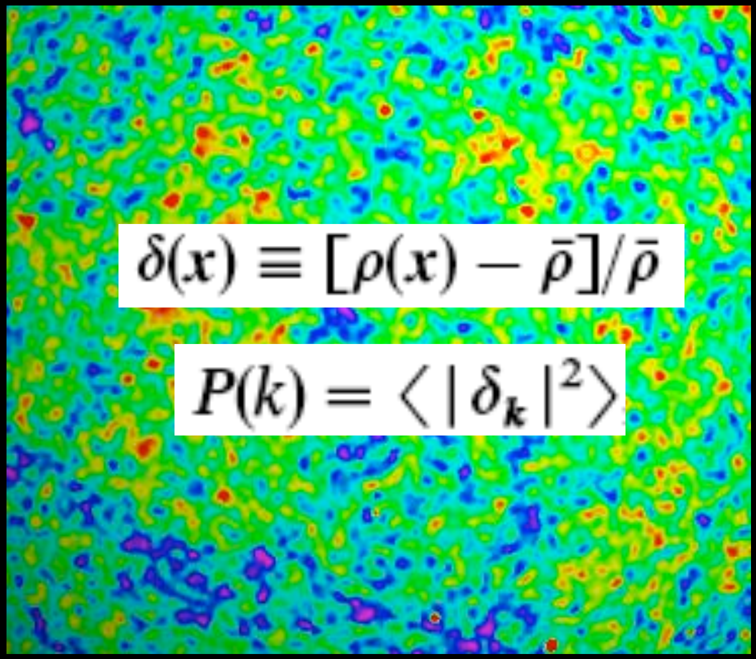
Neutrino Mass from Cosmology & Astrophysics I

Kevork Abazajian
University of California, Irvine

Neutrino Mass: From the Terrestrial Laboratory to the Cosmos - ACFI
December 14, 2015

Large Scale Structure: the cosmological density perturbation spectrum



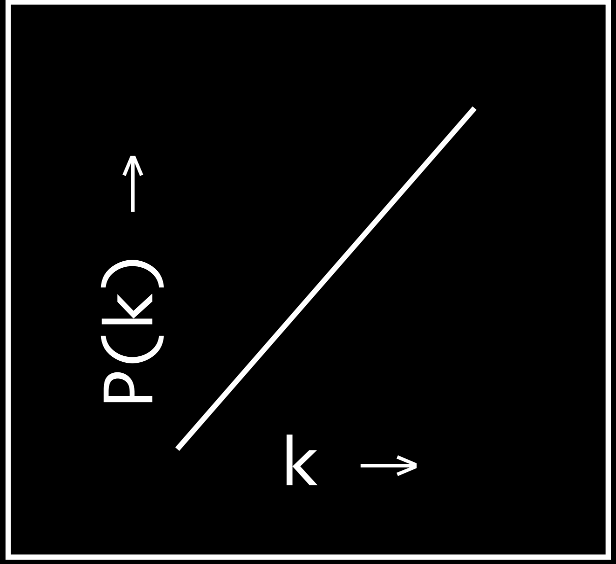
- Power spectrum of cosmological density fluctuations

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

- Primordial Harrison-Zeldovich: from scale invariance

$$P(k) \propto k$$

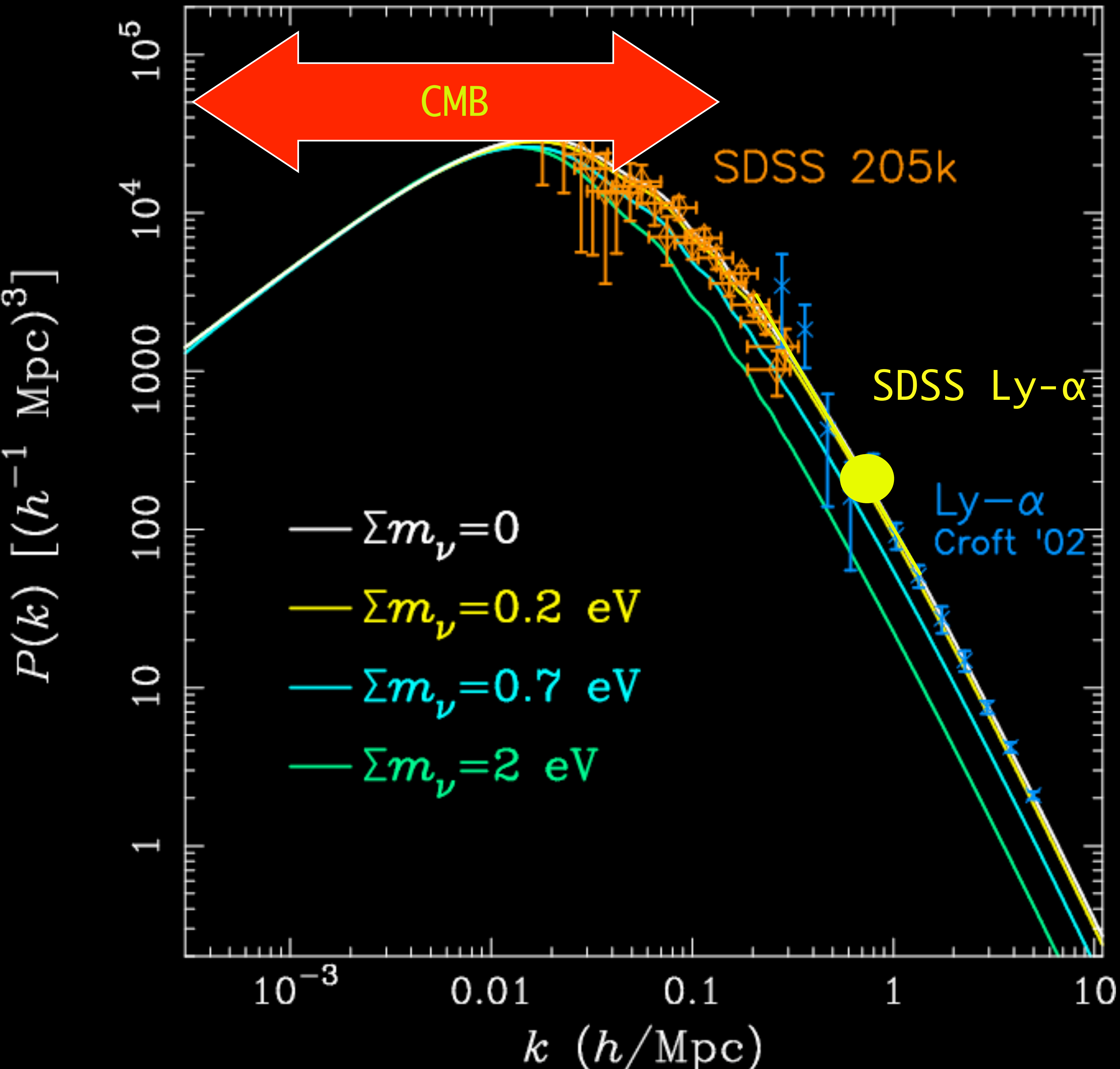
  - Natural solution to perturbation spectrum: self-similar evolution



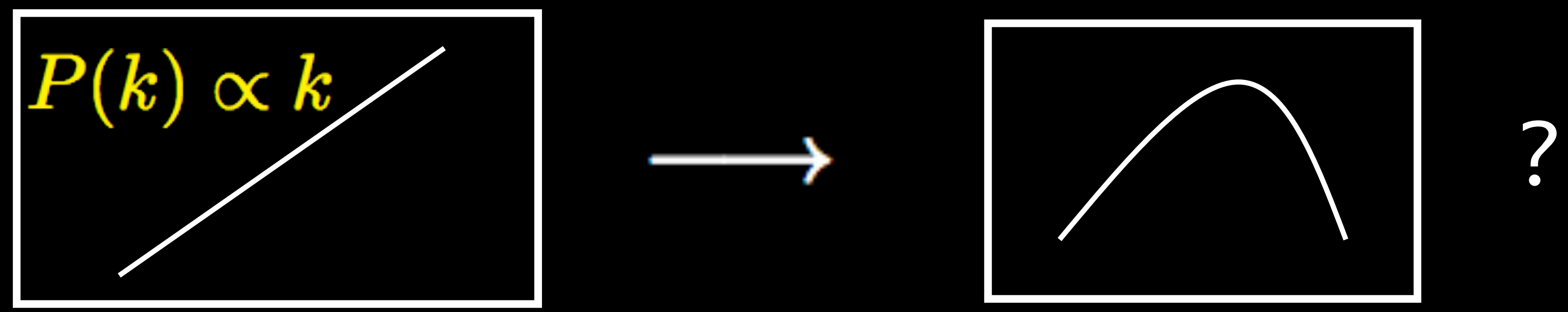
- Predicted by inflation

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

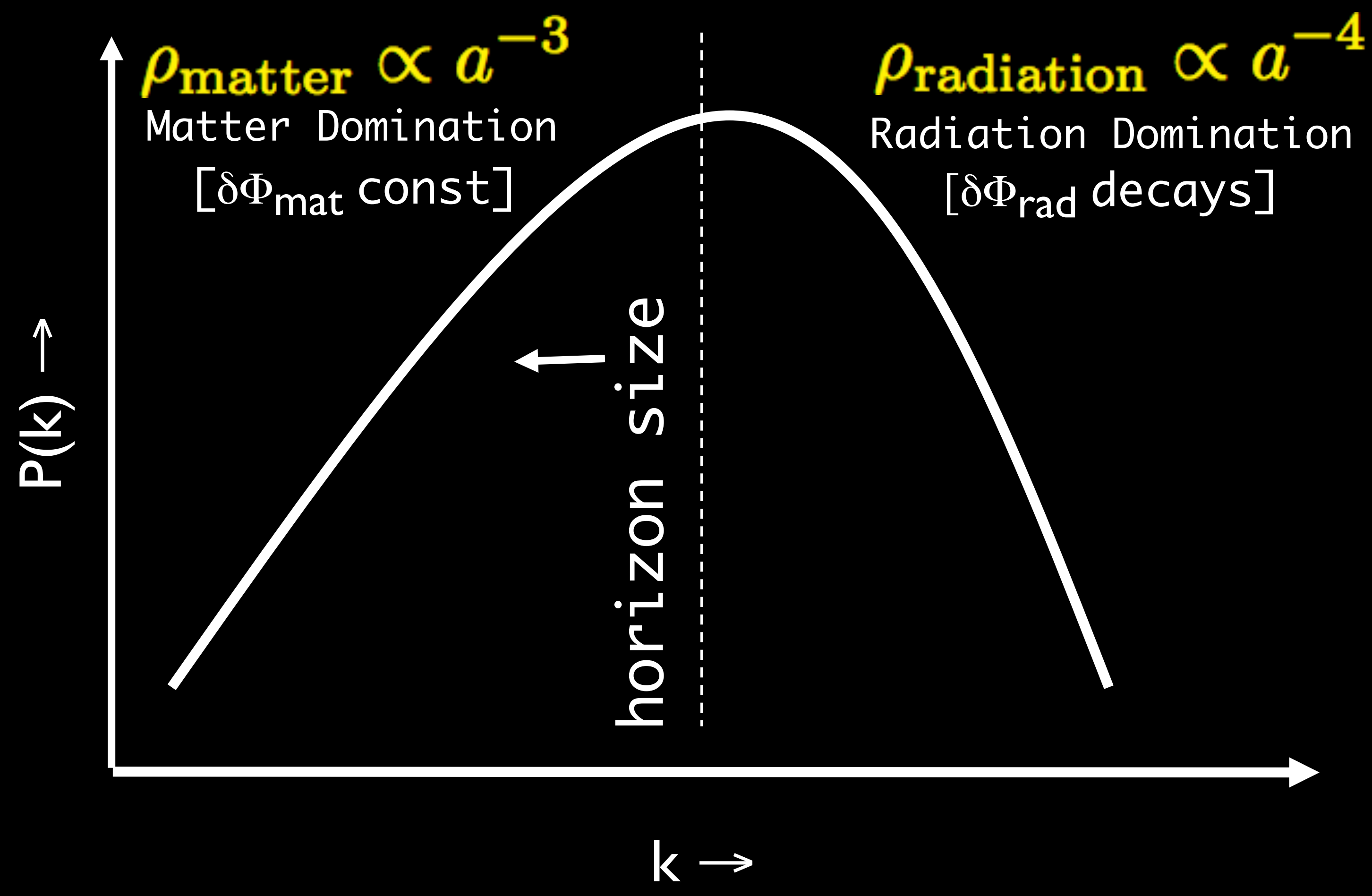
Measuring Large Scale Structure $P(k)$

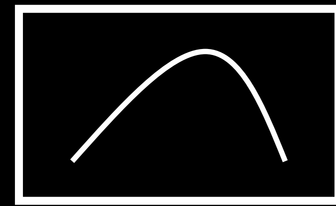


The Cosmological Matter Power Spectrum



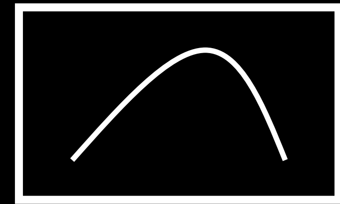
Perturbations enter horizon:



How does  probe neutrinos?

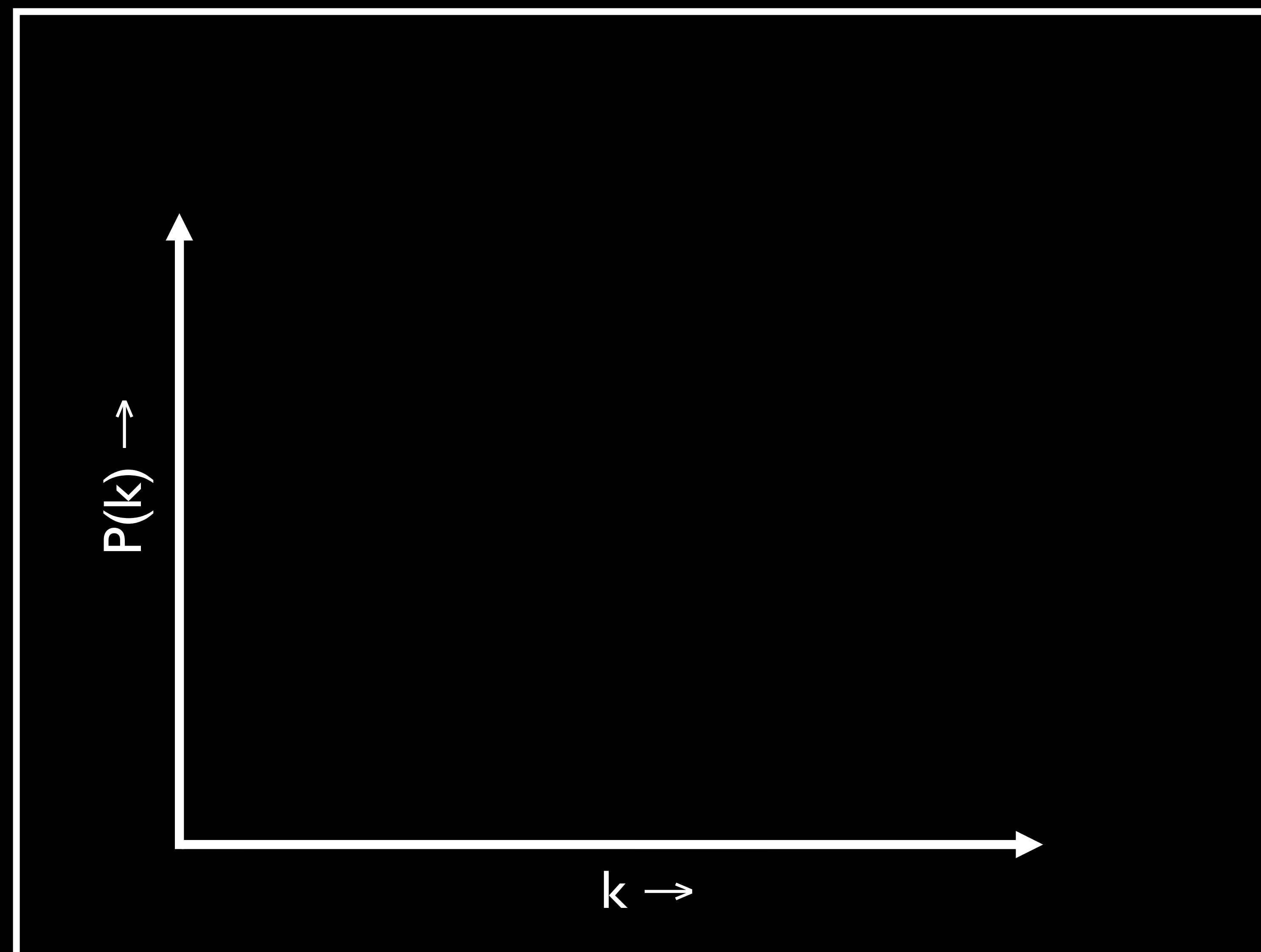
$$n_\nu = N_\nu \times \left(\frac{3}{11}\right) n_\gamma \approx 340 \text{ cm}^{-3}$$

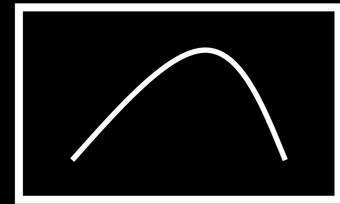
(Assuming thermal equilibrium)

How does  probe neutrinos?

$$n_\nu = N_\nu \times \left(\frac{3}{11}\right) n_\gamma \approx 340 \text{ cm}^{-3}$$

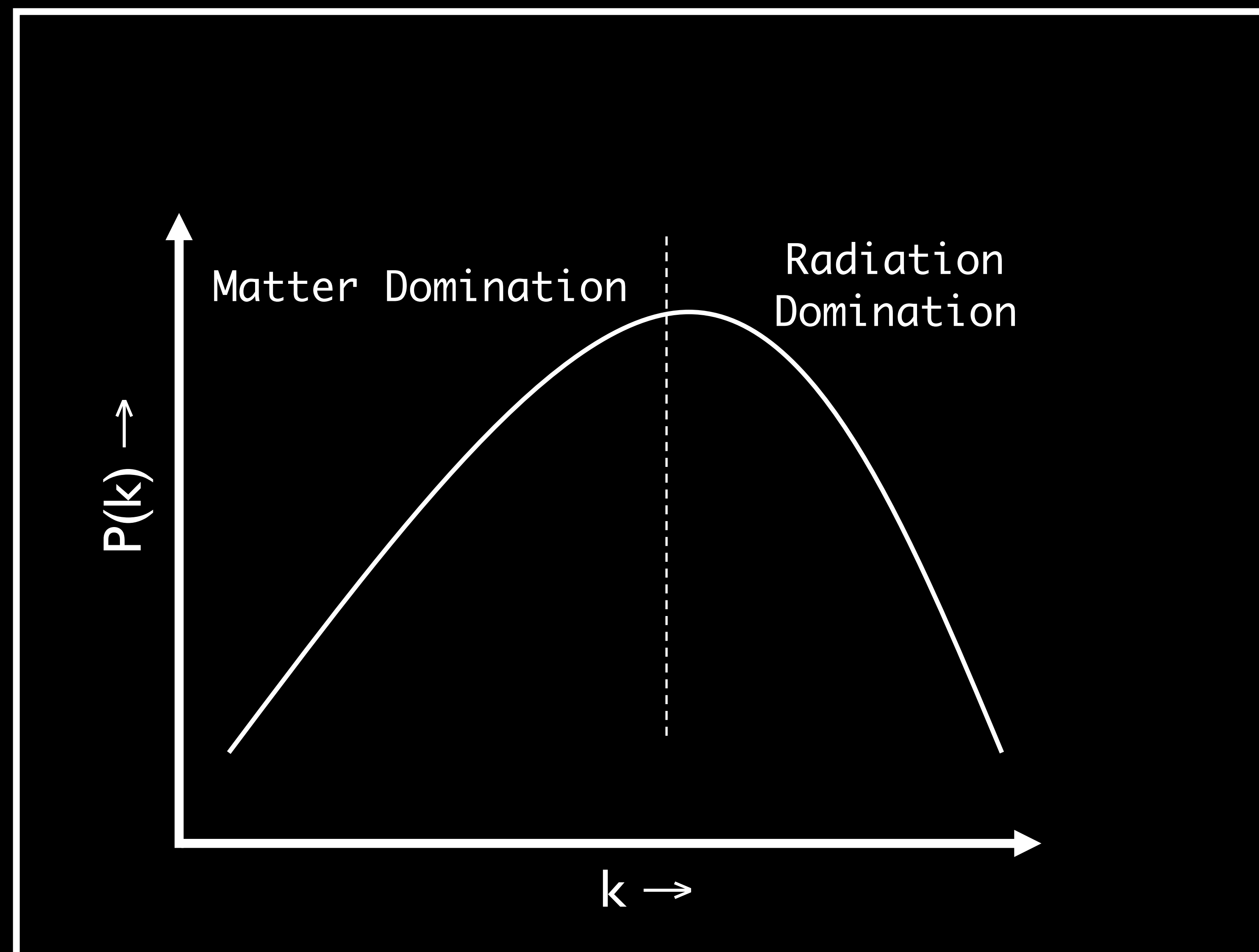
(Assuming thermal equilibrium)

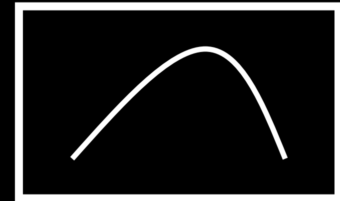


How does  probe neutrinos?

$$n_\nu = N_\nu \times \left(\frac{3}{11}\right) n_\gamma \approx 340\ \mathrm{cm}^{-3}$$

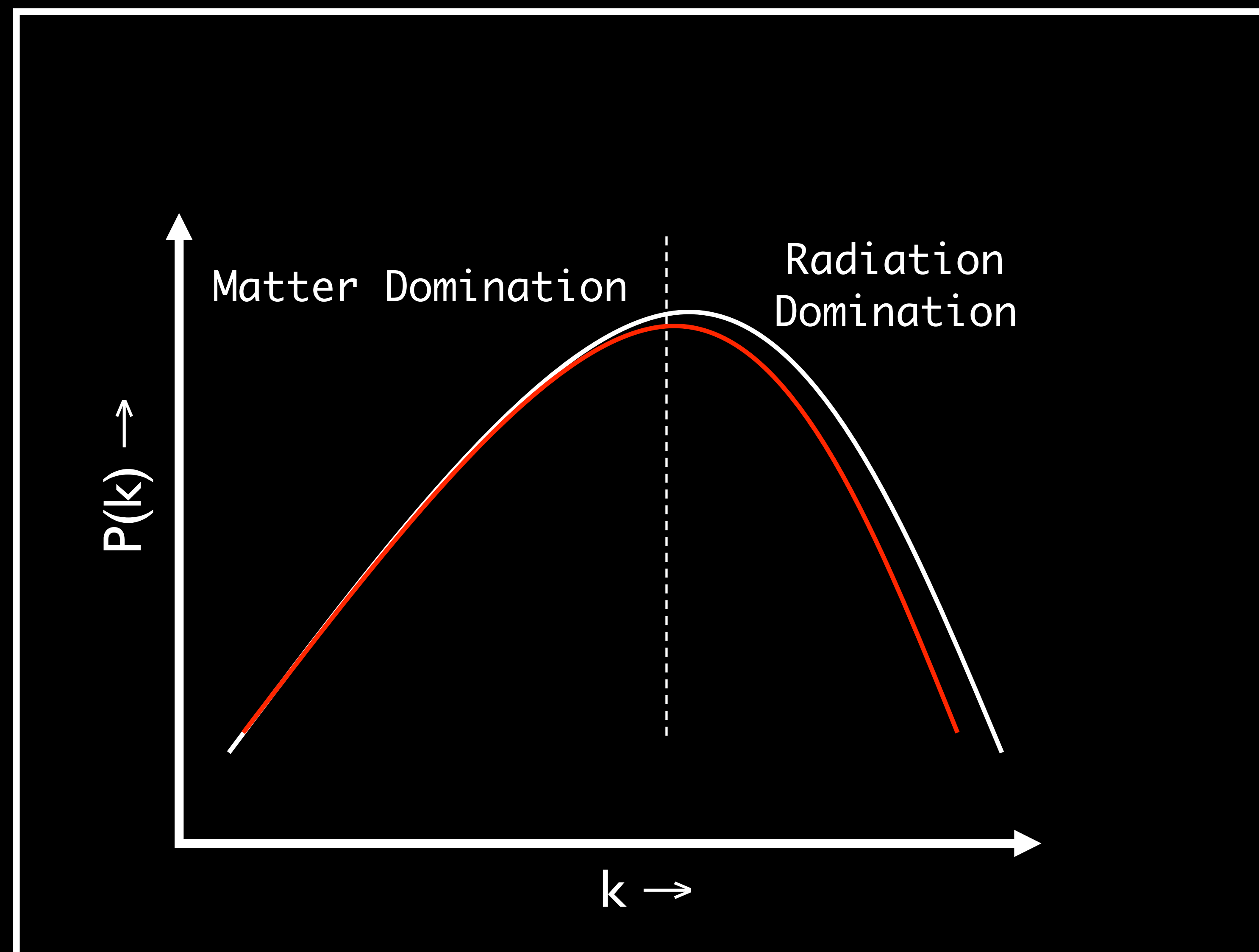
(Assuming thermal equilibrium)

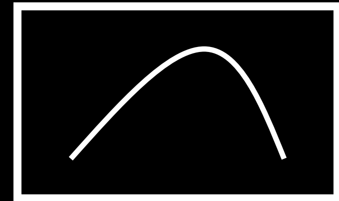


How does  probe neutrinos?

$$n_\nu = N_\nu \times \left(\frac{3}{11}\right) n_\gamma \approx 340\ \mathrm{cm}^{-3}$$

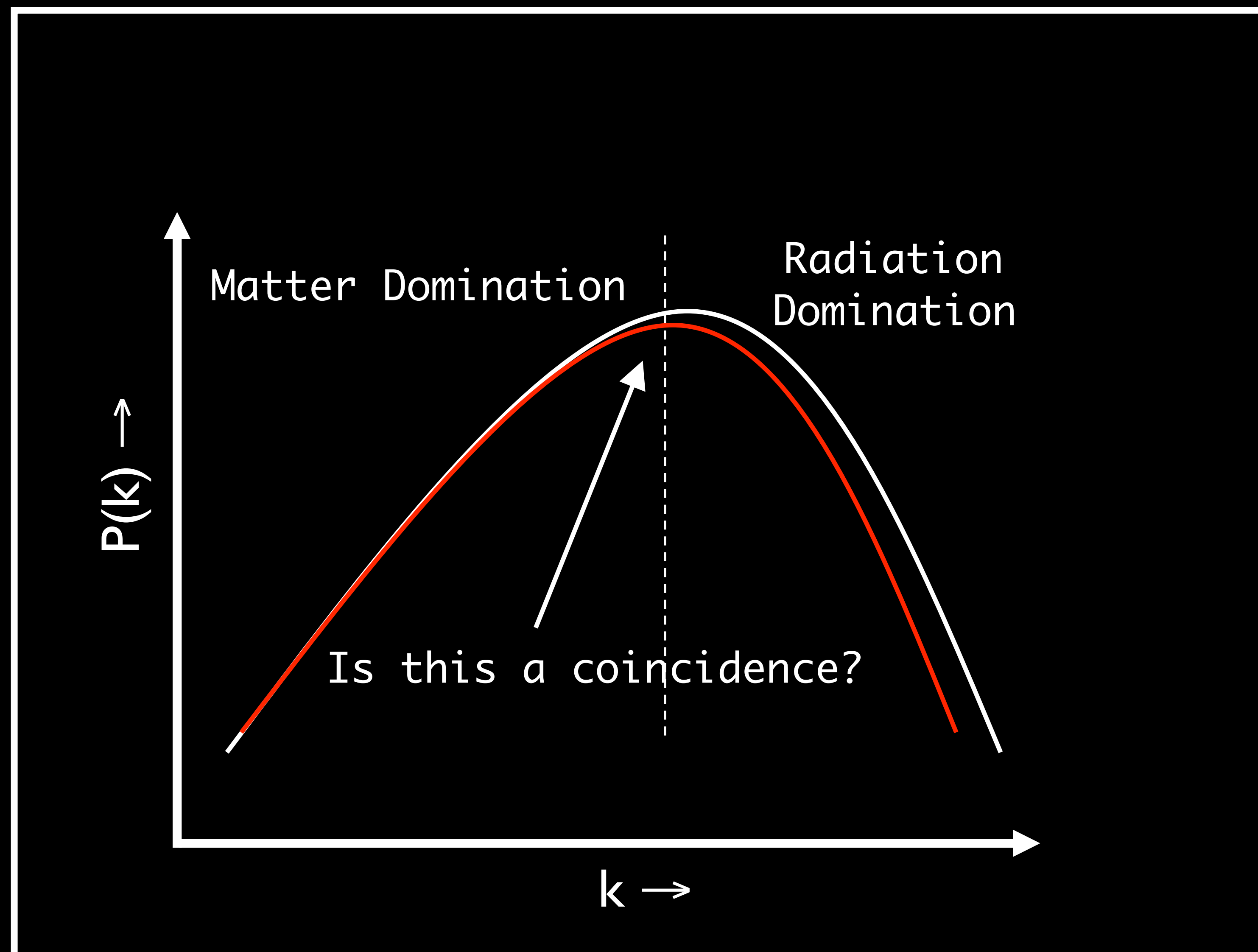
(Assuming thermal equilibrium)

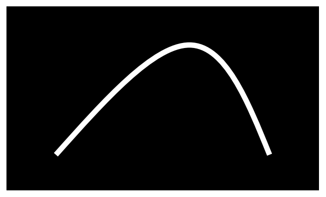


How does  probe neutrinos?

$$n_\nu = N_\nu \times \left(\frac{3}{11}\right) n_\gamma \approx 340 \text{ cm}^{-3}$$

(Assuming thermal equilibrium)



How does  probe neutrinos?

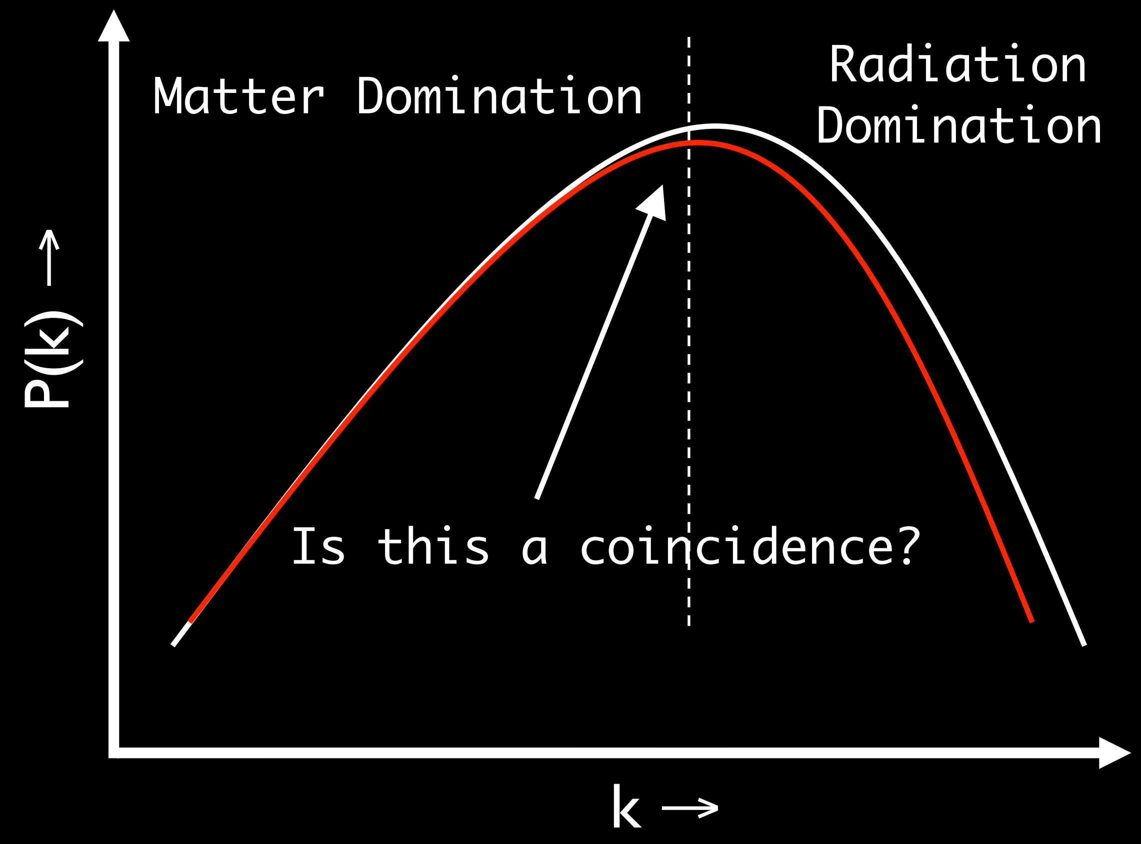
$$n_\nu = N_\nu \times \left(\frac{3}{11}\right) n_\gamma \approx 340\ \mathrm{cm}^{-3}$$

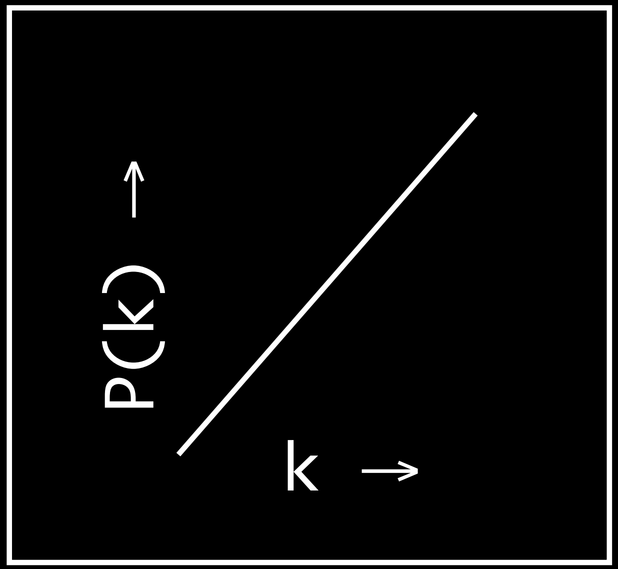
(Assuming thermal equilibrium)

$$\rho_\nu = \sum m_i n_{\nu_i}$$

$$\Omega_\nu \approx \frac{\sum m_{\nu_i}}{93\ h^2\ \mathrm{eV}}$$

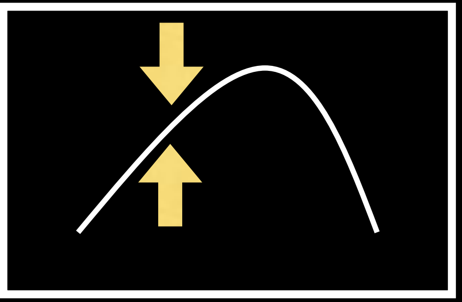
$$E^2 = p^2 + m^2$$





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

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

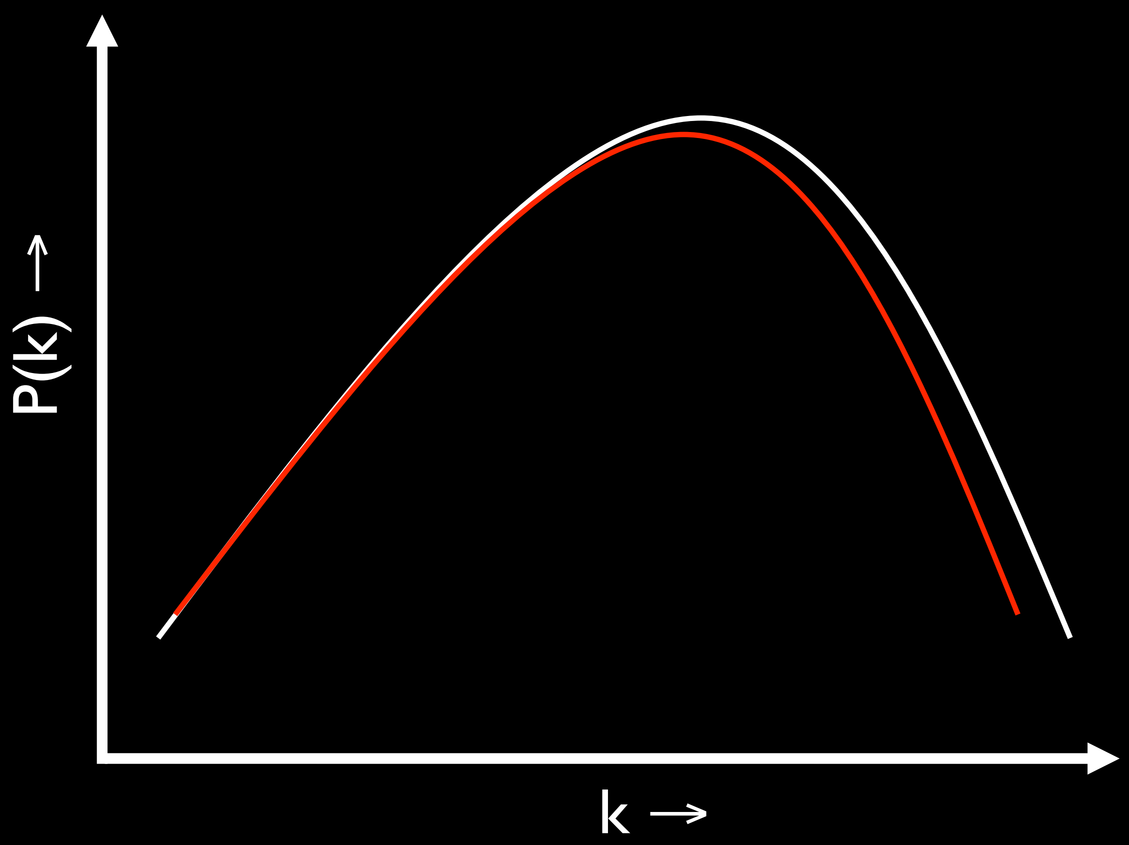


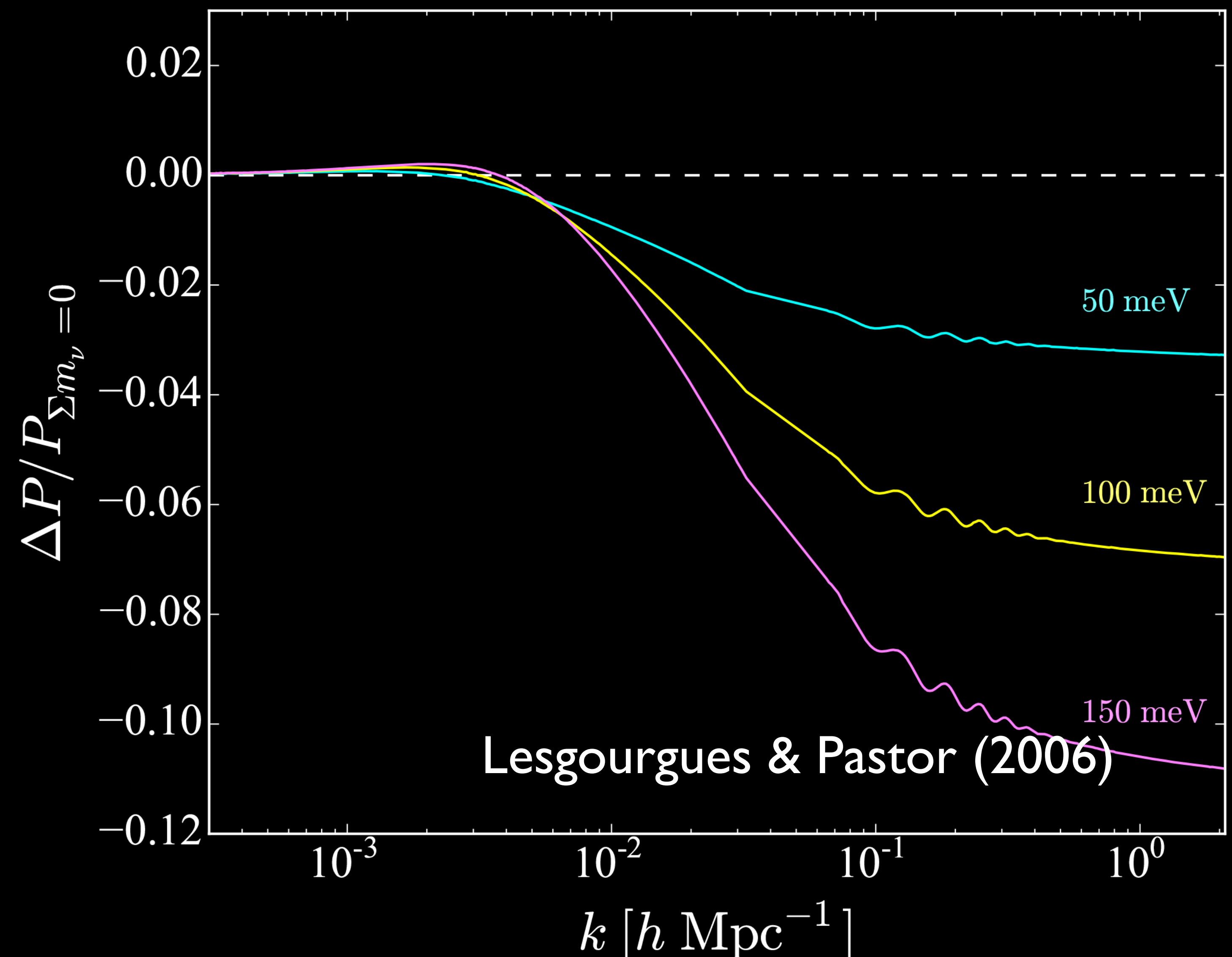
Planck Collaboration 2015:

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

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

Distinguishing Features in the LSS Power Spectrum

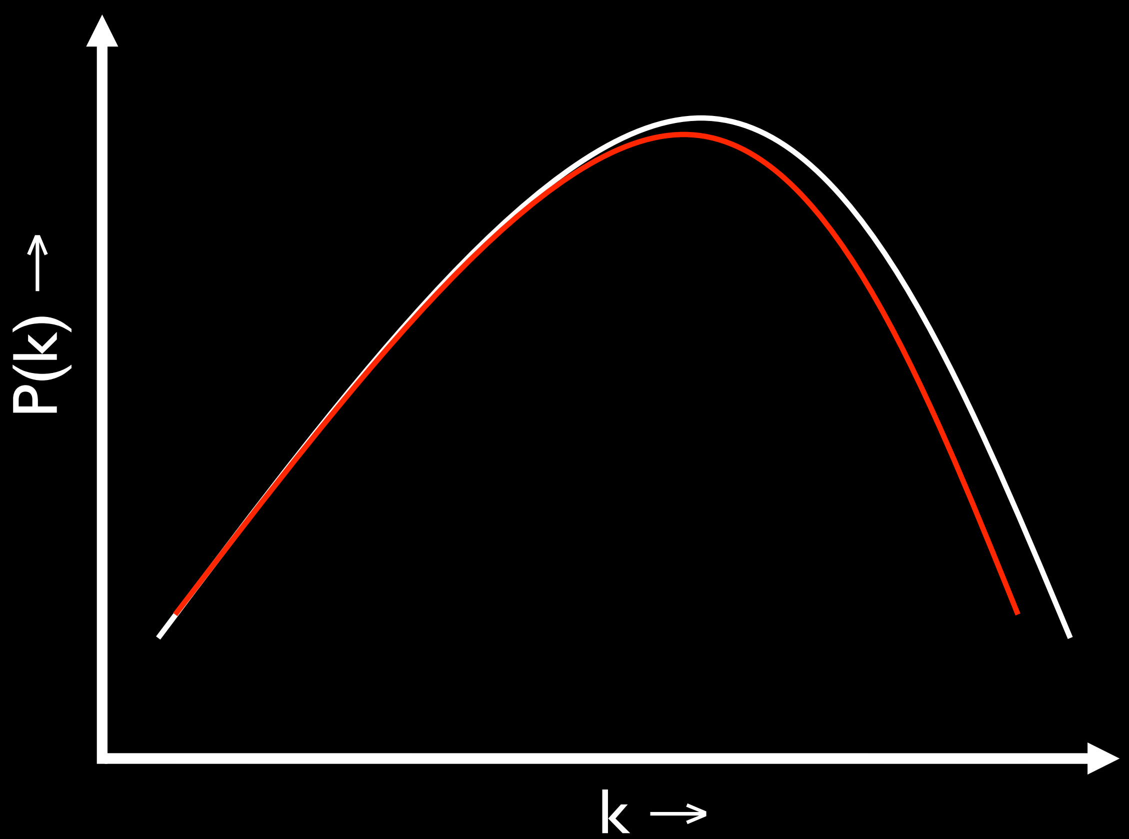


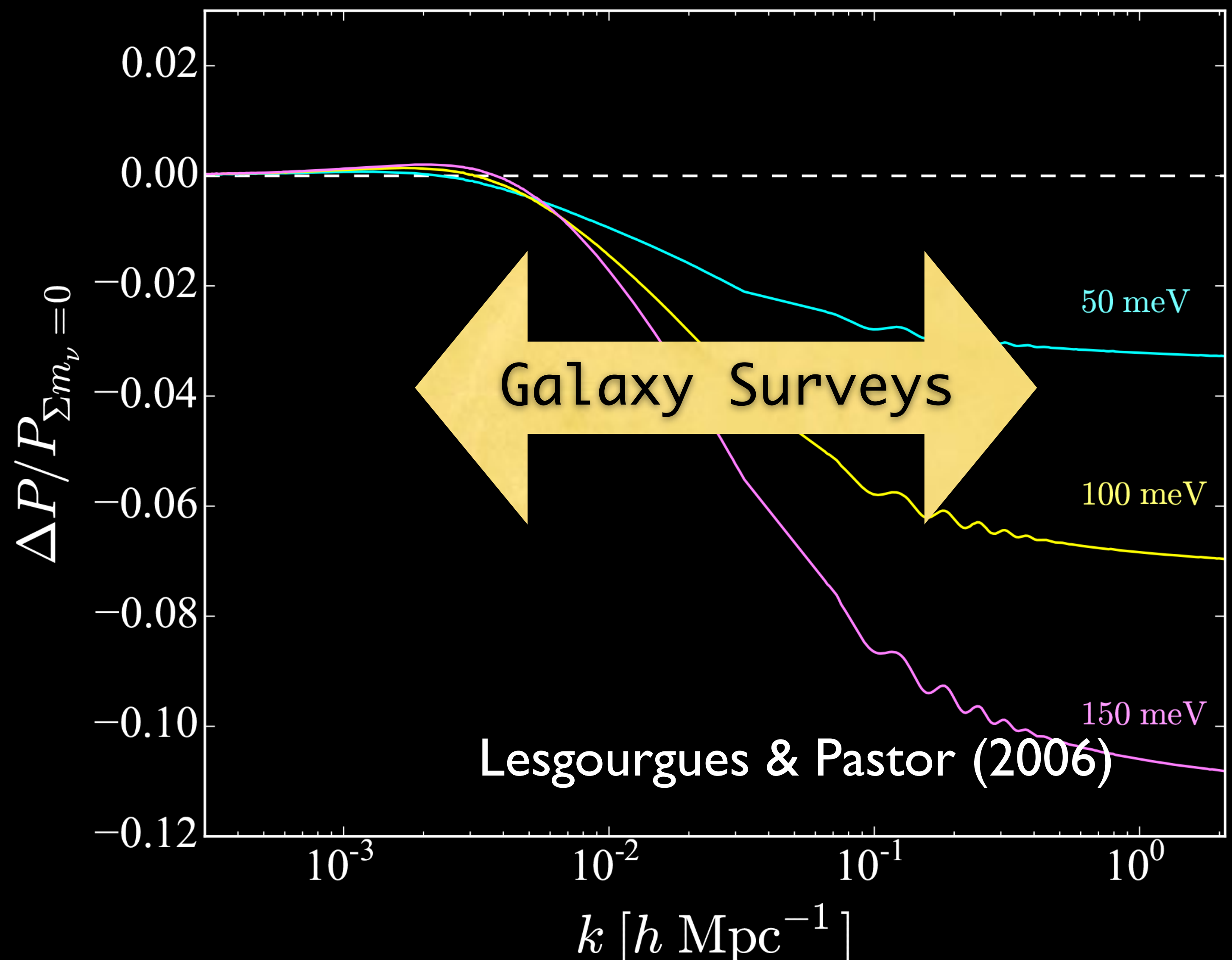


1. Shape Information:
   Galaxy Surveys, Weak Lensing (Future: CMB lensing)

2. Relative Amplitude Information:
   CMB plus Lyman-alpha Forest, Galaxy Bias $\frac{\Delta P(k)}{P(k)} = -8 \frac{\Omega_\nu}{\Omega_m}$

Distinguishing Features in the LSS Power Spectrum

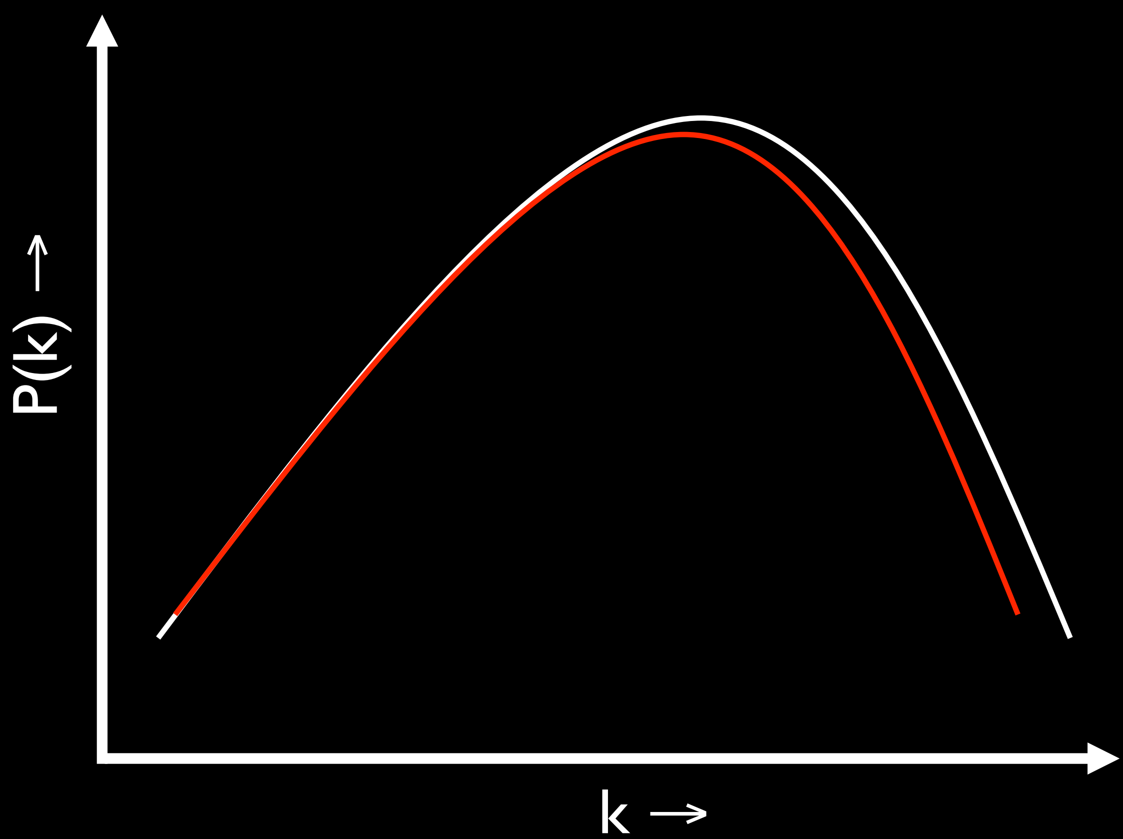


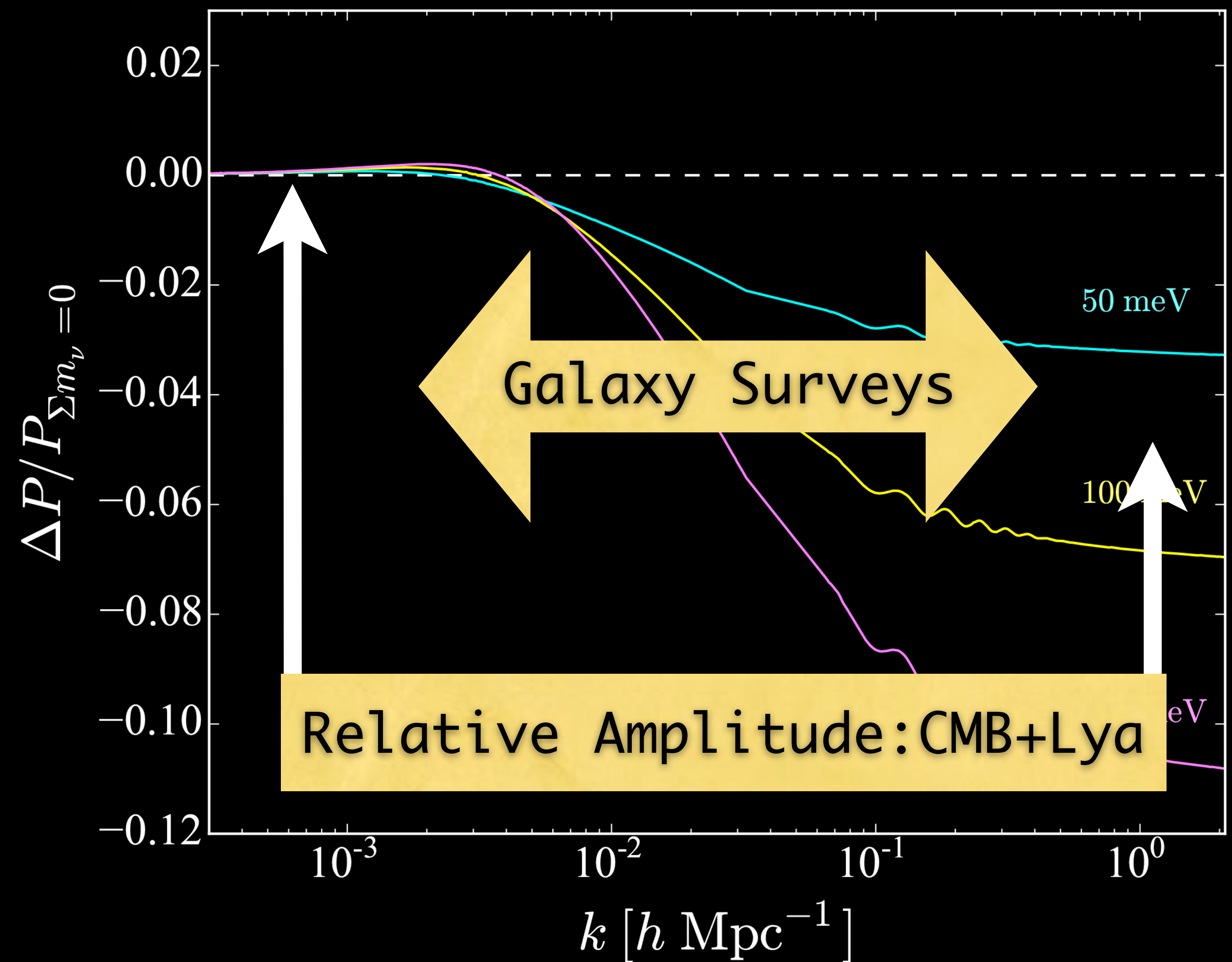


1. Shape Information:
   Galaxy Surveys, Weak Lensing (Future: CMB lensing)

2. Relative Amplitude Information:
   CMB plus Lyman-alpha Forest, Galaxy Bias $\frac{\Delta P(k)}{P(k)} = -8\frac{\Omega_\nu}{\Omega_m}$

Distinguishing Features in the LSS Power Spectrum

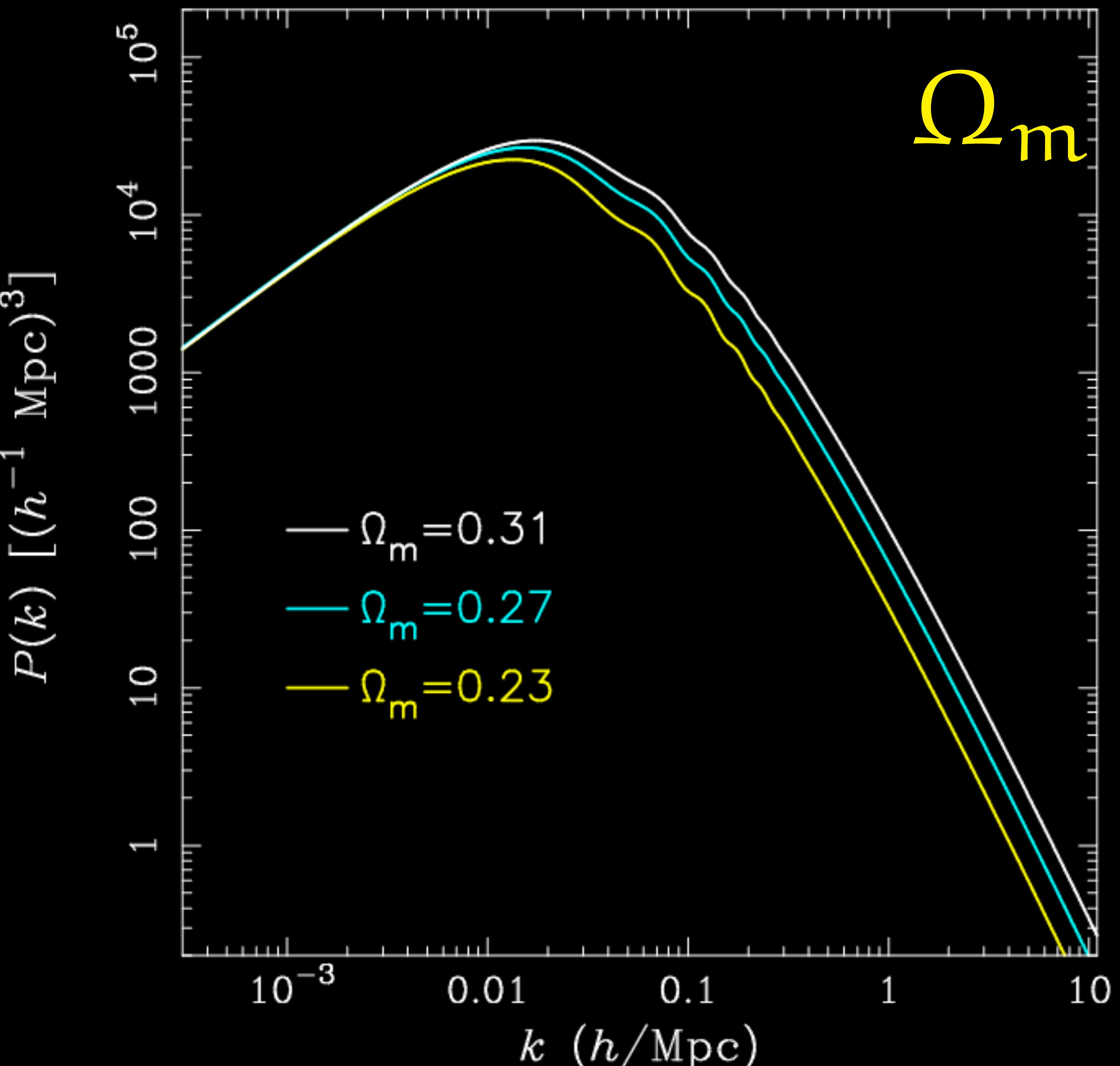




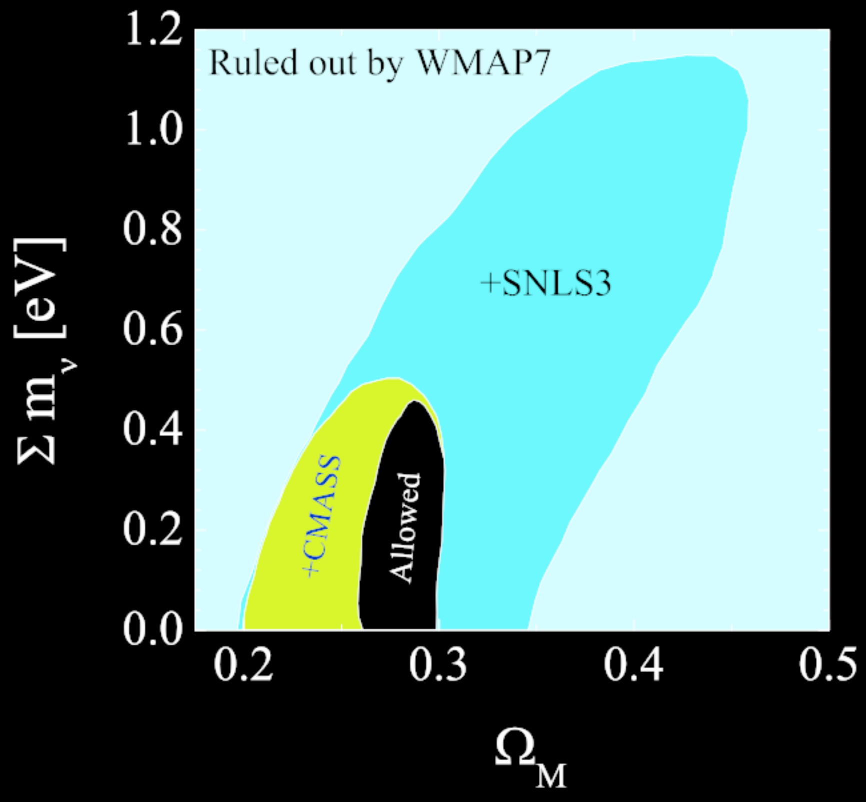
1. Shape Information:
   Galaxy Surveys, Weak Lensing (Future: CMB lensing)

2. Relative Amplitude Information:
   CMB plus Lyman-alpha Forest, Galaxy Bias $\frac{\Delta P(k)}{P(k)} = -8\frac{\Omega_\nu}{\Omega_m}$

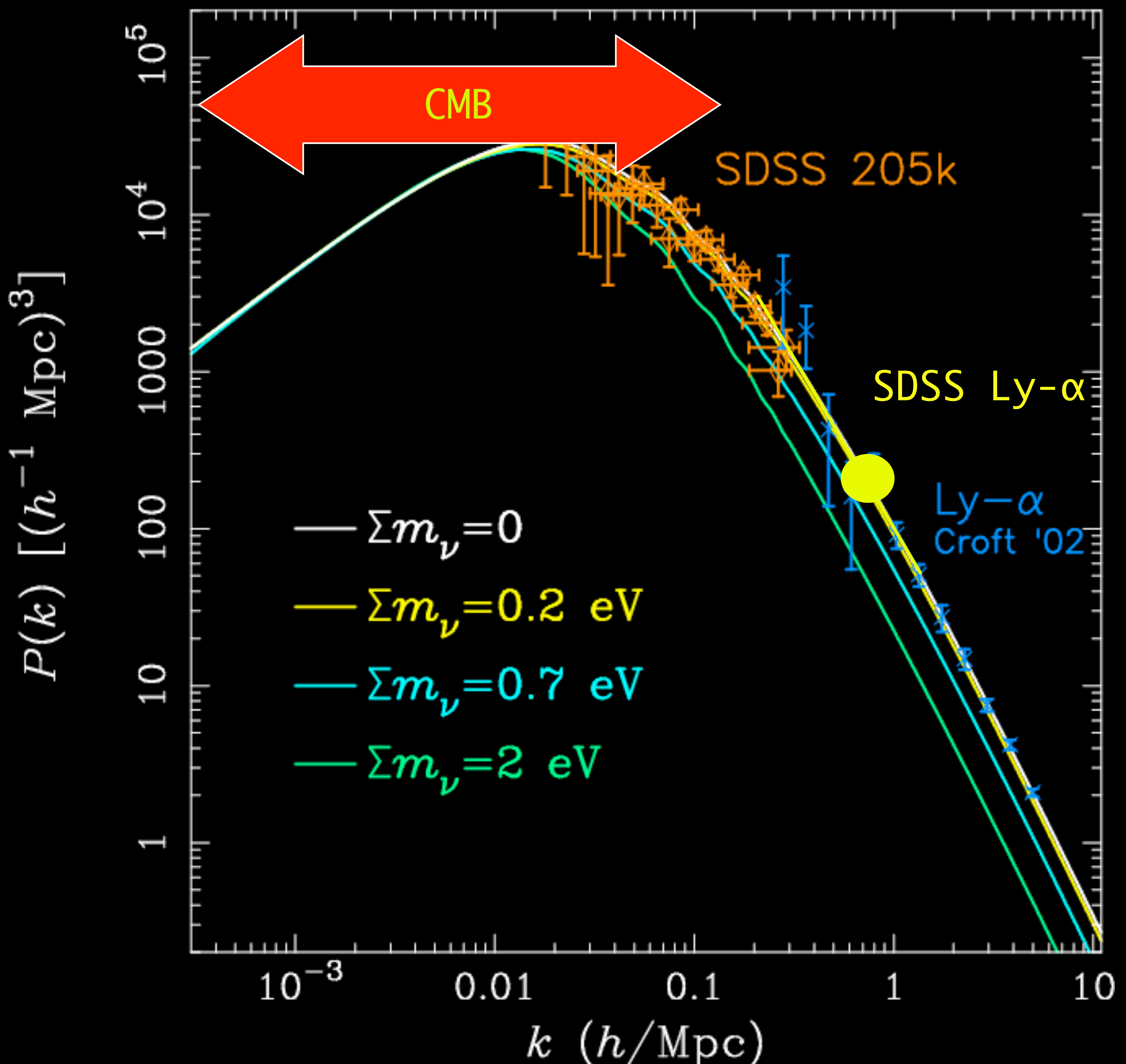
Ω_m & Other Parameter Degeneracy



Included!

