Sterile Neutrino Dark Matter

Production from Scalar Decay

Michael A. Schmidt

23 August 2016 @ NuFact

The University of Sydney

based on

A. Adulpravitchai, MS

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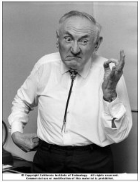
THE UNIVERSITY OF SYDNEY

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

Dark Matter

- Virial theorem $\left(\frac{1}{2}\left\langle v^2\right\rangle = \frac{GM}{R}\right)$ applied to COMA cluster (F.Zwicky 1933)
- Galactic rotation curves $[\mathcal{O}(10s)\mathrm{kpc}]$
- Gravitational lensing $[< \mathcal{O}(200)\mathrm{kpc}]$
- Bullet cluster (X-ray + grav. lensing)
- Cosmic microwave background
  Large scale structure
- ...



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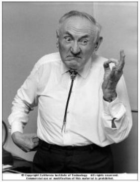

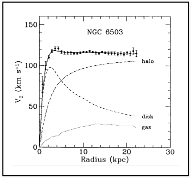

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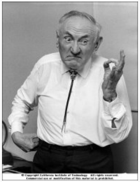

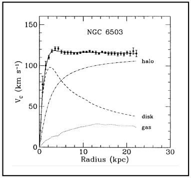

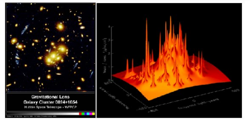

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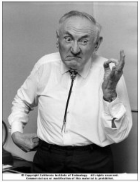

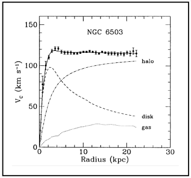

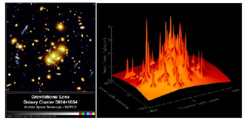

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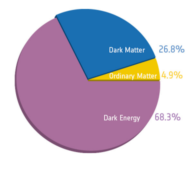
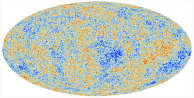
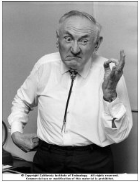
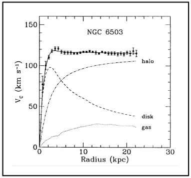
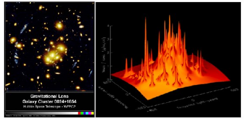








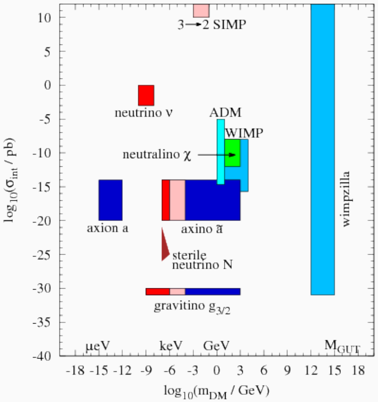


Properties of Dark Matter

- Relic density Planck 1502.01589

$$\Omega_{dm}h^2 = 0.1199 \pm 0.0022$$

- Stable on cosmological time scales
- Neutral
- Structure formation
  $\Rightarrow$ DM sufficiently cold



1407.0017

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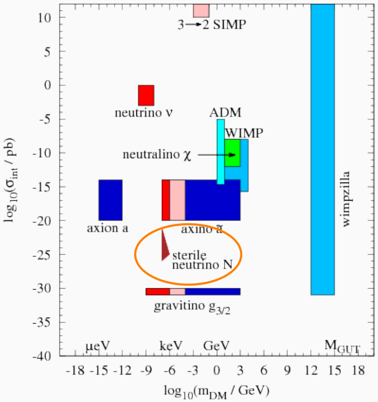

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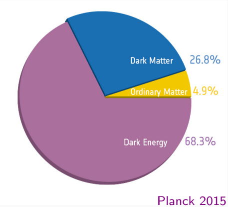
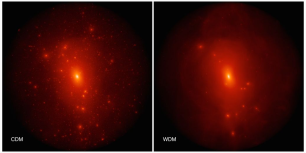


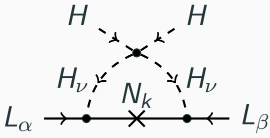
Planck 2015

- Dark matter about a quarter of the energy density
- Interacts with SM particles weakly
- Existence established across many scales
- However problems at small scales

- DM momentum distribution crucial for accretion and structure formation
- Characterised by free-streaming horizon $r_{FS} = \int_{t_i}^{t_0} \frac{\langle v(t) \rangle}{a(t)} dt$



Lovell et al. 1104.2929



- Could be linked to neutrino physics
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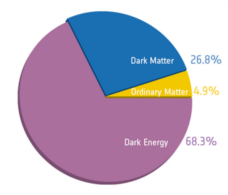

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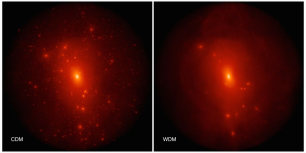

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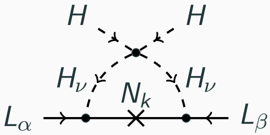

