Late Kinetic Decoupling and Self-Interacting Dark Matter

Jörn Kersten

UNIVERSITY OF BERGEN

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`]
See also yesterday's talk by Pyungwon Ko

Outline

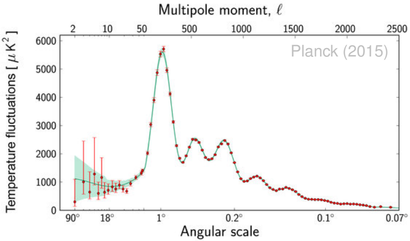
1. Tensions in ΛCDM Cosmology
2. Late Kinetic Decoupling
3. Dark Matter Interacting with Sterile Neutrinos

1. Tensions in ΛCDM Cosmology

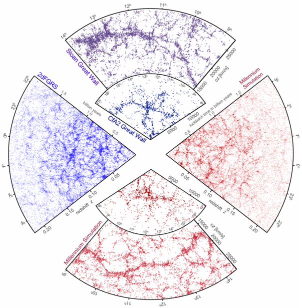
2. Late Kinetic Decoupling

3. Dark Matter Interacting with Sterile Neutrinos

ΛCDM Cosmology Works Great



Planck (2015)



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Supernova Cosmology Project
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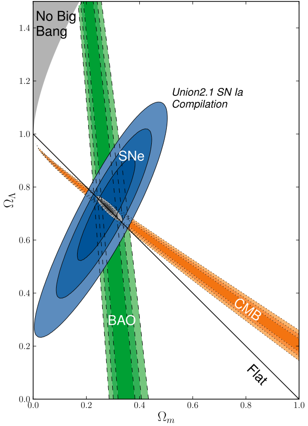

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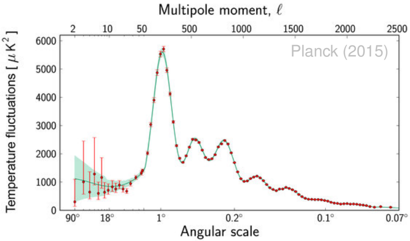

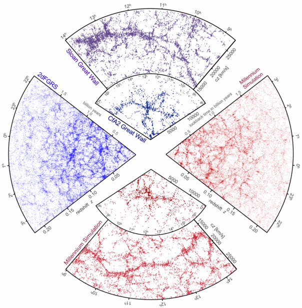

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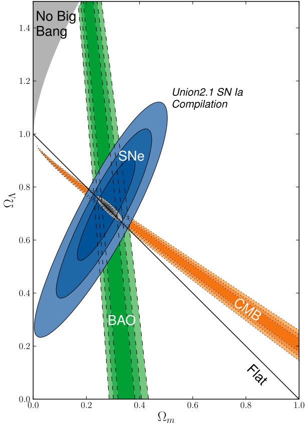
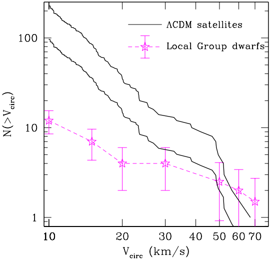


. . . on large scales

Small-Scale Problems of Structure Formation

See also talks by Kenji Kadota and Pyungwon Ko

Missing satellites



Kravtsov, Adv. Astron. (2010)
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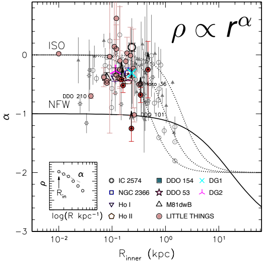
More galactic satellites predicted than observed

Cusp-core



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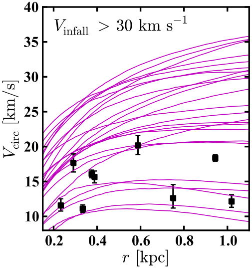
More cuspy density profiles predicted than observed

Too big to fail



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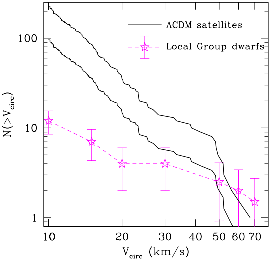

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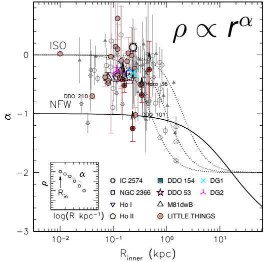

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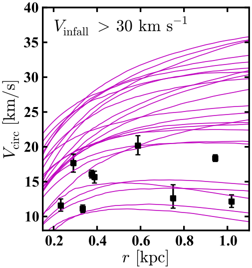

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Astrophysics solutions or new particle physics?

