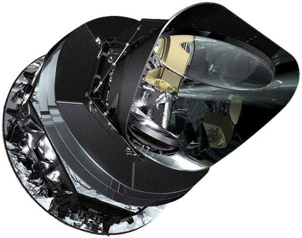
Not So Weakly Interacting Dark Matter Bonding with Sterile Neutrinos

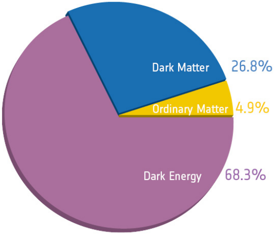
Jörn Kersten

UNIVERSITY OF BERGEN

Outline

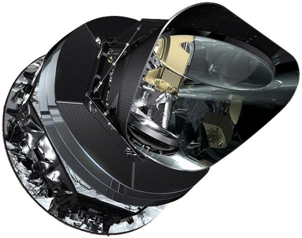
The Universe after Planck

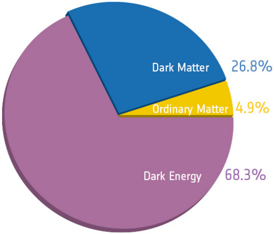




Flat ΛCDM cosmology fits data perfectly Planck, arXiv:1502.01589

The Universe after Planck





Flat ΛCDM cosmology fits data depressingly Planck, arXiv:1502.01589

Or does it?

Hints for Dark Radiation

- Dark radiation: relativistic particles $\neq \gamma, \nu^{\mathrm{SM}}$
- Parameterized via radiation energy density

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

- $T \equiv T_\gamma$
- N_{eff}: effective number of neutrino species
- Standard Model: $N_{\mathrm{eff}} = 3.046$
- Existence of dark radiation $\Leftrightarrow$ $\Delta N_{\mathrm{eff}} \equiv N_{\mathrm{eff}} - 3.046 > 0$

Hints for Dark Radiation

- Dark radiation: relativistic particles $\neq \gamma, \nu^{\text{SM}}$
- Parameterized via radiation energy density

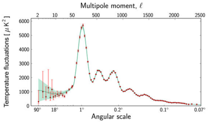
$$\rho_{\text{rad}} \equiv \left[1 + N_{\text{eff}} \, \frac{7}{8} \left(\frac{T_\nu}{T} \right)^4 \right] \rho_\gamma$$

- $T \equiv T_\gamma$
- N_{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):

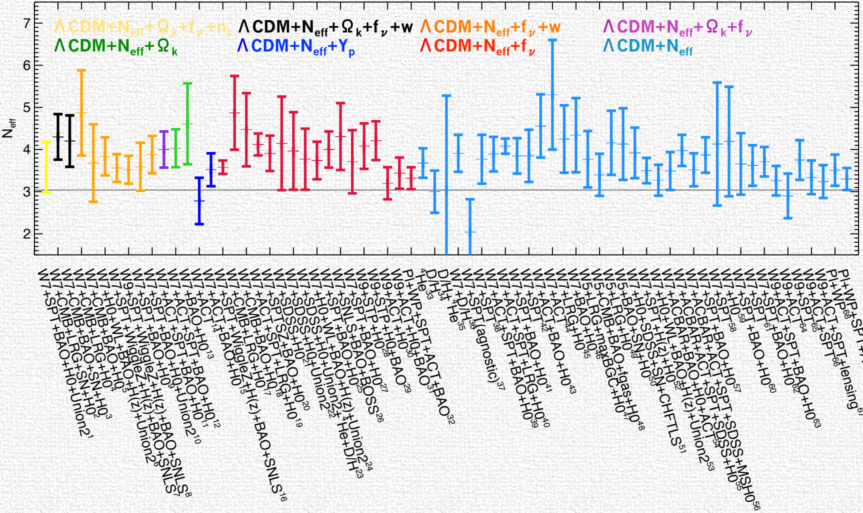
$\Delta N_{\text{eff}} = 1.51 \pm 0.75$ ACT, ApJ **739** (2011)

$\Delta N_{\text{eff}} = 0.81 \pm 0.42$ SPT, ApJ **743** (2011)

$\Delta N_{\text{eff}} = 0.10 \pm 0.23$ Planck, arXiv:1502.01589



Measurements



Modified from Riemer-Sørensen et al. (2013 review) arXiv:1301.7102

Hints for Hot Dark Matter

- $2 \ldots 3\,\sigma$ tension: CMB ($z > 1000$) vs. local ($z < 10$) observations
- Expansion rate
  - Planck: $H_0 = (67.8 \pm 0.9)\frac{\mathrm{km}}{\mathrm{s\,Mpc}}$ arXiv:1502.01589
  - Hubble: $H_0 = (73.8 \pm 2.4)\frac{\mathrm{km}}{\mathrm{s\,Mpc}}$ Riess et al., ApJ **730** (2011)
  - Reanalysis: $H_0 = (70.6 \pm 3.3)\frac{\mathrm{km}}{\mathrm{s\,Mpc}}$ Efstathiou, MNRAS **440** (2014)