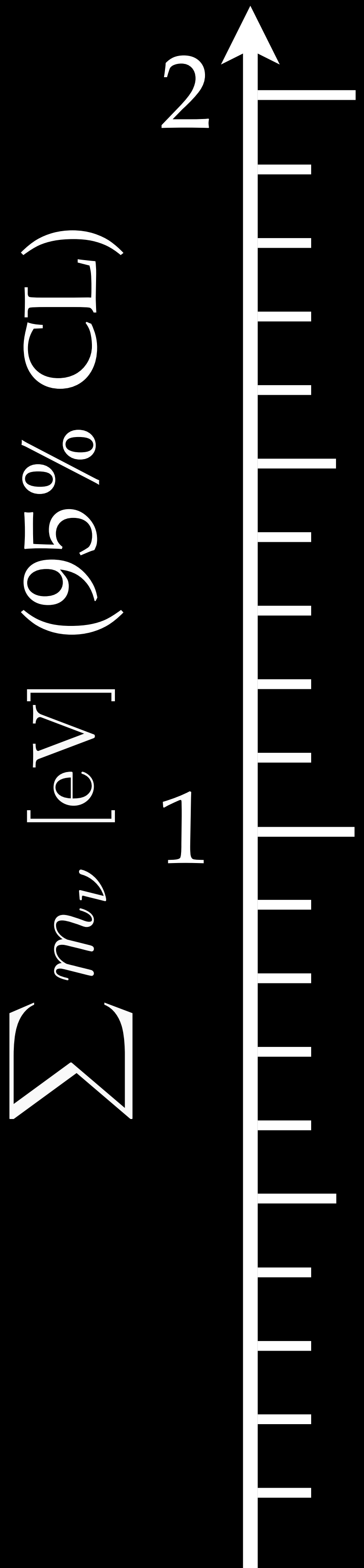


Neutrino Mass and Large Scale Structure: $P(k)$

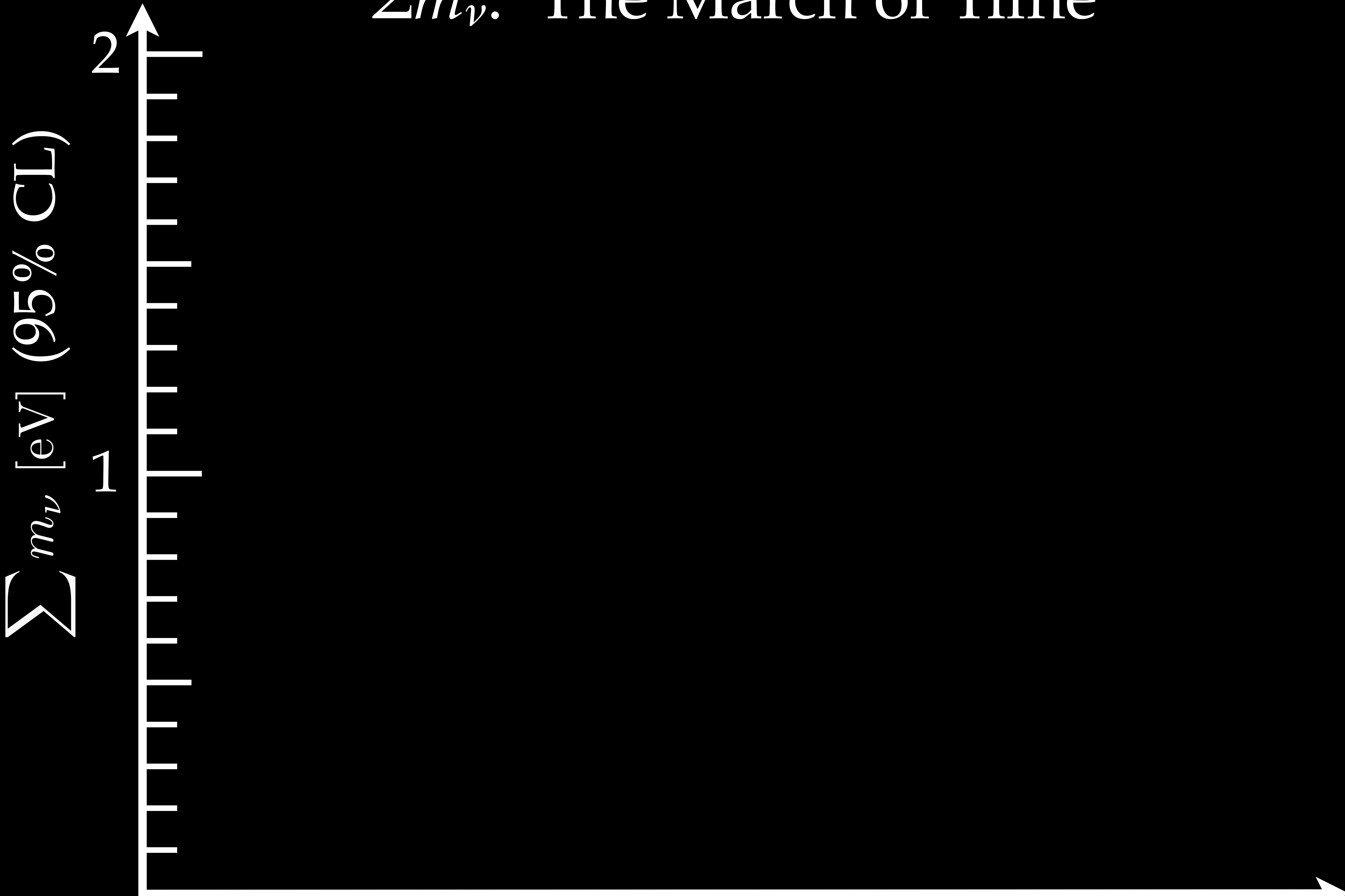


Σm_ν: The March of Time

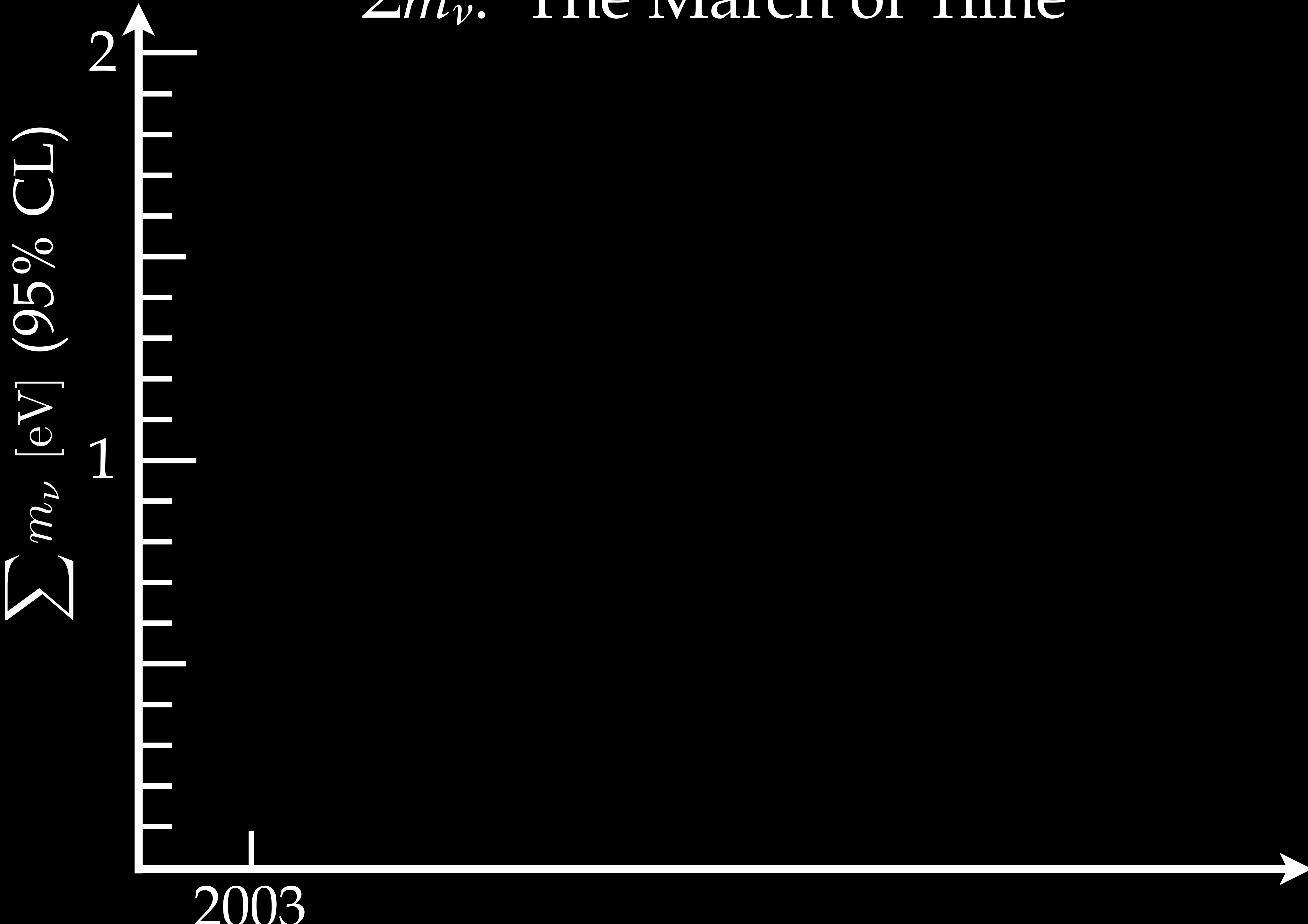
Σm_ν: The March of Time



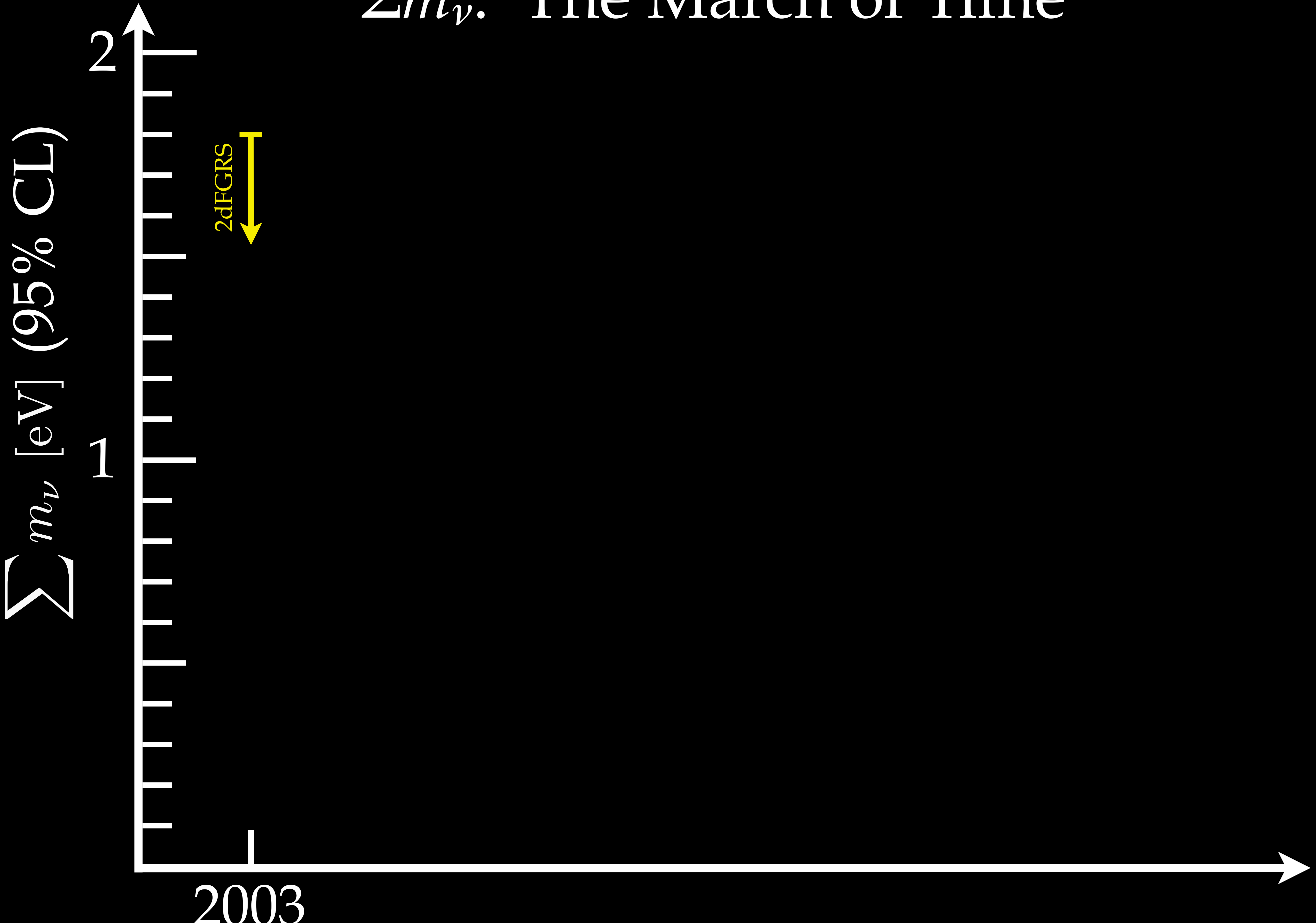
Σm_ν: The March of Time



Σm_ν: The March of Time

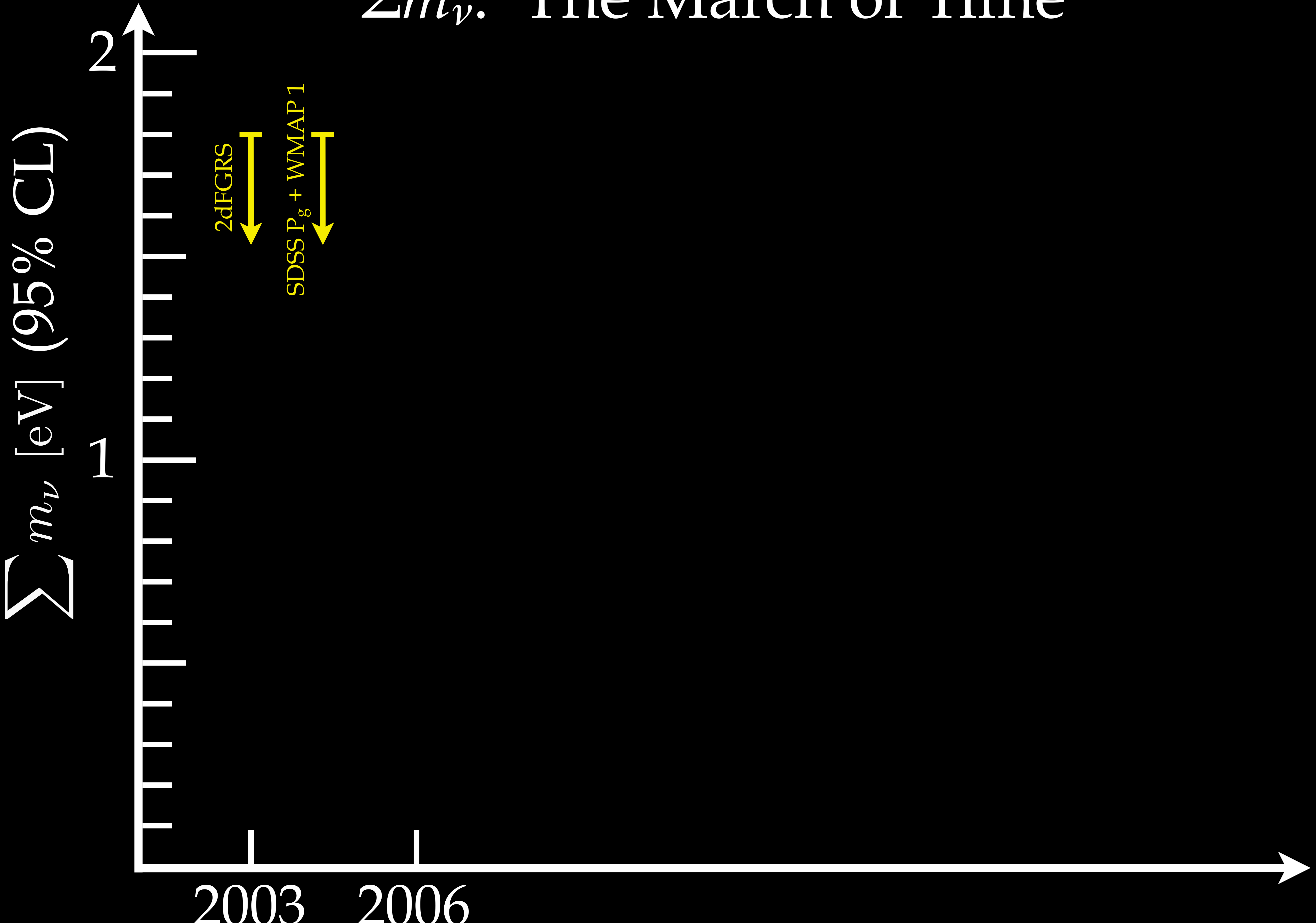


Σm_ν: The March of Time

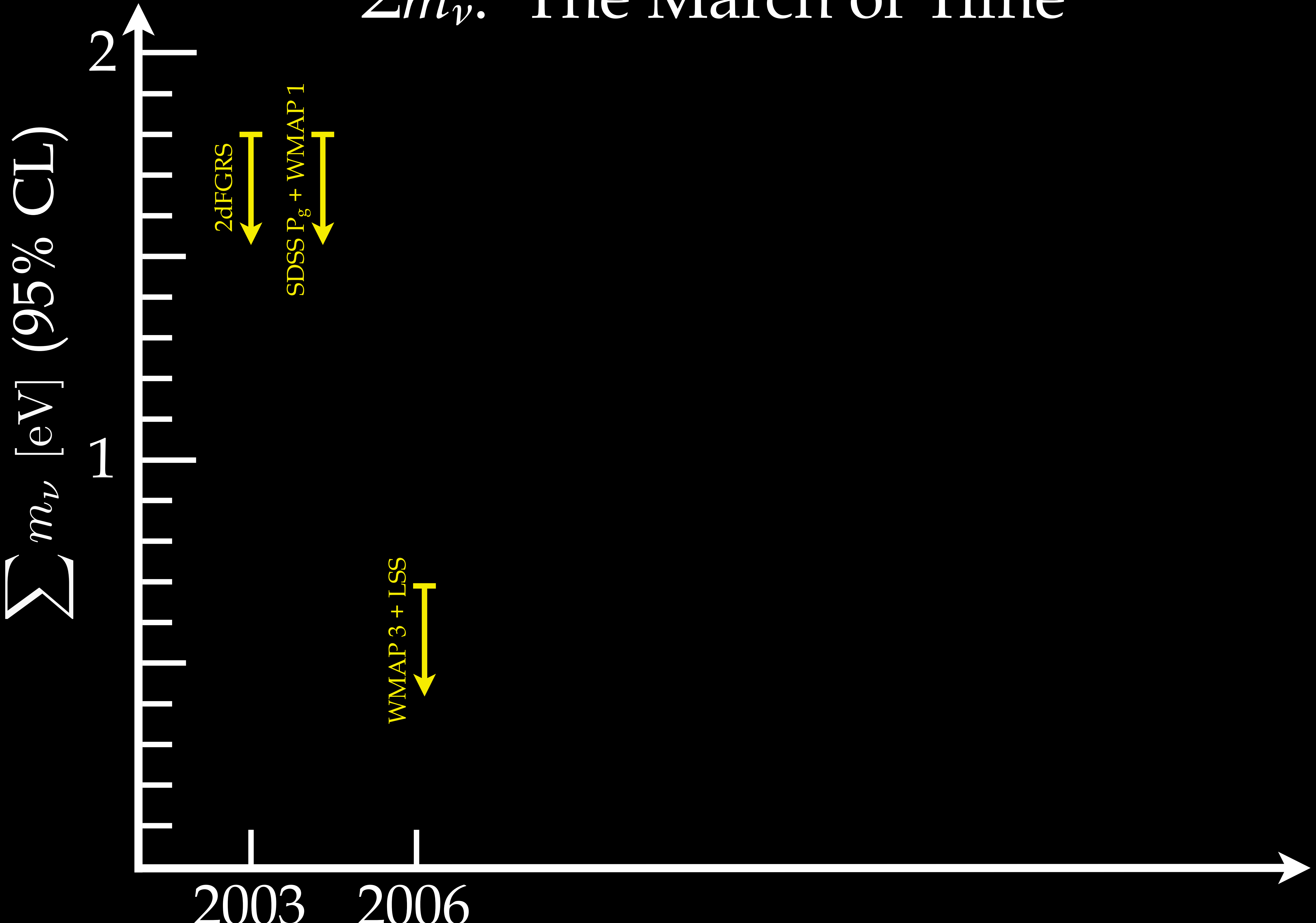


Σm_ν: The March of Time

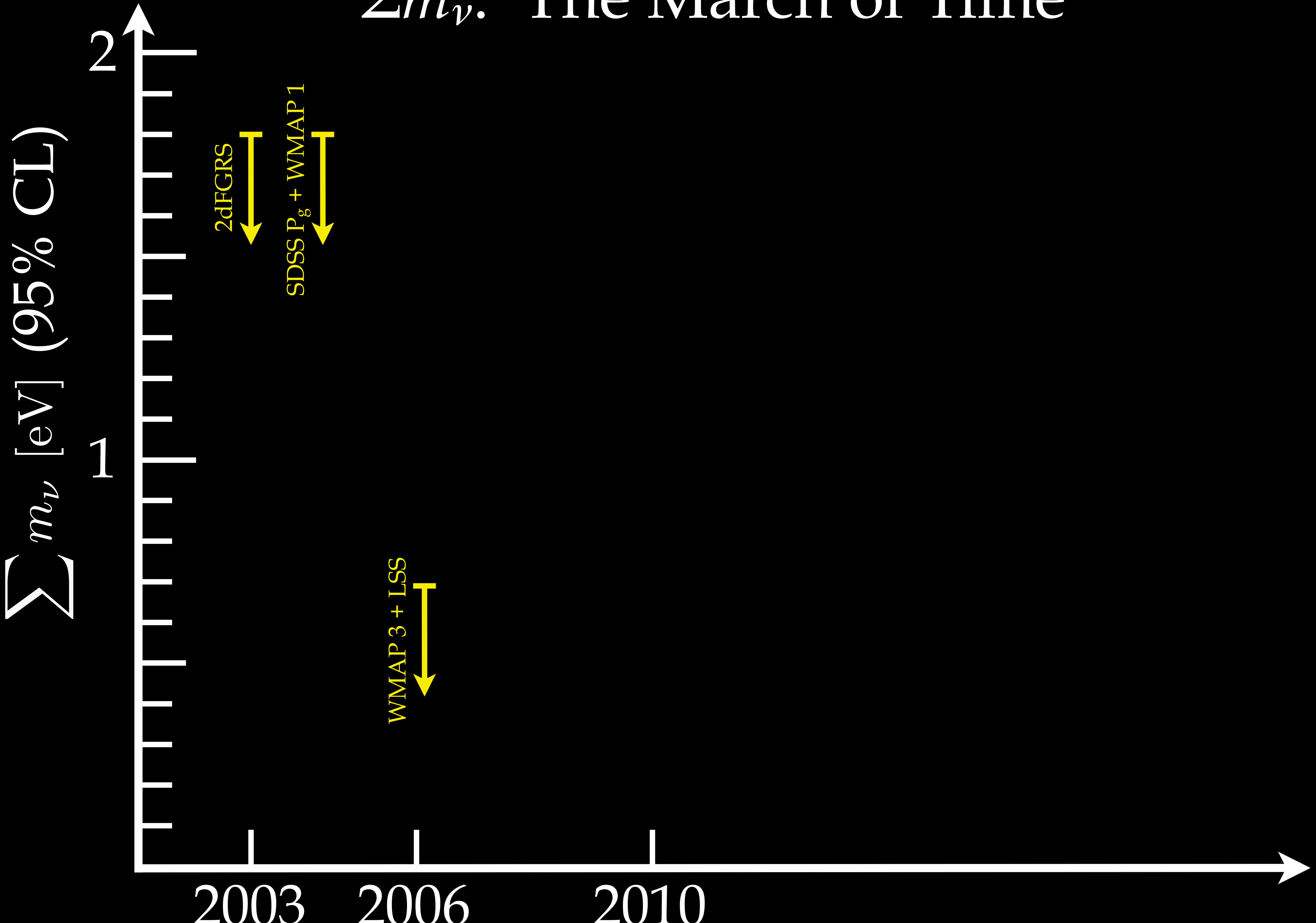
Σm_ν: The March of Time



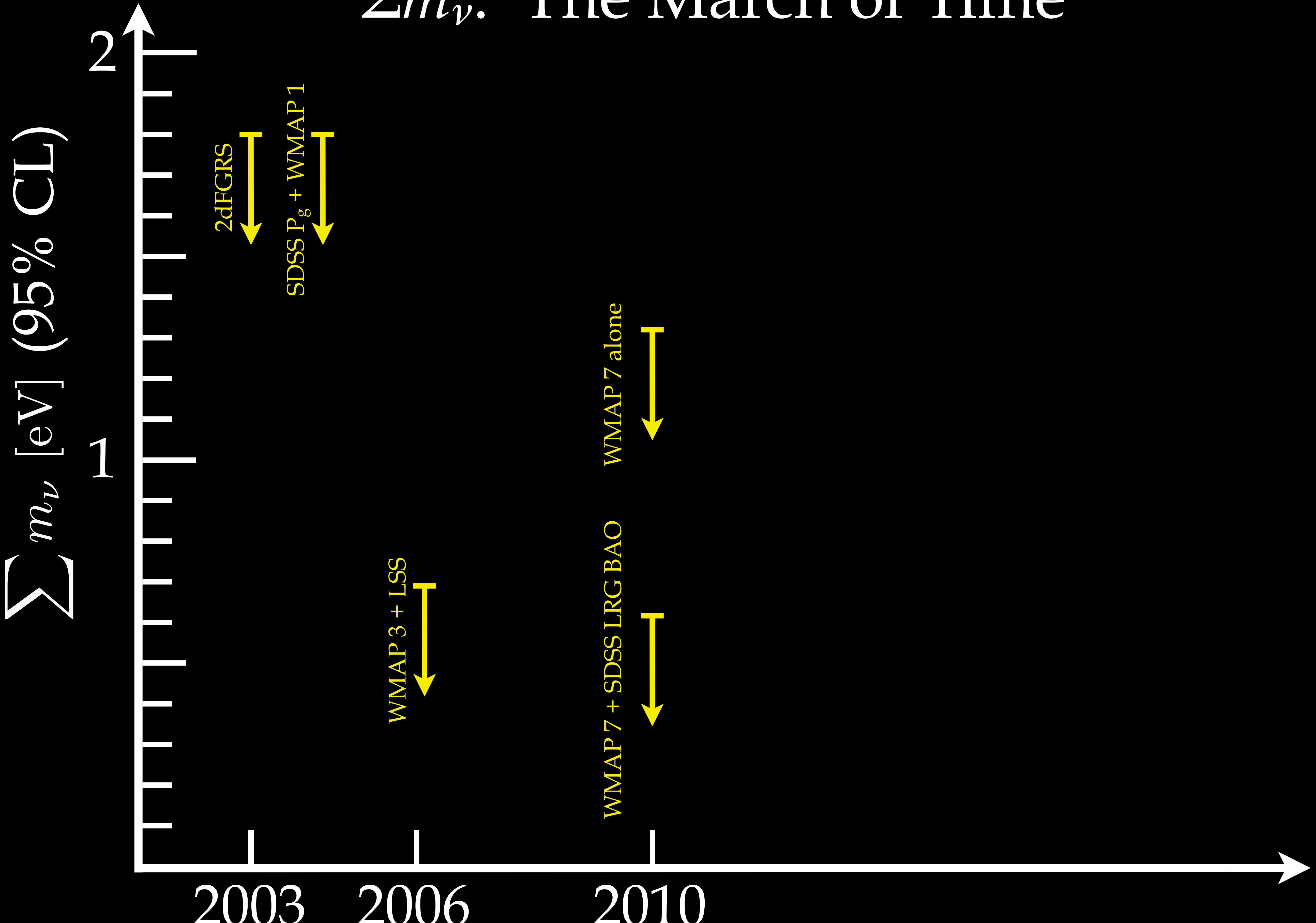
Σm_ν: The March of Time

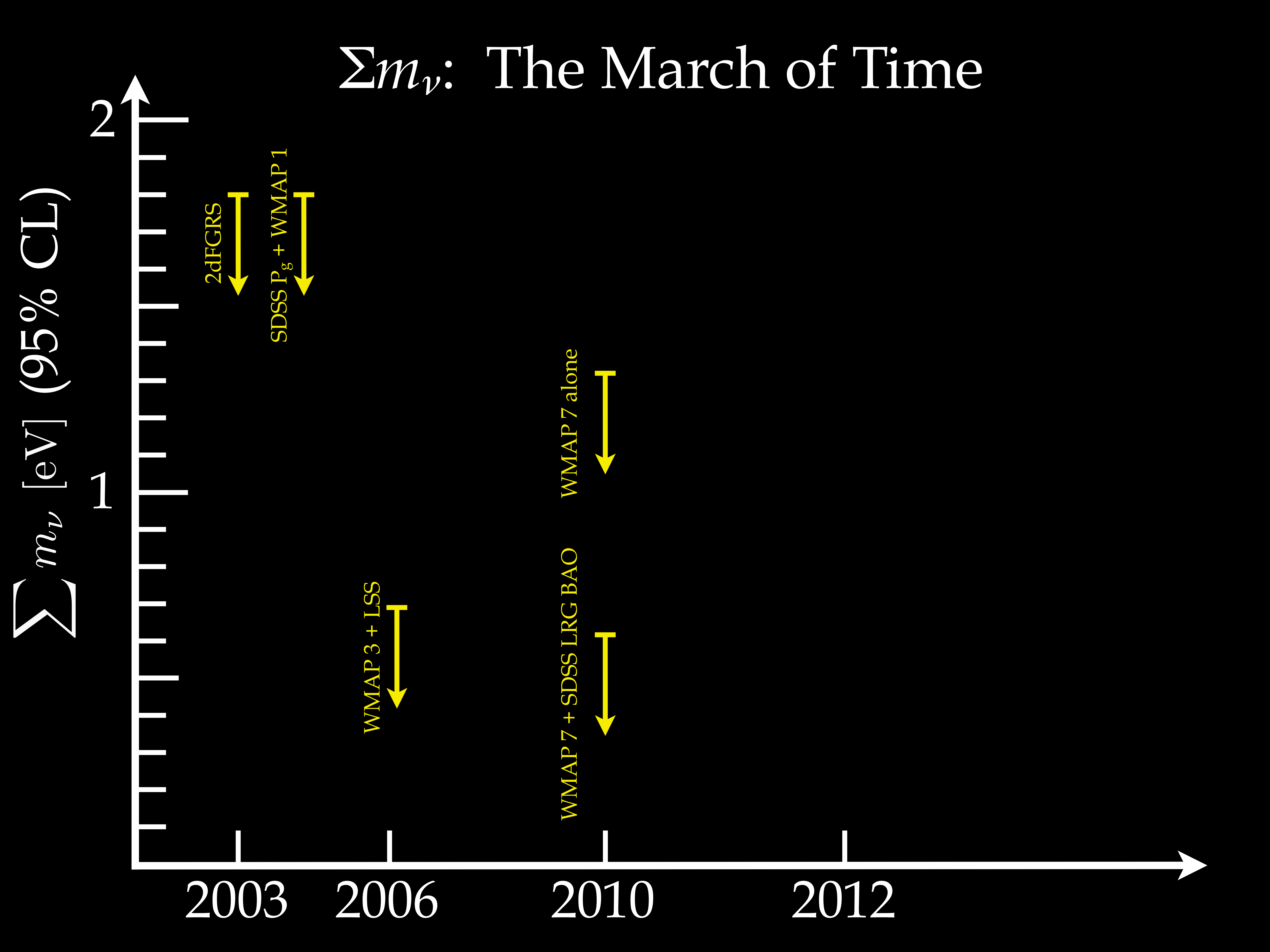


Σm_ν: The March of Time



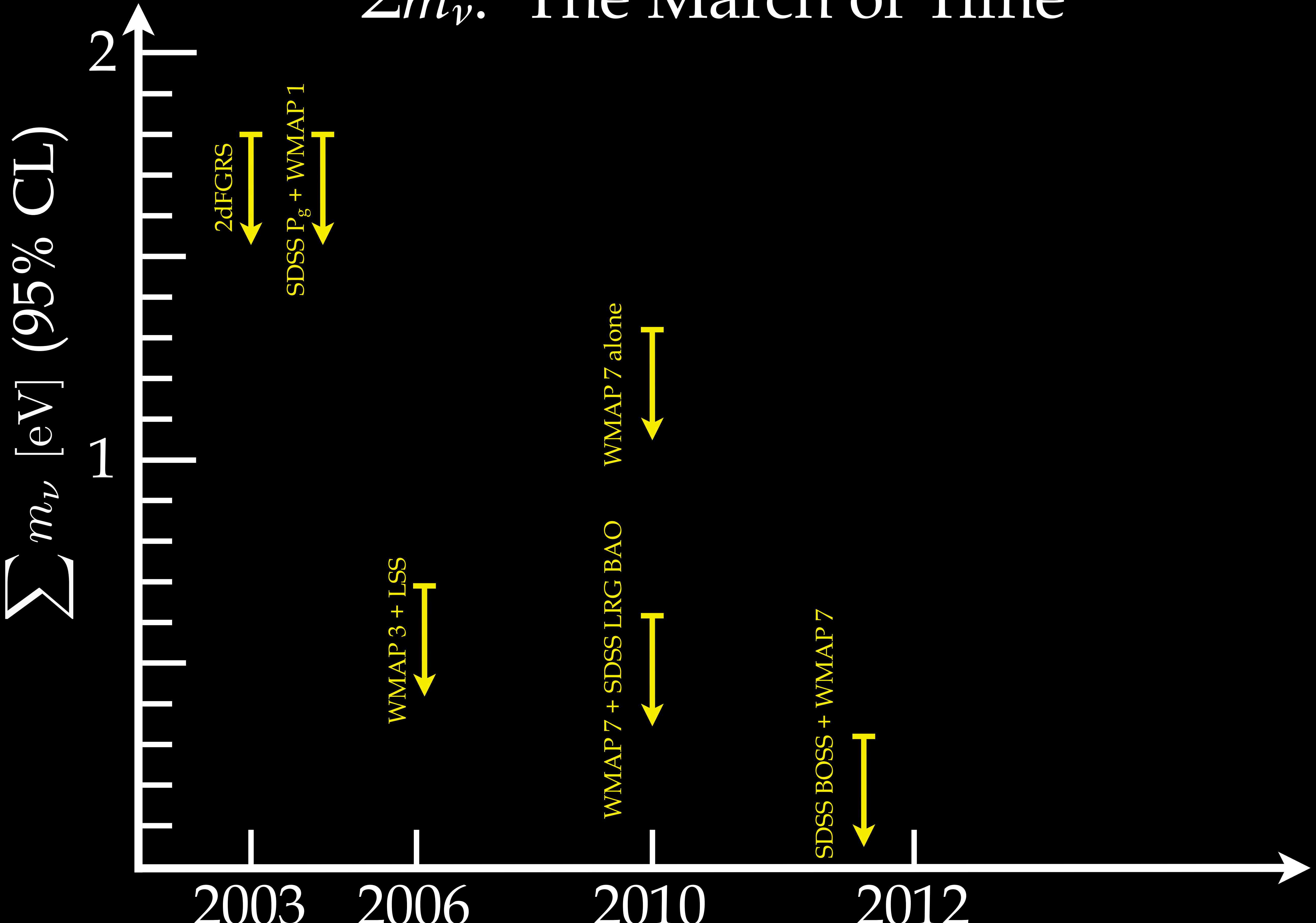
Σm_ν: The March of Time

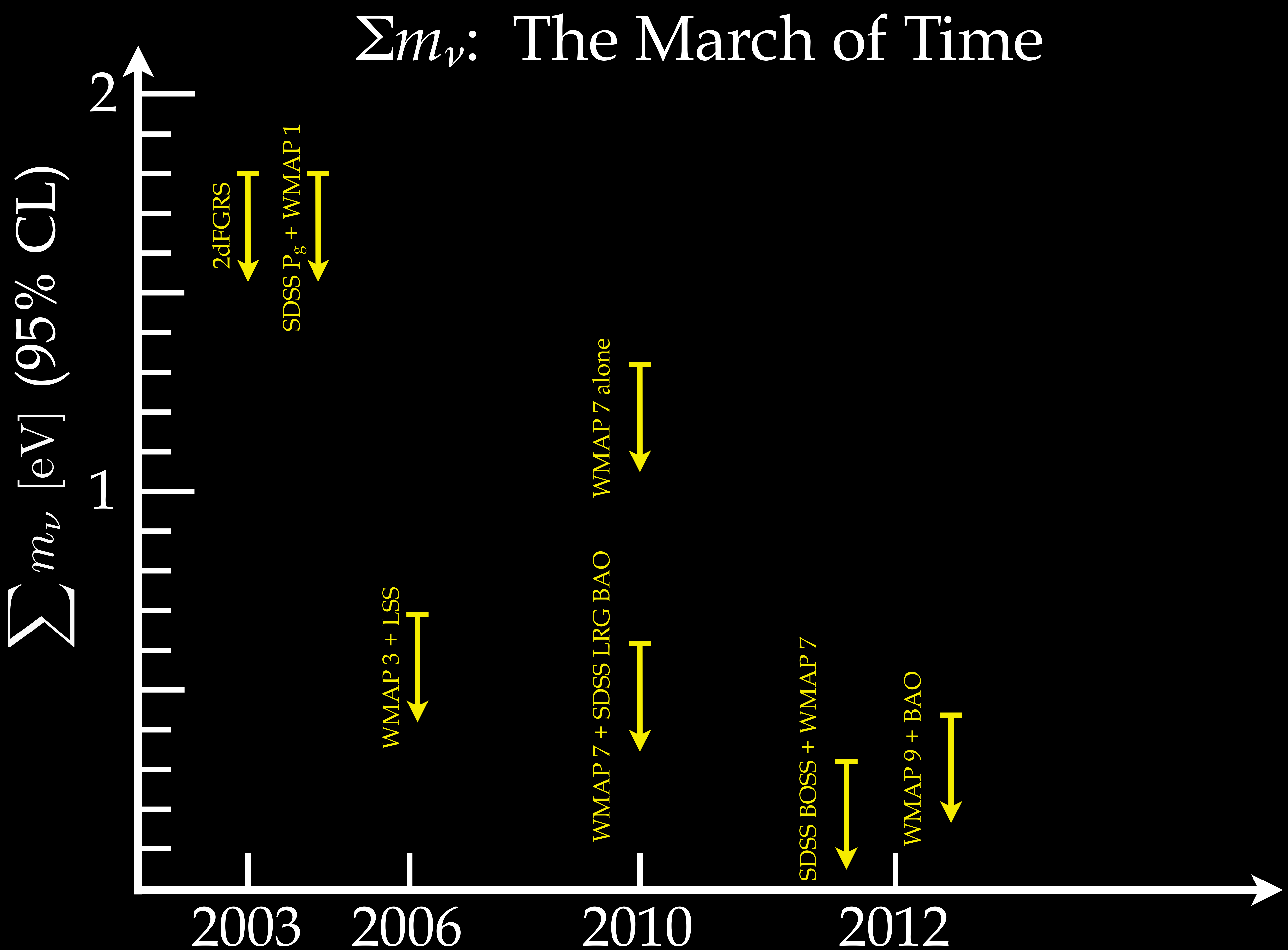




Σm_ν: The March of Time
$\sum m_\nu$ [eV] (95% CL)
2
1
2dFGRS
SDSS P_g + WMAP 1
WMAP 3 + LSS
WMAP 7 alone
WMAP 7 + SDSS LRG BAO
2003
2006
2010
2012

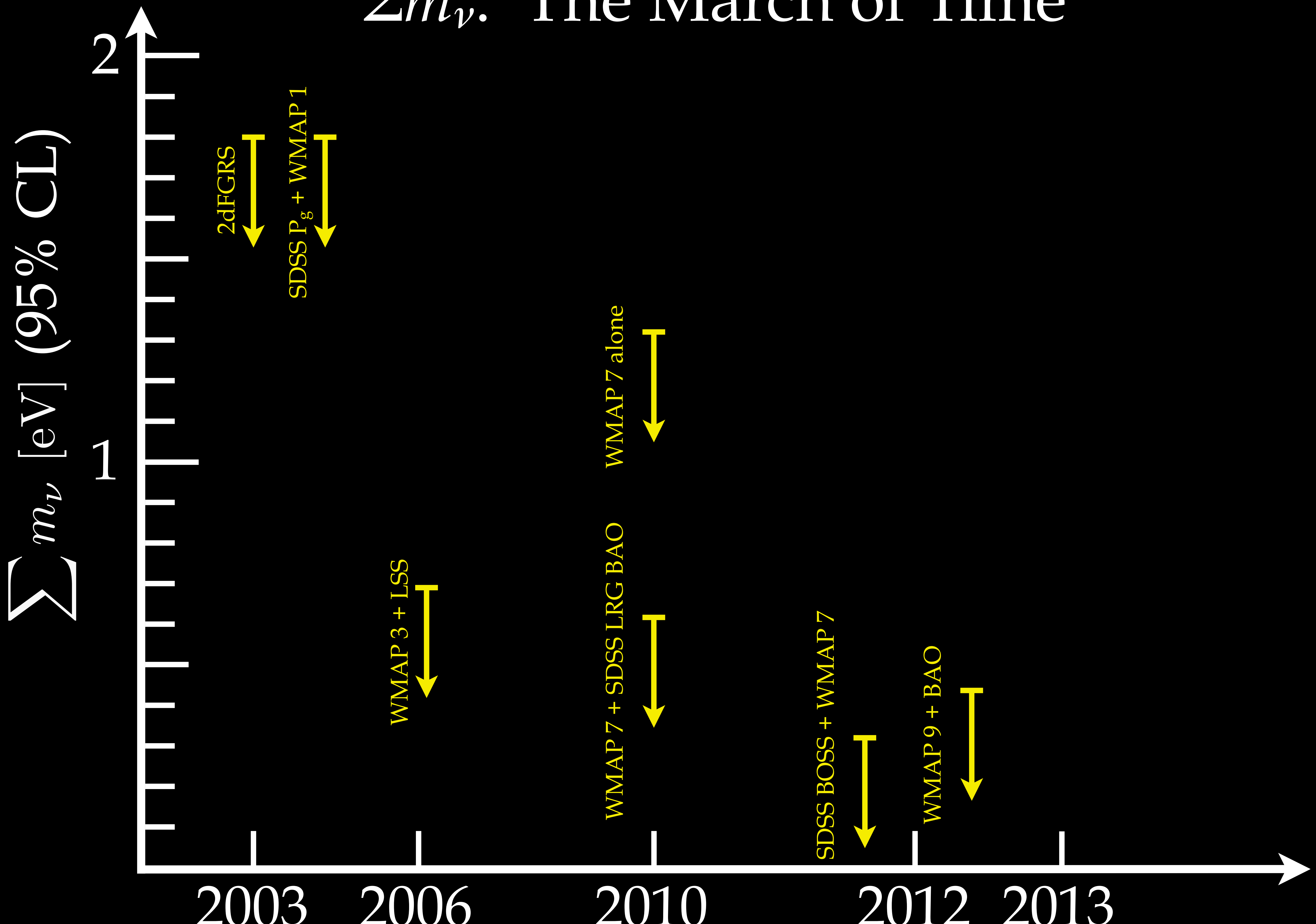
Σm_ν: The March of Time



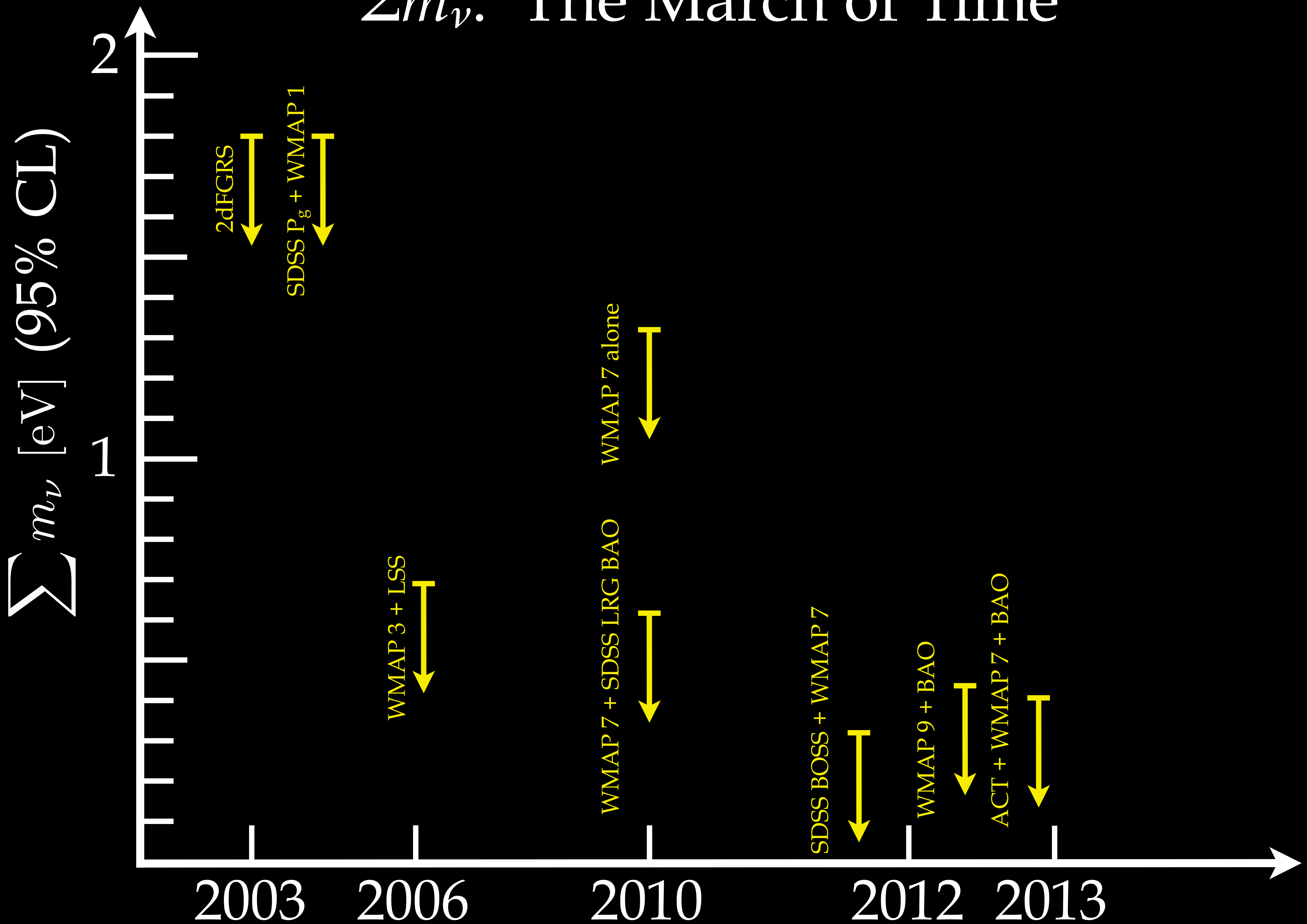


Σm_ν: The March of Time
$\sum m_\nu$ [eV] (95% CL)
2
1
2dFGRS
SDSS P_g + WMAP 1
WMAP 3 + LSS
WMAP 7 alone
WMAP 7 + SDSS LRG BAO
SDSS BOSS + WMAP 7
WMAP 9 + BAO
2003
2006
2010
2012

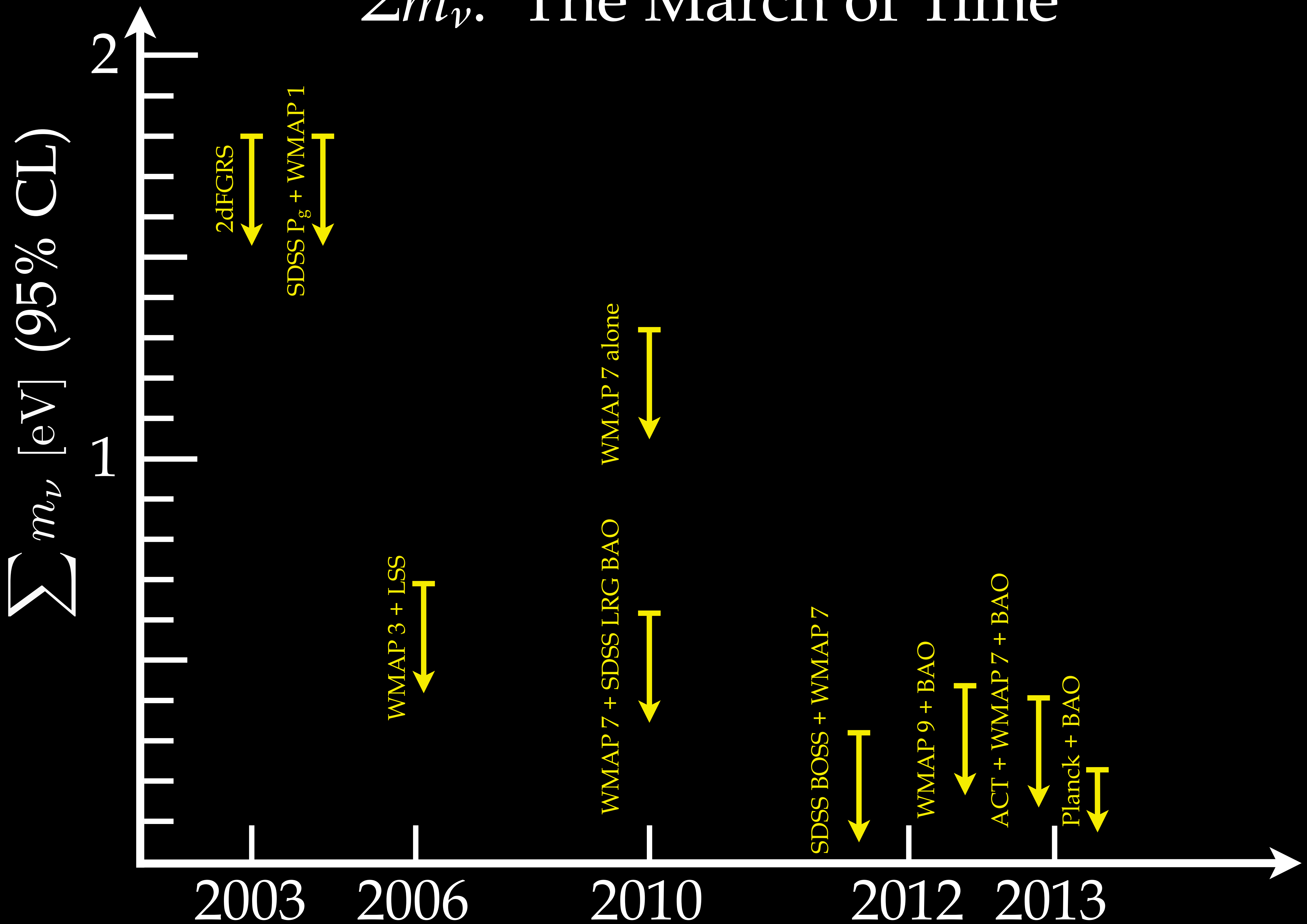
Σm_ν: The March of Time

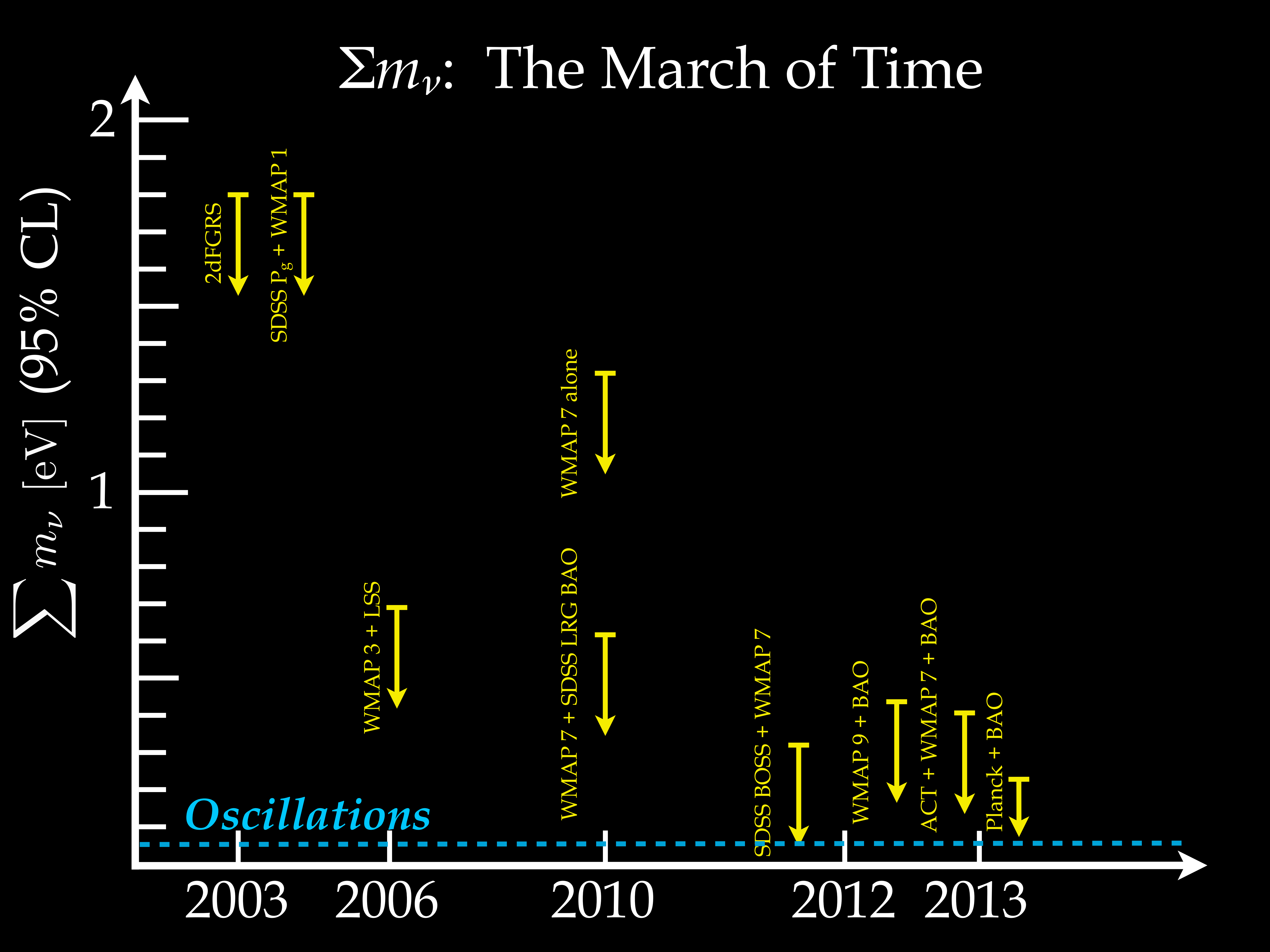


Σm_ν: The March of Time



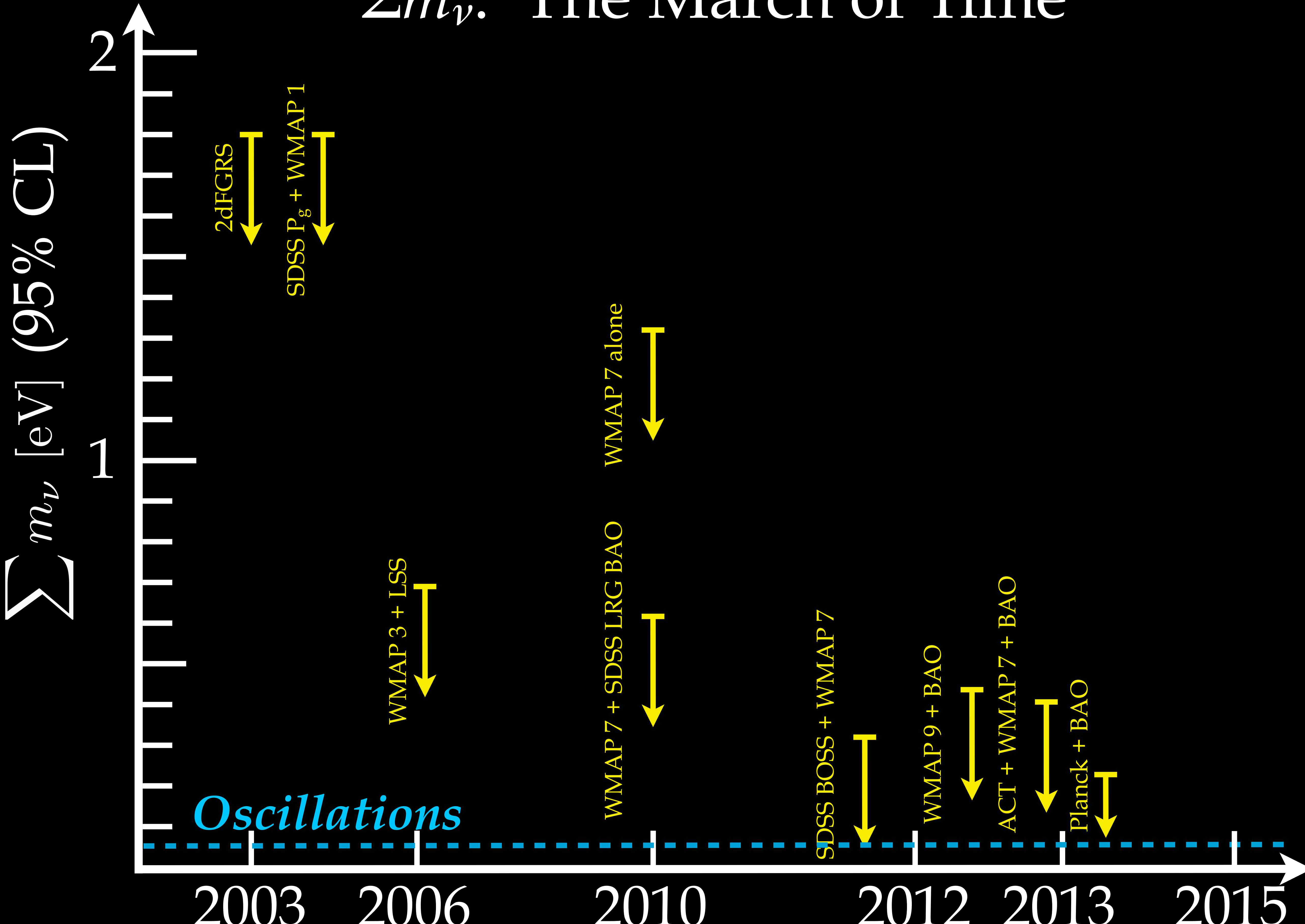
Σm_ν: The March of Time

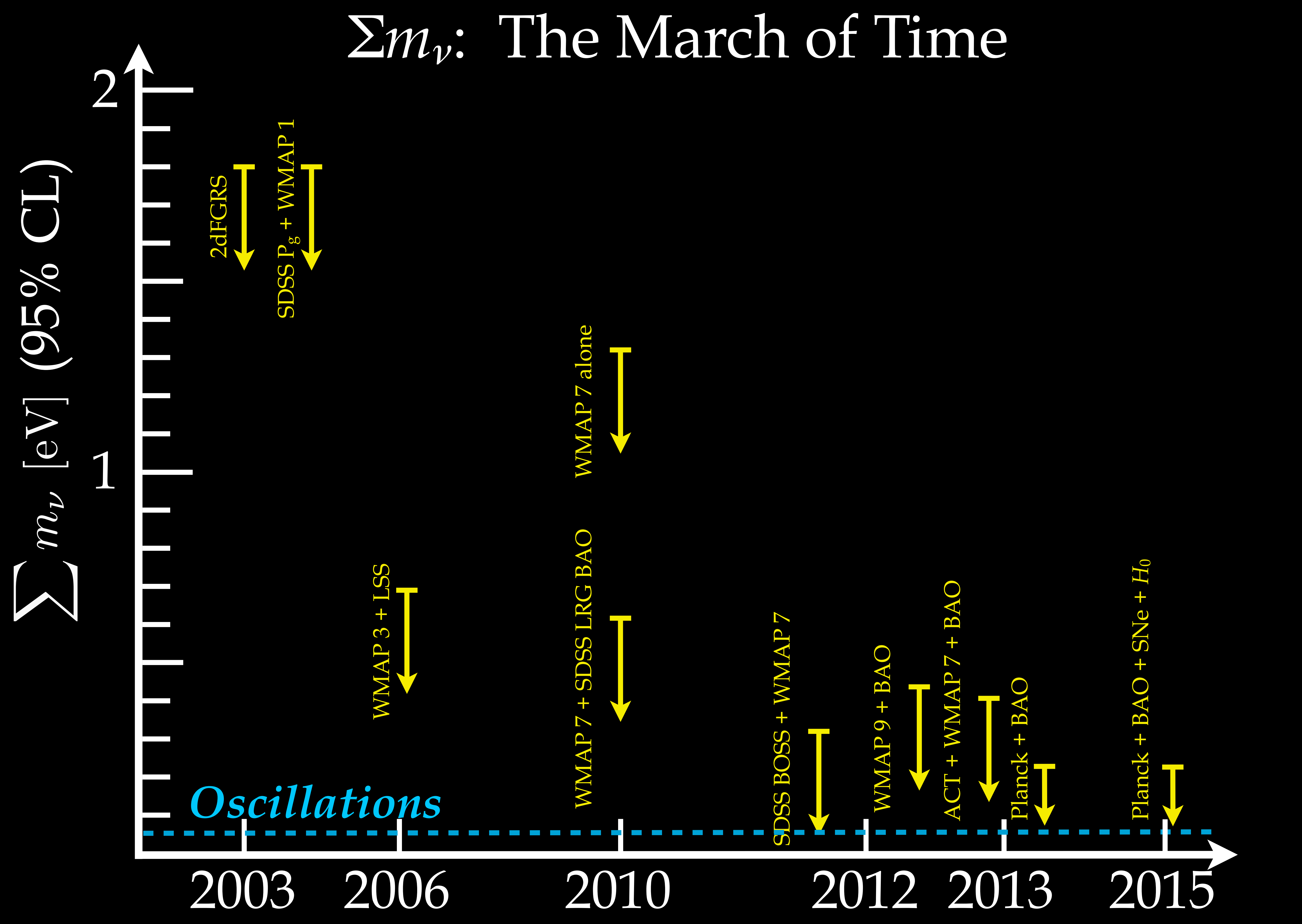




Σm_ν: The March of Time
$\sum m_\nu$ [eV] (95% CL)
2
1
2dFGRS
SDSS P_g + WMAP 1
WMAP 3 + LSS
WMAP 7 alone
WMAP 7 + SDSS LRG BAO
SDSS BOSS + WMAP 7
WMAP 9 + BAO
ACT + WMAP 7 + BAO
Planck + BAO
Oscillations
2003
2006
2010
2012
2013

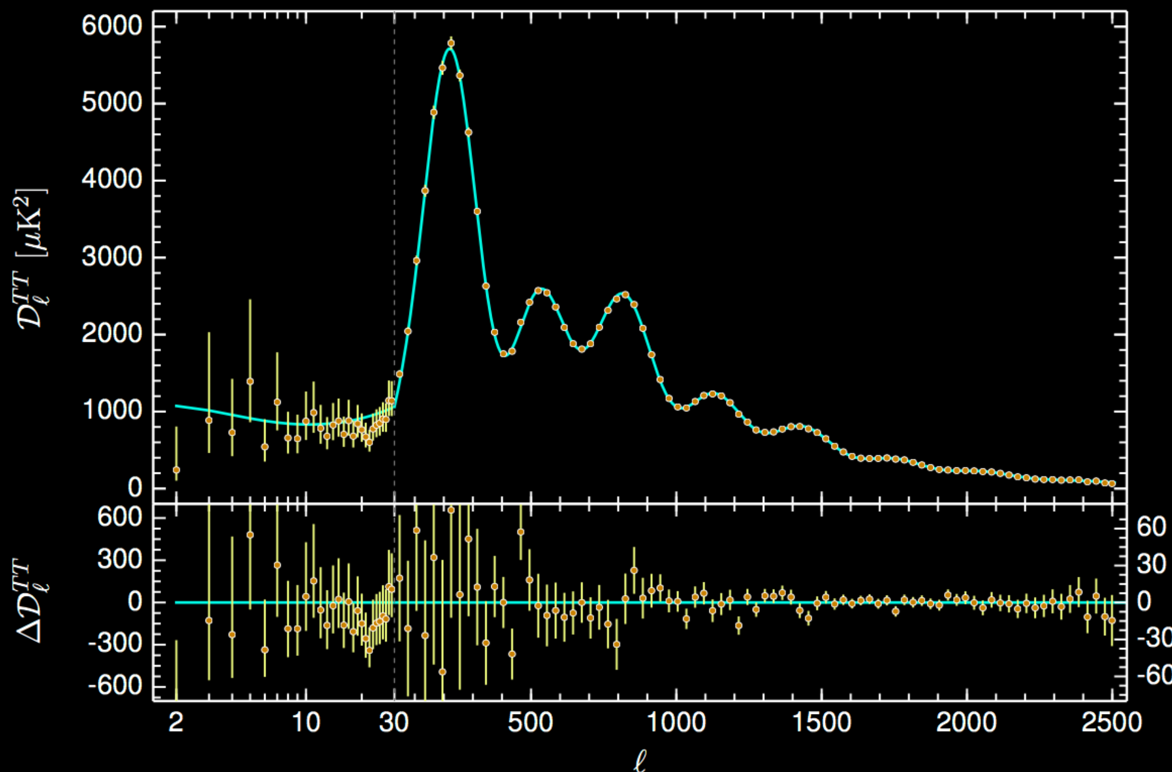
Σm_ν: The March of Time

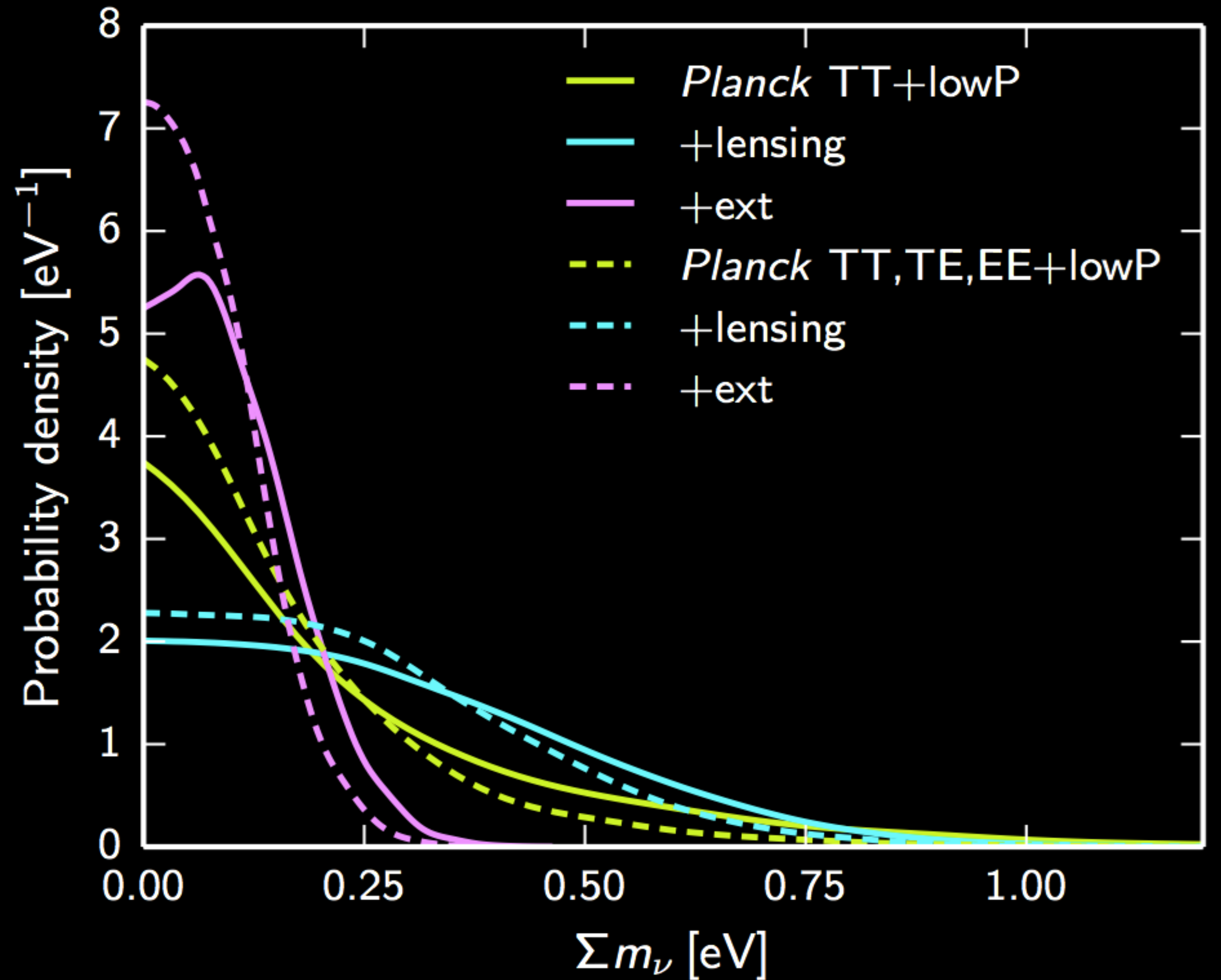




Σm_ν: The March of Time
$\sum m_\nu$ [eV] (95% CL)
2
1
2dFGRS
SDSS P_g + WMAP 1
WMAP 3 + LSS
WMAP 7 alone
WMAP 7 + SDSS LRG BAO
SDSS BOSS + WMAP 7
WMAP 9 + BAO
ACT + WMAP 7 + BAO
Planck + BAO
Planck + BAO + SNe + H_0
Oscillations
2003
2006
2010
2012
2013
2015

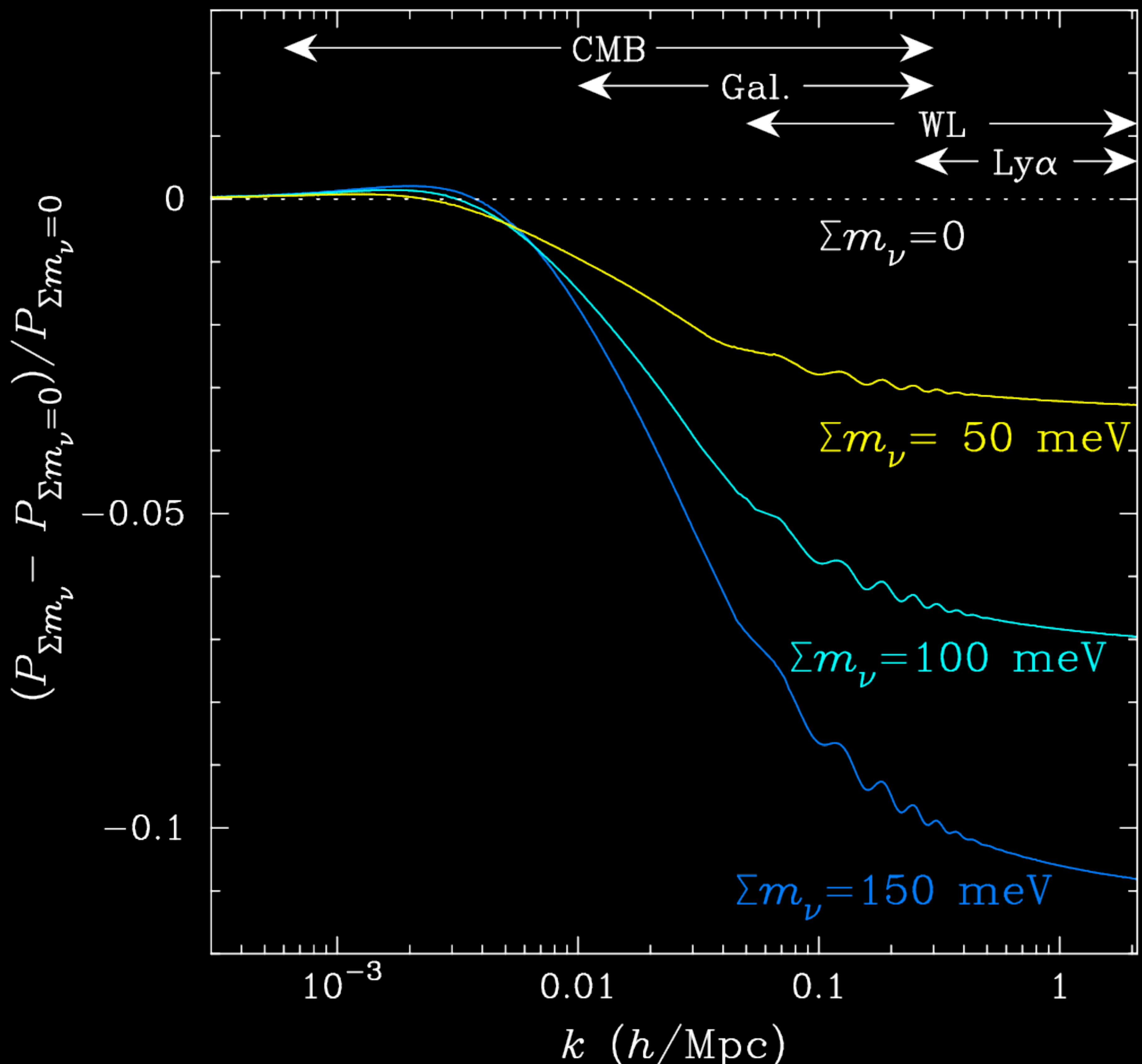
PLANCK **+ LSS** 2015 Ultimate **Σm_ν** Results





Planck CMB + BAO + SNe + H_0 : **$\Sigma m_\nu < 230$ meV (95%)**

Upcoming high-*k* High-Precision Era: Relative Change to *P*(*k*)



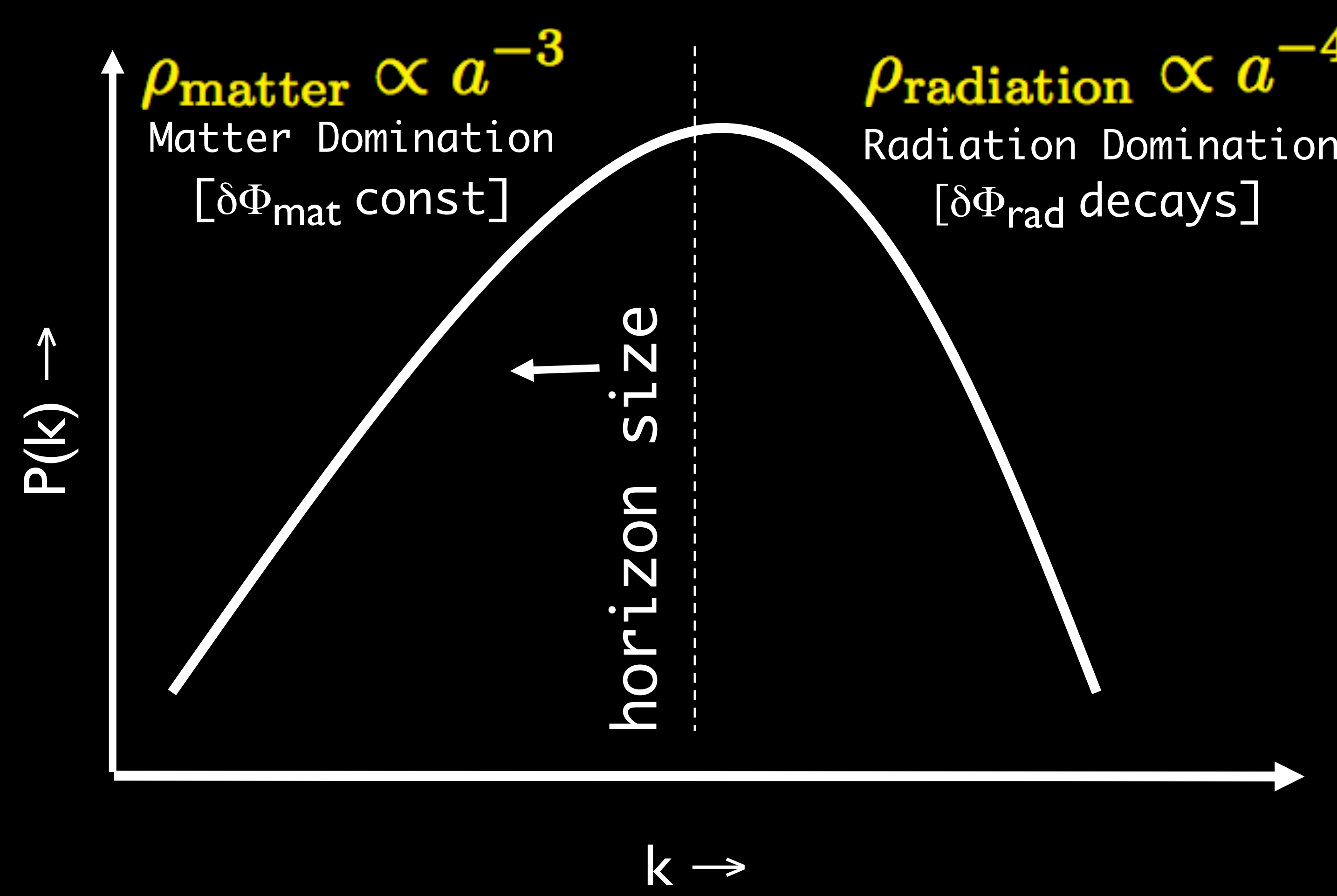
Effective Neutrino Number:

Cosmological Matter Power Spectrum &
CMB Constraints on $N_{\rm eff}$

$$\rho_\nu(m_\nu \ll T_\nu) = N_\nu \times \frac{7\pi^2}{120}\left(\frac{4}{11}\right)^{4/3} T_\gamma^4$$

$$N_{\rm eff} \equiv \frac{\rho_{\text{non-}\gamma\text{-radiation}}}{\frac{7\pi^2}{120}\left(\frac{4}{11}\right)^{4/3} T_\gamma^4}$$

Perturbations enter horizon:



Baryon Acoustic Oscillations

- Suppose we had an object whose length (e.g. in meters) we knew as a function of cosmic epoch. By measuring the angle subtended by this ruler as a function of redshift we map out the angular diameter distance, $d(z)$. By measuring the redshift interval associated with this distance we map out the Hubble parameter, $H(z)$.

- To get competitive constraints on dark energy we need to be able to see changes in $H(z)$ at the 1% level—this would give us statistical errors in the dark energy equation of state w of O(10%) and other energy content.

  - We need to be able to calibrate the ruler accurately over most of the age of the universe.

  - We need to be able to measure the ruler over much of the volume of the universe.

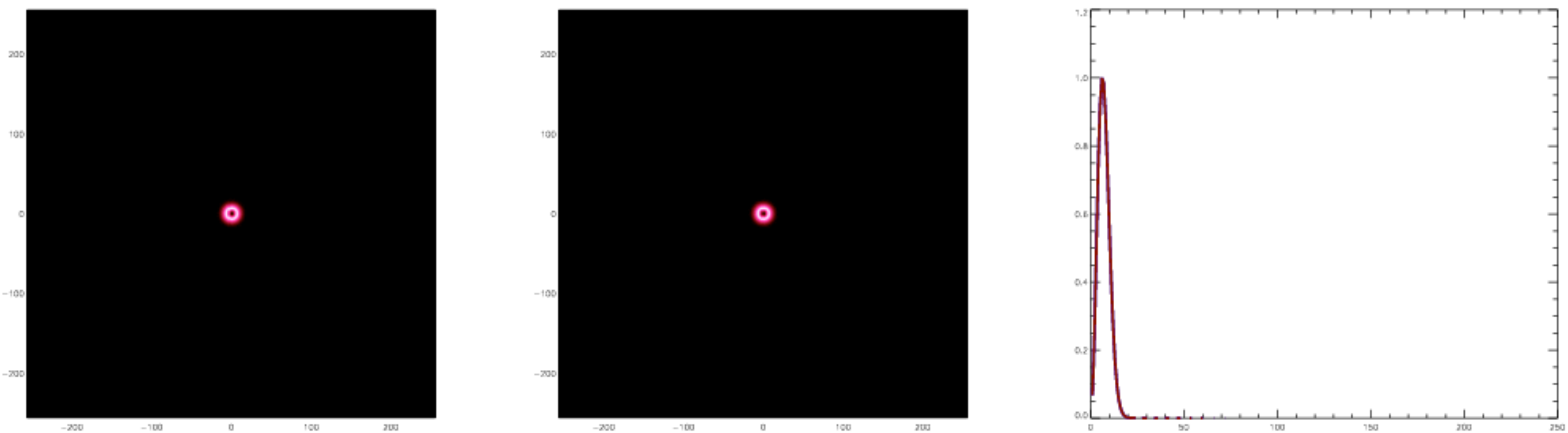
  - We need to be able to make ultra-precise measurements of the ruler.

[HT Martin White]

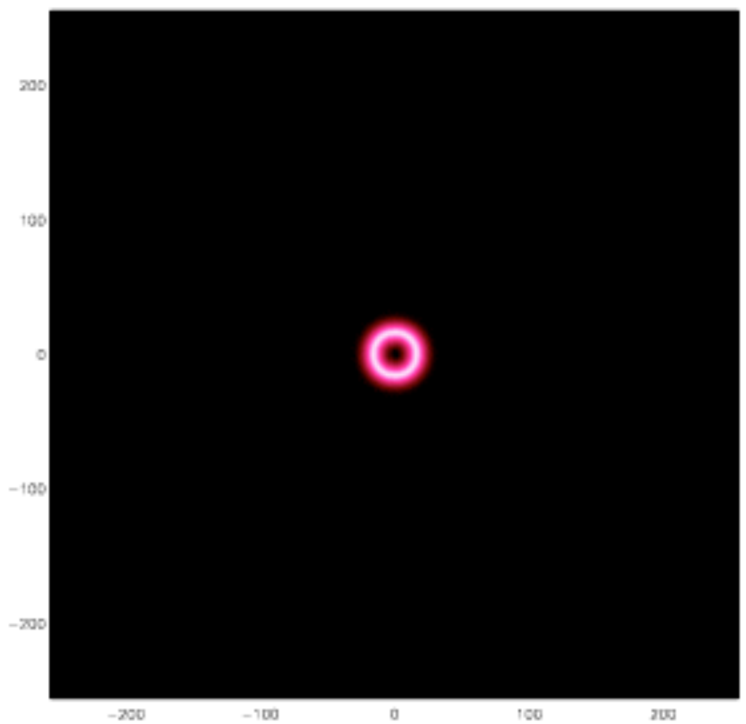
Baryon Acoustic Oscillations

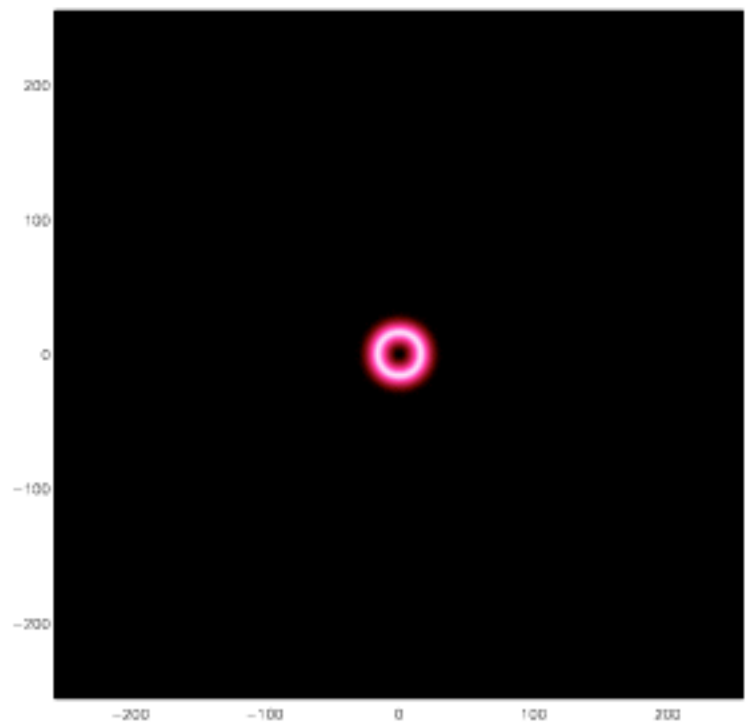
Let us consider the early universe, which was composed of a coupled plasma of energetic photons and ionized hydrogen (protons and electrons) plus other trace elements and the mysterious dark matter. Start with a single perturbation. The plasma is totally uniform except for an excess of matter at the origin. High pressure drives the gas +photon fluid outward at speeds approaching the speed of light. In the panels below we show some snapshots from this process, with the baryon density shown in the left panel, the photon density in the right panel and the mass profile as a graph in the final panel.

