Small-Scale Crisis in Cosmology
Sterile Neutrinos to the Rescue?

Jörn Kersten
Outline

1. Tensions in ΛCDM Cosmology
2. Dark Matter Interacting with Sterile Neutrinos
3. Challenges
1. Tensions in ΛCDM Cosmology

2. Dark Matter Interacting with Sterile Neutrinos

3. Challenges
ΛCDM Cosmology Works Great


\( \Lambda \)CDM Cosmology Works Great

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{cosmology_plot}
\caption{Cosmological model comparison and data sources.}
\end{figure}

\textbf{Planck, A&A 594 (2016)}

\textbf{Springel, Frenk, White, Nature 440 (2006)}

\textbf{... on large scales}
Small-Scale Problems of Structure Formation

Missing satellites


More galactic satellites predicted than observed
Small-Scale Problems of Structure Formation

**Missing satellites**

- More galactic satellites predicted than observed

**Cusp-core**

- More cuspy density profiles predicted than observed
Missing satellites

More galactic satellites predicted than observed


Cusp-core

More cuspy density profiles predicted than observed


Too big to fail

Most massive satellites predicted denser than observed

Boylan-Kolchin et al., MNRAS 422 (2011)
Diversity of dwarf rotation curves

Some observations agree with simulations including baryons

Others don’t
Some observations agree with simulations including baryons

+ a few additional anomalies

Oman et al., MNRAS 452 (2015)

Others don’t

Astrophysics Solutions or New Particle Physics?

But it's clearly all **baryons**, as shown in 1702.xxxxx!

But **baryons** clearly cannot do it, see 1702.yyyyy!

Summary by Kai Schmidt-Hoberg
CMB-Local Tension

- **3σ tension**: CMB ($z > 1000$) vs. low-redshift ($z < 10$) observations

**Expansion rate**
- Planck: $H_0 = (67.4 \pm 0.5) \frac{\text{km}}{\text{s Mpc}}$ [arXiv:1807.06209]
- Hubble: $H_0 = (73.45 \pm 1.66) \frac{\text{km}}{\text{s Mpc}}$ [Riess et al., ApJ 855 (2018)]
- H0LiCOW: $H_0 = (72.5^{+2.1}_{-2.3}) \frac{\text{km}}{\text{s Mpc}}$ [Birrer et al., arXiv:1809.01274]

**Magnitude of matter density fluctuations ($\sigma_8$)**

**Resolved by dark radiation** (additional relativistic particles)?

Hamann, Hasenkamp, JCAP 10 (2013)
Gariazzo, Giunti, Laveder, JHEP 11 (2013)
Wyman, Rudd, Vanderveld, Hu, PRL 112 (2014)
Battye, Moss, PRL 112 (2014)
Feng, Zhang, Zhang, EPJC 77 (2017)
Pan, Kaplinghat, Knox, PRD 97 (2018)
Choudhury, Choubey, arXiv:1807.10294
Buen-Abad, Schmaltz, Lesgourgues, Brinckmann, JCAP 01 (2018)
Tensions in $\Lambda$CDM Cosmology

Dark Matter Interacting with Sterile Neutrinos

Challenges
Self-Interacting Dark Matter

- Dark matter $\chi$ interacts with dark sector
- E.g., $U(1)_\chi$ with light gauge boson $V$, $m_V \sim \text{MeV}$ (dark photon)

$\Rightarrow$ Long-range, velocity-dependent interaction
$\Rightarrow$ Cusp-core, too big to fail, and diversity solved

Feng, Kaplinghat, Yu, PRL 104 (2010)
Loeb, Weiner, PRL 106 (2011)
Kamada, Kaplinghat, Pace, Yu, PRL 119 (2017)

Kamada et al., PRL 119 (2017)
Suppressing Dwarfs by Late Kinetic Decoupling

- Additional light particle $N$ (dark radiation) charged under $U(1)_X$
- Efficient Dark matter – dark radiation scattering

$\Rightarrow$ Late kinetic decoupling

$\Rightarrow$ Structure formation suppressed at small scales

Boehm, Fayet, Schaeffer, PLB 518 (2001)
Green, Hofmann, Schwarz, JCAP 08 (2005)
Loeb & Zaldarriaga, PRD 71 (2005)

$T_{kd} = 0.6$ keV SIDM
$T_{kd} = 1.0$ keV SIDM
$T_{kd} = 1.5$ keV SIDM
$T_{kd} = 2.0$ keV SIDM
$3.5$ keV WDM
$5.3$ keV WDM