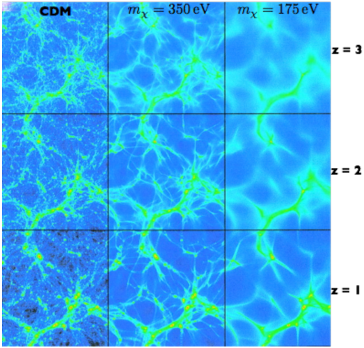
1 Tensions in ΛCDM Cosmology

2 Late Kinetic Decoupling

3 Dark Matter Interacting with Sterile Neutrinos

Warm Dark Matter

- Standard solution to missing satellites problem
- Neither hot nor cold
  $\rightsquigarrow$ some free streaming
  $\rightsquigarrow$ smaller structures washed out



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

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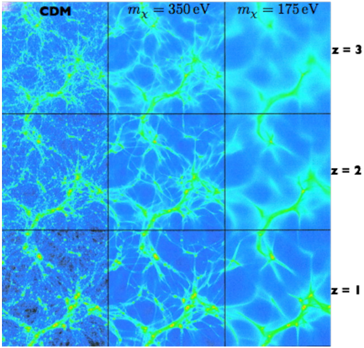

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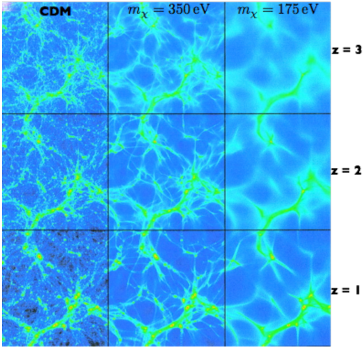
Warm Dark Matter

- 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)



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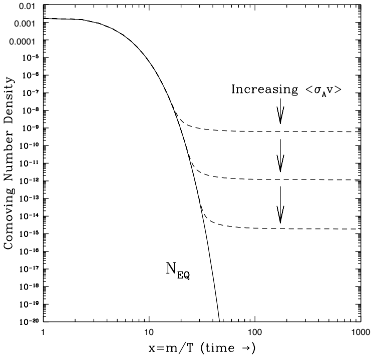
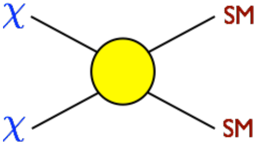
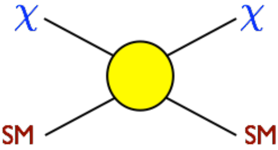
Chemical Decoupling

- Better known as freeze-out (from thermal/chemical equilibrium)
- Typically $T_{\text{fo}} \sim \frac{m_\chi}{25}$
- Determined by DM annihilation





Kinetic Decoupling



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  $\rightsquigarrow$ Kinetic decoupling much later than freeze-out, $T_{\text{kd}} \ll T_{\text{fo}}$

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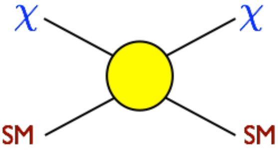
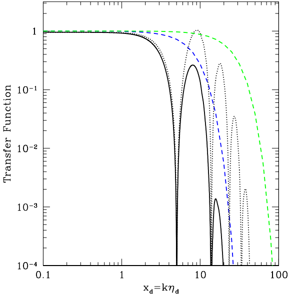
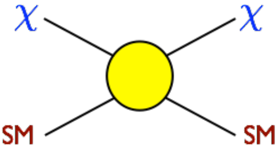
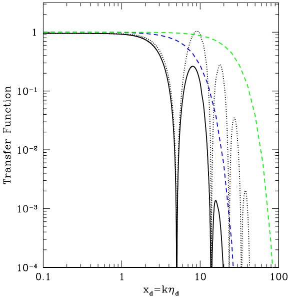




- Many more partners for scattering than for annihilation
  $\rightsquigarrow$ Kinetic decoupling much later than freeze-out, $T_{\mathrm{kd}} \ll T_{\mathrm{fo}}$
- Dark matter shares acoustic oscillations of SM particles
  $\rightsquigarrow$ Structure formation suppressed at small scales
  Loeb & Zaldarriaga, PRD **71** (2005)

