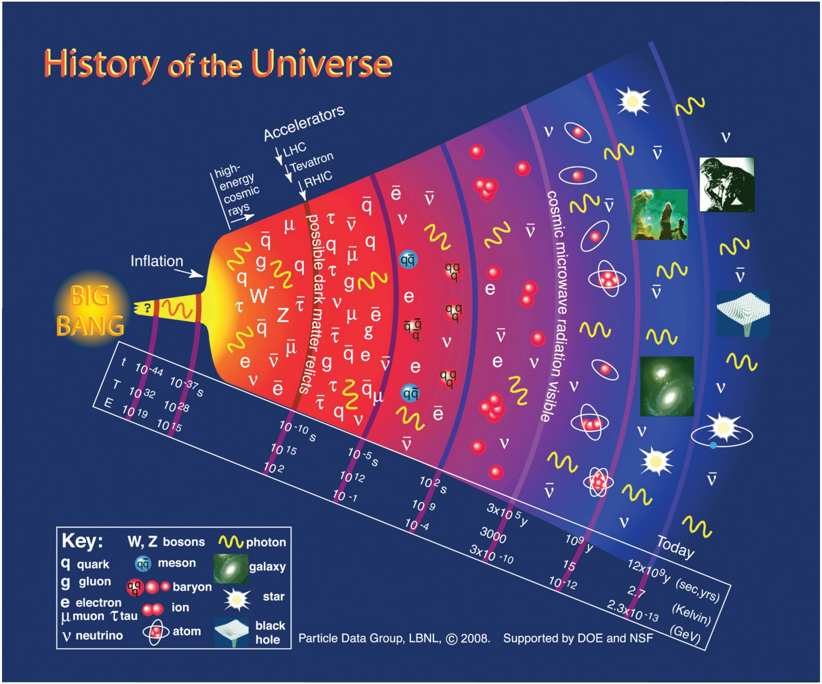
Cosmology Falling in Love with Sterile Neutrinos

Jörn Kersten

UNIVERSITY OF BERGEN

Based on Torsten Bringmann, Jasper Hasenkamp, JK, JCAP **07** (2014)

[arXiv:1312.4947]

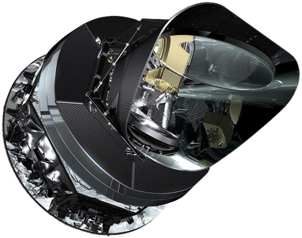


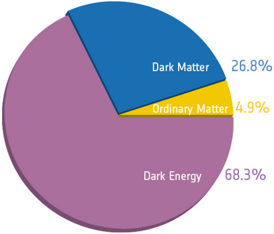
History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
?
possible dark matter relicts
cosmic microwave radiation visible
t 10^{-44} 10^{-37} s
T 10^{32} 10^{28}
E 10^{19} 10^{15}
10^{-10} s
10^{15}
10^{2}
10^{-5} s
10^{12}
10^{-1}
10^{2} s
10^{9}
10^{-4}
$3x10^{5}$ y
3000
$3x10^{-10}$
10^{9} y
15
10^{-12}
Today
$12x10^{9}$ y (sec,yrs)
2.7 (Kelvin)
$2.3x10^{-13}$ (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
µ muon τ tau
atom
black hole
ν neutrino
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Outline

1. Introduction
2. Self-Interacting Dark Matter
3. Dark Matter Interacting with Neutrinos

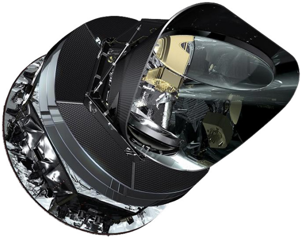
The Universe after Planck

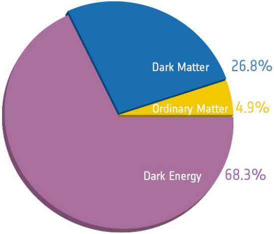




Flat ΛCDM cosmology fits data perfectly Planck, arXiv:1303.5062

The Universe after Planck





Flat ΛCDM cosmology fits data perfectly Planck, arXiv:1303.5062

Or does it?
Tensions in ΛCDM cosmology

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 $\Leftrightarrow \Delta N_{\text{eff}} \equiv N_{\text{eff}} - 3.046 > 0$

