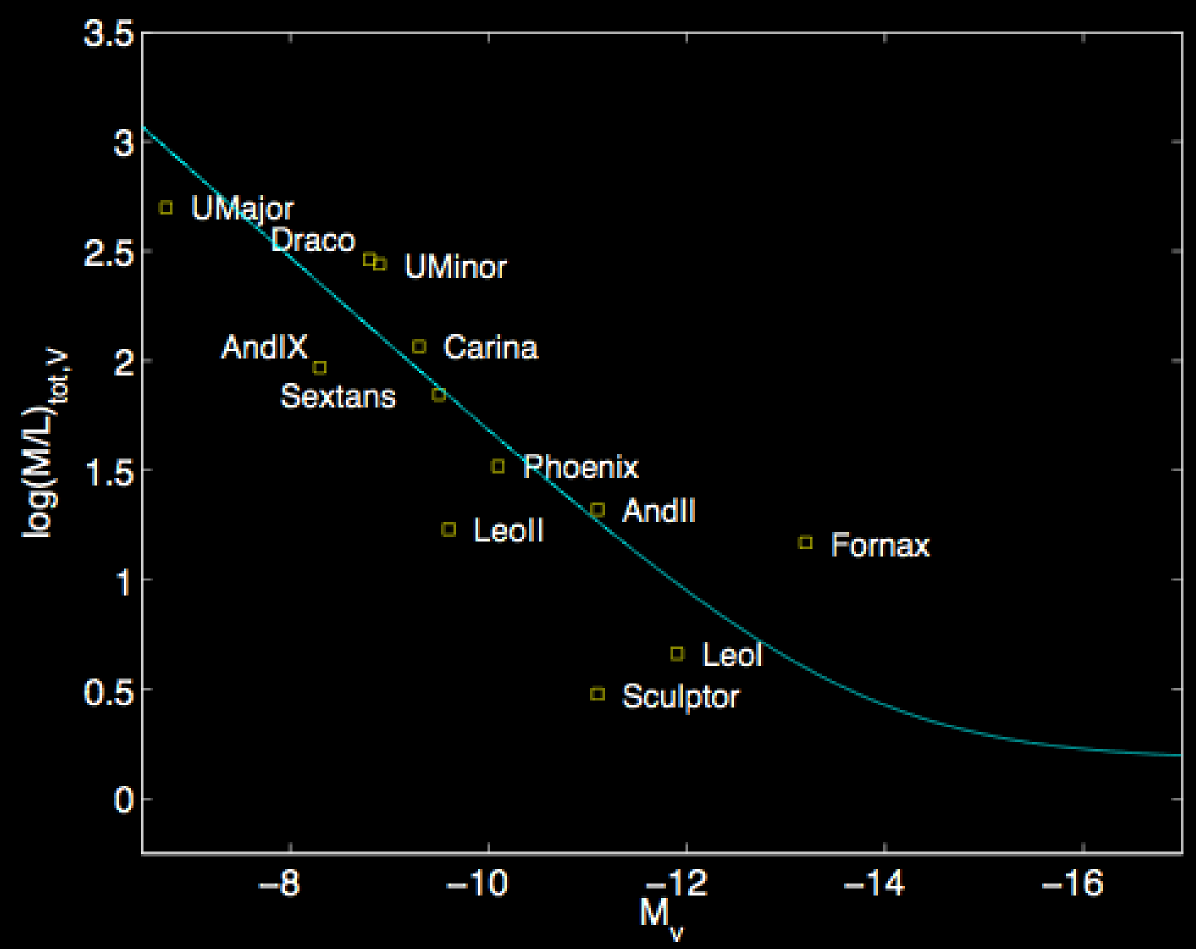
Science understands a great deal about what it terms baryonic matter - the "normal" matter which makes up the stars, planets and people - but it has struggled to comprehend the main material from which the cosmos is constructed.

Dwarf Spheroidal Density Profiles from Radial Stellar Velocity Dispersion

- 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 mass halo consistent with M/L-Luminosity relation





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)

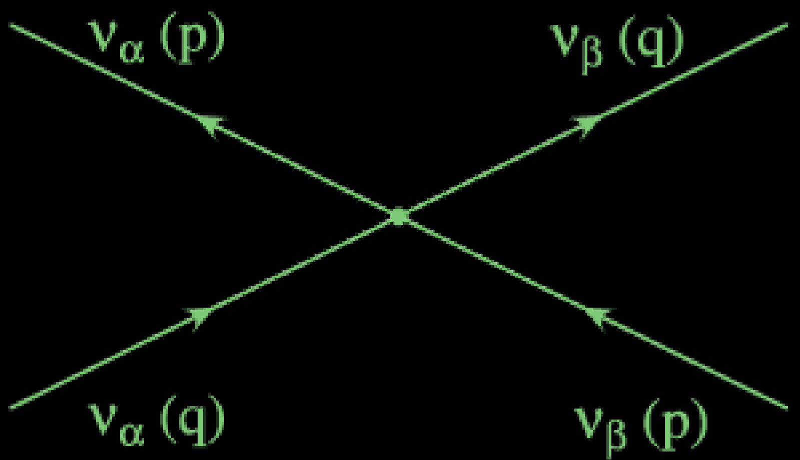
- ν_s Left-Right Symmetric Models (Pati & Salam 1974; Mohapatra & Pati 1975)

- ν_s Higher Dimensional Operators in String-Inspired models (Langacker 1998)

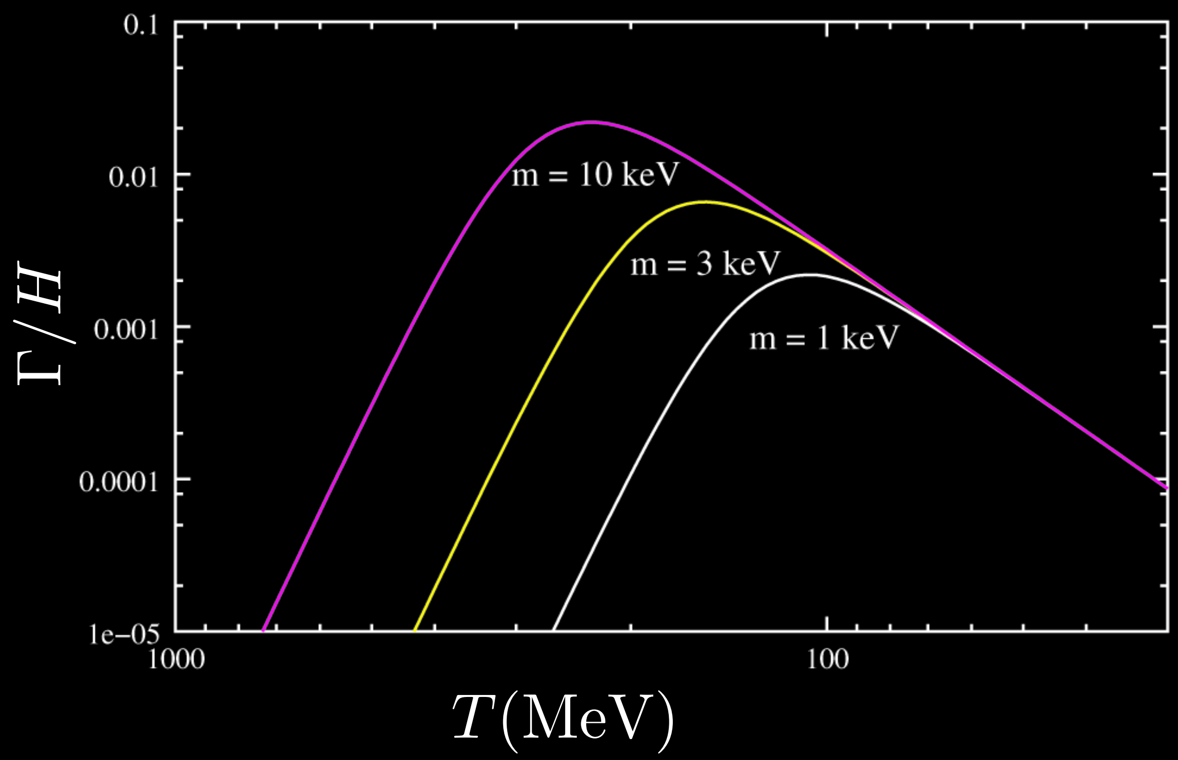
- ν_s Bulk Fermions in Large Extra Dimensions (ADD; Dvali & Smirnov 2000)

- ν_s Axino in R-parity Violating Minimal Supersymmetric Models (Chun & Kim 1999)

Sterile Neutrino Dark Matter Production

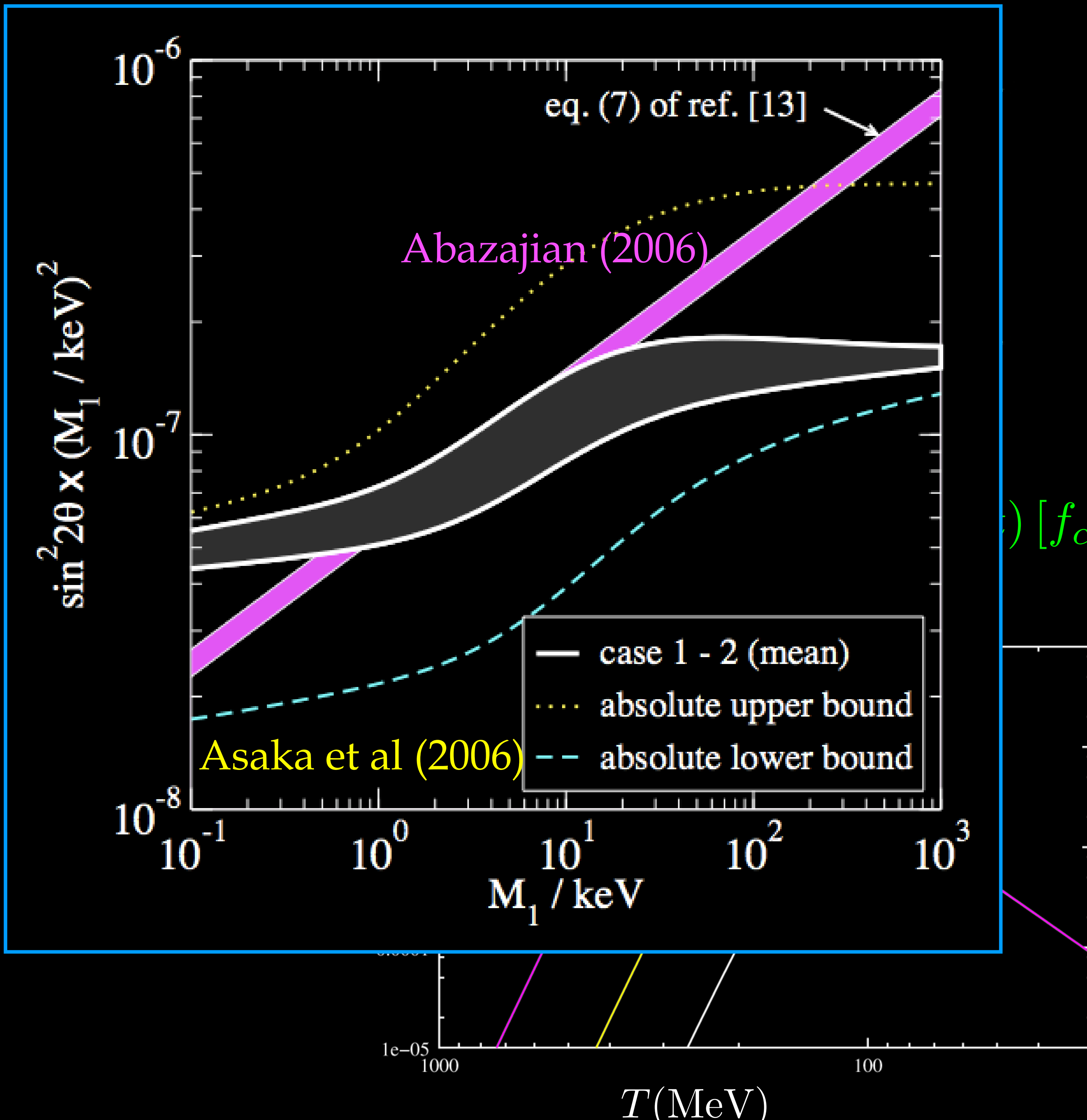


$$\frac{\partial}{\partial t} f_s(p,t) - H\, p\, \frac{\partial}{\partial p} f_s(p,t) \approx \Gamma(\nu_\alpha \to \nu_s; p, t)\,[f_\alpha(p,t) - f_s(p,t)]$$



Dodelson & Widrow (1994)
Abazajian et al (2001)
Abazajian (2006)
Asaka et al (2006)

