Not So Weakly Interacting Dark Matter

Jörn Kersten

UNIVERSITY OF BERGEN

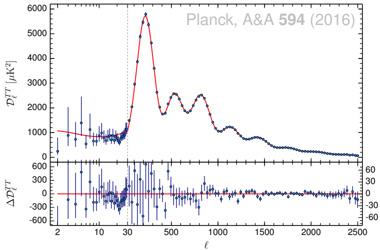
Based on

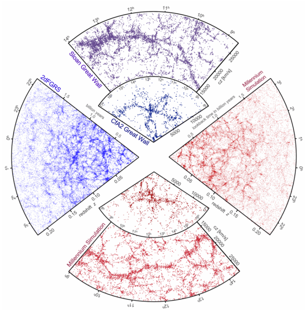
Torsten Bringmann, Håvard Ihle, JK, Parampreet Walia, PRD **94**, 103529 (2016)
[arXiv:1603.04884]

Torsten Bringmann, Jasper Hasenkamp, JK, JCAP **07**, 042 (2014)
[arXiv:1312.4947]

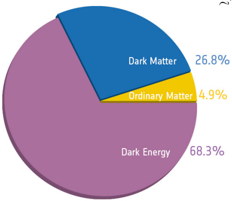
Outline

ΛCDM Cosmology Works Great

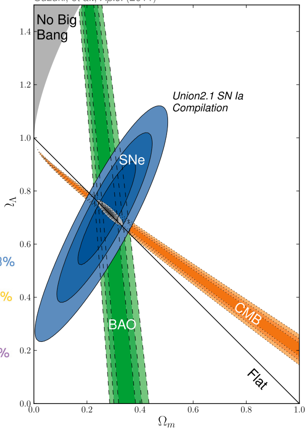




Springel, Frenk, White, Nature **440** (2006)



Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)



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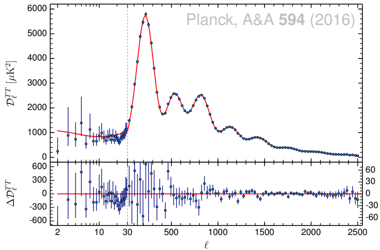

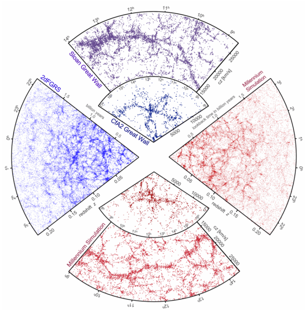

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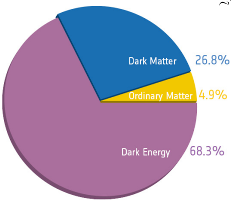

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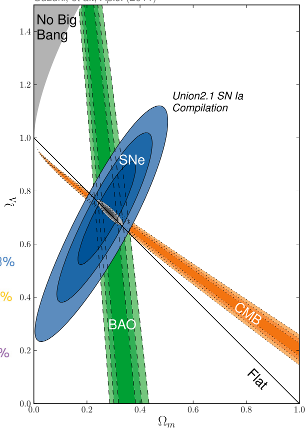
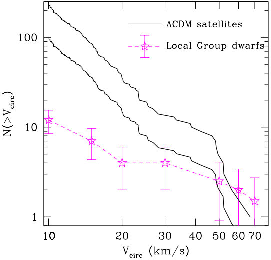


. . . on large scales

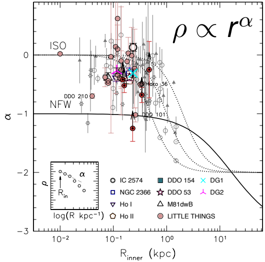
Missing satellites



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

More galactic satellites predicted than observed

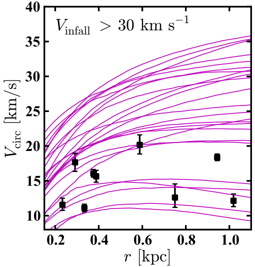
Cusp-core



Oh et al., Astron. J. **149** (2015)
De Blok et al., ApJ **552** (2001)

