Neutrino Mass from Cosmology & Astrophysics I

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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
  \[ P(k) \propto k^n \quad n \lesssim 1 \]
Measuring Large Scale Structure $P(k)$

$P(k) \left[ (h^{-1} \text{Mpc})^3 \right]$ vs. $k (h/\text{Mpc})$

- $\Sigma m_\nu = 0$
- $\Sigma m_\nu = 0.2 \text{ eV}$
- $\Sigma m_\nu = 0.7 \text{ eV}$
- $\Sigma m_\nu = 2 \text{ eV}$

Arrows indicate range from CMB to SDSS Ly-$\alpha$.
The Cosmological Matter Power Spectrum

\[ P(k) \propto k \]

Perturbations enter horizon:

\[ \delta \Phi_{\text{mat}} \text{ const} \]

Matter Domination

\[ \delta \Phi_{\text{rad}} \text{ decays} \]

Radiation Domination

\[ \rho_{\text{matter}} \propto a^{-3} \]

Matter Domination

\[ \rho_{\text{radiation}} \propto a^{-4} \]

Radiation Domination
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 $P(k)$ probe neutrinos?

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Is this a coincidence?
How does probe neutrinos?

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

(Assuming thermal equilibrium)

\[ \rho_{\nu} = \sum m_i n_{\nu_i} \]

\[ \Omega_{\nu} \approx \frac{\sum m_{\nu_i}}{93 \ h^2 \ \text{eV}} \]

\[ E^2 = p^2 + m^2 \]
The Primordial Spectrum:
CMB gives a **Precision** Determination at Large Scales

\[ P(k) = Ak^n \]

Planck Collaboration 2015:

\[
\ln (10^{10} A) = 3.094 \pm 0.034 \quad (1.1\%)
\]
\[
n = 0.9645 \pm 0.0049 \quad (0.51\%)
\]
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

\[ \frac{\Delta P(k)}{P(k)} = -8 \frac{\Omega_\nu}{\Omega_m} \]
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\( \Omega_m \) & Other Parameter Degeneracy

\[ P(k) \left[ (h^{-1} \text{ Mpc})^3 \right] \]

- \( \Omega_m = 0.31 \)
- \( \Omega_m = 0.27 \)
- \( \Omega_m = 0.23 \)

\( \Omega_m \)

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

$P(k)$ \left[ (h^{-1} \text{Mpc})^3 \right]$ vs. $k$ (h/Mpc)
$\Sigma m_{\nu}$: The March of Time
$\Sigma m_\nu$: The March of Time

$[eV]$ (95% CL)
$\Sigma m_\nu$: The March of Time
$\Sigma m_\nu$: The March of Time

$\sum m_\nu$ (eV) (95\% CL)

2003
$\Sigma m_\nu$: The March of Time
$\Sigma m_\nu$: The March of Time

$\Sigma m_\nu$ [eV] (95% CL)

2dFGRS

2003

2006
$\Sigma m_\nu$: The March of Time

$\Sigma m_\nu$ [eV] (95% CL)

2dFGRS
SDSS $P_s +$ WMAP1

2003 2006
$\Sigma m_\nu$: The March of Time

- 2dFGRS
- SDSS $P_\delta$ + WMAP 1
- WMAP3 + LSS

$\sum m_\nu$ [eV] (95% CL)

2003 - 2006
$\Sigma m_\nu$: The March of Time

- 2003: 2dFGRS
- 2006: SDSS $P_g$ + WMAP 1
- 2006: WMAP 3 + LSS

$\Sigma m_\nu$ [eV] (95% CL)
$\Sigma m_\nu$: The March of Time

- 2dFGRS
- SDSS $P_s + \text{WMAP 1}$
- WMAP 7 alone
- WMAP 7 + SDSS LRG BAO

$m_\nu$ [eV] (95% CL)

2003 2006 2010
$\Sigma m_\nu$: The March of Time

- WMAP 7 alone
- WMAP 3 + LSS
- WMAP 7 + SDSS LRG BAO
- 2dFGRS, SDSS $P_s$ + WMAP 1

$\sum m_\nu$ [eV] (95% CL)

2003 2006 2010 2012
$\Sigma m_{\nu}$: The March of Time

- WMAP 1
- WMAP 3 + LSS
- WMAP 7 + SDSS LRG BAO
- SDSS BOSS + WMAP 7

For 95% CL, the constraints are:

- 2003: WMAP 7 alone
- 2006: 2dFGRS
- 2010: SDSS P$_R$ + WMAP 1
- 2012: SDSS BOSS + WMAP 7
$\Sigma m_\nu$: The March of Time

- 2003: 2dFGRS
- 2006: SDSS $P_\delta + \text{WMAP} 1$
- 2010: WMAP 3 + LSS
- 2010: WMAP 7 alone
- 2012: WMAP 7 + SDSS LRG BAO
- 2012: SDSS BOSS + WMAP 7
- 2012: WMAP 9 + BAO

$\sum m_\nu \, [\text{eV}]$ (95% CL)
$\Sigma m_\nu$: The March of Time

- 2dFGRS
- SDSS $P_s$ + WMAP 1
- 2003
- WMAP 7 alone
- WMAP 7 + SDSS LRG BAO
- 2010
- WMAP 3 + LSS
- WMAP 9 + BAO
- 2012
- SDSS BOSS + WMAP 7
- 2013
- WMAP 9 + BAO

$\Sigma m_\nu$ [eV] (95% CL)
$\Sigma m_\nu$: The March of Time

- WMAP 3 alone (2006)
- WMAP 7 alone (2010)
- WMAP 7 + SDSS LRG BAO (2010)
- SDSS BOSS + WMAP 7 (2010)
- ACT + WMAP 7 + BAO (2012)
- WMAP 9 + BAO (2012)
- SDSS P_e + WMAP 1

$\Sigma m_\nu$ [eV] (95% CL)
$\sum m_\nu$: The March of Time

- SDSS $P_g$ + WMAP 1
- WMAP 3 + LSS
- WMAP 7 + SDSS LRG BAO
- WMAP 7
- SDSS BOSS + WMAP 7
- WMAP 9 + BAO
- ACT + WMAP 7 + BAO
- Planck + BAO


$\sum m_\nu$ [eV] (95% CL)
\[ \sum m_\nu: \text{The March of Time} \]

- 2dFGRS
- SDSS \( P_g + \text{WMAP 1} \)
- WMAP 7 alone
- WMAP 3 + LSS
- WMAP 7 + SDSS LRG BAO
- SDSS BOSS + WMAP 7
- WMAP 9 + BAO
- ACT + WMAP 7 + BAO
- Planck + BAO

\[ \sum m_\nu [\text{eV}] \ (95\% \ CL) \]

- 2003
- 2006
- 2010
- 2012
- 2013

Oscillations
\[ \Sigma m_\nu: \text{The March of Time} \]

- 2dFGRS
- SDSS $P_k + WMAP 1$
- WMAP 7 alone
- WMAP 3 + LSS
- WMAP 7 + SDSS LRG BAO
- SDSS BOSS + WMAP 7
- WMAP 9 + BAO
- ACT + WMAP 7 + BAO
- Planck + BAO
- Oscillations

Years:
- 2003
- 2006
- 2010
- 2012
- 2013
- 2015

Energy [eV] (95% CL):
- 1
- 2
\[ \Sigma m_\nu: \text{The March of Time} \]

- 2003: 2dFGRS, SDSS $P_s + WMAP 1$
- 2006: WMAP 3 + LSS
- 2010: WMAP 7 alone
- 2012: WMAP 7 + SDSS LRG BAO
- 2013: SDSS BOSS + WMAP 7
- 2015: WMAP 9 + BAO
- 2015: Planck + BAO + SNe + $H_0$
- 2015: Oscillations

\[ \Sigma m_\nu [eV] \text{ (95\% CL)} \]
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 $N_{\text{eff}}$

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

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

Perturbations enter horizon:

\[\rho_{\text{matter}} \propto a^{-3}\]

Matter Domination $[\delta \Phi_{\text{mat}} \text{ const}]$

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Radiation Domination $[\delta \Phi_{\text{rad}} \text{ decays}]$
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]
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
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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 $\Omega_b/\Omega_m$.
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.

\[
D_V(z) = \left( (1+z)^2 D_A(z)^2 \frac{cz}{H(z)} \right)^{1/3}
\]
BAO measurements