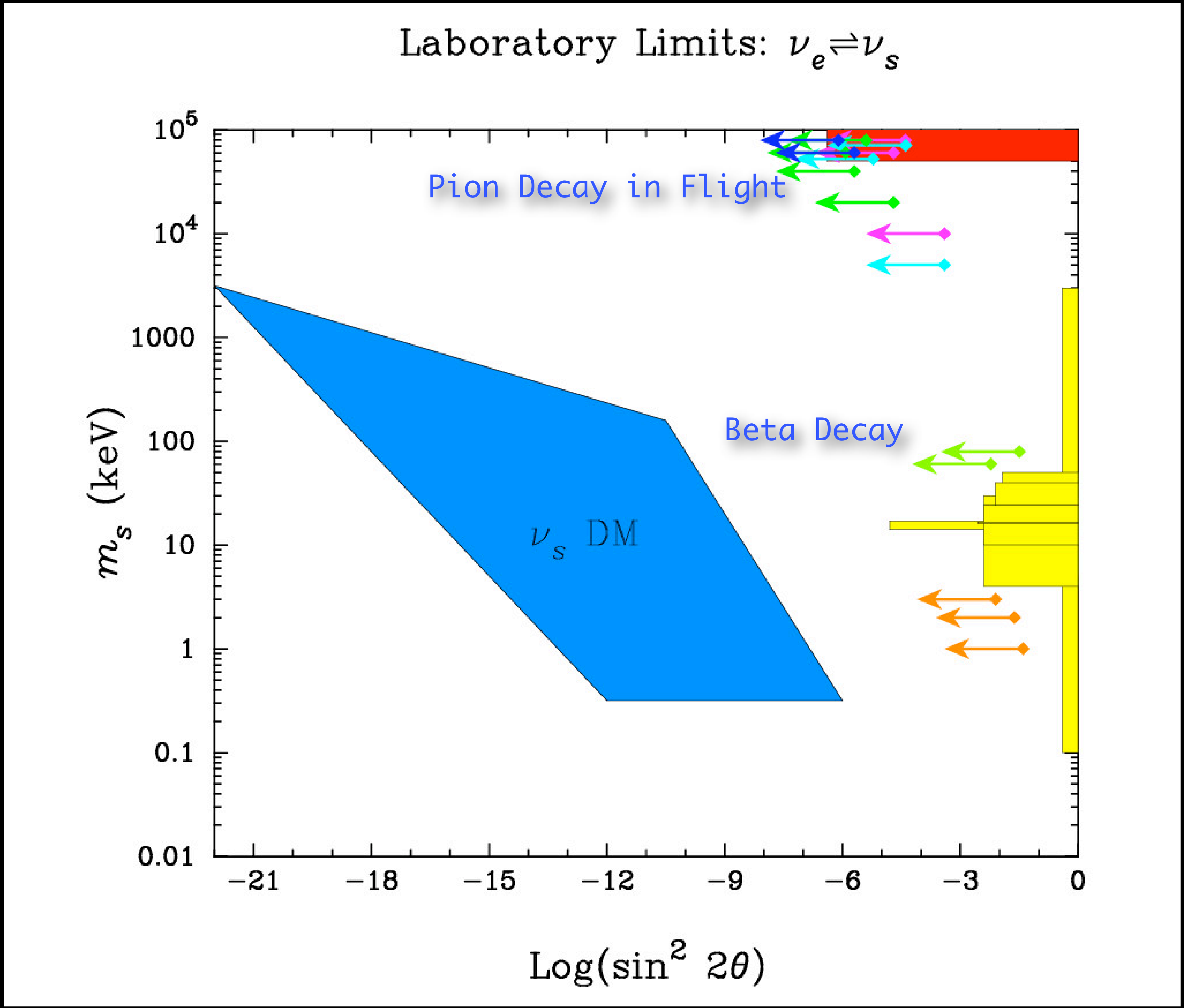
Sterile Neutrino Dark Matter Production



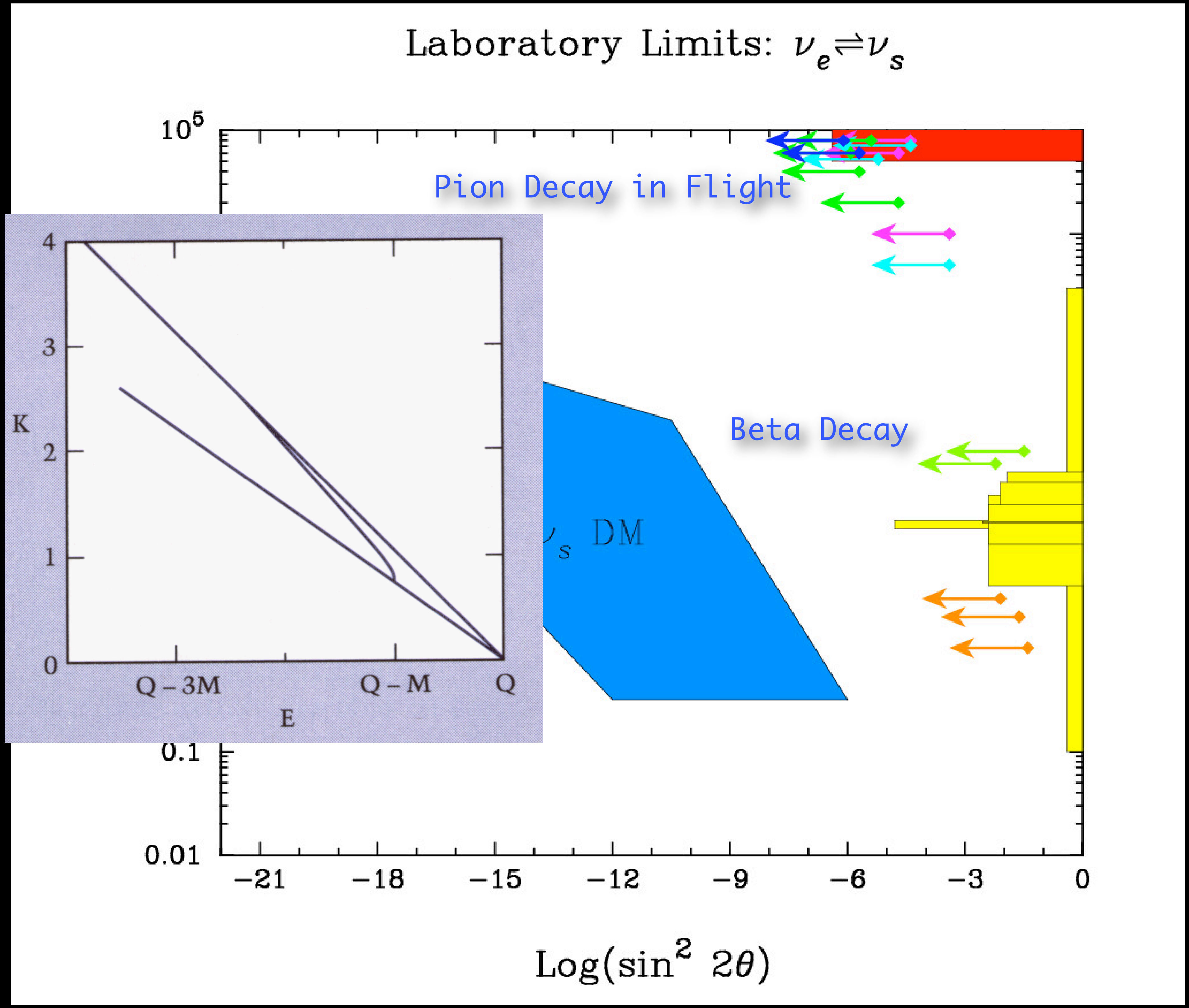
$\ldots) \, [f_\alpha(p,t) - f_s(p,t)]$

Dodelson & Widrow (1994)
Abazajian et al (2001)
Abazajian (2006)
Asaka et al (2006)

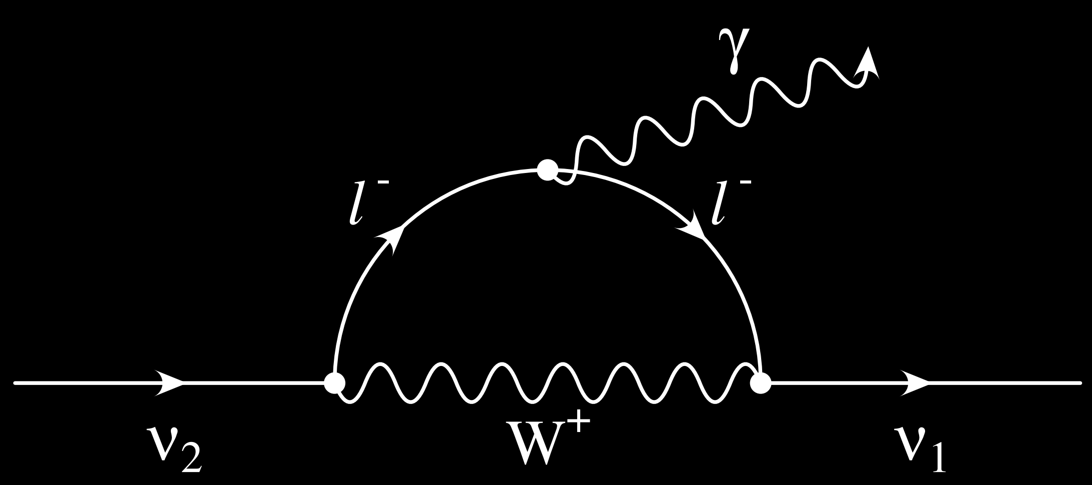
Detecting the Dark Matter: Laboratory Limits



Detecting the Dark Matter: Laboratory Limits



Radiative Decay in the X-ray



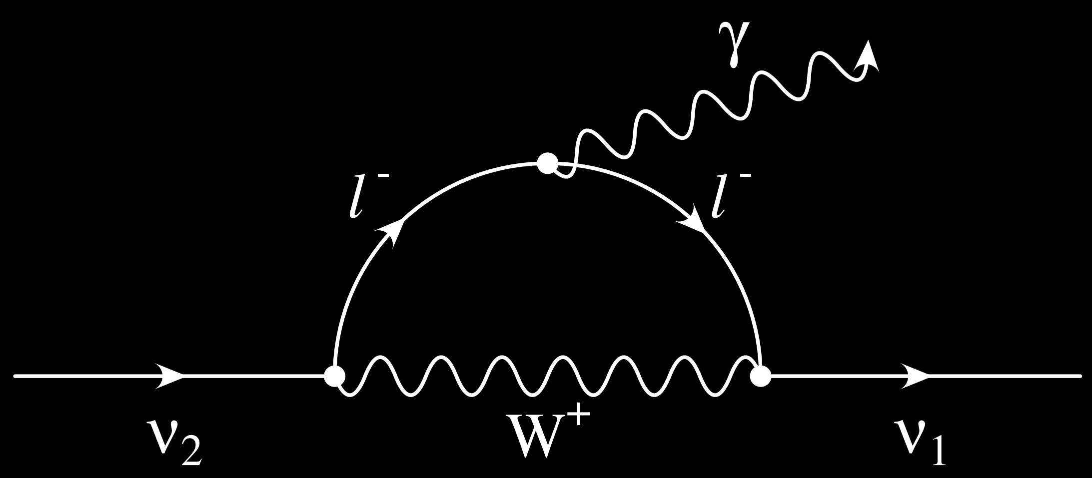
$$\nu_i \longrightarrow \nu_j + \gamma$$

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

Pal & Wolfenstein 1981

$$\Gamma_\gamma(m_s, \sin^2 2\theta) = 1.36 \times 10^{-29} \text{ s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-7}}\right) \left(\frac{m_s}{1 \text{ keV}}\right)^5$$

Radiative Decay in the X-ray



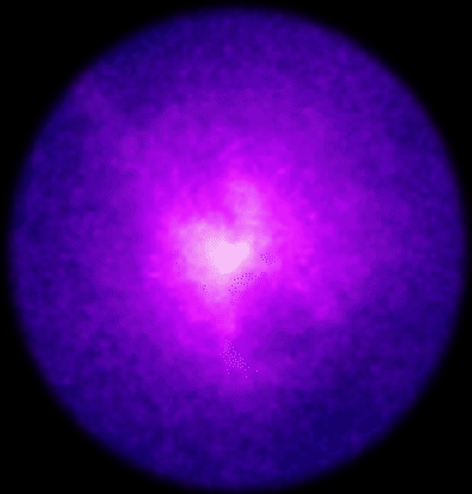
$$\nu_i \longrightarrow \nu_j + \gamma$$

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

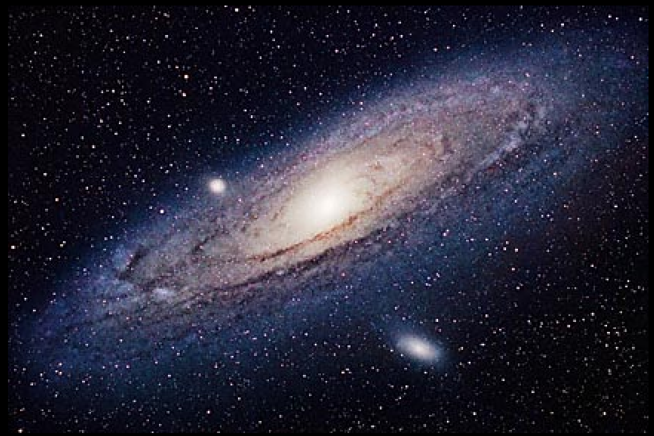
Pal & Wolfenstein 1981

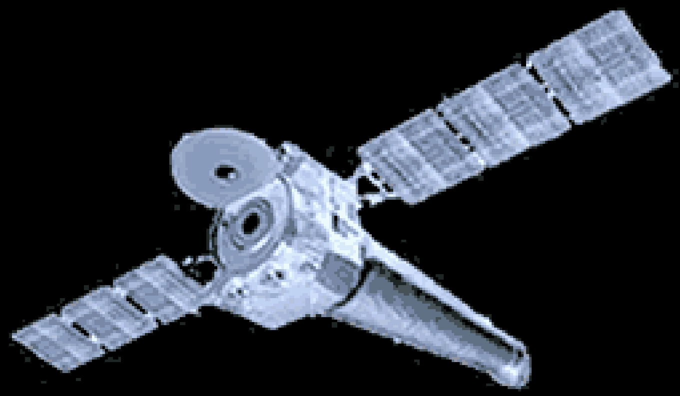
$$\Gamma_\gamma(m_s, \sin^2 2\theta) = 1.36 \times 10^{-29}\ \mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-7}}\right) \left(\frac{m_s}{1\ \mathrm{keV}}\right)^5$$

Dark Matter Halos as Particle Reservoirs: Detecting Decaying Dark Matter

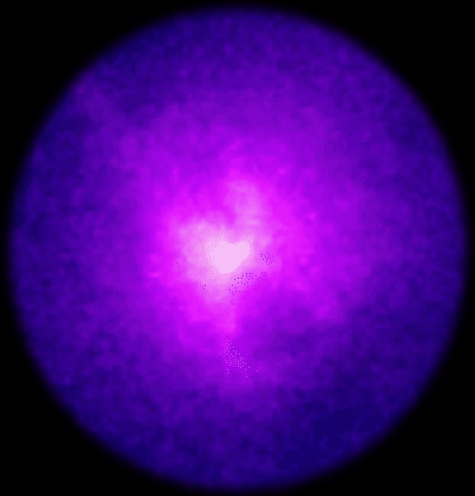


$\sim 10^{70}$ particles

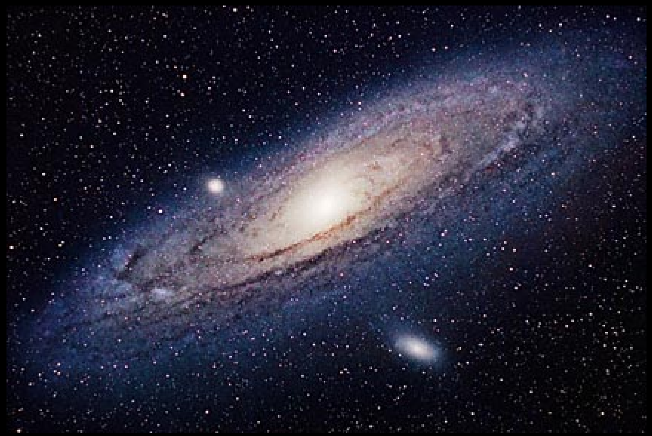


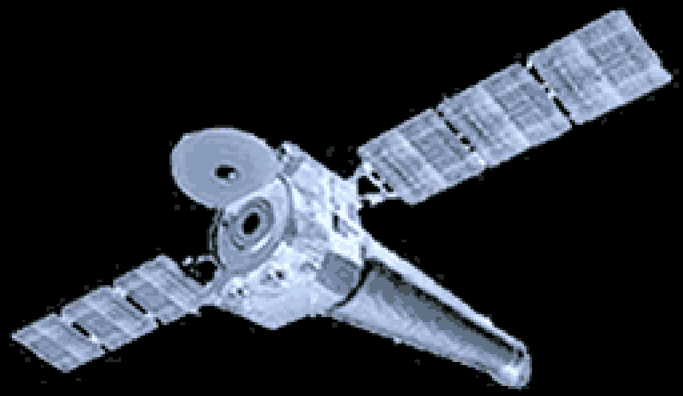


Dark Matter Halos as Particle Reservoirs: Detecting Decaying Dark Matter



$\sim 10^{70}$ particles





Signal:

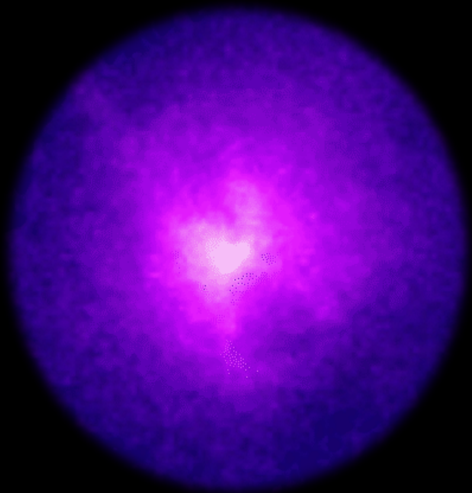
$$F \propto \int d\Omega \; [\text{DM density/distance}^2] \propto J[\Delta\Omega(\theta)]$$

$$J\left[\Delta\Omega(\theta)\right] = \rho_s \int_0^{2\pi} d\phi \int_0^{\theta} \sin\theta' \left[\int_{x_{\min}(\theta')}^{x_{\max}(\theta')} I[\tilde{r}(x)]\, dx\right] d\theta'$$

$$I_{\rm NFW}\left[\tilde{r}(x)\right] = \frac{1}{\tilde{r}(x)\left[1+\tilde{r}(x)\right]^2}$$

$$I_{\rm BUR}\left[\tilde{r}(x)\right] = \frac{1}{\left[1+\tilde{r}(x)\right]\left[1+\tilde{r}^2(x)\right]}$$

Dark Matter Halos as Particle Reservoirs: Detecting Decaying Dark Matter



$\sim 10^{70}$ particles

Background:

- X-ray continuum
- Compact Objects
- Instrumental

Signal:

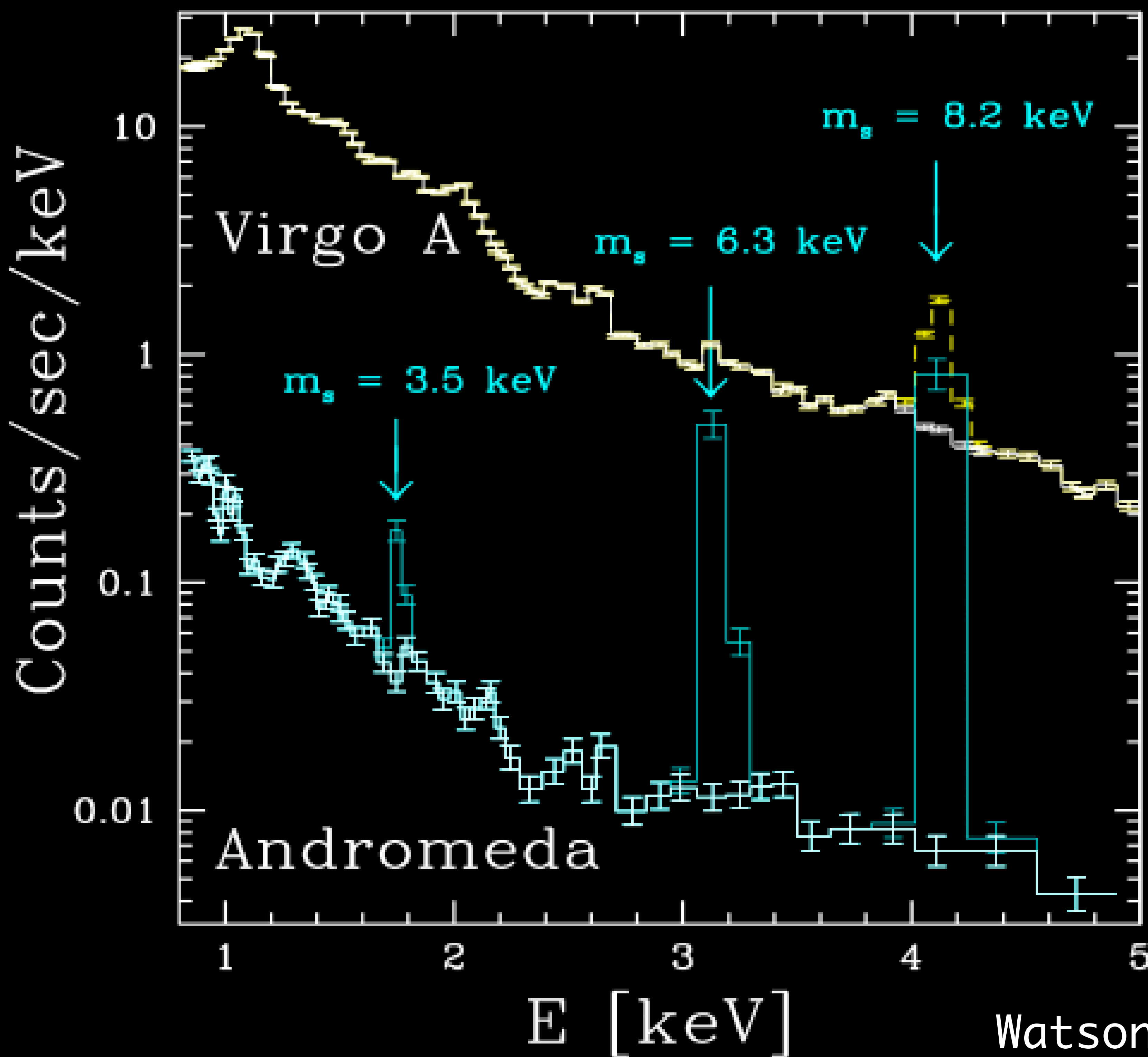
$$F \propto \int d\Omega \;\; [\mathrm{DM\ density/distance}^2] \propto J[\Delta\Omega(\theta)]$$

$$J\left[\Delta\Omega(\theta)\right] = \rho_s \int_0^{2\pi} d\phi \int_0^{\theta} \sin\theta' \left[\int_{x_{\mathrm{min}}(\theta')}^{x_{\mathrm{max}}(\theta')} I[\tilde{r}(x)]\, dx\right] d\theta'$$

$$I_{\mathrm{NFW}}\left[\tilde{r}(x)\right] \quad = \quad \frac{1}{\tilde{r}(x)\left[1+\tilde{r}(x)\right]^2}$$

$$I_{\mathrm{BUR}}\left[\tilde{r}(x)\right] \quad = \quad \frac{1}{\left[1+\tilde{r}(x)\right]\left[1+\tilde{r}^2(x)\right]}$$

X-ray Limits: Virgo and M31

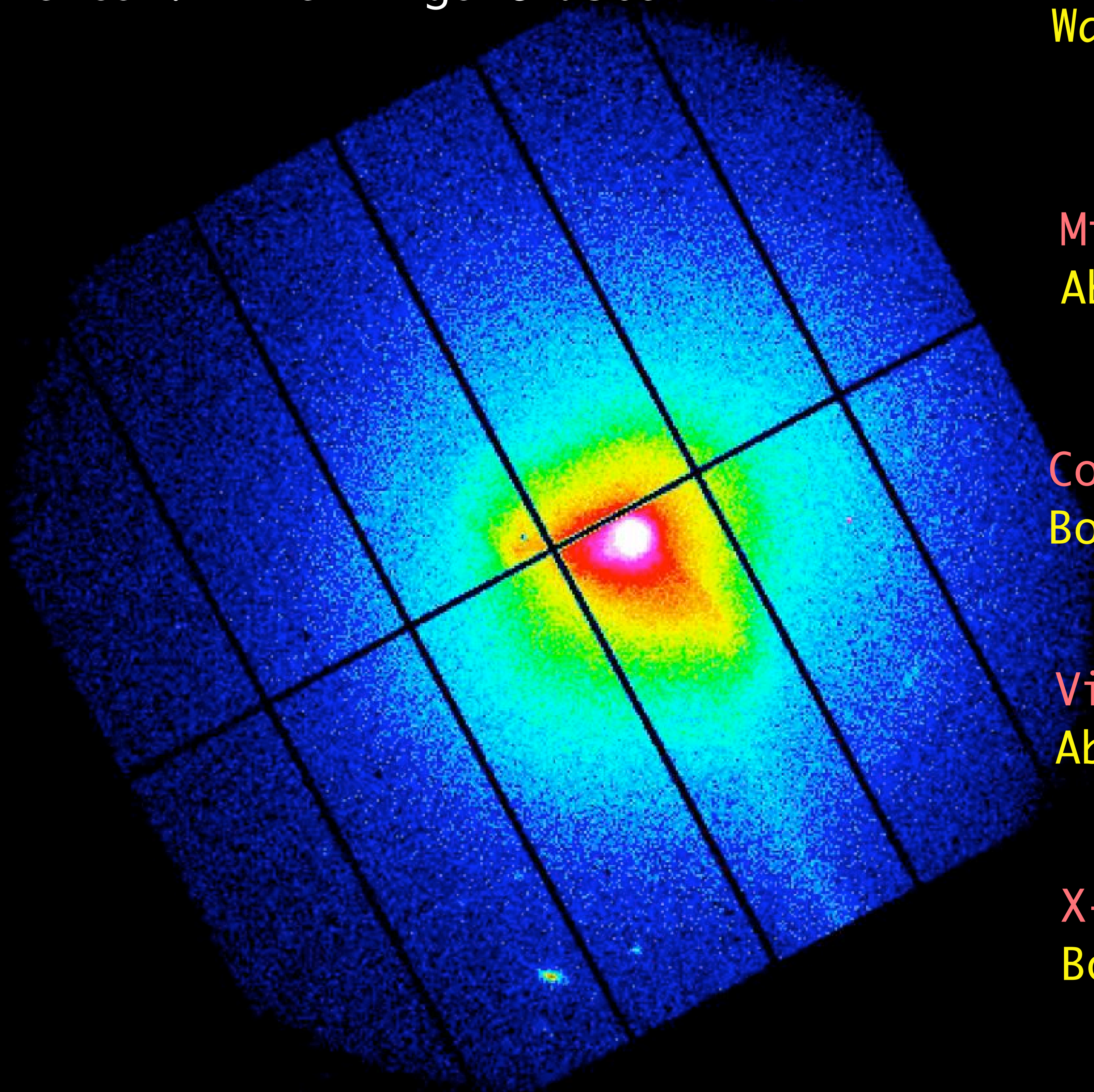


(XMM-Newton)

Watson et al (2006)
Abazajian et al (2001)

