Late Kinetic Decoupling and Self-Interacting Dark Matter

Jörn Kersten

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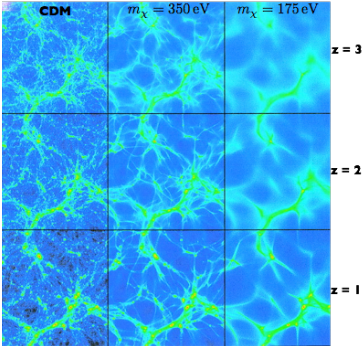
Based on
Torsten Bringmann, Håvard Ihle, JK, Parampreet Walia, PRD **94**, 103529 (2016)
[arXiv:1603.04884]
Torsten Bringmann, Jasper Hasenkamp, JK, JCAP **07**, 042 (2014)
[arXiv:1312.4947]

Outline

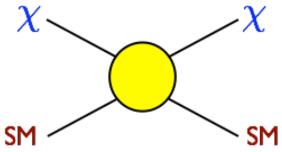
Warm Dark Matter

- Standard solution to missing satellites problem
- Neither hot nor cold
  $\rightsquigarrow$ some free streaming
  $\rightsquigarrow$ smaller structures washed out
- Creates cores in dwarf galaxies
  if free-streaming length $>$ dwarf size
  $\rightsquigarrow$ prevents formation of dwarf
  Catch 22 problem of WDM
  Macciò et al., MNRAS 424 (2012)



Bode & Ostriker, ApJ **556** (2001)

Kinetic Decoupling



- Many more partners for scattering than for annihilation
  $\rightsquigarrow$ Kinetic decoupling much later than freeze-out, $T_{\mathrm{kd}} \ll T_{\mathrm{fo}}$

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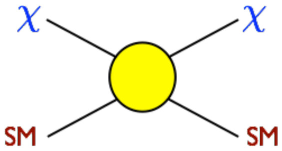

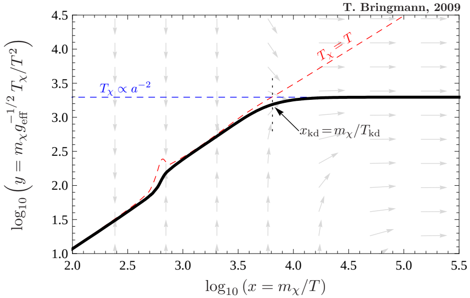

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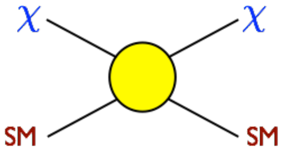
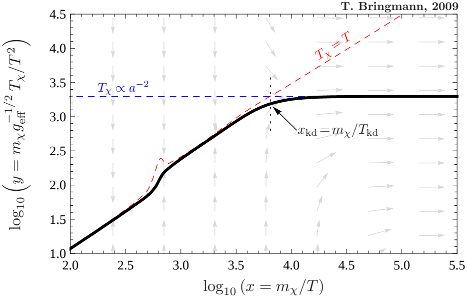
- $T_\chi = T$ until kinetic decoupling

Kinetic Decoupling





- Many more partners for scattering than for annihilation
  $\rightsquigarrow$ Kinetic decoupling much later than freeze-out, $T_{\rm kd} \ll T_{\rm fo}$
- $T_\chi = T$ until kinetic decoupling
- Standard WIMPs: $T_{\rm kd} \gtrsim 1$ MeV $\rightsquigarrow$ effect negligible
  Bringmann, New J. Phys. **11** (2009)

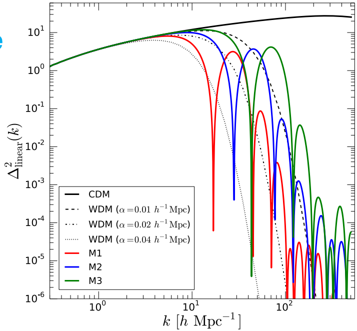
Suppressing Dwarfs by Late Kinetic Decoupling

- Dark matter density fluctuations damped by
  - collisional damping (viscous coupling to SM particles)
  - free-streaming after kinetic decoupling
  - acoustic oscillations shared with SM particles

⇝ Structure formation suppressed at small scales

Green, Hofmann, Schwarz, JCAP **08** (2005)
Loeb & Zaldarriaga, PRD **71** (2005)

See talk by Francis-Yan Cyr-Racine



Vogelsberger et al., MNRAS **460** (2016)

