Neutrino self-interactions in the early Universe and today

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based on

JHEP 03 (2024) 032 [arXiv:2307.15565]
with M. Dias Astros

and

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Sterile neutrinos

- sterile neutrino $\rightarrow$ gauge singlet fermion
- interacts with SM via Yukawa interaction with Higgs and active neutrinos
  $\rightarrow$ mixing with active neutrinos in broken phase

interesting since

- one of the most minimal SM extensions
- challenging to observe directly
- could provide the answer to some of the big open questions in physics: neutrino masses, matter-antimatter asymmetry, dark matter

No SM gauge interaction

$$\Downarrow$$

No interaction?

Self-interacting sterile neutrinos

Minimal setup for a more complex dark sector:

- add one scalar singlet ϕ
  (one new parameter: m_ϕ)
- ϕ interacts with ν_s
  (one parameter: Yukawa coupling y)
- ν_s mixing with SM neutrinos remains only connection to SM

Sterile neutrino dark matter

good DM candidate since it is naturally dark

production from oscillations in early Universe (Dodelson-Widrow mechanism)

- right amount of DM for $\mathcal{O}(keV)$ masses ✓
- decays to photon and SM neutrino (X-ray lines) ✓
- tends to be warm (i.e. affect structure formation) ✓
- current status: excluded ✗

What about interacting sterile neutrinos?

see also Hansen and SV ’17, Fuller and Johns ’19, Bringmann et al ’22

Production in early Universe

sterile neutrinos are produced by “freeze-in" with some extra hoops
Master equation for production

$$\frac{\partial f_s}{\partial t} - Hp\frac{\partial f_s}{\partial p} = \frac{\Gamma_t}{4}\left(\frac{\omega^2 \sin^2(2\theta)}{\omega^2 \sin^2(2\theta) + \frac{\Gamma_t^2}{4} + [\omega\cos(2\theta) - V_{\text{eff}}]^2}\right)[f_a - f_s] + \mathcal{C}_s$$

Sterile's distribution function

Hubble's rate

Vacuum oscillation frequency $\sim \frac{{m_s}^2}{2p}$

Vacuum mixing angle

Total rate

Effective potential

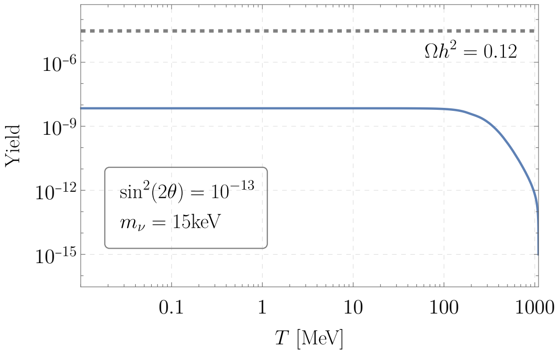
Active's distribution function

Sterile-sterile scattering processes

evolution controlled by

- effective in medium oscillation probabilities, i.e. term in brackets
- total interaction rate of neutrinos, Γ_t
- dark sector thermalization rate, C_s

Production from oscillations



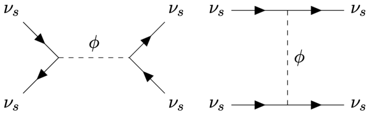
freeze-in type production

- no sterile neutrinos at high T
- most relevant production at $T \sim 200$ to 300 MeV
- yield constant below ~ 100 MeV

Simple modification ...

... with rich effects in sterile neutrino production

- large self-scattering rate for non-vanishing sterile neutrino population

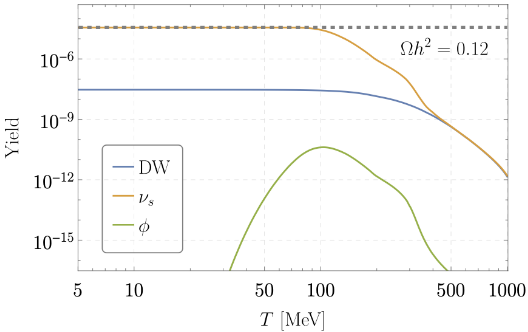


- heuristic: replace one of the initial states with SM neutrino via mixing

the more sterile neutrinos there are the more they scatter
$\Rightarrow$ self-accelerating production rate