Kinetic Decoupling





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- Standard WIMPs: $T_{\text{kd}} \gtrsim 1$ MeV $\rightsquigarrow$ effect negligible
  Bringmann, New J. Phys. **11** (2009)

Suppressing Dwarfs by Late Kinetic Decoupling

- Cutoff in power spectrum of density fluctuations

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

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

$$\text{Warm dark matter} \rightsquigarrow M_{\text{cut}} = 10^{11} \left(\frac{1\text{ keV}}{m_{\text{WDM}}} \right)^4 h^{-1}\, M_\odot$$

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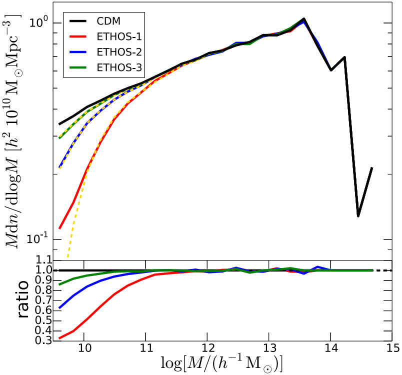

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Particle Physics Models with Late Kinetic Decoupling

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

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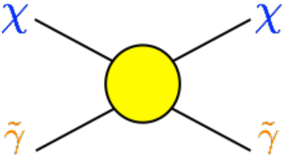
- Scattering amplitude close to kinetic decoupling:

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

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



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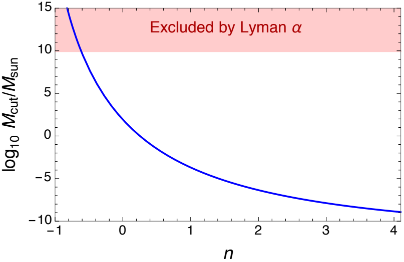

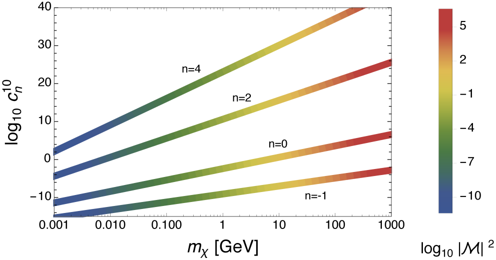

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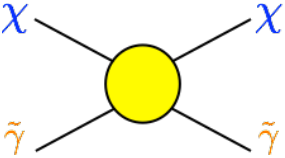

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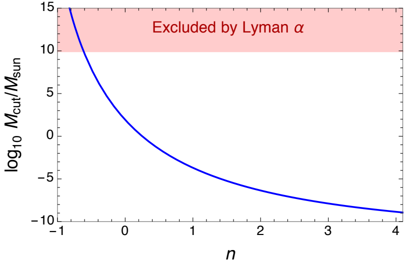

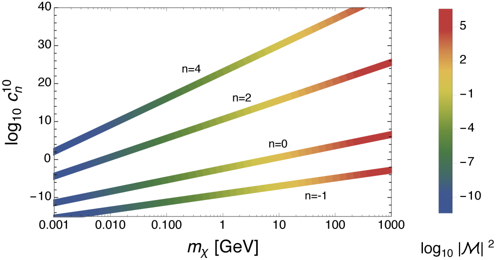

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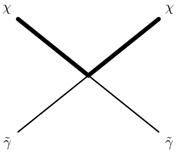
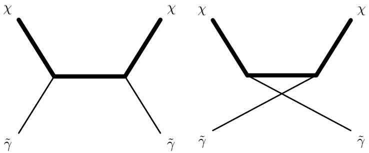
$\rightsquigarrow$ Need large coefficients c_n and/or light dark matter

Model Classification

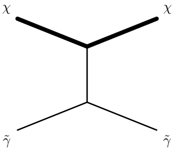
- Consider all dark matter and dark radiation spin combinations
- Assume Z_2 symmetry to stabilize dark matter
- Consider all renormalizable and gauge-invariant interactions
- Types of scattering diagrams:



4-point



s/u-channel



t-channel

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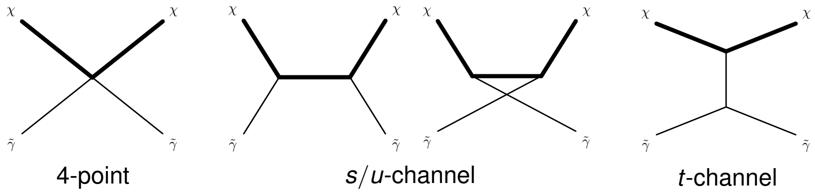

