Neutrinos & Warm Dark Matter from a cosmology perspective

SDSS: a clustering saga

Lyman-α survey

Constraining $\Sigma m_\nu$

Nature of dark matter

N. Palanque-Delabrouille
CEA-Saclay
Clustering in the Universe

500 deg² BOSS galaxies (0.50<z<0.55)

500 deg² random (0.50<z<0.55)
Sloan Digital Sky Survey

- 2.5m telescope (New Mexico)
- 3D map of structures
  - \((\alpha, \delta)\) from
    - BOSS: 10 000 deg\(^2\)
    - eBOSS: 7 500 deg\(^2\)
  - \(z\) from 1000 fibers

BOSS 2009-2014
eBOSS 2014-2020
### SDSS BOSS and eBOSS

<table>
<thead>
<tr>
<th></th>
<th>BOSS</th>
<th>eBOSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>LRG</td>
<td>$1.2 \times 10^6$, $z \sim 0.57$</td>
<td>$+250 \times 10^3$, $z \sim 0.72$</td>
</tr>
<tr>
<td>ELG</td>
<td>—</td>
<td>$200 \times 10^3$, $z \sim 0.87$</td>
</tr>
<tr>
<td>Quasars</td>
<td>—</td>
<td>$500 \times 10^3$, $0.9 - 2.1$</td>
</tr>
<tr>
<td>Lyα</td>
<td>$180 \times 10^3$, $z &gt; 2.1$</td>
<td>$+60 \times 10^3$, $z &gt; 2.1$</td>
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**Image Description:**
- **Lyα forest** at $z \sim 2.5$
- **QSO** at $z \sim 1.5$
- **ELG** at $z \sim 0.87$
- **LRG** at $z \sim 0.57$
Baryon Acoustic Oscillations (BAO)

Propagation of baryon-photon overdensity wave in plasma

Wave frozen at recombination, at comoving $r_s \sim 150$ Mpc

A preferred 3D scale
Standard ruler in LSS
Baryon Acoustic Oscillations (BAO)

Observations

2005: First detection of BAO peak
2012: 5σ confirmation by BOSS

Eisenstein+

Anderson+
MNRAS 427, 3435 (2012)
**Baryon Acoustic Oscillations (BAO)**

**Observations**

- **2005**: First detection of BAO peak
- **2012**: 5σ confirmation by BOSS
- **2014**: First 3D measurements of BAO

**Transverse direction**

\[ \Delta \theta = r_s / [(1+z) D_A(z)] \]

\[ \Rightarrow \text{Angular distance } D_A(z) \]

as SNIa: \[ D_L(z) = (1+z)^2 D_A(z) \]

**Radial direction** (along line of sight)

\[ \Delta z = r_s H(z) / c \]

\[ \Rightarrow \text{Hubble parameter } H(z) \]

---

\[ D_A(z_m)(r_d^{\text{fid}}/r_d)/\text{Mpc} \]

\[ H(z_m)(r_d^{\text{fid}}/r_d)/\text{km s}^{-1}\text{Mpc}^{-1} \]

*Anderson+ MNRAS 441, 24 (2014)*
**Baryon Acoustic Oscillations (BAO)**

Evidence for phase of deceleration prior to present acceleration

Evidence for spatial flatness independently of CMB

**Large redshift-range from galaxies to Lyα**

Bautista+ (2017)

BOSS DR12

Redshift Space Distortion

Measure of gravitational growth

\[ P_F(k) = b_F^2 \times \left[ 1 + \beta \cos(\theta)^2 \right]^2 \times P_L(k) \]

\[ \beta \rightarrow f \sigma_8 \]

