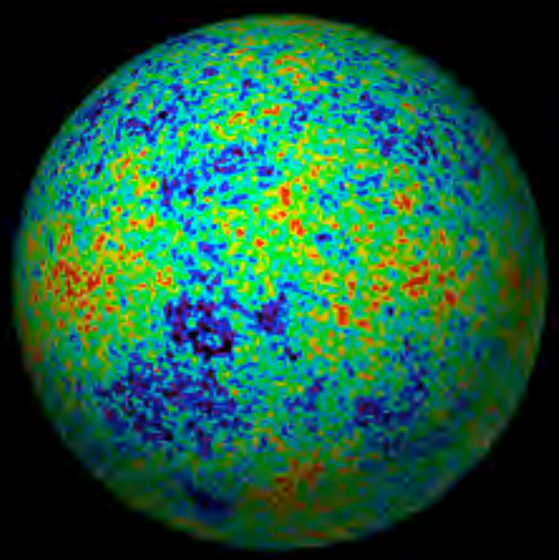
Deviant Dark Matter:

Indirect Indicators of and Constraints on the Nature of Dark Matter

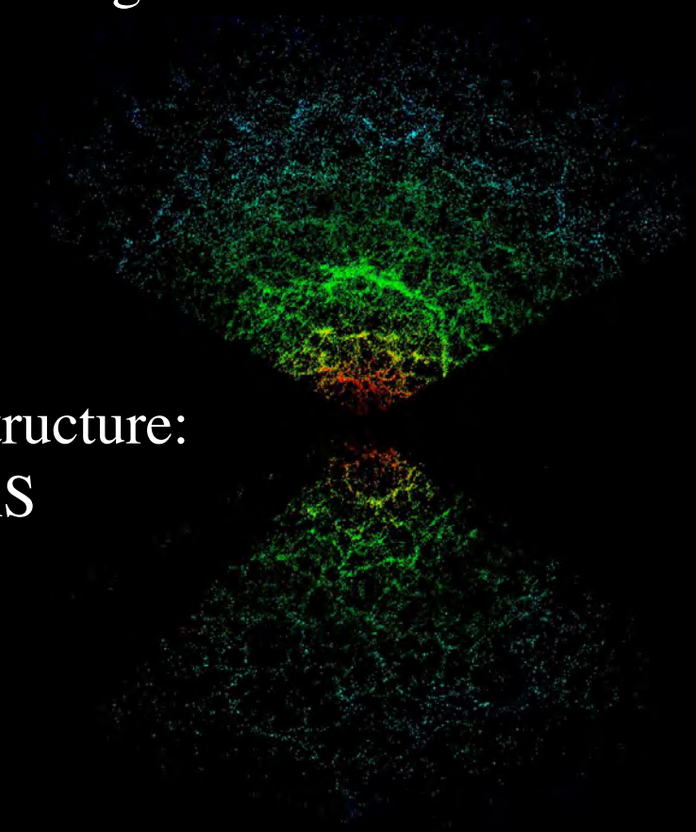
Kevork Abazajian
University of California, Irvine

SCIPP Seminar
March 6, 2012

Dark Matter Today



Cosmic Microwave Background:
WMAP, ACBAR, CBI, Boomerang

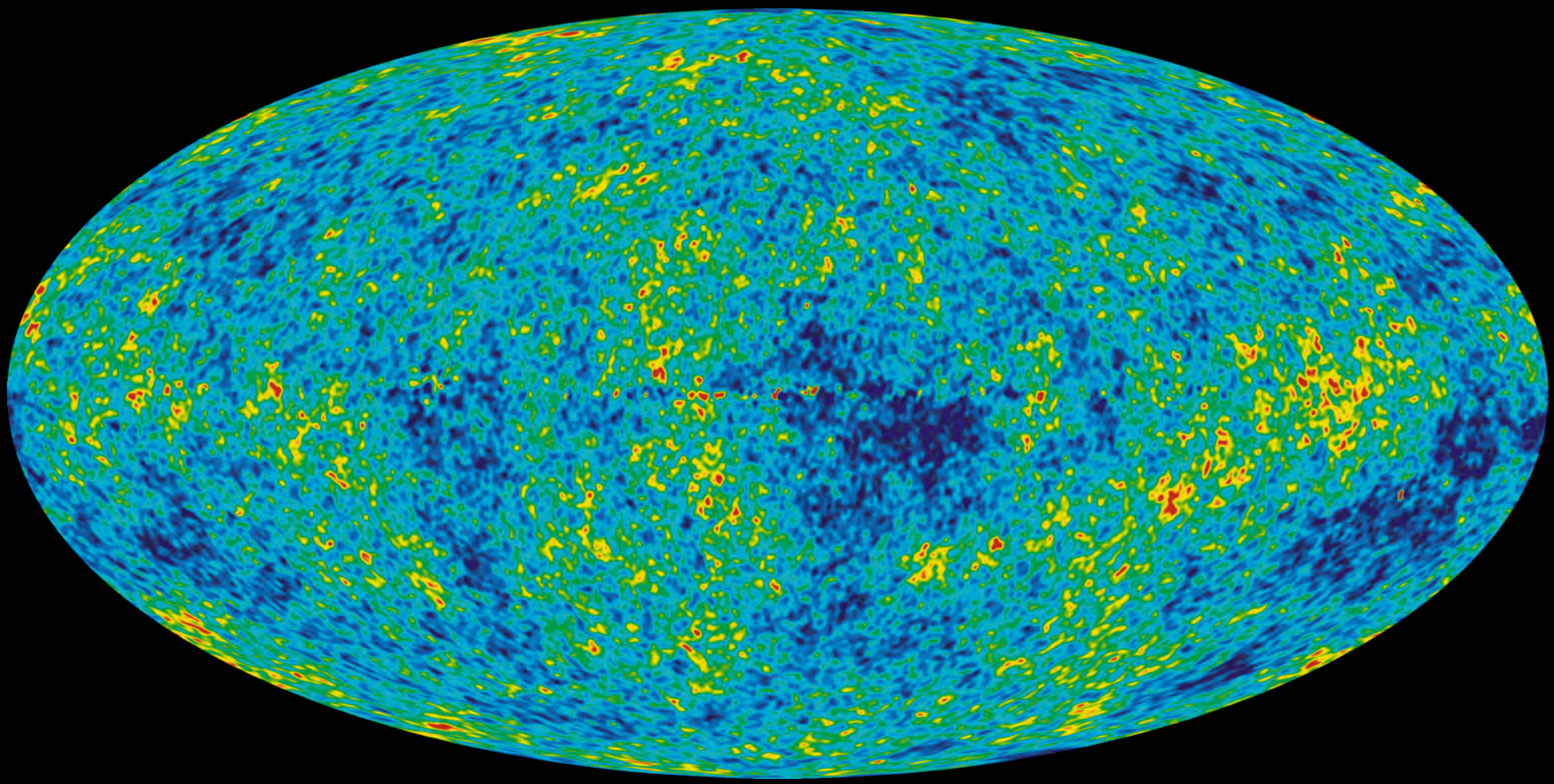


Large Scale Structure:
SDSS, 2dFGRS

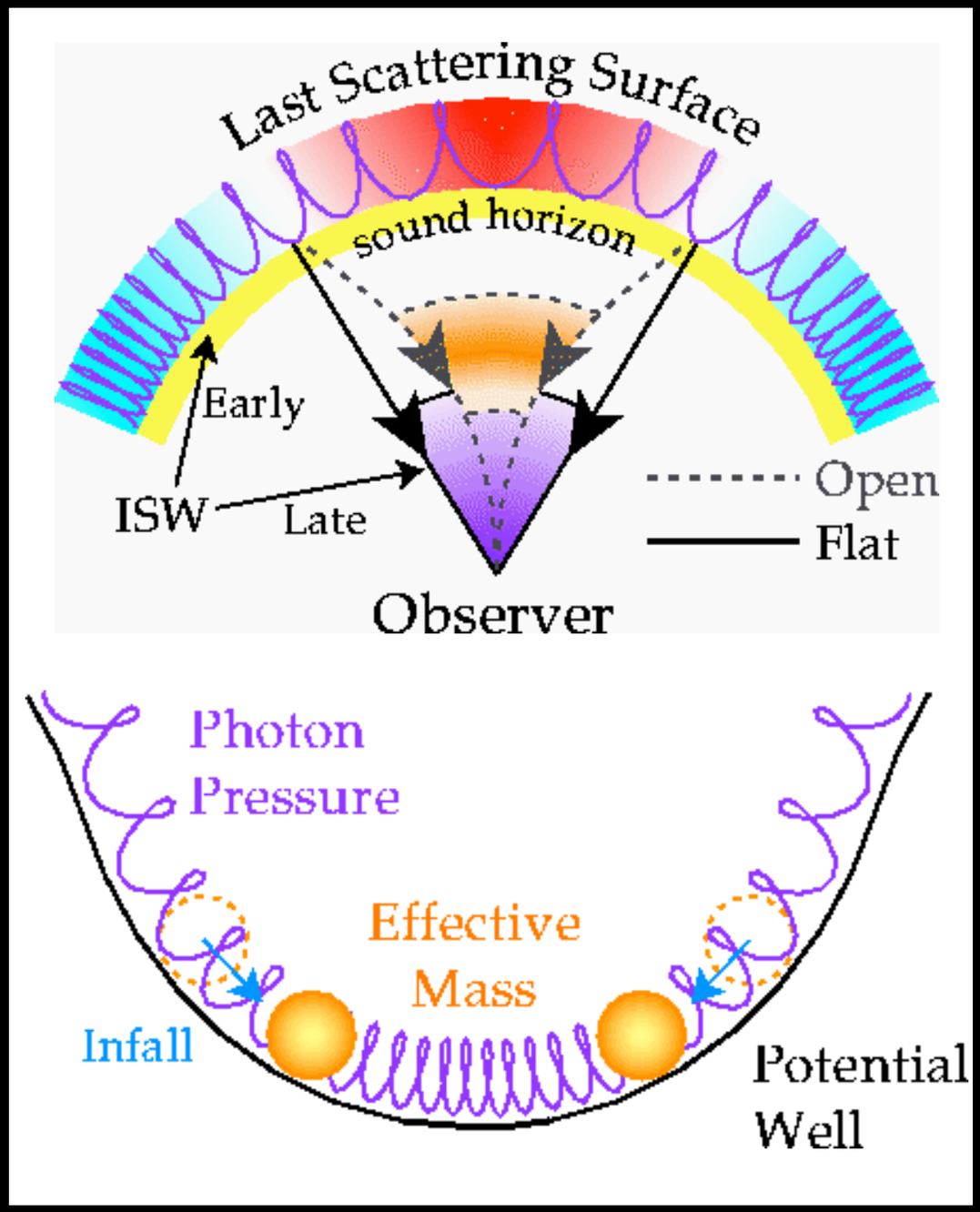
$$\Omega_{\mathrm{DM}} = 0.227 \pm 0.007$$

WMAP7 + SDSS BAO + H_0
(Komatsu et al. 2010)

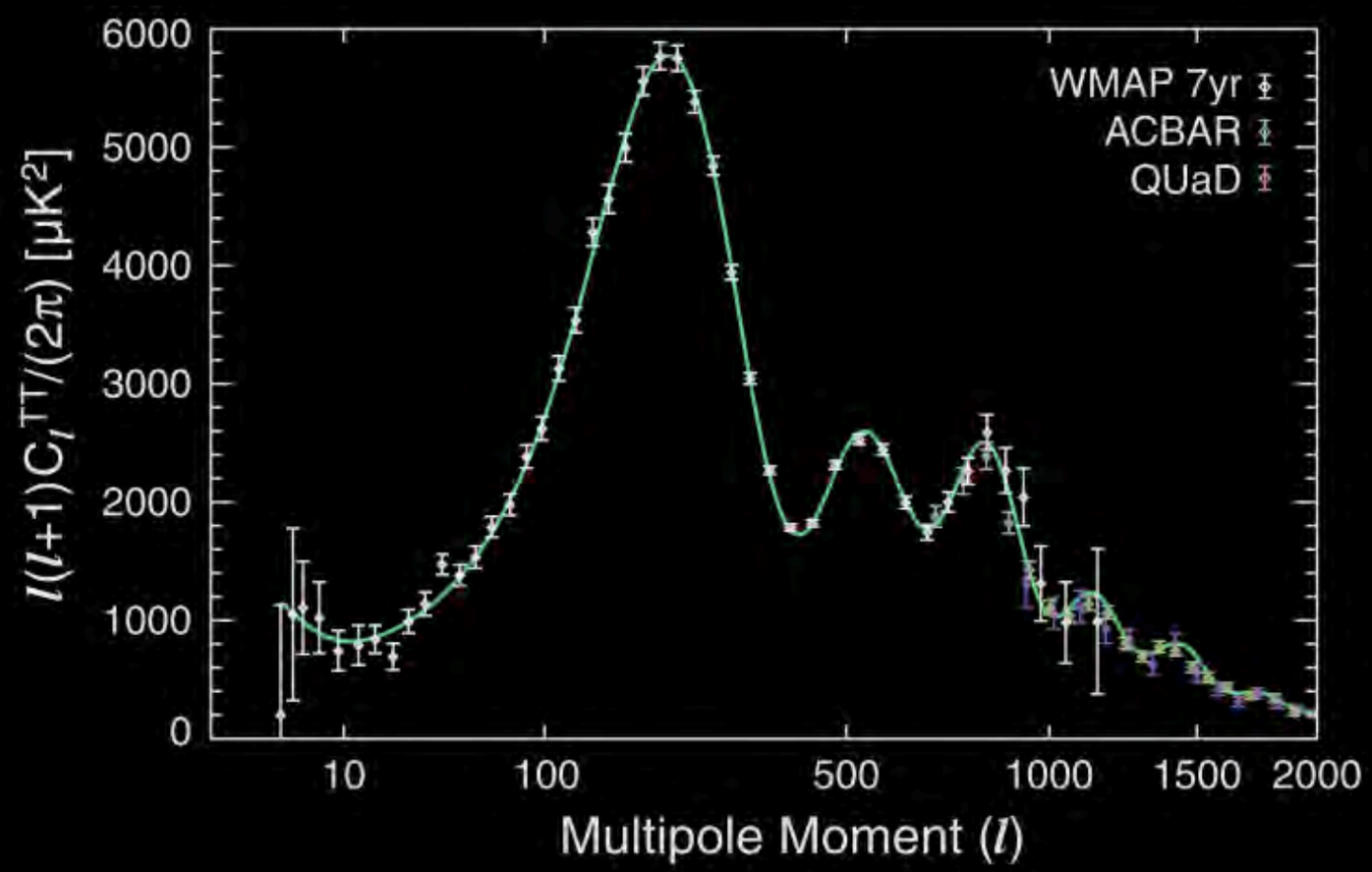
The Cosmic Microwave Background: WMAP, Planck and the Future of LSS



Cosmic Microwave Background: Precision Cosmology



WMAP 7



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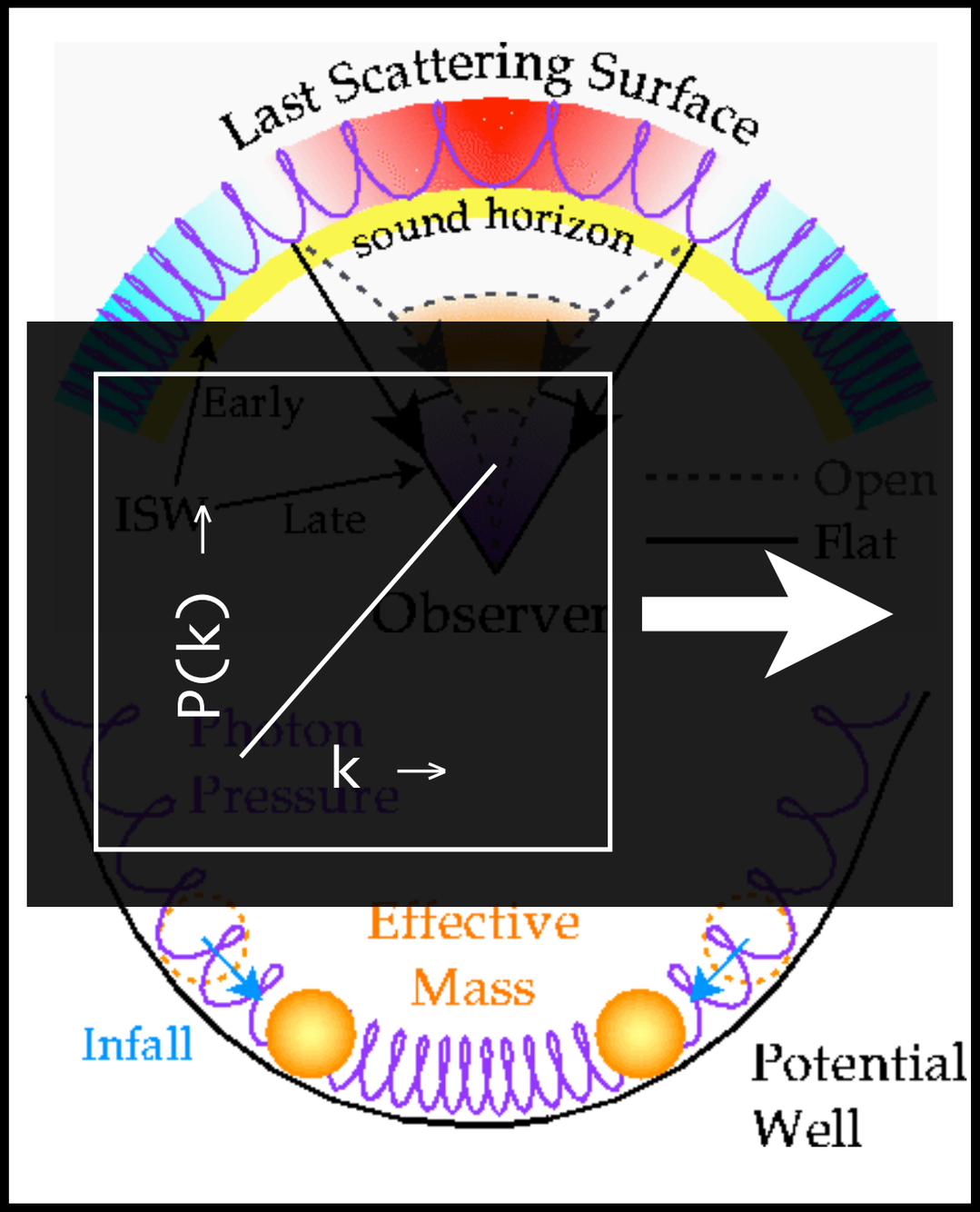

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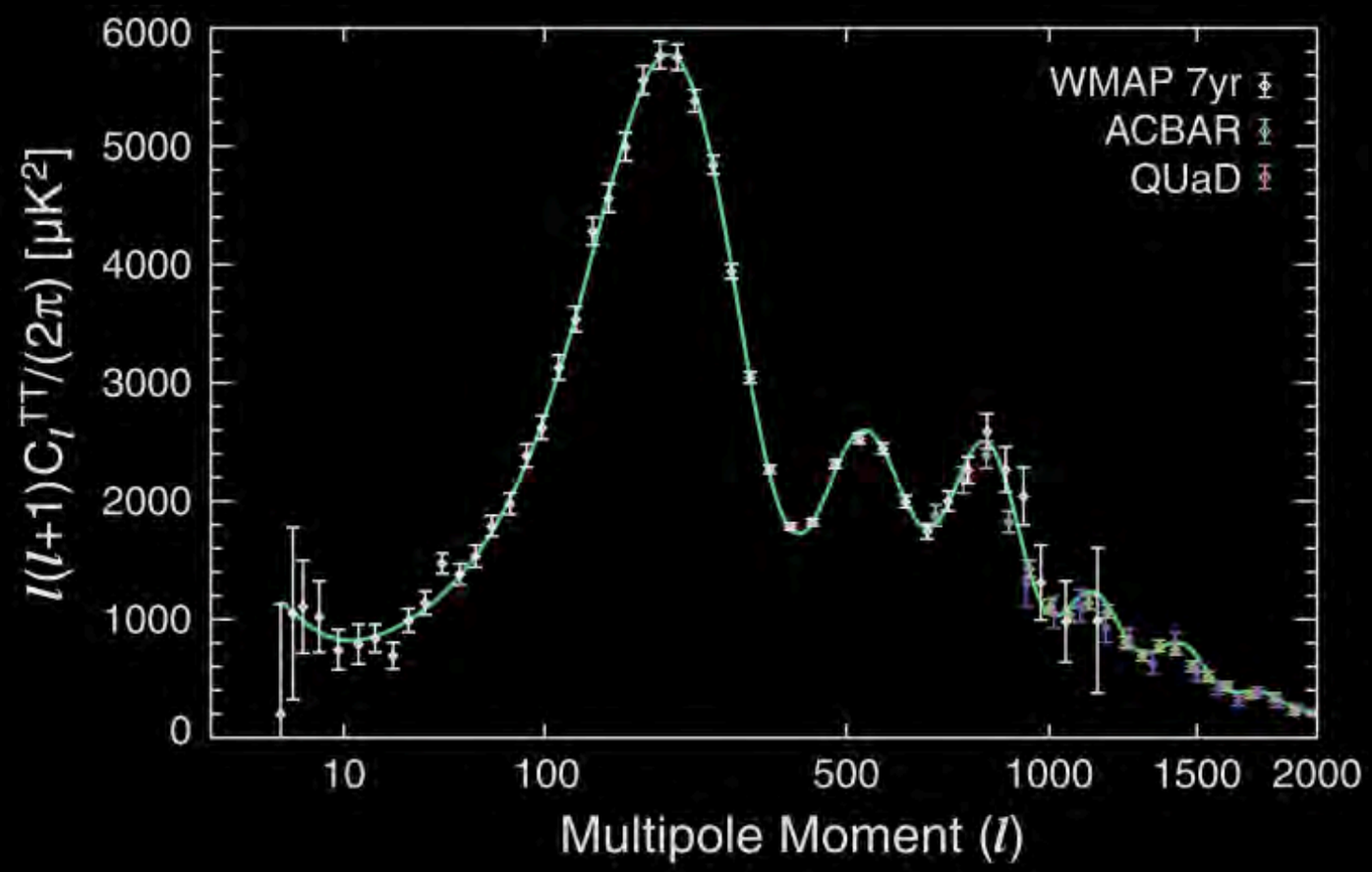
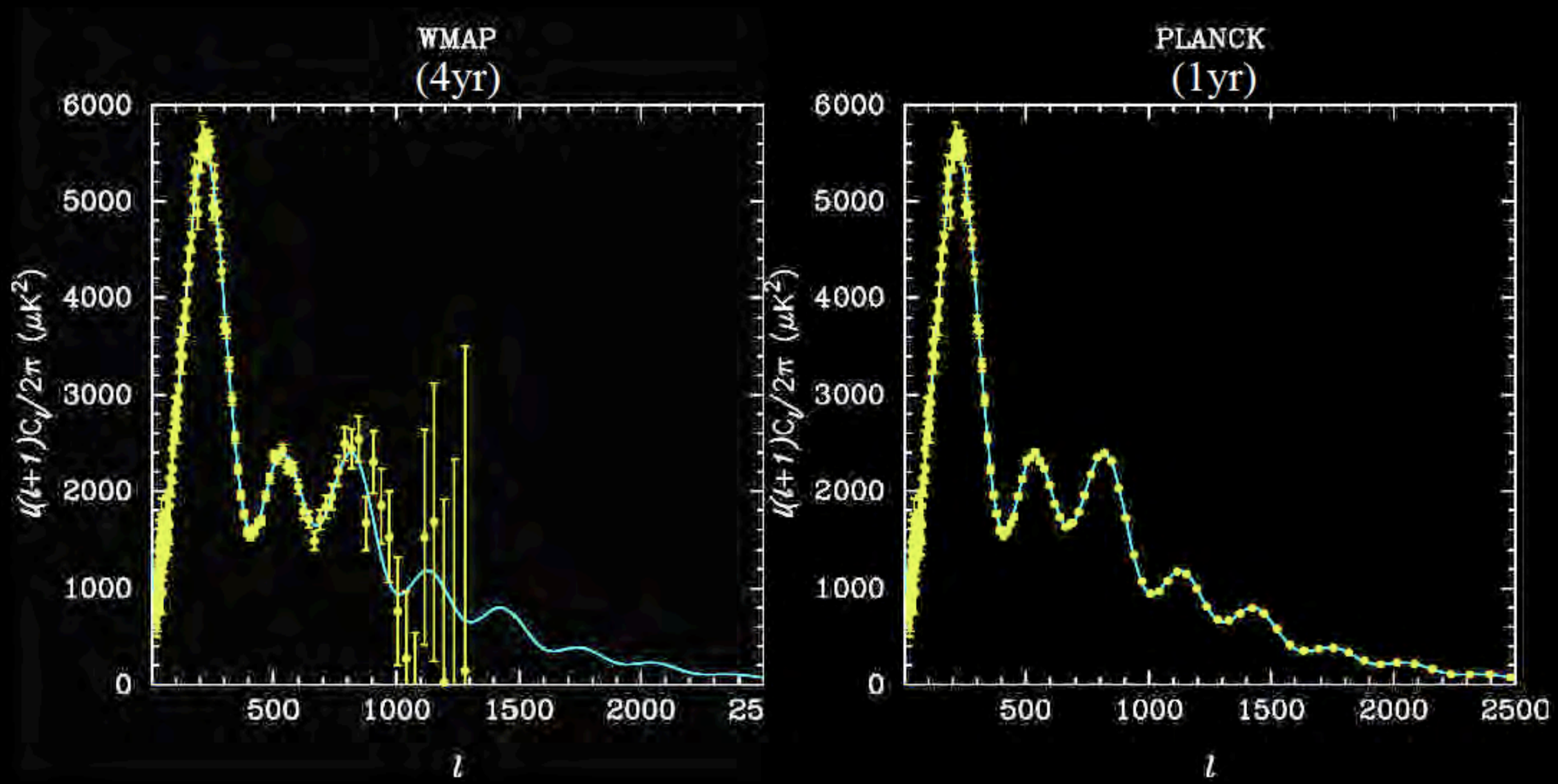
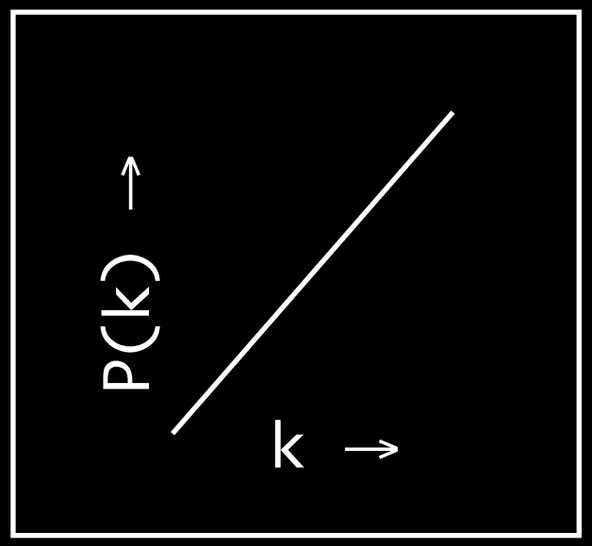


Forecast Precision Cosmology: PLANCK



(Martin White)



The Primordial Spectrum: Precision Determination at Large Scales

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

WMAP 5 + BAO + SN: (Komatsu et al. 2008)

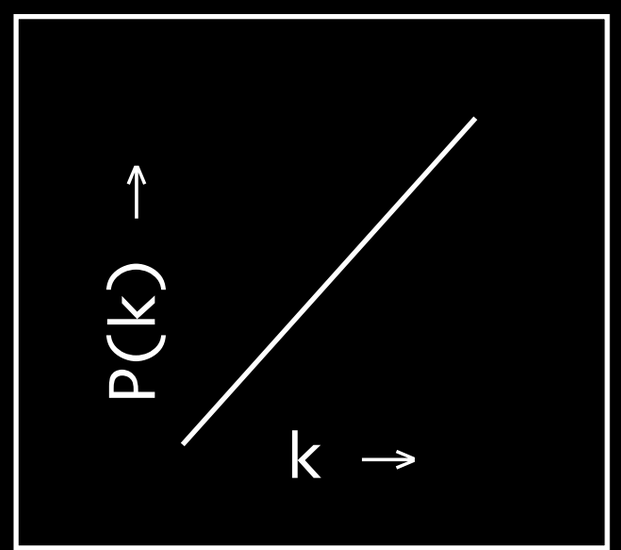
$$A = 2.445 \pm 0.096 \quad (3.4\%)$$
$$n = 0.96 \pm 0.013 \quad (1.4\%)$$

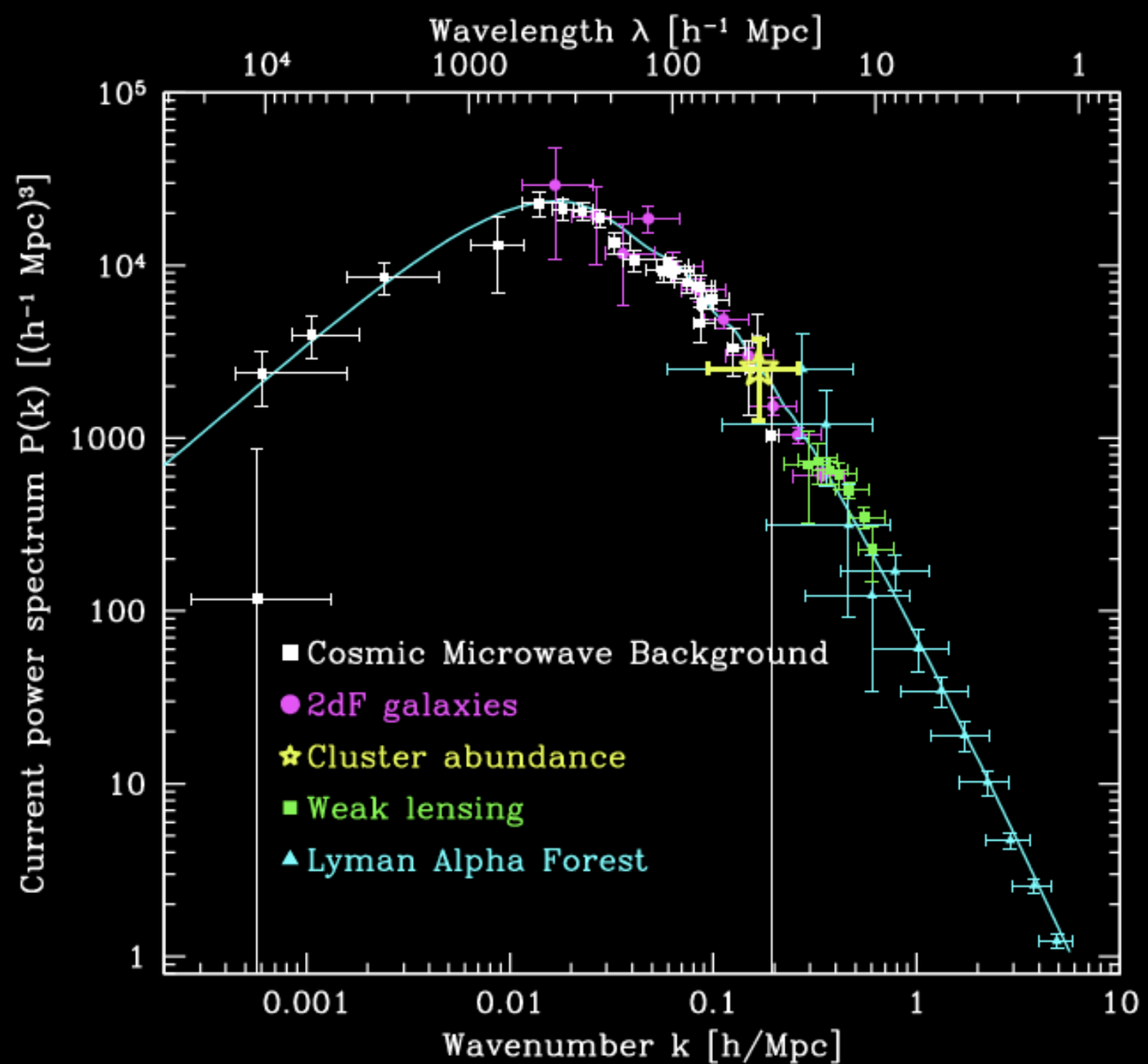
PLANCK + SDSS LRG: (Eisenstein, Hu, Tegmark 1998)

$$A = 2.4450 \pm 0.0085 \quad (0.35\%)$$
$$n = 0.9600 \pm 0.0077 \quad (0.8\%)$$

forecast!

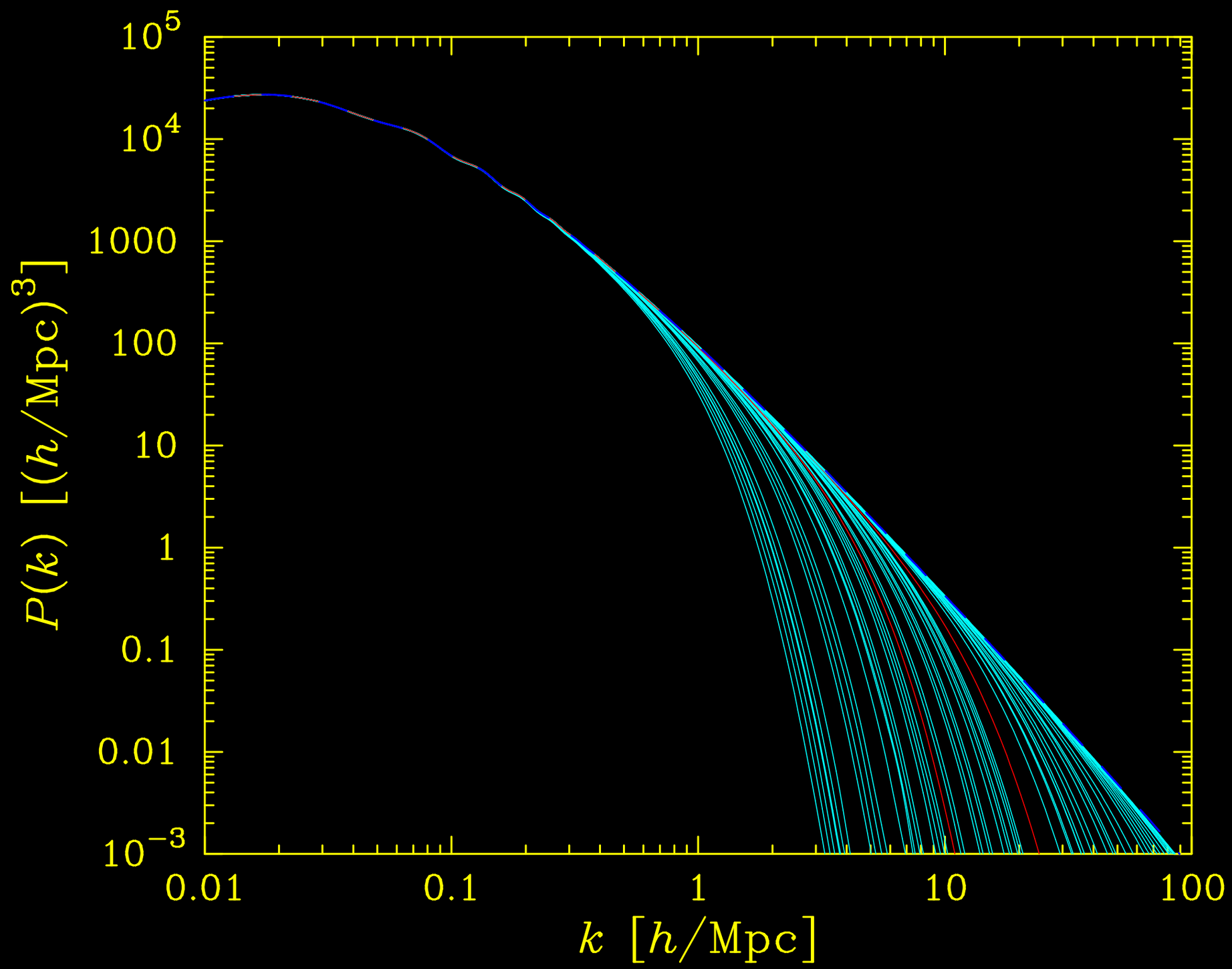
Large Scale Structure and P(k)





Tegmark & Zaldarriaga 2002

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



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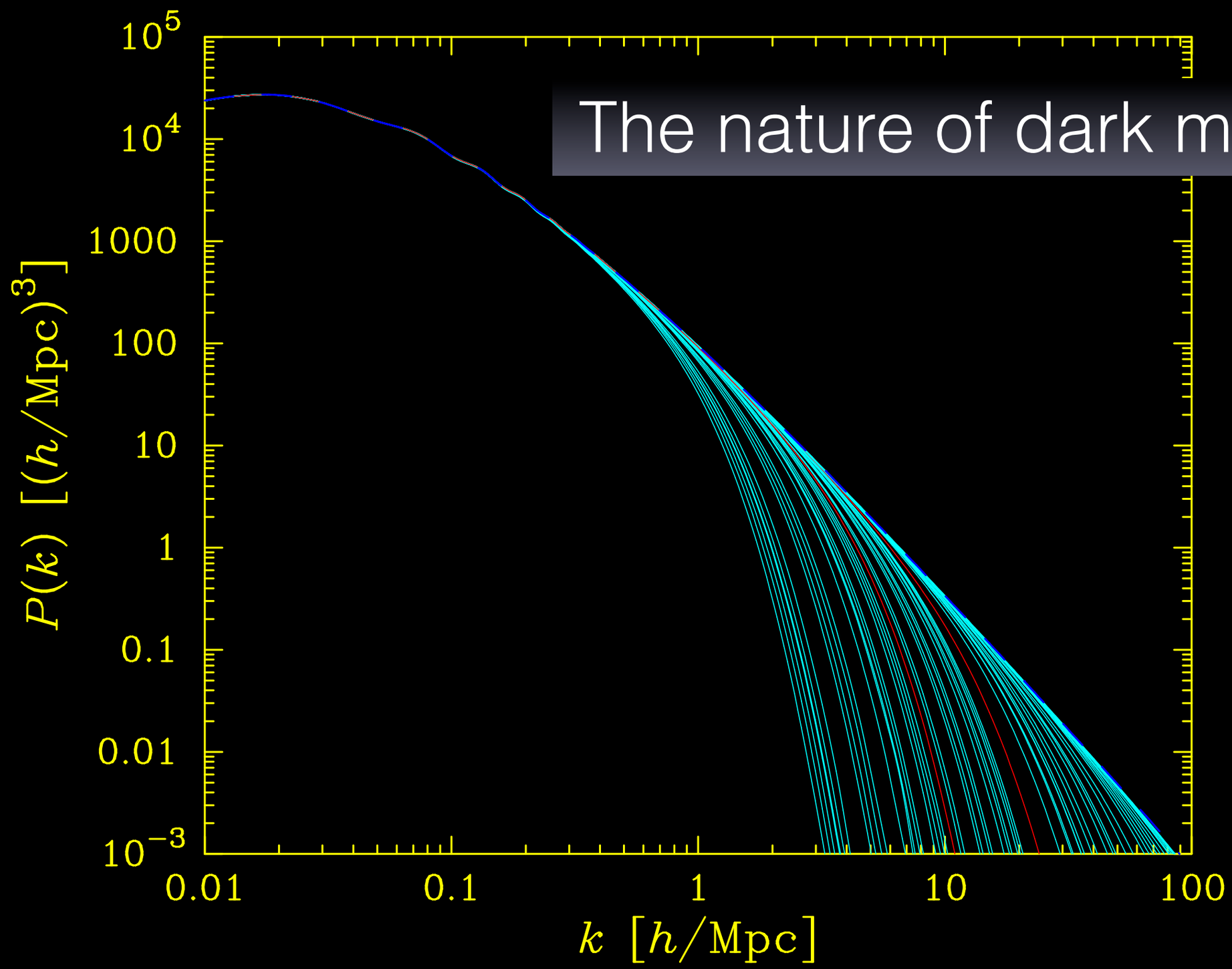
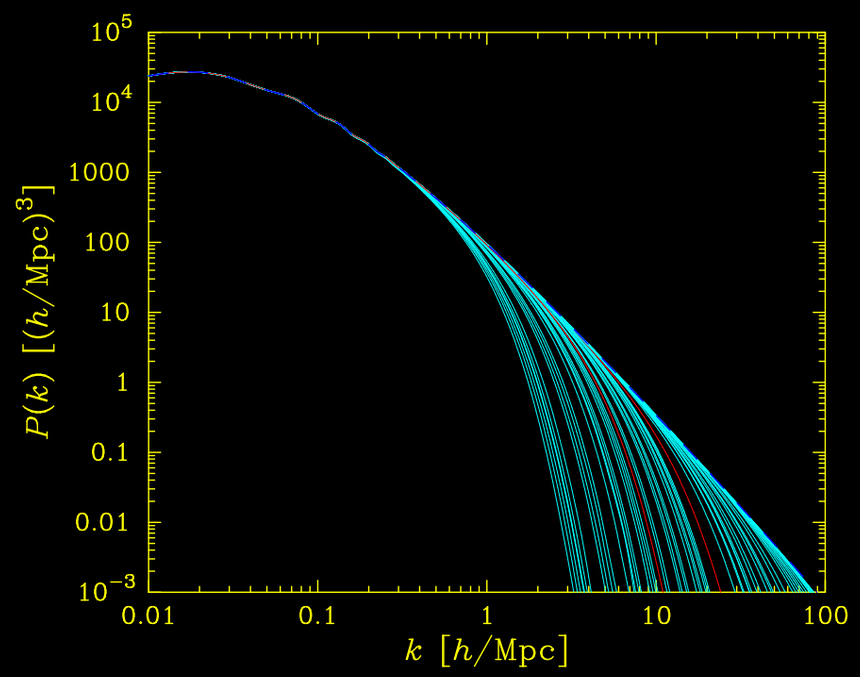


The nature of dark matter...

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



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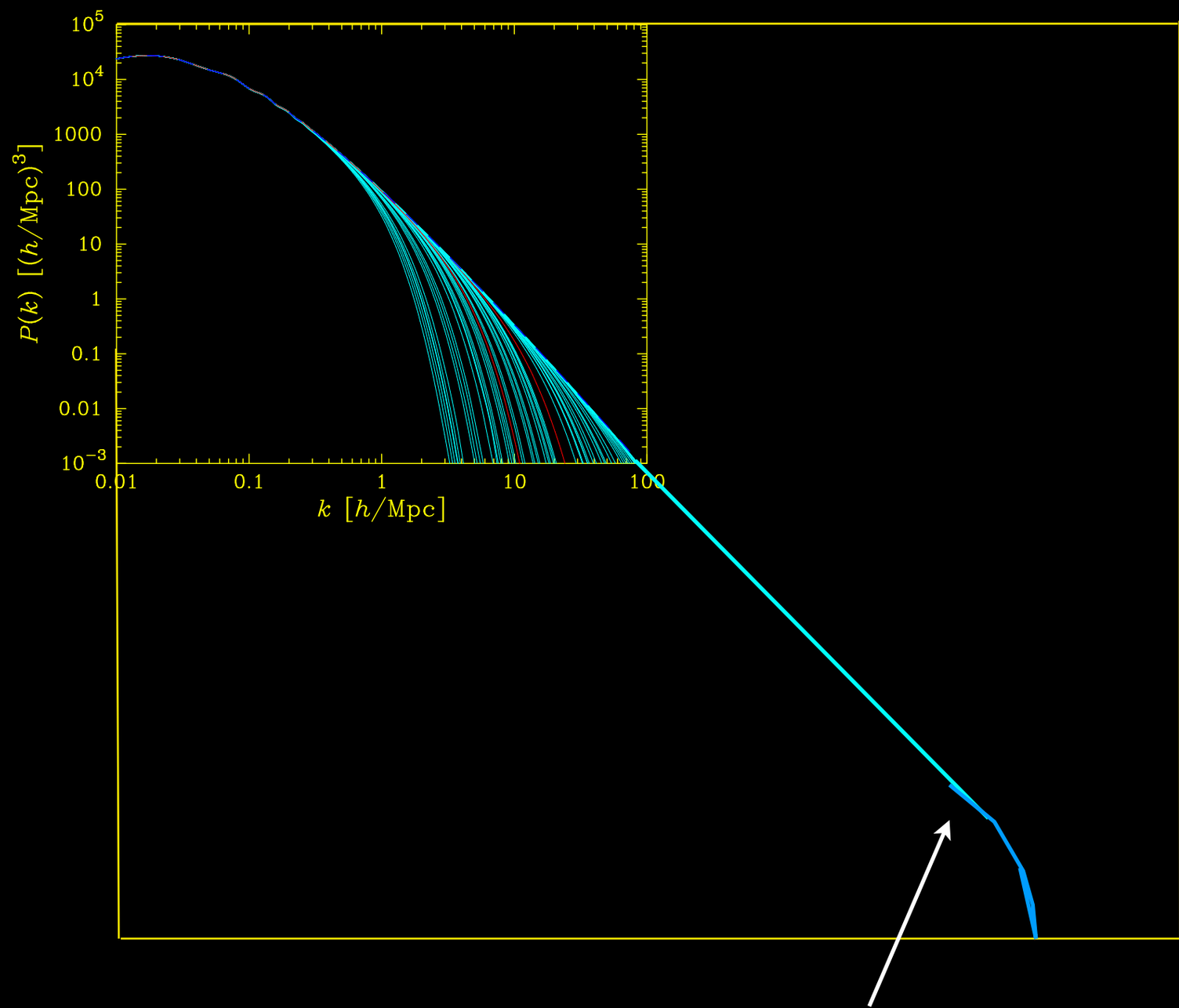

WIMP CDM

$k_c \sim 10^6\ h$/Mpc

(Zaldarriaga & Loeb 2006)

Problems in Cold Dark Matter?