Real space

$z=0.32$
LOWZ DR11

$z=0.57$
CMASS DR11

$\xi_{\perp}(s)$
$\xi_{\parallel}(s)$
$\Lambda$CDM

Fourier space

SDSS-II LRGs

BOSS CMASS

$log_{10} P(k) / P(k)_{\text{smooth}}$

$k / h \text{ Mpc}^{-1}$
BAO in \( k \)-space: neutrino mass constraints

\[ \Sigma m_\nu < 110 \text{ meV (95%)} \]

\[ \Sigma m_\nu = 0.11 \text{ eV} \]

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 flux power spectrum measured here→
The Onset of Nonlinearity at Small Scales
Lyman-alpha Forest Constraints on $m_\nu$

$\Sigma m_\nu < 170$ 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 $T_0 \approx 35000$ K

Viel & Haehnelt (2005); Viel et al 2006
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?

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**Planck13+WP+highL+BAO:**

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Planck Collab. 2013
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South Pole Telescope CMB + SPT SZ Clusters + WMAP 7 + $H_0$
(Hou et al. 2012):

$$0.10 \text{ eV} \leq \sum m_{\nu_i} \leq 0.54 \text{ eV}$$
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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:
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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:

$$\Sigma m_{\nu_i} = 0.39 \pm 0.11 \text{ eV}$$
Combining Planck 2013 CMB + Clusters:
adding sterile neutrinos resolves tension from large and small scales, sterile $m_s$ detected at $3.5\sigma$
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Combining Planck 2013 CMB + Clusters:
adding sterile neutrinos resolves tension from large and small scales, sterile $m_s$ detected at $3.5\sigma$

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

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

Wyman et al PRL 2013
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 $3.5\sigma$

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

Wyman et al PRL 2013

To make this signal go away, systematic error must by three times current estimates.
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.

Wyman et al PRL 2013
CMB+BAO or CMB+Lensing: Signs of Neutrino Mass?

Small scale amplitude $\sigma_8$ vs. matter density $\Omega_m$

Beutler+ 2014: Planck 2013 + LSS

$\Sigma m_\nu = 0.36 \pm 0.10$ eV  
$\rightarrow$ WMAP9, BAO, Lensing
Neutrinoless Double Beta Decay & Cosmology: if you show cosmo constraints, show tension

Fig: Wilkerson, this morning
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Planck Collaboration 2015: $N_{\text{eff}}$ 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”

\[ \Sigma m_\nu < 0.53 \text{ eV (95%)}, \text{ but maximum } L \text{ is nonzero} \]
→ 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

\[ \nu_1 \rightarrow \nu_2 \rightarrow \nu_3 \rightarrow \nu_4 \rightarrow \nu_5 \]

\[ \delta m^2_{\text{atm}} \]

\[ \delta m^2_{\text{sol}} \]
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\[ \delta m^2_{\text{atm}} \]

\[ \delta m^2_{\text{sol}} \]

\[ \nu_1 \]

\[ \nu_2 \]

\[ \nu_3 \]

\[ \nu_4 \]

\[ \nu_5 \]

\[ \sigma_8(\Omega_m / 0.25)^{0.47} \]

\[ \Lambda \text{CDM} \]

\[ \Lambda \text{CDM} + 2\nu_s \]

SALT2 SNe

MLCS

X-ray Clusters
Deviations from a power law primordial power spectrum in the CMB?

Aslanyan, Price, Abazajian & Easther 2014

\[ P(k) \propto k \]
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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: \( w \), \( N_{\text{eff}} \), modified gravity… e.g. degenerate nonzero laboratory \( m_\beta \) or \( m_{\beta\beta} \) with \( \Sigma m_\nu \approx 60 \text{ meV} \) from cosmology could indicate \( w < -1 \).
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

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\[
\Rightarrow \sigma (\sum m_\nu) \lesssim (1\%/8) \times \Omega_m \ (93h^2 \ eV)
\]

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\[ \Omega_\nu \approx \frac{\sum m_{\nu_i}}{93 \ h^2 \ \text{eV}} \]

\[ \implies \sigma (\sum m_\nu) \lesssim \frac{(1\%/8)}{\Omega_m} \times (93h^2 \ \text{eV}) \]

\[ \implies \sigma (\sum m_\nu) \lesssim 20 \ \text{meV} \]
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

\[ \Omega_\nu \approx \frac{\sum m_{\nu_i}}{93 \times 10^{-2} \text{ eV}} \]

\[ \Rightarrow \sigma (\sum m_\nu) \lesssim (1\%/8) \times \Omega_m \left(93h^2 \text{ eV}\right) \]

\[ \Rightarrow \sigma (\sum m_\nu) \lesssim 20 \text{ meV} \]

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)

Growth:

\( w \) & \( m_\nu \) degeneracy

Geometry

Planck+EUCLID

\( \sigma(\Sigma m_\nu) = 11 \) meV (7 param.)