Samushia+ (2014)
Redshift Space Distortion

Assuming Planck ΛCDM cosmology

Amplitude of flattening depends on

\[ f(z)\sigma_8(z) \propto \frac{dG}{d\ln(a)} \]

with G linear growth rate

Test deviation from GR: \[ f\sigma_8 \rightarrow f\sigma_8 [A_{f\sigma_8} + B_{f\sigma_8}(z-z_p)] \]

\[ A_{f\sigma_8} = 0.96 \pm 0.06 \] and \[ B_{f\sigma_8} = -0.62 \pm 0.40 \]
Small-scale clustering and free streaming

Free streaming of relativistic particles (hydrodynamical simulations)

Suppression of small scales

\( \Lambda \text{CDM massless neutrinos} \)

\( \Lambda \text{CDM massive neutrinos} \)

Suppression depends on particle mass

Constraint on \( \Sigma m_\nu \)

Constraint on mass of warm dark matter

Palanque-Delabrouille+ (2015)
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SDSS: a clustering saga

BOSS & Lyman-α

Constraining $\Sigma m_\nu$

Nature of dark matter

N. Palanque-Delabrouille
CEA-Saclay
- Quasars visible to high redshift \( (z \sim 5) \)
- Absorption by neutral H (IGM) on light path
- IGM probes matter density
- Matter distribution on small scales \((v, v_s)\)
- 1D Power spectrum (along line of sight)
Transmitted flux fraction: \[ \delta = \frac{f - \langle f \rangle}{\langle f \rangle} \]

Small density of neutral H in local Universe (\(\sim\)fully ionized)

Higher density of neutral H in distant Universe (higher neutral H Density)
**Lyα forest 1D power spectrum**

Selection of ~14 000 out of 60 000 z>2.1 BOSS QSOs

Detailed study of contributions from

- detector (*spectrograph resolution, noise*)

- astrophysics (*sky lines, correlation with other absorbers*)

\[
P_{\text{Raw}}(k) = [P_{\text{Ly}\alpha}(k) + P_{\text{Ly}-\text{SiIII}}(k) + P_{\text{metals}}(k)] \times W^2(k) + P_{\text{Noise}}(k)
\]
Lyα forest 1D power spectrum

BOSS
NPD, Yeche+ (2013)
12 bins z=2.2 to 4.4

XQ100
Yeche, NPD+ (2017)
Irsic, Viel+ (2017)
z=3.2, 3.6, 3.9

HiRES/MIKE
Viel, Becker+ (2013)
z=4.2, 4.6, (5.4)
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Constraining $\Sigma m_\nu$

Nature of dark matter

N. Palanque-Delabrouille
CEA-Saclay
Why $\nu$’s have mass

Neutrino oscillations $\Rightarrow$ $\nu$'s are massive

- Solar $\delta m^2 \sim 7.5 \times 10^{-5} \text{ eV}^2$
- Atmospheric $\Delta m^2 \sim 2.4 \times 10^{-3} \text{ eV}^2$

Direct $m_\nu$ detection from Tritium $\beta$ decay

$m_e < 2 \text{ eV}$

0.06 eV $< \sum m_\nu < 6 \text{ eV}$

$\sum m > 0.06 \text{ eV}$

$\sum m > 0.10 \text{ eV}$
Why $\nu$’s have mass

In Universe, $\Sigma n_\nu \sim n_\gamma \sim 2 \cdot 10^9 n_p$ (considering all 3 neutrino species)

$\Rightarrow$ even for $m_\nu \sim 0.5 \text{ eV} = 5 \cdot 10^{-10} m_p$

total $\nu$ mass ($\Sigma n_\nu m_\nu$) of order of total stellar mass ($n_p m_p$)!