- Magnitude of matter density fluctuations (σ_8)

Hints for Hot Dark Matter

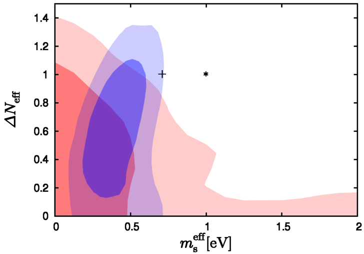
- $2 \ldots 3\,\sigma$ tension: CMB ($z > 1000$) vs. local ($z < 10$) observations
- Expansion rate
  - Planck: $H_0 = (67.8 \pm 0.9) \frac{\text{km}}{\text{s Mpc}}$ arXiv:1502.01589
  - Hubble: $H_0 = (73.8 \pm 2.4) \frac{\text{km}}{\text{s Mpc}}$ Riess et al., ApJ **730** (2011)
  - Reanalysis: $H_0 = (70.6 \pm 3.3) \frac{\text{km}}{\text{s Mpc}}$ Efstathiou, MNRAS **440** (2014)

- Magnitude of matter density fluctuations (σ_8)
- Resolved by hot dark matter component $\simeq$ dark radiation
- Best fit:

$$\Delta N_{\text{eff}} = 0.61$$

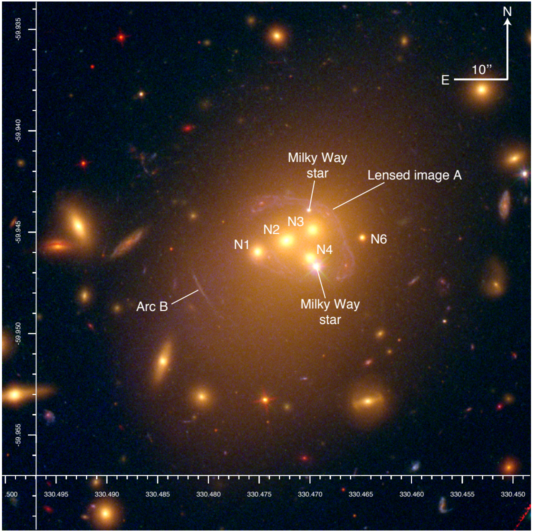
$$m_s^{\text{eff}} \equiv \left(\frac{T_s}{T_\nu}\right)^3 m_s = 0.41\text{ eV}$$

Hamann, Hasenkamp, JCAP **10** (2013)
Wyman, Rudd, Vanderveld, Hu, PRL **112** (2014)
Battye, Moss, PRL **112** (2014)
Gariazzo, Giunti, Laveder, JHEP **11** (2013)



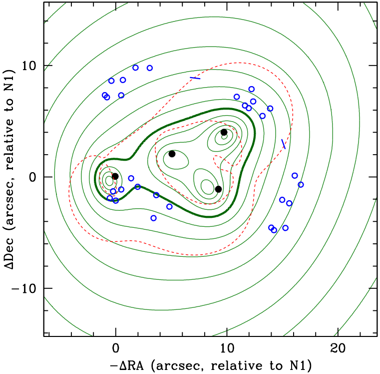
Hint for Dark Matter Self-Interactions

Galaxy cluster Abell 3827



Hint for Dark Matter Self-Interactions

Galaxy cluster Abell 3827

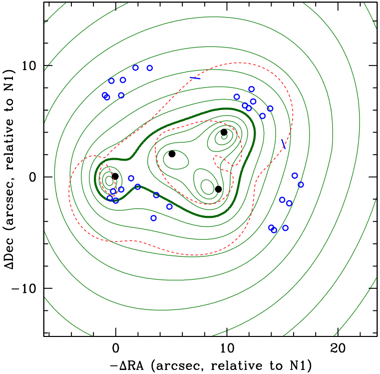


Stars and DM separated ($3.3\,\sigma$) $\rightsquigarrow$ DM-DM interactions

$\sigma/m_{\mathrm{DM}} \sim 1.7 \cdot 10^{-4}\,\mathrm{cm}^2/\mathrm{g}$ Massey et al., MNRAS **449** (2015)