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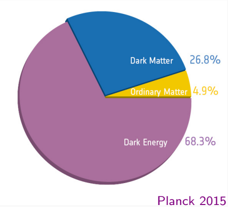

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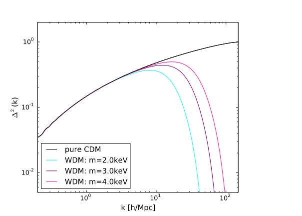

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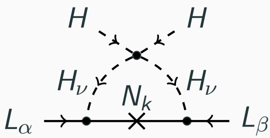

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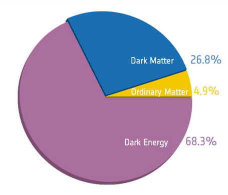

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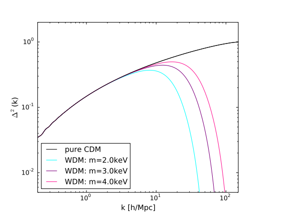

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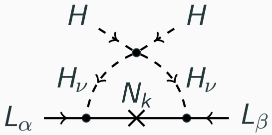

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Constraints

- *X*-ray observations
- Coarse-grained phase space density

  Tremaine,Gunn 1979
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  Viel et. al 1306.2314

  $m_{th} \geq 3.3\text{keV}(2\sigma)$
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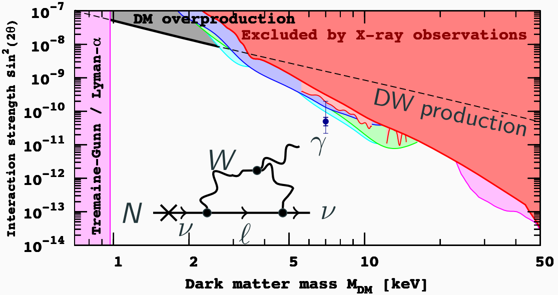
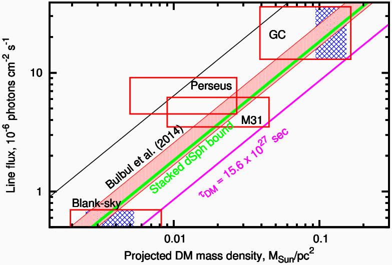


Adhikari et. al 1602.04816



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Hint for 3.5 keV X-ray line

Bulbul et al. 1402.2301; Boyarsky et al. 1402.4119; ...

$\Rightarrow$ Could be explained by 7 keV sterile neutrino with $\sum_\alpha \sin^2(2\theta_\alpha) \simeq 7 \times 10^{-11}$

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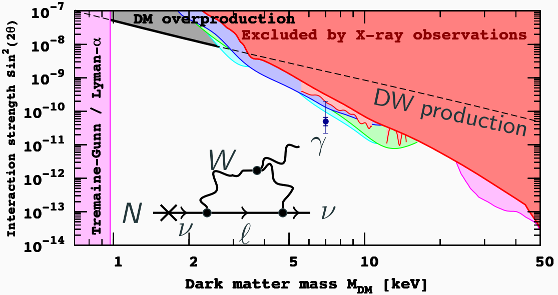

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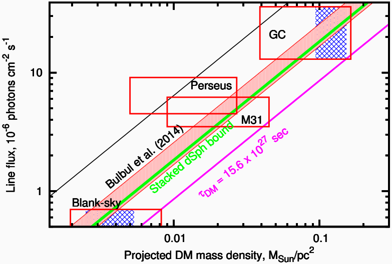

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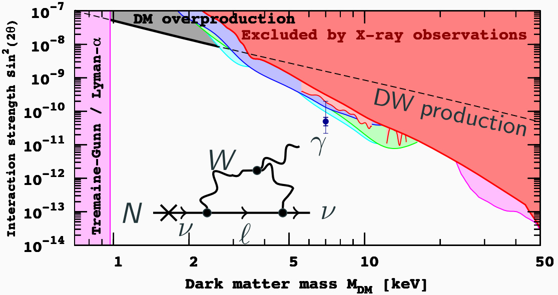

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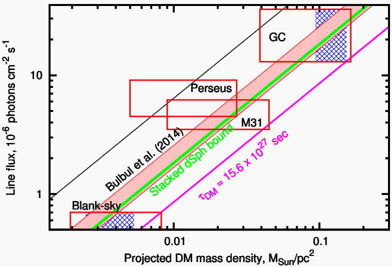

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but challenged e.g. Jeltema, Profumo 1408.1699

no excess in Perseus Hitomi 1607.07420

Sterile Neutrino DM Production

Neutrino oscillations Barbieri, Dolgov 1991; Enqvist, Kainulainen, Maalampi 1991

- Non-resonant oscillations – Dodelson-Widrow mechanism
  Dodeson, Widrow hep-ph/9303287
- Resonant oscillations – Shi-Fuller mechanism Shi, Fuller astro-ph/9810076