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

- Halo Cores and Densities:
  (Gilmore et al 2006; Kuzio de Naray 2008)

- Void Galaxy abundances
  (Peebles 2001)

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

- Disk Dominated Galaxy Formation
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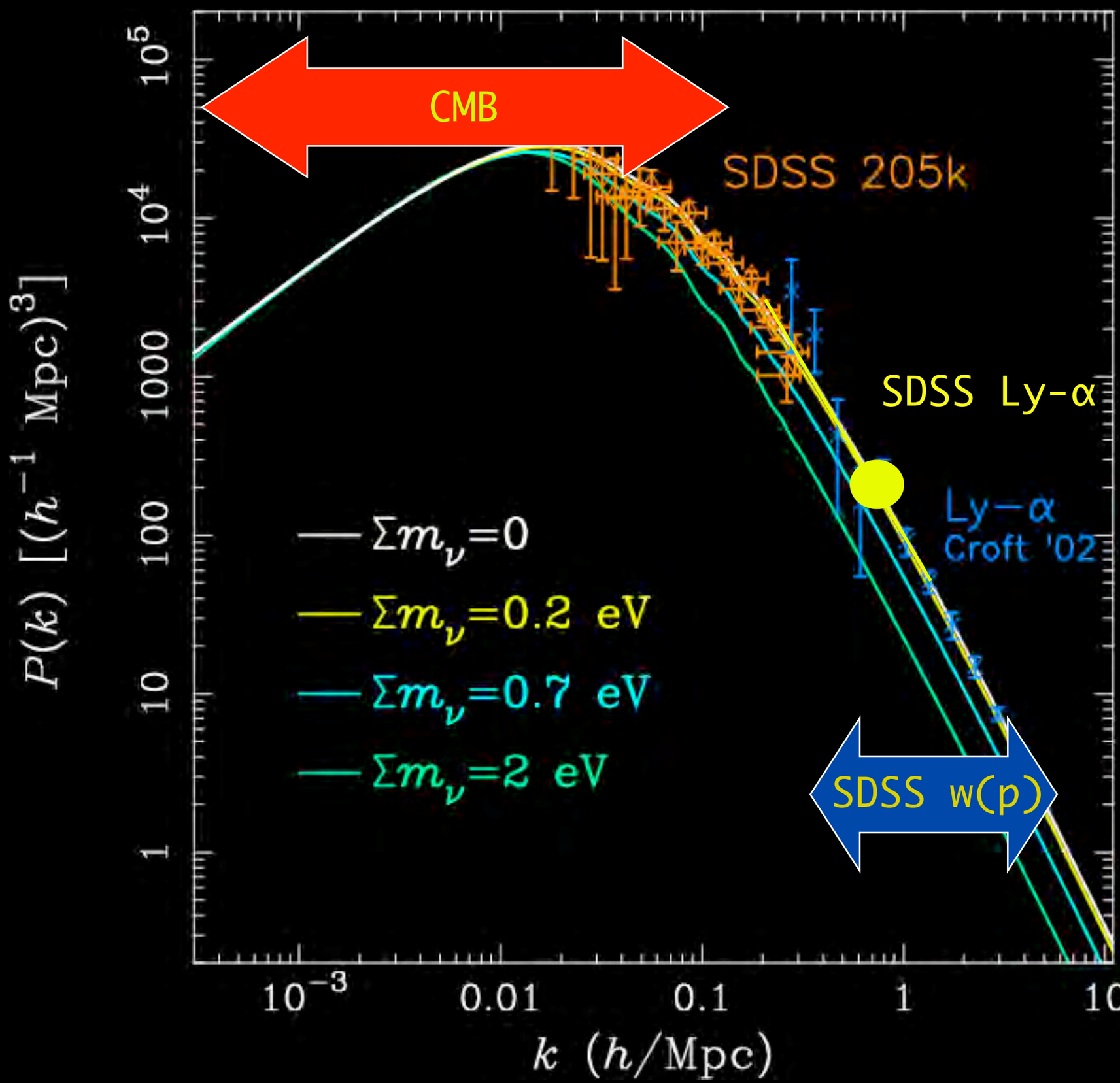
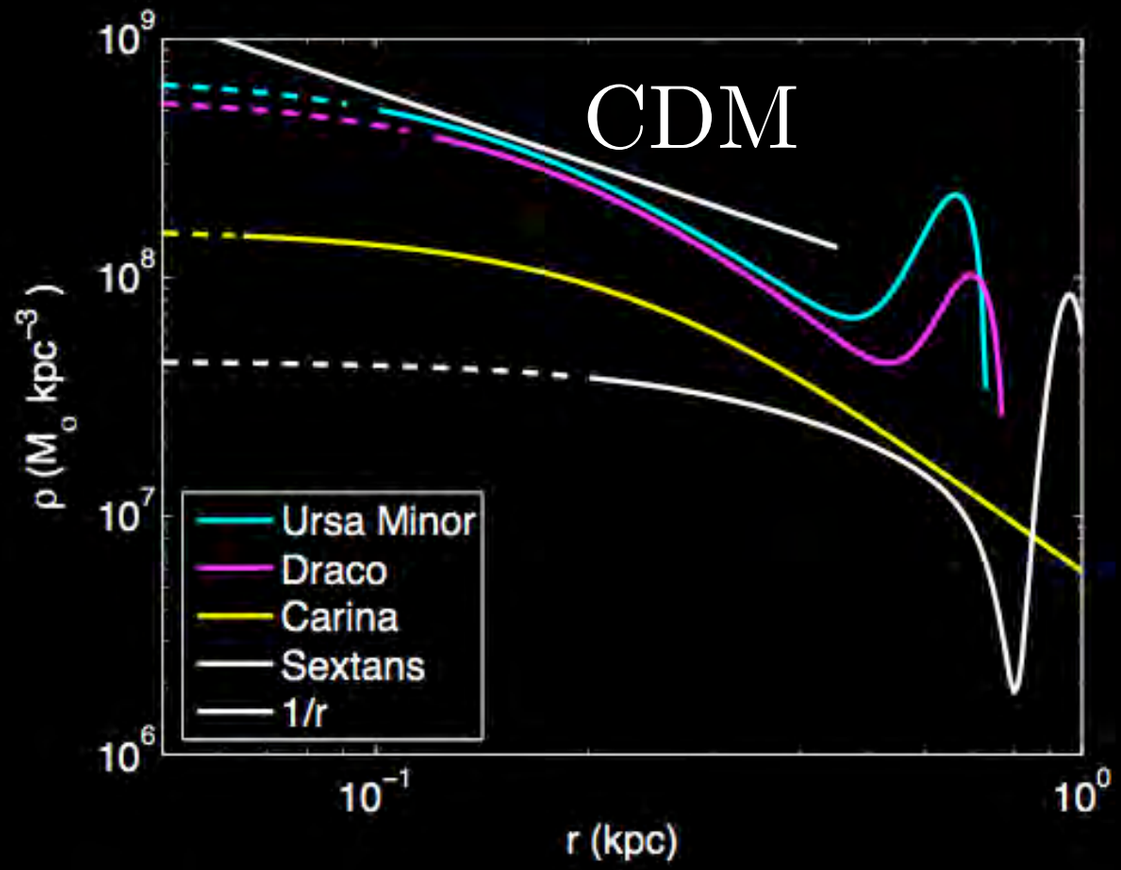
Is the power spectrum different *at small scales?*

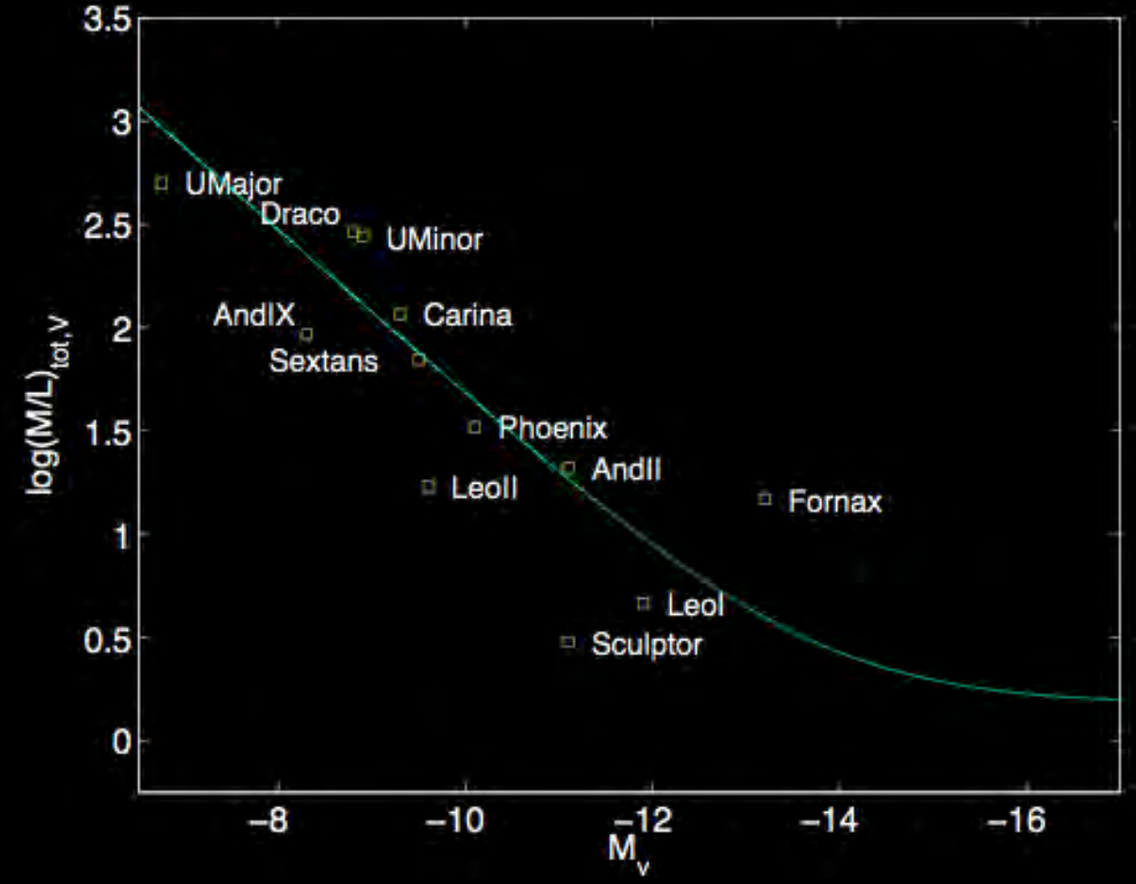
Measuring P(k)



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





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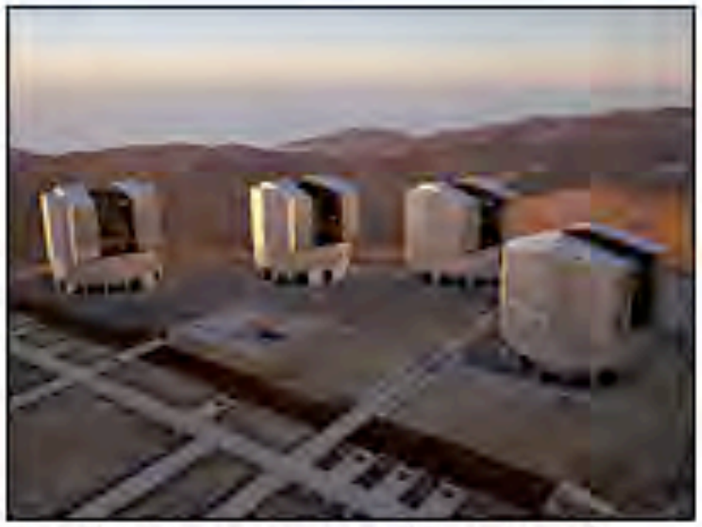
Dark matter comes out of the cold

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.

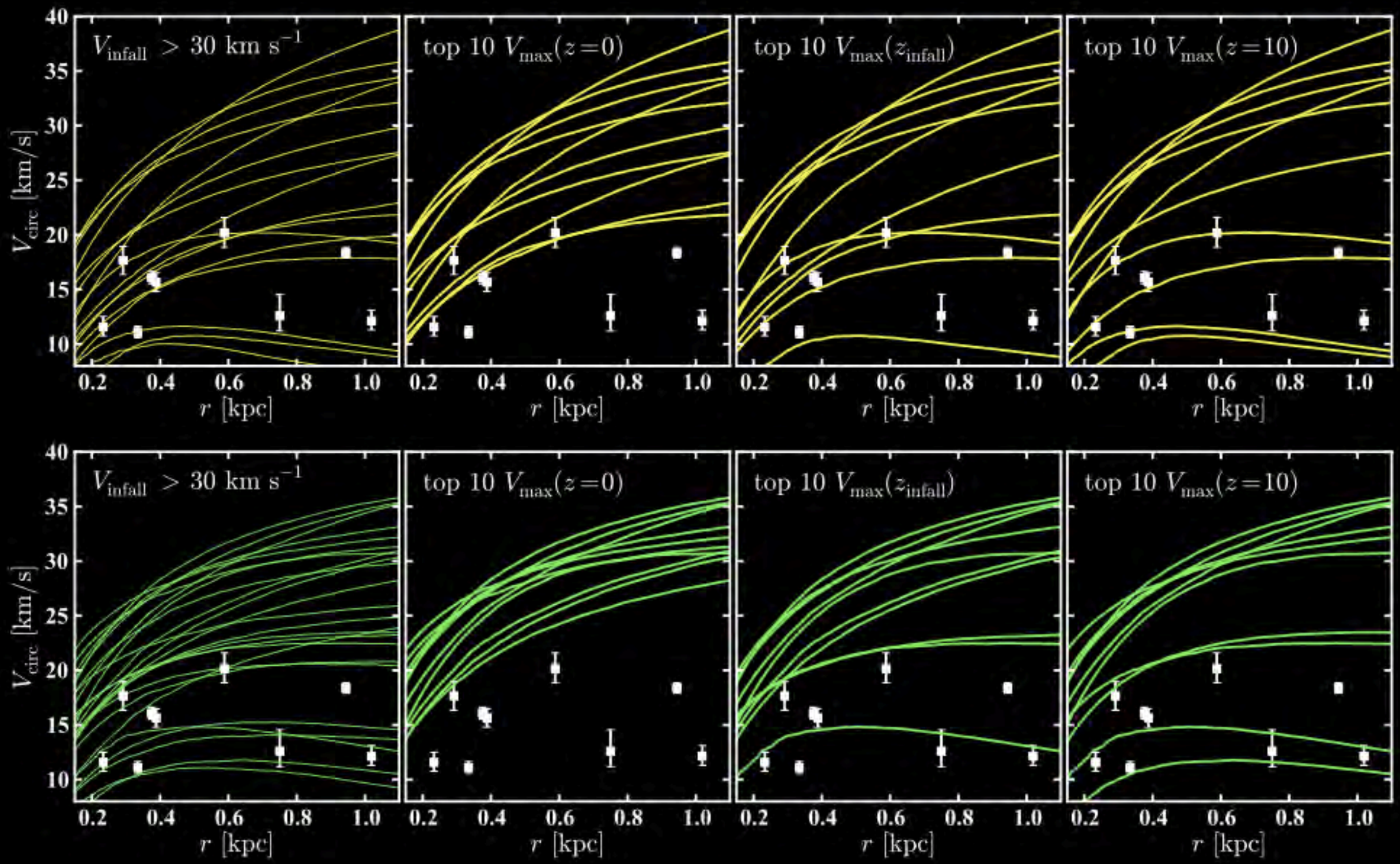
That it exists is one of the few things on which researchers have been certain.

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.

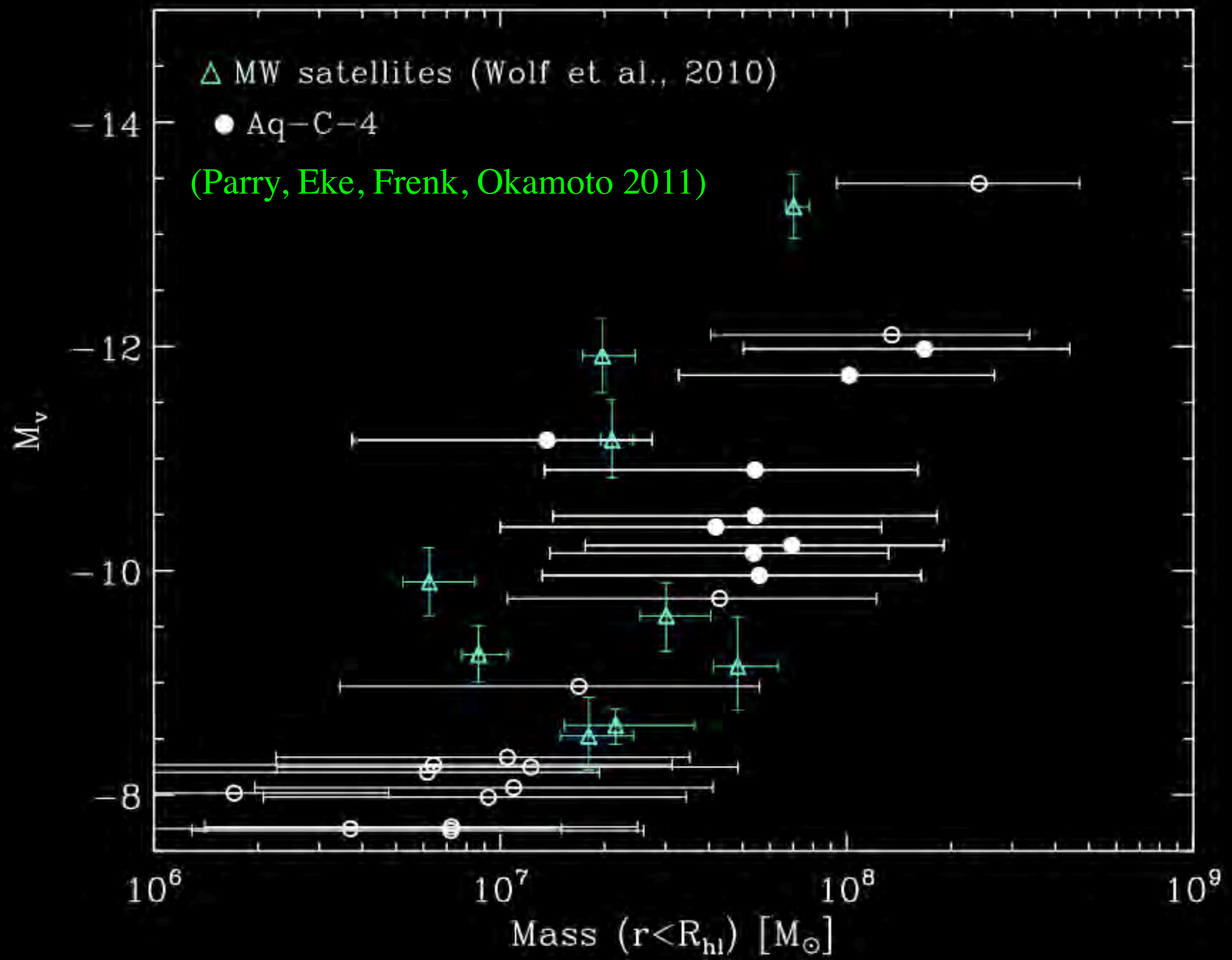
Science understands a great deal about what it terms baryonic matter - the "normal" matter which makes up the stars, planets and people - but it has struggled to comprehend the main material from which the cosmos is constructed.

Dark Matter V_{circ} / Central Concentrations are Much Too Low...



Boylan-Kolchin, Bullock, Kaplinghat 2011

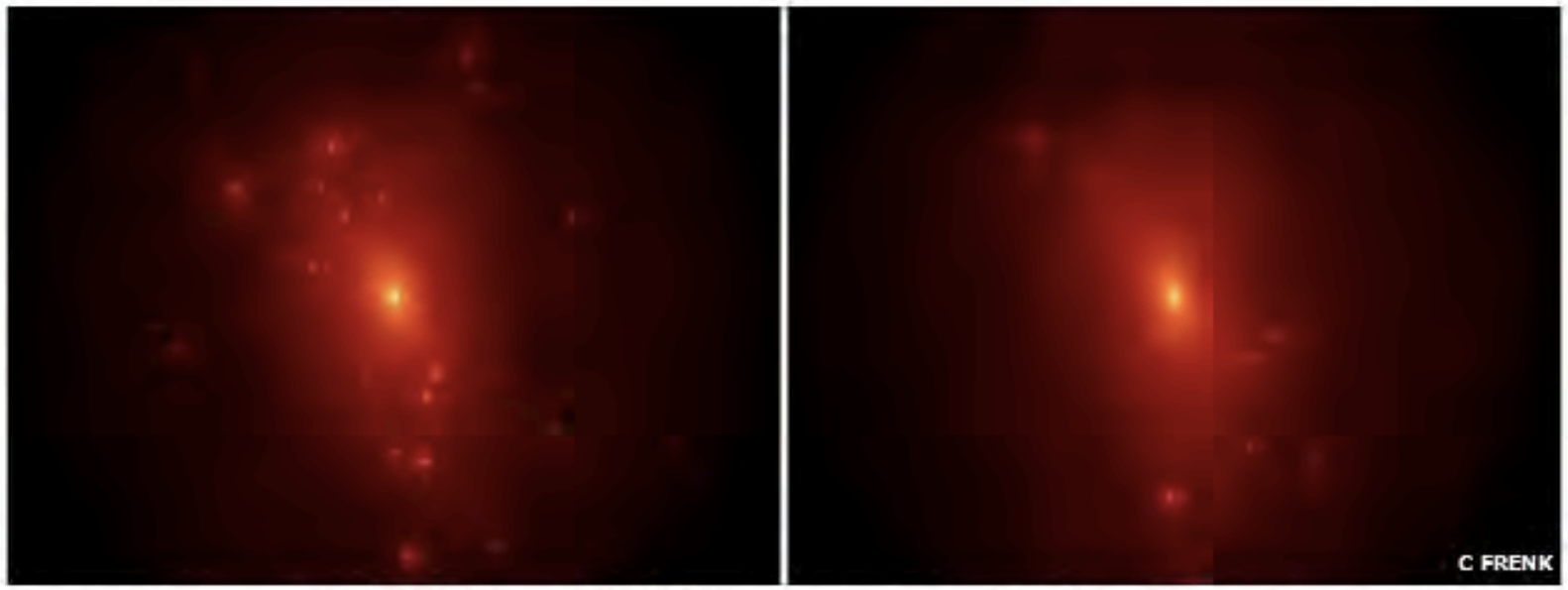
Central densities of Dwarfs are too low relative to latest high-res CDM simulations



16 September 2011 Last updated at 13:47 ET

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

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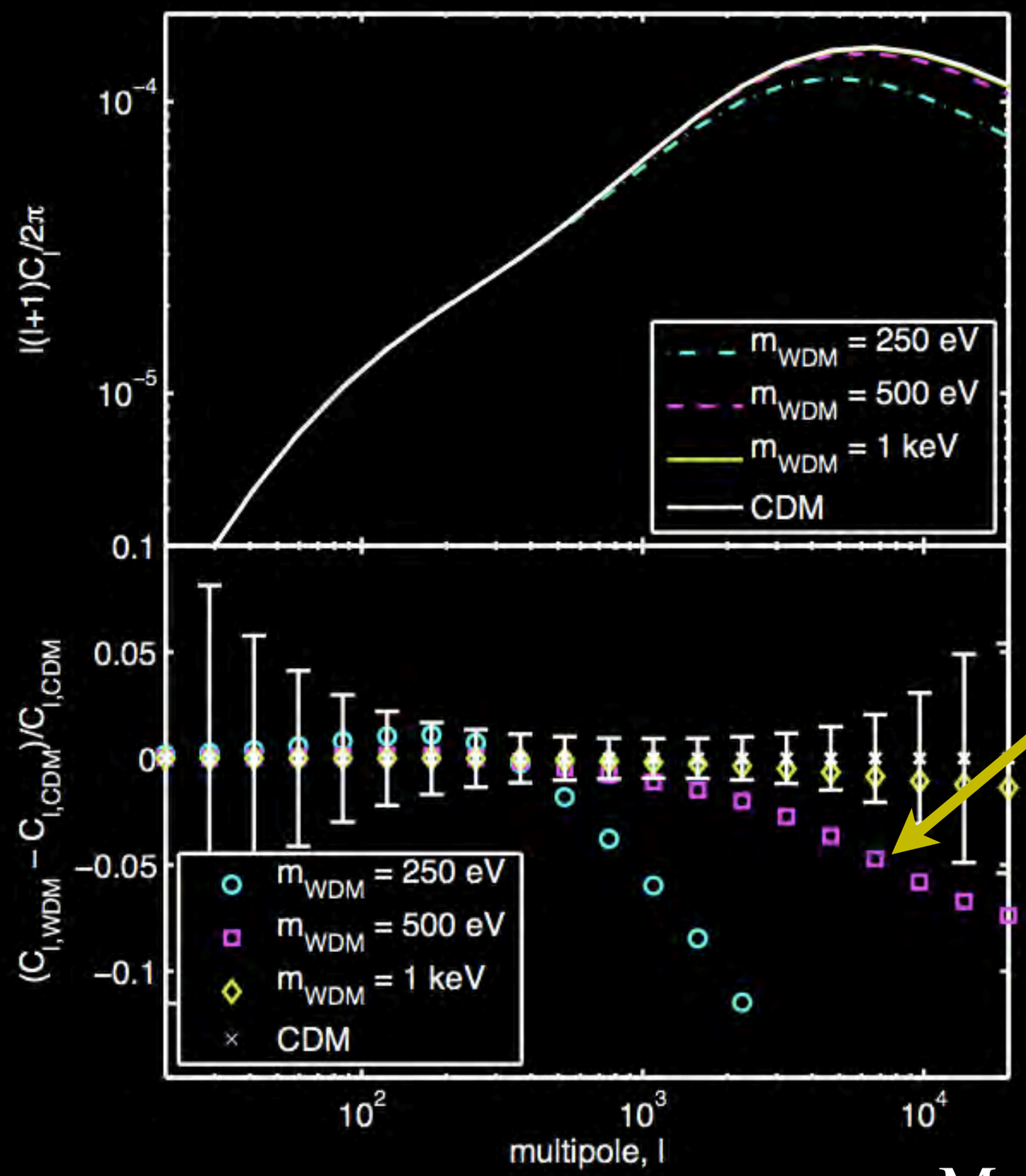
Dark matter hunters see 67 hints

Is LHC closing in on elusive Higgs particle?

'Filaments' hold dark matter test

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

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

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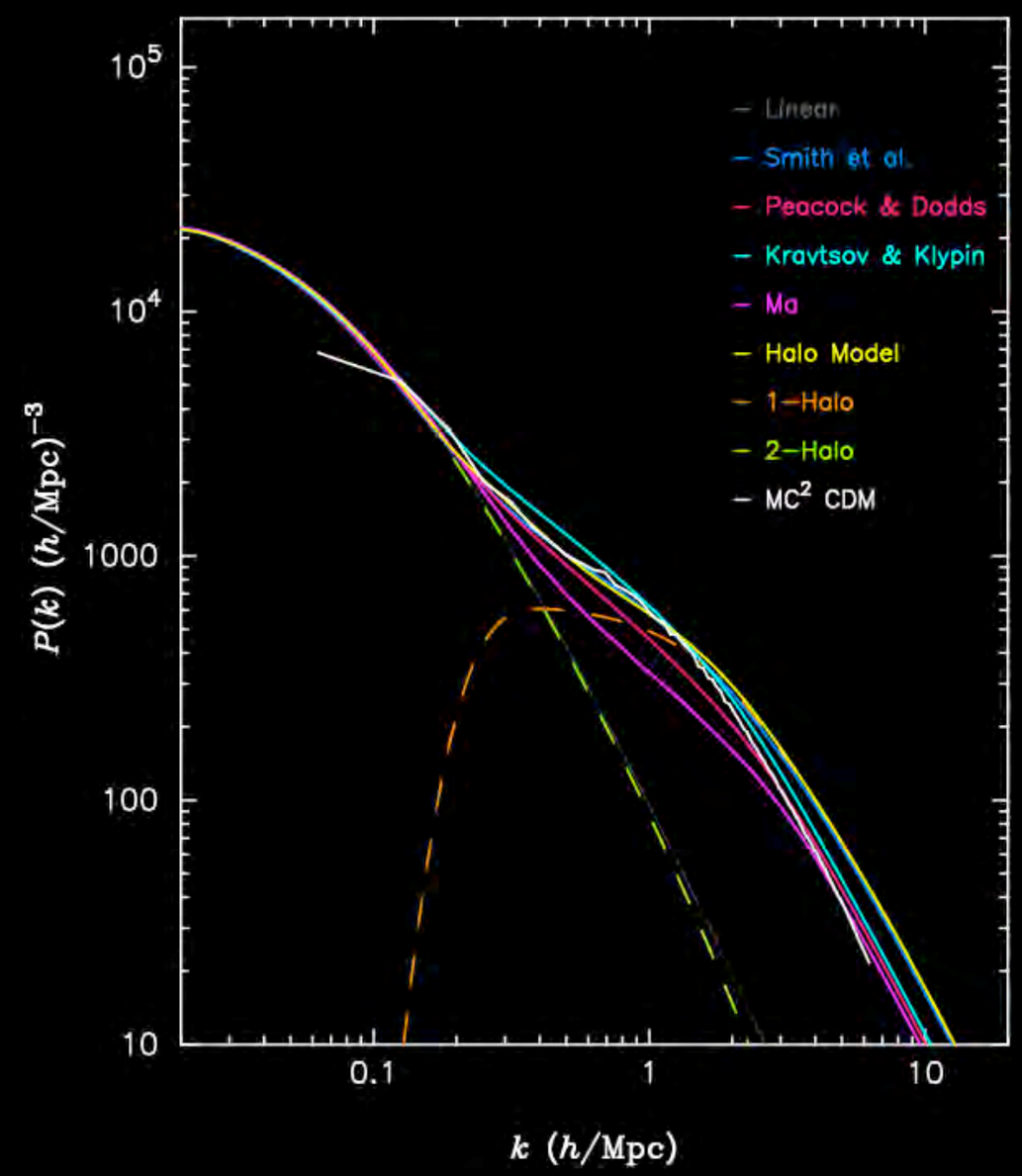
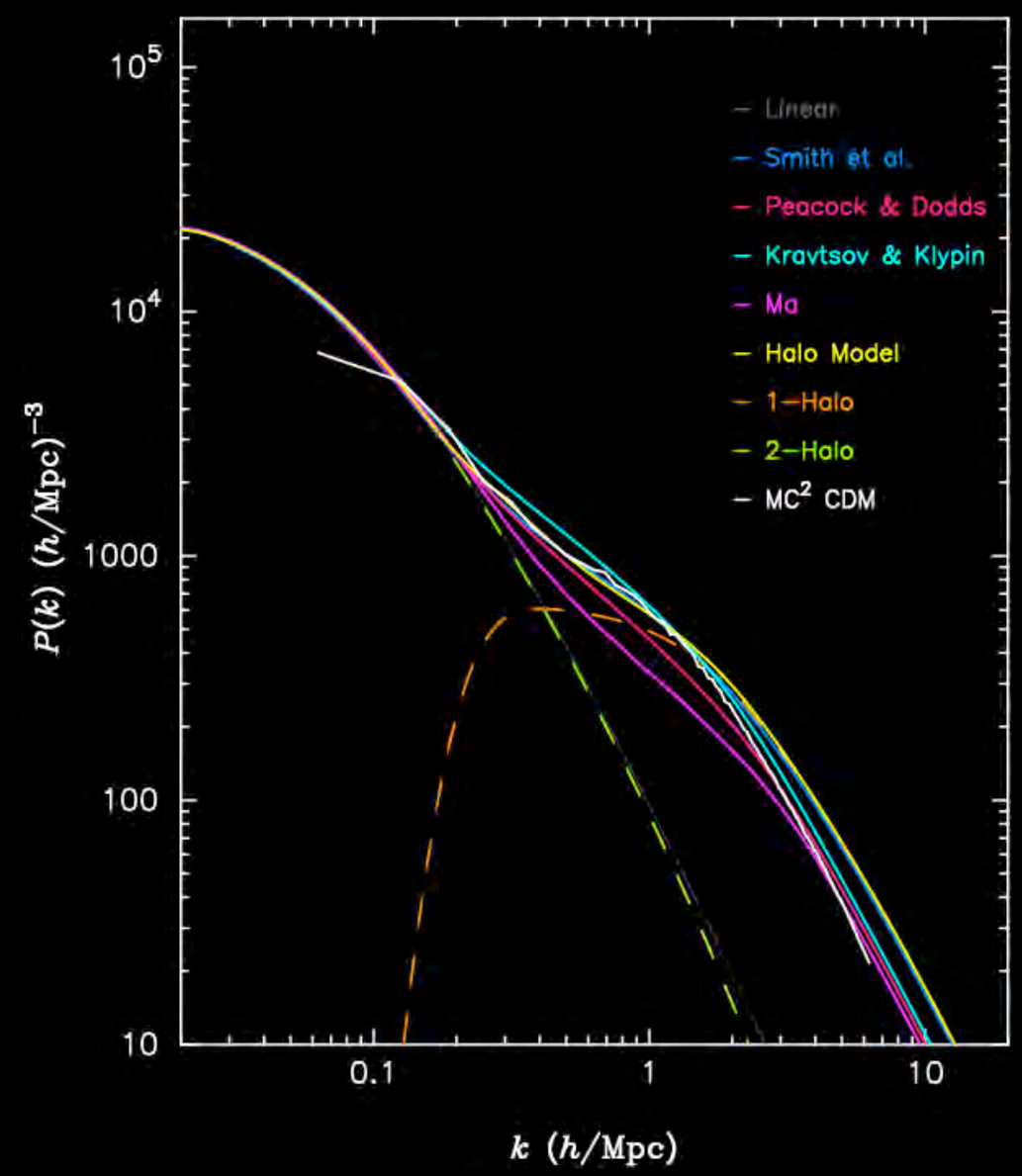


Modeling nonlinear clustering: The full halo model in WDM

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

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



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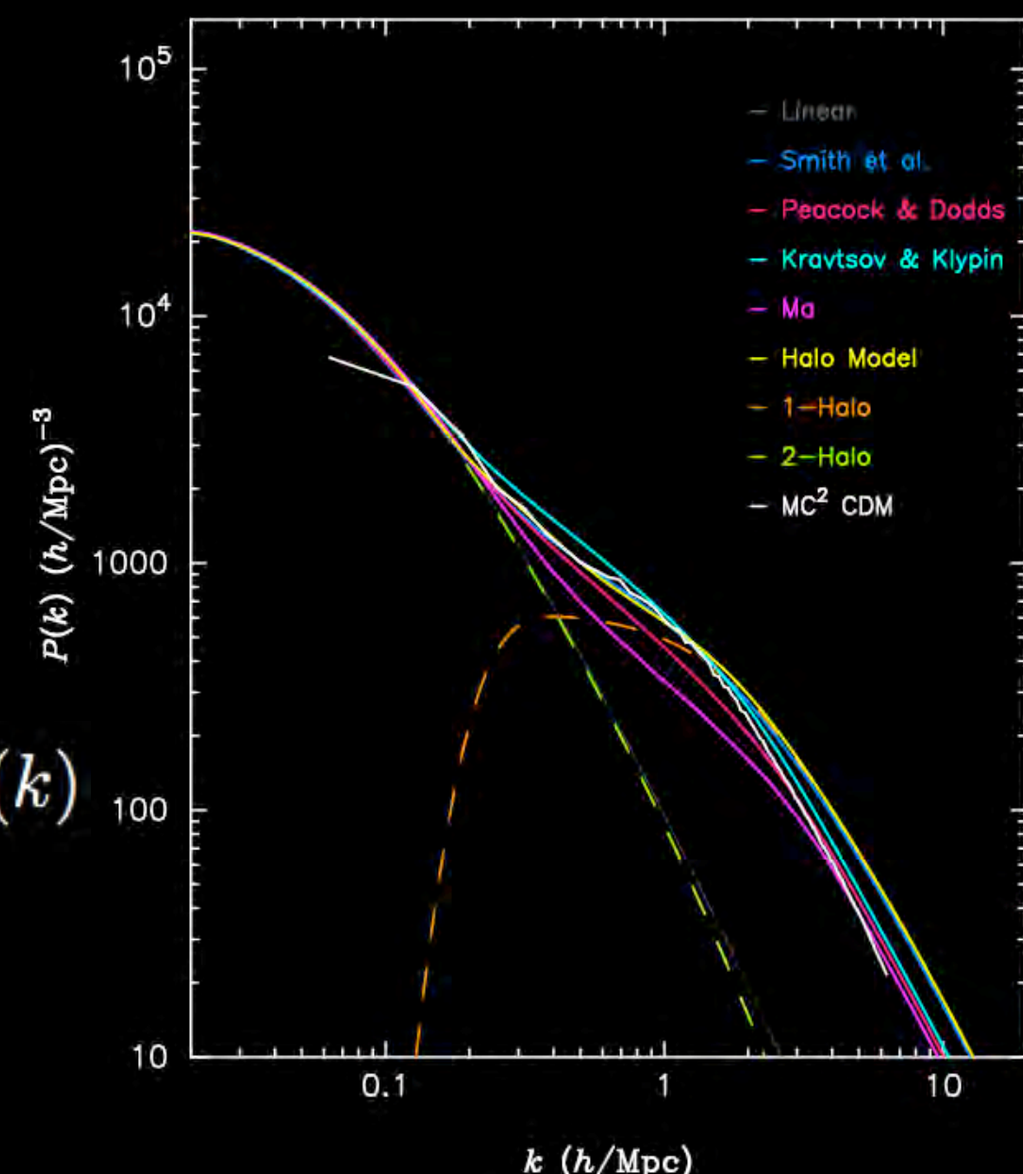
$$P_{\mathrm{hh}}(k \mid M_1, M_2) \approx b_1(M_1)\, b_2(M_2)\, P_{\mathrm{lin}}(k)$$



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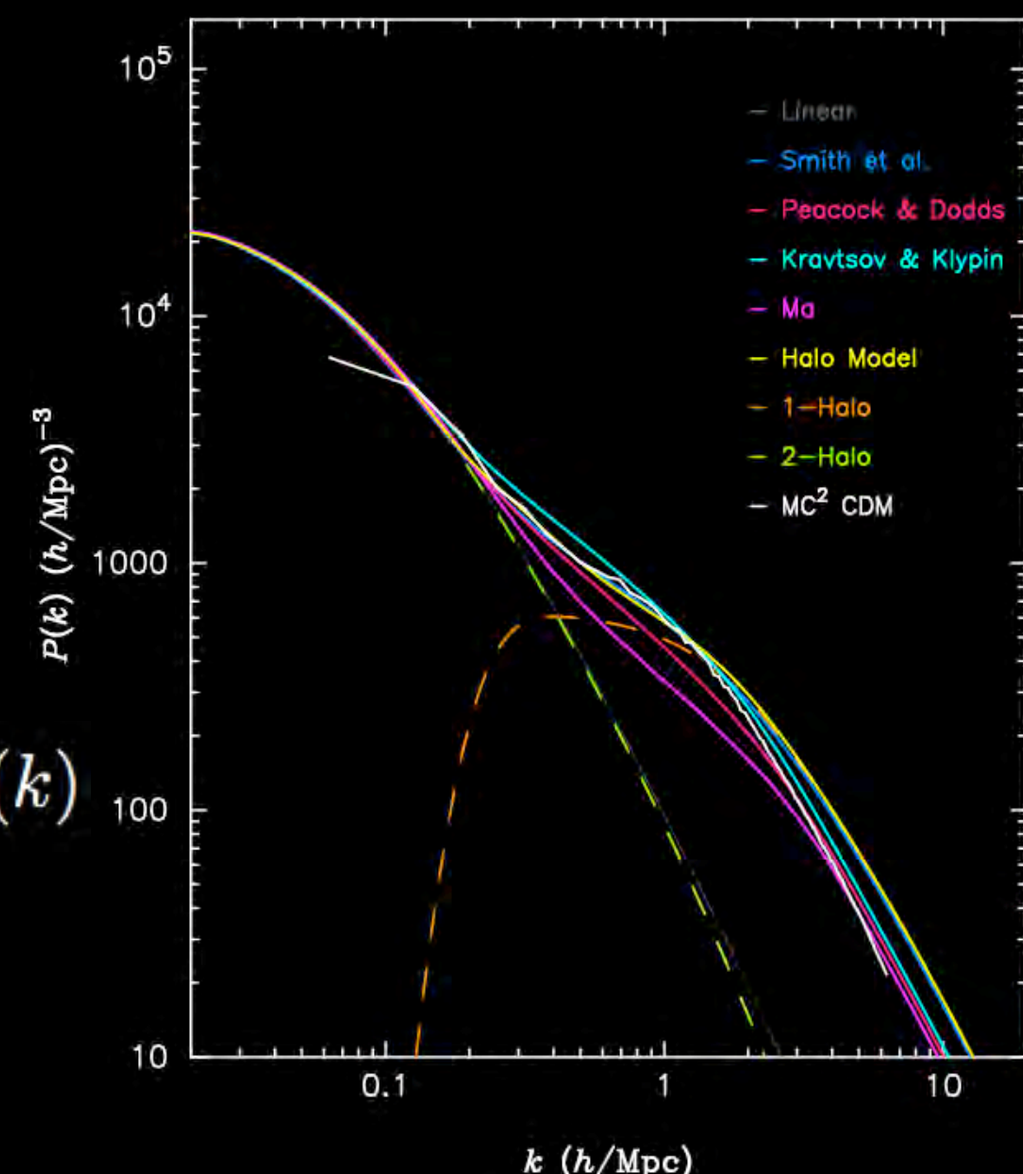

Substructure within 1 halo:

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

Modeling nonlinear clustering: The full halo model in WDM

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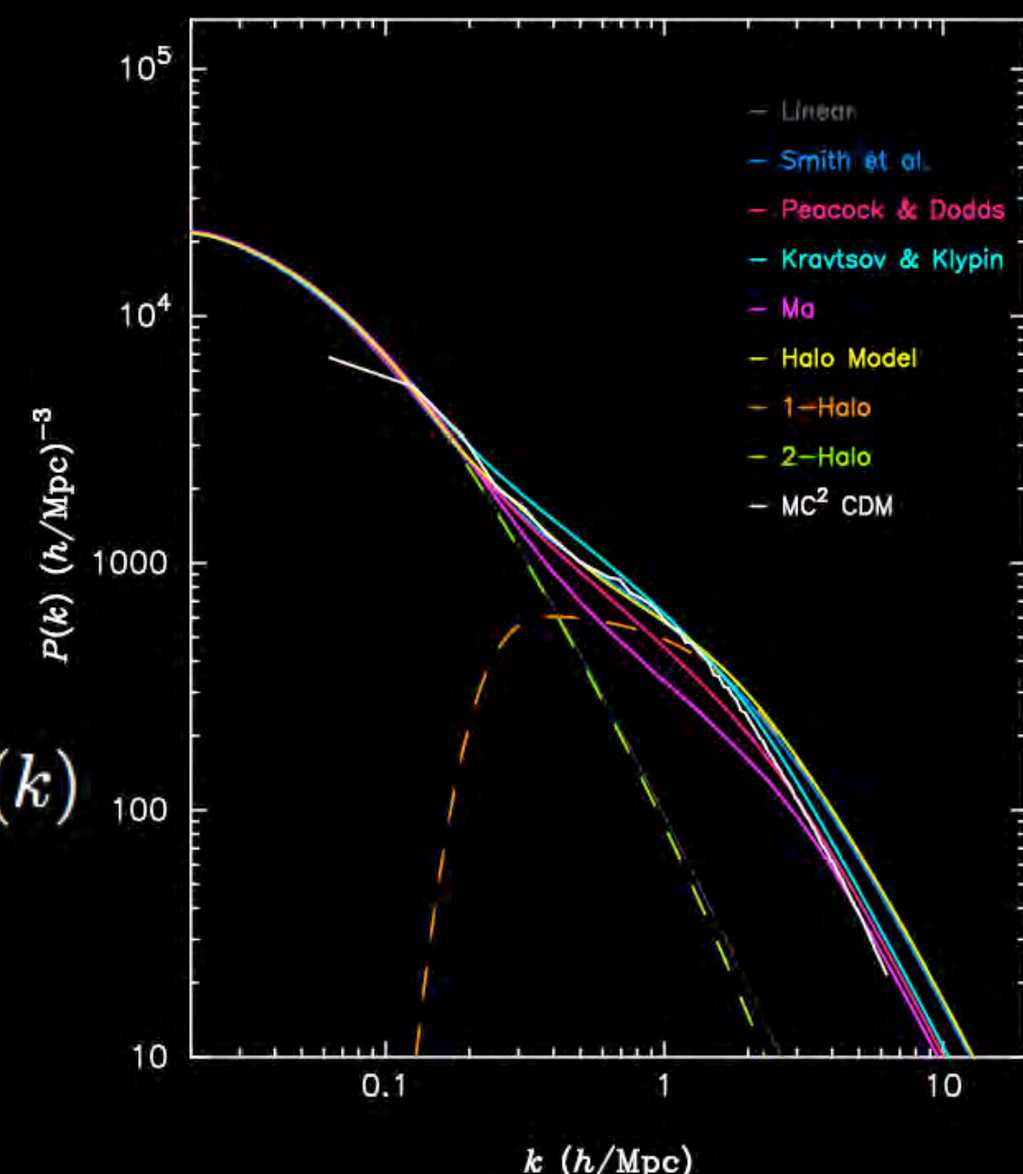