Hint for Dark Matter Self-Interactions

Galaxy cluster Abell 3827

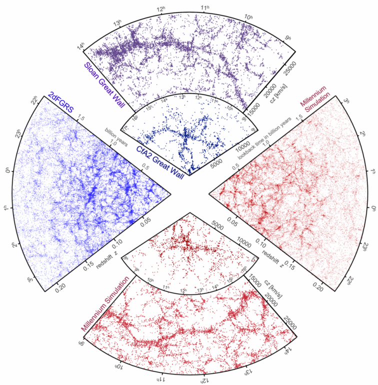


Stars and DM separated (3.3 σ) $\rightsquigarrow$ DM-DM interactions

$$\sigma/m_{\mathrm{DM}} \sim 1.5\,\mathrm{cm}^2/\mathrm{g}$$ Kahlhoefer et al., arXiv:1504.06576

Small-Scale Problems of Structure Formation

Numerical simulations of structure formation with cold dark matter

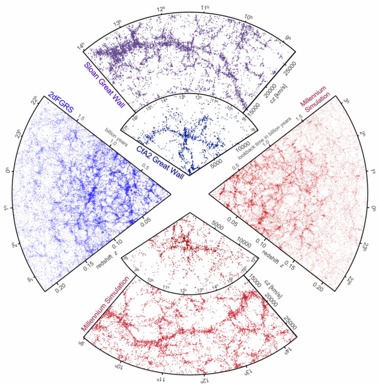


Springel, Frenk, White, Nature **440** (2006)

⇝ Excellent agreement with observations

Small-Scale Problems of Structure Formation

Numerical simulations of structure formation with cold dark matter



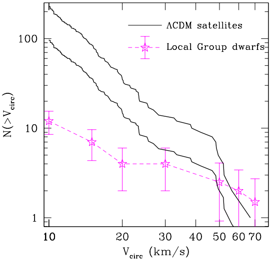
Springel, Frenk, White, Nature **440** (2006)

⇝ Excellent agreement with observations on large scales

Small-Scale Problems of Structure Formation

Talk by N. Yoshida

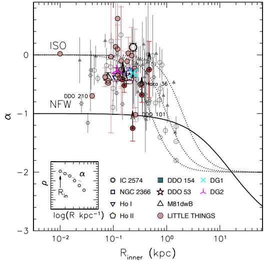
Missing satellites



Kravtsov, Adv. Astron. (2010)
Klypin et al., ApJ **522** (1999)

More galactic satellites predicted than observed

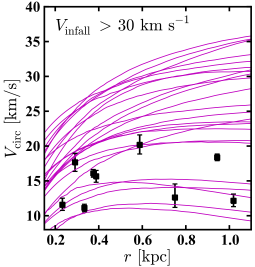
Cusp-core



Oh et al., 1502.01281
De Blok et al., ApJ **552** (2001)

More cuspy density profiles predicted than observed

Too big to fail



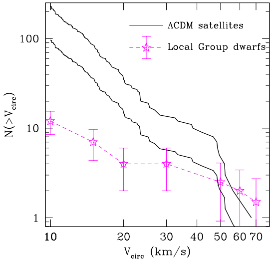
Boylan-Kolchin et al., MNRAS **422** (2011)

Most massive satellites predicted denser than observed

Small-Scale Problems of Structure Formation

Talk by N. Yoshida

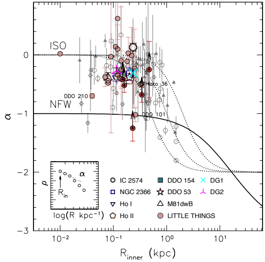
Missing satellites



Kravtsov, Adv. Astron. (2010)
Klypin et al., ApJ **522** (1999)

More galactic satellites predicted than observed

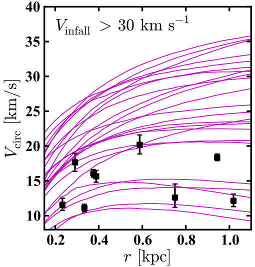
Cusp-core



Oh et al., 1502.01281
De Blok et al., ApJ **552** (2001)

More cuspy density profiles predicted than observed

Too big to fail



Boylan-Kolchin et al., MNRAS **422** (2011)

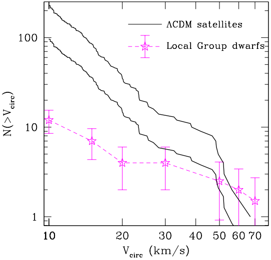
Most massive satellites predicted denser than observed

Latest addition: diversity of dwarf rotation curves Oman et al., arXiv:1504.01437

Small-Scale Problems of Structure Formation

Talk by N. Yoshida

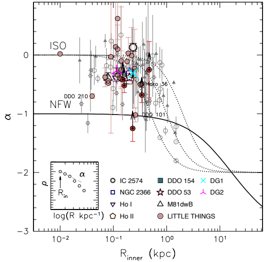
Missing satellites



Kravtsov, Adv. Astron. (2010)
Klypin et al., ApJ **522** (1999)