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- Cutoff in power spectrum of density fluctuations

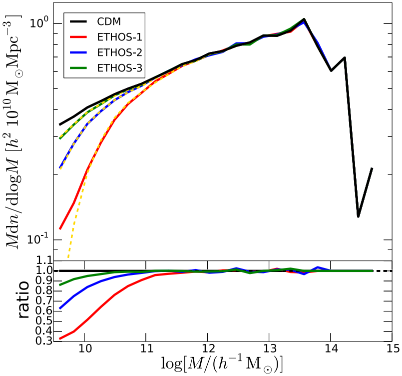
  $\rightsquigarrow$ Minimal halo mass Vogelsberger et al., MNRAS **460** (2016)

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

- Want: $M_{\text{cut}} \simeq 10^{10}\, M_\odot$

  $\rightsquigarrow$ Missing satellite problem solved with cold DM for $T_{\text{kd}} \lesssim 1$ keV

- Similarity to WDM cosmology confirmed by *N*-body simulations



Vogelsberger et al., MNRAS **460** (2016)

Particle Physics Models with Late Kinetic Decoupling

- Need scattering partner $\tilde{\gamma}$ with large abundance until $T_{\text{kd}} \lesssim 1$ keV
  $\rightsquigarrow$ photon, (SM) neutrino, dark radiation
- Here: classification of all minimal possibilities
  Bringmann, Ihle, JK, Walia, PRD **94** (2016)

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  $\rightsquigarrow$ photon, (SM) neutrino, dark radiation
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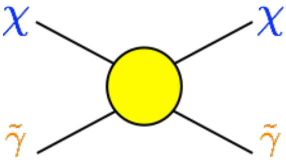
  Bringmann, Ihle, JK, Walia, PRD **94** (2016)
- Scattering amplitude close to kinetic decoupling:

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

$$\rightsquigarrow M_{\text{cut}} \simeq M_n \left(\frac{T_{\tilde{\gamma}}}{T}\right)^{3\,\frac{n+4}{n+2}} \left(\frac{c_n}{10^{-3}}\right)^{\frac{3}{n+2}} \left(\frac{100\text{ GeV}}{m_\chi}\right)^{3\,\frac{n+3}{n+2}}$$



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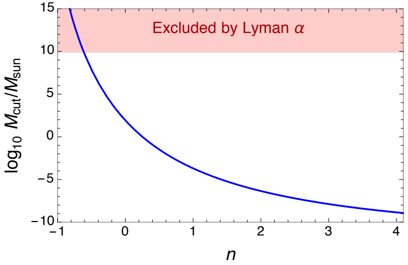

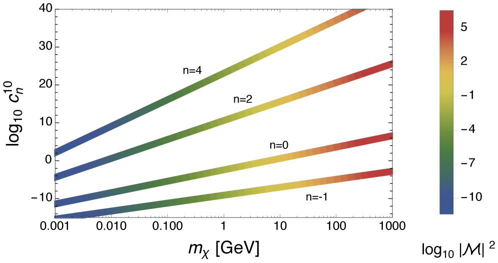

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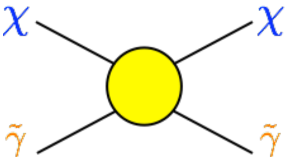

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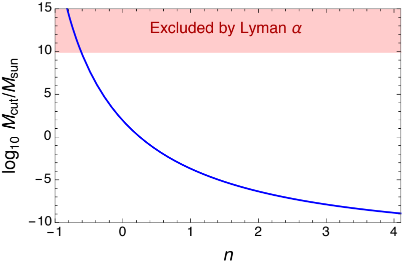

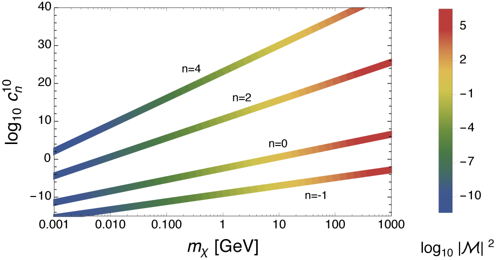

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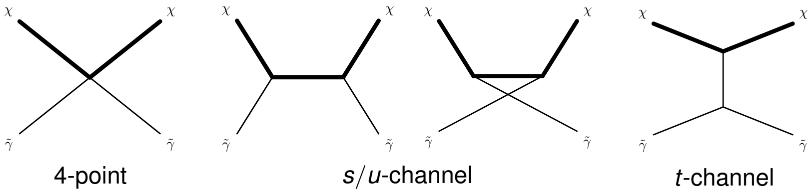
$\rightsquigarrow$ Need large coefficients c_n and/or light dark matter