Thermal production

- Hidden decoupled (mirror) sector
  Berezhiani, Mohapatra hep-ph/9505385; Berezhiani, Dolgov, Mohapatra hep-ph/9511221
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Scalar decays [if via same coupling as oscillations typically subdominant]

- Inflaton decay Shaposhnikov, Tkachev hep-ph/0604236; Bezrukov, Gorbunov 0912.0390
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In thermal equilibrium decay

SM+N+H_ν [1507.05694]

Neutrinophillic Two-Higgs Doublet Model

- New particles odd under Z_2
  Sterile neutrino $N \to -N$
  Second Higgs doublet $H_\nu \to -H_\nu$
- Lagrangian

$$-\mathcal{L}_N = y_{LN} L H_\nu N + \frac{1}{2} m_N N\, N + \text{h. c.}$$

- Scalar potential

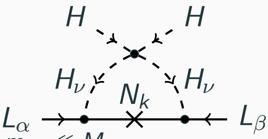
$$V = \mu_\nu^2 H_\nu^\dagger H_\nu + \frac{\lambda_2}{2}(H_\nu^\dagger H_\nu)^2$$
$$+ \lambda_3 H^\dagger H\, H_\nu^\dagger H_\nu + \lambda_4 |H^\dagger H_\nu|^2 + \frac{\lambda_5}{2}[(H^\dagger H_\nu)^2 + \text{h. c.}]$$

- Scalar particle masses $m_{kk}^2 = \mu_\nu^2 + (\lambda_3 + \lambda_4)\, v^2$

$$m_{k,K^0}^2 = m_{kk}^2 \pm \lambda_5 v^2 \qquad m_{K^\pm}^2 = m_{kk}^2 - \lambda_4 v^2$$

Neutrino Mass

Radiative seesaw Ma hep-ph/0601225; Molinaro, Yaguna, Zapata 1405.1259



- H_ν does not obtain VEV
- Radiative neutrino mass generation

$$m_\nu \simeq 10^{-2}\mathrm{eV}\left(\frac{\lambda_5 y_{2,3}^2}{10^{-11}}\right) \times \begin{cases} \left(\frac{1\mathrm{TeV}}{M_{2,3}}\right) & m_{kk} \ll M_{2,3} \\ \left(\frac{1\mathrm{TeV}}{m_{kk}}\right)\left(\frac{M_{2,3}}{m_{kk}}\right) & m_{kk} \gg M_{2,3} \end{cases}$$

- keV sterile neutrino does not (significantly) contribute
- Sterile neutrino is stable

Naturally small seesaw Ma hep-ph/0011121; Haba, Ishida, Takahashi 1407.6827

- Soft-breaking term $V_{\mathrm{soft}} = \mu_{12}^2 H^\dagger H_\nu + \mathrm{h.c.}$

$\Rightarrow$ Induced VEV $\frac{\langle H_\nu \rangle}{v} = \frac{\mathrm{Re}(\mu_{12}^2)}{m_k^2} + i\frac{\mathrm{Im}(\mu_{12}^2)}{m_{K^0}^2}$

- Active-sterile mixing $\theta_\alpha \simeq \frac{y_{LN,\alpha}\langle H_\nu \rangle}{m_N}$

$\Rightarrow$ Possible explanation of 3.5 keV X-ray line

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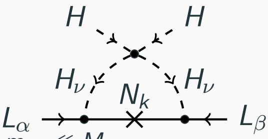

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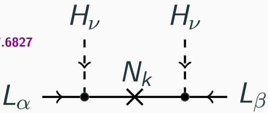


- Soft-breaking term $V_{\mathrm{soft}} = \mu_{12}^2 H^\dagger H_\nu + \mathrm{h.c.}$

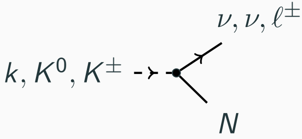
$\Rightarrow$ Induced VEV $\frac{\langle H_\nu\rangle}{v} = \frac{\mathrm{Re}(\mu_{12}^2)}{m_k^2} + i\frac{\mathrm{Im}(\mu_{12}^2)}{m_{K^0}^2}$

- Active-sterile mixing $\theta_\alpha \simeq \frac{y_{LN,\alpha}\langle H_\nu\rangle}{m_N}$

$\Rightarrow$ Possible explanation of 3.5 keV X-ray line

Sterile Neutrino DM Production

Scalar decay

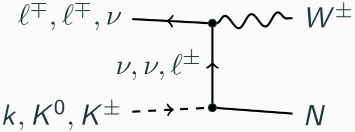


- Dominating for $T \lesssim m_{kk}$
- One daughter has Fermi-Dirac distribution

$\Rightarrow$ Pauli-blocking

Scattering

- Freeze-in IR dominated
- Scattering suppressed for $T \lesssim m_{kk}$
- In agreement with Adulpravitchai, MS 1409.4330
- Neglected in analytic study

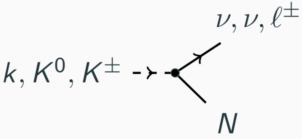


Derived analytic solution to Boltzmann equation

Finite temperature corrections neglected among other approximations.