More galactic satellites predicted than observed

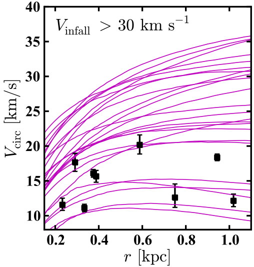
Cusp-core



Oh et al., 1502.01281
De Blok et al., ApJ **552** (2001)

More cuspy density profiles predicted than observed

Too big to fail



Boylan-Kolchin et al., MNRAS **422** (2011)

Most massive satellites predicted denser than observed

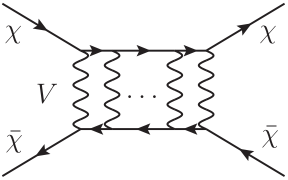
Latest addition: diversity of dwarf rotation curves Oman et al., arXiv:1504.01437

Astrophysics solutions or new particle physics?

Not-so-WIMPy Dark Matter

- Dark matter χ
  - Standard Model singlet
  - Charged under $U(1)_X$ gauge interaction
  - Mass $m_\chi \sim$ TeV
- Light gauge boson V, $m_V \sim$ MeV

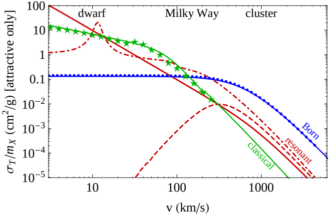
$\rightsquigarrow$ Long-range, velocity-dependent interaction
$\rightsquigarrow$ Less cuspy density profiles
$\rightsquigarrow$ Cusp-core and too big to fail solved



Feng, Kaplinghat, Yu, PRL **104** (2010)
Loeb, Weiner, PRL **106** (2011)
Vogelsberger, Zavala, Loeb, MNRAS **423** (2012)

Velocity-Dependent Self-Interactions

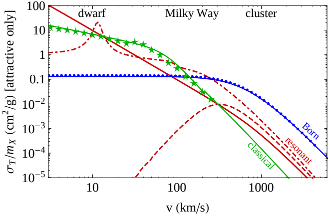
- Described by Yukawa potential $V(r) = \pm \frac{\alpha_X}{r} e^{-m_V r}$
- Desired scattering cross section σ_T:
  - Large in dwarf galaxies
  - Small on larger scales to satisfy experimental limits
    $\rightsquigarrow$ probably too small to explain Abell 3827
- Very different behavior depending on model parameters



Tulin, Yu, Zurek, PRL **110**, PRD **87** (2013)

Velocity-Dependent Self-Interactions

- Described by Yukawa potential $V(r) = \pm \frac{\alpha_X}{r} e^{-m_V r}$
- Desired scattering cross section σ_T:
  - Large in dwarf galaxies
  - Small on larger scales to satisfy experimental limits
    $\rightsquigarrow$ probably too small to explain Abell 3827
- Very different behavior depending on model parameters



Tulin, Yu, Zurek, PRL **110**, PRD **87** (2013)

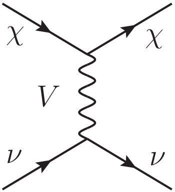
Here: classical regime $\rightsquigarrow$ analytical approximations exist

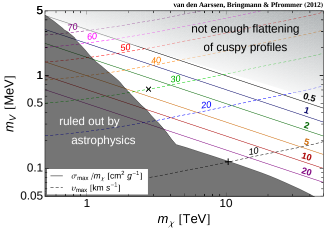
Late Kinetic Decoupling

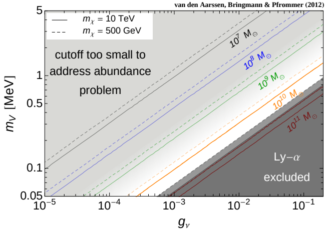
- Standard Model neutrinos coupled to V
- Dark matter scatters off neutrinos

$\rightsquigarrow$ $T_\chi = T_\nu$ until kinetic decoupling at $T \sim 100$ eV
$\rightsquigarrow$ Formation of smaller structures suppressed
$\rightsquigarrow$ Missing satellites solved

Van den Aarssen, Bringmann, Pfrommer, PRL **109** (2012)

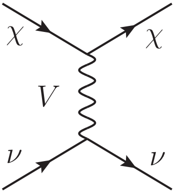






Late Kinetic Decoupling

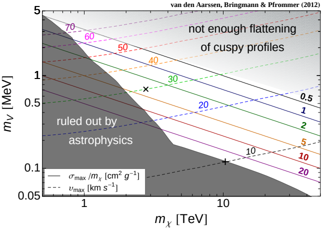
- Standard Model neutrinos coupled to V
- Dark matter scatters off neutrinos