More cuspy density profiles predicted than observed

Too big to fail



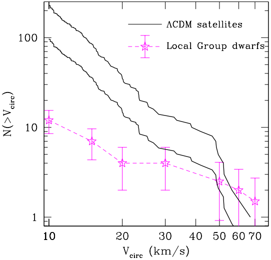
Boylan-Kolchin et al., MNRAS **422** (2011)

Most massive satellites predicted denser than observed

+ a few additional anomalies Bullock & Boylan-Kolchin, 1707.04256

Small-Scale Problems of Structure Formation

Missing satellites



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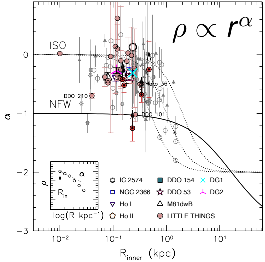

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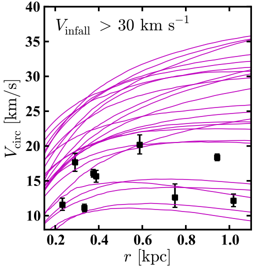

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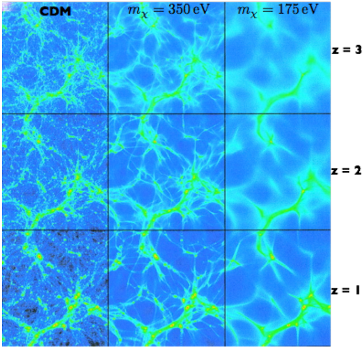
⇝ Astrophysics solutions or new particle physics?

Warm Dark Matter

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



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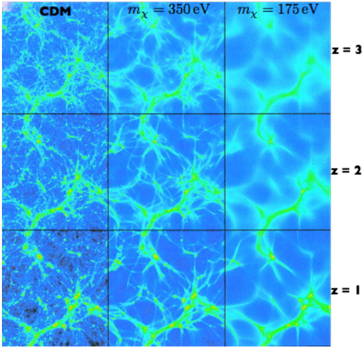
- Creates cores in dwarf galaxies



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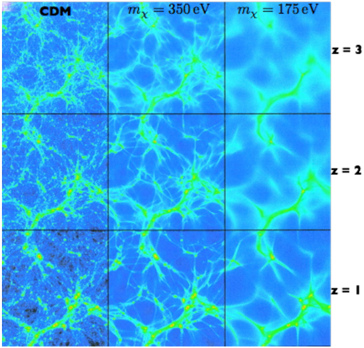
Warm Dark Matter

- 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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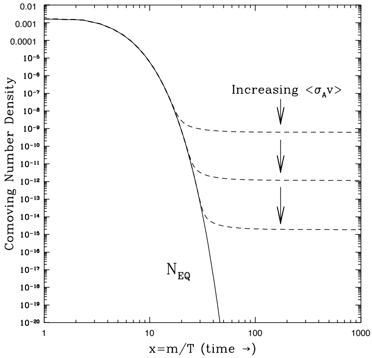
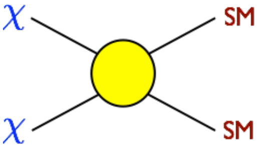
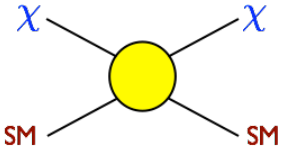
Chemical Decoupling

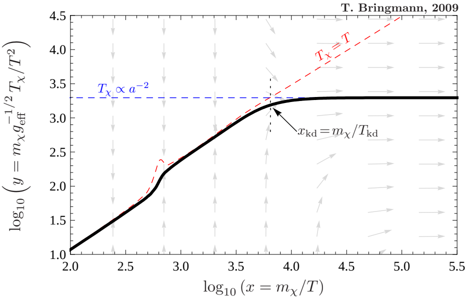
- Better known as freeze-out (from thermal/chemical equilibrium)
- Typically $T_{\text{fo}} \sim \frac{m_\chi}{25}$
- Determined by DM annihilation