Model Classification

- Consider all dark matter and dark radiation spin combinations
- Assume Z_2 symmetry to stabilize dark matter
- Consider all renormalizable and gauge-invariant interactions
- Types of scattering diagrams:



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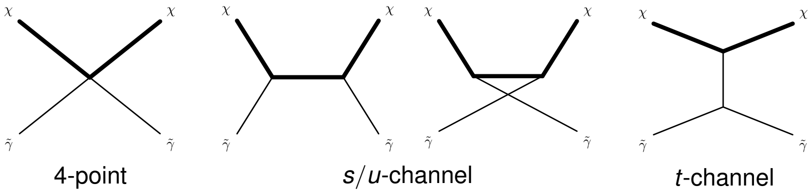

- Take into account inherently related processes
  - Dark matter relic density ($\chi\chi \to \tilde{\gamma}\tilde{\gamma}$)
  - Dark matter self-interactions ($\chi\chi \to \chi\chi$)

Two-Particle Models

Late kinetic decoupling | DM relic density | DM self-interactions

$\tilde\gamma \setminus \chi$		**Scalar**			**Fermion**			**Vector**
	TOP	LKD	TP	σ_T	LKD	TP	σ_T	
Scalar	$4p$	$m_\chi \lesssim$ MeV	Yes	Constant	(only dim > 4)			$\langle\sigma_T\rangle_{30}$
	t	$m_{\tilde\gamma} \sim 1$ keV $m_\chi \gtrsim 100\alpha_\chi^{3/5}$ TeV	$\langle\sigma_T\rangle_{30}$ (for $m_\chi \gtrsim 1$ MeV)	Yukawa	$m_{\tilde\gamma} \sim 1$ keV $m_\chi \gtrsim 100\alpha_\chi^{3/5}$ TeV	$\langle\sigma_T\rangle_{30}$ (for $m_\chi \gtrsim 1$ MeV)	Yukawa	
	s/u	$\langle\sigma_T\rangle_{30}$			$\langle\sigma_T\rangle_{30}$			
Fermion		(only dim > 4 due to Z_2)			(only dim > 4)			Z_2
Vector	$4p$	(only dim > 4)			(only dim > 4)			Z_2
	s/u	$\langle\sigma_T\rangle_{30}$			$\langle\sigma_T\rangle_{30}$			
	$SU(N)$	$m_{\tilde\gamma} \sim 1$ keV $m_\chi \gtrsim 10\alpha_\chi^{3/5}$ TeV	$\langle\sigma_T\rangle_{30}$ (for $m_\chi \gtrsim 1$ MeV)	Yukawa	$m_{\tilde\gamma} \sim 1$ keV $m_\chi \gtrsim 10\alpha_\chi^{3/5}$ TeV	$\langle\sigma_T\rangle_{30}$ (for $m_\chi \gtrsim 1$ MeV)	Yukawa	(only broken $SU(M) \to SU(N)$)

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Late kinetic decoupling — DM relic density — DM self-interactions

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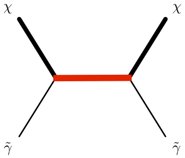
- Massless DR and MeV DM possible for scalar portal: $\mathcal{L} \supset \chi^2\tilde{\gamma}^2$
- Scalar or non-Abelian keV DR and scalar or fermion DM possible

Three-Particle Models

- Additional particle in s/u-channel
  - Nearly degenerate with DM $\rightsquigarrow$ on-shell enhancement
  - Solution of missing satellites possible for $m_\chi \lesssim 10\,\text{GeV}$



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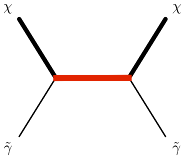
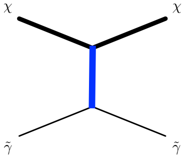
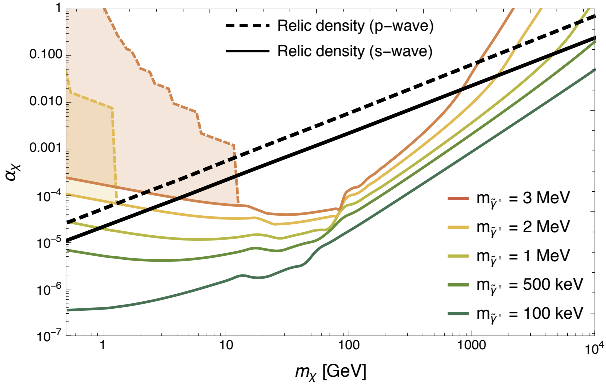