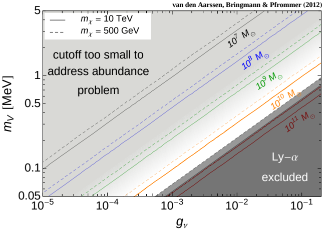


⇝ $T_\chi = T_\nu$ until kinetic decoupling at $T \sim 100$ eV
⇝ Formation of smaller structures suppressed
⇝ Missing satellites solved

Van den Aarssen, Bringmann, Pfrommer, PRL **109** (2012)

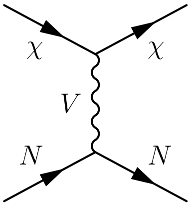
Problem: explicit breaking of $SU(2)_L$





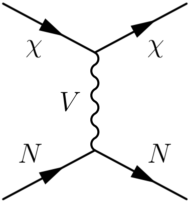
Enter the Sterile Neutrino

- Sterile neutrino N
    - Mass $m_N \lesssim$ eV
    - Standard Model singlet
    - Charged under $U(1)_X$ (“secret interactions”)
    - Forms hot dark matter
- Dark matter scatters off sterile neutrinos



Enter the Sterile Neutrino

- Sterile neutrino N
  - Mass $m_N \lesssim$ eV
  - Standard Model singlet
  - Charged under $U(1)_X$ ("secret interactions")
  - Forms hot dark matter
- Dark matter scatters off sterile neutrinos



$\rightsquigarrow$ Most problems solved

- All small-scale problems of structure formation
- Hot dark matter hint (CMB-local tension)
- Neutrino oscillation anomalies (?)

Bringmann, Hasenkamp, JK, JCAP **07** (2014)
Dasgupta, Kopp, PRL **112** (2014)
Ko, Tang, PLB **739** (2014)
Chu, Dasgupta, PRL **113** (2014)

Dark Matter Production

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

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

- $\langle\Theta\rangle \sim$ MeV breaks $U(1)_X$

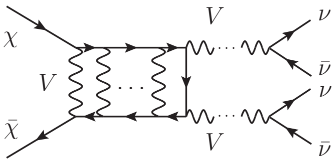
Dark Matter Production

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

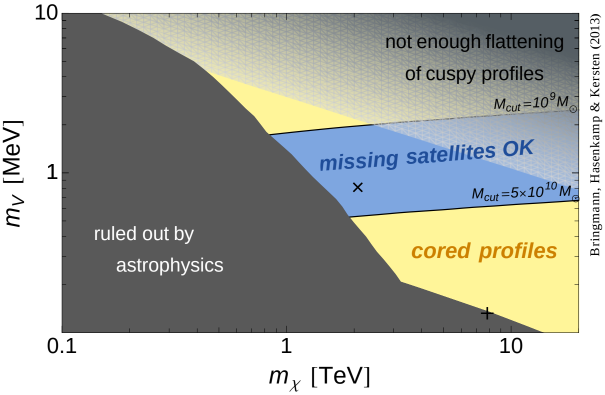
$$\mathcal{L}_{\text{Higgs}} \supset \kappa |H|^2 |\Theta|^2$$

- $\langle \Theta \rangle \sim$ MeV breaks $U(1)_X$
- $T_\chi \sim m_\chi/25$: freeze-out (chemical decoupling) of dark matter

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



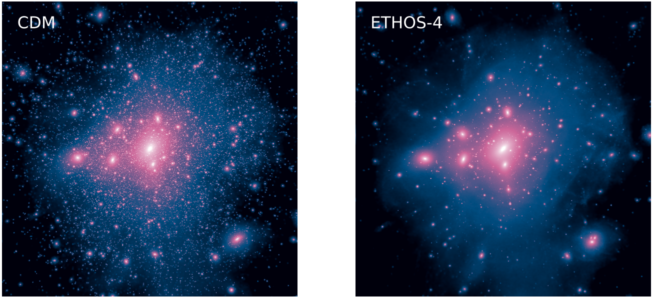
Cold Dark Matter Parameter Space



- Blue band can be moved vertically by changing sterile neutrino charge and temperature
- Crosses: simulations show that too big to fail solved

Simulating Self-Interacting Dark Matter

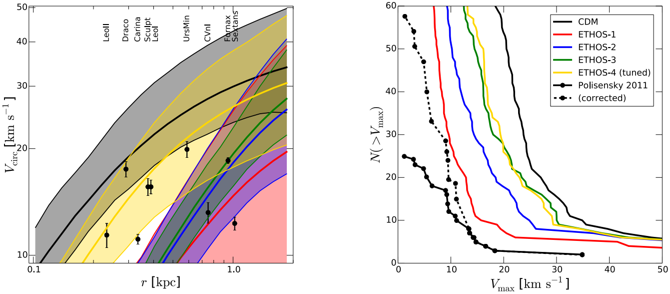
First simulation of structure formation with DM-DM and DM-N interactions obtained from viable particle physics model