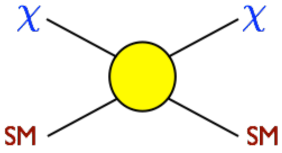
Kinetic Decoupling

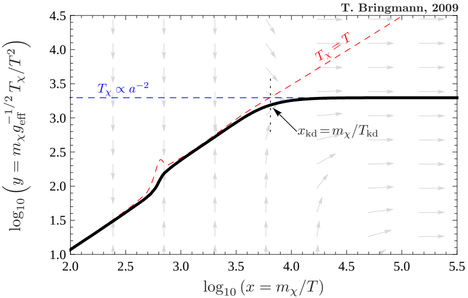




- Many more partners for scattering than for annihilation
  $\rightsquigarrow$ Kinetic decoupling much later than freeze-out, $T_{kd} \ll T_{fo}$
- $T_\chi = T$ until kinetic decoupling

Kinetic Decoupling





- Many more partners for scattering than for annihilation
  $\rightsquigarrow$ Kinetic decoupling much later than freeze-out, $T_{kd} \ll T_{fo}$
- $T_\chi = T$ until kinetic decoupling
- Standard WIMPs: $T_{kd} \gtrsim 1$ 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

  $\rightsquigarrow$ Structure formation suppressed at small scales

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

- Cutoff in power spectrum of density fluctuations

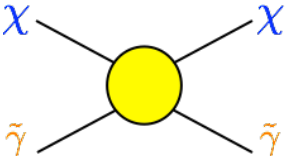
  $\rightsquigarrow$ Minimal halo mass Vogelsberger et al., MNRAS **460** (2016)

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

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

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

Particle Physics Models with Late Kinetic Decoupling



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

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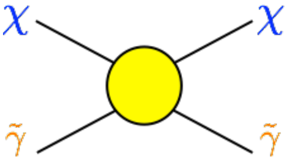

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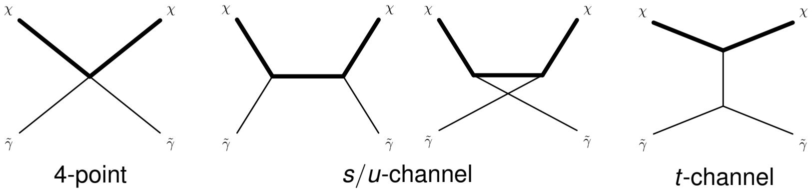
- Scattering amplitude close to kinetic decoupling:

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

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



- 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

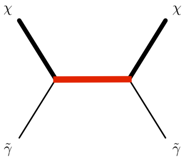
Late kinetic decoupling | DM relic density | DM self-interactions

$\tilde{\gamma} \setminus \chi$		**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	$m_{\tilde{\gamma}} \sim 1\,\text{keV}$ $m_\chi \gtrsim 100\alpha_\chi^{3/5}\,\text{TeV}$	$\langle\sigma_T\rangle_{30}$ (for $m_\chi \gtrsim 1\,\text{MeV}$)	Yukawa	$m_{\tilde{\gamma}} \sim 1\,\text{keV}$ $m_\chi \gtrsim 100\alpha_\chi^{3/5}\,\text{TeV}$	$\langle\sigma_T\rangle_{30}$ (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
	s/u	$\langle\sigma_T\rangle_{30}$			$\langle\sigma_T\rangle_{30}$			
	$SU(N)$	$m_{\tilde{\gamma}} \sim 1\,\text{keV}$ $m_\chi \gtrsim 10\alpha_\chi^{3/5}\,\text{TeV}$	$\langle\sigma_T\rangle_{30}$ (for $m_\chi \gtrsim 1\,\text{MeV}$)	Yukawa	$m_{\tilde{\gamma}} \sim 1\,\text{keV}$ $m_\chi \gtrsim 10\alpha_\chi^{3/5}\,\text{TeV}$	$\langle\sigma_T\rangle_{30}$ (for $m_\chi \gtrsim 1\,\text{MeV}$)	Yukawa	(only broken $SU(M) \to SU(N)$)