Accelerated production

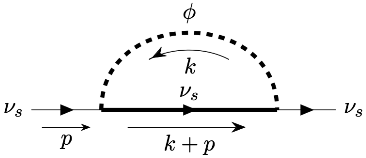
masses: $m_s = 12$ keV, $m_\phi = 1.5$ GeV
mixing $\sin^2(2\theta) = 5 \times 10^{-13}$ and coupling $y \approx 7 \times 10^{-2}$



- high T: DW production
- intermediate T: self-interaction pick up and pull in more stuff
- low T: production shuts of when ϕ becomes massive

... with rich effects in sterile neutrino production

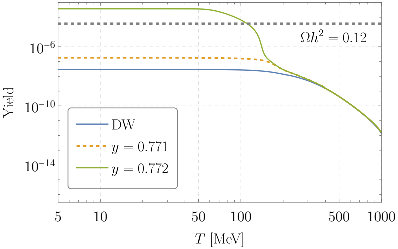
- new physics contribution to thermal potentials

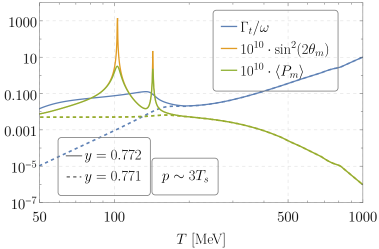


- cancelation in denominator of effective oscillation probability for heavy ϕ and large enough y

$\Rightarrow$ resonant enhancement of the production rate (similar to MSW resonance)

Resonance for large m_ϕ

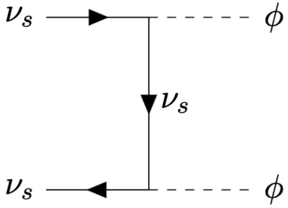




large jump in relic density for very small change in coupling
⇒ highly tuned, typically either too little or too much DM for large m_ϕ

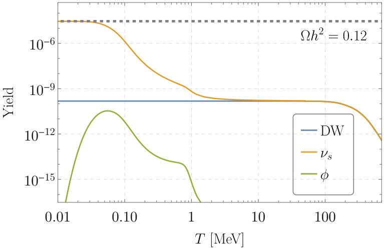
... with rich effects in sterile neutrino production

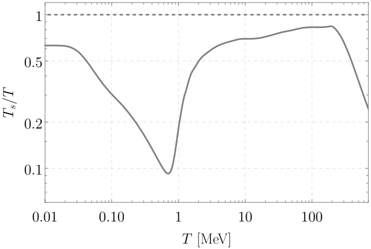
- number changing processes in the sterile neutrino sector



$\Rightarrow$ allows for additional DM production and independent evolution of dark sector temperature

Thermalization



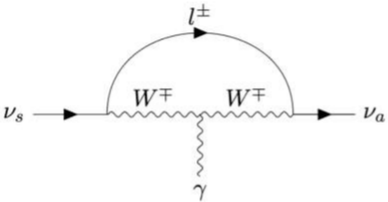


- thermalization leads to a significant decrease in the dark sector temperature early on
- more neutrinos pulled in via self-scattering later

Can this be tested?

Dark matter decay

- sterile neutrinos can decay via their mixing
- dominant mode: 3 neutrinos (not observable)
- loop induced decay to photon and neutrino: rate suppressed by factor ≈ 100 but mono-energetic photon in final state



- constrains from X-ray satellites exclude lifetimes orders of magnitude longer than the age of the Universe

Warm dark matter 101

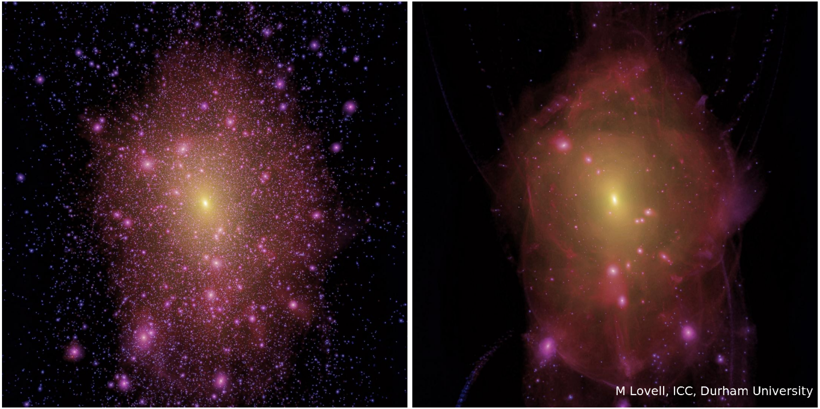
sterile neutrinos are produce late with a large temperature $\Rightarrow$ warm dark matter