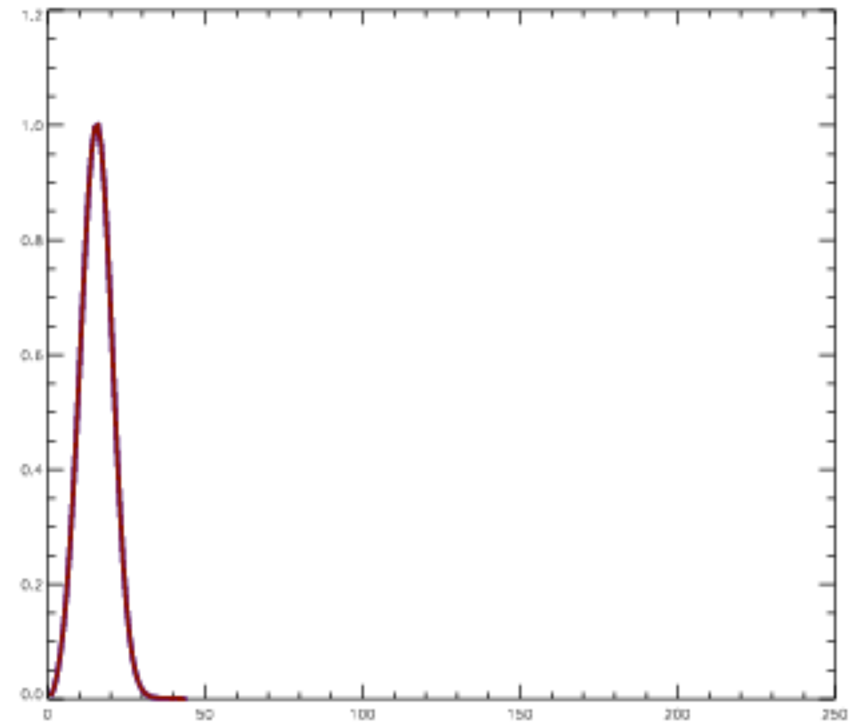
Initially both the photons and the baryons move outward together, the radius of the shell moving at over half the speed of light



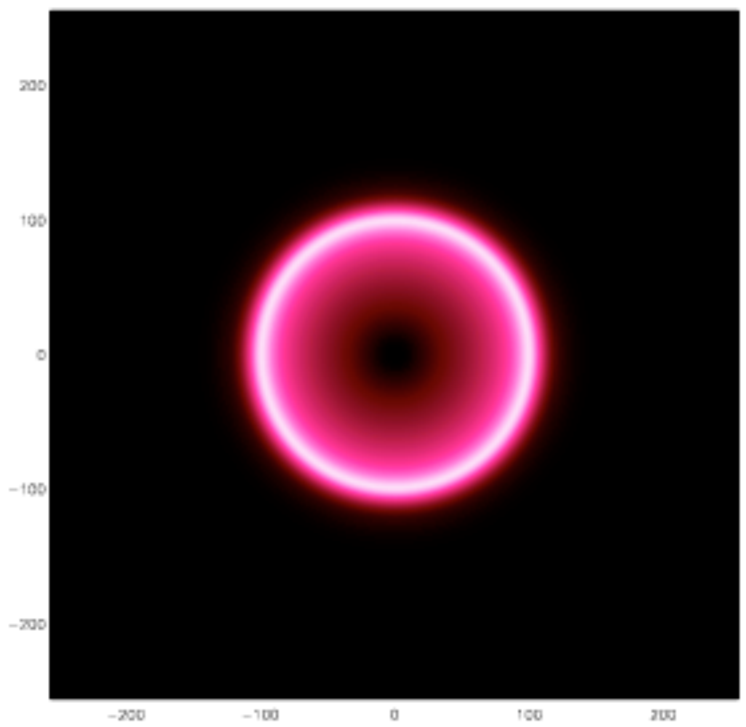
This expansion continues for 10^5 years

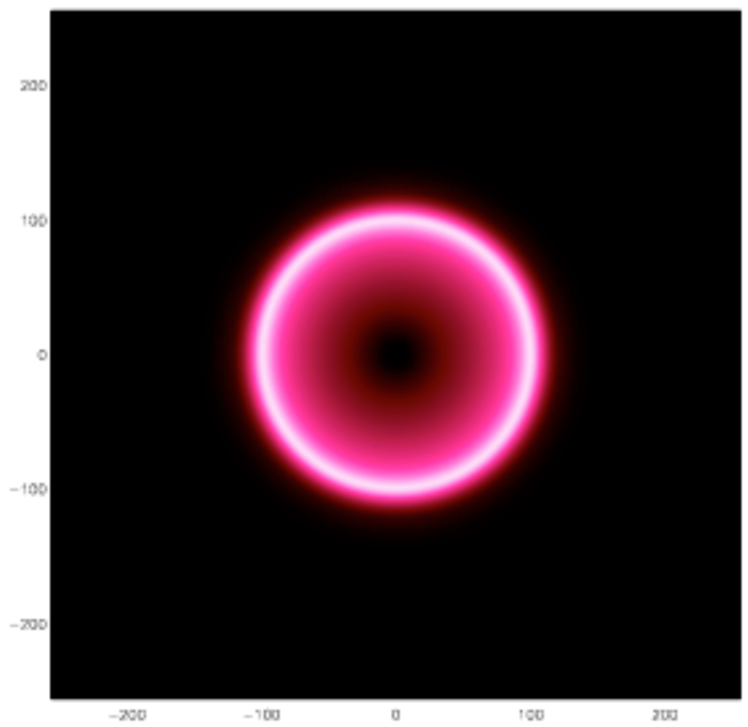


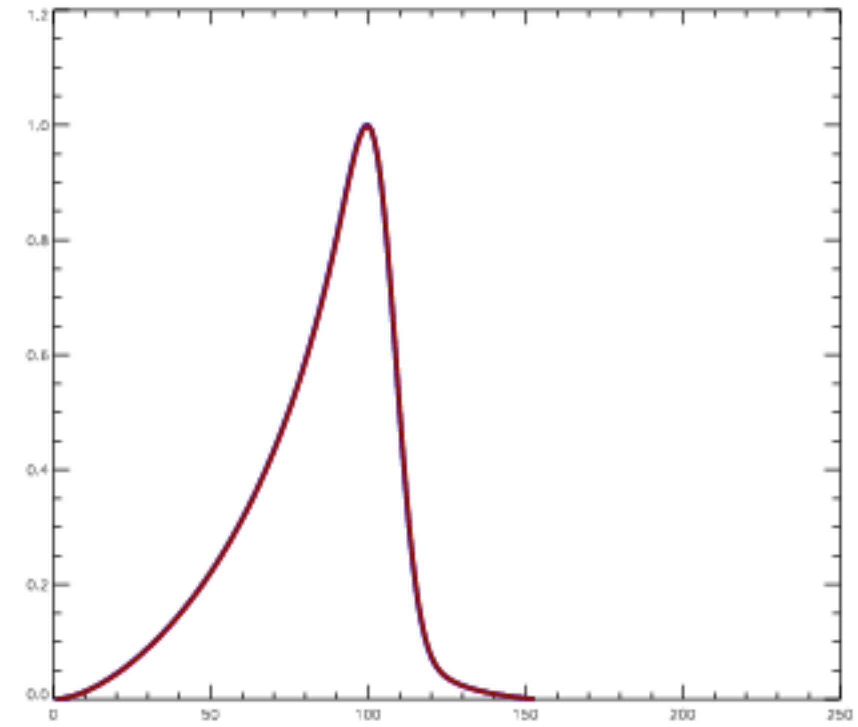




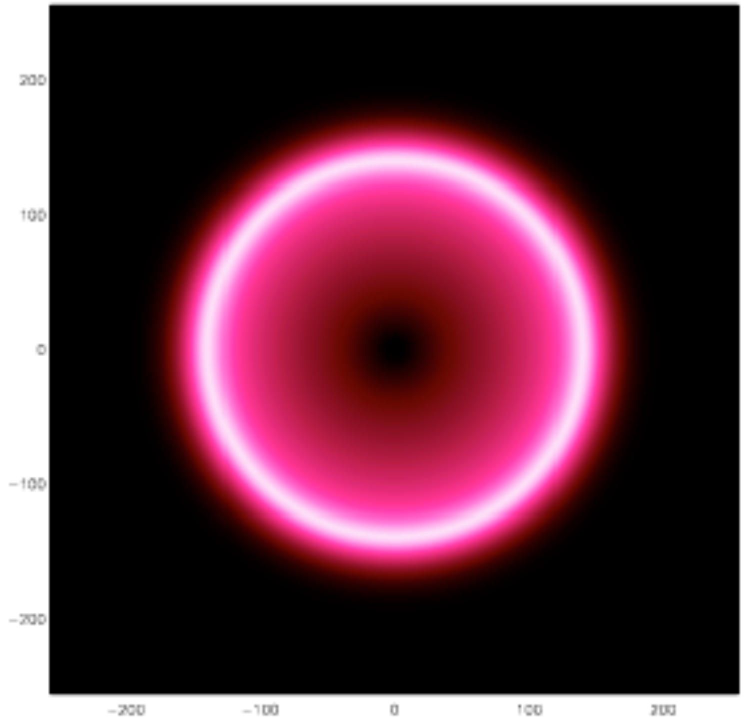
This expansion continues for 10^5 years

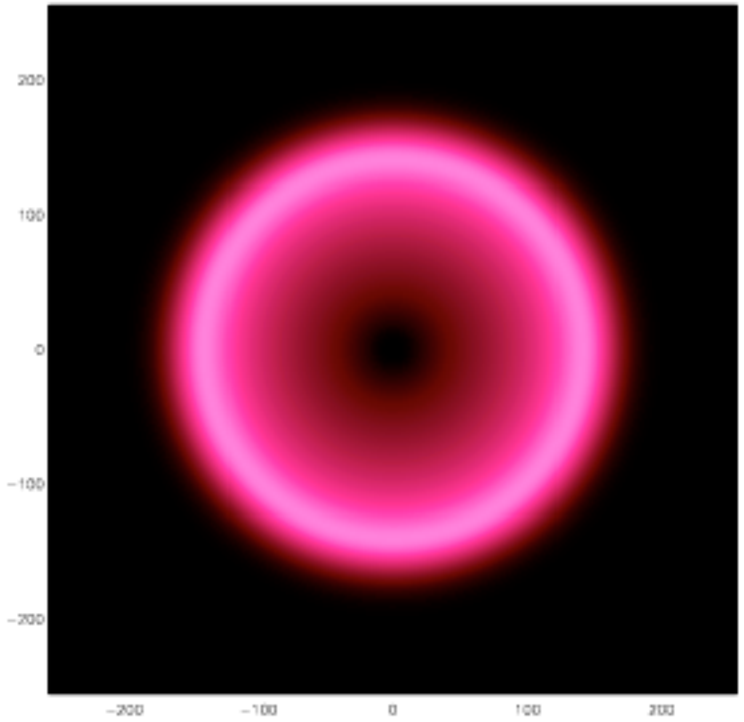


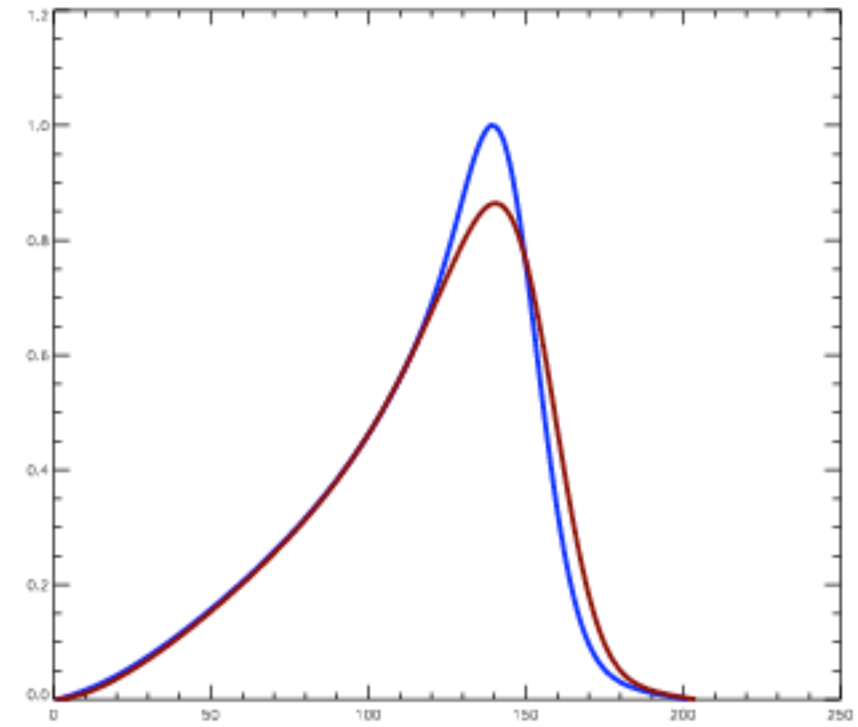




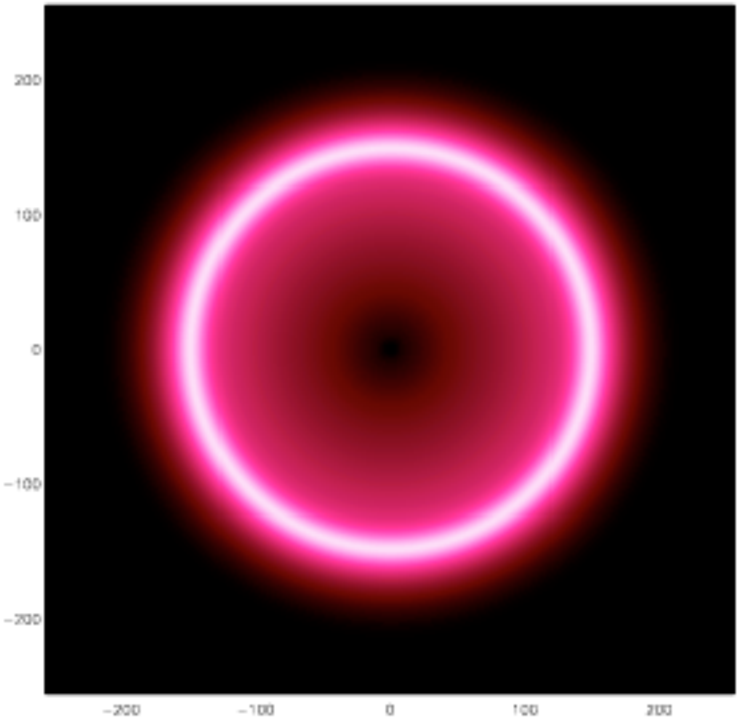
After 10^5 years the universe has cooled enough the protons capture the electrons to form neutral Hydrogen.
This decouples the photons from the baryons.
The former quickly stream away, leaving the baryon peak stalled.

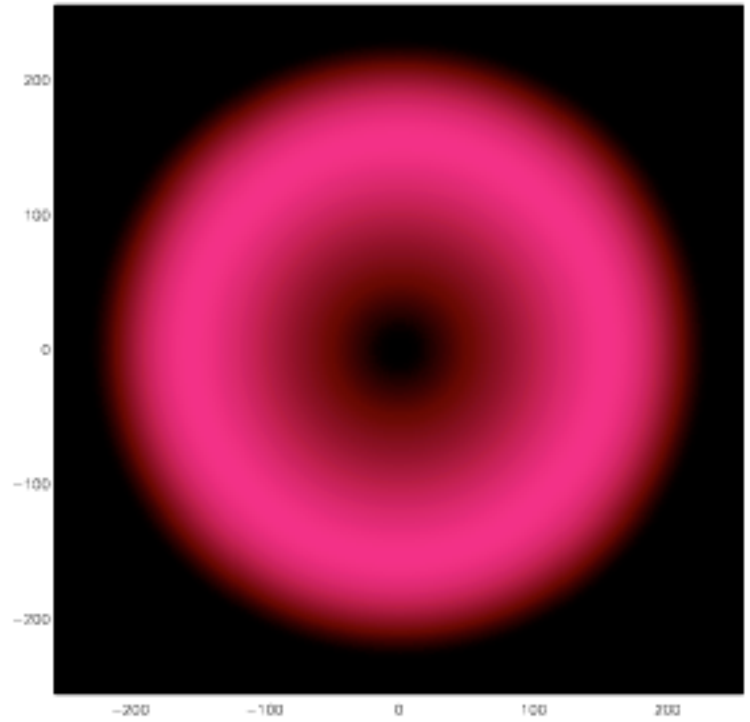


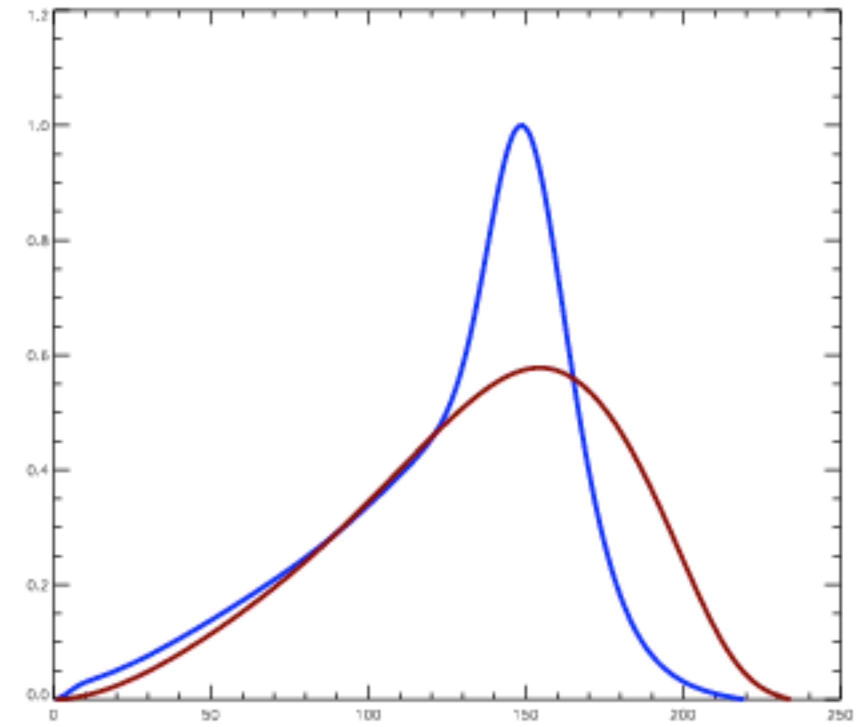




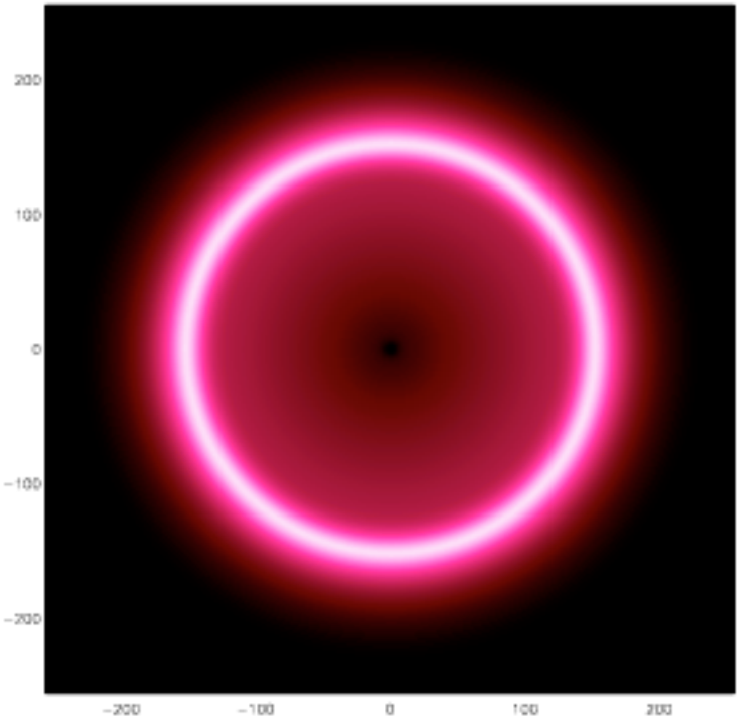
The photons continue to stream away while the baryons, having lost their motive pressure, remain in place.

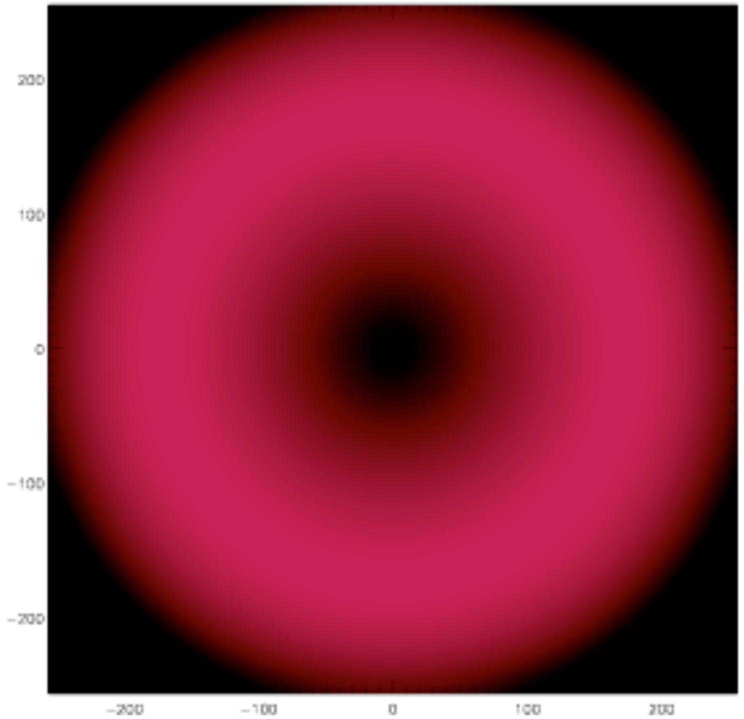


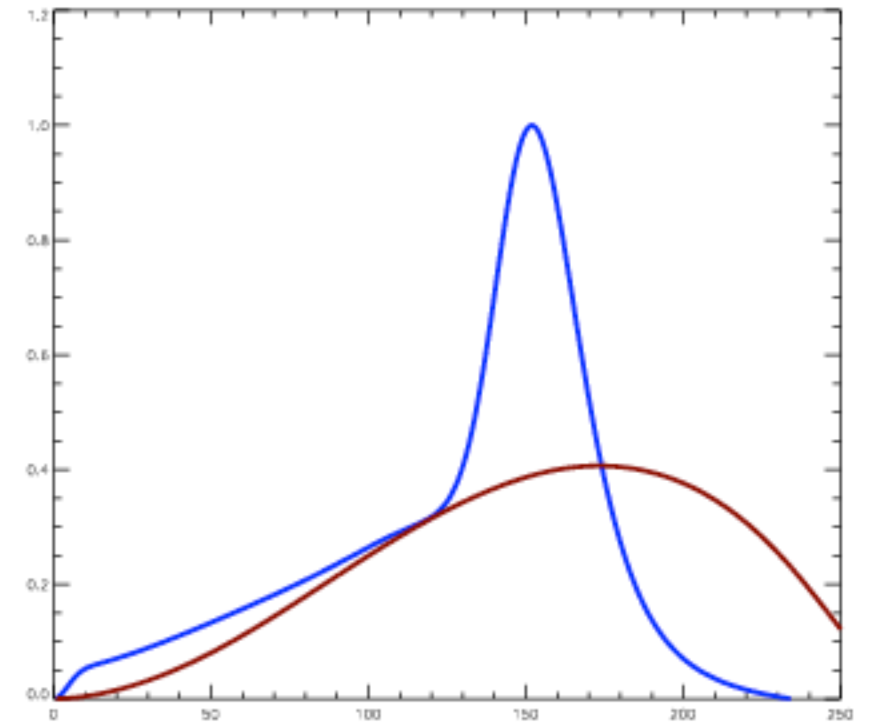




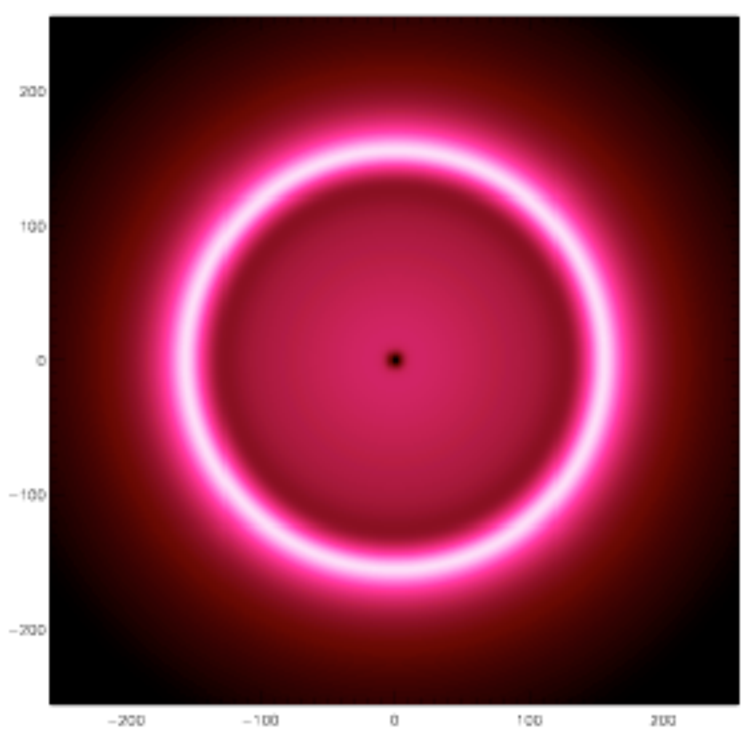
The photons continue to stream away while the baryons, having lost their motive pressure, remain in place.

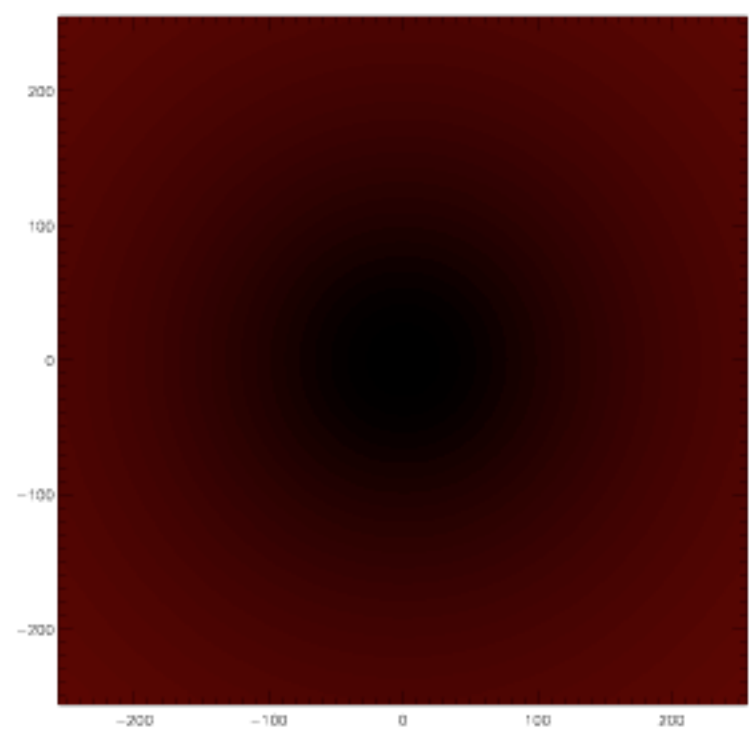


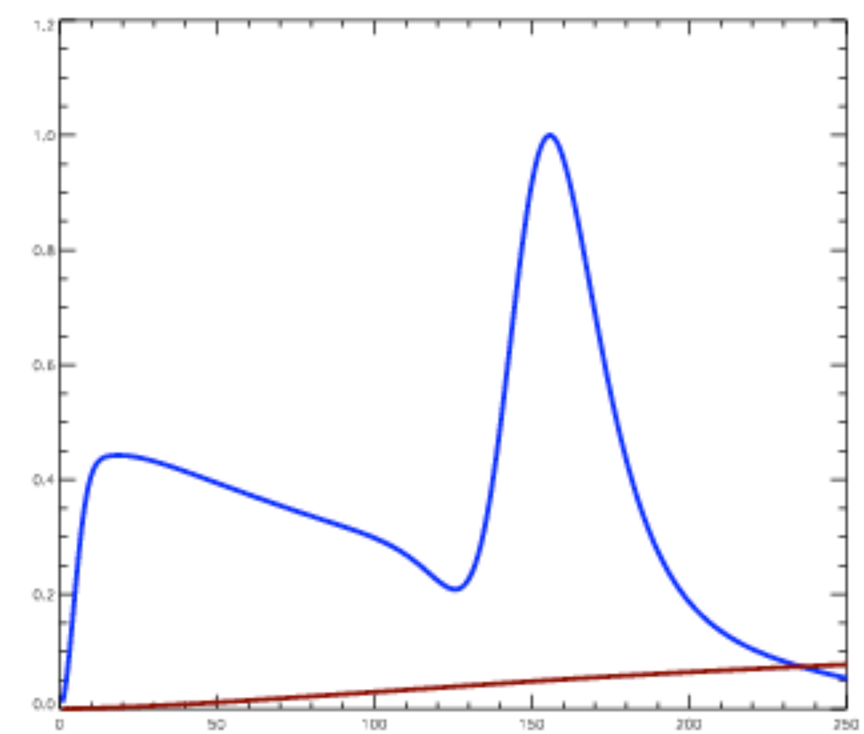




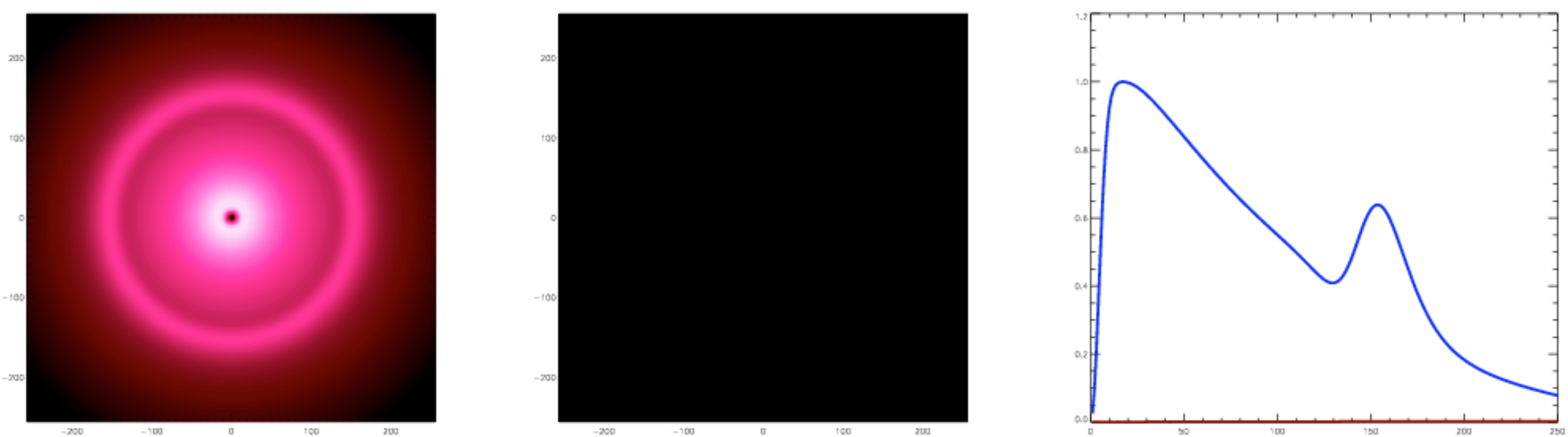
The photons have become almost completely uniform, but the baryons remain overdense in a shell 100 Mpc in radius.
In addition, the large gravitational potential well which we started with starts to draw material back into it.



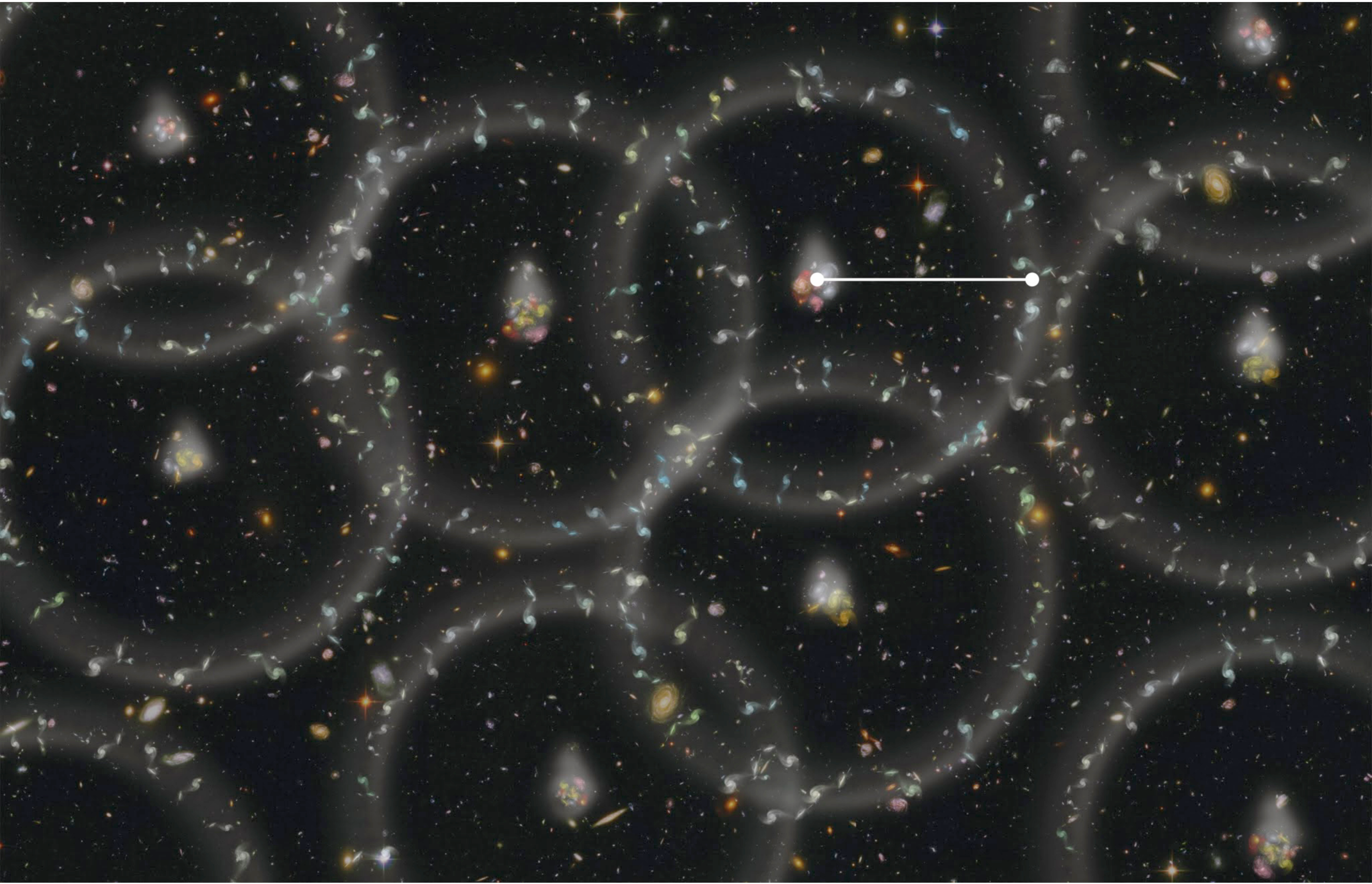




As the perturbation grows by O(1000) the baryons and DM reach equilibrium densities in the ratio Ω_b/Ω_m.
The final configuration is our original peak at the center (which we put in by hand) and an echo in a shell roughly 100 Mpc in radius.
The radius of this shell is known as the sound horizon.



BAO Scale in Galaxy Surveys



Features of BAO

- Positions well predicted once (physical) matter and baryon density known - calibrated by the CMB.

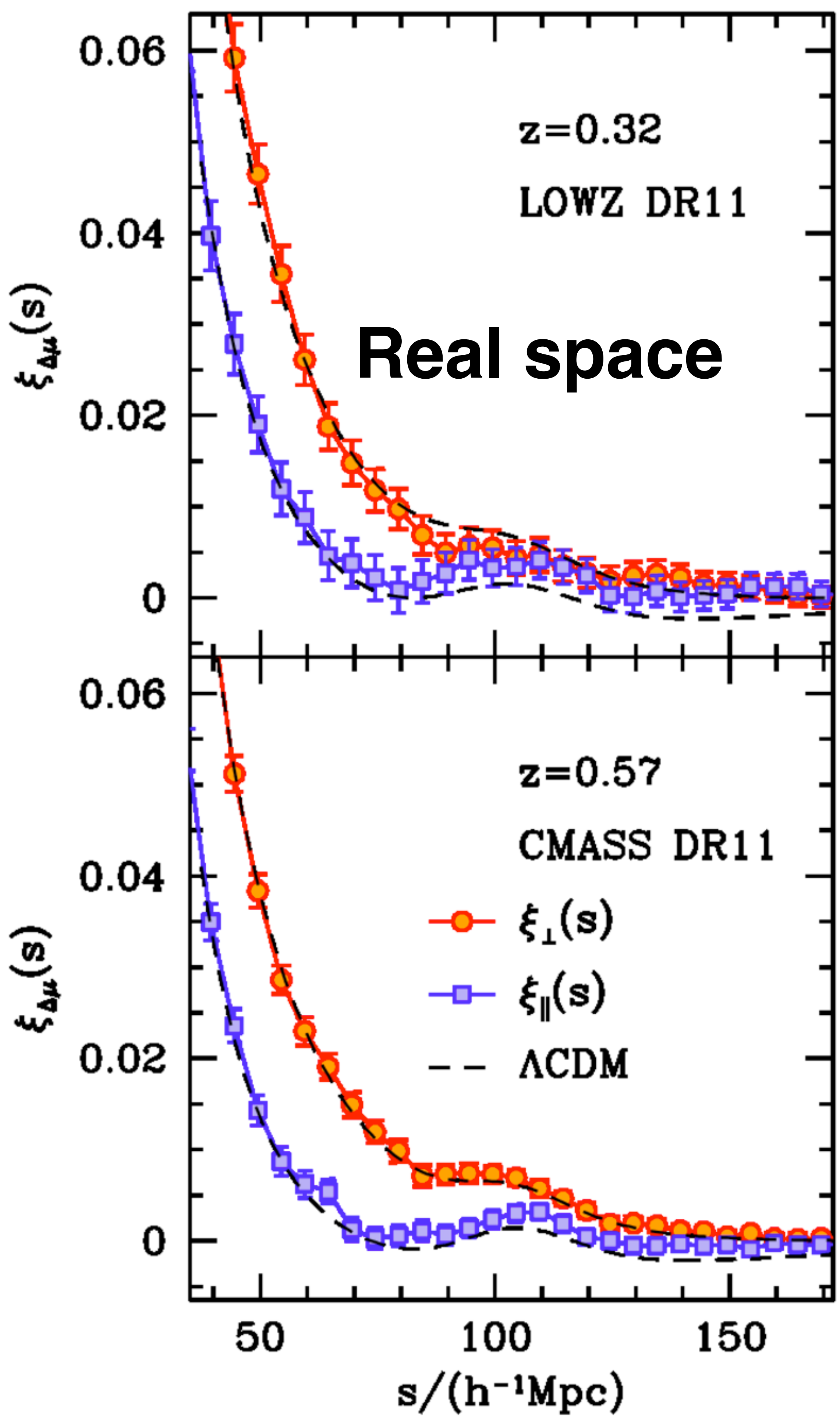
- Oscillations are sharp, unlike other features of the galaxy clustering or matter clustering power spectrum.

- Since have $d(z)$ for several z's can check spatial flatness:
  $d(z_1+z_2) = d(z_1)+d(z_2)+O(\text{curvature})$

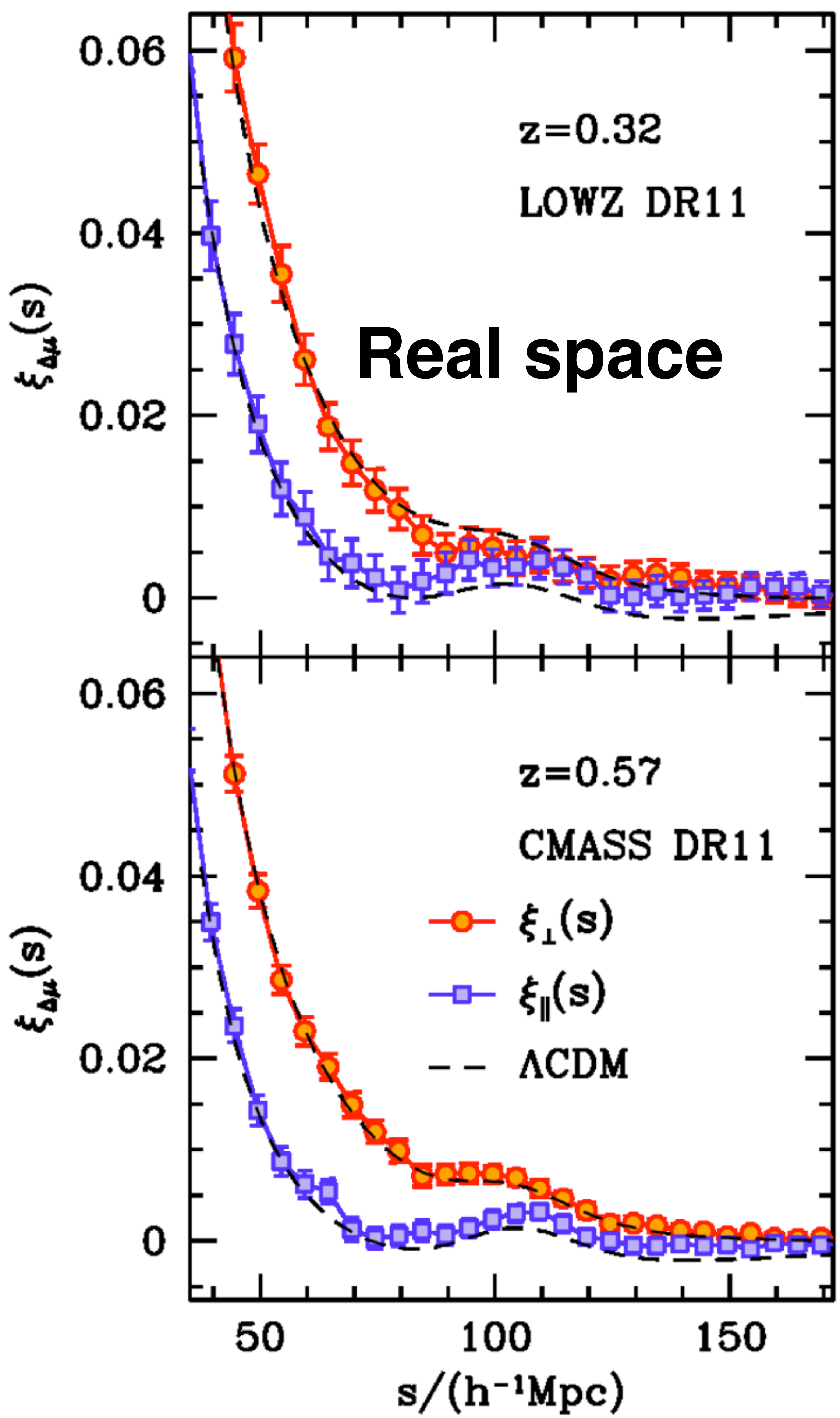
- Ties low-z distance measures (e.g. SNe) to absolute scale defined by the CMB.

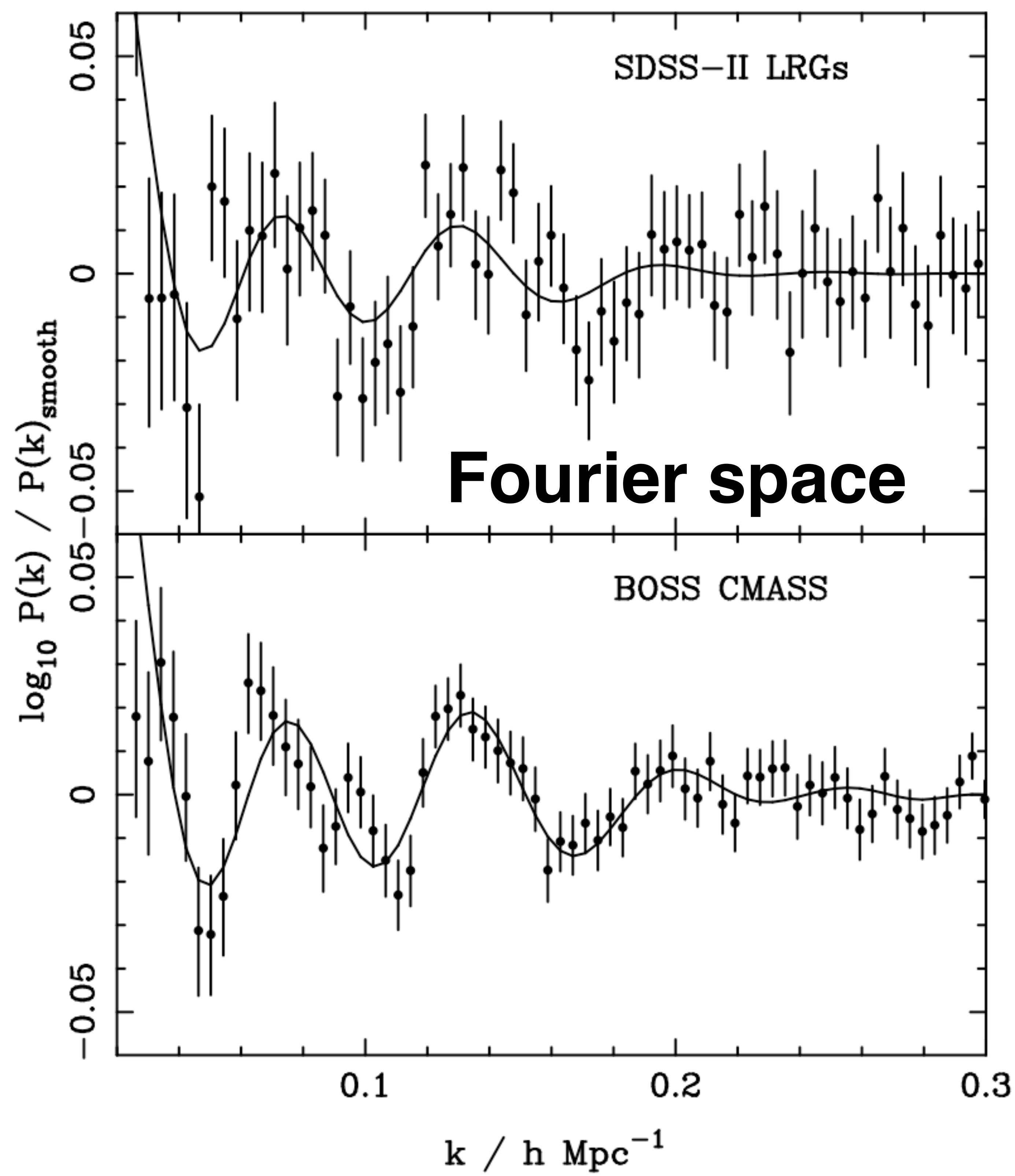
$$D_{\rm V}(z) = \left((1+z)^2 \, D_{\rm A}(z)^2 \frac{cz}{H(z)} \right)^{1/3}$$

BAO measurements



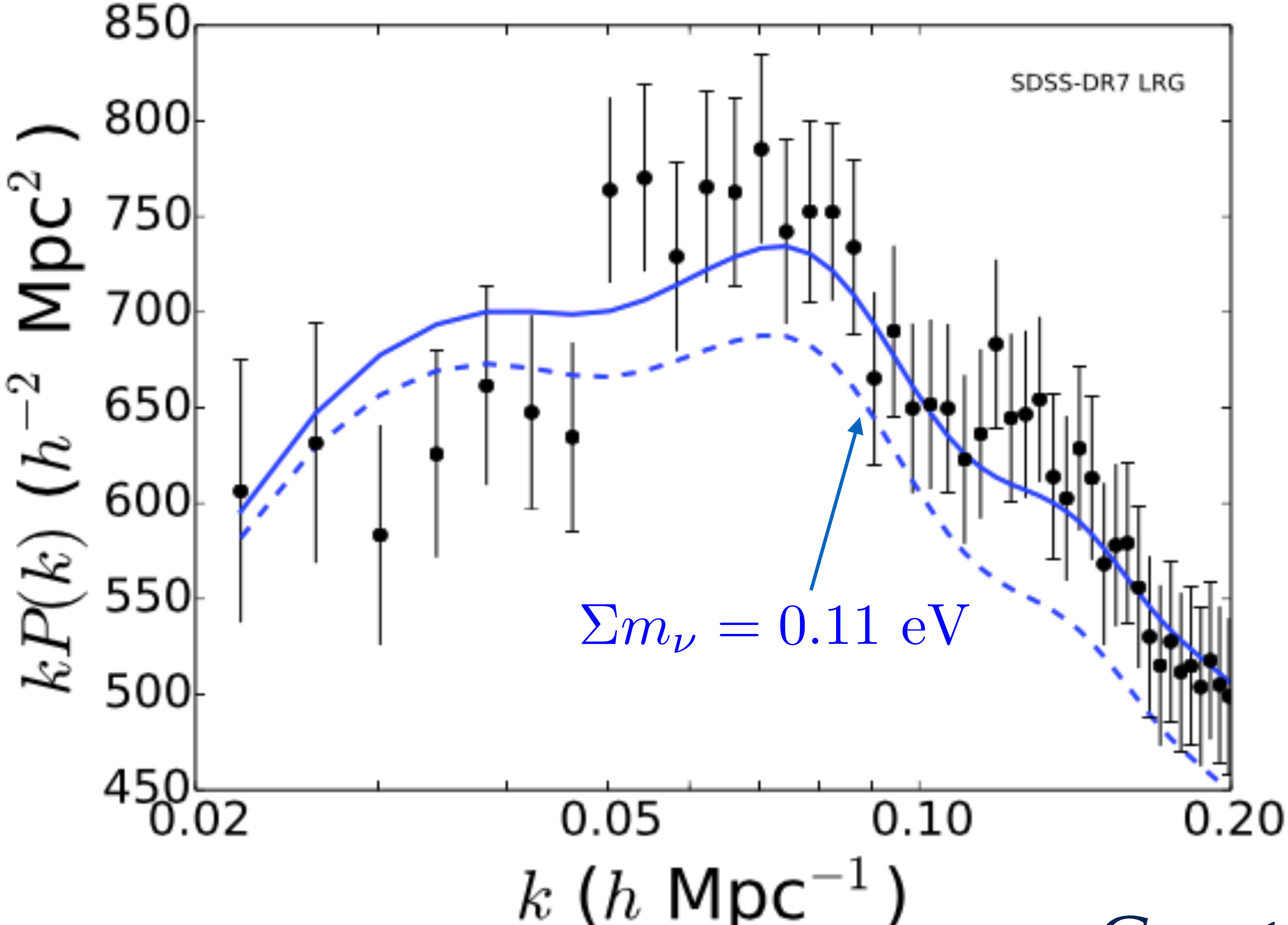
BAO measurements





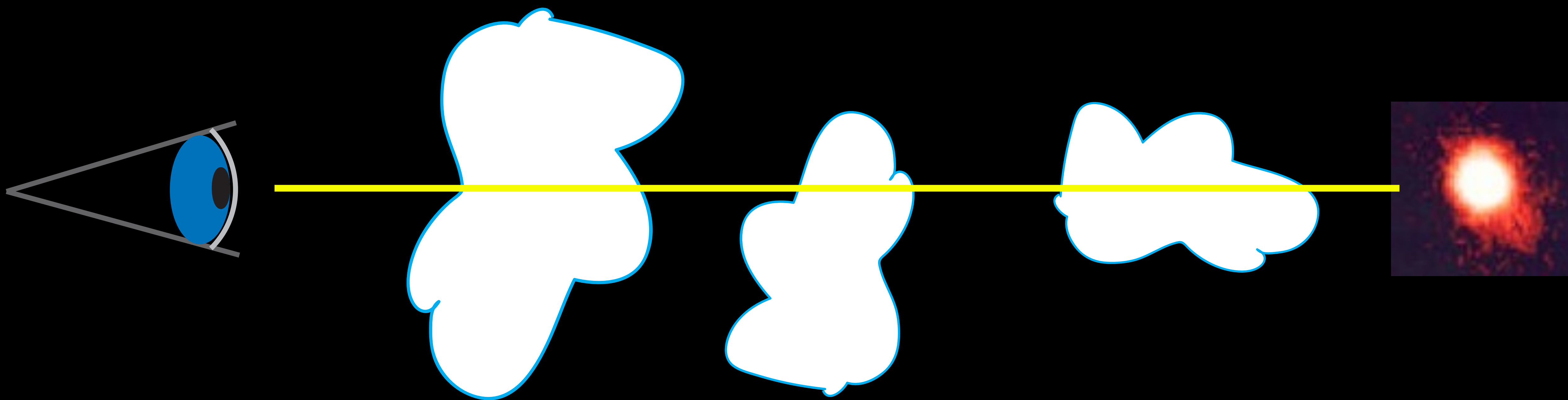
BAO in k-space: neutrino mass constraints

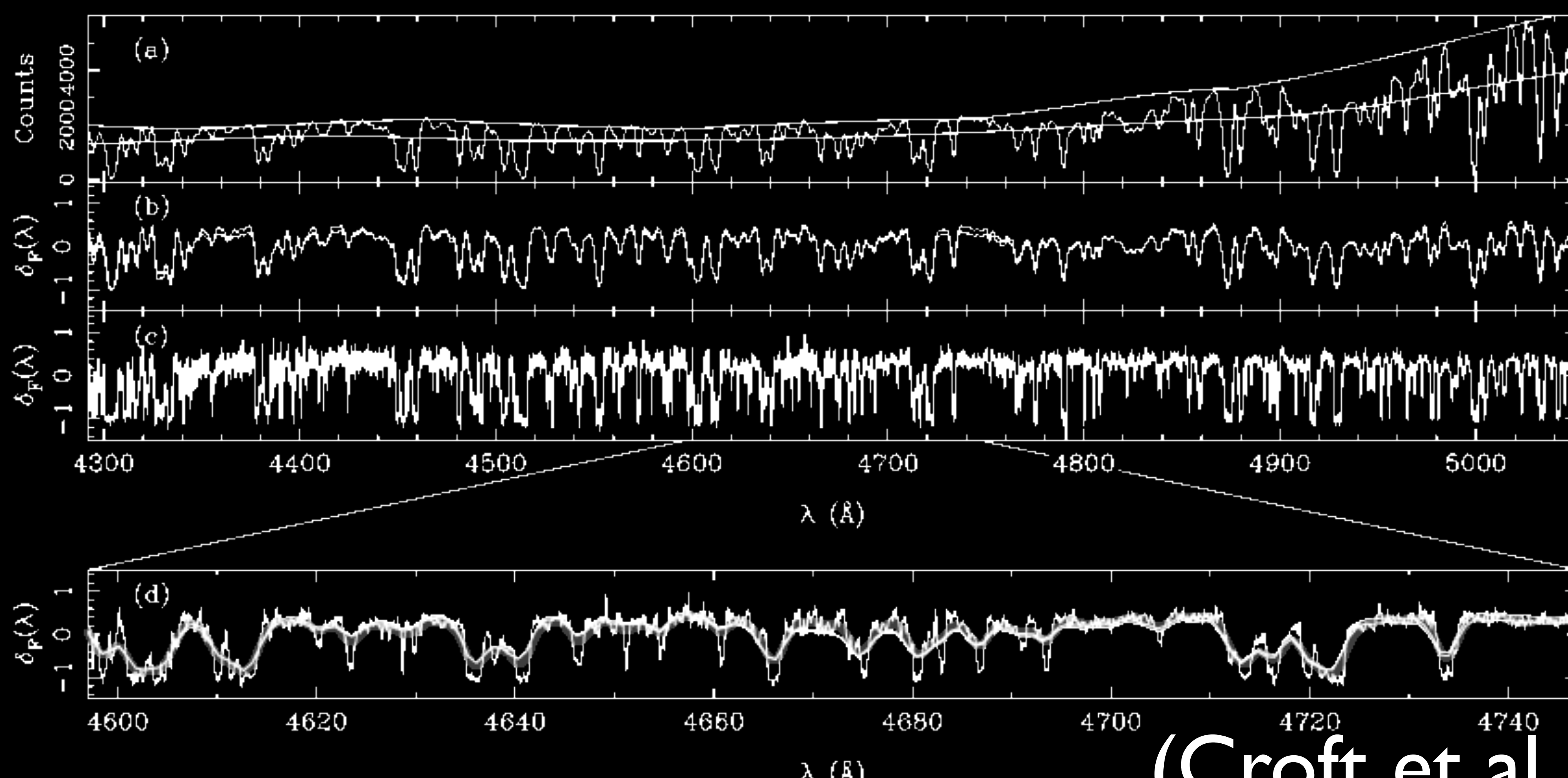
$\Sigma m_\nu < 110$ meV (95%)



Cuesta et al 2015

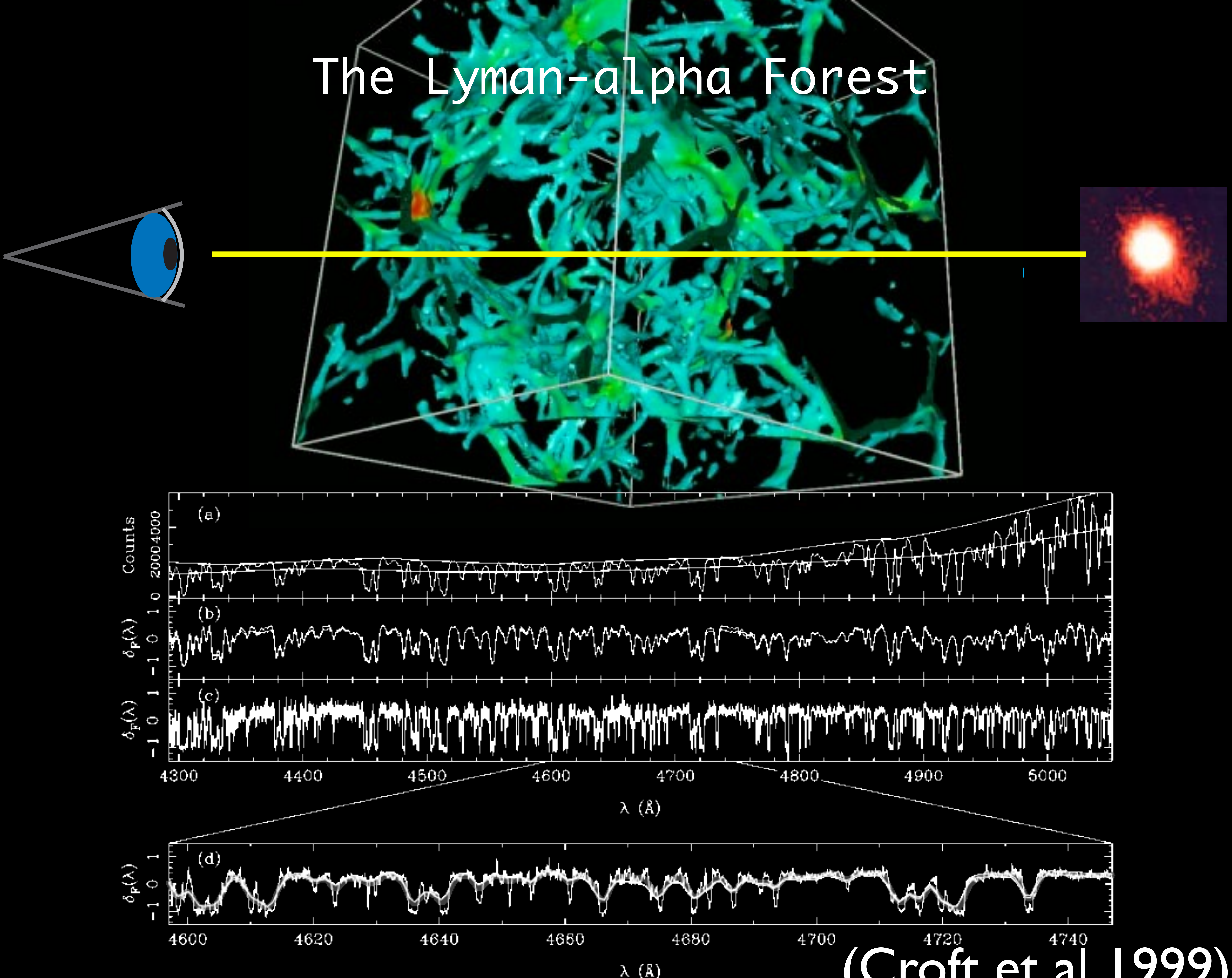
The Lyman-alpha Forest





(Croft et al 1999)

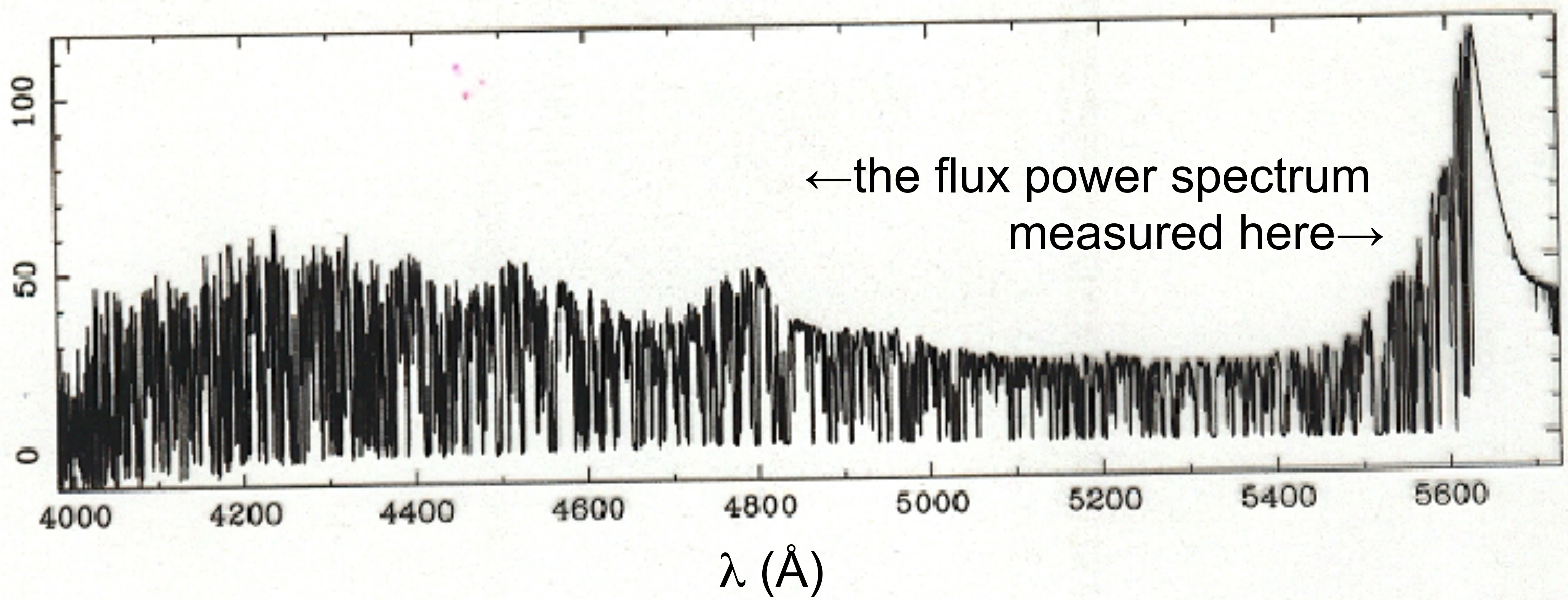
The Lyman-alpha Forest



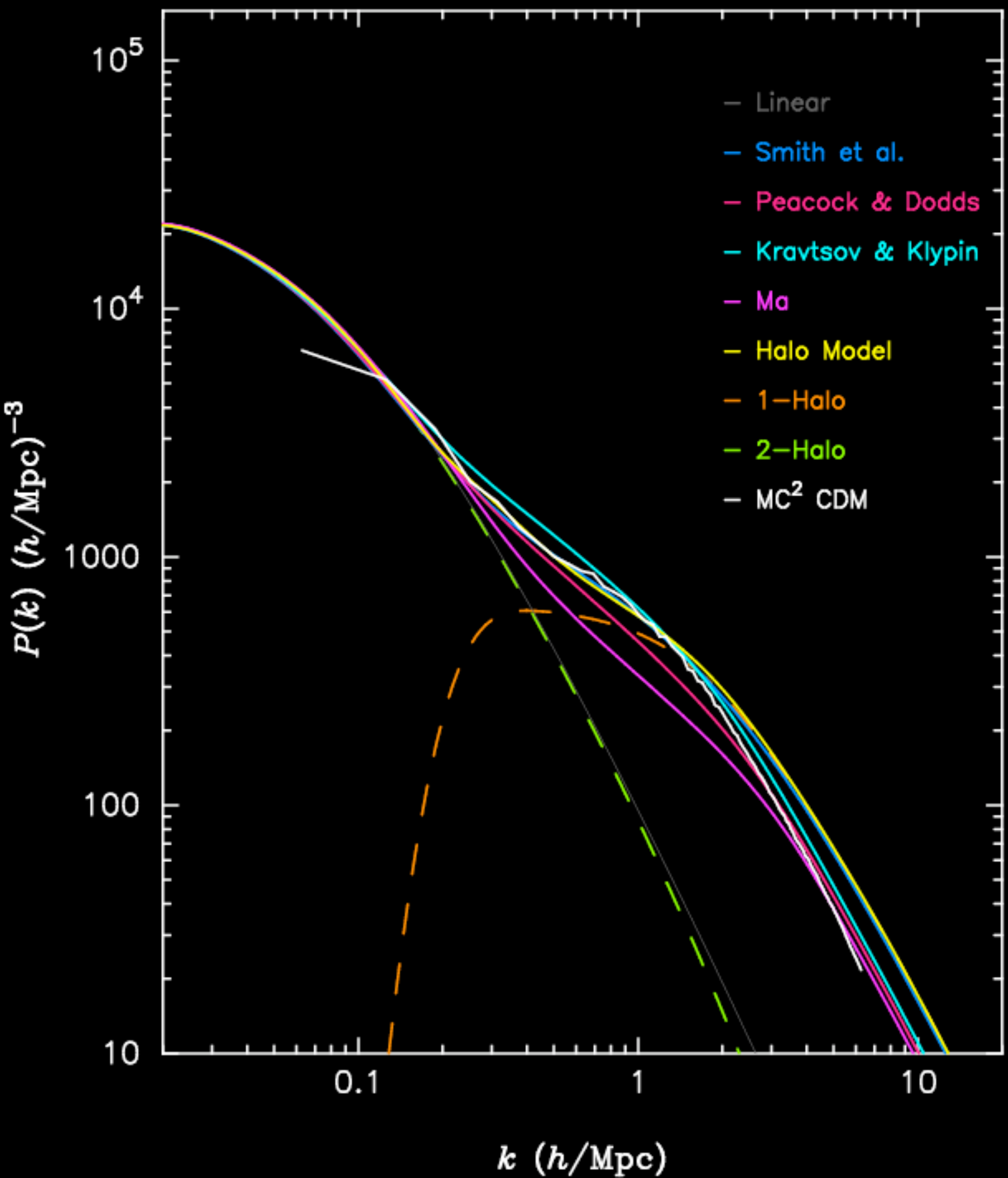
(Croft et al 1999)

Example Lyman-alpha Forest Flux Spectrum

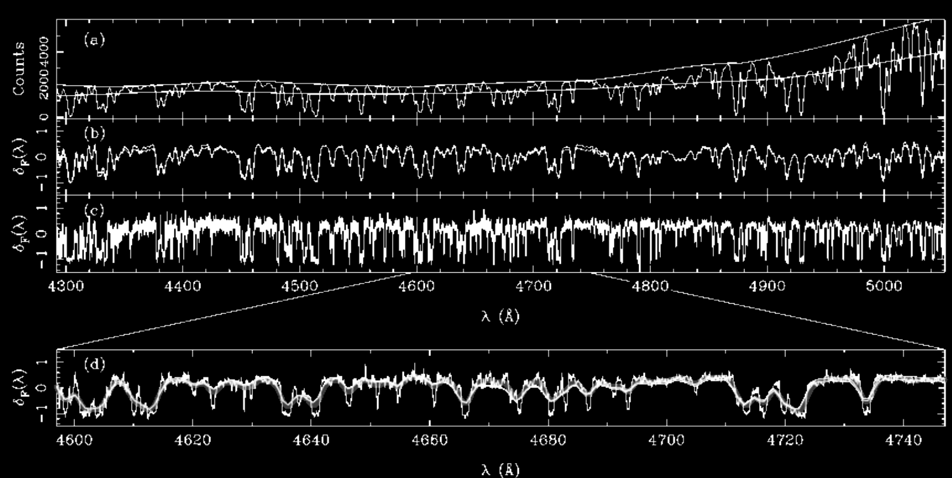
Example Lyman-alpha Forest Flux Spectrum



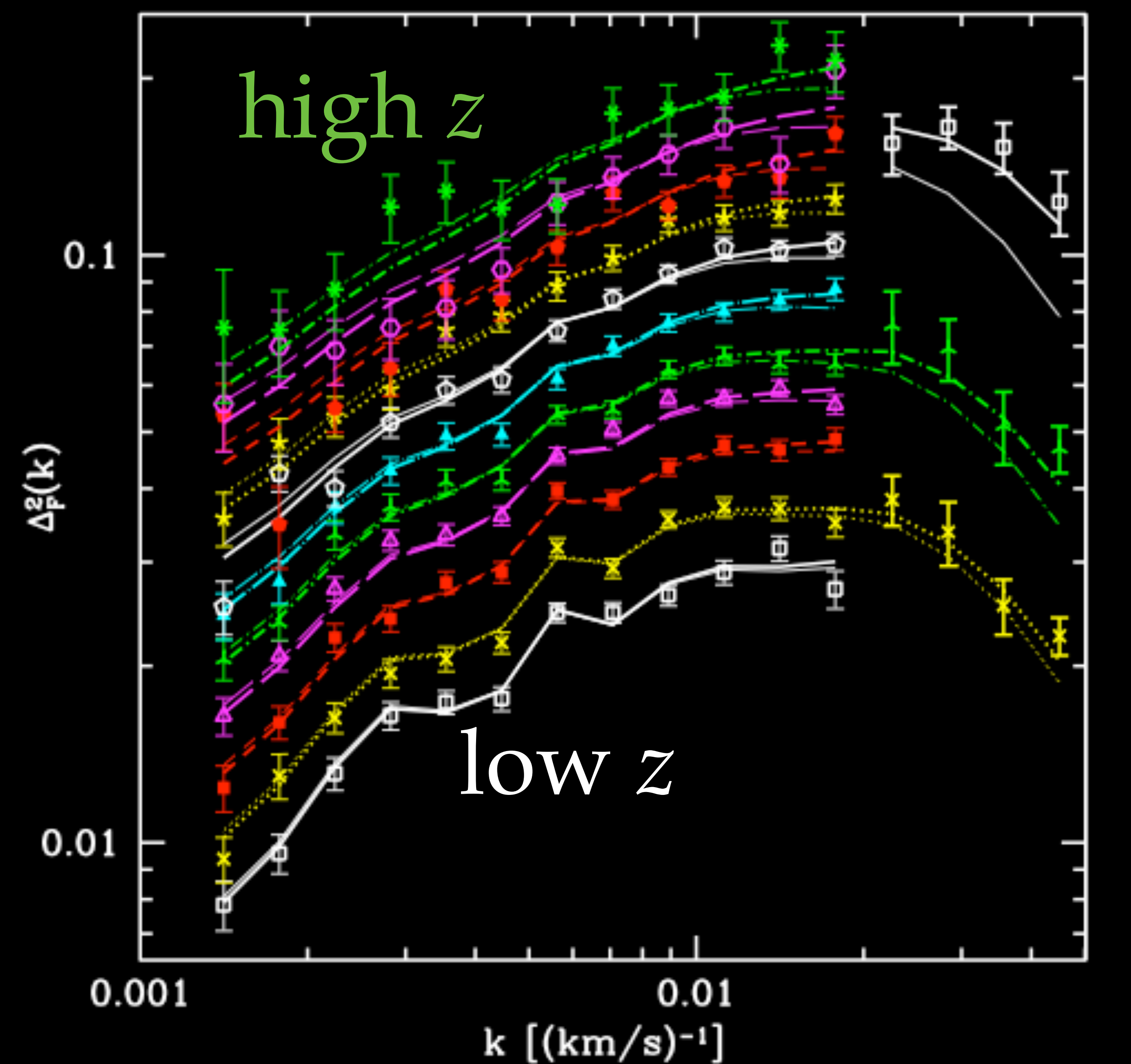
The Onset of Nonlinearity at Small Scales



Lyman-alpha Forest Constraints on m_ν



FFT



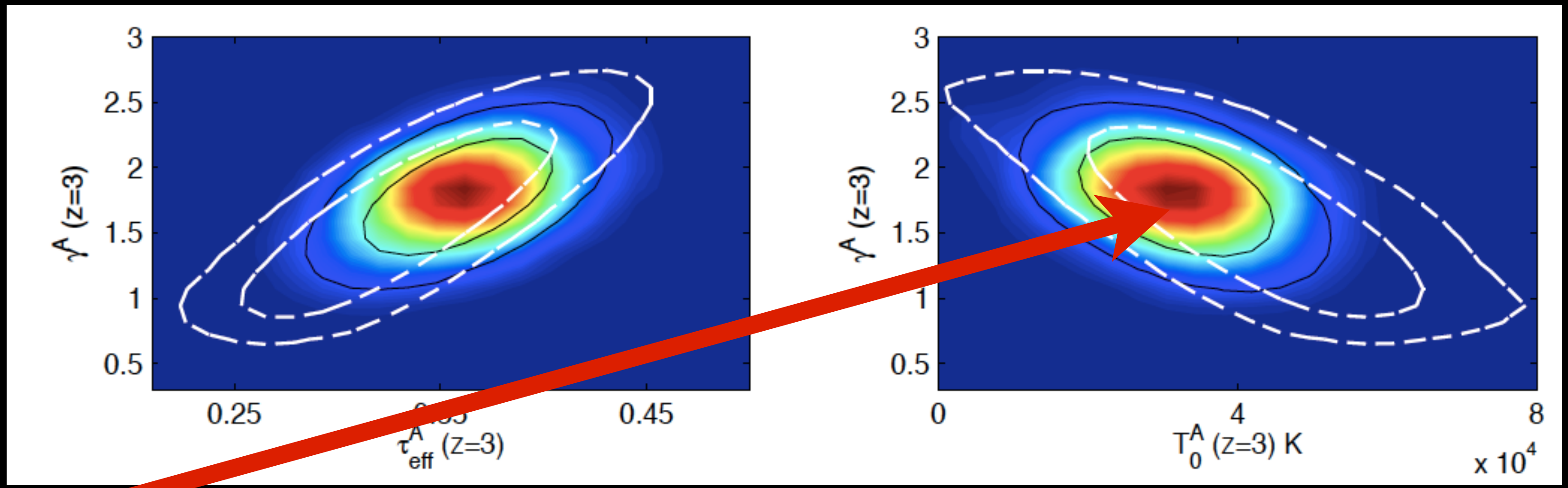
Σm_ν < 170 meV (95%)

Palanque-Delabrouille et al (BOSS Collab.) 2015

McDonald et al 2006

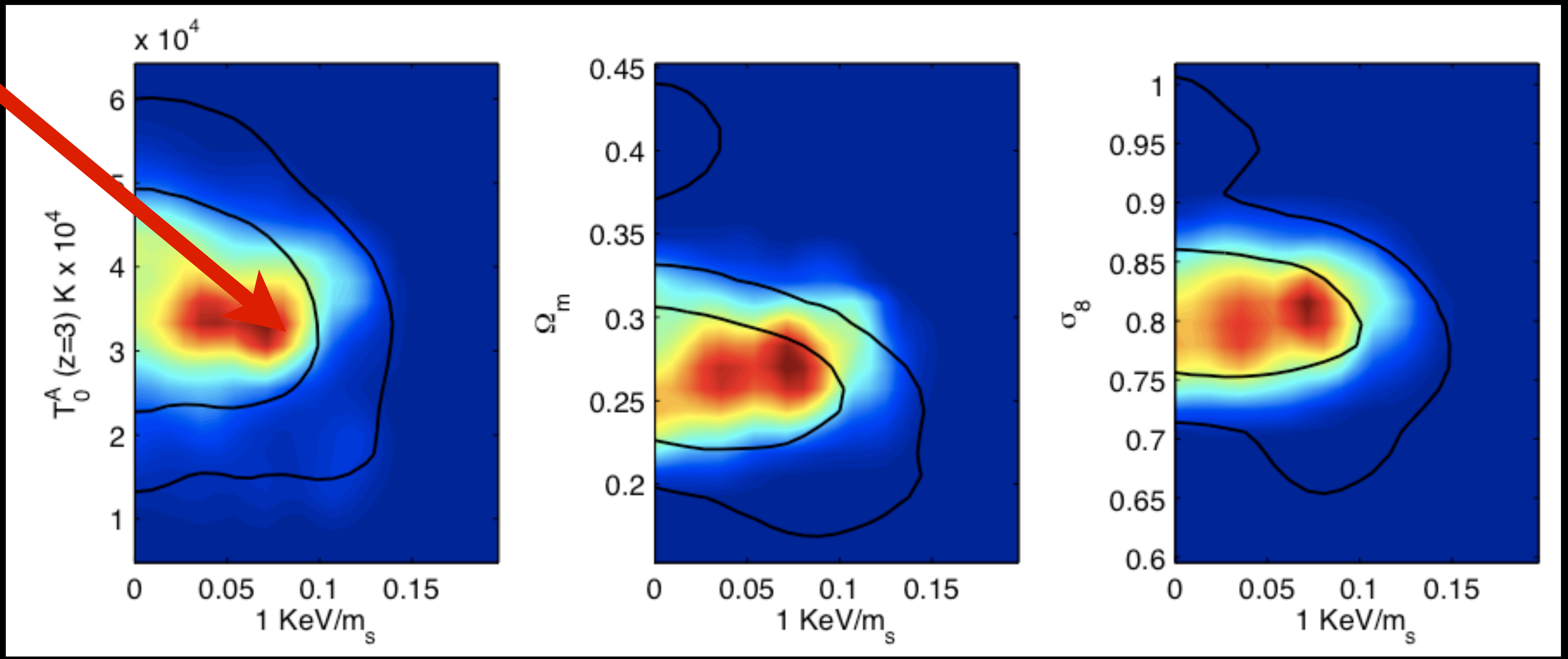
Problems in Temperature Requirements of the IGM?