Substructure within 1 halo:

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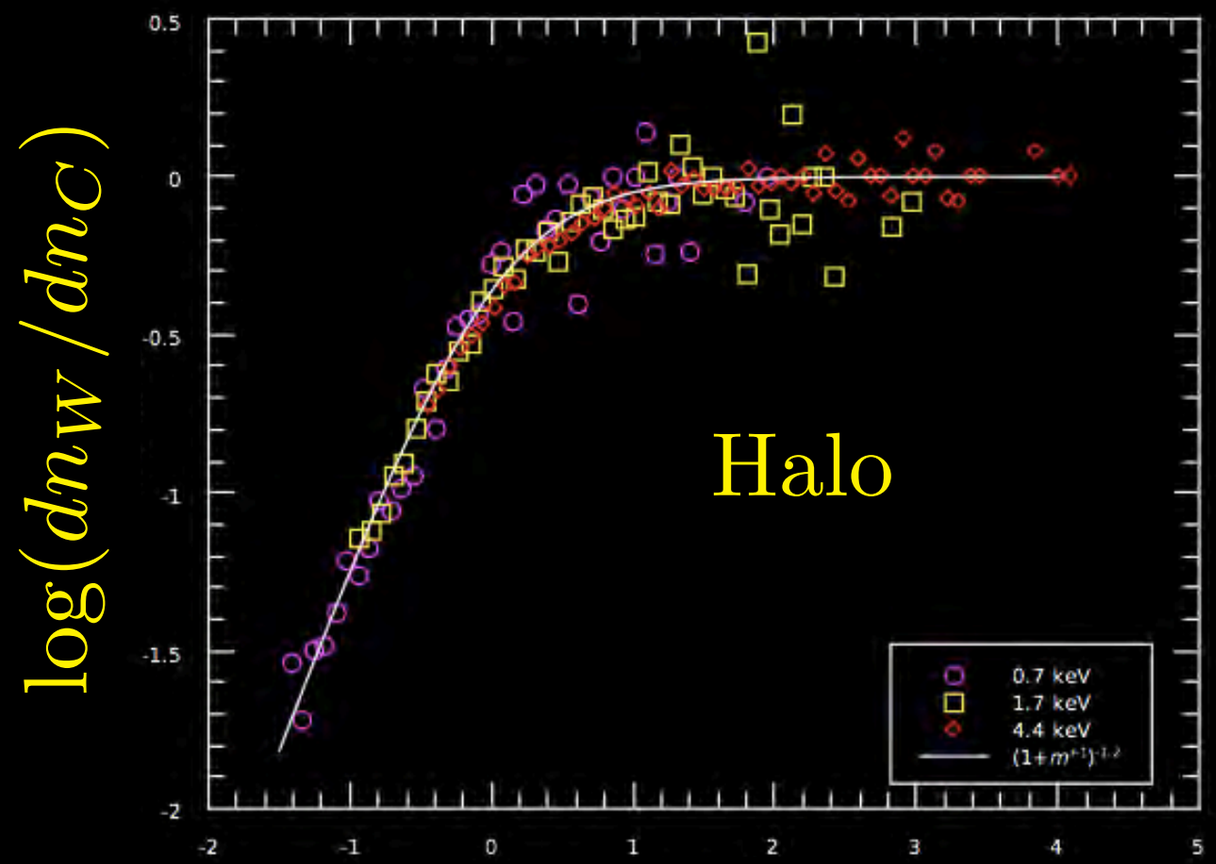
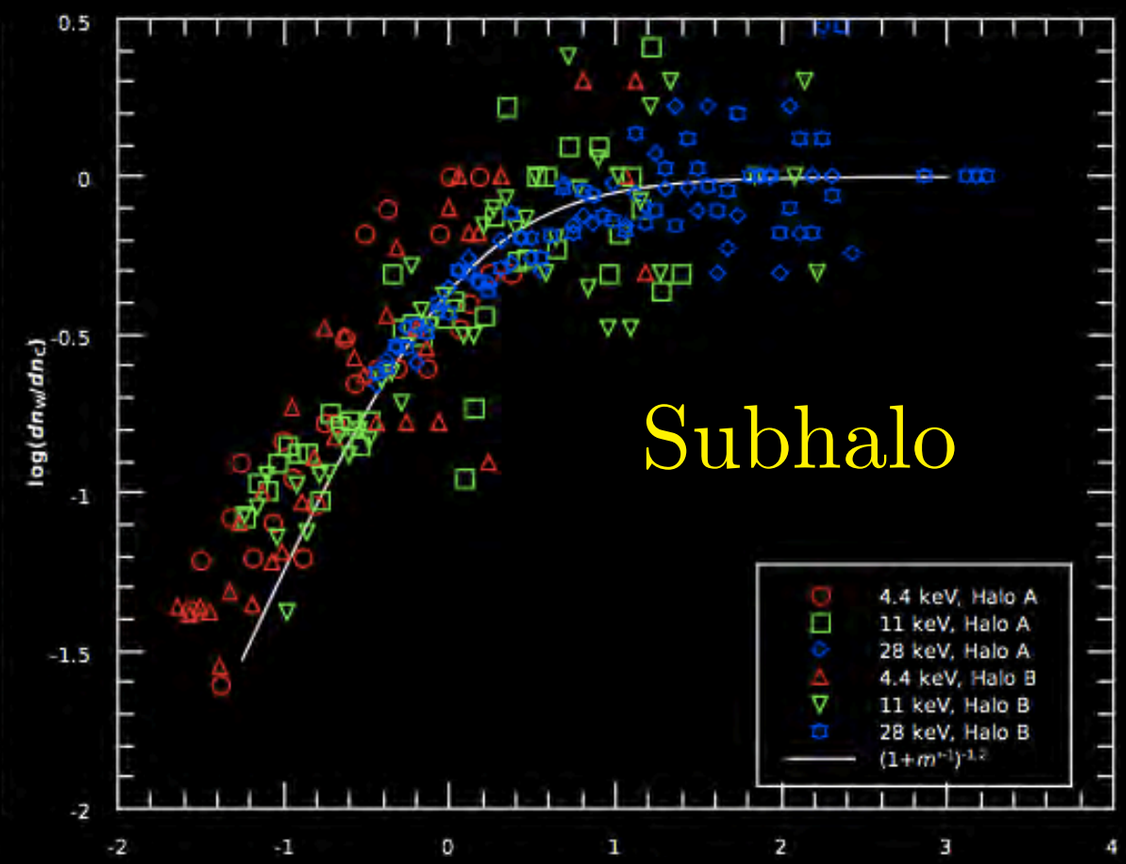
Dunstan, Abazajian, Polisensky & Ricotti 2011

Halo and Subhalo Mass Functions





$\log(M/M_f)$

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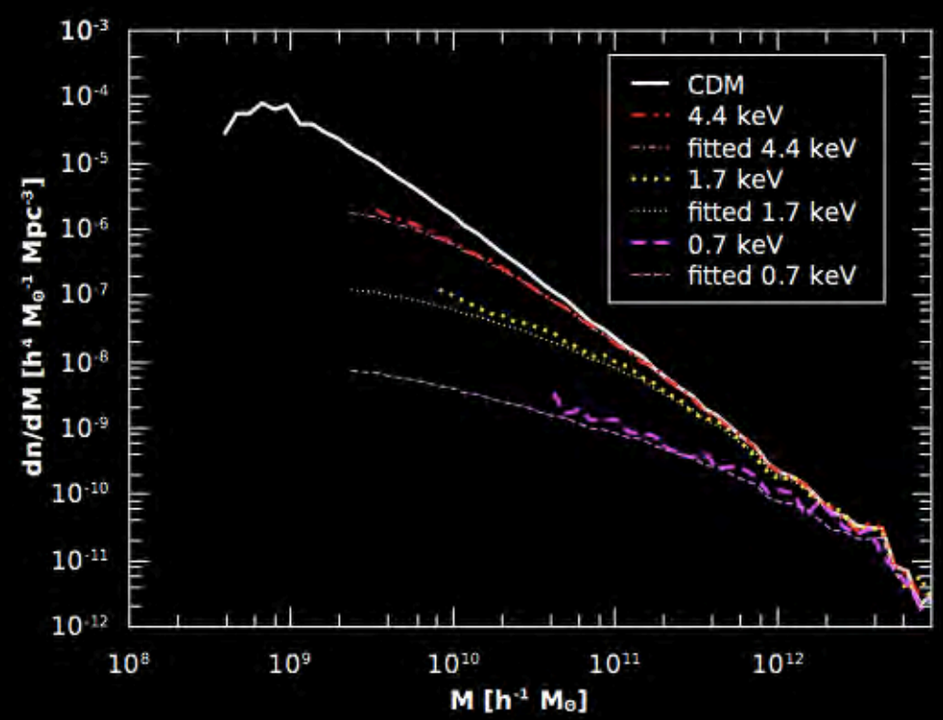
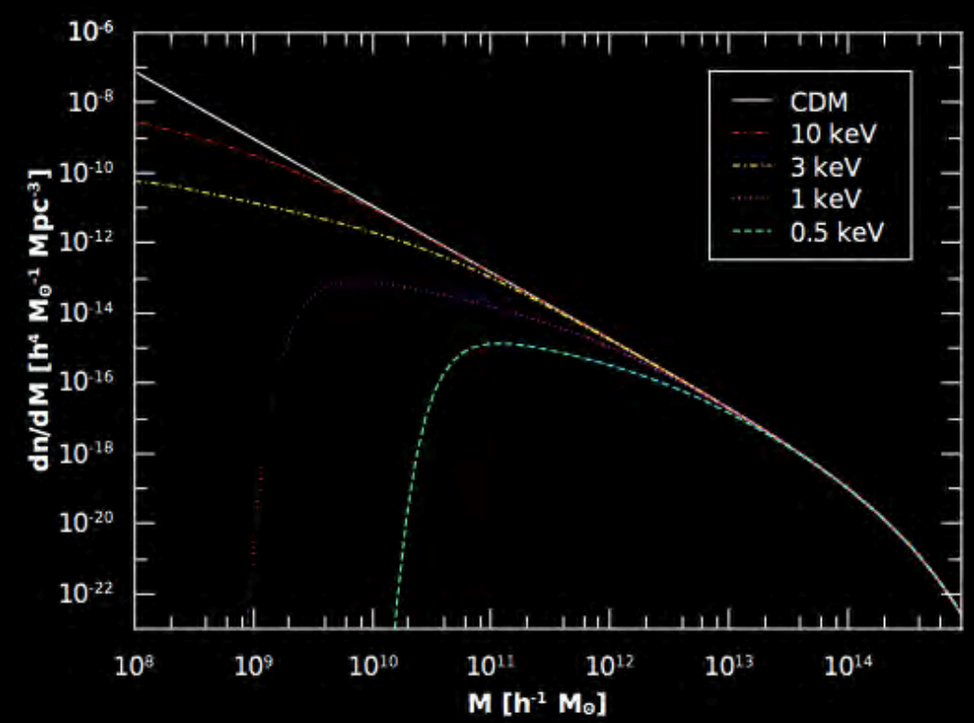
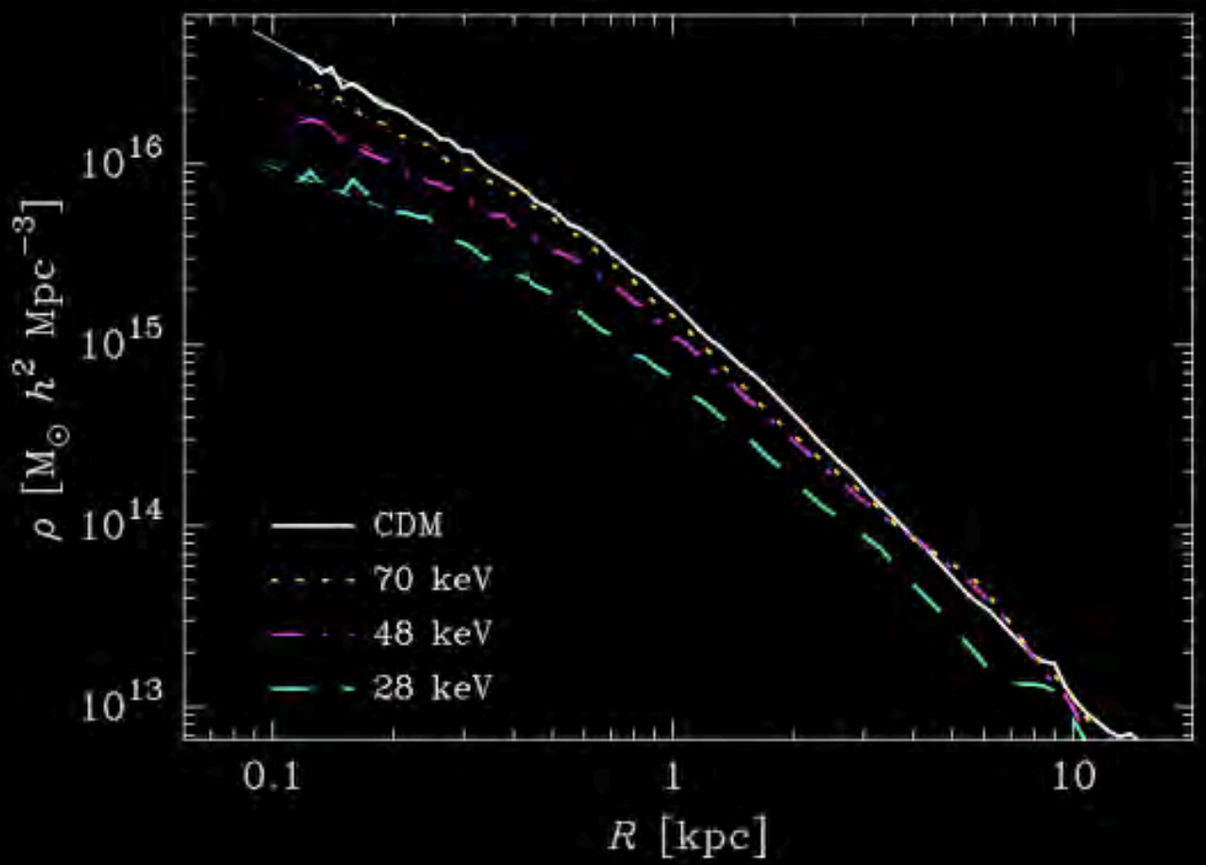
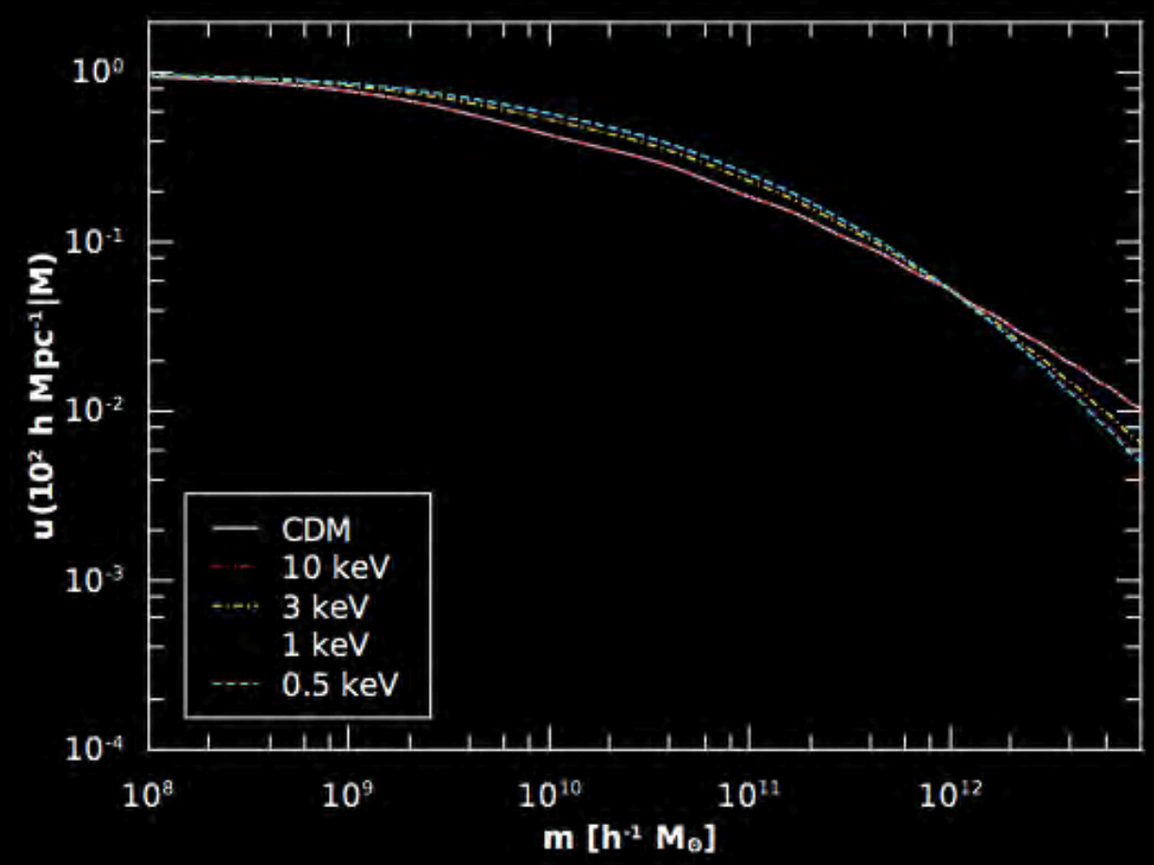
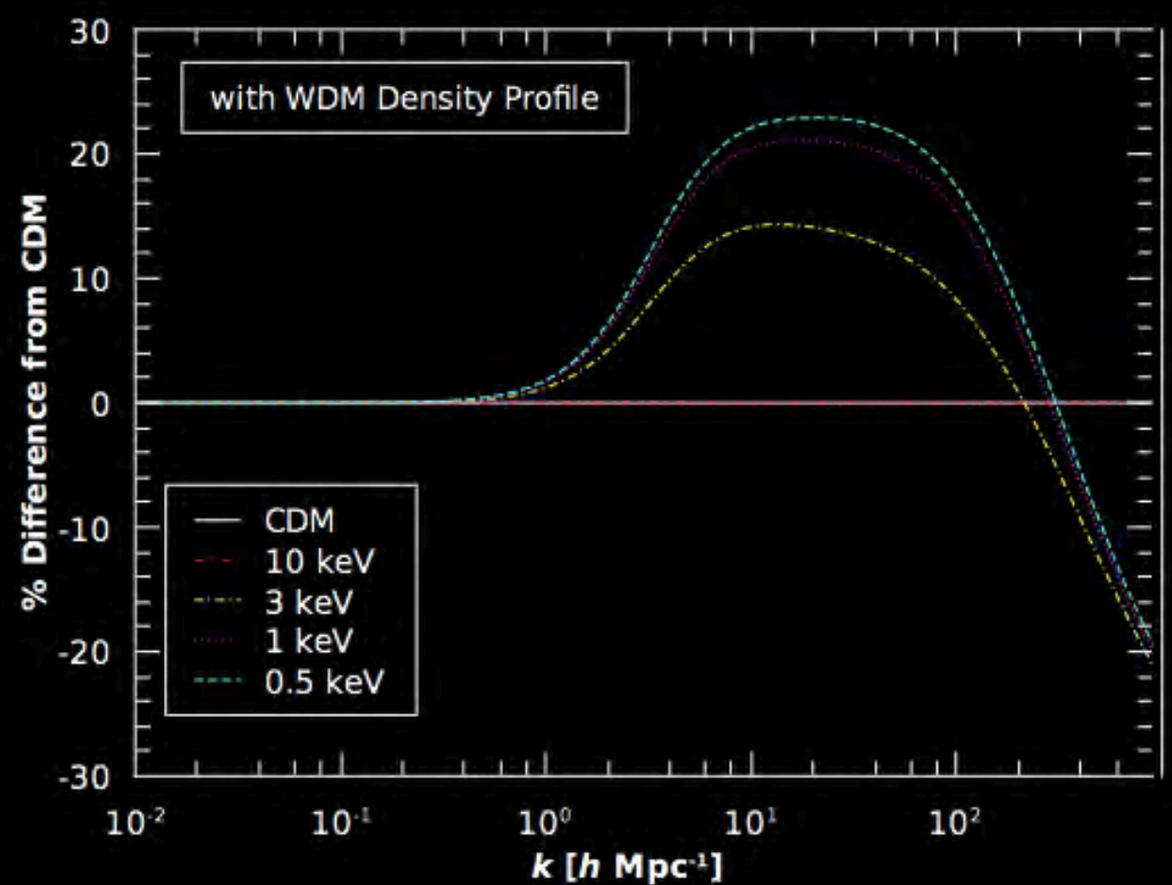




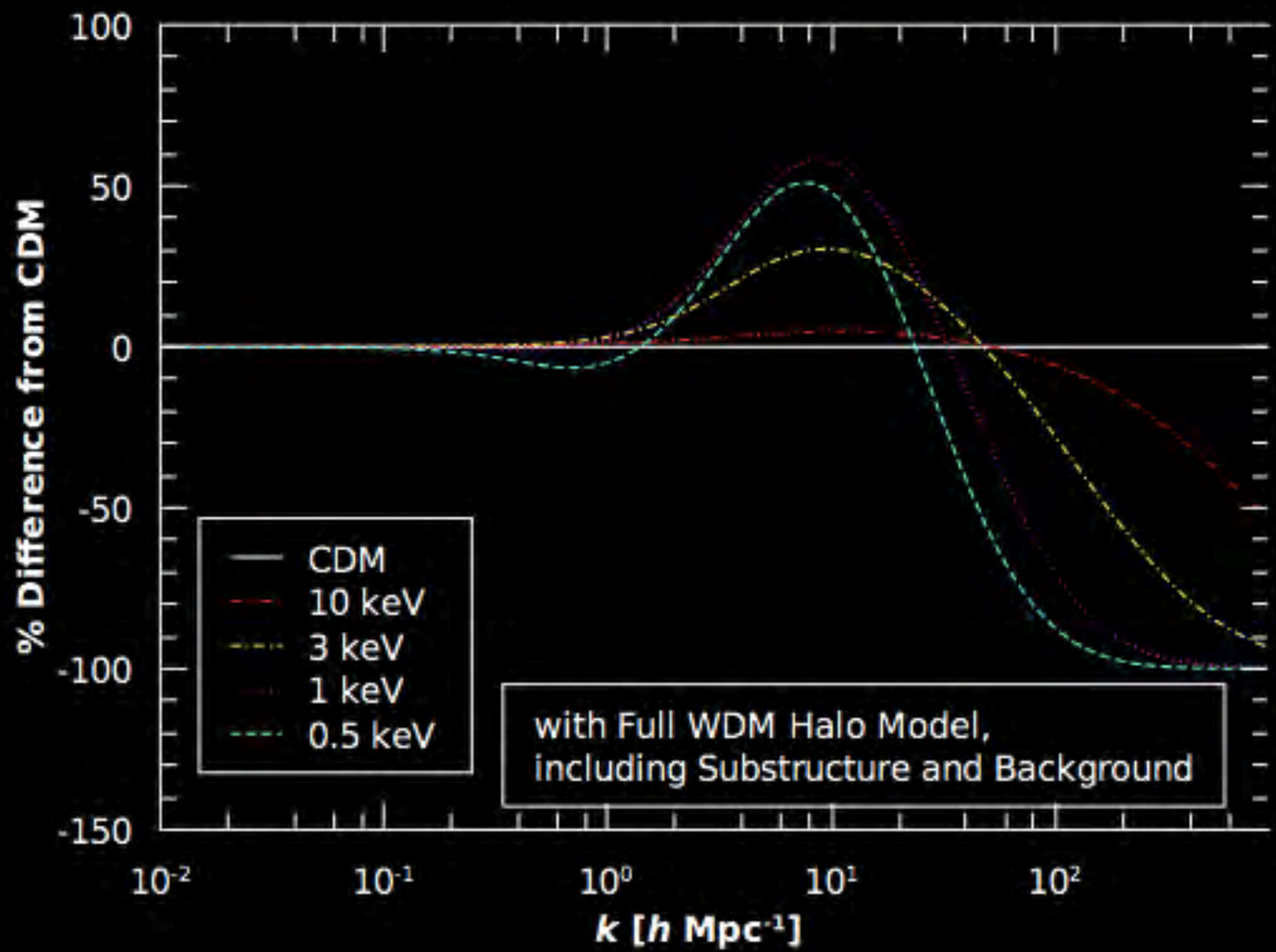
Halo Profile Effects







Results on the Full Nonlinear Effects from the Halo Model



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)

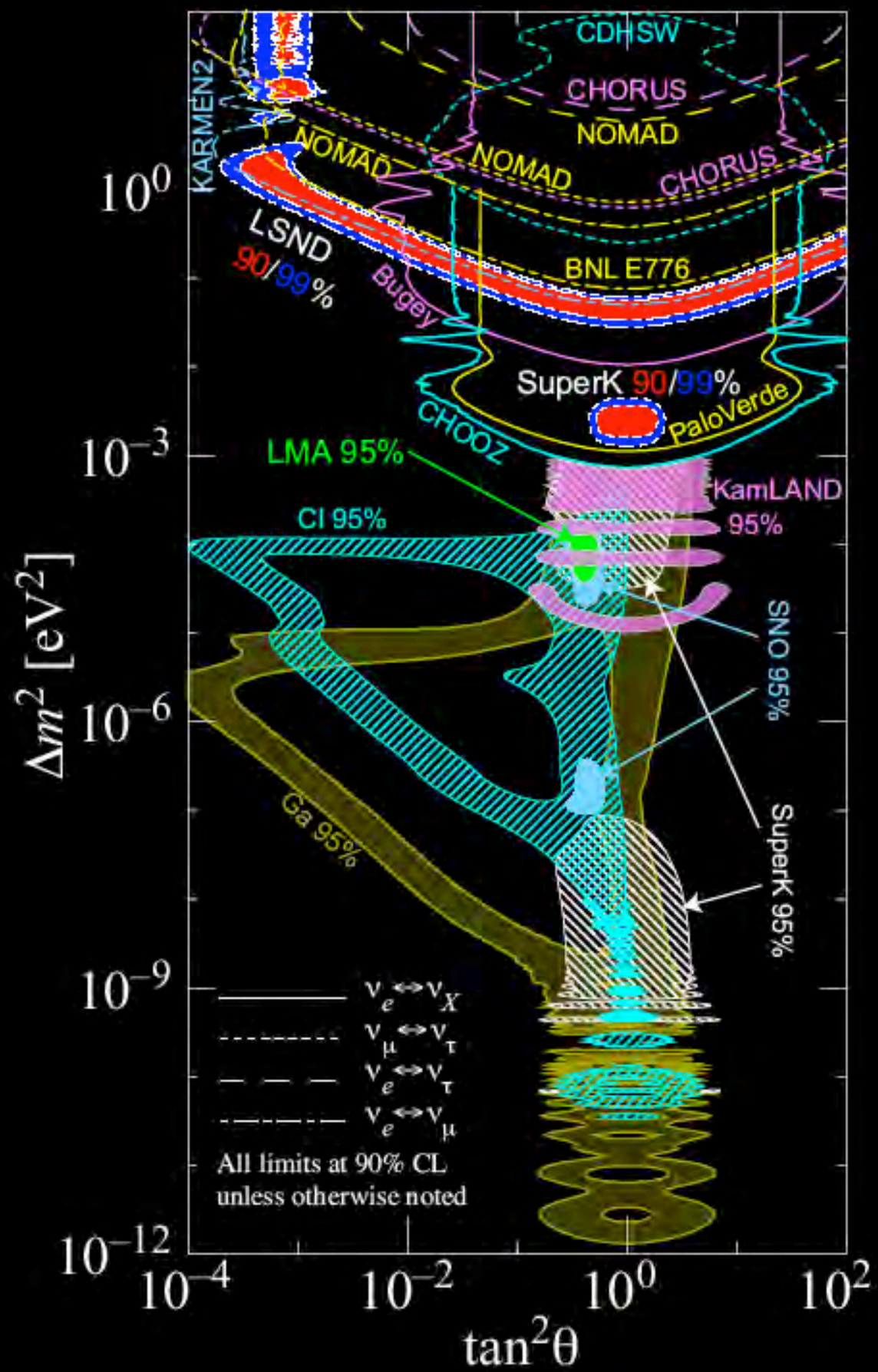
The νMSM : a minimalist model

- The Neutrino Minimal Standard Model of Particle Physics [Asaka, Blanchet & Shaposhnikov 2005]
- Add Dirac & Majorana Neutrino Mass Terms to MSM

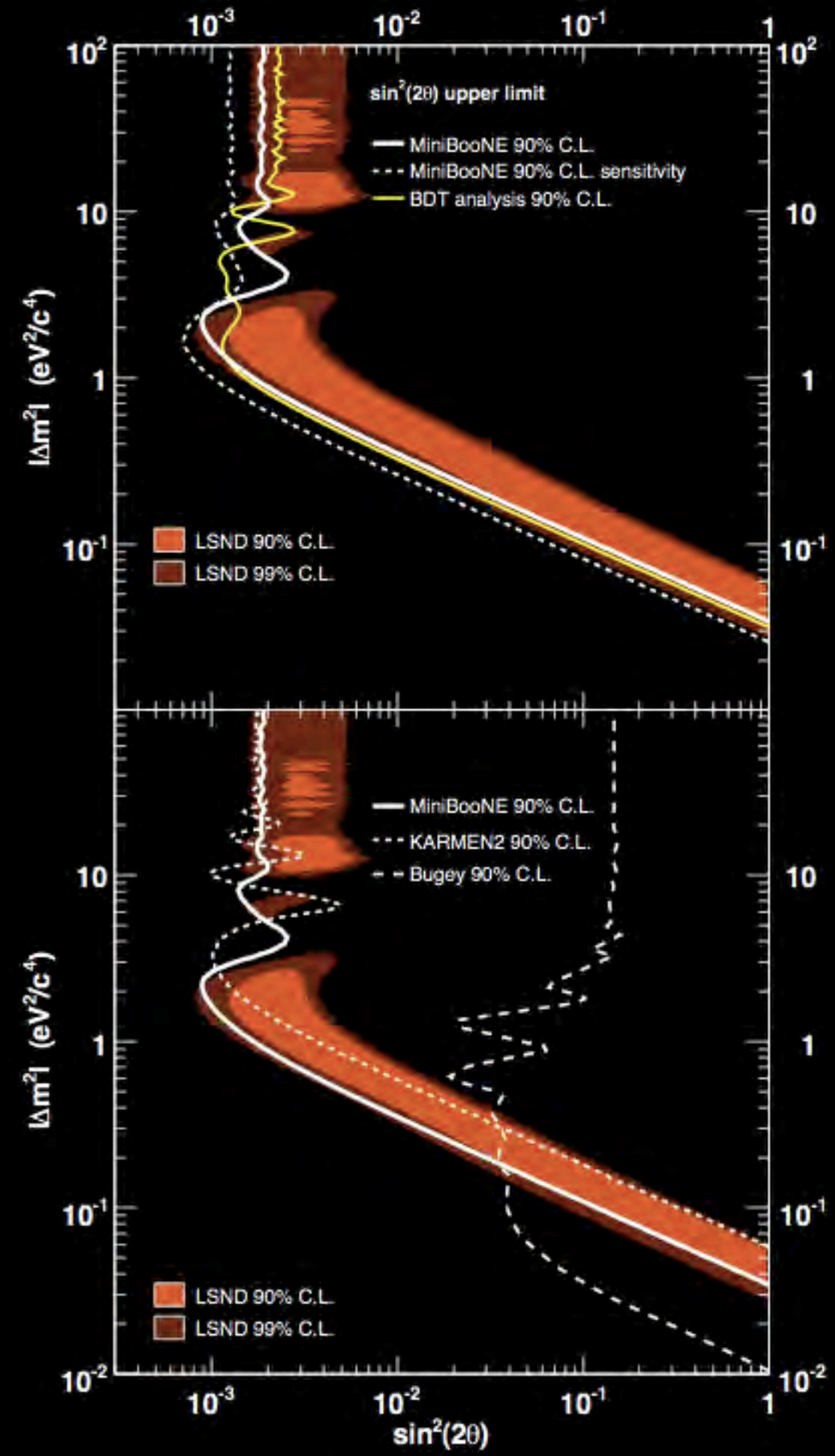
$$\delta\mathcal{L} = \bar{N}_I i\partial_\mu\gamma^\mu N_I - f^\nu_{I\alpha}\Phi\bar{N}_I L_\alpha - \frac{M_I}{2}\bar{N}^c_I N_I + h.c.$$

- Two heavy sterile neutrinos provide atmospheric & solar mass scales
- Baryogenesis via Oscillation-based Leptogenesis in 2 more massive sterile neutrinos
- Light sterile neutrino is the (Warm) Dark Matter

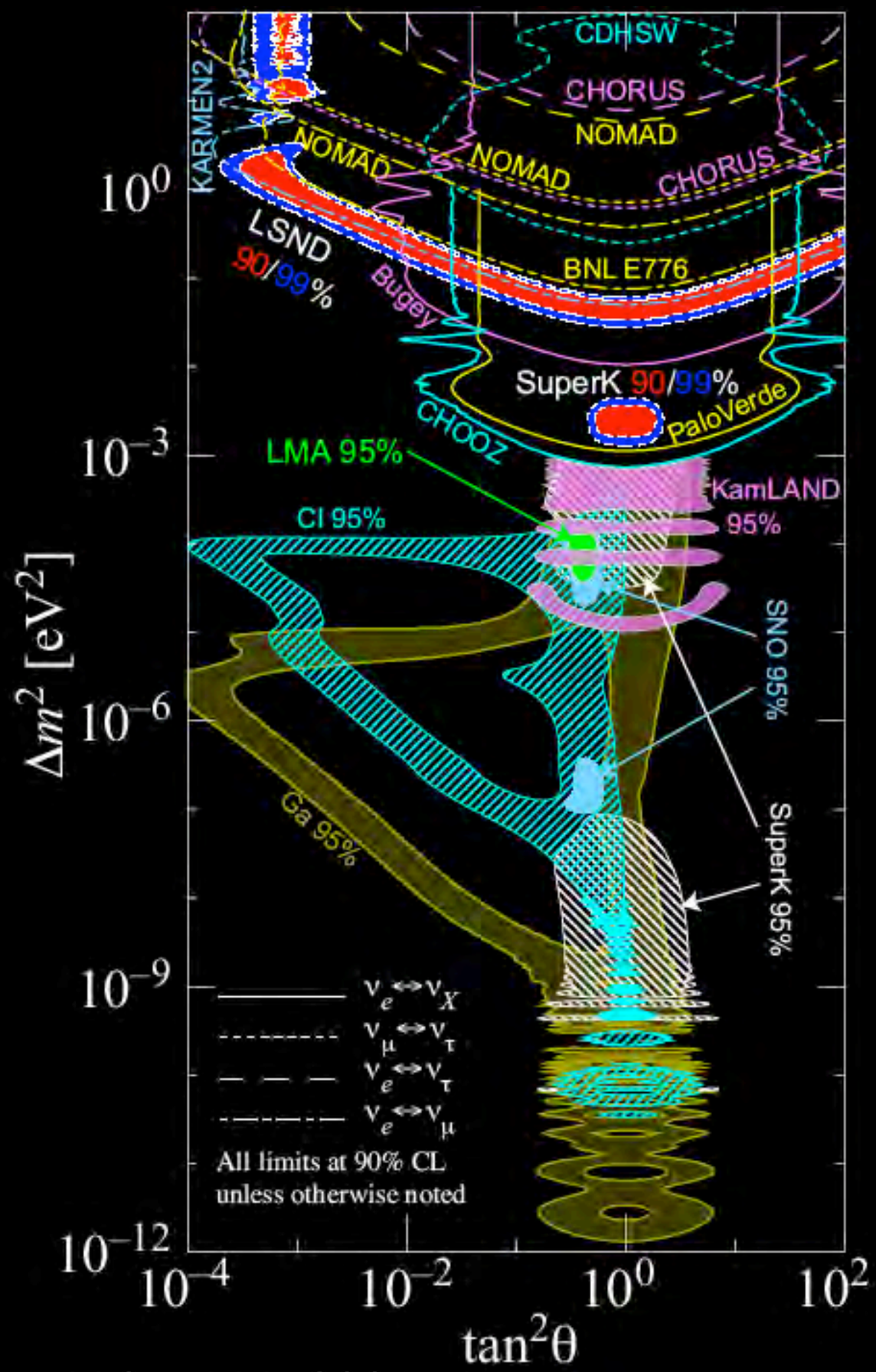
- More involved models generally involve similar insertions for neutrino mass generation



PDG, RPP 2004



Aguilar-Arevalo 2007 [MiniBooNE]



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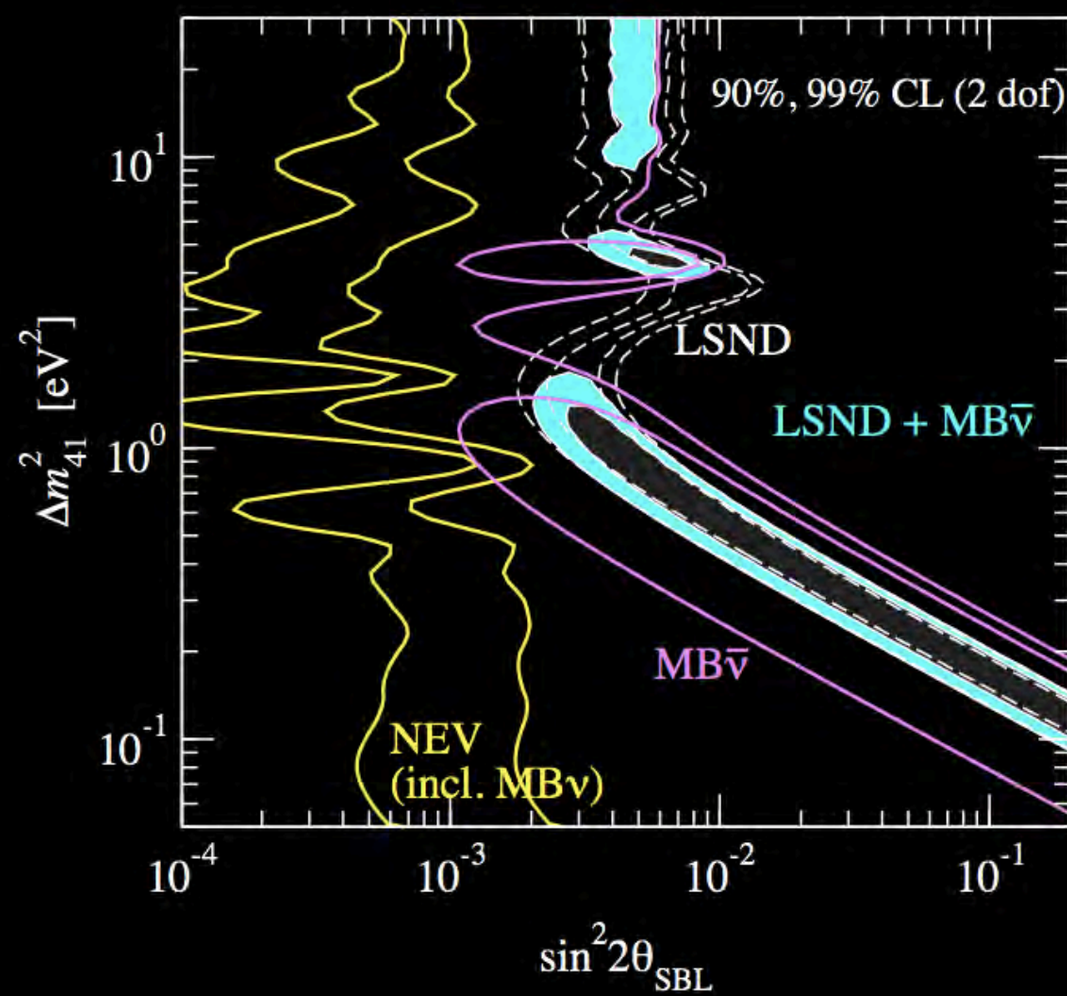
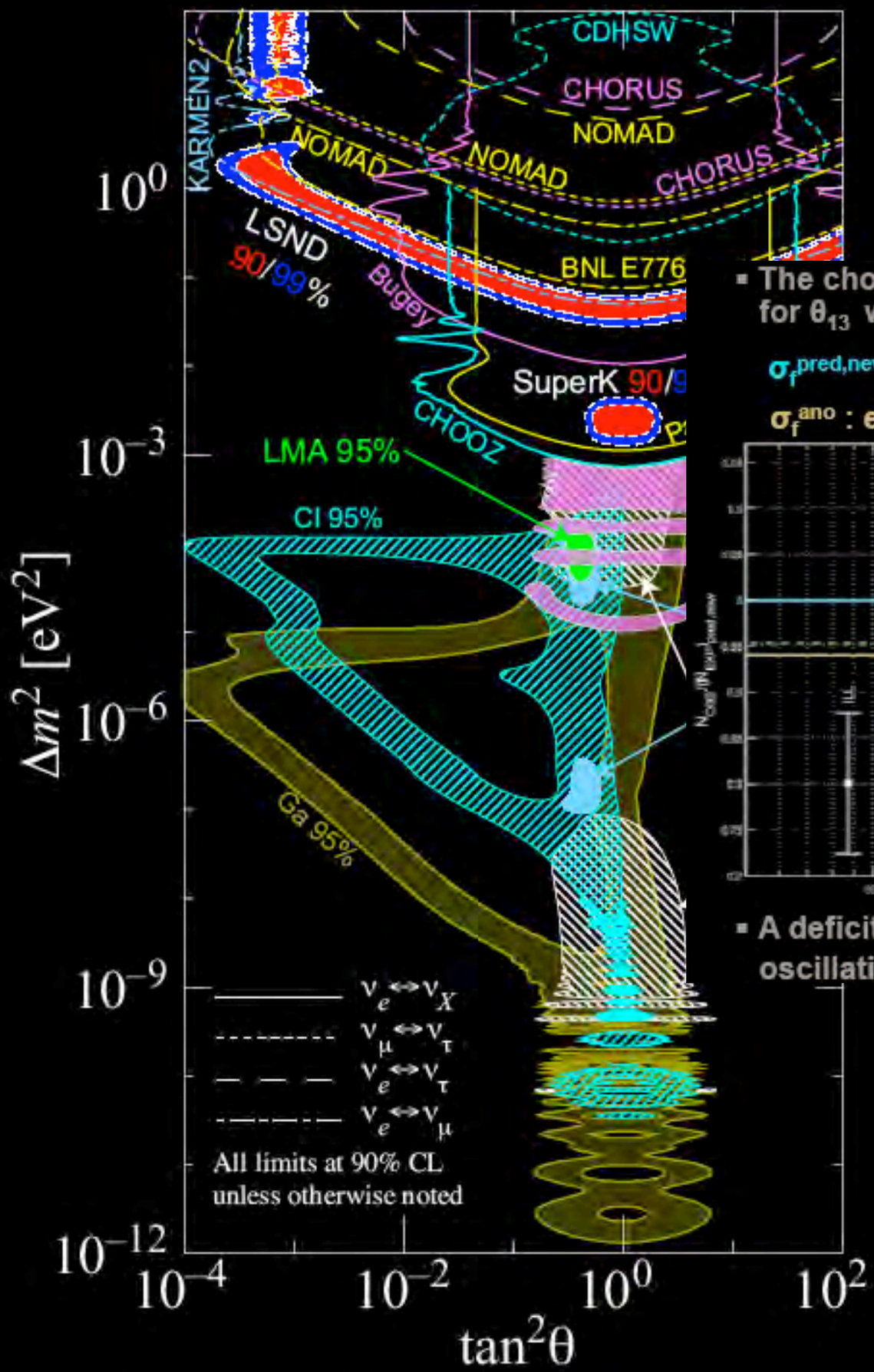