$\Rightarrow$ Can cosmology help?
Neutrinos are relativistic early on
Neutrinos “free stream” at $v=c$ until $t_{nr}$ (actually once they have decoupled)

$\Rightarrow$ Smooth perturbations of wavelength $\lambda < ct_{nr}$
although normal clustering on scales $\lambda > ct_{nr}$

- **Heavy neutrinos ($t_{nr}$ early)**
  - Strong suppression over short range
  - $m_\nu \sim \text{keV} \Rightarrow$ size of dwarf galaxy perturbations smoothed out

- **Light neutrinos ($t_{nr}$ late)**
  - Weak suppression over long range
  - $m_\nu \sim \text{eV} \Rightarrow$ size of galaxy cluster perturbations smoothed out
**Impact of $m_\nu$ on large-scale structures**

**Matter power spectrum**

Real-space (Mpc) ↔ k-space (Mpc$^{-1}$)

Causality horizon ↗ with time
- Early events ↔ small scales
- Late events ↔ large scales

Free-streaming of relativistic $\nu$'s further suppresses power on small scales

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**Diagram:**
- Matter era
- Radiation era
- $k_{eq}$
- Large scales
- Small scales

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N. Palanque-Delabrouille — May 14, 2019 — CERN

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Neutrinos and large-scale structures

Different probes $\iff$ different scales

- Suppression factor $\iff \Sigma m\nu$
- Suppression is $z$-dependent
- Ly-\(\alpha\)
  - Small scales, max effect
  - Large $z$-range [2.1 ; 4.5]

![Graph showing different probes and scales]

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Neutrinos and large-scale structures

Different probes ⇔ different scales

Suppression factor ⇔ Σν

Suppression is z-dependent

Ly-α
- Small scales, max effect
- Large z-range [2.1 ; 4.5]
- Non-linear regime, flux (not mass) P(k) ⇒ Hydro simulations

CMB
Linear

Galaxy LSS

1D Ly-α

Large scales

Small scales
Hydrodynamical simulations

(100 h⁻¹Mpc)³ with 3072³ particles/species

- dark matter
- baryons
- (degenerate-mass) neutrinos

McDonald (2003) splicing approach

Gadget-3

Ly-α power spectrum

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Grid of simulations
→ 2nd-order Taylor expansion for cosmo & astro parameters centered on Planck (2013)

\[
f(x + \Delta x) = f(x) + \sum_i \frac{\partial f}{\partial x_i}(x) \Delta x_i + \frac{1}{2} \sum_i \sum_j \frac{\partial^2 f}{\partial x_i \partial x_j}(x) \Delta x_i \Delta x_j
\]

<table>
<thead>
<tr>
<th>parameter</th>
<th>central</th>
<th>range</th>
</tr>
</thead>
<tbody>
<tr>
<td>keV / m_X</td>
<td>0.0</td>
<td>+0.2 +0.4</td>
</tr>
<tr>
<td>Σm_ν / eV</td>
<td>0.0</td>
<td>+0.4 +0.8</td>
</tr>
<tr>
<td>h</td>
<td>0.675</td>
<td>±0.05</td>
</tr>
<tr>
<td>Ω_M</td>
<td>0.31</td>
<td>±0.05</td>
</tr>
<tr>
<td>σ_8</td>
<td>0.83</td>
<td>±0.05</td>
</tr>
<tr>
<td>n_s</td>
<td>0.96</td>
<td>±0.05</td>
</tr>
<tr>
<td>d n_s / d ln k</td>
<td>0.00</td>
<td>±0.04</td>
</tr>
<tr>
<td>z_reio</td>
<td>12</td>
<td>±4</td>
</tr>
<tr>
<td>N_eff</td>
<td>3.046</td>
<td>±1</td>
</tr>
<tr>
<td>T_0^{z=3} / K</td>
<td>14,000</td>
<td>±7,000</td>
</tr>
<tr>
<td>γ^{z=3}</td>
<td>1.3</td>
<td>±0.3</td>
</tr>
<tr>
<td>A^τ</td>
<td>0.0025</td>
<td>±0.0020</td>
</tr>
<tr>
<td>η^τ</td>
<td>3.7</td>
<td>±0.4</td>
</tr>
</tbody>
</table>

TGCC Bruyères-le-châtel
Hydrodynamical simulations

$z = 15 \rightarrow 0$

3 species
- Baryons
- Dark matter
- Neutrinos

Stars formed from baryons

Boxsize = 20 Mpc/h, LambdaCDM + 0.8 eV neutrinos, $z = 13.42$

Gas

Dark matter

Neutrinos

Stars

@ A. Borde
(CEA-Saclay)
Neutrino mass ($\Sigma m$) or masses ($m_i$)?