See Drewes, Kang 1510.05646 for finite temperature corrections

Scalar decay



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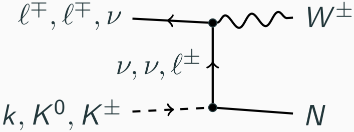

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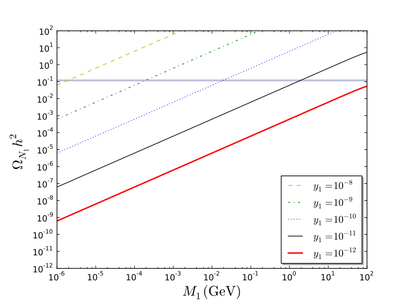
Dark Matter Abundance [Pauli blocking neglected]



study of fermionic FIMP DM in radiative seesaw model Molinaro, Yaguna, Zapata 1405.1259

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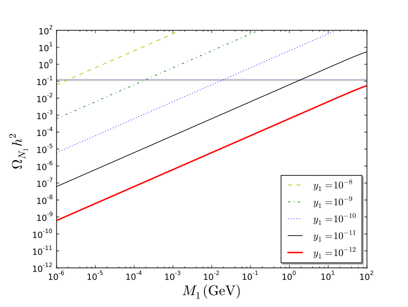

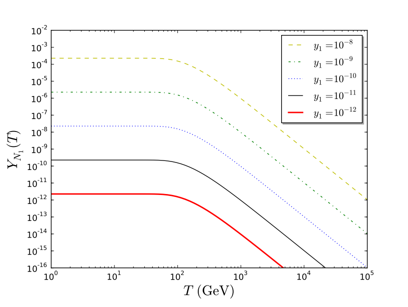

study of fermionic FIMP DM in radiative seesaw model Molinaro, Yaguna, Zapata 1405.1259

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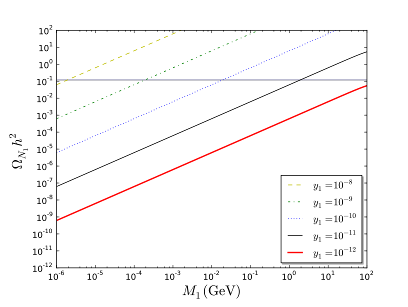
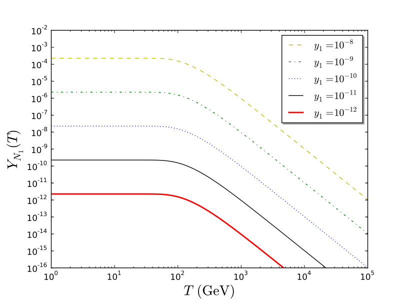
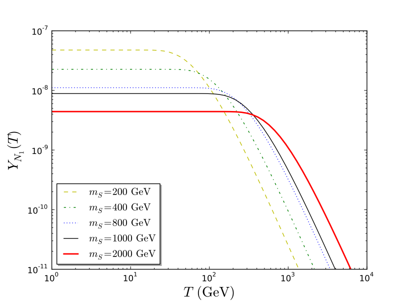
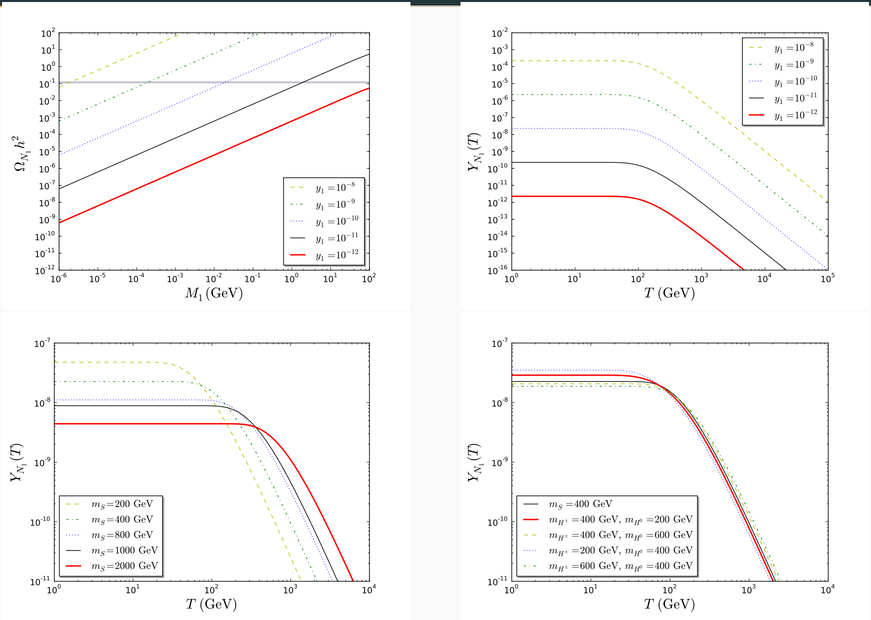