Aguilar-Arevalo 2010 [MiniBooNE]
Akhmedov & Schwetz 2011

Reactor Anomaly

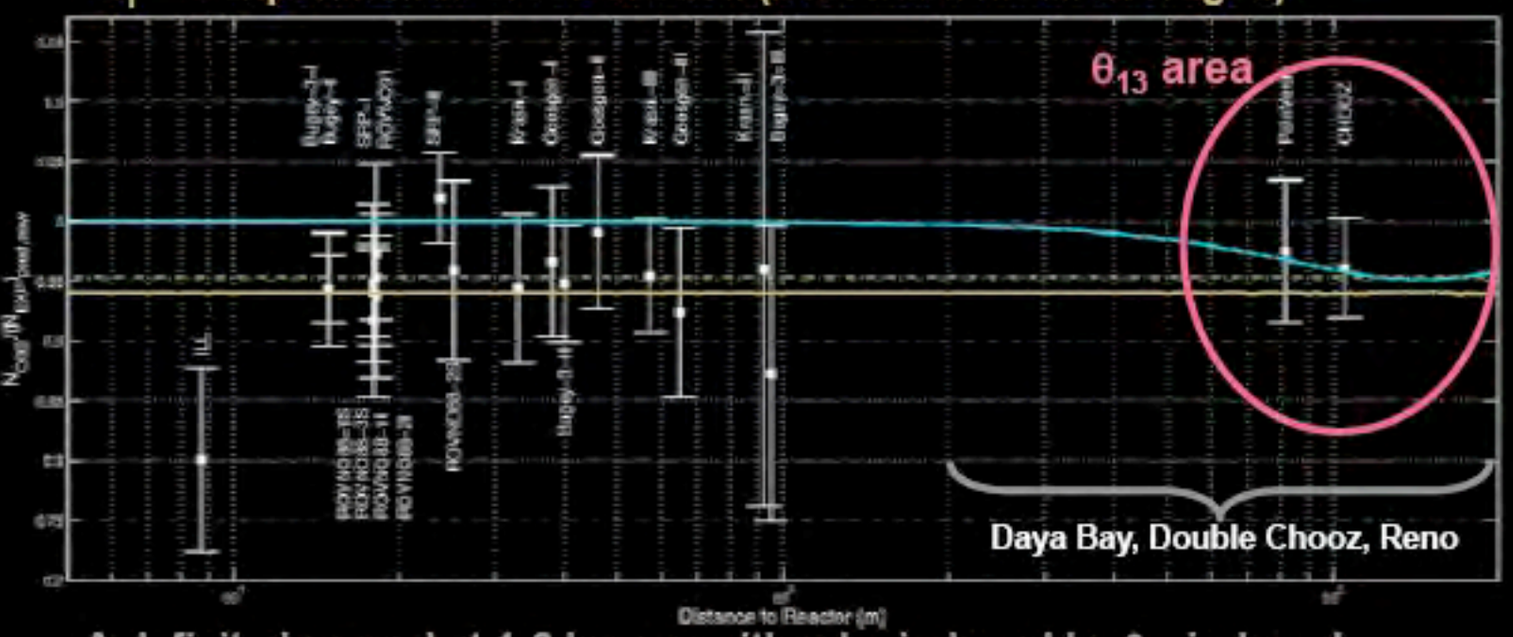


PDG, RPP 2004

- 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

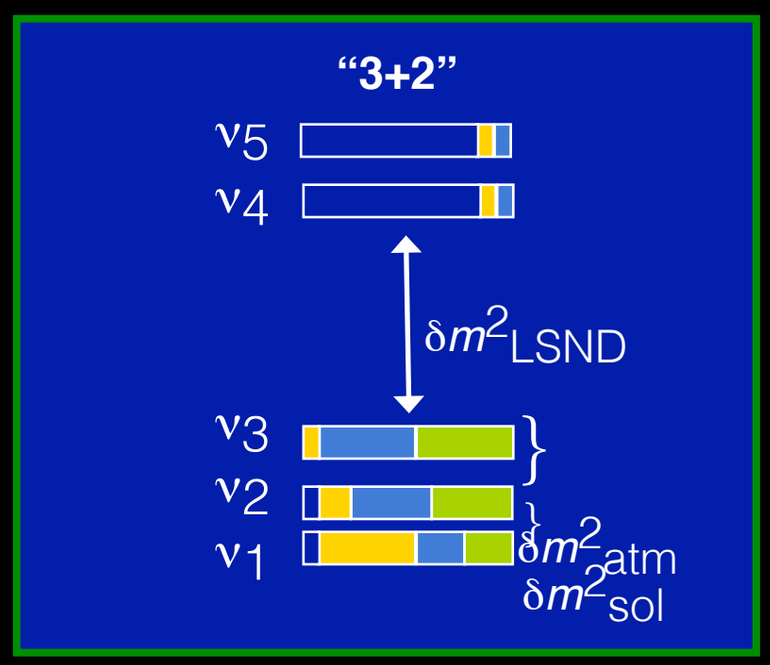
Sterile Neutrino Dark Matter

ν_6

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

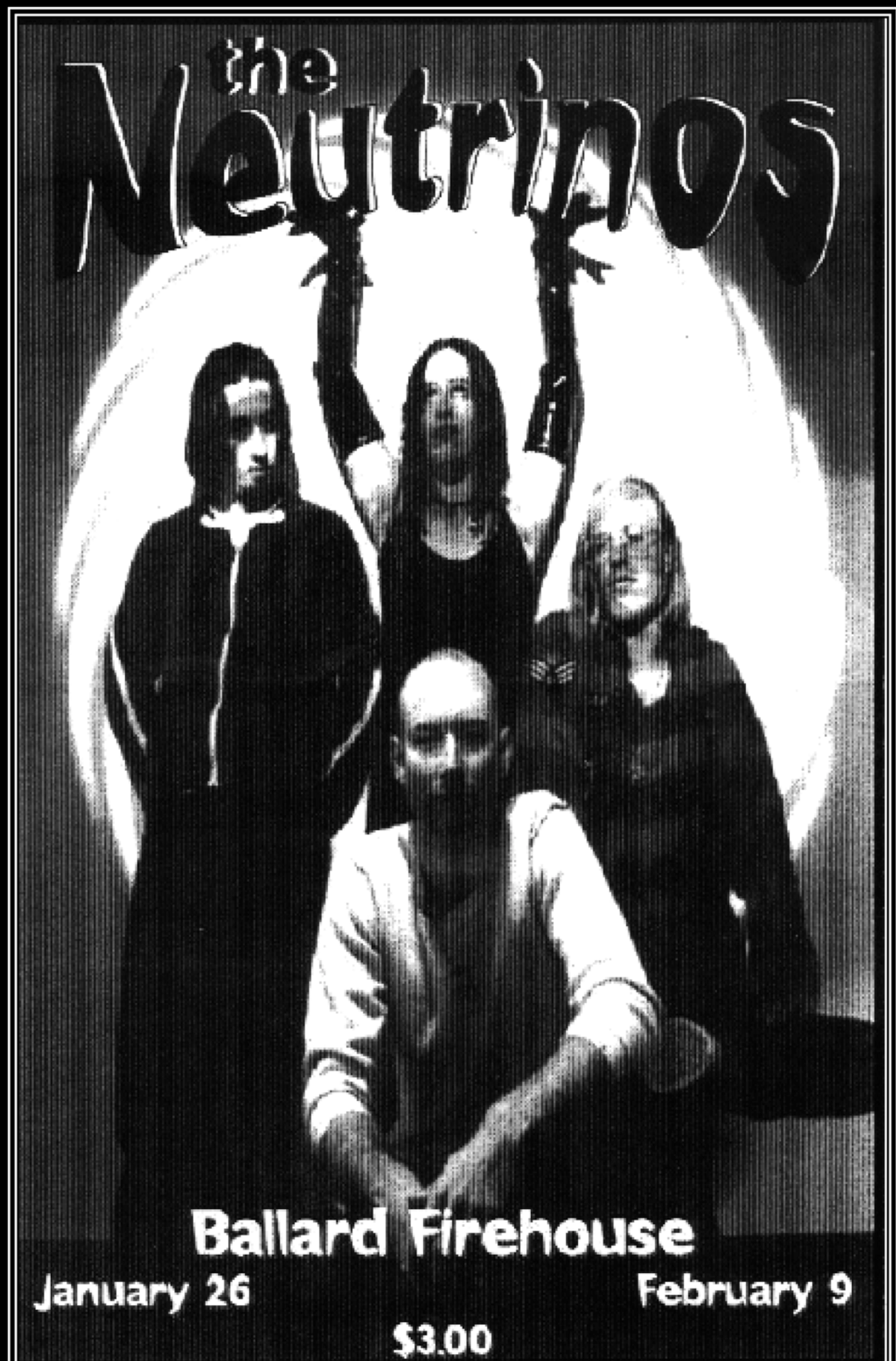
~ 1 keV

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



~ 1 eV

~ 0.01 eV


the
Neutrinos
Ballard Firehouse
January 26
February 9
$3.00

keV Sterile Neutrinos

- Could be the Dark Matter ($m_s \sim 1$ keV)
  (Dodelson & Widrow 1994; Shi & Fuller 1999;
  Abazajian, Fuller & Patel 2001)

- May Solve Several Potential Problems in the cold dark matter paradigm of Galaxy and Small Scale Structure Formation
  (e.g., Bode, Ostriker & Turok 2001)

- Provides pulsar kicks
  (Kusenko & Segre 1999)

- Enhances shock heating of the shock in Type II supernovae
  (Hidaka & Fuller 2006)

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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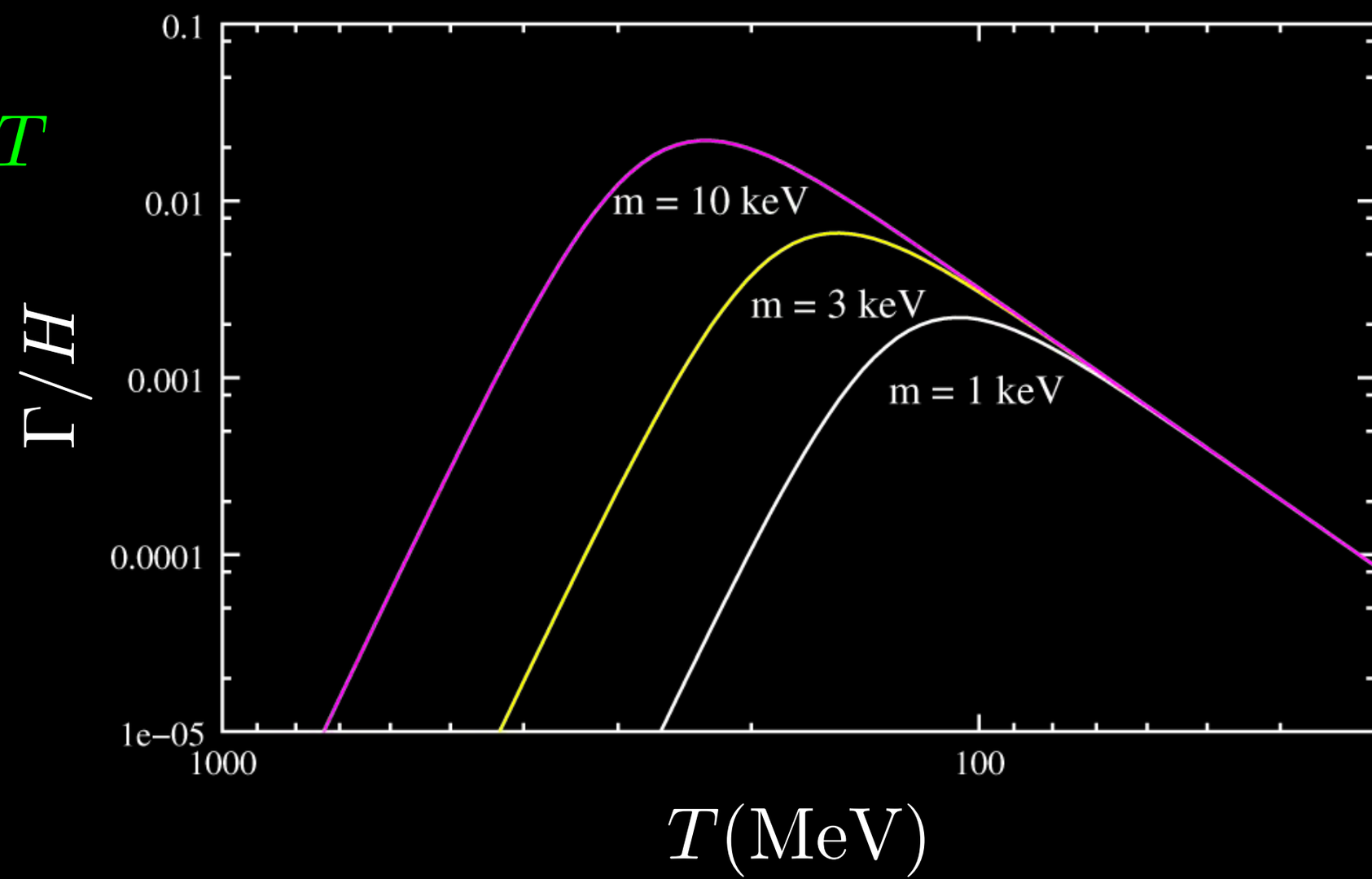

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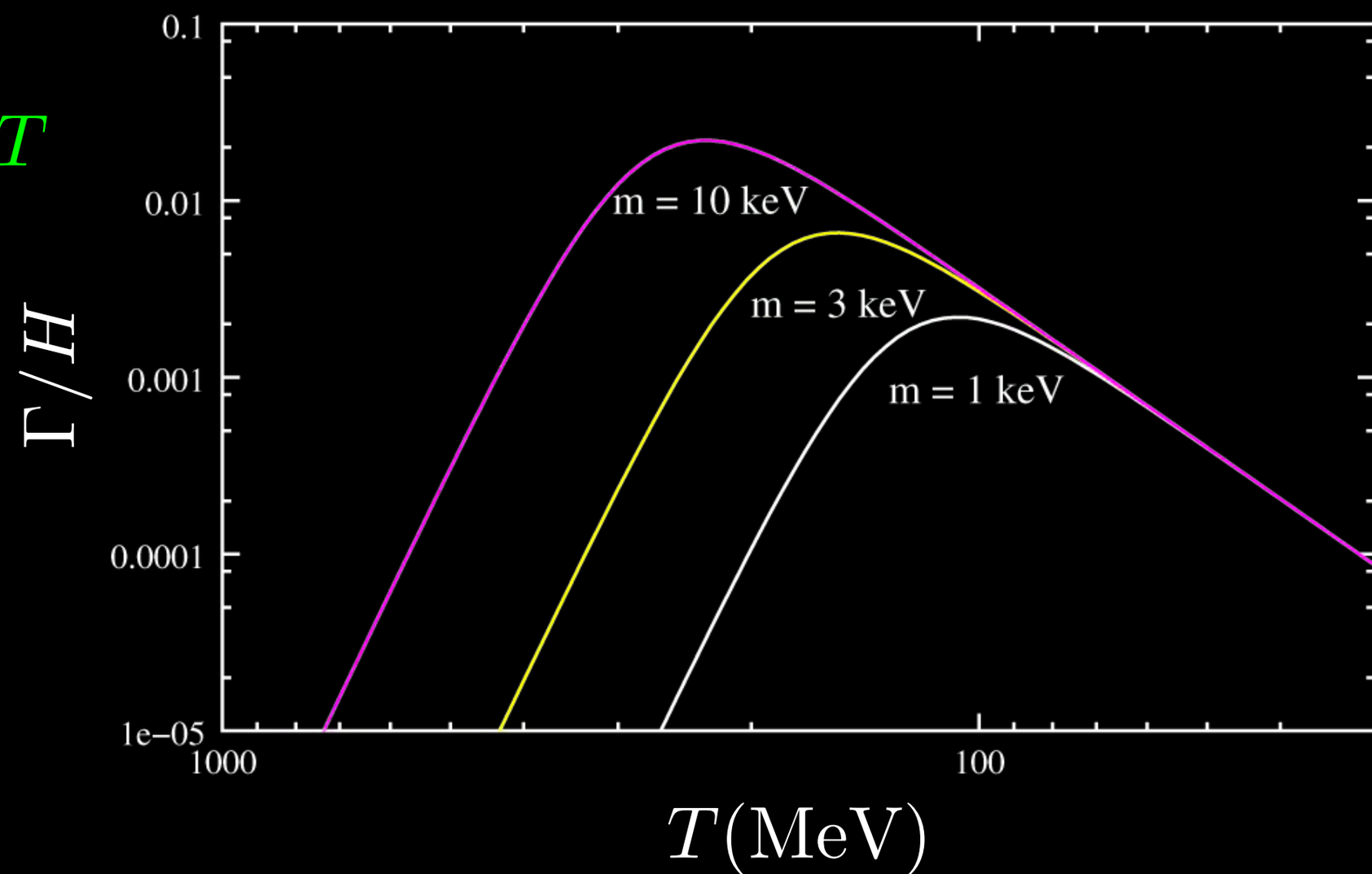
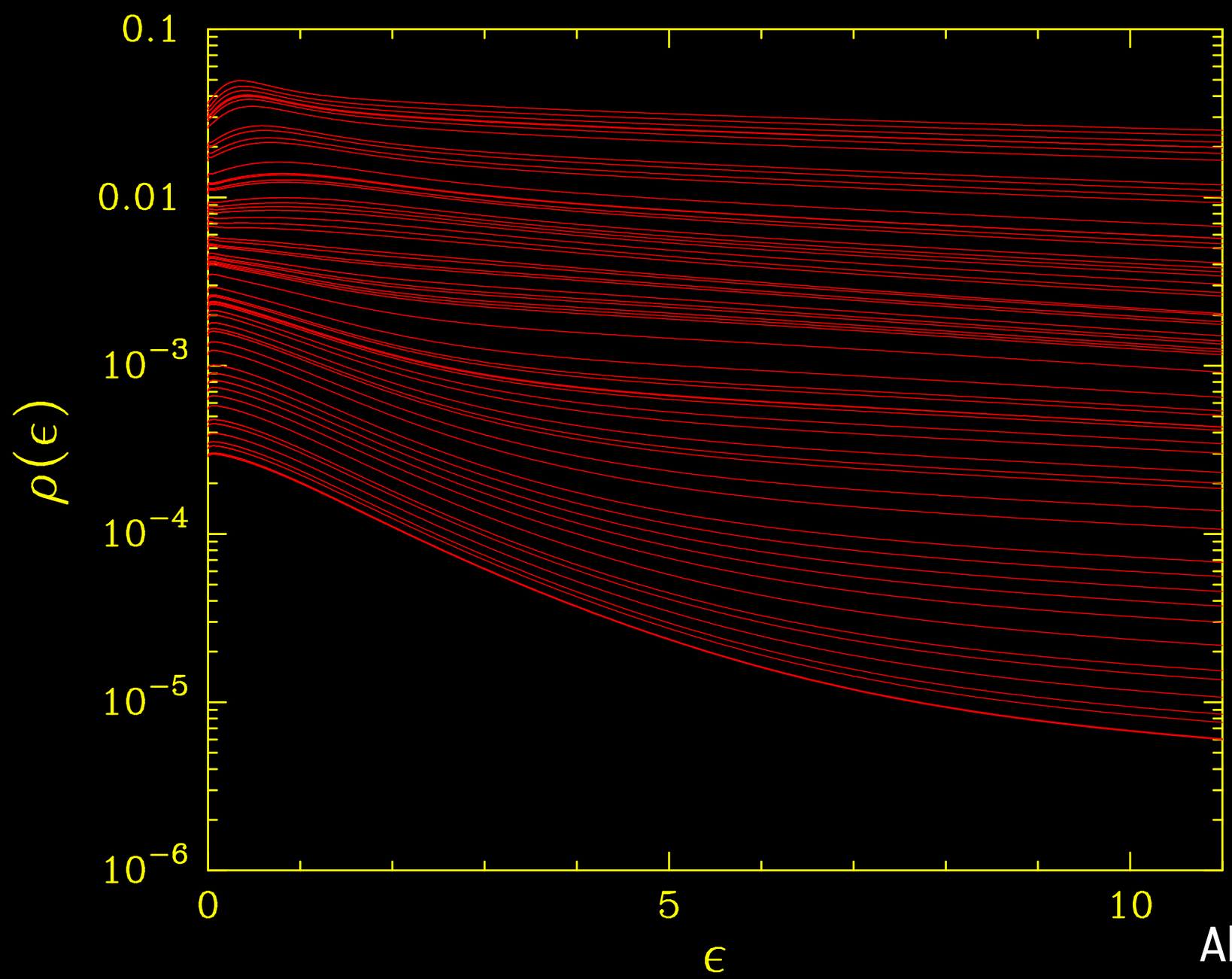
Never in Equilibrium!!



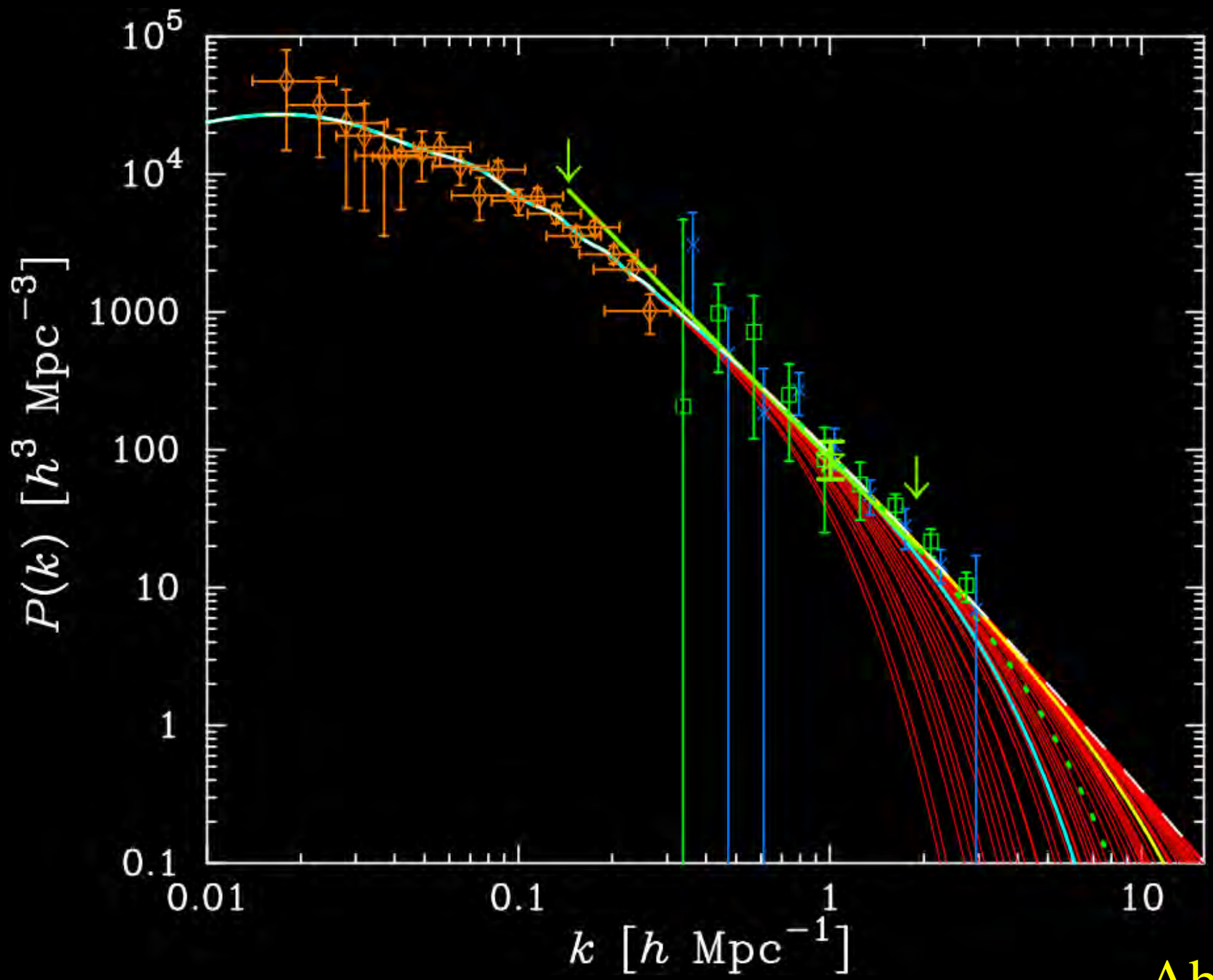
Spectral Distribution

$$\rho(\epsilon) = \frac{f_s(\epsilon)}{f_\nu(\epsilon)} \qquad f_\nu(\epsilon) = \frac{1}{e^\epsilon + 1} \qquad \epsilon = p/T$$



Abazajian 2005

Where does the CDM ansatz fail?



Abazajian 2006

- SDSS 3D P(k) Main Galaxies (Tegmark et al 2003)
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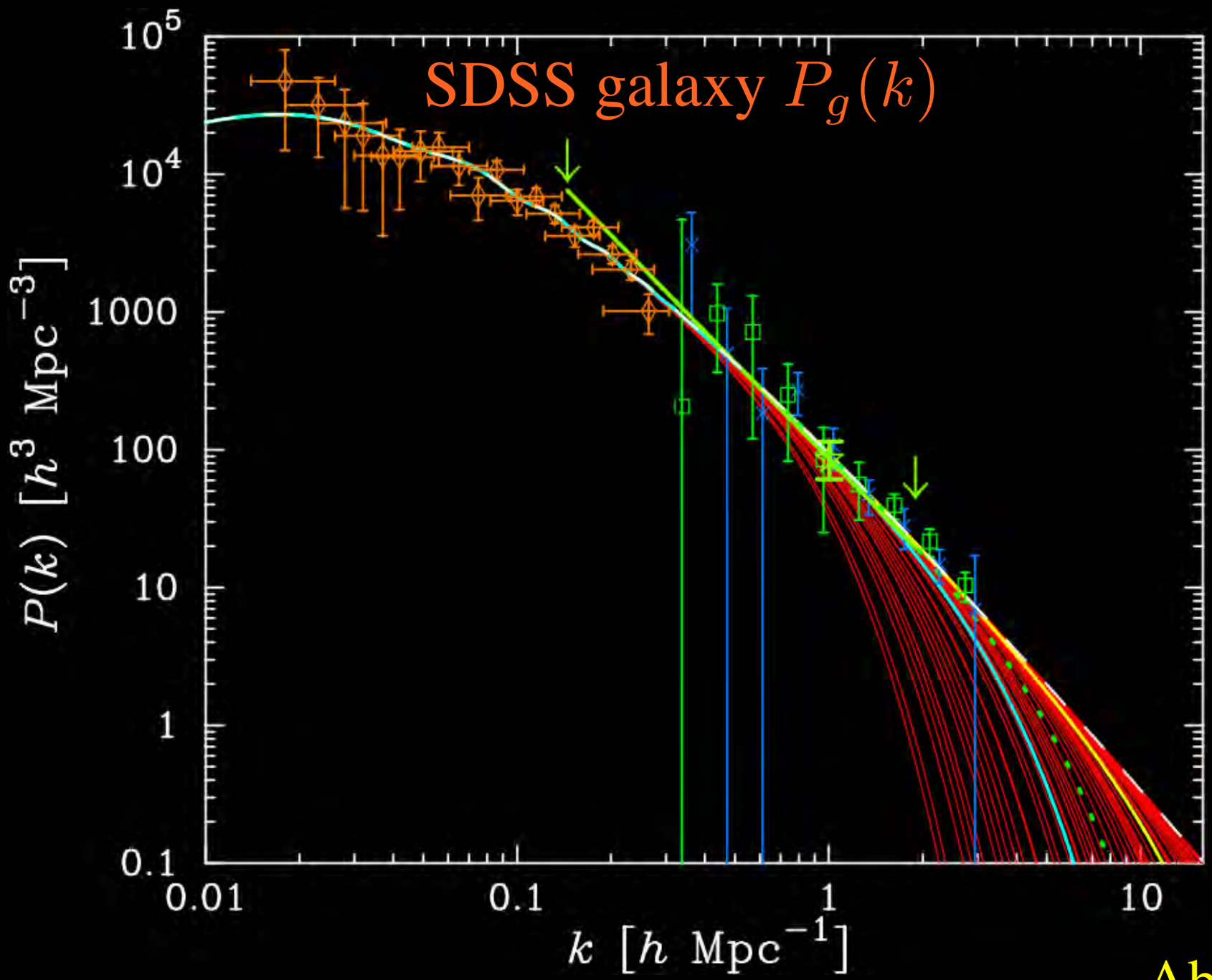

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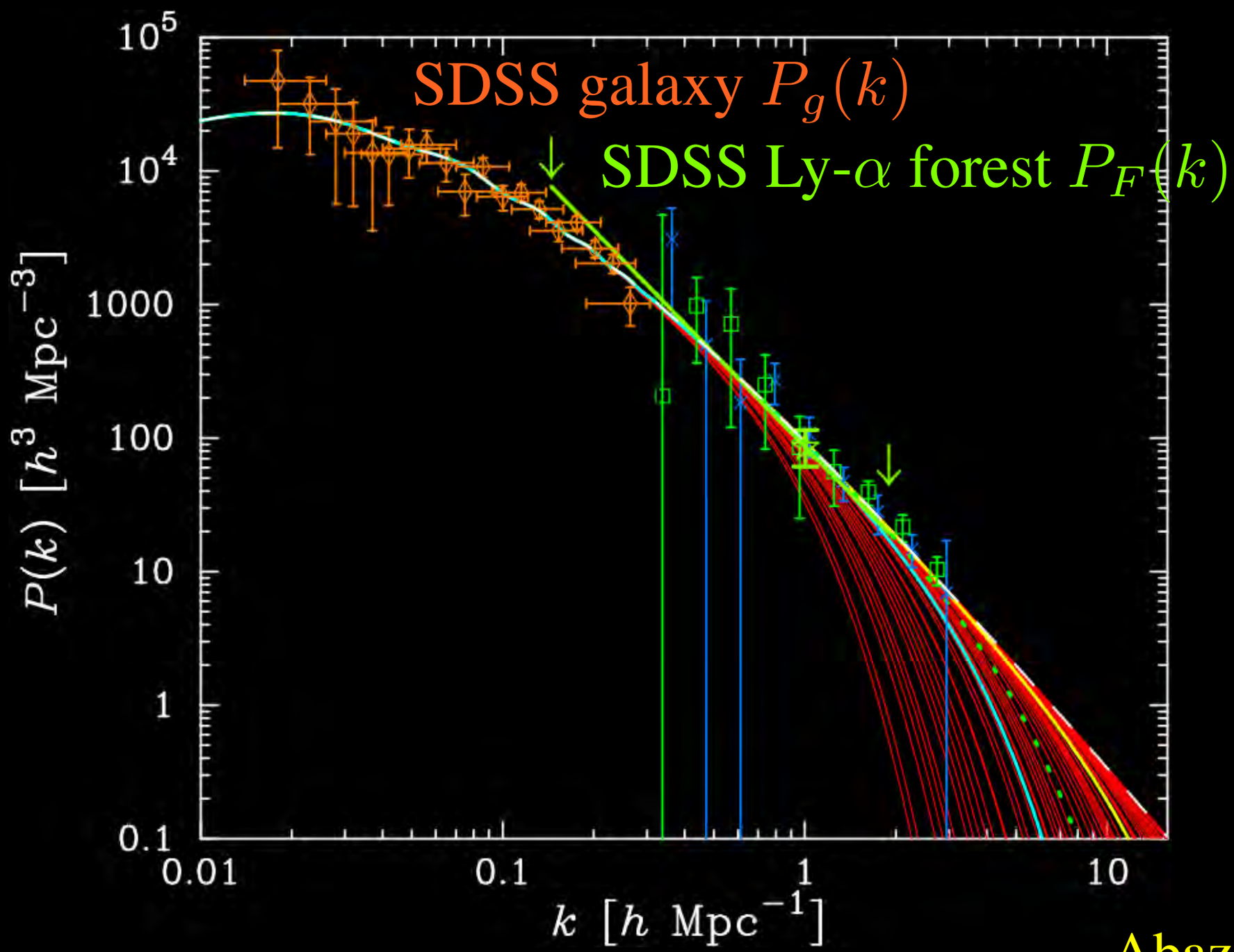

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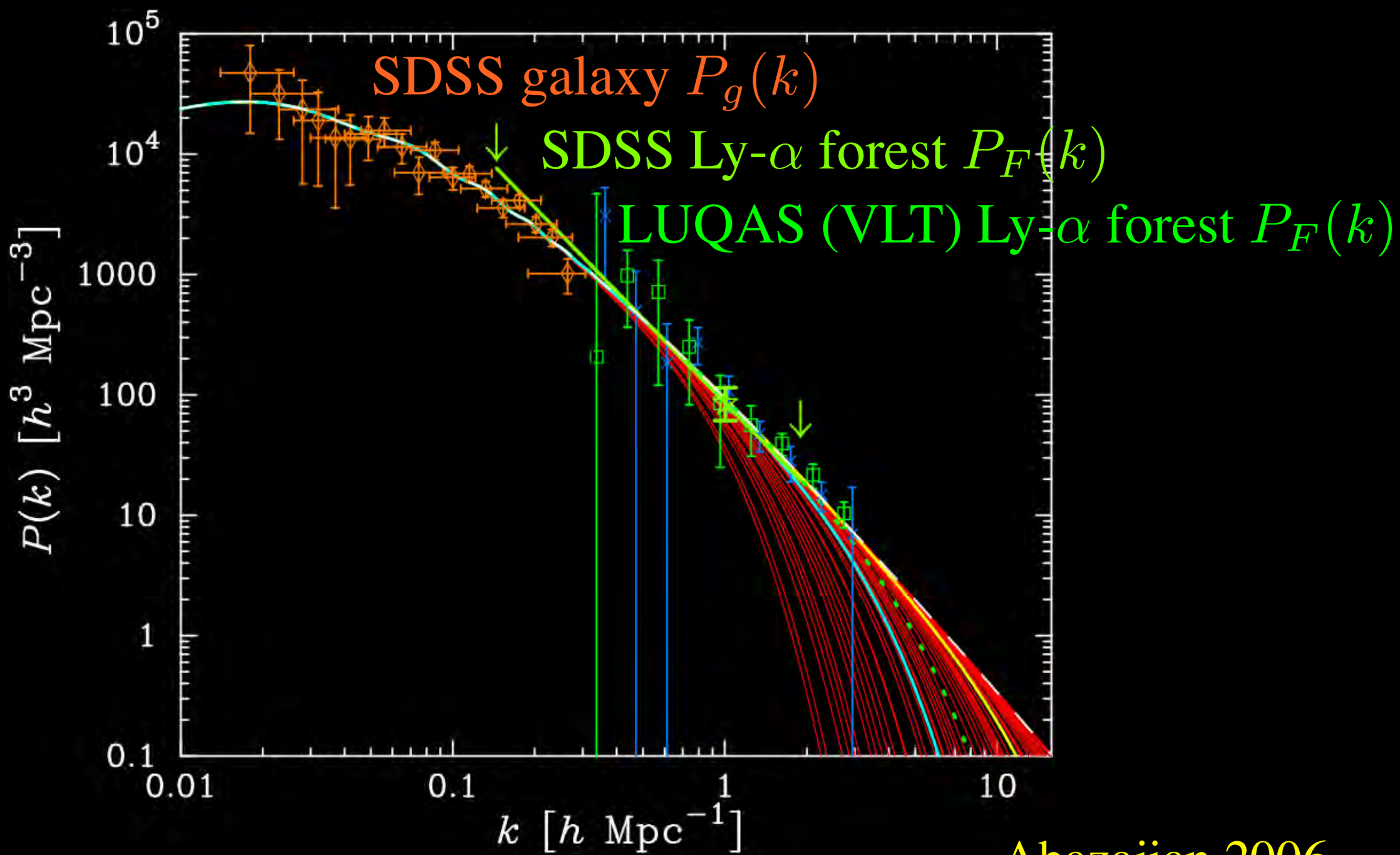

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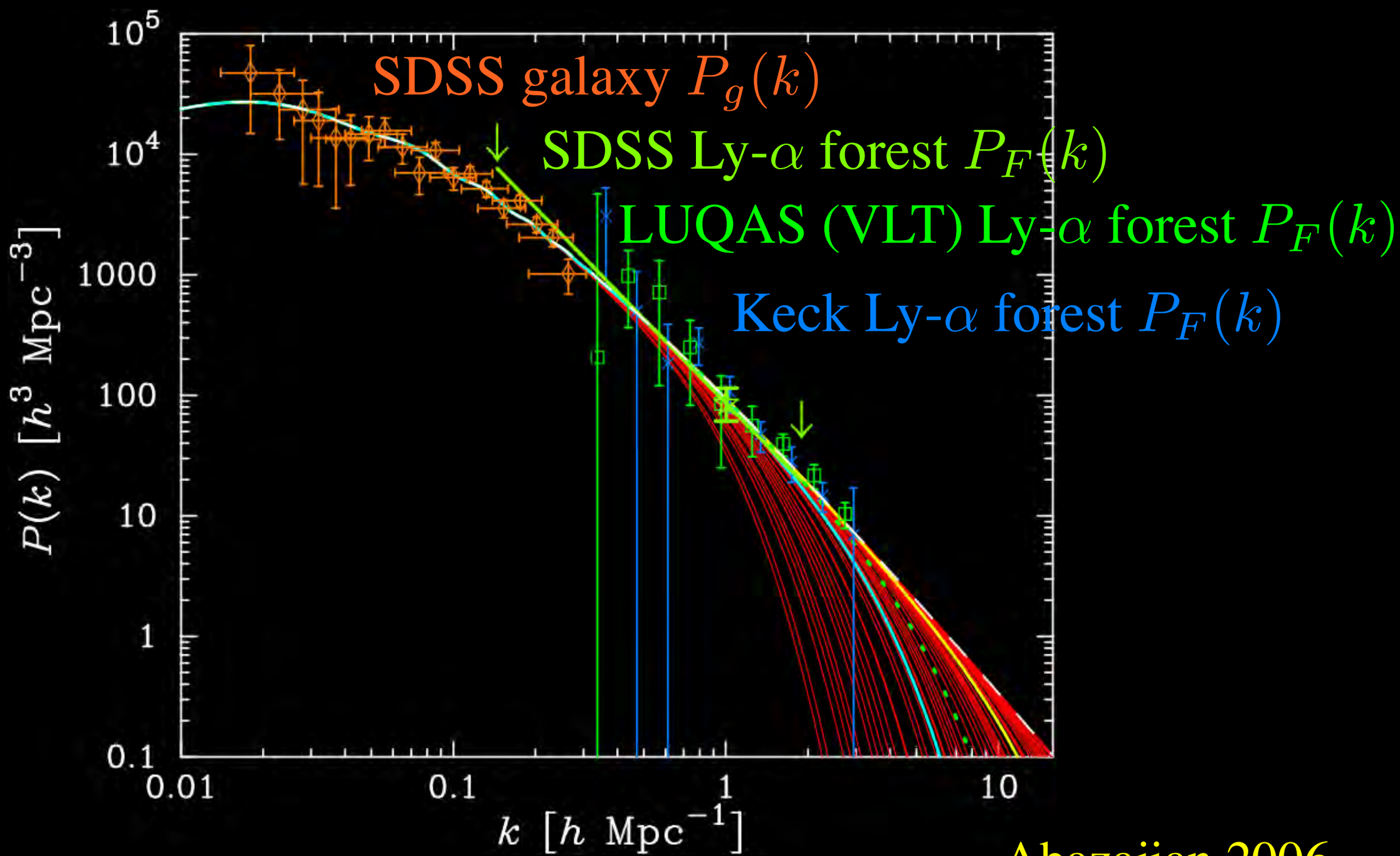

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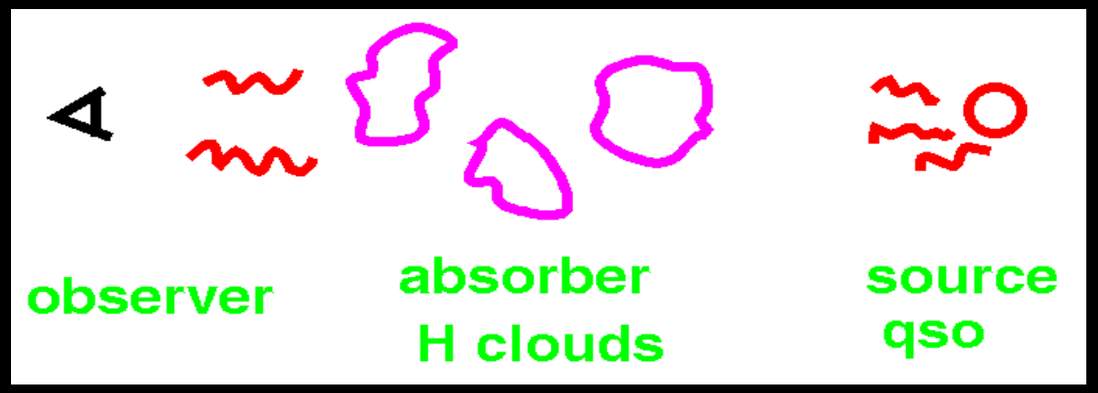
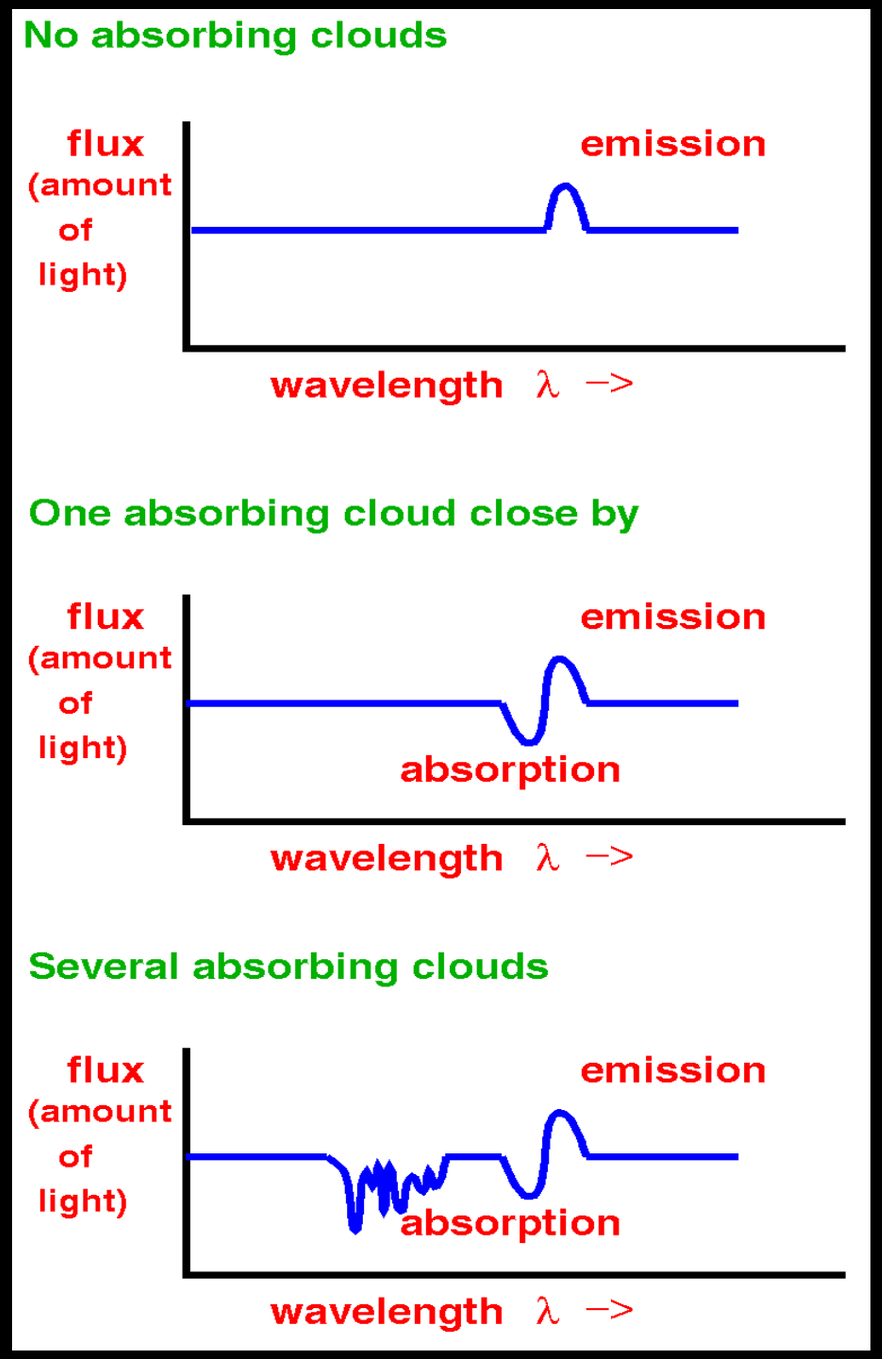
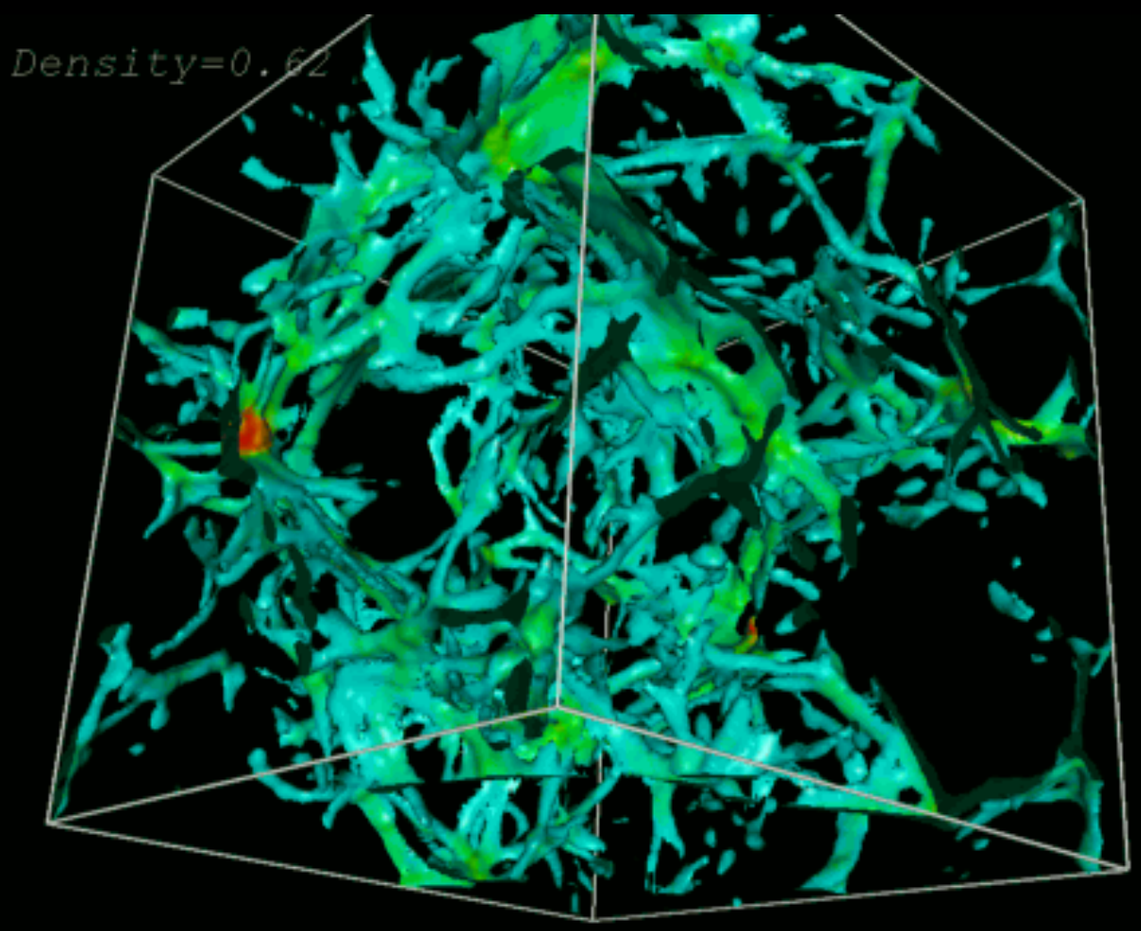
Lyman-α forest: Powerful & Challenging