<table>
<thead>
<tr>
<th>Hierarchy</th>
<th>$m_1$</th>
<th>$m_2$</th>
<th>$m_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degenerate</td>
<td>0.033</td>
<td>0.033</td>
<td>0.033</td>
</tr>
<tr>
<td>Normal</td>
<td>0.022</td>
<td>0.024</td>
<td>0.055</td>
</tr>
<tr>
<td>Inverted</td>
<td>0.0007</td>
<td>0.049</td>
<td>0.050</td>
</tr>
</tbody>
</table>

$\Sigma m = 0.10 \text{ eV}$

‘Exclusively’ a $\Sigma m$ effect

NPD, Yeche, Baur+ (2015)
$M_\nu$ constraint

$\Sigma m_\nu < 1.1 \text{ eV (95\% CL)}$

$P(k) \text{ massive} / P(k) \text{ massless}$

$k_{\text{nr}}$

$0.14 \text{ eV}$

$1.4 \text{ eV}$

Lyman-$\alpha$

$k (h \text{ Mpc}^{-1})$
**Mν constraint**

\[ \Sigma m_\nu < 0.72 \text{ eV} \]

\[ \text{(95\% CL)} \]

\[ \Sigma m_\nu < 1.1 \text{ eV} \]

\[ \text{(95\% CL)} \]

\[ P(k) \text{ massive} / P(k) \text{ massless} \]

\[ k_{\text{nr}} \]

\[ 0.14 \text{ eV} \]

\[ 1.4 \text{ eV} \]

\[ \text{CMB} \]

\[ \text{Ly} \alpha \]

\[ \text{Small scales} \]

\[ \text{Ly} \alpha + \text{CMB} \]

\[ \text{CMB} \]

\[ \text{Large scales} \]

\[ \Sigma m_\nu < 0.12 \text{ eV} \]

NPD, Yèche, Borde et al. (2015)

NPD, Yèche, Baur, et al. (2015)
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CEA-Saclay
Sterile neutrino sector

Beyond the Standard Model to explain $m_\nu$

GeV ± $\epsilon$

Baryogenesis
Oscillations

Sterile $\nu$ sector
$\nu$ Minimal Extension ($\nu$MSM)
Laine & Shaposhnikov

Perseus cluster
Andromeda galaxy
XMM clusters

3.5 keV line (XMM): decay of 7 keV $\nu_s$?
Bulbul++ 2014, Boyarsky++ 2014, Cappelluti++ 2017
Lyman-α forest and cosmology

Active neutrinos
- CMB vs. Lyα $P(k)$ comparison
- Greater impact as $m_\nu$ increases

$\implies$ Upper limit on $m_\nu$

Warm dark matter
- Power cut-off on small scales
- Greater impact as $m_{WDM}$ decreases

$\implies$ Lower limit on $m_{WDM}$

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Matter power spectrum

Lyα flux power spectrum

Fit on data

High-z and high-k bins most constraining
(more sensitive to linear regime cutoff)
**Warm Dark Matter: thermal relic & NRP $\nu_s$**

High-z and high-resolution bins have large constraining power
(closer to linear case, more sensitive to sharp cutoff)

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<th>Data Set</th>
<th>BOSS $z&lt;4.1$</th>
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<td>Lower bound on $m_X$ (keV)</td>
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Baur, NPD+ (2016)

$^1$ Yèche, NPD+ (2017)

$^2$ Irsic, Viel+ (2017)
Warm Dark Matter: thermal relic & NRP $\nu_s$

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Baur, NPD+ (2016)