Huo, Kaplinghat, Pan, Yu, PLB 783 (2018)
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Boehm, Fayet, Schaeffer, PLB 518 (2001)
Green, Hofmann, Schwarz, JCAP 08 (2005)
Loeb & Zaldarriaga, PRD 71 (2005)

$\Rightarrow$ Minimal galaxy mass Vogelsberger et al., MNRAS 460 (2016)

$$M_{\text{cut}} = 5 \cdot 10^{10} \left(\frac{100 \text{ eV}}{T_{kd}}\right)^3 h^{-1} M_\odot$$

$\Rightarrow$ Missing satellite problem solved for $T_{kd} \lesssim 1 \text{ keV} \ (M_{\text{cut}} \simeq 10^{10} M_\odot)$

Boehm, Fayet, Schaeffer, PLB 518 (2001)
One Model to Solve Them All

- **Dark matter** $\chi$
- **Dark radiation** $N$, $m_N \lesssim \text{eV}$
- **Dark photon** $V$ couples to both, $m_V \sim \text{MeV}$
- Some ingredients for anomaly cancellation etc.

\begin{center}
\begin{tikzpicture}
\begin{scope}[transform canvas={scale=0.5}]
\draw[->,thick] (0,0) -- (0,2);
\draw[->,thick] (2,0) -- (2,2);
\draw[->,thick] (-2,0) -- (-2,2);
\draw[->,thick] (0,0) -- (2,2);
\draw[->,thick] (0,0) -- (-2,2);
\draw[->,thick] (-2,2) -- (0,0);
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$\Rightarrow$ All small-scale problems of structure formation solved
$\Rightarrow$ Oscillation anomalies and CMB-local tension solved if $N = \nu_{\text{sterile}}$?

Bringmann, Hasenkamp, JK, JCAP 07 (2014)
Dasgupta, Kopp, PRL 112 (2014)
One Model to Solve Them All

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Bringmann, Hasenkamp, JK, JCAP 07 (2014)
Dasgupta, Kopp, PRL 112 (2014)

- Related models (different particle spins, more sterile neutrinos, . . . )
  - Archidiacono, Hannestad, Hansen, Tram, PRD 91 (2015)
  - Chu, Dasgupta, PRL 113 (2014)
  - Cherry, Friedland, Shoemaker, arXiv:1411.1071
  - Kouvaris, Shoemaker, Tuominen, PRD 91 (2015)
  - Binder et al., JCAP 11 (2015)
  - Tang, PLB 757 (2016)

- Classification of minimal possibilities
Dark Matter Production

- High temperatures: $U(1)_X$ sector thermalized via Higgs portal

  $$\mathcal{L}_{\text{Higgs}} \supset \kappa |H|^2 |\Theta|^2$$

- $\langle \Theta \rangle \sim \text{MeV}$ breaks $U(1)_X$
High temperatures: $U(1)_X$ sector thermalized via Higgs portal

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$T_\chi \sim m_\chi/25$: freeze-out (chemical decoupling) of dark matter

$$\Omega_{\text{CDM}} h^2 \sim 0.11 \left( \frac{0.67}{g_X} \right)^4 \left( \frac{m_\chi}{\text{TeV}} \right)^2$$

(neglecting bound state formation)
Cold Dark Matter Parameter Space

- Calculated by DarkSUSY 6.1
  Bringmann Edsjo, Gondolo, Ullio, Bergstrom, JCAP 07 (2018)
- DM mass $\sim$ TeV or $\lesssim$ GeV
- Light DM region favored by cluster observations?
  Huo, Kaplinghat, Pan, Yu, PLB 783 (2018)
Tensions in $\Lambda$CDM Cosmology

Dark Matter Interacting with Sterile Neutrinos

Challenges
Big Bang Nucleosynthesis

- $T \downarrow \leadsto$ Higgs portal no longer effective
  $\leadsto U(1)_X$ sector decouples at $T_{X}^{\text{dpl}}$ (depending on $\kappa$)

- SM particles becoming non-relativistic afterwards heat SM bath, not $U(1)_X$ bath $\leadsto T_N < T_\nu$ (depending on number of d.o.f. $g_*$)

$$\Delta N_{\text{eff}}|_{\text{BBN}} \approx \left( \frac{46}{g_{*,\nu}(T_{X}^{\text{dpl}})} \right)^{\frac{4}{3}} \gtrsim 0.33$$
Big Bang Nucleosynthesis