Vogelsberger et al., arXiv:1512.05349

Simulating Self-Interacting Dark Matter

First simulation of structure formation with DM-DM and DM-N interactions obtained from viable particle physics model



Vogelsberger et al., arXiv:1512.05349

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

Sterile Neutrino Abundance

- $T \downarrow \rightsquigarrow$ Higgs portal no longer effective
  $\rightsquigarrow U(1)_X$ sector decouples at T_X^{dpl} (depending on κ)
- SM particles becoming non-relativistic afterwards heat SM bath, not $U(1)_X$ bath $\rightsquigarrow T_N < T_\nu$ (depending on number of d.o.f. g_*)

$$\Delta N_{\text{eff}}(T) = \left(\frac{T_N}{T_\nu}\right)^4 = \left(\frac{g_{*,\nu}}{g_{*,N}}\right)^{\frac{4}{3}}\Bigg|_T \left(\frac{g_{*,N}}{g_{*,\nu}}\right)^{\frac{4}{3}}\Bigg|_{T_X^{\text{dpl}}}$$

Sterile Neutrino Abundance

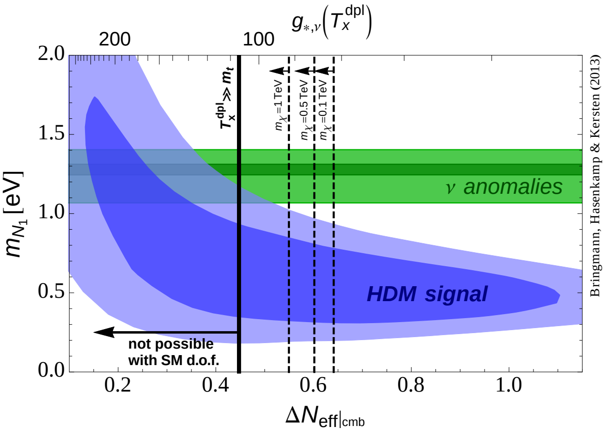
- $T \downarrow \rightsquigarrow$ Higgs portal no longer effective
  $\rightsquigarrow U(1)_X$ sector decouples at T_X^{dpl} (depending on κ)
- SM particles becoming non-relativistic afterwards heat SM bath, not $U(1)_X$ bath $\rightsquigarrow T_N < T_\nu$ (depending on number of d.o.f. g_*)

$$\Delta N_{\mathrm{eff}}(T) = \left(\frac{T_N}{T_\nu}\right)^4 = \left(\frac{g_{*,\nu}}{g_{*,N}}\right)^{\frac{4}{3}}\Bigg|_T \left(\frac{g_{*,N}}{g_{*,\nu}}\right)^{\frac{4}{3}}\Bigg|_{T_X^{\mathrm{dpl}}}$$

$$\Delta N_{\mathrm{eff}}\big|_{\mathrm{BBN}} < \left(\frac{58.4}{g_{*,\nu}(T_X^{\mathrm{dpl}})}\right)^{\frac{4}{3}} \overset{!}{\lesssim} 1$$

$\rightsquigarrow$ BBN bounds satisfied for $T_X^{\mathrm{dpl}} \gtrsim 1$ GeV
$\rightsquigarrow$ Correct order of magnitude for hot dark matter hint

Hot Dark Matter Parameter Space



$$\Delta N_{\text{eff}}|_{\text{CMB}} = \left(\frac{58.4}{g_{*,\nu}(T_X^{\text{dpl}})}\right)^{\frac{4}{3}}$$

Sterile Neutrino Production by Oscillations

- Standard scenario: mixing between active and sterile neutrinos $\rightsquigarrow$ oscillations $\rightsquigarrow$ $\Delta N_{\text{eff}} \simeq 1$
- $U(1)_X$ interactions $\rightsquigarrow$ effective matter potential suppresses mixing $\rightsquigarrow$ no production by oscillations for $T \gtrsim$ MeV

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

Sterile Neutrino Production by Oscillations

- Standard scenario: mixing between active and sterile neutrinos
  $\rightsquigarrow$ oscillations $\rightsquigarrow$ $\Delta N_{\text{eff}} \simeq 1$
- $U(1)_X$ interactions $\rightsquigarrow$ effective matter potential suppresses mixing
  $\rightsquigarrow$ no production by oscillations for $T \gtrsim$ MeV
  Hannestad, Hansen, Tram, PRL **112** (2014); Dasgupta, Kopp, PRL **112** (2014)
- $T <$ MeV: mixing unsuppressed
  $\rightsquigarrow$ additional production of sterile neutrinos via $U(1)_X$?
  Bringmann, Hasenkamp, JK, JCAP **07** (2014)
- Oscillations $+$ $U(1)_X$-mediated scatterings $NN \to NN$
  $\rightsquigarrow$ N re-thermalize: $T_N = T_\nu$
  Mirizzi, Mangano, Pisanti, Saviano, PRD **91** (2015); Tang, PLB **750** (2015)
- Irreversible process $\rightsquigarrow$ only kinetic equilibrium
  Chu, Dasgupta, Kopp, JCAP **10** (2015)