X-ray Constraint Summary for DW Model

XMM Newton: The Virgo Cluster



Andromeda Galaxy:
Watson et al 2006

$$m_s < 3.5 \text{ keV}$$

Milky Way in CXB:
Abazajian et al 2006

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

Coma + Virgo Clusters:
Boyarsky et al 2006

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

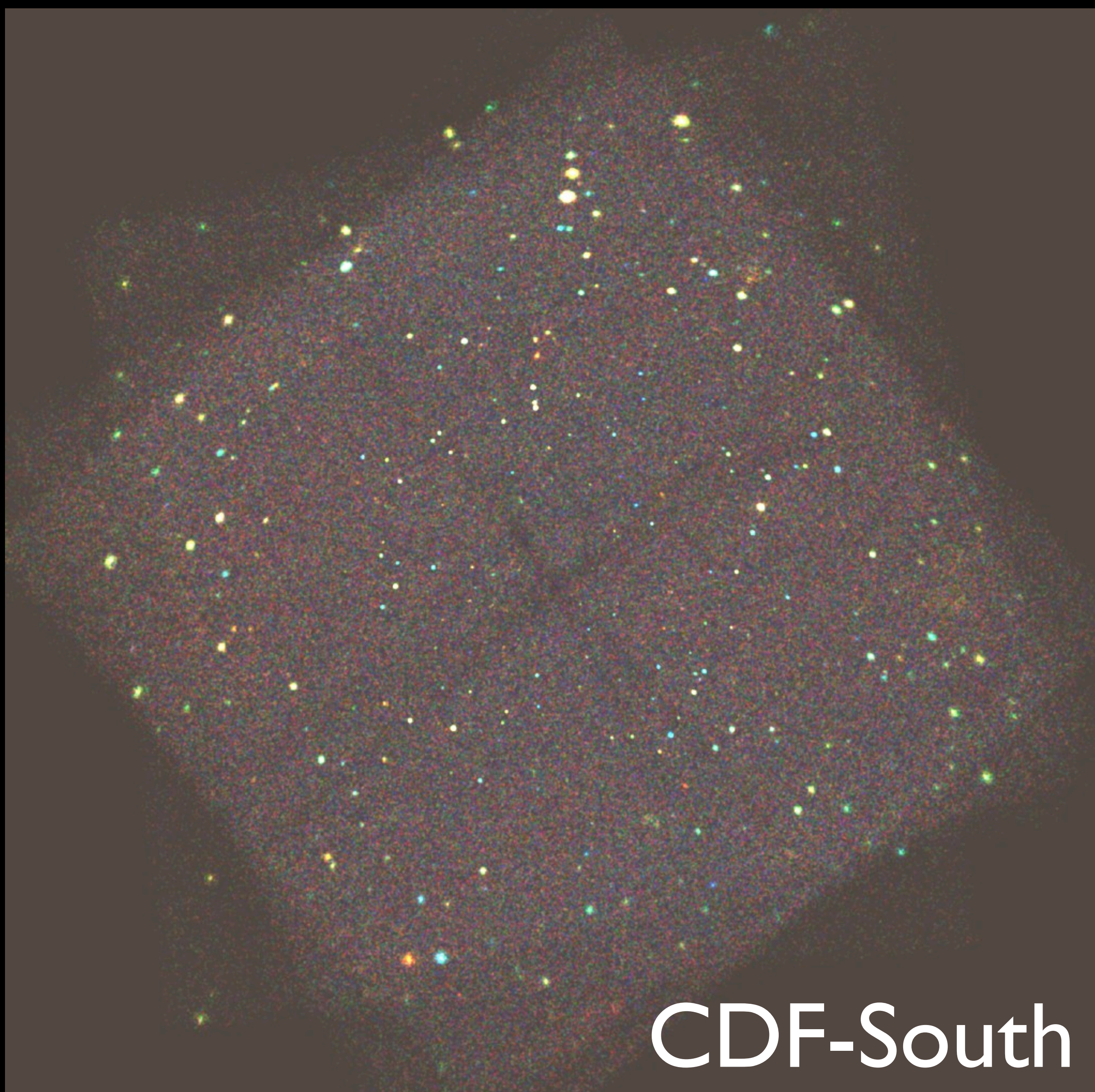
Virgo Cluster:
Abazajian et al 2001

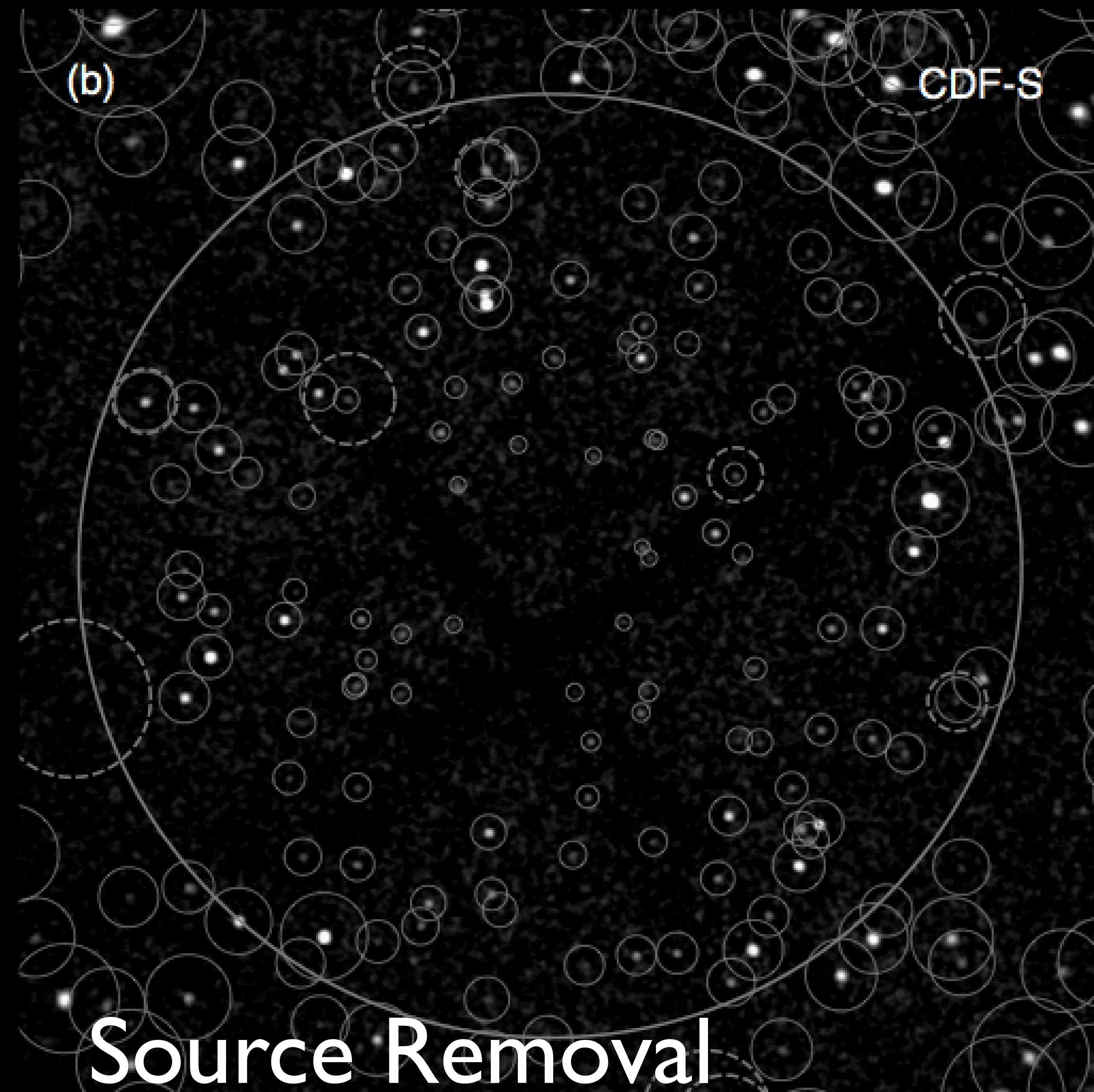
$$m_s < 8.2 \text{ keV}$$

X-Ray Background:
Boyarsky et al 2006

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

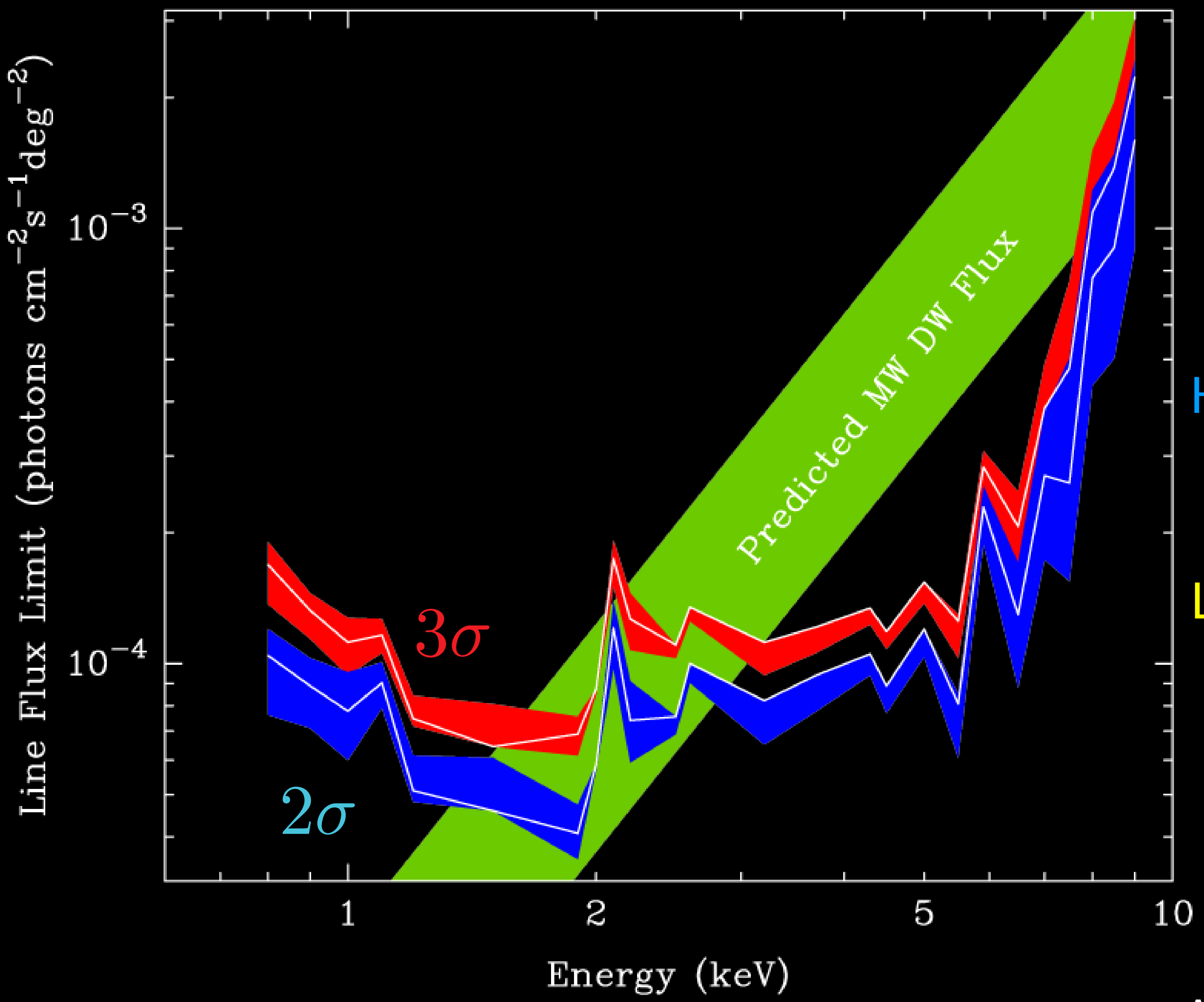
Chandra Deep Field: Milky Way Halo Limits from the Unresesoved X-ray Background





Hickox & Markevitch 2006, 2007

Milky Way Line Flux limits from the Chandra Deep Field of the CXB



High DM mass MW:

$$m_s < 2.95 \text{ keV}$$

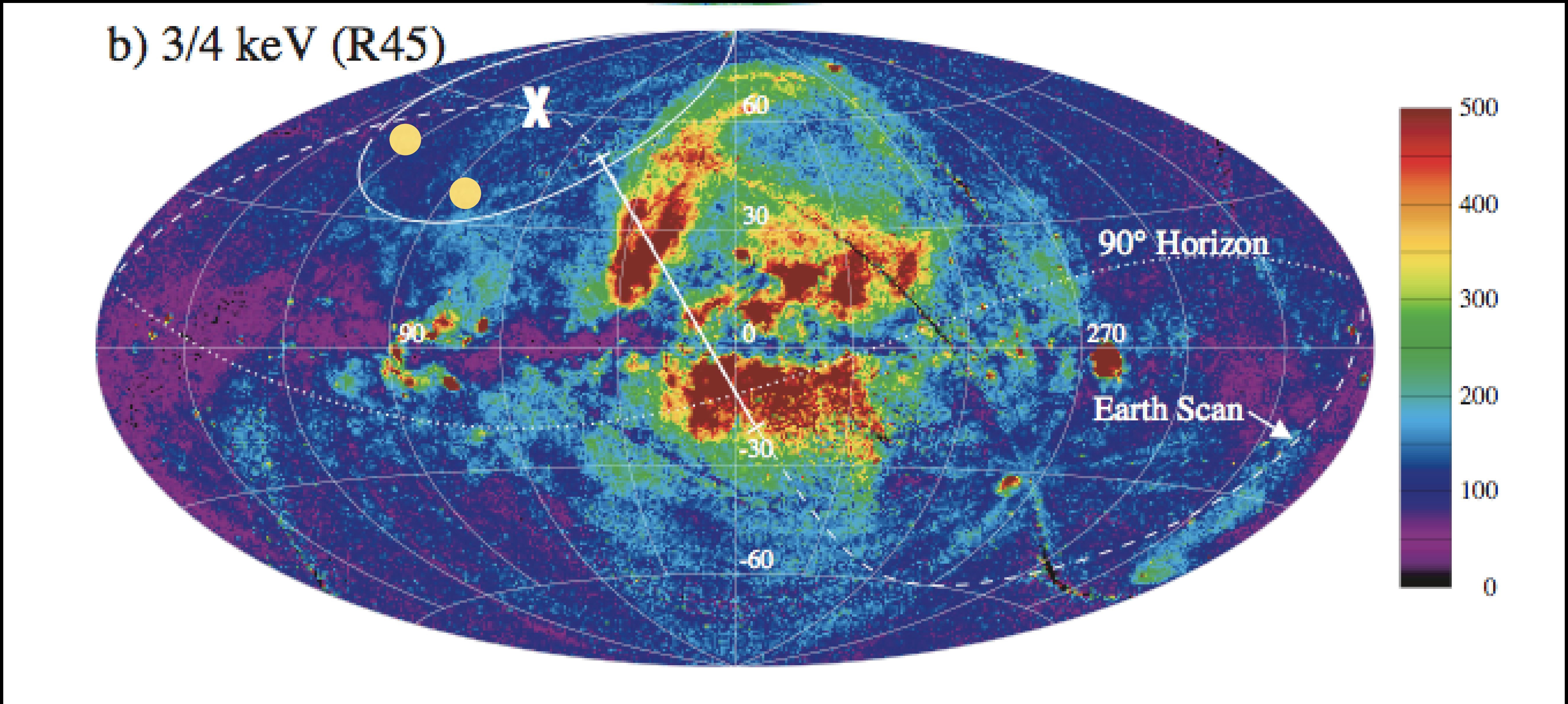
Low DM mass MW:

$$m_s < 5.74 \text{ keV}$$

(2σ)

Abazajian, Markevitch, Koushiappas & Hickox 2007

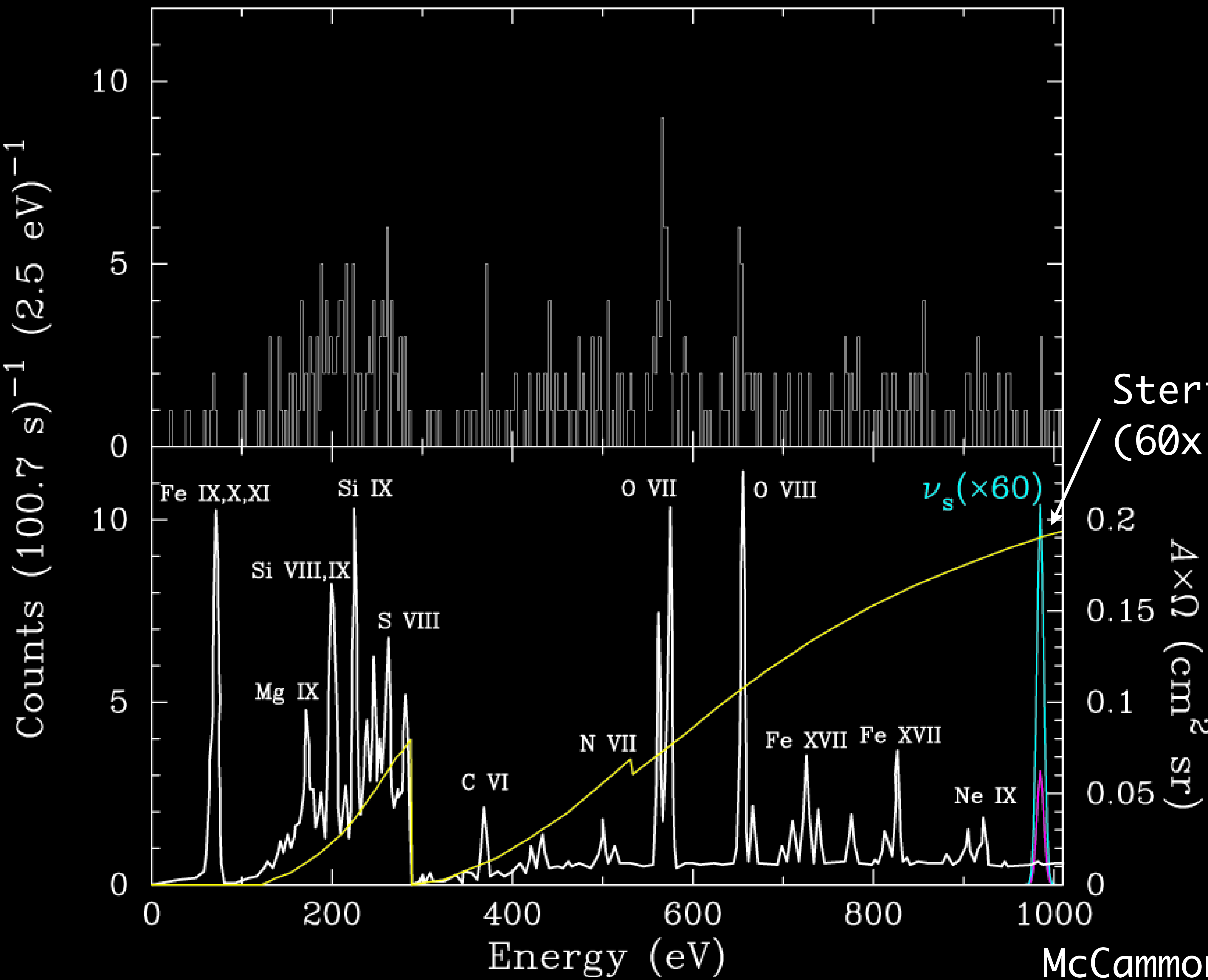
The Soft X-ray Background



100.7 sec X-ray calorimeter exposure
on sounding rocket flight from
White Sands, NM

