Sterile Neutrinos in Cosmology and Astrophysics

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◇ **Particle Physics**

Neutrino Oscillation experiments: neutrinos have mass

◇ **Cosmology and Astrophysics** Plenty of unexplained phenomena

Dark Matter
Pulsar Kicks
Supernova explotions
Matter-Antimatter Asymmetry

Can these issues be attacked on the same ground?

Neutrino masses

The discovery of neutrino masses suggests the existence of right-handed, called *sterile*, neutrinos. The neutrino sector is extended to include:

$$\{\nu_e,\ \nu_\mu,\ \nu_\tau,\ N_1,\ N_2,\ N_3, ...\}$$

The SM Lagrangian is extended to include the new states:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N}_a i \partial\!\!\!/ N_a - y_{\alpha a} \varepsilon^{ij} H_i (\bar{L}_\alpha)_j N_a - \frac{M_a}{2} \bar{N}_a^c N_a + h.c.$$

The neutrino mass mixing matrix becomes:

$$\widetilde{M} = \begin{pmatrix} 0 & D_{3\times N} \\ D^T_{N\times 3} & M_{N\times N} \end{pmatrix}$$

where $D_{3\times N} \sim y\langle H\rangle$ are the Dirac masses
and $M_{N\times N}$ are the Majorana masses of sterile states .

What can experiments and theoretical considerations tell us about sterile neutrinos?

- How many are there?
- What is the scale of their Majorana masses?

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  experiment: **at least 1**

- What is the scale of their Majorana masses?

Seesaw Mechanism and Yukawa couplings

$$\widetilde{M} = \begin{pmatrix} 0 & D \\ D^T & M \end{pmatrix}$$

The eigenvalues of this matrix are:

$$-D^2/M \qquad \text{and} \qquad M$$

In the Standard Model, the matrix D arises from the Higgs mechanism:

$$D_{\alpha a} = y_{\alpha a} \langle H \rangle$$

The smallness of neutrino masses

$$m_\nu \sim y \langle H \rangle \left(\frac{y \langle H \rangle}{M} \right)$$

can be explained by either:

- small Yukawa couplings $y \ll 1$
- **Large** M and $y \sim 1$

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Is $y \sim 1$ better than $y \ll 1$?

Depends on the model:

- If $y \approx$ some intersection number in string theory, then $y \sim 1$ is natural.
- If y comes from wave function overlap of fermions living on different branes in a model with extra-dimensions, then it can be exponentially suppressed, hence, $y \ll 1$ is natural.

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In the absence of theory of the Yukawa couplings, **consider all allowed values for the sterile neutrino masses.**

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  experiment: **at least 1**

- What is the scale of their Majorana masses?

  lack-of-theory + *experiment*: **anything**

What are the cosmological consequences of such particles?

Light sterile neutrino as a Dark Matter candidate

Heavy sterile neutrinos produced in supernovae

Dark Matter

A sterile neutrino of mass $\sim$ keV can be Dark Matter

A good candidate because:

- it is a plausible explanation of **neutrino masses**
- if it is sufficiently light (sub-MeV), it is **stable**
- it constitutes **Warm Dark Matter**, of variable "warmth", depending on the production mechanism

Other hints in favor of such a particle:

- **Pulsar kicks**
- **Star Formation**
- **Matter - Antimatter asymmetry**

$\hookrightarrow$ *Investigate production mechanisms and cosmological properties*

CDM vs WDM

In **large scales**, both CDM and WDM are in complete **agreement** with observations.

In **small scales**, CDM predictions do not match observations:

- **overprediction of satellite galaxies**
- **prediction of central cusps rather than cores**

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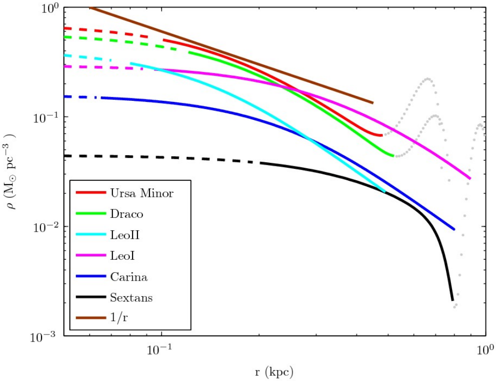

[Gilmore et al. (2007)]

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Quantitatively:

- **free-streaming length**: cutoff scale of the power spectrum of density perturbations; observationally inferred from **Lyman-α forest**

$$\lambda_{FS}(z) \approx 13\ \mathrm{kpc}\ \sqrt{1+z}\left(\frac{\mathrm{keV}}{m_X}\right)\left(\frac{\langle p^{-2}\rangle^{-\frac{1}{2}}}{1.61\,T}\right)\left(\frac{0.2}{\Omega_X}\right)^{\frac{1}{2}}$$