Sterile Neutrino Production by Oscillations

- Standard scenario: mixing between active and sterile neutrinos
  $\rightsquigarrow$ oscillations $\rightsquigarrow$ $\Delta N_{\text{eff}} \simeq 1$
- $U(1)_X$ interactions $\rightsquigarrow$ effective matter potential suppresses mixing
  $\rightsquigarrow$ no production by oscillations for $T \gtrsim$ MeV
  Hannestad, Hansen, Tram, PRL **112** (2014); Dasgupta, Kopp, PRL **112** (2014)
- $T <$ MeV: mixing unsuppressed
  $\rightsquigarrow$ additional production of sterile neutrinos via $U(1)_X$?
  Bringmann, Hasenkamp, JK, JCAP **07** (2014)
- Oscillations $+$ $U(1)_X$-mediated scatterings $NN \to NN$
  $\rightsquigarrow$ N re-thermalize: $T_N = T_\nu$
  Mirizzi, Mangano, Pisanti, Saviano, PRD **91** (2015); Tang, PLB **750** (2015)
- Irreversible process $\rightsquigarrow$ only kinetic equilibrium
  Chu, Dasgupta, Kopp, JCAP **10** (2015)

$\rightsquigarrow$ $\Delta N_{\text{eff}}|_{\text{CMB}} \simeq$ const., but $T_N \uparrow \rightsquigarrow m_s^{\text{eff}} \uparrow$
$\rightsquigarrow$ Cosmology still fine, but neutrino anomalies not explained

Sterile Neutrinos Become Non-Relativistic

$$m_N \sim 1\text{ eV} > T_{\text{rec}} \sim 0.3\text{ eV}$$

$\rightsquigarrow$ sterile neutrinos not highly relativistic during CMB epoch

Jacques, Krauss, Lunardini, PRD **87** (2013)

$$N_{\text{eff}} = N_{\text{eff}}^{\text{rel}} \left(\frac{3}{4} + \frac{1}{4} \frac{P_{m_N = 1\text{ eV}}}{P_{m_N=0}} \right)$$

$\rightsquigarrow$ $N_{\text{eff}} \downarrow$

$\rightsquigarrow$ even $\Delta N_{\text{eff}} < 0$ possible $\rightsquigarrow$ possible test for scenario

Mirizzi, Mangano, Pisanti, Saviano, PRD **91** (2015)

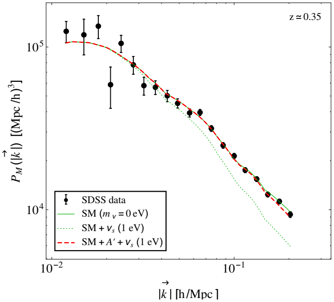
Chu, Dasgupta, Kopp, JCAP **10** (2015)

Cosmological Mass Bound

- CMB $+$ BAO $\rightsquigarrow$ $m_s^{\text{eff}} < 0.38$ eV at 95% CL Planck, arXiv:1502.01589
- Bound due to free-streaming of sterile neutrinos
- $U(1)_X$ interactions $\rightsquigarrow$ free-streaming scale reduced

Cosmological Mass Bound

- CMB + BAO $\rightsquigarrow m_s^{\text{eff}} < 0.38$ eV at 95% CL Planck, arXiv:1502.01589
- Bound due to free-streaming of sterile neutrinos
- $U(1)_X$ interactions $\rightsquigarrow$ free-streaming scale reduced
- Most sensitive constraints from Ly-α forest



Chu, Dasgupta, Kopp, JCAP **10** (2015)

$\rightsquigarrow m_N \sim 1$ eV can be consistent with cosmology

Conclusions

Particle physics solution for tensions in standard ΛCDM cosmology:

1. Self-interacting dark matter
2. Sterile neutrinos N with mass $\lesssim$ eV
3. Secret interactions mediated by gauge boson with mass $\sim$ MeV

- $N \rightsquigarrow$ small hot DM component, oscillation anomalies solved
- DM-DM scattering $\rightsquigarrow$ cusp-core, too big to fail solved
- Hint for self-interactions in Abell 3827 not explained (?)
- DM-N scattering $\rightsquigarrow$ missing satellites solved
- N-N scattering $\rightsquigarrow$ cosmological mass bound satisfied