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$\rightsquigarrow$ Correct order of magnitude for CMB-local tension
$\rightsquigarrow$ Tension with BBN bounds

Hufnagel, Schmidt-Hoberg, Wild, JCAP 02 (2018)
Lyman-$\alpha$ Forest

- Constrains suppression of matter power spectrum by late KD
- Analogous to bounds on warm DM

$\sim$ Number of satellites reduced by only 30%

![Graph showing $m_{WDM}$ vs $\delta A$ and $N_{subhalo}$ vs $T_{kd}$]

Huo, Kaplinghat, Pan, Yu, PLB 783 (2018)

- Systematic effects? Recasting of warm DM bounds ok?
Sterile Neutrino Production by Oscillations

- Standard scenario: mixing between active and sterile neutrinos
  $\leadsto$ oscillations $\leadsto \Delta N_{\text{eff}} \simeq 1$ $\leadsto$ ruled out by Planck and BBN

- $U(1)_X$ interactions $\leadsto$ effective matter potential suppresses mixing
  $\leadsto$ no production by oscillations for $T \gtrsim \text{MeV}$

Hannestad, Hansen, Tram, PRL 112 (2014); Dasgupta, Kopp, PRL 112 (2014)
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- \( T < \text{MeV} \): mixing unsuppressed
  \( \sim \) sterile neutrinos from oscillations + \( U(1)_X \)-mediated scatterings

  Bringmann, Hasenkamp, JK, JCAP 07 (2014)
  Mirizzi, Mangano, Pisanti, Saviano, PRD 91 (2015)
  Tang, PLB 750 (2015)
  Chu, Dasgupta, Kopp, JCAP 10 (2015)
  Cherry, Friedland, Shoemaker, \texttt{arXiv:1605.06506}
  Forastieri et al., JCAP 07 (2017)
  Chu, Dasgupta, Dentler, Kopp, Saviano, \texttt{arXiv:1806.10629}
Sterile Neutrino Production by Oscillations

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Hannestad, Hansen, Tram, PRL 112 (2014); Dasgupta, Kopp, PRL 112 (2014)

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  $\rightsquigarrow \sum m_\nu$ bound violated or too little free-streaming

  $\rightsquigarrow$ Ruled out for $m_N \sim \text{eV}$ and $O(0.1)$ mixing

Chu et al., arXiv:1806.10629
Sterile Neutrino Production by Oscillations

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Hannestad, Hansen, Tram, PRL 112 (2014); Dasgupta, Kopp, PRL 112 (2014)

- $T < \text{MeV}$: mixing unsuppressed
  $\leadsto$ sterile neutrinos from oscillations + $U(1)_X$-mediated scatterings
  $\leadsto \sum m_\nu$, bound violated or too little free-streaming
  $\leadsto$ Ruled out for $m_N \sim \text{eV}$ and $\mathcal{O}(0.1)$ mixing
  $\leadsto$ More complicated dark sector?

Chu et al., arXiv:1806.10629

![Graph showing the dependence of sterile neutrino mass on mediator mass](image)
Particle physics solution for tensions in $\Lambda$CDM cosmology

- **Dark matter** with mass $\sim$ TeV or $\lesssim$ GeV
- **Dark radiation** with mass $\lesssim$ eV
- **Dark photon** with mass $\sim$ MeV $\rightsquigarrow$ secret interactions

$\rightsquigarrow$ **Late kinetic decoupling** solves missing satellites problem

$\rightsquigarrow$ **DM self-interactions** solve cusp-core, too big to fail, diversity
Conclusions

Particle physics solution for tensions in ΛCDM cosmology

- **Dark matter** with mass $\sim$ TeV or $\lesssim$ GeV
- **Dark radiation** with mass $\lesssim$ eV
- **Dark photon** with mass $\sim$ MeV $\Rightarrow$ secret interactions

$\Rightarrow$ Late kinetic decoupling solves missing satellites problem

$\Rightarrow$ DM self-interactions solve cusp-core, too big to fail, diversity

- Dark radiation probably not able to address oscillation anomalies
- Data from astrophysics and cosmology probe DM properties
Dark Radiation

- **Dark radiation**: relativistic particles \( \neq \gamma, \nu^{SM} \)
- Parameterized via radiation energy density

\[
\rho_{\text{rad}} \equiv \left[ 1 + N_{\text{eff}} \frac{7}{8} \left( \frac{T_\nu}{T} \right)^4 \right] \rho_\gamma
\]