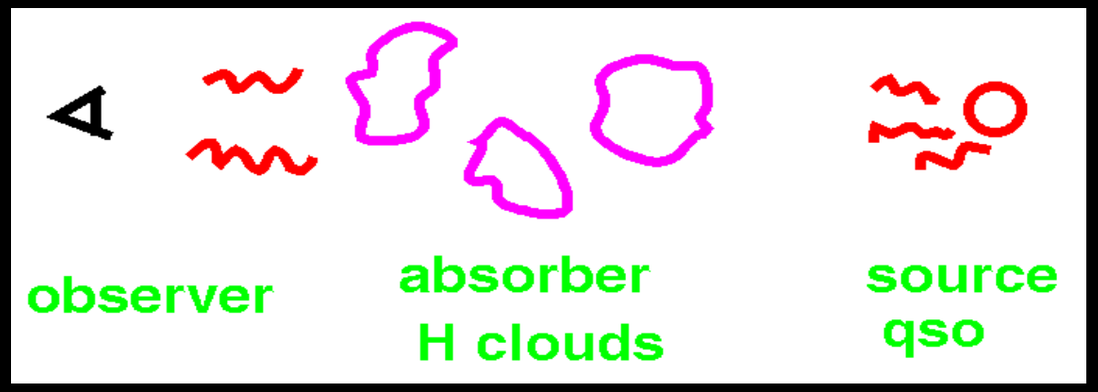


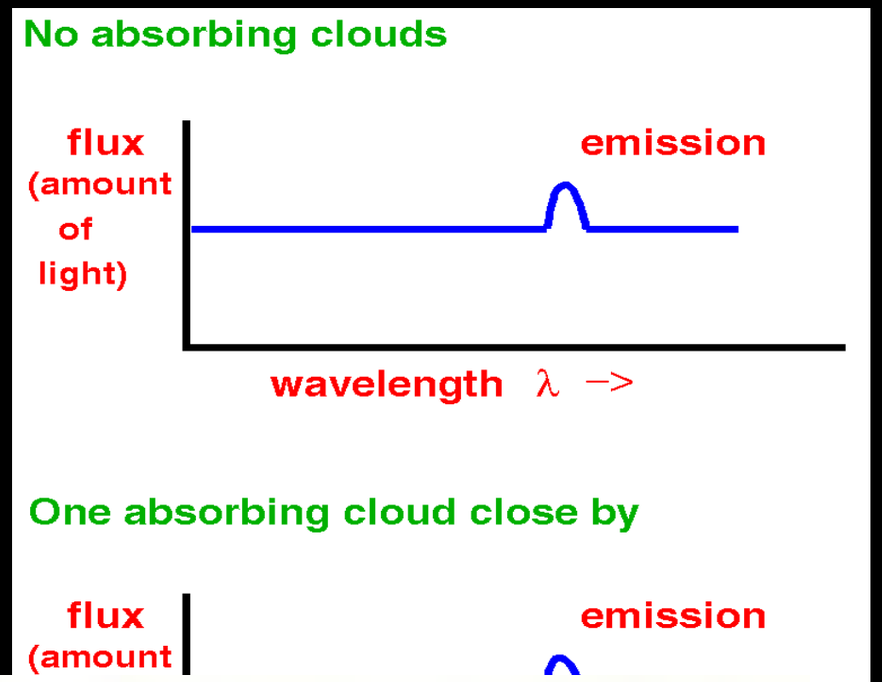


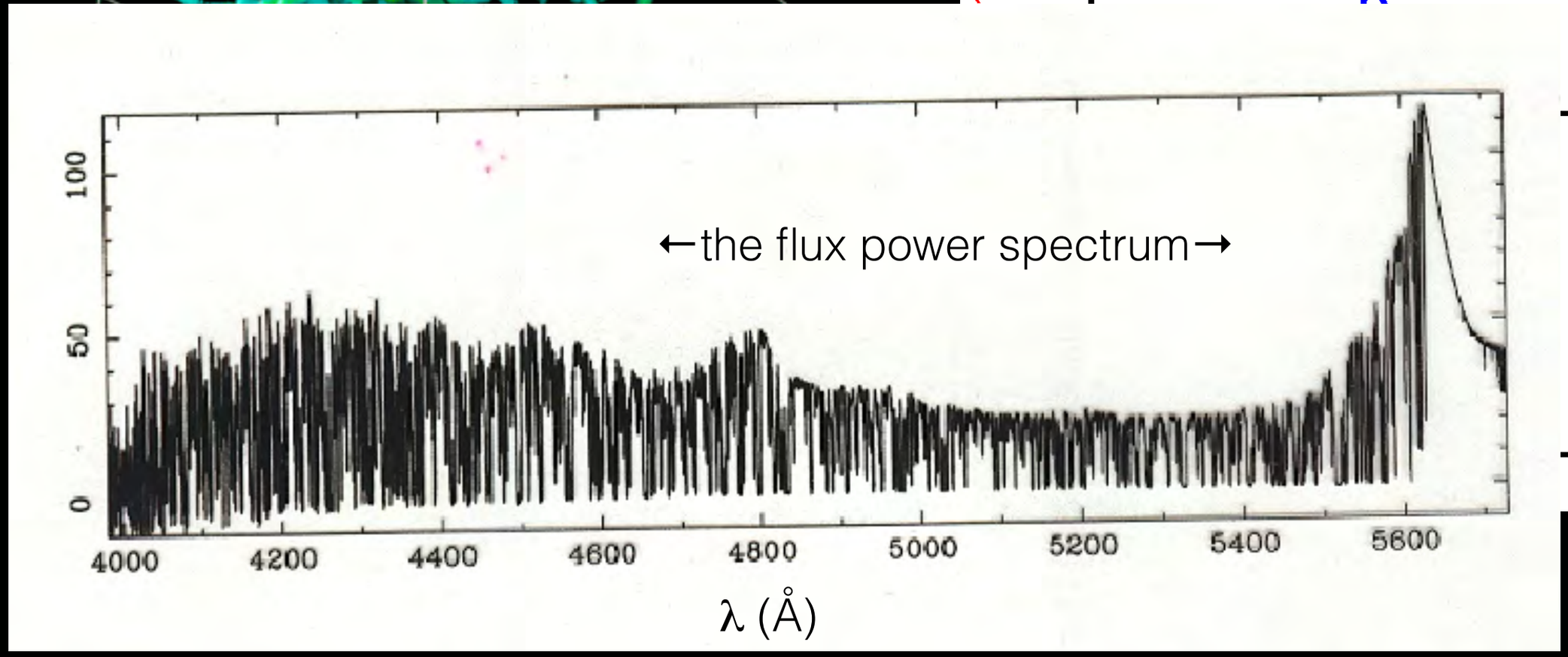


J. Shalf, Y. Zhang (UIUC) et al., GCCC

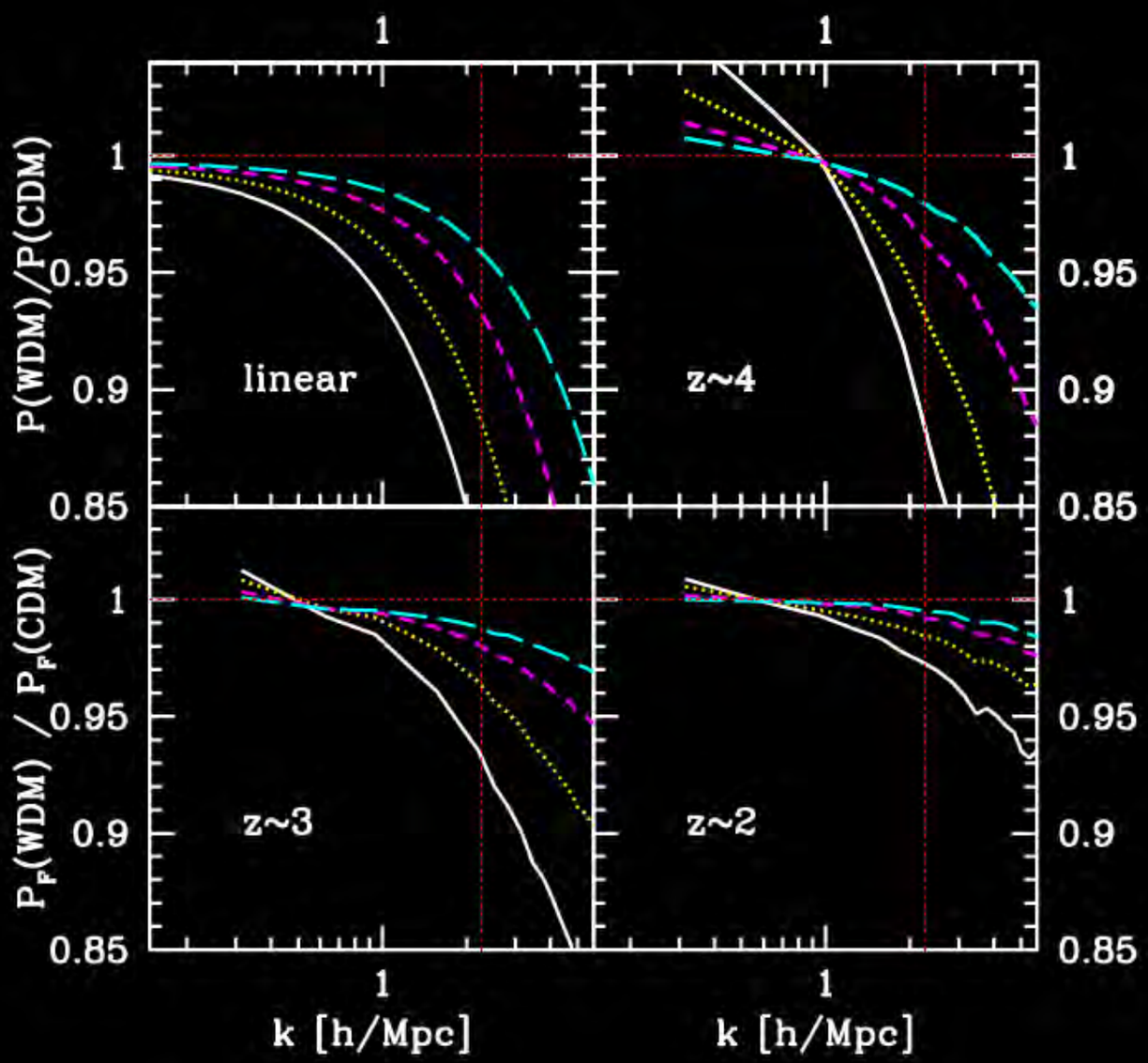
Lyman-α forest: Powerful & Challenging

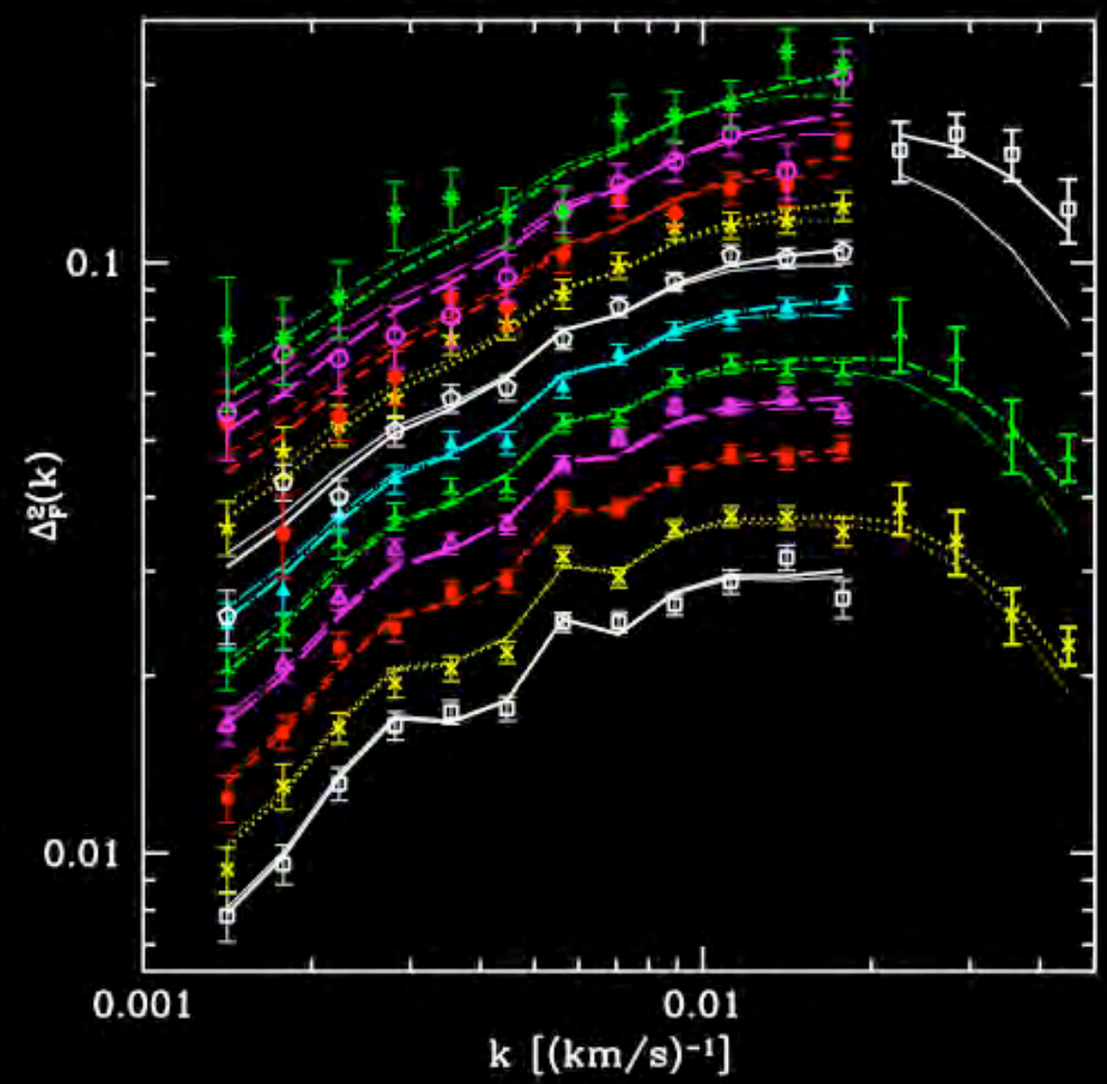






Lyman-alpha Forest Constraints on CDM





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

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

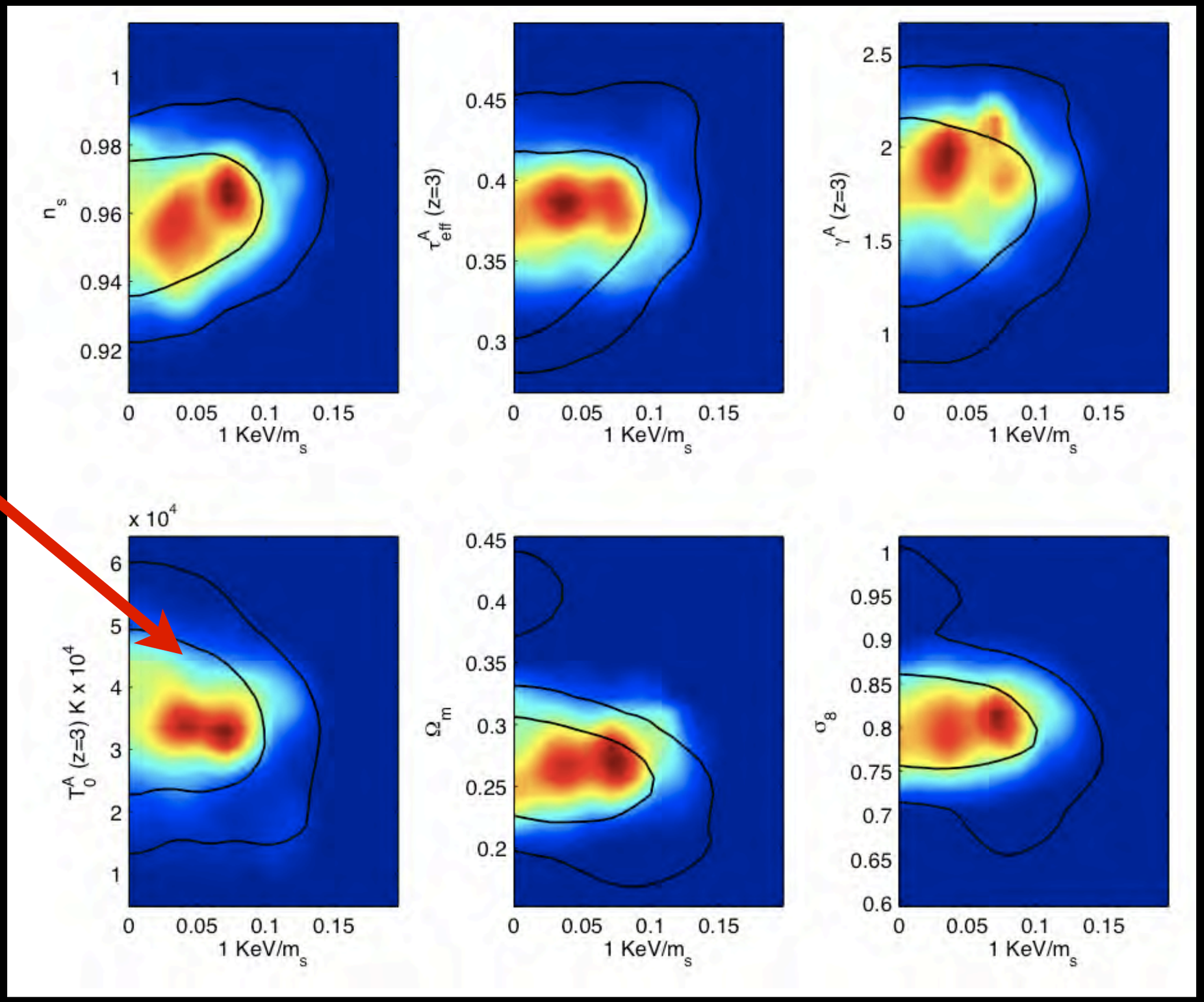
$m_s > 12.1$ keV (SDSS $P_F(k)$ + VLT LUQAS data; Boyarsky et al 2008)

All Depend on the McDonald et al. (2006) SDSS $P_F(k)$ Measurement

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

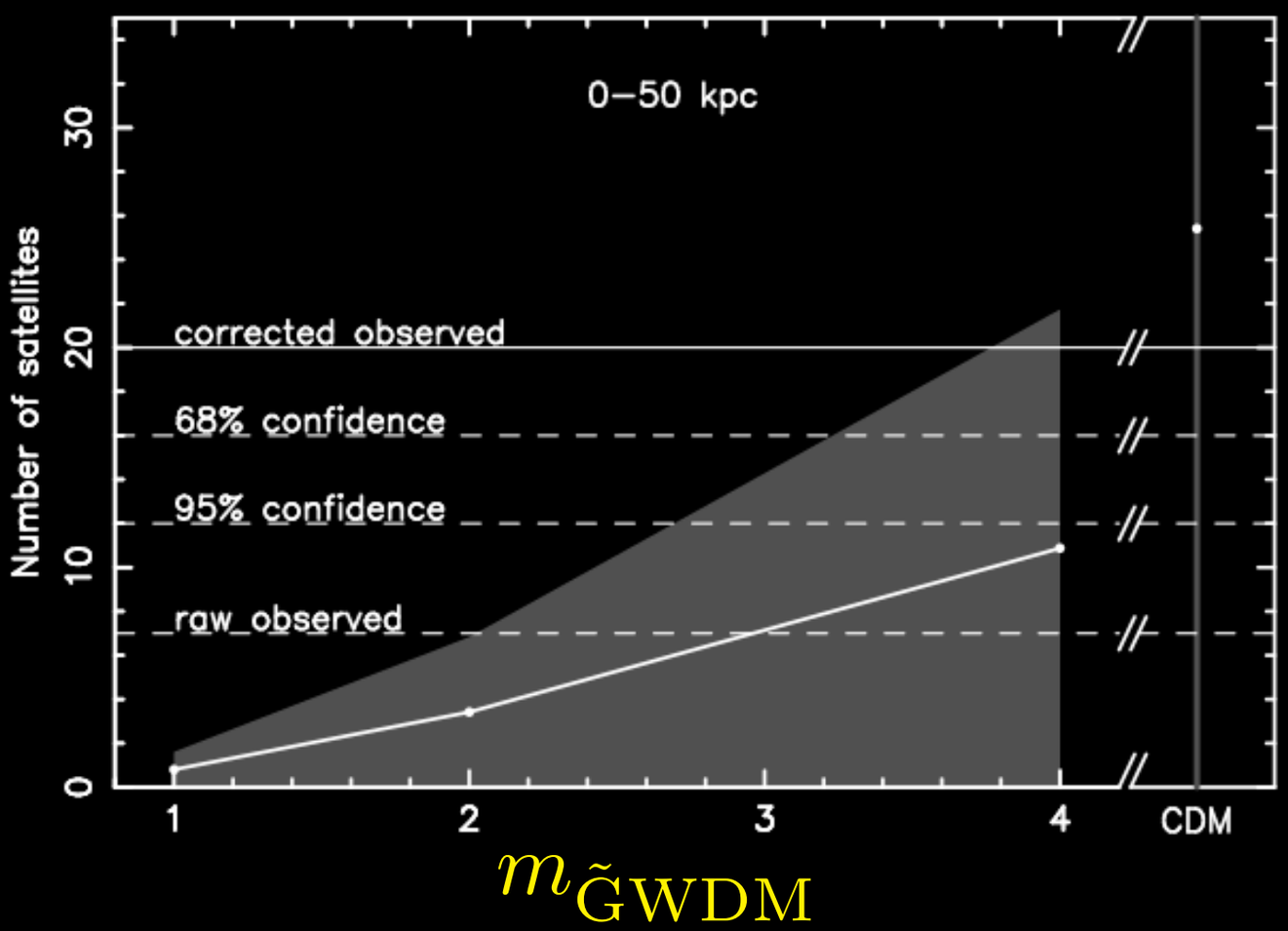
TABLE II. Summary of known Milky Way satellites.

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

Polisensky & Ricotti (2011)

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



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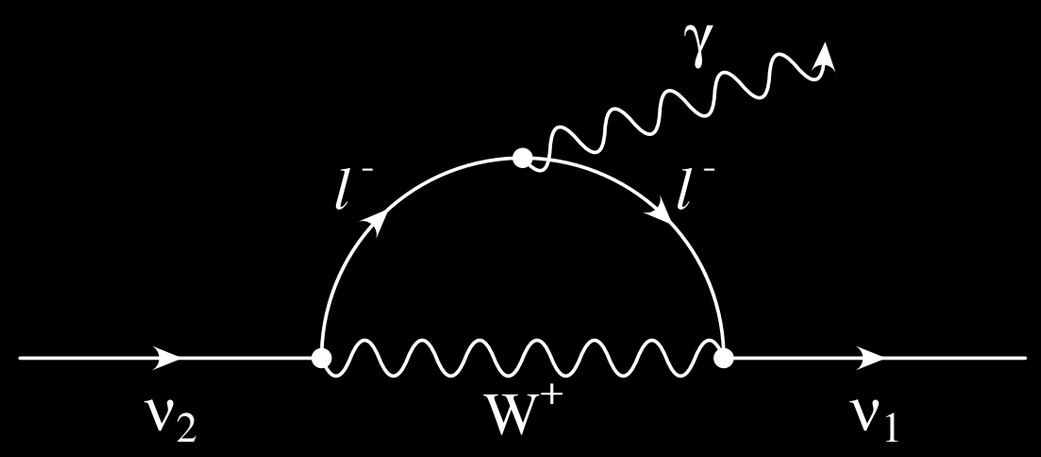
Polisensky & Ricotti (2011)

Radiative Decay in the X-ray

Pal & Wolfenstein 1981



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

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

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

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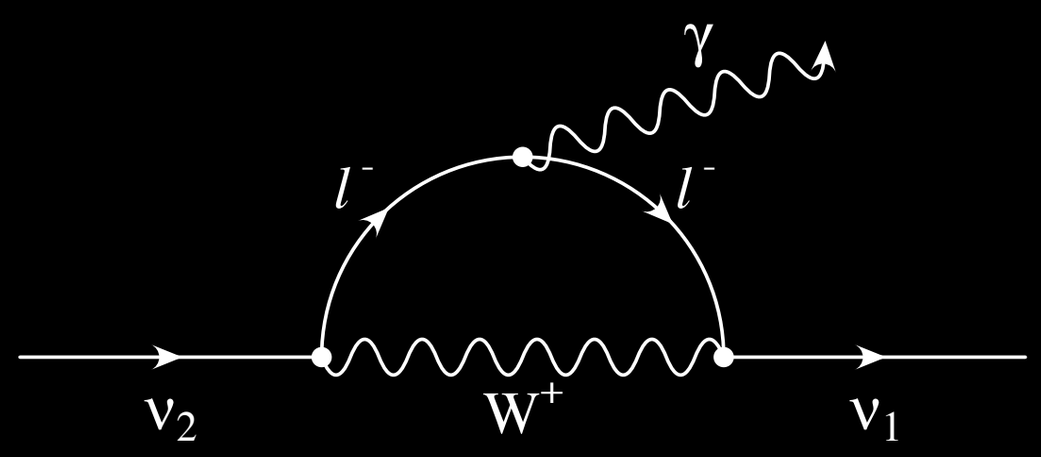
Pal & Wolfenstein 1981



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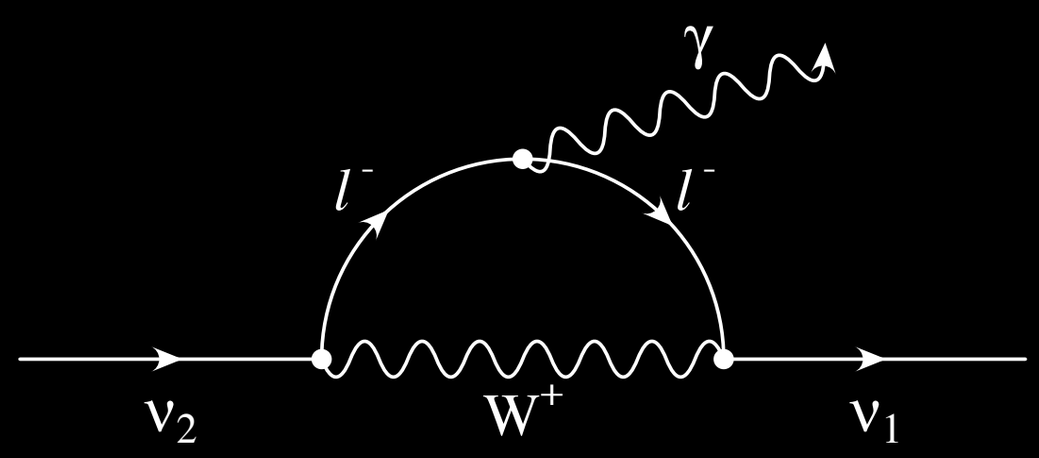

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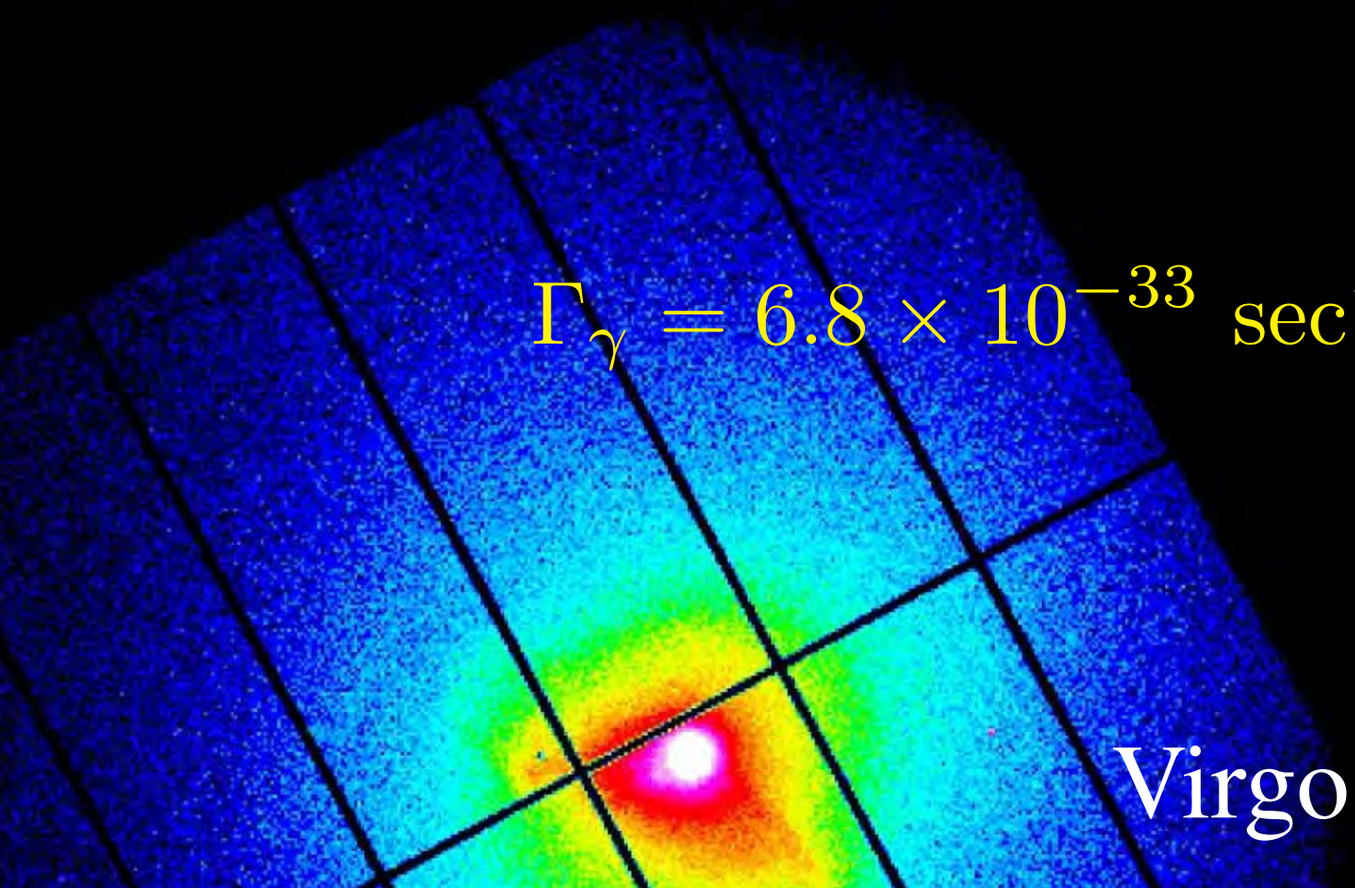
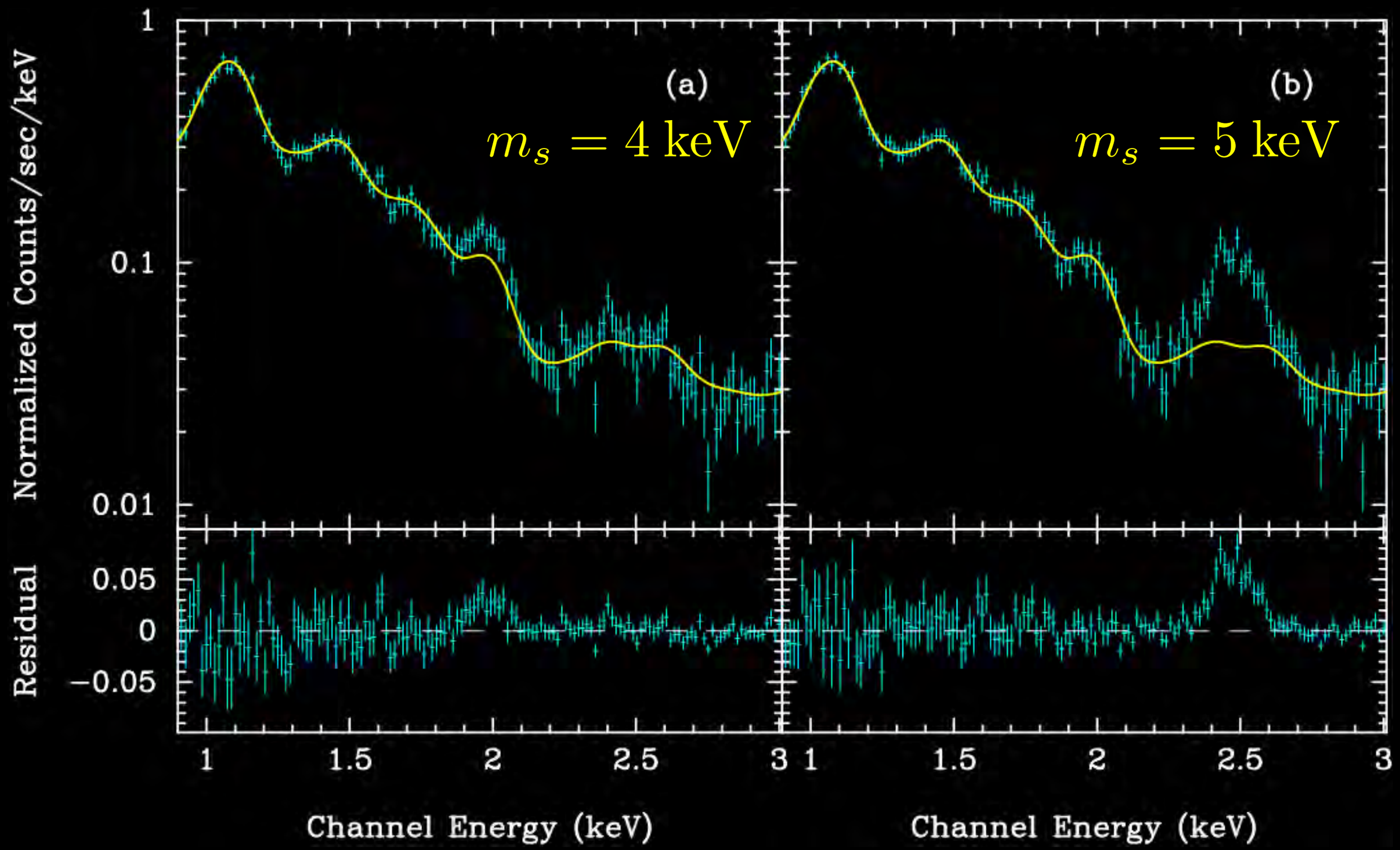


Virgo Cluster: 10^{70} DM particles

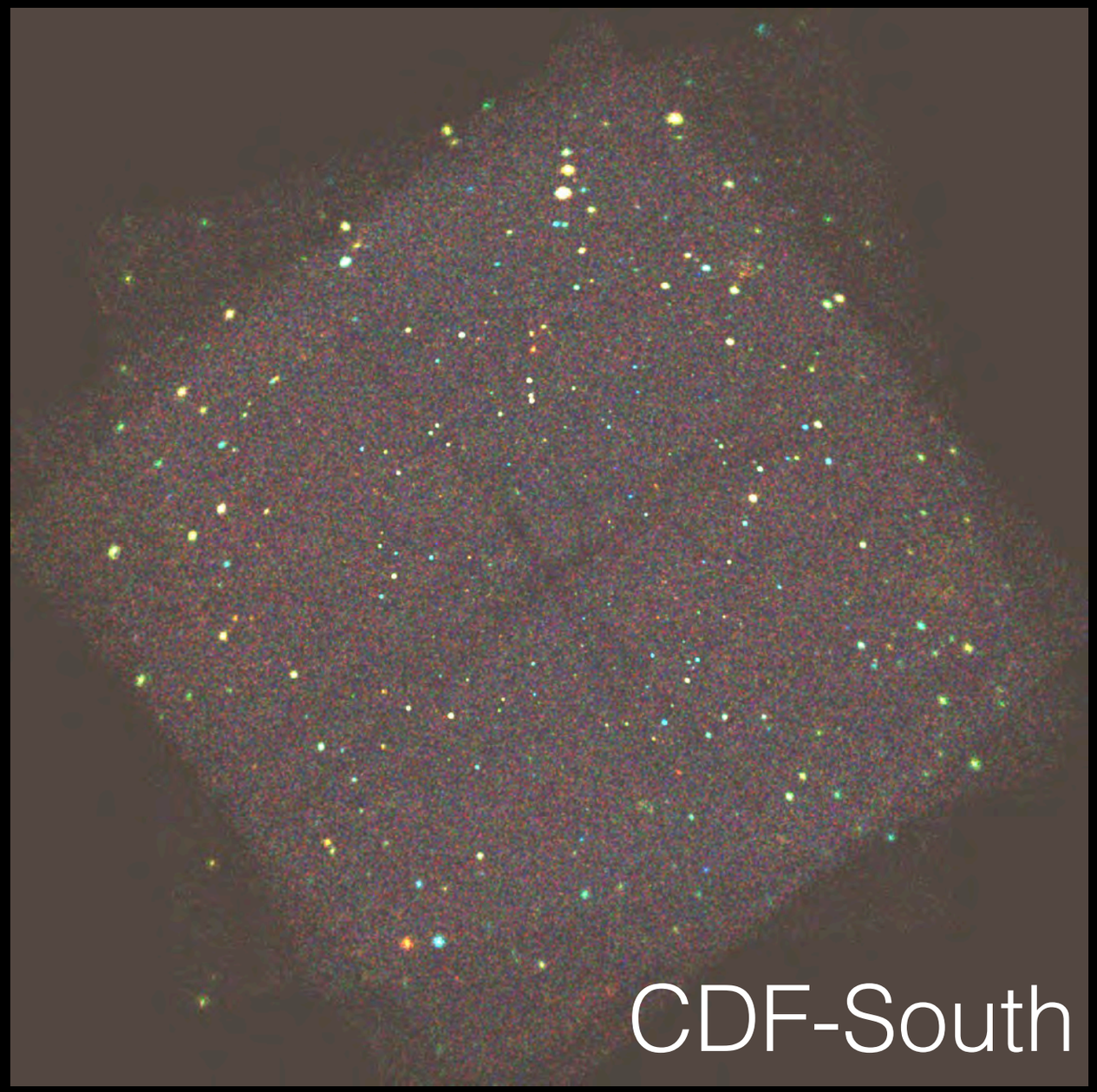
Upper Mass Limit:

X-ray observations of Virgo



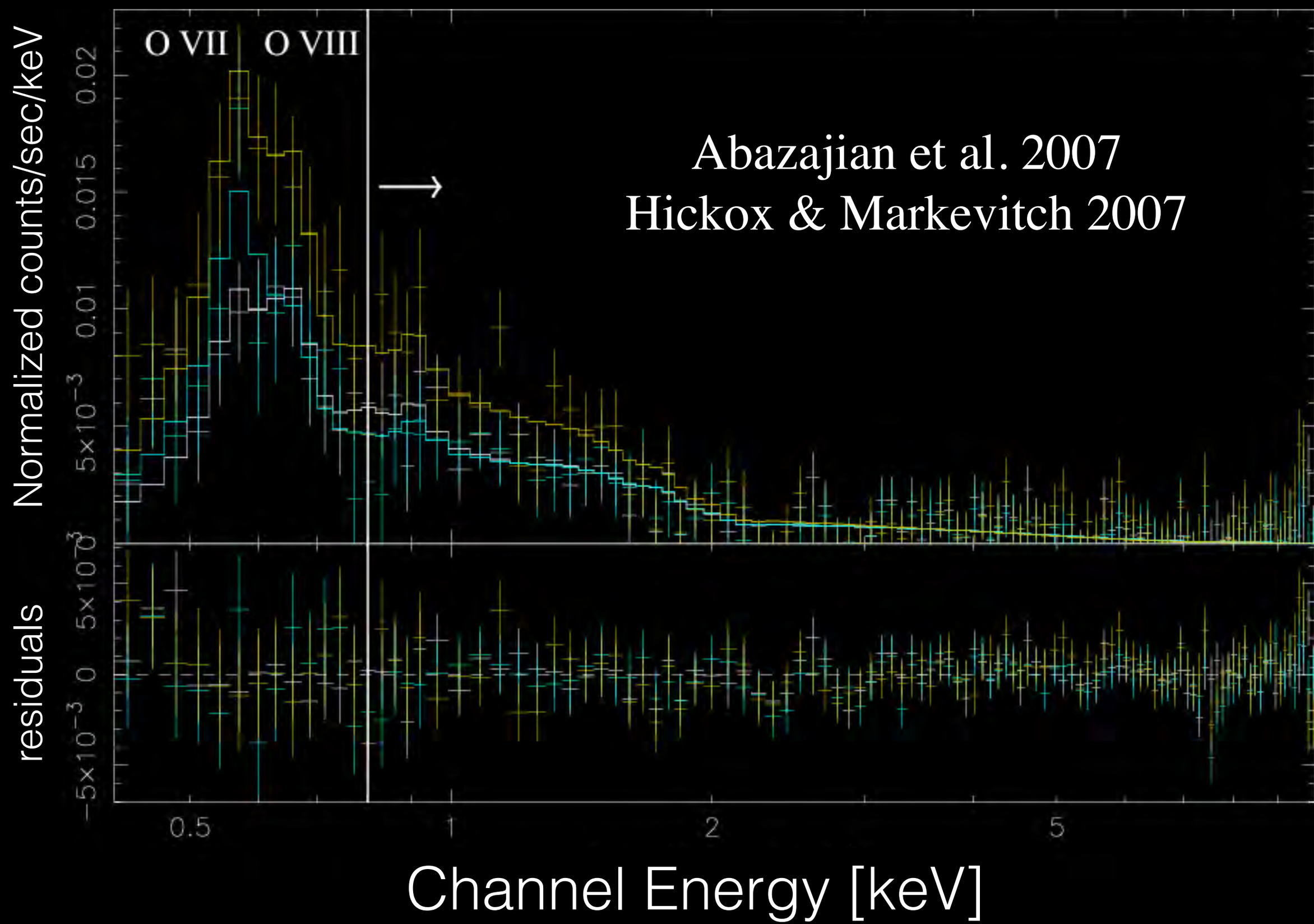
Abazajian, Fuller & Tucker 2001

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



Hickox & Markevitch 2006, 2007

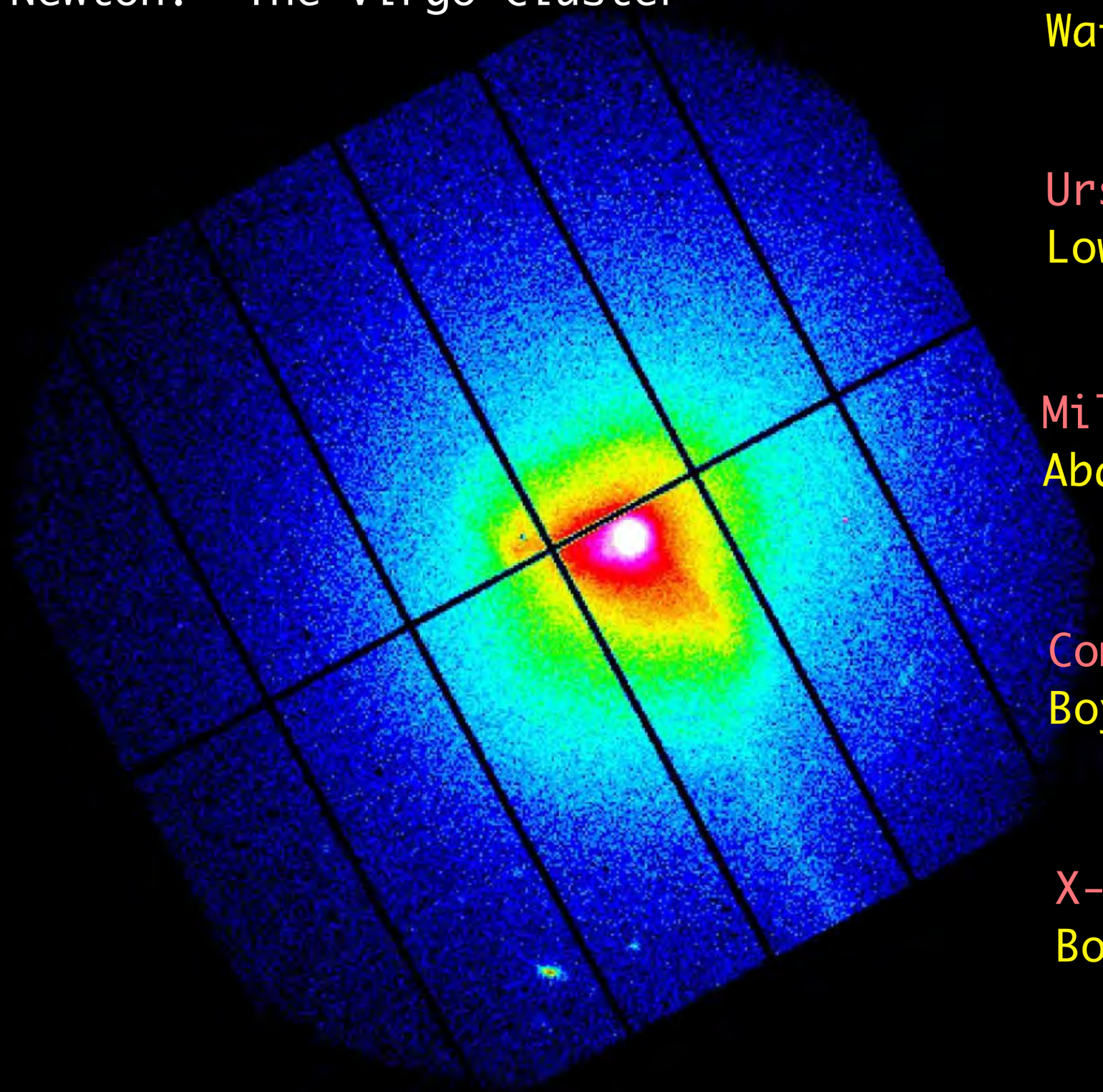
The (Unresolved) Cosmic X-ray Background



Abazajian et al. 2007
Hickox & Markevitch 2007

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

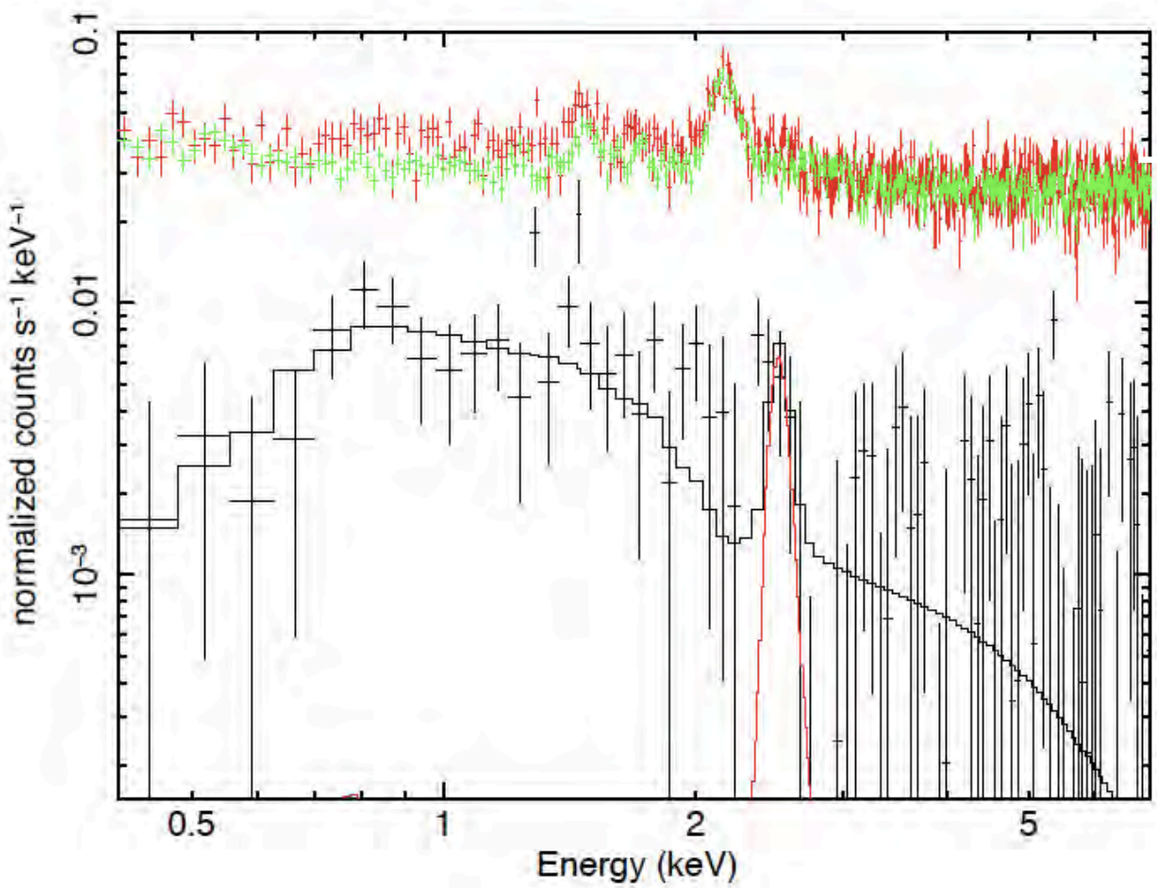
$$m_s < 8.9 \text{ keV}$$

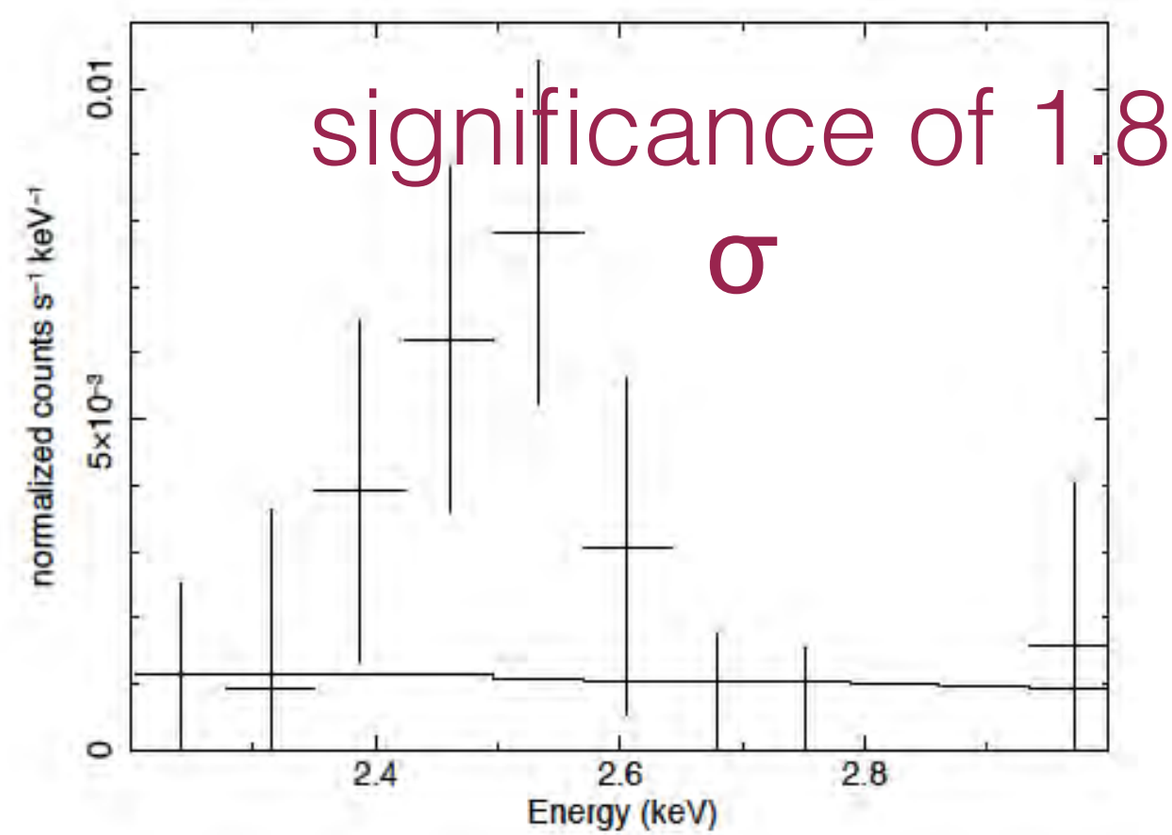
The Detection of a WDM Sterile Neutrino?

Dark Matter Search Using *Chandra* Observations of Willman 1, and a Spectral Feature Consistent with a Decay Line of a 5 keV Sterile Neutrino

Michael Loewenstein[1,2], Alexander Kusenko[3,4]

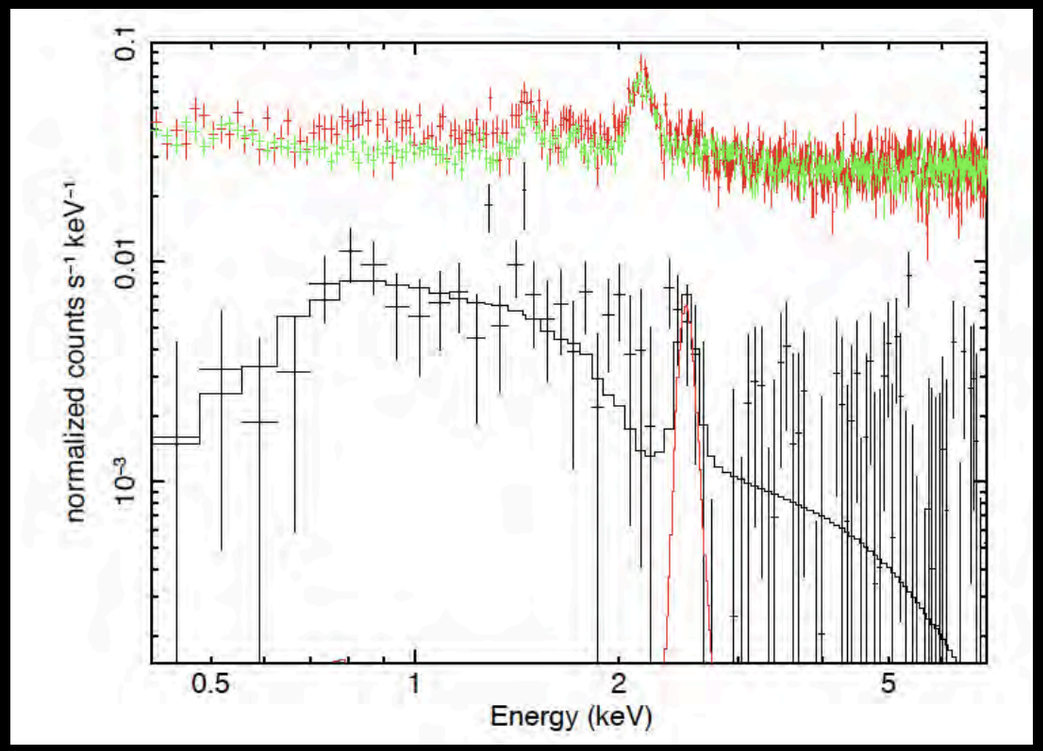
ApJ 2010, arXiv:0912.0552v1

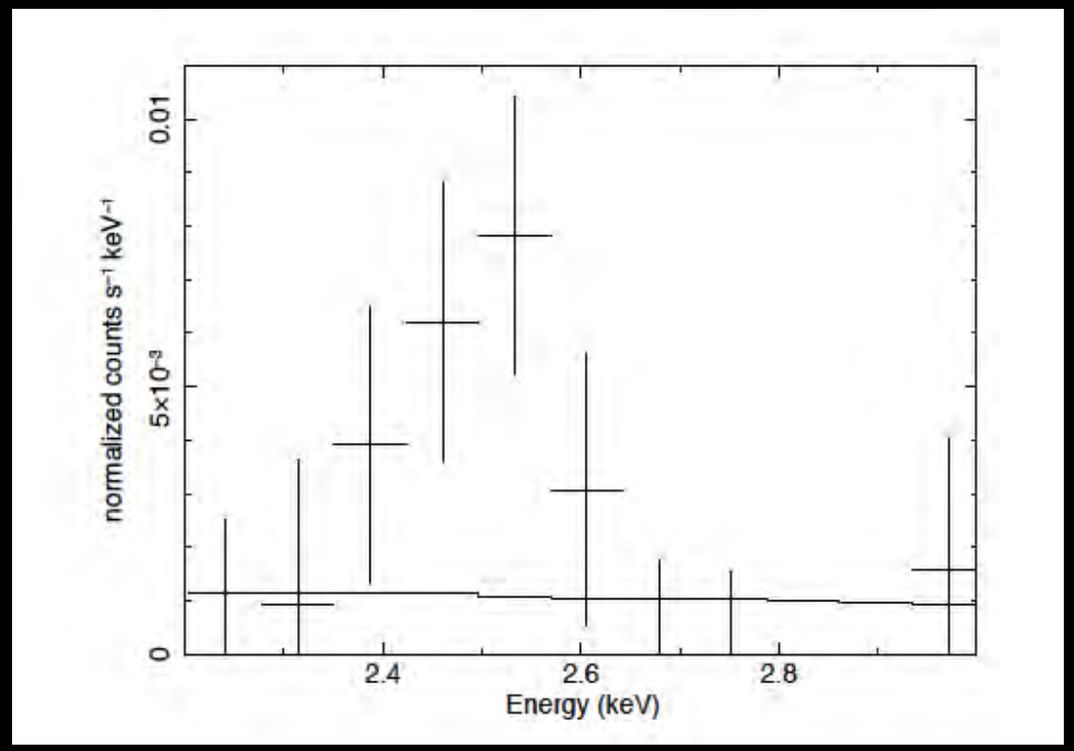




Method of subtraction of the background could be revealing this line (Mirabel & Nieto, arXiv:1003.3745)

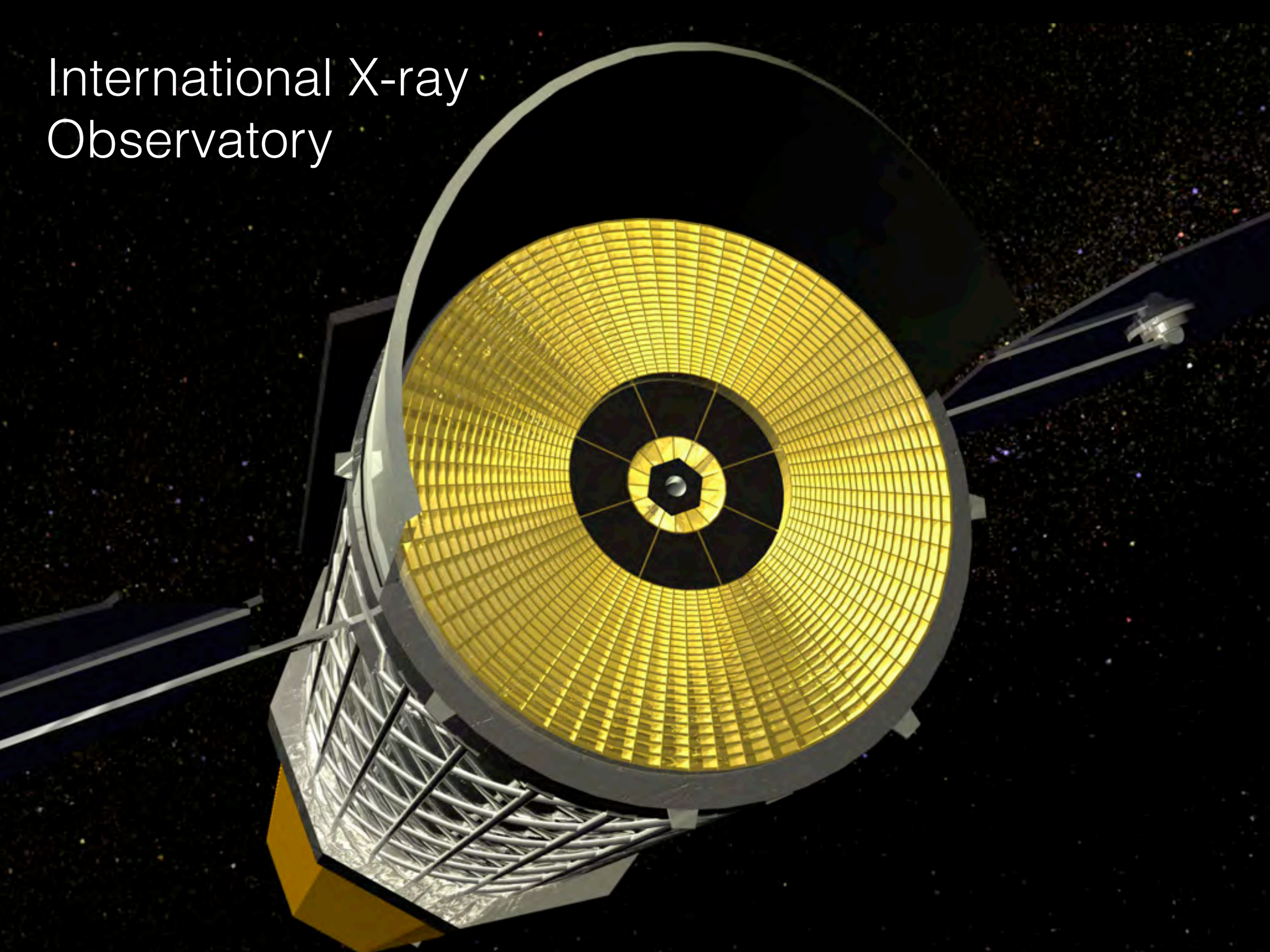
Claimed ν_s line: unaddressed problems...



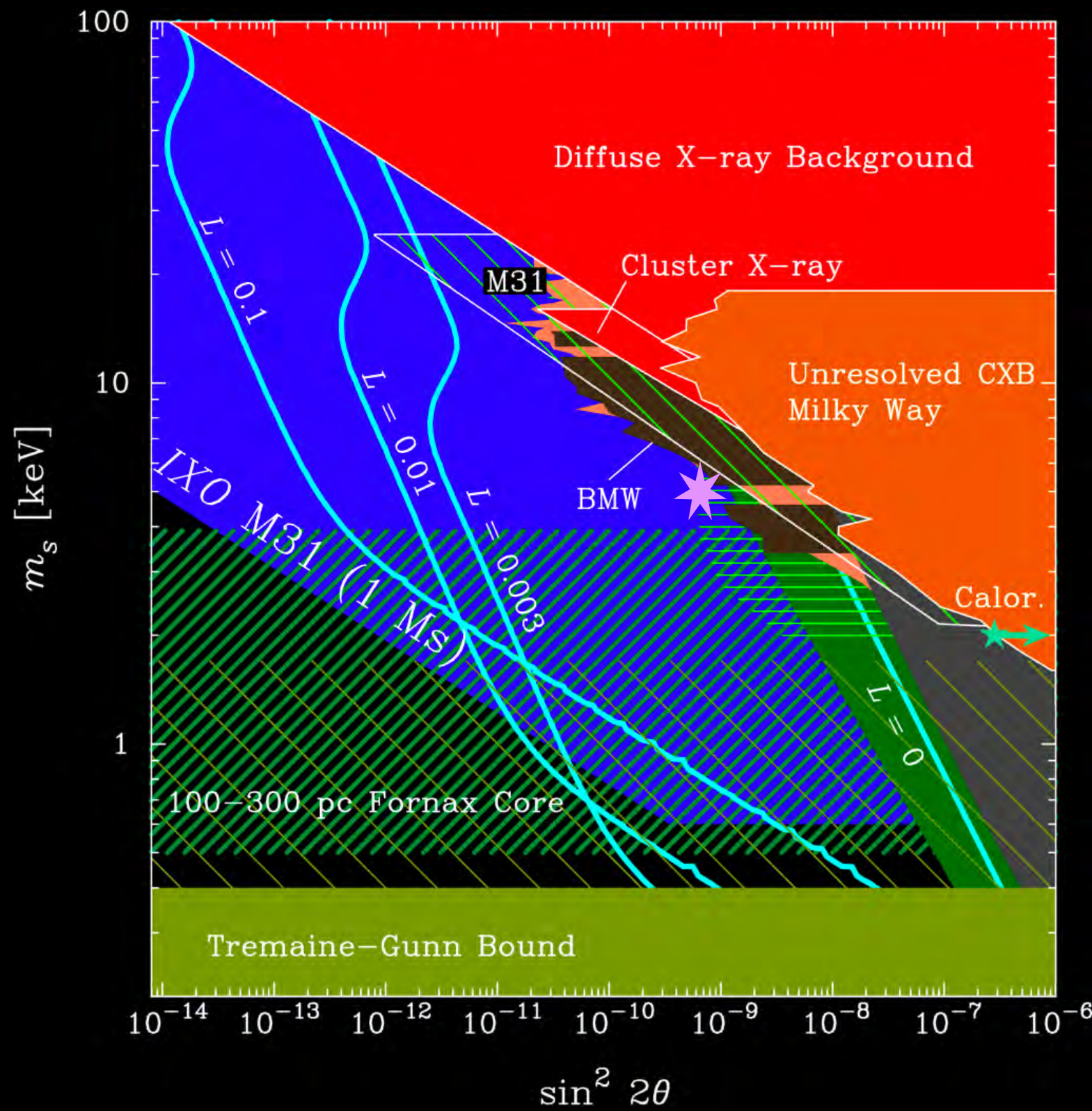


- One should see a line in the noise in a 0.2 keV resolution spectrum from 1 - 7 keV at this level of statistical significance (2.8 σ)
- Sulfur Kα and Kβ lines present in this region
- Subtraction of the background can produce a similar feature (Mirabel & Nieto, arXiv: 1003.3745)
- Presence of feature is inconsistent at > 14σ with limits from Andromeda (M31) observations, even when maximizing Willman I DM profile and minimizing that from M31

International X-ray Observatory

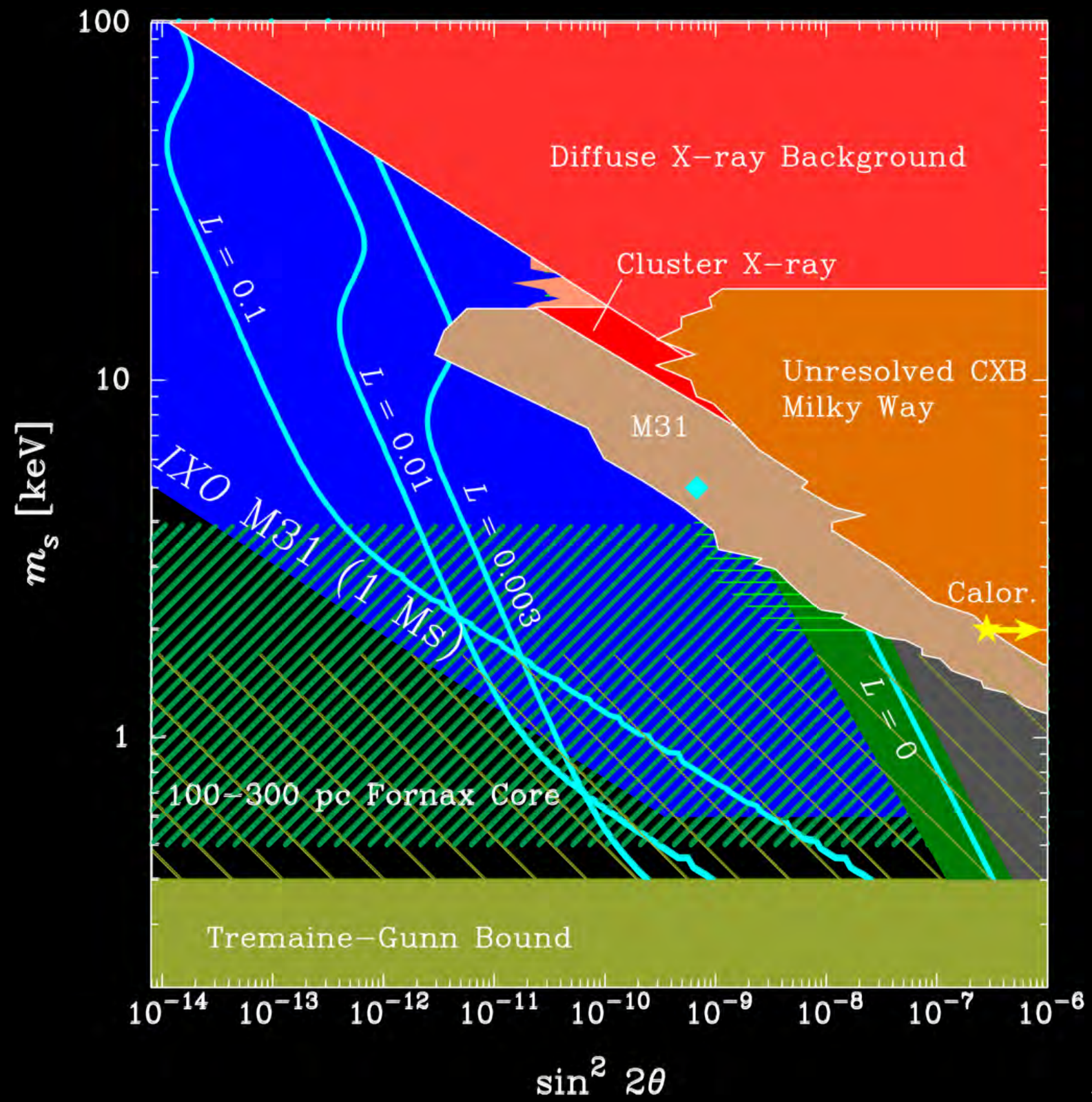


Sterile Neutrino Dark Matter Parameter Space Summary



Abazajian 2011

Sterile Neutrino Dark Matter Parameter Space Summary

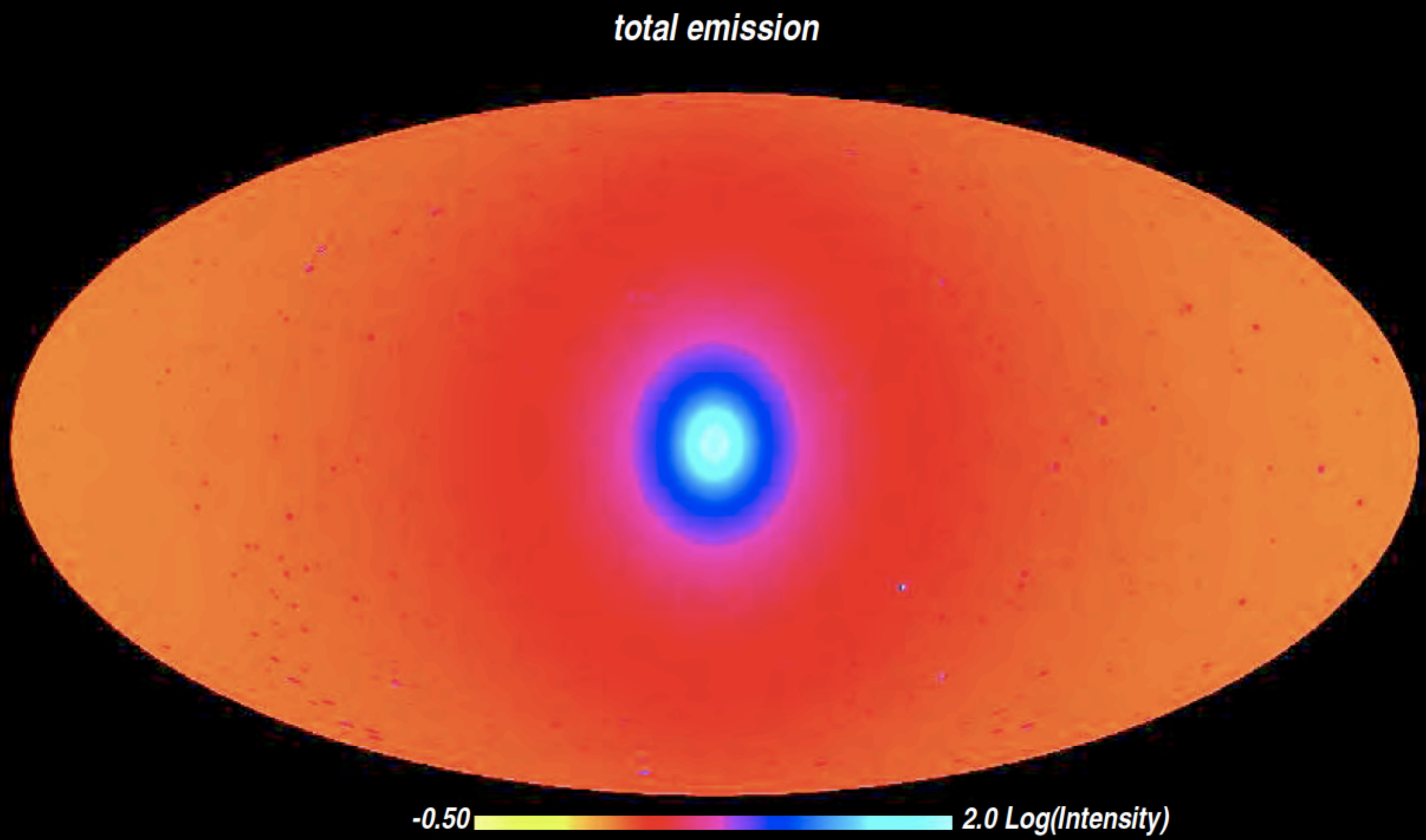


Abazajian 2011

Not-So-Deviant Dark Matter Candidates

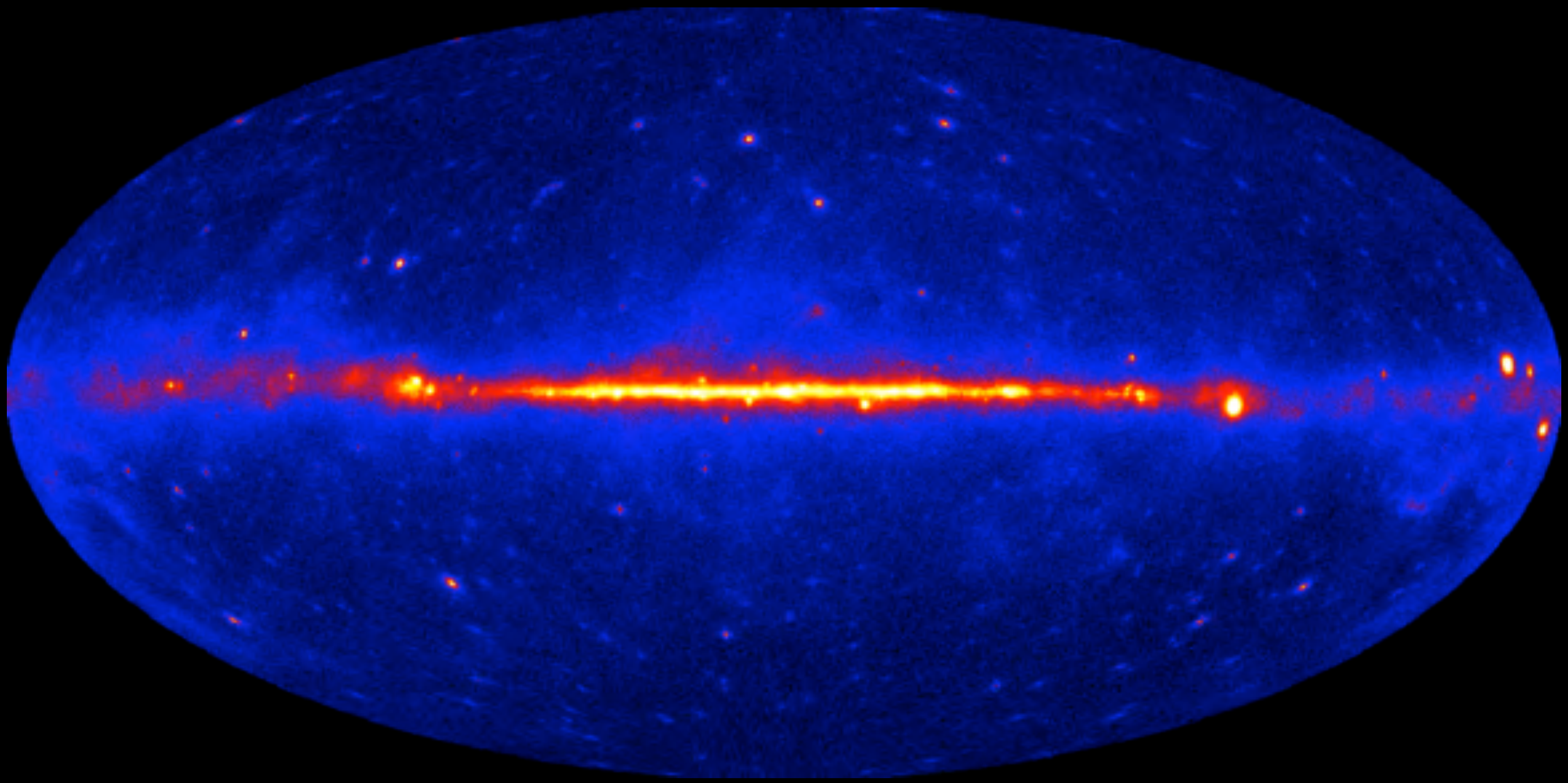
CDM to γ-ray: the potential dark matter sky

$$X_{\rm DM} + X_{\rm DM} \to Y^+ + Y^- ({\rm brems}), \quad X_{\rm DM} \to \gamma + \gamma$$

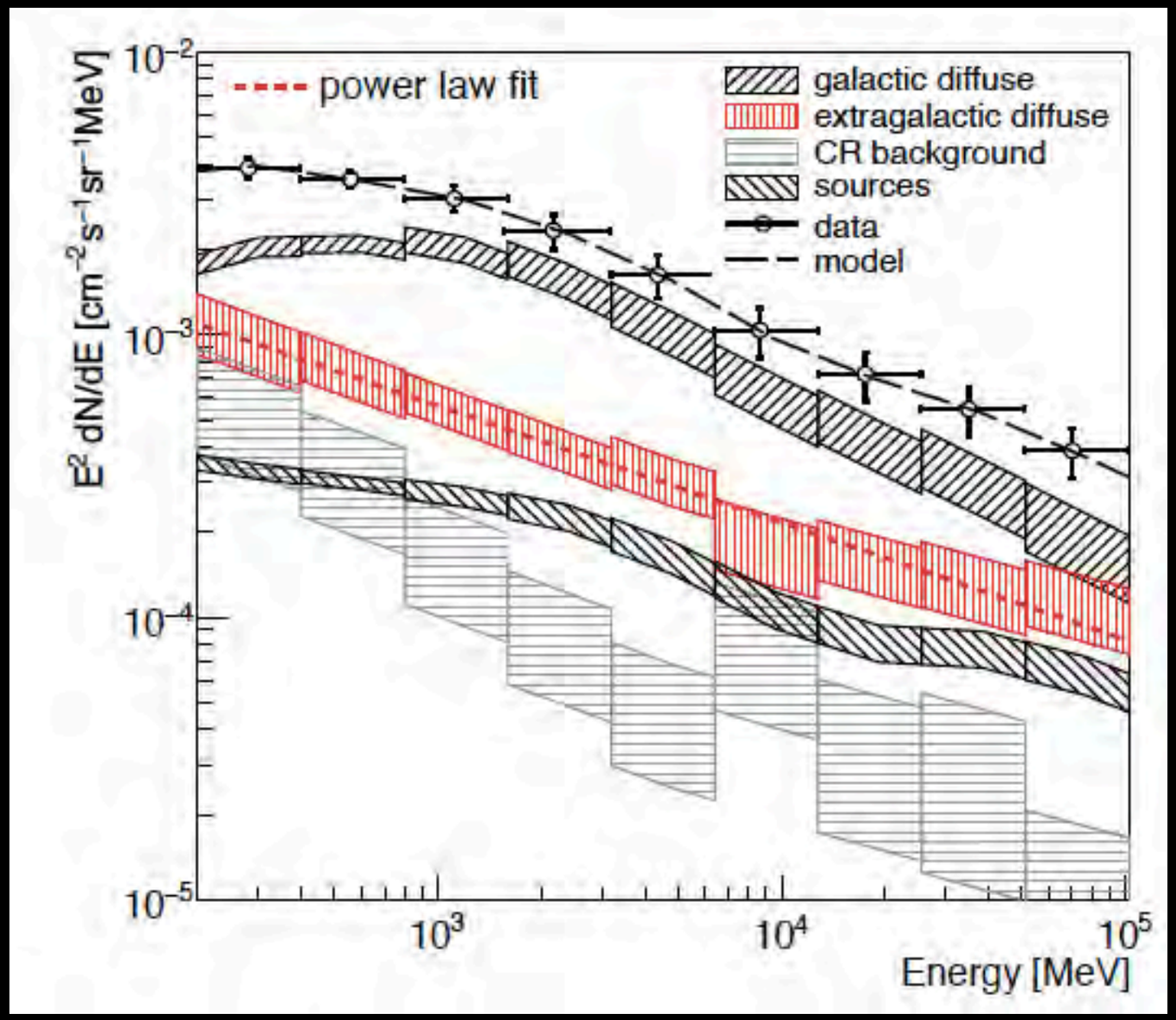


Springel et al 2008

The Observed Fermi-LAT Gamma-Ray

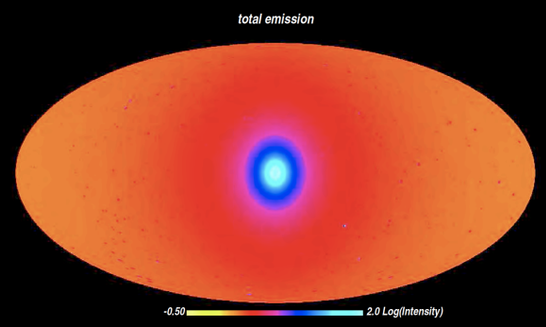


The Observed Isotropic Diffuse γ-ray Spectrum



The Fermi-LAT collaboration (A.A. Abdo et al.) JCAP, arXiv:1002.3603

DM Annihilation: Galactic and Extragalactic Contributions



Galactic:

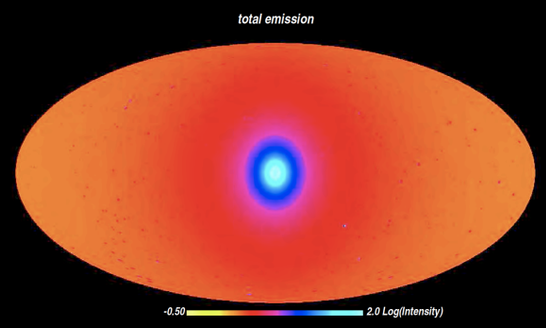
$$\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma_A v \rangle}{2} \frac{\mathcal{J}_{\Delta\Omega}}{\mathrm{J}_0} \frac{1}{\Delta\Omega_{\mathrm{obs}} m_\chi^2} \frac{dN_\gamma}{dE}$$

$$\mathcal{J}(b,\ell) = \mathrm{J}_0 \int_{x_{\min}}^{x_{\max}} \rho^2 \left(r_{\mathrm{gal}}(b,\ell\,,x) \right) dx$$

Extragalactic:

$$\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma_A v \rangle}{2} \frac{c}{\Delta\Omega_{\mathrm{obs}} H_0} \frac{(f_{\mathrm{DM}}\Omega_m)^2 \rho_{\mathrm{crit}}^2}{m_\chi^2} \int_0^{z_{\mathrm{up}}} \frac{f(z)(1+z)^3}{h(z)} \frac{dN(E')}{dE'} e^{-\tau(z,E')} dz$$

DM Annihilation: Galactic and Extragalactic Contributions



Galactic:

"particle"

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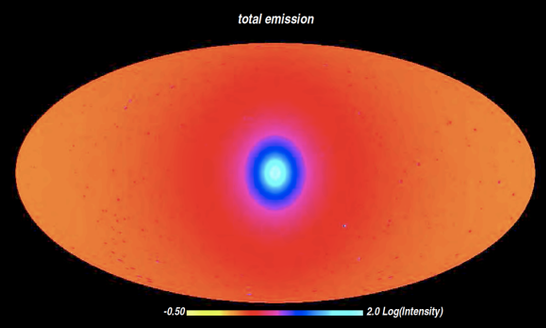

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"astro"

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Extragalactic:

$$\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma_A v \rangle}{2} \frac{c}{\Delta\Omega_{\mathrm{obs}} H_0} \frac{(f_{\mathrm{DM}}\Omega_m)^2 \rho_{\mathrm{crit}}^2}{m_\chi^2} \int_0^{z_{\mathrm{up}}} \frac{f(z)(1+z)^3}{h(z)} \frac{dN(E')}{dE'} e^{-\tau(z,E')} dz$$

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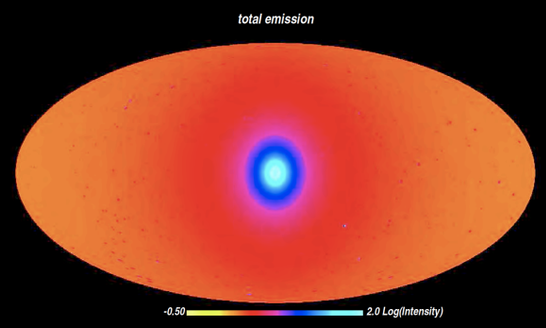