- Additional particle V in t-channel
  - Light $\rightsquigarrow$ enhanced scattering rate
  - Missing satellites solved for almost any DM mass
  - Correct DM density from $\chi\chi \to VV$
  - DM self-interactions $\rightsquigarrow$ all small-scale problems solved



Desired Self-Interactions with t-Channel Mediator



$\rightsquigarrow$ Both $m_\chi \sim$ GeV and $m_\chi \sim$ TeV work

Constraints from Dark Matter Annihilation

See talks by Bryan Zaldivar and this afternoon

Dark matter annihilation to light mediator $\chi\chi \to VV$ enhanced by

- Sommerfeld effect Bringmann, Kahlhoefer, Schmidt-Hoberg, Walia, PRL **118** (2017)
- Bound state formation Cirelli, Panci, Petraki, Sala, Taoso, JCAP **05** (2017)

$\rightsquigarrow$ Ruled out by CMB and indirect DM searches,
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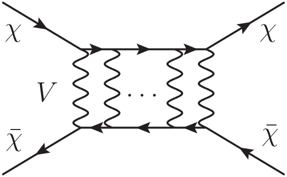
$\rightsquigarrow$ Way out: invisible decays

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

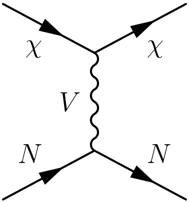
$\rightsquigarrow$ Long-range, velocity-dependent interaction
$\rightsquigarrow$ Less cuspy density profiles
$\rightsquigarrow$ Cusp-core and too big to fail solved



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

Enter the Sterile Neutrino

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



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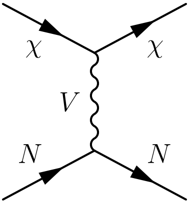

⇝ Late kinetic decoupling

⇝ All small-scale problems of structure formation solved

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

⇝ Dark matter annihilation constraints avoided by decay $V \to NN$

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

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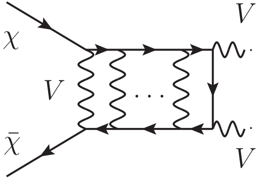
$$\mathcal{L}_{\text{Higgs}} \supset \kappa |H|^2 |\Theta|^2$$

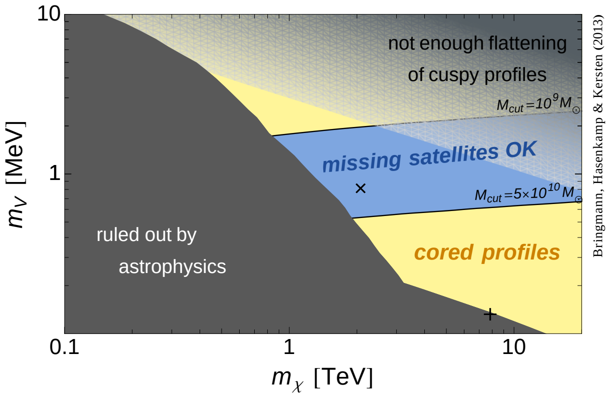
- $\langle\Theta\rangle \sim$ MeV breaks $U(1)_X$
- $T_\chi \sim m_\chi/25$: freeze-out (chemical decoupling) of dark matter

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

(neglecting bound state formation)



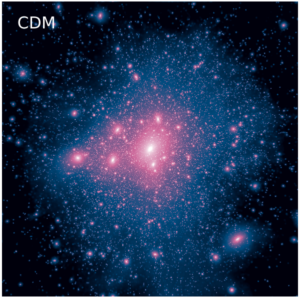
Cold Dark Matter Parameter Space

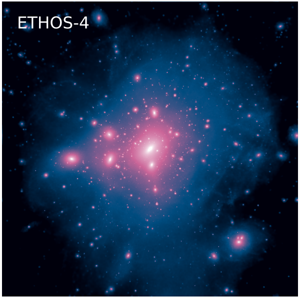


- Blue band can be moved vertically by changing sterile neutrino charge and temperature
- Crosses: simulations show that too big to fail solved

Results from ETHOS

N-body simulation with DM-DM and DM-*N* interactions





Vogelsberger et al., MNRAS **460** (2016)