More conservative

More prone to systematics (thermal history of IGM)

Among the strongest bound to date

In combination with X-ray data ($m_s < 4$ keV), excludes non-resonantly-produced sterile neutrinos

$^1$ Yèche, NPD+ (2017)
$^2$ Irsic, Viel+ (2017)
Sterile neutrinos: a more general scenario

Resonantly produced sterile neutrinos (Shi & Fuller, 1999)

Lepton asymmetry
\[ \mathcal{L} = \frac{|n_\nu - n_{\bar{\nu}}|}{s} \]

Enhanced oscillations
\[ \nu_{e, \mu, \tau} \leftrightarrow \nu_s \]

Non-thermal distribution
Colder dark matter than non-resonant production

\[ m_s = 4 \text{ keV} \]
Phase-space Distribution

Resonant production
\[ (\mathcal{L} = 12 \times 10^{-6}) \]

\[ \sim CDM + 30\% \text{ thermal relics} \]

Non-resonant component
(Fermi-Dirac statistics)

Cold \quad Warm

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Resonantly-produced sterile neutrinos

Lyman-α data in tension with 7 keV sterile ν (X-ray data)

Boyarsky et al. 2014, PRL 113, 251301

Baur, NPD+ (2017)
And beyond?
First year BOSS: Using best 13k out of 60k quasars
Full BOSS + first year eBOSS: Using best 44k out of 200k quasars
**DESI (2020-2025)**

**DESI instrument**
- 4m telescope in Arizona
- 5000 robotic fiber positioners
- 10 spectrographs x 3 bands (B, V, IR)

**DESI survey**
- **14,000 deg²** spectroscopic survey $0 < z < 4.5$ for BAO & RSD
- International collaboration (74 institutes, 46 non-US)
- > 600 members, 40 French engineers & physicists
DESI (2020-2025)

DESI 2020-2025

Fibers positioned in 2 minutes

SDSS 2009-2020

~1 hour per plate
Corrector looks good
→ delivering sub-arcsec images simultaneously across FOV

Was one of the major sources of risk!
DESI (2020-2025)

- Five target classes spanning redshifts $z=0.05 \rightarrow 4.5$
- 35 million redshifts over 14,000 sq. degrees in five years
- x30 larger volume than the SDSS map

2.4 million QSOs
Ly$\alpha$ $z > 2.1$
Tracers $1.0 < z < 2.1$

17 million ELGs
$0.6 < z < 1.6$

6 million LRGs
$0.4 < z < 1.0$

10 million brightest galaxies
$0.05 < z < 0.4$
Improvements compared to SDSS

- **BAO**: 1 order of magnitude better $\sigma(a) \sim 0.1\%$
- **RSD**: better than 1% over the full redshift range
- **Neutrino masses**: precision $\sim 20-25$ meV on $\Sigma m_\nu$
- **Non-gaussianity (inflation)**: $\sigma(f_{NL}) \sim 5$ (DESI-only)
Conclusions

- **Particle physics bounds on neutrino masses:** $0.06 < \sum m < 6 \text{ eV}$

- **Constraint on mass of active neutrinos**
  - Sum of neutrino masses $\sum m_\nu < 0.12 \text{ eV}$ (95% CL) from Ly$\alpha$+CMB

- **Constraint on warm dark matter & sterile neutrinos**
  - $m_s$ (non-resonantly produced) excluded
  - $m_s$ (resonantly produced) in conflict with sterile $\nu$ interpretation of 3.5 keV X-ray line
  - (constraints on fuzzy dark-matter)

- **Prospects**
  - Update with full SDSS BOSS + eBOSS
  - Planck + DESI Ly$\alpha$ $\sigma(\sum m_\nu) = 0.039 \text{ eV}$
  - Planck + DESI Galaxy $\sigma(\sum m_\nu) = 0.024 \text{ eV}$