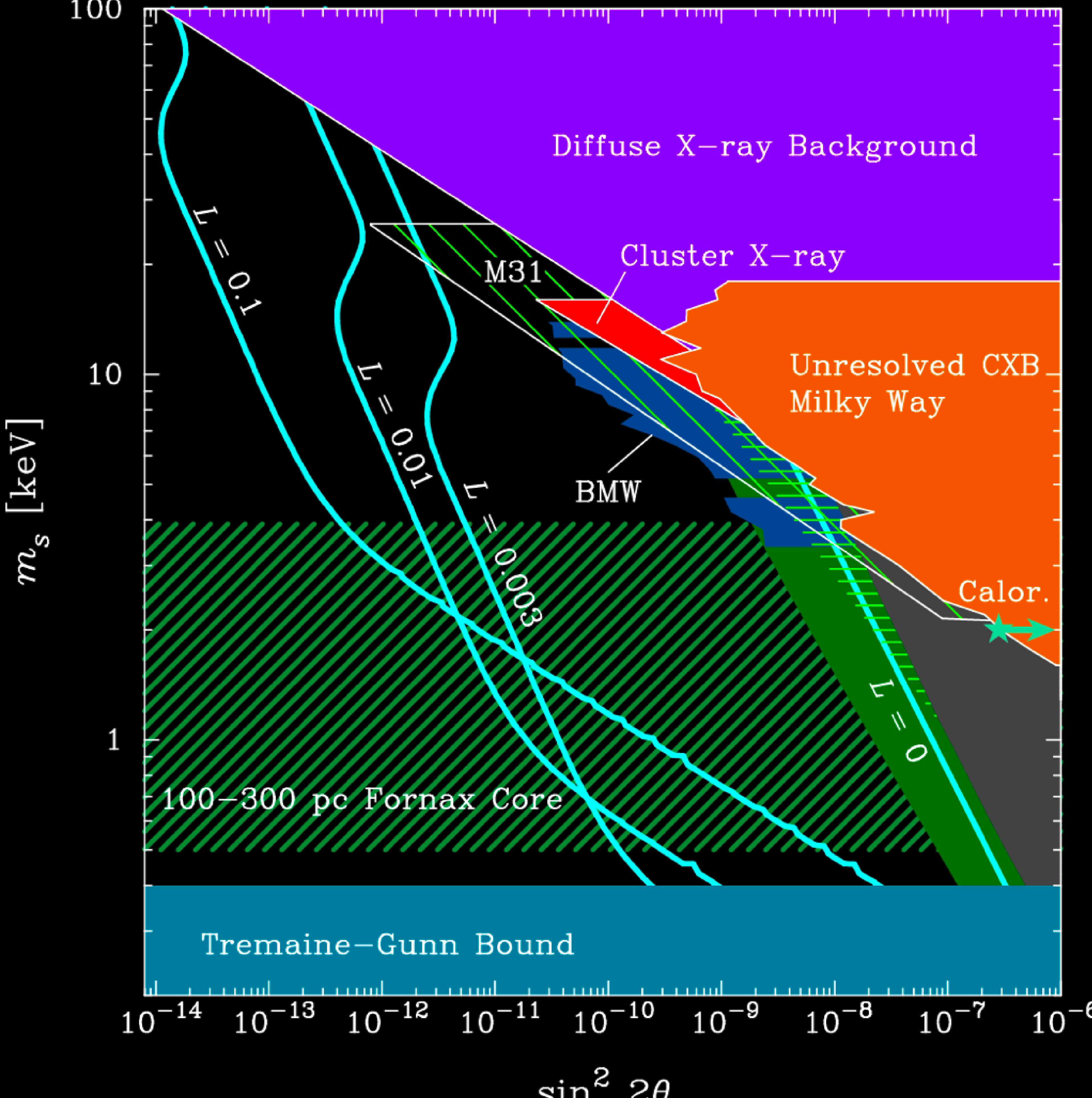
Using modern X-ray quantum calorimeters
Resolution ~9 eV FWHM
(McCammon et al., 2002)

The Soft X-ray Background: Spectrum



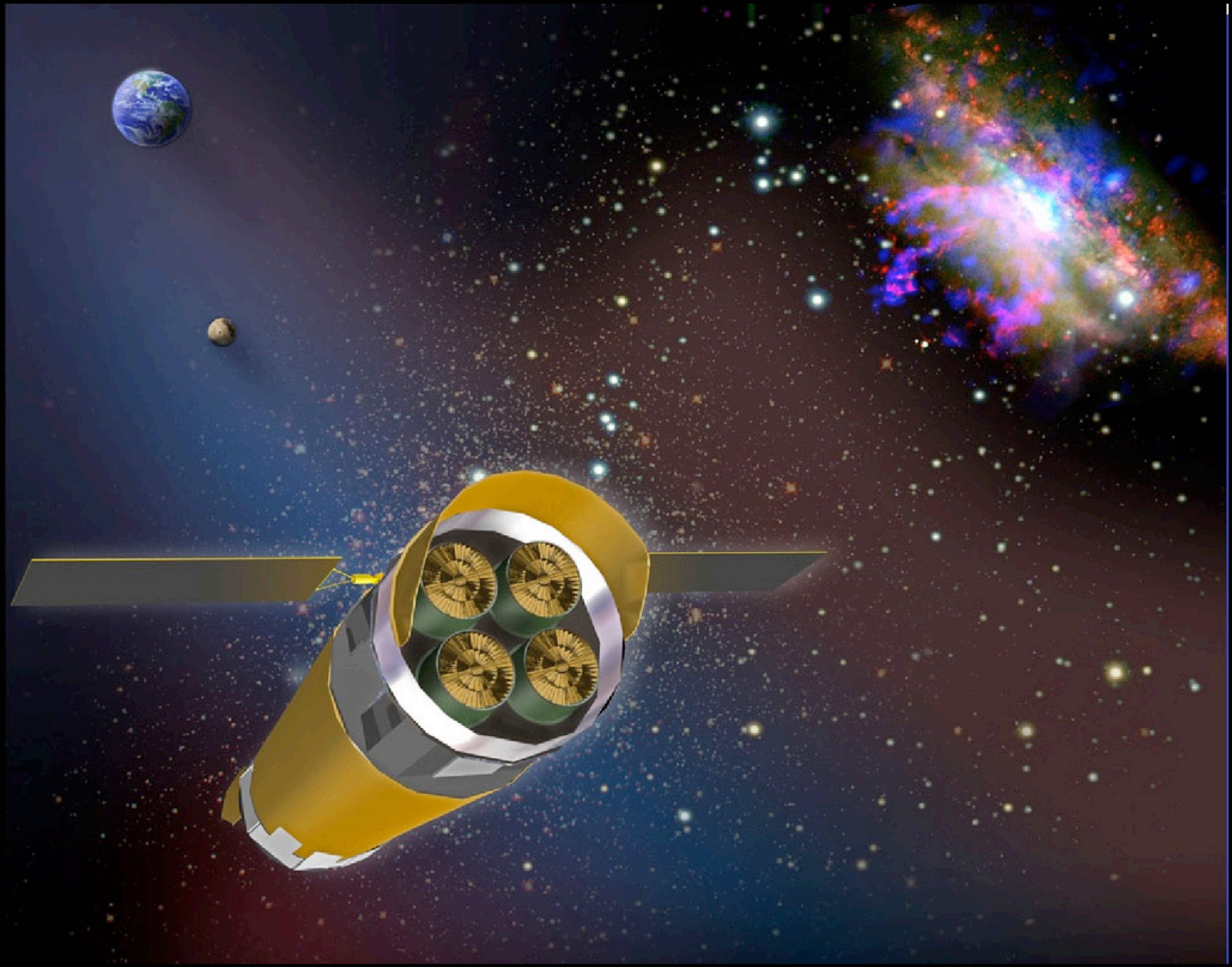
Sterile Neutrino Line
(60x MW Predicted)

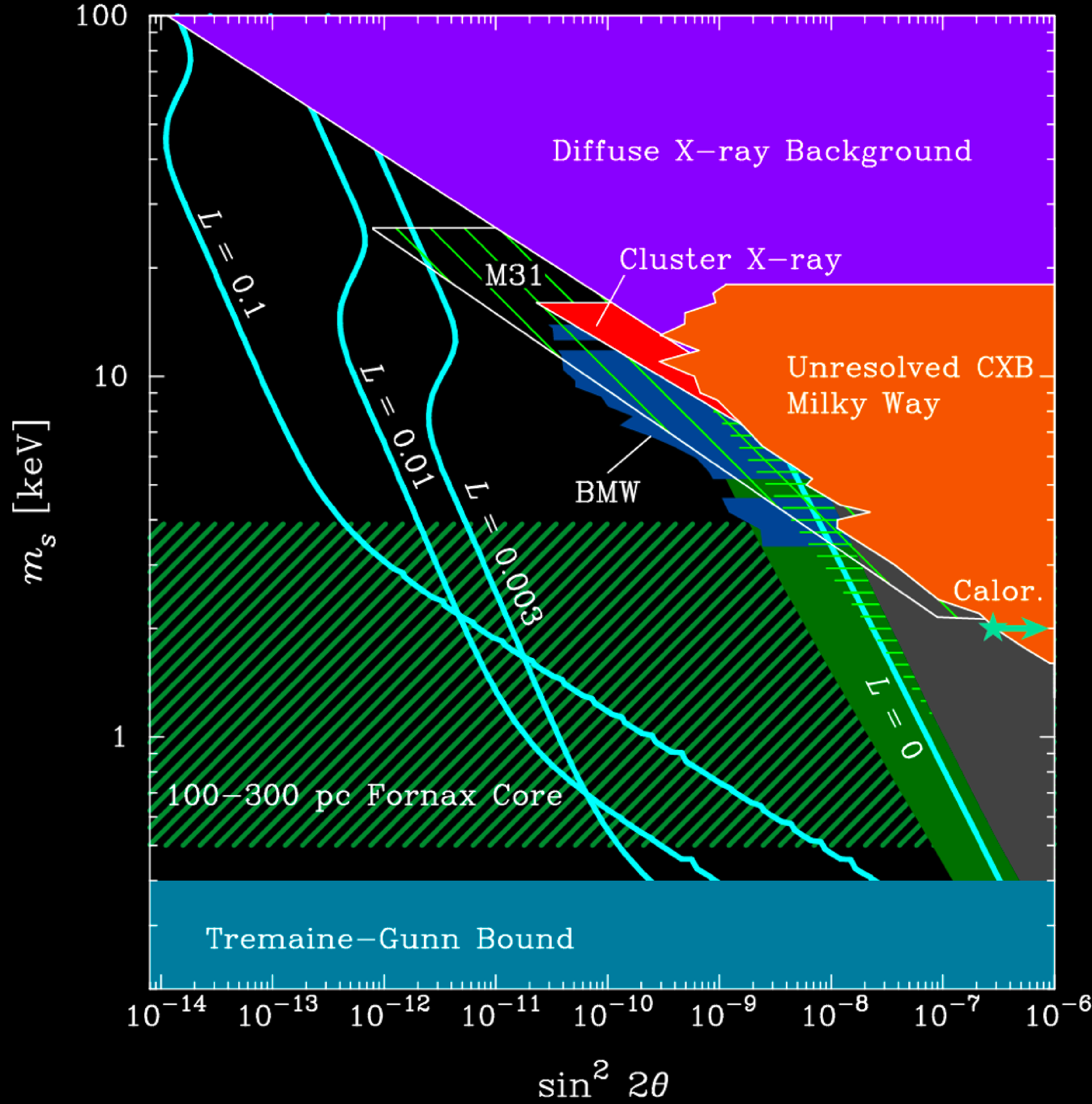
McCammon et al. (2002)
Abazajian et al (2006)