- Take into account inherently related processes
  - Dark matter relic density ($\chi\chi \to \tilde{\gamma}\tilde{\gamma}$)
  - Dark matter self-interactions ($\chi\chi \to \chi\chi$)

Two-Particle Models

$\tilde{\gamma} \setminus \chi$		**Scalar**			**Fermion**			**Vector**
	TOP	LKD	TP	σ_T	LKD	TP	σ_T	
Scalar	$4p$	$m_\chi \lesssim \text{MeV}$	Yes	Constant	(only dim > 4)			$\langle \sigma_T \rangle_{30}$
	t	$m_{\tilde{\gamma}} \sim 1\,\text{keV}$ $m_\chi \gtrsim 100 \alpha_\chi^{3/5}$ TeV	$\langle \sigma_T \rangle_{30}$ (for $m_\chi \gtrsim 1\,\text{MeV}$)	Yukawa	$m_{\tilde{\gamma}} \sim 1\,\text{keV}$ $m_\chi \gtrsim 100 \alpha_\chi^{3/5}$ TeV	$\langle \sigma_T \rangle_{30}$ (for $m_\chi \gtrsim 1\,\text{MeV}$)	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
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Two-Particle Models

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

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

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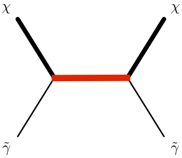
- Massless DR and MeV DM possible for scalar portal: $\mathcal{L} \supset \chi^2\tilde{\gamma}^2$
- Scalar or non-Abelian keV DR and scalar or fermion DM possible

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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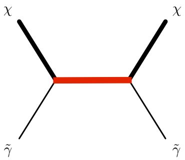
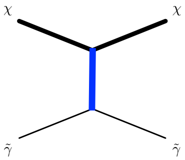


- Additional particle V in t-channel
  - Light $\rightsquigarrow$ enhanced scattering rate
  - Missing satellites solved for almost any DM mass
  - Correct DM density from $\chi\chi \to VV$
  - DM self-interactions $\rightsquigarrow$ all small-scale problems solved



Constraints from Dark Matter Annihilation

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)
  (see talk by Marco Cirelli)

⇝ Ruled out by CMB and indirect DM searches,
if mediator decays dominantly to SM particles

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$\rightsquigarrow$ Way out: invisible decays

1 Tensions in ΛCDM Cosmology

2 Late Kinetic Decoupling

3 Dark Matter Interacting with Sterile Neutrinos

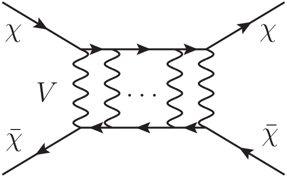
Not-so-WIMPy Dark Matter

- 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

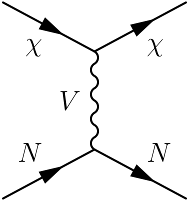
$\rightsquigarrow$ Cusp-core and too big to fail solved



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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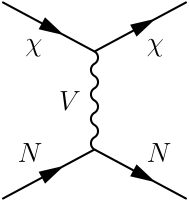

$\rightsquigarrow$ Late kinetic decoupling

$\rightsquigarrow$ 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)

$\rightsquigarrow$ 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 $U(1)_X$

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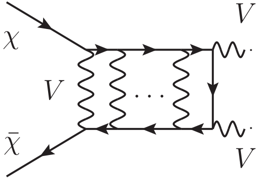
$$\mathcal{L}_{\text{Higgs}} \supset \kappa |H|^2 |\Theta|^2$$

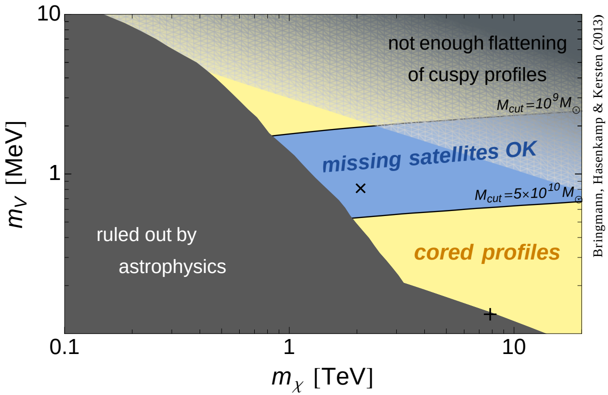
- $\langle\Theta\rangle \sim$ MeV breaks $U(1)_X$
- $T_\chi \sim m_\chi/25$: freeze-out (chemical decoupling) of dark matter