- free streaming erases structures smaller than distance traveled since production

$$\lambda_{FS} = \int_1^{a_{prod}} da \frac{v(a)}{H(a)}$$

- can compute λ_{FS} if T is known
- structures on scales smaller than λ_{FS} are not expected since DM can free-stream out of primordial perturbations

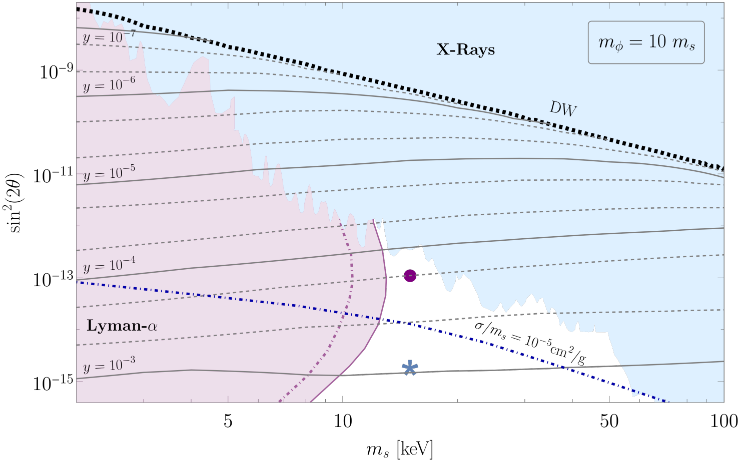
Warm dark matter



- free streaming length of DM sets scale for suppression of structure in the Universe
- with warm DM (i.e. too high velocities) many small structures are washed out

$\Rightarrow$ bound from observations of smallest structures, e.g. Lyman-α forest

Parameter space of sterile neutrino dark matter



- X-ray limits are avoided
- structure formation bounds get strengthened (late production compared to DW)

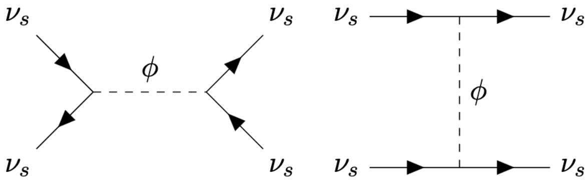
Where else could sterile neutrino interactions show up?

SM neutrino self-interactions

sterile neutrinos mix with active neutrinos

$$y_s \times \sin(\theta) \to y_a$$

with



$$\Rightarrow \sin(\theta)^2\sigma_s \to \sigma_a$$

sterile neutrino self-scattering implies active neutrino self-scattering

Can we test this?

- Not for the small mixing angles and couplings needed for sterile neutrino dark matter

but

- could be possible for larger mixing and coupling
- for simplicity: stay agnostic about origin of active neutrino self-interaction
- effective parametrization (needs UV completion such as mixing!)

$$\mathcal{L} = \frac{1}{2} \sum_{i,j} y_{ij} \nu_i \bar{\nu}_j \phi$$

Challenges:

- Where do we take the neutrinos from? (Source)
- Where can we get neutrinos to scatter on from? (Target)
- How do we detect that neutrinos scattered on neutrinos? (Detection)

Astrophysical neutrino point sources

Answer: neutrinos seen by IceCube

- Source: IceCube observes astrophysical neutrino sources
  first evidence for variable source in 2017, steady sources since 2022
- sources are very distant extragalactic objects
  $\Rightarrow$ Cosmic Neutrino Background (CνB) significant on these scales
- after interaction the neutrinos are scattered out of the line-of-sight
  $\Rightarrow$ non-detection of neutrinos from source