(CDM & WDM analysis)

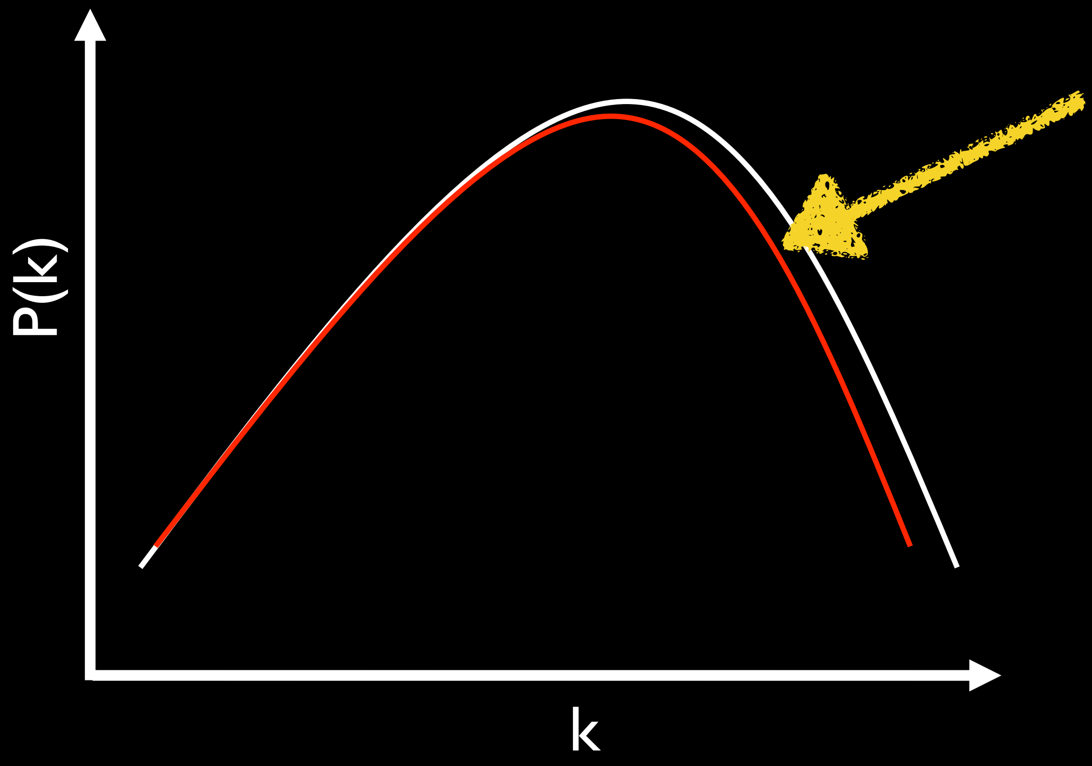


Very high T_0
~35000 K

Viel & Haehnelt (2005); Viel et al 2006

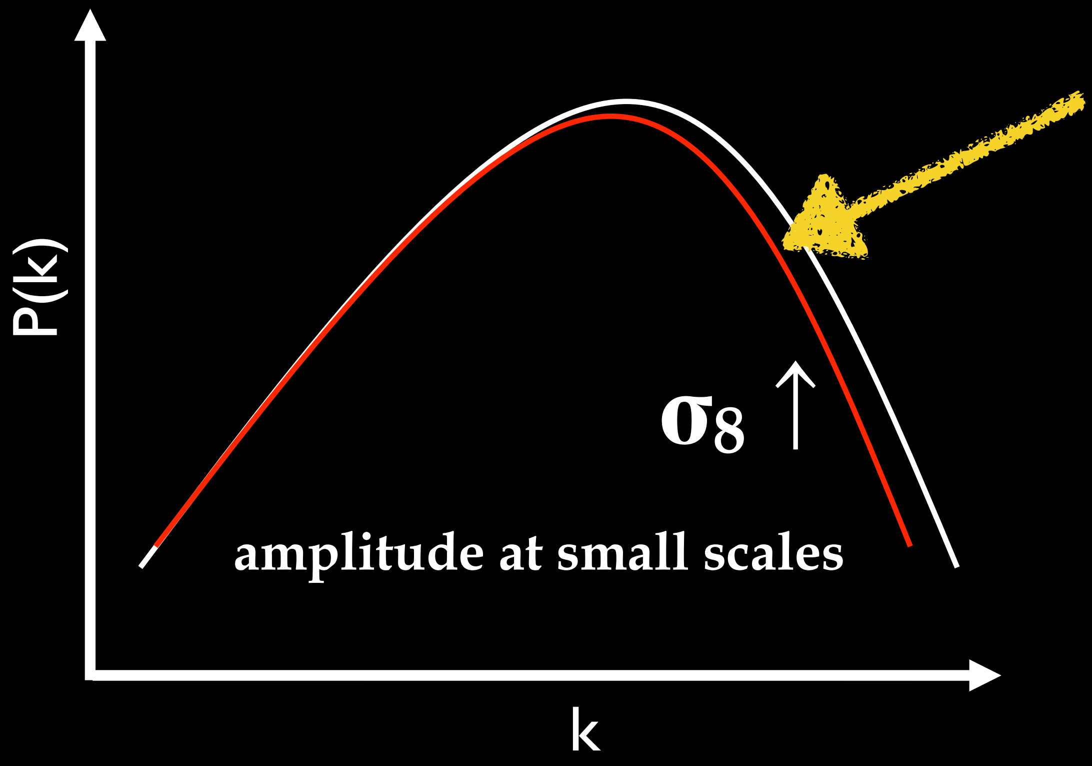


Cosmological Signals of eV-scale Sterile Neutrinos?



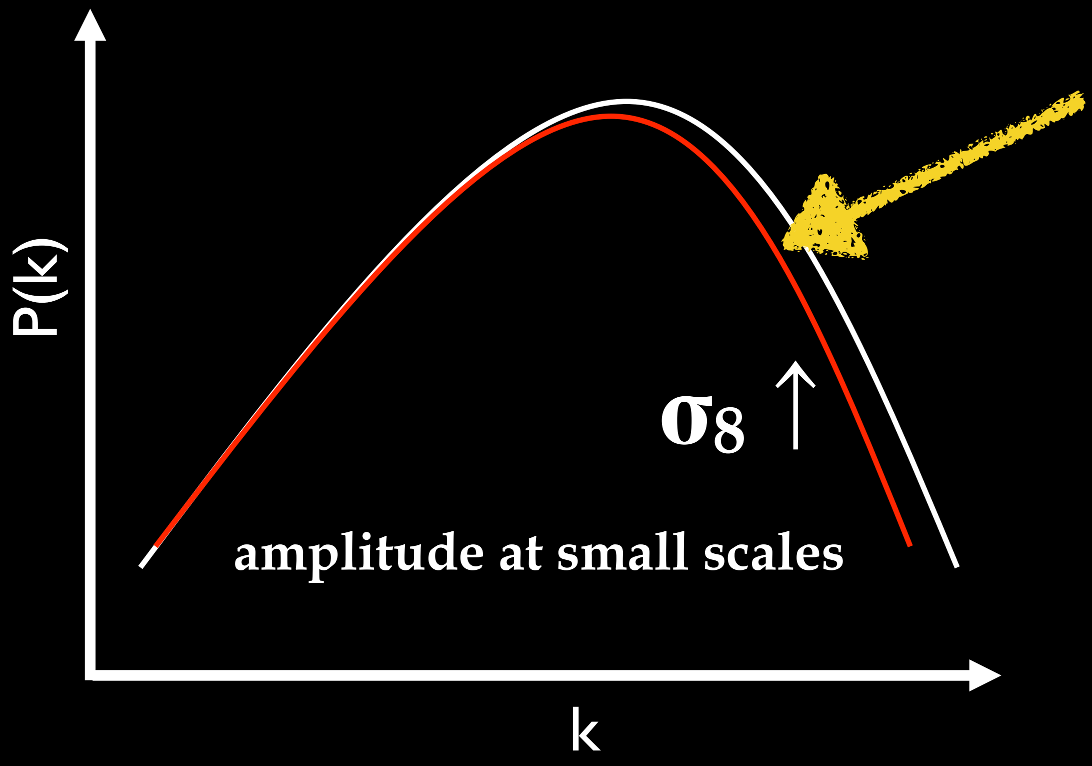
If small-scale measures want smaller power than large-scale (CMB) measures, then it may detect the presence of massive neutrinos

Cosmological Signals of eV-scale Sterile Neutrinos?



If small-scale measures want smaller power than large-scale (CMB) measures, then it may detect the presence of massive neutrinos

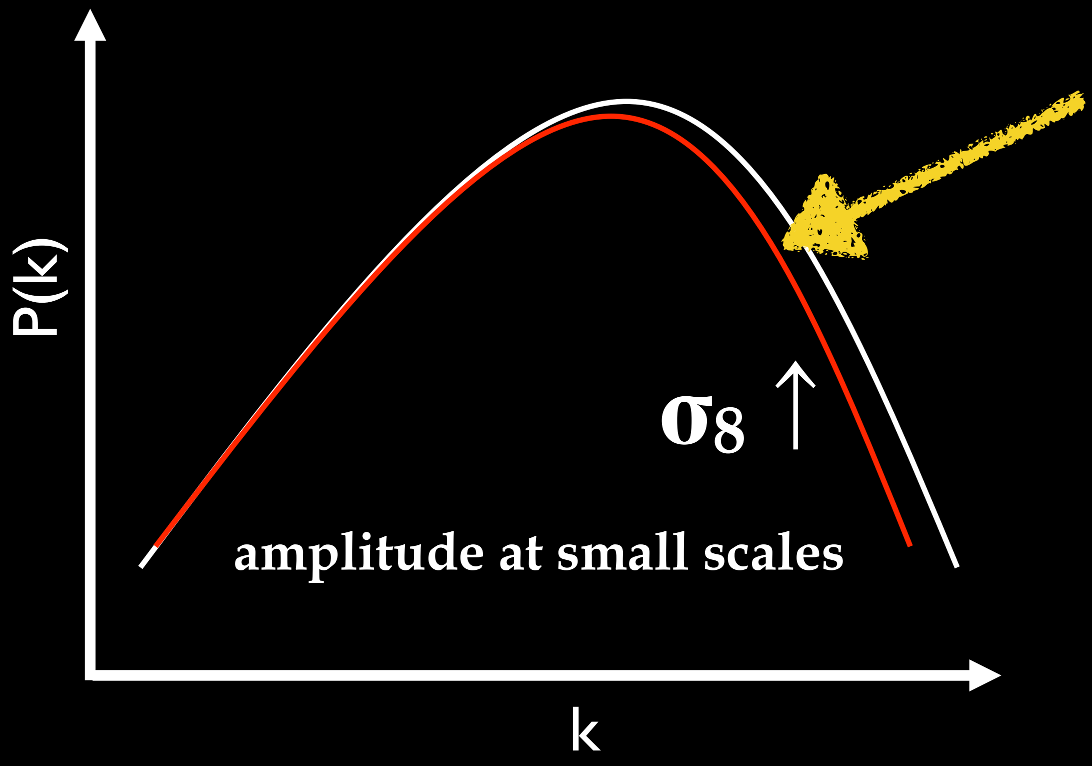
Cosmological Signals of eV-scale Sterile Neutrinos?



If small-scale measures want smaller power than large-scale (CMB) measures, then it may detect the presence of massive neutrinos

X-ray Clusters:

Cosmological Signals of eV-scale Sterile Neutrinos?

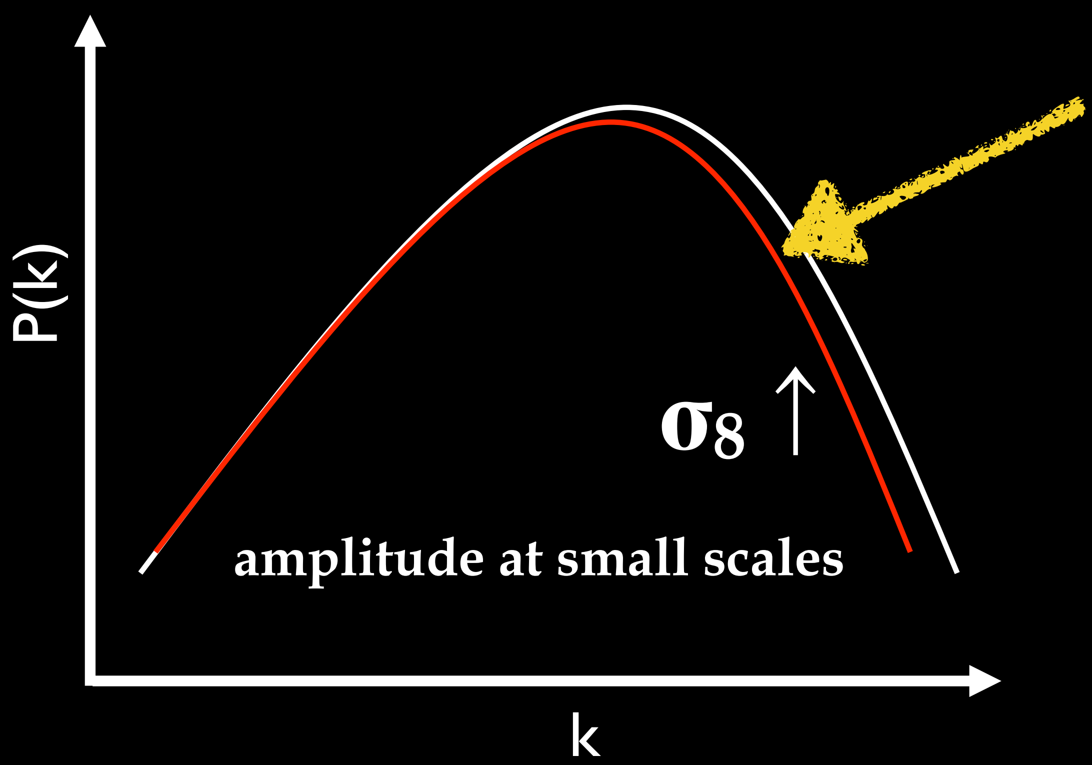


If small-scale measures want smaller power than large-scale (CMB) measures, then it may detect the presence of massive neutrinos

X-ray Clusters:

$$\sigma_8 = 0.803 \pm 0.0105$$

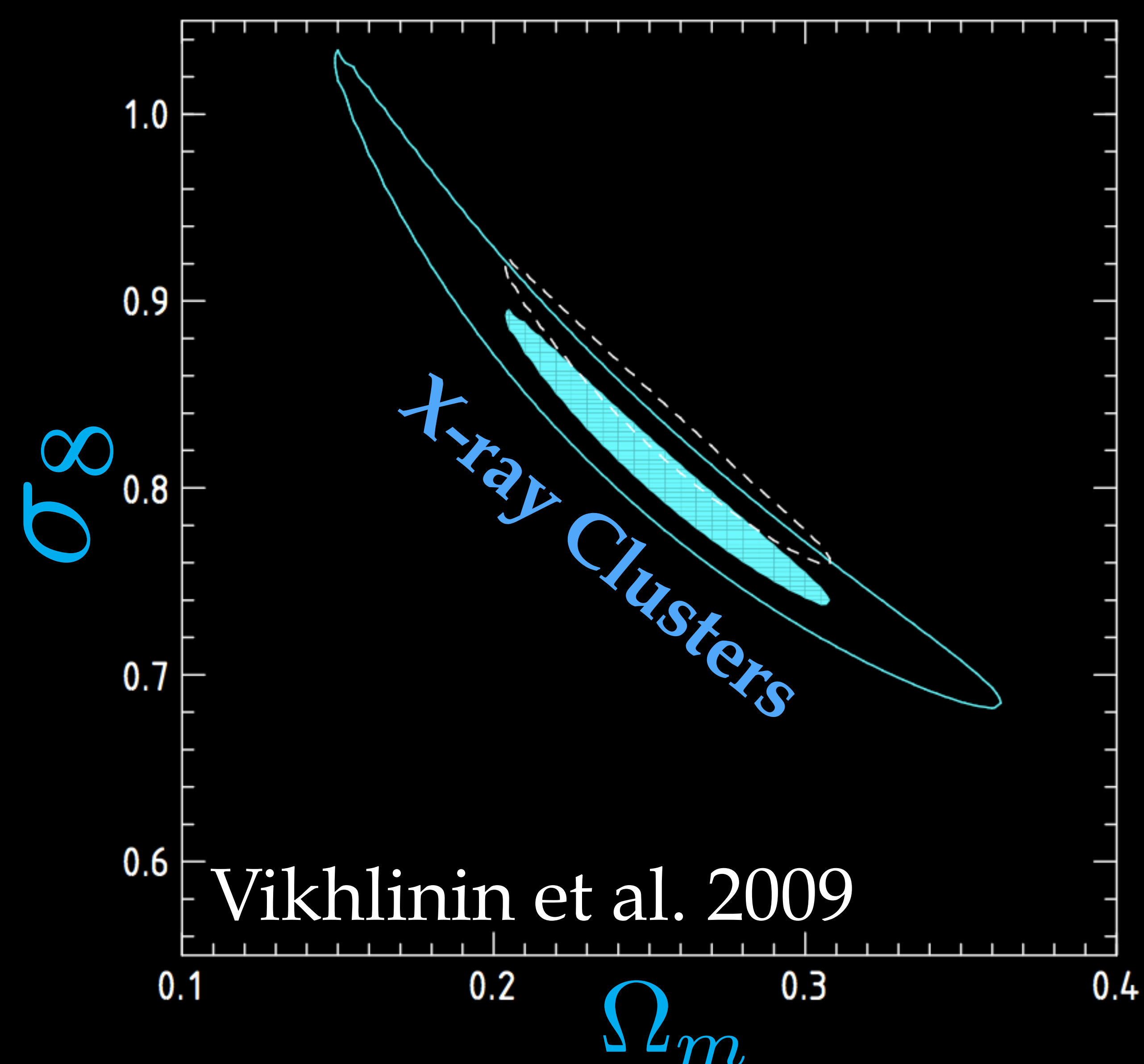
Cosmological Signals of eV-scale Sterile Neutrinos?



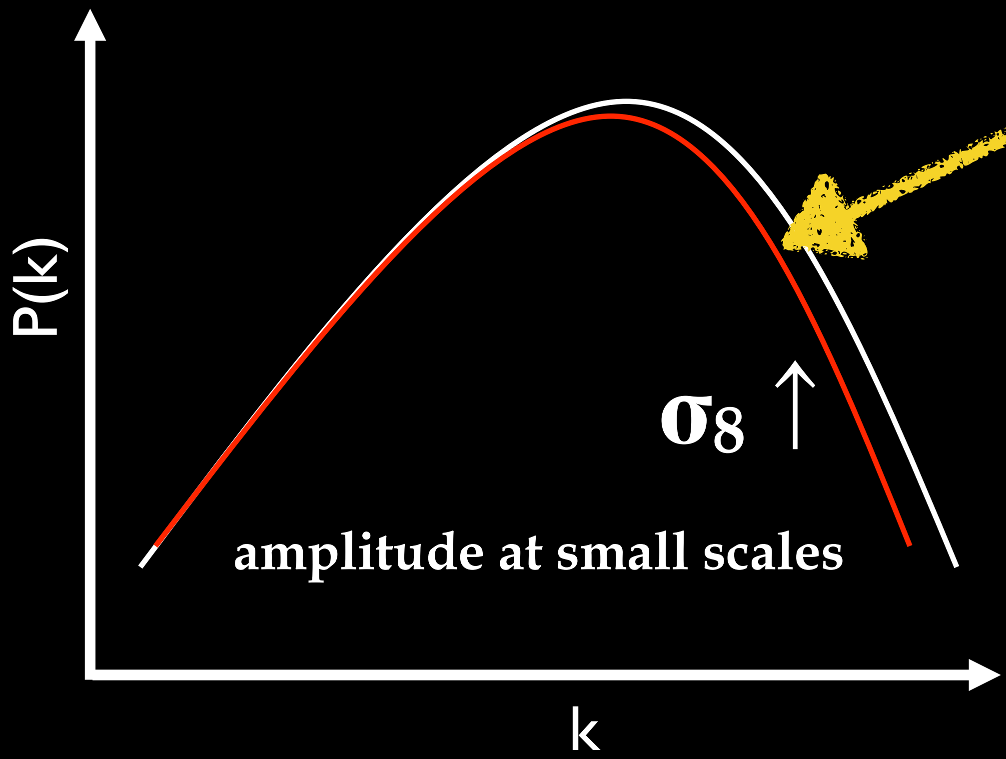
If small-scale measures want smaller power than large-scale (CMB) measures, then it may detect the presence of massive neutrinos

X-ray Clusters:

$$\sigma_8 = 0.803 \pm 0.0105$$



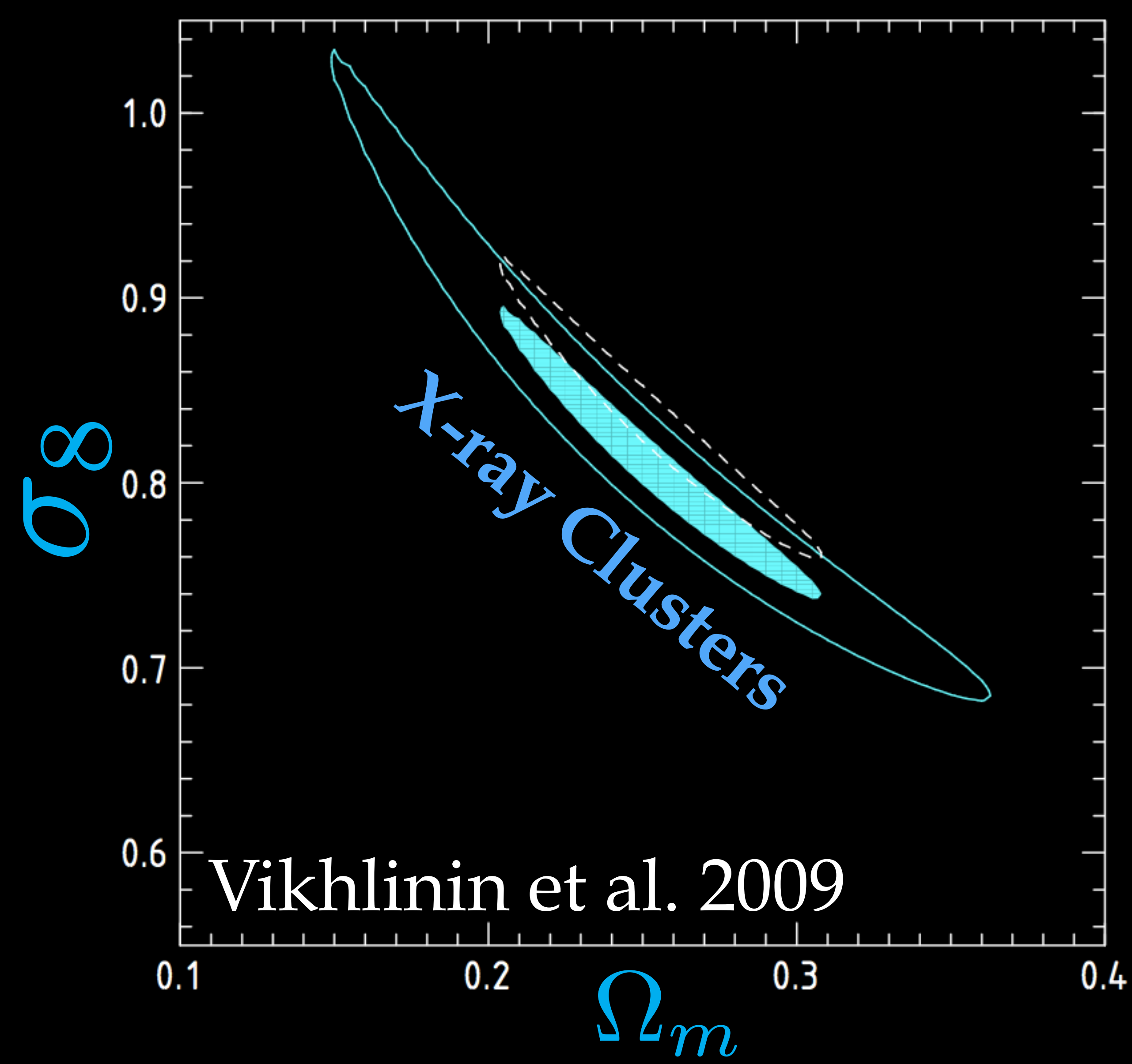
Cosmological Signals of eV-scale Sterile Neutrinos?



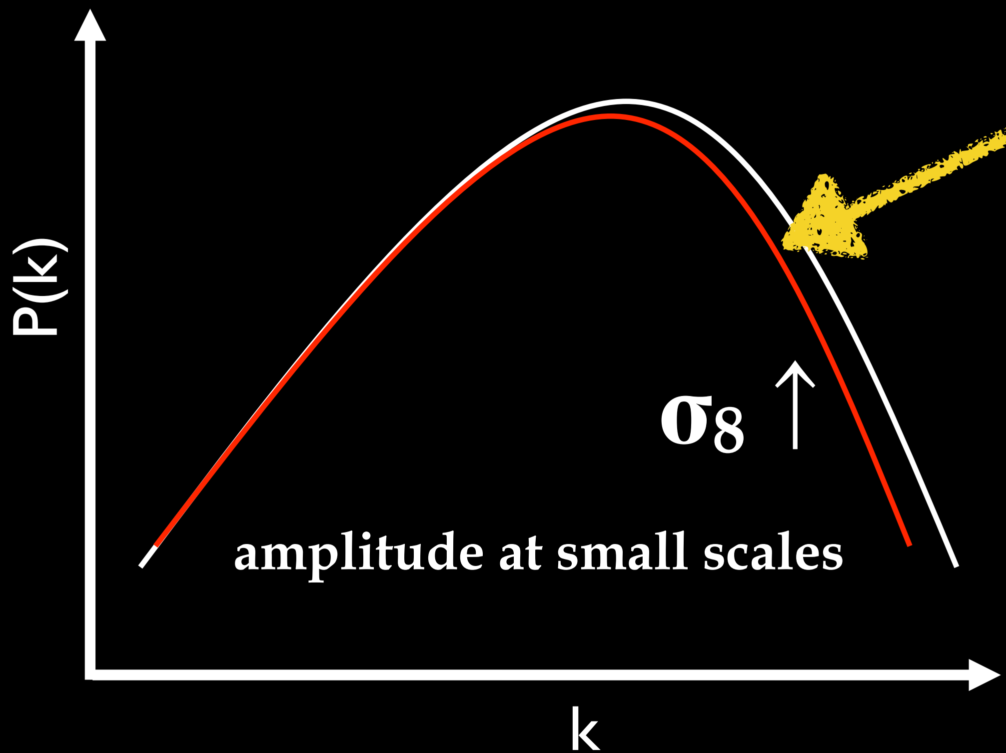
If small-scale measures want smaller power than large-scale (CMB) measures, then it may detect the presence of massive neutrinos

X-ray Clusters:

$$\sigma_8 = 0.803 \pm 0.0105$$
$$\Omega_m \simeq 0.25$$



Cosmological Signals of eV-scale Sterile Neutrinos?



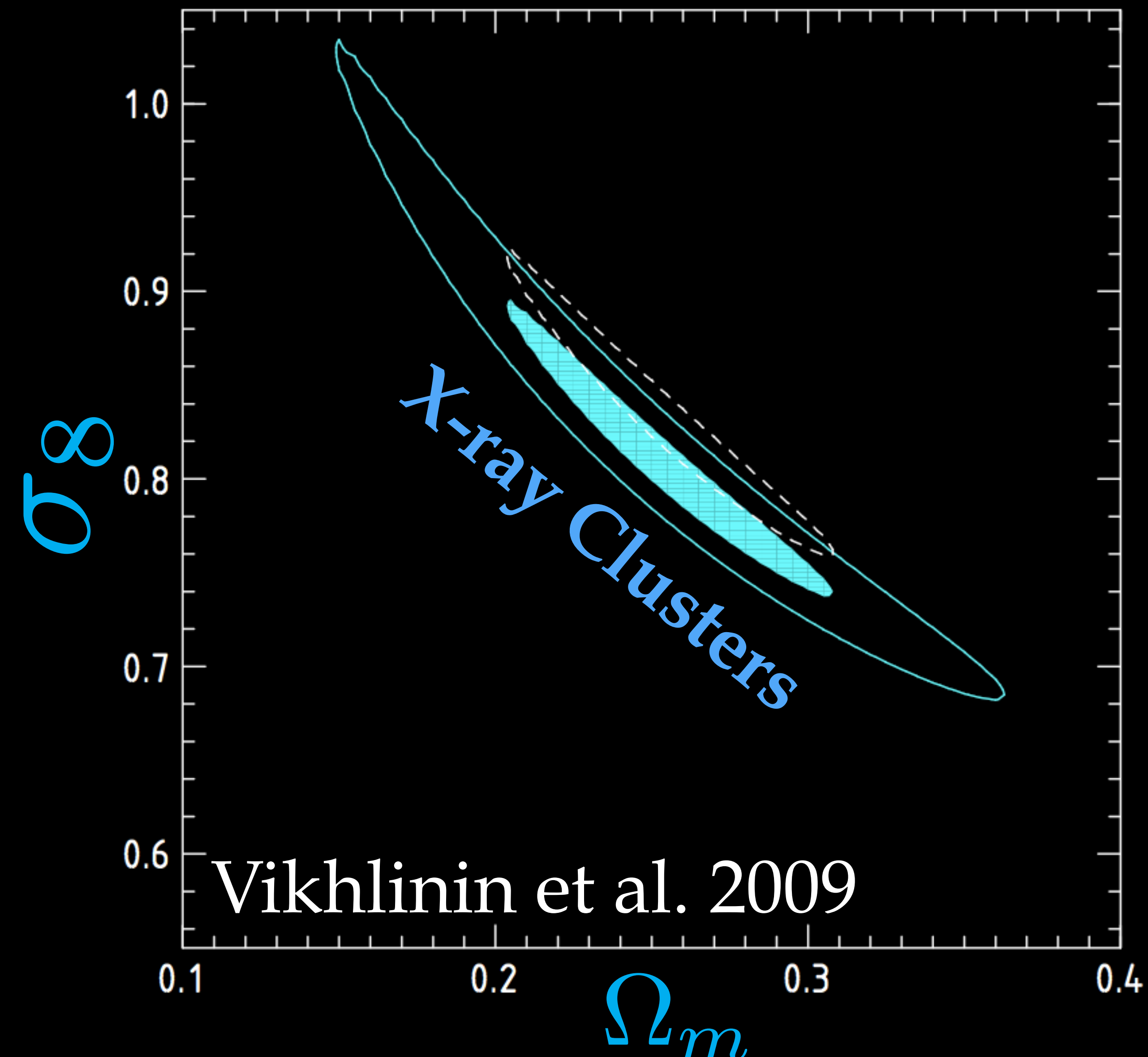
If small-scale measures want smaller power than large-scale (CMB) measures, then it may detect the presence of massive neutrinos

X-ray Clusters:

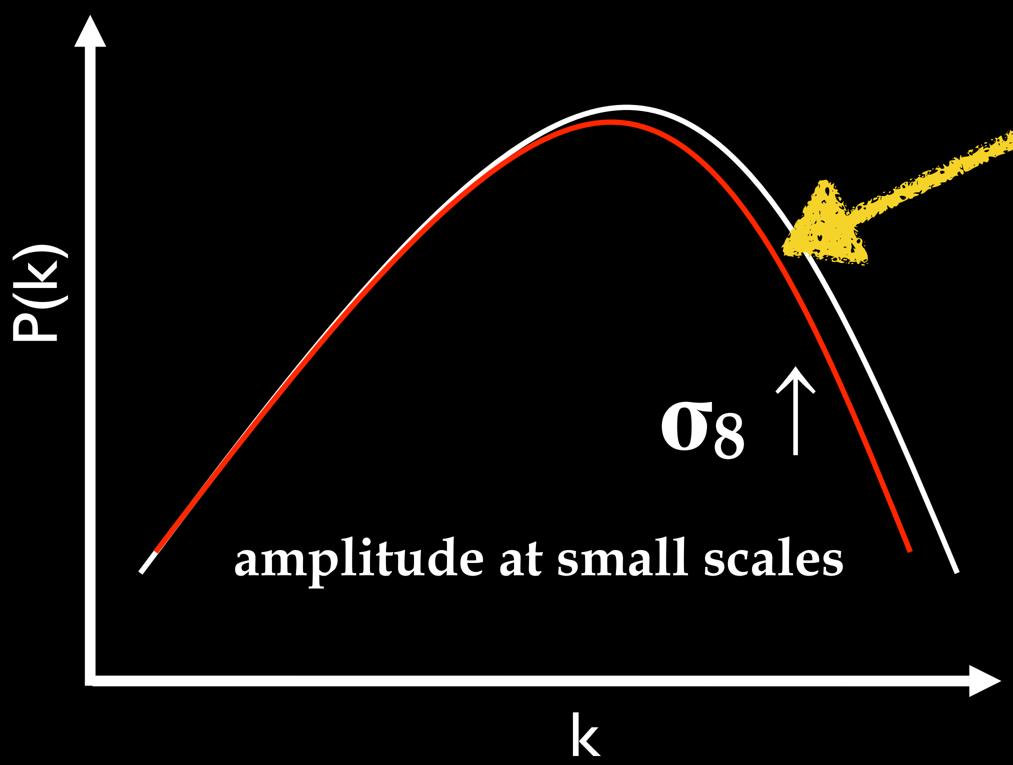
$$\sigma_8 = 0.803 \pm 0.0105$$

$$\Omega_m \simeq 0.25$$

Vikhlinin et al. 2009



Cosmological Signals of eV-scale Sterile Neutrinos?



If small-scale measures want smaller power than large-scale (CMB) measures, then it may detect the presence of massive neutrinos

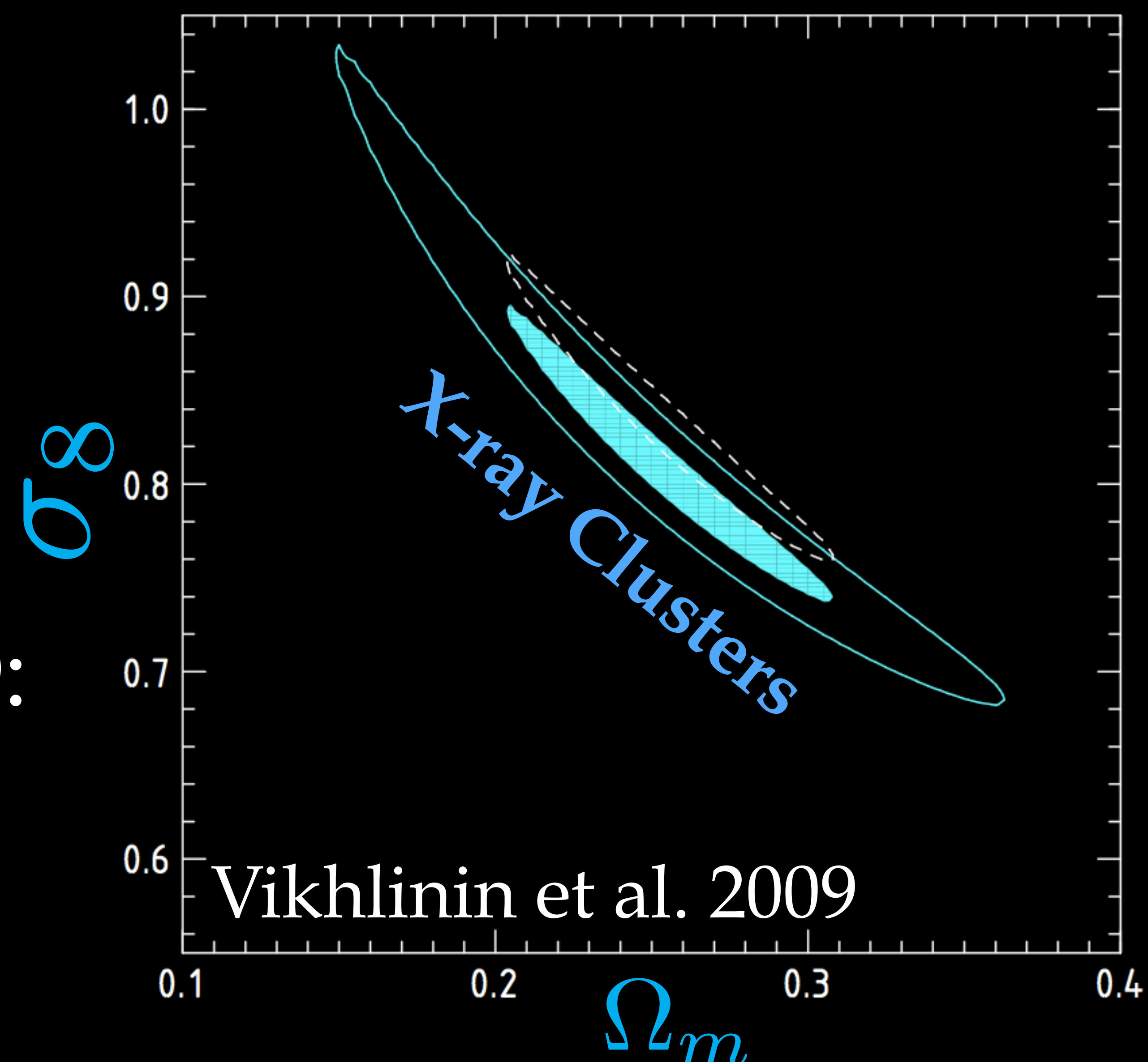
X-ray Clusters:

$$\sigma_8 = 0.803 \pm 0.0105$$

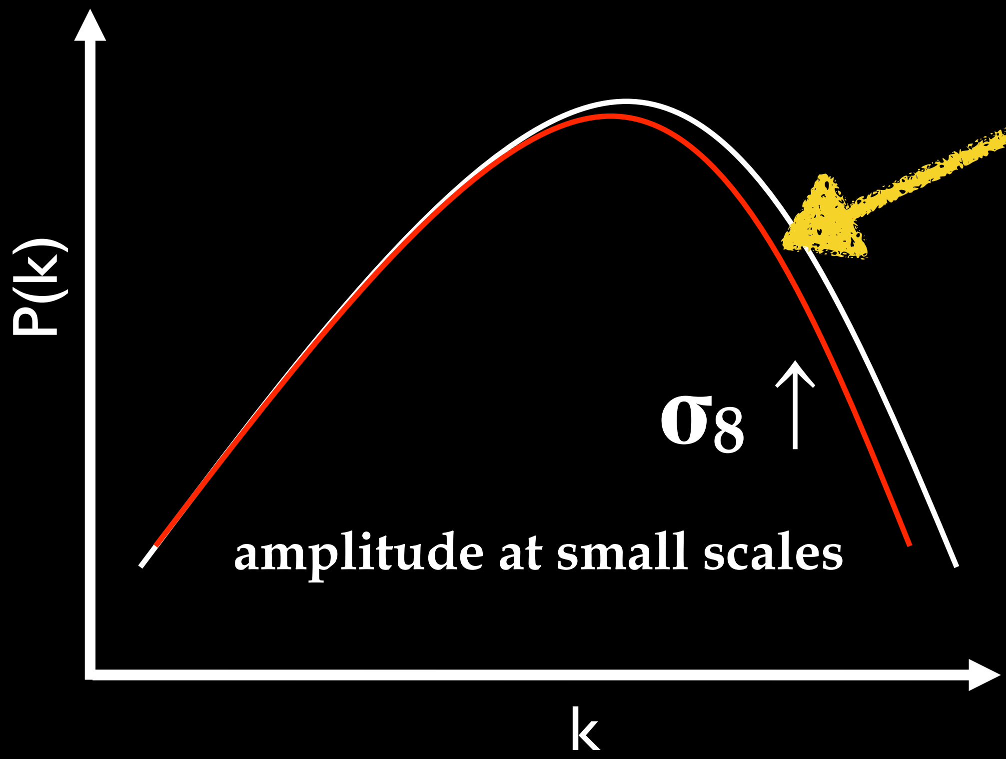
$$\Omega_m \simeq 0.25$$

Vikhlinin et al. 2009

Planck13+WP+highL+BAO:



Cosmological Signals of eV-scale Sterile Neutrinos?



If small-scale measures want smaller power than large-scale (CMB) measures, then it may detect the presence of massive neutrinos

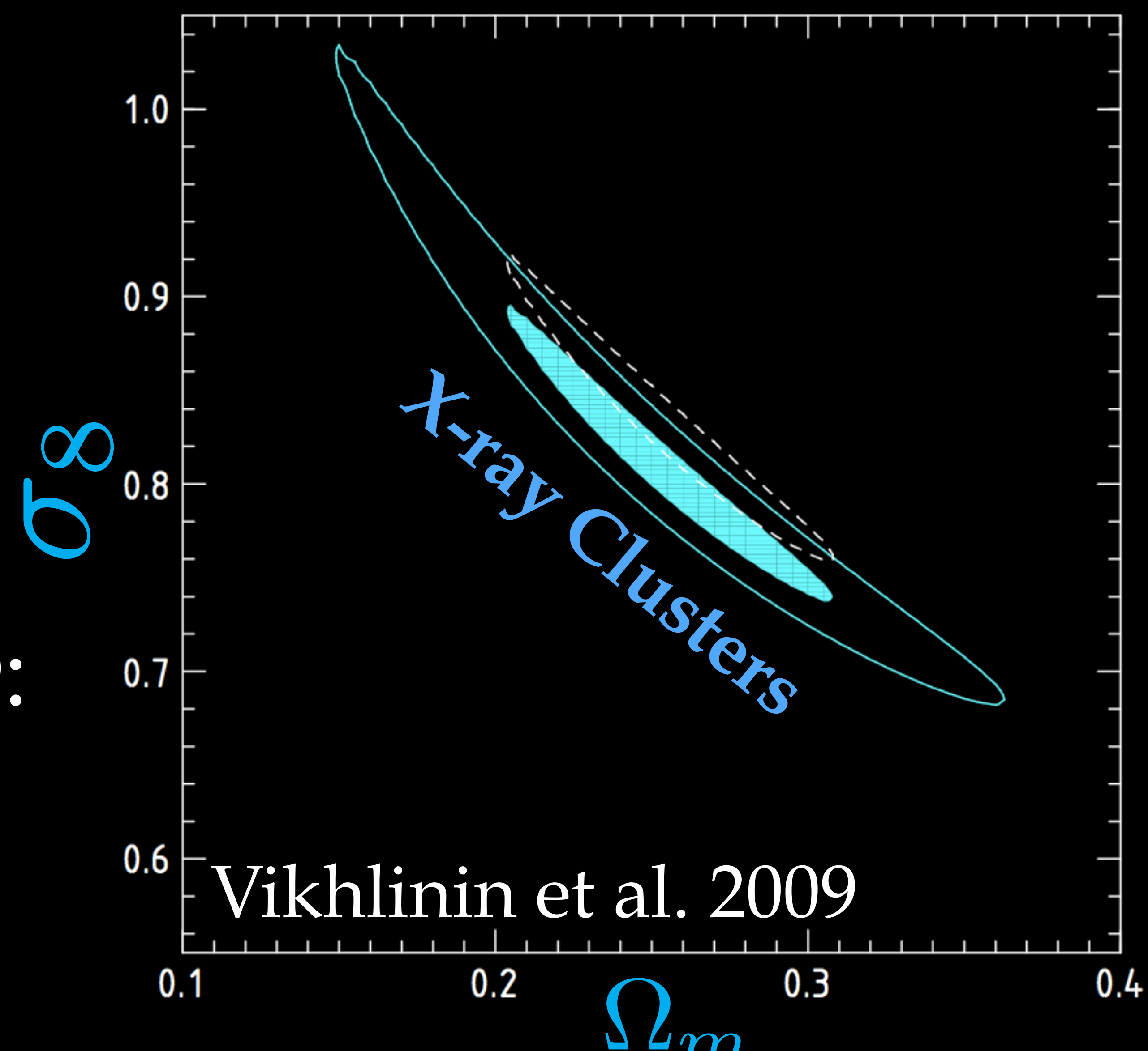
X-ray Clusters:

$$\sigma_8 = 0.803 \pm 0.0105$$
$$\Omega_m \simeq 0.25$$

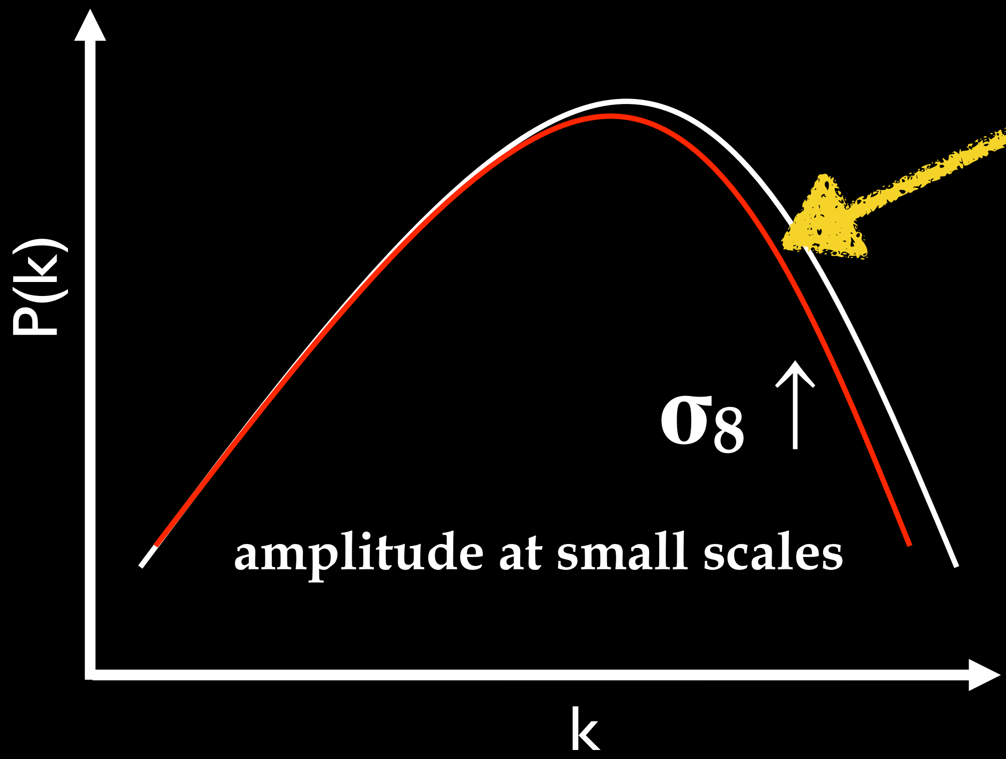
Vikhlinin et al. 2009

Planck13+WP+highL+BAO:

$$\sigma_8 = 0.826 \pm 0.012$$



Cosmological Signals of eV-scale Sterile Neutrinos?



If small-scale measures want smaller power than large-scale (CMB) measures, then it may detect the presence of massive neutrinos

X-ray Clusters:

$$\sigma_8 = 0.803 \pm 0.0105$$

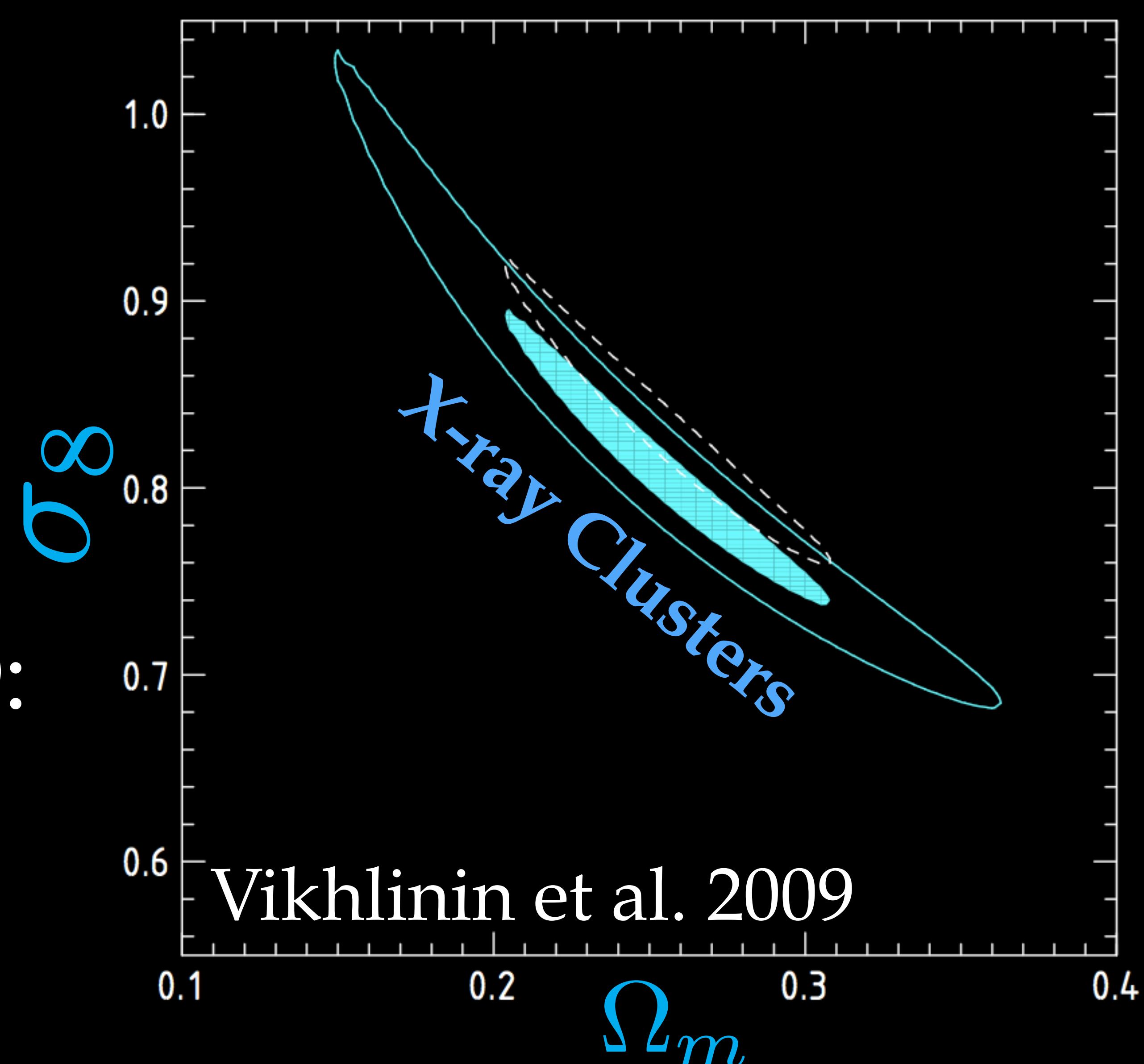
$$\Omega_m \simeq 0.25$$

Vikhlinin et al. 2009

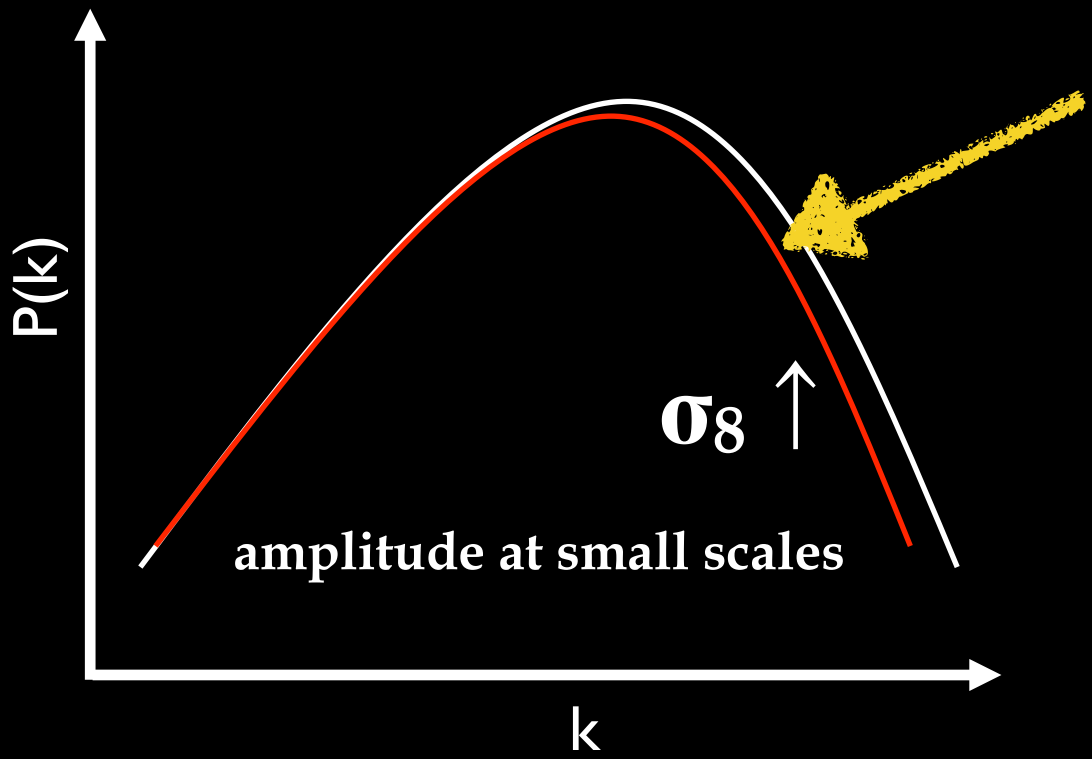
Planck13+WP+highL+BAO:

$$\sigma_8 = 0.826 \pm 0.012$$

$$\Omega_m = 0.308 \pm 0.010$$



Cosmological Signals of eV-scale Sterile Neutrinos?



If small-scale measures want smaller power than large-scale (CMB) measures, then it may detect the presence of massive neutrinos

X-ray Clusters:

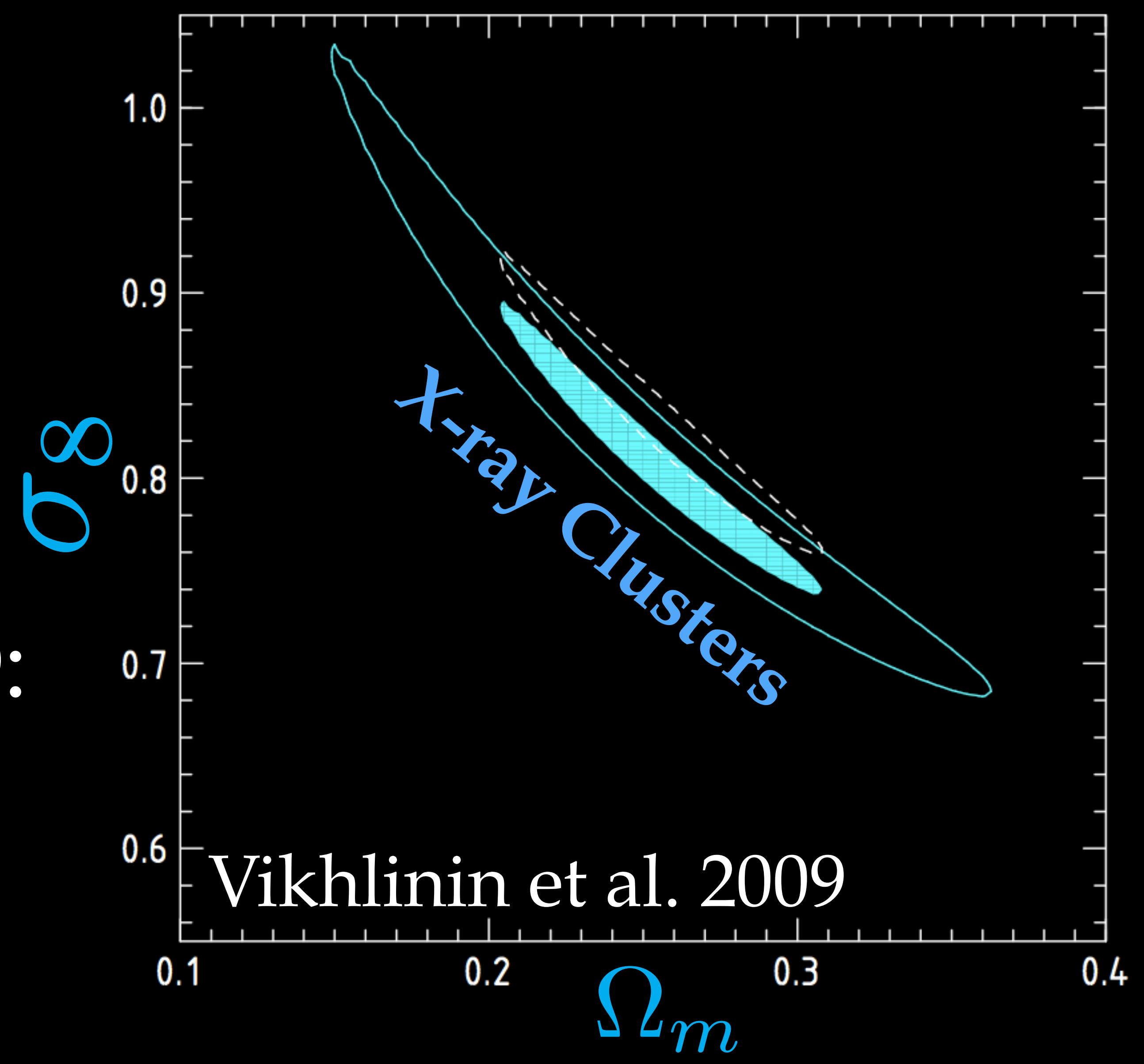
$$\sigma_8 = 0.803 \pm 0.0105$$
$$\Omega_m \simeq 0.25$$

Vikhlinin et al. 2009

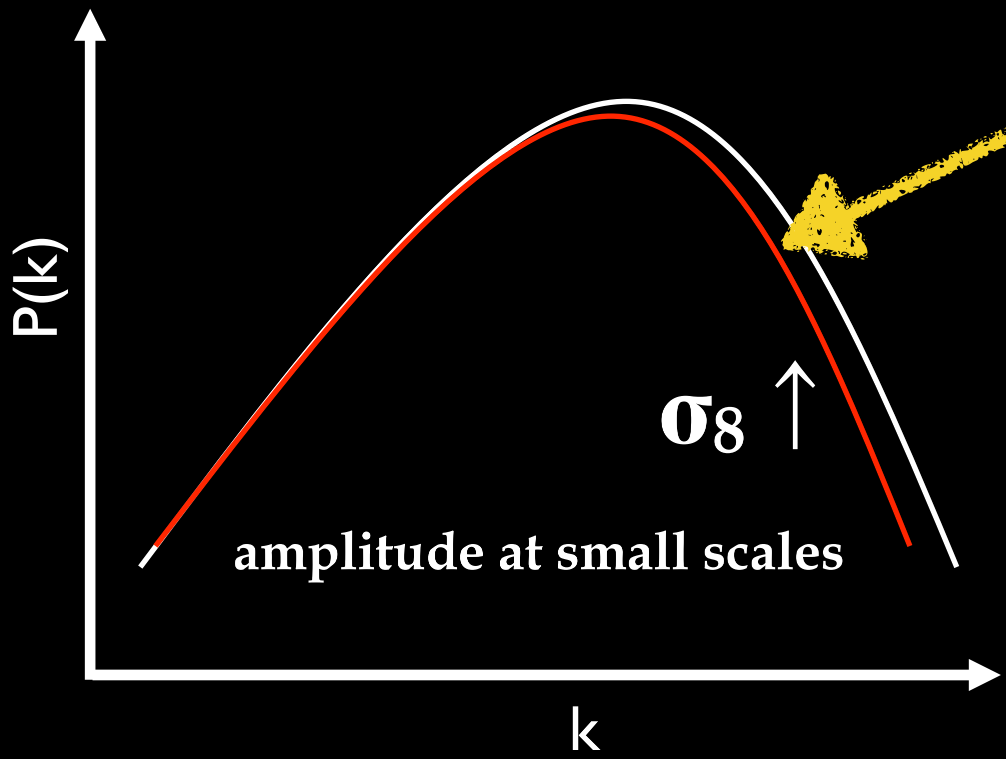
Planck13+WP+highL+BAO:

$$\sigma_8 = 0.826 \pm 0.012$$
$$\Omega_m = 0.308 \pm 0.010$$

Planck Collab. 2013



Cosmological Signals of eV-scale Sterile Neutrinos?



If small-scale measures want smaller power than large-scale (CMB) measures, then it may detect the presence of massive neutrinos

X-ray Clusters:

$$\sigma_8 = 0.803 \pm 0.0105$$

$$\Omega_m \simeq 0.25$$

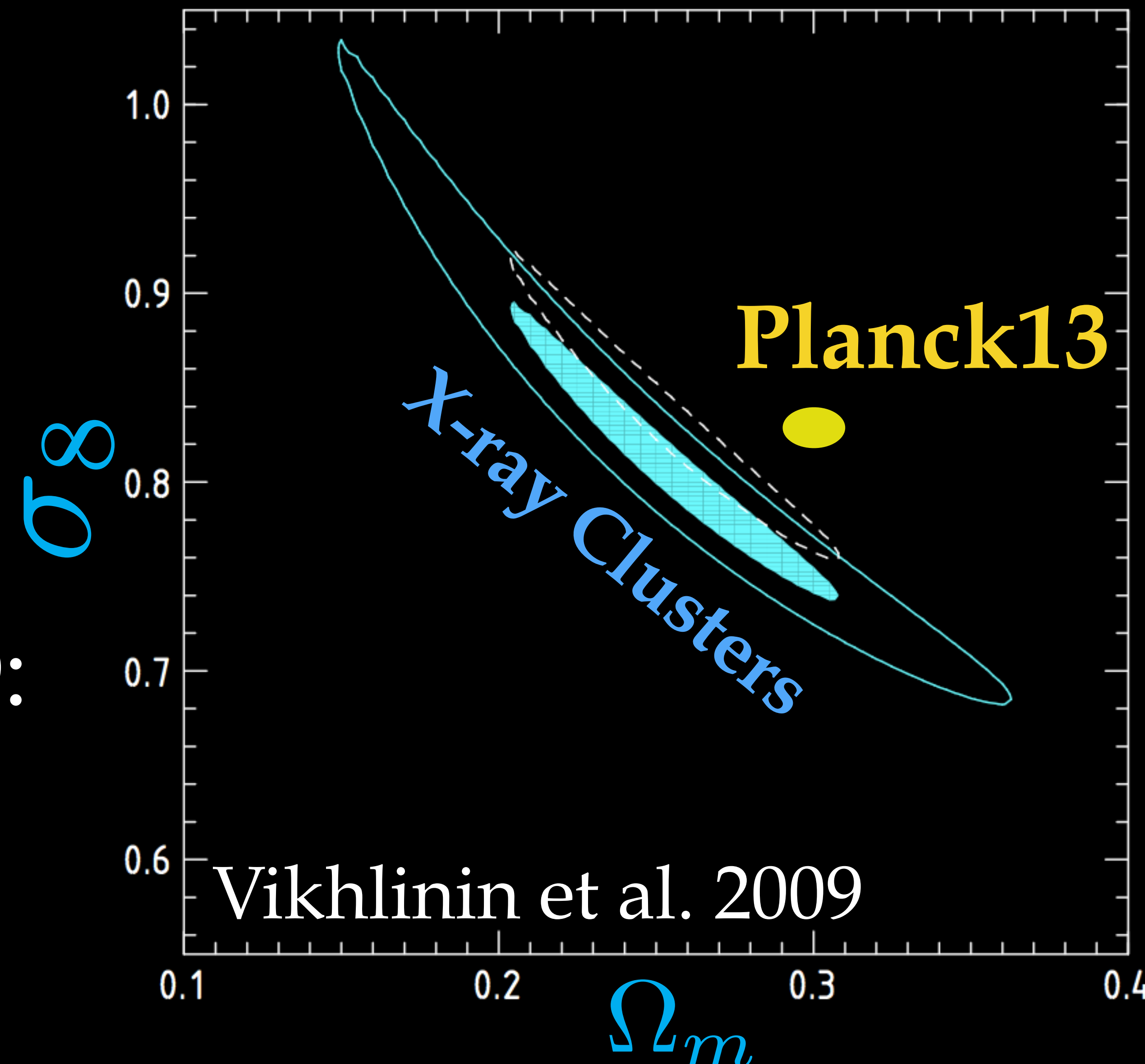
Vikhlinin et al. 2009

Planck13+WP+highL+BAO:

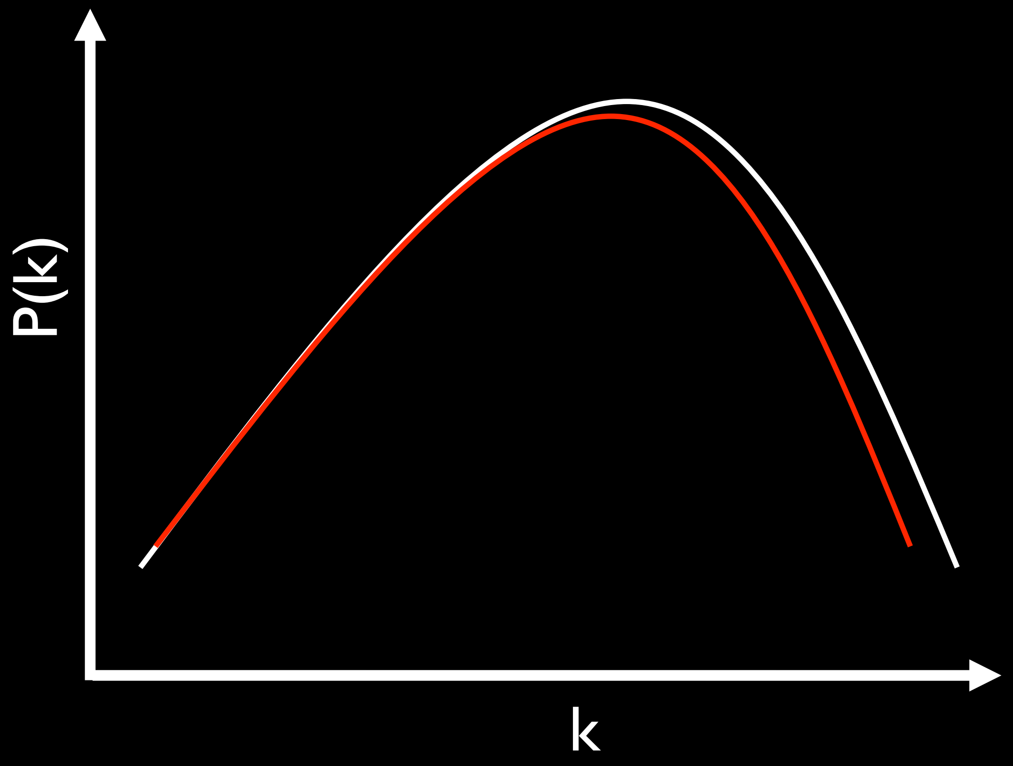
$$\sigma_8 = 0.826 \pm 0.012$$

$$\Omega_m = 0.308 \pm 0.010$$

Planck Collab. 2013

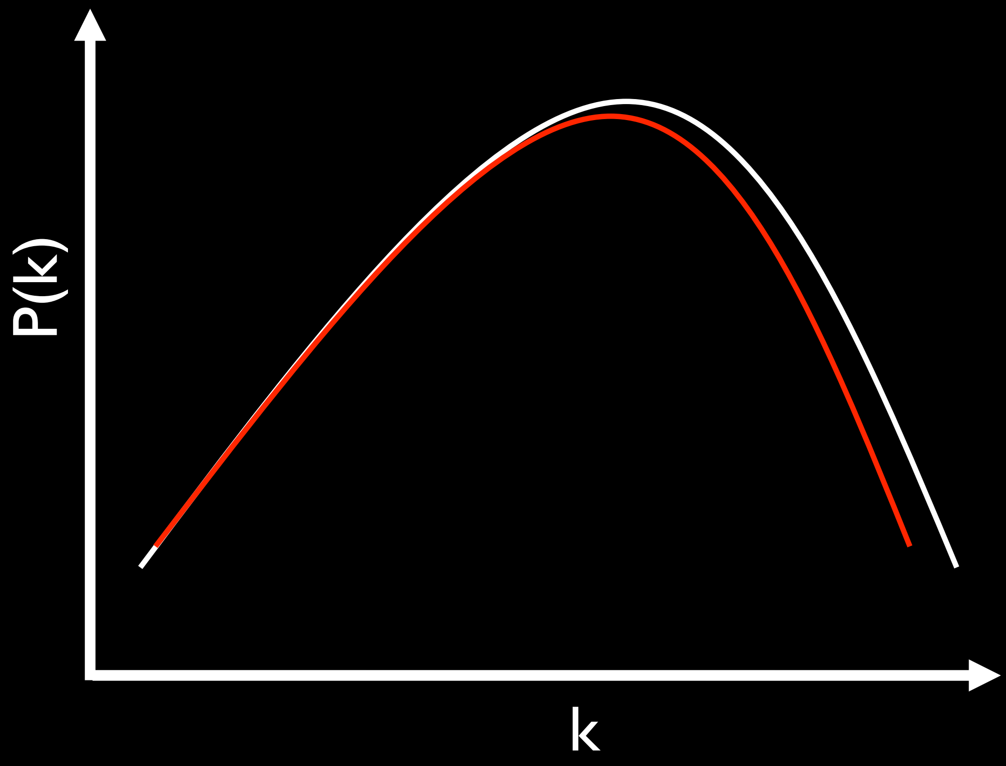


Cosmological Signals of eV-scale Sterile Neutrinos?



Cluster samples detected via Sunayev-Zel’dovich-Effect in the CMB find a similar $P(k)$ suppression necessary, and indications for non-zero Σm_ν

Cosmological Signals of eV-scale Sterile Neutrinos?

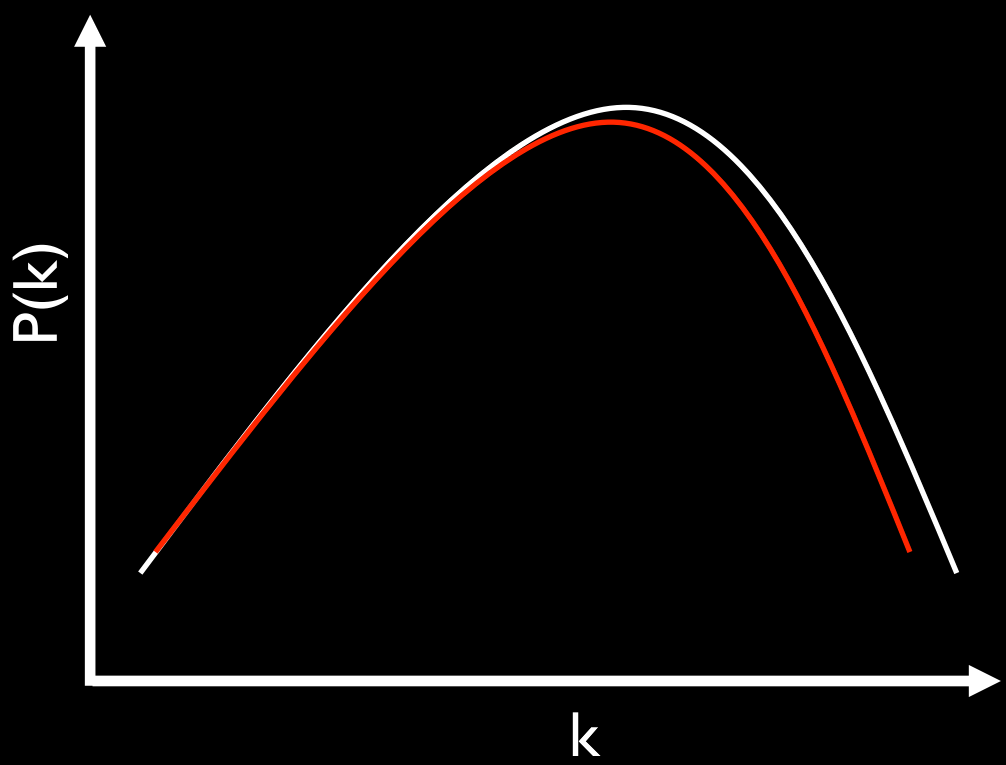


Cluster samples detected via Sunayev-Zel'dovich-Effect in the CMB find a similar $P(k)$ suppression necessary, and indications for non-zero Σm_ν

South Pole Telescope CMB + **SPT SZ Clusters** + WMAP 7 + H_0 (Hou et al. 2012):

$$0.10 \text{ eV} \leq \Sigma m_{\nu_i} \leq 0.54 \text{ eV}$$

Cosmological Signals of eV-scale Sterile Neutrinos?



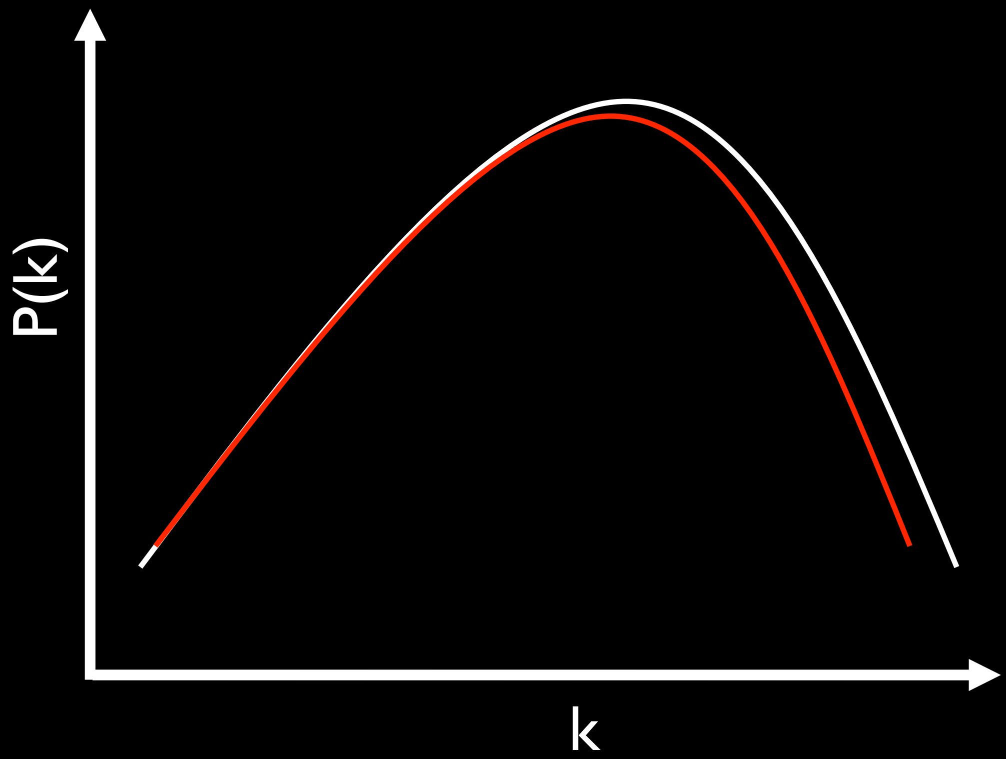
Cluster samples detected via Sunayev-Zel'dovich-Effect in the CMB find a similar $P(k)$ suppression necessary, and indications for non-zero Σm_ν

South Pole Telescope CMB + **SPT SZ Clusters** + WMAP 7 + H_0 (Hou et al. 2012):

$$0.10 \text{ eV} \leq \Sigma m_{\nu_i} \leq 0.54 \text{ eV}$$

Planck 2013 + **Planck SZ Clusters** + H_0 + BAO (e.g. Wyman et al. 2013; Giusarma et al 2014, Hamann & Hasenkamp 2013, Wyman et al. 2013) *active neutrinos*:

Cosmological Signals of eV-scale Sterile Neutrinos?