- **phase-space density**: entropy content; observationally inferred from **Dwarf Spheroidal Galaxies**

$$Q \equiv \varrho \bigg/ \left\langle \frac{p^2}{m^2} \right\rangle^{\frac{3}{2}}$$

Production Mechanisms

Sterile neutrinos can be produced in the early universe through:

◇ **Oscillations**

- off-resonance, at $T_{\text{prod}} \simeq 130\,\text{MeV}$; thermal spectrum [Dodelson, Widrow]
- on-resonance*, at $T_{\text{prod}} \simeq 150\,\text{MeV}$; non-thermal spectrum [Fuller, Shi]
  *if there is large lepton asymmetry
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- **Decays**
  - inflaton decays into sterile neutrinos [Shaposhnikov, Tkachev]
  - **Higgs decays, at the electroweak scale** [Kusenko, KP]

The Majorana Masses

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{N}_a i \partial\!\!\!/ N_a - y_{\alpha a} \varepsilon^{ij} H_i (\bar{L}_\alpha)_j N_a - \frac{M_a}{2} \bar{N}_a^c N_a + h.c.$$

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Can the Majorana masses of sterile neutrinos arise in the same way?

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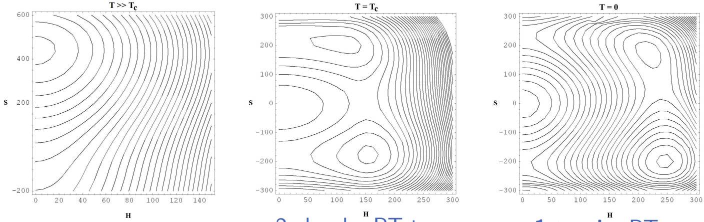
The singlet Higgs couples to the SM Higgs through a scalar potential:

$$V(H,S) = -\mu_{\rm H}^2 |H|^2 + \lambda_{\rm H} |H|^4 - \frac{1}{2}\mu_{\rm S}^2 S^2 + \frac{1}{4}\lambda_{\rm S} S^4 + 2\lambda_{\rm HS} |H|^2 S^2 + \frac{1}{6}\alpha S^3 + \omega |H|^2 S$$

If the parameters of the potential are such that $\langle S \rangle \sim 10^2 \mathrm{GeV}$, then the singlet Higgs will take part in the **EWPT**.

The Electroweak Phase Transition

The presence of the singlet Higgs changes the nature of the EWPT



$S \neq 0, \;\; H = 0$

2nd order PT to $H \neq 0$

1st order PT to the true vacuum

It is possible that the singlet Higgs will be discovered at the LHC
[Profumo, Ramsey-Musolf, G. Shaughnessy (2007); Barger et al. (2008)]

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The singlet Higgs couples to the SM Higgs and takes part in the **EWPT**:

$$V(H,S) = -\mu_{\rm H}^2 |H|^2 + \lambda_{\rm H} |H|^4 - \frac{1}{2}\mu_{\rm S}^2 S^2 + \frac{1}{4}\lambda_{\rm S} S^4 + 2\lambda_{\rm HS} |H|^2 S^2 + \frac{1}{6}\alpha S^3 + \omega |H|^2 S$$

Majorana masses may arise, after spontaneous symmetry breakdown, from the coupling of sterile neutrinos to a **gauge-singlet Higgs**:

$$M = f \langle S \rangle$$

Sterile neutrinos are produced by decays of S bosons: $S \to NN$

Higgs singlet decays

$$\Omega_N \sim 0.2 \left(\frac{f}{10^{-8}} \right)^3 \left(\frac{\langle S \rangle}{m_S} \right) \left(\frac{33}{\xi} \right)$$

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Take $\langle S \rangle \approx m_S$, this sets $f \approx 10^{-8}$
(since $\Omega_N \propto f^3$, f not very sensitive to the changes of the other parameters)

For a sterile neutrino of mass $m_N \sim \text{keV}$ to constitute all of **dark matter**, the singlet Higgs VEV has to be:

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The ξ factor is important because it **redshifts** the sterile neutrinos and results in **colder dark matter**. This weakens the limits derived from the small-scale structure considerations [Kusenko (2006)].

Sterile neutrinos of $m_N \sim \mathbf{keV}$ are produced non-thermally from decays of a singlet Higgs. At production $T \sim 100\,\mathrm{GeV}$:

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As universe expands, relativistic species decouple, releasing entropy. Sterile neutrinos produced at the EW scale appear **redshifted** at later times:

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Chilling...