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

Abazajian & Dodelson (2002)

Hamman, Hannestad, Wong (2012)
Example Forecast sensitivities: Planck + LSST

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

\[ \sigma \left( N_{\text{eff}} \right) = 0.078 \]
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
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 $\Sigma m_\nu = 0.36 \pm 0.10 \text{ eV}$; however, what is considered to be the most robust data has no such signal.

• Robust current claimed constraints are at $\Sigma m_\nu < 230 \text{ meV (95%)}; N_{\text{eff}} = 3.15\pm0.23$ (Planck Collab. 2015: CMB+BAO)

• Strong claims from Lyman-alpha forest (systematics) $\Sigma m_\nu < 170 \text{ meV (95%)}$ (BOSS Collab. 2015: CMB+BAO+Ly$\alpha$)

• Far future: Planck + LSST lensing, galaxies: $\sigma(\Sigma m_\nu) = 23 \text{ meV}; \sigma(N_{\text{eff}}) = 0.078$
CMB-S4 and DESI galaxy survey: $\sigma(\Sigma m_\nu) = 15 \text{ meV} \& \sigma(N_{\text{eff}}) = 0.016$
latter provides $> 3\sigma$ sensitivity to the oscillation-required $\Sigma m_\nu =58 \text{ meV}$ and $>2\sigma$ sensitivity to $N_{\text{eff}}$ (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: $\sigma(\Sigma m_\nu) \approx 100$ meV; $\sigma(N_{\text{eff}}) \approx 0.12$

- **Mid-range future**: SPT-3G forecast $\sigma(\Sigma m_\nu) \approx 74$ meV; $\sigma(N_{\text{eff}}) \approx 0.076$

- **Far-Mid-range future**: Simons Array forecast $\sigma(\Sigma m_\nu) \approx 40$ meV; $\sigma(N_{\text{eff}}) \approx 0.08$

- **Far**: Planck + LSST lensing, galaxies: $\sigma(\Sigma m_\nu) = 23$ meV; $\sigma(N_{\text{eff}}) = 0.078$
  
  CMB-S4 and DESI galaxy survey: $\sigma(\Sigma m_\nu) = 15$ meV & $\sigma(N_{\text{eff}}) = 0.016$

  The latter provides $>3\sigma$ sensitivity to the oscillation-required $\Sigma m_\nu = 58$ meV and $>2\sigma$ sensitivity to $N_{\text{eff}}$ (Wu+ 2014)
Indirect Detection of Sterile Neutrino Dark Matter?
Dark Matter Neutrinos

Sterile Neutrino Dark Matter

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

\[ \nu_6 \]

\[ \sim 1 \text{ keV} \]
\[ \sin^2 2\theta \lesssim 10^{-7} \]

\[ \sim 1 \text{ eV} \]
\[ \sim 0.01 \text{ eV} \]

“3+2”

\[ \delta m^2_{\text{LSND}} \]

\[ \delta m^2_{\text{atm}} \]

\[ \delta m^2_{\text{sol}} \]
Sterile Neutrino Dark Matter

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

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

$$|\nu_5\rangle = -\sin \theta |\nu_a\rangle + \cos \theta |\nu_b\rangle$$

$$|\nu_6\rangle$$

$$\sim 1 \text{ keV}$$

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

$$\sim 0.01 \text{ eV}$$
Sterile Neutrino Dark Matter

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\]

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\[
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\]

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Sterile $\nu$ WDM Radiative Decay in the X-ray

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

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

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

$\Gamma_\gamma = 1.62 \times 10^{-28} \, s^{-1} \left( \frac{\sin^2 2\theta}{7 \times 10^{-11}} \right) \left( \frac{m_s}{7 \, \text{keV}} \right)^5$
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Virgo Cluster: $10^{78}$ DM particles
Upper Mass Limit on $\nu_s$ DM: X-ray observations of Virgo