Cluster samples detected via Sunayev-Zel'dovich-Effect in the CMB find a similar $P(k)$ suppression necessary, and indications for non-zero Σm_ν

South Pole Telescope CMB + **SPT SZ Clusters** + WMAP 7 + H_0 (Hou et al. 2012):

$$0.10 \text{ eV} \leq \Sigma m_{\nu_i} \leq 0.54 \text{ eV}$$

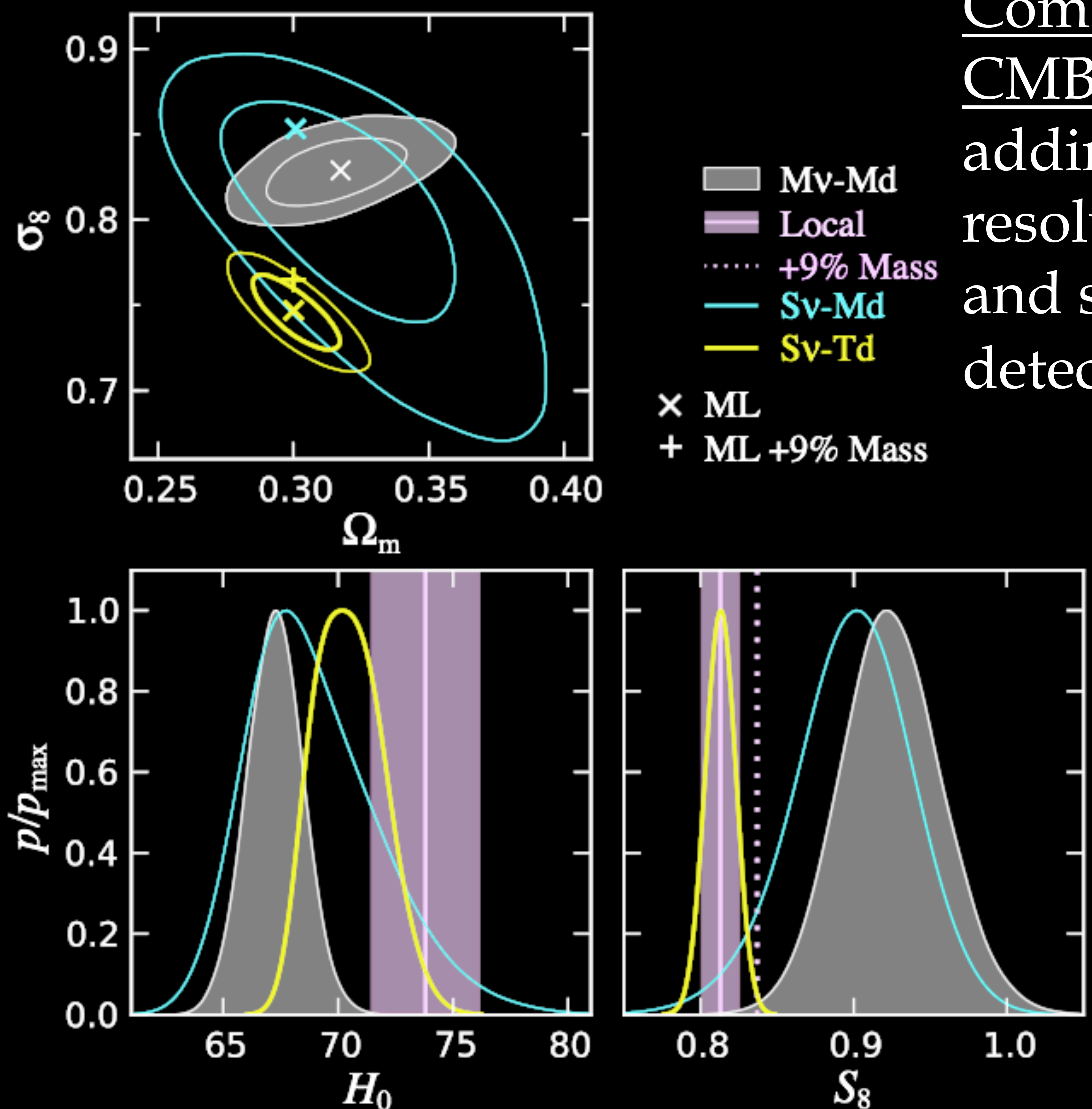
Planck 2013 + **Planck SZ Clusters** + H_0 + BAO (e.g. Wyman et al. 2013; Giusarma et al 2014, Hamann & Hasenkamp 2013, Wyman et al. 2013) *active neutrinos*:

$$\Sigma m_{\nu_i} = 0.39 \pm 0.11 \text{ eV}$$

Cosmological Signals of eV-scale Sterile Neutrinos?

Combining Planck 2013 CMB + Clusters: adding sterile neutrinos resolves tension from large and small scales, sterile m_s detected at **3.5 σ**

Cosmological Signals of eV-scale Sterile Neutrinos?



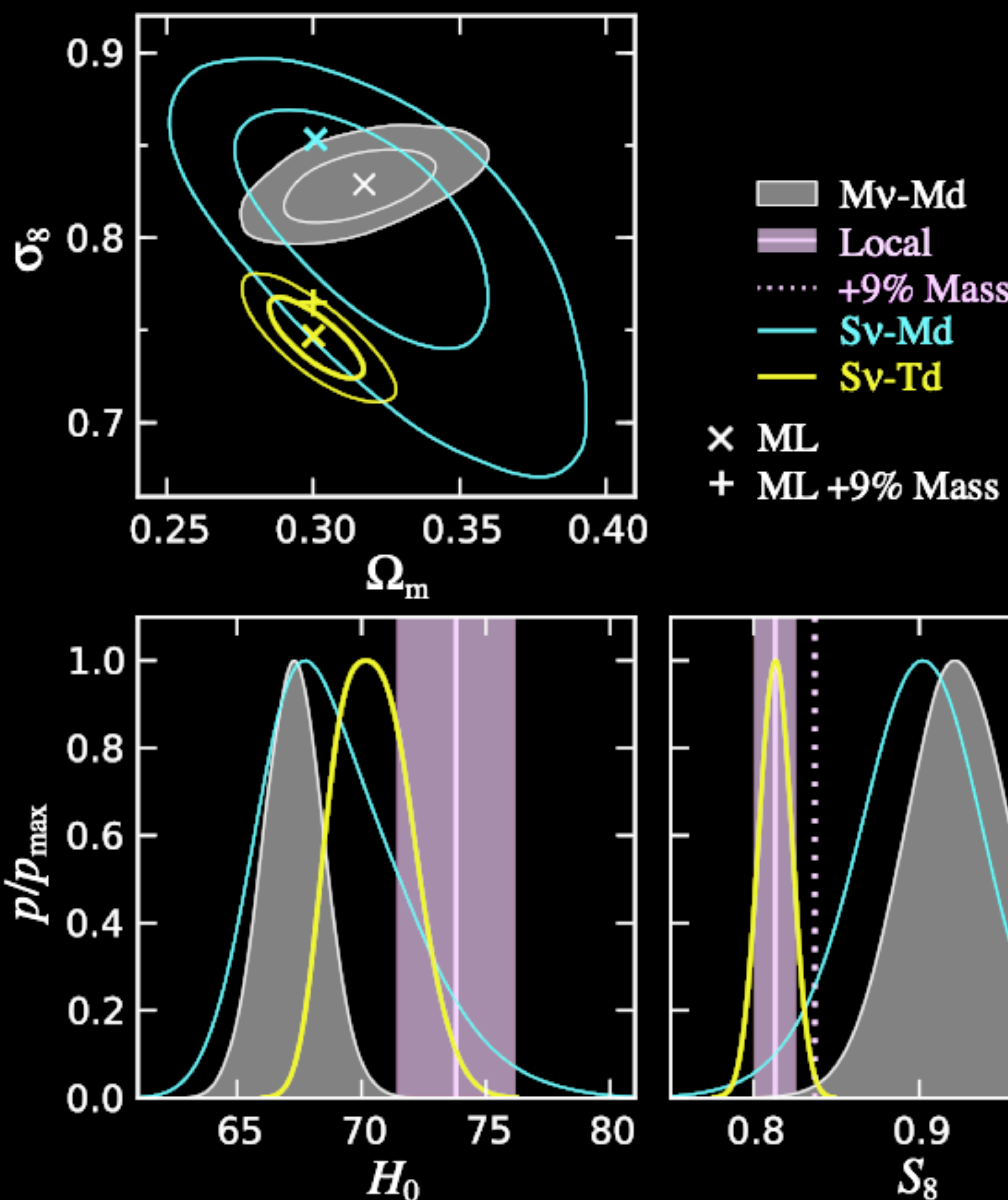
Combining Planck 2013 CMB + Clusters: adding sterile neutrinos resolves tension from large and small scales, sterile m_s detected at **3.5 σ**

$$m_s = 0.44 \pm 0.14 \text{ eV}$$

$$N_{\rm eff} = 3.44 \pm 0.23$$

Wyman et al PRL 2013

Cosmological Signals of eV-scale Sterile Neutrinos?



<u>Combining Planck 2013 CMB + Clusters</u>: adding sterile neutrinos resolves tension from large and small scales, sterile ***m***$_s$ detected at <u>**3.5 σ**</u>

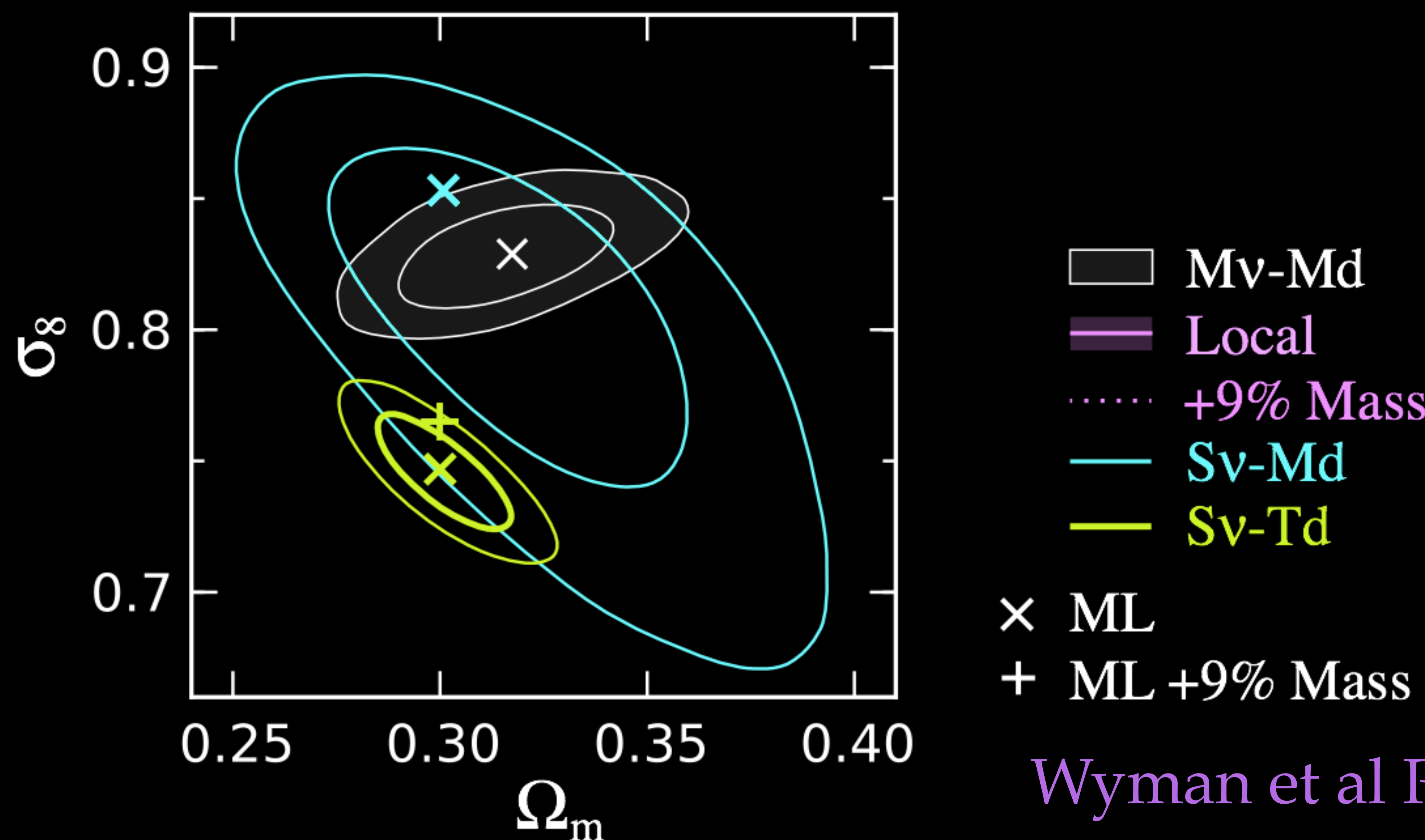
$$m_s = 0.44 \pm 0.14 \text{ eV}$$

$$N_{\rm eff} = 3.44 \pm 0.23$$

Wyman et al PRL 2013

To make this signal go away, systematic error <u>***must by three times***</u> current estimates.

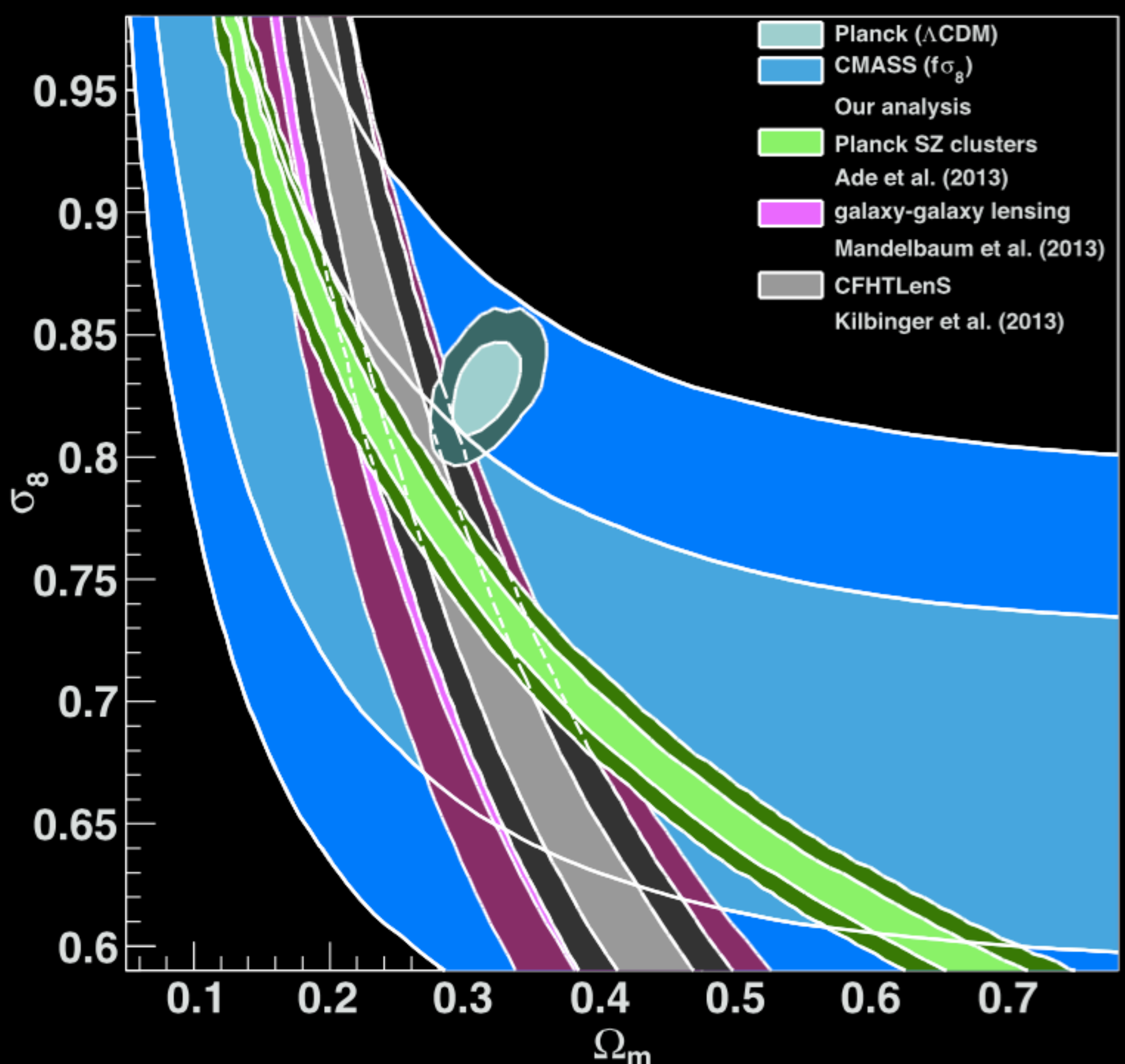
Cosmological Signals of eV-scale Sterile Neutrinos?

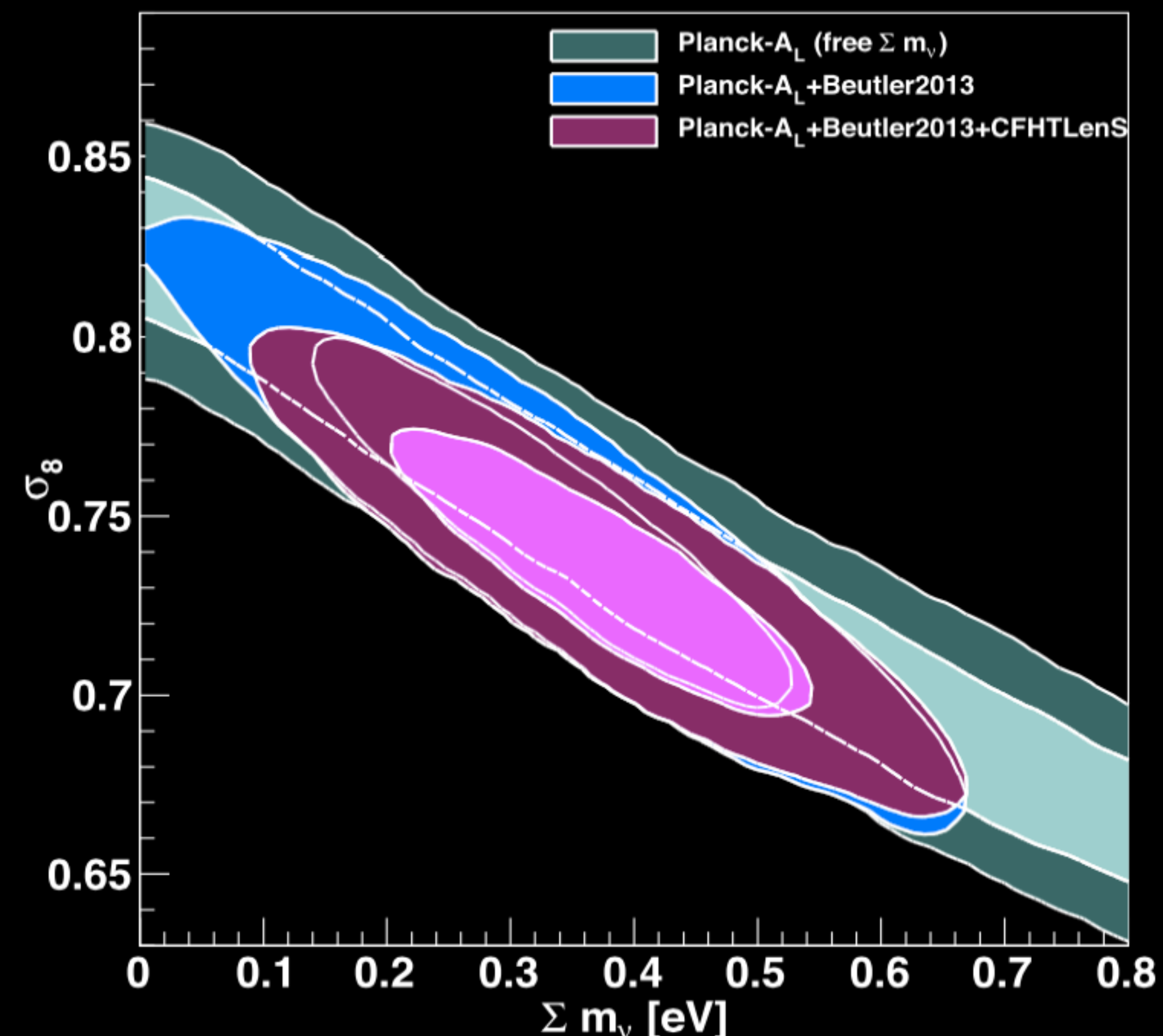


Wyman et al PRL 2013

Clusters' Masses are inferred from an observable (X-ray flux, SZ decrement), which historically has been plagued with systematic uncertainties. Such a systematic error in that would shift away the tension. However, the systematic error ***must by three times*** current estimates.

CMB+BAO or CMB+Lensing:
Signs of Neutrino Mass?
Small scale amplitude σ_8 vs. matter density Ω_m





Beutler+ 2014:
Planck 2013 + LSS

$\Sigma m_\nu = 0.36 \pm 0.10$ eV
→ WMAP9, BAO, Lensing

Neutrinoless Double Beta Decay & Cosmology: if you show cosmo constraints, show tension

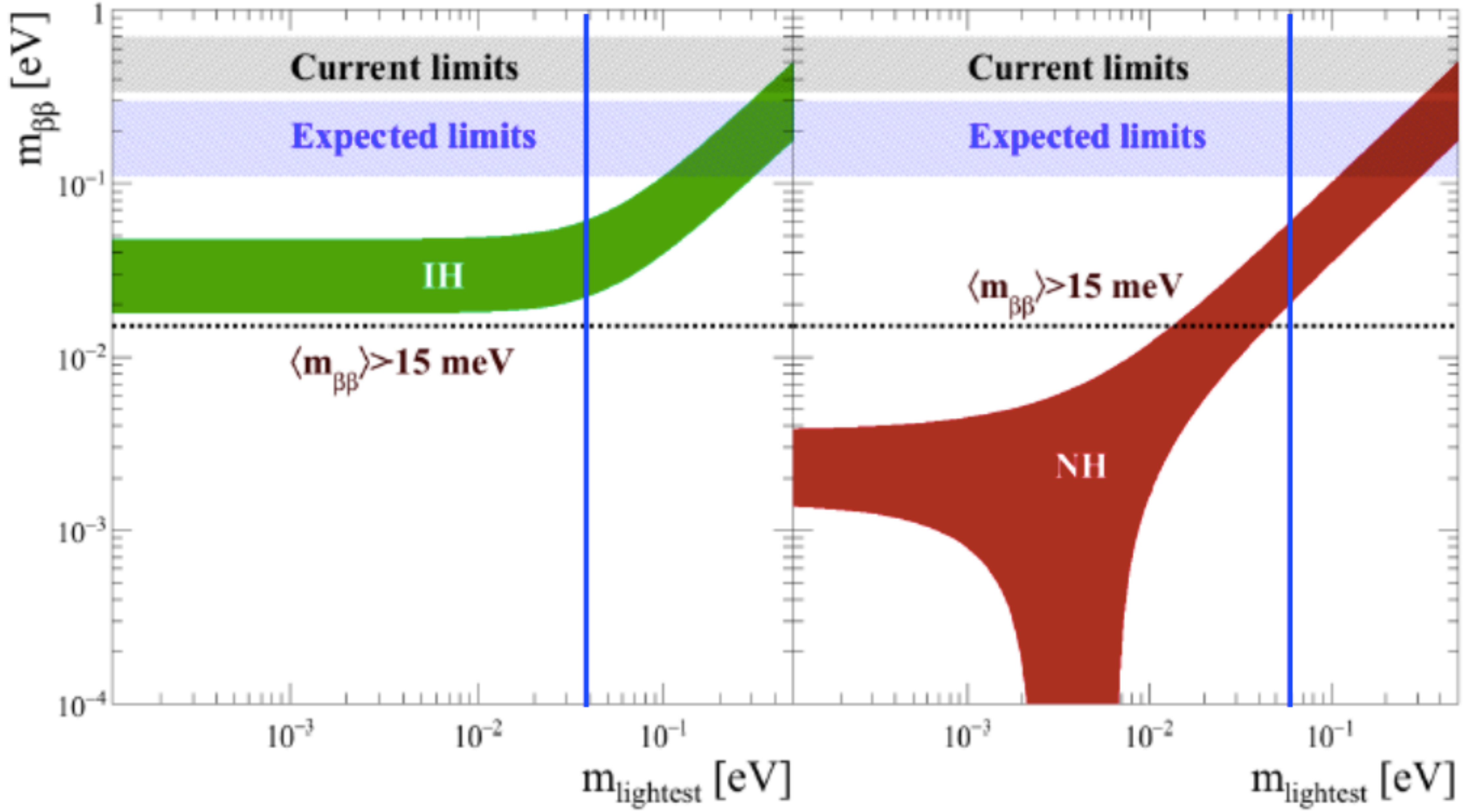


Fig: Wilkerson, this morning

Neutrinoless Double Beta Decay & Cosmology: if you show cosmo constraints, show tension

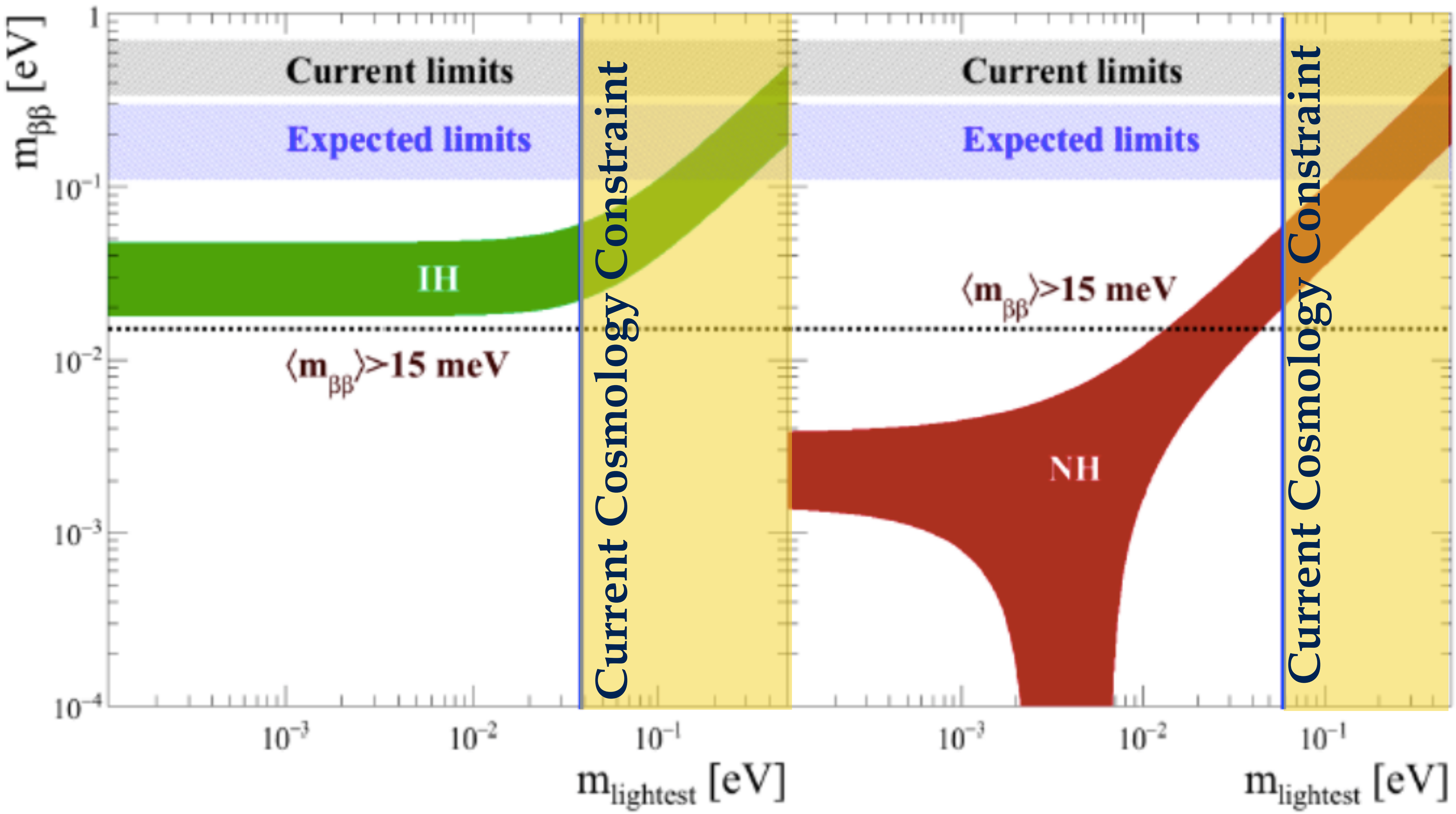


Fig: Wilkerson, this morning

Neutrinoless Double Beta Decay & Cosmology: if you show cosmo constraints, show tension

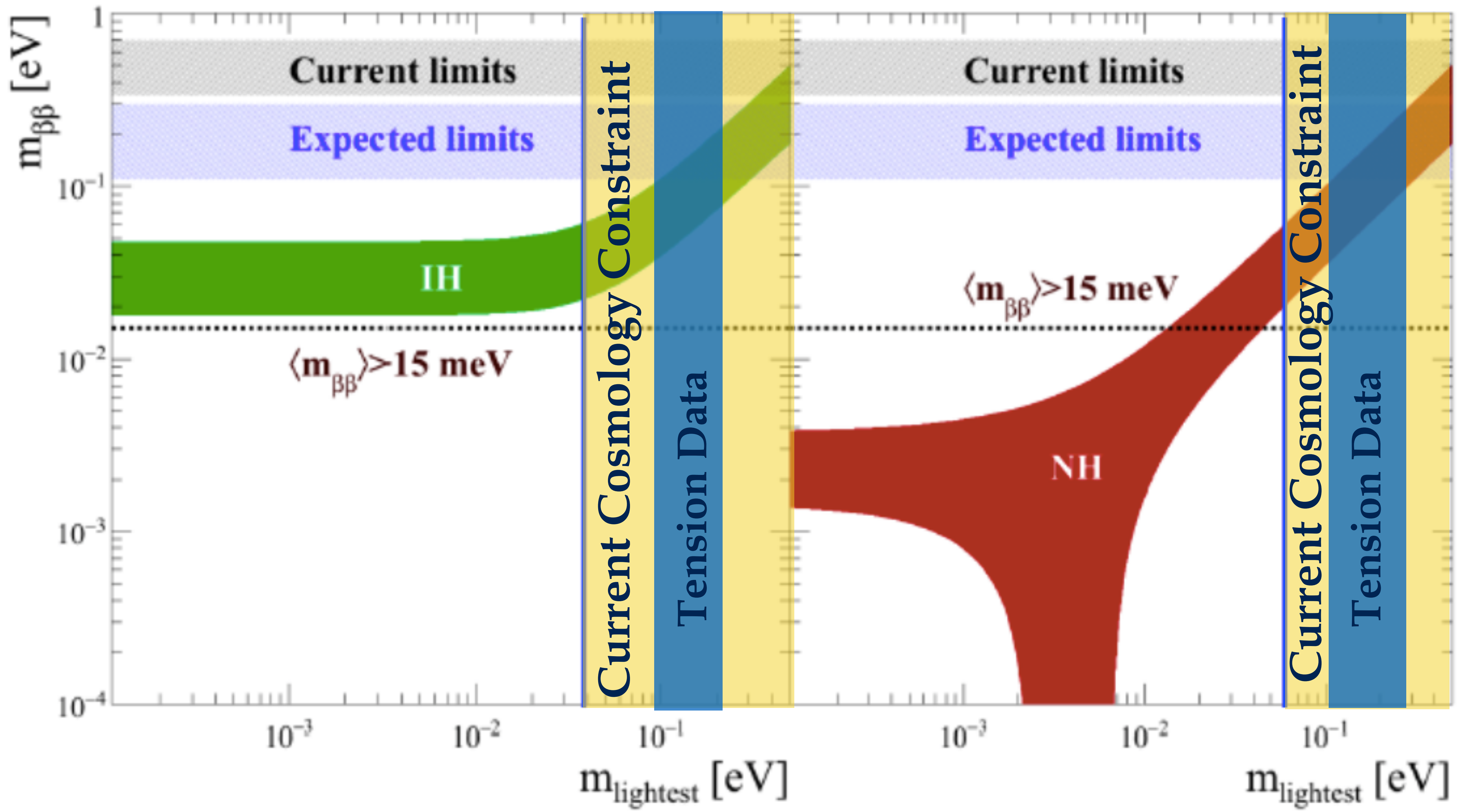
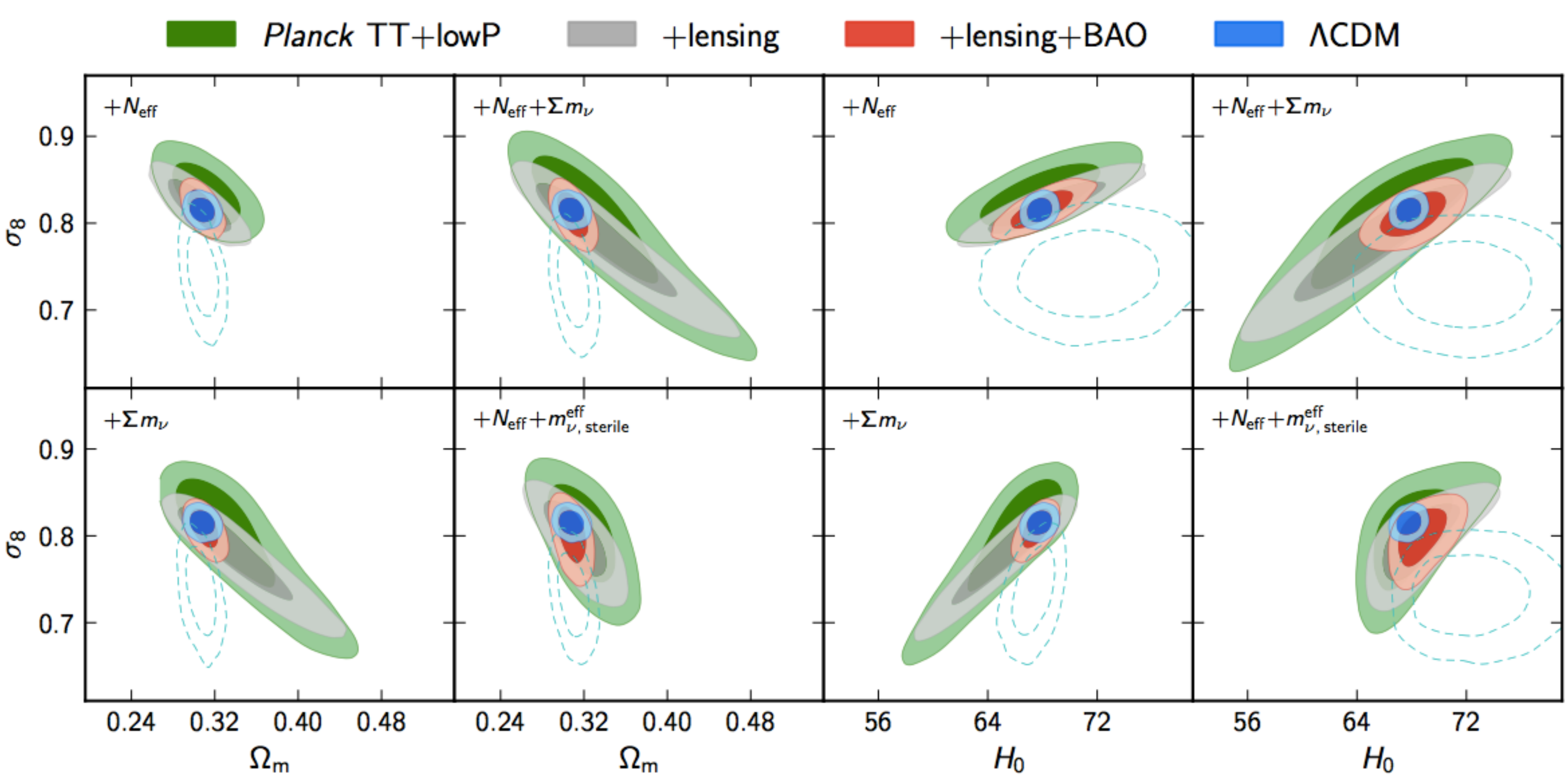
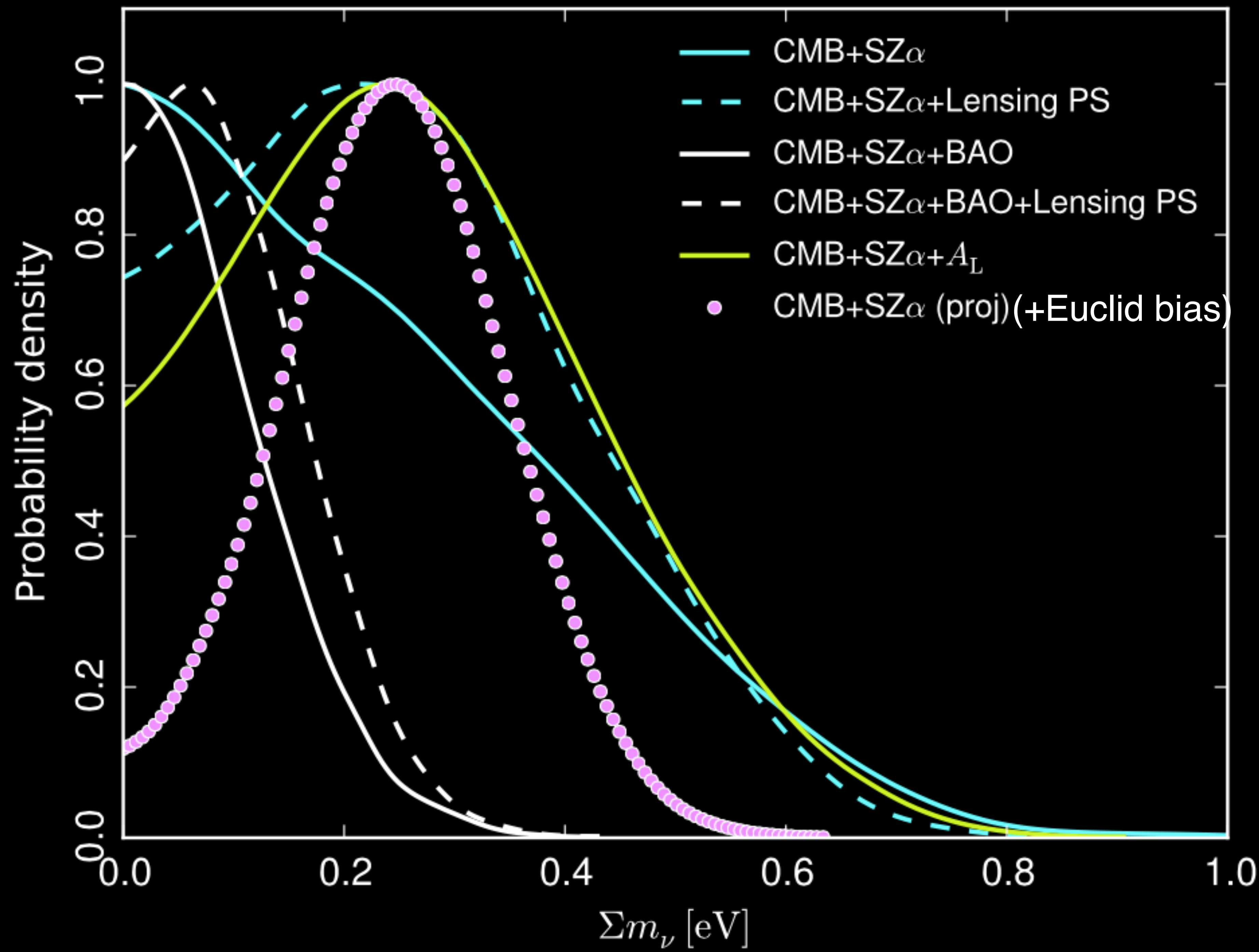


Fig: Wilkerson, this morning

Planck Collaboration 2015: $N_{\rm eff}$ and/or Neutrino Mass ***Do Not Alleviate Tension*** With BAO and Lensing



Planck Collaboration 2015: CMB+SZ Clusters *"combination appear to favour non-minimal neutrino masses"*



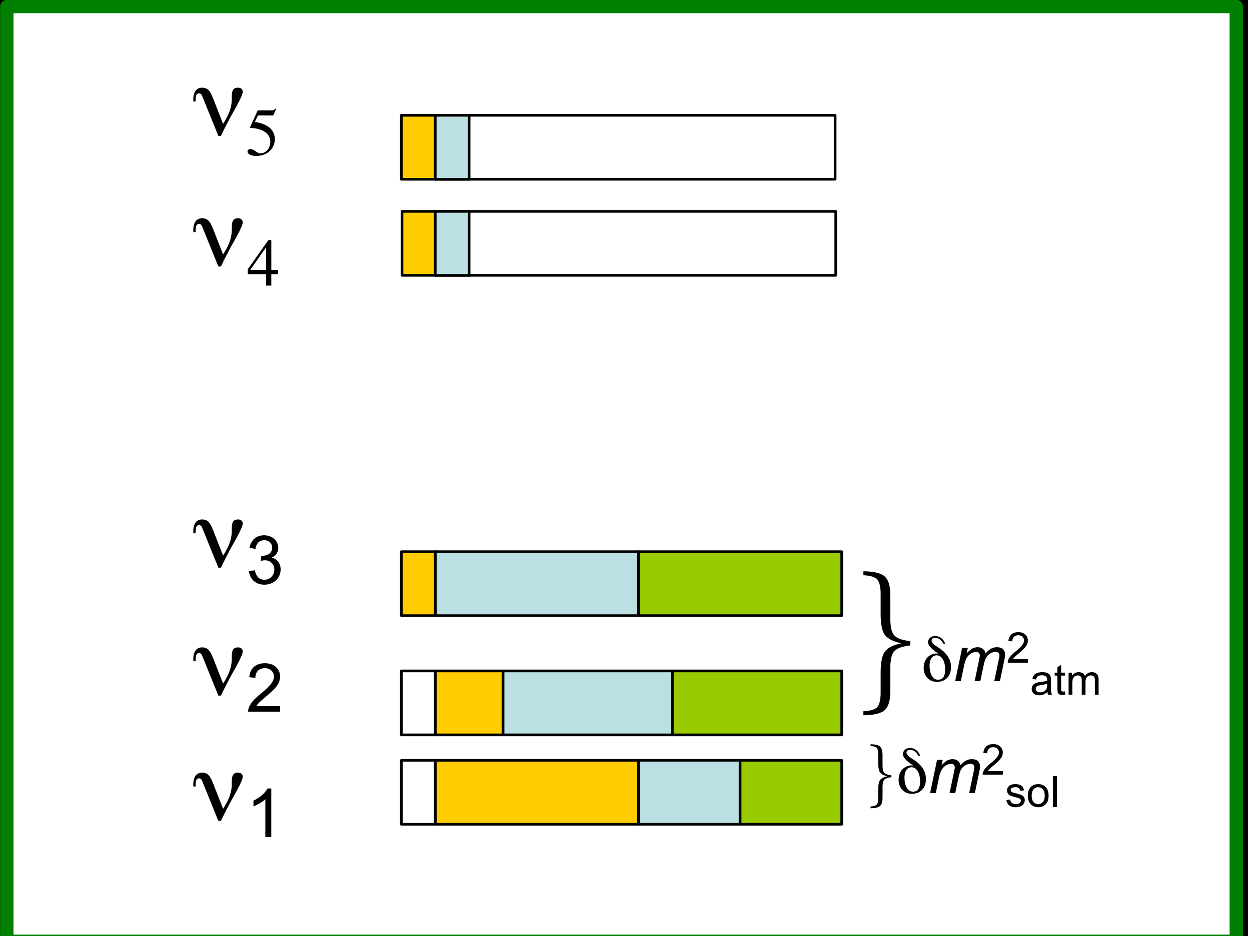
Σm_ν < 0.53 eV (95%), but maximum *L* is nonzero

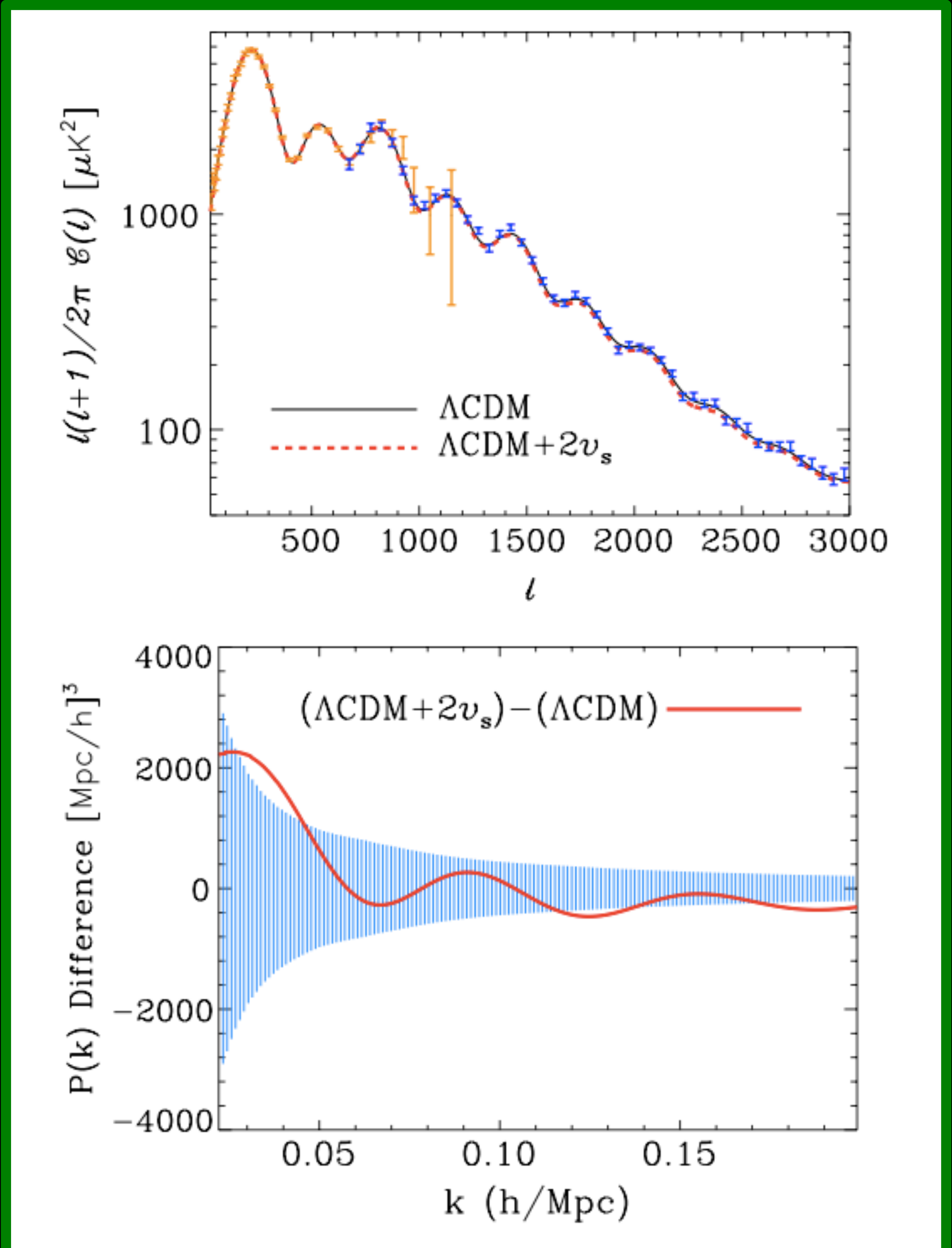
→ **Planck 2015, SZ, BAO, Lensing** (Planck 2015 paper XXIV)

The Need for Cross-Analysis Between Neutrino Experiment and Cosmology

Joudaki, Abazajian & Kaplinghat 2013

⇒ Short baseline oscillations require, minimally, 2 sterile ν′s with specific masses, mixings

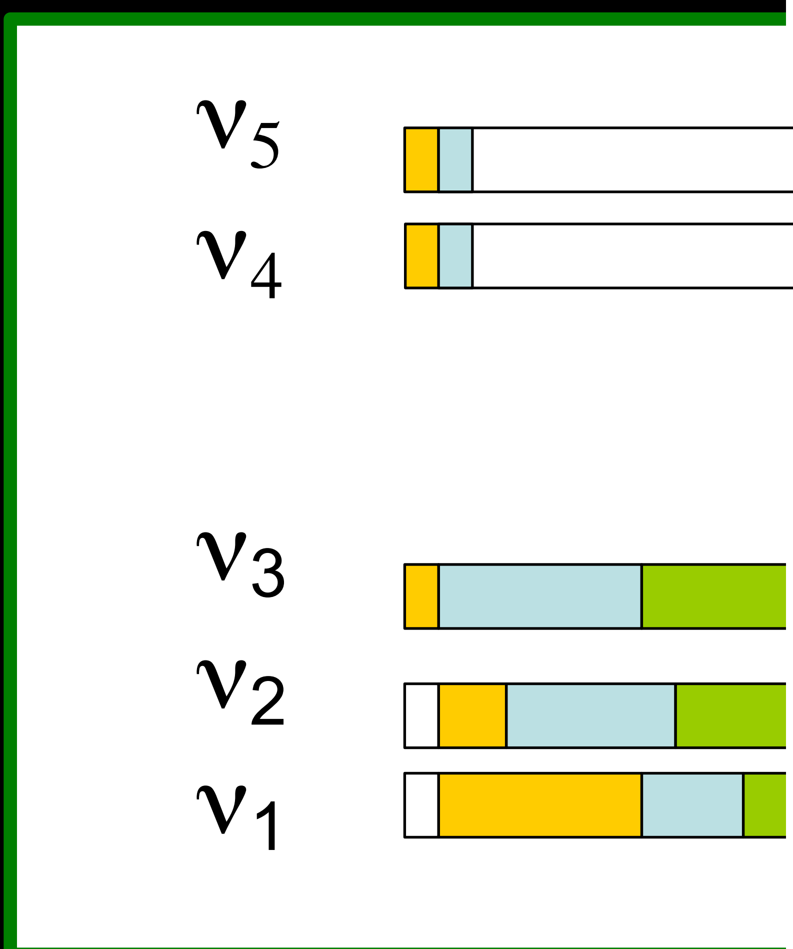


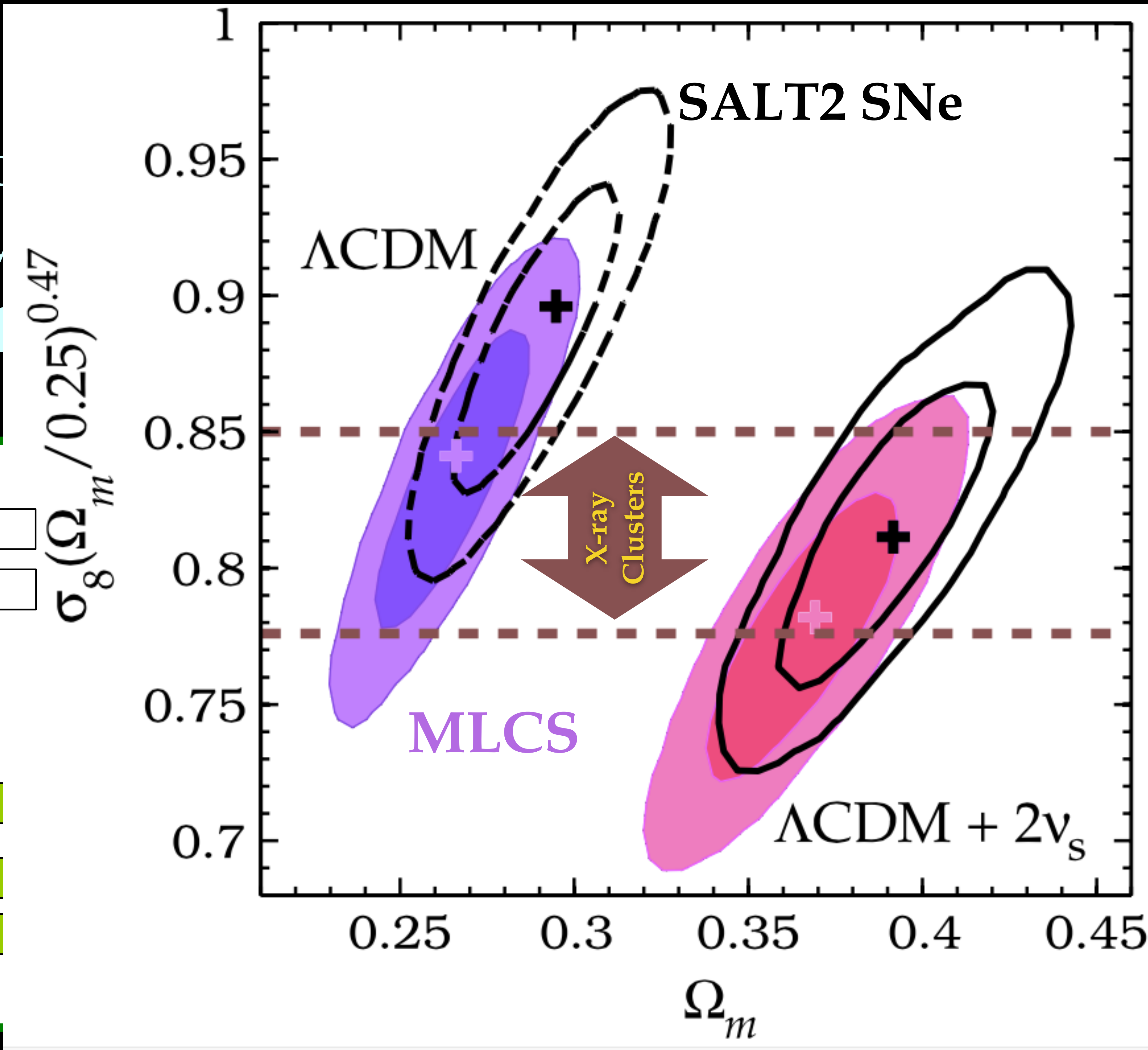


The Need for Cross-Analysis Between Neutrino Experiment and Cosmology

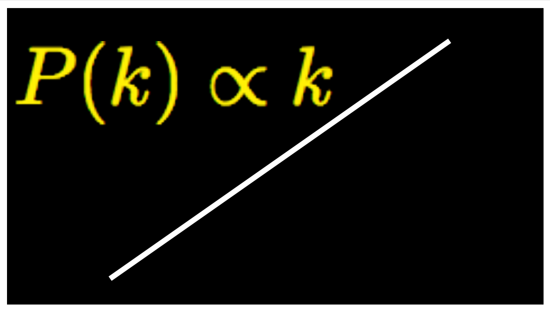
Joudaki, Abazajian & Kaplinghat 2013

⇒ Short baseline c
require, minimally
2 sterile ν's with sp
masses, mixings

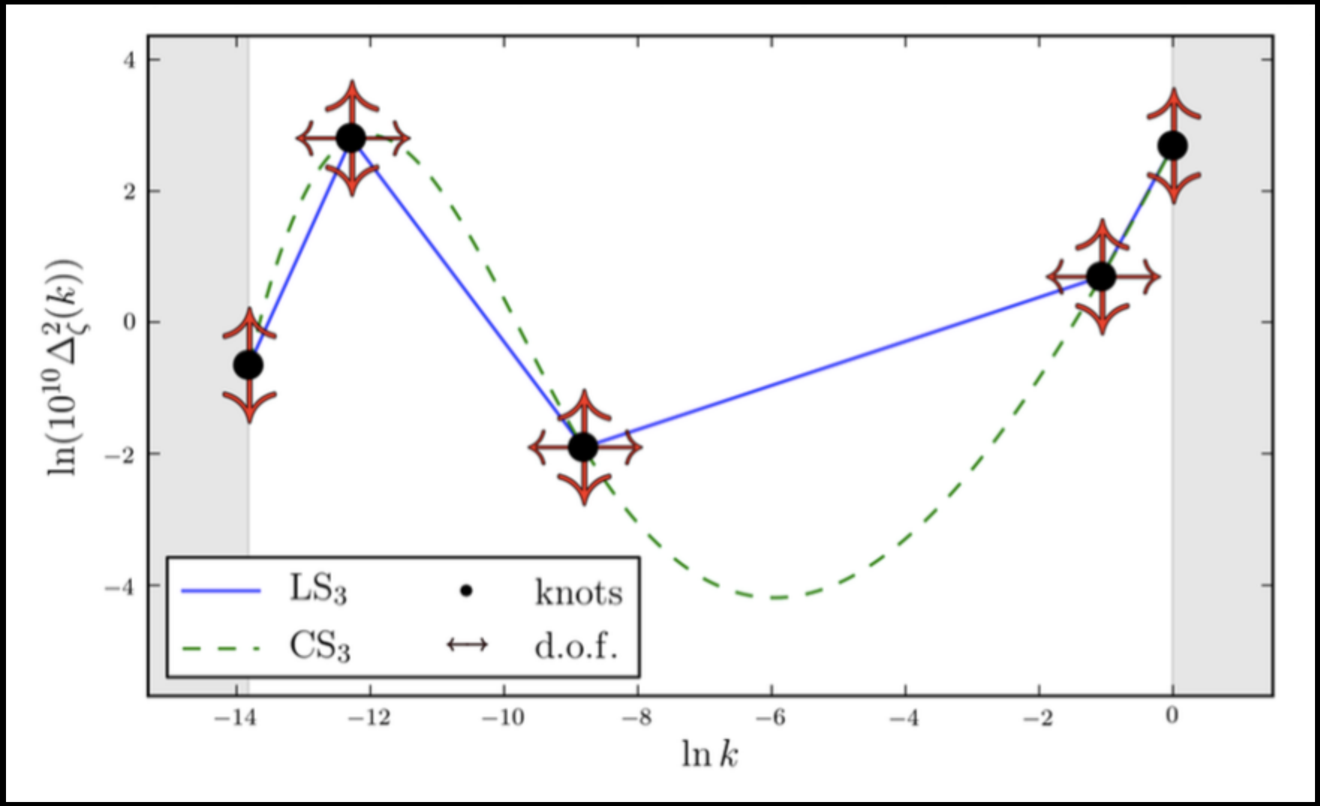




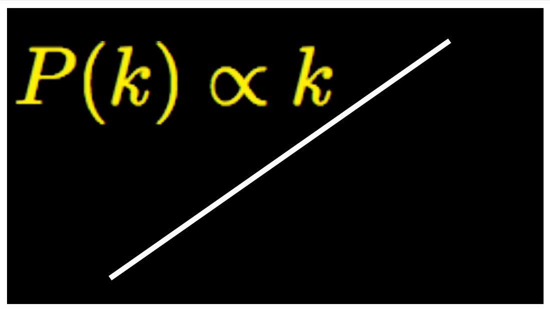
Deviations from a power law primordial power spectrum in the CMB?



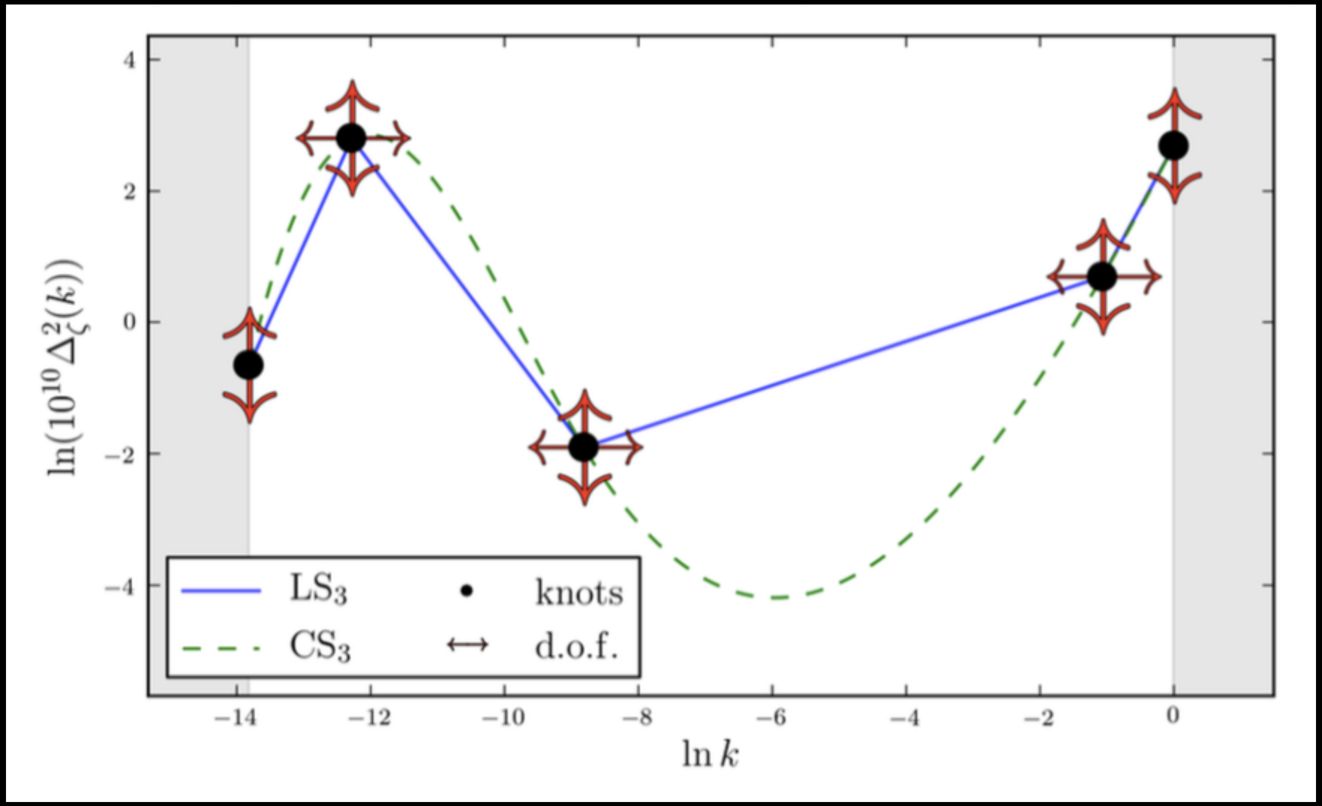
Aslanyan, Price, Abazajian & Easther 2014

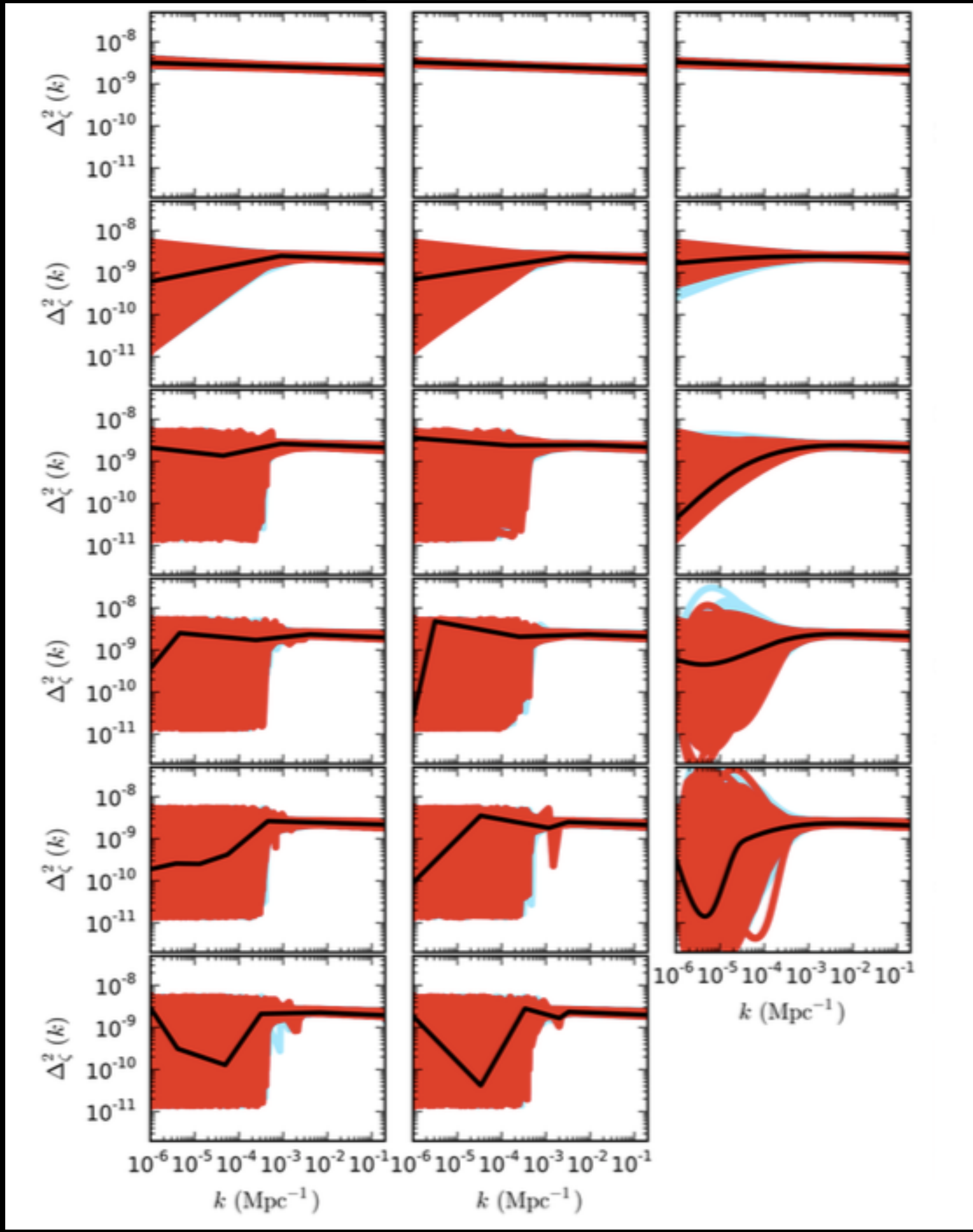


Deviations from a power law primordial power spectrum in the CMB?



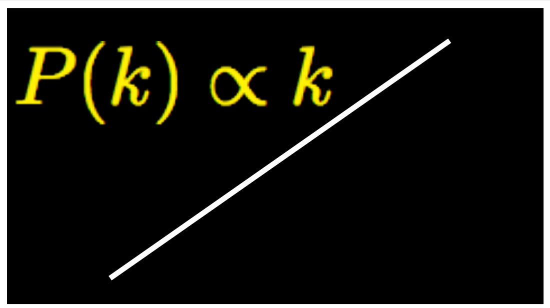
Aslanyan, Price, Abazajian & Easther 2014

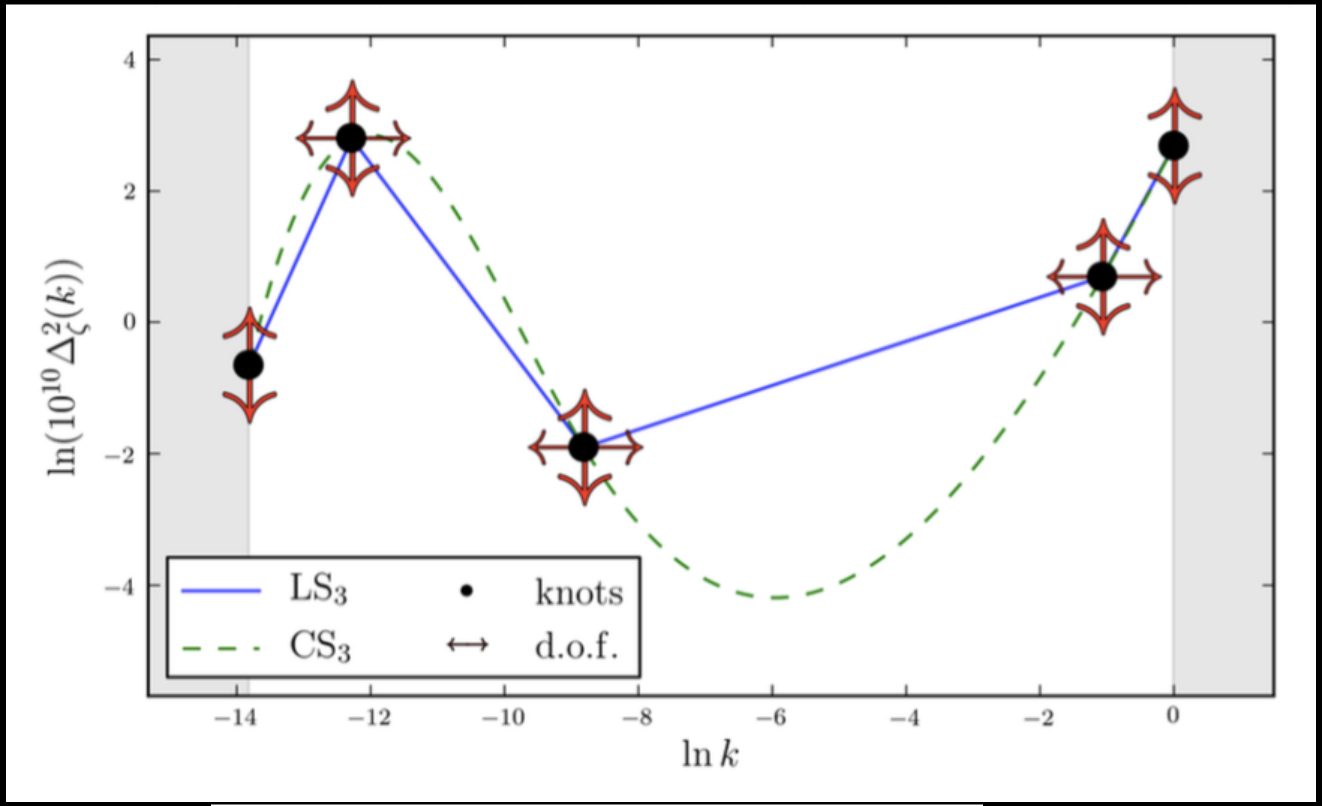


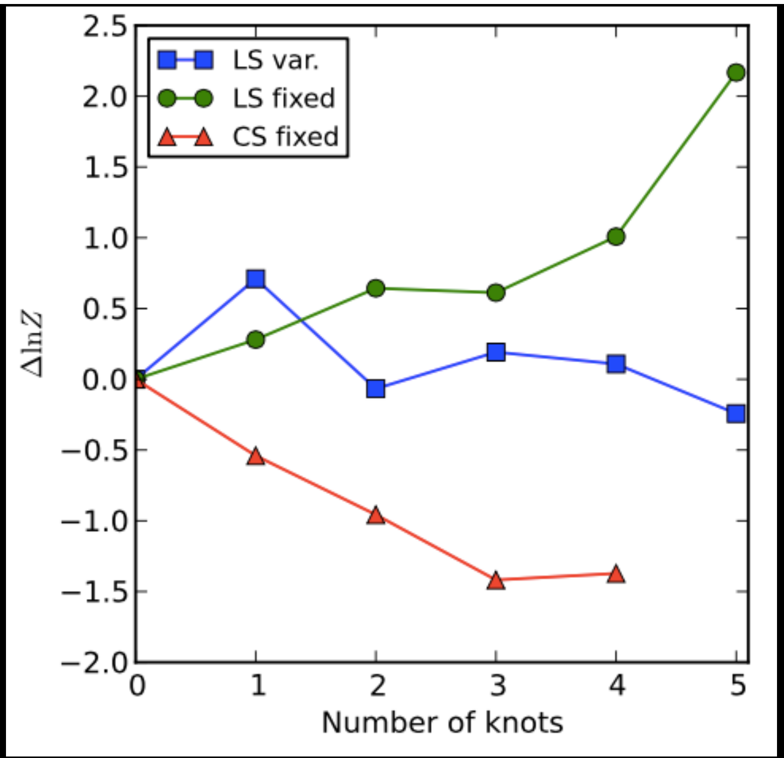


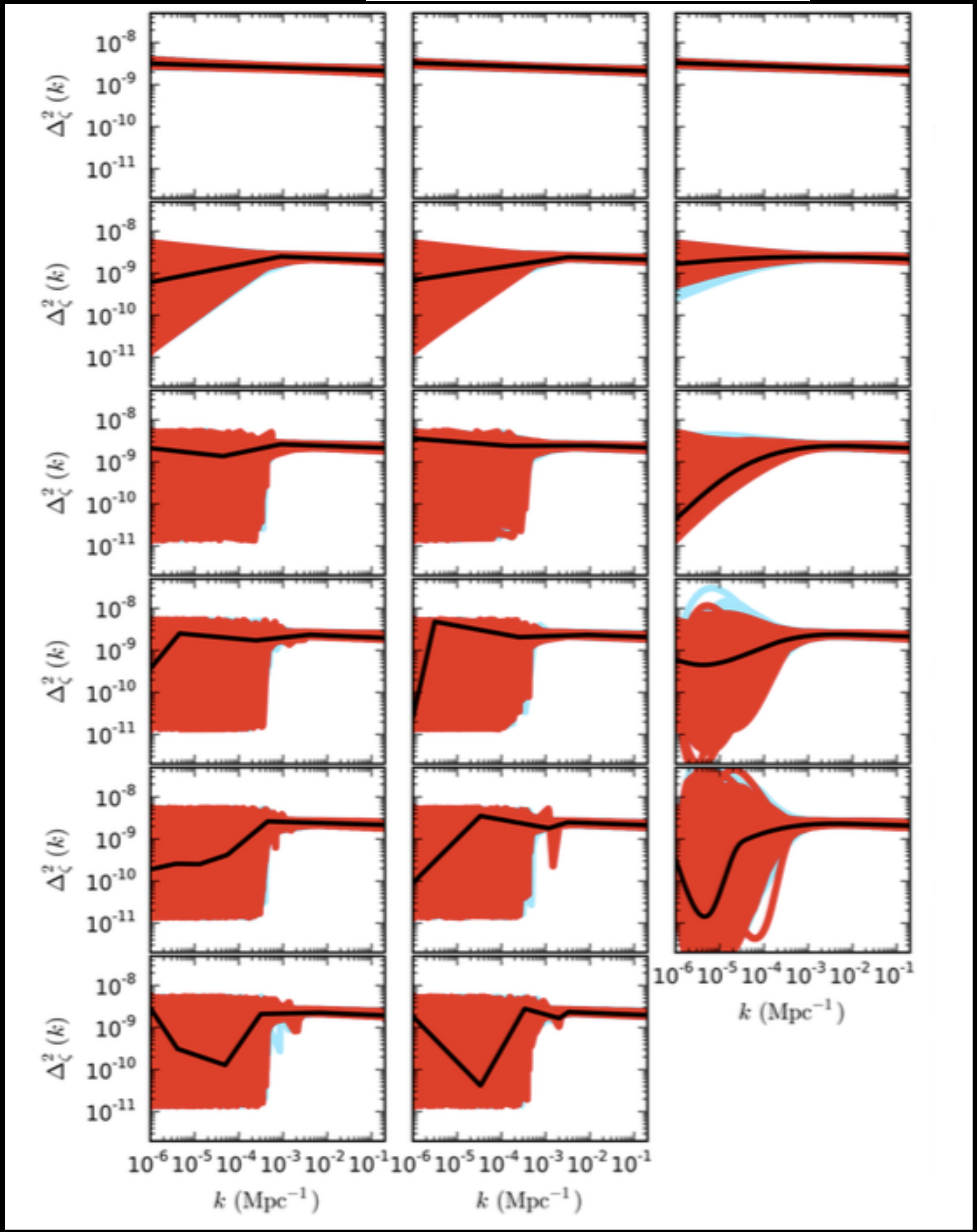
Deviations from a power law primordial power spectrum in the CMB?

Aslanyan, Price, Abazajian & Easther 2014



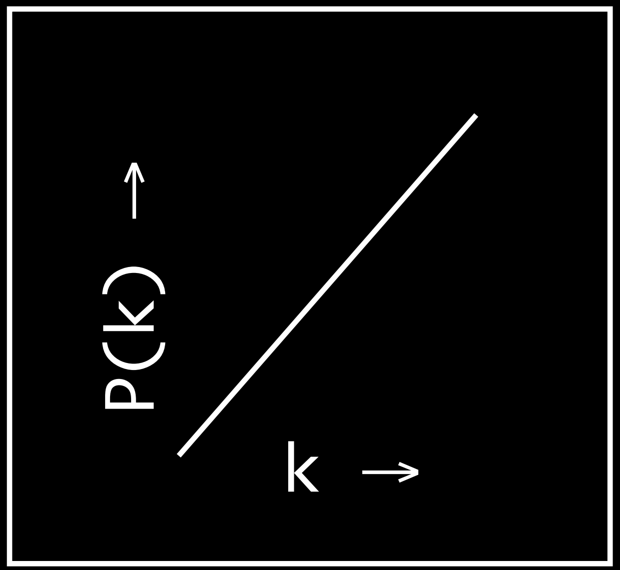




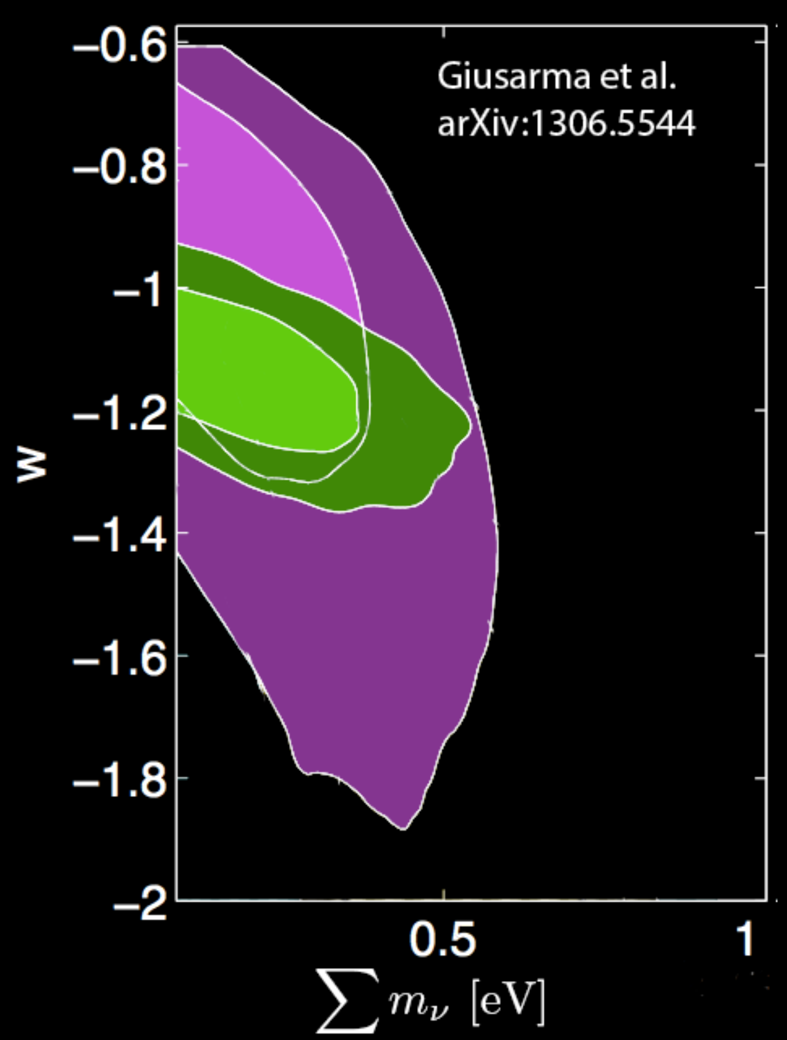


Neutrino Mass from Cosmology: What would break if cosmology and neutrino experiment disagree?