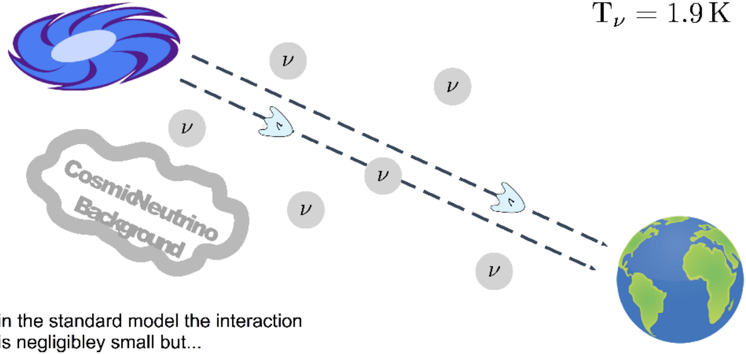
Source fact sheet

Two detected with high significance so far

- TXS 0506+056
  - high energy blazar
  - variable source
  - $\sim$ 100 TeV to $\sim$ 1 PeV neutrinos
  - very distant, $l_{TXS} \approx 1.2$ Gpc (or $z = 0.33$)
- NGC 1068
  - active galaxy
  - consistent with a non-variable source
  - $\sim$ 1 TeV to $\sim$ 10 TeV neutrinos
  - “relatively" close by $l_{NGC} = 14$ Mpc (negligible redshift)
- ... (to be detected)

Propagation from source to earth

$$n_{\rm tot} \approx 340\,{\rm cm}^{-3}$$
$$T_\nu = 1.9\,{\rm K}$$

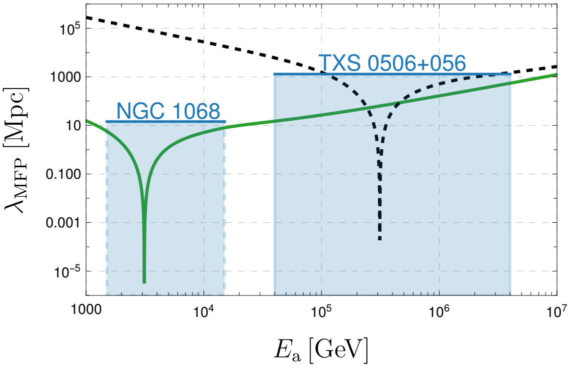


in the standard model the interaction
is negligibley small but...

figure courtesy of C. Doring

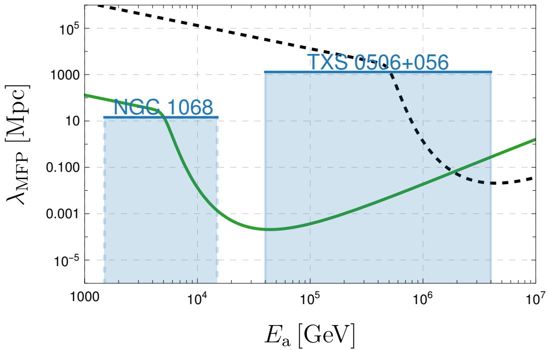
How do we quantify the effect?

Mean free path: case I



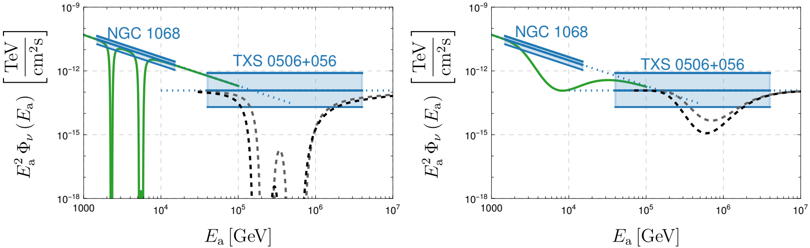
- at least two neutrinos have $T \ll m_i$ today
- scattering in fixed target configuration with $s = 2E_a m_i$
  $\Rightarrow \lambda_{MFP} \approx \frac{1}{\sigma(2E_a m_i)n_i}$
- large resonant enhancement for $E_a \approx m_\phi^2/2m_i$
- example: scattering on a single $m_i = 0.01$ eV neutrino with y= 0.05 for $m_\phi = 0.25$ MeV (green) and $m_\phi = 2.5$ MeV (black)