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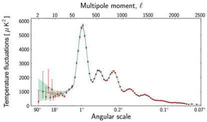
- Existence of dark radiation $\Leftrightarrow \Delta N_{\text{eff}} \equiv N_{\text{eff}} - 3.046 > 0$
- Measurements of Cosmic Microwave Background (CMB):

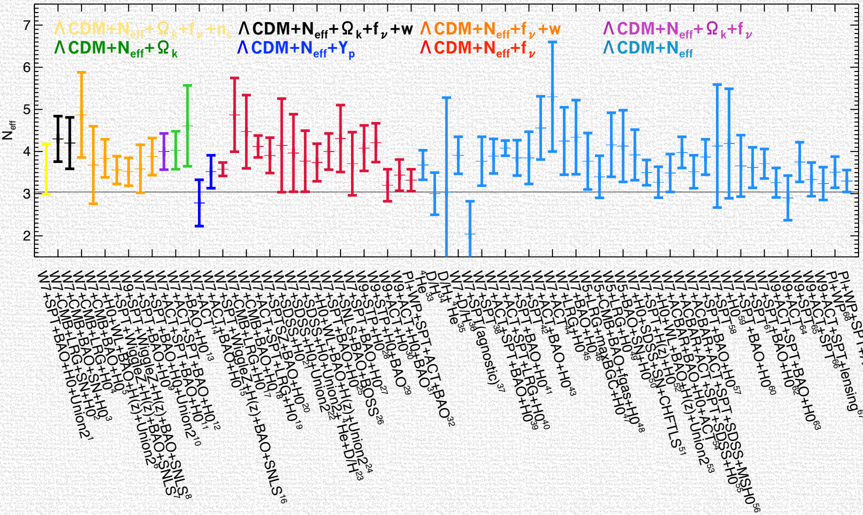
$\Delta N_{\text{eff}} = 1.51 \pm 0.75$ at 68% CL ACT, ApJ **739** (2011)

$\Delta N_{\text{eff}} = 0.81 \pm 0.42$ at 68% CL SPT, ApJ **743** (2011)

$\Delta N_{\text{eff}} = 0.31^{+0.68}_{-0.64}$ at 95% CL Planck, arXiv:1303.5076



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: $H_0 = (67.3 \pm 1.2)\frac{\text{km}}{\text{s Mpc}}$ arXiv:1303.5076
  - Hubble: $H_0 = (73.8 \pm 2.4)\frac{\text{km}}{\text{s Mpc}}$ Riess et al., ApJ **730** (2011)

- Magnitude of matter density fluctuations (σ_8)

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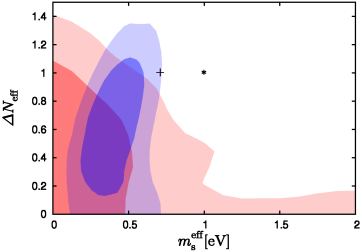
- Magnitude of matter density fluctuations (σ_8)
- Resolved by hot dark matter component $\simeq$ dark radiation
- Best fit:

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

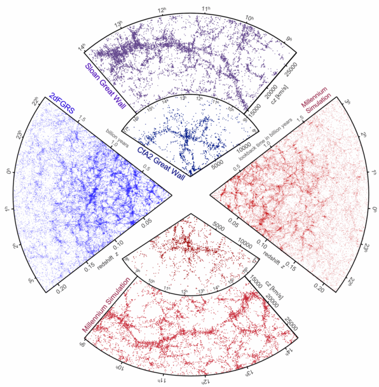
$$m_s^{\text{eff}} \equiv \left(\frac{T_s}{T_\nu}\right)^3 m_s = 0.41\ \text{eV}$$

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



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

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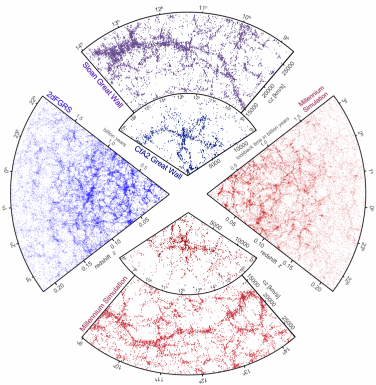
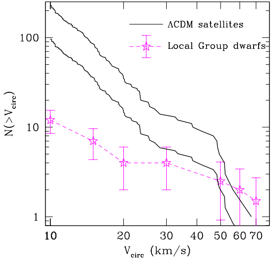