- 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 $m_\chi \lesssim 10$ GeV



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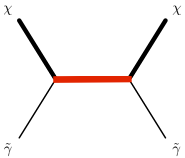
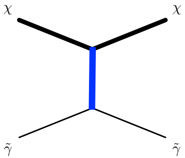


- Additional particle V in t-channel
  - Light $\rightsquigarrow$ enhanced scattering rate
  - Missing satellites solved for almost any DM mass
  - Correct DM density from $\chi\chi \to VV$
  - DM self-interactions $\rightsquigarrow$ all small-scale problems solved



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)

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

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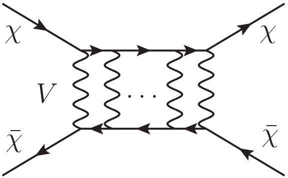
$\rightsquigarrow$ Ruled out by CMB and indirect DM searches,
if mediator decays dominantly to SM particles

$\rightsquigarrow$ 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

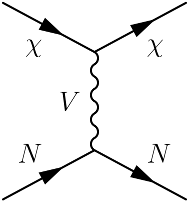
$\rightsquigarrow$ Long-range, velocity-dependent interaction
$\rightsquigarrow$ Less cuspy density profiles
$\rightsquigarrow$ Cusp-core and too big to fail solved



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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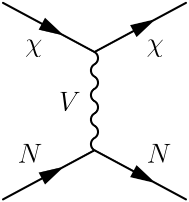


$\rightsquigarrow$ Late kinetic decoupling

$\rightsquigarrow$ 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

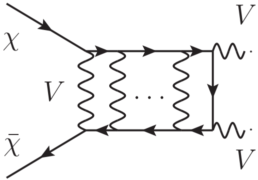
- High temperatures: $U(1)_X$ sector thermalized via Higgs portal

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

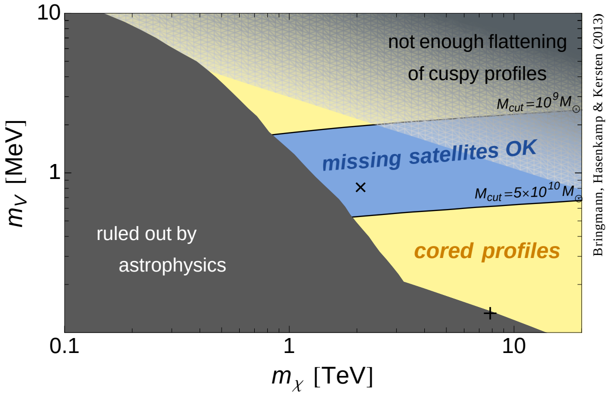
- $\langle \Theta \rangle \sim$ MeV breaks $U(1)_X$
- $T_\chi \sim m_\chi/25$: freeze-out (chemical decoupling) of dark matter

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

(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

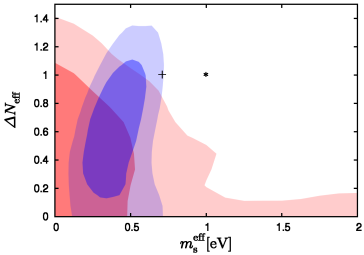
Hints for Hot Dark Matter

- $3\,\sigma$ 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
- 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_*)

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

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

$\rightsquigarrow$ 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)
- $T <$ MeV: mixing unsuppressed
  $\rightsquigarrow$ additional production of sterile neutrinos via $U(1)_X$
  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, `arXiv:1605.06506`
  Forastieri et al., JCAP **07** (2017)