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Dark Matter candidate

ν-chill

Dark Matters

sterile neutrinos	free-streaming length ($z=0$) kpc	primordial phase-space density, in $\frac{\mathbf{M}_\odot/\mathbf{kpc}^3}{(\mathbf{km/s})^3}$
Warm DM via off-res. oscill.	$\mathbf{7}\left(\frac{\mathbf{30}}{g_d}\right)^{\frac{1}{3}}\left(\frac{\mathbf{keV}}{m}\right)$	$\mathbf{2}\cdot\mathbf{10^5}\left(\frac{m}{\mathbf{keV}}\right)^{\mathbf{3}}$
Cool DM via on-res. oscill. w. lepton asymm.	$\mathbf{1.7}\left(\frac{\mathbf{30}}{g_d}\right)^{\frac{1}{3}}\left(\frac{\mathbf{keV}}{m}\right)$	$\mathbf{3.2}\cdot\mathbf{10^7}\left(\frac{m}{\mathbf{keV}}\right)^{\mathbf{3}}$
ν-chill via Higgs decays at the EW scale	$\mathbf{2}\left(\frac{\mathbf{110}}{g_d}\right)^{\frac{1}{3}}\left(\frac{\mathbf{keV}}{m}\right)$	$\mathbf{2.4}\cdot\mathbf{10^5}\left(\frac{m}{\mathbf{keV}}\right)^{\mathbf{3}}$
observations		$Q \gtrsim \mathbf{10^4}-\mathbf{10^5}$ [Gilmore]

[Boyanovsky, Vega, Sanchez (2008); Boyanovsky (2008); KP (2008)]

Astrophysical Hints

- **Pulsar Kicks** [Kusenko, Segrè]

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Pulsars have large velocities $\langle v \rangle \approx 250 - 450$ km/s.

99% of the gravitational energy from the collapse of a supernova $\sim 10^{53}$ erg is emitted in neutrinos.

1% asymmetry in neutrino emission can explain pulsar velocities.

Urca processes produce neutrinos asymmetrically, in the presence of strong magnetic field inside the supernova:

$$p + e^- \rightleftharpoons n + \nu_e \quad \text{and} \quad n + e^+ \rightleftharpoons p + \bar{\nu}_e$$

but asymmetry is washed out as active neutrinos escape from the supernova.

If a **weaker interacting sterile neutrino** is produced in these processes, asymmetry in production will result in asymmetry in emission and give a **pulsar kick**.

Astrophysical Hints

- **Pulsar Kicks** [Kusenko, Segrè]

  from asymmetric emission of sterile neutrinos

- **Star Formation** [Biermann, Kusenko; Stasielak et al.]

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Molecular Hydrogen is necessary for star formation.

$$H + H \quad \rightarrow \quad H_2 + \gamma \quad - \text{ very slow!}$$

In the presence of ions the following reactions are faster:

$$\begin{aligned} H + H^+ \quad &\rightarrow \quad H_2^+ + \gamma \\ H + H_2^+ \quad &\rightarrow \quad H^+ + H_2 \end{aligned}$$

The **X-ray** photons produced by sterile neutrino decays ionize H.
H^+ catalyzes the formation of molecular hydrogen.

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- **Pulsar Kicks** [Kusenko, Segrè]

  from asymmetric emission of sterile neutrinos
- **Star Formation** [Biermann, Kusenko; Stasielak et al.]

  by speeding up H_2 formation
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Lepton asymmetry can be generated by:

Decays of heavy sterile neutrinos

Oscillations of lighter sterile neutrino states

Lepton number can then be converted into baryon number by sphalerons.

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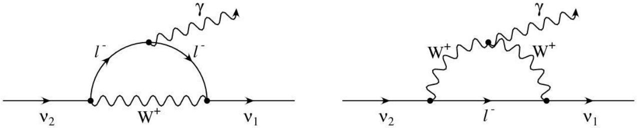
via leptogenesis

Radiative Decay and X-ray detection

Sterile neutrinos with $m \sim \mathbf{keV}$ have lifetimes longer than the age of the universe, but they do decay into **lighter neutrino states** and **photons**:



The rate of the radiative decay is:

$$\Gamma_{N\to\nu\gamma} \approx 1.4 \cdot 10^{-32} \left(\frac{\sin^2 2\theta}{10^{-10}}\right) \left(\frac{m_N}{1\ \mathrm{keV}}\right)^5 s^{-1}$$

Decay rate is very small, but large lumps of dark matter emit some X-rays. [Abazajian, Fuller, Tucker; Dolgov, Hansen; Shaposhnikov et al.]