1. Primordial power spectrum $P(k)$ is not a simple power law (Abazajian+ in prep.)



2. No other prevalent "non-vanilla" cosmological parameters and physics: w, N_{eff}, modified gravity…
   e.g. degenerate nonzero laboratory m_β or $m_{\beta\beta}$ with $\boldsymbol{\Sigma m_\nu \approx 60}$ **meV** from cosmology could indicate $\boldsymbol{w < -1}$



Estimating Upcoming Cosmological Neutrino Mass Sensitivities

$$\frac{\Delta P(k)}{P(k)} \approx 1\% \approx -8\frac{\Omega_\nu}{\Omega_m}$$

Hu, Eisenstein & Tegmark 1998

Estimating Upcoming Cosmological Neutrino Mass Sensitivities

$$\frac{\Delta P(k)}{P(k)} \approx 1\% \approx -8\frac{\Omega_\nu}{\Omega_m}$$

Hu, Eisenstein & Tegmark 1998

$$\Omega_\nu \approx \frac{\sum m_{\nu_i}}{93\ h^2\ \mathrm{eV}}$$

Estimating Upcoming Cosmological Neutrino Mass Sensitivities

$$\frac{\Delta P(k)}{P(k)} \approx 1\% \approx -8\frac{\Omega_\nu}{\Omega_m}$$

Hu, Eisenstein & Tegmark 1998

$$\Omega_\nu \approx \frac{\sum m_{\nu_i}}{93\ h^2\ \mathrm{eV}}$$

$$\Longrightarrow \sigma\left(\Sigma m_\nu\right) \lesssim (1\%/8) \times \Omega_m \left(93h^2\ \mathrm{eV}\right)$$

Estimating Upcoming Cosmological Neutrino Mass Sensitivities

$$\frac{\Delta P(k)}{P(k)} \approx 1\% \approx -8\frac{\Omega_\nu}{\Omega_m}$$

Hu, Eisenstein & Tegmark 1998

$$\Omega_\nu \approx \frac{\sum m_{\nu_i}}{93\ h^2\ \mathrm{eV}}$$

$$\Longrightarrow \sigma\left(\Sigma m_\nu\right) \lesssim (1\%/8) \times \Omega_m \left(93h^2\ \mathrm{eV}\right)$$

$$\Longrightarrow \sigma\left(\Sigma m_\nu\right) \lesssim 20\ \mathrm{meV}$$

Estimating Upcoming Cosmological Neutrino Mass Sensitivities

$$\frac{\Delta P(k)}{P(k)} \approx 1\% \approx -8\frac{\Omega_\nu}{\Omega_m}$$

Hu, Eisenstein & Tegmark 1998

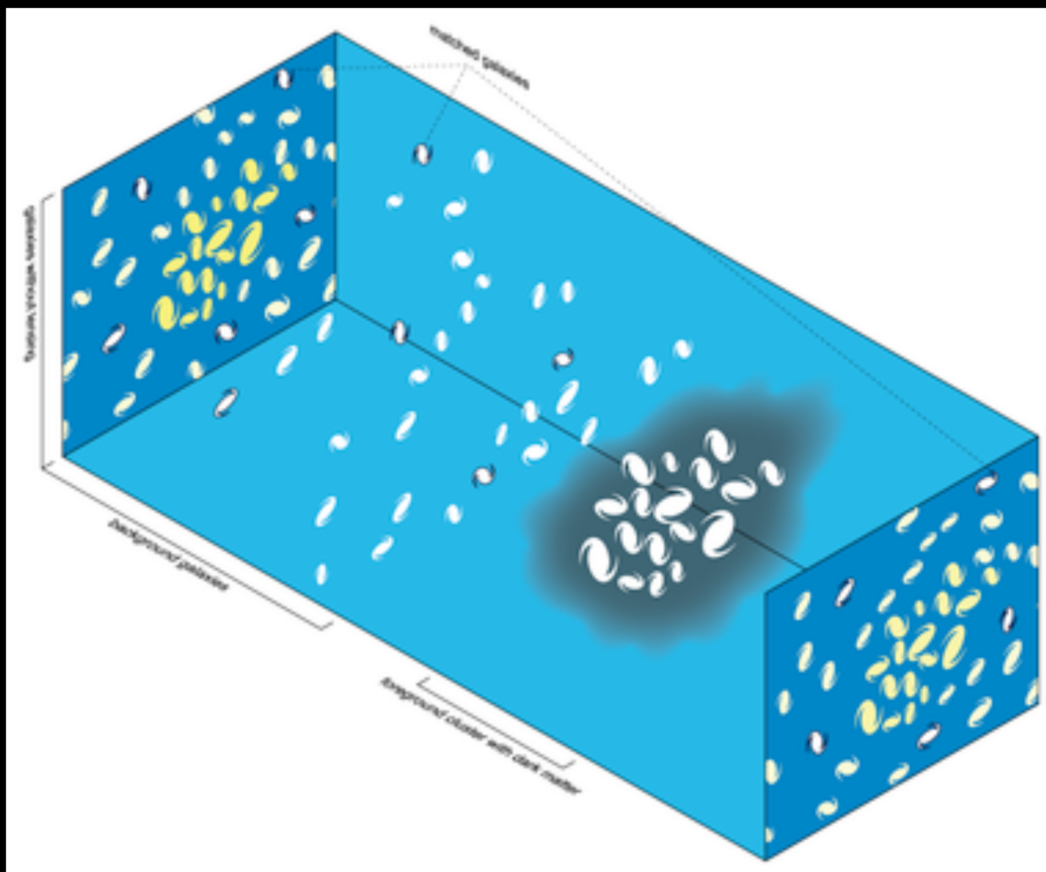
$$\Omega_\nu \approx \frac{\sum m_{\nu_i}}{93\ h^2\ \mathrm{eV}}$$

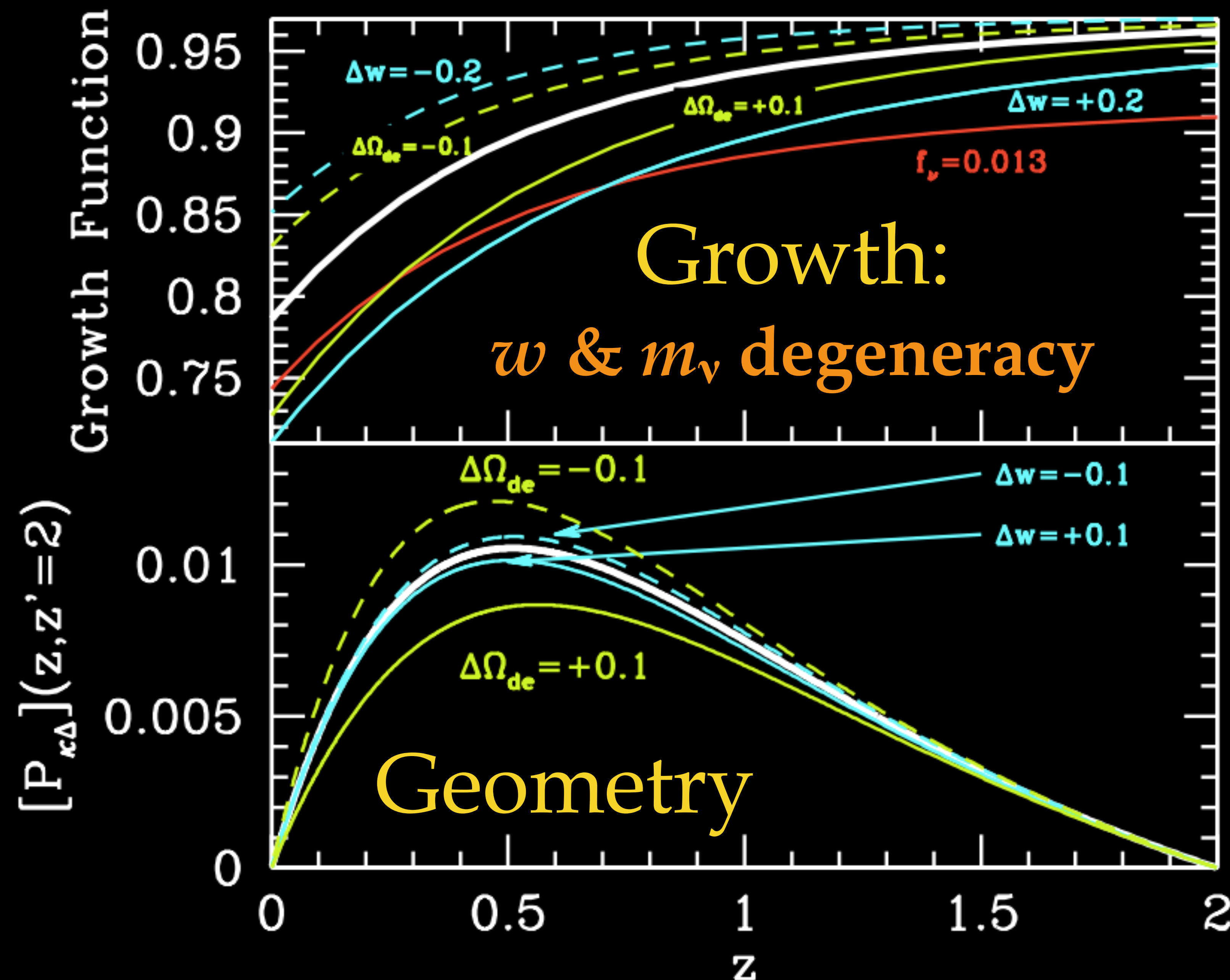
$$\Longrightarrow \sigma\left(\Sigma m_\nu\right) \lesssim (1\%/8) \times \Omega_m \left(93h^2\ \mathrm{eV}\right)$$

$$\Longrightarrow \sigma\left(\Sigma m_\nu\right) \lesssim 20\ \mathrm{meV}$$

Kaplinghat et al PRL 2003 (CMB WL)
Wang et al PRL 2005 (WL Clusters)
De Bernardis et al. 2009 (Opt. WL)
Joudaki & Kaplinghat 2011 (LSST)
Basse et al. 2013 (Euclid)
Abazajian et al. 2014 (Snowmass Report)
Wu et al. 2014 (CMB-S4 + DESI)

Future: Weak Lensing (LSST, EUCLID, WFIRST)





Planck+EUCLID

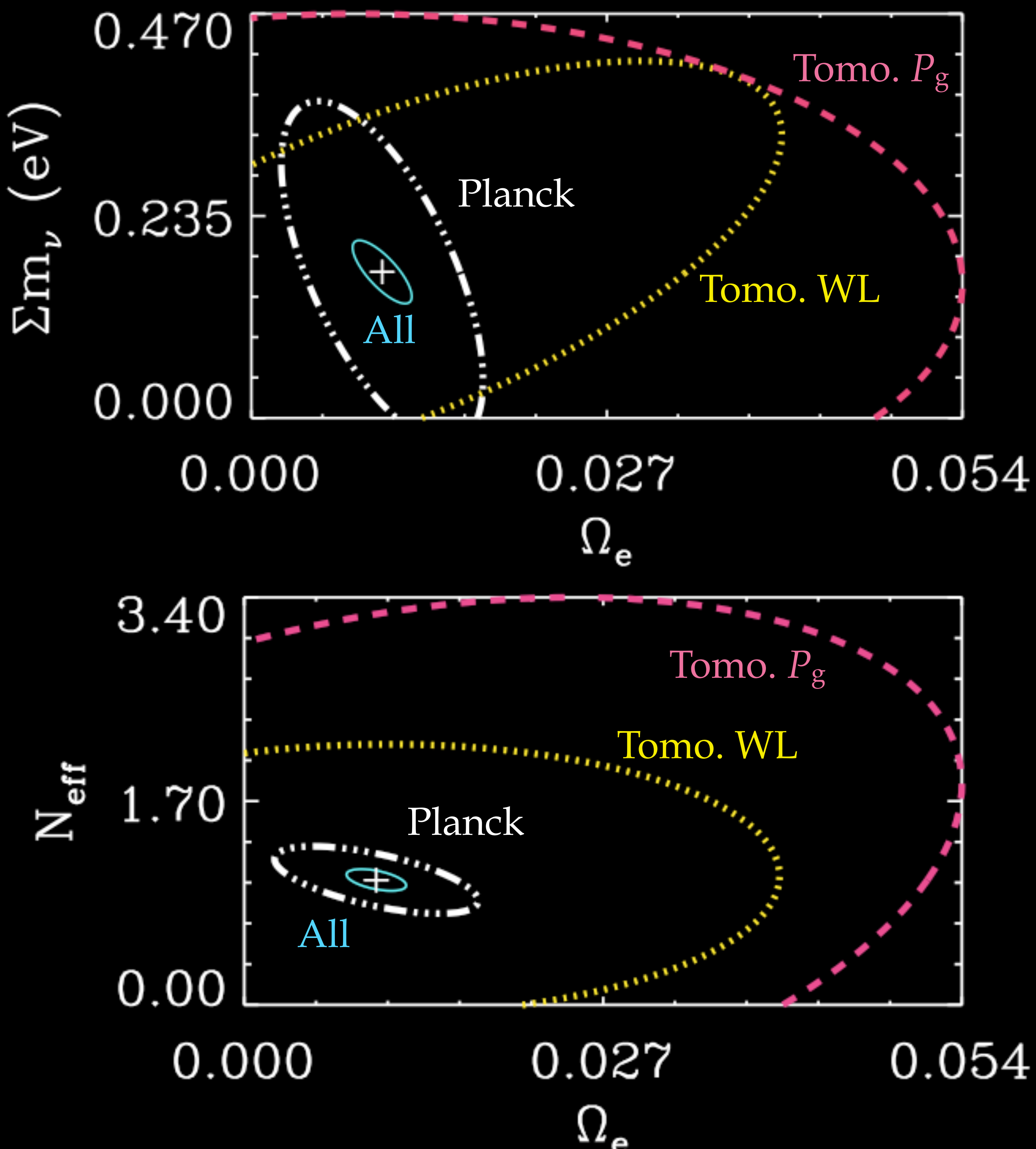
$\sigma(\Sigma m_\nu) = 11 \text{ meV}$ (7 param.)

$\sigma(\Sigma m_\nu) = 42 \text{ meV}$ (9 param: w, $N_{\rm eff}$)

Abazajian & Dodelson (2002)

Hamman, Hannestad, Wong (2012)

Example Forecast sensitivities: Planck + LSST

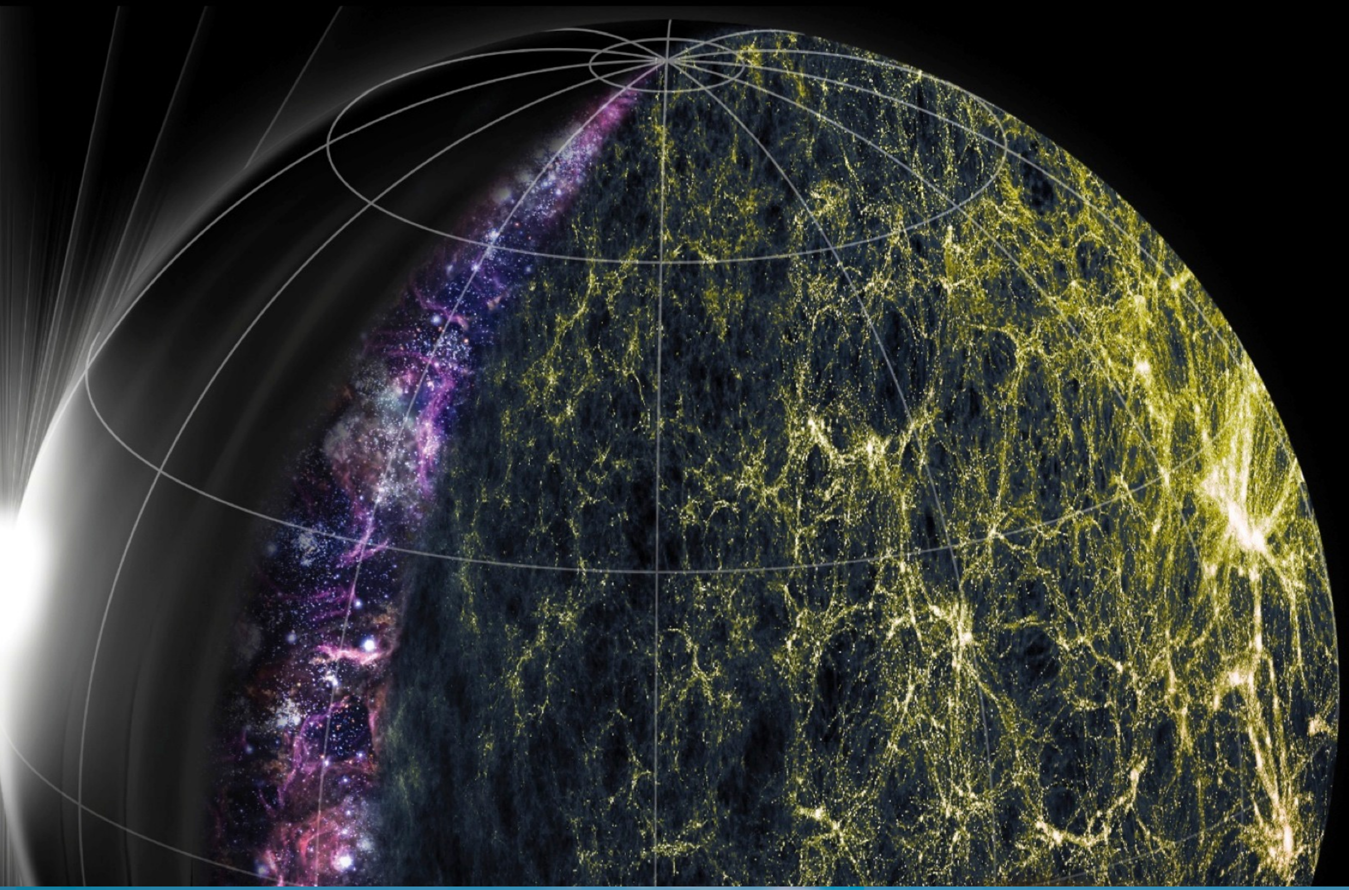


$$\sigma\left(\Sigma m_{\nu_i}\right) = 23 \text{ meV}$$

$$\sigma\left(N_{\text{eff}}\right) = 0.078$$

Joudaki & Kaplinghat 2011

Future: IR + 21 cm Surveys
⇒power over large range of k **and** z



SPHEREx: 1.4 billion galaxies
9.8 million $\sigma(z)/(1+z) = 0.003$
2 orders of magnitude more
k modes than SDSS-BOSS
Doré et al. 2014 (2020+)

SKA: 21 cm emission measure
of "all" gas $4 < z < 8$;
$\sigma(\Sigma m_\nu) = 3$ to 20 meV
Mao et al. (2008) (2020+)

Summary

- Cosmological LSS (with CMB, next) achieves the strongest inferred constraints on the total neutrino mass.
- There is tension among cosmological data set combinations that could indicate quasi-degenerate neutrino mass **Σm_ν = 0.36 ± 0.10 eV**; however, what is considered to be the most robust data has no such signal.
- Robust current claimed constraints are at
  Σm_ν < 230 meV (95%); $N_{\rm eff}$ = 3.15±0.23 (Planck Collab. 2015: CMB+BAO)
- Strong claims from Lyman-alpha forest (*systematics*)
  Σm_ν < 170 meV (95%) (BOSS Collab. 2015: CMB+BAO+Lyα)
- *Far future*: Planck + LSST lensing, galaxies: **$\sigma(\Sigma m_\nu)$ = 23 meV; $\sigma(N_{\rm eff})$ = 0.078**
  CMB-S4 and DESI galaxy survey: **$\sigma(\Sigma m_\nu)$ = 15 meV & $\sigma(N_{\rm eff})$ = 0.016**
  latter provides > 3σ sensitivity to the oscillation-required Σm_ν =58 meV and >2σ sensitivity to $N_{\rm eff}$ (Wu+ 2014)
- The constraints rely on an underlying set of simplifying model assumptions [scale invariance, flatness, w = -1, etc.]. This introduces a level of theoretical model (systematic) uncertainty. Laboratory complementarity is essential.

Future Sensitivity

- *Near future*: ACTPol and SPTPol: **$\sigma(\Sigma m_\nu)$ ~ 100 meV; $\sigma(N_{eff})$ ~ 0.12**
  Mid-range future: SPT-3G forecast **$\sigma(\Sigma m_\nu)$ ~ 74 meV; $\sigma(N_{eff})$ ~ 0.076**
  Far-Mid-range future: Simons Array forecast **$\sigma(\Sigma m_\nu)$ ~ 40 meV; $\sigma(N_{eff})$ ~ 0.08**

- *Far*: Planck + LSST lensing, galaxies: **$\sigma(\Sigma m_\nu)$ = 23 meV; $\sigma(N_{eff})$ = 0.078**
  CMB-S4 and DESI galaxy survey: **$\sigma(\Sigma m_\nu)$ = 15 meV & $\sigma(N_{eff})$ = 0.016**
  latter provides > 3σ sensitivity to the oscillation-required Σm_ν =58 meV and >2σ sensitivity to N_{eff} (Wu+ 2014)

Indirect Detection of Sterile Neutrino Dark Matter?

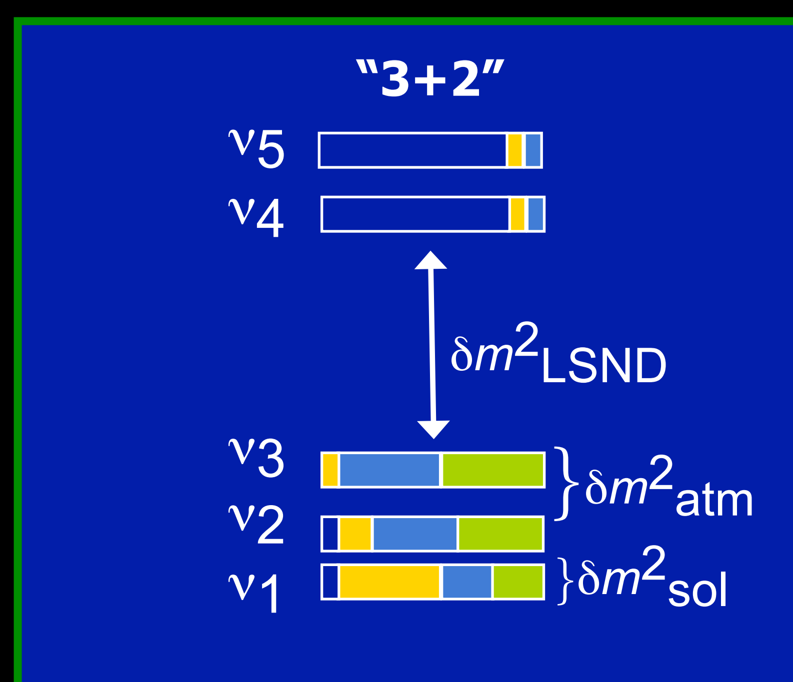
Dark Matter Neutrinos

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

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



~ 1 eV

~ 0.01 eV

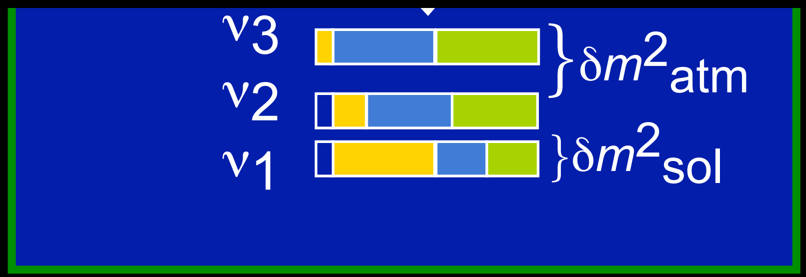
Dark Matter Neutrinos

Sterile Neutrino Dark Matter ν_6

$$
\begin{aligned}
|\nu_\alpha\rangle &= \cos\theta|\nu_a\rangle + \sin\theta|\nu_b\rangle \\
|\nu_s\rangle &= -\sin\theta|\nu_a\rangle + \cos\theta|\nu_b\rangle
\end{aligned}
$$

~ 1 keV

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



~ 0.01 eV

Dark Matter Neutrinos

Sterile Neutrino Dark Matter ν_4

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

~ 1 keV

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

~ 0.01 eV

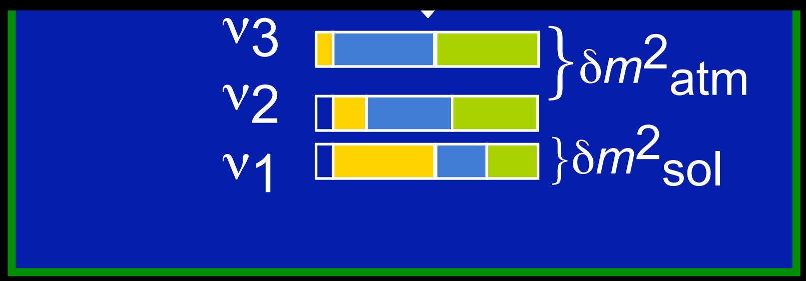
Dark Matter Neutrinos

Sterile Neutrino Dark Matter ν_4

$$
\begin{aligned}
|\nu_\alpha\rangle &= \cos\theta|\nu_a\rangle + \sin\theta|\nu_b\rangle \\
|\nu_s\rangle &= -\sin\theta|\nu_a\rangle + \cos\theta|\nu_b\rangle
\end{aligned}
$$

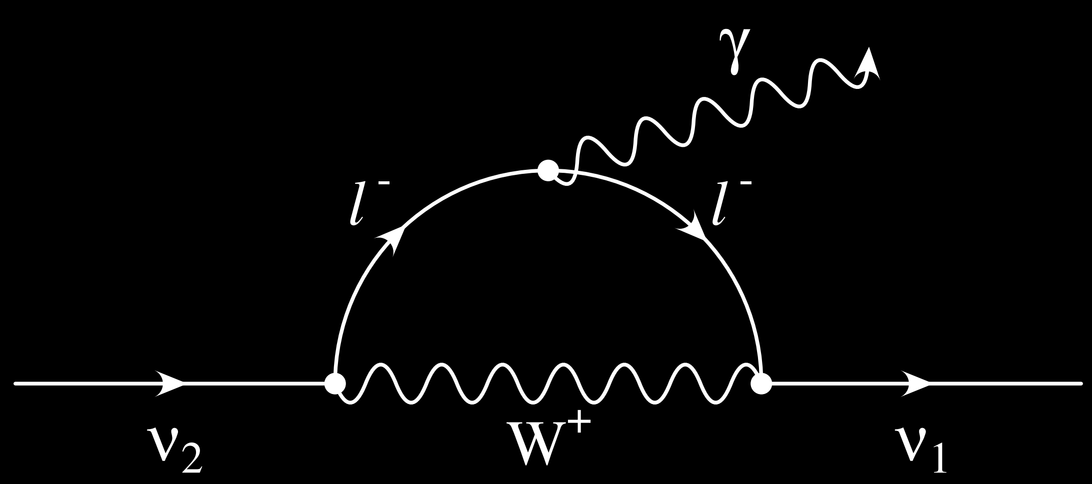
~ 1 keV

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



~ 0.01 eV

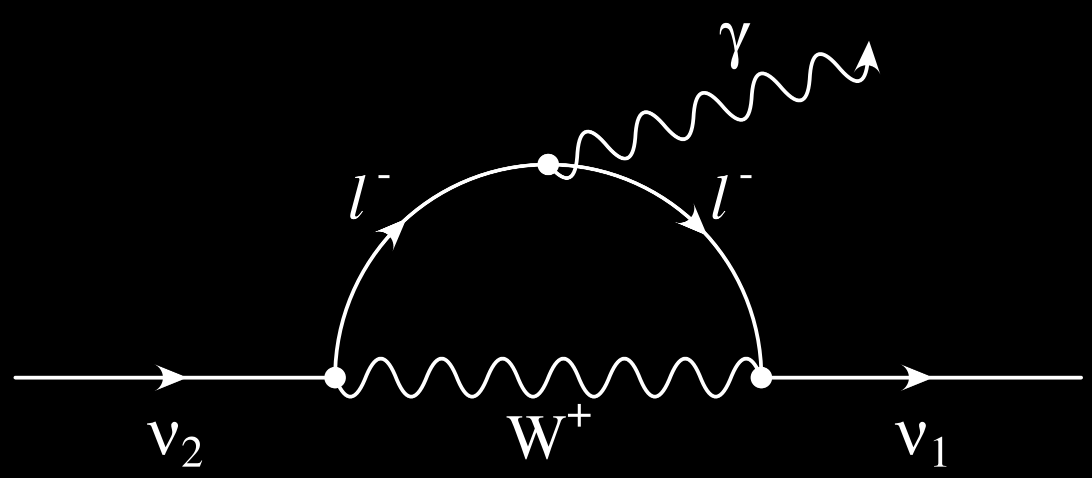
Sterile ν WDM Radiative Decay in the X-ray



Decay: Shrock 1974; Pal & Wolfenstein 1981
X-ray: Abazajian, Fuller & Tucker 2001

$$“\nu_s” \rightarrow “\nu_\alpha” + \gamma$$

Sterile ν WDM Radiative Decay in the X-ray

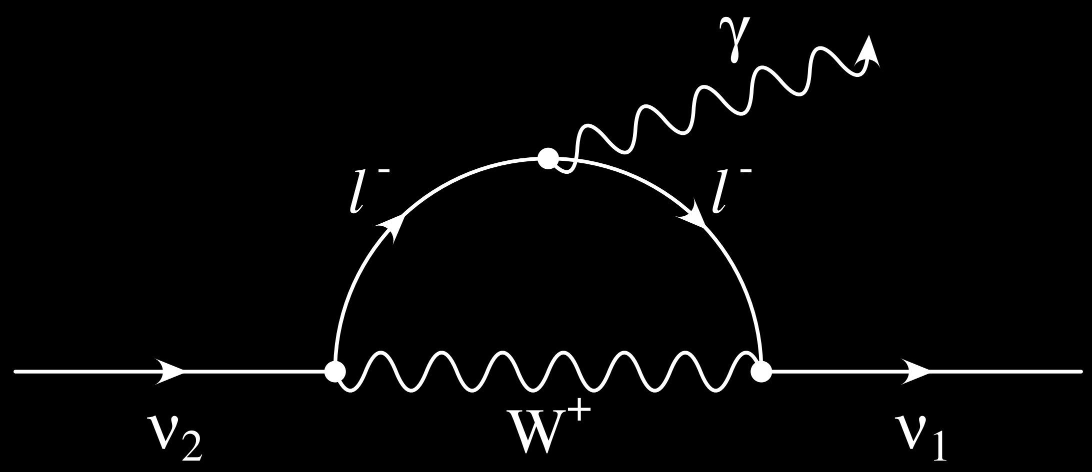


Decay: Shrock 1974; Pal & Wolfenstein 1981
X-ray: Abazajian, Fuller & Tucker 2001

$$``\nu_s" \rightarrow ``\nu_\alpha" + \gamma$$

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

Sterile ν WDM Radiative Decay in the X-ray



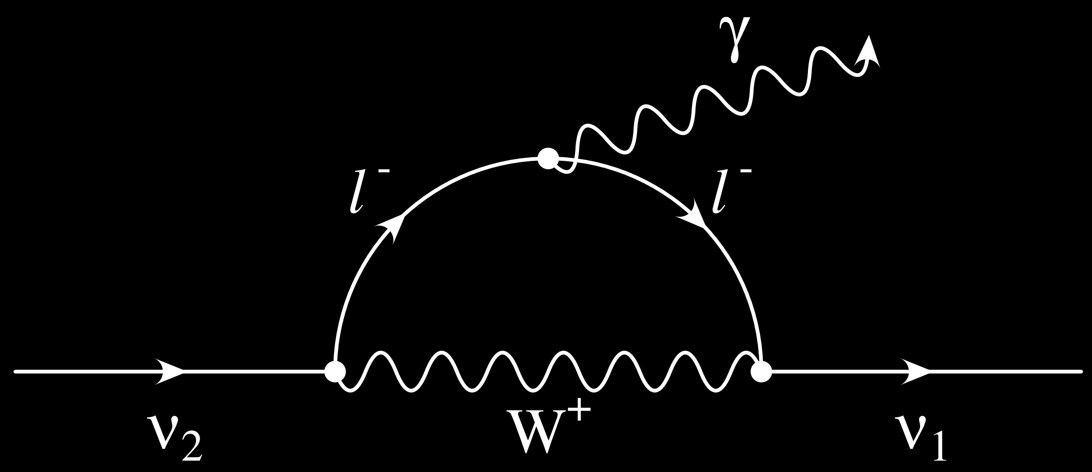
Decay: Shrock 1974; Pal & Wolfenstein 1981
X-ray: Abazajian, Fuller & Tucker 2001

$$\text{``}\nu_s\text{''} \rightarrow \text{``}\nu_\alpha\text{''} + \gamma$$

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

$$\Gamma_\gamma = 1.62 \times 10^{-28} \text{ s}^{-1} \left(\frac{\sin^2 2\theta}{7 \times 10^{-11}}\right) \left(\frac{\text{m}_\text{s}}{7 \text{ keV}}\right)^5$$

Sterile ν WDM Radiative Decay in the X-ray



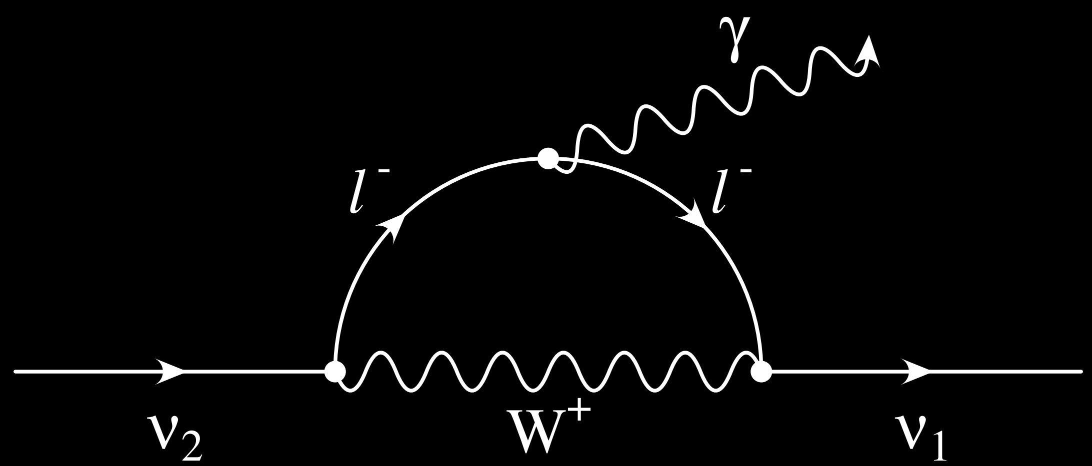
Decay: Shrock 1974; Pal & Wolfenstein 1981
X-ray: Abazajian, Fuller & Tucker 2001

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

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

$$\Gamma_\gamma = 1.62 \times 10^{-28}\ \mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{7\times10^{-11}}\right)\left(\frac{\mathrm{m_s}}{7\ \mathrm{keV}}\right)^5$$

Sterile ν WDM Radiative Decay in the X-ray

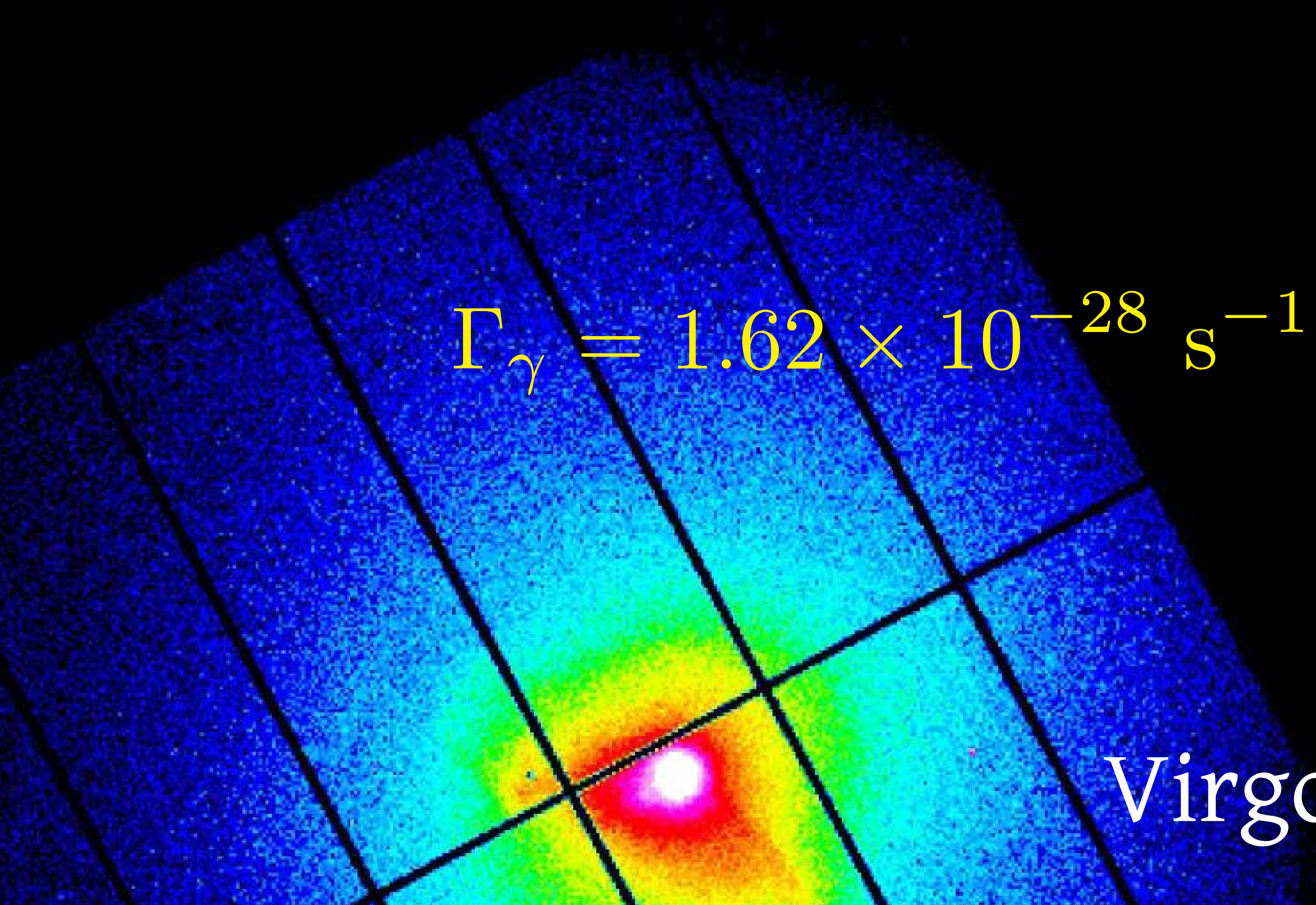


Decay: Shrock 1974; Pal & Wolfenstein 1981
X-ray: Abazajian, Fuller & Tucker 2001

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

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

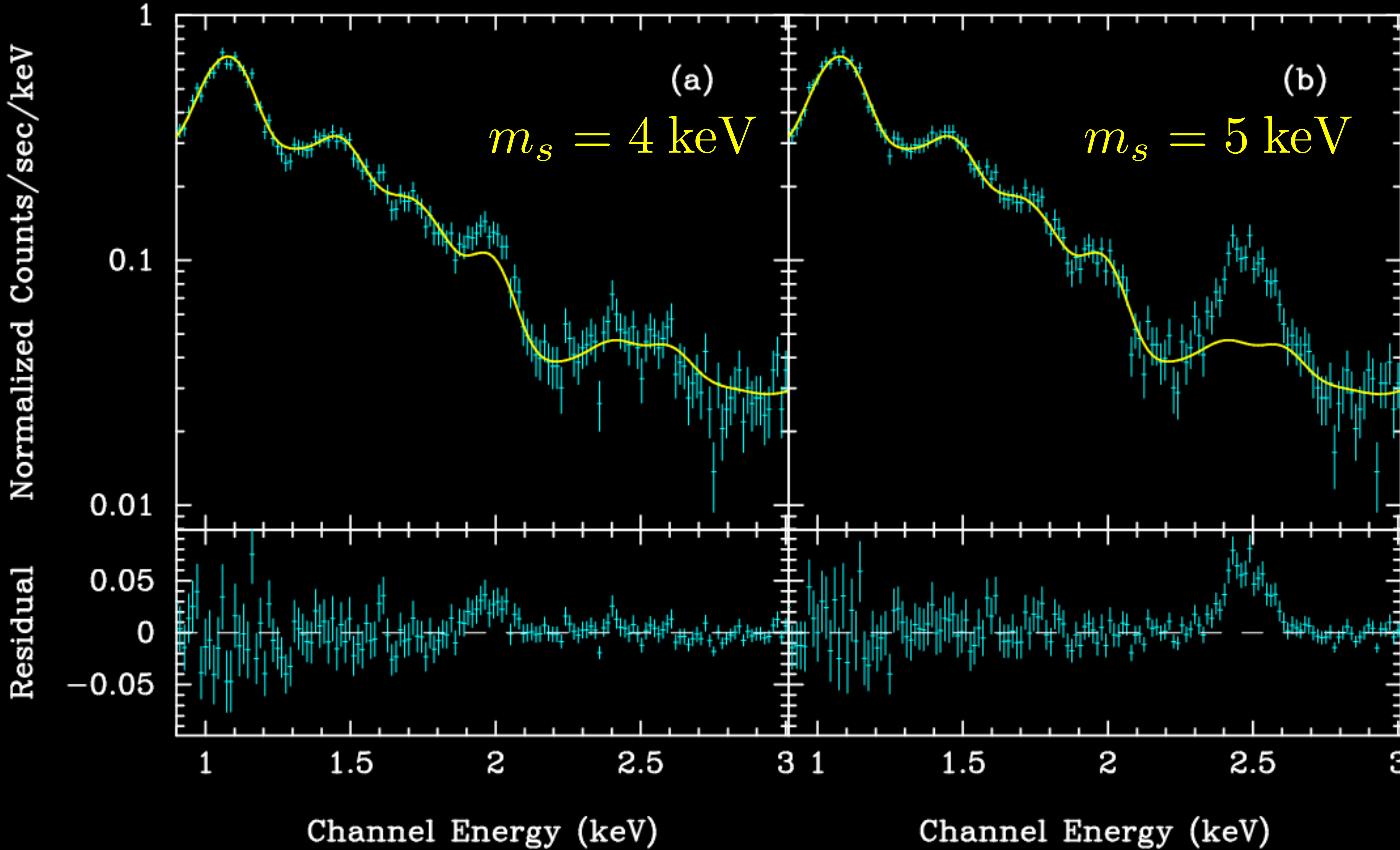
$$\Gamma_\gamma = 1.62 \times 10^{-28}\ \mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{7\times 10^{-11}}\right)\left(\frac{\mathrm{m_s}}{7\ \mathrm{keV}}\right)^5$$



Virgo Cluster: 10^{78} DM particles

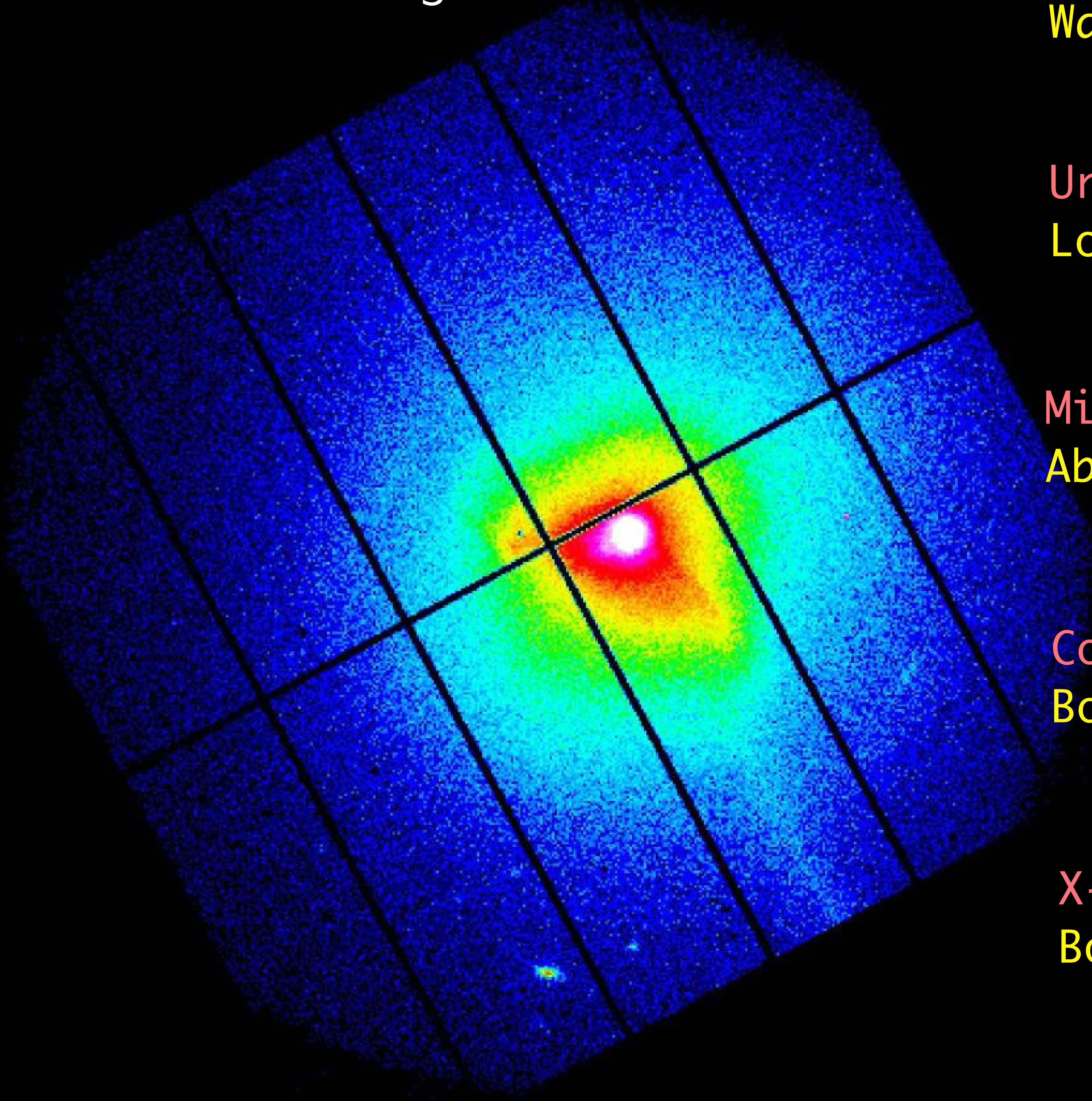
Upper Mass Limit on ν_s DM: X-ray observations of Virgo

Abazajian, Fuller & Tucker 2001



X-ray Constraint Summary

XMM Newton: The Virgo Cluster



Andromeda Galaxy:
Watson et al. 2011

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

Ursa Minor:
Lowenstein et al. 2008

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

Milky Way in CXB:
Abazajian et al. 2006

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

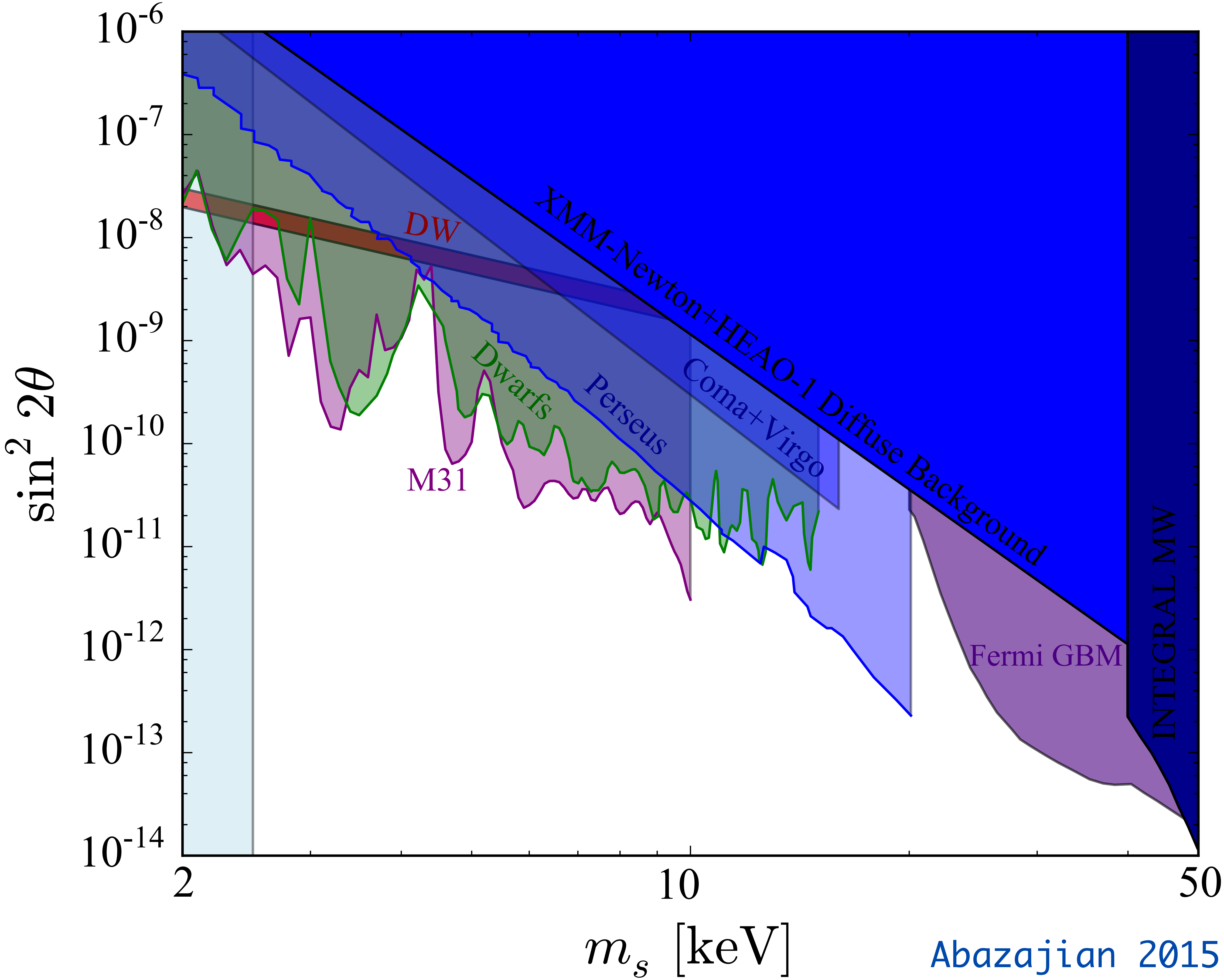
Coma + Virgo Clusters:
Boyarsky et al. 2006

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

X-Ray Background:
Boyarsky et al. 2006

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

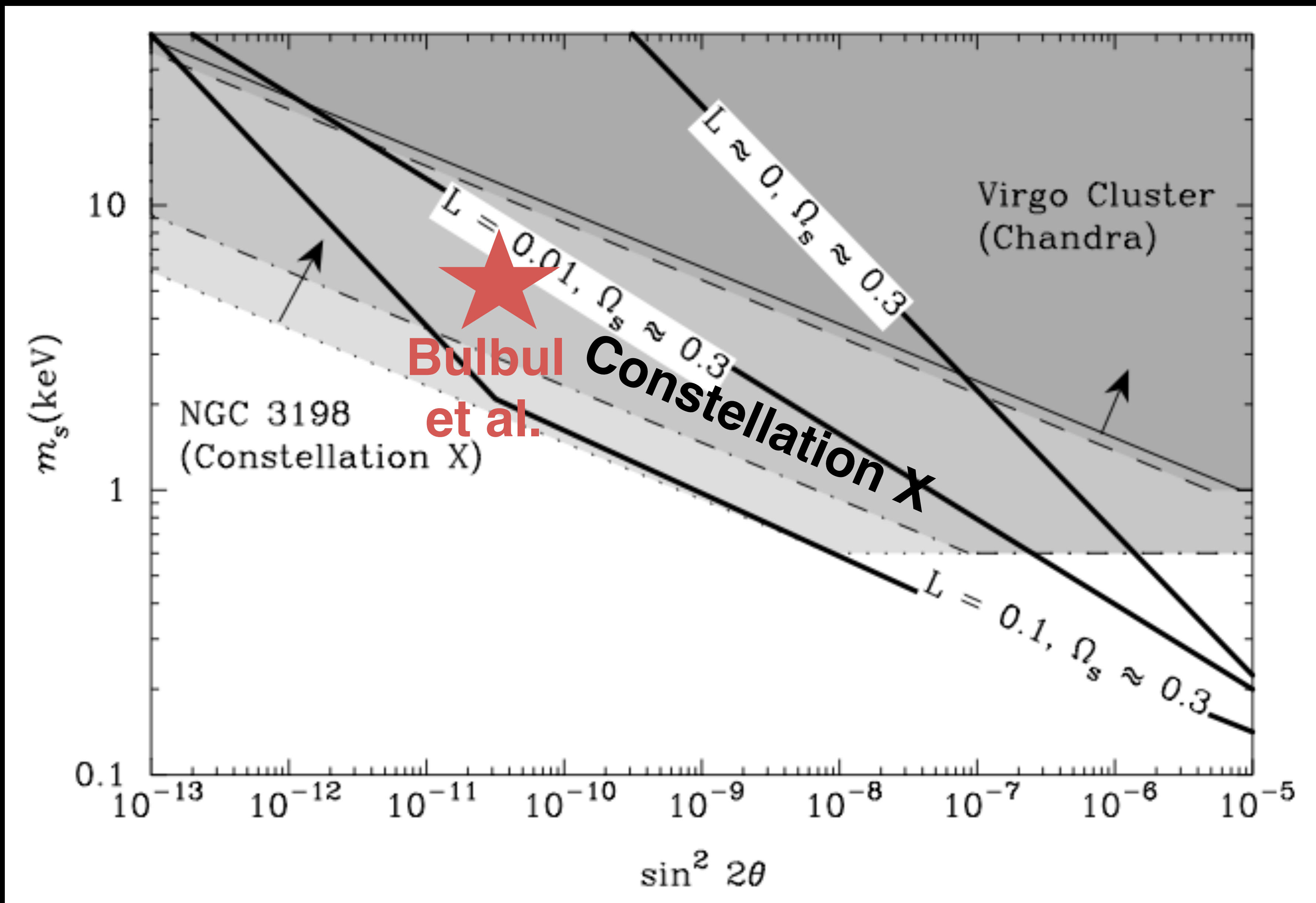
Sterile Neutrino Dark Matter: Parameter Space Summary

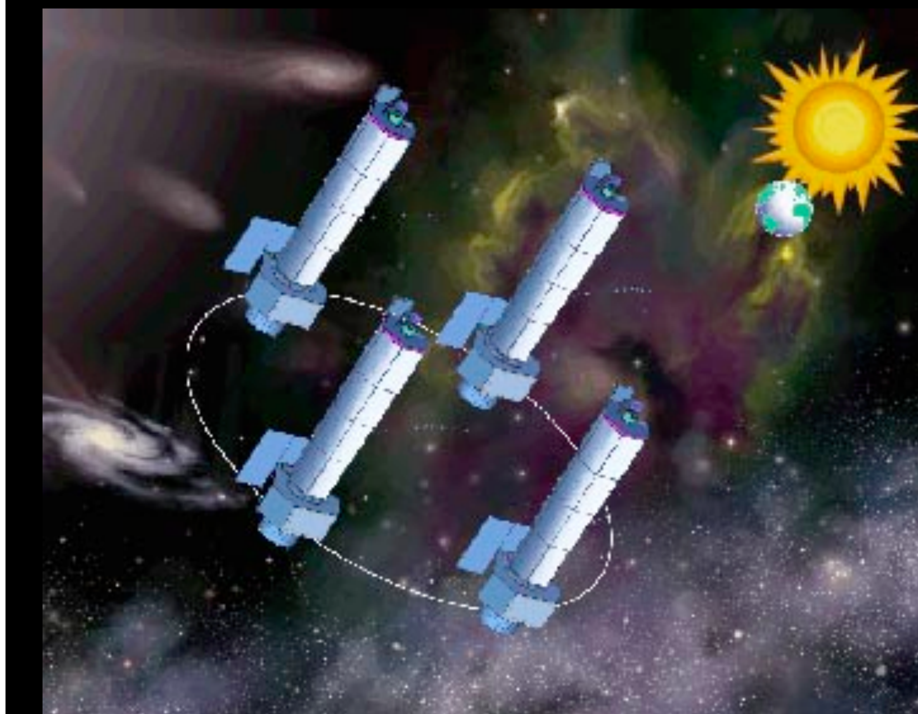


Abazajian 2015

Forecast X-ray Observation Sensitivity for *Constellation-X*

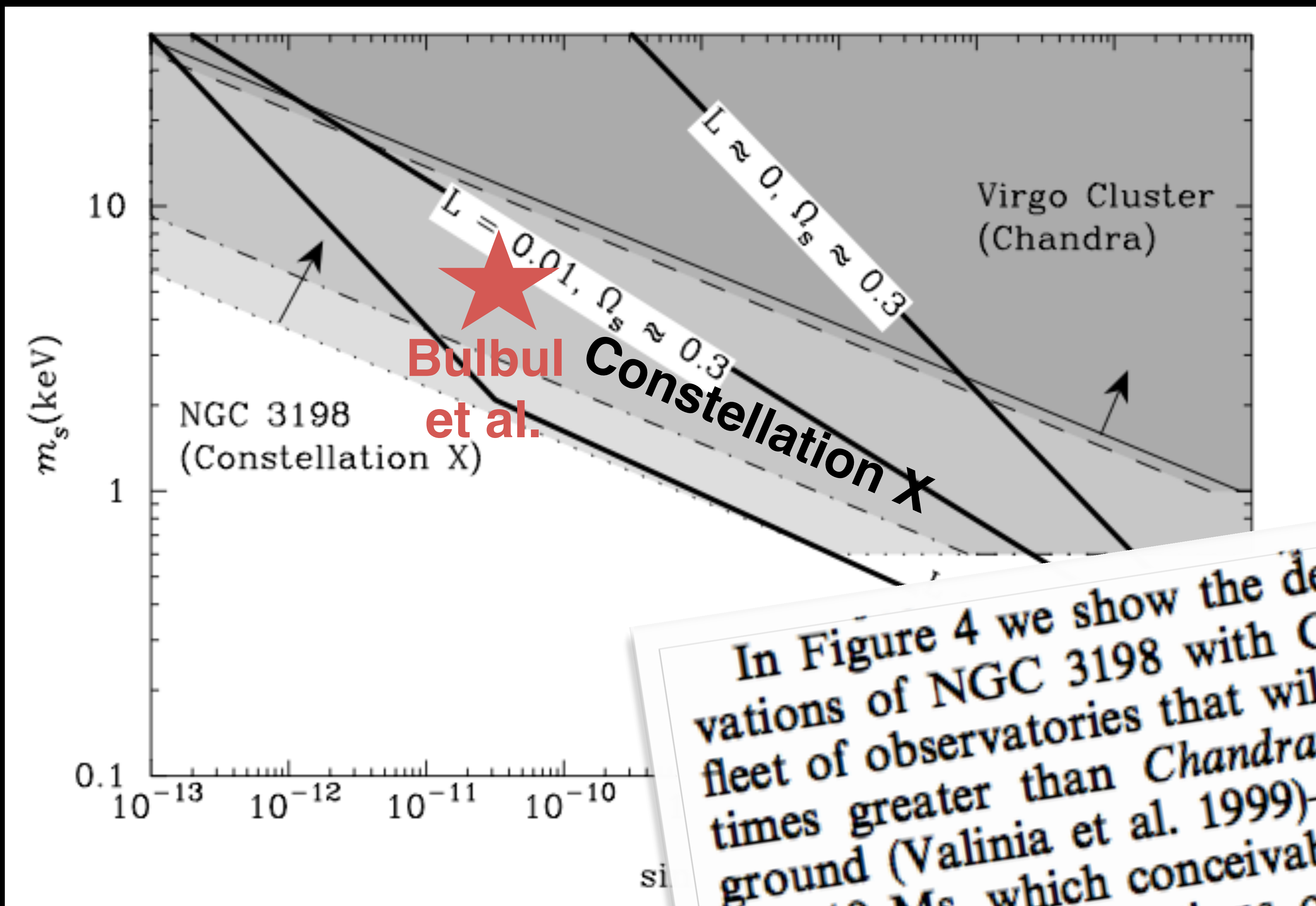
Abazajian, Fuller & Tucker 2001

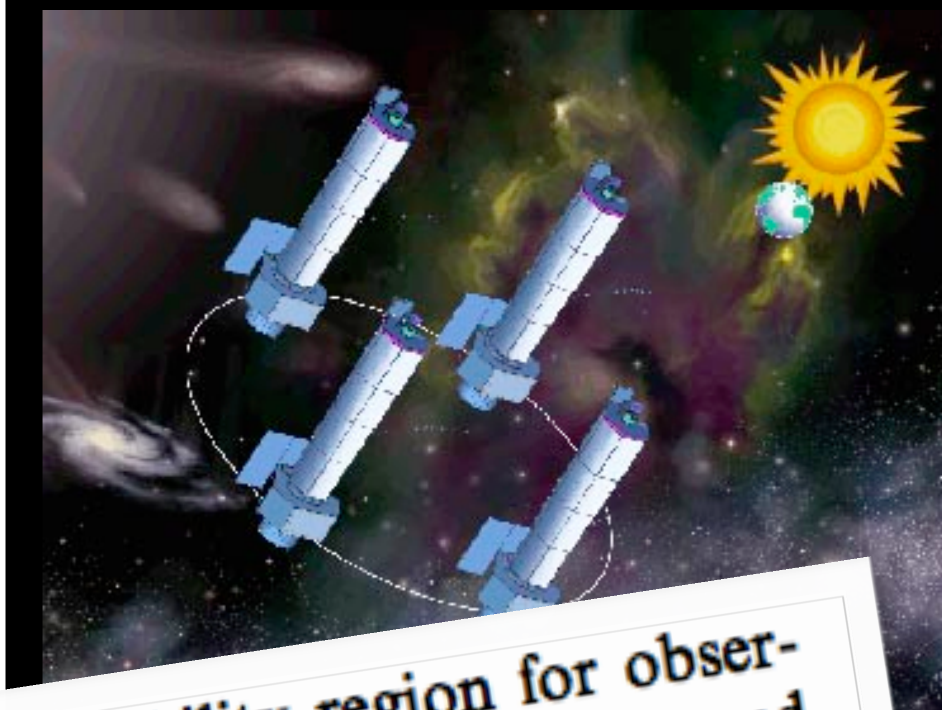




Forecast X-ray Observation Sensitivity for *Constellation-X*

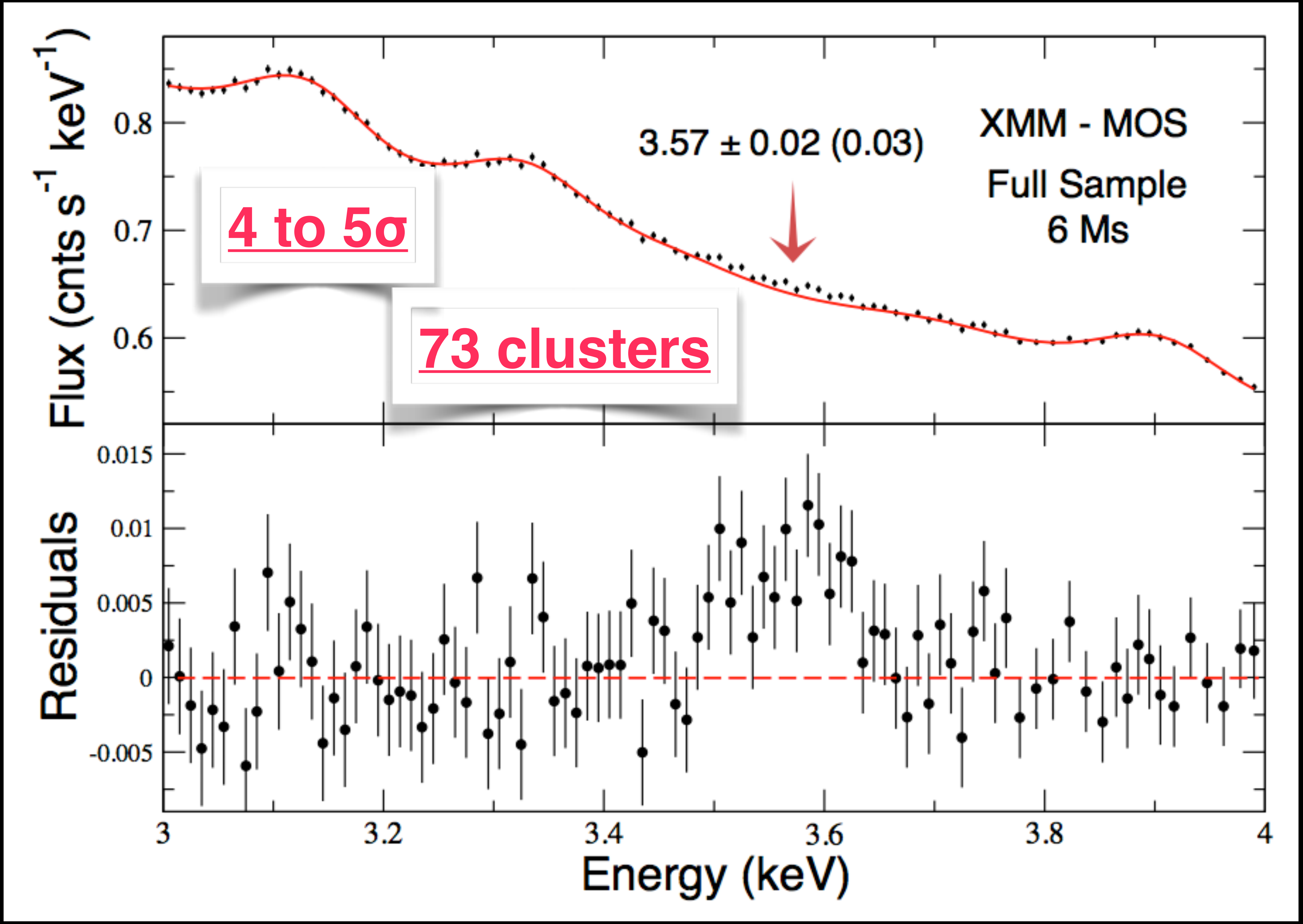
Abazajian, Fuller & Tucker 2001





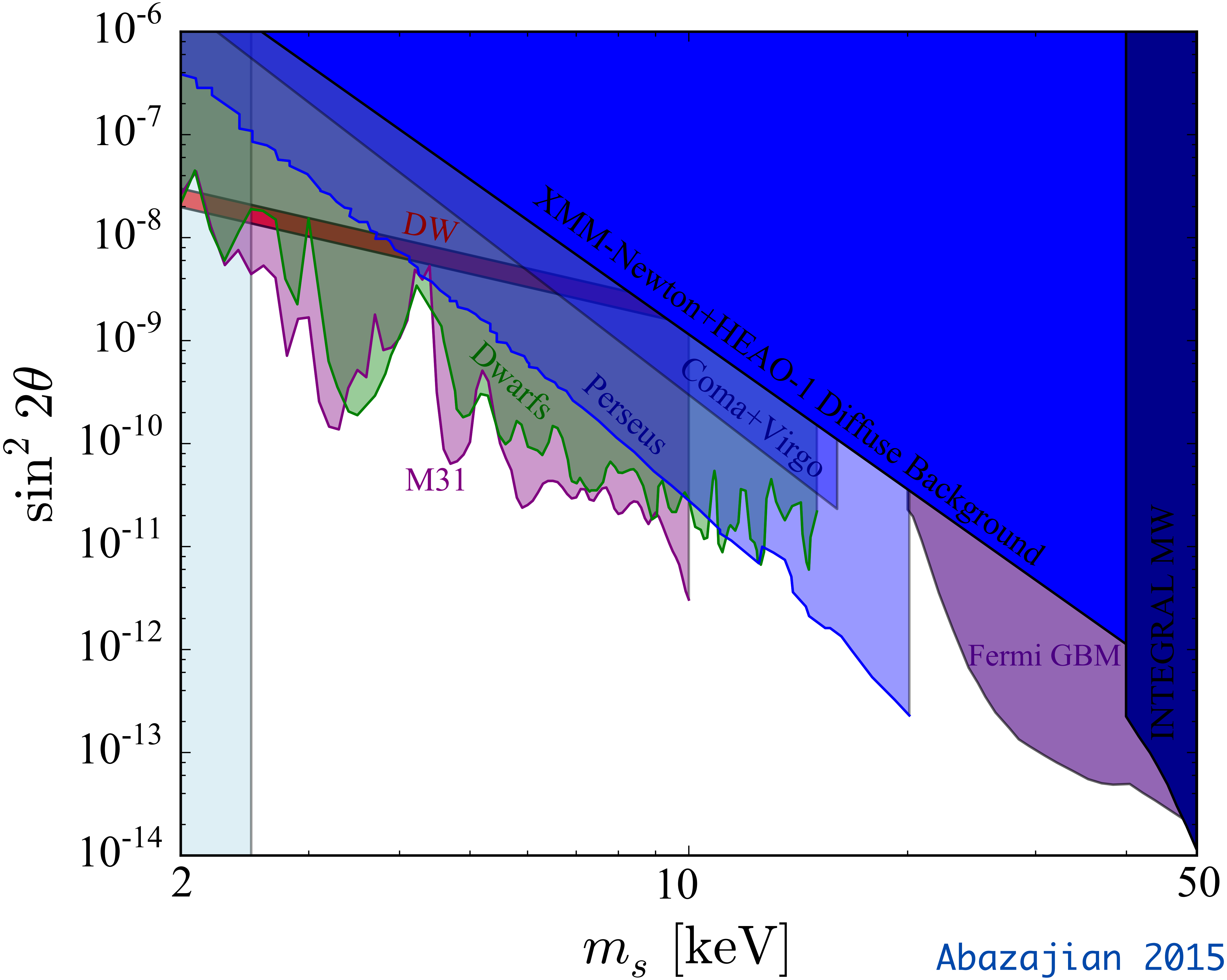
In Figure 4 we show the detectability region for observations of NGC 3198 with Constellation X—a proposed fleet of observatories that will have an effective area ~10 times greater than *Chandra* and no instrumental background (Valinia et al. 1999)—for two integration times, 1 and 10 Ms, which conceivably could be achieved through several long observations over a few years. An exposure equivalent to this could be obtained by a stacking analysis of the spectra of a number of similar clusters (see, e.g., Brandt et al. 2001; Tozzi et al. 2001). Constellation X, with very long integration times, holds out the prospect of covering nearly the entire WDM parameter space of interest for

The Detection of an Unidentified Line



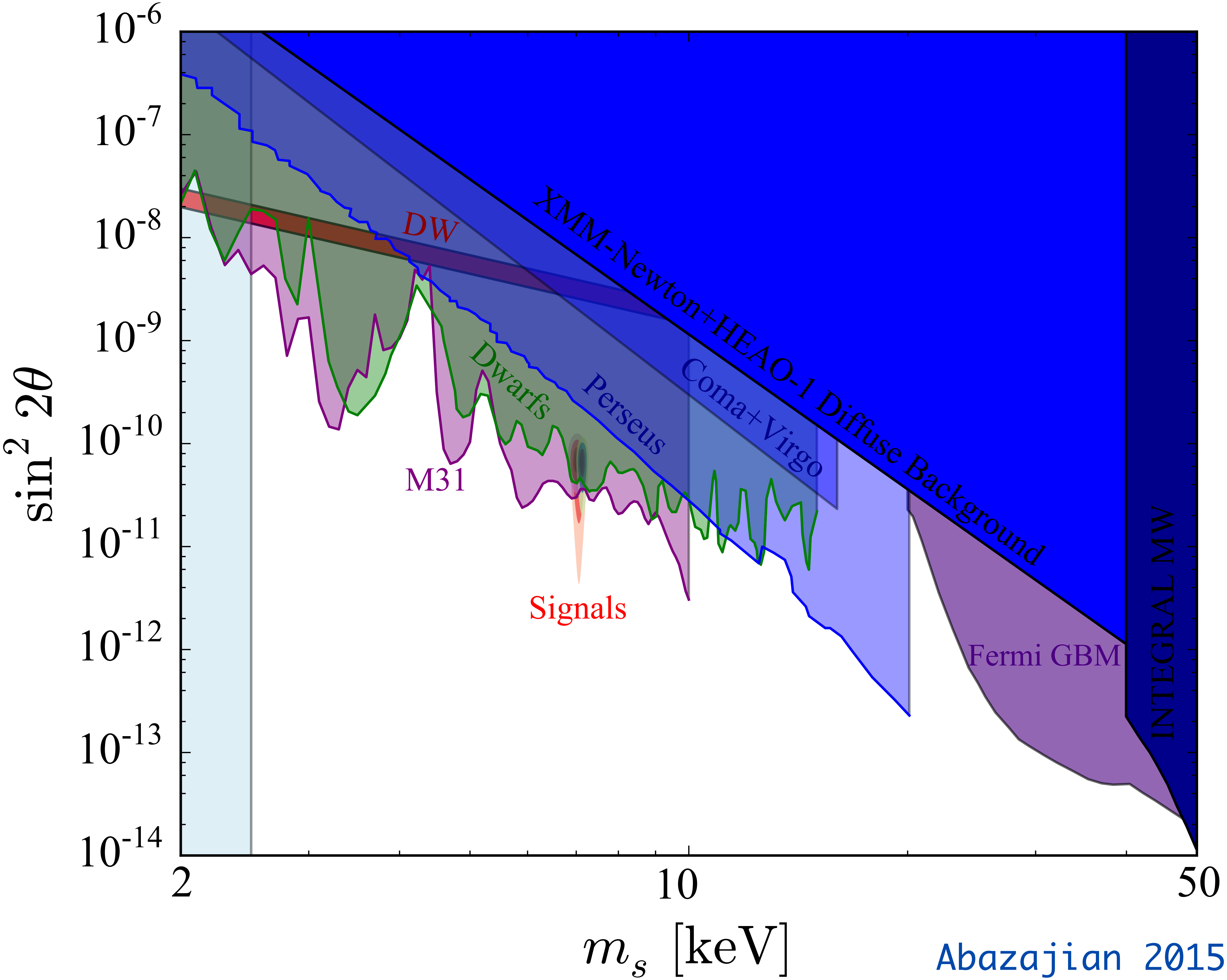
Bulbul et al. ApJ arXiv:1402.2301

Sterile Neutrino Dark Matter: Parameter Space Summary



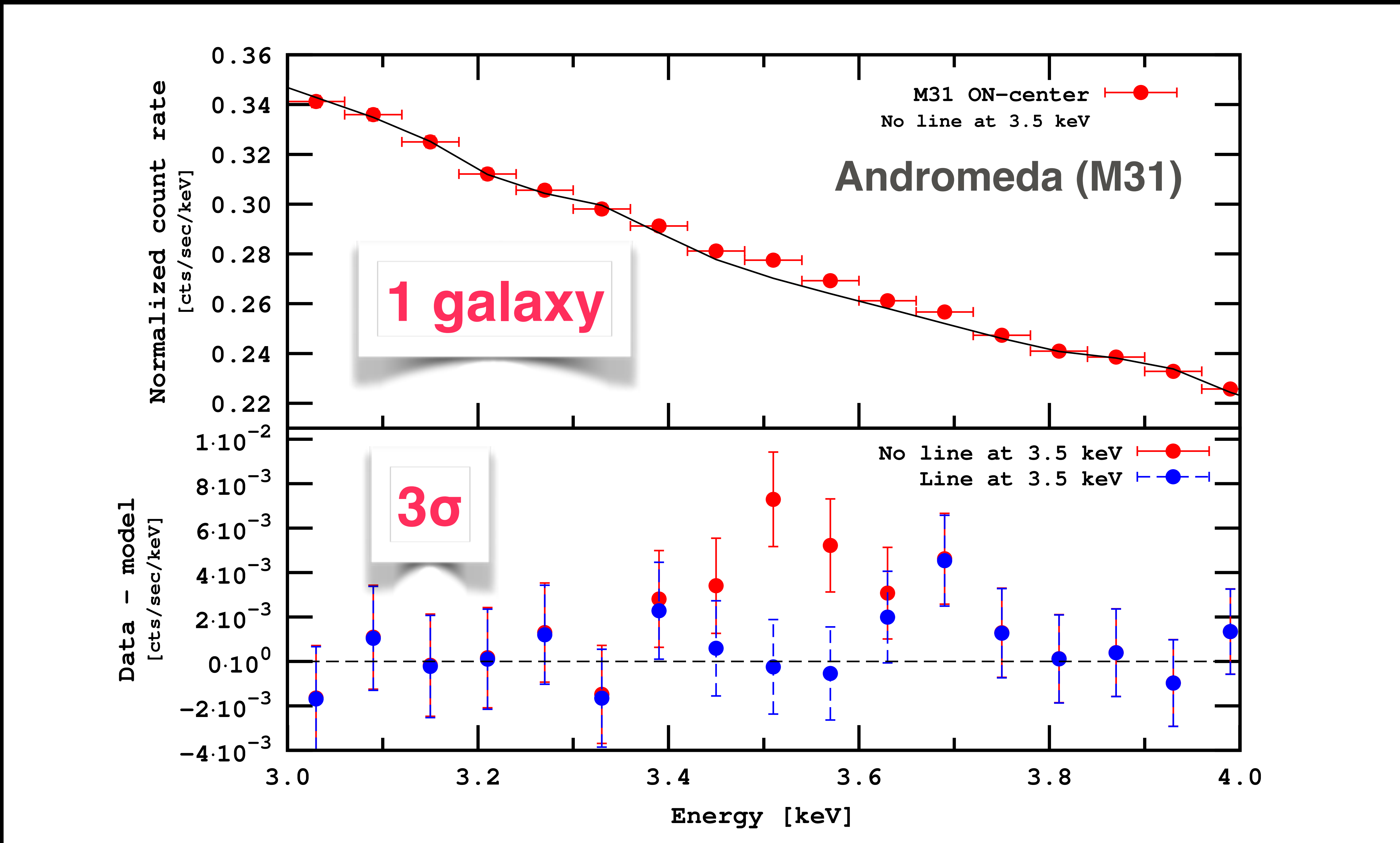
Abazajian 2015

Sterile Neutrino Dark Matter: Parameter Space Summary



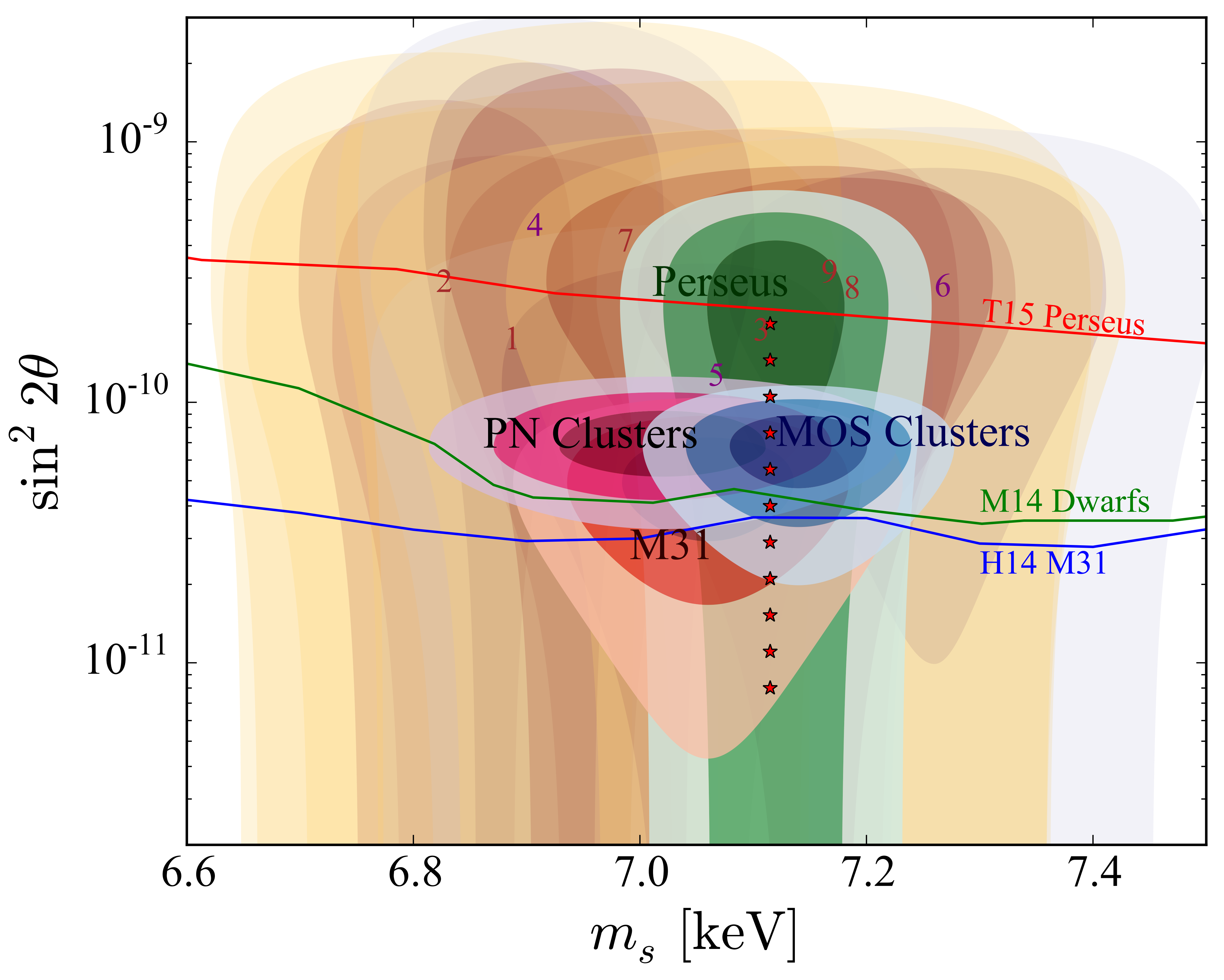
Abazajian 2015

The Detection of an Unidentified Line II



Boyarsky et al. PRL arXiv:1402.4119

8 New Cluster Detections at >2σ Reported in August



Iakubovskyi+ 1508.05186

Galactic Center X-ray Constraints? Potassium Lines? M31?