- \( T \equiv T_\gamma \)
- \( N_{\text{eff}} \): effective number of neutrino species
- Standard Model: \( N_{\text{eff}} = 3.046 \)
- Existence of dark radiation \( \Leftrightarrow \Delta N_{\text{eff}} \equiv N_{\text{eff}} - 3.046 > 0 \)
- Measurements of Cosmic Microwave Background (CMB):

\[
\begin{align*}
\Delta N_{\text{eff}} &= 1.51 \pm 0.75 \quad \text{ACT, ApJ 739 (2011)} \\
\Delta N_{\text{eff}} &= 0.81 \pm 0.42 \quad \text{SPT, ApJ 743 (2011)} \\
\Delta N_{\text{eff}} &= 0.10 \pm 0.23 \quad \text{Planck, A&A 594 (2016)}
\end{align*}
\]
Measurements

\[ \Lambda CDM + N_{\text{eff}} + \Omega_k + f_\nu + n_s \]
\[ \Lambda CDM + N_{\text{eff}} + \Omega_k + f_\nu + w \]
\[ \Lambda CDM + N_{\text{eff}} + f_\nu + w \]
\[ \Lambda CDM + N_{\text{eff}} \]

Modified from Riemer-Sørensen et al. (2013 review) arXiv:1301.7102
Velocity-Dependent Self-Interactions

- Described by Yukawa potential \( V(r) = \pm \frac{\alpha x}{r} e^{-m \nu r} \)
- Desired scattering cross section \( \sigma_T \):
  - Large in dwarf galaxies
  - Small on larger scales to satisfy experimental limits
- Very different behavior depending on model parameters

Here: classical regime \( \rightsquigarrow \) analytical approximations exist

Tulin, Yu, Zurek, PRL 110, PRD 87 (2013)
Particle Physics Models with Late Kinetic Decoupling

Need scattering partner \( \tilde{\gamma} \) with large abundance until \( T_{kd} \lesssim 1 \text{ keV} \) \( \sim \) photon, (SM) neutrino, dark radiation

Here: classification of all minimal possibilities

Bringmann, Ihle, JK, Walia, PRD 94 (2016)

Scattering amplitude close to kinetic decoupling:

\[
|\mathcal{M}|^2 \simeq c_n \left( \frac{E_{\tilde{\gamma}}}{m_\chi} \right)^n
\]

\( M_{\text{cut}} \simeq 10^{10} M_\odot \) needs large coefficients \( c_n \) and/or light dark matter
Desired Self-Interactions with $t$-Channel Mediator

Both $m_\chi \sim \text{GeV}$ and $m_\chi \sim \text{TeV}$ work
Simulating Self-Interacting Dark Matter

N-body simulation of structure formation with DM-DM and DM-N interactions

Vogelsberger et al., MNRAS 460 (2016)
Simulating Self-Interacting Dark Matter

\textit{N}-body simulation of \textbf{structure formation} with DM-DM and DM-\textit{N} interactions

- Confirms solution (alleviation) of \textit{too big to fail}, missing satellites
- \textbf{Cusp-core} and rotation curve diversity unclear

Vogelsberger et al., MNRAS 460 (2016)
Timeline

\[ \gtrsim m_\chi \sim \text{TeV}: \text{thermalization of } U(1)_X \text{ sector via Higgs portal} \]

\[ T_{\chi}^{\text{fo}} \sim m_\chi/25: \text{CDM freeze-out} \]

\[ T_{x}^{\text{dpl}} \gtrsim 10 \text{ GeV}: U(1)_X \text{ sector decoupling} \]

SM particles heat SM bath

matter effects prevent \( N_1 \) overproduction

\[ T_{\nu}^{\text{dpl}} \sim \text{MeV}: \text{active neutrino decoupling} \]

\( U(1)_X \) particles heat \( N_1 \)

\[ T^{\text{kd}}_\chi \sim 100 \text{ eV}: \text{CDM kinetic decoupling} \]

\[ T^{\text{kd}}_{N_1}: N_1 \text{ kinetic decoupling from itself} \]

\[ T_{\text{eq}} \sim 1 \text{ eV}: \text{matter-radiation equality} \]

\[ T_{\gamma}^{\text{dpl}} \sim 0.2 \text{ eV}: \text{photon decoupling} \]

\( N_1 \) becomes non-relativistic

CDM-CDM scattering via Yukawa potential

\[ T_0 \sim 0.2 \text{ meV}: \text{today} \]