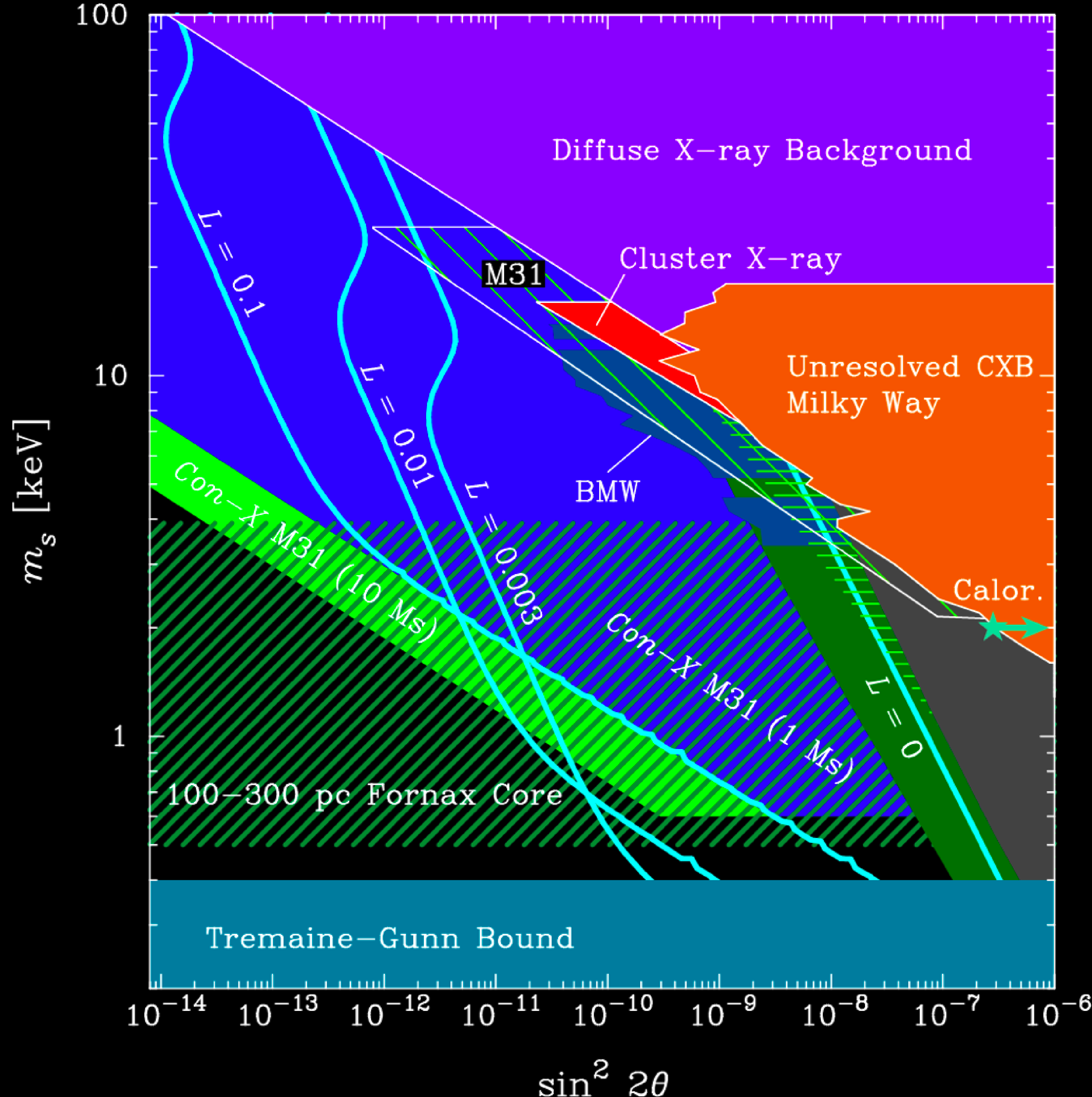
100
10
1
m_s [keV]
10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6}
$\sin^2 2\theta$
Diffuse X-ray Background
Cluster X-ray
M31
Unresolved CXB
Milky Way
BMW
Calor.
$L = 0.1$
$L = 0.01$
$L = 0.003$
$L = 0$
100–300 pc Fornax Core
Tremaine–Gunn Bound

Constellation-X Observatory - Beyond Einstein



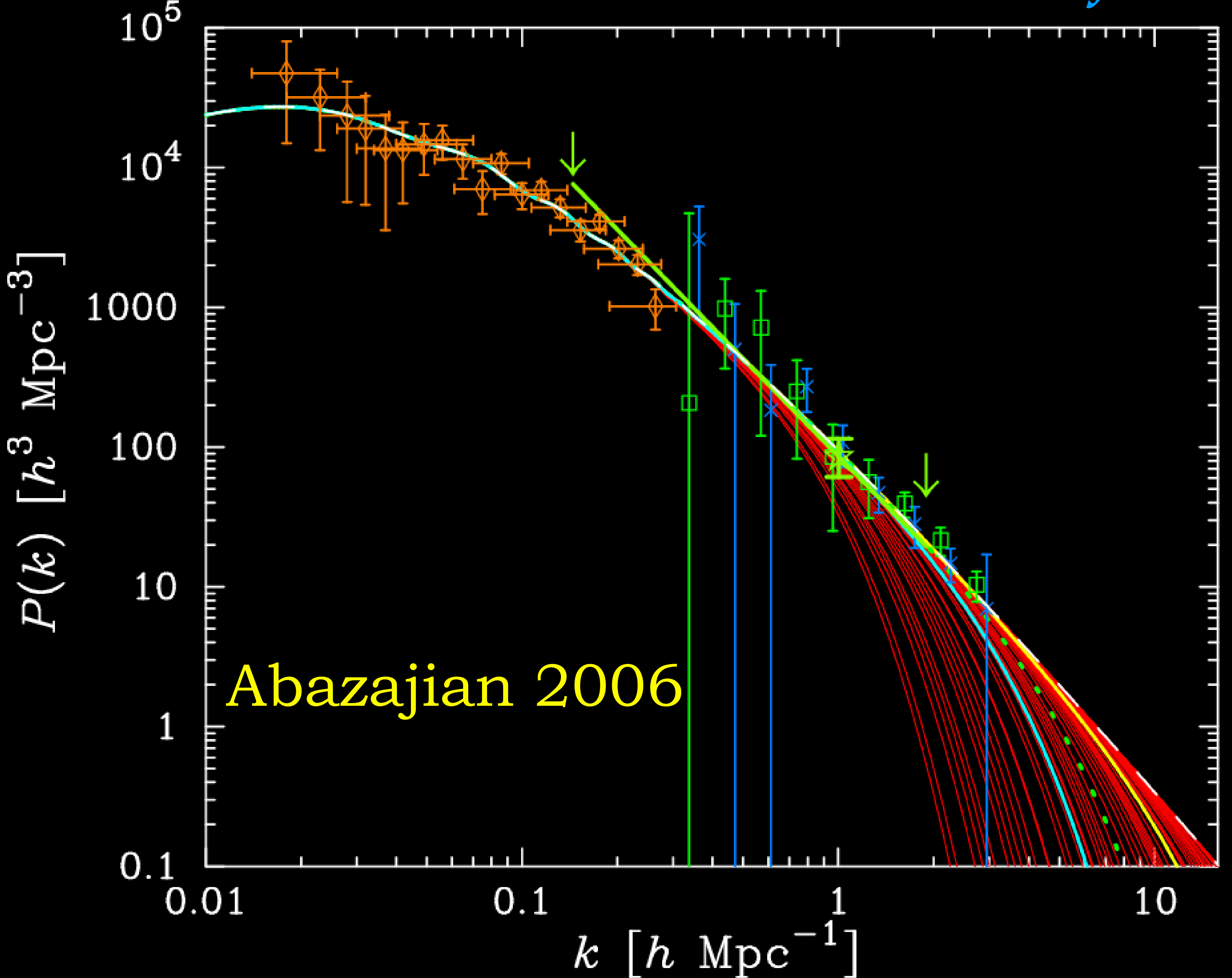


Diffuse X-ray Background
Cluster X-ray
M31
Unresolved CXB
Milky Way
BMW
Calor.
L = 0.1
L = 0.01
L = 0.003
L = 0
100-300 pc Fornax Core
Tremaine-Gunn Bound
100
10
1
m_s [keV]
10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6}
$\sin^2 2\theta$


100
10
1
m_s [keV]
10^{-14}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
$\sin^2 2\theta$
Diffuse X-ray Background
Cluster X-ray
M31
Unresolved CXB
Milky Way
BMW
Calor.
$L = 0.1$
$L = 0.01$
$L = 0.003$
$L = 0$
Con-X M31 (10 Ms)
Con-X M31 (1 Ms)
100-300 pc Fornax Core
Tremaine-Gunn Bound

How warm is too warm?

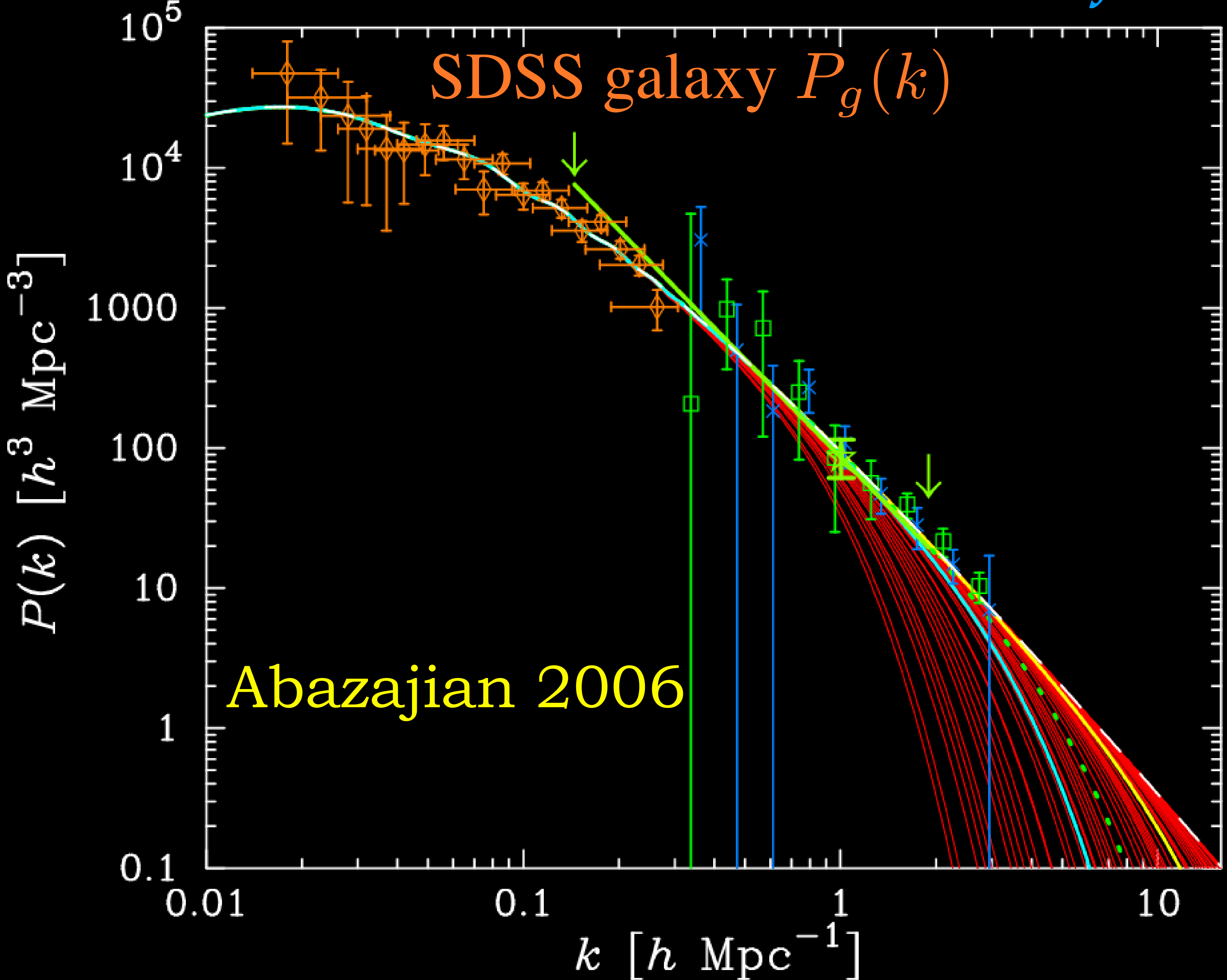
Or, *where does the CDM ansatz fail?*



- 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

How warm is too warm?

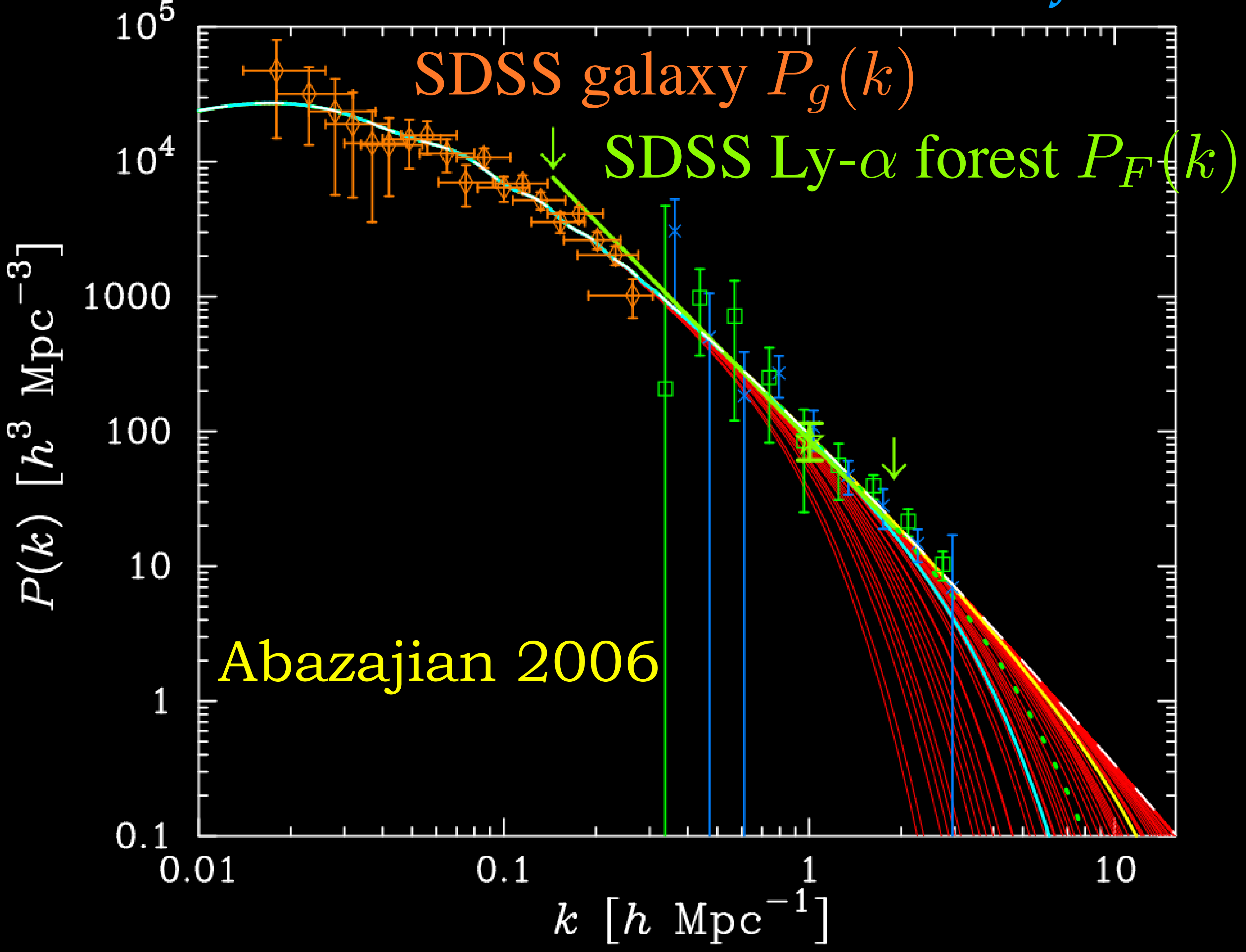
Or, *where does the CDM ansatz fail?*



- 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

How warm is too warm?