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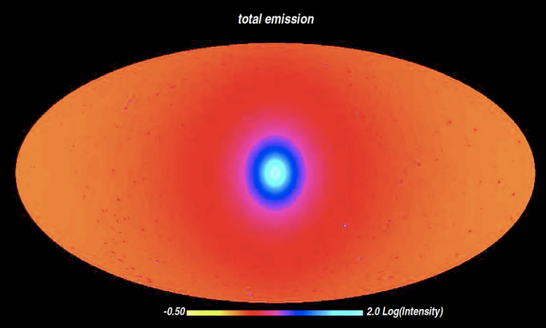

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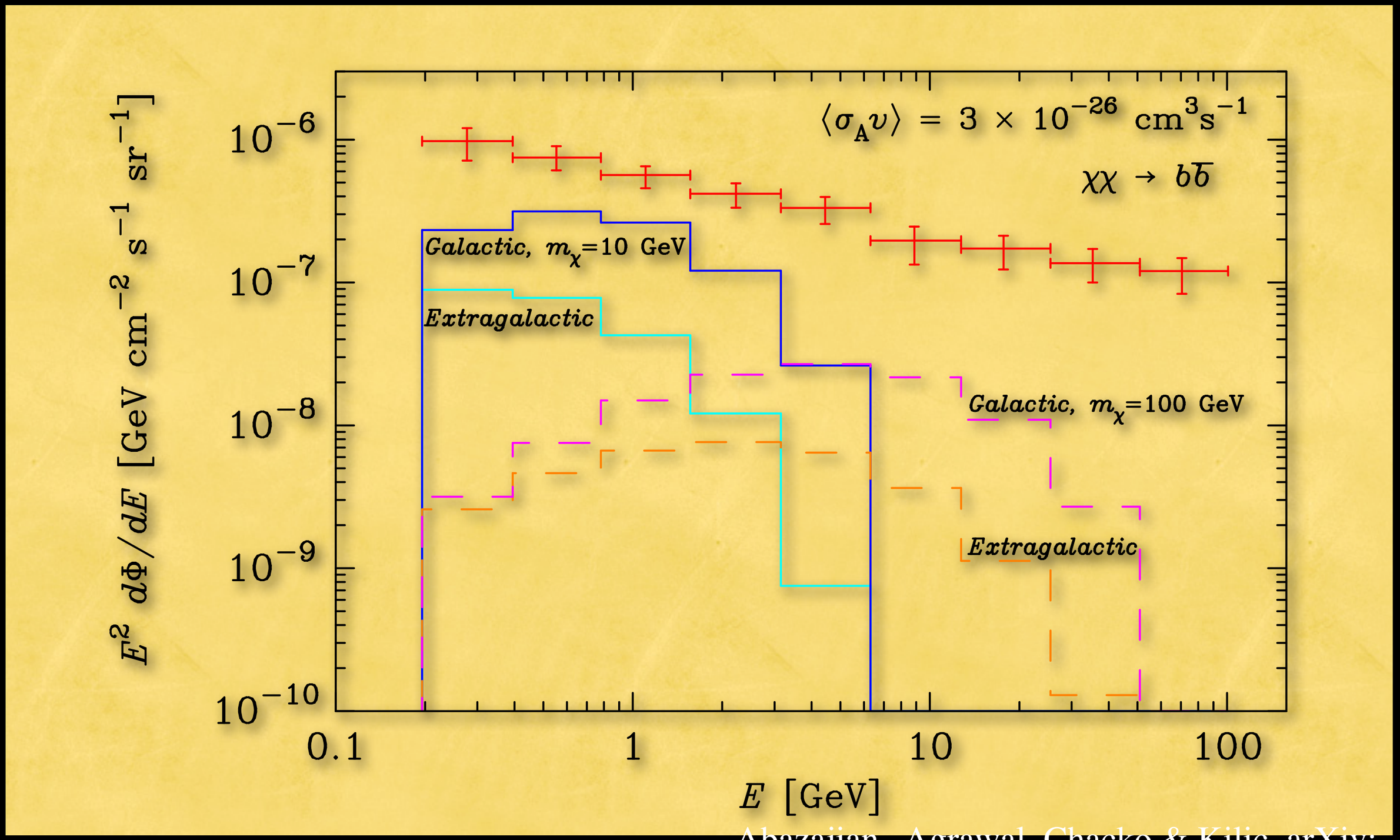
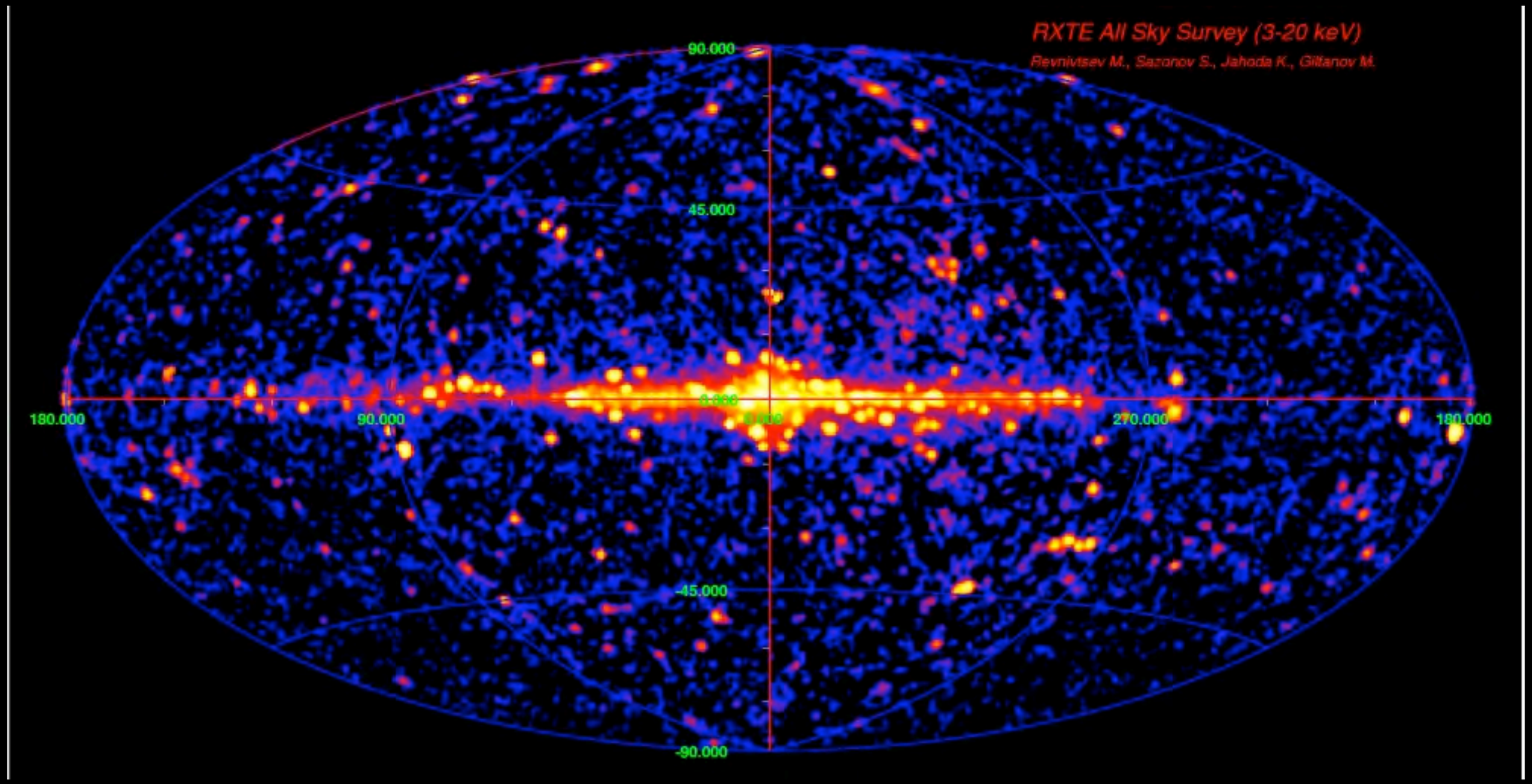
"astro"

Dark Matter in the Isotropic Diffuse Spectrum

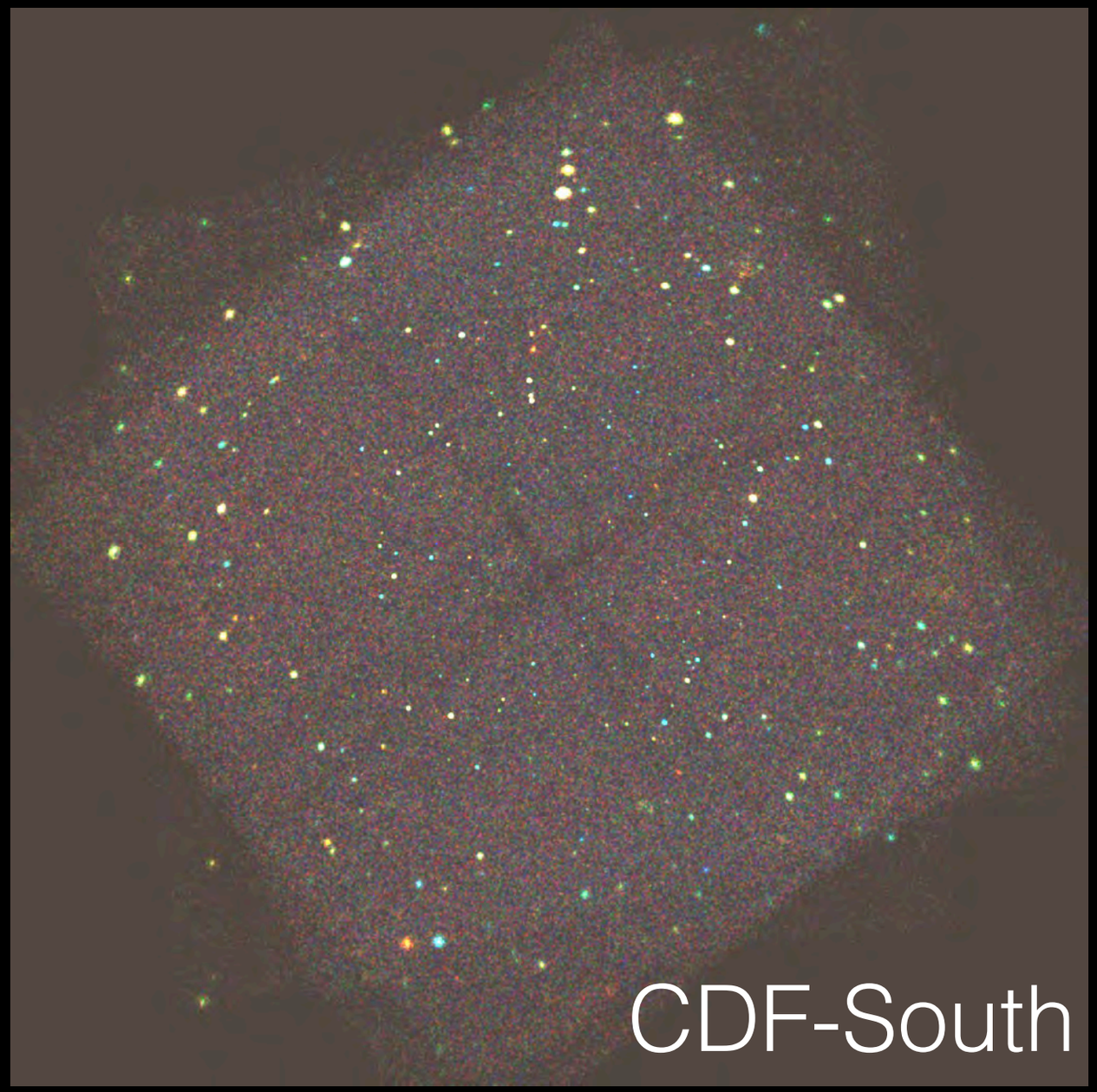


Abazajian, Agrawal, Chacko & Kilic, arXiv: 1002.3820

Lessons from the Cosmic X-ray Background

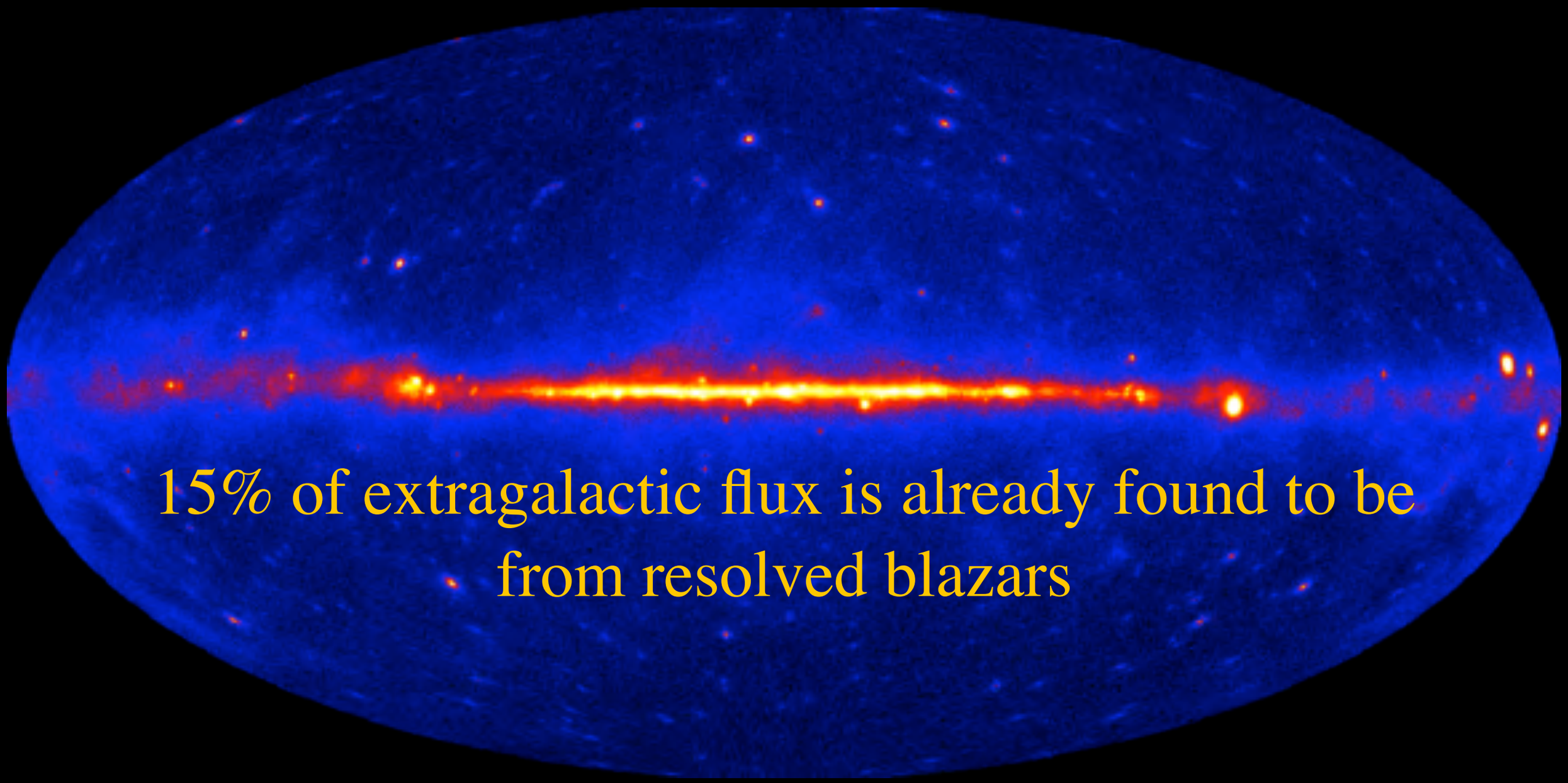


Chandra Deep Field: Milky Way Halo Limits from the Unresoved X-ray Background



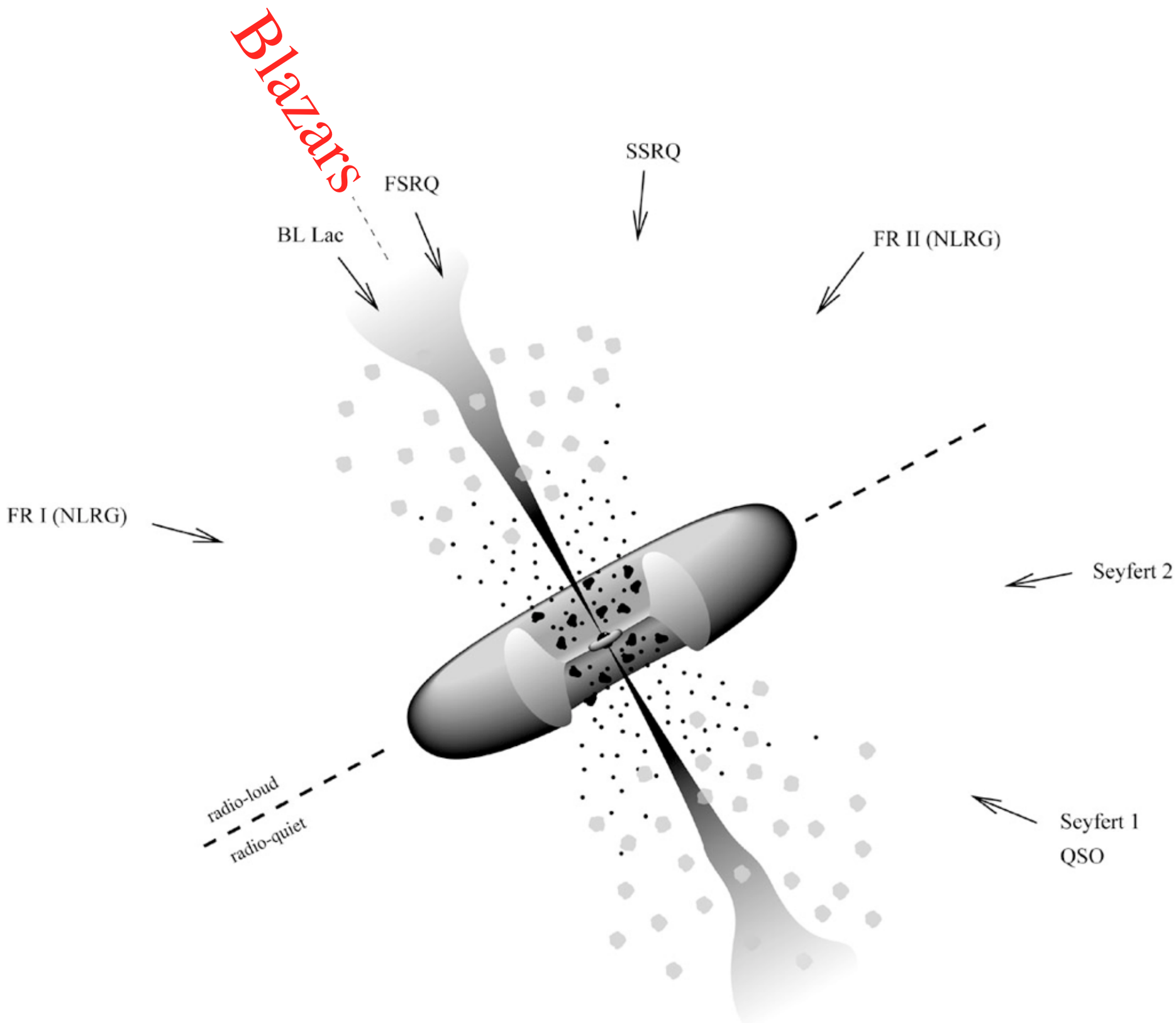
Hickox & Markevitch 2006, 2007

The Observed Fermi-LAT Gamma-Ray

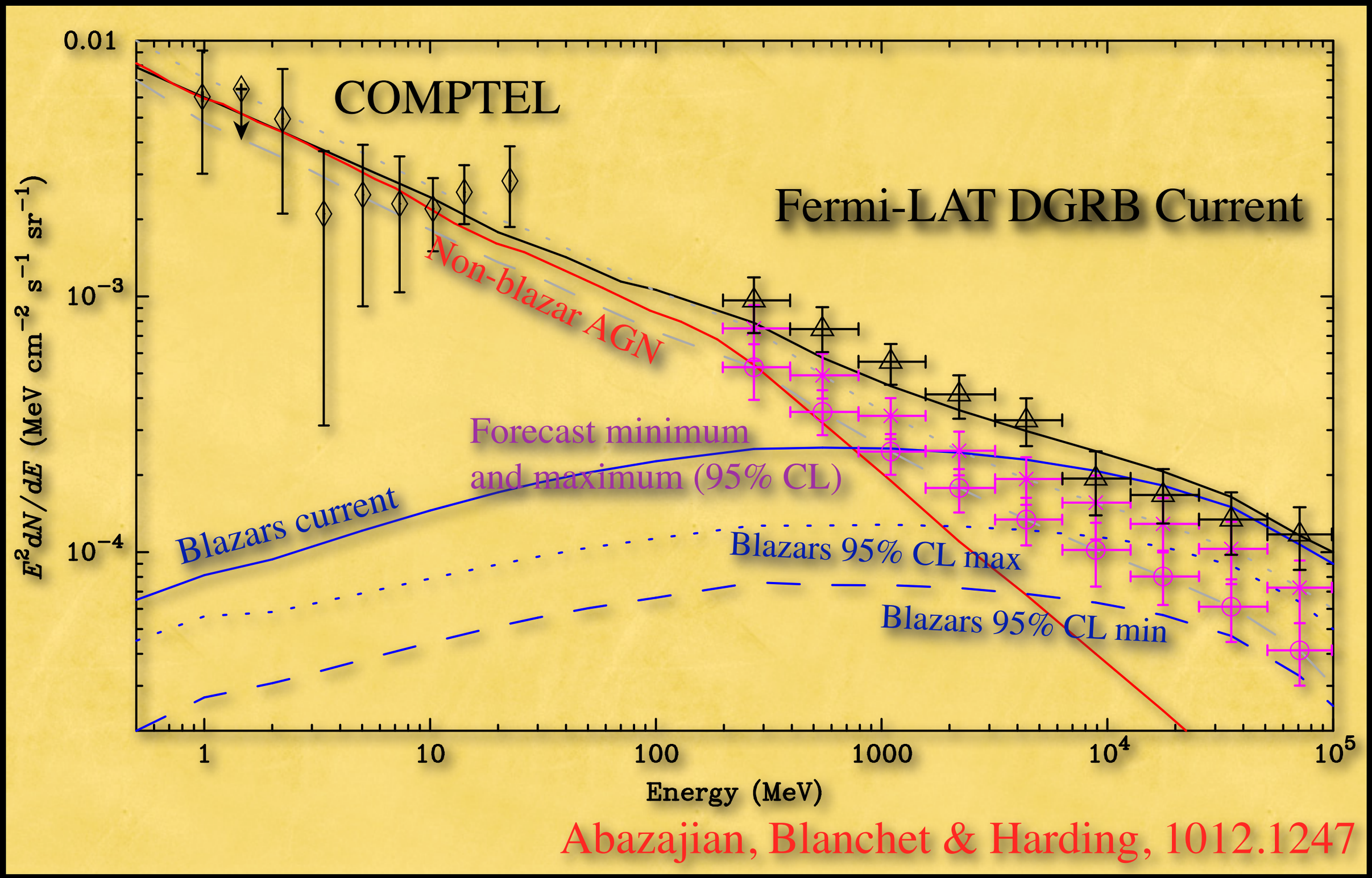


15% of extragalactic flux is already found to be from resolved blazars

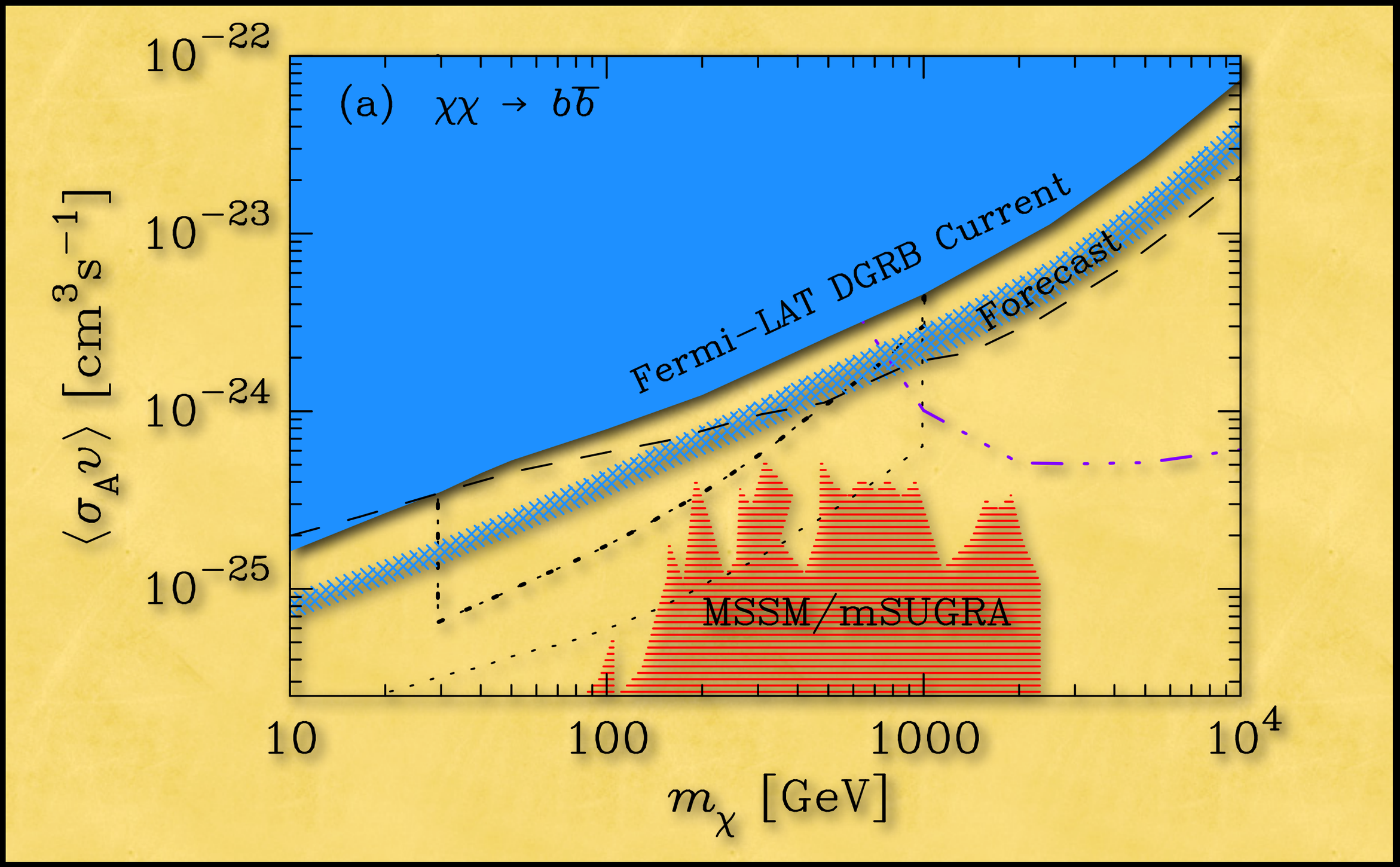
Blazars in the Unified Model of AGN



Allows for Forecasts for Fermi-LAT's DGRB

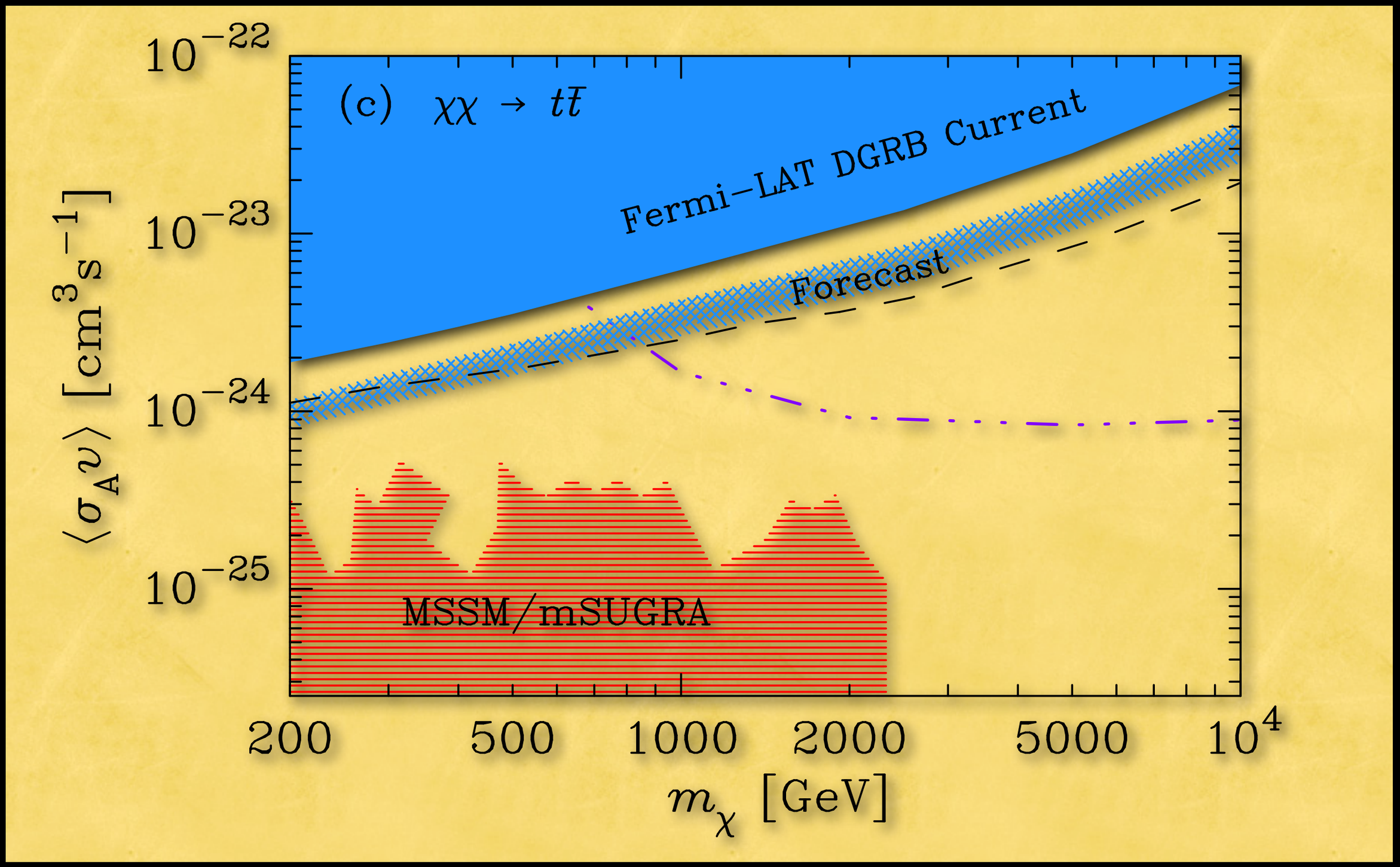


Annihilation Channel Forecasts



Abazajian, Blanchet & Harding 2012

Annihilation Channel Forecasts



Abazajian, Blanchet & Harding 2012

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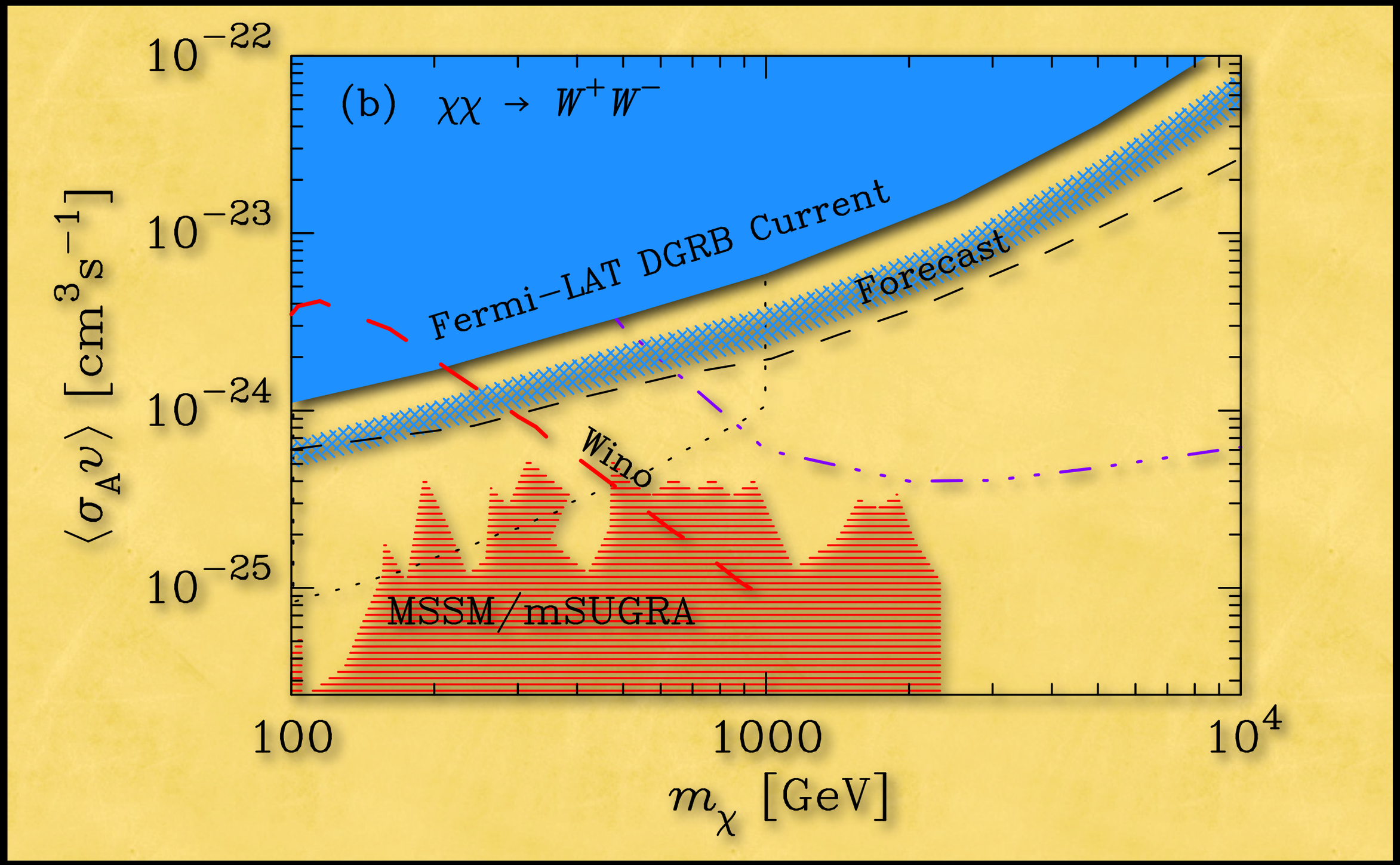

Abazajian, Blanchet & Harding 2012

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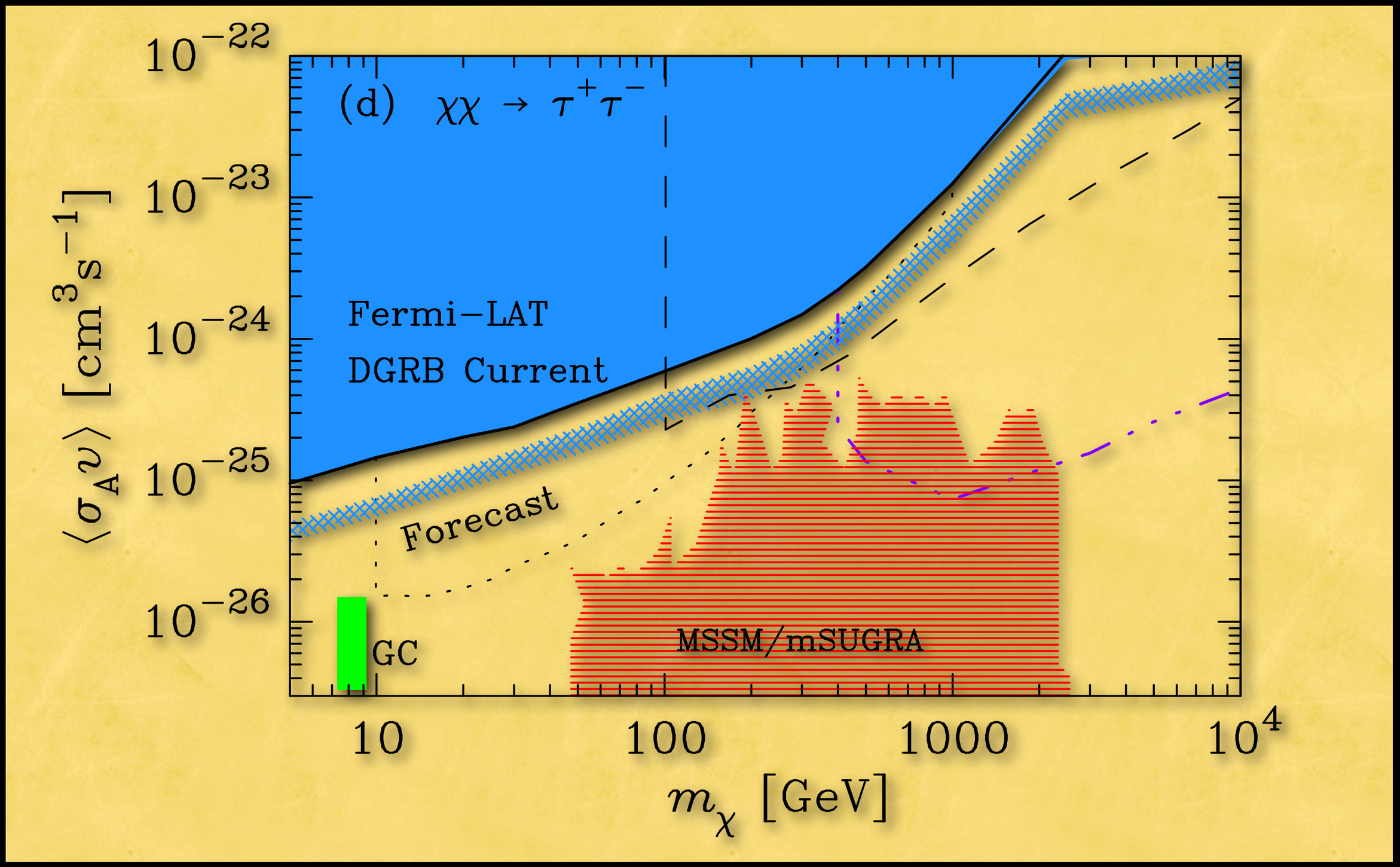
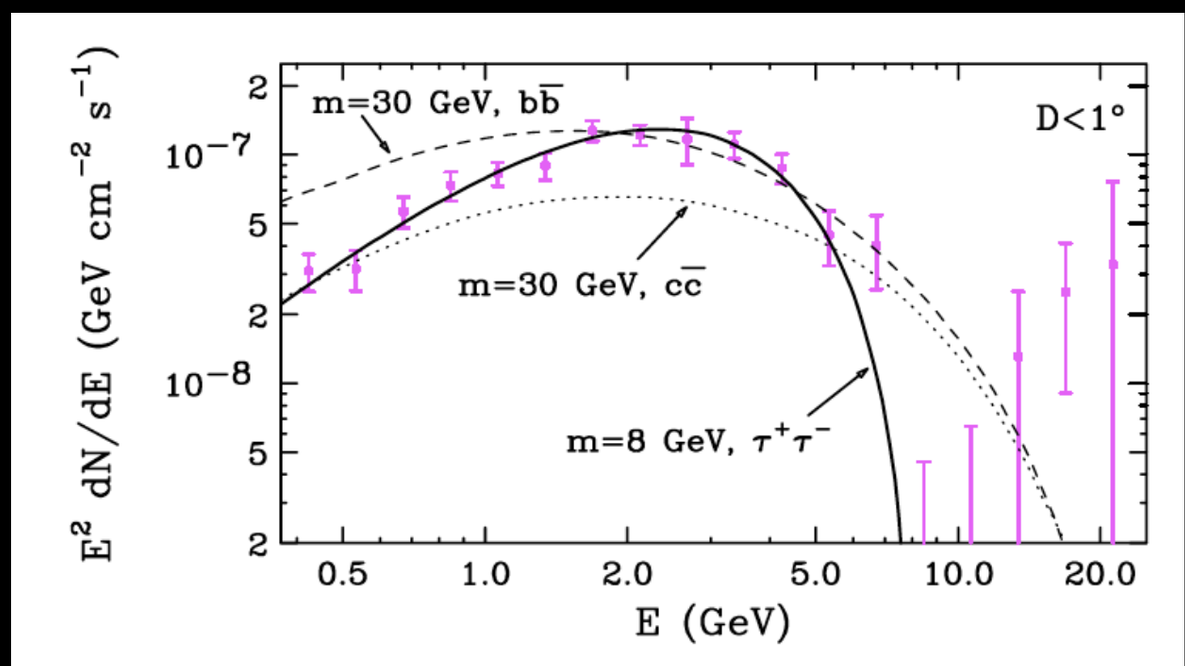
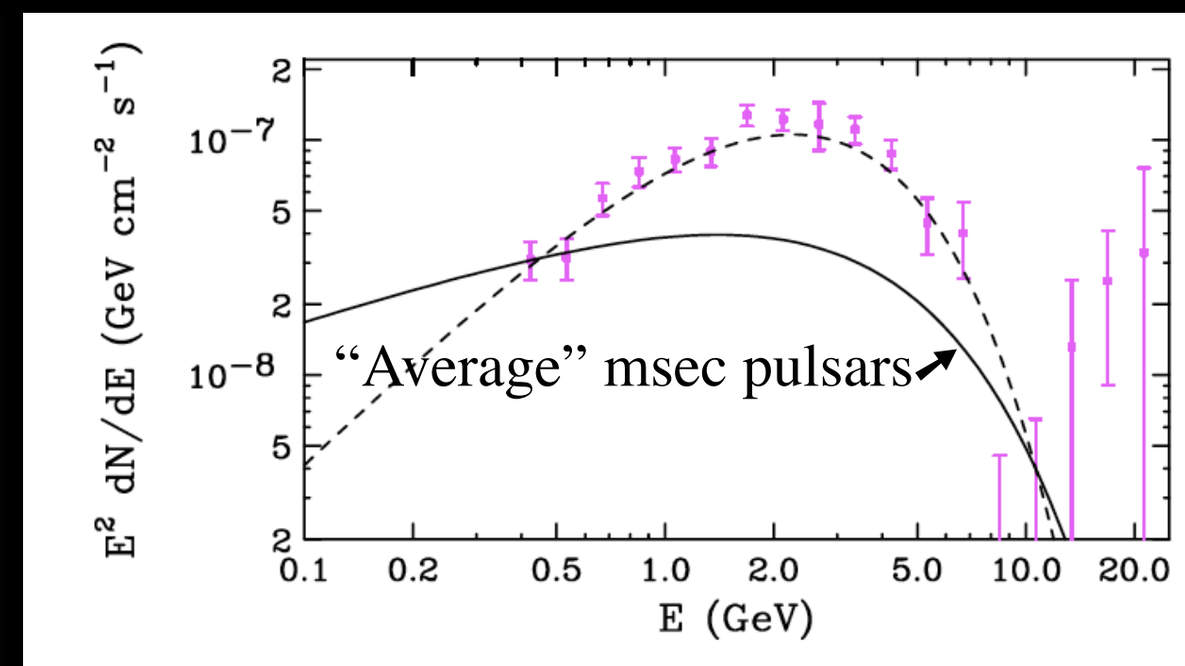


Abazajian, Blanchet & Harding 2012

Dark Matter in the Galactic Center?