Springel, Frenk, White, Nature **440** (2006)

$\rightsquigarrow$ Excellent agreement with observations on large scales

Small-Scale Problems of Structure Formation

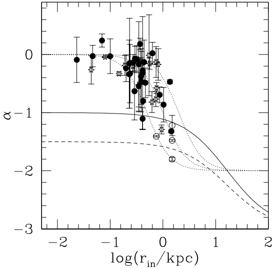
Missing satellites



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

More galactic satellites predicted than observed

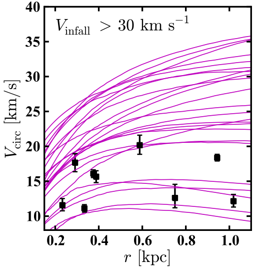
Cusp-core



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

More cuspy density profiles predicted than observed

Too big to fail

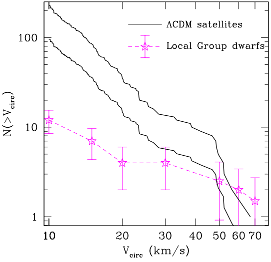


Boylan-Kolchin et al., MNRAS **422** (2011)

Most massive satellites predicted denser than observed

Small-Scale Problems of Structure Formation

Missing satellites



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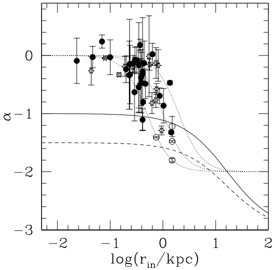

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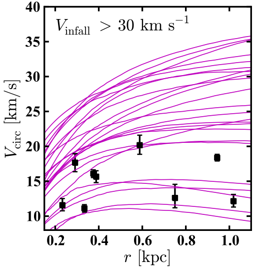


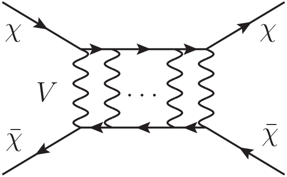
Boylan-Kolchin et al., MNRAS **422** (2011)

Most massive satellites predicted denser than observed

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

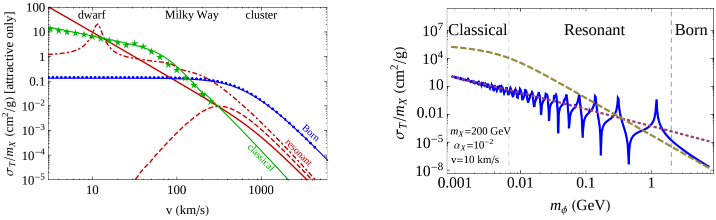


$\rightsquigarrow$ Long-range, velocity-dependent interaction
$\rightsquigarrow$ Less cuspy density profiles
$\rightsquigarrow$ Cusp-core and too big to fail solved

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
- Very different behavior depending on model parameters



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

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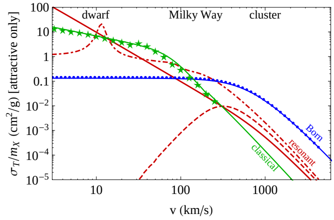

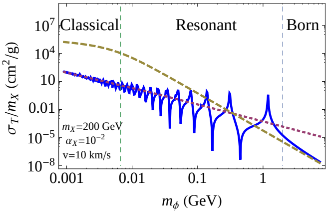

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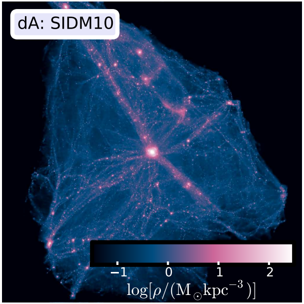
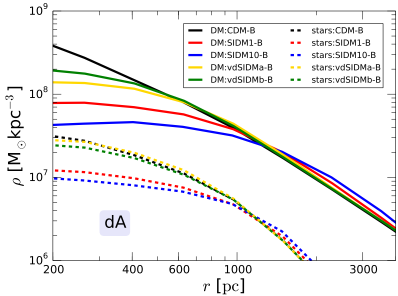
$$\text{Here: } \frac{m_\chi v}{m_V} \sim \frac{\text{TeV}}{\text{MeV}} \frac{10\ \text{km/s}}{3 \cdot 10^5\ \text{km/s}} \sim 30 \gg 1$$