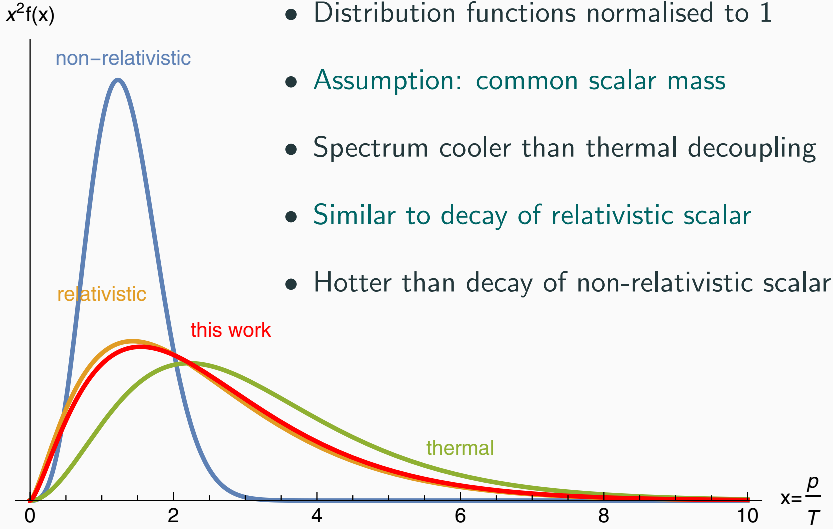
study of fermionic FIMP DM in radiative seesaw model Molinaro, Yaguna, Zapata 1405.1259

Dark Matter Abundance [Pauli blocking neglected]



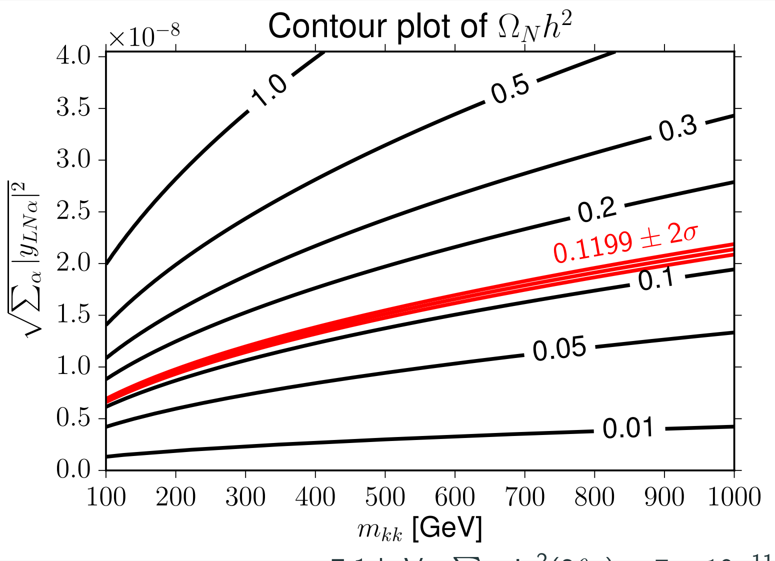
study of fermionic FIMP DM in radiative seesaw model Molinaro, Yaguna, Zapata 1405.1259

Momentum Distribution Function



- Distribution functions normalised to 1
- Assumption: common scalar mass
- Spectrum cooler than thermal decoupling
- Similar to decay of relativistic scalar
- Hotter than decay of non-relativistic scalar