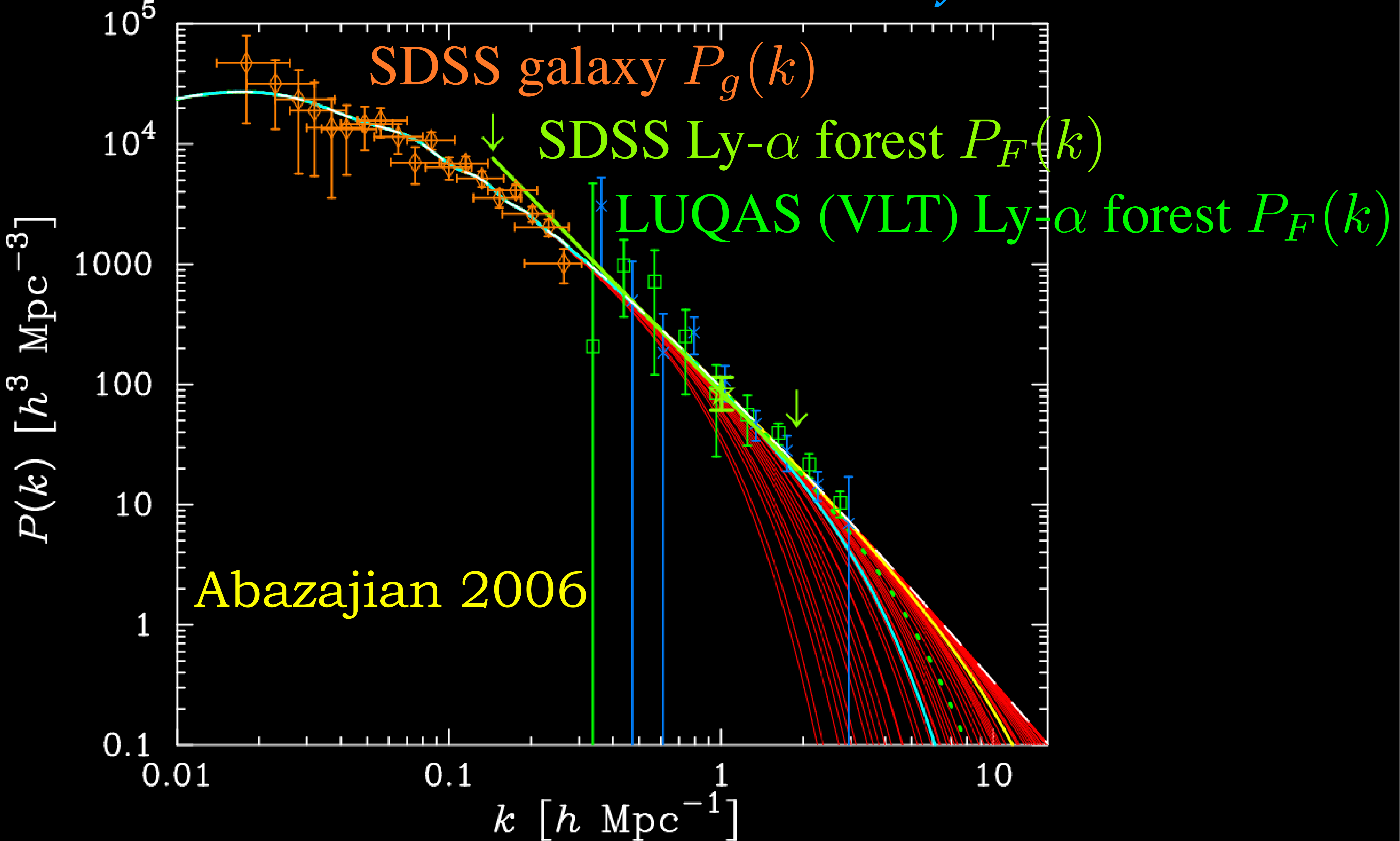
Or, *where does the CDM ansatz fail?*



- 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

How warm is too warm?

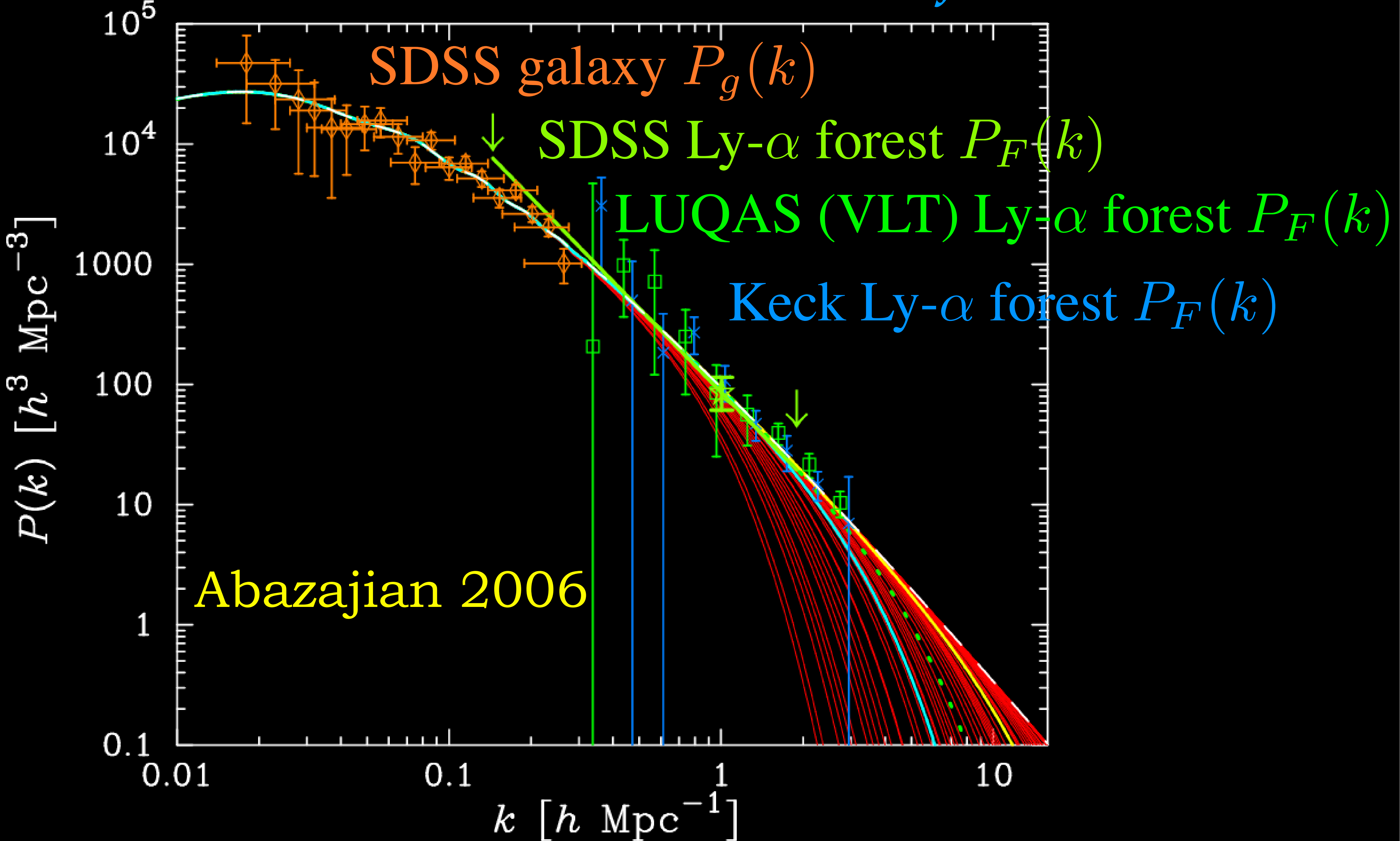
Or, *where does the CDM ansatz fail?*



- 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

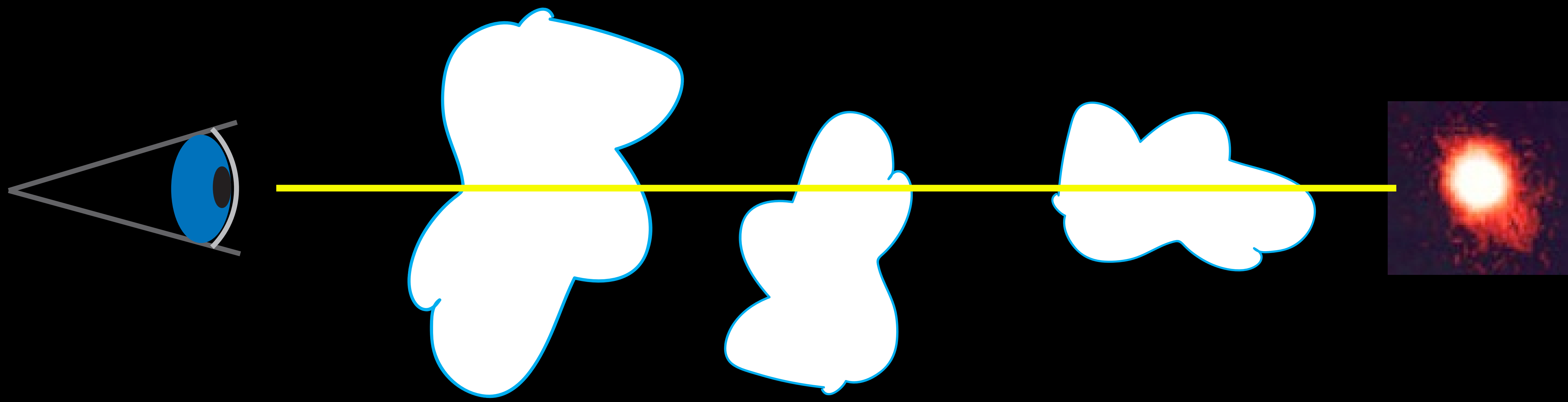
How warm is too warm?