$\rightsquigarrow$ classical regime $\rightsquigarrow$ analytical approximations exist

Simulation: formation of dwarf galaxy with dark matter + baryons



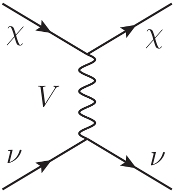


Vogelsberger, Zavala, Simpson, Jenkins, MNRAS **444** (2014)

⇝ Core, size depends on strength of self-interactions

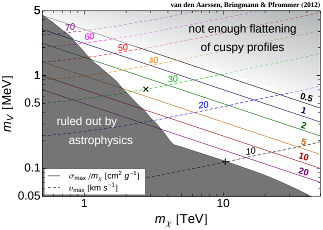
Late Kinetic Decoupling

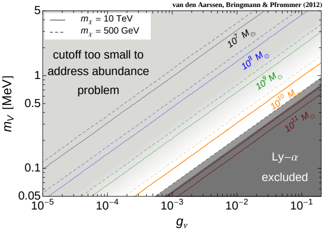
- Standard Model neutrinos coupled to V
- Dark matter scatters off neutrinos

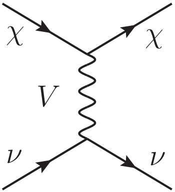


⇝ $T_\chi = T_\nu$ until kinetic decoupling at $T \sim 100\,\mathrm{eV}$
⇝ Formation of smaller structures suppressed
⇝ Missing satellites solved

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







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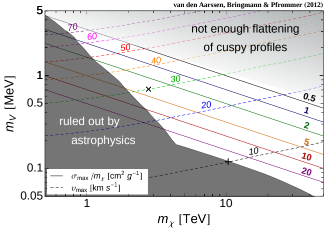
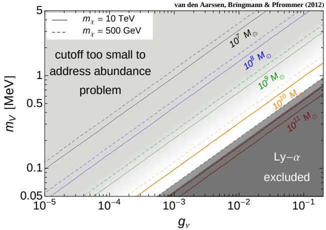
Van den Aarssen, Bringmann, Pfrommer, PRL **109** (2012)

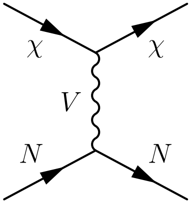
Problem: explicit breaking of $SU(2)_L$





Enter the Sterile Neutrino

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



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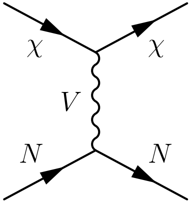


$\rightsquigarrow$ Everything solved

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

Bringmann, Hasenkamp, JK, JCAP **07** (2014)

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

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

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 $U(1)_X$

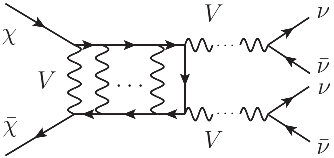
Dark Matter Production

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

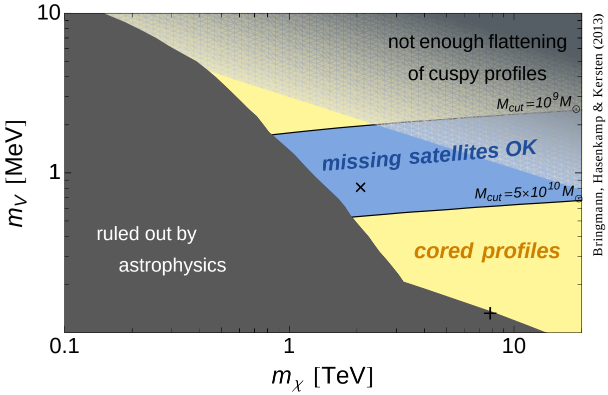
$$\mathcal{L}_{\text{Higgs}} \supset \kappa |H|^2 |\Theta|^2$$

- $\langle\Theta\rangle \sim$ 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

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_*)