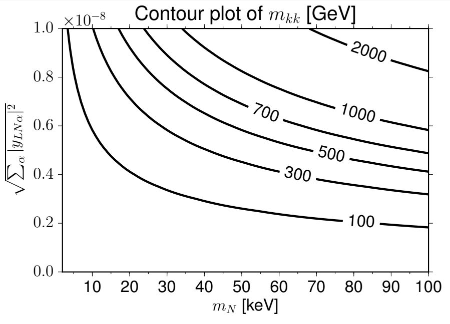
Dark Matter Abundance

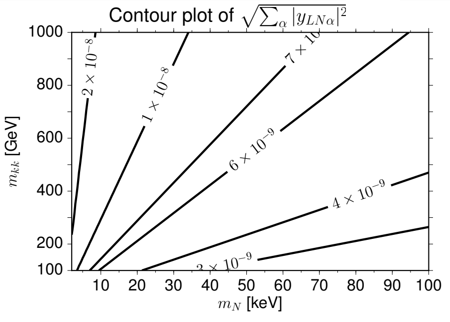


$m_N = 7.1$ keV, $\sum_\alpha \sin^2(2\theta_\alpha) \simeq 7 \times 10^{-11}$

Contribution from non-resonant oscillations negligible

Dark Matter Abundance II





DM abundance

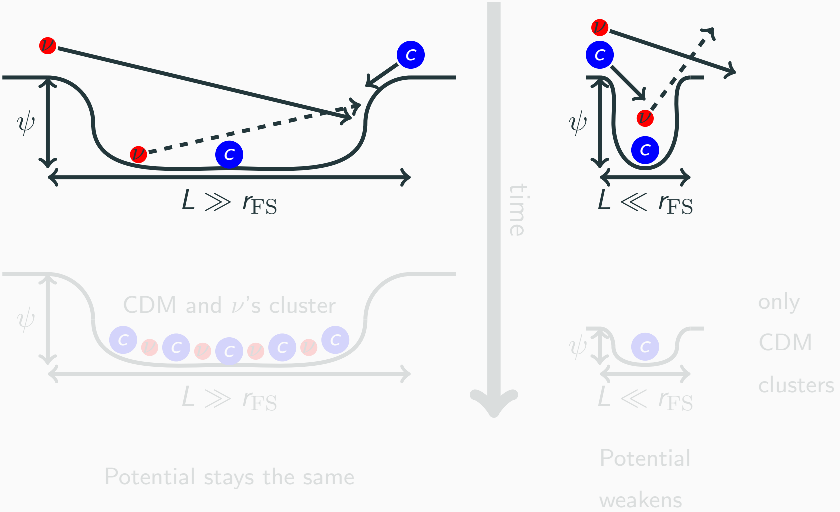
$$\Omega_N h^2 \simeq 3.5 \times 10^{15} \frac{m_N}{10\mathrm{keV}} \frac{100\mathrm{GeV}}{m_{kk}} \sum_\alpha |y_{LN,\alpha}|^2$$

$\Rightarrow$ Yukawa couplings $\sim 10^{-8}$ for scalars at TeV scale

Suppression of Small Scale Structure

Free-streaming scale: r_{FS}

Size of astrophysical object: L



Suppression of Small Scale Structure

Free-streaming scale: $r_{\rm FS}$

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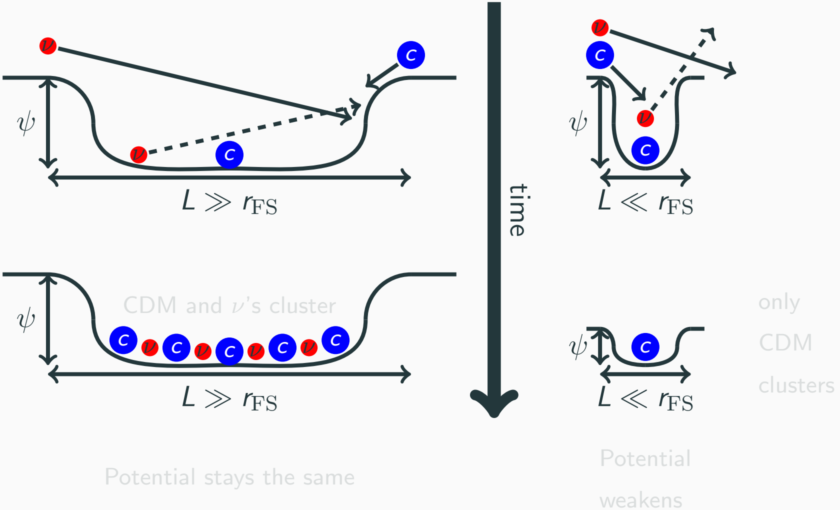

Suppression of Small Scale Structure

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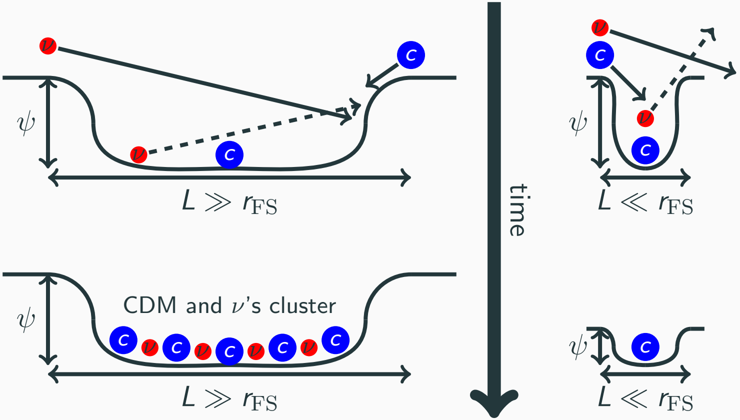


only CDM clusters

Potential stays the same

Potential weakens

Suppression of Small Scale Structure

- Free streaming horizon e.g. Boyarsky, Lesgourges, Ruchayskiy, Viel 0812.0010

$$r_{FS} \simeq \int_{t_d}^{t_0} \frac{\langle v(t) \rangle}{a(t)} dt = \int_{t_d}^{t_{nr}} \frac{1}{a(t)} dt + \int_{t_{nr}}^{t_{eq}} \frac{\langle v(t) \rangle}{a(t)} dt + \int_{t_{eq}}^{t_0} \frac{\langle v(t) \rangle}{a(t)} dt$$

t_d decay time; t_{eq} time of matter-radiation equality; t_0 today

Hasenkamp, Kersten 1212.4160; Merle, Niro, Schmidt 1306.3996; Adulpravitchai, MS 1409.4330