Hooper & Goodenough, arXiv:1010.2752

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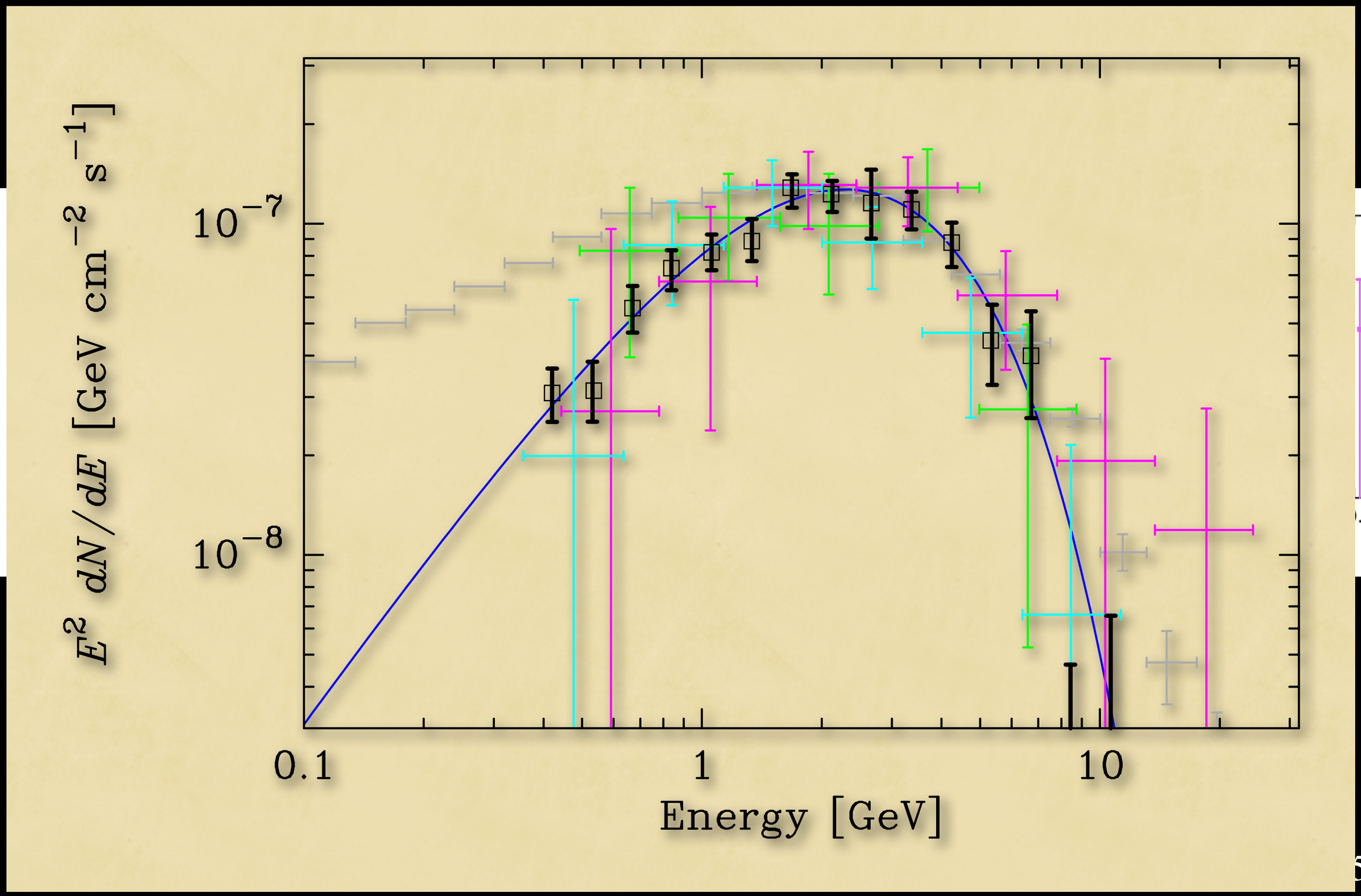

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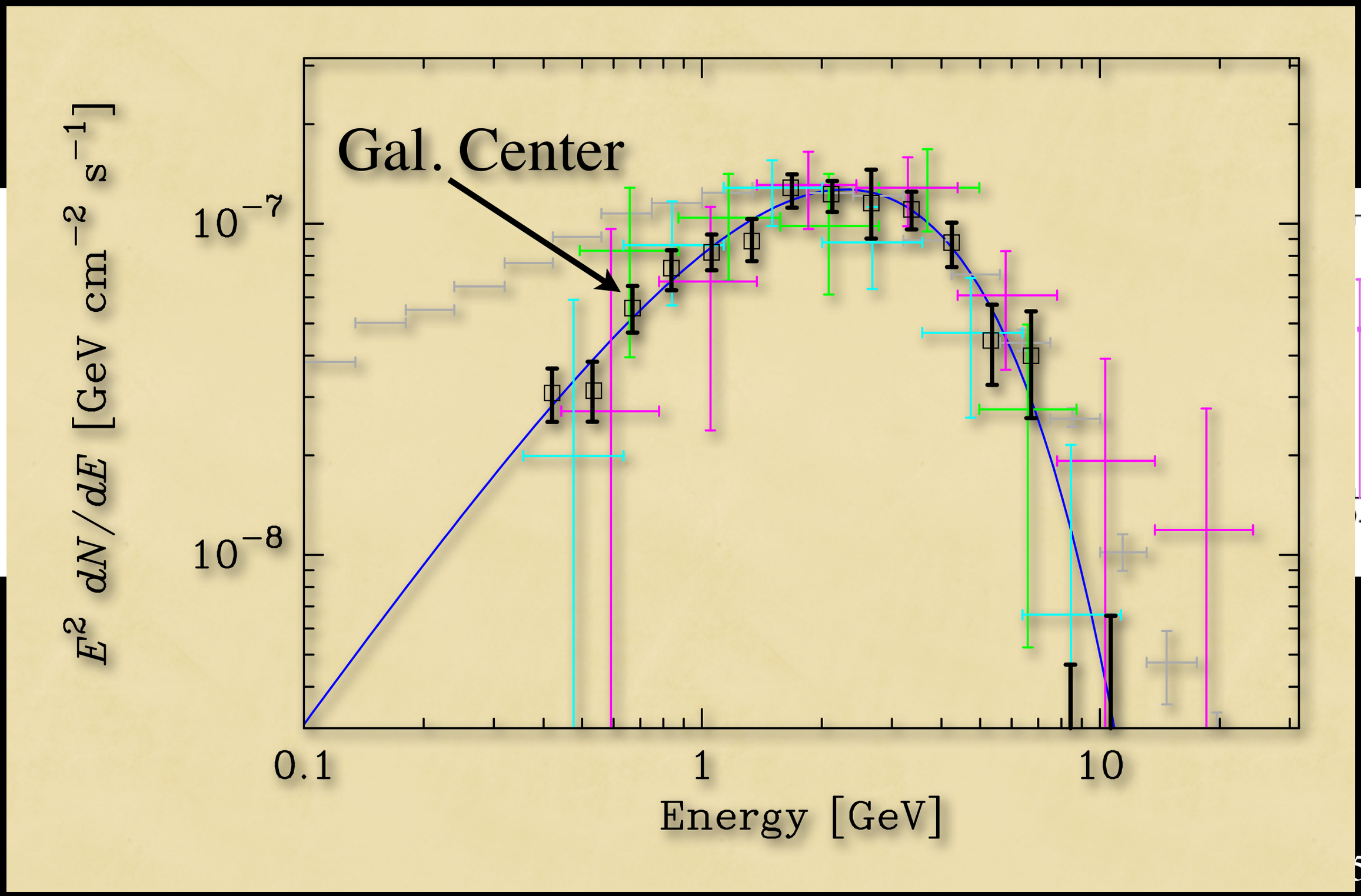

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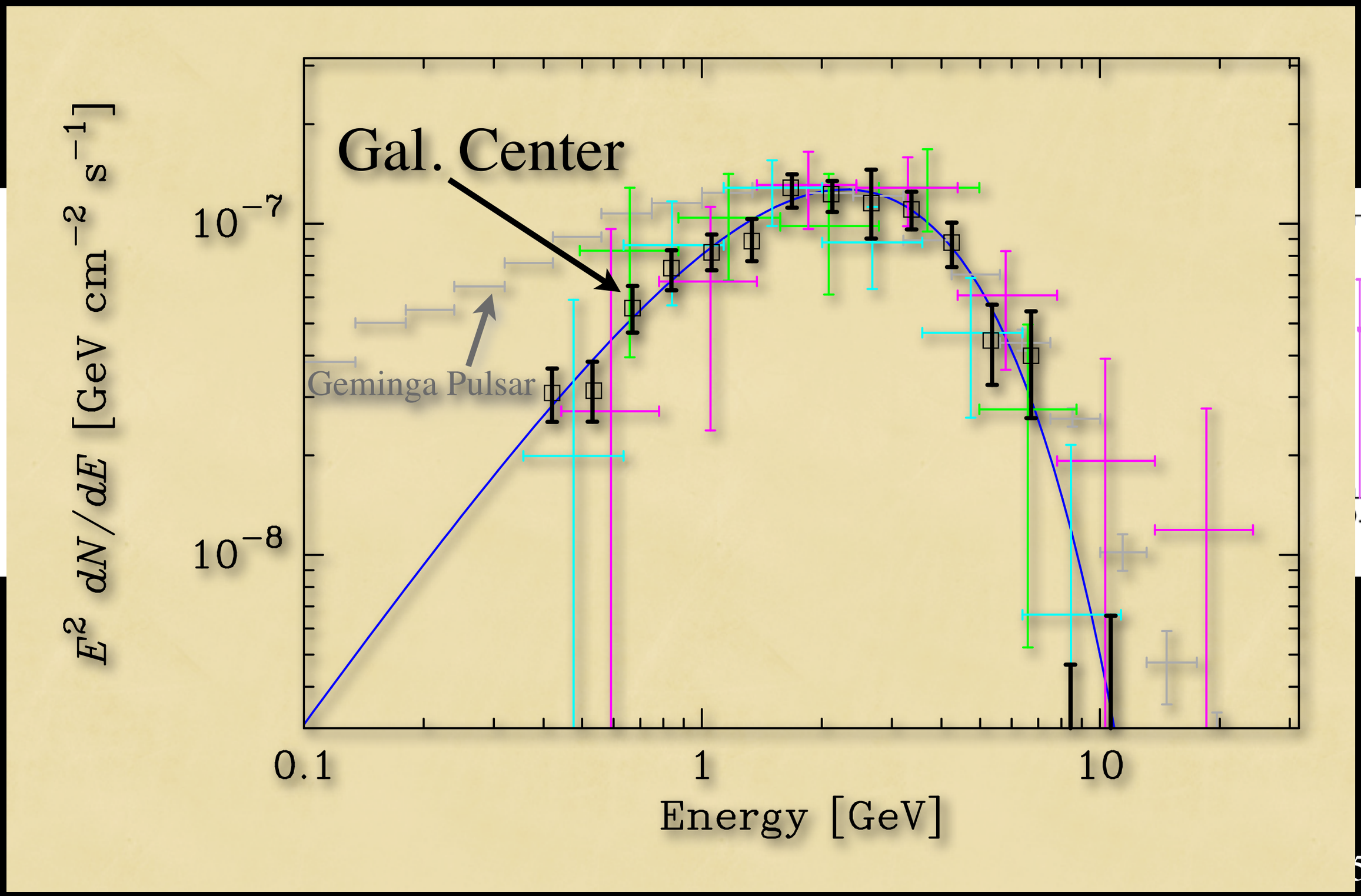

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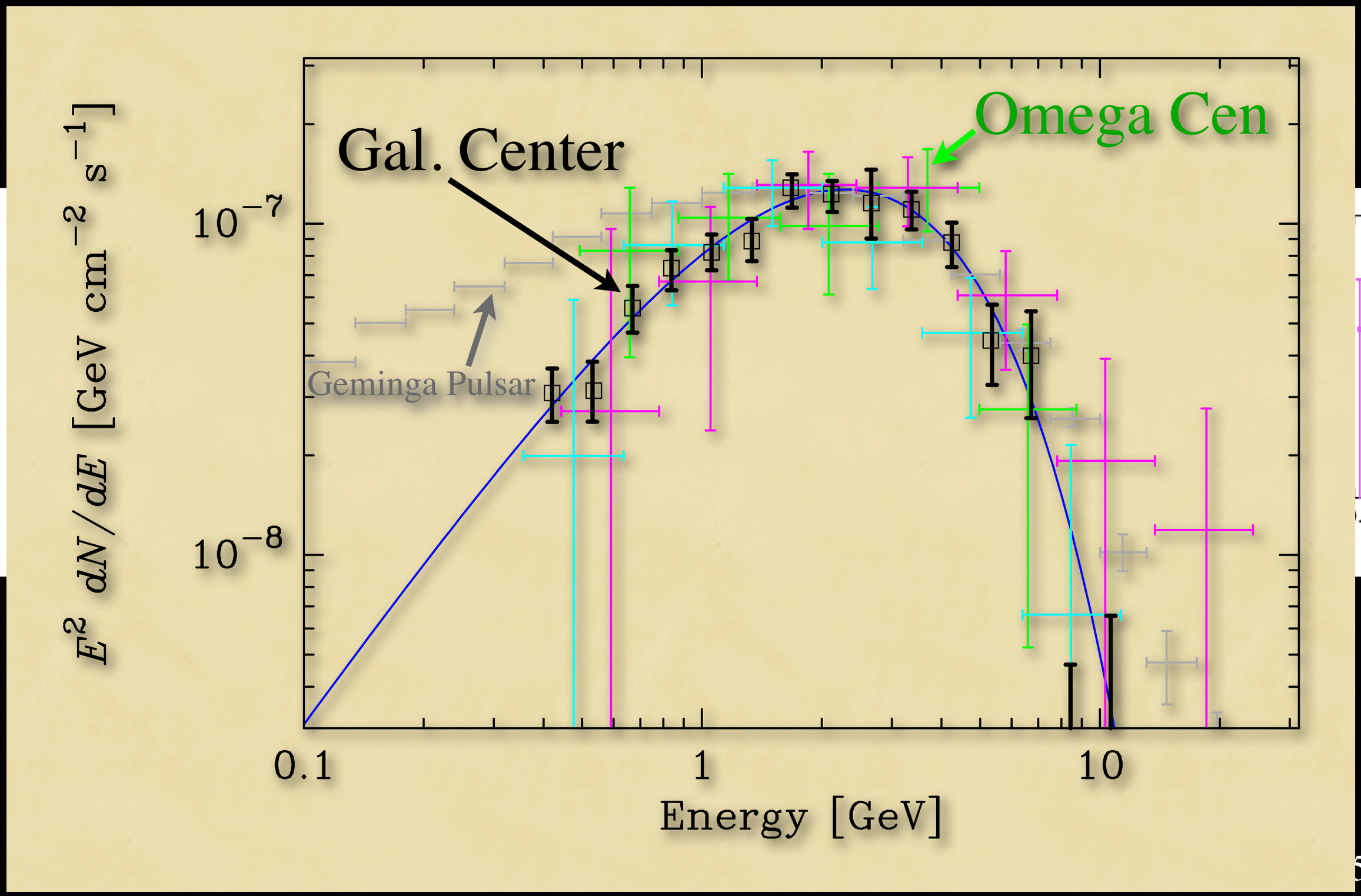
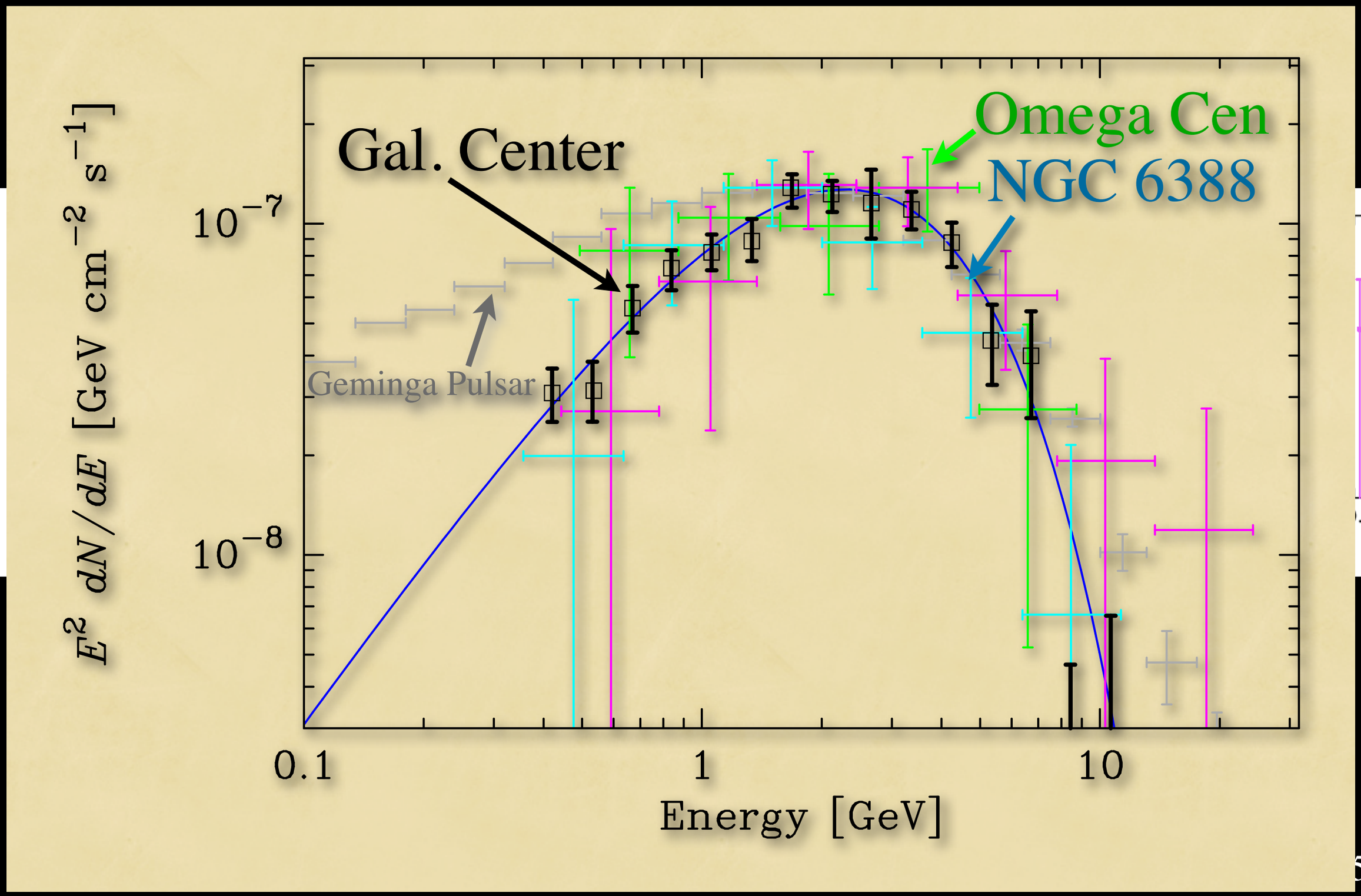
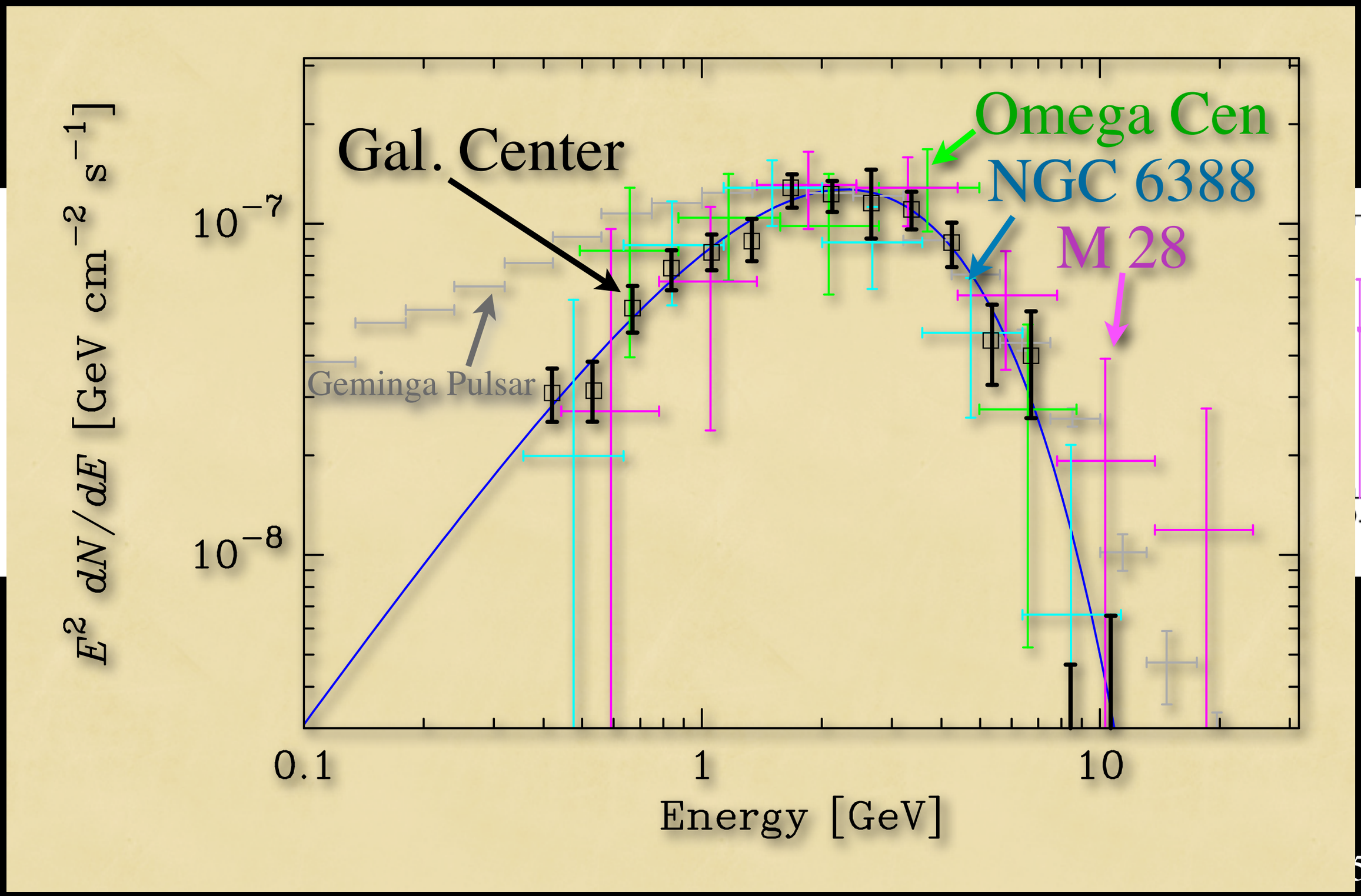


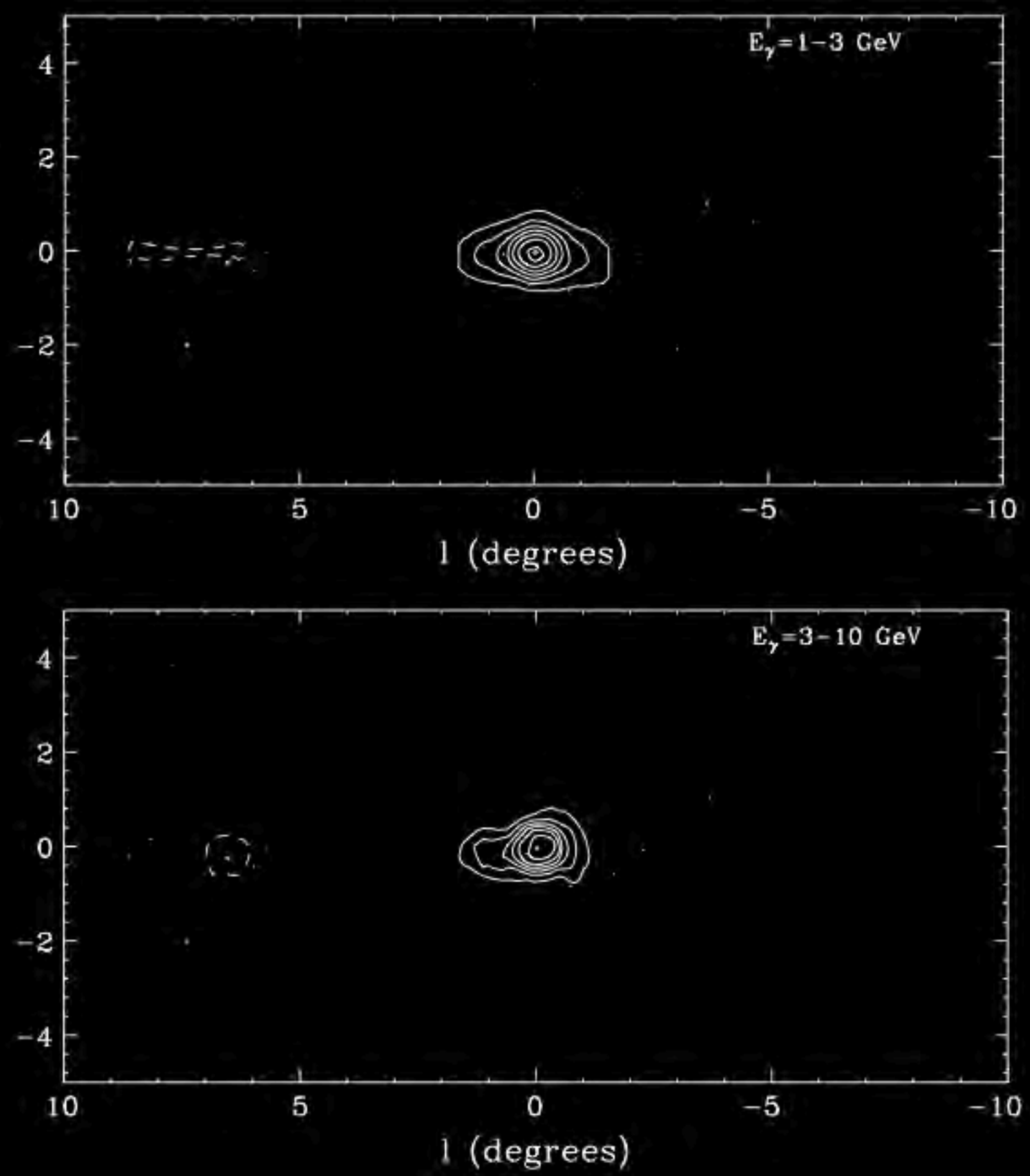
Dark Matter in the Galactic Center?



Dark Matter in the Galactic Center?



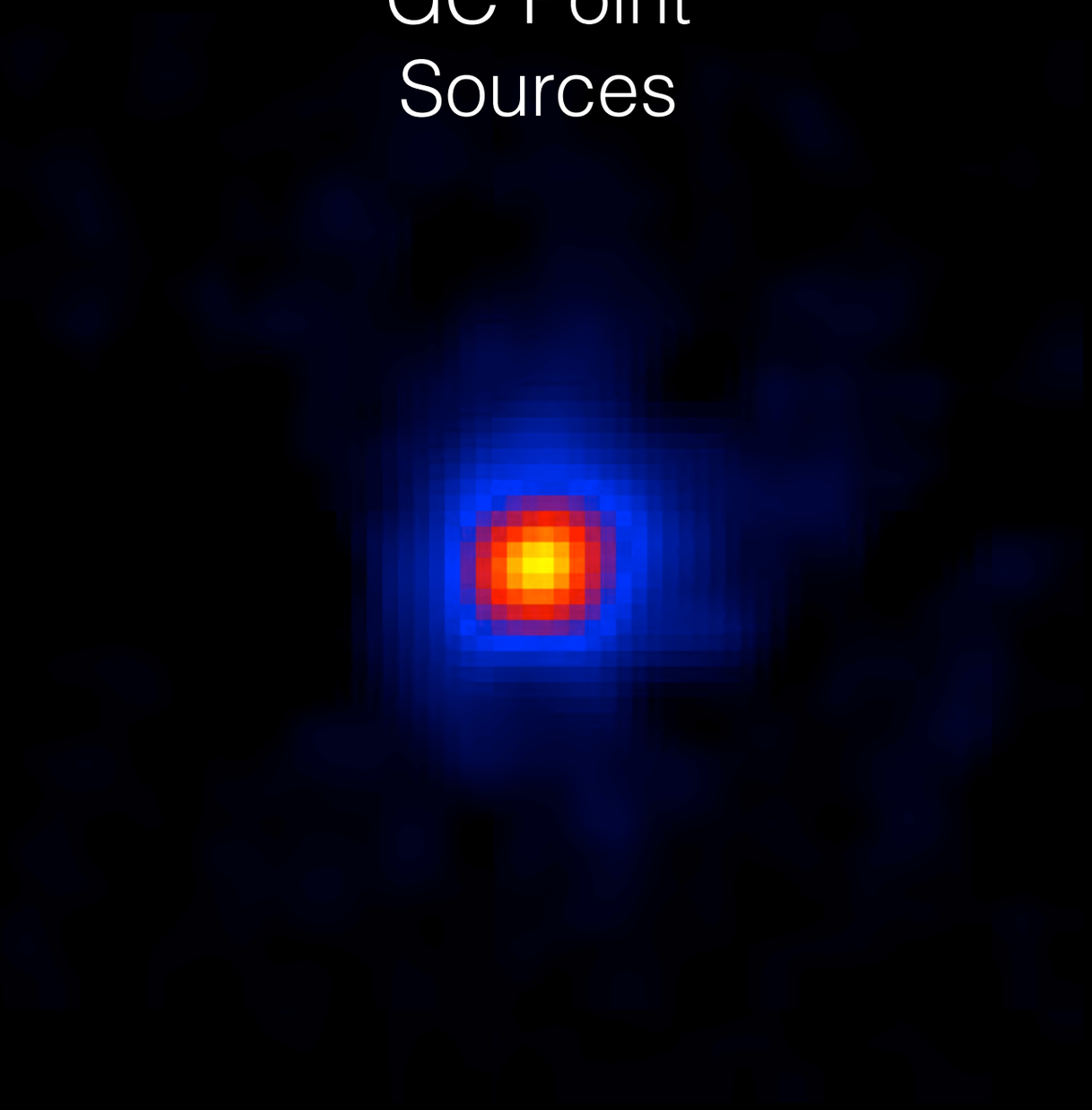
Light DM: Morphological Case?



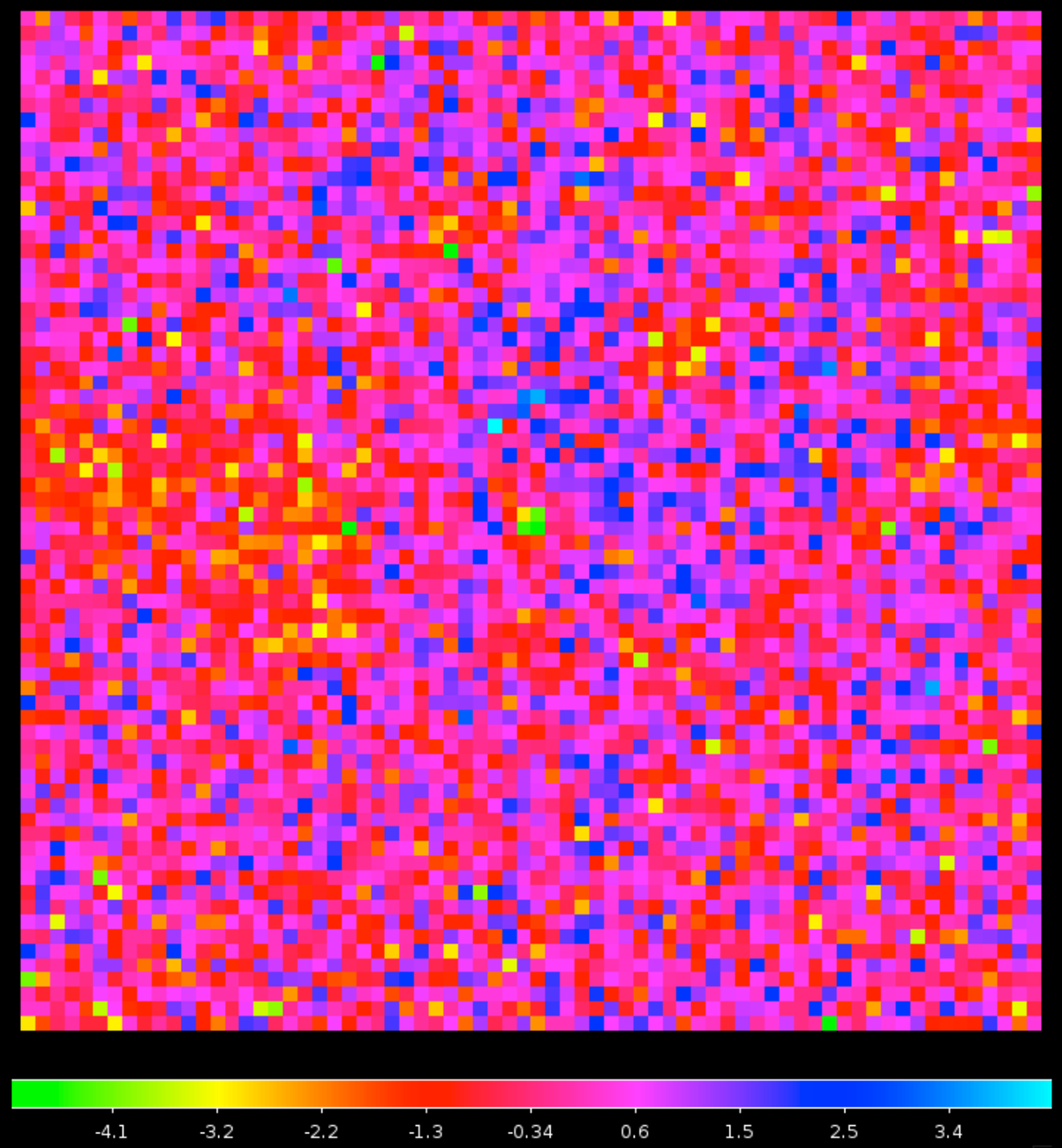
Hooper & Linden 2011

Morphological Evidence Non-

GC Point Sources



GC 2FGL + Gal Diff
σ-Residual

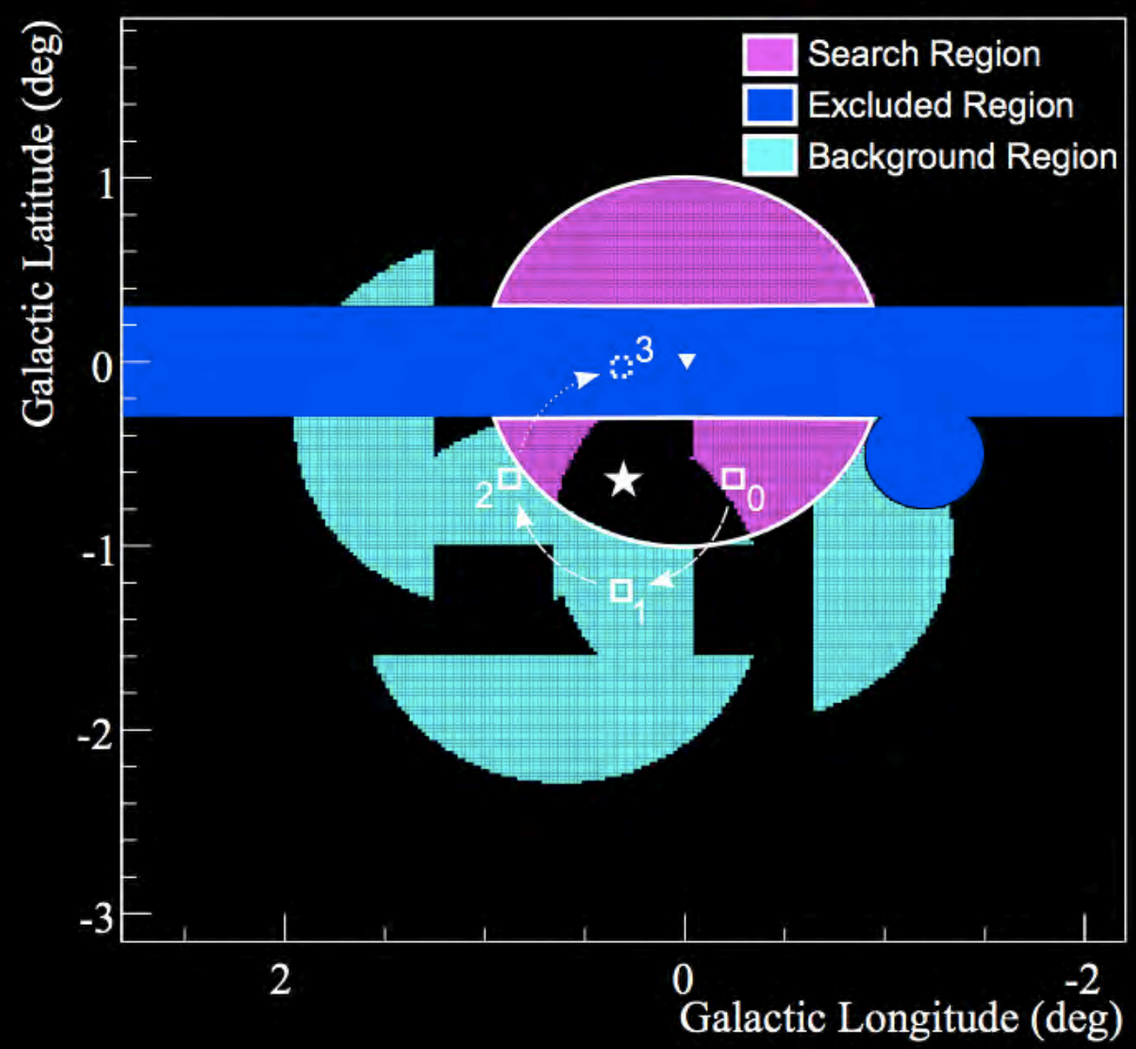


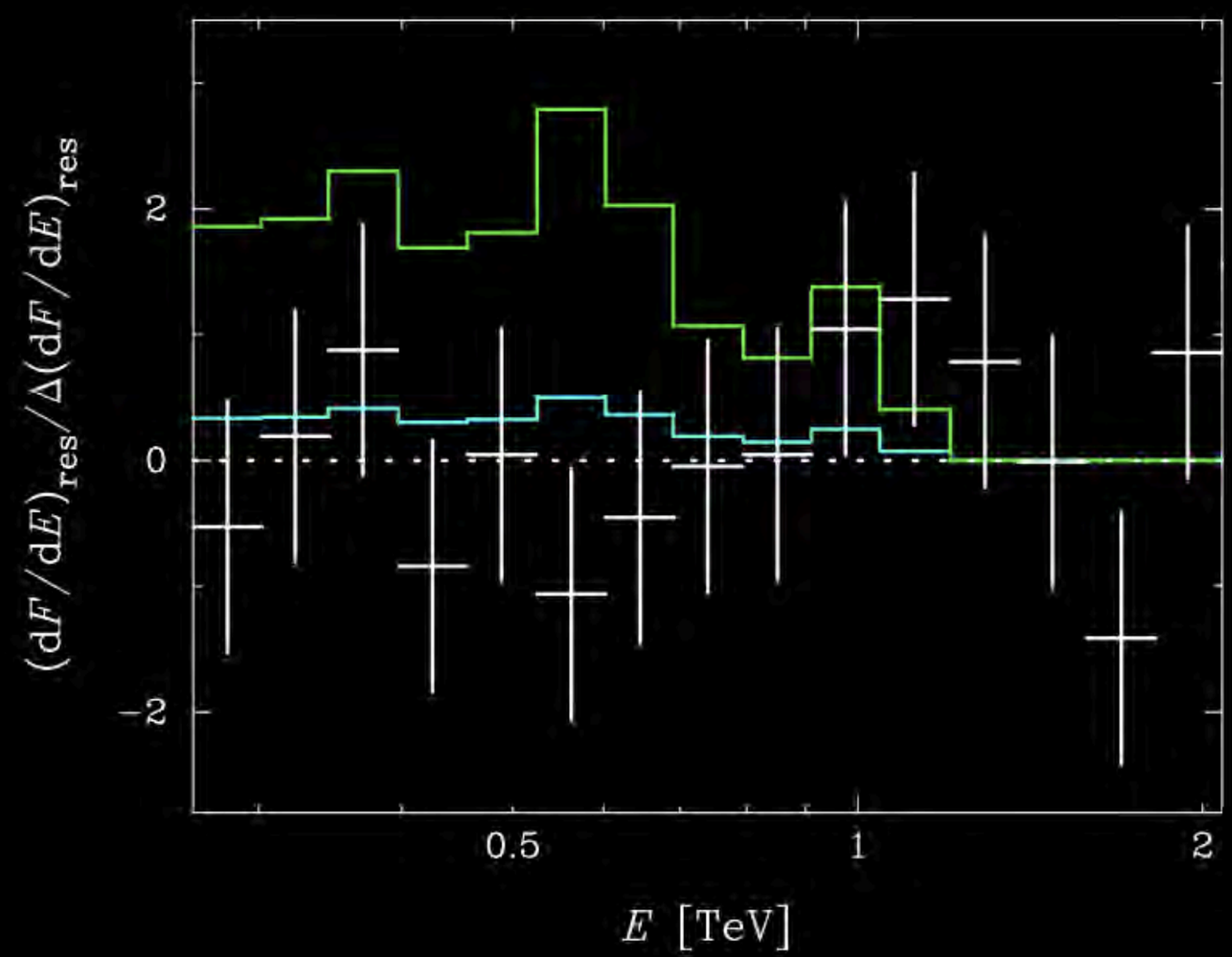
in prep...

High Energy Spectroscopic Survey (HESS) Gamma- Ray Telescope in Namibia

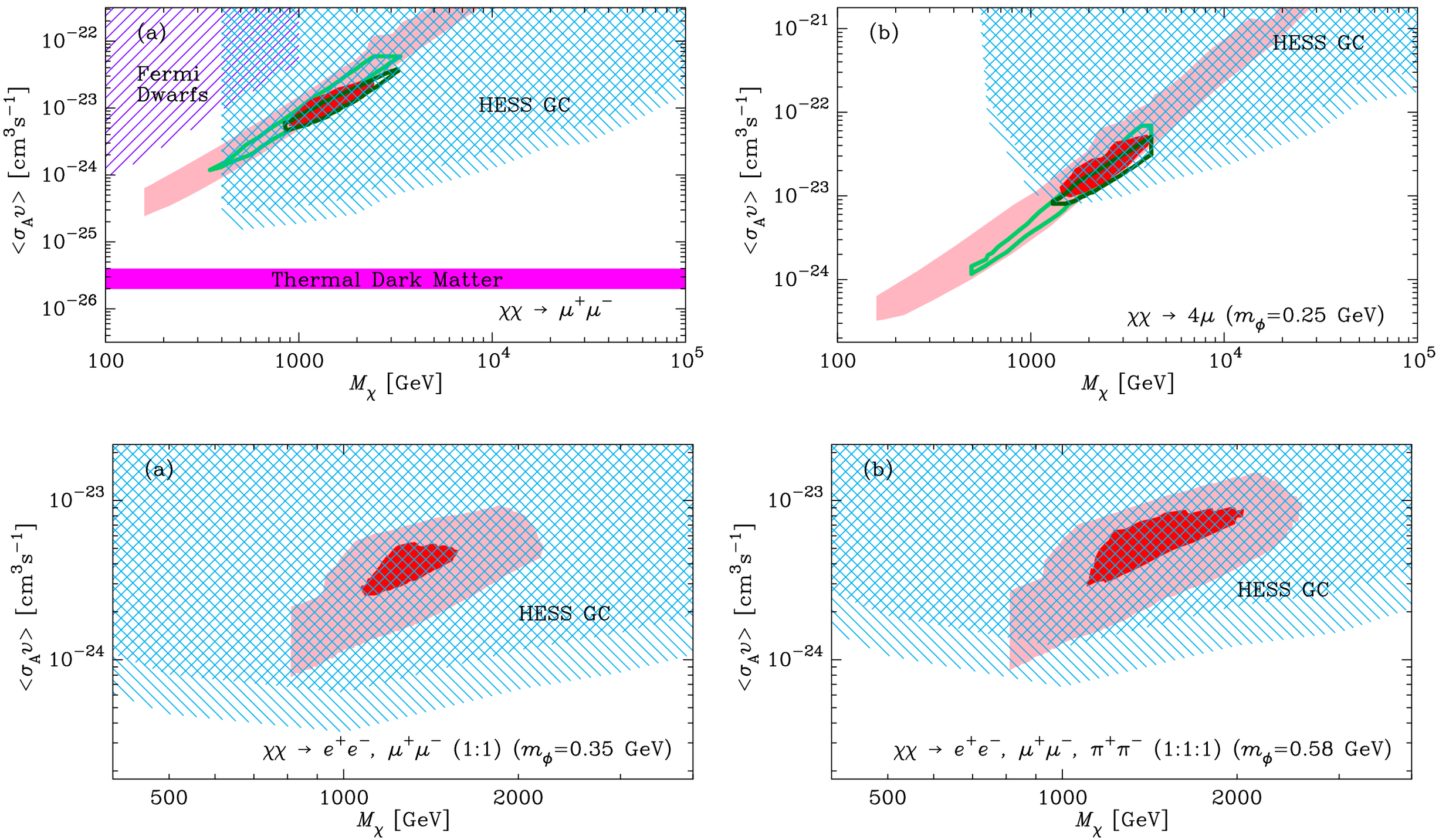
Would detect gamma-rays from annihilation products
in
PAMELA Dark Matter Models

Residual Spectrum Toward the Galactic Center





HESS Galactic Center Constraints on PAMELA Dark Matter Interpretations



Abazajian & Harding 2011

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

WIMP Dark Matter

- The diffuse gamma-ray background is the most conservative and, when including the MW Galactic contribution, a stringent constraint
- The DGRB constraints are dwarfed by Fermi-LAT dwarf galaxy constraints and HESS GC Constraints
- Claims for DM signals from the GC based on both spectral & morphological information do not survive quantitative scrutiny