Abazajian, Fuller & Tucker 2001

$m_s = 4$ keV

$m_s = 5$ keV
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

\[ m_s < 8.9 \text{ keV} \]
Forecast X-ray Observation Sensitivity for *Constellation-X*

Abazajian, Fuller & Tucker 2001

![Graph showing sensitivity of Constellation-X](image)

Key points:
- Virgo Cluster (Chandra)
- NGC 3198 (Constellation X)
- Bulbul et al.
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


[Graph showing flux vs. energy with annotations: 4 to 5σ, 73 clusters, 3.57 ± 0.02 (0.03) XMM - MOS Full Sample 6 Ms]
Sterile Neutrino Dark Matter: Parameter Space Summary

Abazajian 2015
Sterile Neutrino Dark Matter: Parameter Space Summary

$\sin^2 2\theta$ vs. $m_s$ [keV]
The Detection of an Unidentified Line II

Boyarsky et al. PRL arXiv:1402.4119

M31 ON-center
No line at 3.5 keV

Andromeda (M31)

1 galaxy

Data - model
[cts/sec/keV]

Energy [keV]

No line at 3.5 keV
Line at 3.5 keV

3σ
8 New Cluster Detections at >2σ Reported in August

![Graph showing New Cluster Detections at >2σ](image)
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:
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  - 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].
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• 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

[Graph image with the title "XMM-Newton MOS" and the authors' names "Andersen, Churazov & Bregman" overlayed on it.]

The graph shows a plot of $\sin^2 2\theta$ against Neutrino Mass (keV) with data points and curves indicating a research study in astrophysics.
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)
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*Systematic errors are of order the uncertainties on detected $\sin^2 2\theta$*

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Production of Sterile Neutrino Dark Matter: Boltzmann Transport
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\[ 0 = 0 \]
Production of Sterile Neutrino Dark Matter: Boltzmann Transport

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\[ L[f] = C[f] \]
Production of Sterile Neutrino Dark Matter: Boltzmann Transport

\[ 0 = 0 \]

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

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

\[ \sum_{\nu_x + a + \cdots \rightarrow i + \cdots} \int \frac{d^3 p_a}{(2\pi)^3 2 E_a} \cdots \frac{d^3 p_i}{(2\pi)^3 2 E_i} \cdots (2\pi)^4 \delta^4(p + p_a + \cdots - p_i - \cdots) \]

\[ \times \frac{1}{2} \left[ \langle P_m(\nu_\mu \rightarrow \nu_s; p, t) \rangle (1 - f_{\nu_s}) \sum |M|_{i+\cdots\rightarrow a+\nu_\mu+\cdots f_i \cdots (1 \mp f_a) (1 - f_{\nu_\mu}) \cdots} \right. \]

\[ \left. - \langle P_m(\nu_s \rightarrow \nu_\mu; p, t) \rangle f_{\nu_s} (1 - f_{\nu_\mu}) \sum |M|_{\nu_\mu + a + \cdots \rightarrow i + \cdots f_a \cdots (1 \pm f_i) \cdots} \right]. \]
Production of Sterile Neutrino Dark Matter: Boltzmann Transport

\[ 0 = 0 \]

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

\[
\frac{\partial}{\partial t} f_{\nu_s}(p, t) - H p \frac{\partial}{\partial p} f_{\nu_s}(p, t) = \\
\sum_{\nu_{s} + a + \cdots \rightarrow \nu_{s} + \cdots} \int \frac{d^3p_a}{(2\pi)^3 2E_a} \cdots \frac{d^3p_i}{(2\pi)^3 2E_i} \cdots (2\pi)^4 \delta^4(p + p_a + \cdots - p_i - \cdots) \\
\times \frac{1}{2} \left[ \langle P_m(\nu_\mu \rightarrow \nu_s; p, t) \rangle (1 - f_{\nu_s}) \sum |\mathcal{M}|^2_{i+\cdots \rightarrow a+\nu_\mu+\cdots \nu_i \cdots (1 \mp f_a) (1 - f_{\nu_\mu}) \cdots} \\
- \langle P_m(\nu_s \rightarrow \nu_\mu; p, t) \rangle f_{\nu_s} (1 - f_{\nu_\mu}) \sum |\mathcal{M}|^2_{\nu_\mu+\cdots a+\cdots \rightarrow i+\cdots f_a \cdots (1 \mp f_i) \cdots} \right].
\]
A Simplified View of Sterile Neutrino Dark Matter Production