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

(neglecting bound state formation, see talk by Marco Cirelli)



Cold Dark Matter Parameter Space



Bringmann, Hasenkamp & Kersten (2013)

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

Hints for Hot Dark Matter

- $3\,\sigma$ tension: CMB ($z > 1000$) vs. local ($z < 10$) observations
- Expansion rate
  - Planck: $H_0 = (67.8 \pm 0.9)\frac{\text{km}}{\text{s Mpc}}$ 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
  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

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  Mirizzi, Mangano, Pisanti, Saviano, PRD **91** (2015)
  Tang, PLB **750** (2015)
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  Cherry, Friedland, Shoemaker, `arXiv:1605.06506`
  Forastieri et al., `arXiv:1704.00626`

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$\rightsquigarrow$ Cosmology (ΔN_{eff}) still fine, but m_N too small to explain neutrino oscillation anomalies

Conclusions

- Two stages of dark matter decoupling from thermal equilibrium
  1. Chemical decoupling (freeze-out) $\rightsquigarrow$ relic density
  2. Kinetic decoupling $\rightsquigarrow$ size of smallest structures

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  - Need new dark radiation particle as scattering partner
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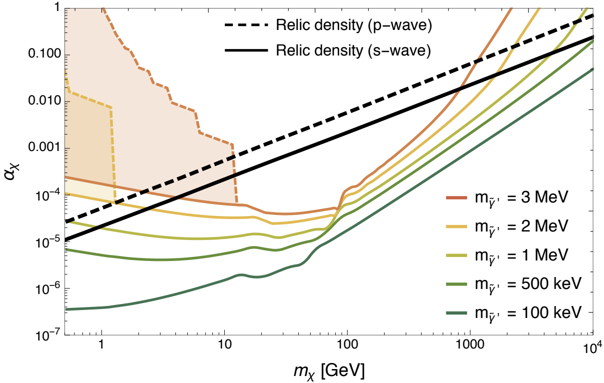
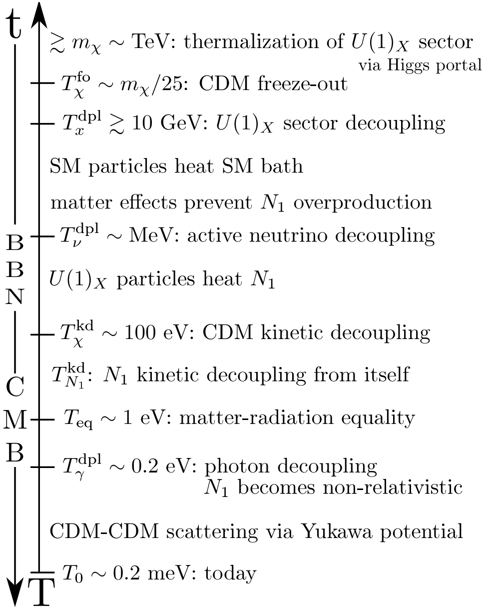
Enticing$^{\text{TM}}$ particle physics solutions for tensions in ΛCDM cosmology

Three-Particle Model with *t*-Channel Mediator

Colored lines: self-interaction rate of 1 cm^2/g at dwarf galaxy scale for different mediator masses



Timeline



$\gtrsim m_\chi \sim$ 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

$T_\nu^{\text{dpl}} \sim$ 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

$T_{\text{eq}} \sim 1$ 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

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

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

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- Oscillations $+$ $U(1)_X$-mediated scatterings $NN \rightarrow NN$ $\rightsquigarrow$ N re-thermalize: $T_N = T_\nu$

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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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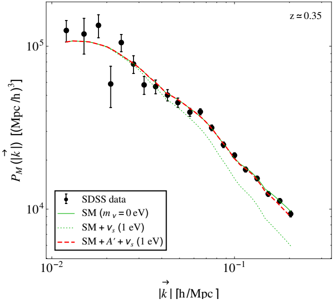

Chu, Dasgupta, Kopp, JCAP **10** (2015)

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