Mean free path: case II



- one neutrino state could still have $T \gg m_i$ today
- average over momentum of background neutrino needed $\Rightarrow$ resonance condition can be met in wide E_a range
- example: same as before but with $m_i \ll T$

Fluxes

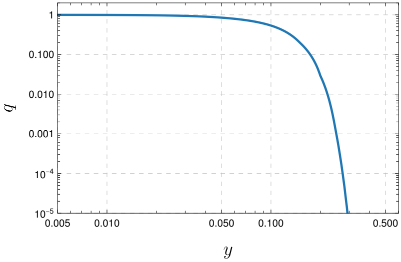


- astro: $\Phi_\nu(E_a) \propto E_a^{-\gamma}$
- here:

$$\Phi_\nu(E_a) \propto E_a^{-\gamma} \exp(-d/\lambda_{MFP})$$

- realistic picture requires taking all mass eigenstates into account
- for distant sources redshift effect appear
  $\Rightarrow$ broadens absorption region

Average extinction



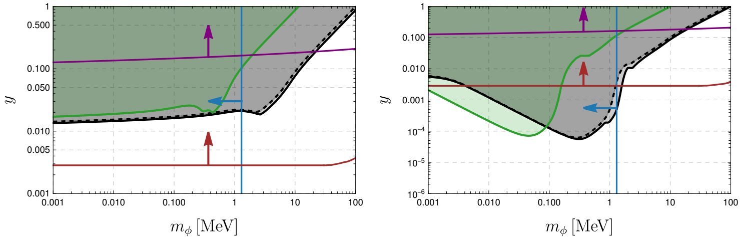
measure for the average effect

$$q = \frac{n}{n_0} = \frac{\int_{E_{\min}}^{E_{\max}} \mathrm{d}E\, A_{\mathrm{eff}}(E)\, \Phi_0(E)\, \exp(-\tau(E))}{\int_{E_{\min}}^{E_{\max}} \mathrm{d}E\, A_{\mathrm{eff}}(E)\, \Phi_0(E)}$$

- strong dependence on y for $q \gtrsim 0.5$
- order one distortion of spectrum measurable see J. Hyde 2307.02361

$\Rightarrow$ assume $q < 0.5$ excluded

Limits

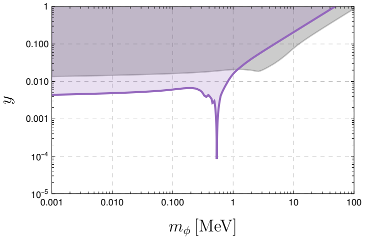


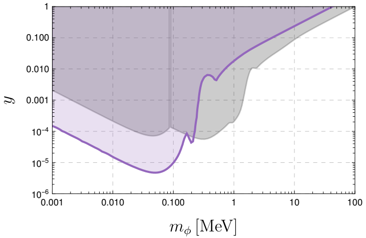
- limits for massive neutrinos dominated by TXS 0506+056
- low mass limits more stringent for massless lightest neutrino
- however, $m_\phi \lesssim 1$ MeV disfavored by cosmology (N_{eff})
- comparison with terrestrial experiments
  - point sources outperform limit on interactions with ν_τ (purple) for $m_\phi \lesssim 10$ MeV
  - low mass limits for massless case even better than terrestrial ν_μ (brown) limits

A bit of speculation: PKS 1424+240

- most significant (3.7 σ locally) source apart from TXS 0506+056 and NGC 1068
- spectral slope similar for NGC 1068, i.e. excess observed mostly in $\sim$ 10 TeV neutrinos
- very far away source, $z = 0.6$ (even more distant than TXS 0505+056)

Potential limits from PKS 1424+240





- significant improvement over NGC throughout the parameter space
- y as low of 10^{-5} in reach
- redshift effect significant $\rightarrow$ downward spike from redshift broadening of energy range that allows for resonant enhancement of scattering

Conclusions

- new interactions of sterile (and active) neutrinos are an interesting possibility
- allows for large boost of keV sterile neutrinos production in early Universe
- new parameter space of sterile neutrino dark matter
- can enable neutrino self-scattering
- testable with astrophysical neutrinos seen by IceCube
- exciting opportunities for novel BSM searches in the era of multi-messenger astronomy