Galactic Center X-ray Constraints? Potassium Lines? M31?

"Dark Matter Searches Gone Bananas" Potassium paper by Jeltema & Profumo arXiv:1408.1699 (JP) called into question Bulbul+ and Boyarsky+ results:

Galactic Center X-ray Constraints? Potassium Lines? M31?

"Dark Matter Searches Gone Bananas" Potassium paper by Jeltema & Profumo arXiv:1408.1699 (JP) called into question Bulbul+ and Boyarsky+ results:

- JP claim that the Galactic Center excludes a dark matter interpretation

Galactic Center X-ray Constraints? Potassium Lines? M31?

"Dark Matter Searches Gone Bananas" Potassium paper by Jeltema & Profumo arXiv:1408.1699 (JP) called into question Bulbul+ and Boyarsky+ results:

- JP claim that the Galactic Center excludes a dark matter interpretation
  - » JP makes the assumption of all of the 3.5 keV flux coming from K XVIII, and then placing constraints on dark matter decay from the Galactic Center after this assumption. The flux from the Galactic Center is in fact consistent with the dark matter mass within the region [Boyarsky+ arXiv:1408.2503].

Galactic Center X-ray Constraints? Potassium Lines? M31?

"Dark Matter Searches Gone Bananas" Potassium paper by Jeltema & Profumo arXiv:1408.1699 (JP) called into question Bulbul+ and Boyarsky+ results:

- JP claim that the Galactic Center excludes a dark matter interpretation
  - JP makes the assumption of all of the 3.5 keV flux coming from K XVIII, and then placing constraints on dark matter decay from the Galactic Center after this assumption. The flux from the Galactic Center is in fact consistent with the dark matter mass within the region [Boyarsky+ arXiv:1408.2503].
- JP claim that there is less than 2σ evidence for the line in XMM-Newton data of M31

Galactic Center X-ray Constraints? Potassium Lines? M31?

"Dark Matter Searches Gone Bananas" Potassium paper by Jeltema & Profumo arXiv:1408.1699 (JP) called into question Bulbul+ and Boyarsky+ results:

- JP claim that the Galactic Center excludes a dark matter interpretation
  - » JP makes the assumption of all of the 3.5 keV flux coming from K XVIII, and then placing constraints on dark matter decay from the Galactic Center after this assumption. The flux from the Galactic Center is in fact consistent with the dark matter mass within the region [Boyarsky+ arXiv:1408.2503].
- JP claim that there is less than 2σ evidence for the line in XMM-Newton data of M31
  - » The Boyarsky team showed how the JP M31 analysis is flawed in using much too narrow of an energy window in their line search modeling, which allows the continuum to float excessively [arXiv:1408.4388].

Galactic Center X-ray Constraints? Potassium Lines? M31?

"Dark Matter Searches Gone Bananas" Potassium paper by Jeltema & Profumo arXiv:1408.1699 (JP) called into question Bulbul+ and Boyarsky+ results:

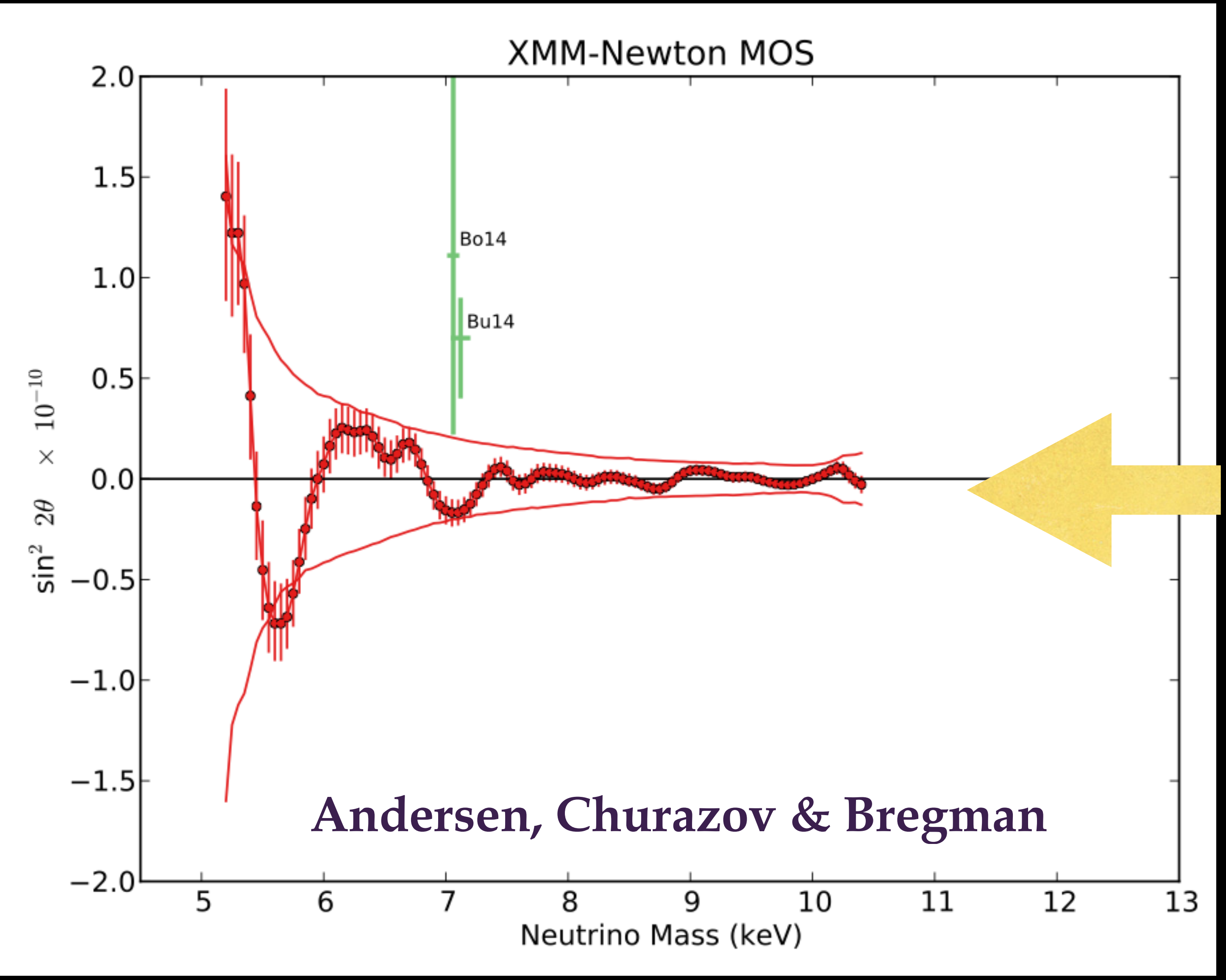
- JP claim that the Galactic Center excludes a dark matter interpretation
  - » JP makes the assumption of all of the 3.5 keV flux coming from K XVIII, and then placing constraints on dark matter decay from the Galactic Center after this assumption. The flux from the Galactic Center is in fact consistent with the dark matter mass within the region [Boyarsky+ arXiv:1408.2503].
- JP claim that there is less than 2σ evidence for the line in XMM-Newton data of M31
  - » The Boyarsky team showed how the JP M31 analysis is flawed in using much too narrow of an energy window in their line search modeling, which allows the continuum to float excessively [arXiv:1408.4388].
- JP claim line ratios in the cluster data do not allow for a consistent model for the temperature of Perseus

Galactic Center X-ray Constraints? Potassium Lines? M31?

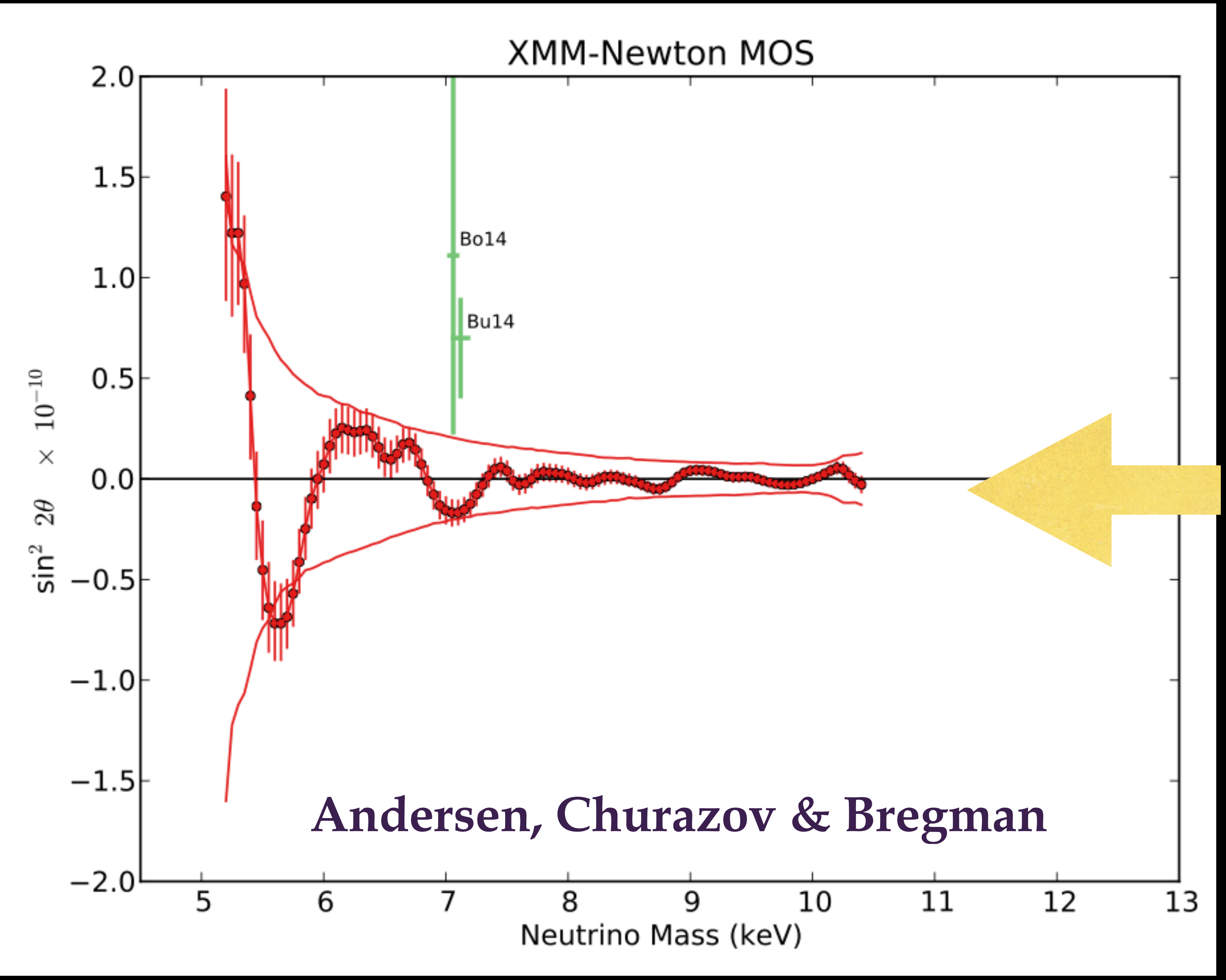
"Dark Matter Searches Gone Bananas" Potassium paper by Jeltema & Profumo arXiv:1408.1699 (JP) called into question Bulbul+ and Boyarsky+ results:

- JP claim that the Galactic Center excludes a dark matter interpretation
  - JP makes the assumption of all of the 3.5 keV flux coming from K XVIII, and then placing constraints on dark matter decay from the Galactic Center after this assumption. The flux from the Galactic Center is in fact consistent with the dark matter mass within the region [Boyarsky+ arXiv:1408.2503].
- JP claim that there is less than 2σ evidence for the line in XMM-Newton data of M31
  - The Boyarsky team showed how the JP M31 analysis is flawed in using much too narrow of an energy window in their line search modeling, which allows the continuum to float excessively [arXiv:1408.4388].
- JP claim line ratios in the cluster data do not allow for a consistent model for the temperature of Perseus
  - The Bulbul+ team showed that JP use over-simplified single-temperature model arguments with incorrect line ratios in their X-ray cluster modeling [arXiv:1409.0920].

Stacked Observations I: Galaxies

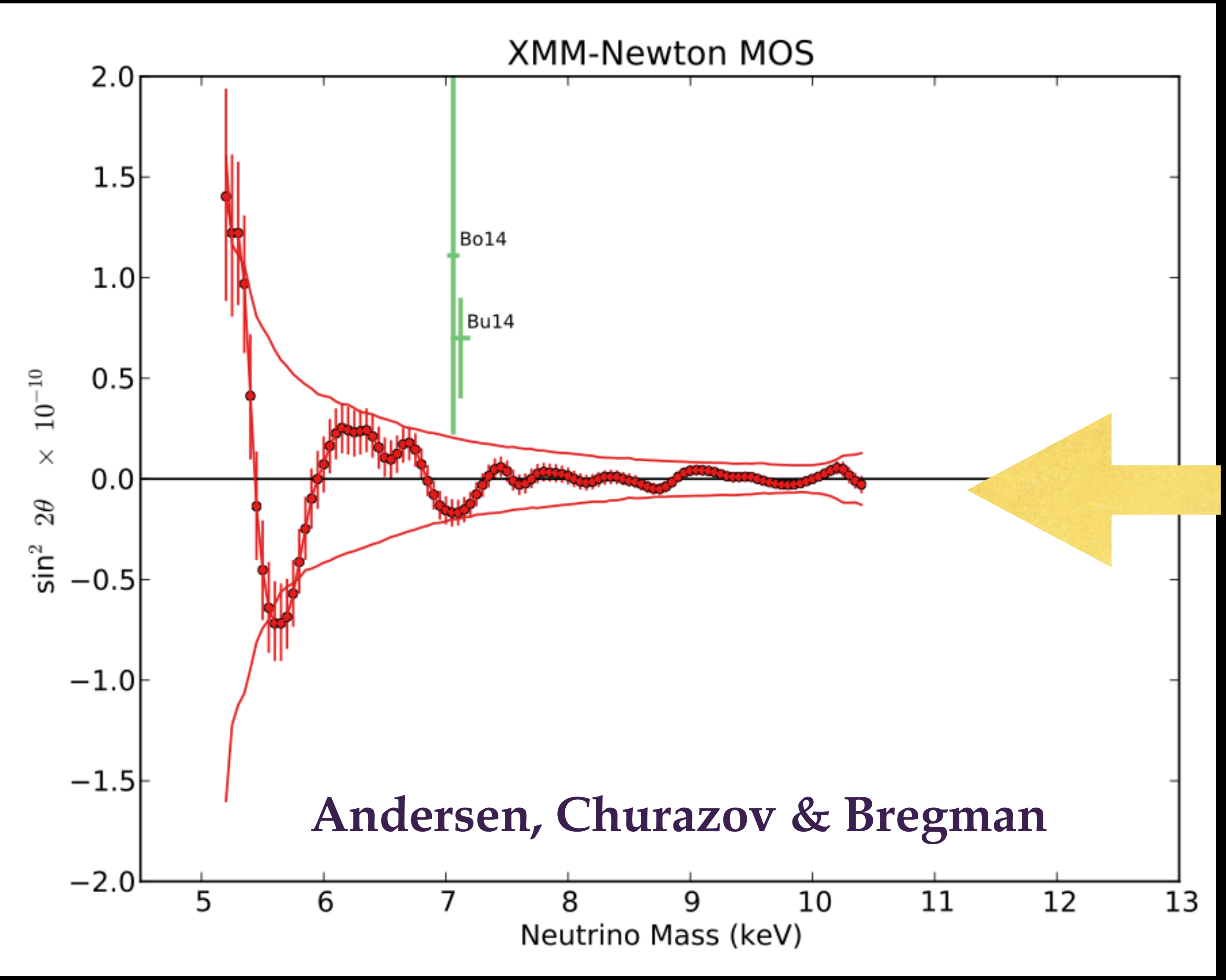


Stacked Observations I: Galaxies



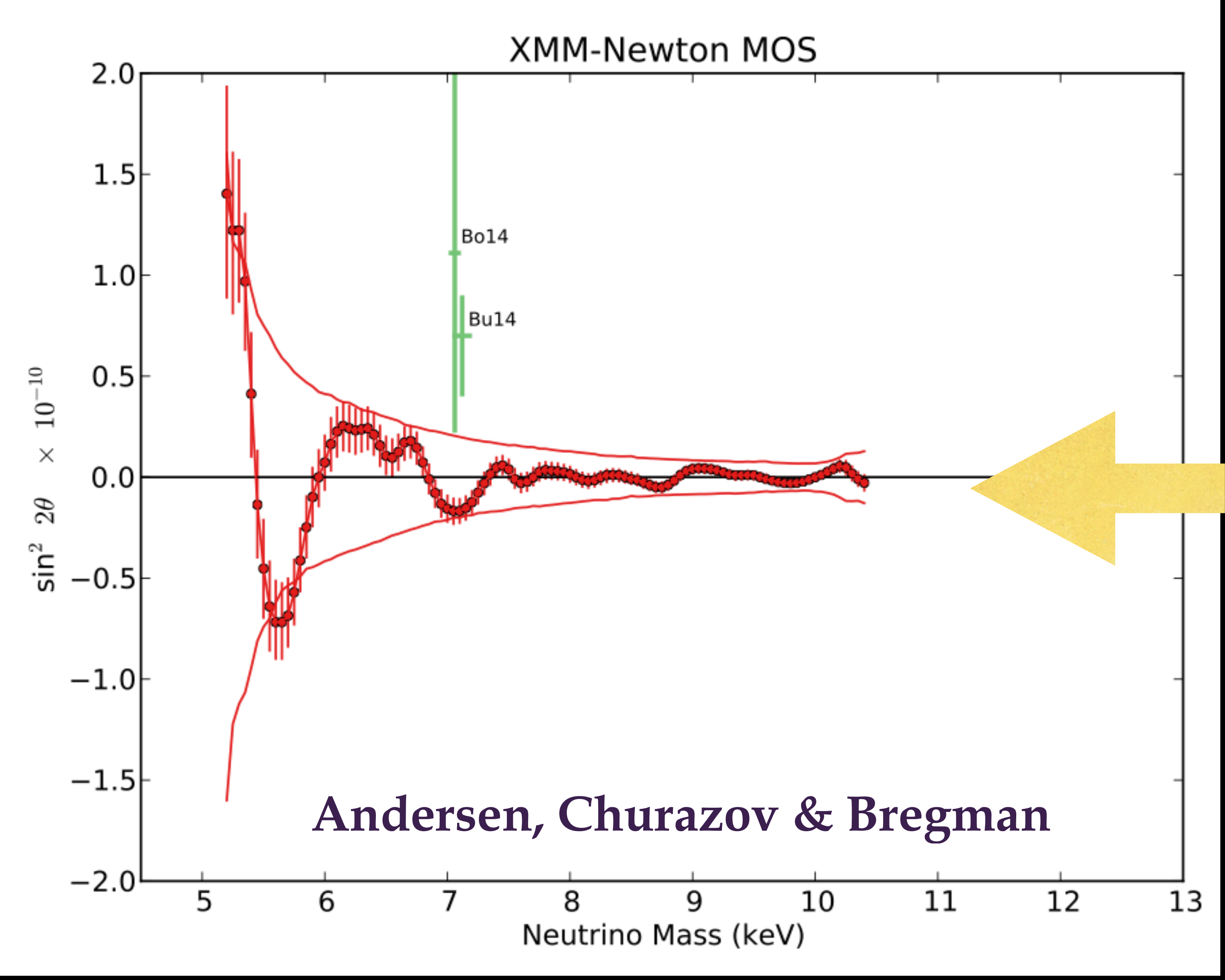
Sample of 81 galaxies observed with Chandra and a sample of 89 galaxies observed with XMM-Newton, using outskirts of the galaxies (Andersen, Churazov & Bregman 2014)

Stacked Observations I: Galaxies



Sample of 81 galaxies observed with Chandra and a sample of 89 galaxies observed with XMM-Newton, using outskirts of the galaxies (Andersen, Churazov & Bregman 2014)

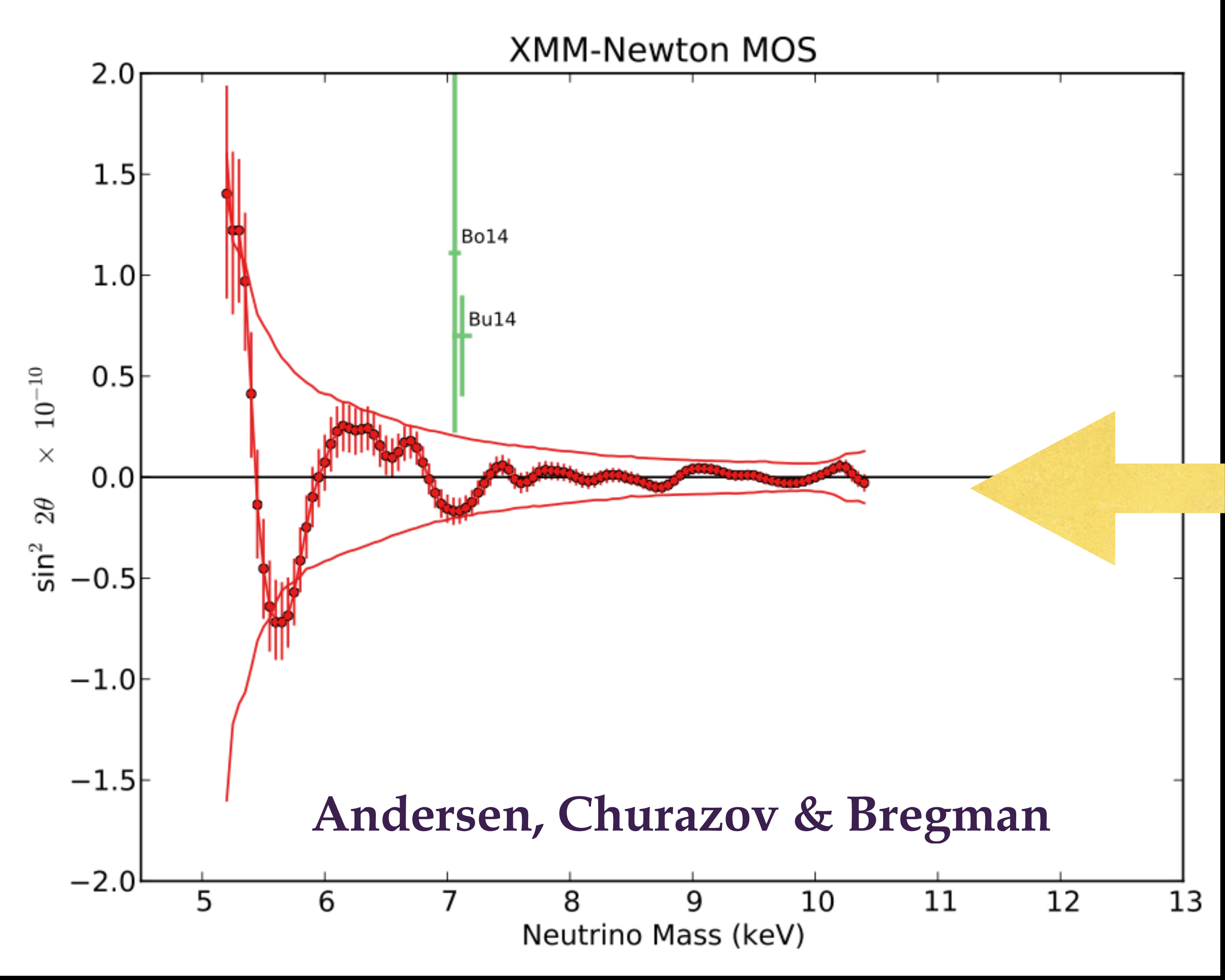
Stacked Observations I: Galaxies



Sample of 81 galaxies observed with Chandra and a sample of 89 galaxies observed with XMM-Newton, using outskirts of the galaxies (Andersen, Churazov & Bregman 2014)

Quoted exclusion of the 3.5 keV line at fixed $\sin^2 2\theta$ by 11.8σ

Stacked Observations I: Galaxies

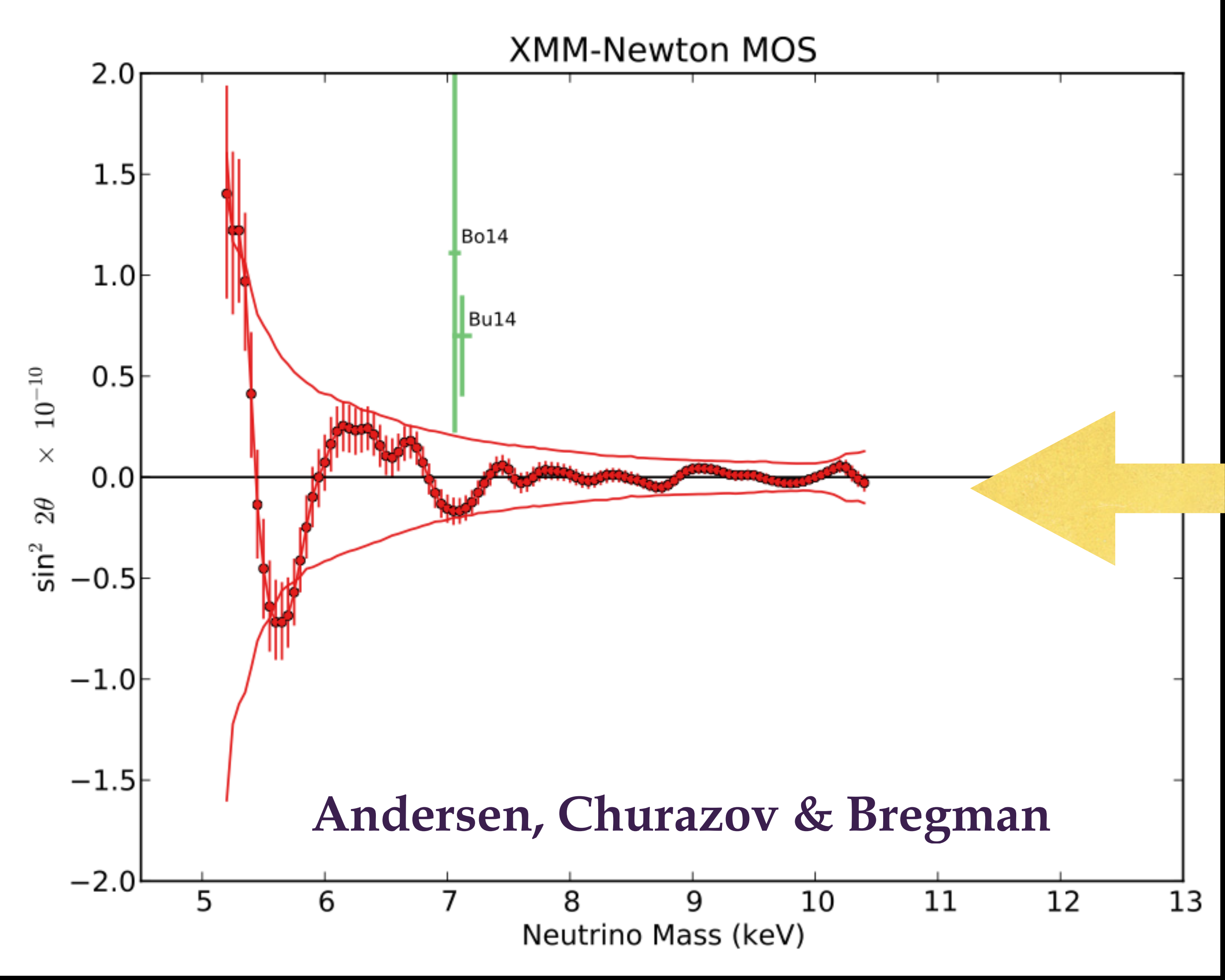


Sample of 81 galaxies observed with Chandra and a sample of 89 galaxies observed with XMM-Newton, using outskirts of the galaxies (Andersen, Churazov & Bregman 2014)

Quoted exclusion of the 3.5 keV line at fixed $\sin^2 2\theta$ by 11.8σ

Systematic errors are of order the uncertainties on detected $\sin^2 2\theta$

Stacked Observations I: Galaxies



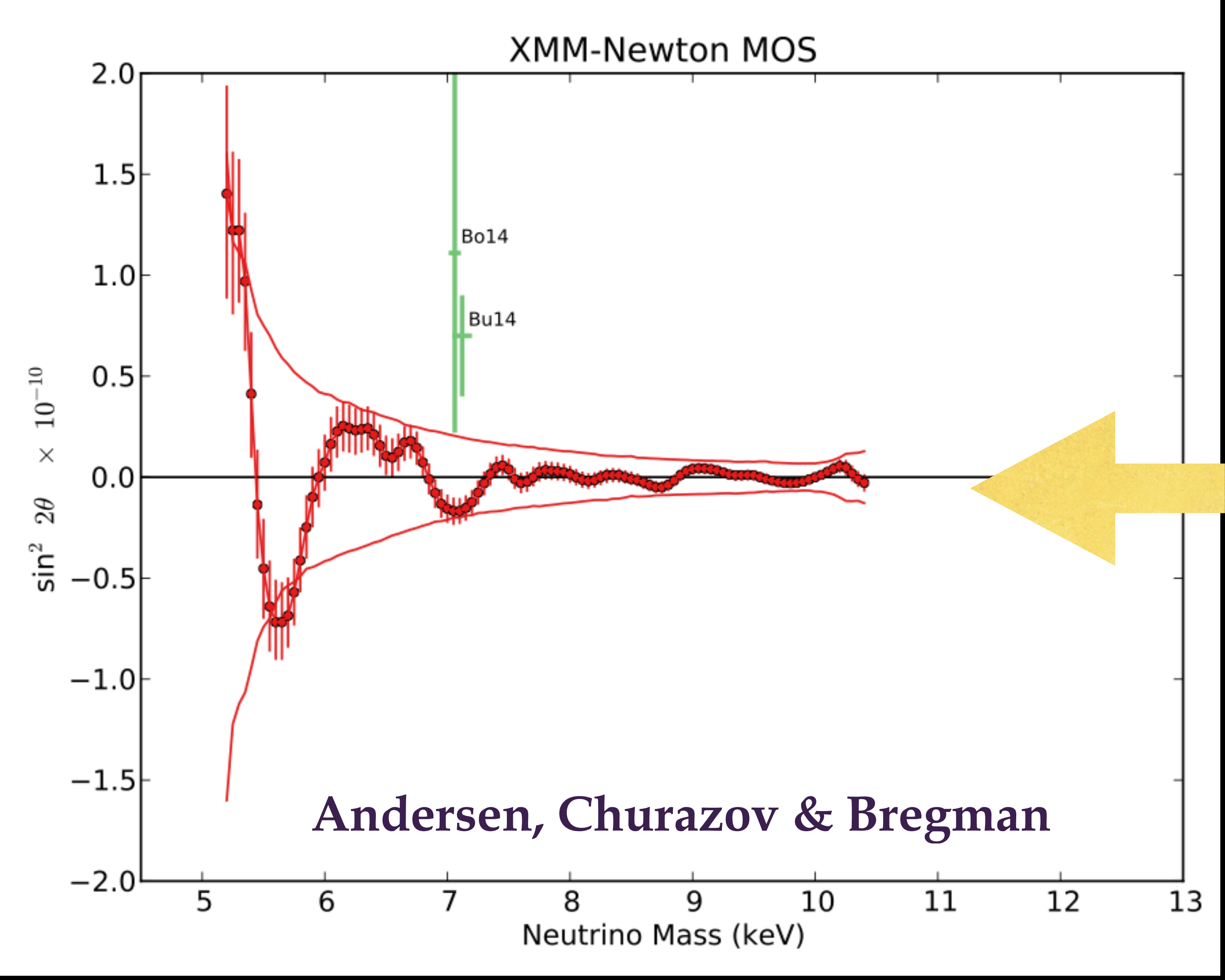
Sample of 81 galaxies observed with Chandra and a sample of 89 galaxies observed with XMM-Newton, using outskirts of the galaxies (Andersen, Churazov & Bregman 2014)

Quoted exclusion of the 3.5 keV line at fixed $\sin^2 2\theta$ by 11.8σ

Systematic errors are of order the uncertainties on detected $\sin^2 2\theta$

There was no test of the line hypothesis in mutual data of clusters plus galaxies (that is: is there any mixing angle that fits all data?), ***no presentation of limits in parameter space***

Stacked Observations I: Galaxies



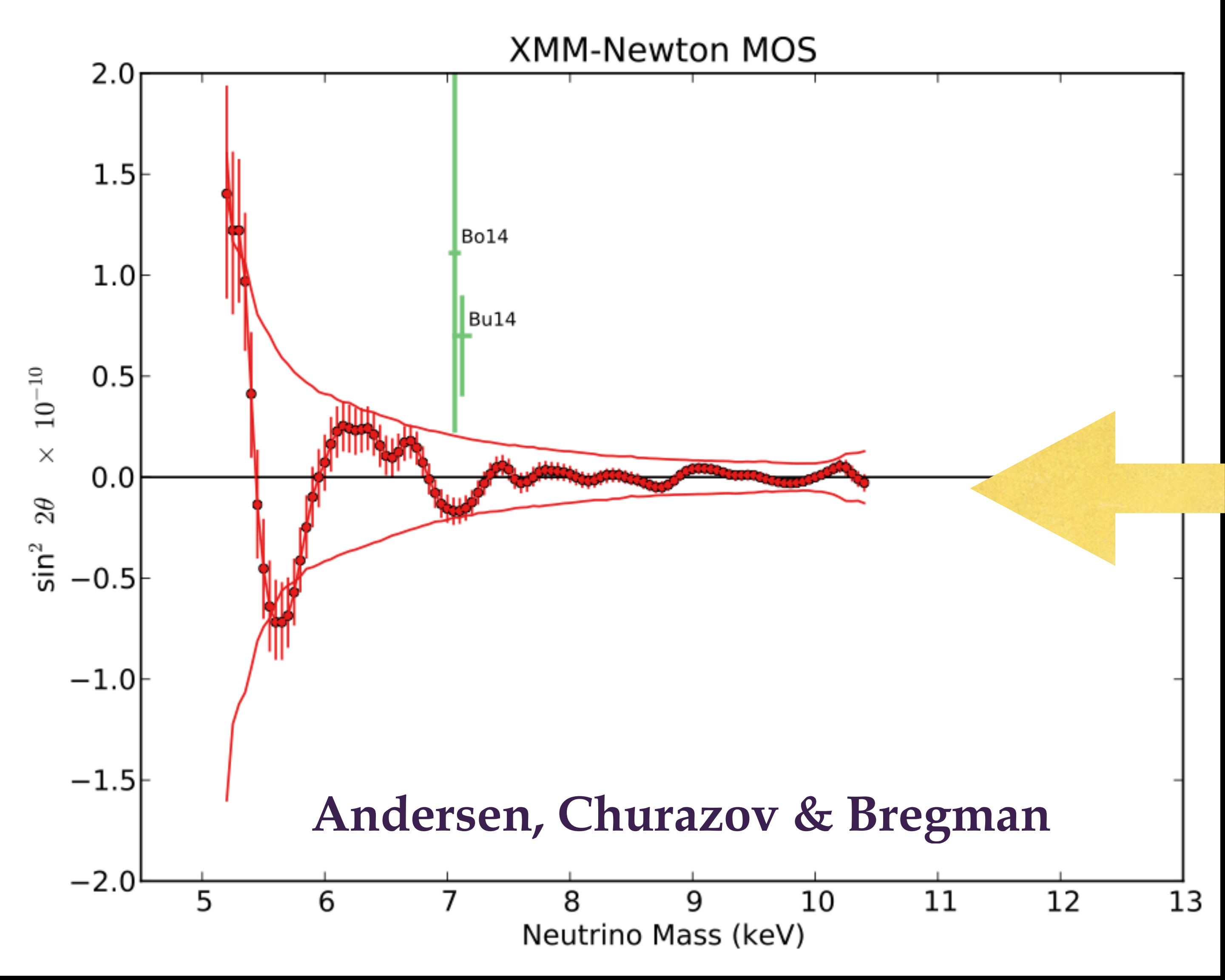
Sample of 81 galaxies observed with Chandra and a sample of 89 galaxies observed with XMM-Newton, using outskirts of the galaxies (Andersen, Churazov & Bregman 2014)

Quoted exclusion of the 3.5 keV line at fixed $\sin^2 2\theta$ by 11.8σ

Systematic errors are of order the uncertainties on detected $\sin^2 2\theta$

There was no test of the line hypothesis in mutual data of clusters plus galaxies (that is: is there any mixing angle that fits all data?), ***no presentation of limits in parameter space***

Stacked Observations I: Galaxies



Sample of 81 galaxies observed with Chandra and a sample of 89 galaxies observed with XMM-Newton, using outskirts of the galaxies (Andersen, Churazov & Bregman 2014)

Quoted exclusion of the 3.5 keV line at fixed $\sin^2 2\theta$ by 11.8σ

Systematic errors are of order the uncertainties on detected $\sin^2 2\theta$

There was no test of the line hypothesis in mutual data of clusters plus galaxies (that is: is there any mixing angle that fits all data?), ***no presentation of limits in parameter space***

Production of Sterile Neutrino Dark Matter: Boltzmann Transport

Production of Sterile Neutrino Dark Matter: Boltzmann Transport

$$0 = 0$$

Production of Sterile Neutrino Dark Matter: Boltzmann Transport

$$0 = 0$$

$$\mathbf{L}[f] = \mathbf{C}[f]$$

Production of Sterile Neutrino Dark Matter: Boltzmann Transport

$$0 = 0$$

$$\mathbf{L}[f] = \mathbf{C}[f]$$

$$\frac{\partial}{\partial t} f_{\nu_s}(p,t) - H\,p\,\frac{\partial}{\partial p} f_{\nu_s}(p,t) =$$

$$\sum_{\nu_x + a + \dots \to i + \dots} \int \frac{d^3 p_a}{(2\pi)^3 2E_a} \dots \frac{d^3 p_i}{(2\pi)^3 2E_i} \dots (2\pi)^4 \delta^4(p + p_a + \dots - p_i - \dots)$$

$$\times \frac{1}{2} \Big[\langle P_{\mathrm{m}}(\nu_\mu \to \nu_{\mathrm{s}}; p, t) \rangle \left(1 - f_{\nu_s}\right) \sum |\mathcal{M}|^2_{i + \dots \to a + \nu_\mu + \dots} f_i \dots (1 \mp f_a) \left(1 - f_{\nu_\mu}\right) \dots$$

$$- \langle P_{\mathrm{m}}(\nu_{\mathrm{s}} \to \nu_\mu; p, t) \rangle f_{\nu_s} \left(1 - f_{\nu_\mu}\right) \sum |\mathcal{M}|^2_{\nu_\mu + a + \dots \to i + \dots} f_a \dots (1 \mp f_i) \dots \Big] .$$

Production of Sterile Neutrino Dark Matter: Boltzmann Transport

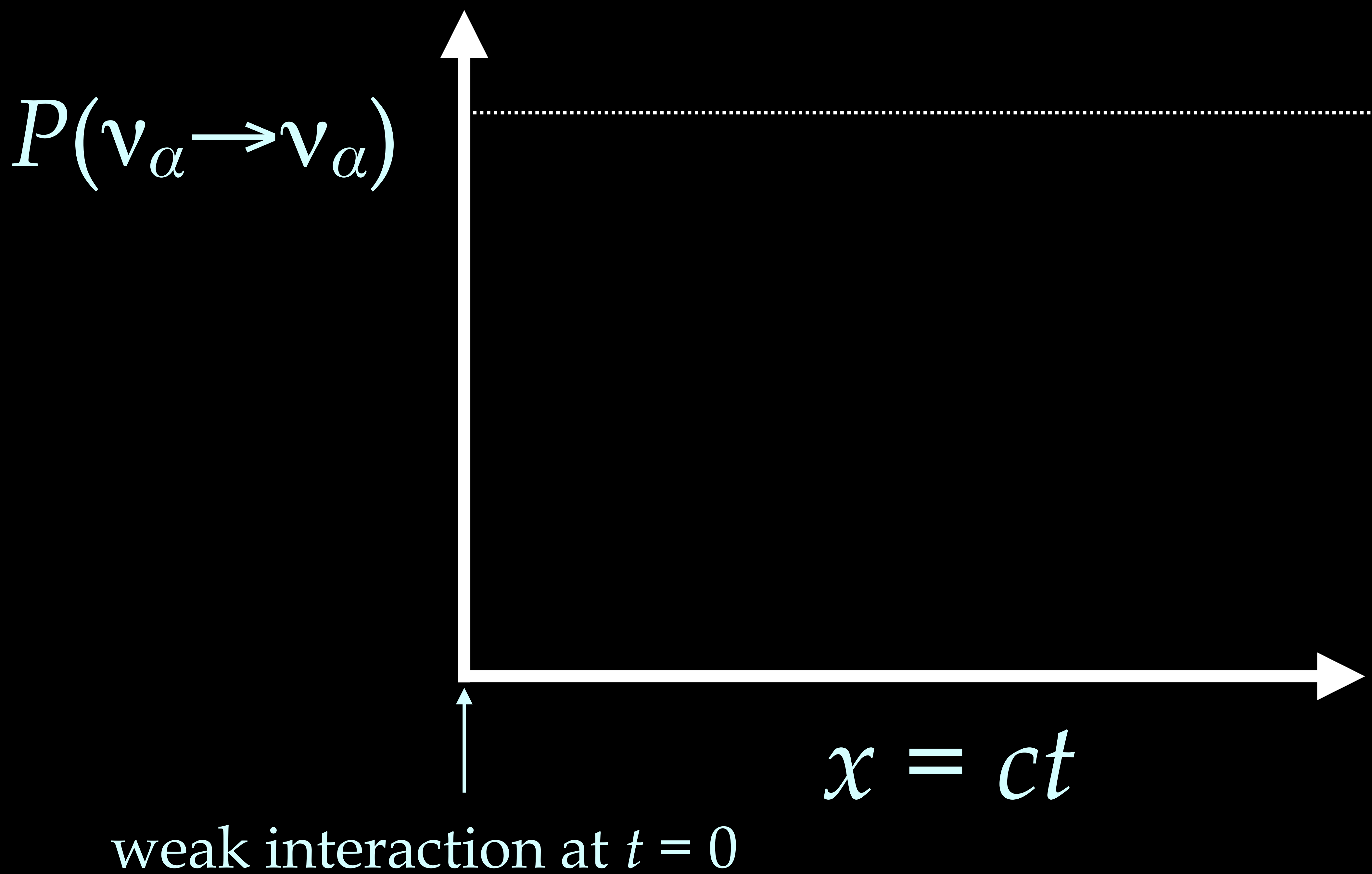
$$0 = 0$$

$$\mathbf{L}[f] = \mathbf{C}[f]$$

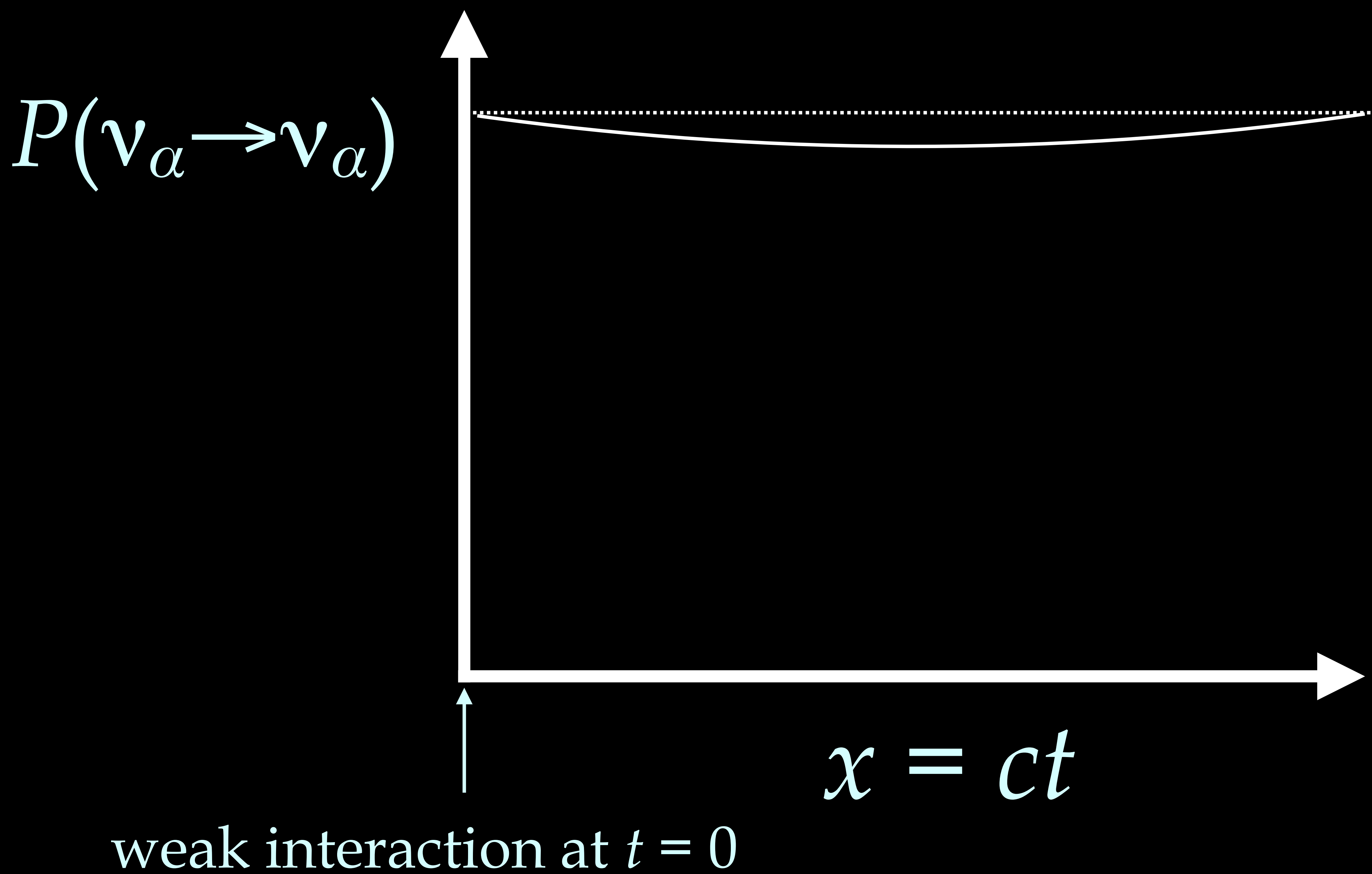
$$\frac{\partial}{\partial t} f_{\nu_\mathrm{s}}(p,t) - H\,p\,\frac{\partial}{\partial p} f_{\nu_\mathrm{s}}(p,t) =$$

$$\sum_{\nu_x + a + \dots \to i + \dots} \int \frac{d^3 p_a}{(2\pi)^3 2E_a} \cdots \frac{d^3 p_i}{(2\pi)^3 2E_i} \dots (2\pi)^4 \delta^4(p + p_a + \dots - p_i - \dots)$$
$$\times \frac{1}{2}\Big[\langle P_\mathrm{m}(\nu_\mu \to \nu_\mathrm{s}; p,t)\rangle (1 - f_{\nu_\mathrm{s}}) \sum |\mathcal{M}|^2_{i+\dots\to a+\nu_\mu+\dots} f_i \dots (1 \mp f_a)(1 - f_{\nu_\mu}) \dots$$
$$- \langle P_\mathrm{m}(\nu_\mathrm{s} \to \nu_\mu; p,t)\rangle f_{\nu_\mathrm{s}} (1 - f_{\nu_\mu}) \sum |\mathcal{M}|^2_{\nu_\mu + a + \dots \to i + \dots} f_a \dots (1 \mp f_i) \dots \Big].$$

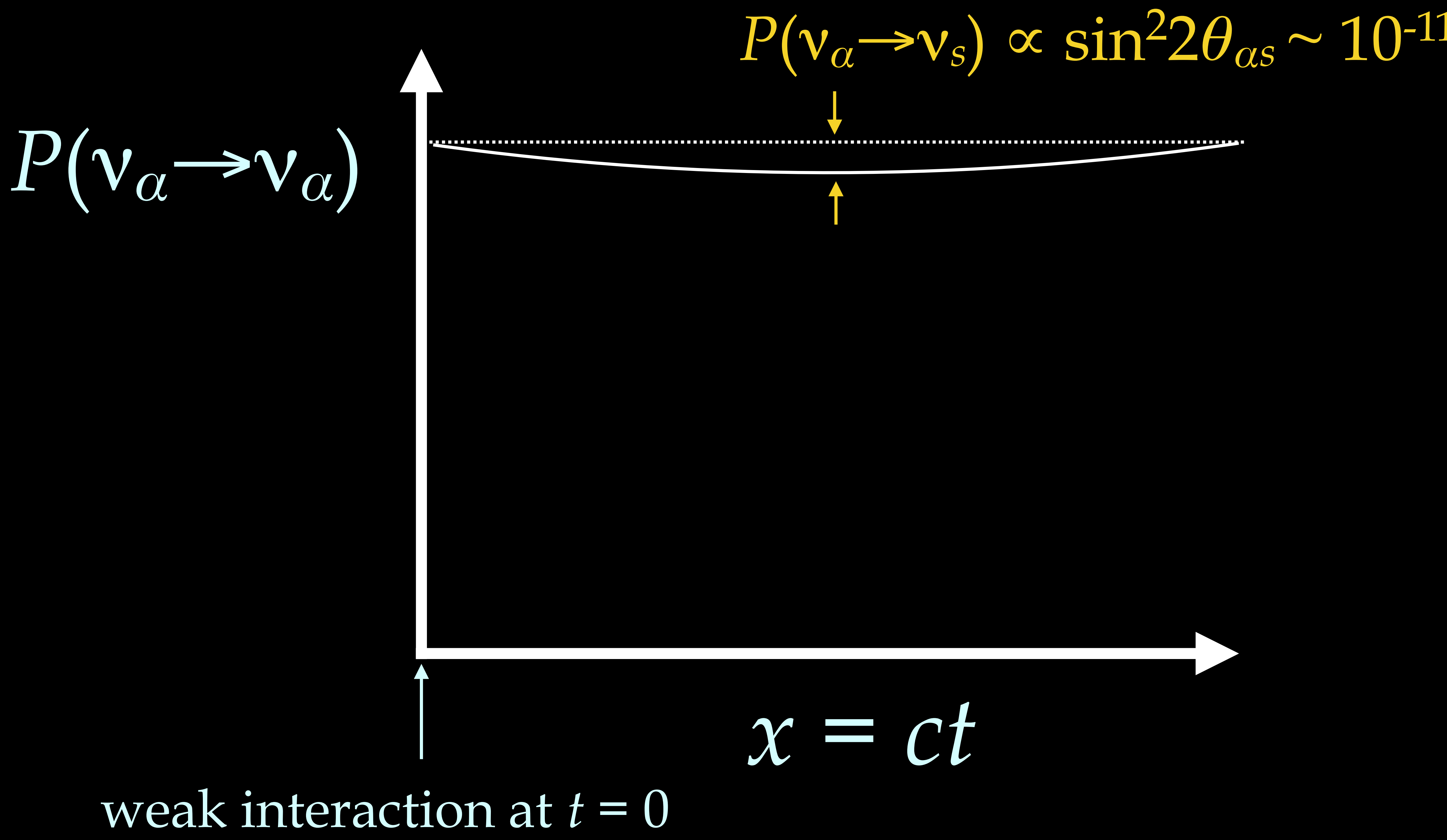
A Simplified View of Sterile Neutrino Dark Matter Production



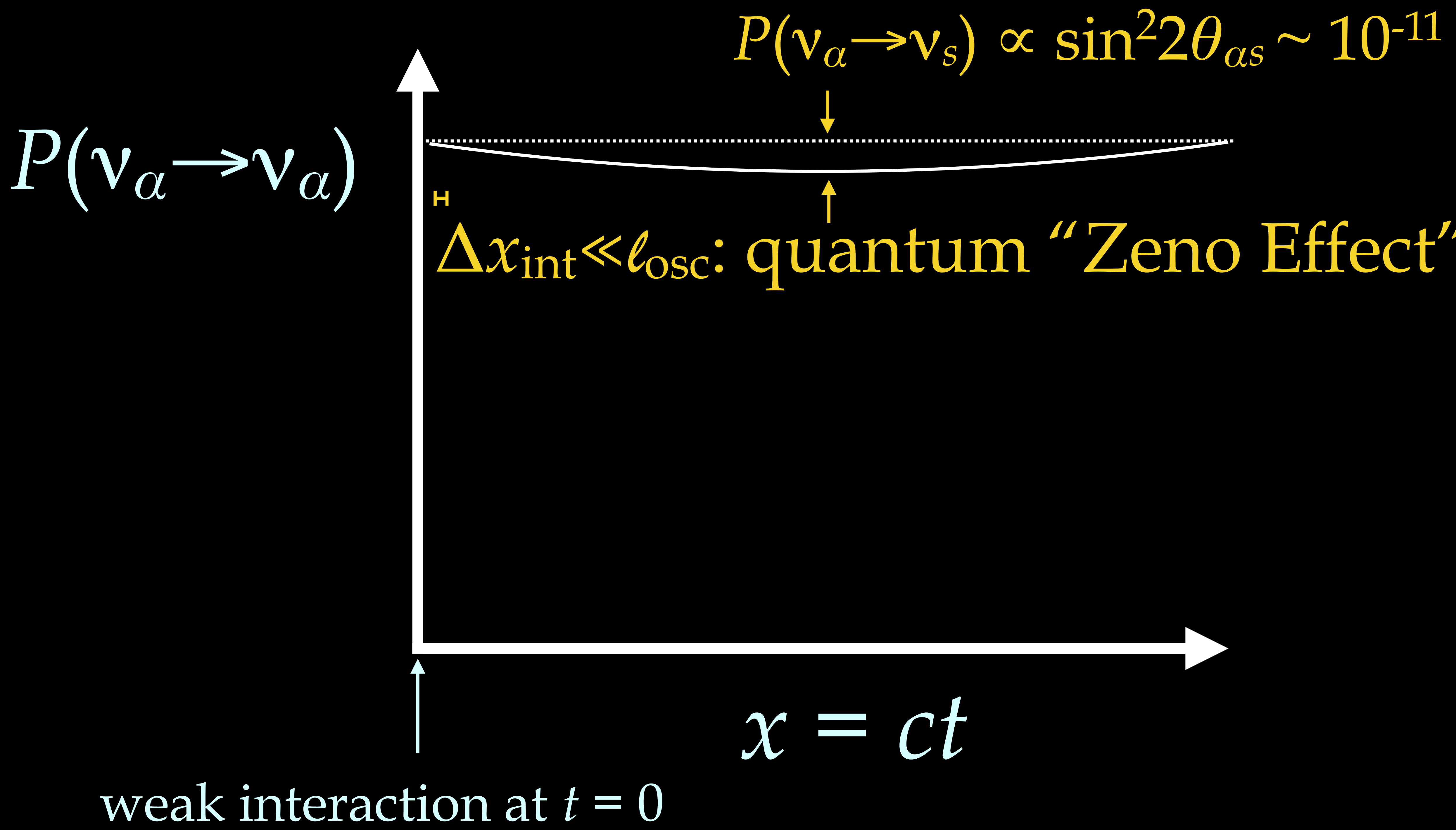
A Simplified View of Sterile Neutrino Dark Matter Production



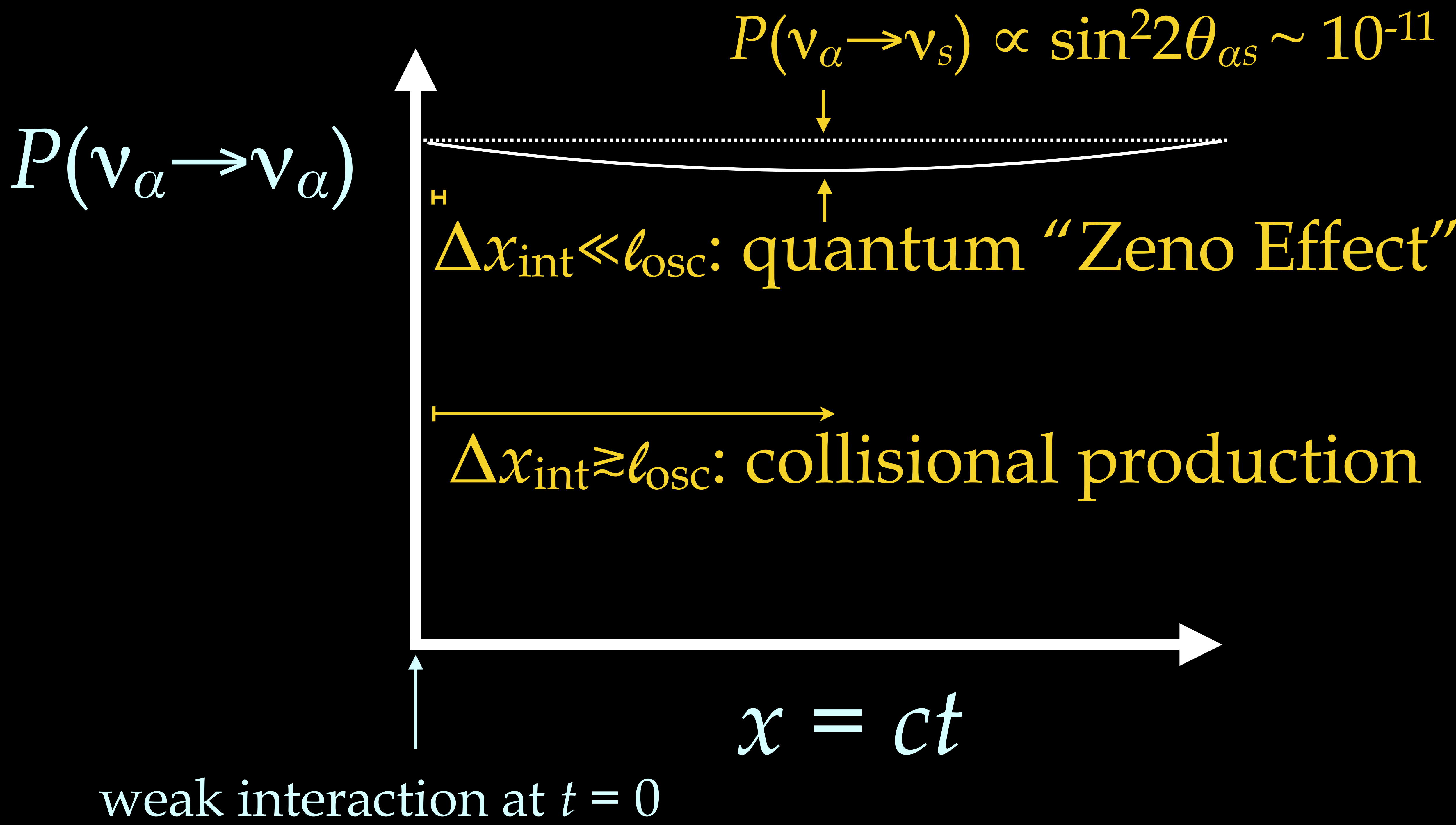
A Simplified View of Sterile Neutrino Dark Matter Production



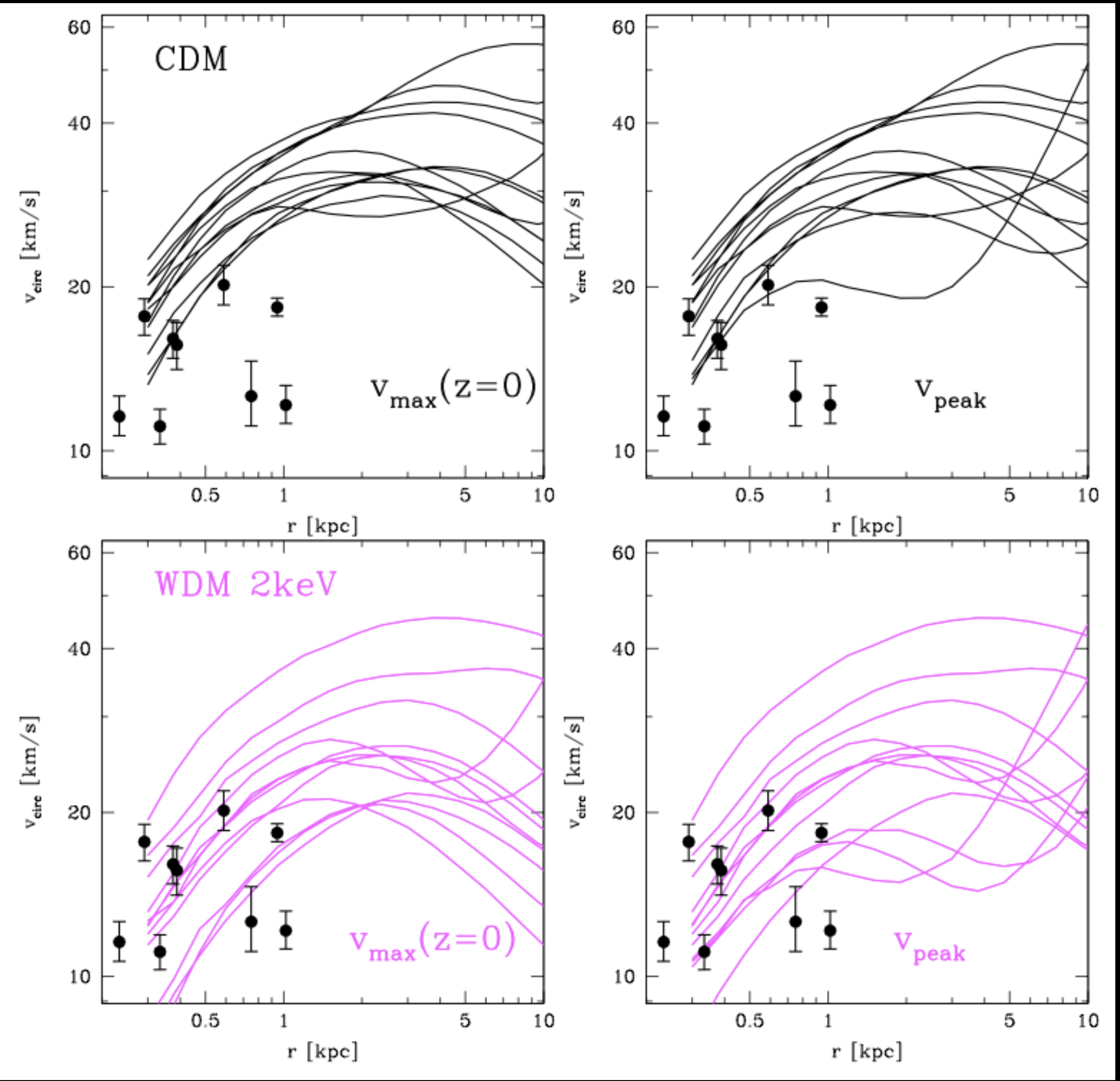
A Simplified View of Sterile Neutrino Dark Matter Production



A Simplified View of Sterile Neutrino Dark Matter Production

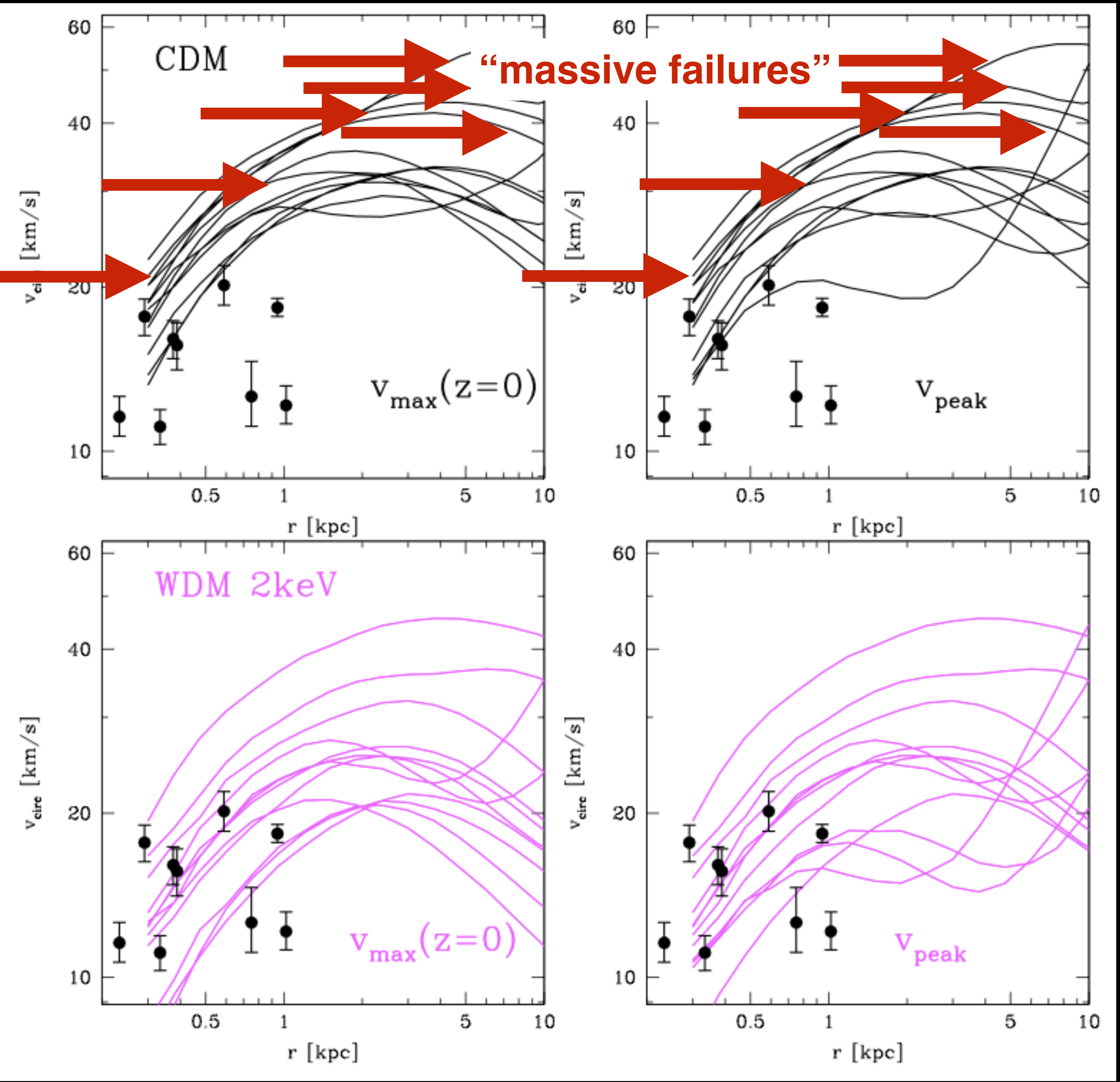


WDM Solution to All Local Group Galaxy Properties? [Boylan-Kolchin+ 2011]



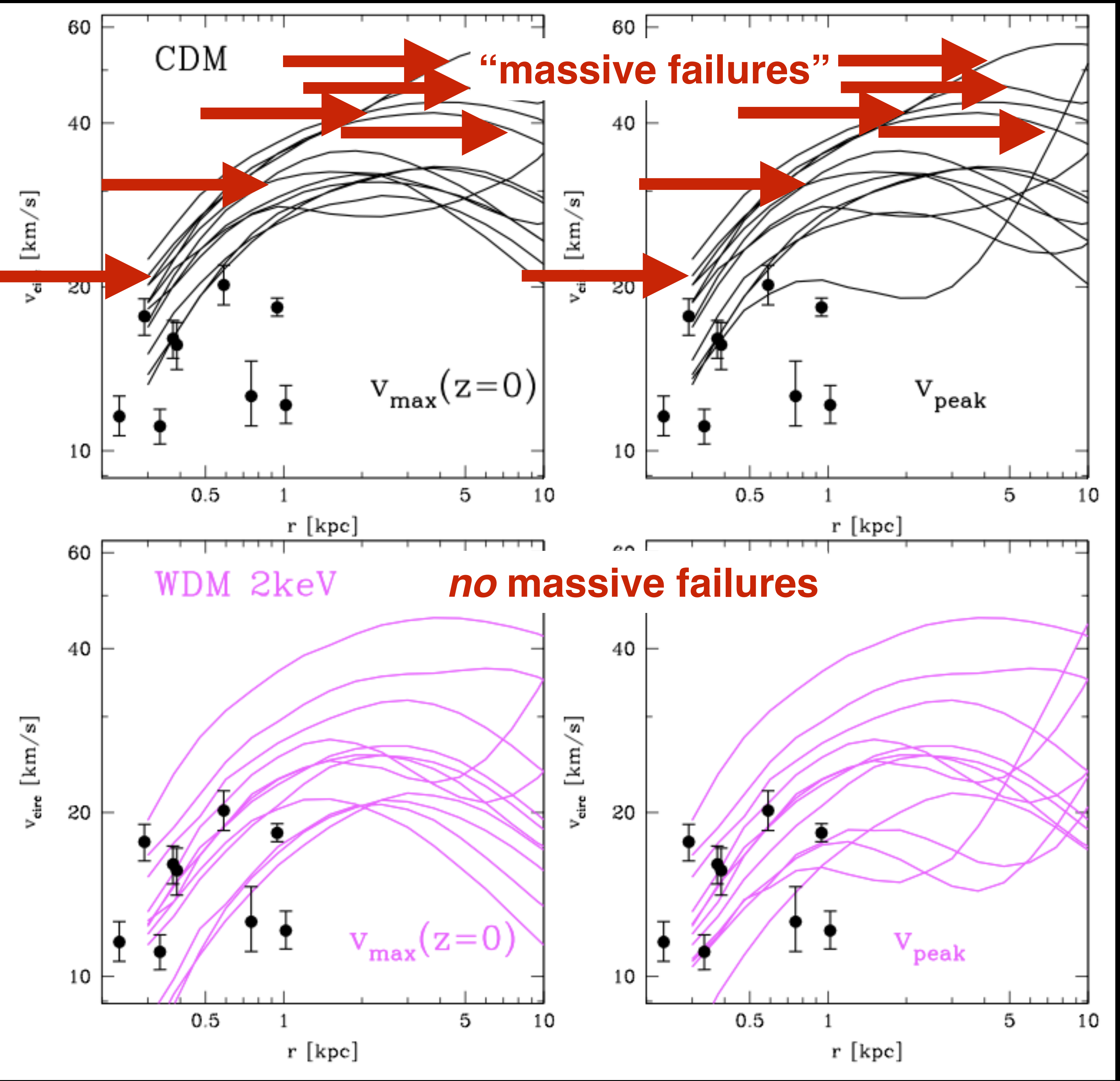
Anderhalden et al. arXiv:1212.2967

WDM Solution to All Local Group Galaxy Properties? [Boylan-Kolchin+ 2011]