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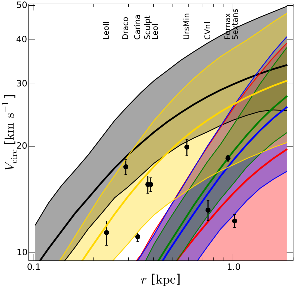
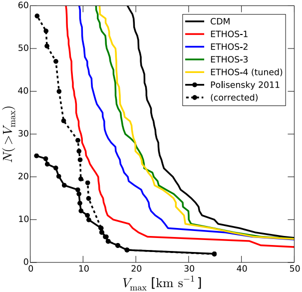




Vogelsberger et al., MNRAS **460** (2016)

- Confirms solution (alleviation) of too big to fail, missing satellites
- Cusp-core and rotation curve diversity unclear
  (but see talk by Hai-Bo Yu)

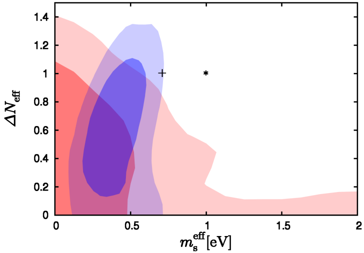
Hints for Hot Dark Matter

- 3 σ tension: CMB ($z > 1000$) vs. local ($z < 10$) observations
- Expansion rate
  - Planck: $H_0 = (67.8 \pm 0.9)\frac{\text{km}}{\text{s Mpc}}$ A&A **594** (2016)
  - Hubble: $H_0 = (73.24 \pm 1.74)\frac{\text{km}}{\text{s Mpc}}$ Riess et al., ApJ **826** (2016)
- 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)
Gariazzo, Giunti, Laveder, JHEP **11** (2013)
Wyman, Rudd, Vanderveld, Hu, PRL **112** (2014)
Battye, Moss, PRL **112** (2014)



$\rightsquigarrow$ Added value of sterile neutrino

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

Sterile Neutrino Production by Oscillations

- Standard scenario: mixing between active and sterile neutrinos $\rightsquigarrow$ oscillations $\rightsquigarrow$ $\Delta N_{\text{eff}} \simeq 1$ $\rightsquigarrow$ ruled out by Planck
- $U(1)_X$ 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 $\rightsquigarrow$ $\Delta N_{\mathrm{eff}} \simeq 1$ $\rightsquigarrow$ ruled out by Planck
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$\rightsquigarrow$ Cosmology (ΔN_{eff}) still fine, but m_N too small to explain neutrino oscillation anomalies

Conclusions

- Late kinetic decoupling can solve missing satellites problem
  - Need new dark radiation particle as scattering partner
  - Favorite scenario: t-channel mediator with mass $\sim$ MeV
    $\rightsquigarrow$ correct dark matter relic density
    $\rightsquigarrow$ DM self-interactions solve cusp-core, too big to fail problems
- Concrete model
  - Dark matter with mass $\sim$ TeV
  - Sterile neutrino with mass $\lesssim$ eV $\rightsquigarrow$ small hot DM component
  - Gauge boson with mass $\sim$ MeV $\rightsquigarrow$ secret interactions

Timeline

t

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

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

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

SM particles heat SM bath

matter effects prevent N_1 overproduction

BBN

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

$U(1)_X$ particles heat N_1

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

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

CMB

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

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

CDM-CDM scattering via Yukawa potential

$T_0 \sim 0.2$ meV: today

T

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

$$\mathcal{L}_N \supset -\frac{Y_M}{2}\Theta^\dagger\,\overline{N^c}N - \frac{Y'_M}{2}\Theta\,\overline{N^c_2}N_2 - \frac{Y_\nu}{\Lambda}\xi\tilde{\phi}\,\overline{\ell_\mathrm{L}}N + \text{h.c.}$$

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$\rightsquigarrow$ $\Delta N_{\text{eff}}|_{\text{CMB}} \simeq$ 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, A&A **594** (2016)
- Bound due to free-streaming of sterile neutrinos
- $U(1)_X$ interactions $\rightsquigarrow$ free-streaming scale reduced

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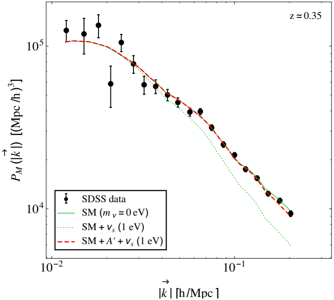
- Most sensitive constraints from Ly-α forest



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

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