Photon energy is $m/2 \Rightarrow$ **detection with X-ray telescopes**.

Suzaku observations of Dwarf Spheroidal Galaxies: Draco and Ursa Minor
[P. Biermann, A. Kusenko, M. Loewenstein]

Supernovae won't explode...

Simulations of core-collapse SN fail to reproduce the shock.

Problem is:

Gravitational energy $\sim 10^{53}$ **erg** initially **trapped in the core**.

At the bounce, **this energy is drained from the core** by active neutrinos.

The **stalled shock** needs only 1% of this energy, $\sim 10^{51}$ **erg**, to propagate successfully.

Energy transport from the core to the vicinity of the shock.
What are we missing?

it might be multi-dimensional hydrodynamic effects, or *new physics*

SN explosions from heavy sterile neutrino decay

A neutral particle, produced in the core, that will **decay inside the envelope**

- **increases the energy of the envelope**
- **melts nuclei in front of the shock**

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A neutral particle, produced in the core, that will **decay inside the envelope**

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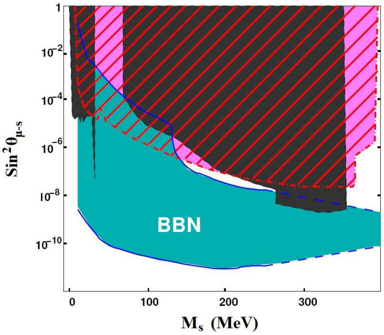
A heavy sterile neutrino could do !

- **produced in the core** from weak interactions
- small mixing means it's **not trapped**: it streams-out freely from the core
- heavy: carries out the right amount of energy $\mathbf{10^{51}}$ **erg**
- short-lived $\tau \sim 0.01 - 0.1$ s: it **decays in the vicinity of the shock**

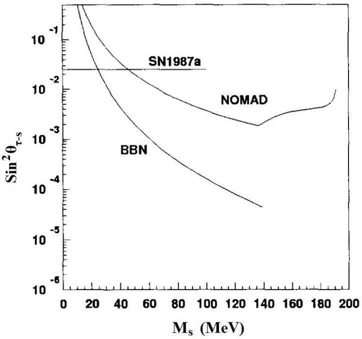
Limits

mixing with ν_μ



[Kusenko, Pascoli, Semikoz (2005)]

mixing with ν_τ



[Nédélec (2001)]

Limits from BBN may loosen under more careful consideration [Fuller, Kusenko, KP, Smith, in preparation].

Calculations show that

A sterile neutrino
$m_s \approx 145 - 250$ MeV
mixing with ν_μ or ν_τ by
$\sin^2\theta \approx 10^{-8} - 10^{-7}$

removes from a typical supernova core

$E_s \approx 10^{51} - 10^{52}$erg
within
1-5 s

Decay mode:

$$N_s \longrightarrow \nu_{\mu,\tau} + \pi^0 \longrightarrow \nu_{\mu,\tau} + 2\gamma$$

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- ◇ In **Core Collapse SN**, the decay products absorbed in the dense envelope, depositing energy that leads to a successful shock.
- ◇ In **Accretion-Induced Collapse SN**, there is no envelope

γ-ray bursts and the galactic positrons

Accretion Induced Collapse SN occur very rarely, but can give **observable signal** from heavy sterile neutrinos decays.

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- Sterile neutrinos decaying in the **baryon-poor** environment of an AIC SN, give $\sim \mathbf{50\ MeV}$ photons

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γ**-ray photons** produced will form a **relativistic fireball** that propagates in the interstellar medium, generating a **short GRB**.

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- Fireball also optically thick to **pair production**

  Positrons produced may account for the **511 keV line** observed in the Milky Way

[Fuller, Kusenko, KP, in preparation]

- **Sterile neutrinos** are introduced to explain the observed **neutrino masses**. The same particles can account for a lot of astrophysical phenomena.

- If one of them is light, $m_s \sim \mathbf{keV}$, it can be the **Dark Matter**.

  Different production mechanisms result in **"colder"** or **"warmer"** DM.

  $S \longrightarrow NN$ decays yield sufficient DM abundance that does not depend on the mixing angle and is in agreement with the small-scale structure.

  The same particle can explain the **pulsar velocities**, speed up the **star formation**, and account for the **matter-antimatter asymmetry**.

  Detection possible through **X-ray observations** of nearby galaxies.

- Heavy sterile neutrinos, $m_s \sim \mathbf{200\ MeV}$, produced in supernovae cores, can **enhance SN explosions**, provide a mechanism for **GRBs** and explain the **511 keV line** of the galaxy.