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$\rightsquigarrow$ Cosmology ($\Delta N_{\rm eff}$) 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

Particle Physics Models with Late Kinetic Decoupling

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

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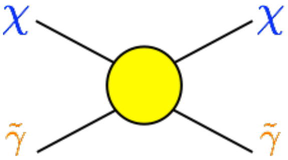
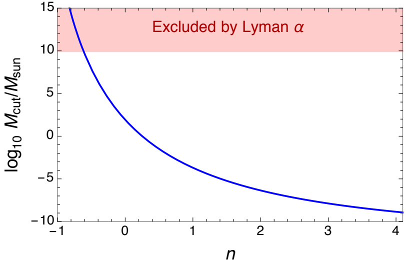
  $\rightsquigarrow$ photon, (SM) neutrino, dark radiation
- Here: classification of all minimal possibilities
  Bringmann, Ihle, JK, Walia, PRD **94** (2016)
- Scattering amplitude close to kinetic decoupling:

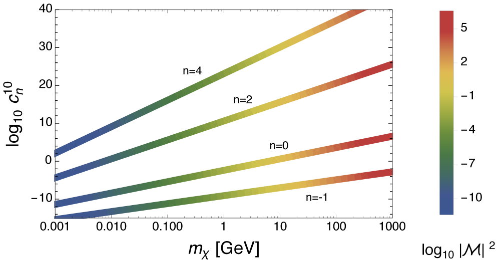
$$|\mathcal{M}|^2 \simeq c_n \left(E_{\tilde{\gamma}}/m_\chi\right)^n$$

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



Particle Physics Models with Late Kinetic Decoupling





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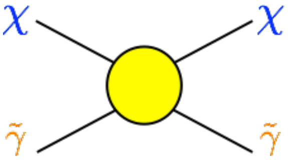
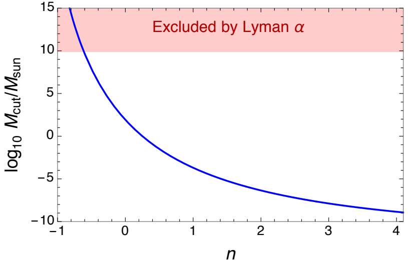
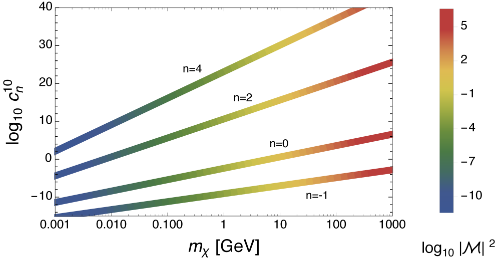


Particle Physics Models with Late Kinetic Decoupling





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

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

Timeline

t ↑ (time) / T ↓ (temperature)

- $\gtrsim m_\chi \sim$ 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
- $T_\nu^{\rm dpl} \sim$ MeV: active neutrino decoupling (BBN)
- $U(1)_X$ 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
- $T_{\rm eq} \sim 1$ eV: matter-radiation equality (CMB)
- $T_\gamma^{\rm dpl} \sim 0.2$ eV: photon decoupling; N_1 becomes non-relativistic
- CDM-CDM scattering via Yukawa potential
- $T_0 \sim 0.2$ meV: today

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

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

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 $NN \rightarrow NN$
  $\rightsquigarrow$ 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)

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

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

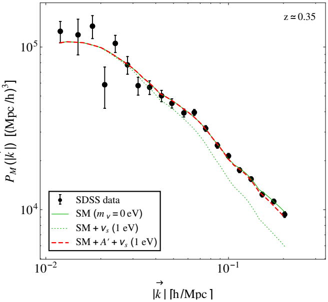
$\rightsquigarrow$ even $\Delta N_{\text{eff}} < 0$ possible $\rightsquigarrow$ possible test for scenario

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, A&A **594** (2016)
- 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