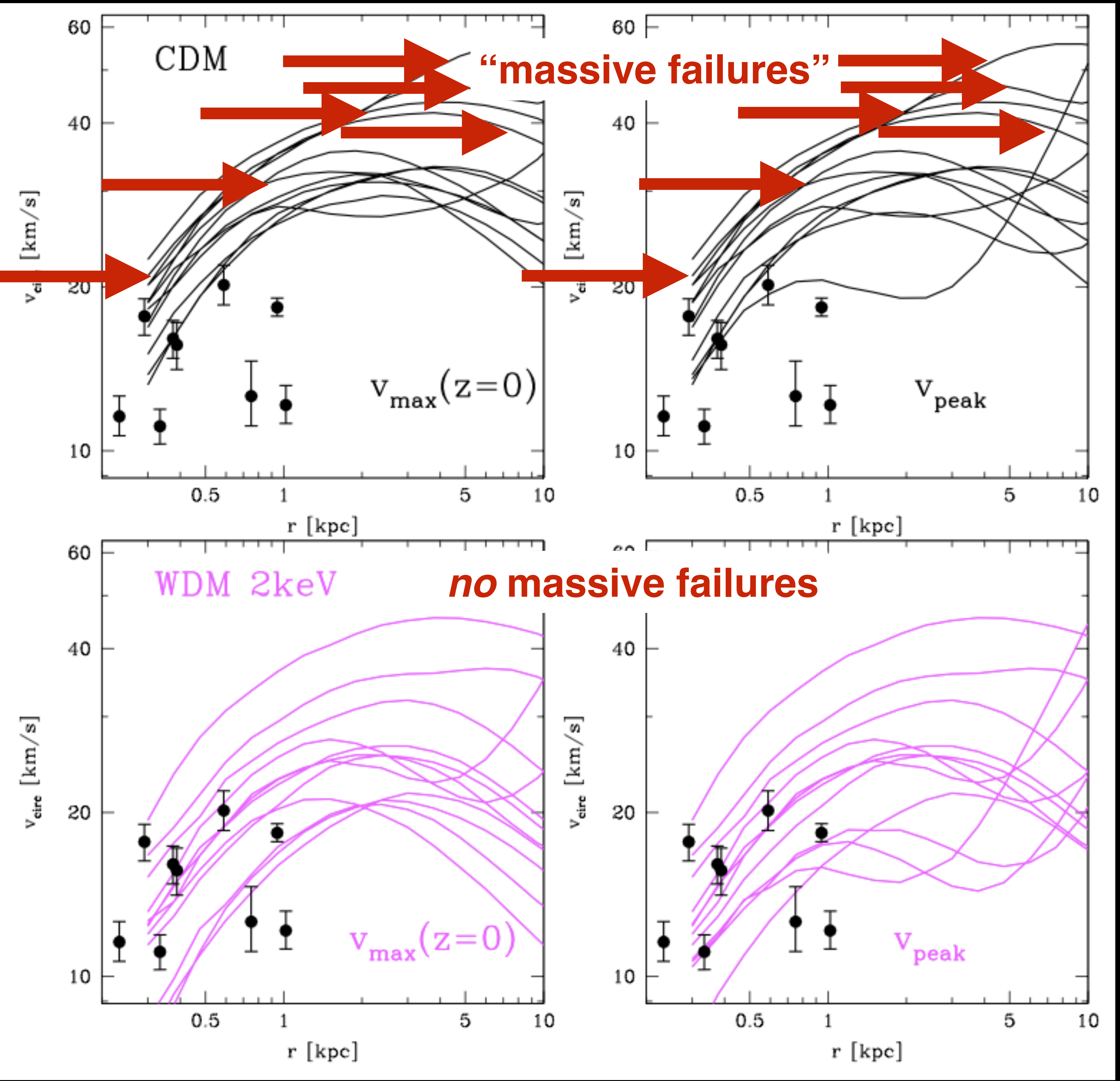
Anderhalden et al. arXiv:1212.2967

WDM Solution to All Local Group Galaxy Properties? [Boylan-Kolchin+ 2011]



Anderhalden et al. arXiv:1212.2967

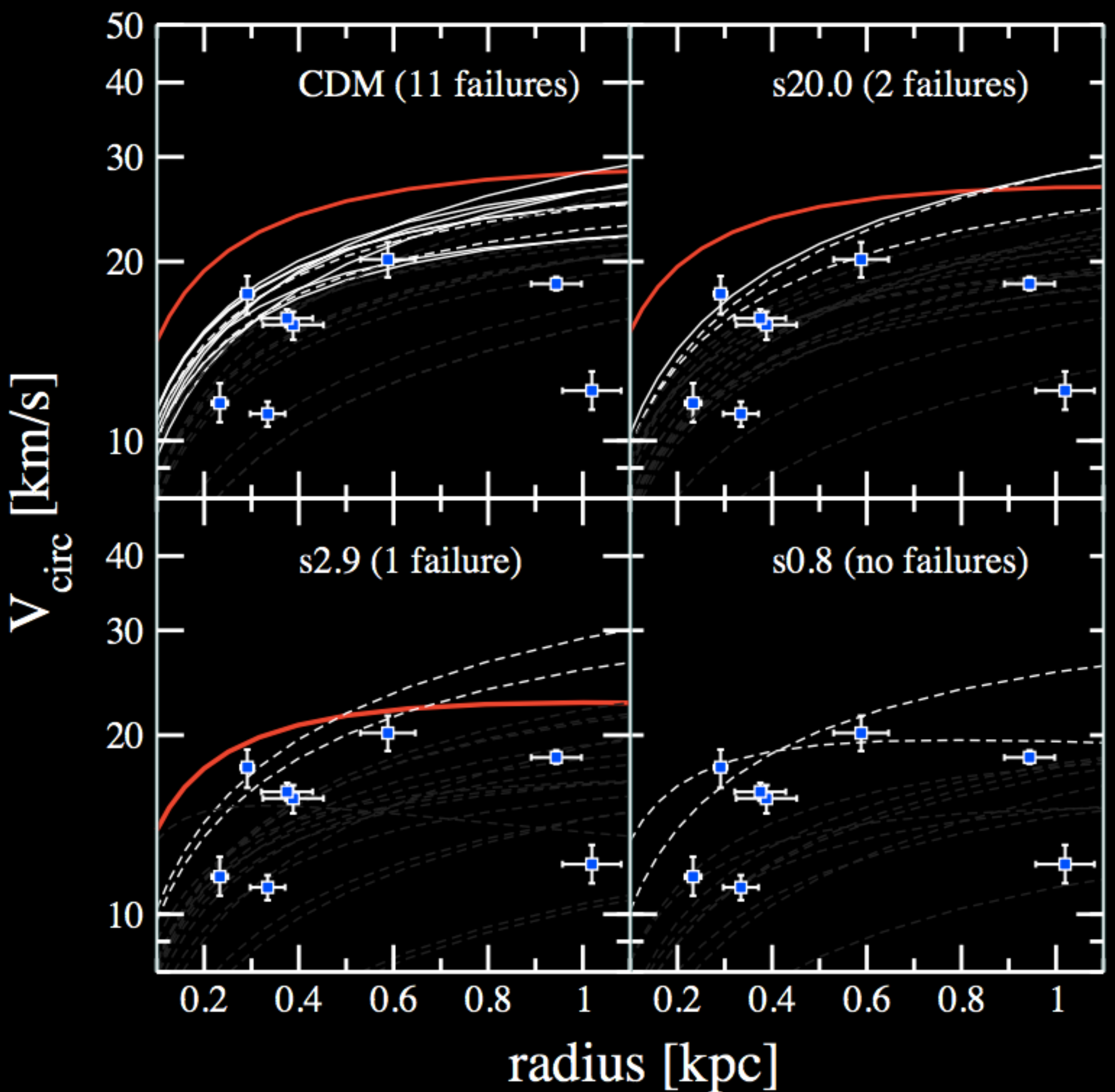
WDM Solution to All Local Group Galaxy Properties? [Boylan-Kolchin+ 2011]

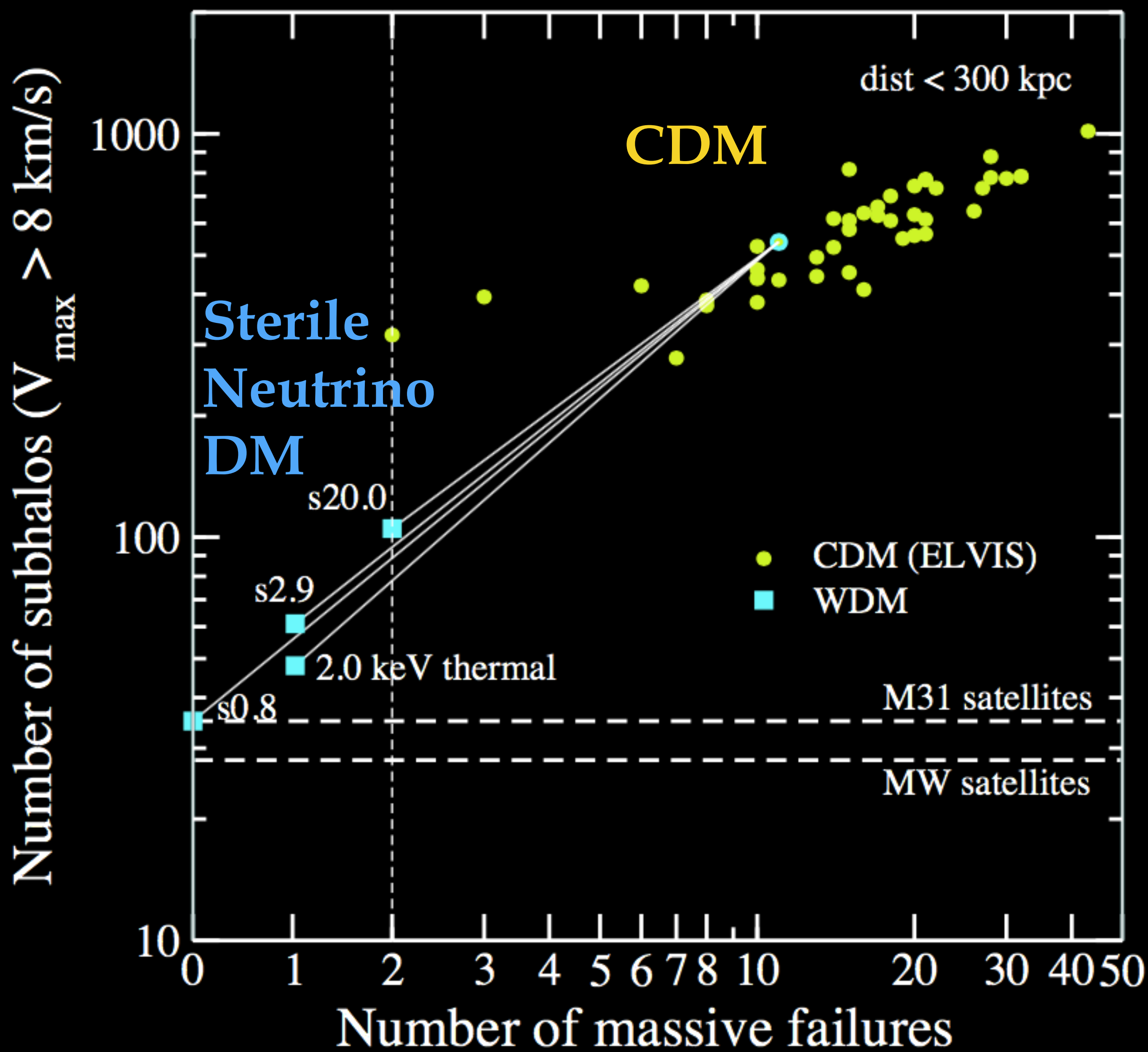


Anderhalden et al. arXiv:1212.2967

"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)

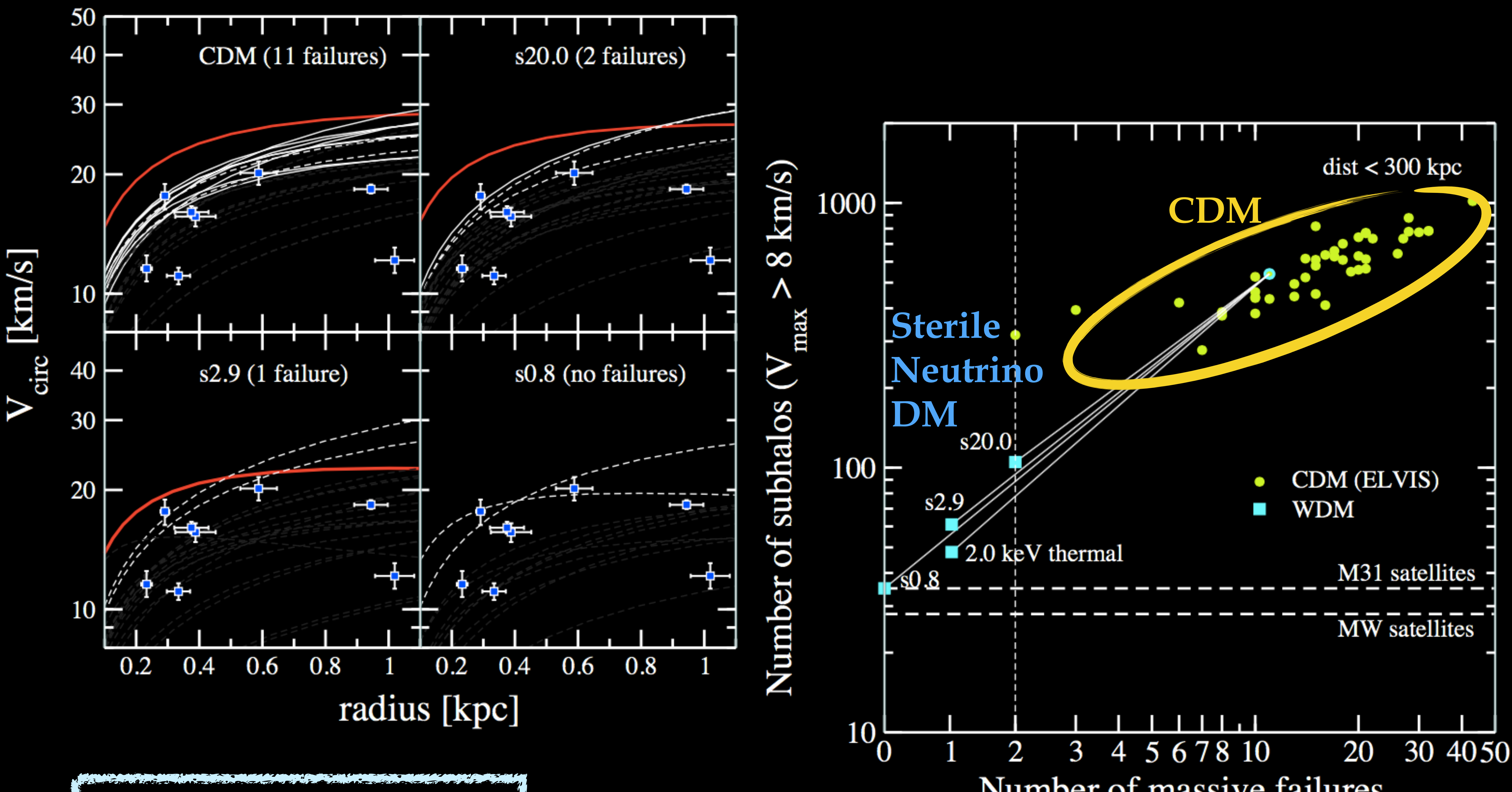
7 keV Alleviation of Too Big To Fail…





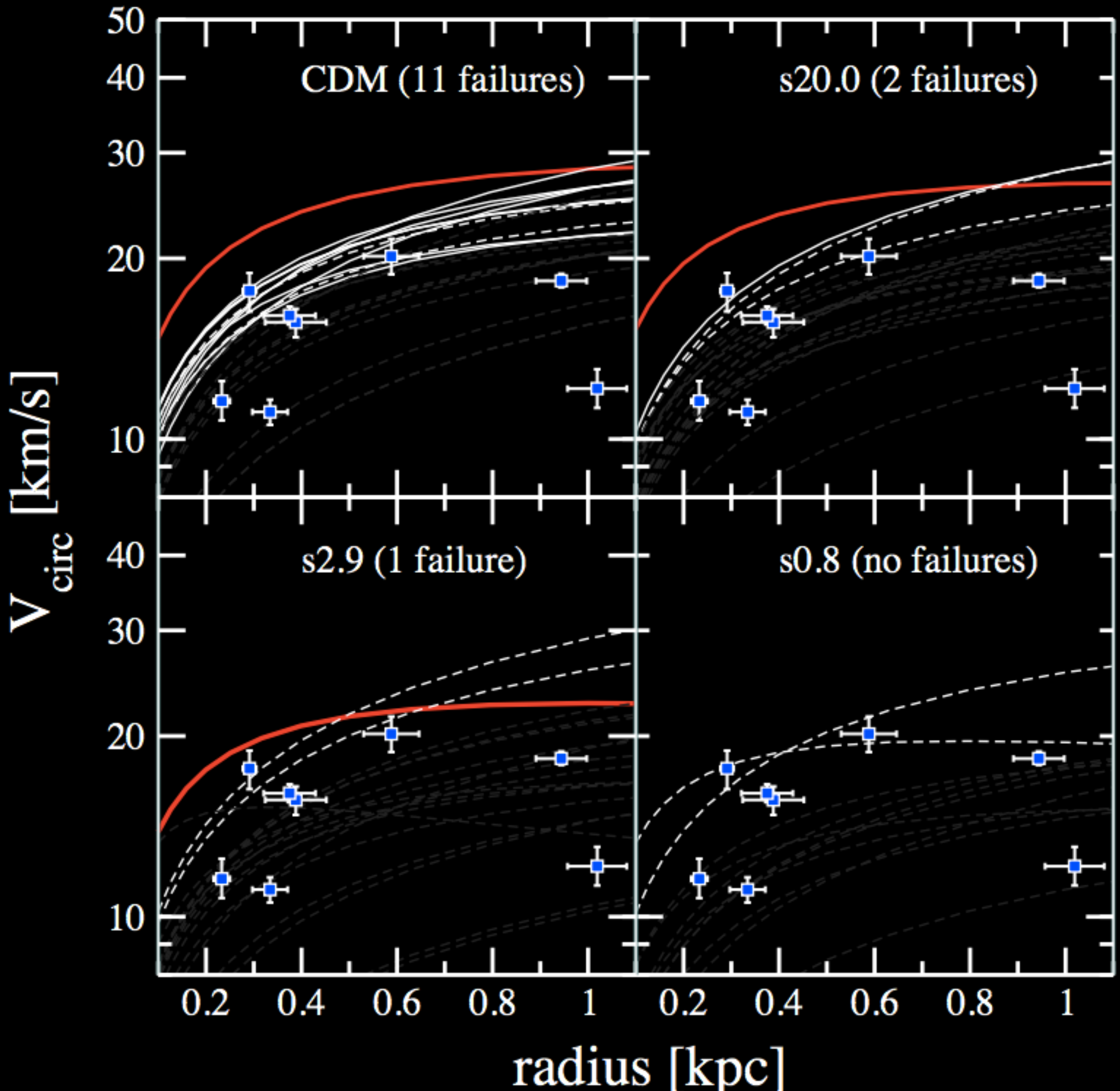
Horiuchi, Bozek, Abazajian+ (2015)

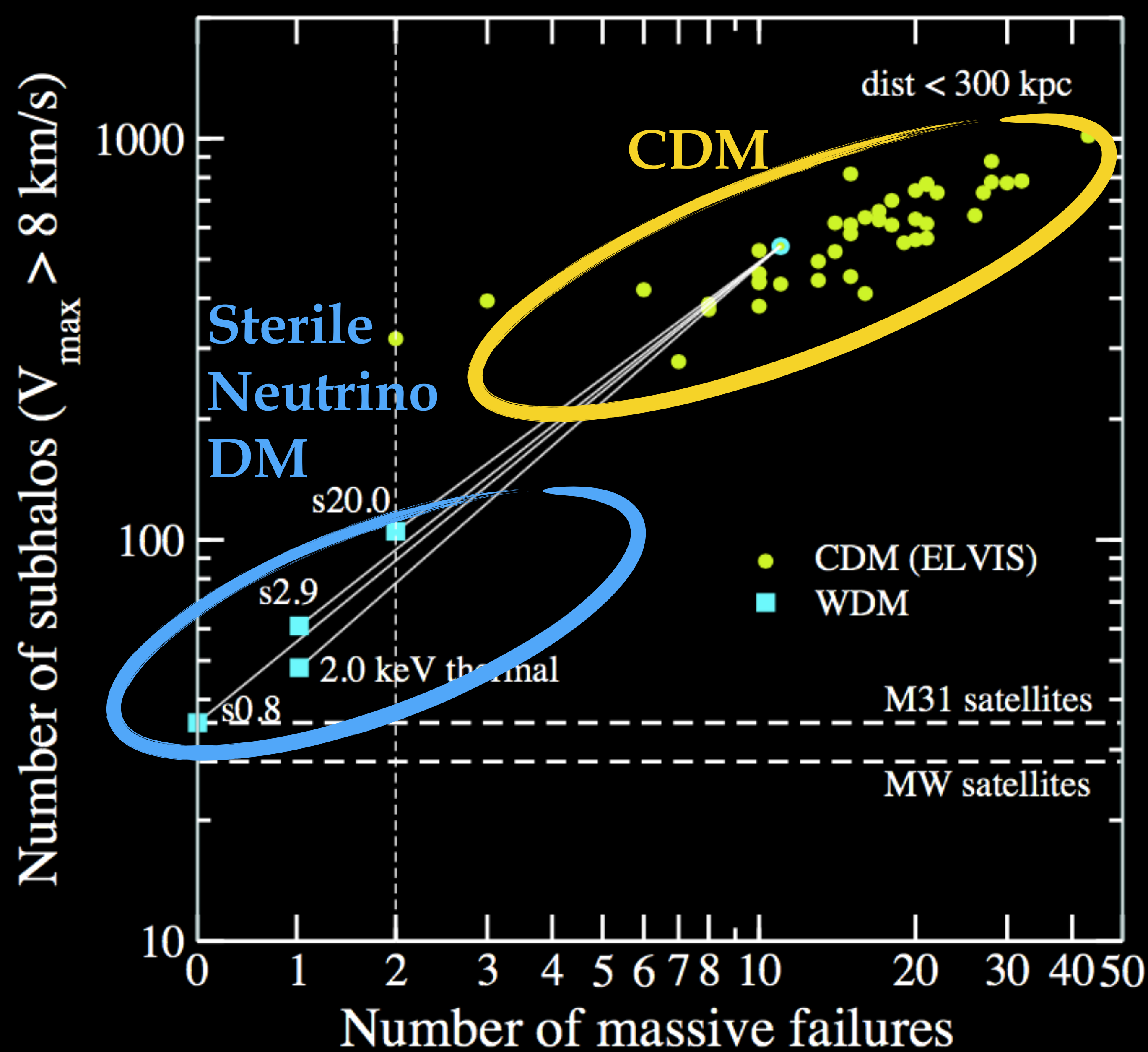
7 keV Alleviation of Too Big To Fail…



Horiuchi, Bozek, Abazajian+ (2015)

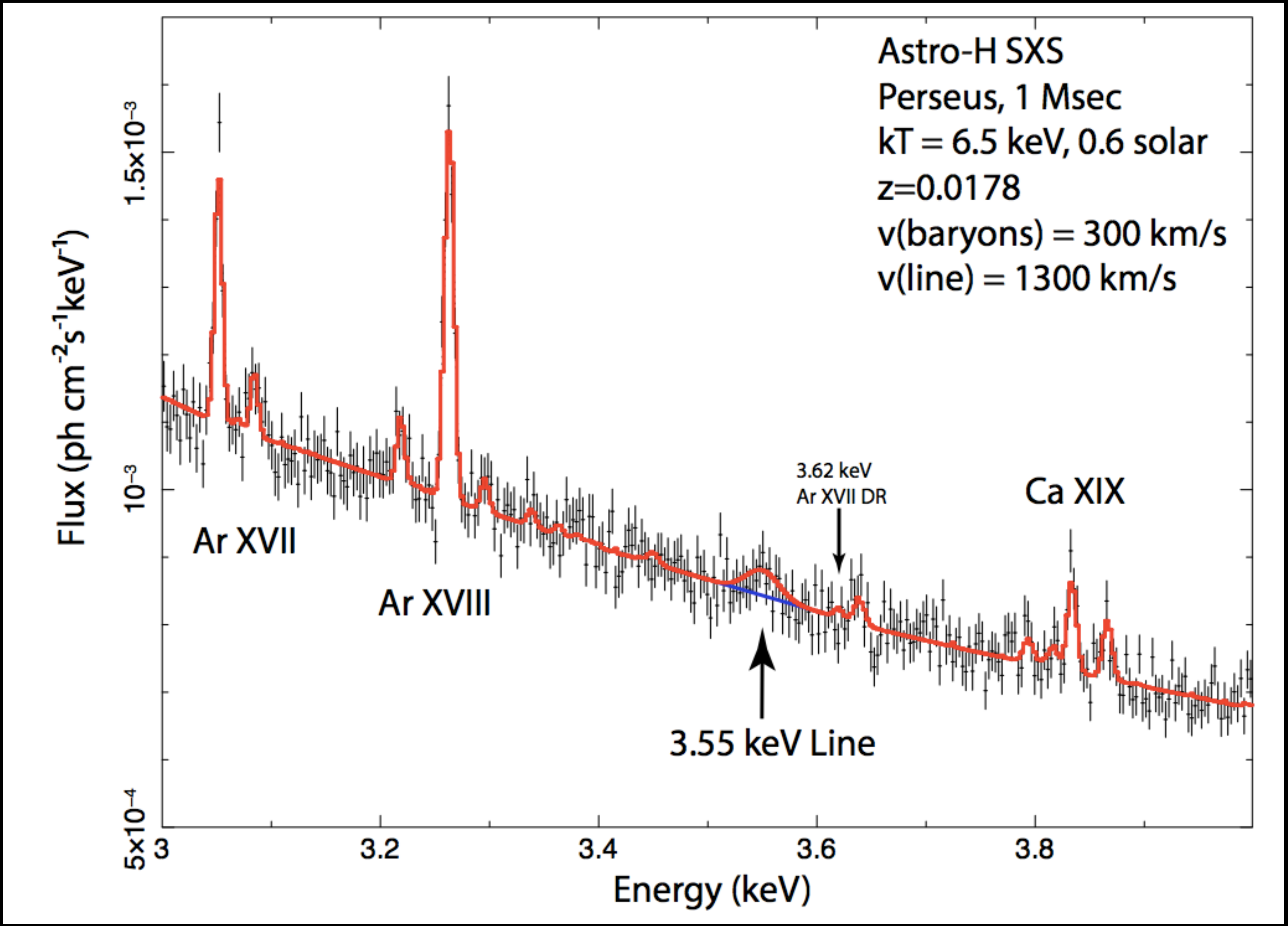
7 keV Alleviation of Too Big To Fail...





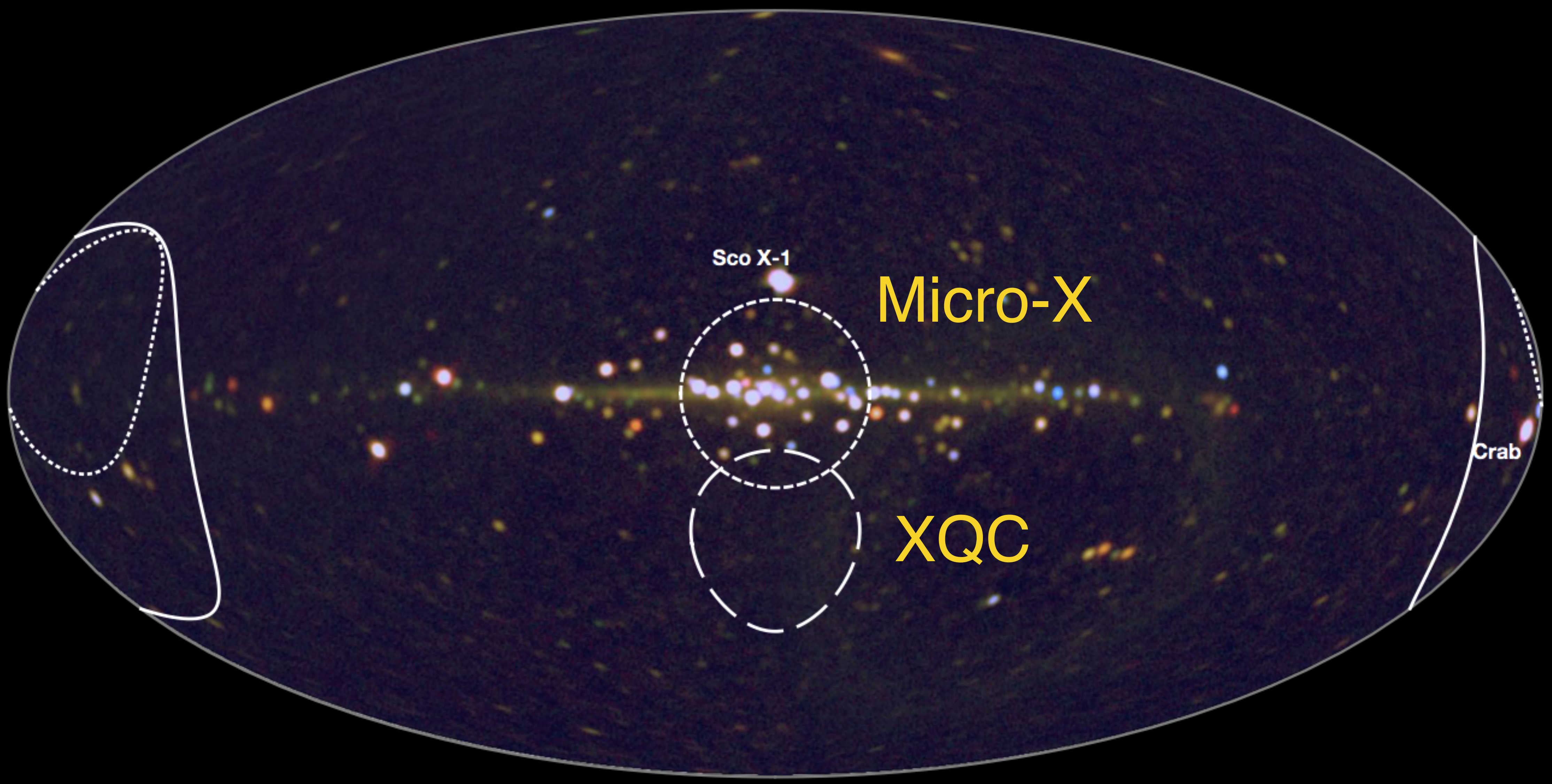
Horiuchi, Bozek, Abazajian+ (2015)

Confirmation: Astro-H launches early 2016



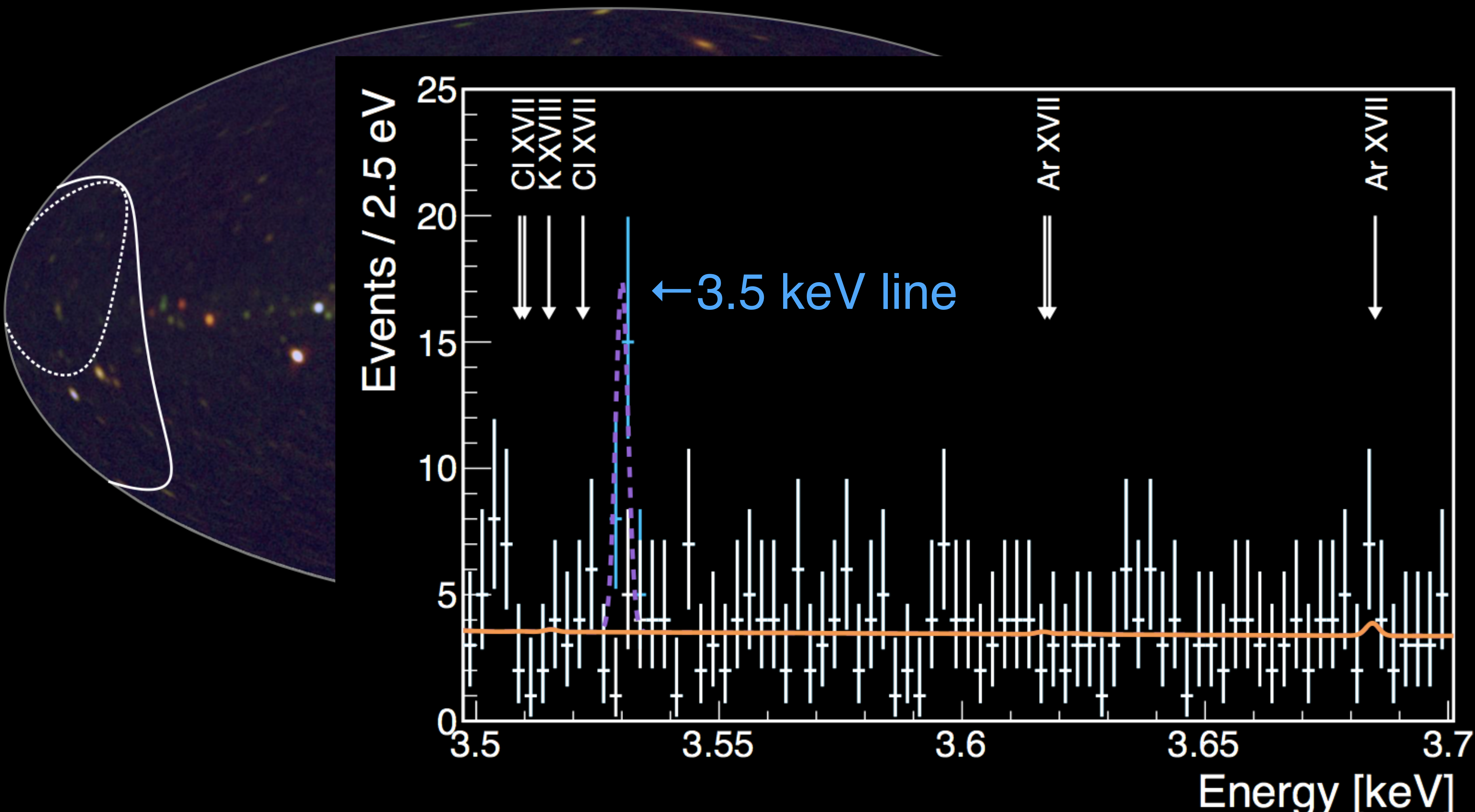
Bulbul et al. arXiv:1402.2301

Confirmation Wish List: #2 Sounding Rocket X-ray Observations: Micro-X & XQC



Figueroa-Feliciano+ 1506.05519

Confirmation Wish List: #2 Sounding Rocket X-ray Observations: Micro-X & XQC



Figueroa-Feliciano+ 1506.05519

Confirmation Wish List:
#3 Deep Local Group Observations

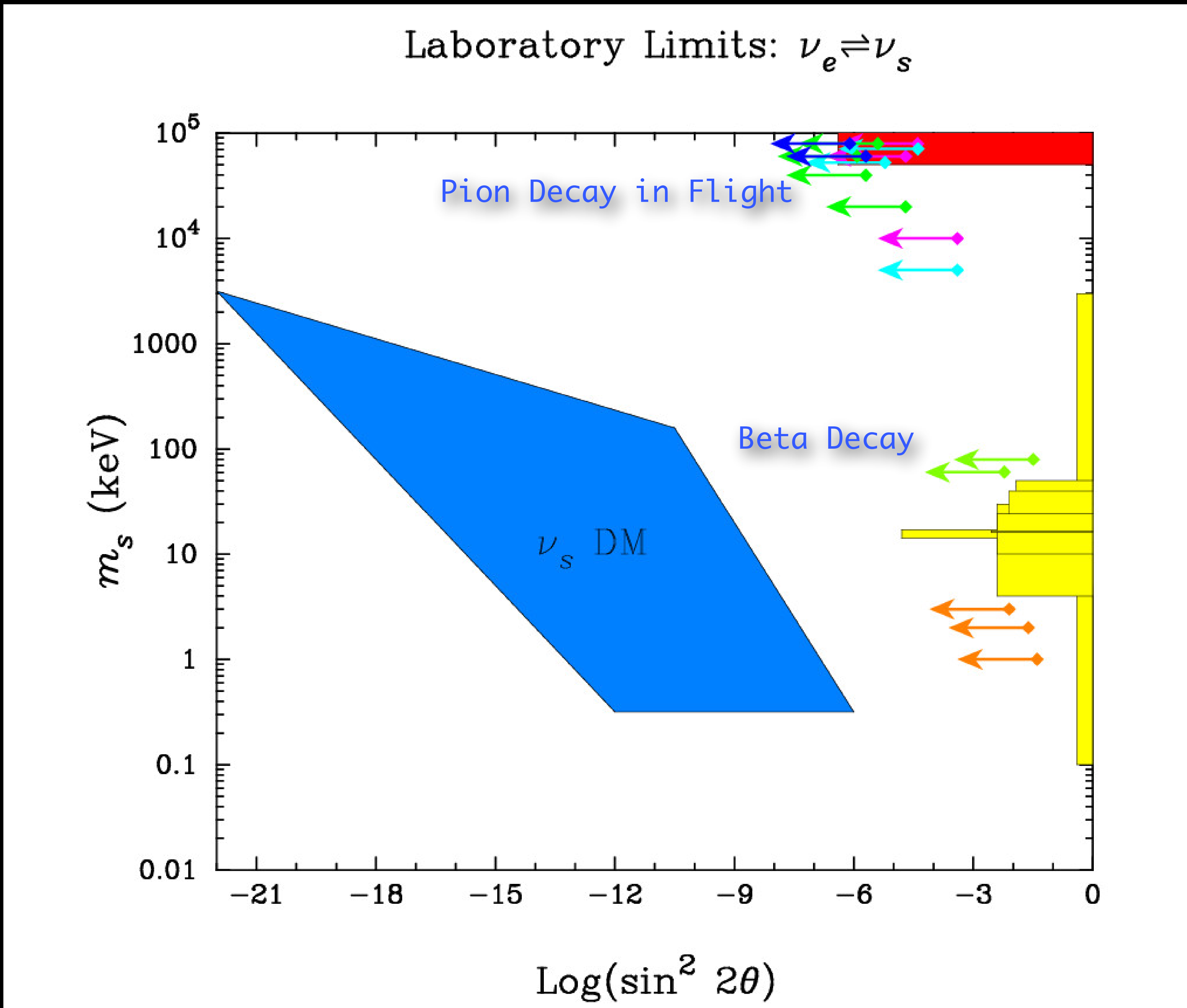
Next: Lots of Draco

Boyarsky et al.

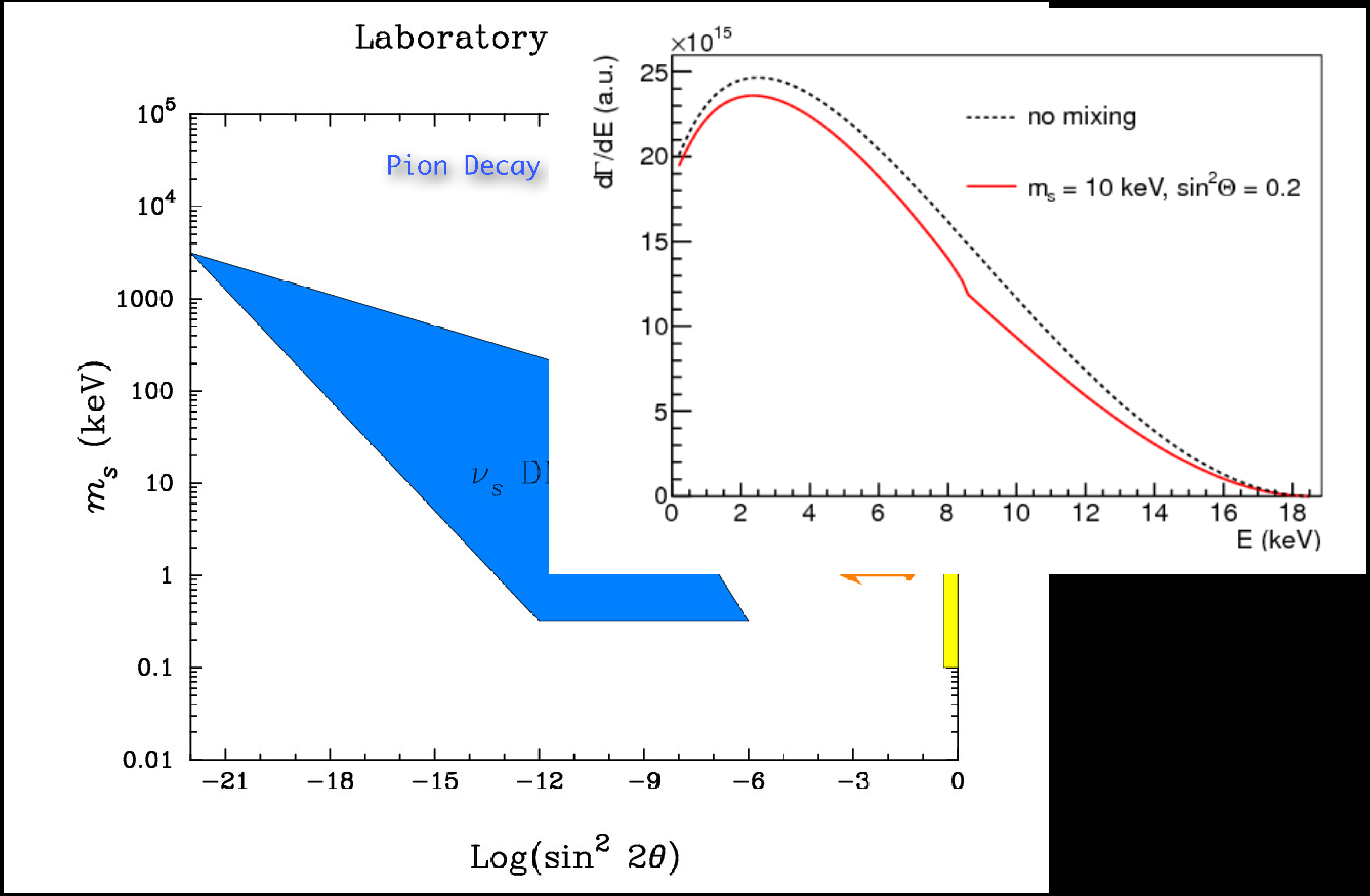
We have been ***awarded 1.4 Ms*** of XMM observations of the Draco dwarf galaxy this year

- Nearby, dark matter dominated object
- Highest expected signal of all dwarf galaxies (Geringer-Sameth+ 2014, Lovell+ 2014)
- Very gas-poor (***do not expect any atomic lines***)
- We will be able to **confirm or deny the DM origin** of the 3.5 keV line somewhere **in 2016**.

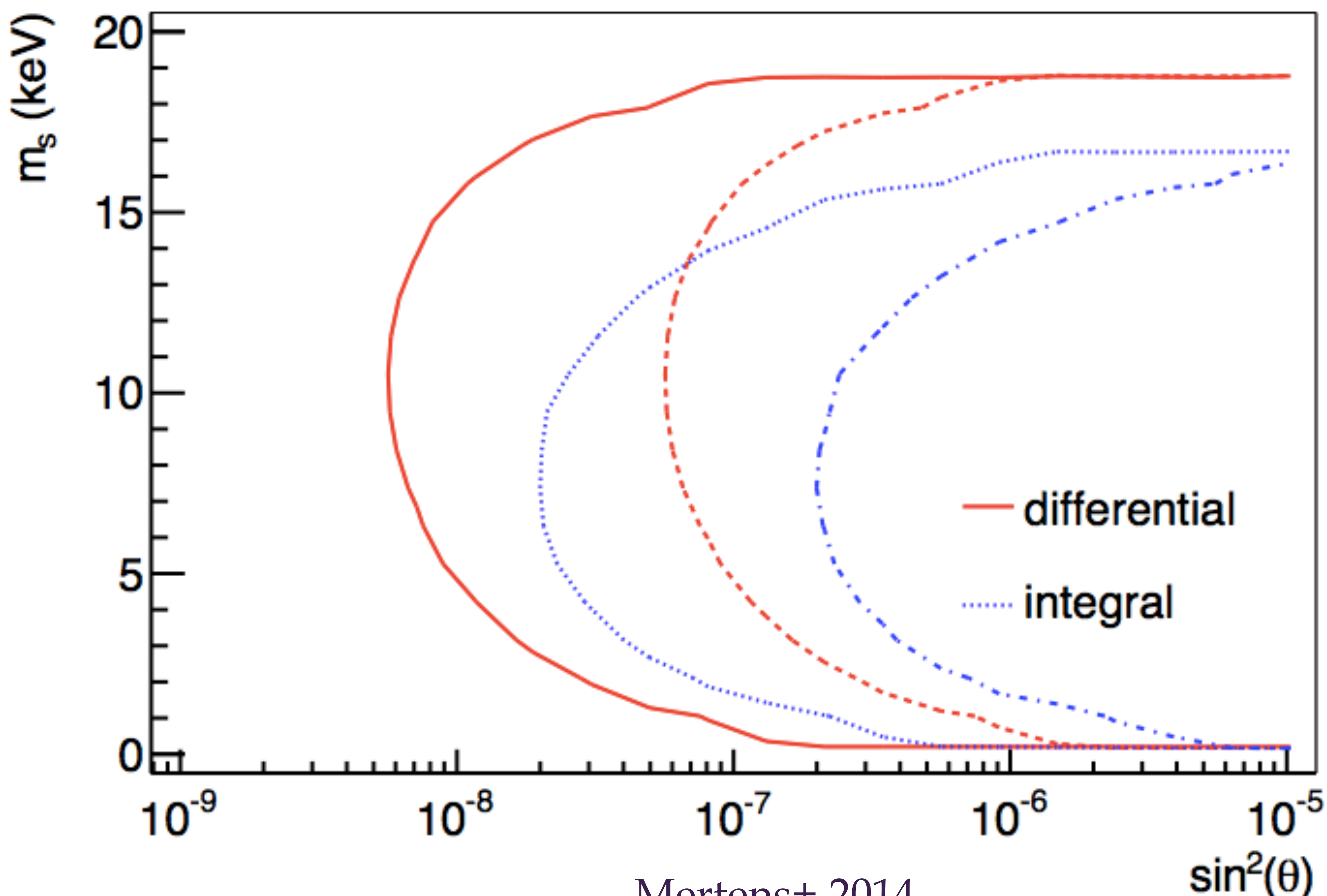
Confirmation Wish List #4: kink searches in nuclear β-decay



Confirmation Wish List #4: kink searches in nuclear β-decay

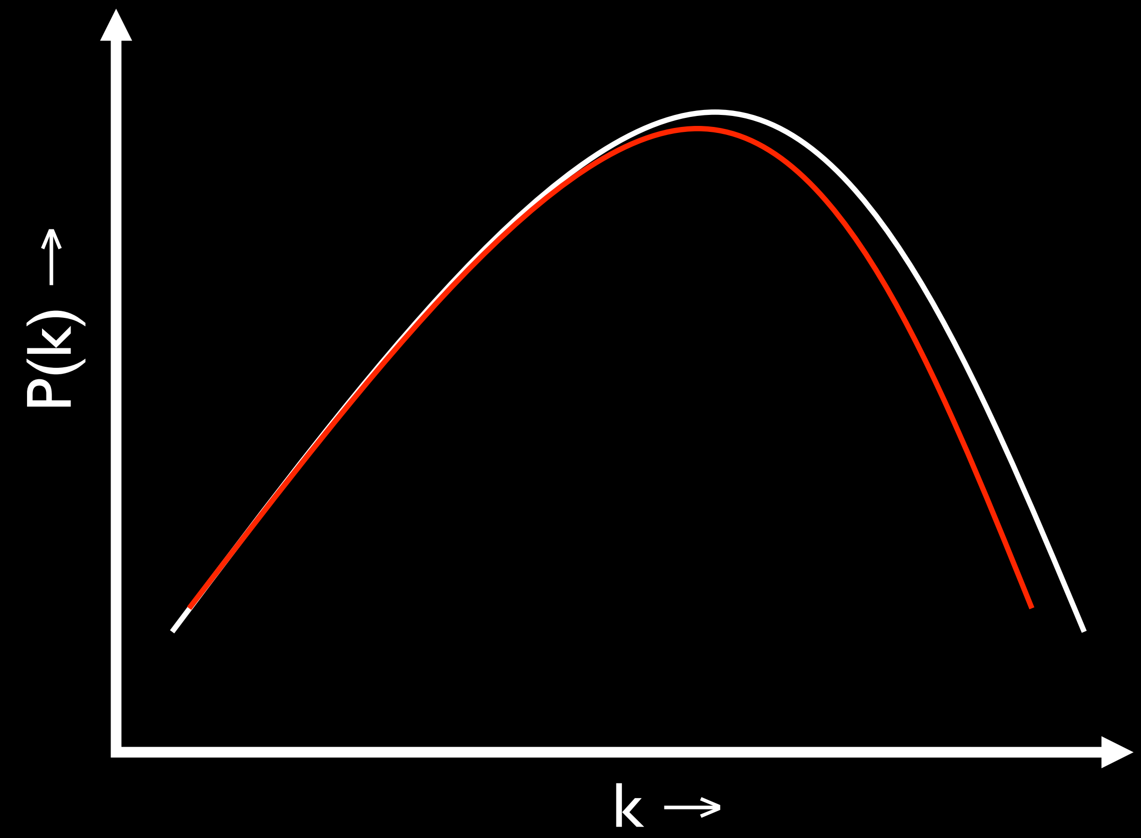


Confirmation Wish List #4: kink searches in nuclear β-decay



Mertens+ 2014

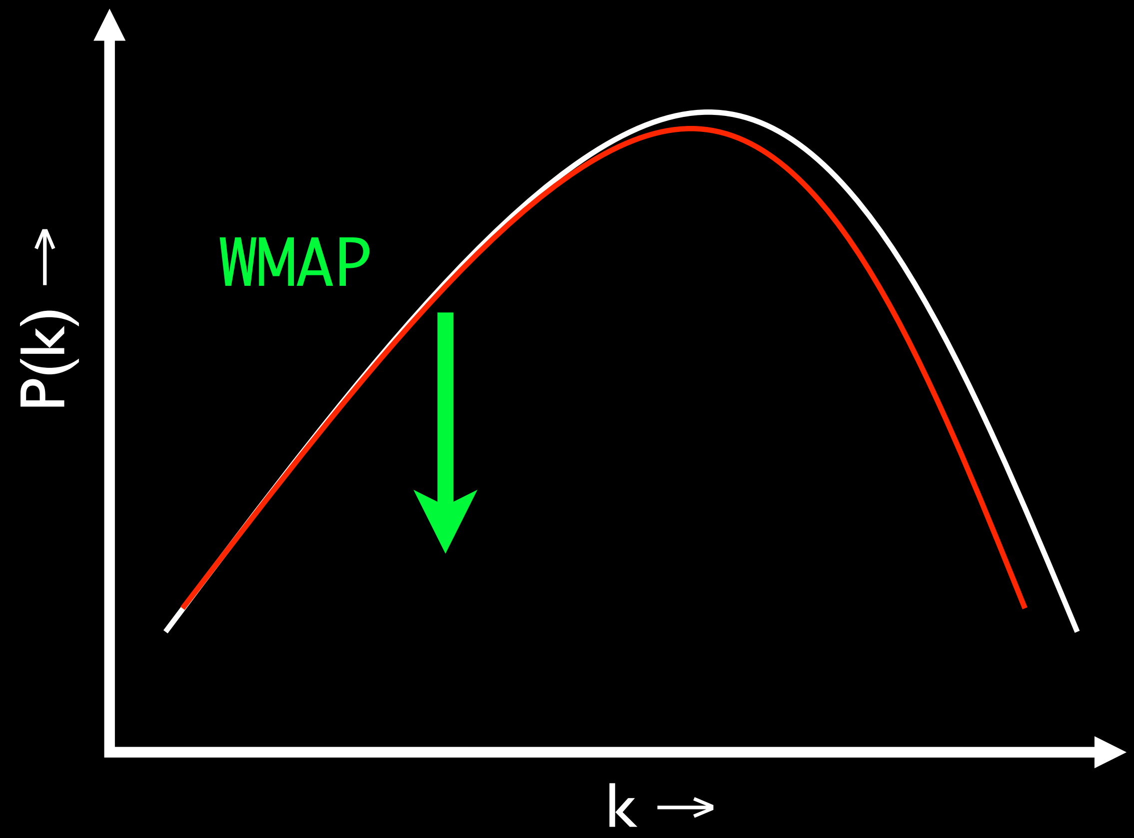
SDSS+WMAP3 Lyman-alpha Constraints (Seljak et al 2006)



SDSS+WMAP3 Lyman-alpha Constraints (Seljak et al 2006)

WMAP3:

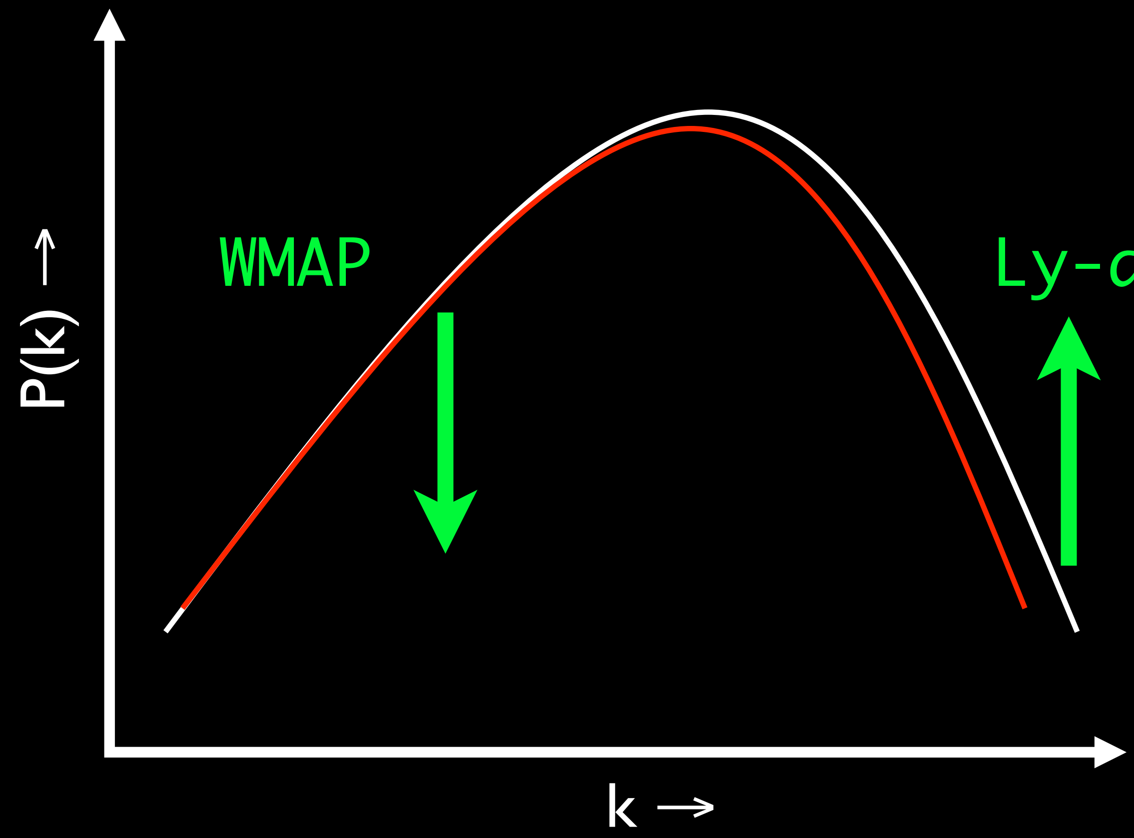
$$\sigma_8 = 0.74^{+0.05}_{-0.04}$$



SDSS+WMAP3 Lyman-alpha Constraints (Seljak et al 2006)

WMAP3:

$$\sigma_8 = 0.74^{+0.05}_{-0.04}$$



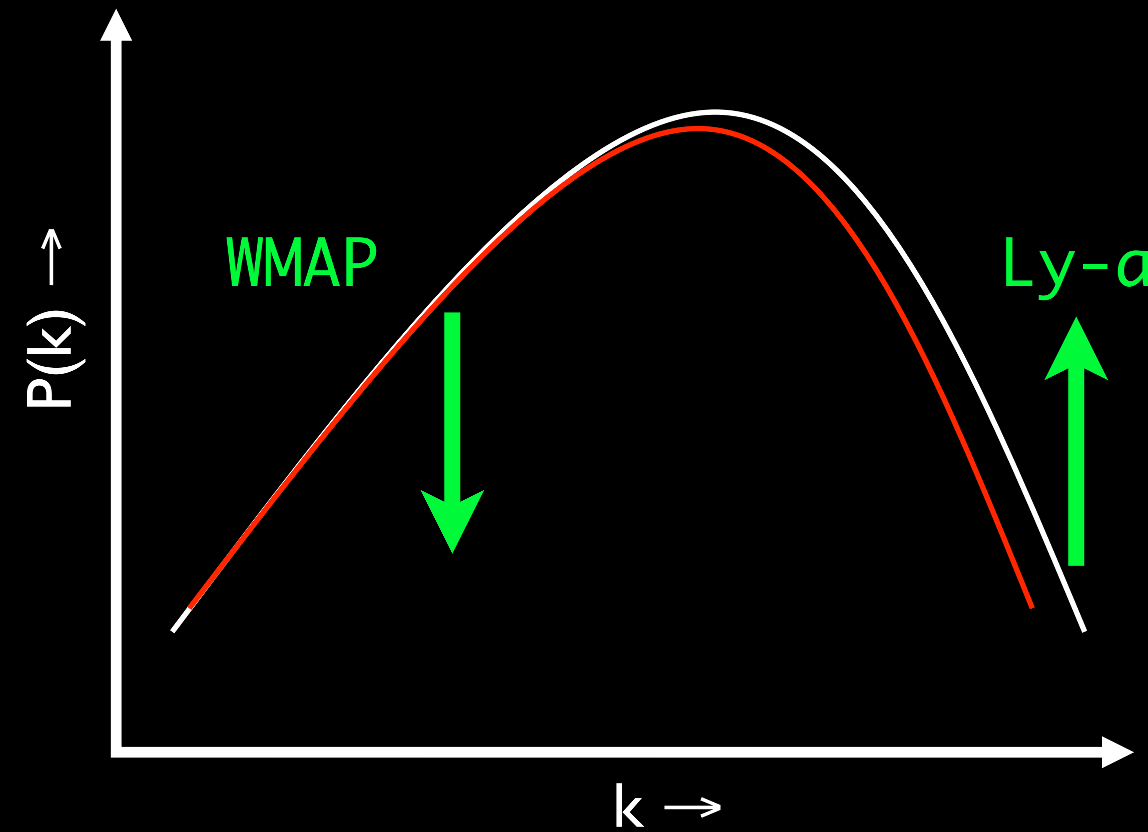
SDSS Ly-alpha (Seljak et al 2003):

$$\sigma_8 = 0.9^{+0.03}_{-0.03}$$

SDSS+WMAP3 Lyman-alpha Constraints (Seljak et al 2006)

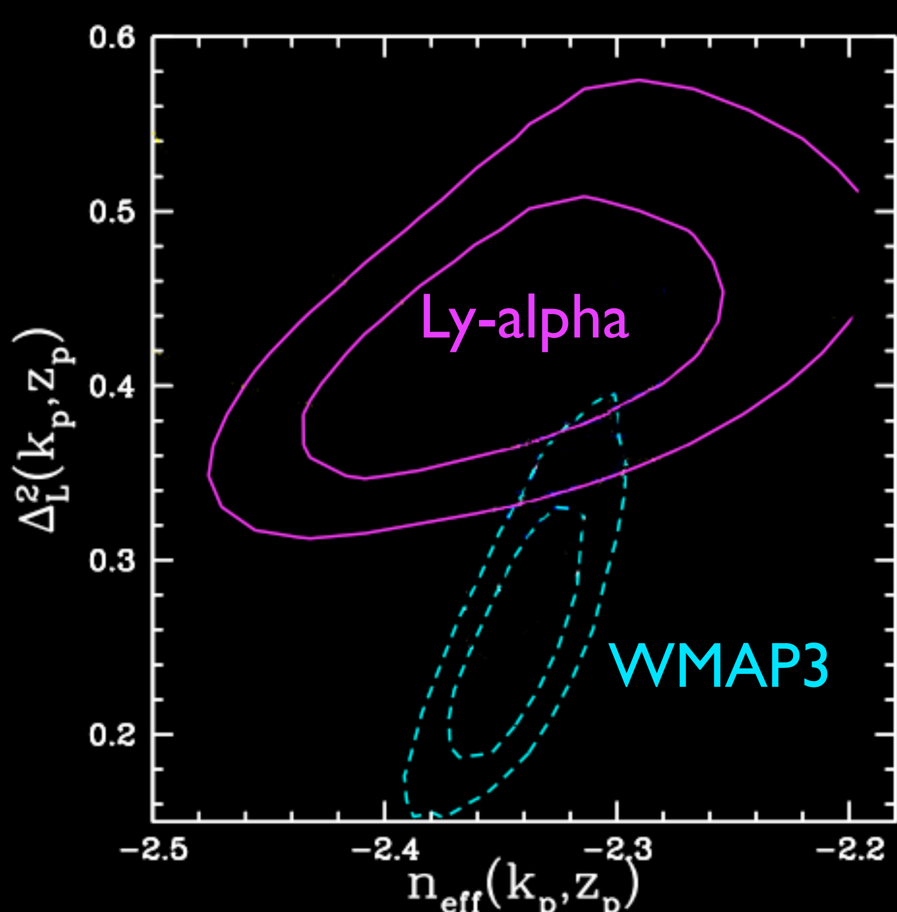
WMAP3:

$$\sigma_8 = 0.74^{+0.05}_{-0.04}$$



SDSS Ly-alpha
(Seljak et al
2003):

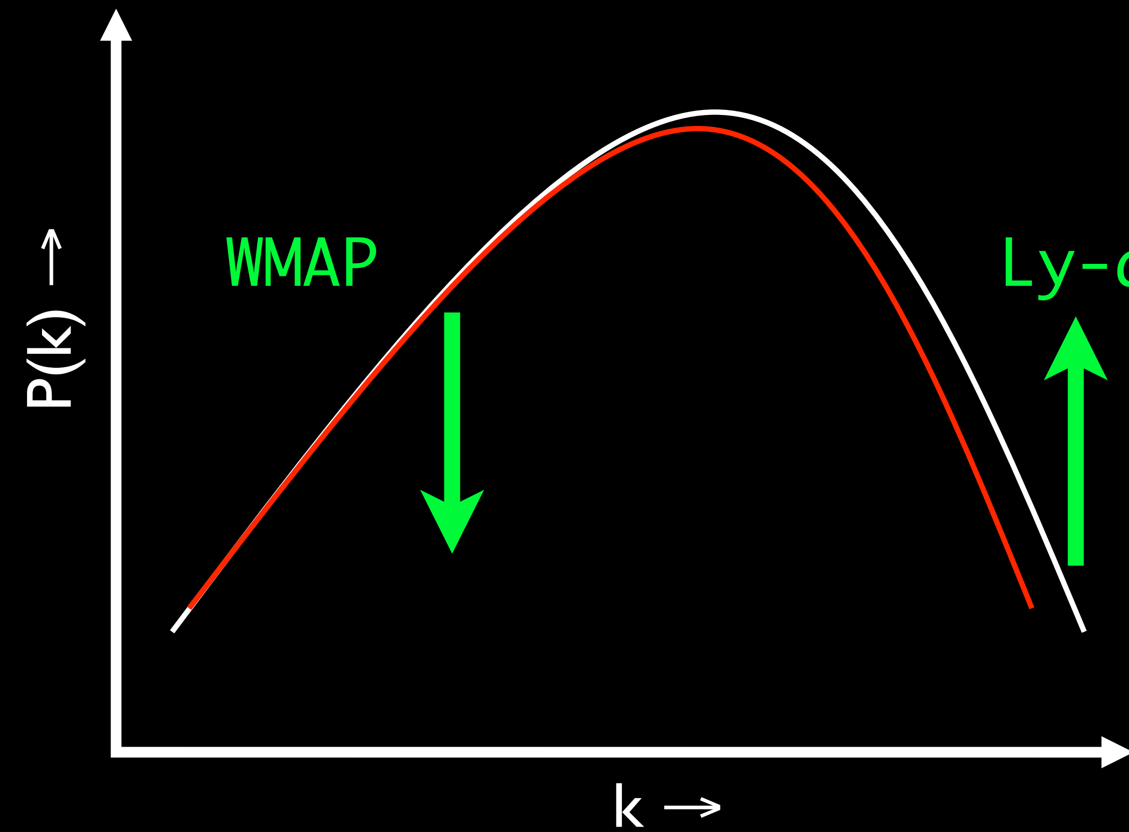
$$\sigma_8 = 0.9^{+0.03}_{-0.03}$$



SDSS+WMAP3 Lyman-alpha Constraints (Seljak et al 2006)

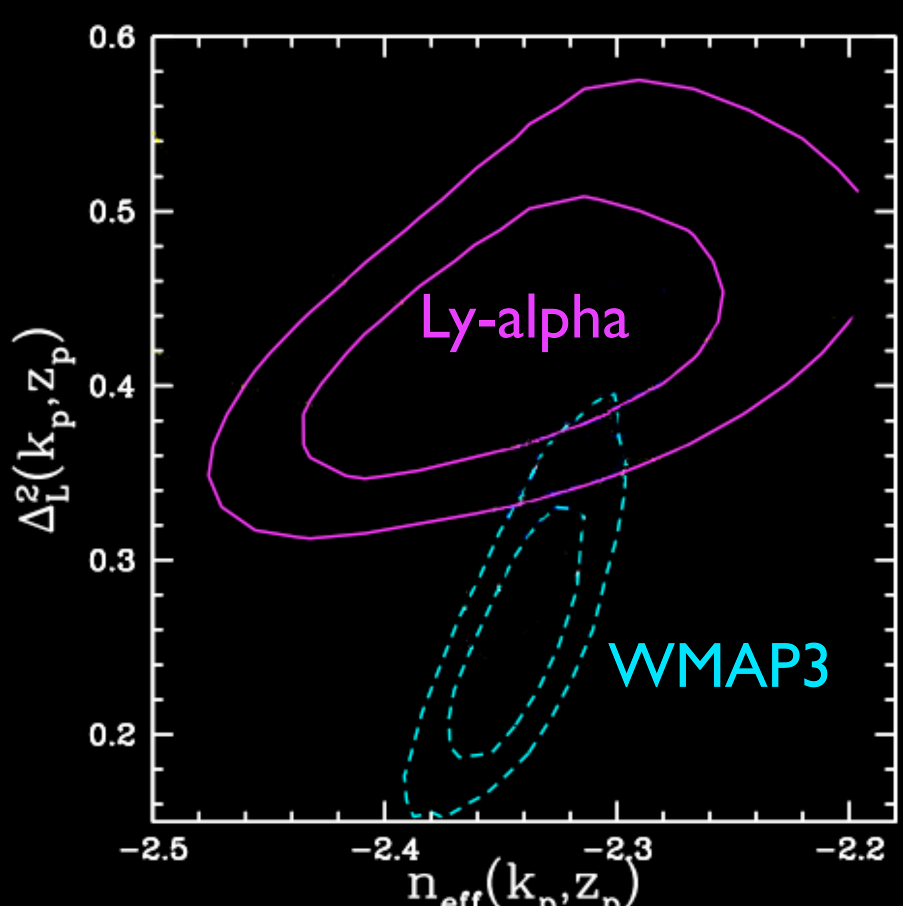
WMAP3:

$$\sigma_8 = 0.74^{+0.05}_{-0.04}$$



SDSS Ly-alpha (Seljak et al 2003):

$$\sigma_8 = 0.9^{+0.03}_{-0.03}$$



$N_\nu = 5.4^{+0.4}_{-0.6}$ Seljak et al. Lyα

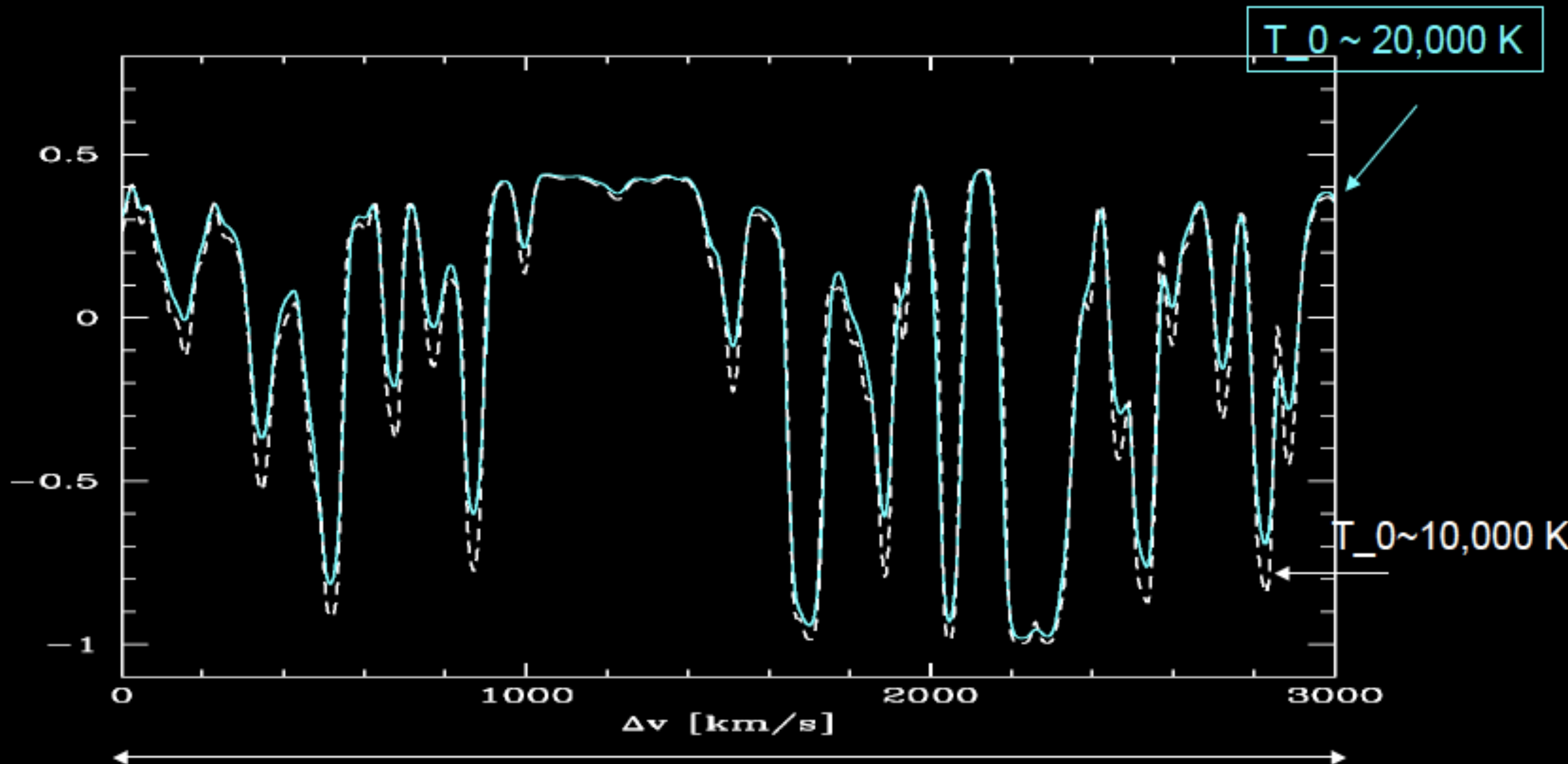
$N_\nu = 3.08^{+0.74}_{-0.68}$

BBN, Cyburt et al. 2004

$N_\nu = 3.04$ (standard model)

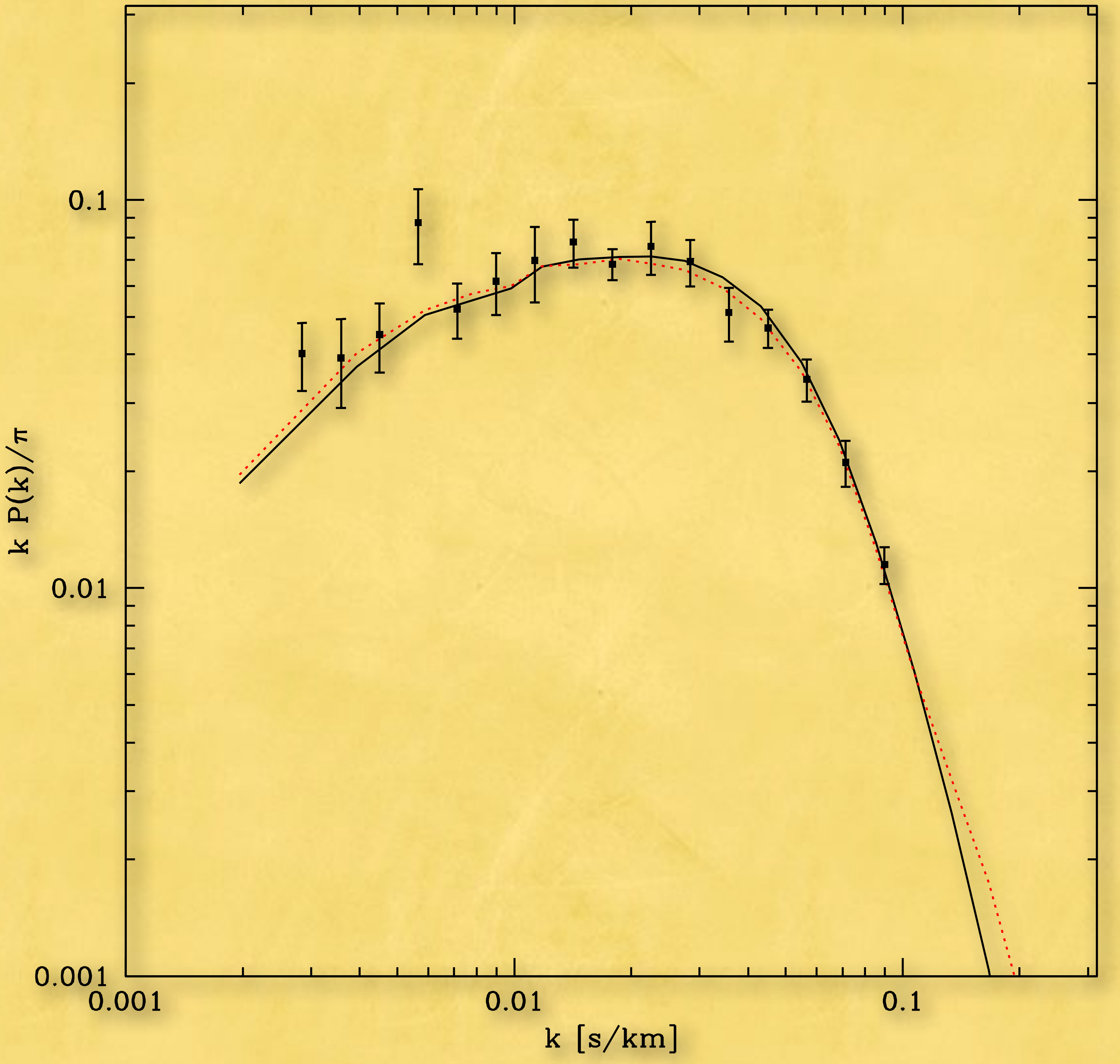
T impacts structure of HI Ly-a Forest

Doppler broadening and Jeans-smoothing….



Abazajian, Lidz, Ricotti, in prep.

T impacts structure of HI Ly-a Forest



Abazajian, Lidz, Ricotti, in prep.