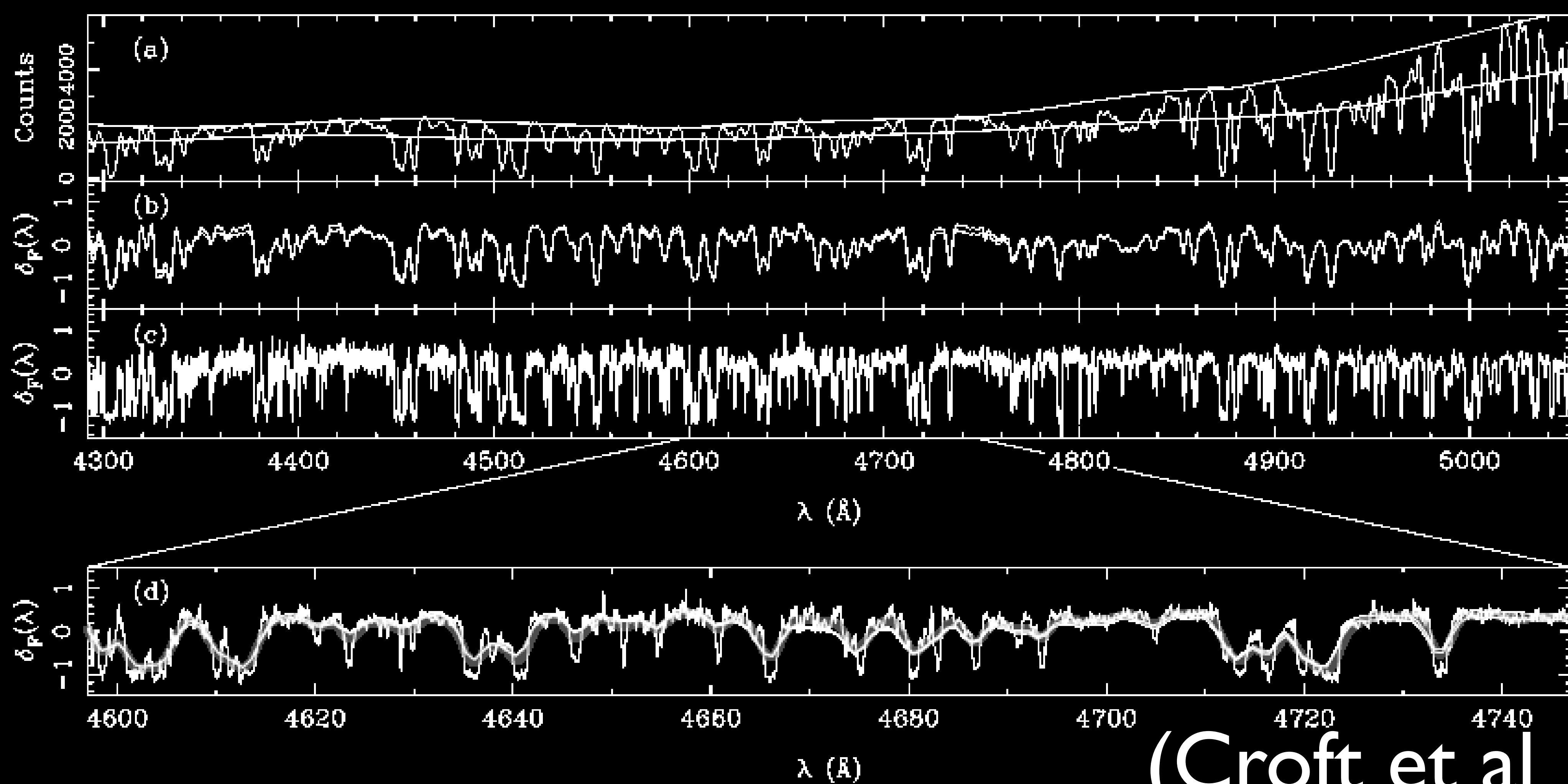
Or, *where does the CDM ansatz fail?*



- 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

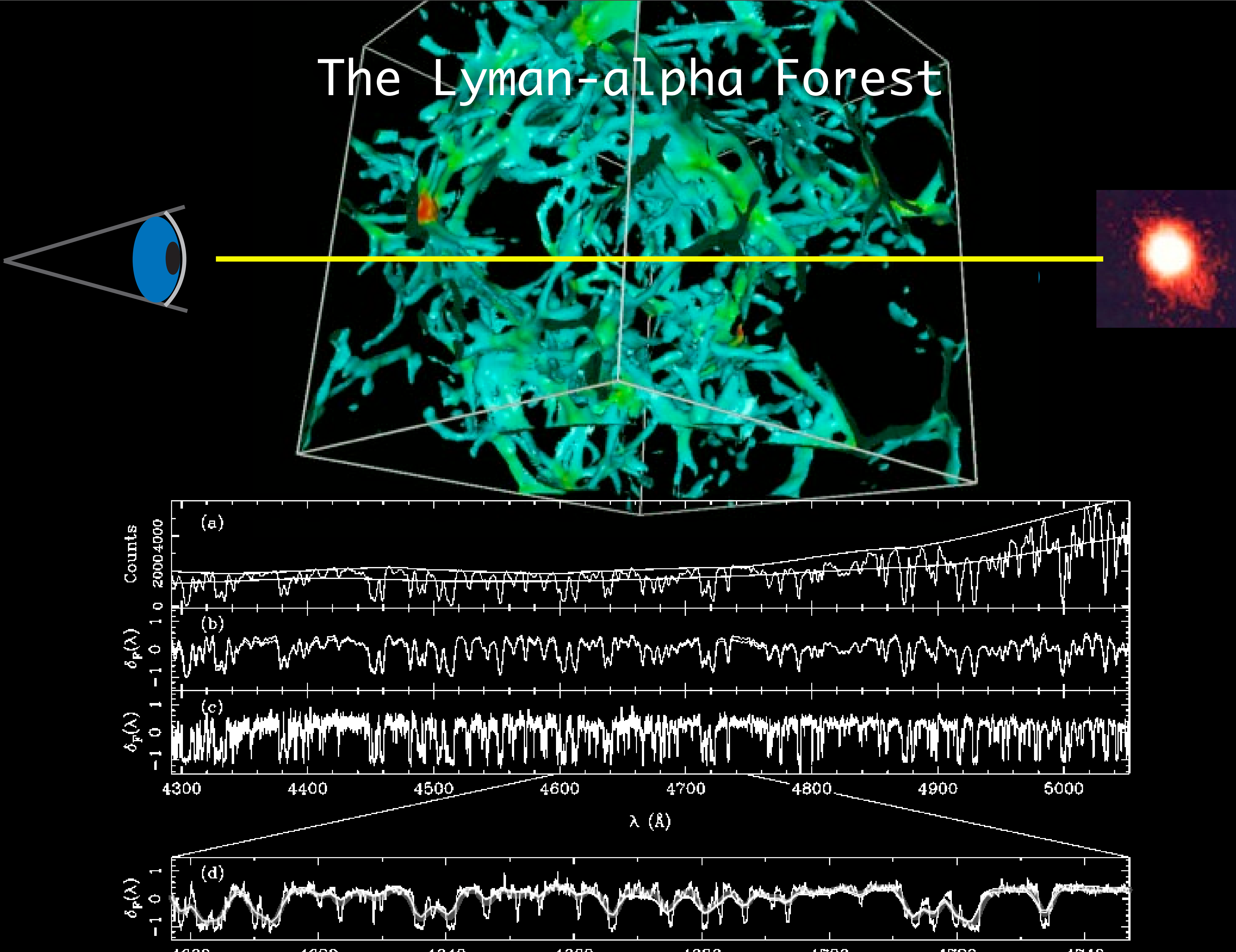
The Lyman-alpha Forest





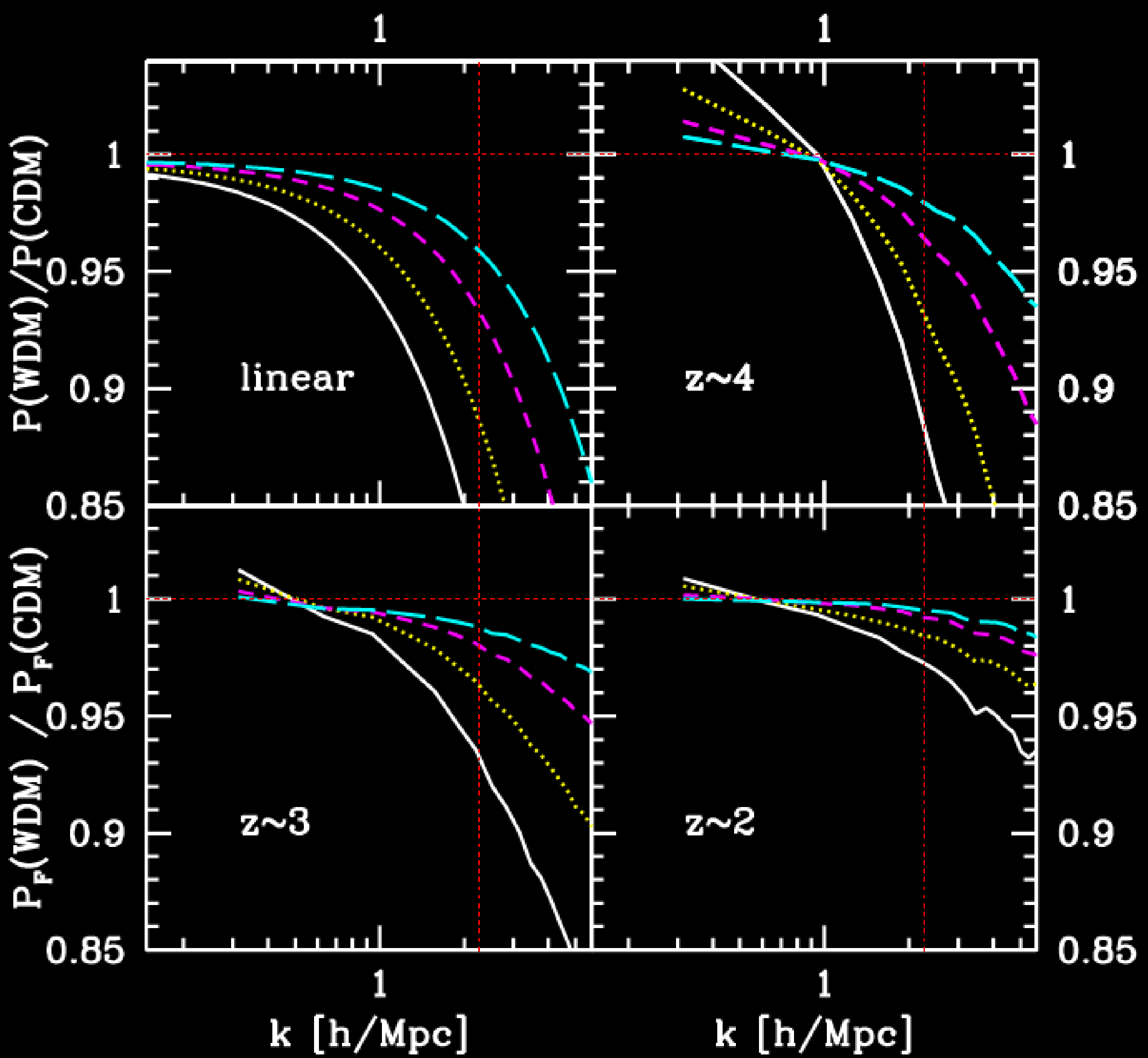
(Croft et al 1999)

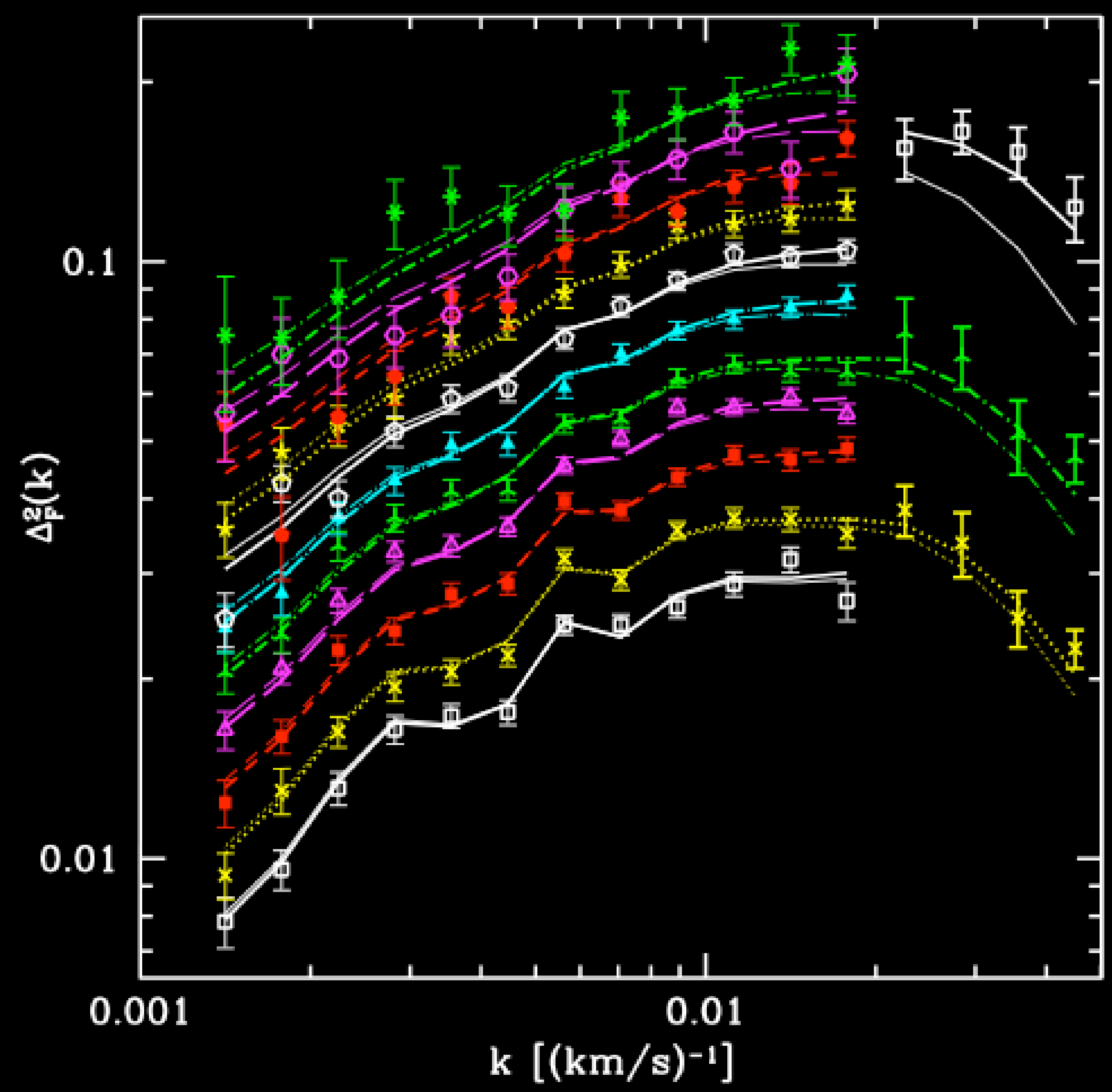
The Lyman-alpha Forest



(Croft et al 1999)

Stringent Lyman-alpha Forest Constraints?





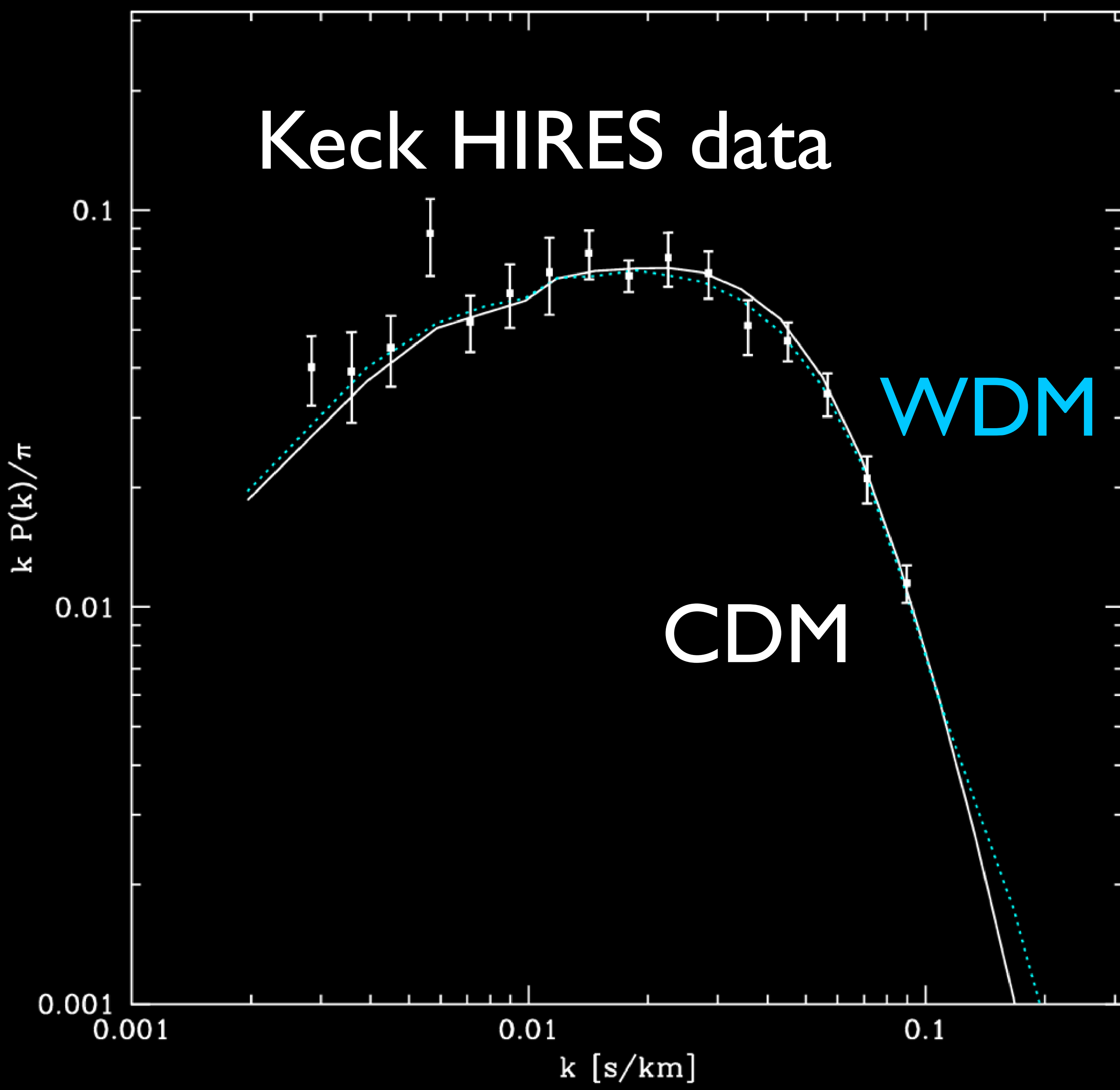
$m_s > 14$ keV Seljak et al 2006: WMAP1 + SDSS Pg(k) + Lya + HR

$m_s > 9$ keV Viel et al 2006: WMAP3 + CMB + 2dFGRS + SDSS Lya

Both depend on the McDonald et al. (2006) SDSS $P_F(k)$ Measurement

Lyman-α Dependence on Thermal History

- CDM with a warmer thermal history can mimic WDM (and vice-versa)
- Thermal broadening of the line and a larger jeans smoothing scale
- Abazajian, Lidz & Dalal (in preparation)



Sterile Neutrino Dark Matter Summary

- Warm Dark Matter has become the "standard alternate" cosmological structure formation scenario, as it may resolve many problems in structure formation
- Sterile Neutrino Dark Matter is a natural, minimal WDM *and* CDM candidate
- Lower-limits mass from the Lyman-alpha Forest are dependent on the thermal history of the universe and uncertain
- Sterile Neutrino Dark Matter, in the standard production scenarios, is detectable or *potentially* excludable with *Constellation-X* satellite