\[ P(\nu_\alpha \rightarrow \nu_\alpha) \]

weak interaction at \( t = 0 \)

\[ x = ct \]
A Simplified View of Sterile Neutrino Dark Matter Production

\[ P(\nu_\alpha \rightarrow \nu_\alpha) \]

weak interaction at \( t = 0 \)

\[ x = ct \]
A Simplified View of Sterile Neutrino Dark Matter Production

\[ P(\nu_\alpha \rightarrow \nu_\alpha) \]

\[ P(\nu_\alpha \rightarrow \nu_s) \propto \sin^2 2\theta_{\alpha s} \sim 10^{-11} \]

Weak interaction at \( t = 0 \)
A Simplified View of Sterile Neutrino Dark Matter Production

\[ P(\nu_\alpha \rightarrow \nu_s) \propto \sin^2 2\theta_{as} \sim 10^{-11} \]

\[ \Delta x_{int} \ll \ell_{osc}: \text{quantum "Zeno Effect"} \]

weak interaction at \( t = 0 \)
A Simplified View of Sterile Neutrino Dark Matter Production

\[ P(\nu_\alpha \rightarrow \nu_\alpha) \]

\[ P(\nu_\alpha \rightarrow \nu_s) \propto \sin^2 2\theta_{\alpha s} \sim 10^{-11} \]

\[ \Delta x_{\text{int}} \ll \ell_{\text{osc}}: \text{quantum "Zeno Effect"} \]

\[ \Delta x_{\text{int}} \geq \ell_{\text{osc}}: \text{collisional production} \]

weak interaction at \( t = 0 \)
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

[Diagrams showing comparisons between CDM and WDM models for various properties like $v_{\text{max}}(z=0)$ and $V_{\text{peak}}$]
Anderhalden et al.
arXiv:1212.2967

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

CMC

“massive failures”

no massive failures

\(v_{\text{max}}(z=0)\)

\(V_{\text{peak}}\)
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)
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

Astro-H SXS
Perseus, 1 Msec
kT = 6.5 keV, 0.6 solar
z=0.0178
v(baryons) = 300 km/s
v(line) = 1300 km/s

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

New & Future Work

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 $\beta$-decay

Laboratory Limits: $\nu_e \Rightarrow \nu_s$

Pion Decay in Flight

Beta Decay

$\nu_s$ DM
Confirmation Wish List #4: kink searches in nuclear $\beta$-decay

- Laboratory

- $m_s$ (keV)
  - $10^5$
  - $10^4$
  - $1000$
  - $100$
  - $10$
  - $1$
  - $0.1$
  - $0.01$
  - $0.001$

- $\nu_s$ Decay

- $d\Gamma/dE$ (a.u.)
  - $10^{15}$
  - $25$
  - $20$
  - $15$
  - $10$
  - $5$
  - $1$

- $m_s = 10$ keV, $\sin^2 \Theta = 0.2$

- No mixing

- Log($\sin^2 2\theta$)
  - $-21$
  - $-18$
  - $-15$
  - $-12$
  - $-9$
  - $-6$
  - $-3$
  - $0$
Confirmation Wish List #4: kink searches in nuclear $\beta$-decay

Mertens+ 2014
SDSS+WMAP3 Lyman-alpha Constraints (Seljak et al 2006)
SDSS+WMAP3 Lyman-alpha Constraints (Seljak et al 2006)

\[ \sigma_8 = 0.74^{+0.05}_{-0.04} \]
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):**

\[ \sigma_8 = 0.9^{+0.03}_{-0.03} \]

**BBN, Cyburt et al. 2004**

\[ N_\nu = 3.04 \] (standard model)
T impacts structure of HI Ly-a Forest

Doppler broadening and Jeans-smoothing....

$T_0 \sim 20,000 \, \text{K}$

$T_0 \sim 10,000 \, \text{K}$

$\sim 30 \, \text{mpc/h co-moving}$

Abazajian, Lidz, Ricotti, in prep.
T impacts structure of HI Ly-a Forest

Abazajian, Lidz, Ricotti, in prep.