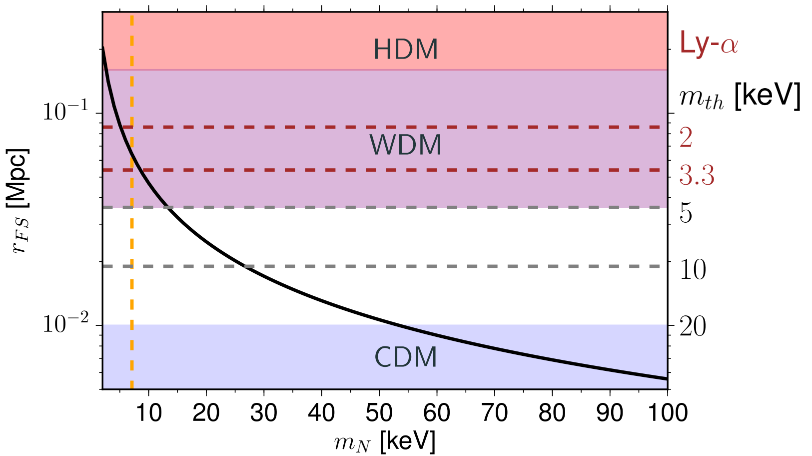
- Average velocity

$$\langle v(t) \rangle = \begin{cases} 1 & \text{for } t < t_{nr} \\ \frac{\langle p \rangle}{m_N} & \text{for } t > t_{nr} \end{cases}$$

- Sterile neutrino become non-relativistic at time t_{nr} with

$$m_N = \langle p(T_{nr}) \rangle \simeq 2.46\, T_{nr} \quad \Rightarrow \quad t_{nr} \simeq 1500\mathrm{s} \left(\frac{10\mathrm{keV}}{m_N} \right)^2$$

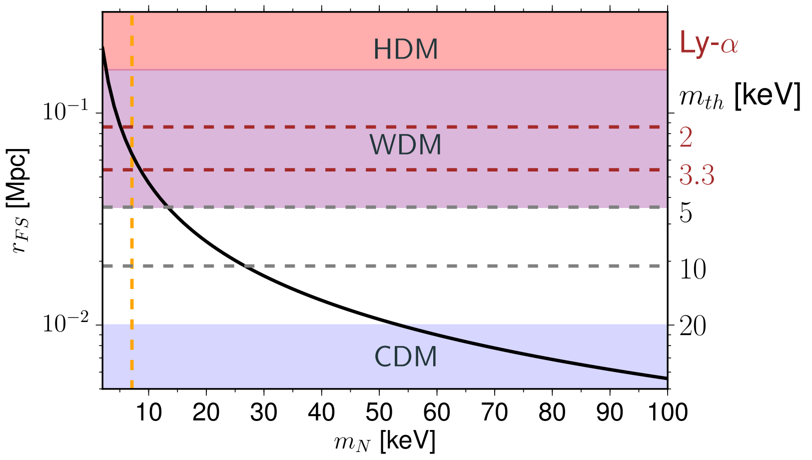
Free-Streaming Horizon



$$r_{FS} = \frac{\sqrt{t_{eq} t_{nr}}}{a_{eq}} \left(5 + \ln \frac{t_{eq}}{t_{nr}}\right) \simeq 0.047\,\mathrm{Mpc} \left(\frac{10\mathrm{keV}}{m_N}\right)$$

$$1\mathrm{keV} < m_{th} < 5\mathrm{keV} \Rightarrow 2.5\,\mathrm{keV} \lesssim m_N \lesssim 13\,\mathrm{keV}$$

Free-Streaming Horizon



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$$1\mathrm{keV} < m_{th} < 5\mathrm{keV} \Rightarrow 2.5\,\mathrm{keV} \lesssim m_N \lesssim 13\,\mathrm{keV}$$

Out-of-equilibrium decay

SM+N+φ [1409.4330]

Model

- New particles and discrete lepton number Z_4: $L \to iL$
  Sterile neutrino $N \to -iN$
  Real scalar $\phi \to -\phi$
- Lagrangian

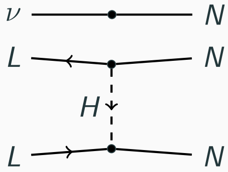
$$-\Delta\mathcal{L} = -\frac{\lambda_{H\phi}}{2} H^\dagger H \phi^2 + \left[y_{LN} LHN + \frac{y_N}{2} \phi N^2 + \mathrm{h.c.} \right]$$

- Small couplings: $\lambda_{H\phi}, \, y_{LN} \ll 1$
- Effective scalar interaction after EWSB
  $[\langle H \rangle = \begin{pmatrix} 0 & v \end{pmatrix}^T$ and $\phi = v_\phi + \sigma]$

$$\Delta V(h, \sigma) = \lambda_{H\phi} \left(\frac{h^2 \sigma^2}{4} + \frac{v}{\sqrt{2}} h \sigma^2 \right)$$

Sterile Neutrino DM Production

SM $\to$ N



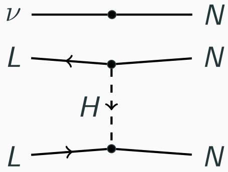
Dominantly two step production

SM $\to \sigma$

$\sigma \to N$

Several approximations:
$g_* = \text{const}$,
no finite T effects, . . .