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

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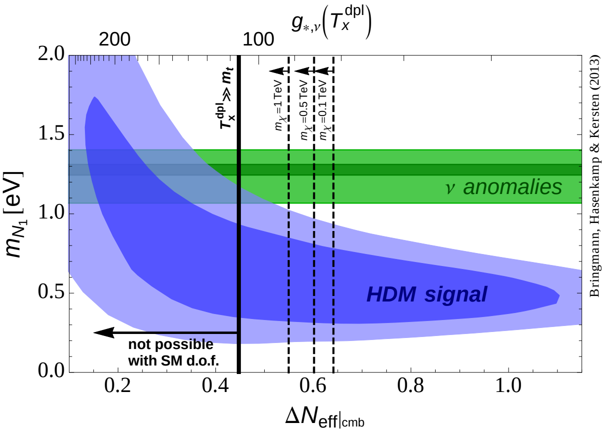
$$\Delta N_{\text{eff}}\big|_{\text{BBN}} < \left(\frac{58.4}{g_{*,\nu}(T_x^{\text{dpl}})}\right)^{\frac{4}{3}} \overset{!}{\lesssim} 1$$

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

Hot Dark Matter Parameter Space



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

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)

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  Hannestad, Hansen, Tram, PRL **112** (2014); Dasgupta, Kopp, PRL **112** (2014)
- $T <$ MeV: mixing unsuppressed
- Oscillations + $U(1)_X$-mediated scatterings $NN \to NN$
  $\rightsquigarrow$ N re-thermalize $\rightsquigarrow$ $T_N = T_\nu$
  Mirizzi, Mangano, Pisanti, Saviano, arXiv:1410.1385
  Cherry, Friedland, Shoemaker, arXiv:1411.1071

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With full re-thermalization:

$$\Delta N_{\text{eff}}\big|_{\text{CMB}} \simeq \text{const.}$$

$$m_N = \frac{2\sqrt{2}}{N_{\text{eff}}\big|_{\text{CMB}}^{3/4}}\, m_s^{\text{eff}} \simeq \frac{2\sqrt{2}}{3.6^{3/4}}\, 0.4\ \text{eV} < 1\ \text{eV}$$

$\rightsquigarrow$ Cosmology still fine but neutrino anomalies not explained

Conclusions

Particle physics solution for tensions in standard ΛCDM cosmology:

Sterile neutrinos N with mass $\lesssim$ eV $+$ self-interacting dark matter

- $N \rightsquigarrow$ small hot DM component
- New interaction mediated by gauge boson with mass $\sim$ MeV
- DM-DM scatterings $\rightsquigarrow$ cusp-core, too big to fail solved
- DM-N scattering $\rightsquigarrow$ missing satellites solved

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Outlook

- Interaction by scalar exchange possible and favorable?
- Further options for model building
- Connection to 3.5 keV X-ray line?
- Re-thermalization
- Improved treatment of scattering in Yukawa potential

Timeline

t

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

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

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

SM particles heat SM bath

matter effects prevent N_1 overproduction

BBN

$T_\nu^{\rm dpl} \sim$ MeV: active neutrino decoupling

$U(1)_X$ particles heat N_1

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

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

CMB

$T_{\rm eq} \sim 1$ eV: matter-radiation equality

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

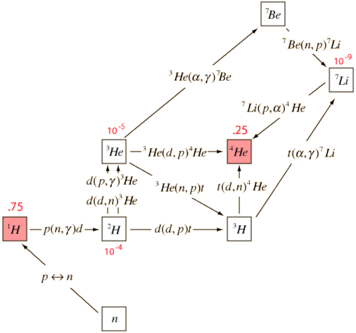
CDM-CDM scattering via Yukawa potential

$T_0 \sim 0.2$ meV: today

T

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: $p + n \to \mathrm{D}$
- Afterwards formation of ^{3}He, ^{4}He, ^{7}Li
- $\rho_{\mathrm{rad}} \uparrow \rightsquigarrow$ faster expansion
  $\rightsquigarrow$ more n available for D fusion
  $\rightsquigarrow$ more ^{4}He
- $N_{\mathrm{eff}} = 3.8^{+0.8}_{-0.7}$ at 2σ CL
  Izotov, Thuan, arXiv:1001.4440
- $\Delta N_{\mathrm{eff}} \leq 1$ 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