Timeline

t ↑ / T ↓

$\gtrsim m_\chi \sim$ TeV: thermalization of $U(1)_X$ sector via Higgs portal

$T_\chi^{\mathrm{fo}} \sim m_\chi/25$: CDM freeze-out

$T_x^{\mathrm{dpl}} \gtrsim 10$ GeV: $U(1)_X$ sector decoupling

SM particles heat SM bath

matter effects prevent N_1 overproduction

BBN — $T_\nu^{\mathrm{dpl}} \sim$ MeV: active neutrino decoupling

$U(1)_X$ particles heat N_1

$T_\chi^{\mathrm{kd}} \sim 100$ eV: CDM kinetic decoupling

$T_{N_1}^{\mathrm{kd}}$: N_1 kinetic decoupling from itself

CMB — $T_{\mathrm{eq}} \sim 1$ eV: matter-radiation equality

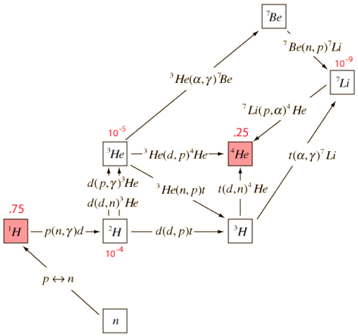
$T_\gamma^{\mathrm{dpl}} \sim 0.2$ eV: photon decoupling
N_1 becomes non-relativistic

CDM-CDM scattering via Yukawa potential

$T_0 \sim 0.2$ meV: today

Dark Radiation and Big Bang Nucleosynthesis

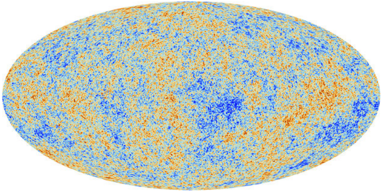
- $T \sim 1$ MeV: freeze-out of $n \leftrightarrow p$
  $\rightsquigarrow$ n/p ratio fixed
- $T \sim 0.1$ MeV: $p + n \to$ D
- Afterwards formation of ^{3}He, ^{4}He, ^{7}Li
- $\rho_{\text{rad}} \uparrow \rightsquigarrow$ faster expansion
  $\rightsquigarrow$ more n available for D fusion
  $\rightsquigarrow$ more ^{4}He
- $N_{\text{eff}} = 3.8^{+0.8}_{-0.7}$ at 2σ CL
  Izotov, Thuan, arXiv:1001.4440
- $\Delta N_{\text{eff}} \leq 1$ at 2σ CL
  Mangano, Serpico, arXiv:1103.1261

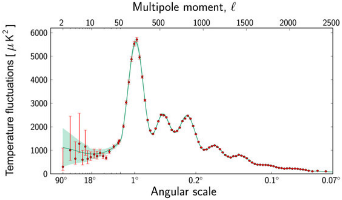


Dark Radiation Effects on the CMB

- $\rho_{\text{rad}} \uparrow \rightsquigarrow$ later matter-radiation equality
- $1^{\text{st}}/3^{\text{rd}}$ peak ratio $\rightsquigarrow$ no change $\rightsquigarrow \rho_{\text{m}} \uparrow \rightsquigarrow t_{\text{eq}}$ unchanged
- $\rho_{\text{rad}} \uparrow \rightsquigarrow$ sound horizon $r_s \propto 1/H \downarrow$
- Peak positions $\rightsquigarrow$ no change of angular size $\theta_s = \frac{r_s}{D_A} \rightsquigarrow D_A \propto 1/H \downarrow$ (by $\rho_\Lambda \uparrow$)
- Remaining effect: increased Silk damping $\rightsquigarrow$ reduced power on small scales

Hou et al., arXiv:1104.2333





Meet the Dark Side

- Dirac fermion χ (dark matter), $m_\chi \sim$ TeV
- Gauge boson V, $m_V \sim$ MeV
- Kinetic mixing $F^X_{\mu\nu}F^{\mu\nu}$, $F^X_{\mu\nu}Z^{\mu\nu}$ negligible
- Scalar Θ breaking $U(1)_X$, $\langle\Theta\rangle \sim$ MeV
- Light sterile neutrino N, $m_N \lesssim$ eV
- Heavier sterile neutrino N_2, $m_{N_2} \sim$ MeV $\rightsquigarrow$ cancel anomalies
- Scalar ξ, $\langle\xi\rangle < \langle\Theta\rangle$ $\rightsquigarrow$ active-sterile neutrino mixing

$$\mathcal{L}_N \supset -\frac{Y_M}{2}\Theta^\dagger\,\overline{N^c}N - \frac{Y'_M}{2}\Theta\,\overline{N_2^c}N_2 - \frac{Y_\nu}{\Lambda}\xi\tilde{\phi}\,\overline{\ell_L}N + \text{h.c.}$$