SM$\rightarrow N$



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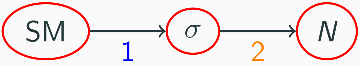
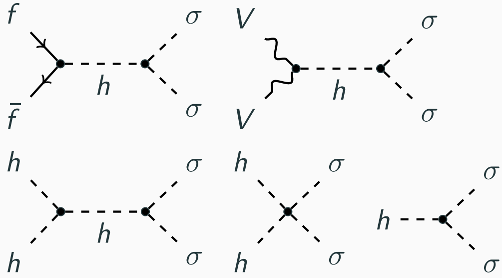
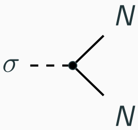


SM $\rightarrow \sigma$



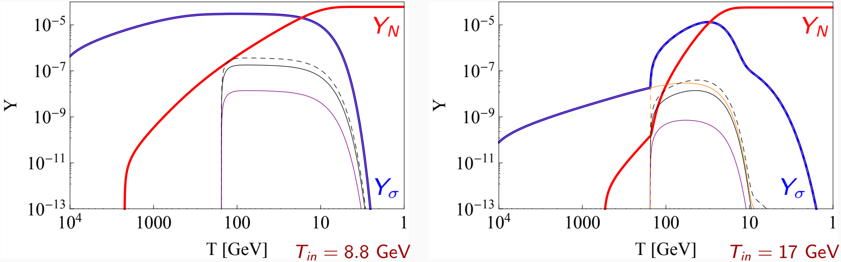
$\sigma \rightarrow N$



Several approximations:
$g_* = \text{const}$,
no finite T effects, ...

Dark Matter Abundance

$m_\sigma = 500\text{GeV};\ \lambda_{H\phi} = 2.7 \cdot 10^{-7}$ $m_\sigma = 30\text{GeV};\ \lambda_{H\phi} = 3.7 \cdot 10^{-9}$



Higgs annihilation solid (decay dashed), ZZ (solid), WW (dashed); $t\bar{t}$

$m_N = 7.1$ keV;$\lambda_\phi = 0.5$

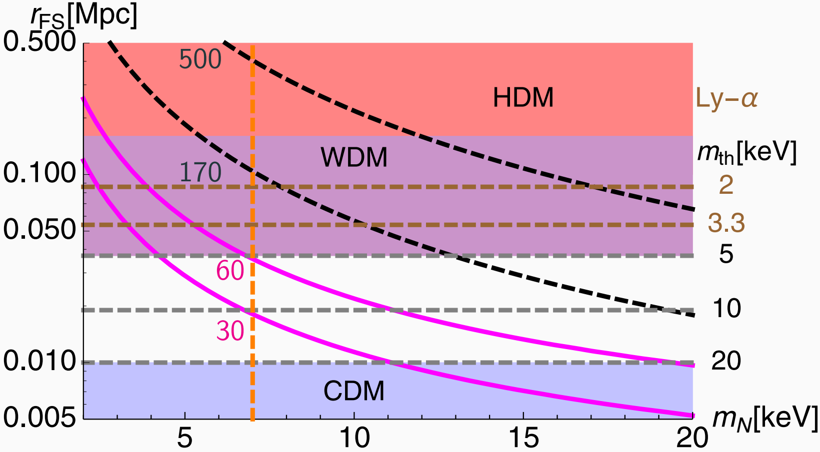
Dark matter abundance [$\Omega_s h^2 \simeq 0.1199 \pm 0.0027$ Planck 1303.5076]

$$\Omega_N \simeq \frac{m_\sigma\, Y_N^\infty\, T_0^3 \frac{g_*^s(T_0)}{g_*^s(T_{in})}}{\rho_c}$$

Higgs decays dominant contribution when kinematically accessible

Free-Streaming Horizon

$$r_{FS} \simeq \frac{\sqrt{t_{eq} t_{nr}}}{a_{eq}} \left(5 + \ln \frac{t_{eq}}{t_{nr}}\right)$$



$$m_N = \langle p(T_{nr}) \rangle \simeq \frac{\sqrt{\pi}}{2} T_{nr} \quad \Rightarrow \quad t_{nr} \simeq \frac{\pi}{16} \frac{m_\sigma^2}{m_N^2} \left(\frac{g_*^s(T_0)}{g_*^s(T_{in})}\right)^{2/3} t_{in}$$

Conclusions

Conclusions

keV sterile neutrino
is a viable DM candidate

Freeze-in production via scalar decay is an interesting alternative to oscillations

Can be both cold or warm DM

13th International Symposium on Cosmology and Particle Astrophysics (CosPA 2016), Sydney, Nov 28 – Dec 2, 2016

LOC: Jan Hamann (USyd), Gary Hill (Adelaide), Archil Kobakhidze (USyd), Geraint Lewis (USyd), Michael Schmidt (USyd), Kevin Varvell (USyd), Yvonne Wong (UNSW)

https://indico.cern.ch/event/491882