Warm DM & Composite Neutrinos

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Warm Dark Matter

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The name seems to indicate two things:

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Actually, the definition of WDM is pretty precise.

The DM candidate that gives the required relic density while having the free-streaming length comparable to the size of the region which subsequently evolved into a dwarf galaxy.

The free-streaming length

The distance a particle can travel until it becomes non-relativistic.

$$\lambda_{FS} \sim 0.1\, Mpc \left(\frac{keV}{m_\chi}\right)^{4/3} \left(\frac{\Omega_\chi\, h^2}{0.2}\right)^{1/3}$$

For $\Omega \sim 0.2$ and $\lambda_{FS} \sim 0.4$ Mpc, $m_\chi \sim$ keV

Cold DM has a small λ_{FS}, which gives a bottom up formation

- may allow too many small galaxies
- may leave a DM "cusp" at the center of halo

Candidates for WDM

Some plausible candidates: Gravitino, Axion, Sterile neutrino...

Like active-ν, WDM particles remained relativistic when they decoupled

$$\Omega_\nu \sim (m_\nu/94\text{eV})$$

$$\Omega_{WDM}^{thermal} \sim \left(\frac{T_{WDM}}{T_\nu}\right)^3 (m_{DM}/94\text{eV}) \simeq \left(\frac{10.75}{g_*(T_D)}\right)(m_{DM}/94\,\text{eV})$$

To produce the sterile-ν:

- Thermal production: need entropy dilution
- Non-thermal production: late decay or oscillation

Non-thermal production of the sterile-ν

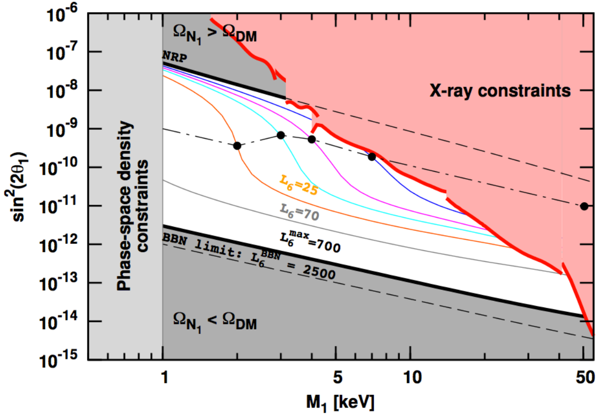
Dodelson-Widrow mechanism (93):

Sterile neutrinos can be produced through neutrino oscillations.

$$\Omega_D \sim 0.2 \left(\frac{\sin^2\theta}{3\times 10^{-9}}\right) \left(\frac{m_s}{3\,keV}\right)^{1.8}$$

- Ω_D is fixed by the mixing angle $\sin\theta$ and the mass m_s
- simplest model has been ruled out by the X-ray and Lyman-α searches!
- can still be valid with the presence of lepton-number asymmetry Shi and Fuller (01)

Experimental Constraints



Boyarsky, Ruchayskiy and Shaposhnikov (09)

WDM and Composite Neutrinos

Composite Neutrino Scenario

Arkani-Hamed and Grossman (99)

Active neutrinos can be naturally light if the right-handed neutrino is a composite state of a hidden sector.

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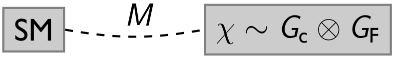

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ν-color and flavor

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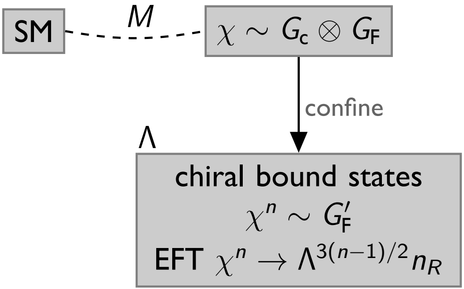

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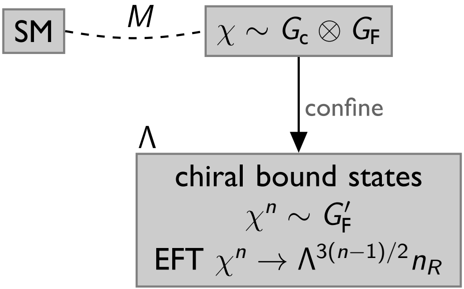

hidden sector with ν-color and flavor

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Light Dirac masses after confinement.

$$\frac{\lambda}{M^{3(n-1)/2}} \bar{L} H \chi^n \xrightarrow{\text{confine}} \lambda \left[\frac{\Lambda}{M}\right]^{3(n-1)/2} \bar{L} H n_R$$

$\left[\frac{\Lambda}{M}\right] \to \equiv \varepsilon$

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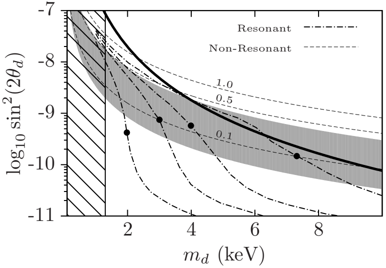
- ξ couples to SM just like n_R

$$\frac{1}{M^{3m/2}}\overline{L}\,H\,\chi^m\xi \longrightarrow \epsilon^{3m/2}\,\overline{L}\,H\,\xi_R.$$

- m: number of perons need to form n_R.
  n: number of perons need to form the condensate.

ξ as keV WDM: Non-thermal production

When $m = n - 1$, we can parametrize the mixing angle and DM mass in turns of the physical quantities $(v,\ m_\nu)$.



- solid curve: lower bound from the X-ray constraint
- black dots: lower bounds on m_d from Lyman-α
- $\Delta Y \sim 10^{-5}$
- for $n = 3$ and $m = 2$: $\Lambda \sim$ TeV and $M \sim 10^4$ TeV.

ξ as keV WDM: Thermal production

For $n = 3$ and $m = 2$, these all occur at the TeV scale:

- ξ freeze out
- Hidden sector confined
- Bound state & SM particles decouple

ξ freeze out relic density with entropy dilution γ

$$\frac{\Omega_d}{\Omega_{\rm DM}} \simeq \frac{Y_\xi m_d s_0}{\rho_c \Omega_{\rm DM}} = \frac{1.1 \times 10^4}{g_{*S}^d \, \gamma} \left(\frac{m_d}{5 \text{ keV}} \right) , \quad \gamma \sim 10^2$$

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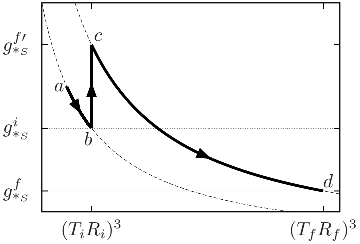
Entropy Dilution from Confinement

Super cooled confinement can produce sufficient entropy for WDM



$$\frac{T_c}{T_i} \geq 6.3 \left(\frac{2\times 10^2}{g_{*S}^d}\right)^{1/3} \left(\frac{m_d}{5\text{ keV}}\right)^{1/3}, \qquad \left.\frac{T_c}{T_i}\right|_{QCD} \leq 1.7$$

Summary

Warm DM particles did two things:

- gave Ω_{DM}
- participated the structure formation

Elementary keV sterile neutrinos are natural ingredient of composite neutrino scenario.

They can be generated through

- non-thermal production with neutrino oscillations
- thermal production with an entropy dilution